

UNIVERSITA' DEGLI STUDI DELL'INSUBRIA

Dipartimento di Scienza ed Alta Tecnologia

Dottorato in Fisica e Astrofisica



Exploiting the potential of dual-readout calorimetry by introducing a silicon photomultiplier light sensing system

Advisors:

Prof. Massimo Caccia

Prof. Romualdo Santoro

Doctoral dissertation of:

Massimiliano Antonello

XXXII Cycle
2016/2019

Massimiliano Antonello

Exploiting the potential of dual-readout calorimetry by introducing a silicon photomultiplier light sensing system

Università degli Studi dell'Insubria

Dipartimento di Scienza ed Alta Tecnologia

Via Valleggio 11

22100 Como

Contents

1	Future e^+e^- colliders	13
1.1	Physics opportunities	14
1.1.1	Higgs studies	14
1.1.2	Electroweak precision measurements	17
1.1.3	Additional physics opportunities	21
1.2	Future leptonic colliders overview	22
1.3	Detectors constraints	28
1.4	CLD detector concept	31
1.5	IDEA Detector	32
2	Calorimetry in High Energy Physics	36
2.1	Physics of shower development	36
2.1.1	Electromagnetic showers	36
2.1.2	Hadronic showers	41
2.2	Energy resolution	44
2.2.1	Electromagnetic calorimeters	44
2.2.2	Hadronic calorimeters	47
3	Dual-readout calorimetry	52
3.1	Dual-readout working principle	53
3.2	The DREAM project	55
3.3	The RD52 project	59
3.3.1	Crystals studies	59
3.3.2	RD52 fibre calorimeter	61
3.3.3	Other results	67
3.4	The Silicon Photomultiplier based readout	70
4	Silicon Photomultipliers	72
4.1	Basic operation principles	72
4.1.1	Single photon avalanche diode	74
4.1.2	Electrical model	74
4.1.3	Single-Photon Time Resolution	76
4.1.4	Gain and amplitude	76
4.2	Photon Detection Efficiency	78

4.3	SiPM noise and secondary effects	82
4.3.1	Dark Count Rate	83
4.3.2	Optical Cross-Talk	84
4.3.3	After-Pulsing	86
4.3.4	Excess Noise Factor	87
4.4	Linearity and dynamic range	88
4.5	Application in particle physics	90
5	SiPM-based dual-readout prototype: system development and qualification	95
5.1	Beam test goals	95
5.2	SiPM system layout	96
5.2.1	Detectors	97
5.2.2	System readout	97
5.3	SiPM equalisation	102
5.4	Breakdown voltage measurement	104
5.5	Photon Detection Efficiency measurement	106
5.6	Sensor non-linearity correction and light distribution	107
6	Beam tests data analysis and results	110
6.1	Experimental set-up	110
6.2	Event selection	112
6.3	Fibre optical cross-talk	114
6.3.1	Direct measurement removing S fibres	114
6.3.2	Direct lab measurement with a LED source	115
6.3.3	Alternative measurement	117
6.4	Cherenkov signal light yield and linearity	119
6.5	Scintillation signal light yield and linearity	122
6.5.1	2017 beam test	123
6.5.2	2018 beam test	125
6.6	Impact on energy resolution	129
6.7	Dual-readout imaging capability	131
6.8	Calorimeter module simulation	135
7	IDEA dual-readout calorimeter full-simulation	140
7.1	4π calorimeter	141
7.1.1	Calorimeter geometry	141
7.1.2	Optical fibres	142
7.2	SiPM response simulation	144
7.3	Calorimeter characterisation	147
7.3.1	Calibration	147
7.3.2	Electromagnetic response	149
7.3.3	Hadronic response	150

7.4 Particle ID capability	153
8 Conclusions and Outlooks	161
8.1 Summary result and discussion	161
8.2 Readout system studies	163
8.3 2020 beam test	165
Bibliography	171

List of Figures

1.1	Schematic layout of the ILC at 250 GeV staged option [39].	23
1.2	Schematic layout of the CLIC complex at 380 GeV [43].	24
1.3	The FCC-ee layout with a zoomed view of the trajectories across interaction point PG. The e^+ and e^- rings are placed 1m outside the booster (green lines) in the arc and are horizontally separated by 30 cm. To reduce the synchrotron radiation at the IP, the beam trajectories toward the interaction points are straighter than the outgoing ones [8].	25
1.4	The CEPC layout and the location of the two straight sections used for physics and the two straight sections used for the superconducting RF cavities [9].	26
1.5	Baseline luminosities expected to be delivered (summed over all interaction points), as a function of the centre-of-mass energy at each of the four worldwide e^+e^- colliders [8].	27
1.6	W and Z separation in their hadronic decays with different jet energy resolutions: (a) $0\%/\sqrt{E}$, (b) $30\%/\sqrt{E}$ and (c) $60\%/\sqrt{E}$ [9].	30
1.7	The CLD concept detector. Left: end view cut through. Right: longitudinal cross section of the top right quadrant [9].	31
1.8	The structure of the IDEA detector and its overall dimensions.	33
2.1	(a) Fractional energy lost in lead by e^- and e^+ as a function of energy [60]. (b) Photon interaction cross section in lead as a function of energy [61].	37
2.2	(Distribution of the energy fraction deposited in the first 5 X_0 by 10 GeV e and γ showering in lead. Results of EGS4 simulations [62].	39
2.3	((a) The energy deposited as a function of depth for 1, 10, 100 and 1000 GeV e showers developing in copper. For an easiest comparison, the curves integrals have been normalized to the same value. (b) The radial distributions of the energy deposited by 10 GeV e showers in copper, at various depths. Results of EGS4 calculations [63].	39
2.4	Average energy fraction contained in a calorimeter with infinite transverse dimensions, as a function of the absorber thickness. (a) Results for showers induced by e at different energies in copper. (b) Results for 100 GeV e showers in different absorber materials. Results of EGS4 calculations [63].	40

2.5	Particle spectra produced in the hadronic cascade generated by 100 GeV p in lead. The ordinate represents the particle track length (in “lethargic” units) differential in $\log(E)$. Each curve integral provides the particle relative fluence. Based on Fluka calculations [64].	42
2.6	Average energy fraction contained in a calorimeter with infinite transverse dimensions, as a function of the absorber thickness [67].	43
2.7	Average energy fraction contained in an infinitely long cylinder of lead-based calorimeter, as a function of its radius, for π s of different energies [68].	43
2.8	(a) The $\langle f_{em} \rangle$ values as a function of energy, for showers developing in copper and lead. (b) The f_{em} distribution values measured for 150 GeV π -induced showers developing in lead. These values were measured as the energy contained in the central tower of the calorimeter. More details can be found in [65] for copper and [68] for lead.	48
2.9	Sketch of the signal per unit deposited energy distributions for em and non-em components of hadron showers for a generic sampling calorimeter. The distributions are normalised to the mips response. The average values of the blue and red distributions are the non-em (h) and the em (e) response, respectively [55].	48
3.1	The S-C diagram of the signals from a DR calorimeter for electrons, γ s, pions and protons of the same energy. The clustered around the straight (red) line that links the points whit $f_{em} = 0$ and $f_{em} = 1$ are hadron events. Protons and pions have different f_{em} distributions and are thus clustered differently around this line [73].	54
3.2	The DREAM calorimeter layout [91].	55
3.3	Signal distributions recorded for 100 GeV π^- by (a) scintillating and (b) Cherenkov fibres. (c) The $C - S$ scatter plot showing the correlation between both types of signals. The signals are expressed in the same units used to calibrate the calorimeter (em GeV) [91].	56
3.4	(a) The total Cherenkov signal distribution for 100 GeV π^- events and (b) the same distribution represented as a collection for 3 sub-samples selected on the basis of the measured f_{em} values [91].	57
3.5	(a) The average Cherenkov and (b) scintillation DREAM signals for 200 GeV “jets” as a function of f_{em} [91].	57
3.6	Average values of the S and C signals from muons traversing DREAM, as a function of the μ energy. Also shown is the difference between these signals. All values are expressed in units of GeV, after the calorimeter calibration with electrons [90].	58

3.7	Time structure of a typical signal from 50 GeV electrons shower measured in the BGO em calorimeter (equipped with a UV filter). The UV signals were used to measure the relative contributions of C (gate 1) and S (gate 2) light [94].	60
3.8	The structure of: the copper- based RD52 fibre calorimeter [99], DREAM [91] and SPACAL [77].	61
3.9	Comparison between (a, b) the em S and C response functions of the RD52 copper-fiber calorimeter [99] and (c, d) the original DREAM copper-fiber calorimeter [101], for 40 GeV electrons. The electron beam incidence angle with the fiber axis (θ , ϕ) was (1.5° , 1.0°) for RD52 and (3.0° , 2.0°) for DREAM.	62
3.10	The em energy resolution obtained with the RD52 copper-fiber calorimeter for the scintillation and Cherenkov signals, and for their combination [99].	63
3.11	(a) The total signal recorded fraction by the tower in which the particle entered. (b) The C/S ratio of the event. (c) The PMT signal starting time, measured with respect to an upstream trigger signal. (d) The ratio of the total integrated charge and the signal amplitude. Data obtained with 60 GeV electrons and pions beams [102].	64
3.12	Scintillation and Cherenkov signal distributions for 20 (a), 60 (c), and 100 (e) GeV π^- beam in the RD52 lead-fibre calorimeter. (b), (d), (f) are the signal distributions obtained using the dual-readout method, with $\chi = 0.45$ [104].	66
3.13	The RD52 lead-fiber calorimeter hadronic energy resolution for single pions. Shown are the results obtained for the C signals alone, and applying the DR method [103].	67
3.14	The S lateral shower profile of 100 GeV electron beam in the RD52 lead-fiber calorimeter [99].	68
3.15	Dependence of the PMT signal starting time (blue line) on the average depth (z) inside the calorimeter where the light is produced, together with the time of the particles to travel to z (green line) and the one it takes the light to travel from z to the PMT (red line) [102].	69
3.16	The DREAM S signals starting time measured distribution, produced by (a) 60 GeV electrons and (b) 60 GeV pions [102].	70
4.1	A picture of the SiPM structure and operating principle [108].	73
4.2	(a) Microphotograph of different cell size SiPM with MQR. (b) Hamamatsu SiPM of area of $1 \times 1 \text{ mm}^2$, $3 \times 3 \text{ mm}^2$ and $6 \times 6 \text{ mm}^2$ and arrays of 8×8 and 4×4 elements for a total active area of $24 \times 24 \text{ mm}^2$ and $12 \times 12 \text{ mm}^2$ [110].	73
4.3	A sketch of a SPAD doping structure and electric field in operation mode [111].	74
4.4	SPAD electrical model with a resistor (R_Q) as quenching element [111]. .	74
4.5	Time evolution of the current into a SPAD [111].	75

4.6	Single photon timing response of a $1 \times 1 \text{ mm}^2$ SiPM by FBK at $2 V_{Ov}$ for $\lambda = 425 \text{ nm}$ [115].	76
4.7	Response of Hamamatsu MPPC S10362-11-100C illuminated by a LED: the oscilloscope output. [117].	77
4.8	Response of Hamamatsu MPPC 13360-1350CS illuminated by a LED: the integrated and digitized signal. [117].	78
4.9	Sketch of the PDE on a blue sensitive device. The effect of each factor of Eq.4.2 is highlighted [111].	79
4.10	(a) SiPM active region of a $25 \mu\text{m}$ cell. (b) Metal Quench Resistor improves the FF [108].	80
4.11	Estimated internal QE vs the wavelength of incident photon for different effective epitaxial layer thickness. [112].	80
4.12	Electric field and trigger probability for n+/p and p+/n structures [111].	82
4.13	The different sources of DCR and their location in the structure of the SPAD [111].	83
4.14	Temperature dependence of the DCR [111].	83
4.15	Sketch of a prompt Cross-Talk event (pCT) [111].	84
4.16	Sketch of a delayed Cross-Talk (deCT) and External Cross-Talk (ExCT) events (redrawing from [111]).	85
4.17	DCR and OCT events frequency in the Hamamatsu S10931 SiPM with $50 \mu\text{m}$ pixel pitch. [112].	85
4.18	Sketch of the optically-induced after-pulsing [111].	86
4.19	Sketch of the different SiPM output noise signals [112].	87
4.20	The Compound Poisson distribution with mean value $\mu = 3$ (left) and $\mu = 15$ (right) and probability of OCT and AP detection $p = 0$ (Pure Poisson), 0.2 and 0.5 [108].	87
4.21	Effective fired cells as a function of the number of photons per pulse on the active SiPM surface (full and zoom) for Hamamatsu S10362-050C type, 250 ns gate length. The total number of cells is indicated by the straight black line on the left hand side. The wider spacing of the data points at larger values of t_{pulse} is due to the constant step size of V_{LED} [136]. . . .	90
4.22	Number of SiPMs (left) and the total sensor area (right) in detectors/experiments as a function of the year of first data taking [139].	91
5.1	Arrangement of the 64 optical fibres in the brass calorimeter absorber structure (left) [1] and the 2016 module front face with one S fibre lighted up from the rear end (right).	97
5.2	Left: PDE as a function of the V_{Ov} and of the gain for $50 \mu\text{m}$ and $25 \mu\text{m}$ cell size of S13615 $1 \times 1 \text{ mm}^2$ (at 450 nm). Right: PDE vs wavelength for the same series [110] (at $V_{Bk} + 3 \text{ V}$ for $50 \mu\text{m}$ and $V_{Bk} + 5 \text{ V}$ for $25 \mu\text{m}$). . . .	98

5.3	(a) 2016 readout board with only one layer for all the sensors coupled to S and C fibres. (b) 2017/18 readout board with two-tier structure: the C fibres are coupled to the SiPMs on the first plane (Top), while the S ones are guided through holes in the first plane and readout on the second (back) tier (Bottom). (c) Schematic of the 2017/18 calorimeter, with two arrays of SiPMs. Each fibre is connected to its own SiPM.	99
5.4	The delrin mechanical fibres support (right) and the 2 spacers (left) designed for the 2017/18 prototypes. Each side was equipped with an o-ring to provide an excellent light insulation between the PCB board layers hosting the SiPMs.	100
5.5	Comparison between the 2017 (left) and 2018 (right) mechanical supports.	100
5.6	The front-end electronics of the SiPM detectors. In the foreground, the 2017/18 two-tier boards hosting the sensors are shown. These are interfaced with the fibres, as shown in fig.5.3. In the background, the mother board is shown. This contains the amplifiers, the shapers and the sensor bias generator/control.	100
5.7	The digitised output signal of the AFE. The integration time was $1.8 \mu s$. . .	101
5.8	Example of the on-line system response to a light pulse in the qualification phase. The multi-photon spectra of 4 different sensors are shown.	101
5.9	Event display of the 64 SiPM matrix for a 10 GeV electron shower (a, b) and a muon (c) traversing the calorimeter.	102
5.10	Signal distributions of 2 SiPMs in response to light signals used for calibration purposes [1].	103
5.11	An example of a multi-Gaussian fit performed in the qualification phase to extract the Δ_{pp} value.	103
5.12	The Δ_{pp} vs V_{Bias} and the linear fit (red line) from which the V_{Bk} (green point) is extracted.	105
5.13	PDE as a function of the V_{Ov} . The blue points are the 21 measurements performed. The red points represent the two principal PDE values considered in the 2017 beam test analysis: $PDE = (25.00 \pm 0.05)\%$ and $PDE_{Low} = (2.01 \pm 0.06)\%$ (see the text).	107
5.14	Intensity distribution of the light coming out from a S fibre homogeneously illuminated by a LED, recorded by a 16-bit CCD camera. The green spots represents some inefficiencies of the fibre in the light propagation due to some cracks or internal scratches.	109
6.1	Schematic layout of the experimental set-up (not to size). Shown are the delayed wire chamber (DWC), the trigger counters (TC), the pre-shower detector (PSD), the DR calorimeter and the muon counter (μ) used in the beam test [1].	111
6.2	The signal distributions examples measured in the muon counter (left) and PSD (right) for 40 GeV and 10 GeV beam particles, respectively.	113

6.3	Left: The DWC data were used to extrapolate, at the calorimeter front face, the events entering in the central region. The blue points are all the electron events selected with the previous 3 cuts while the red ones are the events that pass also the DWC cut. Right: An event display that has passed all the cuts. The red square shows the possible hottest fibre positions. . . .	113
6.4	Experimental set-up for the optical cross-talk between fibres measurements. All the fibres but one were covered with several layers of lead tape and the light was focused on the tested fibre. The LED focuser was mounted on a micrometer system shown in figure.	115
6.5	Left: Fired cells distribution in the 64 sensors, resulting from the illumination of one scintillating fibre with a high light pulse (1456 pe). This distribution represents the average of about 100,000 events where the uncovered fibre ($[x,y] = [3,3]$) was illuminated. Right: The same image with a truncated z axis at 5 pe.	116
6.6	Scintillation (left) and Cherenkov (right) energy signal distributions for 100 GeV μ^+ measured in the (copper-based) DREAM calorimeter with PMT readout [90].	118
6.7	Scintillation (left) and Cherenkov (right) energy signal distributions for 125 GeV μ^+ measured in the 2017 calorimeter module.	119
6.8	The average number of Cherenkov photoelectrons measured per unit of deposited energy, as a function of the electron beam energy. These results were obtained in 2017 beam test for two different electron beam energy scans.	120
6.9	Event display of 40 GeV electron beam for: (a) the 2017 beam test module in which also the SiPMs coupled to the S fibres were biased at $+5.5 V_{Ov}$, (b) the same module but with S sensors biased at $+0.5 V_{Ov}$ and (c) the 2018 module in which a yellow filter was applied between the fibre tips and the sensors (at $+5.5 V_{Ov}$).	122
6.10	(a) The average number of S fired cells measured in the SiPMs divided by the electron beam energy, as a function of the electron energy. Results are shown separately for the hottest fiber (red) and for the sum of the signals measured by the other 31 scintillating fibers (blue). Right: The ratio of these two signals, as a function of the electron beam energy.	123
6.11	Left: The corrected average number of scintillating fired cells measured in the SiPMs divided by the electron beam energy, as a function of the electron energy. Results are shown separately for the hottest fiber (red) and for the sum of the signals measured by the other 31 scintillating fibers (blue). Right: The ratio of these two signals, as a function of the electron beam energy.	124
6.12	Transmittance curves for the three tested: WRATTEN 2 nr. 3 (blue), SILVESTRI nr. 16 (green) and WRATTEN 2 nr. 21 (red).	127

6.13	Left: The measured S spectrum (blue dashed), the WRATTEN nr.21 transmittance spectrum (red), the SiPM PDE curve (black dotted). Right: Zoom of the expected spectrum (black dashed) obtained by folding all the previous curves.	127
6.14	Left: The SiPM detected spectra at 1 m (blue) and 10 cm (red) respectively. Right: Zoom of the spectra obtained by considering the WRATTEN nr.21 filter transmittance.	128
6.15	The average number of scintillation photoelectrons measured per unit of deposited energy, as a function of the electron beam energy. These results were obtained in 2018 beam test applying the WRATTEN 2 nr. 21 filter between the fibre tips and the sensors. The blue points represent the S_{pe}/GeV measured considering all the 32 S fibres, while the red points represent the average value measured for the hottest fibre.	129
6.16	The stochastic term of the S channel alone (blue dotted), the C channel alone (red dashed) and the $C+S$ dual-readout method combination (black) as a function of the filter attenuation. The red points represent the beam test results obtained in 2018.	130
6.17	Event display for 10 GeV electrons. The green points represents the centres of the SiPMs coupled to the S fibres. The red point is the shower axis, calculated from eq.6.3. The radius from the centre of gravity with pitch of 1.2 mm are also plotted in green.	132
6.18	Left: The percentage of the total scintillation signal as a function of r for all the measured events. Right: The same plot, obtained for the Cherenkov channel.	132
6.19	Lateral profiles of em showers in the calorimeter module, measured separately with the C and the S signals.	133
6.20	Left: Radial profiles of em showers in the calorimeter module, measured separately with the C and the S signals. Right: The fraction of the shower energy deposited in a cylinder around the shower axis as a function of the radius of that cylinder, measured separately with the C and the S signals.	133
6.21	Superposition of three event displays of 10 GeV electrons entering the calorimeter very close to three different fibres. Shown are signals from S fibres only, C fibres are left white.	134
6.22	The average fraction of the shower energy deposited in the SiPM calorimeter, as a function of the impact point of the 10 GeV and 100 GeV electrons used for these GEANT4 simulations. Results are given for electrons that entered the calorimeter: (a) along the direction of the fibers (b) at an angle of 0.2° in both the horizontal and the vertical planes [1].	136

6.23	Event display of a simulated 50 GeV electron shower developing in an extended calorimeter structure of the type used in these tests. The figure shows the signals in the individual scintillating fibres. The white patches represent fibres in which no (measurable) energy was deposited. The fibres hosted in the area covered by the tested detectors are indicated in red. The vertical scale represents the energy deposited in the individual S fibre [1].	137
6.24	(a) Lateral profiles of em showers in the 2017 calorimeter module, measured separately with the C and the S signals. (b) The same lateral profiles simulated with GEANT4. (c) Fractional differences between the measured and simulated profiles [1].	137
7.1	Schematic view of the simulated 4π dual-readout calorimeter: the inner length of the barrel (orange) is 5 m long and has a radius of 2.5 m. The endcaps (blue) have an inner radius (at the front face) of about 0.25 m, guaranteeing an angular acceptance of less than 100 mrad.	141
7.2	Schematic view of a single slice of the calorimeter. For each half slice there are 75 different towers. On the bottom side a comparison (not to scale) between the dimensions of tower 40 (the biggest) and 75 (the smallest) is represented.	142
7.3	Example of fibres distribution in tower 75. The fibres with different length were inserted as soon as the geometry allowed a new fibre placement to keep the sampling fraction constant. The chess-board structure between the S (blue) and the C (red) fibres is also well represented.	143
7.4	A sketch of a calibration run for tower 45.	147
7.5	Left: the S light yields, expressed in Spe/GeV , detected in each tower. Right: the C light yields (Cpe/GeV) as a function of the tower number. The green lines represent their mean values and the blue bands the 2σ spread that corresponds to about $\pm 6\%$ for the S channel and $\pm 4\%$ for the C one. . . .	148
7.6	The ratio between the energy reconstructed by the calorimeter after the calibration process and the total energy deposited for the S channel (left) and for the C one (right), respectively. The green lines represent their mean values and the blue bands the 2σ spread.	148
7.7	(a) 20 GeV e^- energies reconstructed from S (x-axis) and C (y-axis) signals. (b) The respective scintillation signal distribution and the Cherenkov one (c).	149
7.8	The em energy resolutions from S , C and combined signals.	150
7.9	Distributions of the 60 GeV π^- energies reconstructed from the S signals (left) and C (right) signals.	151
7.10	Left: The f_{em} distributions for 60 GeV π^- s. Right: The $S/E-C/E$ diagram of the signals from the simulated DR calorimeter for 60 GeV π^- . They clustered around the straight (red) line that links the points whit $f_{em} = 0$ and $f_{em} = 1$. The f_{em} values are calculated from the Monte Carlo truth. .	151

7.11	The average C (left) and S (right) signals for 60 GeV pions as a function of f_{em}	152
7.12	Left: distribution of 60 GeV π^- beam energy, reconstructed by the dual-readout method. Right: The hadronic energy resolution obtained from the DR method.	153
7.13	Distributions of the C/S signal ratio. (a-d) From the hit tower for electrons and pions showering in the lead RD52 calorimeter. (b-e) From the total hit fibres in the lead IDEA calorimeter. (c-f) From the total hit fibres in the copper IDEA calorimeter. Data for 20 GeV (first column) and 60 GeV (second column) beam particles. Figure (a) and (d) are taken from [102] and represent the distribution of real beam test data.	155
7.14	(a-d) Distribution of the energy fraction deposited in the hit tower by electrons and pions showering in the RD52 calorimeter (from [102]). (b-e) Distribution of the radius at which the 95% of the total beam energy is deposited for the lead-based IDEA calorimeter and for the copper-based one (c-f). Data for 20 GeV (first column) and 60 GeV (second column) beam particles. Figure (a) and (d) are taken from [102] and represent the distribution of real beam test data.	156
7.15	(a-c) Distribution of the SiPM signal starting time for the lead-based IDEA calorimeter and for the copper-based one (b-d). Data for 20 GeV (top row) and 60 GeV (bottom row) beam particles.	158
7.16	Values of electron ID (red points) and π^- mis-ID (blue ones) as a function of the threshold cut performed for the C/S variable of the lead-based IDEA calorimeter. Data for 20 GeV (left) and 60 GeV (right).	159
7.17	Scatter plot of the 20,000 combined e^- (red points) and π^- (blue points) events as a function of the three discriminant variable described above. Data from the 60 GeV energy beams in the lead-based IDEA calorimeter. The correlations have been calculated for each pair of variables and are listed below for e^- and π^- , respectively. C/S vs R_{95} : 5% and 60%; C/S vs t_{start} : 31% and 23%; R_{95} vs t_{start} : 7% and 9%.	160
8.1	Multi-photon spectrum of 1 SiPM (red curve) and 9 SiPMs (blue curve) grouped together [3].	163
8.2	The Citiroc 1A block scheme.	164
8.3	The new prototype scheme, based on 2880 tubes.	165
8.4	Multi-photon spectrum of the tested Hamamatsu S14160-1310PS. The sensor was operated with $V_{Ov} = +4.5$ V and the signal was amplified with 40 dB gain.	166

List of Tables

1.1	Comparison between the expected precisions, determined in the k framework, of the H coupling and total decay width of HL-LHC, ILC, CLIC, CEPC and FCC-ee, respectively exploring the 240-380 GeV centre-of-mass energy range. All numbers indicate sensitivities of 68% CL, while the last line provides the 95% CL on the “exotic” branching fraction, accounting for final states that cannot be tagged as SM decays. For HL-LHC projections the BR for $c\bar{c}$ and exotic particles are set to their values in the SM. The last two columns include the additional FCC-ee fit obtained considering also the 1.5 ab^{-1} at $\sqrt{s} = 365$ GeV and the combined fit result with the HL-LHC data, respectively [14].	15
1.2	Measurement of EWPOs at FCC-ee, with their present precisions and the expected FCC-ee statistical and systematic uncertainties [14].	18
1.3	Parameters of the different future leptonic colliders (Status: December 2018) for the ZH production centre-of-beam energy [41].	28
1.4	Physics processes and key measurands and performance requirements used as benchmarks in future experiments as CEPC and FCC.	31
1.5	Comparison of the most important parameters of CLIC and CLD detector concepts.	32
1.6	The most important parameters of IDEA concept detector.	33
5.1	Main parameters of the adopted SiPMs. The listed peak sensitivities of 40% and 25% were obtained for the mentioned operating voltage, and a wavelength of 450 nm. The breakdown voltage was determined by measuring the gain-voltage dependence. Even though this is not the unique definition, it is possibly the relevant quantity for the user [157].	98
7.1	Main simulated properties of the S and C fibres adopted in the beam tests.	143
7.2	The chosen simulation parameters to properly reproduce the SiPM-based DR calorimeter waveform events.	146
7.3	Comparison between the electron ID and pions mis-ID probabilities extracted from the RD52 module and the simulated lead-based and copper-based IDEA calorimeters.	159

Introduction

After 10 years of physics at the Large Hadron Collider (LHC), the high energy particle physics has greatly evolved: the Higgs boson has been discovered and it requires new detailed studies about its properties, aiming a deeper understanding of the electroweak symmetry breaking nature. The next new big collider will be probably an e^+e^- machine. Four different options are currently proposed: two linear colliders have been studied by the International Linear Collider (ILC) and the Compact Linear Collider (CLIC) Collaborations, while two circular ones have been more recently investigated by the Future Circular Collider (FCC) and the Circular Electron Positron Collider (CEPC) study groups. Detector requirements at these future colliders are dictated by the precision physics program envisaged. On the calorimetry side, the next generation of calorimeters has to provide extreme precision in reconstructing energies of both isolated particles and jets springing off the colliding beams. Unfortunately, the fluctuation of the electromagnetic fraction (f_{em}) of the deposited energy is intrinsic to hadronic showers and affects the energy resolution of the non-compensating calorimeters. The dual-readout (DR) method addresses this issue reconstructing f_{em} event-by-event by the simultaneous measurement of the scintillation (S) and the Cherenkov (C) light produced by the shower particles. Over the last 15 years, the DREAM/RD52 collaborations have tested DR fibre calorimeters based on photomultiplier (PMT) readout. A DR calorimeter was chosen by the Innovative Detector for Electron-positron Accelerator (IDEA) concept, that is one of the two baseline detector concepts for FCC-ee and an option for CEPC. Therefore, in order to make this technology applicable to future e^+e^- colliders, in 2016 it was decided to continue the R&D phase, replacing that readout with a system based on SiPMs. The main activity of this Ph.D. work was focused both on the design, production, commissioning and characterisation of these dual-readout calorimeter prototypes in three dedicated beam tests at CERN (2016/17/18) and on their data analysis [1, 2, 3, 4, 5, 6]. Moreover, the optimisation of the design is naturally connected to the system response and it can be performed in an efficient and effective way relying on Monte Carlo simulation. The main contribution in this design was the implementation of a GEANT4 fully projective 4π geometry of a dual-readout calorimeter for IDEA [7], together with the preliminary studies about the particle ID achievable. Part of these measurements and results are also present in both the FCC [8] and CePC [9] Conceptual Design Reports.

In chapter 1, a comparison between the four main future e^+e^- collider projects, together with an overview of the physics case and of the detector requirements is provided. Moreover two possible detector concept solutions: CLD and IDEA, specifically designed for operation at these leptonic colliders, are presented. Chapter 2 describes the main properties of the modern calorimeters adopted in HEP and the physics behind both the electromagnetic and hadronic shower developments. Chapter 3 contains a detailed description of the dual-readout method, together with the results obtained by the related R&D projects (i.e. the DREAM and RD52 Collaborations). Chapter 4 ends the first part of the thesis with an overview of the main properties of the Silicon Photomultipliers (SiPMs), with the description of the most important SiPM parameters and with some examples of applications in particle physics detectors. The second part starts with chapter 5, that reports the description of the prototype layouts, the adopted readout scheme and the measurements performed in the qualification phase. Chapter 6 contains all the beam tests data analysis results (also presented in both the FCC [8] and CePC [9] Conceptual Design Reports). In chapter 7 the implementation of a GEANT4 fully projective 4π geometry of a dual-readout calorimeter in the IDEA framework is presented, together with the preliminary studies about the particle ID achievable. Finally, chapter 8 includes a discussion of the results, the description of the preliminary tests done about the possibility to sum up the analogue output of more than one sensor and the future R&D working plan.

Future e^+e^- colliders

” *There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.*

The European Strategy for Particle Physics Update (2013)

In 2012, the Higgs boson (H) discovery by the [ATLAS](#) and [CMS](#) Collaborations [10, 11] at the [LHC](#) opened a new era in which it will not be only the object of a search but it will become the tool for the new particle physics studies. The Higgs boson is the corner stone of the Standard Model ([SM](#)) and it is directly related to the new questions of modern particle physics like the nature of the Electroweak ([EW](#)) phase transition, the deep origin of the Electroweak Symmetry Breaking ([EWSB](#)) or the "Hierarchy Problem" between the Planck and weak scales. Thanks to its relatively low mass, the Higgs boson can be produced in a clean environment as a new e^+e^- collider one, with high luminosity. Precise measurements of its properties, together with those of the Z and W bosons, will provide important tests of the SM fundamental physics principles and will be essential for the physics Beyond the Standard Model ([BSM](#)) studies. Moreover, the high statistics measurement programme goes far beyond precision Higgs ones: the observation of lepton-flavour-violating decays or flavour changing neutral currents, or the precise measurements of the H and Z invisible decay widths, or the direct observation of particles with extremely weak couplings, are expected to provide signals of new physics. This program will be the most important component of the particle physics road map in the coming decades. Today there are 4 different leptonic collider designs proposed to perform this program: (i) the [ILC](#), in Japan, focused on H studies with a 250 GeV centre-of-mass energy [12]; (ii) the [CLIC](#), at CERN, whose lowest $\sqrt{s}$ point was reduced from 500 to 380 GeV, in order to better study both the H and the t quark [13]; (iii) the [CEPC](#), in China, with a centre-of-mass energy range from 90 up to 250 GeV and born to perform precision measurements on the Z , W , and H bosons [9]; (iv) the Future Circular Collider ([FCC-ee](#), formerly called TLEP), at CERN, which can study the entire EW sector with $\sqrt{s}$ values between 88 and 365 GeV [8]. In this first chapter, after a brief overview of the physics case and a short comparison between these proposed future leptonic colliders, the detector requirements will be analysed, together with the main possible detector concept solution adopted to realise the colliders full physics potential. Finally, the Innovative Detector for Electron-positron Accelerator ([IDEA](#)) concept, specifically

designed for operation at future leptonic circular colliders as FCC-ee or CEPC, will be presented in detail.

1.1 Physics opportunities

This section summarises the principal and common physics measurement goals expected to be reached by the next leptonic colliders generation. The detailed overviews of the physics potential reachable by each one of these colliders are available in the respective Conceptual (or Technical) Design Reports [12, 13, 9, 14]. The majority of the examples and details about the expected performances described in this section refers to FCC-ee. This choice was done both because it is the collider with the largest physics program (thanks to its large spread of available centre-of-mass energies) and since IDEA is one of its two baseline detector concepts.

1.1.1 Higgs studies

After the Higgs boson discovery, LHC provided different studies of its couplings and properties, confirming the expectations of the SM at the 10-20% level. Moreover, significant improvements are expected from the High-Luminosity Large Hadron Collider (HL-LHC) phase, that will reach, in many cases, a few percent precision, where a 5% deviation from the SM could exhibit BSM scales in the 1 TeV range [15]. Achieving a model-independent Higgs boson width and couplings measurements with a sub-percent precision is one of the main goals of the new leptonic collider experimental programmes. This accuracy is required to access (and maybe exceed) the 10 TeV energy scale. Finally, the expected precise measurements, together with the capability in detecting invisible Higgs decays, will give a strong push to the new physics scenarios research, also due to the expected high sensitivity to exotic decay channels (which at the LHC are precluded by backgrounds).

Model-independent coupling determination

The total Higgs production cross section will be mainly measured from its presence as a recoil to the Z in the Higgsstrahlung ($e^+e^- \rightarrow HZ$) process, allowing the absolute H coupling to Z measurement (without the need to tag its decay products as done in LHC). In more detail, the total cross section will be determined independently of the H boson decay, by counting the Higgsstrahlung events characterised by a leptonic decay: $Z \rightarrow l^+l^-$. Thanks to the precise lepton momenta measurement and applying the total energy-momentum conservation, the recoiling system mass (at a centre-of-mass energy of 240 GeV) can be calculated as:

$$m_{Recoil}^2 = s + m_Z^2 - 2\sqrt{s}(E_{l^+} + E_{l^-}). \quad (1.1)$$

Since the HZ events have their recoil mass equal to the H boson one, they can be easily counted from the accumulation around m_H , allowing the HZ cross section (σ_{HZ}) determination and thus providing a powerful testing tool, at the loop level, of the H SM predictions. This method disentangled the H production from its decay, providing a model-independent determination of its total width and its other couplings through branching ratio measurements with a sub-percent precision (about a factor ten better than HL-LHC) [9]. Indeed, the number of HZ events where H decays in two Z bosons is proportional to $\sigma_{HZ} \times \Gamma(H \rightarrow ZZ)/\Gamma_H$ and thus, under the hypothesis that the SM coupling structure formalism is valid also for the H [14], to the Higgs boson coupling to the Z : g_{HZZ}^4/Γ_H . The g_{HZZ} measurements allow the extraction of the total width Γ_H . Similarly, the number of events in which the Higgs boson decays into W^+W^- , $c\bar{c}$, $b\bar{b}$, gg , $\tau^+\tau^-$, $\mu^+\mu^-$, $\gamma\gamma$, $Z\gamma$ or through invisible decays, are proportional to $\sigma_{HZ} \times \Gamma(H \rightarrow XX)/\Gamma_H$. The H couplings and its width are then determined with a global fit (more details can be found in [16]). Table 1.1 summarises the final expected fit results, comparing the HL-LHC projections [15] with the ones obtained from the other leptonic colliders [17, 18] scanning from 240 up to 380 GeV centre-of-mass energy range. Since the model dependence

Collider	HL-LHC	ILC ₂₅₀	CLIC ₃₈₀	CEPC ₂₅₀	FCC-ee ₂₄₀	FCC-ee ₊₃₆₅	
Lumi (ab ⁻¹)	3	2	1	5	5 ₂₄₀	+1.5 ₃₆₅	+HL-LHC
Years	25	15	8	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	2.8	2.7	1.3	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.25	0.2	0.17	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.4	1.3	0.43	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.3	1.3	0.61	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.2	1.7	1.21	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	1.5	1.6	1.01	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.5	1.4	0.74	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	8.7	10.1	9.0	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	3.7	4.8	3.9	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.5	–	–	–	–	–	3.1
BR _{EXO} (%)	SM	<1.7	<2.1	<1.2	<1.2	<1.0	<1.0

Tab. 1.1: Comparison between the expected precisions, determined in the k framework, of the H coupling and total decay width of HL-LHC, ILC, CLIC, CEPC and FCC-ee, respectively exploring the 240-380 GeV centre-of-mass energy range. All numbers indicate sensitivities of 68% CL, while the last line provides the 95% CL on the “exotic” branching fraction, accounting for final states that cannot be tagged as SM decays. For HL-LHC projections the BR for $c\bar{c}$ and exotic particles are set to their values in the SM. The last two columns include the additional FCC-ee fit obtained considering also the 1.5 ab⁻¹ at $\sqrt{s} = 365$ GeV and the combined fit result with the HL-LHC data, respectively [14].

will be removed, a complementary program based on hadron future colliders (e.g. FCC-hh or FCC-eh) will be able to complete the H properties picture [14].

The Yukawa coupling

Unfortunately, the H couplings to the first SM family particles (i.e. e , u and d) will not be directly measurable at these colliders since their masses, and thus their related decay branching ratios, are too small to be observed within the total number (about 10^6) of available events. Nevertheless, running at beam energies next to the H pole mass ($\sqrt{s} \sim 125.09$ GeV), they can contribute to set stringent upper limits to the electron Yukawa coupling (2.5 times the SM values) via the resonant H production [19]. Also the t Yukawa and the H self couplings will not be directly measurable because their masses are too large for a kinematically open decay. Indeed, bounds on both these two couplings are usually extracted from $t\bar{t}H$ and HH production cross section measurements, requiring energies higher than the ones reachable by these leptonic colliders. Only FCC-ee, operating at $\sqrt{s} = 350$ GeV, will have access to the t Yukawa coupling through its effect on the $t\bar{t}$ cross section [8], achieving alone a precision of about 10%. Anyway, this coupling LHC precision ($\sim 20\%$ [20, 21]) will be already further improved at HL-LHC to $\pm 3.4\%$ (model dependent) and to $\pm 3.1\%$ when it will be combined with the FCC-ee data model-independent fit (tab.1.1). Once again, the precise lower energies measurements achievable by these e^+e^- colliders, will be fundamental to fix the strong coupling constant (α_s) value and thus to disentangle at the $t\bar{t}$ vertex the t Yukawa coupling effects from the QCD ones.

The Higgs self-coupling

For what concern the Higgs self-couplings, they are crucial in the H potential characterisation (directly related to the naturalness problem) and control the EW phase transition properties [22]. Moreover, significant deviations in the H self-couplings are predicted by several BSM models. These couplings are practically intangible at LHC, while HL-LHC will provide only a poorly constrain at $\mathcal{O}(1)$ accuracy level. A first step toward the trilinear Higgs coupling measurement should be provided by linear colliders as ILC, that is expected to reach a precision of about $\pm 30\%$ (after more than 20 years of operation at energies of 250 and 500 GeV) [23]. Another solution could be a circular collider like FCC-ee that, thanks to its high luminosity at 240 and 365 GeV, should guarantee the sensitivity to that coupling by the measurement of its centre-of-mass-energy-dependent effects on single H observables like the $\nu\bar{\nu}H$ and the HZ production cross sections [24], providing the possibility of a model-independent H coupling measurement with a final precision of about 32% [22]. At the energy frontier, only a future hadronic

collider as FCC-hh could reach a precision of the order of $\pm 5\%$.

CP studies

Finally, even if at LHC has been demonstrated that the Higgs boson spin-parity quantum numbers are consistent with $J^{PC} = 0^{++}$ [25, 26], a CP violation should manifest itself in the H interactions. In particular, new TeV scale physics could result in a small pseudoscalar contribution in the Higgs boson couplings to fermions. Thanks to the high number of $H \rightarrow \tau^+\tau^- \rightarrow \rho^+\rho^-\nu_\tau\bar{\nu}_\tau$ samples available at future leptonic colliders, the H CP properties can be investigated by the measurement of the CP $H\tau\tau$ coupling phase Δ . This phase determines the mixing angle between the pseudoscalar and scalar contribution: from the subsequent decays $\tau^\pm \rightarrow \rho^\pm\nu_\tau \rightarrow \pi^\pm\pi^0\nu_\tau$, the two charged pions relative orientation provides important information about Δ . From the fully reconstruction of the τ decays, the CP phase will be measured with about 10^0 precision [8].

1.1.2 Electroweak precision measurements

Through the SM it is possible to predict the mass values and the properties of the top and of the Z , W and H bosons. This prediction input comes from both theoretical calculations and precise measurements in the EW sector. As demonstrated by the discoveries that led to the SM consolidation, Electroweak Precision Observables (EWPOs) can establish the existence of new physics and guide its theoretical interpretation. In this sense, EWPOs measurements represent another important component of the future colliders physics program, complementary to the H properties mentioned above. Indeed, based on LEP experience and thanks to their huge statistics at different beam energies and their improved center-of-mass energy calibration (~ 100 keV), the future leptonic colliders will achieve a significant improvement in the precision (more than an order of magnitude with respect to LEP) and provide a broad set of EWPOs, giving access to many possible new physics sources. As example, table 1.2 summarises the most important EWPOs with the expected experimental precision at FCC-ee, compared to the present ones. Furthermore, because of the high statistics that will be available, it will be possible to perform ancillary measurements of the precision-limiting input parameters required by the precision EW calculation like the mass of the top (via the $t\bar{t}$ production threshold scan) or the QED running coupling constant at the Z mass (measurable from the $Z - \gamma$ interference), or the strong coupling constant (thanks to the Z , W and τ hadronic to leptonic branching fractions measurements). The importance of this program is highlighted by the SM fit to the precision measurements available to date [31]. The SM prediction about the mass of W boson and the effective weak mixing angle (i.e. $\sin^2\theta_W^{eff}$) [32],

Observable	Present value	Stat.	Syst.	Dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	5	100	From Z line shape scan beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	8	100	From Z line shape scan beam energy calibration
$R_l^Z (\times 10^3)$	$20,767 \pm 25$	0.06	0.2-1.0	Ratio of hadrons to leptons acceptance for leptons
$\alpha_S(m_Z) (\times 10^4)$	1196 ± 30	0.1	0.4-1.6	From R_l^Z above [27]
$R_b (\times 10^6)$	$216,290 \pm 660$	0.3	<60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [28]
$\sigma_{had}^0 (\times 10^3)$ (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement
$N_\nu (\times 10^3)$	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff} (\times 10^6)$	$231,480 \pm 160$	3	2-5	From $A_{FB}^{\mu\mu}$ at Z peak beam energy calibration
$1/\alpha_{QED}(m_Z) (\times 10^3)$	$128,952 \pm 14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak [29]
$A_{FB}^{b,0} (\times 10^4)$	992 ± 16	0.02	1-3	b -quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau} (\times 10^4)$	1498 ± 49	0.15	<2	τ polarisation and charge asymmetry τ decay physics
m_W (MeV)	$80,350 \pm 15$	0.5	0.3	From WW threshold scan beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan beam energy calibration
$\alpha_S(m_W) (\times 10^4)$	1170 ± 420	3	Small	From R_l^W [30]
$N_\nu (\times 10^3)$	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	$172,740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm 30\%$	0.5-1.5%	Small	From $E_{CM} = 365$ GeV run

Tab. 1.2: Measurement of EWPOs at FCC-ee, with their present precisions and the expected FCC-ee statistical and systematic uncertainties [14].

based both on the input parameters ($\alpha_{QED}(m_Z)$, $\alpha_S(m_Z)$, G_F , m_H , m_Z , m_{top}) and actual estimates of theoretical uncertainties, are in good agreement with their direct measurements mean values ($m_W = 80.379 \pm 0.012$ GeV and $\sin^2\theta_W^{eff} = 0.23153 \pm 0.00016$) but the uncertainties coming from the theoretical and parametric errors are comparable with the present experimental ones. This agreement between the measurements and the predictions highlights the fact that, if any, a possible new physics effect, must be smaller than the current uncertainties. The next goal is therefore the reduction of these uncertainties by

at least an order of magnitude.

The Z pole

In more detail, at Z pole, the future leptonic colliders will deliver about 2×10^5 times the LEP integrated luminosity and will reach EWPOs statistical uncertainty from few per mil to 10^{-5} (i.e. 300 times smaller). The $\sin^2 \theta_W^{eff}$ regulates the left and right-handed fermion couplings to the Z boson. Polarisation and forward-backward asymmetries can thus provide its measurement. Indeed, for unpolarised incoming beams, the Z polarisation at production is:

$$\mathcal{A}_e = \frac{g_{L,e}^2 - g_{R,e}^2}{g_{L,e}^2 + g_{R,e}^2} \frac{2v_e/a_e}{1 + (v_e/a_e)^2}, \text{ with } (v_e/a_e) \equiv 1 - 4\sin^2 \theta_W^{eff}. \quad (1.2)$$

The related forward-backward asymmetry is $A_{FB}^{ff} = \frac{3}{4} \mathcal{A}_e \mathcal{A}_f$ and, thanks to the available continuous measurements of the beam polarisation (needed for the beam energy calibration), each beam longitudinal polarisation experimental control can be performed with high accuracy. At beam energies around the Z pole, one of the most interesting processes for the A_{FB}^{ff} precise measurement is the $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ since, in this situation, $A_{FB}^{\mu\mu}$ shows a strongly dependence on $\sqrt{s}$:

$$A_{FB}^{\mu\mu}(s) \simeq \frac{3}{4} \mathcal{A}_e \mathcal{A}_\mu \times \left[1 + \frac{8\pi\sqrt{2}\alpha_{QED}(s)}{m_Z^2 G_F (1 - 4\sin^2 \theta_W^{eff})^2} \frac{s - m_Z^2}{2s} \right]. \quad (1.3)$$

This dependence is caused by the off-peak interference between the γ exchange and the Z boson. Continuously measuring (using the resonant depolarisation) the non-colliding bunch energies, it should be possible to reach an uncertainty of about 100 keV, corresponding to an $A_{FB}^{\mu\mu}$ error of 9×10^{-6} and to a final uncertainty on the effective weak mixing angle of 6×10^{-6} [14]. Moreover, thanks to its scatter angle dependence, the $\tau \rightarrow \pi\nu_\tau$ decay mode and the related τ polarisation asymmetry, will provide not only a similar accurate $\sin^2 \theta_W^{eff}$ determination, but also a separate measurement of both $\mathcal{A}_e$ and $\mathcal{A}_\tau$. Combining this two measurements with the relative leptonic partial width and the $A_{FB}^{\mu\mu}$ ones, it is possible to extract the axial and vector couplings for each lepton type. In a similar way, the heavy-quark forward-backward asymmetries, combined with their Z decay partial widths and the know $\mathcal{A}_e$ value, will give access to the individual axial and vector coupling of the heavy quarks. Within the same Z scan, both the leptonic and hadronic final state cross sections will be determined with a 10^{-4} precision. Among the expected results of this Z scan (summarised in tab.1.2) have to be mentioned: (i) the measurements of m_Z and Γ_Z with a systematic error of ~ 100 keV and a statistical uncertainty of 5 and 8 keV respectively, (ii) the determination of the hadronic-to-leptonic partial widths ratio (R_l^Z), needed

to extract the $\alpha_S(m_Z)$, with a precision below 0.00016, i.e an improvement of one order of magnitude, that also allows the light neutrino species determination with a 0.001 precision, (iii) the neutral current lepton universality test at the 10^{-5} level (reachable thank to the expected lower uncertainty of the Z leptonic widths ratios), (iv) the life-time τ decays and the universality test of the charged current from the semi-leptonic decays measurements with a similar precision.

The light neutrino species number

Another interesting measurements in this EW programme is the direct test (through the Z decays width into invisible states measurement) of the right-handed quasi-sterile neutrinos existence or of the neutrino mixing matrix unitarity. The value measured by LEP (mostly at the Z pole from the peak leptonic and hadronic cross-sections) was $N_\nu = 2.984 \pm 0.008$. Its error is dominated by the systematic uncertainties in the peak hadronic cross-section measurements caused by both the experimental absolute integrated luminosity determination and the theoretical low-angle Bhabha-scattering cross section predictions [33]. At future leptonic colliders these systematics will be below to 0.001. Moreover, at higher $\sqrt{s}$ values, the $e^+e^- \rightarrow Z\gamma$ process offers a more accurate measurements, providing a clear on-shell Z bosons γ sample that can be used to extract the properties of the Z . For example, at WW threshold scan, more than 50×10^6 samples in which Z decays in $\nu\bar{\nu}$ (and the related γ is in the detector acceptance), are expected to be produced. Thanks to the huge statistics available also for the leptonic Z decays samples (more than 25×10^6 events), it will be possible to eliminate both the absolute luminosity and the photon detection efficiency uncertainties simply by the direct measurements of the $\Gamma_Z^{inv}/\Gamma_Z^l$ ratio [14]. Data at high energies should also improve the dominant statistical error by about the 20%. Finally, if a lower (e.g. 125 GeV) centre-of-mass energy will be used (increasing in this way both the $Z\gamma$ cross section and the luminosity), this important measurements should be done with a statistical precision of about 0.0004.

The W^+W^- and $t\bar{t}$ thresholds

The masses and widths of W and t can be determined measuring the $e^+e^- \rightarrow W^+W^-$ and $e^+e^- \rightarrow t\bar{t}$ cross section (at the production thresholds) sharp increase at a $\sqrt{s}$ value of about 2 times their masses: a simultaneous fit of the W mass and width yields allows an experimental precision of 0.5 and 1.2 MeV, respectively. For what concern the top quark, because of its large mass (the present measured value from ATLAS [34] and CMS [35] is about 172.5 ± 0.5 GeV), it represents the particle that most strongly influences the H and its potential, leading to prominent puzzles about the EW symmetry breaking origin. Moreover, its mass is also very close (within 1%), to the critical value that separates the H

potential stability domain (up to the Planck scale) from the one in which this potential becomes unstable (well before that scale) [36]. Although today the direct measurements of the top quark properties is domain of hadron colliders, operating at and above the $t\bar{t}$ threshold, FCC-ee will be able to measure m_{top} and Γ_{top} with an unprecedented uncertainty of 17 and 45 MeV, respectively. To reach such precision, FCC-ee will record data at 8 different $\sqrt{s}$ values. Indeed, on one hand, additional data at centre-of-mass energy slightly above the $t\bar{t}$ threshold are required to fit away the cross section dependence on the top Yukawa coupling (due to the H exchange at the $t\bar{t}$ vertex). On the other hand, the background has to be extracted from data taken at energy just below that threshold. Additionally, to properly produce an accurate map of the full threshold shape, a multipoint energy scan of few GeV will be performed [14].

Summarising this EW section, tab.1.2 is only a sub-sample of the huge set of new-physics sensitive EWOPs measurements that can be done at the future leptonic colliders with an expected precision improvement by a factor 20-50 (or more). Moreover, they will allow a direct measurement of $\alpha_{QED}(m_Z)$ and a big improvement also in the input parameters ($\alpha_{QED}(m_Z)$, $\alpha_S(m_Z)$, G_F , m_H , m_Z , m_{top}), considerably reducing the EW prediction parametric uncertainties.

1.1.3 Additional physics opportunities

QCD measurements

Thanks to their high luminosities, clean environments and precise fully kinematic determination of the QCD initial states, the future e^+e^- colliders provide a unique possibility to probe gluon and quark dynamics with a very large statistics. Contrary to pp collisions, in the e^+e^- environments, QCD phenomena manifest themselves only in the final state and are susceptible to perturbative calculations over the most of accessible phase space [14]. These colliders provide the best possible conditions both to precisely extract the strong coupling and for parton fragmentation and radiation studies (through gluons, cleanly-tagged light quarks and heavy ones). A detailed summary of the QCD physics can be found in [27, 37]. The main goals will be: (i) the α_S estimation at per mil level, (ii) High-precision non-perturbative studies as, e.g., parton hadronisation, colour reconnection, very rare hadron decays and final-state multiparticle correlations, (iii) Perturbative parton radiation high-precision analyses, light-quark/heavy-quark/gluon discrimination and studies about the q,g,c,b parton-to-hadron fragmentation [37].

Thanks to the huge statistics available at future leptonic colliders (more than 10^{12} events at the Z peak run) of b - and c -flavoured hadrons, they will be the B factories natural continuation. For example, FCC-ee will provide 200,000 $B_0 \rightarrow K^*(892)e^+e^-$, about 1000 B_S and $K^*(892)\tau^+\tau^-$, and 100 B_0 events (one order of magnitude more than the upgrade of LHCb) [22]. With this statistics and the expected improved detectors sensitivity, the Cabibbo–Kobayashi–Maskawa (CKM) matrix parameters determination will sensibly improve. For the first time, it should be possible to observe the CP violation in B mixing and to provide another new BSM physics test up to a 20 TeV energy scale. Moreover, thanks to the 3×10^{11} τ produced (a factor three more than Belle II (50 ab^{-1}) statistics), a collider as FCC-ee can reach a precision in both the leptonic BR and the charged l - ν weak couplings measurements of 10^{-5} . This will allow G_F measurement and charged-weak-current universality test with the same accuracy. Finally, the 10^{-9} - 10^{-10} precision level reachable for the lepton-number-violating processes like $Z \rightarrow \tau X$ (with $X = \mu, e$), or $\tau \rightarrow \mu\mu\mu, \mu\gamma$, or $e\gamma$, offers sensitivity to several new physics types, especially ν -mass-generation models [14].

1.2 Future leptonic colliders overview

After the discovery of the Higgs bosons, the design of different possible e^+e^- colliders, operating as Higgs factories, was started. Many intriguing options are still under discussion and in this section the 4 main leptonic accelerators, 2 linears and 2 circulars, will be presented. On one hand ILC (based on Superconducting RF technology) and CLIC (based on two-beam acceleration scheme) are two flagship programs of the international Linear Collider Collaboration [38]. On the other hand, FCC-ee and CEPC are the principal candidates to be the future circular leptonic machines. The main advantages of these linear colliders are: (i) the extensive design and prototyping work already done by the international collaborations. (ii) The R&D on the key technologies is practically completed. (iii) There is a well-organised international Linear Collider Collaboration. (iv) Polarised beams can be created (80% for e^- and 30% for e^+). The principal drawbacks are: (i) their high cost. (ii) The fact that machine can deliver beam to only one interaction point (IP). (iii) The low luminosity achievable (if compared to the circular one, especially at the Z pole). Among the advantages of 100 km circular colliders have to be cited: (i) a higher luminosity at 240 GeV (and below) than a linear collider. (ii) The possibility to have more than one IP. (iii) Their development are based on mature technology and a good experience (coming e.g. from LEP). (iv) The possibility to enrich the overall physics program simply

reusing the same tunnel for a pp collider. Clearly they have also limitations to be taken into account as: (i) the limited energy reachable, due to the synchrotron radiation losses ($P_{SR} \approx E^4$). (iii) The beamstrahlung effect that limits the beam lifetime, requiring a second ring as injector for the top-up injection scheme. (iv) The absence of transverse polarisation for high energies beams (due to their large energy spread).

International Linear Collider

The ILC is an e^+e^- linear collider with a centre-of-mass energy of 200-500 GeV, extendible to 1 TeV. The ILC Collaboration has presented a TDR in 2013 [12] with 500 GeV centre-of-mass energy option as the baseline. The R&D continued in order to reduce the cost of the machine. It was estimated that a first stage at $\sqrt{s}$ of 250 GeV will result in about 40% cost reduction [39]. In this first stage ILC will measure the H parameters and their model-independent determination with high-precision. It will also search for new physics hints in exotic decays of H and in pair-production of weakly interacting particles. An ILC sketch of the 250 GeV stage is shown in fig.1.1. Moreover, the use of polarised e^- and e^+ beams will offer new capabilities and scenarios that add to the physics reach: ILC can be upgraded to reach up to 1 TeV centre-of-mass energy, enabling t precision studies and the top Yukawa coupling measurements, together with the H self-coupling. The ILC accelerator is based on the technology of super-conducting

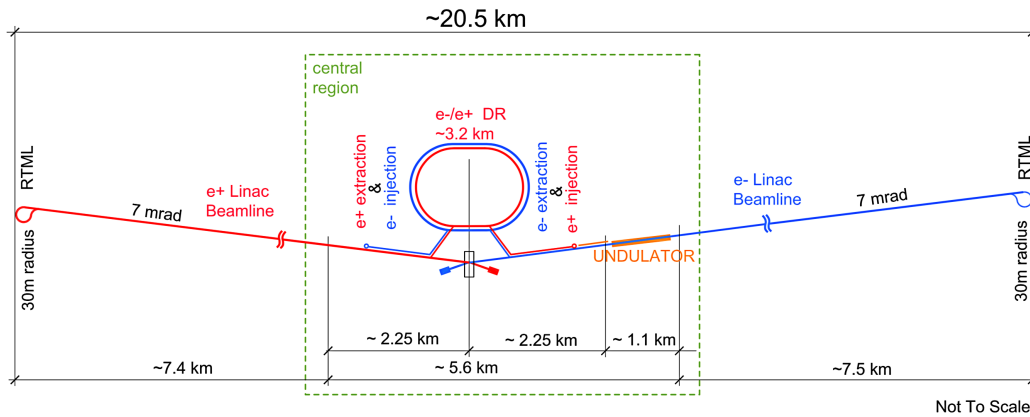


Fig. 1.1: Schematic layout of the ILC at 250 GeV staged option [39].

radio-frequency cavities that has been applied already for the construction of the European X-ray Free Electron Laser (E-XFEL), at DESY/Hamburg and other light sources that use the ILC technology (as the Linac Coherent Light Source-II (LCLS-II) at SLAC [40]) are under construction. It has to be highlighted that about 10% of the E-XFEL cavities feature a gradient higher than 40 MV/m [41]. Therefore, thanks to the active field of super-conducting accelerator facilities, gradients even higher should be expected at the time of the ILC construction [41]. The estimated power consumption at the three centre-of-mass energy

centre-of-mass energy stages are [13]: 168 MW (at 380 GeV), 364 MW (at 1.5 TeV) and 589 MW (at 3 TeV).

Future Circular Collider

FCC-ee is designed to provide the highest possible statistics for the Z , W , H , and t studies, together with the b , c and τ ones (related to the Z decays). Indeed, its centre-of-mass energy spread will range from 88 up to 365 GeV, with four main $\sqrt{s}$ operating points at: (i) the Z pole (91 GeV), (ii) the W^+W^- production threshold (160 GeV), (iii) the ZH one (240 GeV), (iv) the $t\bar{t}$ threshold and above (340-365 GeV). The FCC-ee layout (fig.1.3) has been developed to maximise the luminosity for each operating point and to allow its integration into the present CERN accelerator complex. Except for a section (± 1.2 km) around each one

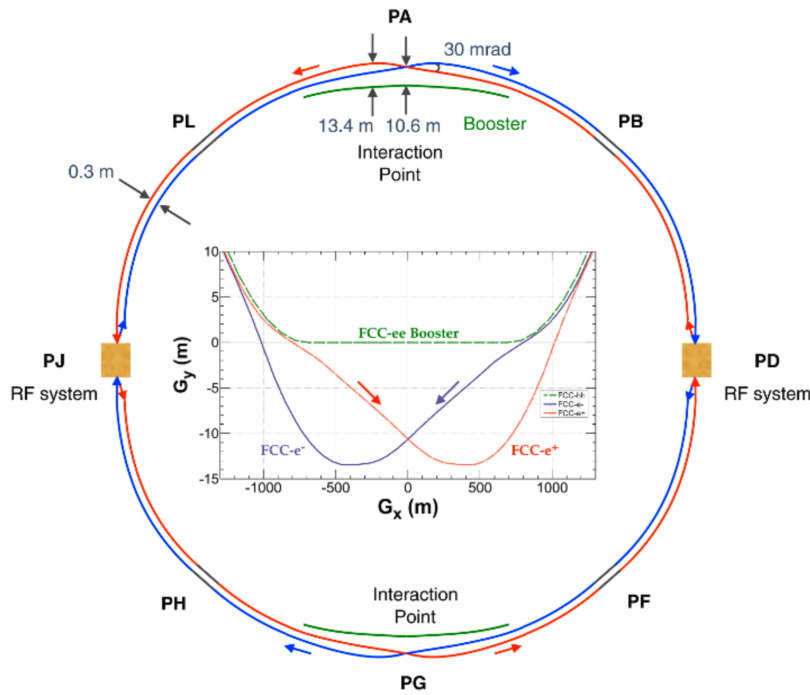


Fig. 1.3: The FCC-ee layout with a zoomed view of the trajectories across interaction point PG. The e^+ and e^- rings are placed 1m outside the booster (green lines) in the arc and are horizontally separated by 30 cm. To reduce the synchrotron radiation at the IP, the beam trajectories toward the interaction points are straighter than the outgoing ones [8].

of the 2 IPs (located at PA and PG in figure) with an horizontal crossing angle of 30 mrad, this collider has a circumference of 97.75 km (the same that will be used for FCC-hh) [45], with a synchrotron radiation power limited, at all energies, to 50 MW/beam. The free area length around the IP and the detector solenoid strength are kept constant at 2.2 m and 2 T, respectively, for all energies. Moreover, FCC-ee has a B -factory-like double-ring collider configuration, that allows both (i) a large number of bunches (e.g. at Z pole, more than 16,000 bunches have to be stored to reach the desired luminosity), (ii) the so called

"tapering" scheme [46] that scales the magnets strengths according to the local beam energy, to properly restore the particles ideal orbit and optics changed by the synchrotron radiation energy losses (especially at the highest $t\bar{t}$ energy) [8]. Additionally, the adoption of a novel collision scheme (called crab waist [47, 48] and already successfully adopted in DAΦNE), provides a very small beam size at the IP (about 50 times smaller than at LEP) and a high beam-beam tune shift. Finally, the synchrotron radiation critical energy of the incoming beams at the IPs is kept below 100 keV [46, 49]. Two RF sections (common for both e^+ and e^- in the $t\bar{t}$ case) per ring are placed in PD and PJ.

Circular Electron Positron Collider

CEPC is a large international scientific project to be hosted in China. This circular collider is designed to operate at centre-of-mass energies of 240 GeV (H factory via $e^+e^- \rightarrow ZH$), 91.2 GeV (Z pole) and 160 GeV (W^+W^- threshold scan). Similarly to FCC-ee, it has a double ring scheme (fig.1.4) with two interaction points and a circumference of 100 km. The instantaneous luminosities are expected to reach 3×10^{34} , 32×10^{34} and $10 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, respectively. It will produce large samples (more than one million) of Higgs, one trillion of Z bosons and about 100 million of W^+W^- events, allowing precision measurements of their properties as well as searches for BSM physics. The colliding beams bunch

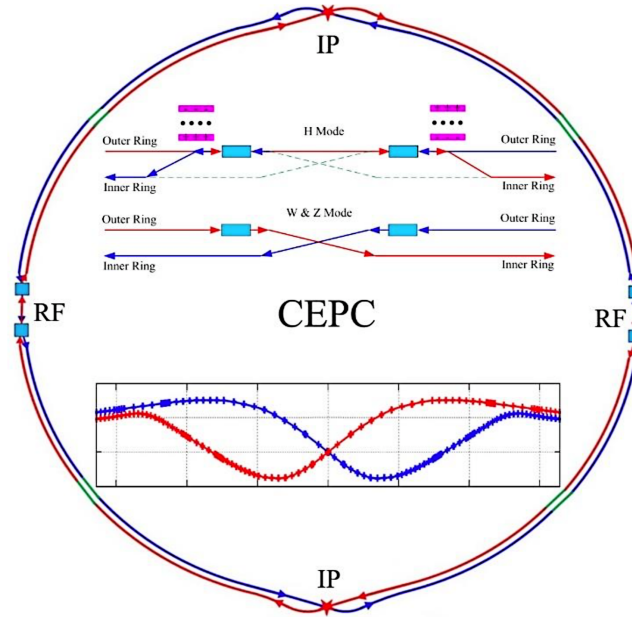


Fig. 1.4: The CEPC layout and the location of the two straight sections used for physics and the two straight sections used for the superconducting RF cavities [9].

spacing differ greatly for the three $\sqrt{s}$ (680 ns, 25 ns, and 210 ns, respectively) as do the event rates and the background levels. The CEPC accelerator complex will consist of a Linac and a damping ring (that will be built at ground level), a

Booster and the Collider (both located in an underground tunnel). Since CEPC can operate simultaneously as a powerful synchrotron radiation light source, two gamma-ray beam-lines are than included in the design. Also in that tunnel design, space will be reserved for a future pp upgrade: the Super Proton Proton Collider (SPPC).

Performance comparison

The main difference between linear and circular colliders is summarised in fig.1.5, representing the expected integrated luminosities at each energy of the four colliders project. While linear colliders could reach the TeV scale (with few upgrades), the luminosity at the H and Z peaks would be one and two order of magnitude lower, respectively, than the one achievable with a circular collider. Thanks to the transverse polarisation reachable for beam energies up to

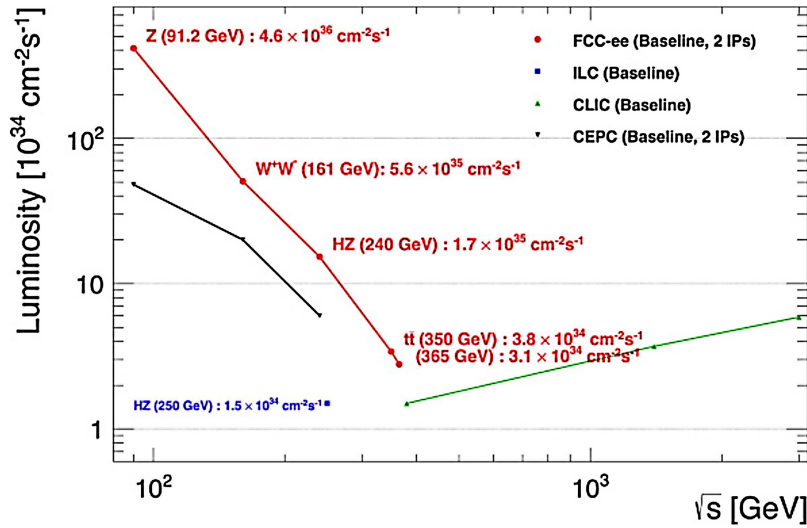


Fig. 1.5: Baseline luminosities expected to be delivered (summed over all interaction points), as a function of the centre-of-mass energy at each of the four worldwide e^+e^- colliders [8].

over 80 GeV [8], a unique feature of circular machines is also to provide high precision centre-of-mass energy calibration at the Z and W energies. Therefore, FCC-ee and CEPC offer high statistical precision for the SM particle properties measurements, allowing the possibility of new rare processes detection and of symmetries violations observation. Finally, as already discussed above, the main H production channel will be via Higgsstrahlung by annihilating an e^+e^- pair with a centre-of-mass energy of ~ 240 GeV. A summary of the main parameters for the four e^+e^- colliders, in their Higgs factory stages, is given in tab.1.3.

Parameters	ILC ₂₅₀	CLIC ₃₈₀	CEPC ₂₄₀	FCC-ee ₂₄₀
Centre-of-mass energy: $\sqrt{s}$ (GeV)	250	380	240	240
Luminosity/IP: $\mathcal{L}$ ($\times 10^{34}$ cm ² s ⁻¹)	1.35	1.5	3	8.5
Beam polarisation e^-/e^+ : $\mathcal{P}$ (%)	80/30	80/0	0/0	0/0
Repetition rate: f_{rep} (Hz)	5	50	–	–
Bunches/pulse: n_{bunch}	1312	352	–	–
Bunches/beam: n_{beam}	–	–	242	328
Bunch population: N_e ($\times 10^{10}$)	2	0.4	15	18
Bunch interval: Δt_b (ns)	554	0.5	680	827
Bunch current/pulse: I_{pulse} (mA)	5.8	2002	–	–
Beam pulse duration: t_{pulse} (μ s)	727	0.176	–	–
Beam current: I_{beam} (mA)	–	–	17.4	29
Average beam power/beam: P_{beam} (MW)	2.65	3.35	–	–
SR power/beam: P_{SR} (MW)	–	–	30	50
Site length/circumference: $L_{site/ring}$ (km)	20.5	22.8	100	97.75

Tab. 1.3: Parameters of the different future leptonic colliders (Status: December 2018) for the ZH production centre-of-beam energy [41].

1.3 Detectors constraints

The precision physics program sets stringent requirements on the detector performances. Among these, large and precise solid angle coverage, excellent particle ID, high energy resolution, efficient vertex reconstruction are fundamental. Indeed, as Higgs, W and Z boson factory, the future e^+e^- colliders have to reconstruct and identify their decay products with high efficiency, purity and precision. The principal requirements are listed below [9]:

Tracking performance: for tracks with transverse momentum larger than 1 GeV, a track finding efficiency better than 99% is required. A per mille level relative momentum resolution is a necessary requirement to measure $H \rightarrow \mu^+\mu^-$ signal and to reconstruct the Higgs boson mass from the recoil mass distribution at $ZH \rightarrow l^+l^-H$ events. Moreover, a large solid angle coverage (the benchmark is $|\cos(\theta)|=0.99$) is essential for large acceptance and for the separation of different processes.

Lepton identification: a lepton identification with an efficiency higher than 99% and a misidentification smaller than 2% is required for isolated leptons with energy $E > 5$ GeV. This is a crucial point since leptons help to classify different physics processes (as the $e^+e^- \rightarrow l^+l^-H$, that produces approximately the 7% of

the Higgs boson, playing an important role in the mass recoil analysis).

Charged kaon identification: for the $Z \rightarrow q\bar{q}$ sample at $\sqrt{s} = 91.2$ GeV, the charged kaon identification should have both the efficiency and the purity higher than 90%.

Photon identification: in the $H \rightarrow \gamma\gamma$ measurements and in the τ -leptons final states studies, photons and their discrimination play a crucial role, especially in e^+e^- collisions where they are prevalent. For the reconstruction of unconverted and isolated photons with $E > 1$ GeV, an identification efficiency greater than 99%, combined with a misidentification below 5%, is required. While, in order to identify the τ -leptons, the γ s should be discriminated from π^0 s with an efficiency of 95%. Moreover, the photon energy should be measured with a precision better than $20\%/\sqrt{E} \oplus 1\%$.

Flavour tagging: The identification of jet flavours allows to separate processes in which b or c heavy quarks, light quarks or gluones are involved. The jets classification depends strongly on the reconstruction of secondary vertex. For example, using $Z \rightarrow q\bar{q}$ sample at $\sqrt{s} = 91.2$ GeV, the efficiency and purity should be greater than 80% (for b -jet) and 60% (for c -jet). These, consequently, impose to achieve an excellent impact parameter resolution $\sigma_{r\phi}$, that can be parametrised (in the $r\phi$ plane) as:

$$\sigma_{r\phi} = a \oplus \frac{b}{p(\text{GeV})(\sin \theta)^{2/3}} \quad (1.4)$$

where p is the track momentum and θ the polar angle track. The first term (a) is the vertex detector intrinsic resolution (in absence of multiple scattering) and is about $5 \mu\text{m}$, while the second term is due to the multiple scattering ($b \sim 15 \mu\text{m} \cdot \text{GeV}$). The main physics performance goals for the vertex can be reached with a three concentric cylinders of double-layer pixelated vertex detectors with a single point resolution of the first layer $< 3 \mu\text{m}$ (located close to the IP, at a radius of 16 mm from the beam pipe), a material budget below 0.15% X_0 per layer and a detector occupancy not exceeding 1% [9].

Hadronic energy resolution: for the physics program, that aims to clearly discriminate the $H \rightarrow ZZ^* \rightarrow 4j$ and $H \rightarrow WW^* \rightarrow 4j$ final states, the energy resolution provided by the calorimetry system for hadronic jets needs to be pushed to $\sim 30\%/\sqrt{E}$ at energies below 100 GeV. This requirement (a factor two better than the operating calorimeters at the LHC) would improve the separation of the W and Z bosons in their hadronic decays (fig.1.6). Two different technology approaches could possibly offer the solution. One aiming to measure individual particles in a jet using a high granularity calorimeter:

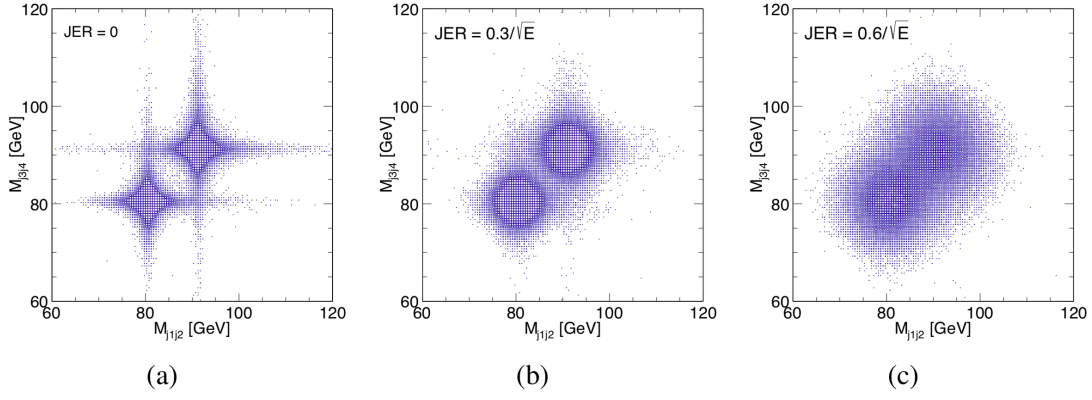


Fig. 1.6: W and Z separation in their hadronic decays with different jet energy resolutions: (a) $0\%/\sqrt{E}$, (b) $30\%/\sqrt{E}$ and (c) $60\%/\sqrt{E}$ [9].

the particle flow concept. The basic idea of the particle flow is to use optimal detector subsystem in order to determine the energy and momentum of each particle in a jet. Therefore, this method requires high spatial granularity and so these calorimeters present finely segmented, three-dimensional granularity and compact, spatially separated, particle showers to reconstruct and identify every single particle shower in a jet. Usually this type of calorimeters consists of an electromagnetic calorimeter (ECAL, for measurements of photons and electrons) and a hadronic calorimeter (HCAL, for hadronic shower). The jet energy is determined by combining the best measurement in a detector system of each single particle in the jet: the charged particles track momenta measured by the tracking system, the energies of photons by the ECAL, while the energies of neutral hadrons by the ECAL+HCAL system. The second, alternative, approach is based on the so called dual-readout concept, that will be described in details in cap.3.

Tab.1.4 summarised all the principal requirements described above. It should be highlighted that the most of these requirements are driven by the Higgs physics program, while other are necessary for the precision EW measurements (as for the Z and W decays). To properly address all these requirements (and all the other machine and physics driven ones [9, 14]), many R&D studies and simulation works were carried out and many international collaborations provided different detector concepts alternatives. As main examples, in the next two sections will be briefly described the two baseline detector concepts envisaged at FCC-ee and presented in the FCC Conceptual Design Report [8]: CLD and IDEA.

Physics process	Measurands	Detector sub-system	Performance requirement
$ZH, H \rightarrow e^+e^-, \mu^+\mu^-$ $H \rightarrow \mu^+\mu^-$	$m_H, \sigma(ZH)$ BR	Tracker	$\Delta(1/p_t) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\text{GeV})(\sin \theta)^{2/3}}$
$H \rightarrow b\bar{b}/c\bar{c}/gg$	BR	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\text{GeV})(\sin \theta)^{2/3}} (\mu m)$
$H \rightarrow q\bar{q}, WW^*, ZZ^*$	BR	ECAL HCAL	$\sigma_E^{jet} = 3 \sim 4\%$ at 100 GeV
$H \rightarrow \gamma\gamma$	BR	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\text{GeV})}} \oplus 0.01$

Tab. 1.4: Physics processes and key measurands and performance requirements used as benchmarks in future experiments as CEPC and FCC.

1.4 CLD detector concept

CLD, derived from the most recent CLIC detector model [50], features a silicon pixel vertex detector, a silicon tracker and highly granular calorimeters (a silicon-tungsten ECAL and a scintillator-steel HCAL). A superconducting solenoid generates a 2 T magnetic field (surrounding the calorimeter), and a steel yoke interleaved with resistive plate muon chambers (RPC) closes the field (fig.1.7). The key parameters of CLD, compared with the CLIC ones, are listed in table 1.5.

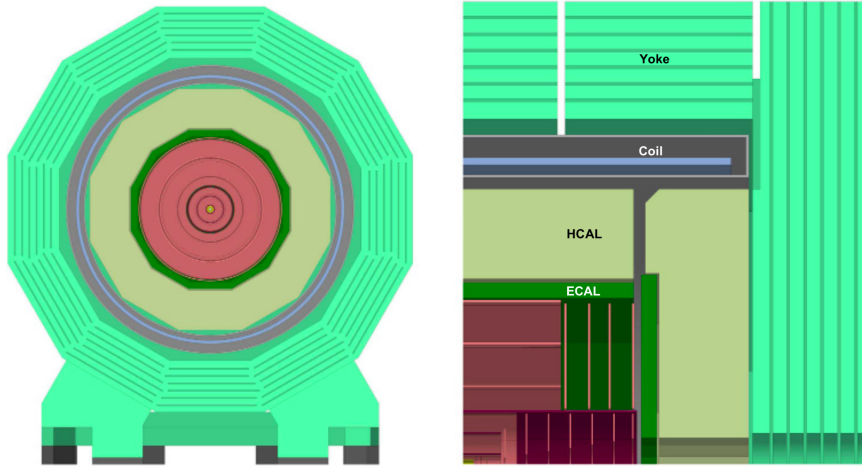


Fig. 1.7: The CLD concept detector. Left: end view cut through. Right: longitudinal cross section of the top right quadrant [9].

The CLD vertex detector, based completely on silicon, is a cylindrical barrel closed by disk in the forward direction. It is made of three double layers, $0.63 X_0$ each, and the forward region is covered by three double disks ($0.70 X_0$). Through

Parameters	CLIC _{det}	CLD
Vertex inner radius (mm)	31	17
Tracker half length (m)	2.2	2.2
Tracker outer radius (m)	1.5	2.1
ECAL absorber	W	W
ECAL X_0	22	22
HCAL absorber	Fe	Fe
HCAL λ_I	7.5	5.5
Solenoid field (T)	4	2
Overall height (m)	12.9	12.0
Overall length (m)	11.4	10.6

Tab. 1.5: Comparison of the most important parameters of CLIC and CLD detector concepts.

full simulation studies, the single point resolution of each vertex sub-detector is found to be $3 \times 3 \mu\text{m}^2$, regarding the inner tracker resolutions of $5 \times 5 \mu\text{m}^2$ for the innermost disk and $7 \times 90 \mu\text{m}^2$ for the outer layers are estimated. Moreover, studies showed a tracking efficiency of 100% for single muons with a transverse momentum higher than 1 GeV [8]; it falls to 96% for momenta ~ 0.1 GeV. The combination of a silicon tracker with a high granularity calorimetry may be an option to reach a jet energy of $\sim 4\%$ using the particle flow technique. An ECAL segmentation of $5 \times 5 \mu\text{m}^2$ fits the requirements for the jet discrimination. The technology chosen is a silicon-tungsten sandwich structure, for a total depth of $22 X_0$. The HCAL consists in steel absorber plates (19 mm thick), interleaved with polystyrene scintillator tiles (size $30 \times 30 \text{ mm}^2$ and thickness 3 mm). The total depth of the ECAL and HCAL results in $6.5 \lambda_{int}$. Finally, regarding the detector magnetic system, the CLD detector magnet is based on the concept of the CMS solenoid [51]. Two different configurations with different operational currents, 20 and 30 kA, are considered: the first currently in use in ATLAS and CMS and the second proposed for the FCC-hh detector magnets.

1.5 IDEA Detector

The second baseline detector concept of FCC-ee is [IDEA](#), it is also considered as a viable solution in the CEPC CDR [9]. It is based on cost performance optimisation and relies on state of the art sub-detectors technologies. The structure of IDEA is shown in [fig.1.8](#) and the most important parameters are listed in [tab.1.6](#). A key element is a 30 cm thick and low mass ($0.8 X_0$) solenoid with a magnetic field of 2 T located between the calorimeter and the tracking volume. The low-magnetic field minimises the impact on emittance growth and allows for manageable

Parameters	
Vertex technology	silicon
Vertex inner/ outer radius (cm)	1.7/34
Tracker technology	drift chamber and silicon wrapper
Tracker half length (m)	2.0
Tracker outer radius (m)	2.0
Solenoid bore radius/half length (m)	2.1/3.0
Preshower/calorimeter absorber	Pb/Cu
Preshower inner/outer radius (m)	2.4/2.5
DR calorimeter inner/outer radius (m)	2.5/4.5
Overall height/length (m)	11/13

Tab. 1.6: The most important parameters of IDEA concept detector.

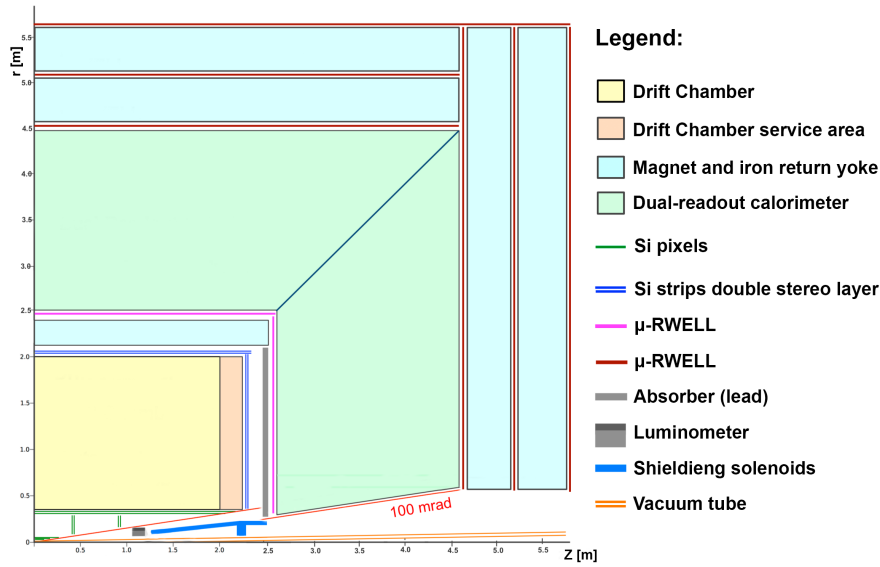


Fig. 1.8: The structure of the IDEA detector and its overall dimensions.

fields in the compensating solenoids. The detector consists of a silicon pixel detector, a large volume extremely light short-drift wire chamber surrounded by a layer of silicon micro-strip detectors, the solenoid, a pre-shower detector, a dual-readout calorimeter and muon chambers within the magnet return yoke. The drift chamber, evolving from the successful detectors of KLOE and MEG2 experiments [52], is a full stereo, unique volume, with high granularity and low mass, short-drift wire chamber and co-axial with the 2 T solenoid field. The special feature of this detector is its high transparency: the total amount of material in radial direction, towards the barrel calorimeter, is of the order of 1.6% X_0 , whereas, in the forward and backward directions, this is equivalent to about 5.0% X_0 . The drift chamber is 400 cm long, with an inner radius of 35 cm and an outer one of 200 cm. The sensitive volume comprises 56,448 squared

drift cells with an edge ranging between 12 to 14.5 mm. The chamber is filled with a very light gas mixture (90% He and 10% iC_4H_{10}), corresponding to a maximum drift of ~ 400 ns. The number of ionization clusters generated by a MIP in this gas mixture is about 12.5 cm^{-1} , allowing for the exploitation of the cluster counting/timing techniques for improving both spatial resolution ($\sigma_x < 100 \text{ }\mu\text{m}$) and particle ID ($\sigma(dN_{cluster}/dx)/(dN_{cluster}/dx) \approx 2\%$). For the whole range of momenta, particle separation with cluster counting outperforms dE/dx technique by more than a factor of two, estimating an expected pion/kaon separation better than three standard deviations for all momenta below 850 MeV and slightly above 1.0 GeV [53]. The vertex detector will be based on monolithic active pixel sensors. In particular, technologies relying on fully depleted high resistivity substrates [54] are being considered, together with architectures implementing on-pixel sparsification and data driven, time-stamped read-out schemes. The ongoing activities are targeting resolutions at a few micron level, thickness in the 0.15-0.30% X_0 range and power dissipation not exceeding 20 mW/cm^2 . A pre-shower detector (based on the Micro Pattern Gaseous Detector (MPGD) technology) is located between the magnet and the calorimeter in the barrel region and between the drift chamber and the endcap calorimeter in the forward region. Moreover, a copper-based dual readout fibre calorimeter [55] surrounds the pre-shower (chapter 7). The results obtained so far with prototypes [1], support the statement that this calorimeter may reach resolutions of the order of $11\%/\sqrt{E}$ for em showers and around $30\%/\sqrt{E}$ for hadronic showers, together with good particle ID capabilities. Similarly to the pre-shower detector, the choice of a MPGD such as the so called micro-Resistive WELL (μ -RWELL) [56], would perfectly match the specifications required for the IDEA muon detection system, providing good tracking efficiency and both precise space resolution on the coordinates of a muon track (about 200-300 μm) and good time resolution. They also lead to a significant reduction of the cost to equip extremely large surfaces with tracking chambers outside the calorimeter volume. The μ -RWELL is a compact single amplification stage intrinsically spark protected MPGD. It is composed of two elements: the drift cathode and the μ -RWELL PCB, which merges, in a unique structure, a WELL patterned matrix as single amplification stage, a resistive layer and a rigid PCB readout electrode. The best option is using tiles of μ -RWELL detectors of a size $50 \times 50 \text{ cm}^2$ to realise three or four detector stations. Each station could be equipped with a couple of layers of μ -RWELL detectors. This would make the whole muon system very modular with components which can be mass produced by industry. Finally, as cited above, for the IDEA magnetic system, an innovative design is proposed: a much smaller, ultra-thin, and transparent solenoid, positioned in front of the dual-readout calorimeter, minimising its cost. The main feature is that the solenoid can be

positioned between the tracker volume and the calorimeter system, a solution currently present in ATLAS [57]. By positioning the coil inside the calorimeter, the stored energy is reduced by a factor four and the cost can be halved [58].

Calorimetry in High Energy Physics

” *The word calorimetry comes from latin: “calor”, meaning heat and the greek: “μέτρον”(métron), meaning measure.*

Originally invented for cosmic-ray studies, calorimetry refers to the detection of particles and the measurement of their properties, using blocks of instrumented material. They can be divided in two different types: homogeneous and sampling calorimeters. Homogeneous calorimeters are composed by only one, high density material that provides both the functions of absorbing the particles and detecting the signal produced in this process. Instead, in sampling calorimeters the particle absorption is performed by a material (passive medium) while the signal generation is exercised by a different one (active medium). In a calorimeter, particles to be measured are fully absorbed and their energy is transformed into a measurable quantity (like charge or light) [59]. Typical processes suitable to detect this energy are: ionization of the medium, scintillation light and the Cherenkov light produced by relativistic particles. This chapter describes the physics behind both the electromagnetic and hadronic shower developments, provides the most important definition adopted in this field and introduces the fundamental energy resolution concept.

2.1 Physics of shower development

Since particles inside a calorimeter undergo a destructive process, it is useful to briefly introduce the basic physics of particle shower development [55].

2.1.1 Electromagnetic showers

Electromagnetic showers are produced by electrons, positrons and gammas. Contrary to their apparently complex phenomenology, the QED processes that play a role in an em shower development are few and well understood. Moreover the main shower features can be parametrised in few equations. Fig.2.1 shows the average energy lost by electrons in lead (left plot) and the interaction cross section of photons (right plot) as a function of energy. For low energies,

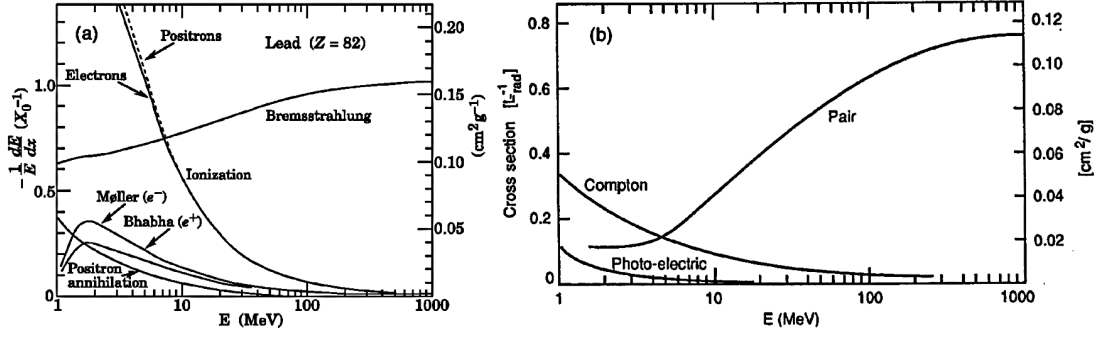


Fig. 2.1: (a) Fractional energy lost in lead by e^- and e^+ as a function of energy [60]. (b) Photon interaction cross section in lead as a function of energy [61].

electrons (and positrons) lose their energy primarily by ionisation and thermal excitation, while photons through Compton and photoelectric effect. At a higher energy regime ($E > 10$ MeV) the main mechanism for energy loss by electrons is bremsstrahlung and photon interaction is governed by pair production. Finally, at energies of 1 GeV or higher, both these processes become roughly energy independent and electrons and photons initiate em showers on the calorimeter: e produces secondary photons (by bremsstrahlung) and γ secondary e^-e^+ pairs. This mechanism is replicated by these secondary particles giving rise to a shower of particles that progressively lose their energy. The number of particles constituting the shower increases until the electron component energy decreases below the so called critical energy ϵ . It is defined as the energy at which both ionization and bremsstrahlung losses become equal. It is roughly inversely proportional to the Z value of the absorber material and (for solids) is approximately given by:

$$\epsilon = \frac{610 \text{ MeV}}{Z + 1.24}. \quad (2.1)$$

ϵ is also defined (Rossi, 1952) as the energy at which the electron energy E equals the ionisation loss per radiation length:

$$\frac{dE}{dx}(\text{ionisation}) = \frac{E}{X_0}. \quad (2.2)$$

Both these two definitions are equivalent in the approximation:

$$\frac{dE}{dx}(\text{bremsstrahlung}) \simeq \frac{E}{X_0}. \quad (2.3)$$

The so called radiation length X_0 , is one of the most useful parameters used to describe the main features of em showers as their lateral and longitudinal sizes.

It depends only on the material characteristics and is defined as:

$$X_0(g/cm^2) \simeq \frac{A \cdot 716 \text{ gcm}^{-2}}{Z(Z+1) \ln(287/\sqrt{Z})} \quad (2.4)$$

where A and Z are the material atomic weight and number, respectively. X_0 represents the average distance x , travelled in a material, by an e to reduce its original energy E_0 of $1/e$:

$$\langle E(x) \rangle = E_0 \cdot e^{-(x/X_0)}. \quad (2.5)$$

Therefore, an electron loses on average, about the 63% of its energy traversing $1 X_0$ of material. Similarly, the mean free path of a high-energy γ beam in the same material is $x = \frac{9}{7} X_0$, i.e. after that distance its intensity is reduced to $1/e$ of its original value I_0 :

$$\langle I(x) \rangle = I_0 \cdot e^{-(7/9)(x/X_0)}. \quad (2.6)$$

The latest two equations show that both e and γ -induced shower developments can be described more or less independently of the absorber material if expressed in terms of X_0 . Nevertheless, the X_0 has a different meaning for e and γ : their shower initial developments are quite different. When electrons enter in the calorimeter, they start to radiate immediately, emitting thousands of bremsstrahlung photons through few mm of material. High-energy γ s instead have a certain probability to not convert in the same material thickness and, in this case, they do not lose energy. However, they also can convert early on, possibly losing energy as much as electrons in the same material thickness. Fig.2.2 represents exactly this difference: in the same $5 X_0$ lead thickness, electrons lose on average a larger energy fraction than γ s but the latter have a larger spread. The depth at which the largest number of secondary particles is produced is called shower maximum. It is approximately located at:

$$t_{max} \simeq \ln \frac{E_0}{\epsilon} + t_0 \quad (2.7)$$

where E_0 is the energy of the incident particle, t_0 is equal to -0.5 ($+0.5$) for e (γ) and t_{max} is measured in units of X_0 . The logarithmic energy dependence of the shower length allows an em calorimeter thickness of few tens of cm also for expected particles energies of the order of few TeV. Indeed, the calorimeter thickness (always expressed in radiation lengths) that contains 95% of the shower energy is:

$$t_{95\%} \simeq t_{max} + 0.08Z + 9.6. \quad (2.8)$$

This means for example, that for a 300 GeV e , $25X_0$ calorimeter thickness is enough to obtain a longitudinal leakage of much less than 1% [61]. Concerning

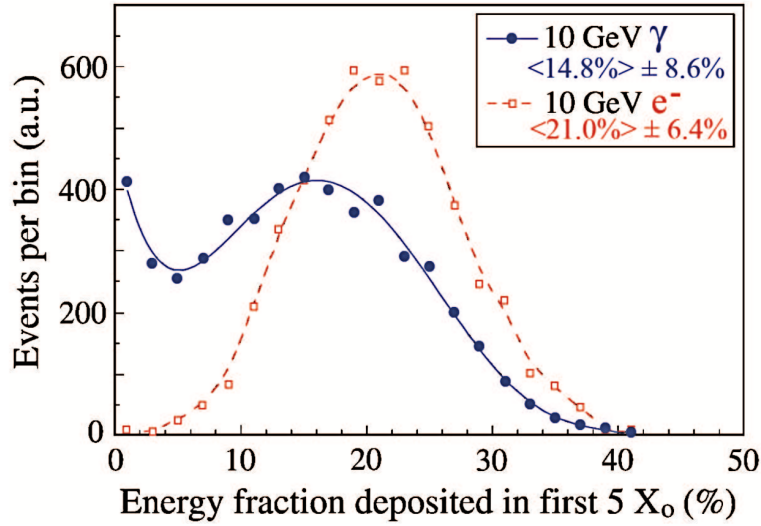


Fig. 2.2: (Distribution of the energy fraction deposited in the first $5 X_0$ by 10 GeV e and γ showering in lead. Results of EGS4 simulations [62].

the transverse size, the em shower lateral development is due both to: (i) the multiple scattering of electrons and positrons away from the shower axis (ii) the photons and electrons produced in isotropic processes (photoelectric effect and Compton scattering) that can also move away from the shower axis. The first process dominates the early shower development stages while the latter becomes more important beyond the shower maximum [59]. Fig.2.3b, that shows the radial energy density for e showers in copper at three different calorimeter depths, highlights these two components and their own characteristic exponential scale. A measurement of the shower radial size, integrated over the full shower depth,

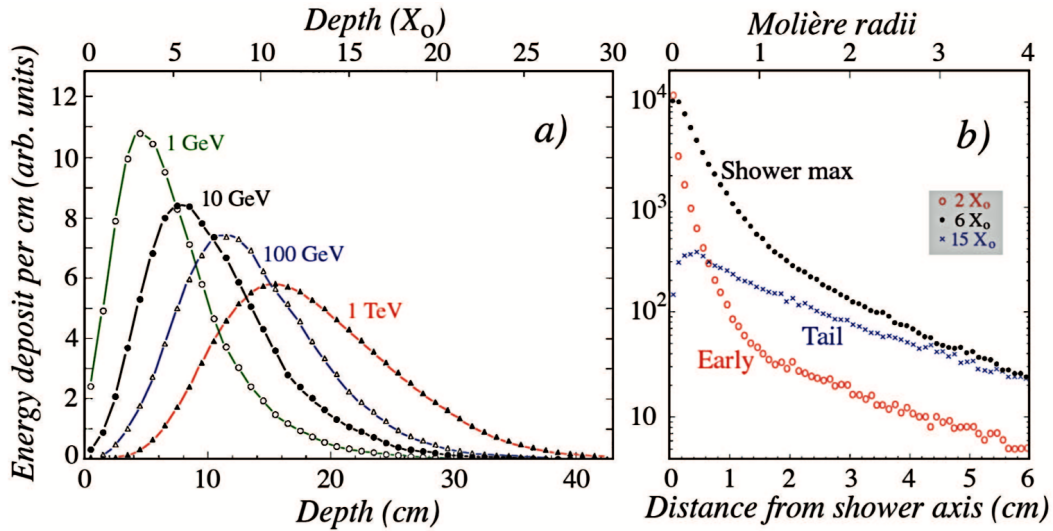


Fig. 2.3: ((a) The energy deposited as a function of depth for 1, 10, 100 and 1000 GeV e showers developing in copper. For an easiest comparison, the curves integrals have been normalized to the same value. (b) The radial distributions of the energy deposited by 10 GeV e showers in copper, at various depths. Results of EGS4 calculations [63].

is provided by the so called Molière radius (R_M). It is defined through the ratio:

$$R_M \simeq 21 \text{ MeV} \frac{X_0}{\epsilon(\text{MeV})} \quad (2.9)$$

and represents the average lateral deflection of electrons at the ϵ (as defined in eq.2.2) traversing 1 X_0 [61]. A cylinder with a radius of 1 R_M contains, on average, the 90% of the shower energy [59]. When expressed in g/cm², the Molière radius scales as A/Z , while the radiation length as A/Z^2 . Therefore, R_M is roughly energy independent and less material dependent than X_0 : e.g. lead and copper have similar R_M , but their X_0 differ by a factor 3. Moreover, since for the majority of calorimeters the Molière radius measures only few cm, electromagnetic showers are usually very narrow. Therefore, if the calorimeter is used for precision measurements of the position of the shower, their cells (or fibres) size must be smaller than 1 R_M . Even if the em shower profiles scale with R_M and X_0 , this scaling is only an approximation: for high- Z materials, particles continue their multiplication down to lower energies and decrease slower beyond the t_{max} than in calorimeters with low- Z absorber. Fig.2.4 represents both the

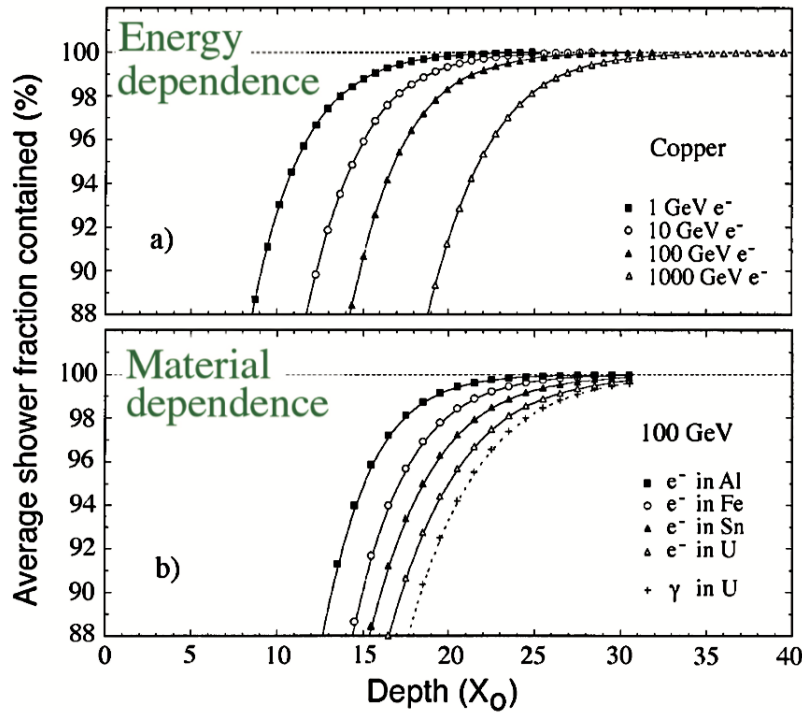


Fig. 2.4: Average energy fraction contained in a calorimeter with infinite transverse dimensions, as a function of the absorber thickness. (a) Results for showers induced by e at different energies in copper. (b) Results for 100 GeV e showers in different absorber materials. Results of EGS4 calculations [63].

energy and absorber material dependence of the thickness needed for the em shower containment: the difference between low- Z and high- Z absorbers (for 99% containment) can be also more than 10 radiation lengths (and it can be even

more for γ induced showers). The material differences for the lateral shower containment are much smaller than for the longitudinally one. These deviations are observed because X_0 and R_M are scaling variables and so can not properly describe the Compton scattering and photoelectron production processes that dominate at energies well below ϵ (more details can be found in [59]).

2.1.2 Hadronic showers

Similarly to em showers, the hadron energy degradation in the calorimeter absorber material is reached through an increasing number of interactions. However, in this case, the hadronic ones are responsible for two effects that increase the complexity of the shower development. First, the secondary produced hadrons have momenta at the GeV scale (thus a significant fraction of the primary hadron one) and their mean free path between interaction (called nuclear interaction length) scales as $\lambda_{int} \approx 35A^{1/3} \text{ g/cm}^2$: more than a factor 30, if compared to X_0 for high- Z materials ($\lambda_{int}/X_0 \propto A^{4/3}$) [59]. Second, the occurrence of nuclear reactions (e.g. excitation, spallation, nucleon evaporation, etc.), requires a significant amount of the primary particle energy necessary to provide the nuclear binding energy ($\sim 8 \text{ MeV/nucleon}$). Since this energy does not contribute to the calorimeter signal, it is called invisible energy. As a consequence, the signals generated by hadrons are usually smaller than the ones coming from electrons impinging the calorimeter with the same energy. This effect is known as calorimeter non-compensation (sec.2.2.2). The physics richness of the particles production in the shower is well represented by fig.2.5, which shows the particle spectra produced in the hadronic cascade (generated by 100 GeV protons in lead). The high-energy spectrum component contains neutrons, protons and pions ($\sim 90\%$), while the soft-energy part electrons, photons, positrons and low-energy neutrons. Due to the hadronic interaction charge independence, about 30% of the pions produced are π^0 s. That neutral pions decay in 2 γ s inducing an em cascade as described above. The so called f_{em} , i.e. the hadronic shower energy fraction carried by the em component, can be very different event-by-event. It has also an energy dependence: e.g. the f_{em} for pion-induced showers in a lead-based calorimeter increases from $\sim 30\%$ at 10 GeV up to $\sim 50\%$ at 100 GeV [65]. This growth is due to the further production of π^0 by secondary (and high-order) shower particles: the larger the energy, the higher particles generation, the larger f_{em} . Due to this f_{em} energy dependence, a non-compensating calorimeter is non-linear for hadron detection (sec.2.2.2). The remaining shower energy (always in lead¹) is deposited by ionising particles

¹In lighter absorber materials the remaining shower energy distribution is slightly different: in iron the contribution of the ionising particles is 74%, neutrons account for 5% and the remaining 21% corresponds to the invisible energy.

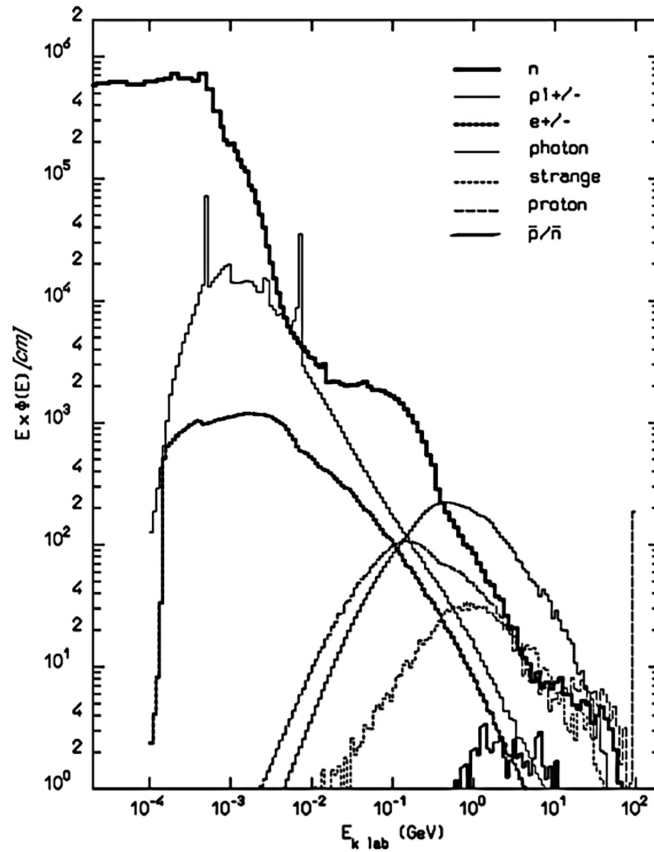


Fig. 2.5: Particle spectra produced in the hadronic cascade generated by 100 GeV p in lead. The ordinate represents the particle track length (in “lethargic” units) differential in $\log(E)$. Each curve integral provides the particle relative fluence. Based on Fluka calculations [64].

(56%), very soft (~ 3 MeV) neutrons (10%) and invisible energy (34%). Two thirds of energy deposited by the ionising particles are due to protons (of about 50-100 MeV each one) generated by nuclear spallation processes: the majority of the non-em shower component energy is thus deposited through nucleons instead of relativistic particles (as π s). Regarding the hadronic shower profiles, on average, they are very similar to the em ones shown in fig.2.3 but the scale factor is larger: for example, in lead λ_{int} is 17.10 cm while X_0 is only 0.56 cm (30 times less). This difference is one of the most useful discriminating factors used to distinguish between em and hadronic showers. Also for the hadronic cascades the calorimeter depth needed to fully contain the shower increases logarithmically with the energy (fig.2.6). However, the hadronic showers have large longitudinal fluctuations due to smaller number of generations and particles produced [66]. Due to these fluctuations, the leakage effects can have an important role even if the calorimeter has, on average, 99% of energy containment: an adequate calorimeter thickness is therefore needed to reach a full hadronic containment. Instead, regarding the hadronic shower lateral size,

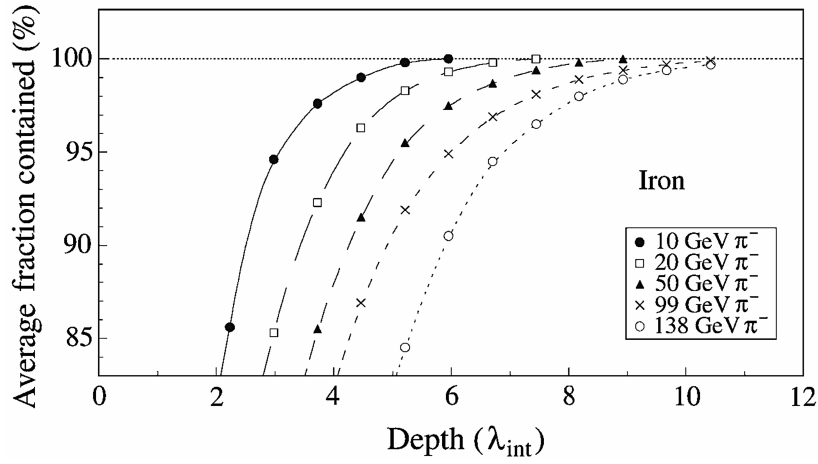


Fig. 2.6: Average energy fraction contained in a calorimeter with infinite transverse dimensions, as a function of the absorber thickness [67].

fig.2.7 represents the average energy fraction contained for an infinitely long cylinder of a lead-based calorimeter, as a function of the radius, for different impinging pions energies. High-energy hadronic showers are much narrower than

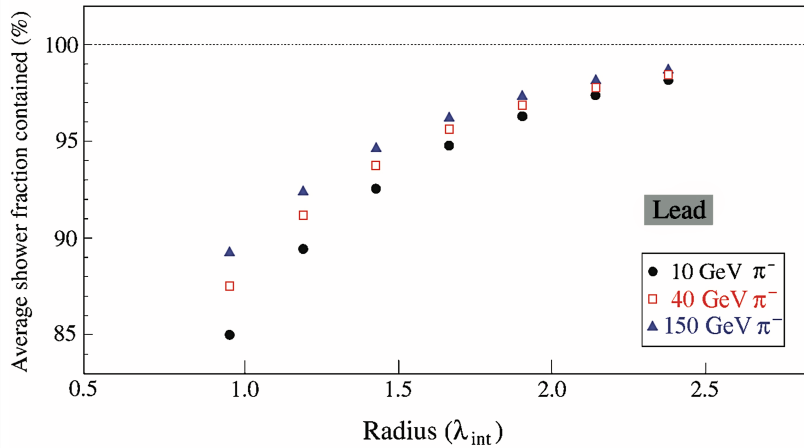


Fig. 2.7: Average energy fraction contained in an infinitely long cylinder of lead-based calorimeter, as a function of its radius, for π s of different energies [68].

low-energy ones. This is because f_{em} increases with energy and em showers develop closer to their shower axis (as described in the previous section).

Summarising, some very important considerations for calorimetry can be extracted on the basis of the shower development characteristics discussed above:

- In the absorption processes, the majority of the energy is deposited by very low-energy particles: in particular, for em showers, both Compton and photo-electrons dominate the energy deposit process and thus the calorimeter signal. Due to their isotropic angular distribution, these particles lose the primary information about the incoming particle direction [69]. There-

fore, the active layers in a sampling calorimeter can be oriented along any direction required by the particular geometry design of the calorimeter itself.

- The scale for a useful sampling frequency in a well designed em calorimeter is set by the very short range of $\sim 1\text{MeV } e$ (the typical em shower particle): about 1 mm.
- Similarly to the previous point, the $\sim 1\text{ cm}$ range of the 50-100 MeV spallation protons sets the sampling frequency scale for hadronic calorimeters. Soft neutrons travel several cm between interactions and are important for the signal only if they have enough probability to interact in the active material generating detectable reaction products. As will be discussed in the next section, the low-energy particles are not only important for the absorption processes but also for the response function of the calorimeter.

2.2 Energy resolution

Calorimeters are detectors built to measure energy: the energy resolution is the precision with which this is done and it is typically determined as the relative width (σ/E) of the calorimeter signal distribution obtained. Not surprisingly, it is considered one of the most important parameters used to describe the calorimeter performance and often it is a very important criterion for a comparison between different calorimeter options in a new experiment design.

2.2.1 Electromagnetic calorimeters

The assumption of a well known proportionality between the energy released in a calorimeter by the shower and the energy of the incident particle E_0 is the calorimetry key point. Indeed, the total track length of an em shower (T_0), i.e. the sum of all the ionisation tracks due to all the shower charged particles, is proportional to:

$$T_0 \text{ (g/cm}^2\text{)} \propto X_0 \frac{E_0}{\epsilon} \quad (2.10)$$

where E_0/ϵ is the number of shower particles. Therefore, a measurement of the signal induced by the shower charged tracks provides a measurement of E_0 . In the hypothesis of an ideal calorimeter (i.e. infinite size and no response deterioration) the intrinsic energy resolution is due to the T_0 fluctuations. Since the cascade development is a stochastic phenomenon and T_0 depends on the number of track segments in the shower, the intrinsic resolution consists in a

purely stochastic term:

$$\sigma(E) \propto \sqrt{T_0}. \quad (2.11)$$

From eq.2.10, the relationship between energy and resolution can be derived:

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{T_0}} \propto \frac{1}{\sqrt{E_0}}. \quad (2.12)$$

In a real calorimeter the resolution is deteriorated by other effects that can be summarised in two additional terms to be added in quadrature: a noise term and a constant one. The actual realistic calorimeter resolution can be thus be written in a more general way as [61]:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c. \quad (2.13)$$

A brief overview of these three terms is proposed below, together with a short description of the main others non-negligible additional contributions to the em energy resolution.

Stochastic Term

This term, as already discussed, is due to the fluctuations of the total length shower development. As expected, in a homogeneous calorimeter, for a given incident particle energy, the energy deposited in the active volume does not fluctuate event-by-event. While, in a sampling calorimeter, in which active volumes and absorber layers are interleaved, this is not true. This characteristic, defined as sampling fluctuations, is the main limiting factor for this type of calorimeters. More in detail, sampling fluctuations are variations in the number of different shower particles that contribute to the calorimeter signal combined with fluctuations in the total deposited energy in the active volume. They depend both on the sampling frequency (i.e. the number of different sampling elements in the showers development region) and on the sampling fraction, defined as the ratio between active and passive materials [59]. Sampling fluctuations are stochastic and contribute to the relative energy resolution as [70]:

$$\frac{\sigma}{E} = \frac{a_1}{\sqrt{E}} \text{ with } a_1 = 0.027 \sqrt{d/f_{samp}} \quad (2.14)$$

where E (in GeV) is always the particle energy, d (in mm) corresponds to the single active sampling layer thickness (or the fibre diameter) and f_{samp} is the sampling fraction for mips:

$$f_{samp} = \frac{E_{mip}(active)}{E_{mip}(active) + E_{mip}(absorber)} \quad (2.15)$$

in which $E_{mip}(active)$ and $E_{mip}(absorber)$ are the energies deposited in the active and absorber calorimeter parts by a mip, respectively. Another important contribution to the sampling calorimeter stochastic term (and so to be summed in quadrature with the previous one) is given by the fluctuations of the total number of signal quanta constituting the signal. These fluctuations are often negligible both for detectors that use as signal electrons produced in ionisation processes (e.g. calorimeter with krypton argon or xenon as active material) and for the ones using scintillation light signal. Indeed, since in these cases the number of signal quanta is at the order of several hundred per GeV of deposited energy, the contribution to the stochastic term is typically less than $5\%/\sqrt{E}$. Nevertheless, this effect may dominate the em energy resolution of Cherenkov-based calorimeters as the dual-readout, in which the number of available signal quanta can be only of few tens of photoelectrons/GeV.

Noise Term

The noise term is due to the electronic noise of the readout chain and, at energies below few GeV, it can become the dominant term in the em resolution. Therefore, for some GeV applications, the noise equivalent energy is usually required to be below 100 MeV. This term also depends on the readout technique implemented: on one hand, calorimeters based on light detection can reach low noise levels because of the intrinsic original signal high gain multiplication provided by the photosensitive detectors adopted in the first step of the electronic chain. On the other hand, in calorimeters based on charge collection, the noise term is higher, since the equivalent noise charge Q depends on the bandwidth (δF) of the preamplifier of the readout chain as $\sqrt{\delta F}$ [61]. Therefore, an intrinsic limitation exists for that calorimeters type, especially at high rates. Finally, in sampling calorimeters, it is possible to mitigate the noise term by increasing the sampling fraction: the larger the f_{samp} , the larger the signal from the active layers, the higher the Signal to Noise Ratio (SNR).

Constant Term

In this term all the energy independent contributions as imperfection in the mechanical structure or geometry, temperature gradients or variations with time, detector ageing and/or radiation damage, are included. Each of these effects causes variations of the calorimeter response with particle impact point (or with time) and produces response non-uniformities that add an energy smearing for particles distributed over large areas (resulting in a constant term). Typically this term is kept at 1% level. With the increasing energies of the future experiments, and thus the relative decrease of the stochastic term, the constant term will become more and more dominant for the calorimeter energy resolution.

Additional Contributions

Other external factors can limit the performances of a calorimeter (both em and hadronic), especially when integrated in a big experiment:

- Longitudinal leakage: costs and space constraints can limit the calorimeter thickness and part of the energy shower can be lost beyond the end of the active volume. This changes event-by-event, deteriorating the resolution.
- Lateral leakage: usually a relatively smaller cluster of calorimeter cells/fibres is used for the shower energy reconstruction. On one hand this limits the contribution of the electric noise, of other particles in the same physics event and of the event pile-up (if operating at high-luminosity colliders). On the other hand, a fraction of the shower energy can be lost outside the cluster size and its values varies event-by-event, introducing an additional smearing.
- Upstream energy losses: in a HEP experiment, particles have to cross a non-negligible amount of dead material before reaching the calorimeter and can interact with them losing part of their energy. The amount of energy loss varies event-by-event, resulting in a worse resolution.
- Non-hermetic coverage: the presence of calorimeter cracks and/or dead regions deteriorates the resolution since part of the energy shower is lost there and can not be detected. These losses give rise to a low-energy tail in the reconstructed incident particles energy spectrum.

2.2.2 Hadronic calorimeters

The hadronic shower properties described in sec.2.1.2 determine the intrinsic fluctuations and hence the calorimeter energy resolution. More in detail, f_{em} has been measured [71] to increase with energy following a power law:

$$\langle f_{em} \rangle = 1 - \left(\frac{E}{E_0} \right)^{k-1} \quad (2.16)$$

where $k \sim 0.82$ and E_0 is a constant, related to the average multiplicity in hadronic interactions, depending on the absorber material. An example of this dependence is shown in fig.2.8a: for π -induced showers E_0 is 0.7 GeV in copper and 1.3 GeV in lead. Moreover, the event-by-event f_{em} fluctuations are large and non-Poissonian [68] (fig.2.8b) and this has important consequences for the so called calorimeter response. The latter is defined [59] as the conversion

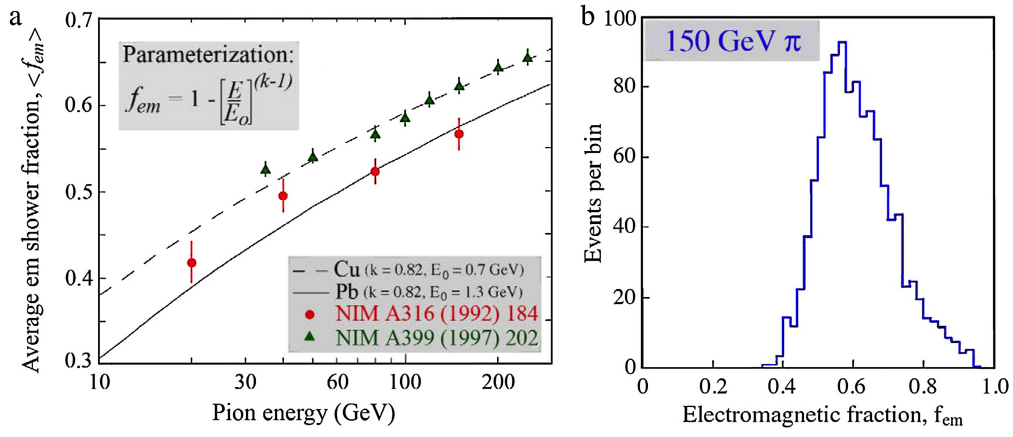


Fig. 2.8: (a) The $\langle f_{em} \rangle$ values as a function of energy, for showers developing in copper and lead. (b) The f_{em} distribution values measured for 150 GeV π -induced showers developing in lead. These values were measured as the energy contained in the central tower of the calorimeter. More details can be found in [65] for copper and [68] for lead.

efficiency from deposited energy to generated signal, normalised to mips. As represented in fig.2.9, the calorimeter response to mips is higher from that to showers (because of shower sampling inefficiencies [72]) and the em response function e (i.e. the normalised signals distribution around the mean value) is usually higher and narrower than the non-electromagnetic one (h). This is due to the event-by-event fluctuations in the invisible energy component² [73]. Each

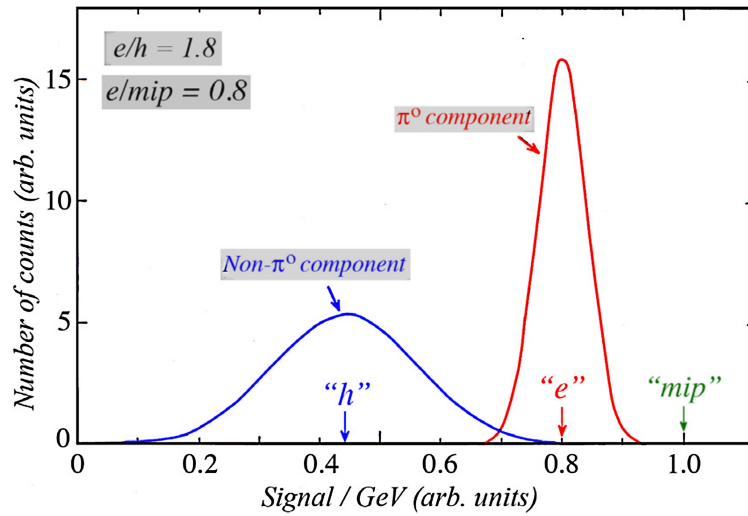


Fig. 2.9: Sketch of the signal per unit deposited energy distributions for em and non-em components of hadron showers for a generic sampling calorimeter. The distributions are normalised to the mips response. The average values of the blue and red distributions are the non-em (h) and the em (e) response, respectively [55].

calorimeter is characterised by its intrinsic e/h ratio value (equal to 1.8 in the example) [63]. For a high-energy pion, since the induced shower has both

²The invisible energy fluctuates considerably even for fixed f_{em} .

em and non-em component, the calorimeter response function will be centred between the fully em (e) and fully non-em (h) responses, at a value given by:

$$\pi = \frac{\langle f_{em} \rangle \cdot e + (1 - \langle f_{em} \rangle) \cdot h}{mip}. \quad (2.17)$$

The calorimeter response to pions increases with energy (because $\langle f_{em} \rangle$ increases as well) and thus is non-linear for hadron detection. Calorimeters with $e/h \neq 1$ are called non-compensating. The e/h value can not be directly measured, however it can be derived from a series of experimental e/π signal ratios measurements spanning a large energy range [74]. In more detail, the e/π ratio can be directly calculated by comparing the calorimeter signals from electrons and pions at the same energy. Thanks to eq.2.17 (with $mip = 1$), for each energy E , this ratio can be expressed as:

$$\frac{e}{\pi}(E) = \frac{e}{\langle f_{em} \rangle \cdot e + (1 - \langle f_{em} \rangle) \cdot h} \quad (2.18)$$

where $\langle f_{em} \rangle$ is the average fraction of energy going into π^0 production in the hadronic shower. Substituting $\langle f_{em} \rangle$ with eq.2.16:

$$\frac{e}{\pi}(E) = \frac{1}{1 - (1 - h/e)(E/E_0)^{m-1}}. \quad (2.19)$$

The e/h value is then extracted as the parameter of the best fit, performed with this expression, of the e/π experimental data (versus the energy). Because of invisible energy losses in the non-em shower component, typically e/h values are larger than 1, but it is also possible to build calorimeters with $e/h < 1$. Calorimeters with $e/h > 1$ and $e/h < 1$ are called under-compensating and over-compensated, respectively. In practice the most used calorimeters are under-compensating ones, with typical e/h values of 1.2-2.0 [75]. To mitigate all these effects, a quantity correlated to the invisible energy has to be measured: the stronger the correlation, the better the calorimeter performances. Two quantities are usually considered for this scope: the total non-em shower energy (that will be described at the end of this section) and the total neutron kinetic energy released in the hadronic cascade development. The second is used to reach the so called calorimeter compensation: the relative magnitude of the signal provided by neutrons can be properly tuned to equalise the em and non-em calorimeter response, i.e. to obtain $e/h = 1$. In this process, the most important part of the sampling calorimeter is the active material, since it has to detect the high number of neutrons produced (in high-Z absorber materials) in the shower with high efficiency. Neutrons lose their energy only through the products of the nuclear reactions they undergo [63]. At ~ 3 MeV (the typical energy scale of the

neutrons produced in the hadronic shower), the most important process is the elastic scattering. In this case the transferred energy fraction is, on average:

$$f_{elastic} = \frac{2A}{(A+1)^2} \quad (2.20)$$

where A is the target nucleus atomic number [59]. Since in hydrogen $f_{elastic}$ is 50%, while in lead it is 100 times smaller, in a Pb/H₂ calorimeter structure (50% each one in terms of number of nuclei) the 98% of the neutrons kinetic energy is transfer to H nuclei. Compensation can thus be achieved using hydrogenous active material and an high- Z absorber. To reach the compensation the response to neutrons is boosted exactly by the factor needed to equalise e and h and this requires a very specific sampling fraction ($\sim 2\%$ for Pb/scintillating-plastic calorimeters [76, 77, 78]). Currently, the best hadronic energy resolution is reached by ZEUS ($\sigma/E \sim 35\%/\sqrt{E}$) with a similar calorimeter [79]. The effect of non-compensation on the hadronic energy resolution is often described as a constant term but this is not properly true since it was demonstrated that, for calorimeters with large e/h , the f_{em} fluctuations dominate the resolution in the TeV regime [80]. The measured effects of these fluctuations can be more properly described by a term similar to eq.2.16 and should be added in quadrature to the $E^{-1/2}$ scaling term [81]:

$$\frac{\sigma}{E} = \frac{a_1}{\sqrt{E}} \oplus a_2 \left(\frac{E}{E_0} \right)^{l-1} \quad (2.21)$$

where l is a factor determined by the $\langle f_{em} \rangle$ energy dependence [71] (e.g. is ~ 0.72 in copper), E_0 is again the constant related to the average multiplicity in hadronic interactions and $a_2 = |1 - h/e|$ is a factor that spreads from 0 (for compensating calorimeters) to 1 (for extremely non-compensating ones) [71]. The compensated calorimeters have unfortunately also 3 main disadvantages:

- They have a high- Z absorber material and thus a small e/mip value (typically ~ 0.6) that produces non-linearities for low-energy hadrons since they lose their kinetic energy trough ionisation of the absorber instead of through shower development [82]. Moreover, these particles provide a significant energy fraction of high-energy jets as e.g. the ones produced in the hadronic decay of Z and W bosons [55]. As a result the energy resolution for these intermediate vector bosons is worse than for single hadrons.
- They have a small sampling fraction, which sets a lower limit on the sampling fluctuations contribution limiting especially the em energy resolution

(e.g. in ZEUS uranium calorimeter was only $18\%/\sqrt{E}$) but also contribute to the hadronic energy resolution.

- To properly detect the neutrons kinetic energy, a signal integration over relatively large volumes ($\sim 1 \text{ m}^3$) and times ($\geq 30 \text{ ns}$) is required.

An alternative approach, adopted by the so called dual-readout method (that will be described in the next chapter), is to measure event-by-event the f_{em} of the hadronic shower. On one hand, it was demonstrated [65] that the Cherenkov light (used as a calorimeter signal source) responds only to the em shower component. This is due to the fact that both the electrons and positrons of the shower (through which the em component energy is deposited) are relativistic until energies below $\sim 200 \text{ keV}$. On the other hand, the shower energy coming from the non-em shower component is primarily deposited by non-relativistic protons generated in nuclear reactions that can generate a signal in active materials as plastic scintillators. For each event, combining the simultaneous measurement of Cherenkov light and of dE/dx , the f_{em} value can be determined and its fluctuations eliminated. Therefore, for dual-readout calorimeters, the measurable quantity related to the invisible energy is the total non-em energy, derived from the measurement of both the em shower fraction and the total deposited energy. Since this method does not require neutron detection, the limitations described above for compensating calorimeters are overcome: any absorber material (as copper or brass) can be used, the sampling fraction can be chosen as desired and large integration volumes and times are not required.

To be thorough, the compensation can also be achieved by the so-called "software compensation" technique: different weights are assigned to the em and hadronic energy deposits, event-by-event. Because the nuclear interaction length is much longer than the radiation length for the usual absorber materials adopted in hadronic calorimeters, this characteristic allows identifying the origin of energy deposits. Indeed, electromagnetic sub-showers are more compact than purely hadronic ones, usually resulting in a higher energy density of the em component. The "software compensation" technique relies on lateral and longitudinal calorimeter segmentations to provide the necessary information for a measurement of the energy density of particle showers. This technique is applied in many experiments and R&Ds, such as the ATLAS calorimeter system [83] and the CALICE AHCAL [84].

Dual-readout calorimetry

” *Dual-readout calorimetry is a technique for the measurement of the high-energy single particle and jet properties, that offers many advantages with respect to the calorimeters currently adopted for this purpose in high-energy frontier experiments.*

In the proposed new experiments for the future e^+e^- colliders, one of the most important design goal is measuring the four-vectors of the particles (i.e. leptons, photons and jets) produced during the collision with the highest precision achievable. On this side, calorimeters are attractive for a number of crucial tasks: (i) they are sensitive to all types of particles (both neutral and charged) produced in the interaction and can provide precise measurement about the event energy flow (missing momentum, jet production, etc.). (ii) Their energy resolution improves with the energy of the impinging particle as $1/\sqrt{E}$. (iii) They are versatile detectors: can be also used in the trigger system (due to their fast signals), provide the direction and the position of the shower, can measure the particle arrival times and their information are useful for particle ID (e.g. the discrimination of electrons and photons from muons and pions). While detection of electromagnetic (em) showers is already performed with a 1% level resolution [85, 86], the success of the next e^+e^- collider generation of experiments, will also depend on the hadron calorimetry quality [73]. These considerations have determined the calorimeter R&D of the last 15 years and two different approaches have been followed: the Particle Flow Analysis (PFA) and the Dual-Readout calorimetry (DR). In the first approach, the tracker provides the charged jet fragment momenta, while the calorimeter measures the energy of the neutral ones. The main problem here is the double counting because also the charged fragments generate showers in the calorimeter. This issue is solved with a fine-grained structure of the calorimeter itself. A detailed review about all the R&D developed can be found in [87]. The second approach is very different: the dual-readout calorimetry is a technique that allows to overcome one of the main limiting factor for the hadronic energy resolution (the non-compensation problem) by the simultaneous measurement of two different types of signals (the Cherenkov and the scintillation light) produced by the shower particles in the

active material using only one calorimeter for both em and hadronic showers. In this chapter, a detailed description of the DR method, together with the results obtained by the related R&D projects will be provided.

3.1 Dual-readout working principle

In a dual-readout calorimeter both scintillation (S) and Cherenkov (C) signals are produced. The mean values of both signals are calibrated (i.e. the ADC-to-GeV conversion factor is measured) with an electron beam of known energy E so that, for em showers, $\langle S \rangle = \langle C \rangle = E$ and the calorimeter response is: $R_{em} = \langle S \rangle / E = \langle C \rangle / E = 1$. Then, the hadronic signals can be written (for each event) as the sum of the em (f_{em}) and non-em shower ($1 - f_{em}$) components:

$$S = E [f_{em} + (h/e)_S (1 - f_{em})], \quad (3.1)$$

$$C = E [f_{em} + (h/e)_C (1 - f_{em})], \quad (3.2)$$

where the $(h/e)_S \neq (h/e)_C$ values are constant and known (these two ratios can be determined with the procedure already described in sec.2.2.2). If f_{em} or $h/e = 1$, the hadronic shower response (R_h) matches the fully em one, i.e. $R_h = 1$, but typically $h/e \neq 1$ and the em fraction is less than one, thus the reconstructed energy is different (usually smaller) than E . Since there are two measured (S and C) and two unknown (E and f_{em}) values, the system has always a simple analytical solution. Therefore, the C/S ratio:

$$\frac{C}{S} = \frac{f_{em} + (h/e)_C (1 - f_{em})}{f_{em} + (h/e)_S (1 - f_{em})} \quad (3.3)$$

is independent¹ of the shower energy and is in a one-to-one correspondence with f_{em} , that can be calculated (for each event) by:

$$f_{em} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1 - (h/e)_S] - [1 - (h/e)_C]}. \quad (3.4)$$

It is possible to rewrite eq.3.1 and eq.3.2 as:

$$S/E = (h/e)_S + f_{em}[1 - (h/e)_S], \quad (3.5)$$

$$C/E = (h/e)_C + f_{em}[1 - (h/e)_C]. \quad (3.6)$$

Fig.3.1 shows the C/E vs S/E diagram of the signals from a generic DR calorimeter for electrons, pions and protons showers. The experimental data for electrons

¹Clearly, this is true only if the h/e ratio is energy independent. Actually, since the instrumental effects are well understood and can be properly considered, this is a good approximation.

are always around the point $[1,1]$ for which f_{em} is 1. On the contrary, the points obtained for hadron showers are clustered along a straight line that links $[1,1]$ to the $[(h/e)_S, (h/e)_C]$ point where f_{em} is 0. The slope of this line (i.e. the θ

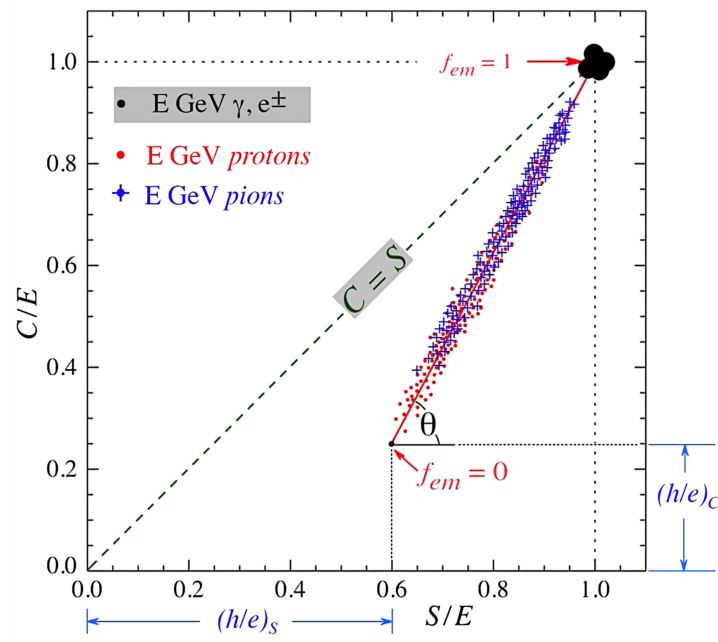


Fig. 3.1: The S-C diagram of the signals from a DR calorimeter for electrons, γ s, pions and protons of the same energy. The clustered around the straight (red) line that links the points where $f_{em} = 0$ and $f_{em} = 1$ are hadron events. Protons and pions have different f_{em} distributions and are thus clustered differently around this line [73].

angle) is energy independent because it is determined only by the two e/h values and thus it depends only on the calorimeter material and geometry. Moreover, even if the f_{em} distributions for hadronic showers produced by different types of hadrons are quite different², the dual-readout calorimeter will always provide signal distributions with the same average value. Thanks to the energy and particle type independence of θ , it is possible to define the parameter:

$$\chi = \frac{1 - (h/e)_S}{1 - (h/e)_C} = \cot(\theta). \quad (3.7)$$

Finally, event-by-event, the S and C signals can be used to reconstruct the energy of each particular hadron shower in an unique way:

$$E = \frac{S - \chi C}{1 - \chi}. \quad (3.8)$$

²This is a result of the baryon number and strangeness conservation in the shower development that prevents the production of a leading π^0 [88].

3.2 The DREAM project

The usefulness of the dual-readout method was demonstrated for the first time in a R&D study for the Advanced Cosmic Composition Experiment at the Space Station ([ACCESS](#)) [89], with an instrument intended to measure cosmic hadrons at the PeV scale. The $1.4 \lambda_{int}$ deep prototype was equipped with both plastic-scintillator (S) and quartz (Q) optical fibres to measure the scintillation and Cherenkov light, respectively. The most important goal reached was that the Q/S signals ratio was found to be a good event-by-event measurement of the shower energy fraction carried by π^0 generated in the first interaction and thus for the shower leakage dominating this thin calorimeter energy resolution (more details can be found in [55] and [89]). Inspired by this success, a $10 \lambda_{int}$ deep calorimeter known as Dual-REAdout Method ([DREAM](#)) was built and tested [90, 91]. The detector basic element (fig.3.2) is a 200 cm long, hollow, extruded copper rod of $4 \times 4 \text{ mm}^2$ cross section in which 3 scintillating and 4 clear fibres are inserted in the 2.5 mm wide hole. The two kind of fibres are split at the end of the rod into different bunches, creating a hexagonal structure read out by 2 PMTs (one for each fibres type). The whole detector consists of 5580 such basic elements, 5130 equipped with fibres. The effective R_M is

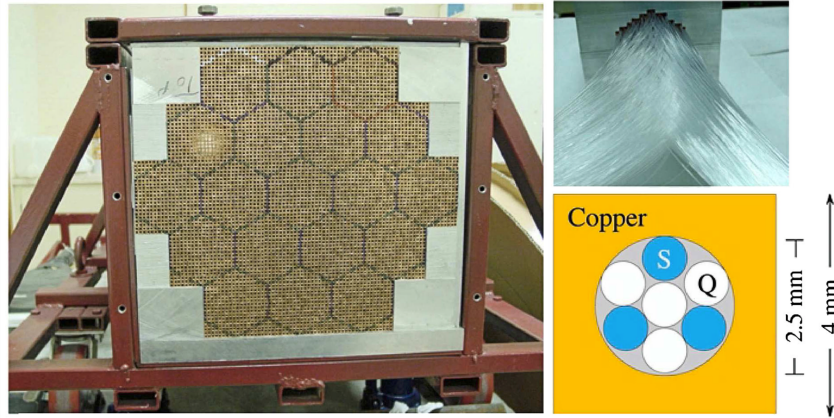


Fig. 3.2: The DREAM calorimeter layout [91].

20.4 mm, X_0 is 20.1 mm, $\lambda_{int} = 200$ mm and the sampling fraction is 2.1%. The principal results obtained by this collaboration are shown below. Fig.3.3 (a and b) represents the signal distributions for 100 GeV π -induced showers. As expected, the two distributions exhibit the typical asymmetric shape for hadrons in a non-compensating calorimeter, reflecting the characteristic f_{em} fluctuations effect. The central values are also smaller than the electrons ones used for the calorimeter calibration, by 36% and 18% for the Cherenkov and scintillating signals, respectively. In fig.3.3c, the $C - S$ scatter plot of the calibrated signals represents the correlation between them, showing the complementarity of these

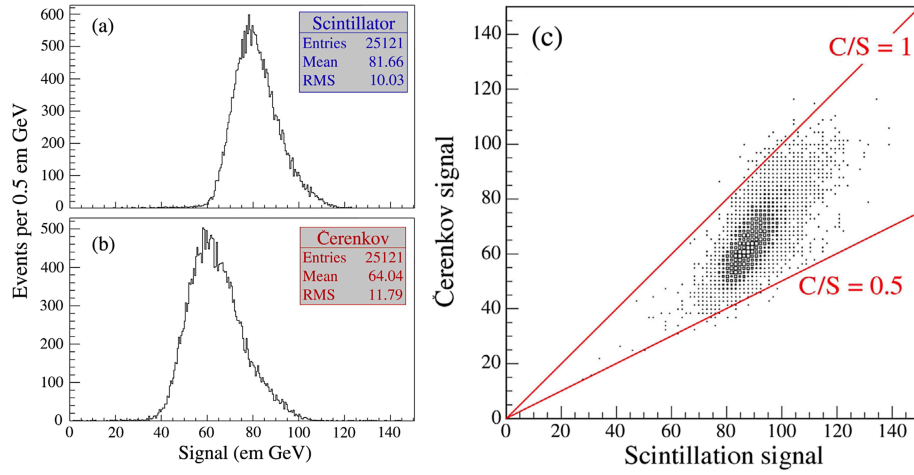


Fig. 3.3: Signal distributions recorded for 100 GeV π^- by (a) scintillating and (b) Cherenkov fibres. (c) The $C - S$ scatter plot showing the correlation between both types of signals. The signals are expressed in the same units used to calibrate the calorimeter [91].

two informations (i.e. events are not distributed along the diagonal) [91]. Thanks to eq.3.4:

$$\frac{C}{S} = \frac{f_{em} + 0.21 (1 - f_{em})}{f_{em} + 0.77 (1 - f_{em})} \quad (3.9)$$

the C/S ratio can be measured and used (in eq.3.9) to extract f_{em} event-by-event. The two values 0.21 and 0.77 are the h/e ratios for Cherenkov and scintillator DREAM structures, respectively. The dual-readout merits are presented in fig.3.4: in the upper plot (a) the overall distribution of the Cherenkov signal for 100 GeV π^- is shown, while the second one (b) represents three sub-samples selected using their f_{em} values. These plots highlight that the overall asymmetric signal distribution is a superposition of many Gaussian distributions. Therefore, thanks to the known f_{em} value, it is possible to correct both S and C signals improving the energy resolution and reproducing correctly the hadronic energy. These results were obtained by DREAM both for 100 GeV single pions and for 200 GeV "jets" (i.e. not real fragmenting quarks or gluons, but unknown composition of multi-particles created by π s impinging on a target placed before the calorimeter [91]). If more than three f_{em} bins are used to plot the average signal of calorimeter (fig.3.5), it is also possible to prove the linear relationship between f_{em} and these signals (confirming eq.3.5 and 3.6) and to check the h/e values used above (measured through the procedure described in sec.2.2.2). The calorimeter response R should indeed vary from h/e (when $f_{em} = 0$) up to 1 (for $f_{em} = 1$). In DREAM, $R = 1$ was reached considering that the real incoming "jets" beam energy was 188 GeV (instead of the nominal value 200 GeV) since some particles produced in the target were not detected (because of the geometrical acceptance and the lateral leakage).

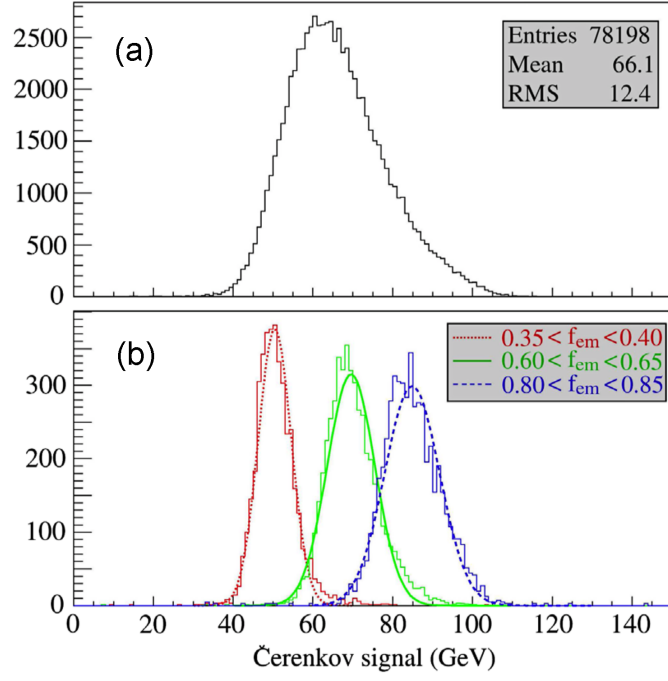


Fig. 3.4: (a) The total Cherenkov signal distribution for 100 GeV π^- events and (b) the same distribution represented as a collection for 3 sub-samples selected on the basis of the measured f_{em} values [91].

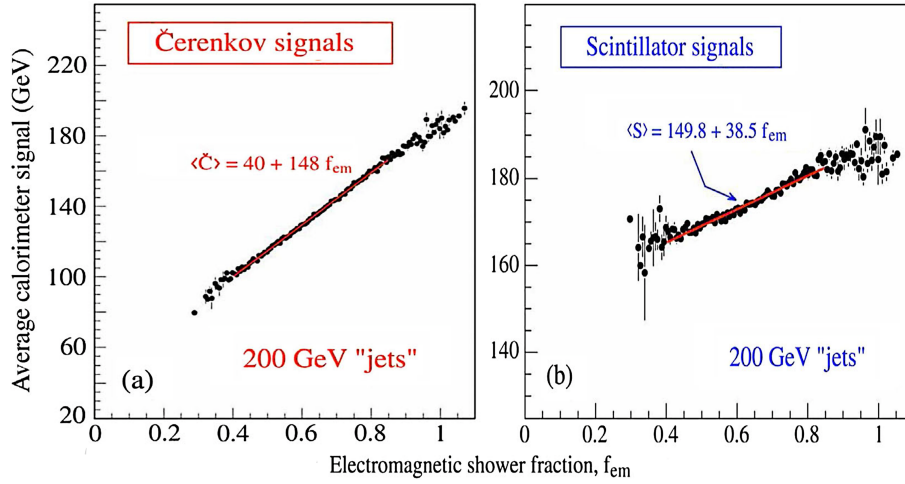


Fig. 3.5: (a) The average Cherenkov and (b) scintillation DREAM signals for 200 GeV “jets” as a function of f_{em} [91].

Fitting the data of fig.3.5, the ratios $(e/h)_S = 188/150 = 1.3$ and $(e/h)_C = 188/40 = 4.7$ can be extracted and inverted to obtain exactly the 0.77 and 0.21 values of eq.3.9. Finally, using the eq.3.8, the correct shower energy value (based on the current measured f_{em} one) can be calculated. Summarising, the comparison between the S and C signals allows: (i) to correct the experimental data for the non-compensation effects, improving in that way the calorimeter energy resolution, (ii) to have more Gaussian signal distributions, (iii) to cor-

rectly reproduce the (single and "jets") hadronic energy. As example, thanks to that method, the 200 GeV "jets" C channel resolution was improved from 14% to less than 5%³, a proper jet energy reconstruction (within a few percent level) was achieved (the raw data before the calibration was 133.1 GeV) and the hadronic signal linearity was restored as well (more details about the procedure and the results can be found in [91]). Any remaining effects were most probably due to side leakage and should be likely eliminated using a larger detector (as demonstrated by Monte Carlo simulations in [92]).

Another interesting result, that will be exploited in the analysis (sec.6.5), is the unique capability of the DR calorimeters to separate the energy loss by muons into radiative and non-radiative components [90] through the simultaneous detection of S and C lights produced in the cascade development. Fig.3.6 represents both the S and C average signals recorded by DREAM from muons traversing the calorimeter along the fibres direction as a function of the μ energy. The response increases with energy since the radiative energy loss component

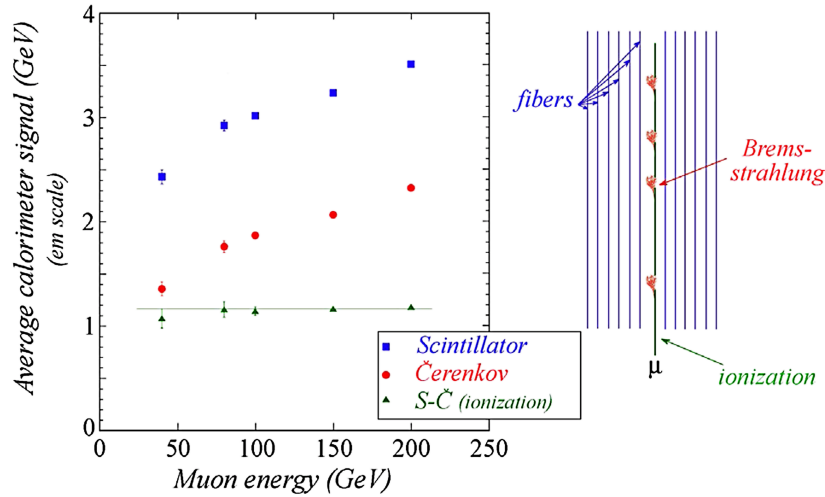


Fig. 3.6: Average values of the S and C signals from muons traversing DREAM, as a function of the μ energy. Also shown is the difference between these signals. All values are expressed in units of GeV, after the calorimeter calibration with electrons [90].

(i.e. bremsstrahlung) to the signal increases as well. Since the primary Cherenkov radiation emitted by the muons falls outside the fibres numerical aperture, the C signal is sensitive only to that component and since both the signals (S and C) are calibrated using em showers, also the S response has the same trend. Moreover, the difference between the signals recorded by both the DREAM channels, is energy independent and represents the muons ionisation energy loss component [90].

³The state-of-the-art HCAL resolution (reached by CALICE Collaboration) is: $50\%/\sqrt{E} \oplus 2\%$.

3.3 The RD52 project

Following the DREAM project results, the new RD52 Collaboration was formed (as one of the officially supported CERN detector R&D programs). In this section the principal results reached by this new R&D project are summarised.

3.3.1 Crystals studies

After eliminating the dominant effect, due to f_{em} fluctuations, the energy resolution of the DREAM calorimeter was limited by other fluctuation sources: (i) the side leakage, (ii) the sampling fluctuations, (iii) the very low Cherenkov light yield ($\sim 8 C$ photoelectrons per GeV). Only the latter effect contributed $35\%/\sqrt{E}$ to the final energy resolution. While the first issue can be solved adopting a sufficiently large detector, the other two points could, in principle, be reduced by using crystals as active material. In particular for some high- Z crystals, like PWO_4 (lead tungstate) or $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (also known as BGO, bismuth germanate), the Cherenkov light may account for more than 15% of the total signal [93]. In this configuration the main goal is to separate efficiently the Cherenkov light from the more dominant scintillation signal. For the proof-of-concept PWO_4 crystals were used. The main disadvantage of this material is the small light yield (less than 1/300 of the widely used NaI(Tl) and CsI(Tl) [93]), while the large refraction index allows a reasonable Cherenkov light production (as said above up to 15% of the total crystal signal). Both the ends of the crystal were equipped with two PMTs. The Cherenkov light is emitted in a cone with a characteristic angle θ_C that depends on the refractive index n and the velocity β as $\cos(\theta_C) = 1/n\beta$. Therefore, depending on the crystal orientation θ , the directional emitted light contributes differently to the left and right PMT signals (L and R respectively). The contribution of the Cherenkov light can be estimated by measuring the response asymmetry $(R - L)/(R + L)$ as a function of θ [93]. It was found that the Cherenkov component is more efficiently detected when the crystal axis is oriented at θ_C with the shower axis. Another important feature, to distinguish the scintillating and the Cherenkov contributions, is the different time structure of the two signals and the emitted light spectra. In other words, whereas the difference in angular dependence demonstrates that some of the emitted light in the crystal is due to the Cherenkov effect, the combination of time structure and spectral information allows to separate the different contributions in real-time. This was proved testing a BGO-based calorimeter [94]. In this crystal the Cherenkov radiation is only a small part of the emitted light, but some BGO characteristics make it suitable for DR calorimetry [95]. In particular, this crystal presents a longer scintillation decay time (~ 300 ns)

and the scintillation spectrum peaks at 480 nm, while Cherenkov radiation has a λ^{-2} spectrum. In fig.3.7 the time structure of BGO signals, recorded with a UV filter, is shown. The "prompt" component observed in the UV signal is due

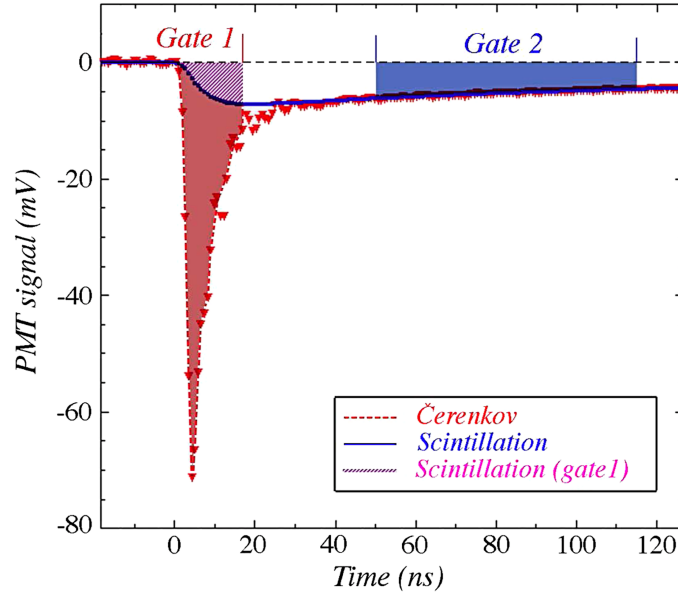


Fig. 3.7: Time structure of a typical signal from 50 GeV electrons shower measured in the BGO em calorimeter (equipped with a UV filter). The UV signals were used to measure the relative contributions of C (gate 1) and S (gate 2) light [94].

to the Cherenkov radiation. A small fraction of the scintillation light passes the filter, allowing to reconstruct the C/S ratio event-by-event using only one signal. More in detail, an external trigger opens two gates: the first (gate 1 in figure) of 10 ns integrates the "prompt" component, the second (gate 2), delayed by 30 ns and 50 ns wide, integrates only the scintillation signal. The latter can also be used to extract the S contribution to the light collected in gate 1 (more details in [94]). After many studies about different crystals and many efforts to fit the dual-readout calorimeter requirements with them [94, 96, 97], the RD52 Collaboration decided that this was not the promising development for DR calorimetry. The main problem was the strong C light attenuation in crystal, due to the short-wavelength emitted light. The short attenuation length induces some response non-linearities and causes the signal dependency on where the light is produced [98]. Moreover, some results on energy resolution did not exhibit a sensible improvement (also in this case the contribution of Cherenkov photoelectrons statistics to the energy resolution was $13.5\%/\sqrt{E}$) in respect to the fibre sampling calorimeter. Finally, the long integration time required to separate the two types of signals, together with the high cost of the crystals and the fact that they should be prone to radiation damage effects, had an influence to pursue other alternatives.

3.3.2 RD52 fibre calorimeter

The main goal in the new DR fibre calorimeter design was the reduction of the two main factors that limited the DREAM hadronic resolution, i.e. the low C signal (~ 8 Cpe/GeV) and the sampling fluctuations. Fluctuations in the number of C photoelectrons could be reduced increasing the Cherenkov Light Yield (LY). This could be done in three ways: (i) increasing the PMT photocathodes Quantum Efficiency (QE), (ii) increasing the Numerical Aperture (NA) of the C fibres ($LY \propto NA^2$) and (iii) aluminizing their upstream end. Moreover, sampling fluctuations can be limited improving the calorimeter sampling fraction: (i) maximising the fibres packing fraction (i.e. doubling the DREAM fibres number per unit) or (ii) using a different absorber structure embedding each fibre individually (instead of in groups). Fig.3.8 compares the different structures of the RD52, DREAM and SPACAL (spaghetti calorimeter) on the same scale. In

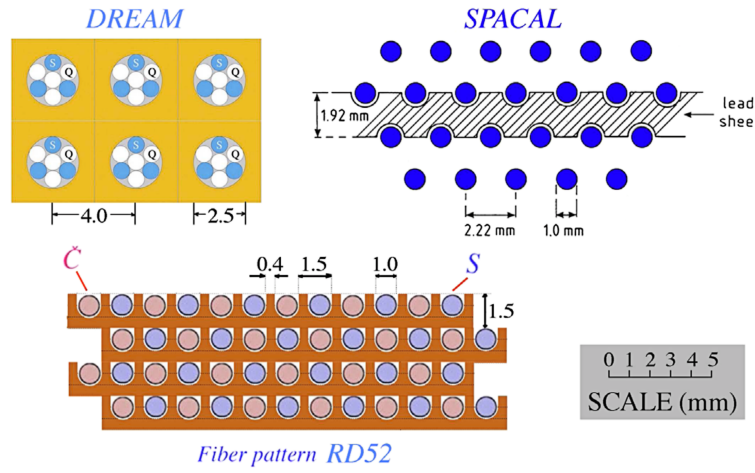


Fig. 3.8: The structure of: the copper- based RD52 fibre calorimeter [99], DREAM [91] and SPACAL [77].

the RD52 modules the number of fibres per unit volume, and thus the sampling fraction, was doubled if compared to DREAM. Also the sampling frequency increased since the RD52 absorber structure embedding each fibre individually. A sensitive improvement in the em energy resolution was thus expected because of the sampling fluctuations dependence on both these factors (eq.2.14). In theses new calorimeters, the Cherenkov LY was increased by substituting the DREAM quartz fibres ($NA = 0.33$) with clear plastic ones ($NA = 0.50$) and increasing the C fibres density by $\sim 65\%$. Furthermore, new PMTs with higher QE were adopted. The number of Cherenkov photoelectrons was increased from 8 to 33 Cpe/GeV [99]. Each RD52 module consisted of 4 towers, read out by 8 PMTs (2 for each tower, 1 for S and 1 for C signals). The readout (based on a Domino Ring Sampler circuit [100]) allowed to measure each signal

time structure with 5 GHz sampling rate (i.e. 0.2 ns time bins). Finally, since the production of copper-based absorber plates compliant with the required specification was very difficult, the collaboration built, at the early R&D stages, nine lead-based modules (which were easier to extrude), adopting at a later stage also several copper-based ones.

Electromagnetic performance

All the RD52 modules were tested in the H8 beam of CERN's Super Proton Synchrotron (SPS) with electrons beams of energies from 6 up to 80 GeV. Fig.3.9 shows a comparison between the response functions (both scintillating and Cherenkov) for 40 GeV electrons, measured for RD52 and DREAM. As expected

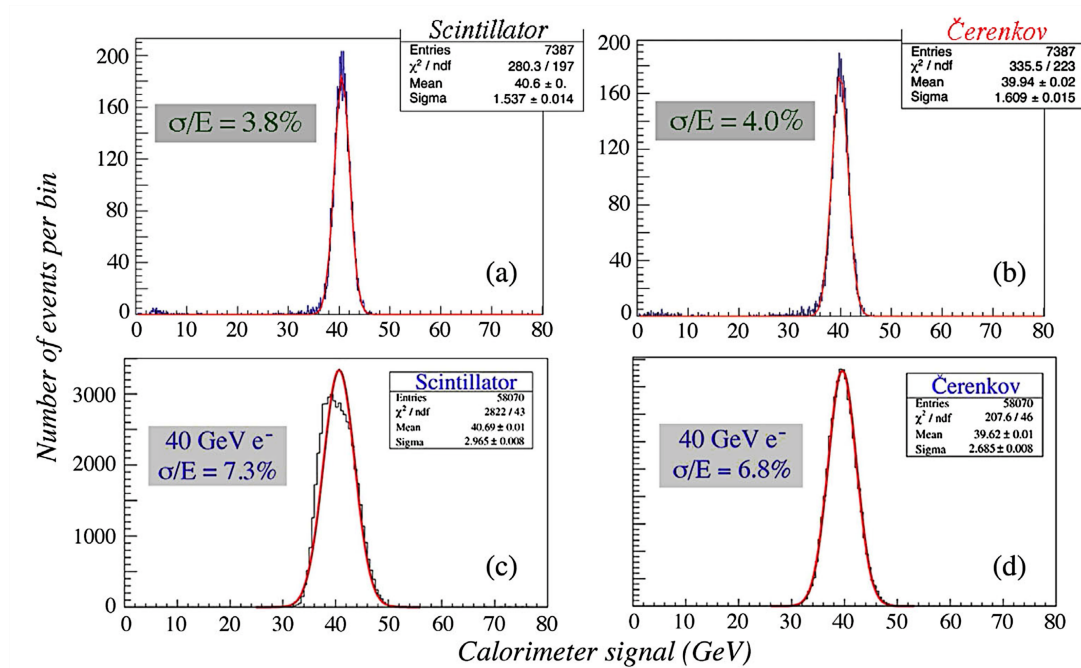


Fig. 3.9: Comparison between (a, b) the em S and C response functions of the RD52 copper-fiber calorimeter [99] and (c, d) the original DREAM copper-fiber calorimeter [101], for 40 GeV electrons. The electron beam incidence angle with the fiber axis (θ , ϕ) was (1.5° , 1.0°) for RD52 and (3.0° , 2.0°) for DREAM.

the energy resolution was considerably improved and the response functions were more Gaussian (especially for S signals) even if the electron beam incidence angle with the fiber axis (θ , ϕ) was (1.5° , 1.0°) for RD52 [99] and (3.0° , 2.0°) [101] for DREAM. Indeed, the scintillation resolution was found to have a dependence on the particles incidence angle if it is small ($<3^\circ$) and the electron energy is high (a dedicated discussion of that effect will be provided in sec.3.3.3). Thus, the improvement in the em S resolution is even larger than what suggested by fig.3.9. This energy resolution improvement was also due to the new fibres pattern adopted in RD52 modules, because in this case the S and C readout are

completely independent sampling structure (in DREAM both fibre types sampled the shower in the same way). The em energy resolution measured by the RD52 copper-fibre module with C , S fibres and with the combination of both signals is shown in fig.3.10. The sampling fluctuations contribution to the em resolution was found to be $8.9\%/\sqrt{E}$, while the term due to the number of Cherenkov photoelectrons fluctuations increased the total stochastic term to $13.9\%/\sqrt{E}$. It is important to highlight that the combined signal deviates from the expected $E^{-1/2}$ scaling, adding a constant term of less than 1%. A proper data analysis [99] showed that this term was due to the S response dependence on the beam impact point but also that this dependence did not affect the linearity response of the calorimeter (the average signals were proportional to the electron energy to within 1%).

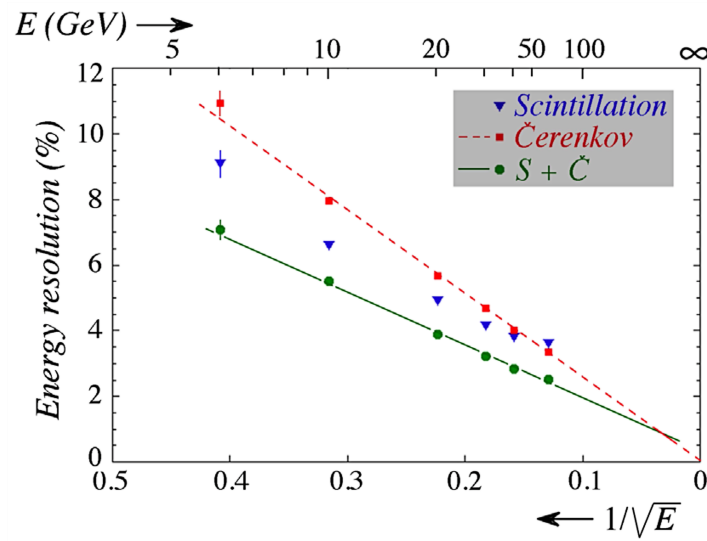


Fig. 3.10: The em energy resolution obtained with the RD52 copper-fiber calorimeter for the scintillation and Čerenkov signals, and for their combination [99].

Particle identification

The RD52 calorimeters are longitudinally unsegmented, i.e. there is no separation between em and hadronic sections. This eliminates the inter-calibration issues of the signals coming from the different longitudinal sections and allows a 4π calorimeter structure more hermetic and homogeneous, with less "dead areas" caused by the need to transport signals to the detector outside part. Even if the traditional longitudinal segmentation has advantages in particle identification, especially for γ s and electrons, it is demonstrated [102] that also a DR fibre calorimeter offers excellent possibilities to distinguish between different particle types, in particular between hadrons and electrons. In a dedicated study [102] 4 different ID methods, based on the DR signals characteristics, were used

to distinguish between electrons and pions. The data were obtained from 60 GeV electrons and pions beam. Fig.3.11 summarises the results of these four methods. The first one is based on the large difference between the two lateral

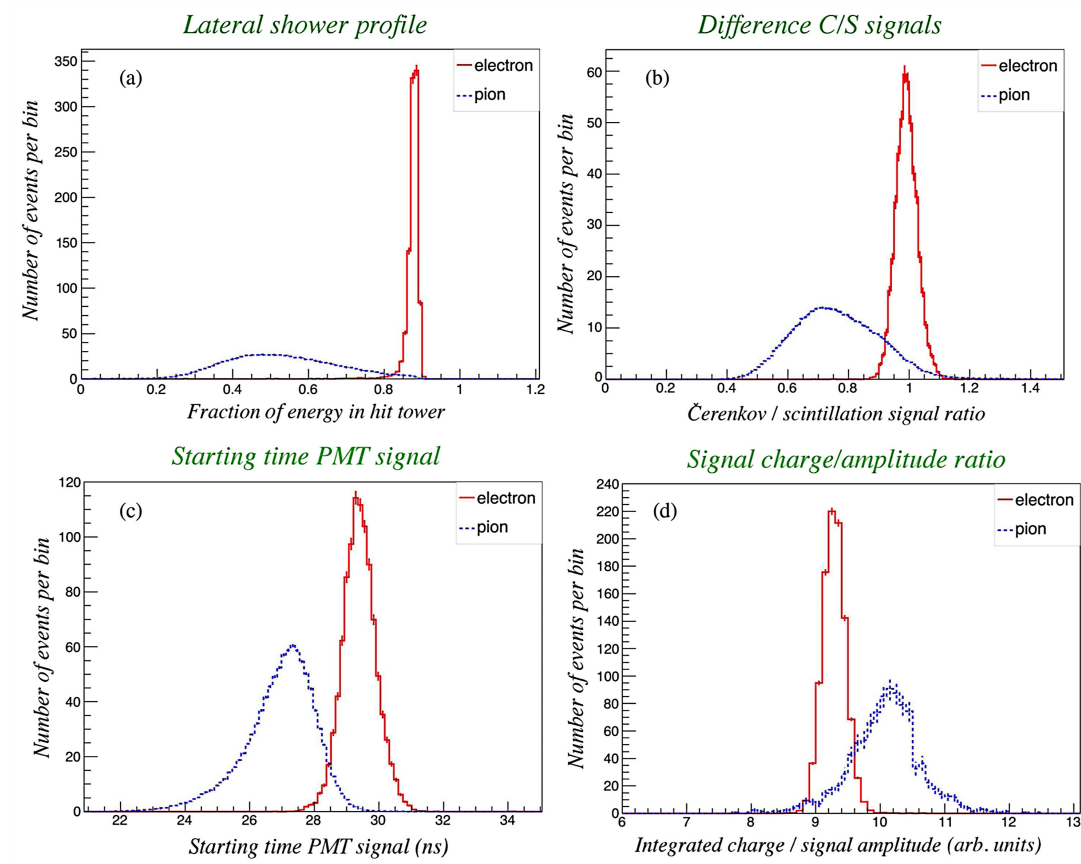


Fig. 3.11: (a) The total signal recorded fraction by the tower in which the particle entered. (b) The C/S ratio of the event. (c) The PMT signal starting time, measured with respect to an upstream trigger signal. (d) The ratio of the total integrated charge and the signal amplitude. Data obtained with 60 GeV electrons and pions beams [102].

shower sizes. Thanks to the fine lateral granularity of the RD52 module, it was possible to measure precisely the fraction of the shower energy deposited in the tower located on the shower axis. The distributions of these values (both for electrons and pions) are shown in fig.3.11a. The second method is based on the essence of the dual-readout method: since the module signals were calibrated using electrons, the C/S ratio is 1 for electrons (by definition) and smaller than this for hadrons (to an extent determined by e/h and f_{em}). It is represented in fig.3.11b. Another interesting phenomenon (used for the latter methods) is that the speed of the light produced in the fibres is c/n (where n is the fibres reflective index), while the particles that produced that light typically travel at c [102]. Therefore, the light produced deeper inside the calorimeter (i.e. coming from the hadronic showers) reaches the PMT earlier than for the one produced close to the calorimeter front face (and induced by electrons). The

third method is based on the PMT signals starting time, measured with respect to an upstream trigger signal (3.11c). The last method uses the same phenomenon, but measures the ratio of the total integrated charge and the amplitude of the signal (3.11d): since the light is produced over a larger region in depth for pions than for electrons, the width of the hadron signal is larger. Combining all these e/π discrimination methods with a multivariate analysis, an electron identification of 99.8% was obtained with a pion mis-ID of 0.2% [102]. The finer lateral segmentation achievable by a DR calorimeter is crucial for recognising closely spaced particles, especially electrons near to other showering particles, as separate entities. If each single fibre is coupled to a Silicon Photomultiplier, it can be read out separately and the particle separation capabilities can improve considerably. It will be one of the main topic of chapter 7, in which all these results will be extensively discussed and compared with the ones obtained by a fully projective DR calorimeter simulation.

Hadronic performance

Unfortunately, the hadronic performances were measured only for the RD52 lead-based module that was, as the DREAM one, too small for a full hadronic shower containment. The calorimeter has 72 different signals (36 Cherenkov and 36 scintillating) and it is composed by 9 modules (subdivided in 4 different towers each one). A 20 plastic scintillations counter array (surrounding the detector) provides a rough estimation of the hadronic shower leakage. Each calorimeter module was calibrated using electrons while for the leakage counters a muon beam was used [103]. Then, pion beams of 20, 60 and 100 GeV were sent into the calorimeter central region. Fig.3.12 shows both the S and C signal distributions obtained, together with the ones derived by the dual-readout method [104]. The last column highlights the usual DR method improvements, i.e. Gaussian, relatively narrow, signal distributions centred around the correct mean value. Fig.3.13 represents the hadronic energy resolution obtained for the C channel alone and applying the dual-readout method. The latter scales with $E^{-1/2}$ unlike the one obtained using a single channel. The result of about $70\%/\sqrt{E}$ is not so different from the one obtained with DREAM ($64\%/\sqrt{E}$) since for both detectors the leakage fluctuations are the dominant term of the hadronic energy resolution. This statement is supported by a detailed data analysis [103] showing that a considerable improvement of the energy resolution is reached when the leakage counters signals are considered for the containment, even if they provide only an incomplete measurement of that. An elaborate Geant4 based Monte Carlo simulation has been performed [92] in order to estimate the expected hadronic energy resolution of a DR calorimeter that contains the full

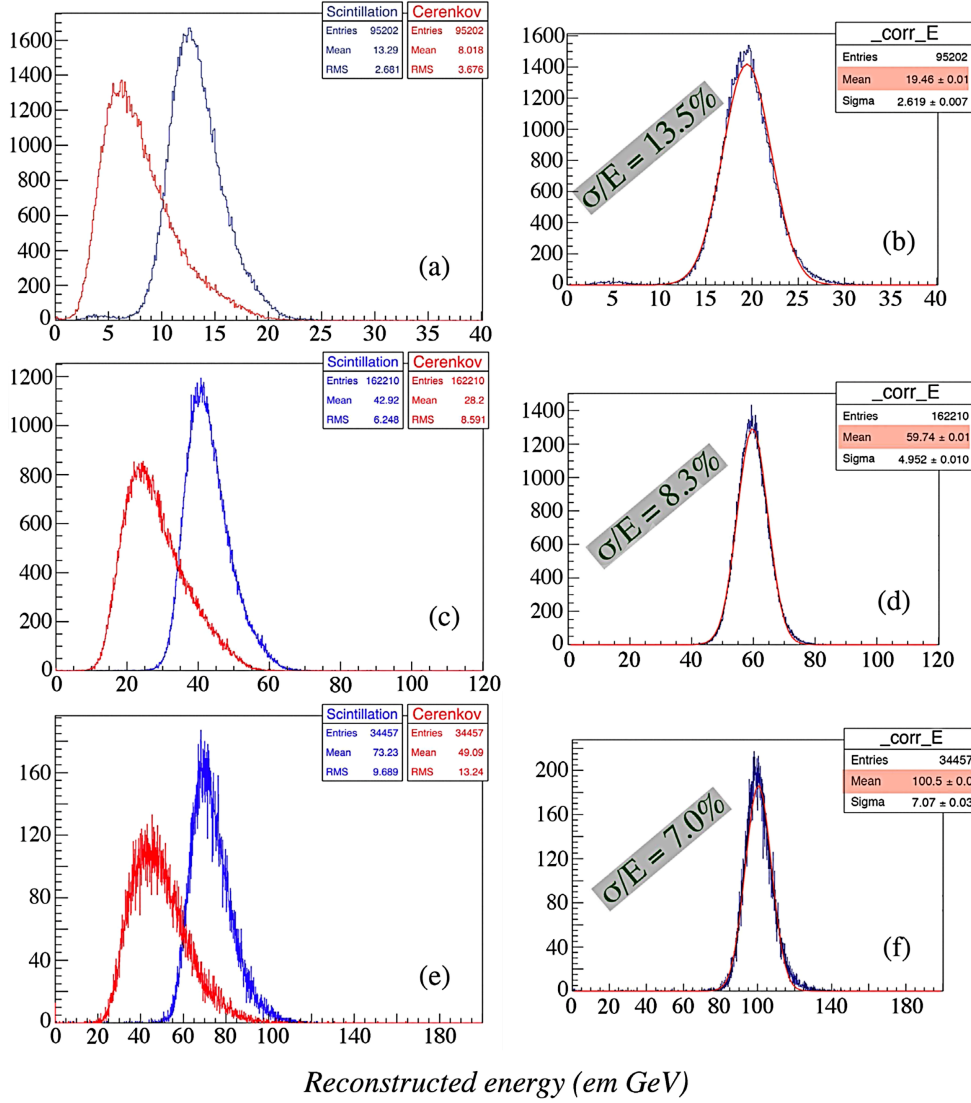


Fig. 3.12: Scintillation and Cherenkov signal distributions for 20 (a), 60 (c), and 100 (e) GeV π^- beam in the RD52 lead-fibre calorimeter. (b), (d), (f) are the signal distributions obtained using the dual-readout method, with $\chi = 0.45$ [104].

shower. The response of a copper-based RD52 calorimeter of $65 \times 65 \text{ cm}^2, 10\lambda_{int}$ deep, was simulated for 100 and 200 GeV pions beams [92]. The simulation validation was done comparing its results with the DREAM experimental data. While some aspects like the C signal and the radial profiles were well described, the simulated S signal distribution was found to be less asymmetric, more narrow and with a reconstructed beam energy systematically too low. This is due to the Geant4 poor description of the non-relativistic component of the shower (dominated by nuclear processes). Anyway, using the high precision version of the hadronic shower simulation package (FTFP_BERT_HP), which provides a much precise treatment of neutrons, the average reconstructed energy signal was equal to the nominal one within a few percent (95.6 GeV for a nominal 100

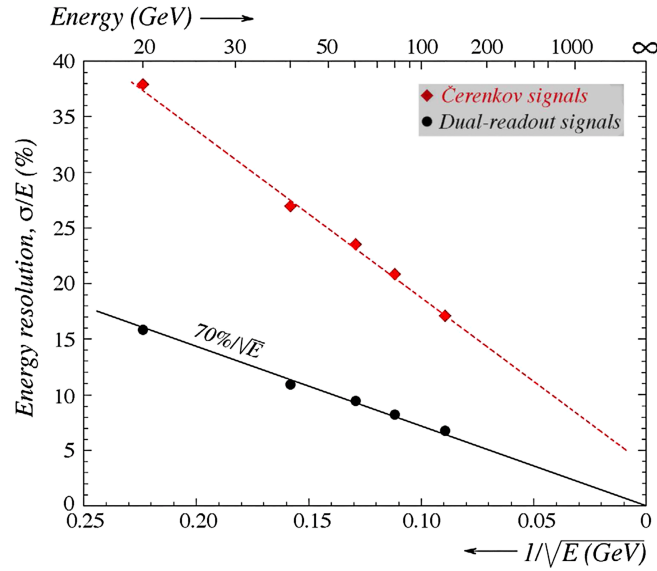


Fig. 3.13: The RD52 lead-fiber calorimeter hadronic energy resolution for single pions. Shown are the results obtained for the C signals alone, and applying the DR method [103].

GeV pions beam and 191 GeV for the 200 GeV one) and the energy resolution was also improved (3.2% and 2.4% for the 100 and 200 GeV beams respectively) [105]. These results are valid for single hadrons, the jet energy resolution of a copper-based DR module should be better than that of high- Z compensating calorimeters because the e/mip ratio is closer to one [106].

3.3.3 Other results

Electromagnetic shower profiles

The fine grained RD52 calorimeter allows to address some precise measurements of the lateral em shower profile, obtained by moving a 1 mm wide electron beam across the boundary of two neighbouring towers and measuring the fraction energy deposited in each of them. In fig.3.14 the S lateral profile for a 100 GeV electron beam is shown. About 20% of the energy is deposited in a cylinder with a radius of 1 mm about the shower axis [99]. This feature has relevant consequences, especially for calorimeters where the distance between fibres of the same type is more than 2 mm. Indeed, the generated signals are strongly dependent on the impact point of the incident particle, if these enter parallel to the calorimeter [55]. As the incident angle increases, this dependence is reduced since the collimated shower component is sampled more and more uniformly as the rest of the shower. Moreover, at small incident angles, this effect results, in first approximation, in an additional term, energy independent, to the em energy resolution. This angle dependence affects only the S signal, since the collimated shower component does not contribute to the C one: the

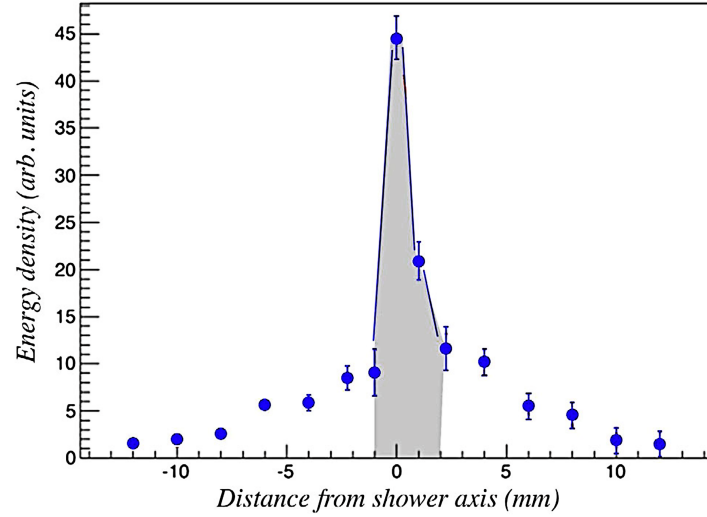


Fig. 3.14: The S lateral shower profile of 100 GeV electron beam in the RD52 lead-fiber calorimeter [99].

Cherenkov light, produced by particles travelling in the same fibres direction, falls outside the fibres numerical aperture. As shown in fig.3.10, the constant term added to the em resolution in the scintillation signal (blue line), is not present in the Cherenkov one (red line). Moreover, it was demonstrated [107] that the calorimeter response is independent to the incidence angle. The average signal per GeV deposited energy for 20 GeV electrons was measured to be the same (within 1%) for angles ranging from -4° to $+4^\circ$. This is true both for S and C light. Therefore, the small position-dependent differences in the early shower component sampling fraction, which affect the em energy resolution, do not result in systematic response variations as a function of the incidence angle. Another important result, reached by RD52, is about the Molière radius (R_M) and the lateral calorimeter granularity: the latter is usually chosen on the basis of R_M but, as discussed above, the em shower has a pronounced and collimated core whose radial dimension is smaller than this. Therefore, a fibres calorimeter as RD52 one, with a granularity finer than a Molière radius, can help to resolve and recognise the jets em component.

Time structure

The time development of the calorimeter signal provides important information that could be used, as already described: (i) to extrapolate the C and S components of light produced in crystal calorimeters (ii) to distinguish showers started by electrons and photons. Especially for fibres calorimeters, the timing information is crucial. Indeed, the depth at which the light is emitted fluctuates at the level of a nuclear interaction length (i.e. ~ 25 cm for RD52 calorimeter)

and this can affect the calorimeter hadronic performances. The light attenuation for the fibres used by RD52 has been measured for both scintillating (~ 8 m) and Cherenkov (~ 20 m) channels. The depth fluctuations in light production can produce an additional constant term of about 1% to the hadronic energy resolution. The calorimeter performances can be improved by an event-by-event measurement of the light production depth. It can be extrapolated thanks to the fact that the light produced in the fibres travels at a speed c/n (e.g. for the typical polystyrene fibres the refractive index is 1.59 and the light speed is 17 cm/ns) while the particle that initiates the shower travels at a speed close to c . In fig.3.15 it is shown how the PMTs starting time is expected to change with the depth at which the light is produced. The green line is the curve space vs time of

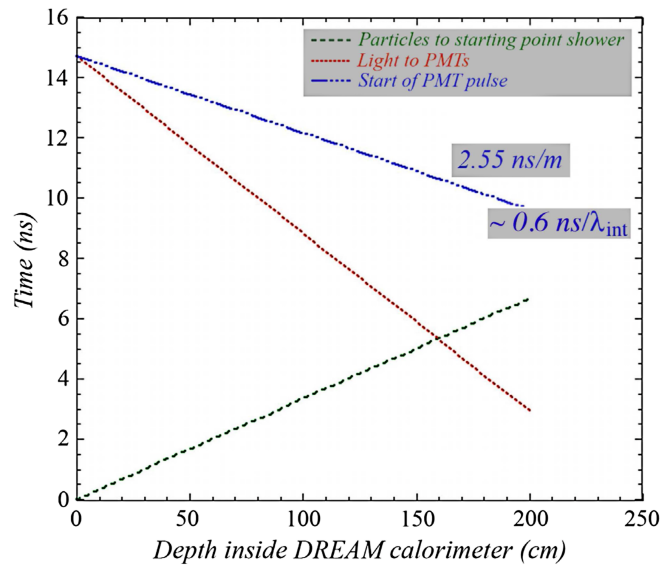


Fig. 3.15: Dependence of the PMT signal starting time (blue line) on the average depth (z) inside the calorimeter where the light is produced, together with the time of the particles to travel to z (green line) and the one it takes the light to travel from z to the PMT (red line) [102].

the particle travelling at c , the red one represents the light travelling at 17 cm/ns and the blue curve is the sum of the previous two contributions: higher the depth, earlier the starting time. For the RD52 lead module the variation of time with depth was 2.55 ns/m. This was measured with 60 GeV pion and electron beams, using a Time to Digital Converter (TDC). The start was performed by the signal of the scintillator used as trigger installed upstream of the calorimeter while the stop was given by the first signal in the central tower of the module. Fig.3.16 represents the time distribution recorded by the TDC for electrons and pions. The light is produced, on average, ~ 12 cm inside the calorimeter, with an event-by-event variation of few cm. The pions distribution peak is about 1.5 ns earlier than the electrons one. This means that the light produced by pions is emitted, on average, 60 cm deeper inside the calorimeter.

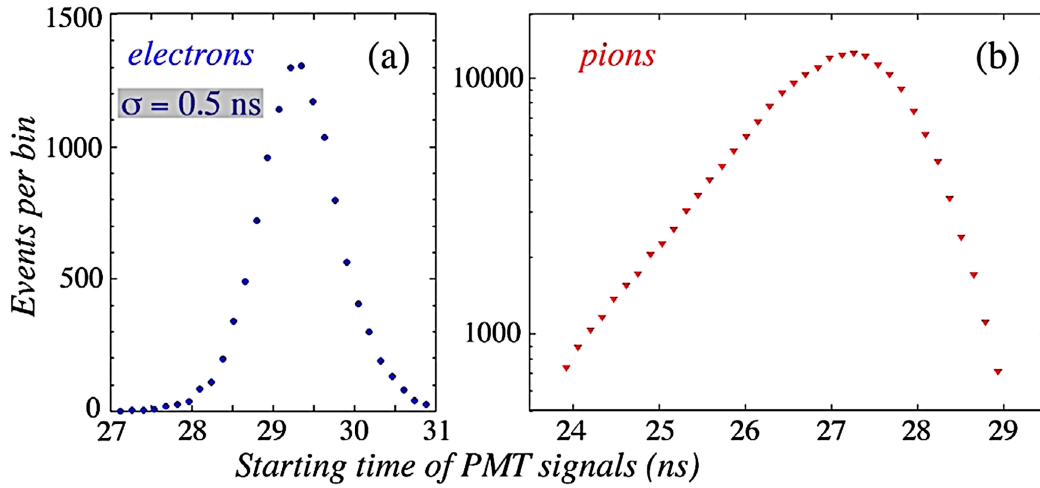


Fig. 3.16: The DREAM S signals starting time measured distribution, produced by (a) 60 GeV electrons and (b) 60 GeV pions [102].

3.4 The Silicon Photomultiplier based readout

As discussed above, in the past 15 years, the properties of DR fibre calorimetry have been extensively studied by the ACCESS, DREAM and RD52 Collaborations and its properties was shown to be very suitable for experiments at proposed future e^+e^- colliders. In these modules, PMTs were used to detect the signals from the two types of fibres, which needed to extend about 30 cm from the rear of the calorimeter to allow bunching and separation. In order to make this detector more suitable for the future e^+e^- colliders, starting from 2016, this readout was replaced by a SiPM-based system. These devices, offer important advantages with respect to PMTs:

- They allow to eliminate the forests of optical fibres that stick out at the rear end of the calorimeter, producing an oversampling of late developing hadronic showers.
- They can operate in a magnetic field (e.g. IDEA will have a 2 T one).
- They have a larger PDE. This is important since fluctuations in the number of C photoelectrons is a limiting factor for the DR calorimeter energy resolutions.
- Their compact readout allows to separate the calorimeter into longitudinal segments, if so desired.

There are also potential drawbacks as the SiPM non-linear response and the signal saturation. Another major challenge for this particular detector is the optical cross-talk between fibres: SiPMs have to read the signals from a grid of closely spaced fibres of two different kinds, where the light intensity in the C type is more than an order of magnitude smaller than that in the S ones. In the next chapter an overview of the main SiPMs parameters and characteristics will be provide, while in chapters 5 and 6 will be presented the system and the results obtained in the first beam tests of the small DR fibre calorimeter prototype with SiPM readout.

Silicon Photomultipliers

” *Silicon Photomultipliers are the state of-the-art light sensors with unprecedented photon number resolving capability and single photon sensitivity.*

SiPMs, also referred to as Multi Pixel Photon Counters (**MPPCs**) or Geiger mode Avalanche Photo-Diodes (**G-APDs**), are solid state light sensors featuring high internal gain, single-photon sensitivity, unprecedented photon number resolving capability, high Photon Detection Efficiency (**PDE**) and dynamic range, excellent time resolution, low bias voltage and magnetic field insensitivity. They represent an interesting alternative to the vacuum-based technologies due to their compactness, ruggedness, low cost and high-volume production capability. SiPMs benefit from the fast evolution of the silicon technology and the investment of different companies in terms of high quality mass production and design flexibility, enabling also a class of new applications spreading from the industrial and consumer technology sectors to fundamental research, as High Energy Physics (**HEP**). In this chapter, an overview of the main properties of these detectors will be provided, together with the description of the most important SiPM parameters and with some examples of applications in particle physics detectors.

4.1 Basic operation principles

SiPM is a high density (up to $10^4/\text{mm}^2$) matrix of Single-Photon Avalanche Diodes (**SPADs**), called pixels¹ or cells, arranged on a common substrate with a common load and connected in parallel to a single readout output. The photo-diodes are usually p/n junctions, designed to be biased few volts above breakdown voltage (V_{Bk}) in limited Geiger-Müller regime. due to the high electric field in the depletion region, initial charge carriers generated by an absorbed photon (or by thermal effects, sec.4.3.1) trigger an exponential charge multiplication by impact ionization (fig.4.1). The process is stopped when the

¹Even if they are not indexed.

current spike across the quenching resistance induces a drop in the operating voltage. due to its intrinsic charge amplification mechanism, requiring only a single carrier to detect the light pulse, SPAD features high single photon sensitivity. As a first order approximation, each diode provides the same signal with $\sim 10^6$ gain independent of the number of primary carriers generated. Thus the SiPM can be seen as a collection of binary pixels: by counting the number of fired cells it can provide information about the intensity of the incoming light. The typical SiPM cells size ranges between $10 \times 10 \mu\text{m}^2$ and $100 \times 100 \mu\text{m}^2$

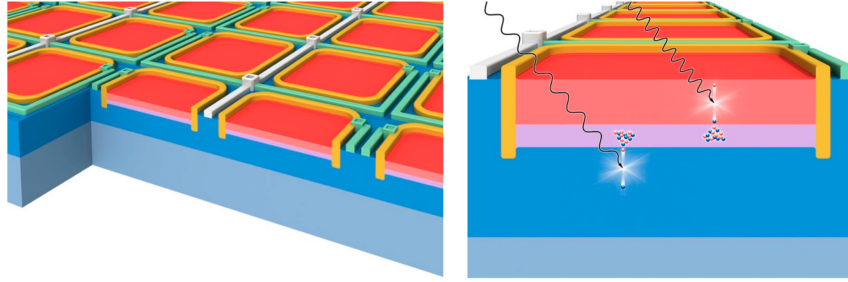


Fig. 4.1: A picture of the SiPM structure and operating principle [108].

(fig.4.2a), while the SiPM total areas from $1 \times 1 \text{ mm}^2$ up to $6 \times 6 \text{ mm}^2$ are available (fig.4.2b). Some companies have been also engineered arrays up to $24 \times 24 \text{ mm}^2$ of active area, relying on four side buttable sensors with Through Silicon Via (TSV) interconnection technology [109].

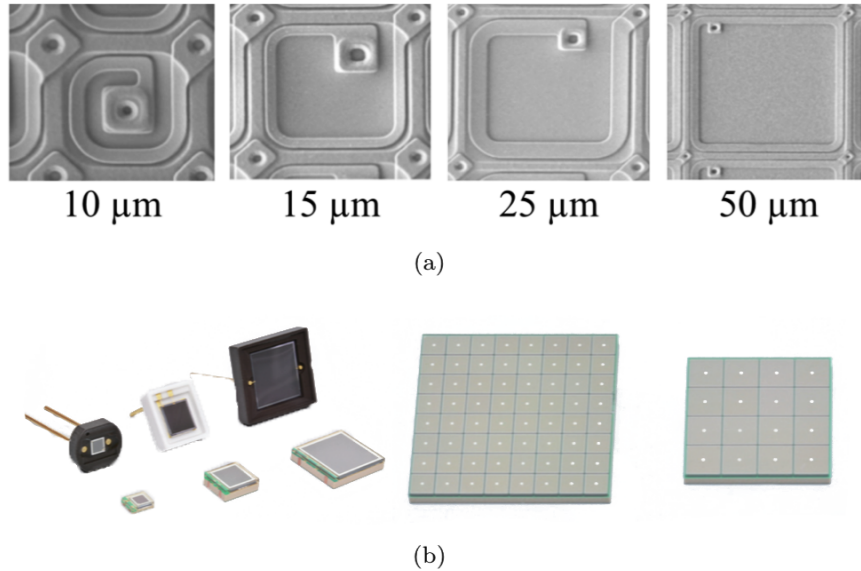


Fig. 4.2: (a) Microphotograph of different cell size SiPM with MQR. (b) Hamamatsu SiPM of area of $1 \times 1 \text{ mm}^2$, $3 \times 3 \text{ mm}^2$ and $6 \times 6 \text{ mm}^2$ and arrays of 8×8 and 4×4 elements for a total active area of $24 \times 24 \text{ mm}^2$ and $12 \times 12 \text{ mm}^2$ [110].

4.1.1 Single photon avalanche diode

Fig.4.3 represents an illustrative picture of the SPAD doping structure: applying a reverse bias, the p-side is fully depleted and generates an electric field similar to that shown on the right side of the figure. The thin (0.1-1.5 μm) n+ side receives

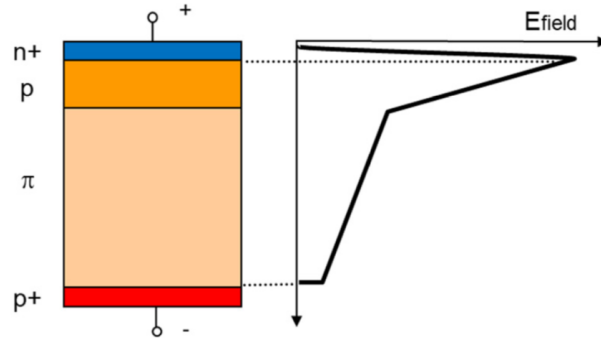


Fig. 4.3: A sketch of a SPAD doping structure and electric field in operation mode [111].

the impinging photons through a window, while the multiplication region of high electrical field (in the order of few 10^5 V/cm) is placed between the n+ and π layers and is thin 0.7-0.8 μm . Its nearly uniform field allows the electron-hole pairs separation and drifts them towards the n+ and p+ sides, respectively. When the drifting electron reaches the junction volume, it is accelerated by the high field and initiates the avalanche by impact ionization.

4.1.2 Electrical model

The SPAD can be modelled as the circuit of fig.4.4: a parallel connection between the inner depletion region capacitance (C_D) and the internal space-charge resistance of the avalanche region (R_S). Each single photodiode has in series a

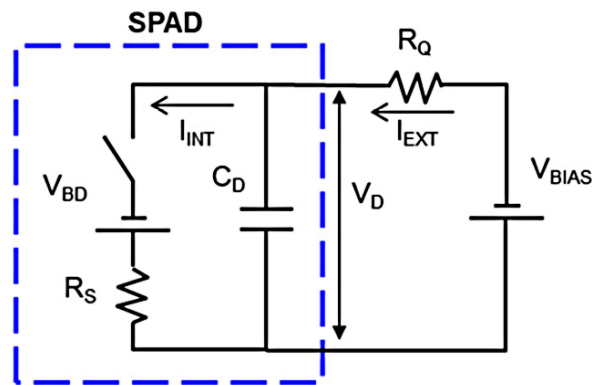


Fig. 4.4: SPAD electrical model with a resistor (R_Q) as quenching element [111].

quenching resistor (R_Q). The current flowing through the switch is called I_{INT} ,

while the external current is the I_{EXT} . Before photon detection, the switch is open (OFF condition) and C_D is charged to the bias voltage (V_{Bias}). Upon an avalanche discharge, the switch is closed (ON condition) and the C_D capacitance discharges through the resistor R_S down to the breakdown voltage with a time constant $\tau_D = C_D R_S$ [111]. I_{INT} decreases exponentially from $(V_{Bias} - V_{Bk})/R_S$ while I_{EXT} increases with the same time constant τ_D . Both currents tend to the asymptotic value: $(V_{Bias} - V_{Bk})/R_Q$. In this phase the diode current is low (less than 10-20 μA), and a statistical fluctuation can quench the avalanche bringing the number of carriers in the multiplication region to zero. The switch is again open and the circuit returns in its initial OFF configuration. I_{INT} goes suddenly to zero, while I_{EXT} decreases exponentially. The capacitance C_D starts recharging to its original V_{Bias} with a time constant (called cell recovery time) $\tau_r = C_D R_Q$. Finally the SPAD is ready to detect a new photon [112]. The easiest way to obtain a SPADs array is to connect them in parallel (building a SiPM). The SiPM current signal is the sum of the I_{EXT} coming from each SPAD fired by a photon and its amplitude and/or the signal charge are proportional to the impinging light intensity. Fig.4.5 represents the current flowing during a discharge of a SPAD and its output signal time development. due to the very

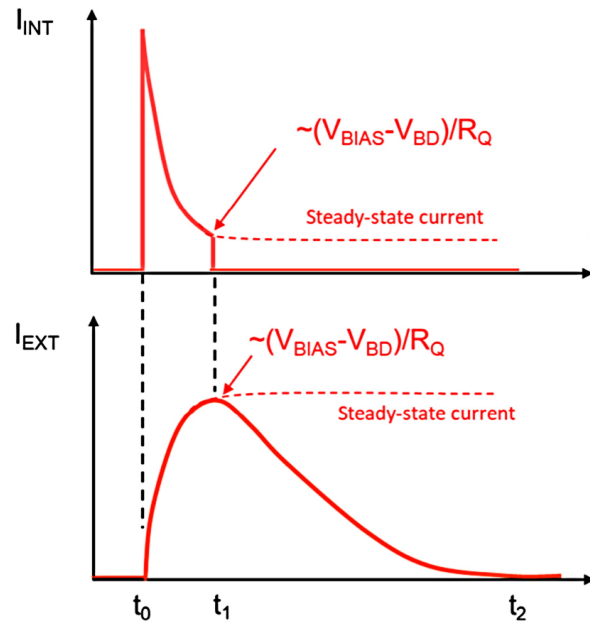


Fig. 4.5: Time evolution of the current into a SPAD [111].

thin depletion layer and the extremely short avalanche discharge development duration, the SPAD response is intrinsically very fast. The signal rise time (< 500 ps) follows an exponential function with τ_D time constant and does not depend on the number of fired cells and bias voltage applied [113]. The falling signal is an exponential with time constant τ_r . The total recovery time ranges between 20 and 250 ns, accordingly to the quenching resistance value and to the capacity,

which scales with the cell size.

4.1.3 Single-Photon Time Resolution

The time resolution is one of the key features of SiPMs. The timing performances are evaluated using the Single-Photon Timing Resolution (SPTR), i.e. the precision of arrival time estimation of a visible photon impinging the SiPM active area. Fig.4.6 represents the SPTR for photons absorbed in the depletion region [114, 115]. On one hand, avalanche fluctuations are caused by the mechanisms

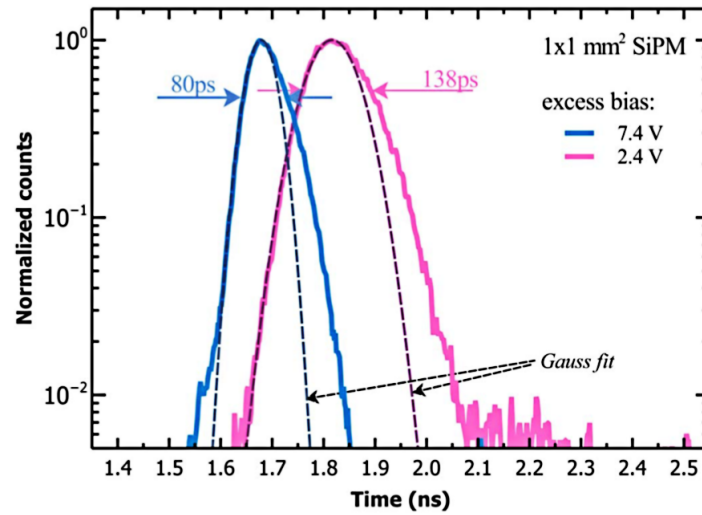


Fig. 4.6: Single photon timing response of a $1 \times 1 \text{ mm}^2$ SiPM by FBK at $2 V_{Ov}$ for $\lambda = 425 \text{ nm}$ [115].

involved in the avalanche spreading over the SiPM area. The main contribution is the lateral spreading by diffusion (depending on the device geometry). When the seed point is in the junction area center, the activation of the SPAD is faster and the rise time of the avalanche current is shorter. On the other hand, the exponential tail to the right is related to carriers created in field free regions and then collected by diffusion several nanoseconds later. The tail length depends on the thickness and on the minority carriers lifetime of these regions. If the gain is low, the lateral spread of the avalanche in the depleted region can be incomplete, creating the diffusion tail. Operation at high bias voltage can thus improve the time resolution [116].

4.1.4 Gain and amplitude

The gain of each SPAD represents the number of carriers flowing per each triggered avalanche. It is well defined by the internal capacitance and the

integrated resistor and its average value is generally expressed as:

$$G = \frac{V_{Ov} \cdot C_D}{q}, \quad (4.1)$$

where $V_{Ov} = V_{Bias} - V_{Bk}$ is the excess bias with respect to the breakdown voltage at which the SiPM is operated and $q = 1.602 \cdot 10^{-19}$ C is the elementary charge. Fig.4.7 shows the typical SiPM response to a low-intensity, nanosecond long pulsed light, emitted by a LED, that conveyed few photons onto the sensor sensitive area. Each band of traces corresponds to a different number of fired cells. Since the typical gain value is high (in the order of 10^6 up to 10^7) compared to the noise level, traces are well separated, providing the good SiPM photon number resolving capabilities. It can be also estimated by the charge spectrum

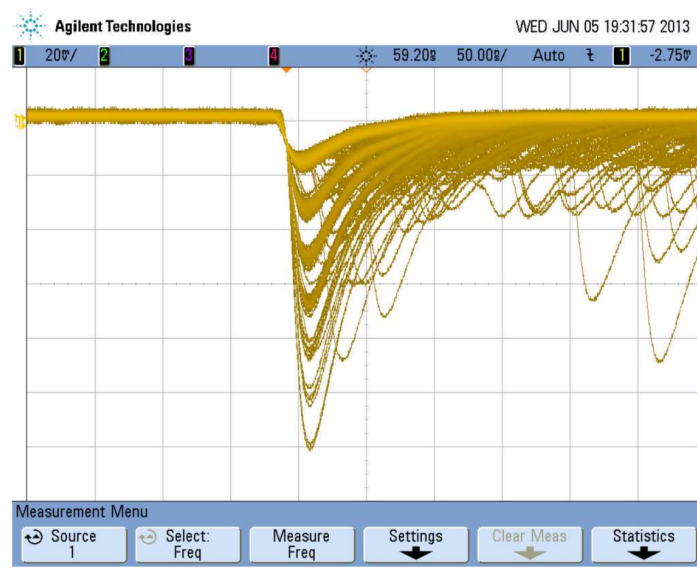


Fig. 4.7: Response of Hamamatsu MPPC S10362-11-100C illuminated by a LED: the oscilloscope output. [117].

obtained integrating the SiPM signal, synchronous with the light pulses, over a certain time (fig.4.8). Each entry corresponds to the recorded, digitized and integrated pixel current signal while each peak represents the number of cells with Geiger discharges at the same time (i.e. the number of fired cells). Their areas are related to the Poisson statistical property of the light source: the lowest peak corresponds to no detected photons and its width σ_0 provides a measure of the stochastic fluctuations in the output signal (the noise of the system). The distance between two peaks, called peak-to-peak distance, is given by: $\Delta_{pp} = q \cdot G$ and can be turned directly into the SiPM gain. Moreover, its value is the gauge to turn the digitised signal into the number of fired pixels. Usually the multi-photon spectrum is also shown in units of photoelectrons (pe), by scaling the ADC channels axis by $1/\Delta_{pp}$ and shifting the first peak mean value

at zero. The peak at one photo-electron has a slightly larger width σ_1 . This is

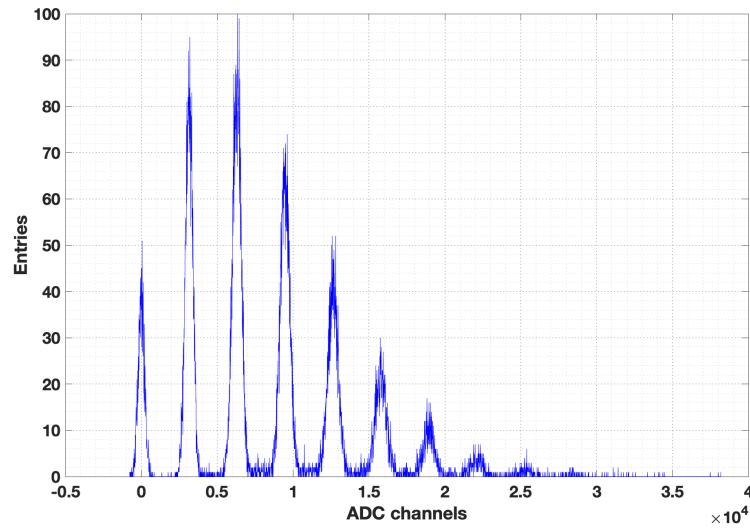


Fig. 4.8: Response of Hamamatsu MPPC 13360-1350CS illuminated by a LED: the integrated and digitized signal. [117].

related to the fact that, even if the pixel structure production is high uniform, not all of the cells were born equal: the avalanches generated in various pixels can have a difference of about 10% in the number of electrons generated (the so called cell-to-cell gain variation) [118]. Since the distribution of the fired cells in the SiPM sensitive area is random, the residual gain differences become evident broadening the peak and adding an extra contribution with respect to the 0 peak width. The peak width increases with the number of fired cells (N_{FC}), following a $\sqrt{N_{FC}}$ law and limiting the maximum number of resolved peaks. The same information can also be extracted if, instead of the charge, the SiPM signal amplitude is analysed.

There is a complex relation between the SiPM performance parameters and the technological implementation of the different device components. A brief overview of the principal parameters will be discussed in the next sections.

4.2 Photon Detection Efficiency

Since each specific application can have various requirements in terms of wavelength sensitivity, the Photon Detection Efficiency is one of the first parameters to consider designing a SiPM-based detector. The silicon light absorption coefficient varies by several order of magnitude in the wavelength range from UV to infrared light (IR). PDE quantifies the probability of a SiPM to detect an impinging photon [113, 118] and is defined as the ratio between the number of fired cells

and the total number of photons hitting the detector N_γ . It is a function of the wavelength λ of the incident photon, of the temperature T and of the overvoltage V_{Ov} and can be calculated as:

$$PDE = \frac{\langle N_{FC} \rangle}{\langle N_\gamma \rangle} = FF \cdot QE(\lambda) \cdot P_T(\lambda, V_{Ov}, T) \quad (4.2)$$

where FF is the geometrical fill factor (i.e. the ratio between the sensitive and the total device area), QE is the quantum efficiency (i.e. the probability for a photon with wavelength λ , to enter in the sensitive SiPM area and to create a primary eh pair) and P_T is the avalanche breakdown triggering probability (i.e. the probability that the carriers generates a Geiger discharge) [119]. Fig.4.9 is a sketch that shows how each factor of eq.4.2 modifies the PDE. Starting with a PDE

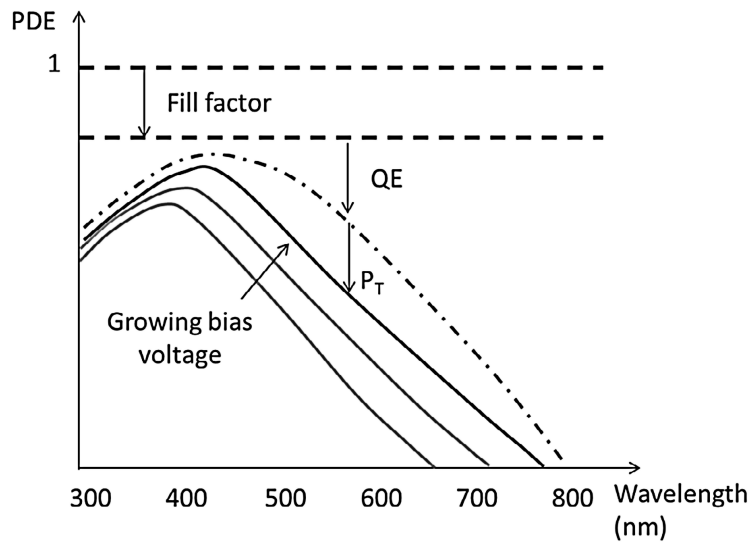


Fig. 4.9: Sketch of the PDE on a blue sensitive device. The effect of each factor of Eq.4.2 is highlighted [111].

equal to 1, since the FF is (as first approximation) wavelength independent, it gives a first constant reduction. QE gives the second PDE wavelength dependent decrease. Finally, last reduction comes from the P_T .

Geometrical fill factor

The geometrical fill factor is the ratio between the sensitive area and the total area of the device. It is linked to the presence of dead regions in the SPAD structure (fig.4.10): each cell is surrounded by the guard ring (to quickly decrease the electric field at the border), the quenching resistors, the bias lines and the isolation structure providing the electrical and optical separation between the cells. One of the most used technique is trench isolation: a narrow and depleted region surrounding the active area and blocked up with a dielectric layer. This allows a strong reduction of the optical cross-talk (sec.4.3.2) between the cells,

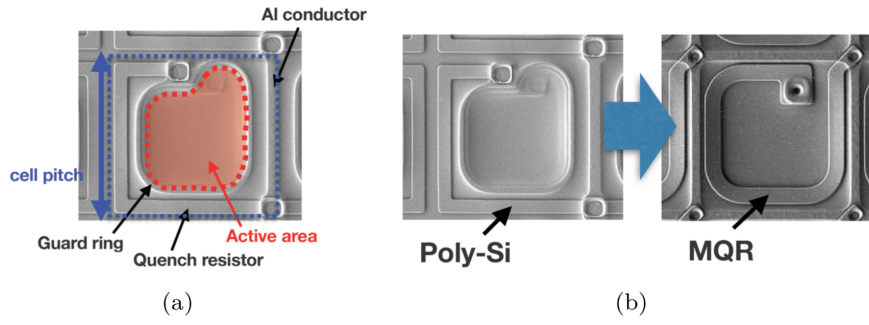


Fig. 4.10: (a) SiPM active region of a 25 μm cell. (b) Metal Quench Resistor improves the FF [108].

especially if some absorbing material is inserted in the trench between the two dielectric layers. Both the trench isolation and the guard ring are usually designed together to minimise their width and to maximise the FF . This parameter has to be optimised for each specific application: e.g. if the number of impinging photons is small, the best solution can be using SiPM with few bigger cells (i.e. 100 μm pixel size), while in case of a high number of photons expected, SiPMs with small pixel sizes (10-25 μm) are needed to avoid saturation. Currently, FF ranges from 90% for 100 μm down to 30% for 10 μm pixel pitch.

Quantum efficiency

The SiPM quantum efficiency depends on the wavelength of the impinging photon and on the absorption region thickness (fig.4.11). More in detail, QE depends on two factors: the probability that a photon crosses the anti-reflective coating (ARC) layer on top of the sensor and the one that a photon generates an eh pair in the high-field region. The ARC is usually composed by a stack of

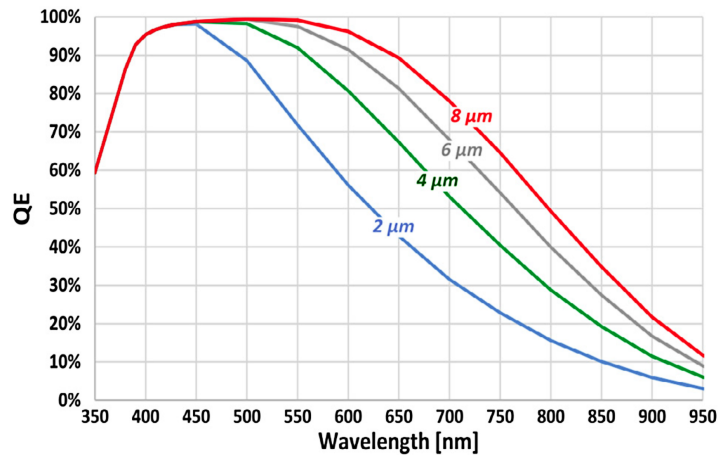


Fig. 4.11: Estimated internal QE vs the wavelength of incident photon for different effective epitaxial layer thickness. [112].

different dielectric layers on top of the SiPM and should be optimised for each

application. The second probability depends on the absorption depth of photons in silicon, that grows with the wavelength from ~ 10 nm range for the UV/blue light, up to tens of microns for the near-infrared (NIR) light [120]. The thickness of the active region has to be adequately chosen according to the wavelength specific for each application. Considering a n+/p (p+/n) junction, for very short wavelengths photons, the absorption depth is really small, the eh pairs are mainly photo-generated above the junction and only holes (electrons) are drifted towards the avalanche region. In this case a proper design of that layer is needed to allow the carriers diffusion towards the avalanche region and to minimise the recombination. Instead, for visible part of the spectra, light is absorbed both above and below the high field region and thus both carriers can trigger the avalanche. Finally, NIR photons generate mostly electrons (holes) that trigger the avalanche below the junction. Since the two junction types generate different types of carriers triggering the avalanche, even considering the same QE and the same structure of the device, a difference PDE spectral shape is expected [121, 122, 123].

Avalanche breakdown trigger probability

The avalanche breakdown trigger probability P_T is the probability that a carrier starts an avalanche passing through the SPAD high-field region. It depends on the electric field, i.e. on the overvoltage and on where the carriers are produced. When an eh pair is created in the depletion region, the two carriers starts to drift in opposite direction, both contributing to the trigger probability:

$$P_T = P_h + P_e - P_h P_e \quad (4.3)$$

where P_h and P_e are the hole and electron breakdown initiation probabilities. These terms depend on the generation position, are governed by the ionisation rates of holes and electrons, respectively, increase with the electric field and with low temperature. Electrons trigger the avalanche in a most efficient way because they have an impact ionization rate of $5 \cdot 10^5$ V/cm, about twice higher than holes. Fig.4.12 represents the triggering probability as a function of the carrier generation depth both for n+/p and p+/n configurations. P_T has its maximum where the electrons can cross entirely the high-field zone: for the p+/n structure it is within the p+ layer near to the junction, while for the n+/p case it is the drift region π . In case of very short wavelength, i.e. for UV/blue light, the best solution is a buried n+/p structure. In this case electrons are generated near to the p+ layer and can enter in the high-field region, while holes move towards the electrode and do not contribute to the P_T . When moving to the green-red light detection (that have an absorption depth in silicon of about $3 \mu\text{m}$) the best option is a p-type structure with a thin n+ layer ($\sim 0.1\text{-}1.5 \mu\text{m}$) and a thicker

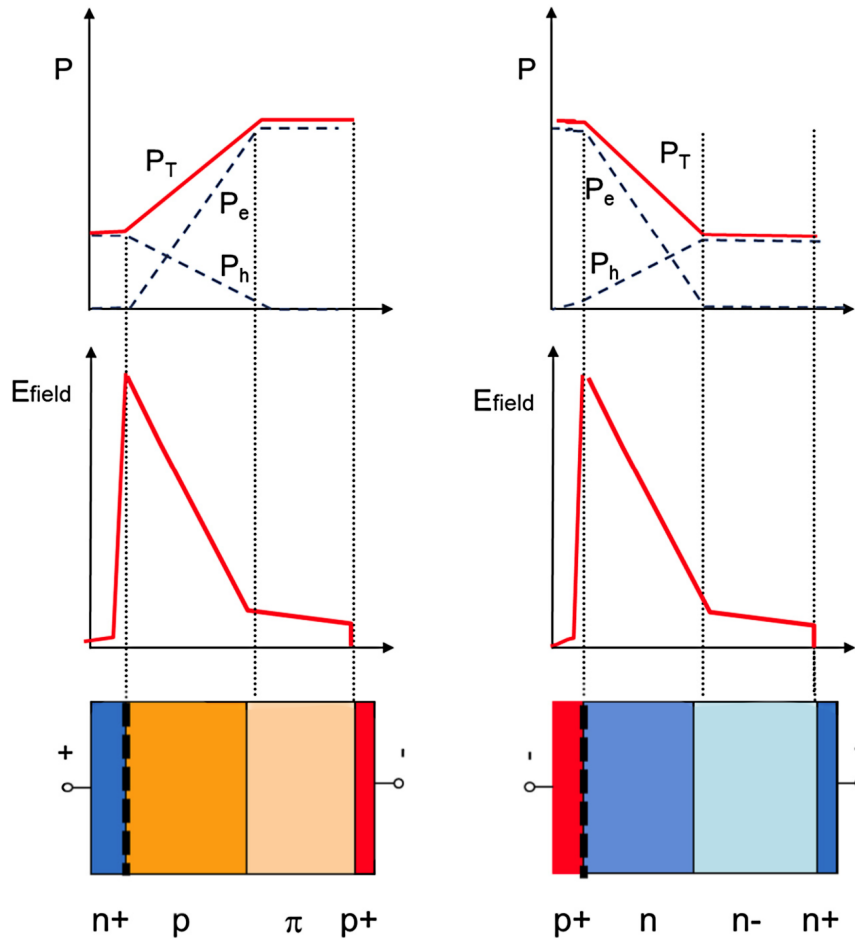


Fig. 4.12: Electric field and trigger probability for n+/p and p+/n structures [111].

drift region ranging from 3 to 10 μm . For the NIR light, since the thickness of the high-field area is negligible with respect to the absorption depth, the proper choice is always a n+/p junction with illumination that can be from both the drift or the junction side.

4.3 SiPM noise and secondary effects

The main sources of the SiPM noise can be distinguished in two general categories called primary and correlated noise. The first category identifies the avalanche triggered by thermal generated free carriers or related to the field-assisted generation (i.e. by tunneling generation) [111]. The correlated noise identifies all the avalanches discharges triggered in the SiPM by the primary ones, thus "correlated". The generation of these pulses is due to both the optical cross-talk (sec.4.3.2) in neighboring SiPM cells and the afterpulsing (sec.4.3.3) in the same cell [112].

4.3.1 Dark Count Rate

The primary noise source, that limits the SiPM single photon resolution, is the Dark Count Rate (DCR). It is due to the avalanche triggered by any generation of eh pair in the depletion region, resulting in random and spurious avalanches that occur independently from the incoming light. Fig.4.13 shows the main sources of DCR along the SPAD depth. At room temperature, the main contribution is due to the thermal generation of the carriers in the bandgap, i.e. the Shockley-Read-Hall (SRH) generation-recombination [124]. The impurities and crystal defects of the epitaxial layer (in terms of number of activation energy and deep levels) define the generation rate: with a higher defect concentration, the equivalent "lifetime" (τ_{SRH}) becomes lower and thus the DCR increases. So, the sensor design and production technology play a crucial role to limit the dark count rate. SRH is also affected by the electric field present in the avalanche region. Fig.4.14

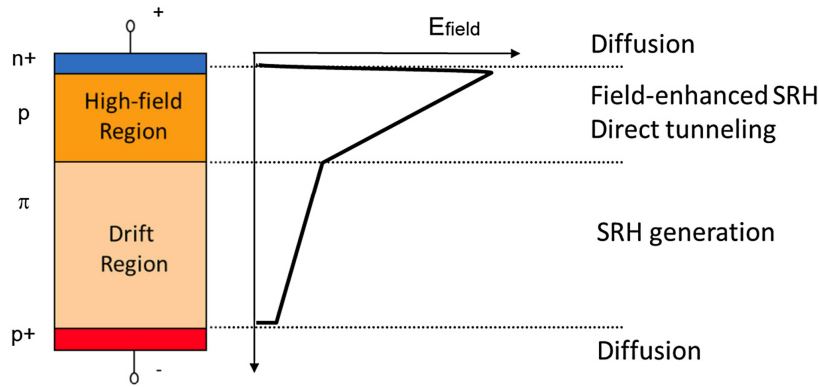


Fig. 4.13: The different sources of DCR and their location in the structure of the SPAD [111].

represents the temperature dependence of the DCR. On one hand, at higher temperature, the diffusion current near the depleted regions (from the neutral ones) becomes not negligible too. On the other hand, at lower temperature, the

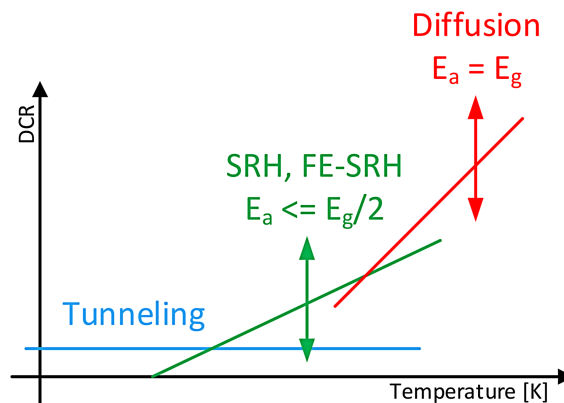


Fig. 4.14: Temperature dependence of the DCR [111].

tunneling generation becomes more important and it is the dominant effect in the cryogenic applications [125]. DCR is also depending on the total active area and on the depletion region thickness. To reduce as much as possible the DCR, the SiPM has to be operated at low bias voltage and temperature, employing small area devices. The actual values (at room temperature) for DCR range from 1 MHz for the $6 \times 6 \text{ mm}^2$, to about tens of kHz for the $1 \times 1 \text{ mm}^2$, depending on the producer.

4.3.2 Optical Cross-Talk

The number of secondary photons produced in an avalanche has been measured to be about $3 \cdot 10^{-5}$ per charge carrier crossing the junction [126]: with a SiPM gain of 10^6 , about 30 visible photons are generated during a cell breakdown avalanche. These secondary photons are emitted isotropically and can be absorbed in the active volume of a neighbouring cells, triggering secondary avalanches resulting in a SiPM output pulse with two or three times the single-pixel amplitude (fig.4.15). This phenomenon is called "direct" or "prompt"

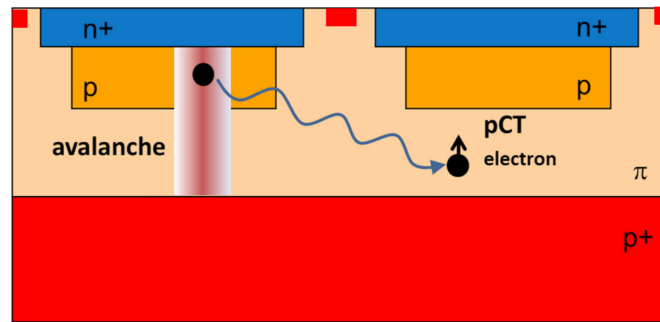


Fig. 4.15: Sketch of a prompt Cross-Talk event (pCT) [111].

Optical Cross-Talk (OCT) since the sum of the travel time of the photon from the first to the second pixel, the carrier drift time and the time needed to trigger the secondary avalanche is tens of picosecond and thus not distinguishable from the first avalanche with typical electronics. In addition to this, another type of OCT exists: the "delayed" OCT. It is caused by secondary photons generating an eh pair in the bulk or in the neutral regions next to the depleted area (fig.4.16). The generated carriers can diffuse to the active region and trigger a new avalanche. Another possible origin of OCT comes from photons exiting the silicon and reflected back in the avalanche region by e.g. the change of material reflective index fig.4.16. This can be defined as External OCT. Two examples of external reflector are the top surface of glass/resin layer added in some SiPM to protect the detector surface from environmental and mechanical stresses or a scintillator with diffusing/reflective surfaces. Contrary to prompt

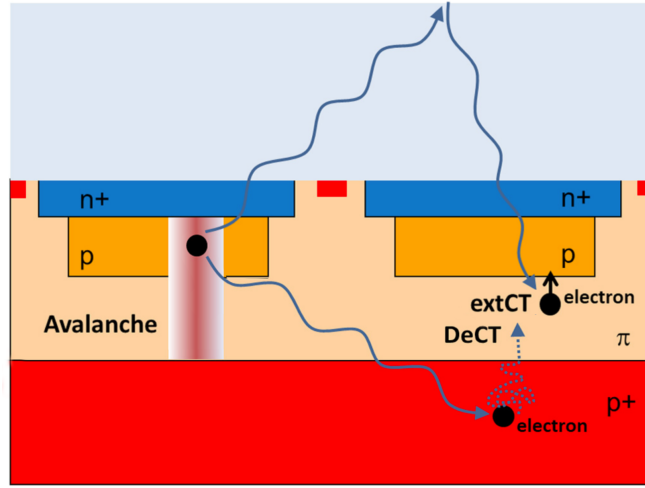


Fig. 4.16: Sketch of a delayed Cross-Talk (deCT) and External Cross-Talk (ExCT) events (re-drawing from [111]).

OCT, in this case the secondary avalanche production time can be long enough (from few ns up to μ s) to separate it from the starting time of the primary one and thus to identify two different and subsequent events. Anyway, due to the finite bandwidth and sampling rate available in the front-end and in the SiPM signal acquisition, part of the delayed OCT events can be identified as prompt OCT. Fig.4.17 shows an example of the DCR and OCT events frequency for a SiPM: higher order OCT decreases rapidly with the number of fired cells. The

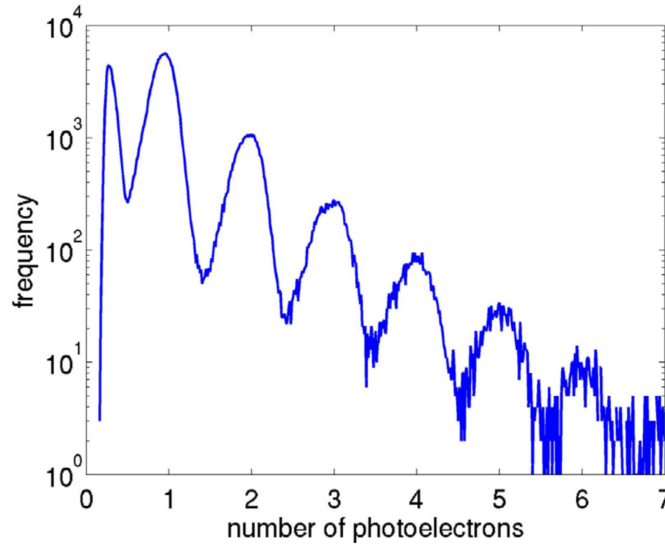


Fig. 4.17: DCR and OCT events frequency in the Hamamatsu S10931 SiPM with 50 μ m pixel pitch. [112].

probability of simultaneously triggering N avalanches due to the optical cross-talk can be described exponentially decreasing with N [112]. Often this simple model is sufficient and can be used to phenomenologically include OCT in Monte Carlo

simulations. However, this is a very simple, first order approximation, model and a more complex and exhaustive description of the OCT probability as a branching Poisson process can be found in [127] and in [128]. OCT increases with higher bias voltage: increasing the V_{Bias} , the number of photons produced during the avalanche increases and a larger triggering probability is expected. The OCT probability increases also reducing the SiPM pixel pitch due to the smaller average distance that photons have to travel before reaching the neighbour cells. Nowadays, to reduce properly the OCT down to a value of 1-2%, optical trenches between the SiPM pixels are inserted [129].

4.3.3 After-Pulsing

After-pulsing (AP) is a correlated noise generated when the carriers produced in an avalanche are trapped by an impurity in the high-field region and subsequently released after a time that spreads from ns up to several μs , generating (on the same pixel) a delayed secondary avalanche with a reduced amplitude (due to an incomplete reset of the cell) [116]. Thus, the AP probability depends on the sensor technology, i.e. on the number of traps and impurities present in the silicon lattice and on their (multi-exponential [111]) release time constant compared to the pixels recovery time τ_r . It is also depending on the overvoltage because, when the gain increases, the correspondent avalanche trigger probability increases too. The general procedure to reduce this kind of correlated noise is to minimise the gain and the silicon impurities and to find an adequate hold-off cell time that allows the majority of trapped carriers to be released when the pixel is not yet completely recharged. AP can also be "optically-induced": secondary photons produced by an avalanche can be re-absorbed in the neutral region of the same cell below the active region (fig.4.18). Then, the carrier can reach the avalanche region by diffusion and trigger a new discharge. For this kind of AP, the carrier

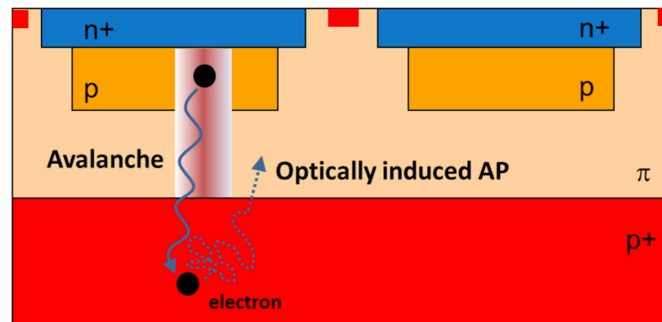


Fig. 4.18: Sketch of the optically-induced after-pulsing [111].

lifetime in the neutral region corresponds to the trap release time constant of the previous one and in the substrate this ranges between few to hundred of ns [130].

The optically-induced AP can be reduced using a low-lifetime substrate compared to the pixel recharged time constant or introducing a second p/n junction to block all the carriers coming from the backside [131]. Fig.4.19 summarises the SiPM output signal of the different noise sources: primary, prompt and delayed OCT and afterpulsing events.

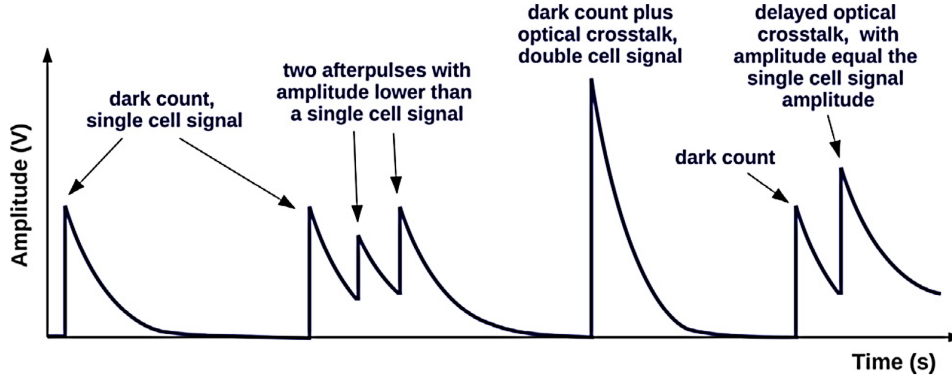


Fig. 4.19: Sketch of the different SiPM output noise signals [112].

4.3.4 Excess Noise Factor

OCT and AP occur stochastically, changing the probability distribution function of output signals (fig.4.20) and causing a not negligible multiplication noise with respect to an ideal detector. The deterioration of the response and, consequently,

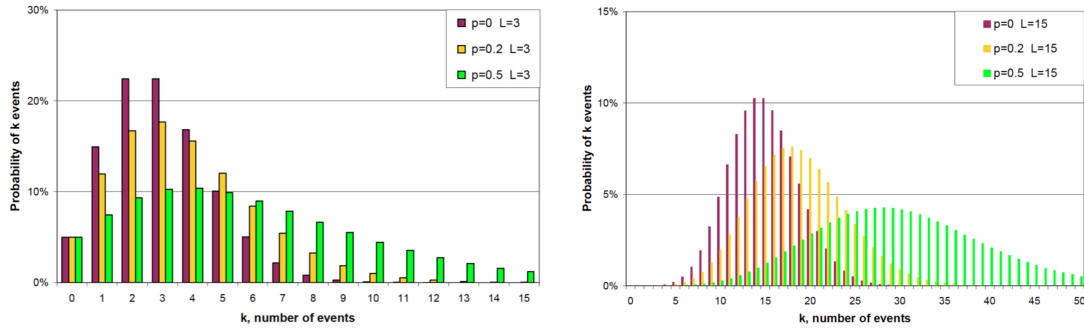


Fig. 4.20: The Compound Poisson distribution with mean value $\mu = 3$ (left) and $\mu = 15$ (right) and probability of OCT and AP detection $p = 0$ (Pure Poisson), 0.2 and 0.5 [108].

of the performances is usually described by a parameter called Excess Noise Factor (ENF). The ENF for amplification of noisy signal is defined as:

$$ENF = \left(\frac{SNR_{in}}{SNR_{out}} \right)^2 \quad (4.4)$$

i.e. the square of the degradation in SNR (the ratio between the mean and the variance square root) from the detector input to the output. The input signal is a Poissonian distribution with mean value μ while the output one is described by a Compound Poisson distribution (a detailed explanation is provided in [117]). The SNR can thus be expressed as:

$$SNR_{in} = \sqrt{\mu} \quad \text{and} \quad SNR_{out} = \sqrt{\frac{\mu}{1+p}}, \quad (4.5)$$

where p is a parameter related to the probability to detect OCT and AP events. The ENF due to the stochastic noise given by AP and OCT is:

$$ENF_{st} = 1 + p \quad (4.6)$$

and can not reach values higher than 2. If also the photon detection excess noise factor contribution is considered, the final expression for ENF becomes:

$$ENF = \frac{1+p}{PDE}. \quad (4.7)$$

It can be measured from the charge distribution of the single photoelectron and calculated using [132]:

$$ENF = 1 + \frac{\sigma^2}{G^2}, \quad (4.8)$$

where G and σ^2 are the SiPM gain (i.e. the total charged released by the mean number of fired cells) and variance, respectively. Nowadays the value of ENF ranges from 1.01 to 1.5 (more details can be found in [108]).

4.4 Linearity and dynamic range

For calorimetric measurements, the sensor dynamic range is one of the most important parameters since it defines the range in which the calorimeter response is linear with the particle energy. High gain and PDE , single photon detection and high dynamic range are often requirements that can hardly be reached simultaneously with SiPMs. Unfortunately, all the nuisance parameters described above, as the DCR or the correlated noise, contribute to the effective SiPM dynamic range [119]. Since the single charge is approximately the same for each pixel of a SiPM, if the number of photons in the detected pulse N_γ , multiplied by the PDE , is small with respect to the total number of available cells N_{tot} , the SiPM response N_{FC} is close to linear and independent of the photons arrival time. Nevertheless, if the light on the sensor increases, SiPMs exhibits saturation and non-linearity effects as long as the probability of having more than one photon

per cell (and thus busy pixels) is not negligible. In this case a parametrisation based on a physical model becomes very difficult [133]. Anyway, since N_{FC} is a random variable, its expected value can be extrapolated considering the process of random distribution of a defined number of photons detected by the sensor ($N_{pe} = N_\gamma \cdot PDE$) in the total available cells [134]. In this case, the number N_{FC} of cells triggered simultaneously by one or more photo-electron can be estimated by:

$$N_{FC} = N_{tot} \cdot \left[1 - \left(1 - \frac{1}{N_{tot}} \right)^{N_{pe}} \right] \quad (4.9)$$

The distribution of N_{FC} is approximately Gaussian when $N_{tot}, N_{pe} \rightarrow \infty$ and N_{pe}/N_{tot} is a finite value: in a regime of high incident light, since the total number of cells in a SiPM is usually greater than 100, it can be expressed as:

$$N_{FC} = N_{tot} \cdot \left(1 - e^{-\frac{N_\gamma \cdot PDE}{N_{tot}}} \right) \quad (4.10)$$

It should be highlighted that this formula is an approximation, since it applies to ideal circumstances that are not exactly met in practice. E.g., it is based on the assumption that all SiPM cells are uniformly irradiated, that there is no prompt OCT and that there are no effects of pulse recovery. Moreover, high DCR, e.g. due to some radiation damage, can also decrease the PDE because some pixels are still in recharging state after the Geiger discharge (a detailed review can be found in [135]). Furthermore the signal pulse shape depends on the number of simultaneous fired cells and, due to the pixel recovery time constant (τ_r is several ns), it also depends on the arrival time distribution of the photons [136]. More in detail: if the photons arrival time is spread, it should be possible that some cells will have already recovered (at least partially) before the next photons arrives, thus a signal exceeding N_{tot} is expected and actually observed. For example, in [136], a detailed dynamic range study was performed using a LED to generate light pulses of different durations (τ_{light} of 12, 35 and 73 ns) and with a light intensity of more than $10^5 N_\gamma$ hitting the sensor. The analysis was done on 3 different SiPMs: one, produced by KETEK, with $N_{tot} = N_{pix} = 3600$ and pitch = 50 μm and two by Hamamatsu with $N_{pix} = 3600$ and 900 and pitch = 50 and 100 μm , respectively. Fig.4.21 shows the effective fired cells as a function of N_γ on the active SiPM surface for the Hamamatsu S10362-050C for various V_{Ov} and t_{pulse} values. The authors' conclusion is that in the linear regime (i.e. after a $n_{eff} \sim 0.2 \cdot N_{pix}$) the SiPM response is practically independent of the τ_{light} used, while increasing the N_γ value, also the response increases with τ_{light} exceeding the total available cells number. It should be emphasised that actually the SiPM dynamic range and non-linearity studies pointed out that some observation [119], as the change of the pulse shape with the number of avalanches in a single

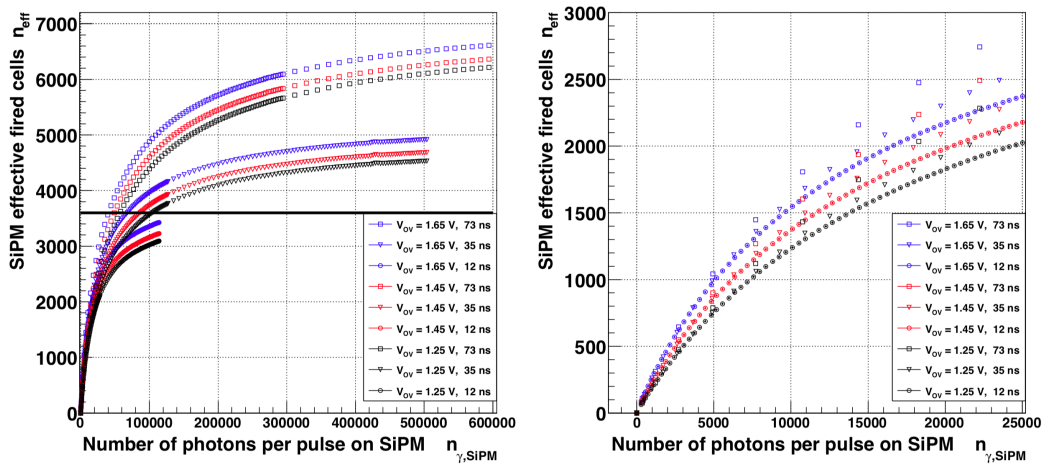


Fig. 4.21: Effective fired cells as a function of the number of photons per pulse on the active SiPM surface (full and zoom) for Hamamatsu S10362-050C type, 250 ns gate length. The total number of cells is indicated by the straight black line on the left hand side. The wider spacing of the data points at larger values of t_{pulse} is due to the constant step size of V_{LED} [136].

cell or the measurement of a number of fired cells exceeding the total number of available pixels, are not yet well understood. SiPM non-linearity and saturation description is thus quite complex, however, the SiPM response function for each particular situation can be measured, allowing a non-linearity correction based on a dedicated phenomenological parametrisation [136].

4.5 Application in particle physics

After first large-scale applications in calorimetry (CALICE AHCAL in 2006 [137]) and in neutrino detectors (T2K experiment [138] in 2011), SiPMs have seen a fast increasing use in nuclear and particle physics. This adoption is driven by the always better SiPMs capabilities and properties, combined with the progresses obtained in modern microelectronics, which provide new detector systems with a high number of electronic channels [139]. Indeed, SiPMs are replacing in many applications PMTs, but also enabling new applications which were previously not possible, especially where very large number of channels or stringent space constraints are required. Fig.4.22 represents the number of SiPMs (left plot) and the total device areas (right) in particle physics experiments/detectors as a function of the year of the first beam for the system. This is an illustrative picture of the state-of-the-art: the number of SiPMs implemented in the experiments spreads from few tens of devices to more than 100,000 and will reach several millions in the next years. Nowadays, the active sensor areas are below 1 m² but with several square meters expected for the next generation of detectors. Calorimetry appears to be the most common use for SiPM-based devices, both

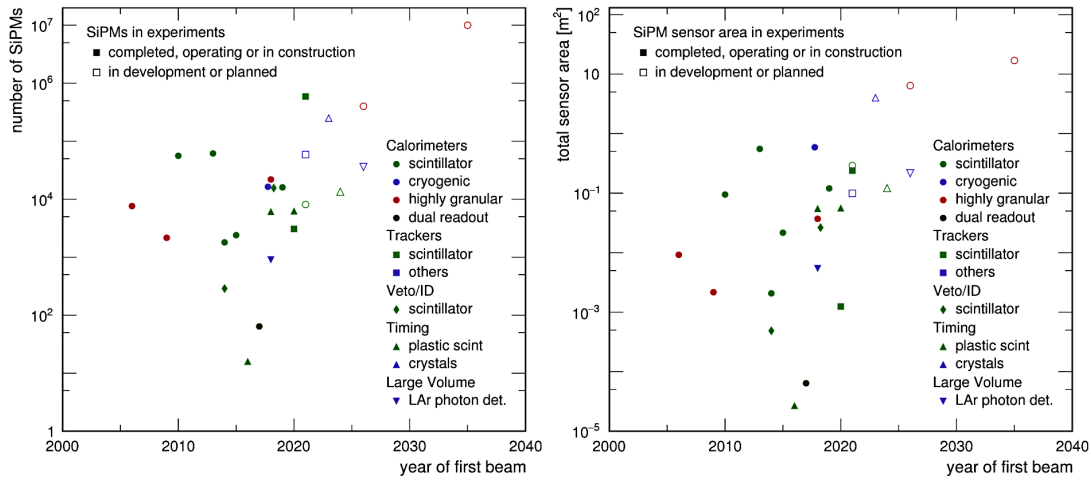


Fig. 4.22: Number of SiPMs (left) and the total sensor area (right) in detectors/experiments as a function of the year of first data taking [139].

in present and future projects, however also other applications, as timing or tracking detectors, are getting more and more important. As already discussed above, the two main motivations for using SiPMs in HEP are: (i) developing new technologies otherwise impossible (or at least very impractical) with other photon detectors (ii) upgrading the already existing devices with SiPMs because of their improvements in performances, features and/or cost saving. At the beginning, SiPMs served as an enabling technology, offsetting the early generations limitation, nevertheless, their continuous improvement in terms of noise, AP and OCT reduction (together with a downward trend in cost per unit area), enables their use also in low-amplitude environments as trigger and has made possible their use also with high degrees of radiation damage (i.e. high noise rate). The possibility to operate SiPMs at low temperature (on the order of -40°C) reducing the DCR and the level of noise caused by the radiation damage, enables the use of SiPMs also in high fluence areas as LHC experiments. As mentioned above, calorimeters are the particle physics detectors in which SiPMs are most used (from LHC detector upgrades to R&D developments for future collider experiments) due to their compactness, magnetic field insensitivity, high PDE and low operation voltage.

CALICE collaboration

The first detector with a large number of SiPMs operated in a particle beam experiment from 2006 was the CALICE Analog Hadron Calorimeter (AHCAL) prototype, hosting 7608 photon sensors [137, 140], complemented from 2007 by the Tail Catcher and Muon Tracker (TCMT), also making use of SiPMs. The SiPMs are used to read out the scintillating light emitted by plastic scintillator. Wavelength-shifting fibres embedded in the plastic scintillator match the wave-

length to the sensitivity in the green spectral region of the first-generation SiPMs used. The basic detection scintillator of the CALICE AHCAL physics prototype, is a $3 \times 3 \times 0.5 \text{ cm}^3$ plastic tile. The diameter of the wavelength-shifting fibre is 1 mm. To reduce the number of channels of the prototype, larger tiles with a size of 6×6 and $12 \times 12 \text{ cm}^2$ are used in the outer regions and rear part of the detector. The SiPMs in use have a sensitive area of $1.1 \times 1.1 \text{ mm}^2$, with a pitch of $32 \mu\text{m}$, resulting in 1156 cells per each. The limited dynamic range results in a critical saturation behaviour, especially for the em shower core. This saturation effect is addressed by the cell-by-cell application of a correction algorithm which gives the expected true number of photons for a given number of fired cells (more details can be found in [141]) allowing the recovery of the response linearity over a wide energy range. This correction leads a systematic in energy reconstruction for electromagnetic shower above 40 GeV, while it is negligible for hadronic shower. Therefore, the hadronic resolution reached is $\sim 44\%/\sqrt{E} + 1.8\%$ [142]. In these early large-scale applications, the SiPMs proved to be capable to achieve the performance expected during the design phase. Following the successful tests of the CALICE AHCAL physics prototype, the technology for highly granular scintillator-based calorimeters was further developed, making a scintillator-based detector system with millions of readout channels a credible option. This detector concept has been extended to an electromagnetic calorimeter with 10 mm wide, 45 mm long and 3 mm thick plastic scintillator strips with a wavelength-shifting fibre inserted in an extruded 1.5 mm diameter channel in the scintillator [143]. One scintillator end is coupled to a Hamamatsu SiPM and is covered by a screening foil in order to achieve a uniform response by blocking photons from reaching the sensor without being first absorbed in the wavelength-shifting fibre (avoiding a larger signal response for particles passing the scintillator close to the SiPM). The scintillator elements are placed in a tungsten carbide absorber structure with 3.5 mm thick absorber plates. A full prototype, consisting of 30 sampling layers for a total thickness of $21.5 X_0$ (266 mm), a lateral dimension of $180 \times 180 \text{ mm}^2$ and integrating 2160 scintillator strips and SiPMs, was build and tested in electron and hadron beams [144]. The subsequent development and availability on the market of SiPMs with the peak sensitivity in blue spectral region (the same of the most common plastic scintillator peak emission spectrum) allowed to eliminate the wavelength shifter, obtaining a direct coupling between tiles and sensors. To preserve the response uniformity (previously guaranteed by the wavelength shifting fibre collecting the light produced), a specific geometry design of the coupling, based on “dimples”, was implemented. A key parameter for this detector is the light yield for minimum ionizing particle (MIP) given by the most probable value of the number of detected photons. This value should be high enough to ensure

high efficiency, but, at the same time, low enough to preserve a high dynamic range (for the AHCAL CALICE the goal is $\sim 15\text{--}20$ photons per MIP) [145]. In this case, a detector element of the prototype has an area of $360 \times 360 \text{ mm}^2$, hosting 144 sensors (controlled by 4 ASICs) and $30 \times 30 \times 3 \text{ mm}^3$ scintillating tiles. Finally, a full hadronic calorimeter prototype, with a volume of $\sim 1 \text{ mm}^3$, integrating 22,000 SiPMs has been tested at the CERN SPS in May 2018 and a similar design was chosen for the phase II upgrade of the CMS endcap calorimeter system [146].

The CMS calorimeters upgrade

The upgrade of the existing hadronic barrel and endcap calorimeters of CMS experiment is one of the most interesting examples of the SiPM implementation in HEP [147]. In this CMS phase I upgrade, 16,000 SiPMs (produced by Hamamatsu) will be installed during this second long LHC shutdown, replacing the Hybrid Photo-Diodes (HPDs) used in the original detector. Due to the smaller size of SiPMs compared to HPDs, a larger number of devices can be installed, providing a finer longitudinal segmentation of the calorimeter. This will increase both the detector shower separation capabilities and the identification of particle signatures in the deeper regions of the calorimeter. Moreover, SiPMs have about three times higher *PDE*, which directly reduces the impact of the position-dependent light yield degradation caused by the increasing plastic scintillator radiation damage [148]. The chosen SiPMs are compliant with the required dynamic range due to their 4500 pixel/mm^2 (i.e. $15 \text{ }\mu\text{m}$ pixel pitch) and to their recovery time of less than 10 ns (obtained using quench resistor of $500 \text{ k}\Omega$). Indeed, that short recovery time, compared to the scintillation light collection time of $\sim 40 \text{ ns}$, allows a cell to be fired more than once and thus extends the range of linear response by about a factor three [147]. Finally, Peltier elements, steered by a software control loop (based on the SiPMs temperature input), provide the required precise temperature stabilisation of the sensors. The hadron calorimeter barrel upgrade addresses also the improvements required for the HL-LHC phase, while the endcap will be entirely replaced, in the third long shutdown, with a highly granular sampling calorimeter that will adopt about 400,000 SiPMs (all the details can be found [146]).

The LHCb SciFi Tracker

More stringent requirements are imposed by tracking detectors since they are in environments with more radiation load. Nevertheless, the magnetic field insensitivity, together with their small size, make SiPMs also an available option for scintillator-based tracking system since they can be installed directly outside of the sensitive region. This option, explored for the first time with balloon

experiments [149], was also chosen for the main scintillating fibre tracker upgrade of the LHCb experiment, that will take place at CERN until 2020. The new "LHCb SciFi Tracker" [150] will consist of "fibre mats", i.e. 6 staggered layers of scintillating fibres (2.5 m long, with a 250 μm diameter) with a mirrored tip to increase the light yield and assembled together using a special epoxy glue (loaded with TiO_2) to reduce the optical cross-talk between fibres. The other side of each fibre mat is coupled to an array of 104 SiPMs, composed by two dies with 64 channels each. Each array is 250 μm wide, matching the fibres diameter, and 1.62 mm high, covering the full fibre mat thickness. The total sensitive area is about 340 m^2 , read-out by more than 590,000 Hamamatsu SiPMs with $57 \times 62 \mu\text{m}^2$. Since the fibres are staggered and not aligned with SiPMs within the array, usually two sensors are needed to collect the light of a single fibre and thus multiple fibres contribute to the total signal of each SiPM. The particle track is reconstructed from the center of gravity calculated by the signals coming out from several adjacent SiPMs: a spatial resolution of about 50 μm is reached in beam tests using the full amplitude information available, while $\sim 80 \mu\text{m}$ are achieved using the 2 bit LHCb readout [151]. SiPMs OCT is in the order of 5.5%, while the AP is kept to a negligible value with a high quench resistor, resulting in a recovery time larger than the electronic integration time. This prevents the position resolution deterioration caused by a possible signal sharing of additional pulses not directly produced by the scintillation light. The LHCb expected ionisation dose is about 80 Gy, with a neutron fluence of $10^{11} \text{ n}_{eq}/\text{cm}^2$. This will have an impact on the DCR, increasing its value of 3 orders of magnitude (tens of MHz per channel at room temperature). To not spoil the tracking precision with this high noise level, SiPMs are cooled to -40°C keeping DCR well below 1 MHz also at the LHC run 3 end [151].

These are only three examples of the wide range of different detectors types used in HEP, that spreads from calorimeters and trackers to particle ID, veto detectors, timing systems and large volume detectors for neutrino physics. With the continuous improvements of the SiPMs performances and their cost reduction, the adoption of these devices for light detection in HEP experiments will increase more and more, making SiPMs the new standard solution for more detector systems. A full and detailed review about all these applications can be found in [139].

SiPM-based dual-readout prototype: system development and qualification

” *First comes thought; then organization of that thought, into ideas and plans; then transformation of those plans into reality.*

Napoleon Hill

The aim of the previous chapters was to give an overview of the physics motivations, the international context and the pre-existing know-how in the dual-readout calorimetry (DR) R&D phase, together with an introduction on Silicon Photomultipliers (SiPMs) and their main features. This second part will be focused on the work done on the first SiPM-equipped dual-readout fibre calorimeter prototype. A detailed preliminary calibration and a proper system qualification are important ingredients for a successful beam test: this chapter thus reports the description of the prototype layout, the adopted readout scheme and the measurements performed in the qualification phase.

5.1 Beam test goals

As described above, the use of SiPMs for reading out a sampling calorimeter was pioneered by the CALICE Collaboration [152]. A similar approach is used in the shashlyk calorimeter for the COMPASS II experiment [153]. The Pb/scintillating-fibre barrel calorimeter of the GlueX experiment at Jefferson Lab is read out with multi-pixel photon counters that are directly coupled to the fibres [154, 155]. However, SiPMs have never before been used to detect the light generated by individual scintillating or Cherenkov fibres that are the active media of a dual-readout sampling calorimeter. On one hand, as already described in sec.3.4, these solid state light detectors present specific advantages with respect to PMTs: (i) they provide the possibility to eliminate the forests of optical fibres that stick out at the rear end. These fibre bunches occupy a lot of space causing oversampling of late developing hadronic showers. (ii) The compact readout

allows to separate the calorimeter into longitudinal segments, if needed. (iii) Unlike the PMTs used in the previous studies, SiPMs can operate in a magnetic field. (iv) The PDE can be considerably increased with respect to PMTs. This is especially important for the C light detection, where the intrinsically low yield has proven to be a limiting factor for both em and hadronic energy resolutions of the previous DR calorimeters. On the other hand, SiPMs are a collection of binary cells and therefore are prone to response non-linearity and signal saturation effects, requiring dedicated corrections on single-channel level to restore linearity. Since the SiPM-based readout collects light from a grid of close fibres and the S and C signals differ by about a factor 50, avoiding any possible contamination (the light optical cross-talk) of the Cherenkov fibres signal with scintillating light is required. The activity described in the following completed a proof-of-concept, highlighting also the main challenges to be addressed in the future R&D studies. Four major aspects were investigated:

- The light optical cross-talk between the scintillating and clear fibres.
- The saturation and non-linearity SiPM response.
- The overall calorimeter linearity response.
- The Cherenkov and Scintillation light yields and the impact of these measurements on the energy resolution.

Moreover, the millimetric spatial resolution achieved coupling independently each fibre to a SiPM, gave access to an extremely refined two-dimensional imaging of showering particles. As a result, it was possible to measure the lateral profiles of em showers very close to the shower axis.

5.2 SiPM system layout

For each beam test performed in 2016, 2017 and 2018, a new module was built with slightly different configurations or improvements, especially in the mechanics and in the readout system. All the significant changes to the set-up will be highlighted and properly described.

5.2.1 Detectors

All the calorimeters used for these studies consisted of 10 brass¹ plates (Cu^{260}); each layer was 112 cm long, with a lateral cross section of $15 \times 1.5 \text{ mm}^2$, had 10 grooves wide and was skived from CDA 2 Brass. 64 optical fibres, 32 scintillating² and 32 clear plastic³, were embedded in that absorber in a chessboard like structure (fig.5.1). All fibres had an outer diameter of 1.0 mm and a cladding thickness of $20 \text{ }\mu\text{m}$. The metal absorber made up 49% of the calorimeter volume,

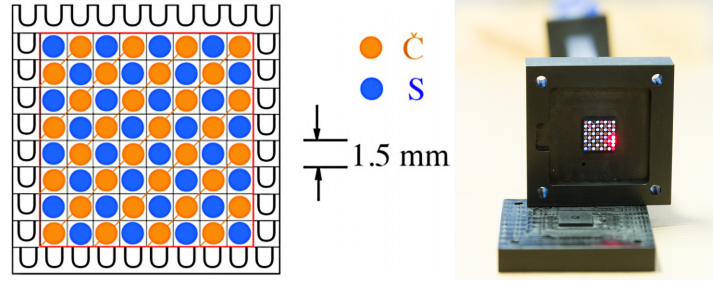


Fig. 5.1: Arrangement of the 64 optical fibres in the brass calorimeter absorber structure (left) [1] and the 2016 module front face with one *S* fibre lit up from the rear end (right).

while the fibres represented 35% of the instrumented one (i.e., the $1.2 \times 1.2 \text{ cm}^2$ region in which the fibres were embedded) and air accounted for the remaining 16%. The effective radiation length (X_0) and the Moliere radius (R_M) of the instrumented volume amounted to 29 mm and 31 mm, respectively. The calorimeters were thus $39 X_0$ deep. Because of the small lateral cross section, the fibres sampled the electron showers with an effective Moliere radius of $0.20 R_M$, equal to 6.5 mm. The em shower energy containment (calculated by a dedicated GEANT4 simulation as described in sec.6.8) was $\sim 45\%$ for the scintillation signal and $\sim 36\%$ for the Cherenkov one (for beam energies below 100 GeV).

5.2.2 System readout

Each fibre was interfaced to a SiPM. The 2016 prototype was equipped with the Hamamatsu S13615-1050 series sensors, featuring an active area of $1 \times 1 \text{ mm}^2$ and a pitch of $50 \text{ }\mu\text{m}$, for a total number of 396 cells/sensor. The 2017 and 2018 modules mounted the Hamamatsu S13615-1025, i.e. the same series but with a $25 \text{ }\mu\text{m}$ pixel pitch and thus an extended dynamic range of 1584 cells/sensor. The circular fibre tip covered an area of 0.79 mm^2 , however the SiPMs had a glass front cover of 0.3 mm thickness and the light exited the fibre in a cone

¹70% Cu, 30% Zn, 1/2 hard temper, by Interplex, East Providence, RI.

²Polystyrene based SCSF-78, produced by Kuraray.

³PMMA based SK40, produced by Mitsubishi.

defined by its numerical aperture (0.55) and the distance travelled by the light⁴. Therefore, the outgoing light illuminates most of the sensor area even if not in a uniform way (a detailed discussion is done in sec.5.6). The main sensor features are listed in table 5.1, while fig.5.2 represents their PDE dependences from the overvoltage (left) and the wavelength (right). The peak sensitivity corresponds to $\lambda_p = 450$ nm, with a related PDE of 40% for the 50 μm pitch sensors (measured at 25° , $+3 V_{Ov}$) and 25% for the 25 μm ones (measured at 25° , $+5 V_{Ov}$).

Hamamatsu S13615	1050	1025
Cell pitch [μm]	50	25
Sensitive area [mm^2]	1×1	1×1
Pixels number	396	1584
Peak Photon Detection Efficiency [%]	40	25
Breakdown voltage V_{Bk} [V]	52	52
Recommended operational voltage V_{op} [V]	$V_{Bk} + 3$	$V_{Bk} + 5$
Gain @ V_{op}	1.7×10^6	7.0×10^5
Dark Count Rate @ V_{op} [kps]	50	50
After Pulse Rate @ V_{op} [%]	< 2	< 2
Optical Cross-Talk @ V_{op} [%]	3	1

Tab. 5.1: Main parameters of the adopted SiPMs. The listed peak sensitivities of 40% and 25% were obtained for the mentioned operating voltage, and a wavelength of 450 nm. The breakdown voltage was determined by measuring the gain-voltage dependence. Even though this is not the unique definition, it is possibly the relevant quantity for the user [157].

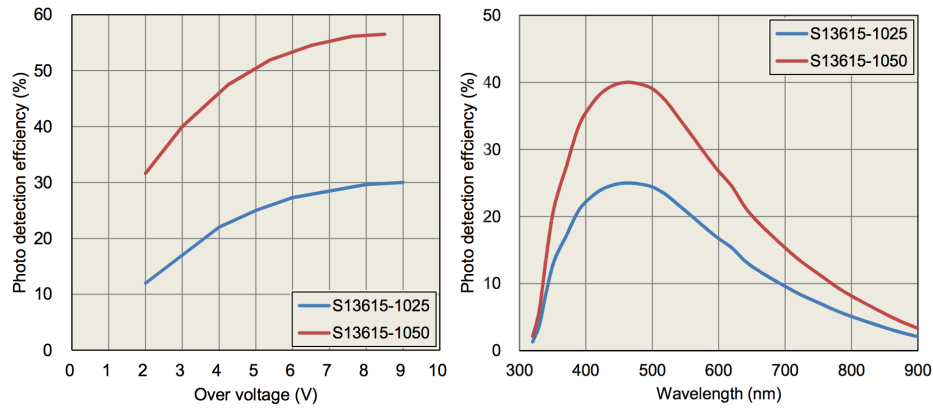


Fig. 5.2: Left: PDE as a function of the V_{Ov} and of the gain for 50 μm and 25 μm cell size of S13615 $1 \times 1 \text{ mm}^2$ (at 450 nm). Right: PDE vs wavelength for the same series [110] (at $V_{Bk} + 3 \text{ V}$ for 50 μm and $V_{Bk} + 5 \text{ V}$ for 25 μm).

⁴The opening angle of this cone depends on the distance travelled by the light in the fibre, e.g. because of imperfections in the quality of the core/cladding interface and the contribution of cladding light [156].

The system readout has been developed in cooperation with Nuclear Instruments SRL [158]. The SiPMs, in chip size packaging technology, were soldered on a dedicated board (with a pitch of 1.8 mm) providing individual bias and on-board temperature measurements. The adopted HV generator allowed a fine control (at mV level) for each sensor in the 0-3 V range and thus, the SiPM response equalisation and temperature compensation. For the tested prototypes, two different sensor boards were designed. In 2016 a single board hosting a matrix of 64 sensors was tested (fig.5.3a). Even if the coupling of each fibre with its SiPM was performed through a dedicated mechanical support (shown in fig.5.1), the absence of any optical separation between neighbour sensors caused an optical cross-talk between the S and C signals of the order of 25% (sec.6.3.1). Since the total separation between the two signals of a DR calorimeter is a fundamental requirement, in 2017, the cross-talk was reduced by two order of magnitude due to a new board design (sec.6.3.2). In more details, sensors

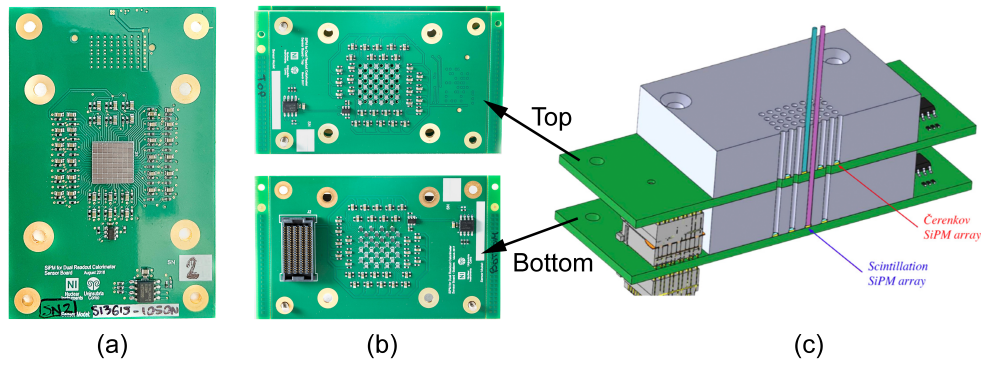


Fig. 5.3: (a) 2016 readout board with only one layer for all the sensors coupled to S and C fibres. (b) 2017/18 readout board with two-tier structure: the C fibres are coupled to the SiPMs on the first plane (Top), while the S ones are guided through holes in the first plane and readout on the second (back) tier (Bottom). (c) Schematic of the 2017/18 calorimeter, with two arrays of SiPMs. Each fibre is connected to its own SiPM.

were mounted on a two-tier structure (fig.5.3c), where the signals from the 32 C fibres were read out by the SiPMs on the front tier (top of fig.5.3b) and the S ones by the SiPMs on the back (bottom of fig.5.3b). Moreover, a new mechanical fibre support and 2 spacers (showed in fig.5.4) were specifically designed, allowing a higher light insulation between the S and C layers. In 2018 the optical cross-talk was further reduced insulating the fibres exiting from the calorimeter and entering in their mechanical support with a special black paint (fig.5.5). The signals from the sensors board were then fed into a mother board (through a 64-channel coaxial cable, fig.5.6) providing both the amplification and shaping stages and routing the signals to the digitisation system. This Active Front End (AFE) hosted 64 DC-coupled amplifiers, performed an exponential

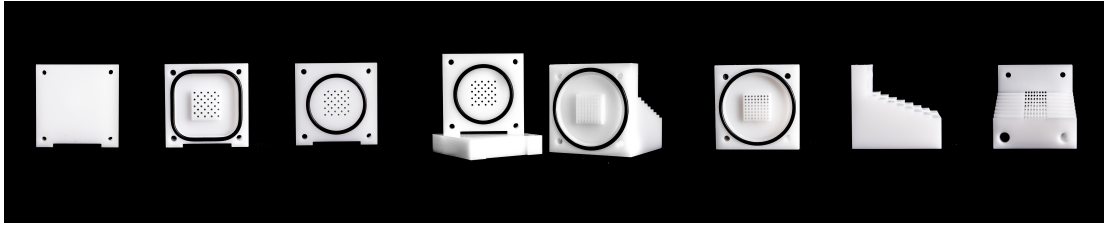


Fig. 5.4: The delrin mechanical fibres support (right) and the 2 spacers (left) designed for the 2017/18 prototypes. Each side was equipped with an o-ring to provide an excellent light insulation between the PCB board layers hosting the SiPMs.

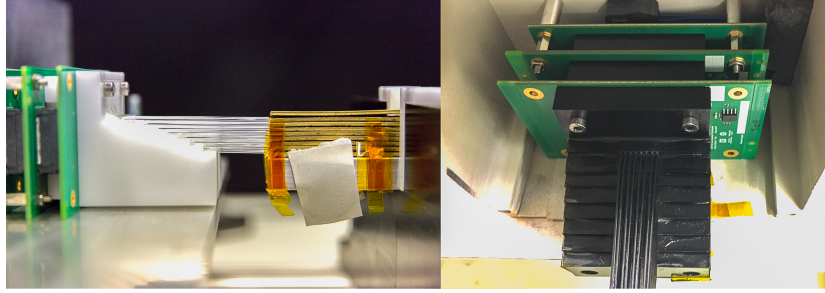


Fig. 5.5: Comparison between the 2017 (left) and 2018 (right) mechanical supports.

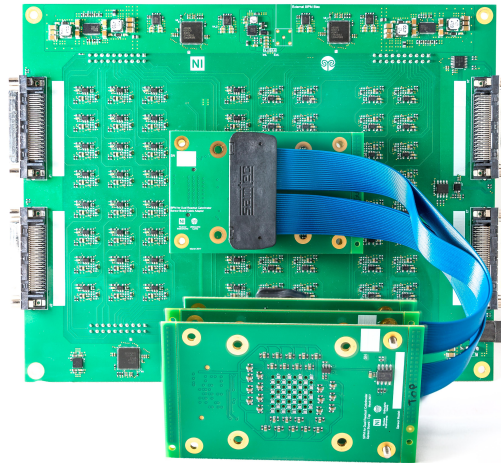


Fig. 5.6: The front-end electronics of the SiPM detectors. In the foreground, the 2017/18 two-tier boards hosting the sensors are shown. These are interfaced with the fibres, as shown in fig.5.3. In the background, the mother board is shown. This contains the amplifiers, the shapers and the sensor bias generator/control.

signal shaping with a τ_{signal} of 320 ns (to be compliant with the 80 MS/s digitiser sampling rate) and provided a linear response over the full sensor dynamic range⁵. The shaped signals (fig.5.7) were then read out using 2 Multichannel Analog to Digital Acquisition System (MADA): two 32 channel digitisers integrating a FPGA that can be programmed to implement most common readout features (as complex trigger logic and pulse height analysis) [158]. Each of the

⁵When operated at the recommended operational voltage ($V_{op} = V_{Bk} + 5V$).

two boards digitised all the channels at a rate of 80 MS/s and 14-bit ADCs performed a real-time charge integration on the FPGA: the final output is therefore a list of time-stamp events providing the integrated signal in every sensor. One

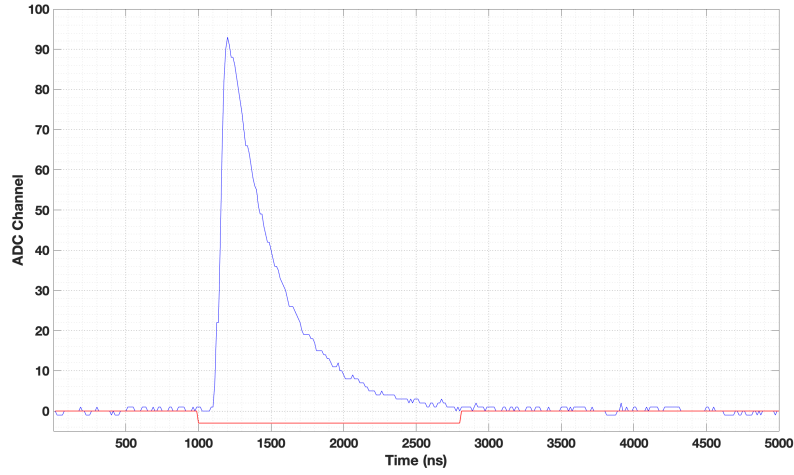


Fig. 5.7: The digitised output signal of the AFE. The integration time was 1.8 μ s.

important feature of this system, especially in that earlier R&D phase, is the possibility to have an on-line monitor (fig.5.8) providing, for each sensor, all the necessary information for a real-time calibration, debugging and analysis as the temperature, the biasing voltage, the signal waveform, the multi-photon spectrum and the SiPM matrix image. This system has simplified all the beam

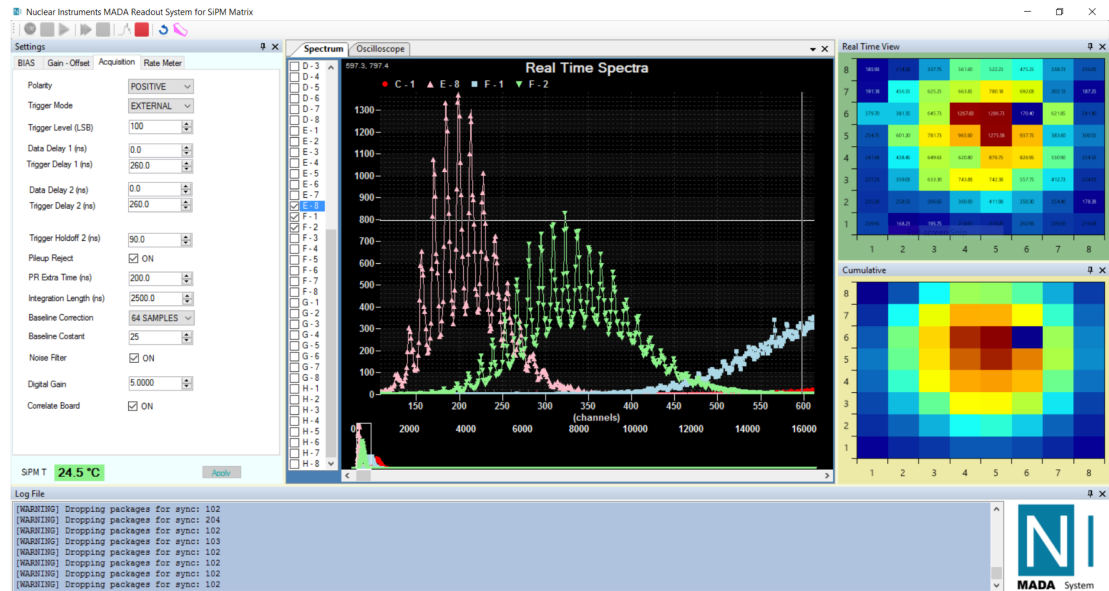


Fig. 5.8: Example of the on-line system response to a light pulse in the qualification phase. The multi-photon spectra of 4 different sensors are shown.

test data takings, allowing a correct alignment of the calorimeter with respect to the beam (simply looking its 2-D image) and a real-time monitor of the SiPMs parameters for each run. An example of the 2-D imaging properties of this system is illustrated in fig.5.9 for 10 GeV electrons and muons. The checker board appearance is due to the fact that the C light yield was about 50 times smaller than the S one.

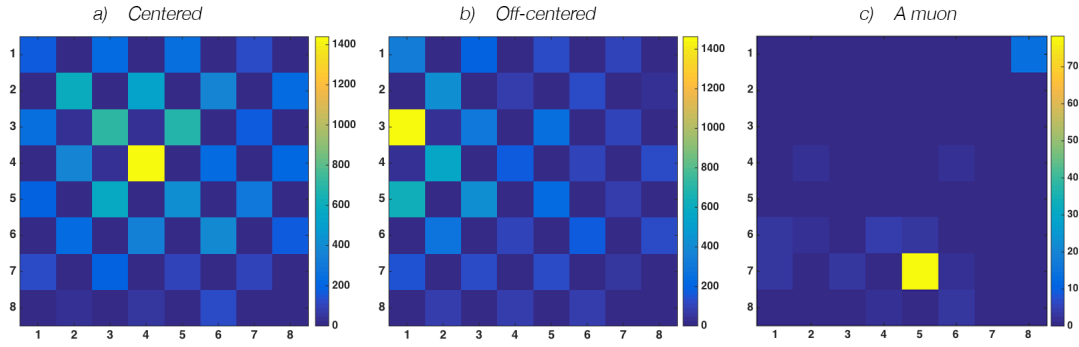


Fig. 5.9: Event display of the 64 SiPM matrix for a 10 GeV electron shower (a, b) and a muon (c) traversing the calorimeter.

5.3 SiPM equalisation

The primary goal of each calorimeter is a linear response to the energy released by particles in the shower development. The first step is to have sensors equalised. The SiPMs calibration is greatly simplified by their signal charge distributions: the multi-photon spectra (sec.4.1.4). Figure 5.10 shows an example for two sensors: each entry represents the digitised signal area (measured in ADC channels) and the spectra are characterised by peaks corresponding to different number of fired cells at the same time. Two sensors are equalised when their peak-to-peak (Δ_{pp}) distances are equal. Indeed, Δ_{pp} is linked to the gain of a single cell and, due to the high homogeneity of the SiPM response, is expected to be constant with respect to the number of fired cells. Moreover, its value was the gauge to turn the digitised signal into the (raw) number of fired cells:

$$N_{FC} = \frac{ADC - Pedestal}{\Delta_{pp}}, \quad (5.1)$$

where the pedestal value is extracted from a Gaussian fit on the first peak of the multi-photon spectrum. Before each beam test, all the 64 SiPMs, operated at the nominal biasing voltage, were tested and equalised in lab: a multi-photon spectrum was recorded for each SiPM. The spectrum was obtained as a large statistics sample of ns-long light pulses (generated by a LED) that conveyed

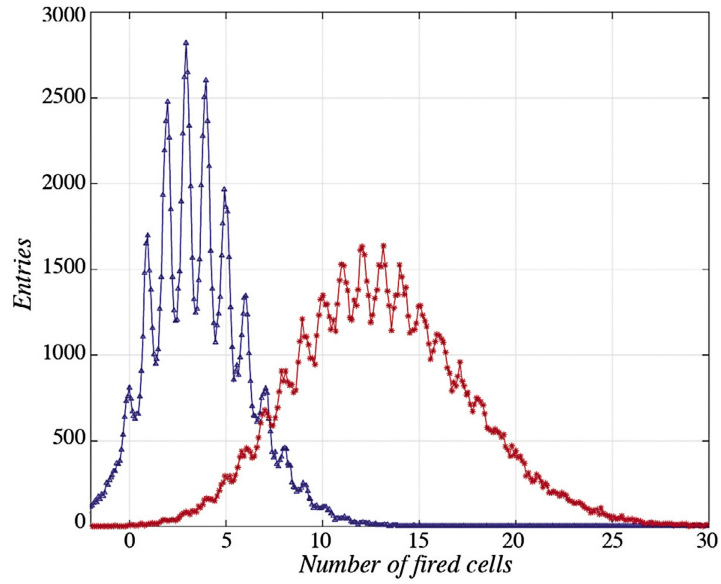


Fig. 5.10: Signal distributions of 2 SiPMs in response to light signals used for calibration purposes [1].

a small number of photons onto the sensor sensitive area. Then, the Δ_{pp} was extracted from a multi-Gaussian fit as the mean distance between all the peaks of that spectrum (fig.5.11) [117].

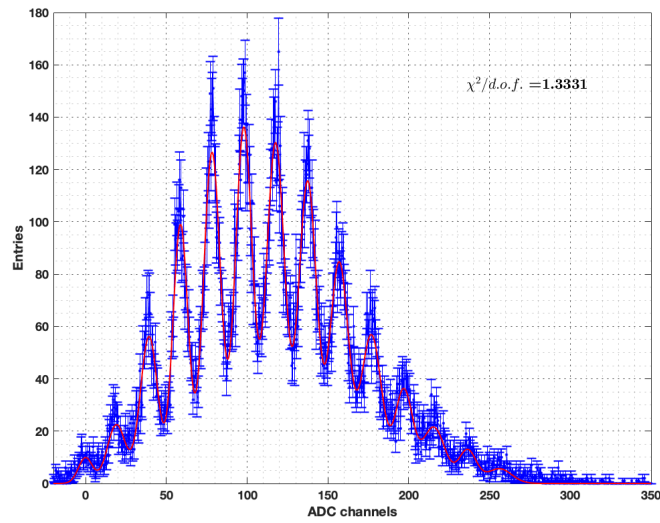


Fig. 5.11: An example of a multi-Gaussian fit performed in the qualification phase to extract the Δ_{pp} value.

Finally, iteratively, all these 64 values were compared and the bias voltage of each sensor (i.e. its gain) was properly tuned (at mV level) equalising all the Δ_{pp} within ± 1 ADC. The homogeneity of the sensor responses was verified illuminating (with LED) each fibre with the same light intensity (corresponding

to ~ 100 fired cells). The correct centring of the light spot with respect to the fibre axis was carried out by a 3-axis micrometer system, maximising the on-line sensor response spectrum (i.e. the integral of the sensor signal). Further detailed studies about the breakdown voltages, the Photon Detection Efficiency, the light distribution and the correction for the non-linearity were carried out and are presented in the sections below.

5.4 Breakdown voltage measurement

The breakdown voltage (V_{Bk}) defines the minimum bias above which the diode operates in Geiger mode. It exhibits a linear increase with temperature [159]: for the sensors equipped in the beam tests, the dV_{Bk}/dT coefficient was ~ 54 mV/°C⁶. This dependence is usual for a silicon junction: higher the temperature, higher the energy required to ionise the electrons from the valence to the conduction band (sec.4.1.2). Furthermore, since the gain dependence from the V_{Bk} is linear (eq.4.1), an inverse proportionality between the gain and the temperature is expected: a temperature increase results in a gain decrease (due to the decreasing of the avalanche current at steady voltage) [160]. Therefore, the precise measurement of V_{Bk} , performed in the qualification phase, allowed an off-line correction of the Δ_{pp} values of each sensor for the temperature variation between different runs in the analysis. The maximum temperature variation between the runs was always less than 2°C, while during the same run it was negligible.

At a given temperature, the SiPM gain (and the Δ_{pp}) increases linearly with the bias voltage. Therefore, a Δ_{pp} measurement at different bias voltages allows an extrapolation of the V_{Bk} by a linear fit. Figure 5.12 shows the result obtained measuring 14 different Δ_{pp} , corresponding to 14 different bias voltages for a reference SiPM. Each point was taken at 21.5 °C, in the same light conditions: tens of photons coming from a sub-ns light pulser⁷. Each Δ_{pp} and its error were extracted from the multi-Gaussian fit procedure already mentioned. The lowest measured point was 54.4 V because below this bias voltage the peaks of the spectrum were no longer distinguishable. The breakdown voltage was then extracted from the linear fit:

$$\Delta_{pp} = m \cdot V_{Bias} + q, \quad (5.2)$$

as the biasing voltage at which $\Delta_{pp} = 0$, i.e. $V_{Bk} = -q/m$, where $m = 7.49 \pm 0.04$ and $q = -387 \pm 2$. A value of $V_{Bk} = 51.71 \pm 0.02$ V was measured (with a spread

⁶Value extracted from datasheet.

⁷PicoQuant PDL 800.

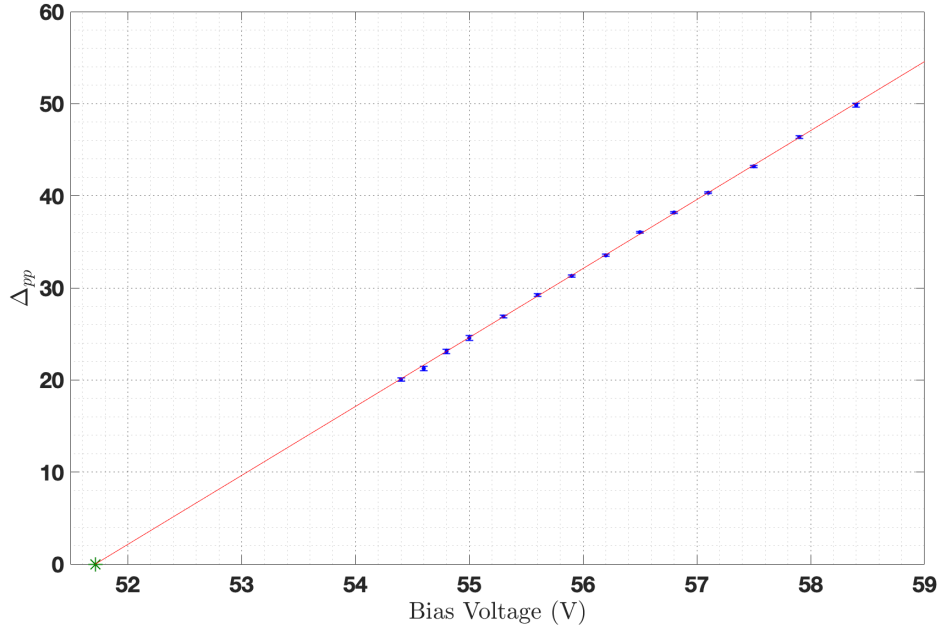


Fig. 5.12: The Δ_{pp} vs V_{Bias} and the linear fit (red line) from which the V_{Bk} (green point) is extracted.

between sensors of 0.3 V). Since all the 64 sensors were previously equalised, the m and q fit parameters were used as reference to correct, run-by-run, the Δ_{pp} for the temperature variation by eq.5.2, in which V_{Bias} was calculated as:

$$V_{Bias} = V_{Bias}^* - 0.054V \cdot (T - 21.5^\circ C), \quad (5.3)$$

where V_{Bias}^* is the nominal bias voltage (in Volt) applied to the considered SiPM, 0.054V is the dV_{Bk}/dT coefficient describe above, T is the temperature measured in the run and 21.5°C is the temperature at which the reference measurement was performed. The uncertainty ($\sigma_{\Delta_{pp}}$) of the peak-to-peak value so extracted, was calculated considering the correlation between the m and q parameters:

$$\sigma_{\Delta_{pp}} = \sqrt{\left(\frac{\partial \Delta_{pp}}{\partial q}\right)^2 \sigma_q^2 + \left(\frac{\partial \Delta_{pp}}{\partial m}\right)^2 \sigma_m^2 + 2 \left(\frac{\partial \Delta_{pp}}{\partial q \partial m}\right) \sigma_{q,m}}. \quad (5.4)$$

The drift of the gain due to the temperature variations has to be carefully considered in the design phase. One solution could be the direct control of the sensor temperature through a cooling system that guarantees the needed temperature stability. Another option could be adjusting the sensors V_{Bias} (through an on-line algorithm), in order to keep constant the SiPM gain values [141]. Since neither method has been implemented in this readout system, in order to properly consider the effect of the temperature variation in the analysis, a reference curve of

the sensor PDE was measured in lab before the beam tests.

5.5 Photon Detection Efficiency measurement

The Photon Detection Efficiency is the probability that a SiPM produces an output signal in response to an incident photon. As described in sec.4.2, it is a function of the overvoltage, the incident light wavelength and the temperature (that changes the V_{Bk}). The PDE temperature dependence was an important aspect of the beam tests data analysis. Since the V_{Bias} applied to each sensor was kept constant (to preserve the equalisation), the temperature variation between different runs could change the V_{Bk} and thus the V_{Ov} . In order to properly take into account these variations, a PDE reference curve (from which the correct PDE values were extracted) was produced. Moreover, as will be described in details in sec.6.5, in the 2017 beam test, the sensors reading the S signals exhibited saturation and signal non-linearity. To limit these effects, SiPMs coupled to the S fibres were operated at $0.5 V_{Ov}$. Therefore, the reference curve was also fundamental for the extrapolation of the expected PDE at these low bias operating voltages (PDE_{Low}). To perform an absolute PDE measurement, the exact number of impinging photons has to be known. This requires a calibrated photon source and makes the measurement more complex. Instead, to avoid these issues, a relative PDE curve was extrapolated measuring the total number of expected fired cells (N_{pe}), not limited by the sensor occupancy, for 21 different biasing voltages (and thus different PDE values), keeping constant the number of photons impinging on the sensor. Indeed, the LED source provided an amount of light that both: (i) guaranteed a SiPM response sufficiently low (the non-linearity correction was about 12% $\sim$ for 360 fired cells, i.e. 23% of sensor occupancy at nominal V_{Bias}) for a reliable correction, (ii) allowed a separation between the noise peak and the signal at low V_{Ov} . The number of fired cells for each measurement (N_{FC}^i) was calculated from eq.5.1, where ADC was extrapolated by a Gaussian fit⁸ and Δ_{pp} was calculated using the procedure already described. The N_{pe}^i was calculated from the inverse function of eq.4.10 (a detailed explanation will be provided in the next section). The value N_{pe}^* , measured at the nominal $V_{Bias} = 57.5$ V (for which the absolute PDE is known from the datasheet), was chosen as reference point to calculate the ratios:

$$R_{PDE}^i = \frac{N_{pe}^i}{N_{pe}^*} = \frac{N_{\gamma} \cdot PDE^i}{N_{\gamma} \cdot PDE^*}. \quad (5.5)$$

⁸The number of impinging photons was too high to have a multi-photon spectrum.

It is worth mentioning that the R_{PDE} provides directly the relative PDE measurement since the number of impinging photons (N_γ) was kept constant for all the measurements and thus can be simplified in the ratio. Finally, the absolute PDE reference curve (fig.5.13) was obtained considering the 25% PDE⁹ for the reference point and scaling the other ratios accordingly. For each run, the proper

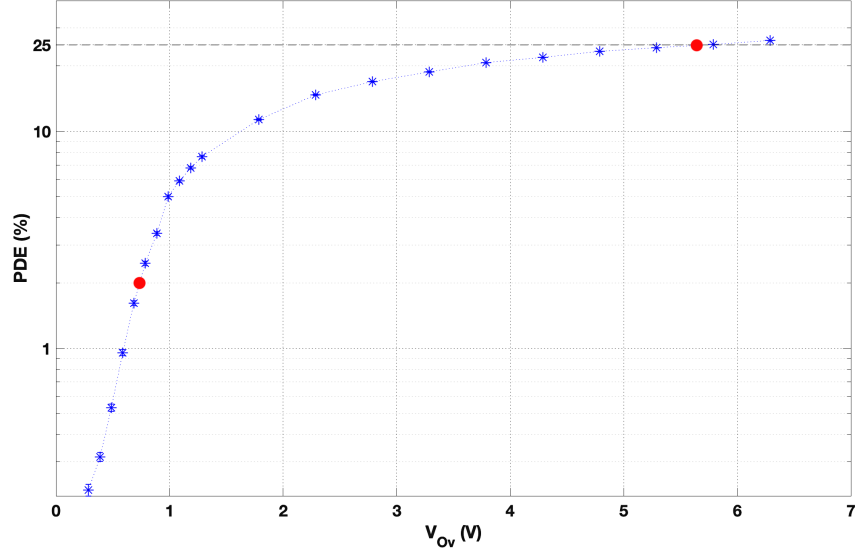


Fig. 5.13: PDE as a function of the V_{Ov} . The blue points are the 21 measurements performed. The red points represent the two principal PDE values considered in the 2017 beam test analysis: $PDE = (25.00 \pm 0.05)\%$ and $PDE_{Low} = (2.01 \pm 0.06)\%$ (see the text).

V_{Ov} was calculated (considering also the temperature variation between this reference curve and the one measured in the run) and the correct PDE value was extracted. In figure the red points represent the two principal PDE values considered in the 2017 beam test analysis: (i) $PDE = (25.00 \pm 0.05)\%$, which referred to the standard operational conditions ($V_{Ov} \sim +5.5$ V, at 23.0°C) and (ii) $PDE_{Low} = (2.01 \pm 0.06)\%$, that was the expected PDE when the SiPMs coupled to the S fibres were operated at low bias conditions to avoid the saturation ($V_{Ov} \sim +0.5$ V, at 22.5°C). A detailed discussion is postponed to the next chapter.

5.6 Sensor non-linearity correction and light distribution

Another crucial condition for a linear calorimeter response is the sensor linearity. The SiPM output signal to a photon flux firing many cells is proportional to the incident light intensity since it is obtained as the sum of the single cell

⁹Since the value from datasheet was measured at 25°C , while the calibration was done at 24.5°C , this temperature difference was considered in the final result, even if its effect was found to be negligible.

pulse amplitudes. However, as already discussed in sec.4.4, the number of fired cell is not always proportional to the number of impinging photons. The finite number of SiPM cells determines its dynamic range, and it leads to response non-linearities when the number of fired cells approaches the total number of cells (i.e. when the probability that more than one photon hits the same cell becomes not negligible). The number of fired cells N_{FC} is a function of the total number of the available cells N_{tot} (396 and 1584 for the tested sensors) and of the expected number of fired cells, not limited by the sensor occupancy, $N_{pe} = N_{\gamma} \cdot PDE$. It was already demonstrated (sec.4.4) that it can be approximated as:

$$N_{FC} = N_{tot} \left(1 - e^{-\frac{N_{\gamma} \cdot PDE}{N_{tot}}} \right). \quad (5.6)$$

From the inverse formula:

$$N_{pe} = N_{\gamma} \cdot PDE = -N_{tot} \cdot \ln \left(1 - \frac{N_{FC}}{N_{tot}} \right) \quad (5.7)$$

it is possible to extract the expected number of photoelectrons, providing a first order correction for the non-linearity SiPM response. It should be emphasized that this formula is an approximation, since it applies to ideal circumstances that are not exactly met in practice. Indeed, it is based on the assumption: (i) that all photons arrive simultaneously in time, (ii) that there are no effects of pulse recovery, (iii) that there is no prompt cross talk and (iv) that all pixels of the SiPM are uniformly irradiated. The effects of the first two assumptions will be tackled in chapter 7, where all the simulation details will be provided. For what concern the cross-talk (X_t) of the sensors, it was found to be negligible. Indeed, in order to account for it, eq.5.6 can be written as:

$$N_{FC} = N_{tot} \left(1 - K \cdot e^{-\frac{N_{\gamma} \cdot PDE}{N_{tot}}} \right), \quad (5.8)$$

where:

$$K = e^{-\frac{N_{\gamma} \cdot PDE}{N_{tot}} \cdot X_t}, \quad (5.9)$$

which means that the number of cells that would be fired in an ideal sensor of "infinite granularity" should be: $N_{\gamma} \cdot PDE \cdot (1 + X_t)$. For the sensors adopted in the 2017/18 beam tests, $X_t < 0.01$ (when operated at $+5.5V_{Ov}$) and thus $K \sim 1$. The cross-talk was much below that value when operated at lower biasing voltages, making its contribution even more negligible. Finally, the light coming out from the fibre illuminates most of the sensor area¹⁰ but not uniformly. A direct measurement of this effect was performed by homogeneously illuminating one fibre tip with a LED¹¹ and coupling the other one to a 16-bit

¹⁰The circular fibre tip covered an area of about 0.79 mm².

¹¹The wavelength was 400 nm.

CCD camera. As shown in fig.5.14, about the 97% of the light impinging on a $1 \times 1 \text{ mm}^2$ sensor area was contained in a circle with a diameter of $\sim 0.95 \text{ mm}$. This area corresponds to about 1120 pixels of the total 1584 ones available.

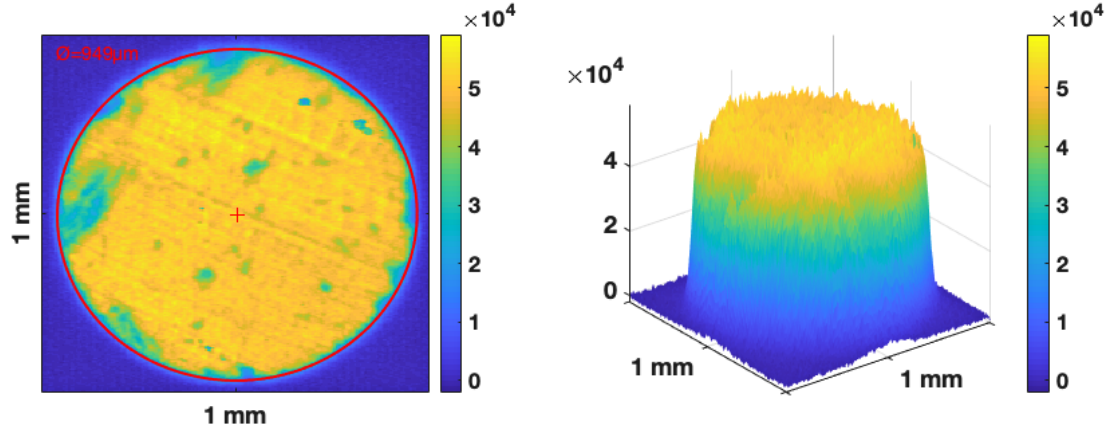


Fig. 5.14: Intensity distribution of the light coming out from a *S* fibre homogeneously illuminated by a LED, recorded by a 16-bit CCD camera. The green spots represents some inefficiencies of the fibre in the light propagation due to some cracks or internal scratches.

Therefore, to account also for this effect, eq.5.7 was modified as follows:

$$N_{pe} = -1120 \cdot \ln \left(1 - \frac{0.97 \cdot N_{FC}}{1120} \right) - 464 \cdot \ln \left(1 - \frac{0.03 \cdot N_{FC}}{464} \right). \quad (5.10)$$

Clearly, this equation allows only a first order approximation correction of the actual value of photoelectrons and was made necessary by the saturation found in 2017 of some sensors reading the *S* channel. Undeniably, the fluctuation in the number of detected photons has an impact on the calorimeter performances since it increases the stochastic term in the ultimate energy resolution. Therefore, on one hand it is preferable to increase the light yield to reduce this term, but, on the other hand, it was demonstrated that the non-linearity correction can be considered accurate only within a limited range of occupancy values [161]. A trade-off between these two aspects is one of the most important aspect to be evaluated in a future design phase of a calorimeter of this type (an extensive discussion will be done in the next chapter).

Beam tests data analysis and results

” *Physics is about questioning, studying, probing nature. You probe, and, if you are lucky, you get strange clues.*

Lene Hau

In this chapter the description of the experimental set-up, the measurements conditions and the analysis methods will be presented, together with the principal results obtained from the data analysis of all the beam tests performed on the modules described in sec.5.2. These results completed the proof-of-concept but also pointed out some crucial points to be addressed to make SiPM a reliable solution for dual-readout calorimetry.

6.1 Experimental set-up

Beam line and detectors

For these studies, secondary and tertiary beams derived from the 400 GeV proton beam delivered by the CERN Super Proton Synchrotron (SPS) were used. These particle beams were steered through the H8 line into the DR fibre calorimeter. The experimental set-up consisted of the SiPM calorimeter described above and some auxiliary detectors, which were intended to limit and define the effective size of the beam spot and to determine the individual beam particles identity. Fig.6.1 shows a schematic layout, in which the positions of these auxiliary counters are indicated. Two Delay Wire Chambers (DWCs) [162] were used to extract the impact point location of the beam particles at the calorimeter surface with a precision of few mm (depending on the beam energy). Three small scintillation counters provided the signals that were used to trigger the data acquisition (DAQ) systems. These trigger counters were 2.5 mm thick, with an overlapping area between the first two (T_1, T_2) of $4 \times 4 \text{ cm}^2$. Downstream from these two, a third scintillation counter (T_H) with a 10 mm radius hole was installed. The (anti-)coincidence between these three counters logic signals provided the trigger ($T_1 \cdot T_2 \cdot \overline{T_H}$). About 2 m upstream of the calorimeter, a



Fig. 6.1: Schematic layout of the experimental set-up (not to size). Shown are the delayed wire chamber (DWC), the trigger counters (TC), the pre-shower detector (PSD), the DR calorimeter and the muon counter (μ) used in the beam test [1].

Pre-Shower Detector (PSD), consisted of a 5 mm thick lead plate, followed by a 5 mm thick plastic scintillator, allowed the electrons identification: e^- started developing showers in this device, while muons and hadrons typically produced a signal characteristic of a minimum ionizing particle (mip) in the scintillator plate. Finally, about 20 m downstream of the calorimeter, after a series of concrete blocks ($\sim 8\lambda_{int}$), a $50 \times 50 \text{ cm}^2$ scintillation counter (μ) allowed to identify the muons in the particle beams.

Data acquisition

Two independent DAQ systems, receiving the same trigger ($T_1 \cdot T_2 \cdot \overline{T_H}$), were used: one dealt with the SiPM data (and already described in sec.5.2.2) and another with the signals from the auxiliary detectors. The recorded information from both systems was synchronised and merged off-line into n-tuples that were used for the data analyses. In the counting room, signals from the PSD and the muon counter were integrated and digitised with a sensitivity of 100 fC/count and a 12-bit dynamic range in a charge ADC (CAEN V862AC). The signals from the wire chamber were recorded with 140 ps resolution in a 16-channel CAEN V775N TDC, and converted into (x, y) coordinates of the point where the beam particle traversed the chamber. This data acquisition system used VME electronics. All information was collected using gate widths of the order of 100 ns, and read out event-by-event through the V2718 CAEN optical link bridge with a dead time of $\sim 300 \mu\text{s}$. The event rates were such that pileup effects were negligible: i.e. the readout scheme optimised the data taking efficiency (and the CPU utilisation) using the SPS accelerator cycle bunch structure (which lasted between 36 and 54 s, depending on the various tasks of the accelerator complex), during which period beam particles were provided to the experiment by means of either one or two extractions with a duration of 4.8 s each.

Experimental data

For each beam test, either 60 or 180 GeV secondaries beams¹ were used. Moreover, low energy tertiary beams were produced off a target installed in the 60 GeV secondary beam, and beams with energies above 60 GeV were derived similarly from the 180 GeV secondary ones. The secondary beams were also used to provide 125 GeV μ^{+2} beams. The tertiary ones had a mixed composition: for energies below 50 GeV, they consisted primarily of e^- , with small admixtures of hadrons and muons while, for higher energies, pions gradually became a very significant contribution and at energies above 100 GeV muons were dominant. In 2016/17, to measure the C and S light yields and the module linearity response, dedicated runs with tertiary beams were carried out for the following energies: 6, 10, 20, 30, 40 and 50 GeV (from 60 GeV secondaries) and 40, 60, 80, 100 and 125 GeV (from 180 GeV secondaries) while in 2018 the energy spread ranged from 10 to 40 GeV. As described in the next section, dedicated cuts were made to select pure electron and muon event samples from the collected data. This event selection was done to ensure the same em shower energy containment (estimated by a proper Geant4 simulation, as explained in sec.6.8).

6.2 Event selection

Off-line, 5 different cuts were implemented in order to select electron (or muon) events. (i) A preliminary cut of the SiPMs noise and environmental background events was done selecting only the events where the number of fired cells (i.e. the sum on all the 64 SiPMs signals) was greater than 20 photoelectrons. (ii) Then, electrons (or muons) were selected on the basis of the signals in the muon counter. The left plot of fig.6.2 shows an example of the signal distribution in this counter for a 40 GeV beam particles: events with a signal above the indicated cut-off value were tagged as muons, while the rest of events, compatible with the muon counter electronic noise (i.e. the pedestal), were considered as possible electron events. (iii) Pure electrons were then identified as particles that produced a signal in the PSD that was larger than the combined signals from at least three minimum ionizing particles (mips) traversing this detector. The right plot of fig.6.2 shows a typical PSD signal distribution (for 10 GeV electrons) with the mentioned cut-off value. (iv) The DWC information were used to select the events within a small beam spot covering the calorimeter central region, typically with a radius <3 mm and an incidence angle (θ) of ± 1 mrad (fig.6.3 left). (v) This geometrical selection has been further refined by a cut based on the energy

¹Produced by 400 GeV protons from the SPS accelerator on a target shared by several beam lines.

²Obtained by blocking all other particles with upstream absorbers.

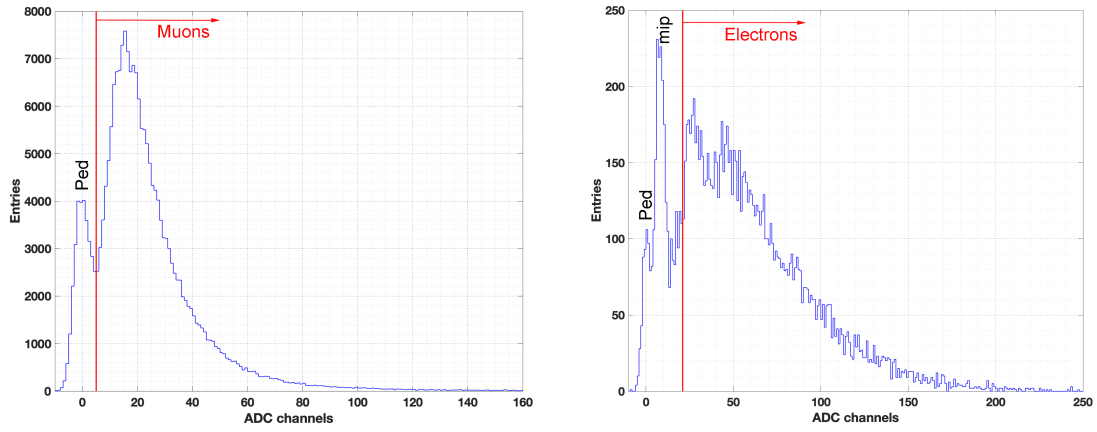


Fig. 6.2: The signal distributions examples measured in the muon counter (left) and PSD (right) for 40 GeV and 10 GeV beam particles, respectively.

deposit pattern in the calorimeter itself, i.e. by selecting events in which the fibre with the largest signal (from now on defined as hottest fibre) was located in the central 4×4 fibre region (fig.6.3 right). Finally, from each pure electron

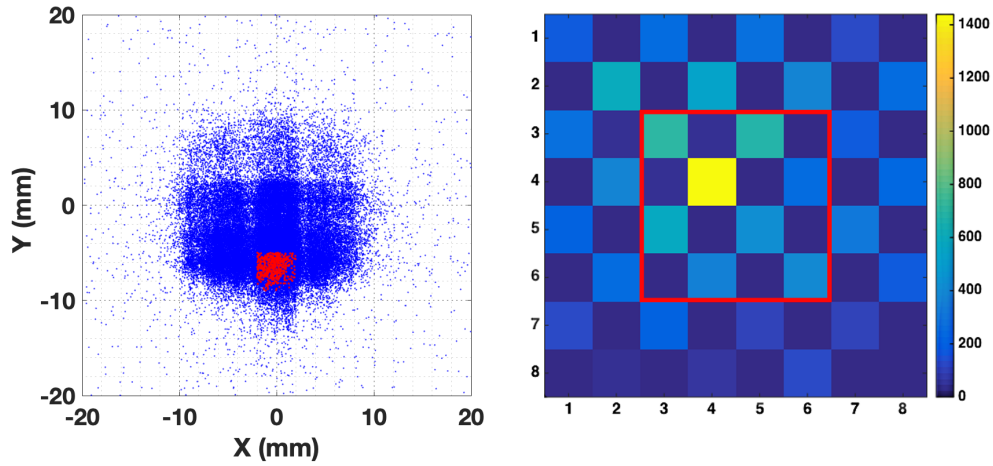


Fig. 6.3: Left: The DWC data were used to extrapolate, at the calorimeter front face, the events entering in the central region. The blue points are all the electron events selected with the previous 3 cuts while the red ones are the events that pass also the DWC cut. Right: An event display that has passed all the cuts. The red square shows the possible hottest fibre positions.

sample obtained with such procedure (i.e. for each run), the number of fired cells was extrapolated from a Gaussian fit on the selected data distribution. All the following analysis were carried out by applying all the cuts described.

6.3 Fibre optical cross-talk

The dual-readout method requires a full separation between Cherenkov and scintillation signals. Since the difference in light yields between these two channels was found to be, at least, a factor of 50 (sec.6.5), one of the major challenges for these prototypes was the suppression of the optical cross-talk between fibres. For example, the C signals would increase by 50% if 1% of the S light is detected by the SiPMs that read out the signals from the Cherenkov fibres. In order to quantify this contribution, the best way would be a measurement in which the S fibres are physically removed and compare the results with the C signals measured in the set-up mounting all the 64 fibres. Something similar was performed in 2016 beam test (sec.6.3.1), where 2 different modules were built. Unfortunately, in 2017 and 2018, only one module was available and thus two alternative methods were performed to estimate the cross-talk: a direct lab measurement with a LED (sec.6.3.2) source and one based on high-energy muon run (125 GeV) information (sec.6.3.3).

6.3.1 Direct measurement removing S fibres

In 2016, two different modules, one with both S and C fibres and one with only the 32 C ones, were equipped with the readout board described in sec.5.2.2, hosting all the 64 SiPMs on the same layer. The sensors adopted for this first test were the Hamamatsu S13615-1050, having 50 μm pixel pitch and a total number of available cells of only 396. Unfortunately, due to this low dynamic range, the saturation of the sensors coupled to the scintillating fibres occurred for all the beam energies, affecting all the measurement based on the S channel. Anyway, since this issue did not affect the C signals, two important results were achieved: (i) a linear response (within few percent) of the C signal up to 100 GeV, with a Cherenkov light yield of about 26 Cpe/GeV (sec.6.4) and (ii) the measurement of the optical cross-talk. This cross-talk was calculated as:

$$X_{Talk} = \left[1 - \frac{N_{FC}(C)}{N_{FC}(C + S)} \right] \cdot 100, \quad (6.1)$$

where $N_{FC}(C)$ is the total number of fired cells of all the 32 SiPMs coupled to the C fibres and $N_{FC}(C + S)$ the one in which also the contribution of the sensors with no coupled fibres were considered. In 2016, it was found a X_{Talk} value of more than 25%. Since the X_{Talk} was mainly due to the absence of any optical separation between neighbouring sensors hosted in the same board, in the 2017/18 beam tests, a new board design based on two tiers structure was adopted (as described in sec.5.2.2). It is worth mentioning that this procedure is

the most straightforward way to provide a precise measurement of this effect, while the other solutions described below can provide only an upper limit.

6.3.2 Direct lab measurement with a LED source

The result obtained in 2016 was far from the goal of no cross-talk required for a successful DR calorimeter. In 2017 the two-layer structure designed to minimise the contamination between the two signals (sec.5.2.2) was qualified in lab as follows. At the front face of the calorimeter module, all the fibre tips, with the exception of one, were masked with several lead light-tight tape layers. A LED³ illuminated the uncovered tip with a high intensity light pulse (corresponding to ~ 960 fired cells). The light was focused on the fibre tip. The focal spot size was smaller than 1 mm to avoid the direct light contamination on the neighbouring *C* fibres. The correct centring of the light spot with respect to the fibre axis was carried out by a 3-axis micrometer system (fig.6.4), maximising the on-line sensor response spectrum (i.e. the integral of the sensor signal). Once the best

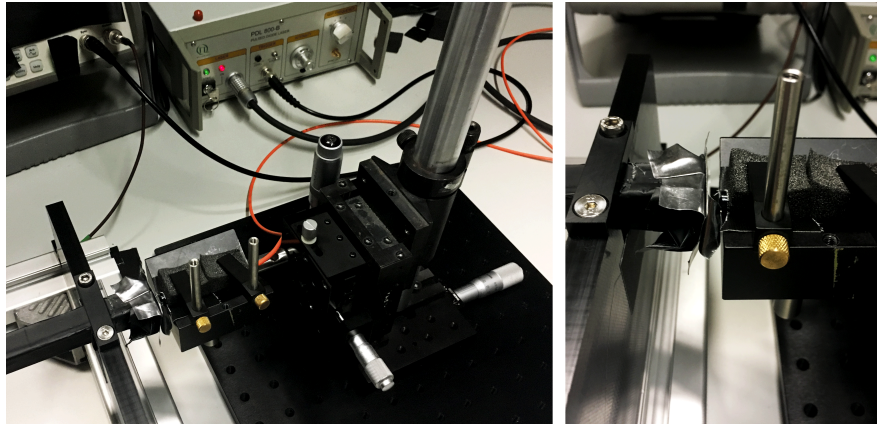


Fig. 6.4: Experimental set-up for the optical cross-talk between fibres measurements. All the fibres but one were covered with several layers of lead tape and the light was focused on the tested fibre. The LED focuser was mounted on a micrometer system shown in figure.

alignment was reached, all the 64 SiPM signals were simultaneously recorded for a total of 100,000 light pulses. For each event, the (raw) number of fired cells measured by each sensor was converted in photoelectrons with eq.5.10. The information of all the sensors reading the same type of fibre (*C* or *S*) were then added together. The optical cross-talk was calculated as:

$$X_{Talk} = \frac{C_{Mean} - C_{Pedestal}}{S_{Mean} - S_{Pedestal}} \cdot 100, \quad (6.2)$$

³The PicoQuant PDL 800. The wavelength was $\lambda = 445$ nm.

where C_{Mean} (S_{Mean}) was the distribution mean value of the total number of C (S) photoelectrons measured for all the events. $C_{Pedestal}$ ($S_{Pedestal}$) was the mean value of the same distribution but where signals were recorded in no light⁴ conditions. This procedure was performed for the eight scintillating fibres hosted in the calorimeter central region (i.e. the 4×4 fibres region considered in the electron events selection) and a mean value of $0.3\% \pm 0.1\%$ was found. It is worth mentioning that all the experimental conditions (as e.g. the light intensity and the temperature) were kept constant for all the measurements and a homogeneous cross-talk spatial distribution was found⁵. Fig.6.5 represents an example for one fibre of the average result of 100,000 events. The non-zero

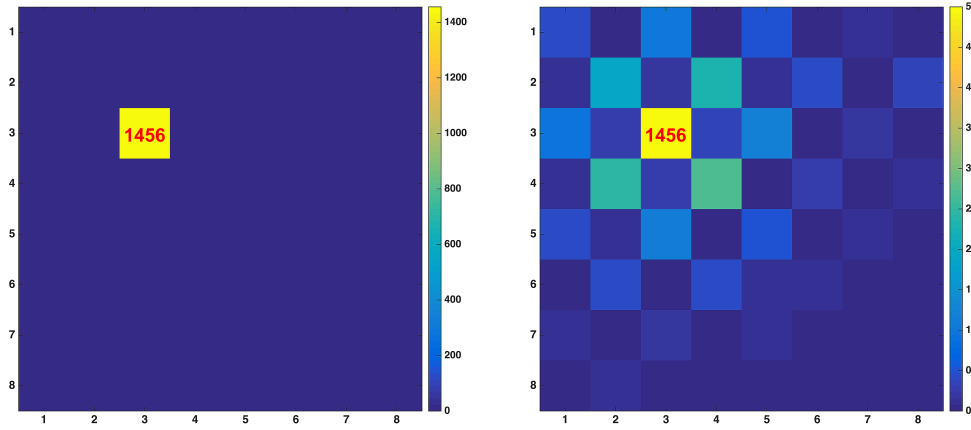


Fig. 6.5: Left: Fired cells distribution in the 64 sensors, resulting from the illumination of one scintillating fibre with a high light pulse (1456 pe). This distribution represents the average of about 100,000 events where the uncovered fibre ($[x,y] = [3,3]$) was illuminated. Right: The same image with a truncated z axis at 5 pe.

signals are clearly concentrated in the neighbouring sensors of the illuminated fibre, for both S and C types. This result should be considered an upper limit because some small fraction of the LED light could have entered directly into a neighbouring Cherenkov fibres. Moreover, to have an adequate sensitivity (i.e. at least few fired cells in the C channel), high intensity light pulses were required and non-linearity sensor response occurred. Eq.5.10, from which the number of fired cells was converted into the number of photoelectrons, should be underestimated since the distribution of the light impinging on the fibre tip was no longer uniform. Indeed, as described above, the focal spot size was smaller than 1 mm, resulting in a Gaussian light distribution with a FWHM smaller than the diameter considered in the correction (0.95 mm, sec.5.6). Since it was not possible to easily extract a precise estimation of the spot diameter for each fibre, it was decided to apply that correction to all the measurements, providing an

⁴Moreover, the SiPMs noise measured in this background datasets was found to be, on average 5 and 6 photoelectrons for the C and S channel, respectively, always consistent with the expected DCR.

⁵Indeed, no sensible differences between the eight measurements results were measured.

upper limit.

The cross-talk reduction of two order of magnitude reached in 2017 (with respect to the 2016 module), confirmed that the two-tier structure was a good solution, allowing a spatial and optical separation of the signals on two different planes. Nevertheless, with that cross-talk level, the impact of the S light on the C signal was not yet negligible. Due to the estimated (sec.6.5) S/C light yield ratio for em showers of ~ 50 , about 15% of the Cherenkov total signal was expected to come from scintillation light, meaning that the optical crosstalk must be further reduced. A possible explanation for the residual cross-talk is the absence of optical insulation between the fibres at the rear end of the module between the end of the calorimeter and the jig that guides them to match the SiPMs. This hypothesis was confirmed in 2018 when, due to the further improvements in the mechanics and fibres insulation, a cross-talk between fibres compatible with the sensitivity of this method ($\sim 0.1\%$) was obtained. It is worth mentioning that, for each beam test, all the fibres (and thus the coupling between fibre and SiPM) have been replaced with 64 new ones.

6.3.3 Alternative measurement

In 2017, an alternative measurement about the cross-talk effect was carried out in the beam line at CERN. This method was based on the fact that the signals from muons are quite different for the S and C channels. Indeed, as already described in sec.3.2, the Cherenkov fibres do not produce a signal for the ionisation part of the energy loss of the muons in the calorimeter, since the light produced falls outside their numerical aperture. Therefore, these fibres are only sensitive to the radiative processes (bremsstrahlung) that also contribute to the energy loss and this signal component should be equal for the two channels (sec.3.3.3). This is illustrated in fig.6.6, which shows the signal distributions for 100 GeV μ^+ , measured with the copper-based DREAM calorimeter, read out with PMTs. This module was calibrated with electrons, and the response to these particles, i.e., the average signal per unit deposited energy, was equalised for both channels. The horizontal scale in fig.6.6 is based on this energy calibration. As shown in figure, the most probable value (MPV) of the C signal is 1.20 GeV smaller with respect to the S channel. The DREAM Collaboration found that this difference was constant for muons of different energies, ranging from 40-200 GeV [90]. The energy lost by minimum ionizing particles (in the DREAM calorimeter structure) was estimated to be ~ 7 MeV/cm, i.e., 1.40 GeV for the total 2 m long detector. This was found to be in good agreement with the difference measured between the signals from the S and C fibres.

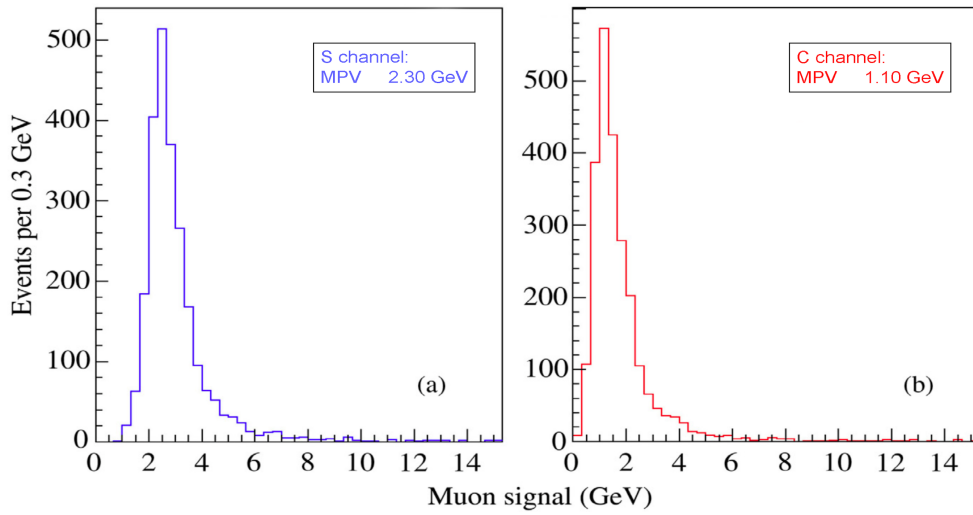


Fig. 6.6: Scintillation (left) and Cherenkov (right) energy signal distributions for 100 GeV μ^+ measured in the (copper-based) DREAM calorimeter with PMT readout [90].

This phenomenon offered the possibility to have a second and independent measurement of the cross-talk in the SiPM calorimeter prototype. Based on the results described above, for 125 GeV μ^+ , the most probable energy deposit measured with the C fibres in the SiPM-based calorimeter was expected to be a factor 2.03 (i.e., $2.271/1.117$) smaller than that measured in the S channel. Given the detector length ($39X_0$ vs. $100X_0$) and the measured effects in the DREAM calorimeter, the difference between the S and C signals was expected to be ~ 0.45 GeV [1]. Therefore, any larger signal for the Cherenkov fibres, or any smaller difference with the scintillation signals, would indicate a cross-talk contribution. Fig. 6.7 represents the signal distributions (already converted in the energy) measured with the 2017 SiPM prototype for 125 GeV muon beam. The S fibres signals were corrected for the non-linearity sensor response and the pedestal contribution (i.e. signals observed in the absence of light, on average corresponding to 9 and 6 photoelectrons for the S and C channel, respectively) was already subtracted for both the signals. Moreover, the two different energy containment estimated for the C ($\sim 36\%$) and S ($\sim 45\%$) were considered for the energy conversion (more details will be provided in the next two sections). The most probable energy deposit measured by the S channel was 0.93 ± 0.06 GeV. According to the above considerations, in the absence of cross-talk and given the measured S signal, the expected most probable C energy deposit signal was 0.47 ± 0.04 GeV⁶ [1]. The measured muon C signal corresponded to an energy deposit of 0.48 ± 0.05 GeV, a value compatible with no cross-talk effect. It is worth mentioning that these results were based on the energy containment estimation (performed by GEANT4) considered in the conversion from the total number of

⁶Namely, 0.46 ± 0.03 GeV based on the S/C signal ratio, 0.48 ± 0.06 GeV considering the $S-C$ value.

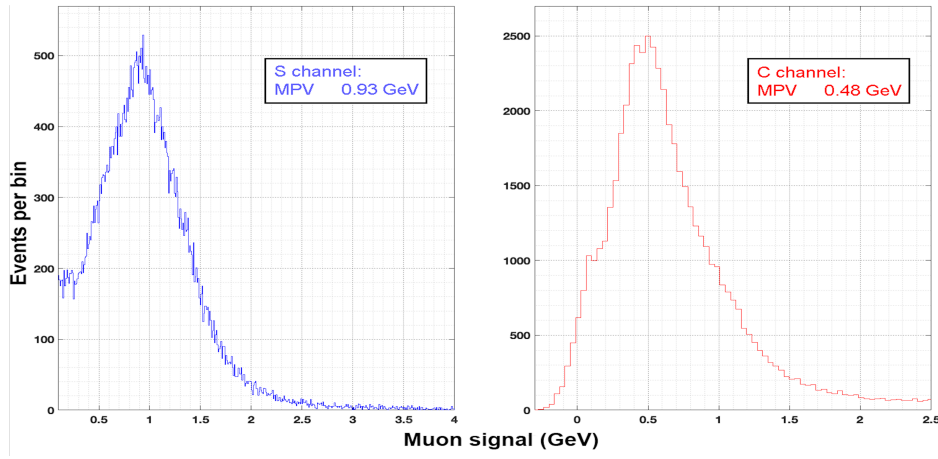


Fig. 6.7: Scintillation (left) and Cherenkov (right) energy signal distributions for 125 GeV μ^+ measured in the 2017 calorimeter module.

photoelectrons to the energy value (sec.6.8). Since a proper estimation of the energy containment in such small prototypes was not an easy task, the upper limit provided by the lab measurement described in the previous section (i.e. $X_{Talk} = 0.3 \pm 0.1\%$) was chosen as the cross-talk value adopted in the 2017 data analysis (sec.6.4 and 6.5).

6.4 Cherenkov signal light yield and linearity

The fluctuations in the number of detected photons increase the stochastic term of the calorimeter energy resolution (sec.2.2.1). On one hand, a high light yield (LY) can reduce the impact of this fluctuation, on the other hand if the light intensity impinging on a SiPM is too high, the probability of having more than one photon per cell is not negligible and non-linearity effects occur (sec.4.4). A trade-off between these two aspects is required. For the tested modules, the scintillation light yield was found to be more than 50 times higher than the Cherenkov signal (sec.6.5.1). Therefore, the strategies to obtain a linear response for both channels have to be different and separately addressed.

A first hint of a Cherenkov signal linearity was found already in the 2016 beam test. In 2017 it was assessed with dedicated measurements over an electron beam energy range spreading from 6 up to 125 GeV. In this test, SiPMs were operated at the nominal biasing voltage (57.5 V, $+5.5 V_{ov}$), chosen since it offered a high and stable PDE of 25% (sec.5.5) and, at the same time, the non-linearity effects were negligible. All the sensors were equalised as described in sec.5.3 to guarantee their gain homogeneity along all the measurements. Fig.6.8 shows the average number of detected Cherenkov photoelectrons (i.e. the sum of all the 32

C signals) per GeV, as a function of the electron beam energy. The procedure

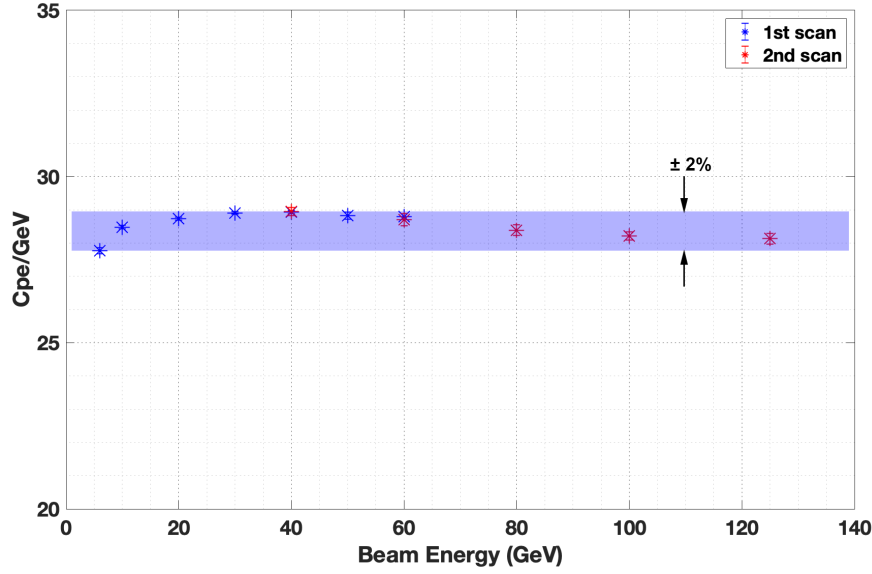


Fig. 6.8: The average number of Cherenkov photoelectrons measured per unit of deposited energy, as a function of the electron beam energy. These results were obtained in 2017 beam test for two different electron beam energy scans.

adopted to extract each point of this plot can be summarised as follows:

- For each run, the Δ_{pp} and $\sigma_{\Delta_{pp}}$ (eq.5.2 and eq.5.4) were extracted from the procedure described in sec.5.4. Since SiPMs were equalised (within 1 ADC channel), it was possible to assign the same peak-to-peak value to all the C sensors.
- Event-by-event, the ratio between the digitised signal⁷ of each SiPM and the Δ_{pp} (eq.5.1) provided the number of fired cells (N_{FC}^i).
- All the 32 N_{FC}^i were then added together providing the total number of C fired cells of the event (N_{FC}^C). The error ($\sigma_{N_{FC}^C}$) was calculated as the quadratic sum of all the 32 $\sigma_{N_{FC}^i}$.
- A Gaussian fit of the N_{FC}^C distribution of all the selected electron events (sec.6.2) provided the mean value of the number of C detected photoelectrons (Cpe). Also in this case the fit uncertainty was negligible compared to the $\sigma_{N_{FC}^C}$ (but anyway considered in the error propagation).
- Finally, the ratio between Cpe and the nominal beam energy value E , provided the average number of C photoelectrons, measured per unit of

⁷At which the pedestal value was already subtracted.

deposited energy (C_{pe}/GeV).

Moreover, to properly account for the PDE temperature dependence, a normalisation to a defined PDE value was performed to allow a fair comparison between the points at different beam energies. The chosen value was: $PDE^* = (25.00 \pm 0.05)\%$, i.e. the point of the PDE curve, extracted in sec.5.5, corresponding to the optimal operational conditions (V_{Ov} of +5.5 V). Normalisation was done extrapolating the V_{Ov} , accordingly to the temperature difference between each run and the reference (23°C), and extracting the PDE from the curve obtained in the calibration phase (fig.5.13). Finally, the value obtained with this method for the 10 GeV beam energy (PDE_{10}) was used to equalise all the results (i.e. each point was multiplied for the ratio between PDE_{10} and its PDE). It should be highlighted that, in this optimal biasing voltage condition, the applied temperature corrections did not change sensibly the Δ_{pp} and PDE values⁸, confirming the robustness of the C results.

The 2017 results exhibit a linear response of the C channel within 2% over the full energy range (fig.6.8) and a Cherenkov LY mean value of (28.6 ± 0.4) Cpe/GeV. This confirms two important points: (i) there was no saturation or visible non-linearity sensor response effects in the Cherenkov signals, (ii) the average shower containment was independent of the electron energy (it was also demonstrated by the simulation, sec.6.8). Correcting for the average C shower containment ($\sim 36\%$), the C light yield should be: $28.6/0.36 \sim 79$ Cpe/GeV in a sufficiently large module. Finally, after correcting for the S light cross-talk⁹ contribution (10 ± 4 photoelectrons, as described in sec.6.5.1), the Cherenkov LY in such a calorimeter would thus be 69 ± 5 Cpe/GeV. It is about twice larger than what was measured for the similar PMT-based DR calorimeters. This difference is due to the higher PDE of these SiPMs compared to the PMTs used for the DREAM/RD52 modules. This increased LY should improve the stochastic term in the em energy resolution from $13.9\%/\sqrt{E}$ to $12.5\%/\sqrt{E}$, bringing this resolution somewhat closer to the limit set by sampling fluctuations alone ($8.9\%/\sqrt{E}$ [99]). These results confirm also that the non-linearity sensor response can be considered negligible and do not impact on the linearity of the Cherenkov signal. They may still affect the resolution (because the calorimeter response depends whether the shower maximum coincides with one fibre or is shared by several ones): a detailed discussion about the correction and the impact of the LY on the energy resolution can be found in sec.6.6.

For a future upgrade of this prototypes, considering that the sampling fluctuation contribution to the energy resolution is $\sim 9\%$, increasing the Cherenkov light

⁸The maximum temperature variation spread between runs was 2°C.

⁹Under the hypothesis (conservative) of an optical cross-talk between fibres of 0.3% of the S signals.

yield closer to (or possibly even above) 100 pe/GeV would be enough to limit the impact of its fluctuation on the stochastic term. This could be done: (i) using fibres with higher numerical aperture (ii) adding an aluminised glass mirror at their free end, (iii) adopting SiPMs with a higher PDE to the UV-blue component of the spectra¹⁰.

6.5 Scintillation signal light yield and linearity

Whereas signal saturation and non-linearity did not affect the sensors coupled to the Cherenkov fibres, this was not true for the scintillation signals. The high number of impinging S photons saturated the SiPMs and made impossible to measure (in 2017) the S light yield in the same configuration chosen for the C sensors. This effect is well represented in fig.6.9a, where an event display of a 40 GeV electron beam is shown for the 2017 prototype. In this example both the C and S sensors were operated at the optimal biasing condition, corresponding to $+5.5 V_{Ov}$. In this example both S SiPMs closer to the shower axis were saturated, recording a (raw) number of fired cells equal to their maximum dynamic range (i.e. 1584). Setting a lower biasing voltage ($+0.5V_{Ov}$), the saturation was

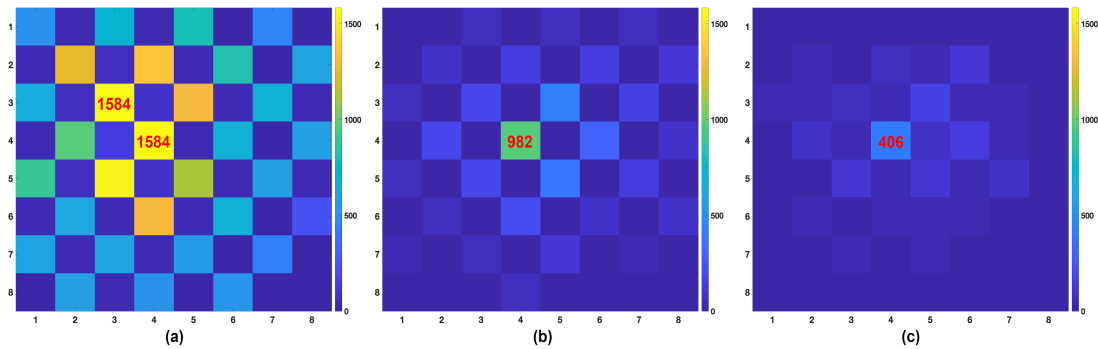


Fig. 6.9: Event display of 40 GeV electron beam for: (a) the 2017 beam test module in which also the SiPMs coupled to the S fibres were biased at $+5.5 V_{Ov}$, (b) the same module but with S sensors biased at $+0.5 V_{Ov}$ and (c) the 2018 module in which a yellow filter was applied between the fibre tips and the sensors (at $+5.5 V_{Ov}$).

avoided but a non-linear sensor response was still present (fig.6.9b), especially for the SiPM coupled to the most energetic fibre (the hottest fibre), requiring a proper correction in the data analysis (sec.6.5.1). In 2018, this effect was reduced (fig.6.9c) by attenuating the intensity of the S light adding an optical filter between fibres and sensors (sec.6.5.2).

¹⁰The development of dedicated SiPMs with a PDE of $\sim 20\%$ in the UV region (as the new Hamamatsu VUV-MPPC 1337 series) has just begun, but it could be a good starting point also for these specific applications.

6.5.1 2017 beam test

In 2017 beam test, to reduce the signal saturation and non-linearity effects without disassemble the module, all the S channel sensors were operated at a biasing voltage of ~ 52.5 V, i.e. $+0.5V_{Ov}$. Indeed, the PDE was lowered to $\sim 2\%$ (fig.5.13), avoiding the sensors saturation. That was clearly an undesired operating point because small variations of the V_{Bk} resulted in a higher PDE dependence on temperature variation, which further complicated the analysis, and also the gain variation with the temperature increases by a factor 10. Moreover, the Δ_{pp} extrapolation was more difficult: recording a multi-photon spectrum was actually impossible since the gain was so low that the resolution was spoiled both by the system noise and by the ADC granularity. Therefore, the only way to provide the S peak-to-peak distance was the extrapolation of its value following the procedure adopted for the Δ_{pp} temperature variations correction on the Cherenkov channel (already described in sec.5.4). For example, for the 10 GeV run dataset, the extrapolated peak-to-peak distance was 1.43 ± 0.04 ADC (at 22.5°).

Nevertheless, the residual non-linearity SiPM response turned out to be already noticeable at the low end of the electron energy range studied, even when the PDE was lowered to only a few percent. This is illustrated in fig.6.10a, which shows the raw data obtained with an electron beam energy spread from 10 up to 50 GeV, separately for the hottest fibre (red) and for the sum of the signals measured by the other 31 scintillating fibres (blue). The number of fired cells

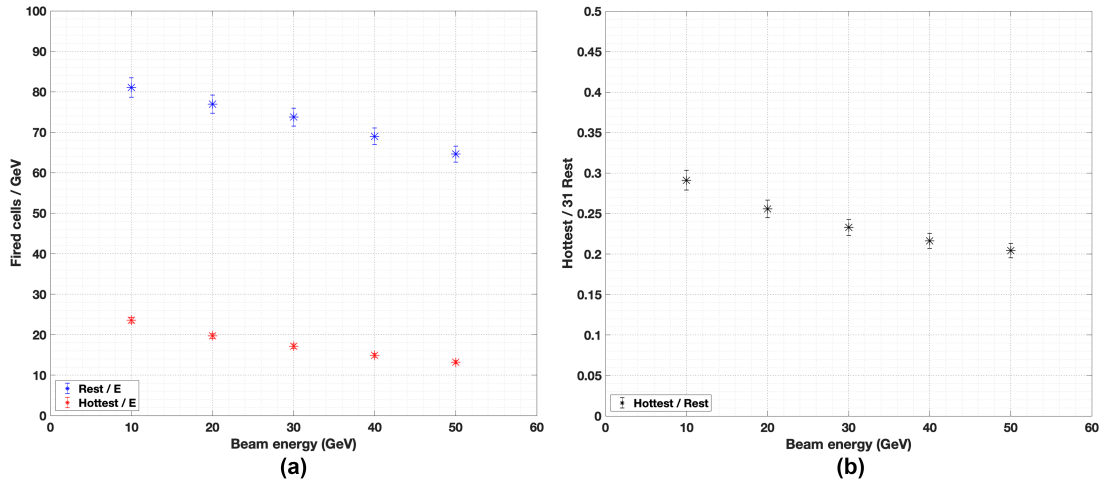


Fig. 6.10: (a) The average number of S fired cells measured in the SiPMs divided by the electron beam energy, as a function of the electron energy. Results are shown separately for the hottest fiber (red) and for the sum of the signals measured by the other 31 scintillating fibers (blue). Right: The ratio of these two signals, as a function of the electron beam energy.

(N_{FC}) in the hottest fibre was extracted as the mean value of their distribution on the total number of selected events¹¹. The ratio between N_{FC} and the nominal beam energy, which was measured to be constant over the entire energy range for the C signals, decreased by more than a factor two in the hottest fibre. A decrease of 25% was measured in the rest of the fibres because, moving away from the shower axis, the signal generated in each fibre was greatly reduced and thus the non-linearity effect for each sensor was less relevant. Fig.6.10b shows the ratio of these two signals, i.e., a measurement for the relative contribution of the central fibre to the total signal. Since the lateral shower profile is independent of the electron energy, the decrease of this ratio indicates that this energy dependence was caused by a non-linear sensor response. Therefore, for each event, the raw number of fired cells recorded by each SiPM (coupled to a S fibre) was corrected and converted in photoelectrons (eq.5.9), adopting a procedure similar to what described for the C channel. After this correction, much of the non-linearity disappeared (fig.6.11). Comparing fig.6.11a and fig.6.10a, can

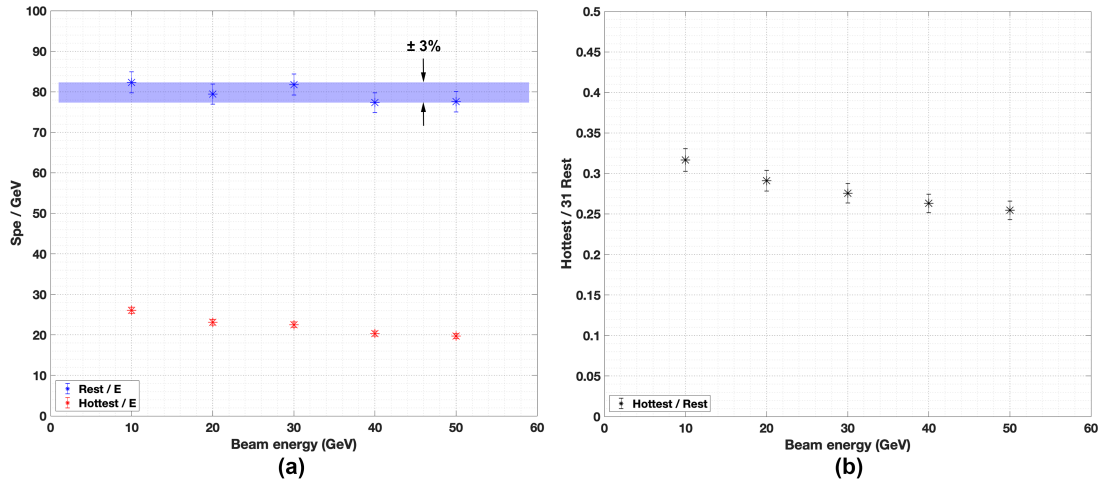


Fig. 6.11: Left: The corrected average number of scintillating fired cells measured in the SiPMs divided by the electron beam energy, as a function of the electron energy. Results are shown separately for the hottest fiber (red) and for the sum of the signals measured by the other 31 scintillating fibers (blue). Right: The ratio of these two signals, as a function of the electron beam energy.

be observed that the linearity is restored in the sum of 31, but that the hottest fibre still exhibits remnants of this effect. Actually the blue points also show a small falling trend. This can be probably due to the fact that the effective total number of cells should be a bit smaller than assumed. This is also evident from fig.6.11b, which shows that the ratio of the signals in the hottest fibre and the 31 neighbours still decreases with the beam energy, albeit to a lesser extent than in fig.6.10b. At low V_{Ov} , a slight variation in temperature produces a significant

¹¹ A mean value is used instead of the Gaussian fit, because saturation induced a peak asymmetry.

variation in PDE: the ΔT between the first and the last point of these energy scans was only 1°C , but this was enough to change the PDE from 2.01% to 1.78%. Therefore, the same corrections to the Δ_{pp} and PDE values applied in the C signal were adopted to properly consider these effects. Again, the value so extracted for the 10 GeV beam energy ($\text{PDE}_{10} = 2.01 \pm 0.06\%$) was selected to equalise all the S channel results.

In order to translate these results into a scintillation LY that may be compared with that measured for the C one, the numbers from fig.6.11a have to be corrected for the S channel shower containment ($\sim 45\%$) and also for the difference between the PDE values at which the measurements of the two types of signals were carried out (i.e. $25.00/2.01 \sim 12.44$). Considering the sum of all 32 signals measured for the 10 GeV (in which the non-linearity effects were the lowest) the expected S light yield is $\sim 108 \times 12.44 / 0.45 \approx 2985$ Spe/GeV. Since the non-linearity effects seem to be dominant only in the hottest fibre, it was also decided to consider only the sum of the others 31 signals (i.e. ~ 80 Spe/GeV as shown in fig.6.11a). In this case, the effective containment was estimated to be 29% of the deposited energy, leading to an expected S light yield of $80 \times 12.44 / 0.29 \approx 3430$ Spe/GeV. Therefore, an average value of $\sim 3200 \pm 200$ Spe/GeV represents a first order approximation (due to all the applied corrections) for the scintillating light yield at the nominal biasing voltage. As discussed in sec.6.3, the contribution of optical cross-talk to the Cherenkov signals was $0.3 \pm 0.1\%$ of the scintillation channel, corresponding to $3200 \times 0.003 \approx 10 \pm 4$ Cpe/GeV and leading to 69 ± 5 Cpe/GeV. This means that $\sim 15\%$ of the measured Cherenkov signals was in fact the result of the scintillation light. Therefore, the estimated S/C ratio of the 2017 module was $(3200 \pm 200) / (69 \pm 5) = 46 \pm 6$.

6.5.2 2018 beam test

The number of scintillation photoelectrons per GeV of deposited energy estimated in the 2017 beam test provided a fair estimation of the S light intensity order of magnitude. The saturation and non-linearity response issues can be tackled both at sensor level and reducing conveniently the light yield. On one hand, concerning the sensor, the easiest solution should be adopting SiPM with higher density of cells, currently at the level of $10,000/\text{mm}^2$. On the other hand, the attenuation of the number of impinging photons may also be provided by an optical bandwidth filter placed between scintillating fibres and sensors. For example, with the appropriate spectral response, a yellow filter not only can attenuates the light, but also improves the fibre response uniformity. Before the 2018 beam test, a detailed study about the proper filter to be used for the SiPM-based module was carried out.

Filter studies

One of the main motivations for using fibres as active material for a calorimeter is the very high sampling frequency and spatial granularity. Another advantage offered by sampling calorimeters where fibres run longitudinally (as in SPACAL, RD52), is the signal uniformity achievable since the edge effects are essentially absent [156]. Nevertheless, in order to limit instrumental effects on the calorimeter performance, the signal should not depend on where the fibres are hit by the shower particles. This phenomenon is mainly important for hadron showers, where the variations in the longitudinal shower development are on a scale set by the effective nuclear interaction length λ_{int} . Unfortunately, the depth profile of the light production varies event by event and the resulting signal is affected by the fibres light attenuation. As first approximation, assuming an exponential light attenuation (with a characteristic length λ_{att}), the contribution of fluctuations in the longitudinal shower profile to the energy resolution is $\sim \lambda_{int}/\lambda_{att}$ [156]. This effect can be reduced by cutting off the short wavelength component of the S spectra (as discussed below). The RD52 Collaboration has successfully adopted different yellow filters, interposing them between the S fibres and the PMTs. Among those were also the WRATTEN 2 gelatine filters, produced by Kodak [163]: a special type of filter created by dissolving organic dyes in a gelatin material to achieve the desired spectral performance. They offer a uniform thickness of only 0.1 mm (making the light divergence negligible), an excellent optical quality (assuring filter is functionally the same among batches), a consistent performance and a good reliability. Moreover they can be easily cut and stick to the mechanical support of the sensors.

The incident light attenuation can be adjusted by selecting the wavelength at which the filter cuts the S fibre spectrum and merging it with the sensor PDE curve. The absorbances¹² (A) of three different filters were measured in lab by a spectrophotometer¹³ with a wavelength precision of 1 nm. The tested filters were the WRATTEN 2 nr. 3 (adopted for the lead-based RD52 module, with a wavelength cut-off at ~ 460 nm), the SILVESTRI nr. 16 (a cheaper polyester filter, with a cut-off at ~ 540 nm) and the WRATTEN 2 nr. 21 (with a more stringent cut-off at ~ 550 nm). The related filters transmittances, defined as $T = 10^{-A}$, are reported in fig.6.12. The direct measurement of the radiation spectrum emitted by the S fibres was performed using a 350 nm UV lamp to excite the fibres at 1 m from a fluorometer¹⁴ (fig.6.13 blue dashed line of the left plot). By merging this spectrum with the SiPM PDE¹⁵ curve (black dotted line), it was possible to

¹²Defined as the measurement of the quantity of the light absorbed by a sample.

¹³Perkin Elmer Lambda2.

¹⁴PTI fluorescence master system.

¹⁵Data extrapolated from datasheet.

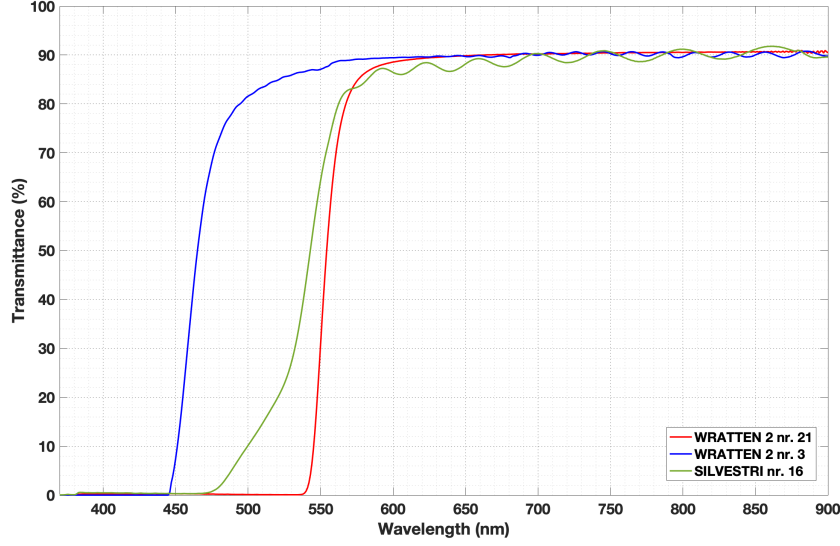


Fig. 6.12: Transmittance curves for the three tested: WRATTEN 2 nr. 3 (blue), SILVESTRI nr. 16 (green) and WRATTEN 2 nr. 21 (red).

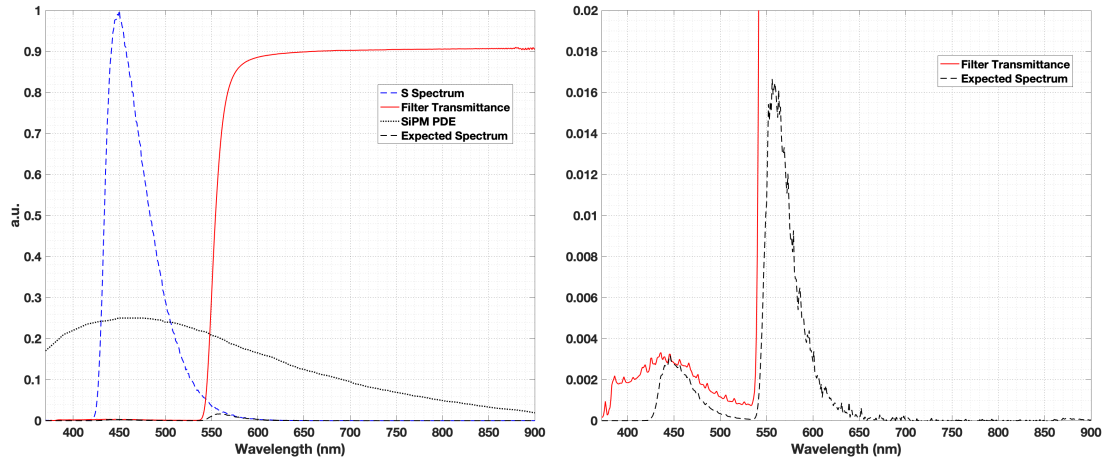


Fig. 6.13: Left: The measured S spectrum (blue dashed), the WRATTEN nr.21 transmittance spectrum (red), the SiPM PDE curve (black dotted). Right: Zoom of the expected spectrum (black dashed) obtained by folding all the previous curves.

extrapolate the expected SiPM detection spectrum. The final spectrum (shown in the right plot of fig.6.13) was obtained by folding the measured transmission curve of the yellow filter (red curve). The selected filter was the WRATTEN 2 nr. 21, since its transmittance curve was the sharpest (allowing a more accurate wavelength selection) and the ratio between the light intensity with and without the filter (i.e. the ratio between the areas under the curves of fig.6.13), corresponded to an attenuation factor of $\sim 77^{16}$ (estimated to be enough to avoid

¹⁶All these measurements were performed with the Kuraray SCSF-78 fibres adopted in the 2018 beam test, that were found to have a light yield higher than the ones adopted in 2017.

the SiPM saturation). The fibre homogeneity response improvement provided by this filter is shown in fig.6.14, where the SiPM detected spectrum obtained by exciting the fibre with the UV light (350 nm) at 1 m (blue curve) from the fluorometer is compared with the same spectrum at 10 cm (red curve). The

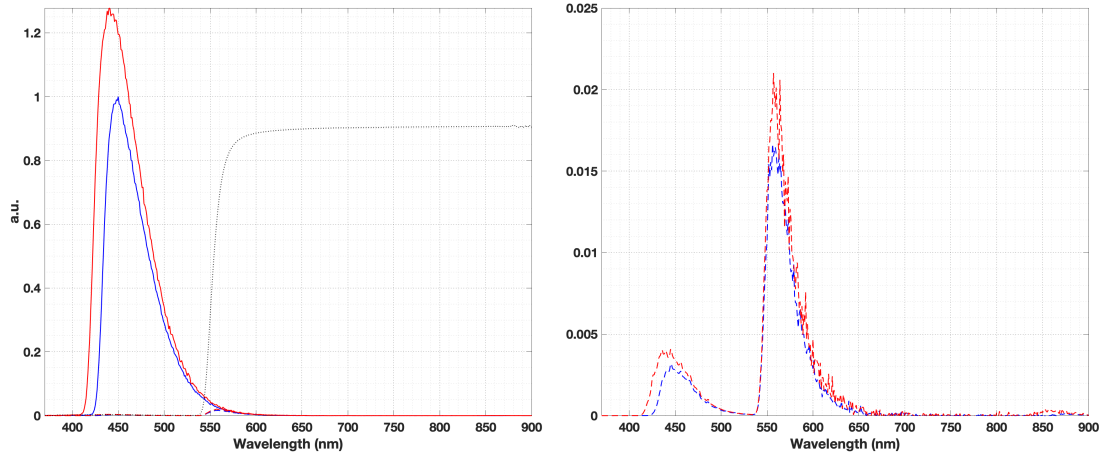


Fig. 6.14: Left: The SiPM detected spectra at 1 m (blue) and 10 cm (red) respectively. Right: Zoom of the spectra obtained by considering the WRATTEN nr.21 filter transmittance.

difference between these two intensities (i.e. areas under the curves) is $\sim 30\%$ when the filter was not included and becomes $\sim 21\%$ if it was added ($\sim 17\%$ if the peak at 450 nm, caused by some imperfections of the filter under test, is neglected). For the purpose of the 2018 beam test, in which only electron beams were used, the dependence of the signal on the shower development depth was not an issue, since all the em showers develop in a very similar way. Nevertheless, the expected fluctuations in the longitudinal development of hadronic showers require dedicated studies in this respect. This will be carried out, together with a detailed study on both the S and C fibres characteristics, for the beam test planned in 2020 (sec.8.3). This effect would also disappear with a longitudinal segmentation.

Scintillating signal linearity recovery

In 2018, due to the S light reduction provided by the WRATTEN 2 nr. 21 filter interposed between the fibre tips and the sensors, the S signals linearity was fully recovered. Fig.6.15 shows the usual average number of detected Spe/GeV (i.e. the sum of all the 32 S signals), as a function of the electron beam energy, without non-linearity correction. The procedure adopted to extract each point of this plot was the same described in sec.6.4. As shown in figure, the S signal is linear within 3% over the full energy range explored (10-40 GeV), with a mean light yield of 41.9 ± 1.2 Spe/GeV. In addition, the hottest fibre has a mean value of 9.8 ± 0.1 Spe/GeV, linear within 1%. Finally, correcting for the average S

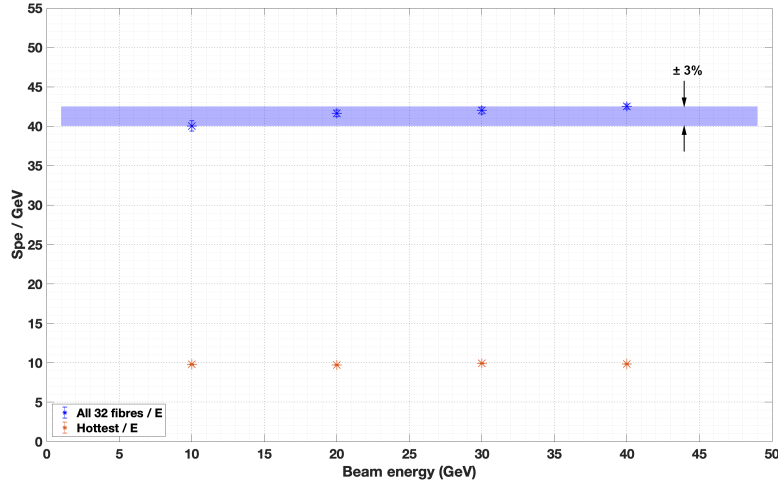


Fig. 6.15: The average number of scintillation photoelectrons measured per unit of deposited energy, as a function of the electron beam energy. These results were obtained in 2018 beam test applying the WRATTEN 2 nr. 21 filter between the fibre tips and the sensors. The blue points represent the Spe/GeV measured considering all the 32 S fibres, while the red points represent the average value measured for the hottest fibre.

shower containment ($\sim 45\%$), the measured S light yield is 93 ± 3 Spe/GeV . This result is a noticeable contribution from photoelectrons statistics to the stochastic term. Since non-linearity corrections have not been applied, the optimal LY working point is probably higher.

6.6 Impact on energy resolution

Summarising the results obtained:

- **The fibre optical cross-talk:** the main challenge for the tested DR calorimeter prototypes was the implementation of a design (sec.5.2.2) that minimises the optical cross-talk between the two types of fibres, which are located very close to each other and carry light signals that have an intensity differing by about a factor 50¹⁷. The experimental data, which were obtained with beams of high-energy electrons and muons as well as in lab tests, illustrate to what extent this challenge was met.
- **The Cherenkov light yield:** the limiting factor for the energy resolution of a DR calorimeter (3.3.2). With this new readout, the C light yield was doubled (due to the higher PDE of the SiPMs compared to the previously PMT-based configurations), improving the overall em energy resolution.

¹⁷In the 2017 module.

- **The Scintillation light yield:** the two modules tested in 2016 and 2017 revealed a non-linear response to the scintillation light, due to the high number of photons generated by the S fibres. Consequently, in 2018, a yellow filter between the S fibres and the sensors was interposed, restoring the signal linearity.

Once the modules linearity response is verified and both the S and C light yields are measured, some considerations about their impact on the ultimate energy resolution can be done. The poissonian fluctuation in the number of detected photons per GeV of deposited energy ($\sigma_{N_{pe/GeV}}$) has an impact on the stochastic term of each channel, that can be estimated by the quadratic sum of $\sigma_{N_{pe/GeV}}$ and the sampling fluctuation term (σ_{samp}):

$$\frac{a}{\sqrt{E}} = \frac{\sigma_{N_{pe/GeV}} \oplus \sigma_{samp}}{\sqrt{E}}$$

The estimated sampling fluctuation terms for the tested prototypes are: $\sigma_{samp}(C) \sim 9.5\%$ and $\sigma_{samp}(S) \sim 10.0\%$. Considering the measured light yields¹⁸, the related poissonian fluctuation terms become: $\sigma_{N_{pe/GeV}}(C) \sim 12.1\%$ and $\sigma_{N_{pe/GeV}}(S) \sim 10.4\%$. Thus, the resulting stochastic terms are about $15.3\%/\sqrt{E}$ for the C channel and $14.4\%/\sqrt{E}$ for the filtered S signal. The weighted average of these two terms provides a final expected stochastic term of $\sim 10.5\%/\sqrt{E}$. Reducing the number of S photons impinging the sensor, the yellow filter has a direct impact on the $\sigma_{N_{pe/GeV}}$ and therefore on the final stochastic term. In fig. 6.16 this is plotted as a function of the attenuation factor provided by the filter. The red dashed

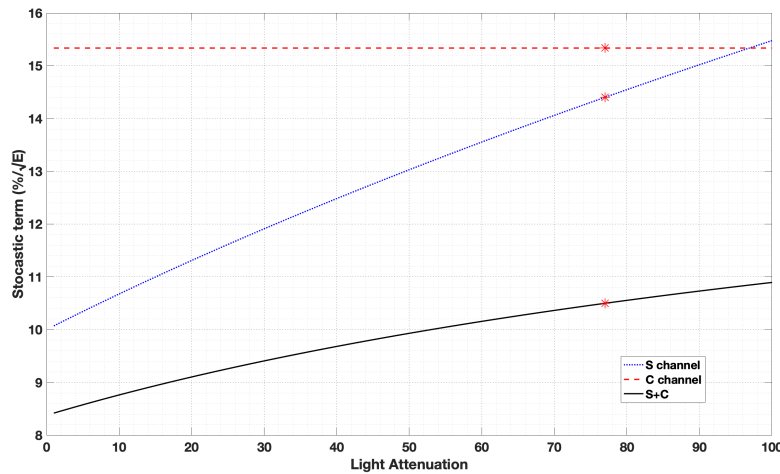


Fig. 6.16: The stochastic term of the S channel alone (blue dotted), the C channel alone (red dashed) and the $C+S$ dual-readout method combination (black) as a function of the filter attenuation. The red points represent the beam test results obtained in 2018.

¹⁸ 69 Cpe/GeV and 93 Spe/GeV.

line represents the stochastic term obtained considering the C channel alone. In this case, it is kept constant since the C signal is not attenuated. The blue dotted line represents the stochastic term for the S signal, while the black line shows the final expected stochastic term when the C and S terms are averaged. The red points are the results obtained in the 2018 beam test. As expected, increasing the S light impinging on the sensors (i.e. decreasing the light attenuation) the contribution of the LY fluctuation to the stochastic term decreases and becomes negligible compared to the sampling fluctuation term.

An estimated em energy resolution of about $11\%/\sqrt{E}$ is a very encouraging result, similar to what was measured by the RD52 collaboration with a bigger module [99]. Even if it is true that some other instrumental effects (i.e. the finite fibre attenuation length) has to be included in the energy resolution estimation, it is also true that the stochastic contribution of the LY can be further reduced simply reducing the S signal attenuation. A possible goal, tested in more detail with a full GEANT4 simulation in chapter 7, should be a scintillation LY of about 400 Spe/GeV, meaning a $\sigma_{N_{pe}/GeV}(S)$ of only $5\%/\sqrt{E}$. This could be obtained, for example, attenuating the S light 18 times (instead of 77) and adopting SiPMs with 10 μm pixel pitch (and 10,000 cells) to preserve the signal linearity.

6.7 Dual-readout imaging capability

The fact that each fibre was read out separately, made it possible to measure the lateral profiles of em showers in unprecedented detail, very close to the shower axis. These profiles were measured as follows. (i) A clean sample of electrons was selected (sec.6.2). (ii) For each event, the coordinates of the impact point were determined from the centre of gravity $(\bar{x}, \bar{y})$ of the energies (E_i) deposited in the 32 fibres that contributes to the total signal:

$$\bar{x} = \frac{\sum_i x_i E_i}{\sum_i E_i} \quad \text{and} \quad \bar{y} = \frac{\sum_i y_i E_i}{\sum_i E_i}. \quad (6.3)$$

The coordinates x_i, y_i were the centres of each SiPM with respect to its position in the readout matrix (fig.6.17). (iii) Then, the radial distance (r_i) between each individual fibre (i) and the centre of gravity was determined as:

$$r_i = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2}. \quad (6.4)$$

Therefore, event-by-event, it was possible to measure the contribution of each fibre to the total signal as a function of its distance from the beam axis¹⁹ (fig.6.18).

¹⁹For each event, 100% corresponded to the sum of all the 32 fibre signals.

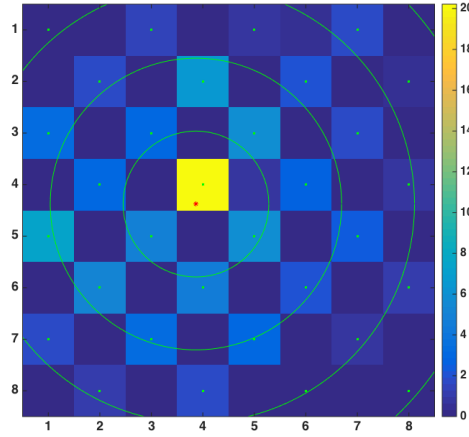


Fig. 6.17: Event display for 10 GeV electrons. The green points represents the centres of the SiPMs coupled to the S fibres. The red point is the shower axis, calculated from eq.6.3. The radius from the centre of gravity with pitch of 1.2 mm are also plotted in green.

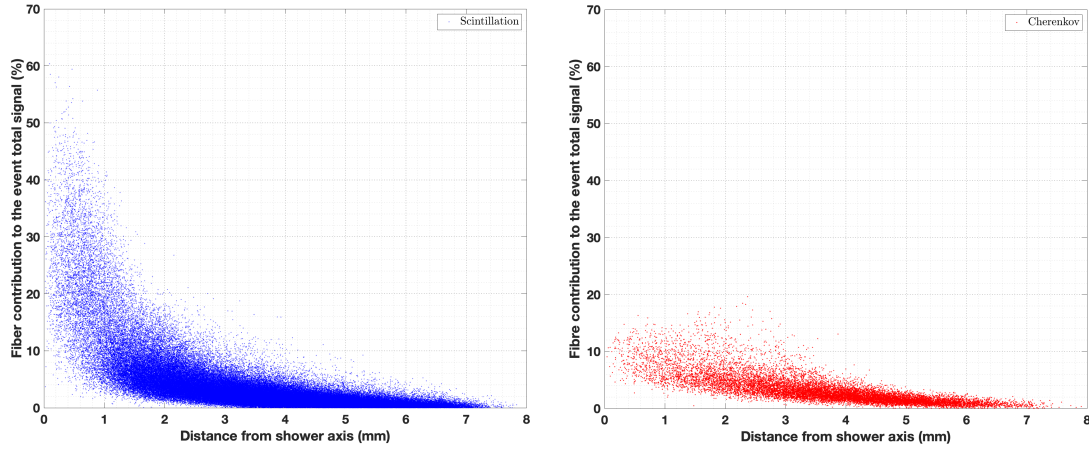


Fig. 6.18: Left: The percentage of the total scintillation signal as a function of r for all the measured events. Right: The same plot, obtained for the Cherenkov channel.

(iv) All data were then binned with a pitch of 0.6 mm²⁰ and the mean values were calculated (and normalised²¹) for each bin. With this procedure, the average signal in an individual fibre could be determined as a function of r and this represents the lateral shower profile (fig.6.19). Moreover, the signals from individual fibres located in the same r -bin (e.g., 1.2-1.8 mm from the shower axis) were summed. The average values of these summed signals were then plotted as a function of r . These are the radial shower profiles represented in fig.6.20 (left). The integral of these profiles were normalised to the two fractions of the shower

²⁰The distance between two SiPM centres was 1.2 mm.

²¹To properly represent the measured lateral shower profiles, a new normalisation was performed: 100% corresponded to the sum of all the bin mean values so obtained.

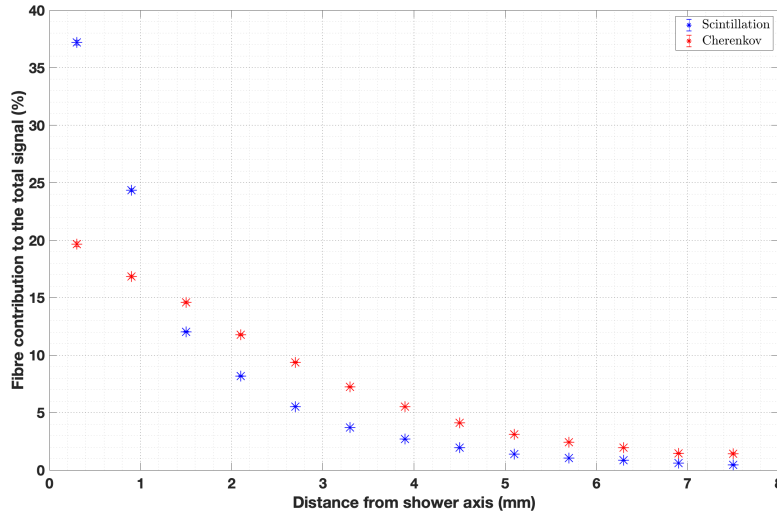


Fig. 6.19: Lateral profiles of em showers in the calorimeter module, measured separately with the C and the S signals.

energy deposited in the calorimeter module: 45% (S) and 36% (C). Fig. 6.20 (right), illustrates what fraction of the total shower energy was deposited within a certain distance from the shower axis, separately for the C and S signals. These

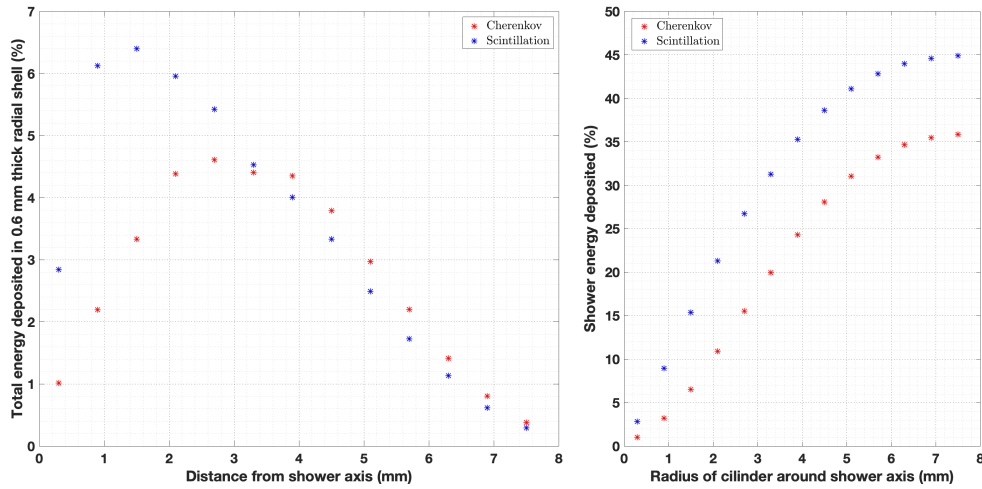


Fig. 6.20: Left: Radial profiles of em showers in the calorimeter module, measured separately with the C and the S signals. Right: The fraction of the shower energy deposited in a cylinder around the shower axis as a function of the radius of that cylinder, measured separately with the C and the S signals.

figures show a remarkable difference between the profiles measured by the two types of fibres. Since the early, extremely collimated component of the developing shower does not contribute to the C signals (because the Cherenkov light falls outside the fibre numerical aperture), the C light is less concentrated in and near

the central fibre than the S one. The consequences of this phenomenon were earlier observed in the muon signals (sec.3.2) and in the angular dependence of the RD52 dual-readout fibre calorimeter em resolution (sec.3.3.3) already mentioned. The fact that a large fraction of the shower signal comes from only one fibre is already clear from fig.6.11b, which shows that at 10 GeV, the hottest fibre carried $\sim 25\%$ of the total recorded signal. As also represented in fig.6.20 (right), about 10% of the entire em shower energy was deposited within one mm from the fibre axis and contributed to the signal of a single fibre. This extremely collimated nature of em showers should lead to optimal results in a calorimeter able to sample showers with a millimetric spatial resolution: fig.6.21 shows the superposition of three event displays of 10 GeV electrons, entering the tested calorimeter very close to different fibres. As a result, in a small area of about $1.2 \times 1.2 \text{ cm}^2$, these peaks appear clearly separated. It is worth mentioning that,

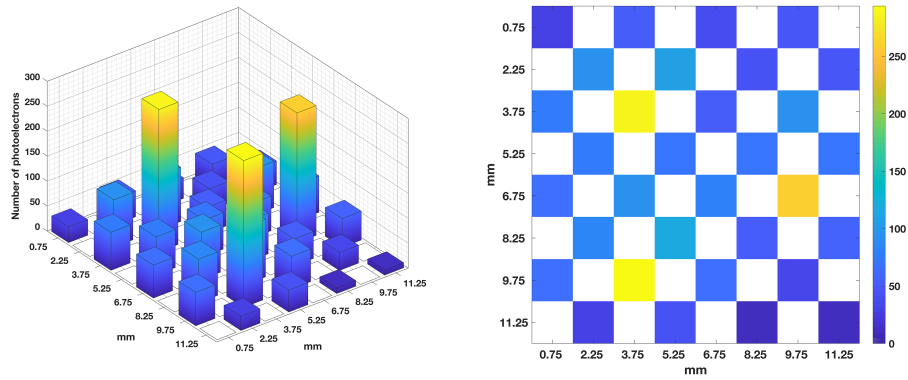


Fig. 6.21: Superposition of three event displays of 10 GeV electrons entering the calorimeter very close to three different fibres. Shown are signals from S fibres only, C fibres are left white.

since their incidence angles with respect to the fibres axis were small ($\sim 0.1^\circ$), each electron was oversampled in a single fibre due to the channeling effect, artificially increasing the discrimination between the events. Nevertheless, even if the expected discrimination capability for a properly tilted calorimeter will be less efficient, this is an encouraging results about the possibility of this ultra granular readout to identify em showers coming from a single electron (or γ) and from a π^0 (reconstructing the 2 γ 's from its decay). The first results about the particle ID capability of a simulated 4π geometry dual-readout calorimeter will be provided in the next chapter.

6.8 Calorimeter module simulation

For the tested SiPM-based DR calorimeters, the signal calibration from em showers was straightforward, since they offer the possibility to count the number of fired cells. However, in order to determine the total light yield, i.e., the absolute response in photoelectrons per GeV deposited energy, it was important to determine what fraction of the showers was deposited in these small prototypes. A dedicated GEANT4 simulation [164] was developed for that purpose.

A dual-readout fibre sampling calorimeter with a copper based structure and a geometry reproducing the SiPM based module was performed. All of the optical characteristics requested to simulate light production, transportation and detection (core and cladding refractive indices, light yield, attenuation lengths and SiPM PDE) were considered and properly simulated. On one hand, to take into account the directionality and the low statistics of the Cherenkov process, the C photon emission was included in simulation. On the other hand, the signal from scintillating fibres was parametrised simply considering the energy deposited in them. Indeed, the simulation results [165] showed how fluctuations of the S signal are dominated by the energy deposition process (without any light attenuation filter applied) while, for the C signal, the lower photoelectrons statistics dominate over sampling fluctuations. The results discussed below were obtained with the GEANT4.10.3.p01 version and the FTFP_BERT_HP physics list. All the details about the simulation parameters can be found in [165].

Electromagnetic shower energy containment

The simulation results about the em shower energy containment are shown in fig.6.22, for 10 GeV and 100 GeV electrons. The average fraction of the electron energy deposited in the calorimeter is shown as a function of the particle impact point. Two sets of simulations were performed. In the first set (fig.6.22a), the electrons entered the detector along the fibre direction. To avoid channeling effects, in which particle travels over a very long distance inside an individual fibre, the detector was rotated by a small angle (0.2° in both the vertical and horizontal plane). The results of this second simulation set are shown in fig.6.22b. The effects of this rotation, due to the incomplete lateral shower containment, are clearly visible. However, if the impact points are limited to a region with a radius of about 3 mm around the geometrical center of the calorimeter (as done by cuts described in sec.6.2), the containment fraction is rather insensitive to the electron impact point, and the average shower containment is $\sim 45\%$, for both sets of simulated data. The statement that the lateral shower containment is practically energy independent is well supported by the results shown in

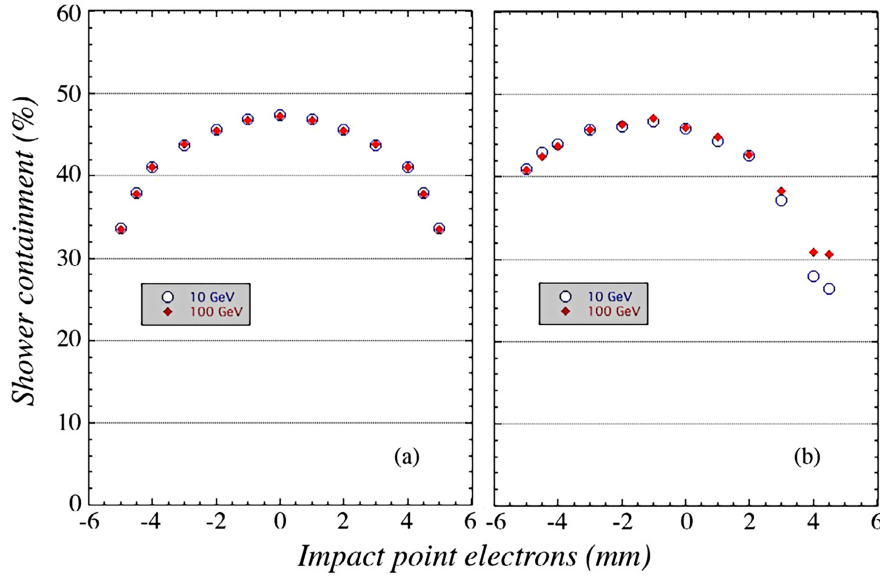


Fig. 6.22: The average fraction of the shower energy deposited in the SiPM calorimeter, as a function of the impact point of the 10 GeV and 100 GeV electrons used for these GEANT4 simulations. Results are given for electrons that entered the calorimeter: (a) along the direction of the fibers (b) at an angle of 0.2° in both the horizontal and the vertical planes [1].

fig.6.22a: they are essentially identical for 10 and 100 GeV. The small differences observed when the module was tilted (fig.6.22b) reflect the difference in the longitudinal shower development. Moreover, additional GEANT4 simulations of a calorimeter that was large enough to contain the em showers, were performed. In these simulations, the signals from the two types of fibres were determined as well. This made it possible to determine what fraction of the total signal was recorded in the small calorimeter tested. The results showed that the S signal was in excellent agreement with the expected value based on the energy deposit by the 10 GeV electrons used for these simulations: 45% of the total signal came from the area covered by the module. Fig.6.23 shows an event display of a simulated 50 GeV electron shower developing in an extended calorimeter structure of the type used in these beam tests. The lego plot represents the signals in individual S fibres, with the red ones located in the area covered by the tested small calorimeter. For this example, the total energy deposited in these fibres amounted to 1.982 GeV, of which 0.902 GeV (45.5%) was distributed among the calorimeter. For the Cherenkov signals, the prototypes only accounted for 36% of the total. This can be explained more in details starting from fig.6.24, that shows the lateral profiles obtained (in 2017) for experimental data (fig.6.24a) and the results of GEANT4 simulation (fig.6.24b). The fractional differences between the experimental and simulated profiles (fig.6.24c) confirms the good agreement between data and simulation. Both these lateral profiles, together with the radial

profiles of fig.6.20, indicate that the em showers were less efficiently sampled in the C signals, compared to the S ones.

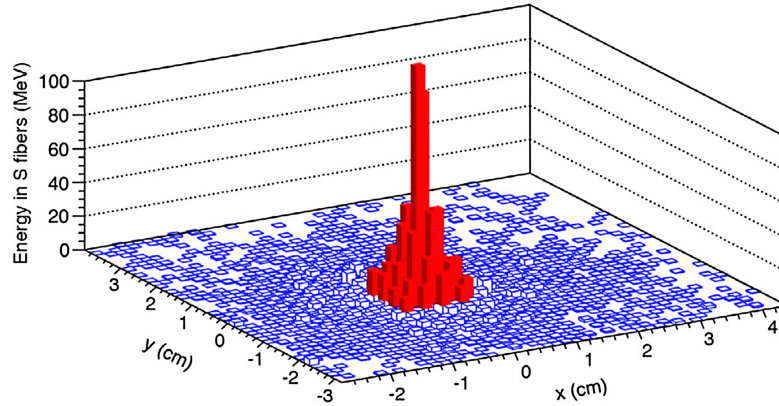


Fig. 6.23: Event display of a simulated 50 GeV electron shower developing in an extended calorimeter structure of the type used in these tests. The figure shows the signals in the individual scintillating fibres. The white patches represent fibres in which no (measurable) energy was deposited. The fibres hosted in the area covered by the tested detectors are indicated in red. The vertical scale represents the energy deposited in the individual S fibre [1].

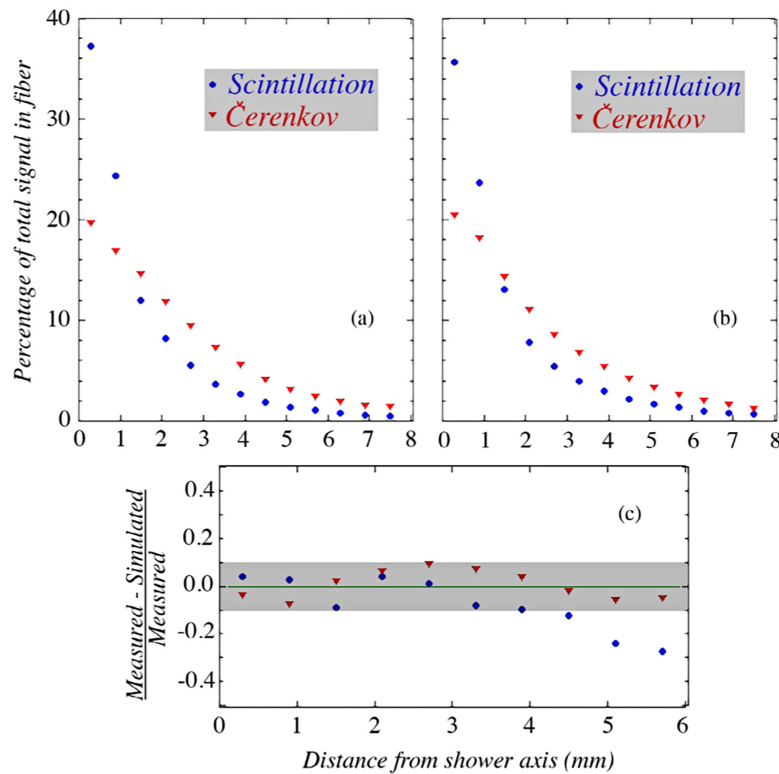


Fig. 6.24: (a) Lateral profiles of em showers in the 2017 calorimeter module, measured separately with the C and the S signals. (b) The same lateral profiles simulated with GEANT4. (c) Fractional differences between the measured and simulated profiles [1].

Measurements made with DR calorimeters that were laterally much larger than these modules showed no fundamental containment differences. For example, in DREAM [101], which had a module size with a radius of $1.8 R_M$, the lateral containment was measured to be 92% for the S signals and 93% for the C ones, and in RD52 [99] ($0.9 R_M$), the lateral containment was 85%, both for the S and C signals. These results were based on the measured energy sharing between the central detector cell and the surrounding ones. However, these results were a consequence of the conspiracy of two effects which both tend to reduce the effective sampling fraction measured with the Cherenkov signals: (i) The radial tails of em showers are dominated by soft electrons from Compton scattering and photoelectric absorption, which are isotropically distributed with respect to the direction of the incoming beam particle, just like the photoelectrons produced by scintillation light. However, C light is only produced by electrons with kinetic energies larger than ~ 200 keV ($\beta > 0.67$), and therefore the calorimeter is not fully efficient for detecting the soft electron component in the C channel. (ii) The early, very collimated component of the shower is not (efficiently) detected by the C fibres, due to the directional sensitivity (as clearly demonstrated by the measurements presented in the previous sections). This component made a substantial contribution to the signals of these small (radius $0.22 R_M$) calorimeters. The reduced efficiencies for detecting the Cherenkov component of the light produced in the absorption of em showers near the shower axis and in the radial tails had (approximately) the same net effect on the overall calorimeter signals, thus explaining the containment results mentioned above. However, in these small modules, only the second effect played a role, resulting in a smaller effective sampling fraction than that obtained for the scintillation signals.

Energy resolution

A further validation of this simulation can be found in the comparison between the expected em energy resolution calculated in sec.6.6 and those extracted by simulating a calorimeter large enough ($\sim 30 \times 30 \times 100$ cm³) to fully contain the em showers. The energy resolution so obtained shows a good linear scaling with $E^{-1/2}$, with the interesting result that the C signal leads to a better resolution at high energies (> 50 GeV), respect to the S one. This is due to the S signals dependence on the impact point that introduces a constant term (of 1.1%). Indeed, as already described, the C signal is largely independent of it since the Cherenkov light emitted by the early part of the shower lies outside the fibre angular acceptance. The combined ($C + S$) resolution is: $\sigma/E = 10.3\%/\sqrt{E} + 0.3\%$ [4], very similar to the value extracted from the measured S and C light yields. Finally, also an hadronic calorimeter of $\sim 80 \times 80 \times 250$ cm³, with an

average hadronic containment of 99%, was simulated. The estimated hadronic energy resolution for this ideal homogeneous detector is $\sim 34\%/\sqrt{E}$ (more details can be found in [4]).

IDEA dual-readout calorimeter full-simulation

” *Physics is the only profession in which prophecy is not only accurate but routine.*

Neil deGrasse Tyson

The comparison (sec.6.8) between the results obtained with the beam test data analysis and the GEANT4 simulation allowed its validation, since a fine adjustment of the simulation parameters was performed on the basis of the measured quantities. Together with the R&D work on the small SiPM-based prototypes, a simulation of an ideal 4π fully projective DR calorimeter was developed [7]. The IDEA concept (sec.1.5) includes a calorimeter composed by different towers (wedges), pointing to the IP and opening up from the inner surface to the outer one. To properly host the tracker, the solenoid and the pre-shower detectors, the calorimeter inner part will consist of a 5 m long cylindrical surface, with an inner radius of 2.5 m. Even though the simulation work is just at its beginning, it can provide in this early stage, some useful informations about: (i) the impact of the calorimeter geometry and absorber material on both the expected energy resolutions and particle ID capabilities, (ii) the impact of using SiPMs (instead of PMTs) and an estimation of the sensor properties (e.g. DCR, dynamic range, time resolution, etc.) needed to address all the requirements described in sec.1.3. This chapter starts (sec.7.1) with a description of the design and the implementation of this complex geometry in the GEANT4 framework. Moreover a detailed simulation, modelling the sensor response to the light coming from the fibres, was performed in MATLAB[®]. Sec.7.2 describes the most significant SiPM simulation parameters. The results of a brass SiPM-based DR calorimeter characterisation are then reported in sec.7.3. Finally, in sec.7.4 a comparison between the particle ID capability (for single particles) assessed by the RD52 Collaboration (sec.3.3.2) and the preliminary results obtained with this simulated IDEA calorimeter will be provided.

7.1 4π calorimeter

7.1.1 Calorimeter geometry

The implemented DR calorimeter geometry of IDEA is sketched in fig.7.1. The barrel inner length is 5 m (as its inner diameter) and the overall outer calorimeter diameter measures 9 m. Both endcaps have an inner radius (at the front face) of about 0.25 m, guaranteeing the required 100 mrad angular acceptance. The

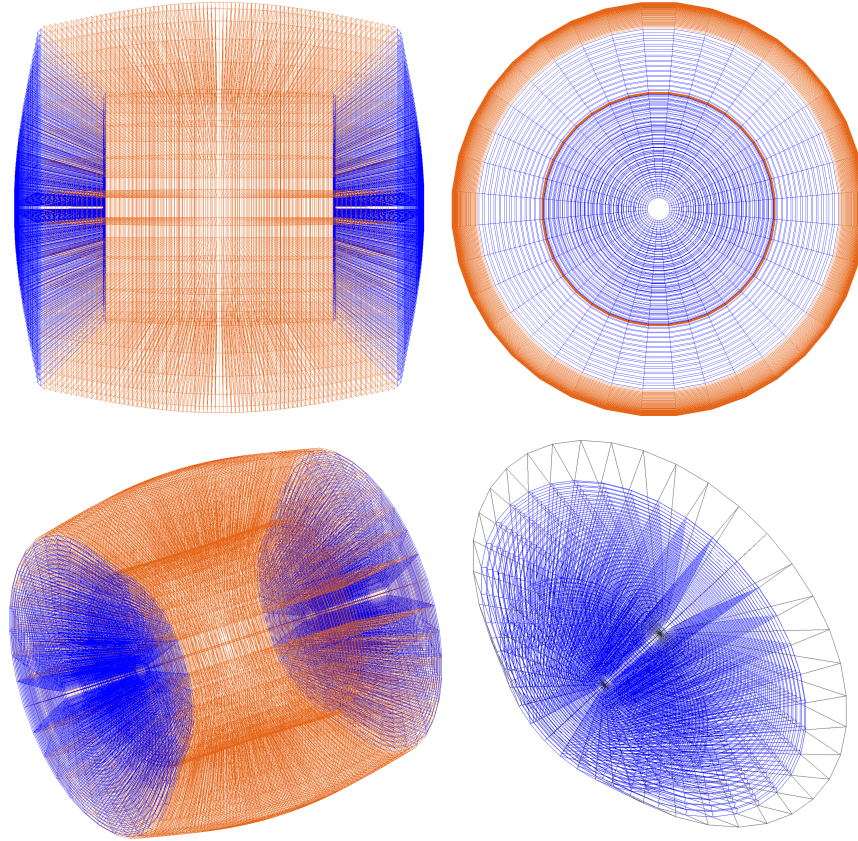


Fig. 7.1: Schematic view of the simulated 4π dual-readout calorimeter: the inner length of the barrel (orange) is 5 m long and has a radius of 2.5 m. The endcaps (blue) have an inner radius (at the front face) of about 0.25 m, guaranteeing an angular acceptance of less than 100 mrad.

actual geometry consists of 36 equal edges, obtained by rotating the first one around the z axis, called slices. As shown in fig.7.2, each half slice is composed by 75 different towers (40 for the barrel and 35 for the endcap), 2 m long, for a total number of 5400 wedges. The trapezoidal inner faces of each tower have different dimensions: the biggest one (i.e. the outer-most tower of the barrel, tower 40 in figure) has a greater side of about 7.8 cm, with a height of ~ 7 cm, while the smaller one (i.e. tower 75) measures a side of ~ 5.2 cm and is 5 cm

height. Moreover, a uniform magnetic field of 2 T is generated and 1 X_0 lead

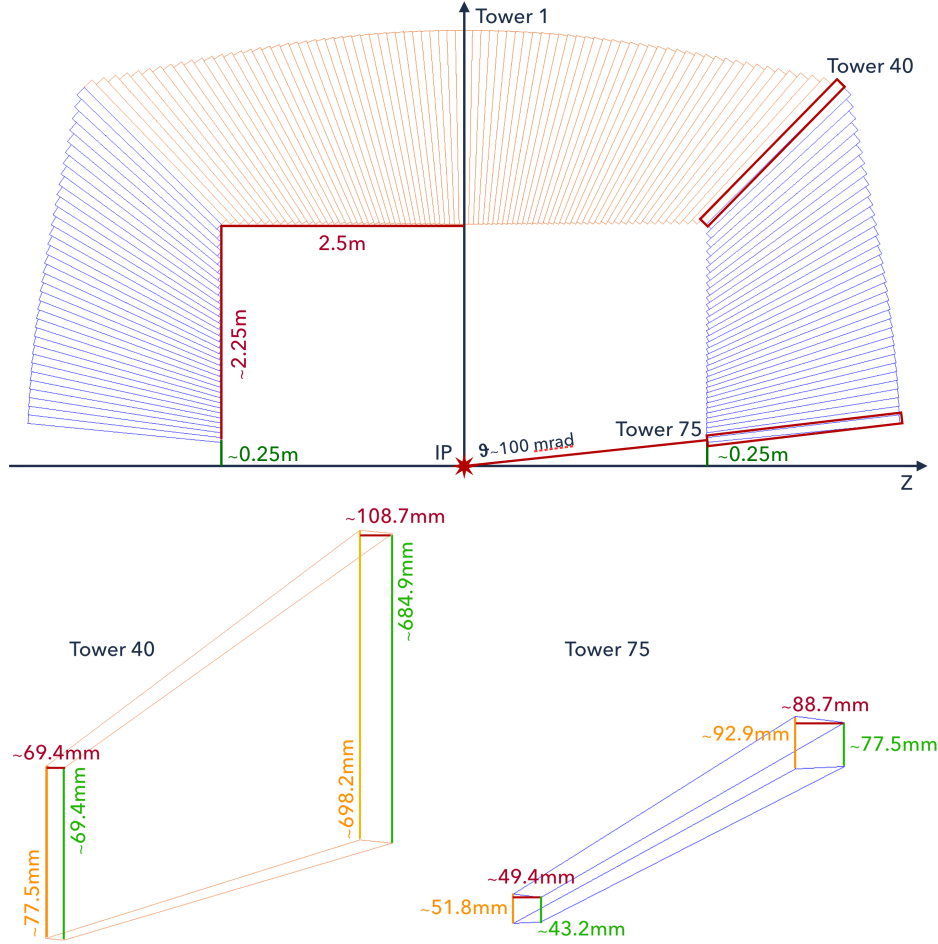


Fig. 7.2: Schematic view of a single slice of the calorimeter. For each half slice there are 75 different towers. On the bottom side a comparison (not to scale) between the dimensions of tower 40 (the biggest) and 75 (the smallest) is represented.

pre-showers are placed in front of both the barrel and endcap regions.

7.1.2 Optical fibres

Using fibres as sensitive elements of a projective calorimeter poses stringent requirements on its geometry: since the absorber volume increases with the distance from the IP, new fibres, starting at different depths inside the calorimeter, have to be placed in order to keep the sampling fraction constant (fig.7.3). Therefore, the number of fibres hosted by each one of the 75 different towers, ranging from a number of 3311 fibres in the smallest tower (75) up to about 33,140 in the biggest one (tower 40). The total number of fibres (corresponding also to the total number of SiPMs) is 130,729,608. The *S* and *C* fibres implemented are the ones adopted in the tested SiPM based modules and are embedded in

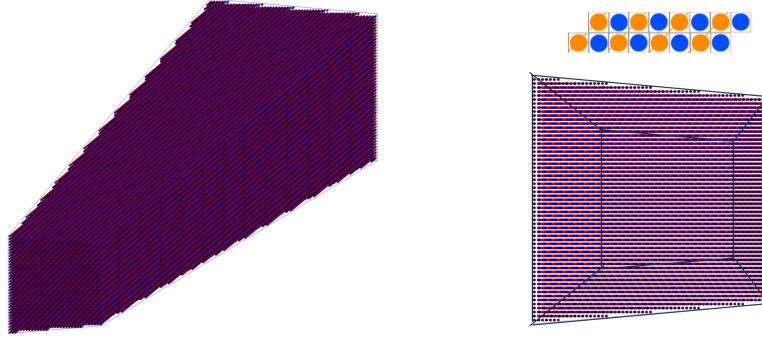


Fig. 7.3: Example of fibres distribution in tower 75. The fibres with different length were inserted as soon as the geometry allowed a new fibre placement to keep the sampling fraction constant. The chess-board structure between the S (blue) and the C (red) fibres is also well represented.

the same check-board copper absorber structure (sec.5.2). The fibre principal properties are summarised in tab.7.1. The simulated fibre tips at the calorimeter

Kuraray SCSF-78	
Core:	$r = 0.485$ mm, Polystyrene (C_5H_5), $\rho = 1.05$ g/cm ³ , $n = 1.59$
Cladding:	Thickness = 2% of r , PMMA ($C_5H_8O_2$), $\rho = 1.19$ g/cm ³ , $n = 1.49$
Main properties:	Emission constant = 2.8 ns, LY = 10,000 photons/MeV, $\lambda_{att} = 4$ m
Mitsubishi SK-40	
Core:	$r = 0.485$ mm, PMMA ($C_5H_8O_2$), $\rho = 1.19$ g/cm ³ , $n = 1.49$
Cladding:	Thickness = 2% of r , Fluorinated Polymer (C_2F_2), $\rho = 1.43$ g/cm ³ , $n = 1.42$
Main properties:	$\lambda_{att} = 8.9$ m

Tab. 7.1: Main simulated properties of the S and C fibres adopted in the beam tests.

front face (i.e. the ones not coupled to the SiPM) are composed by a completely blacked surface, avoiding reflections at the beginning of the fibres and assuming that all the light that reaches the sensor is the one emitted towards its direction. The light transport is determined only by the fibre refractive indices (as consequence of the Snell's law [165]). Also in this case, the Cherenkov photon emission was included in the simulation, while the signal from the scintillating fibres (dominated by the energy deposition process) is parametrised accordingly to the deposited energy. The results discussed below are obtained with the GEANT4.10.3.p01 version and the FTFP_BERT physics list (the standard for HEP calorimetric simulations).

For each event, the simulation output provides all the useful information: the event ID, the impact point coordinates of the primary particle and its kinetic energy, the hit towers and slices, the total energy deposited for each tower, the f_{em} ,

the number of hit S and C fibres (and their positions). Moreover, step-by-step, the energy deposited by the particles (or the number of C generated photons) in each hit fibre, together with their distances (R) from the SiPM and the time t_0 of the step (calculated with respect to the $t_{start} = 0$ s at which the primary particle is generated in the IP) are also extracted.

Light propagation

Since the propagation of each photon produced in the fibre would require an extremely long computational time, light propagation in fibres has to be properly parametrised to obtain a final number of photons (and their arrival times) very similar to the expected ones. Regarding the propagation of the C photons in the clear fibres, they are tracked in GEANT4 until their first interaction at the core-cladding boundary (i.e. R). Then, step-by-step, if their emission angle falls inside the fibre numerical aperture, they are added to the final number of photons impinging on the sensor (after a Poissonian smearing on their number). For each photon, the time at which it reaches the sensor is estimated as:

$$t_C = t_0 + R \frac{n_C}{c}, \quad (7.1)$$

where n_C is the fibre refractive index ($n_C = 1.49$) and c is the speed of light.

The signal considered in the S fibres is provided only by the energy deposited by the interacting particle. This energy is then converted in the number of scintillating photons (considering the S fibre LY). A Poissonian smearing is then applied (on the number of S photons) and the time needed by each photon to reach the SiPM is calculated as:

$$t_S = t_0 + R \frac{n_S}{c \cdot \cos(\theta)} + t^*, \quad (7.2)$$

where the refractive index n_S is $n_S = 1.59$ and t^* is a random time that take into account the fibres decay time, chosen from an exponential distribution with mean value of 2.8 ns. If the internal reflection in the fibre is considered, the photon path length l depends on the covered distance along the fibre axis R and the angle θ relative to the axis: $l(x, \theta) = x / \cos(\theta)$. Therefore, $\cos(\theta)$ is chosen randomly in the range of $[\cos(\alpha), \cos(0)]$, where α is the fibre critical angle and is equal to 20.4° .

7.2 SiPM response simulation

These results represent the input of a second Monte Carlo simulation, performed in MATLAB®, which models the SiPM response to a light source of photons

(spread in time) and reproduces the waveforms recorded with a digitiser [166]. The aim of this simulation is to provide a useful tool to investigate the sensor requirements needed to provide the expected performances of the DR calorimeter. The simulation allows to set all the principal SiPM parameters:

- **Geometrical parameters:** the sensor dimensions and the pixel pitch.
- **Sensor parameters:** Photon Detection Efficiency, Dark Count Rate, After-pulsing, Optical Cross-Talk.
- **Signal parameters:** rise time constant, decay time constant, AP arrival constant, cell-to-cell gain variation.
- **Waveform parameters:** number of points, integration window, sampling time, noise frequency, SNR.

For each event and fibre, the position of each impinging photon inside the sensor is randomly chosen (according to a uniform distribution). The number of fired cells is obtained assigning to each emitted photon a certain probability to be detected (i.e. the sensor PDE). In this case, this parameter was properly tuned to provide both S and C LY mean values of ~ 400 Spe/GeV and ~ 100 Cpe/GeV, respectively (i.e. the expected signals discussed in sec.6.5 and sec.6.4). Moreover, a control ensures that if a cell has been hit more than once, the number of detected photons is not increased. Then, an OCT probability is associated to each detected photon, following the geometric distribution described in [117]. If the generation of an OCT event occurs, its position is limited to the neighbouring cells of the primary pulse. The generated waveform consists of a over-imposition of pulses, taking into account the different time of arrival (t_S and t_C) provided for each photons by the input file from GEANT4. Each pulse is obtained as a combination of two exponentials: one has a very short time constant (τ_{rise}) to describe the signal rise time and the other (τ_{fall}) takes account of the falling time of the signal. Therefore, the signal time development is calculated as:

$$y(t) = A \cdot \left[e^{-t/\tau_{fall}} - e^{-t/\tau_{rise}} \right], \quad (7.3)$$

where A is the signal amplitude. A Gaussian spread in the signal amplitude has been considered to simulate the cell to cell gain variation. For each event and fibre, the total signal is generated as the sum of all the single amplitudes generated by the impinging photons in correspondence of their different arrival times. Once the primary signal is created, all the SiPM spurious effects are included. First of all the DCR contribution is added to the waveform: the number

of spurious pulses and their time distribution follow the Poisson distribution (with a mean value correspondent to the selected DCR). For the DCR, the probability it starts an OCT is also considered. Finally, the AP probability is included, together with its position in time, which follows an exponential distribution with two time constant τ_{APf} and τ_{APs} for the fast and the slow AP components, respectively. The after-pulse amplitude depends on its time occurrence (since it is related to the single cell recovery time, sec.4.3). Once the signal is formed, a white noise¹ is added and the signal can be digitised with the desired temporal granularity (100 ps in this case). The simulation parameters have been chosen in order to reproduce a waveform event similar to the SiPM signal displayed at the oscilloscope. The different settings adopted for the analysis described below are listed in tab.7.2. All these parameters were chosen on the basis of the direct

Geometric parameters	
Number of cells	10,000
Pixel pitch	10 μm
Sensor area	1 $\times$ 1 mm ²
Physical parameters	
DCR	200 kHz
OCT	1%
AP	2%
Signal parameters	
Rise time constant	1 ns
Decay time constant	50 ns
Cell-to-cell gain variation	5%
Waveform parameters	
Time window	600 ns
Time integration	250 ns
Time sampling	0.1 ns
SNR	25 dB

Tab. 7.2: The chosen simulation parameters to properly reproduce the SiPM-based DR calorimeter waveform events.

measurements, described in the previous chapters, or from the data-sheet values, in particular, the total number of cells was setted to 10,000 to avoid, in this first validation stage, any complication given by a possible sensor non-linearity response. Each waveform is then treated with the typical front-end procedures: the simulation output provides, for each fibre, the event and fibre IDs (needed for the event synchronisation), the real number of photons reaching the fibre, the integral of the signal (in a.u., integrating on a proper time window), the peak value (in a.u.), the peaking time, the starting time (i.e. when signal is above a fixed threshold at 3.5 pe) and the time over this threshold. Finally, to properly convert the signal integral into the number of fired cells, the Δ_{pp} was extracted (with the usual fitting procedure, sec.5.3), from a multi-photon spectrum obtained generating, event-by-event, a number of photons impinging

¹In the form of a Gaussian spread on each waveform point.

on the sensor according to a Poisson distribution with a mean value of 12 photoelectrons.

7.3 Calorimeter characterisation

7.3.1 Calibration

Once the full chain has been qualified, a full characterisation of the 4π DR calorimeter was performed. The first step was the equalisation of all the different tower signal responses, that was greatly simplified by the symmetry of the calorimeter. The calibration was performed by sending a 20 GeV electron beam only on each tower of the first slice (fig.7.4). For these measurements the

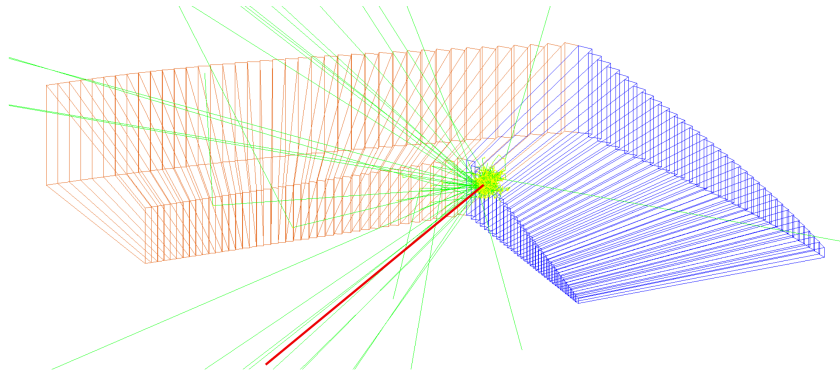


Fig. 7.4: A sketch of a calibration run for tower 45.

magnetic field was disabled and the lead pre-showers removed. Moreover, to avoid the oversampling due to the channelling effect, the beam direction was slightly tilted with respect to the tower centre axis ($\theta = 0.2^\circ$ and $\phi = 1.5^\circ$). The calibration procedure consists in two iterations: in the first one, the tower energy containment (ranging from 85% up to 95%) was estimated (from the GEANT4 output) and used to calculate the equalisation constant of the tower for both the S and C channels, defined as:

$$TW_S^i = \frac{Spe(TW^i)}{E_{cont}} \quad \text{and} \quad TW_C^i = \frac{Cpe(TW^i)}{E_{cont}}, \quad (7.4)$$

i.e. as the ratio between the total number of photoelectrons read out by the fibres hosted in the tower and the total energy deposited in it. The equalisation constant of each tower was then extracted from a Gaussian fit on the distribution over all the 2000 simulated events. The equalisation was performed with respect to the mean of all the 75 values (green lines in fig.7.5). In the second iteration, the numbers of photoelectrons read out by all the hit fibres (inter-calibrated from

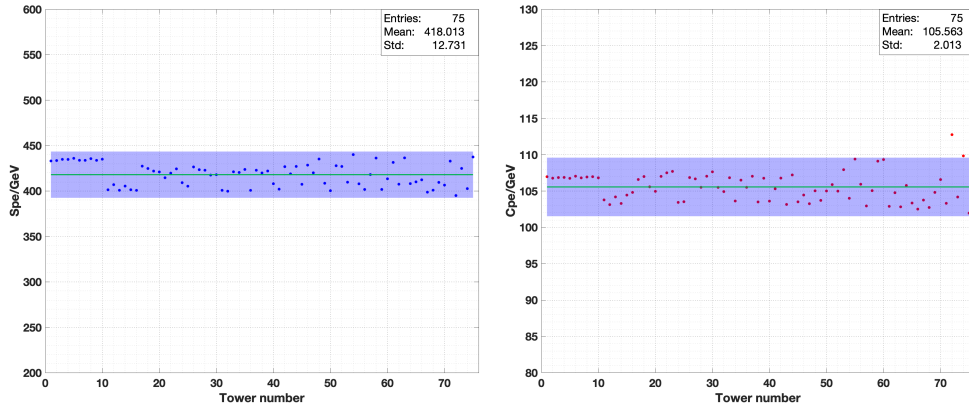


Fig. 7.5: Left: the S light yields, expressed in Spe/GeV , detected in each tower. Right: the C light yields (Cpe/GeV) as a function of the tower number. The green lines represent their mean values and the blue bands the 2σ spread that corresponds to about $\pm 6\%$ for the S channel and $\pm 4\%$ for the C one.

the first iteration) were summed together and the calorimeter energy calibration constants K_S and K_C were calculated (for each tower) as the ratio between these sums and the total energy deposited (E_{dep}) in the calorimeter:

$$K_S^i = \frac{Spe(Tot)}{E_{dep}} \quad \text{and} \quad K_C^i = \frac{Cpe(Tot)}{E_{dep}}. \quad (7.5)$$

Finally, the mean values of all the calibration constants, $K_S = 416.1 \pm 0.5 \text{ Spe/GeV}$ and $K_C = 103.6 \pm 0.9 \text{ Cpe/GeV}$ were considered for the calorimeter energy reconstruction performed below. Fig. 7.6 shows the ratio between the beam energy reconstructed from the calibrated calorimeter and the total energy

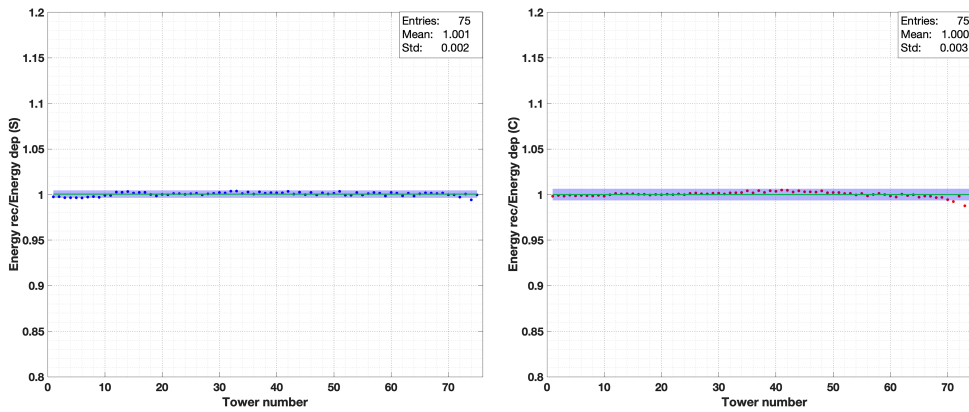


Fig. 7.6: The ratio between the energy reconstructed by the calorimeter after the calibration process and the total energy deposited for the S channel (left) and for the C one (right), respectively. The green lines represent their mean values and the blue bands the 2σ spread.

deposited in the calorimeter by the primary particle as a function of the tower

number. As expected, the value for each tower is always around 1, with a constant response within 0.5% for the S channel and 0.9% for the C one.

7.3.2 Electromagnetic response

Once calibrated, the calorimeter can reconstruct the electron energies independently for both the S and C channels. Therefore, since these two signals represent (for electrons) two independent samples of each event, no correlation between them is expected. This is well illustrated in fig.7.7a, where the reconstructed energy from both channels for 20 GeV electron beams (10,000 events) are represented. Moreover, as shown in fig.7.7b and fig.7.7c, distributions

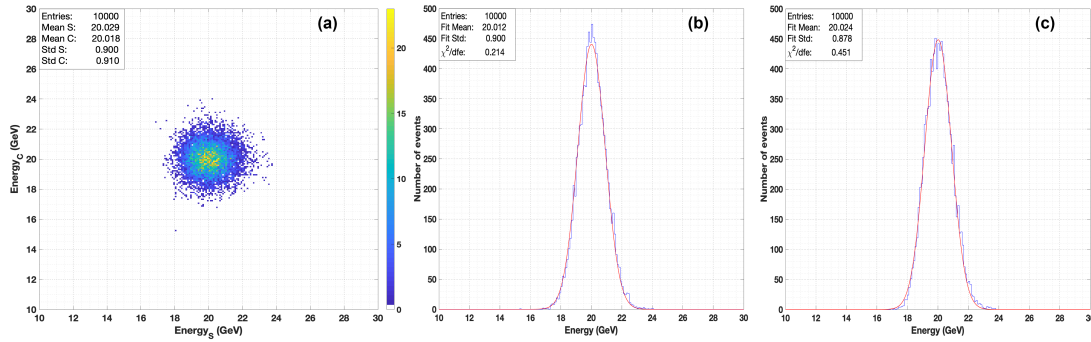


Fig. 7.7: (a) 20 GeV e^- energies reconstructed from S (x-axis) and C (y-axis) signals. (b) The respective scintillation signal distribution and the Cherenkov one (c).

from both these signals are Gaussian and correctly centred on the true values. This aspect of the DR calorimeters allows to combine the two signals (i.e. to average these two signals event-by-event), improving the em energy resolution. To extract the em energy resolution of the simulated 4π DR calorimeter, 10,000 events of 20, 40, 60 and 80 GeV electron beams were simulated². Fig.7.8 shows a comparison between the σ/E values extracted from the S , C and the combined $C + S$ channels as a function of $1/\sqrt{E}$. The corresponding energy resolutions were extrapolated from linear fits:

$$\frac{\sigma}{E}(S) = \frac{16.8\%}{\sqrt{E}} + 0.6\%, \quad (7.6)$$

$$\frac{\sigma}{E}(C) = \frac{18.2\%}{\sqrt{E}} + 0.3\%, \quad (7.7)$$

$$\frac{\sigma}{E}(S + C) = \frac{11.5\%}{\sqrt{E}} + 0.5\%. \quad (7.8)$$

²To properly consider the IDEA pre-shower effect, the 1 X_0 lead pre-shower was placed again in front of the calorimeter.

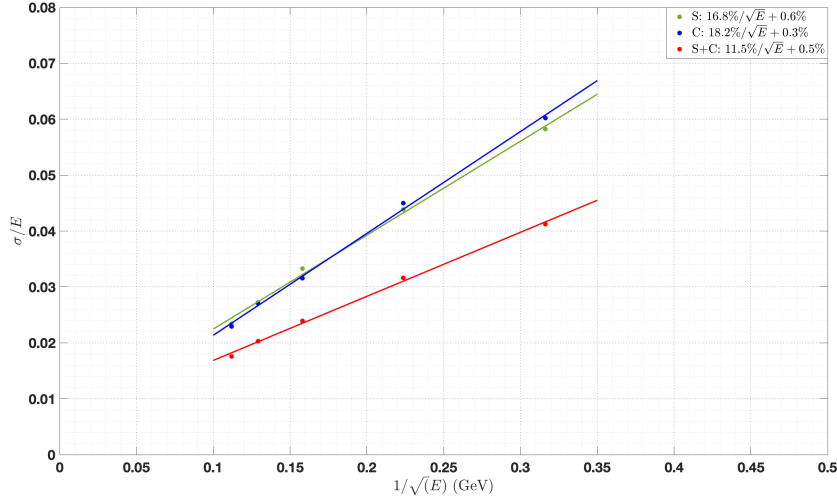


Fig. 7.8: The em energy resolutions from S , C and combined signals.

The constant term of the S channel is greater than the C one because, as already explained in the previous chapters, the em shower is very narrow and thus, in a fibre calorimeter, its deposited energy depends on the particle impact point. Since the C light produced by the early component of the em shower development falls outside the fibre numerical aperture, this effect does not affect the Cherenkov channel. The C energy resolution is only spoiled by the fluctuations of the number of detected Cherenkov photoelectrons and of the deposited energy in the clear fibres. As a result, the C energy resolution is better than the S one at high beam energies (already around 50 GeV). Moreover, the combination of the two signals exhibits the best performances achievable up to about 1 TeV beam energy.

7.3.3 Hadronic response

To assess the IDEA calorimeter hadronic performances, 100,000 events of 20, 40, 60 and 80 GeV π^- beams were simulated. Fig.7.9 shows the distributions of the reconstructed energy, for the S and C channels, of the 60 GeV π^- beam. Clearly these distributions are not correctly centred around the real value (60 GeV). This is caused by three main effects: (i) part of the hadronic shower energy is lost due to the invisible energy contribution³. (ii) Heavy charged particles produce saturation effects in the light emitted in the S fibres⁴. This

³The energy spent to break up atomic nuclei or lost in nuclear recoil.

⁴Deviations from linearity of a scintillator response are due to quenching interactions between the excited molecules created by the passage of the incident particle. Therefore, part of the energy can not be used for the luminescence effect: higher the excited molecules number, higher the quenching interaction one, smaller the scintillating response.

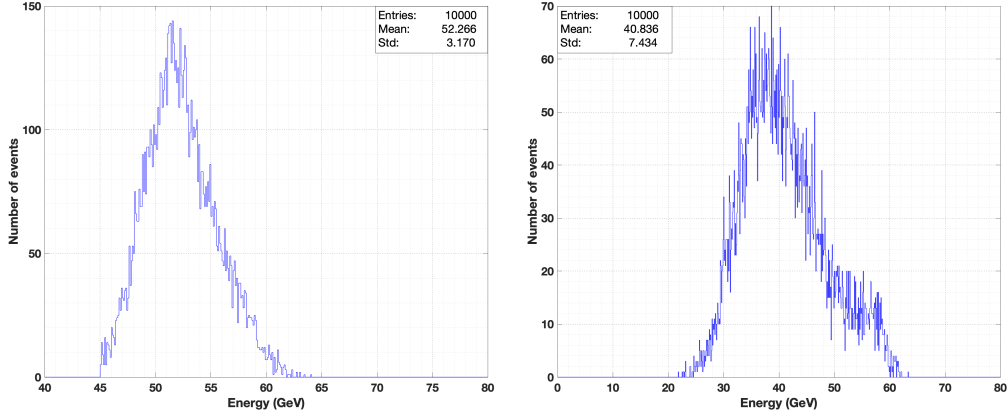


Fig. 7.9: Distributions of the 60 GeV π^- energies reconstructed from the S signals (left) and C (right) signals.

behaviour is parametrised in the GEANT4 simulation applying the Birks' law (more details can be found in [165]). (iii) For the C channel, the contribution to the total deposited energy provided by the non-em component is due to ~ 100 MeV protons and heavy charged particles that are not relativistic at these energies (i.e. their contribution to the signal is limited) and it is due to ~ 3 MeV neutrons (that can not provide any C signal since they have no charge, sec.2.1.2). Also the expected distribution asymmetries are properly reproduced. This is primary due to the non Gaussian fluctuations of the em fraction (left plot of fig.7.10), as described in sec.2.2.2. The signal is higher when the em

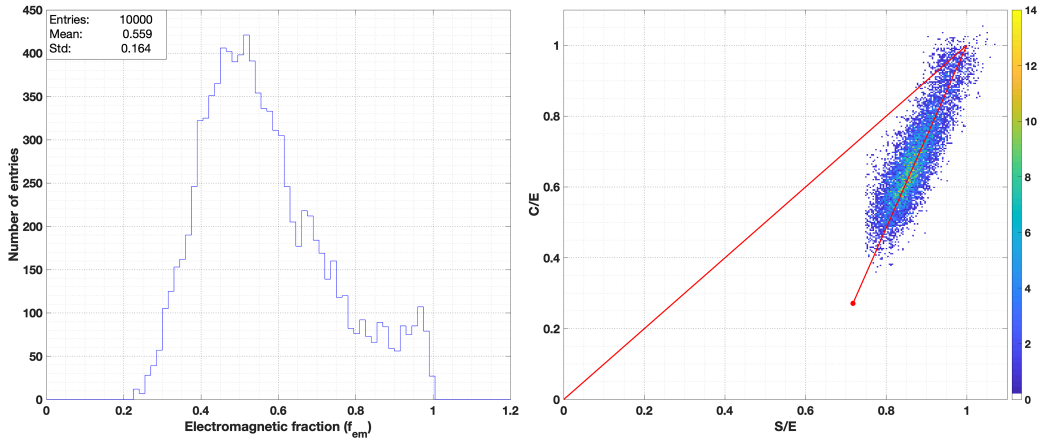


Fig. 7.10: Left: The f_{em} distributions for 60 GeV π^- s. Right: The S/E - C/E diagram of the signals from the simulated DR calorimeter for 60 GeV π^- . They clustered around the straight (red) line that links the points whit $f_{em} = 0$ and $f_{em} = 1$. The f_{em} values are calculated from the Monte Carlo truth.

component of the shower increases. Since $e/h > 1$ for both channels, when the f_{em} increases, also the S and C signals become larger. This can be verified from the correlation between the reconstructed energies highlighted in the right plot

of fig.7.10, showing the S/E - C/E diagram of the signals from for the 60 GeV π^- events.

h/e estimation

To properly apply the dual-readout method, it is necessary to extract the h/e values for both the S and C channels. These values were extracted with a procedure similar to that described in sec.3.2 for the DREAM detector. In particular, for each event, the reconstructed energy from the C and S signals was plotted as a function of the f_{em} ⁵ (fig.7.11). Fitting the data, the ratios $(h/e)_C = 16.30/60 = 0.27$ and $(h/e)_S = 43.06/60 = 0.72$ were extracted, leading to a χ value of 0.39.

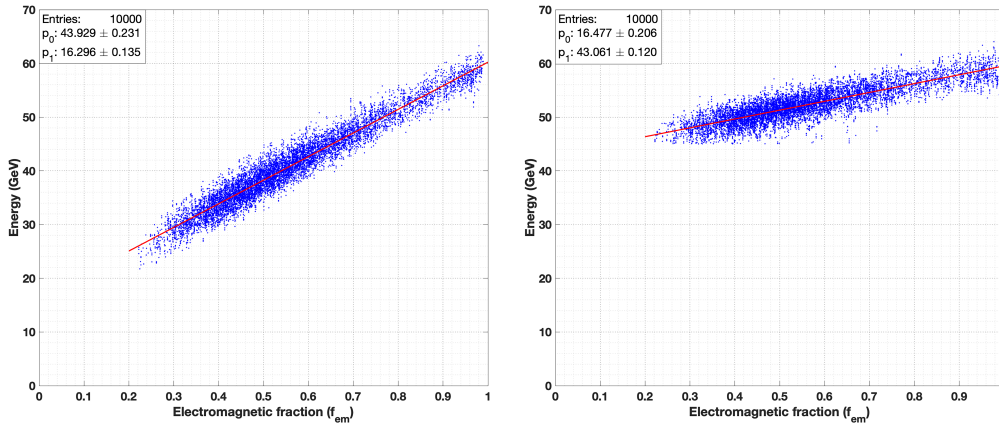


Fig. 7.11: The average C (left) and S (right) signals for 60 GeV pions as a function of f_{em} .

Energy reconstruction and resolution

Due to the dual-readout method, it was possible to reconstruct the correct value of the energy deposited in the calorimeter event-by-event:

$$E^i = \frac{S^i - \chi C^i}{1 - \chi}, \quad (7.9)$$

where S^i and C^i are the number of Spe and Cpe detected in the event for the S and C channels, respectively, and $\chi = 0.39$. Fig.7.12 (left plot) shows the distribution of the reconstructed energy applying the DR method for 60 GeV π^- s. As expected, the distribution symmetry has been restored and the average value is closer to the real deposited energy (the energy deposited in the pre-shower detector was found to be on average ~ 0.36 GeV in this case). The right plot of fig.7.12 shows the σ/E , obtained from the DR method, as a function of $1/\sqrt{E}$.

⁵ f_{em} is calculated as the ratio between the total deposited energy and the energy carried out by the em component. These two values are extracted event-by-event from the Monte Carlo truth.

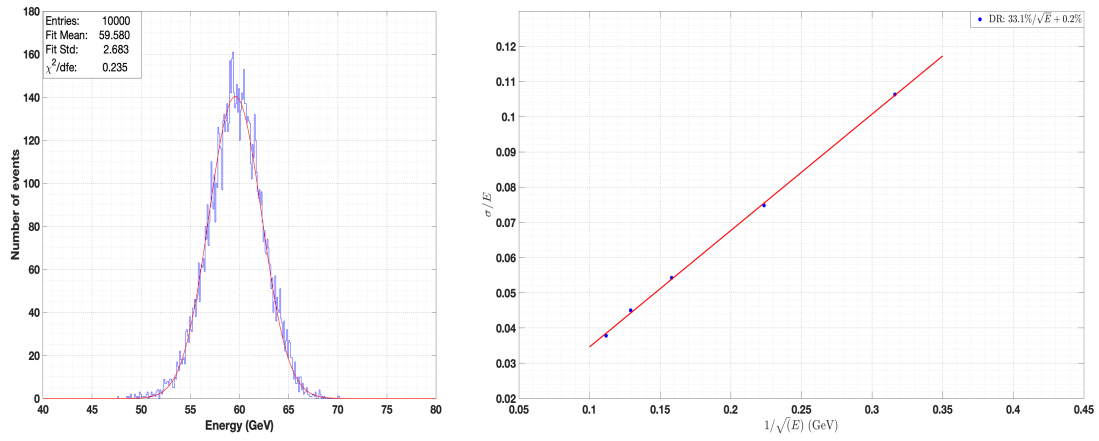


Fig. 7.12: Left: distribution of 60 GeV π^- beam energy, reconstructed by the dual-readout method. Right: The hadronic energy resolution obtained from the DR method.

The hadronic energy resolution, extracted from the linear fit, is:

$$\frac{\sigma}{E}(DR) = \frac{33.1\%}{\sqrt{E}} + 0.2\%. \quad (7.10)$$

This is an encouraging result, close to the $30\%/\sqrt{E}$ required for the future e^+e^- collider experiments. It is worth mentioning that, even if the SiPM contribution to the energy resolution was already considered in these simulations, other instrumental effects, as the finite fibre attenuation length, have to be included for more accurate studies. It is especially true for the hadronic resolution, where the contribution of the light attenuation in fibres is more important⁶ and could increase the constant term.

7.4 Particle ID capability

The identification of isolated particles (as electrons, pions and muons) will be one of the most important points to be addressed to study the H boson decays in the future leptonic colliders. Traditionally, the calorimeter systems in HEP experiments have been separated into the em and the hadronic sections. Usually, in these calorimeters, the e/π separation is achieved due to the fact that in high- Z absorber materials, the longitudinal size of hadron showers is typically much larger than what obtained for an em shower of the same energy. However, similar differences can be found also into the lateral shower size, which can also be used to distinguish between electrons and hadrons. It was demonstrated, that also a DR fibre calorimeter can reach an electron ID of 99.8% (with a π mis-ID of

⁶This happens because the hadronic showers start deeper inside the calorimeter, resulting in a higher signal compared to the one obtained from an electron beam of the same initial energy.

only 0.2%) [102] even if it is not longitudinally segmented⁷. These results were obtained by the lead-based RD52 fibre calorimeter (sec.3.3.2). In this section, a comparison between these results and the ones obtained with the simulated IDEA calorimeter is presented. Even if a direct comparison is not possible, since many details are different (as, e.g., the absorber material, the different fibre geometry and readout), to validate the simulation performances, the IDEA calorimeter was made as similar as possible to that of RD52. The absorber material (copper) was replaced with lead, the beam was sent always at the centre of tower 1 and 1 X_0 lead pre-shower (i.e. the same adopted by RD52) was interposed between the beam and the calorimeter. In these studies, 3 main different ID variables, based on the DR signals characteristics, were used to distinguish between electrons and pions. The data were obtained from both 20 and 60 GeV electrons and pions beams. Similarly, a comparison between two possible IDEA layouts (with lead or copper as absorber) was carried out simulating 10,000 events of electrons at 20 and 60 GeV. The discriminant variables were extracted from the waveforms of the signals provided by the SiPM simulation. The arrival time of each photon to the sensor was simulated as described in sec.7.1.2 and a SiPM signal time granularity of 100 ps was considered.

C/S ratio

The first discriminant variable exploits the possibility to sample the shower development separately with two uncorrelated signals (C and S). Since the DR calorimeters were calibrated using electrons, the C/S ratio is around 1 for electrons and smaller for hadron showers. Fig.7.13 shows the C/S distributions for electron and pion beams, at 20 (first column) and 60 GeV (second column) for RD52 module (a and d), the lead-based IDEA calorimeter (b and e) and the copper-based one (c and f). At 60 GeV the electron distribution is narrower: the larger width at 20 GeV is indeed the result of increased event-to-event fluctuations. Moreover the pions distribution shifts to larger values⁸. This is due to the fact that the average em shower fraction increases with the hadron energy. These two effects affect the e/π separability in opposite ways and tend to cancel each others. Moreover, there is a significant difference between the lead-based and copper-based IDEA calorimeters pions distributions. This is because the f_{em} is, on average, higher for copper than for lead, resulting in a higher C/S ratio. This should be an important point to be taken into account choosing the calorimeter absorber material. Indeed, the particle ID discrimination power in a lead-based calorimeter is much more efficient than in copper one.

⁷Results obtained combining three discrimination methods with a multivariate analysis.

⁸From an average of ~ 0.6 to ~ 0.7 for the RD52 calorimeter, from 0.58 to 0.62 for the lead IDEA and from 0.72 to 0.77 for the copper IDEA.

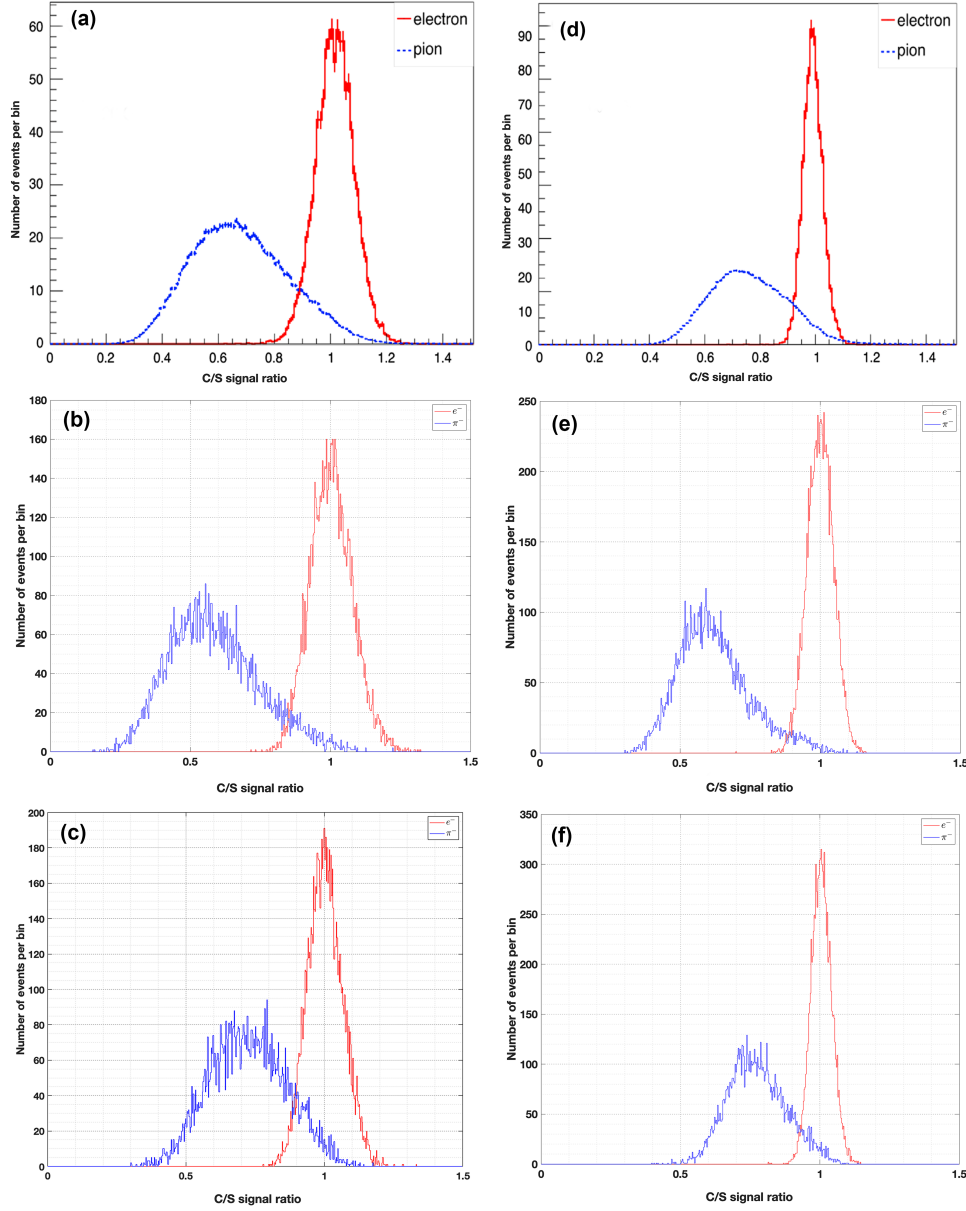


Fig. 7.13: Distributions of the C/S signal ratio. (a-d) From the hit tower for electrons and pions showering in the lead RD52 calorimeter. (b-e) From the total hit fibres in the lead IDEA calorimeter. (c-f) From the total hit fibres in the copper IDEA calorimeter. Data for 20 GeV (first column) and 60 GeV (second column) beam particles. Figure (a) and (d) are taken from [102] and represent the distribution of real beam test data.

Shower profiles

Another powerful variable that can be used to discriminate electrons and pions is the difference between their lateral shower profiles. One of the major advantages of a DR calorimeter structure is that the lateral granularity is very small (~ 1 mm). For the RD52 lead module, the tower dimensions were $1.6 \times 1.6 R_M$. It was found that about the 85% of the energy deposited by the electrons in the

centre of a tower, was contained in it [102], while hadrons released only 40-50% of their energy. Considering the distribution of the shower energy fraction

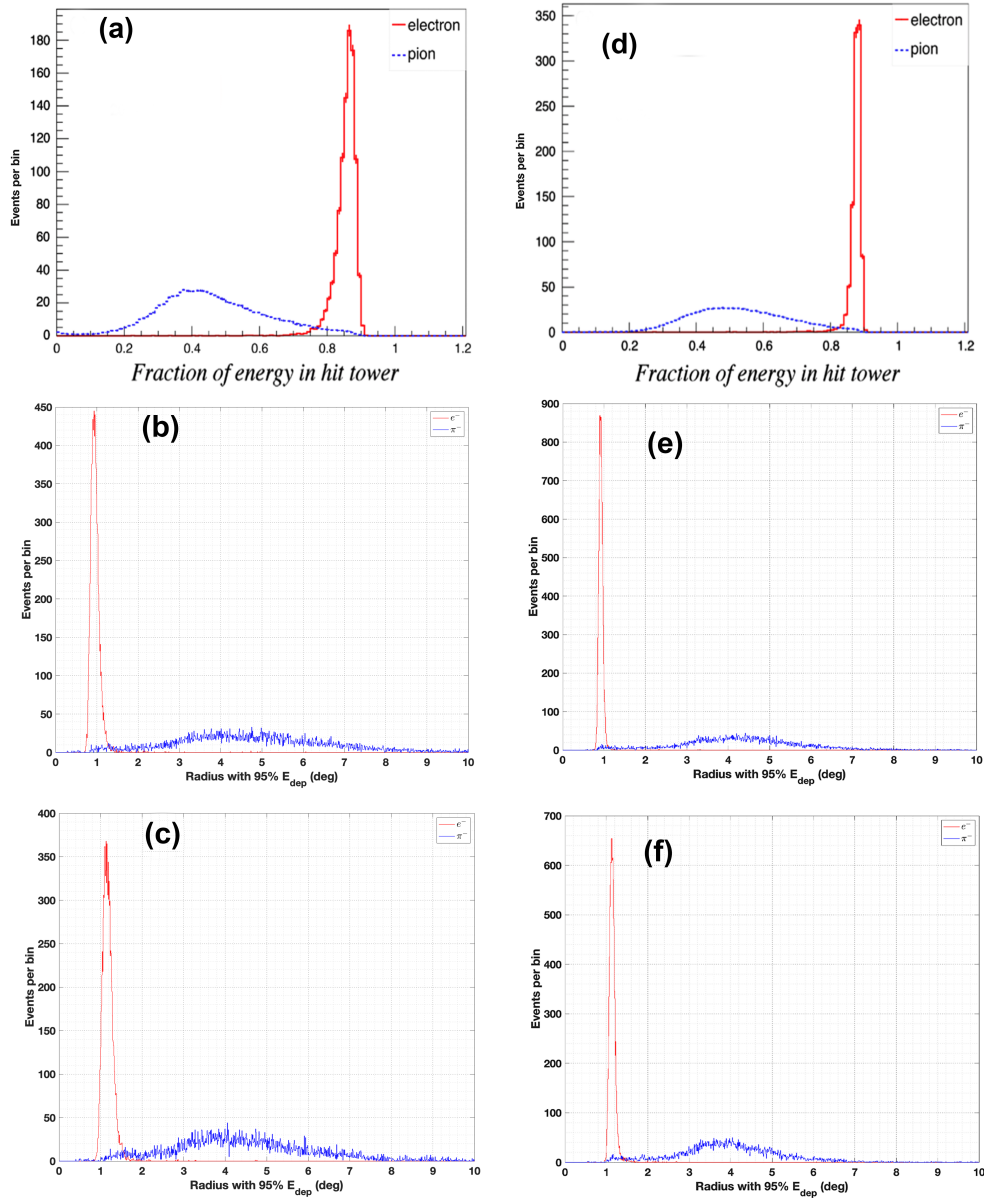


Fig. 7.14: (a-d) Distribution of the energy fraction deposited in the hit tower by electrons and pions showering in the RD52 calorimeter (from [102]). (b-e) Distribution of the radius at which the 95% of the total beam energy is deposited for the lead-based IDEA calorimeter and for the copper-based one (c-f). Data for 20 GeV (first column) and 60 GeV (second column) beam particles. Figure (a) and (d) are taken from [102] and represent the distribution of real beam test data.

contained by the hit tower for 20 and 60 GeV, the RD52 Collaboration confirmed that the average lateral em shower profile is practically energy independent and, as already observed with the C/S ratio, that: (i) the average energy deposited by pions in the hit tower clearly increases with the energy of the beam particles, (ii)

the electron distribution becomes narrower as the energy increases. Similarly to what described above, the electron distribution width becomes more narrow, due to the reduced effects of event-to-event fluctuations, while the average value of the energy deposited in the hit tower for pion showers increases because of the increased f_{em} . The possibility, offered by the SiPM-based readout, to read each fibre separately, opened a new possibility to improve the calorimeter transversal granularity. Indeed, instead of the energy fraction deposited in the hit tower, for the two simulated IDEA calorimeters, it was considered as discriminant variable the radius at which the 95% of the total beam energy was deposited (for both the 20 and 60 GeV energies). Fig.7.14 shows the comparison between the method used by RD52 and the new one for both the 20 and 60 GeV energy beams. As will be highlighted in the summary table 7.3, this discriminant variable is less material dependent (with respect to the C/S ratio) and leads, alone, to an electron identification higher than 99% (with a π mis-ID always smaller than 3.8%) for both the energies and absorber materials.

Signal starting time

Another discriminant variable between the em and hadronic showers is the measurement of the average depth at which the light is produced inside the calorimeter. Since the DR calorimeter is not longitudinally segmented, this information is extracted from the arrival time of the first signal in the calorimeter. This method is based on the fact that the effective speed of the light generated in the fibres is $\sim c/n$ (where n is the fibre reflective index) while the particles generating this light typically travel with a speed close to c (all the details about that principle was already described in sec.3.3.3). Considering the reflective index of the polystyrene fibres adopted both in the RD52 module and in the prototypes tested with SiPMs ($n_S = 1.59$), a speed of ~ 17 cm/ns is expected. Therefore, the light produced deeper inside the calorimeter will generate an earlier sensor signal (for the tested S fibres the effect amounts to ~ 2.55 ns/m [102]). The RD52 Collaboration has tested this method with 60 GeV e^- and π^- events, using the TDC readout of the central tower of the calorimeter. The starting signal was provided by the first counter (used as trigger) installed upstream the calorimeter ([102]), while the stopping one by the PMT signal of the central tower. The measured distribution has been shown in fig.3.16. In this test, the light generating from electrons was, on average, produced at a depth of ~ 12 cm inside the calorimeter (with event-to-event variations at the level of few cm). Moreover, the distribution from π was found to peak ~ 1.5 ns earlier than that of the electrons (meaning that the light was produced about 60 cm deeper inside the calorimeter) and it was asymmetric, with an exponential tail towards early starting times (i.e., light production deep inside the calorimeter). The

main difference from these measurements and the simulated IDEA calorimeters is the readout system. The signals analysed by RD52 was extracted from the PMT of the central tower, that was coupled to many S fibres. On the contrary, each fibre of the simulated IDEA calorimeter has its own sensor. In this case the starting time was chosen as the earliest time of arrival signal (over all the hit S fibres) that was above a threshold of 3.5 fired cells (to reduce the possibility to be triggered by some DCR events)⁹. Fig.7.15 shows the results for both the lead and copper-based IDEA calorimeters, for 20 (top row) and 60 (bottom row) GeV energy beams. As expected, at 60 GeV, all the time distributions are

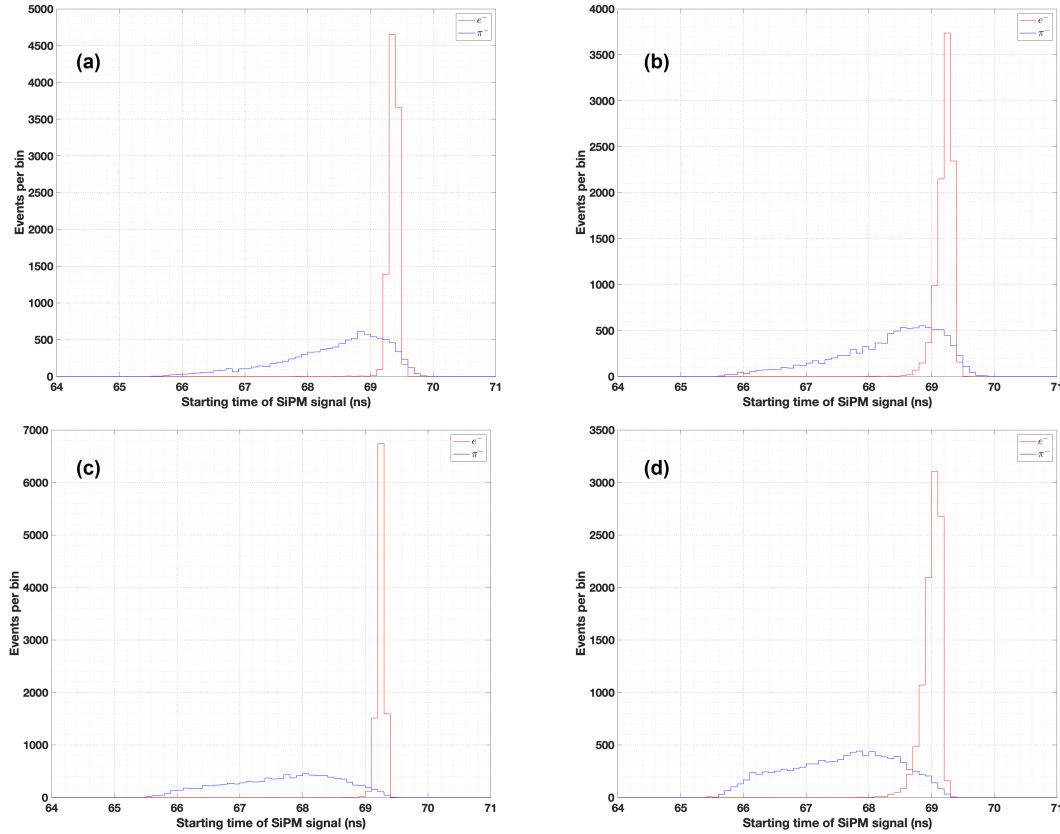


Fig. 7.15: (a-c) Distribution of the SiPM signal starting time for the lead-based IDEA calorimeter and for the copper-based one (b-d). Data for 20 GeV (top row) and 60 GeV (bottom row) beam particles.

shifted to lower values. This reflects the fact that the initial particles interact, on average, deeper inside the calorimeter with respect to the 20 GeV energy beams. Moreover, since for example, in lead λ_{int} is 17.10 cm while X_0 is only 0.56 cm (30 times less), the discrimination power of these method sensibly improves by increasing the beam energy.

⁹ $t_0 = 0$ is considered the time at which the particle is generated in the IP

Electron ID efficiency

The electron ID efficiency (and the probability for mis-ID a pion as an electron) can be extracted by a scan on all possible threshold values (f_{cut}) of the considered parameters, which defines a particle as an electron/pion when its value is larger/smaller than the threshold cut. Fig.7.16 shows the scan performed on the C/S threshold values, for the lead-based IDEA calorimeter for both the 20 (left) and 60 GeV (right) beam energies. The results relative to the particle

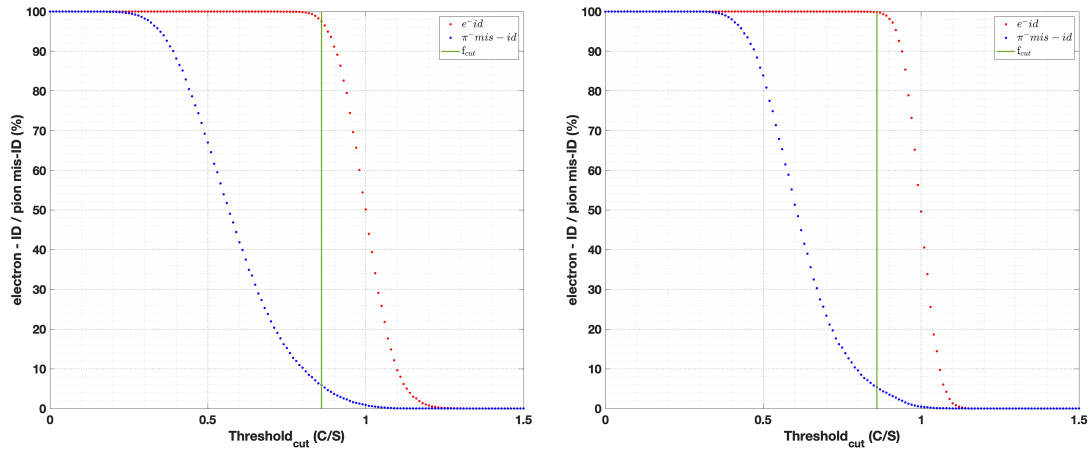


Fig. 7.16: Values of electron ID (red points) and π^- mis-ID (blue ones) as a function of the threshold cut performed for the C/S variable of the lead-based IDEA calorimeter. Data for 20 GeV (left) and 60 GeV (right).

ID capability of each method are summarised in tab.7.3 for each one of the three calorimeters discussed above. For an easy comparison, the results are given by fixing an electron ID of about 99%. To understand how much the

Energy	RD52		IDEA (Pb)		IDEA (Cu)	
	e^- ID (%)	π^- mis-ID (%)	e^- ID (%)	π^- mis-ID (%)	e^- ID (%)	π^- mis-ID (%)
<i>C/S</i> ratio						
20 GeV	99.0	16.9	98.9	7.1	99.0	17.2
60 GeV	98.0	13.9	99.0	4.0	99.0	9.7
Shower profiles						
20 GeV	99.1	6.9	99.4	3.2	99.3	3.8
60 GeV	99.1	5.1	99.8	2.5	98.7	3.2
Signal starting time						
20 GeV	-	-	98.7	17.3	99.0	33.2
60 GeV	99.1	11.3	98.5	3.2	99.0	15.3
Multivariate Analysis						
20 GeV	-	-	99.4	0.8	99.3	1.4
60 GeV	99.8	0.2	99.8	0.4	99.3	1.8

Tab. 7.3: Comparison between the electron ID and pions mis-ID probabilities extracted from the RD52 module and the simulated lead-based and copper-based IDEA calorimeters.

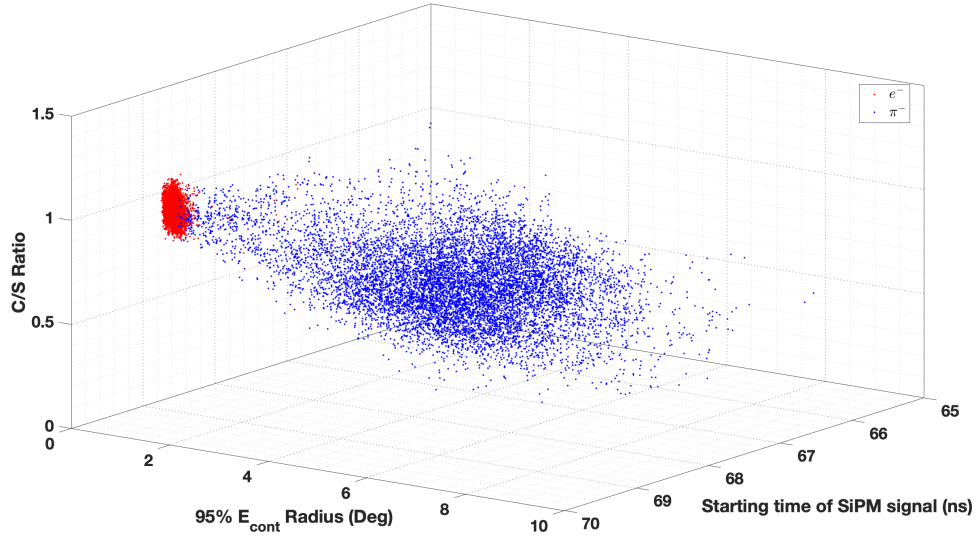


Fig. 7.17: Scatter plot of the 20,000 combined e^- (red points) and π^- (blue points) events as a function of the three discriminant variable described above. Data from the 60 GeV energy beams in the lead-based IDEA calorimeter. The correlations have been calculated for each pair of variables and are listed below for e^- and π^- , respectively. C/S vs R_{95} : 5% and 60%; C/S vs t_{start} : 31% and 23%; R_{95} vs t_{start} : 7% and 9%.

three different discriminating variables are correlated (fig.7.17), i.e. to what extent the mis-ID particles are either the same or different ones for each variable, the different e/π separation methods were combined together in a multivariate analysis¹⁰ [167]. The results are presented in the last part of tab.7.3 and assess efficiencies comparable to what obtained by the RD52 Collaboration with a similar multivariate analysis. The remaining mis-ID pions should be the ones that interact close to the front face of the calorimeter and transfer a large energy fraction to one or more π^0 s (as e.g. the charge exchange reactions: $\pi^- + p \rightarrow \pi^0 + n$) [102]. Clearly different cut combinations can achieve similar or better results. Further improvements may be expected adding other variables (as the standard deviation of the photons arrivals times for each fibre, the number of fired fibres outside $2 R_M$, the time over threshold, etc.) that are currently being tested to find the best set of variables to be used in the multivariate analysis.

¹⁰The multi-layer perceptron response (MLPBFGS) was considered.

Conclusions and Outlooks

8.1 Summary result and discussion

The main purpose of the work described in this thesis is to find a readout method that would make the dual-readout fibre calorimeter suitable for a future collider experiment. This requires the sensors converting the light signals into electric pulses to be mounted as close as possible to the calorimeter. SiPMs offer this possibility since they can be directly coupled to each fibre. This is the first time that a DR calorimeter has been equipped with a SiPM readout and tested on beam. The most important results of these tests are summarised below.

Optical cross-talk between fibres: An important consequence of the large light yield difference between the S and C signals (about a factor of 50) is the fact that the calorimeter is prone to optical cross-talk effects between fibres. This cross-talk has to be considered and needs to be reduced as much as possible. The S and C signals measure two complementary aspects of the shower development and both these information are crucial for a correct implementation of the DR method. It was found that with a proper readout mechanical structure and fibre insulation, this issue can be reduced at the per mille level. Further studies about the impact of this effect on the calorimeter performances will be done to provide a tolerable upper limit.

C and S light yields: The light yield of the Cherenkov fibres was a limiting factor for the hadronic energy resolution of the DR calorimeters. A value of about 30 Cpe/GeV was measured for the PMT-based RD52 module. With the new SiPM readout, the C LY was increased up to 69 ± 5 Cpe/GeV, more than two times larger. This number was measured to be constant (within 2%) for an electron beam energy scan ranging from 6 GeV up to 125 GeV. Similarly, once that the S light was attenuated by a yellow filter, also the scintillation signal linearity was restored (within 3%) and a value of 93 ± 3 Spe/GeV was measured. It was also shown how, with the appropriate spectral response, the yellow filter not only attenuates the light, but also improves the fibre response uniformity. The sensors adopted in these tests were not ideal in terms of dynamic range, but this was the best solution available on the market at the time of the beam tests. For the next beam test (planned for 2020), SiPMs with 10 and 15 μm pixels

pitch have already been considered and their characterisation has just started (sec.8.3). A higher dynamic range is especially important for the SiPMs coupled to the S signals. For the C channel, SiPMs with an increased PDE ($\sim 20\%$) in the blue/UV region of the optical spectrum are being considered. The Cherenkov LY can be also increased replacing the clear fibres with new ones having a higher numerical aperture and aluminizing their upstream free ends. Based on the RD52 experience with these techniques, an increase of about 50% is expected. This could further reduce the difference between the C and S light yields.

The em shower profiles: One of the main benefits of the SiPM-based readout system is the increased transversal segmentation which allows to have a projected imaging of the shower with unprecedented precision. Whereas it is commonly assumed that the radial shower profile scales with the Molière radius (which was 31 mm in these prototypes), it was found that more than half of the shower energy was deposited within few mm from the shower axis and $\sim 10\%$ within 1 mm. The results also confirmed the large differences between the shower profiles measured with S and C light, earlier observed in the muon signals and in the angular dependence of the em energy resolution by the DREAM and RD52 Collaborations.

IDEA calorimeter simulation: A fully projective geometry of the IDEA calorimeter was developed, together with a second Monte Carlo simulation that models the SiPM response and reproduces the waveforms used to extract all the needed information (as the values of the signal integral or its starting time). The simulation results are consistent with the expected behaviour of such detector, especially in the hadronic shower energy reconstruction, performed by the DR method (after the calibration with electrons). The expected em and hadronic energy resolutions are $\sim 11.5\%/\sqrt{E} + 0.5\%$ and $\sim 33.1\%/\sqrt{E} + 0.2\%$, respectively. Moreover, the agreement between the particle ID results obtained for the IDEA lead-based calorimeter and the ones measured with a similar module by the RD52 Collaboration further validates these simulations. These preliminary studies suggest that this DR calorimeter can be used to identify electrons with high degree of accuracy combining the information about the C/S ratio, the starting time of the first S signal and the lateral shower profiles: more than 99% of e^- ID, with $\sim 1\%$ π mis-ID was found for the simulated 4π copper-based IDEA calorimeter¹. The progress in the simulation work allows to characterise the calorimeter performances and represents the starting point for other future studies as the calorimeter energy resolution to jets and the particle ID performances in a multi-particles environment. Both a multivariate analysis and a particle discrimination method based on machine learning are currently under

¹For the sake of clarity, to assess the correct particle ID capability, further studies (as e.g. a scan over impact points and angles) are required.

development. The final goal will be the development of a stand alone GEANT4 simulation of all the IDEA detectors to allow physics studies with this detector concept.

8.2 Readout system studies

Electrical grouping

In a full scale module, the number of readout channels will be of the order of 10^8 and this could increase the complexity of the acquisition system, the power consumption and the cost of the calorimeter. The possibility to sum up the analogue output of more than one sensor was studied. On one hand, it is important to guarantee both the linearity response of each SiPM and the correct equalisation between the sensors grouped together and, on the other hand, it is essential to optimise the calorimeter spatial granularity. The first preliminary test was performed using a dedicated board that allowed to investigate the SiPM performances when the signals were analogically grouped (by groups of 1, 2, 4, 6 and 9 SiPM). The sensors tested were the Hamamatsu S13615-10253 (i.e. the same adopted in the beam tests). Each grouped signal was read out with a custom DC-coupled pre-amplifier with a $1\ \mu\text{s}$ shaping time, followed by an AC-coupled differential amplifier. The board also provided temperature measurement and allowed a fine control for each sensor biasing voltage in the 0-5 V range. The results are summarised in fig.8.1, where a multi-photon spectrum obtained with a single SiPM (red curve) is superimposed to the one obtained with 9 SiPMs grouped together (blue curve). This result was an indication that

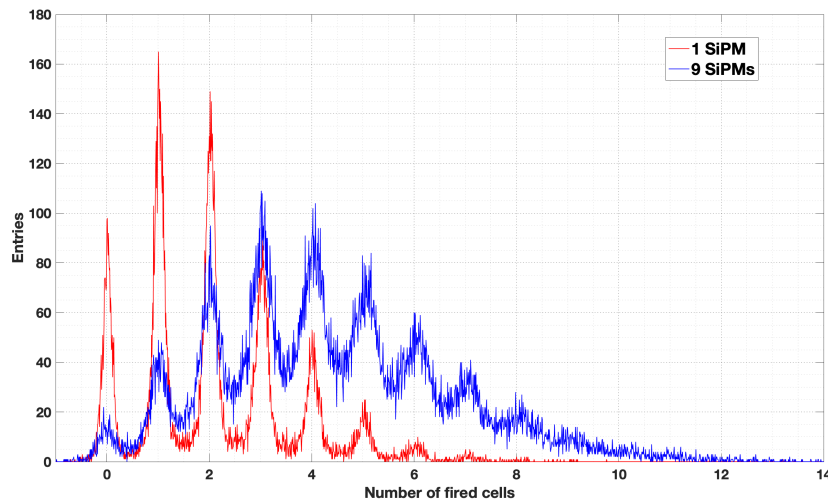


Fig. 8.1: Multi-photon spectrum of 1 SiPM (red curve) and 9 SiPMs (blue curve) grouped together [3].

grouping can be done, preserving a good quality of the multi-photon spectrum and thus the possibility of real-time information on sensor equalisation and the temperature variations. Clearly, this solution requires a system configuration in which the non-linearity corrections can be neglected because, after grouping, they can not be applied anymore.

ASIC: preliminary studies

For a high density and cost-effective integration of multi-channel readout electronics into small size and low power modules, a front-end based on Application Specific Integrated Circuit (ASIC) chips is the desired solution. The first step was a preliminary characterisation of the Citiroc 1A ASIC, designed by WEEROC (fig.8.2). This ASIC integrates the front-end for 32 SiPMs with tunable bias for

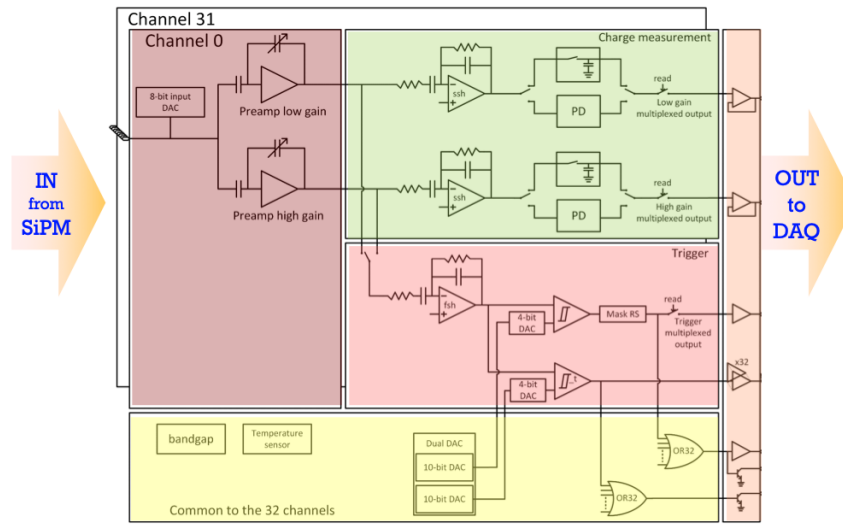


Fig. 8.2: The Citiroc 1A block scheme.

each individual channel in a range of 0-4.5 V. Each channel has two independent branches with different amplification, allowing to characterise the multi-photon spectrum (useful for the sensors inter-calibration) and to exploit a large dynamic range (0-400 pC i.e ~ 2500 photoelectrons with a typical gain of $\sim 10^6$) at the same time. The signals from both branches are processed through a peak detection and track & hold circuit and the output is externally digitised. A timing information is also available: the signal feeds a fast shaper amplifier before going into the fast comparator which allows to obtain time stamp with time resolution up to 100 ps. The initial ASIC qualification was performed using a general-purpose board DT5702 (produced by CAEN S.p.A) which provides the common bias to all the SiPMs together with the access to the basic functionalities of the Citiroc 1A and data acquisition. A comprehensive analysis was performed using the new DT5550W board, featuring the full control of the ASIC functionality.

A third board, the FERS-5200 (produced by CAEN S.p.A.), providing the same functionalities described above, will be available from the begin of 2020 and should be the compact ($15 \times 6 \text{ cm}^2$) and scalable solution that will be adopted in the next beam test.

8.3 2020 beam test

A new beam test (at [DESY](#)) is scheduled for autumn 2020. A new prototype, with 9 towers, for a total volume of about $10 \times 10 \times 100 \text{ cm}^3$ will be built (fig.8.3). The main feature of this prototype is the absorber material structure: each fibre

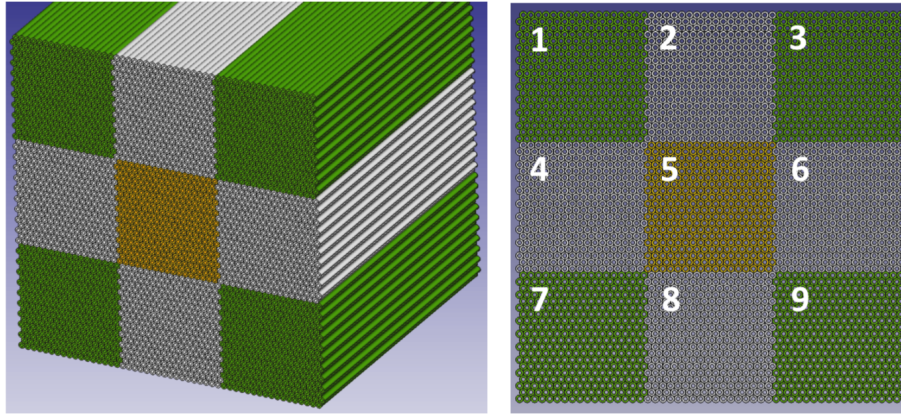


Fig. 8.3: The new prototype scheme, based on 2880 tubes.

is embedded in a 1 m long tube, providing light insulation and avoiding the fibre optical cross-talk. Each tube is made of CuZn37 and has an internal diameter of 1.1 mm and an outer one of 2.0 mm. Each tower consists of $16 \times 20 = 320$ tubes, glued with Araldite 2011-A/B. The central tower (number 5 in figure) will be read out by SiPMs, while the other towers by PMTs. SiPMs will be read out by 5 FERS-5200, each one hosting two Citiroc 1A ASICs. The possibility to integrate SiPMs with 10 or 15 μm of pitch is currently under study. Both the Hamamatsu S14160-1310PS (10 μm) and S14160-1315PS (15 μm) are being characterised. Compared to the sensors adopted in the previous beam tests, they have a sensitive area of $1.3 \times 1.3 \text{ mm}^2$ and offer an increased dynamic range of 16,675 and 7,296 cells, respectively. Moreover, they have a lower gain of 1.8×10^5 ($\sim 14,000$ cells for the ASIC dynamic range) and 3.6×10^5 ($\sim 7,000$ cells). A preliminary characterisation of the multi-photon spectrum² (fig.8.4) was carried out by means of the CAEN Silicon Photomultiplier Kit that contains a SP5600 CAEN power supply and three-stage Amplification Unit ([PSAU](#)) and a DT5720A CAEN Desktop Digitiser³ and with the automatic software tool described in [117].

²Illuminating the sensor with a ultra-fast LED

³250 Ms/s over with 12 bit dynamic range of 2 V

Finally, the PDE (at 460 nm) is 18% for 10 μm and 32% for 15 μm . This is an

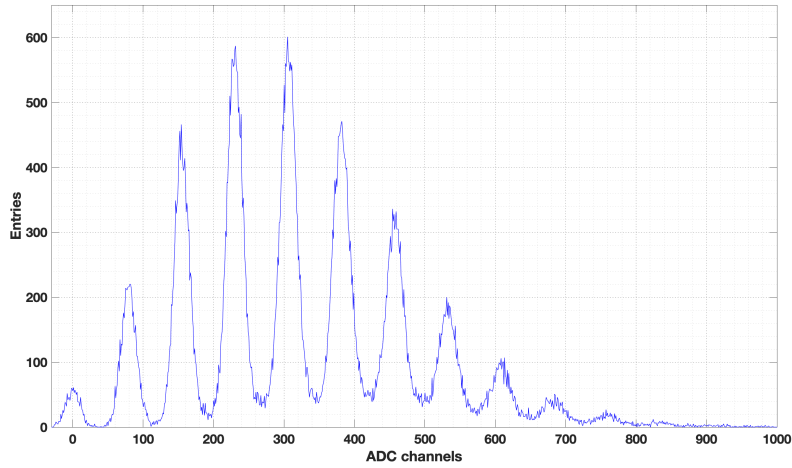


Fig. 8.4: Multi-photon spectrum of the tested Hamamatsu S14160-1310PS. The sensor was operated with $V_{Ov} = +4.5$ V and the signal was amplified with 40 dB gain.

important aspect for the design of the prototype readout: one valuable solution should be to couple the S14160-1310PS sensors to the *S* fibres (decreasing the filter light attenuation) and the S14160-1315PS ones to the *C* channel since they present an higher PDE in the blue spectral region (increasing the number of Cpe/GeV).

All the results reported in this thesis show the impressive potential of the DR as a novel calorimetric approach for future high energy physics experiments and represent a very encouraging starting point for further beam tests and a new R&D phase. In particular, the SiPM-based readout promises of fully unfolding this physics potential, maximising the intrinsic high transverse granularity and providing an unprecedented shower imaging capability. Finally, the simulation results boost additional studies about the DR particle ID capability in a multi-particle and jets environment.

List of acronyms

ACCESS Advanced Cosmic Composition Experiment at the Space Station

AFE Active Front End

AHCAL Analog Hadron Calorimeter

AP After-pulsing

ASIC Application Specific Integrated Circuit

ATLAS A Toroidal LHC ApparatuS

BSM Beyond the Standard Model

CEPC Circular Electron Positron Collider

CKM Cabibbo–Kobayashi–Maskawa

CLIC Compact Linear Collider

CMS Compact Muon Solenoid

DAQ data acquisition

DCR Dark Count Rate

DESY Deutsches Elektronen-Synchrotron

DR Dual-Readout calorimetry

DREAM Dual-REAdout Method

DWCs Delay Wire Chambers

ENF Excess Noise Factor

E-XFEL European X-ray Free Electron Laser

EW Electroweak

EWSB Electroweak Symmetry Breaking

EWPOs Electroweak Precision Observables

FCC Future Circular Collider

f_{em} electromagnetic fraction (of the hadronic shower)

FPGA Field Programmable Gate Array

G-APDs Geiger mode Avalanche Photo-Diodes

HEP High Energy Physics

HL-LHC High-Luminosity Large Hadron Collider

HPDs Hybrid Photo-Diodes

IDEA Innovative Detector for Electron-positron Accelerator

ILC International Linear Collider

LCLS-II Linac Coherent Light Source-II

LEP Large Electron-Positron Collider

LHC Large Hadron Collider

LHCb Large Hadron Collider beauty

LY Light Yield

MADA Multichannel Analog to Digital Acquisition System

mip minimum ionizing particle

MPGD Micro Pattern Gaseous Detector

MPPCs Multi Pixel Photon Counters

NA Numerical Aperture (of the fibres)

OCT Optical Cross-Talk

PDE Photon Detection Efficiency

PFA Particle Flow Analysis

PSAU Power Supply and Amplification Unit

PSD Pre-Shower Detector

PMT PhotoMultiplier Tube

QE Quantum Efficiency

SiPMs Silicon Photomultipliers

SLAC Stanford Linear Accelerator Center

SM Standard Model

SNR Signal to Noise Ratio

SPADs Single-Photon Avalanche Diodes

SPS Super Proton Synchrotron

SPPC Super Proton Proton Collider

SPTR Single-Photon Timing Resolution

SRH Shockley-Read-Hall

TCMT Tail Catcher and Muon Tracker

TDC Time to Digital Converter

TSV Through Silicon Via

Bibliography

- [1] M.Antonello et al. « Tests of a dual-readout fiber calorimeter with SiPM light sensors ». In: *Nuclear Inst. and Methods in Physics Research, A* **899** 52-64 (2018). DOI: [10.1016/j.nima.2018.05.016](https://doi.org/10.1016/j.nima.2018.05.016) (cit. on pp. 11, 34, 97, 103, 111, 118, 136, 137).
- [2] M.Antonello et al. « Linearity response measurement of a SiPM-based dual-readout calorimeter for future leptonic colliders ». In: *Nuclear Inst. and Methods in Physics Research, A* **958** 162136 (2020). DOI: [10.1016/j.nima.2019.04.090](https://doi.org/10.1016/j.nima.2019.04.090) (cit. on p. 11).
- [3] M.Antonello et al. « Development of a Silicon Photomultiplier based dual readout calorimeter: The pathway beyond the proof-of-concept ». In: *Nuclear Inst. and Methods in Physics Research, A* **936** 127-129 (2019). DOI: [10.1016/j.nima.2018.10.169](https://doi.org/10.1016/j.nima.2018.10.169) (cit. on pp. 11, 163).
- [4] R.Ferrari et al. « Dual-readout calorimetry ». In: *Int. Journ. of Mod. Phys. A* **34** 1940019 (2019). DOI: [10.1142/S0217751X19400190](https://doi.org/10.1142/S0217751X19400190) (cit. on pp. 11, 138, 139).
- [5] L.Pezzotti et al. « Dual-readout fibre-sampling calorimetry with SiPM light sensors ». In: *IOP Conference Series: 1162, 012014* (2019). DOI: [10.1088/1742-6596/1162/1/012014](https://doi.org/10.1088/1742-6596/1162/1/012014) (cit. on p. 11).
- [6] R.Aly et al. « First test-beam results obtained with IDEA, a detector concept designed for future lepton colliders ». In: *Nuclear Inst. and Methods in Physics Research, A* **958** 162088 (2020). DOI: [10.1016/j.nima.2019.04.042](https://doi.org/10.1016/j.nima.2019.04.042) (cit. on p. 11).
- [7] M.Antonello et al. « Dual-readout calorimetry, an integrated high-resolution solution for energy measurements at future electron–positron colliders ». In: *Nuclear Inst. and Methods in Physics Research, A* **958** 162063 (2020). DOI: [10.1016/j.nima.2019.04.017](https://doi.org/10.1016/j.nima.2019.04.017) (cit. on pp. 11, 140).
- [8] A.Abada et al. « Future Circular Collider: Conceptual Design Report, vol. 2: FCC-ee: The Lepton Collider ». In: *Eur. Phys. J. Spec. Top.* **228**: 261 (2019). DOI: [10.1140/epjst/e2019-900045-4](https://doi.org/10.1140/epjst/e2019-900045-4) (cit. on pp. 11–13, 16, 17, 25–27, 30, 32).
- [9] CEPC Study Group. « CEPC Conceptual Design Report: Volume 2 - Physics & Detector ». In: *IHEP-CEPC-DR-2018-02* (2018). URL: <http://arxiv.org/abs/1811.10545v1> (cit. on pp. 11–15, 26, 28–32).

- [10] ATLAS Collaboration. « Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ». In: *Physics Letters B* **716** 1-29 (2012). DOI: [10.1016/j.physletb.2012.08.020](https://doi.org/10.1016/j.physletb.2012.08.020) (cit. on p. 13).
- [11] CMS Collaboration. « Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ». In: *Physics Letters B* **716** 30-61 (2012). DOI: [10.1016/j.physletb.2012.08.021](https://doi.org/10.1016/j.physletb.2012.08.021) (cit. on p. 13).
- [12] H.Bauer et al. « The International Linear Collider Technical Design Report - Volume 2: Physics ». In: *ILC-REPORT-2013-040* (2013). URL: <http://arxiv.org/abs/1306.6352v1> (cit. on pp. 13, 14, 23, 24).
- [13] CLIC Collaboration. « Physics and Detectors at CLIC: CLIC Conceptual Design Report ». In: *CERN-2012-003* (2012). URL: <http://arxiv.org/abs/1202.5940v1> (cit. on pp. 13, 14, 24, 25).
- [14] A.Abada et al. « Future Circular Collider: Conceptual Design Report, vol. 1: Physics Opportunities ». In: *Eur. Phys. J. C* **79**: 474 (2019). DOI: [10.1140/epjc/s10052-019-6904-3](https://doi.org/10.1140/epjc/s10052-019-6904-3) (cit. on pp. 14-16, 18-22, 30).
- [15] A.Hoecker. « Private communication ». In: (2018). URL: <https://indico.cern.ch/event/716380/contributions/2944841/attachments/1660046/2660284/epfaculty-hoecker-1jun2018.pdf> (cit. on pp. 14, 15).
- [16] M.E.Peskin. « Comparison of LHC and ILC Capabilities for Higgs Boson Coupling Measurements ». In: *SLAC-PUB-15178* (2013). URL: <https://arxiv.org/abs/1207.2516v3> (cit. on p. 15).
- [17] T.Barklow et al. « Improved formalism for precision Higgs $\gamma\gamma$ and gg couplings ». In: *Phys. Rev. D*, **97**, 053003 (2018). DOI: [10.1103/PhysRevD.97.053003](https://doi.org/10.1103/PhysRevD.97.053003) (cit. on p. 15).
- [18] H.Abramowicz et al. « Higgs physics at the CLIC electron-positron linear collider ». In: *Eur. Phys. J. C* **77**: 475 (2017). DOI: [10.1140/epjc/s10052-017-4968-5](https://doi.org/10.1140/epjc/s10052-017-4968-5) (cit. on p. 15).
- [19] D.d'Enterria et al. « Higgs physics at the Future Circular Collider ». In: *PoS ICHEP 2016*, 434 (2017). DOI: [10.22323/1.282.0434](https://doi.org/10.22323/1.282.0434) (cit. on p. 16).
- [20] ATLAS Collaboration. « Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector ». In: *Physics Letters B* **784** 173-191 (2018). DOI: [10.1016/j.physletb.2018.07.035](https://doi.org/10.1016/j.physletb.2018.07.035) (cit. on p. 16).
- [21] CMS Collaboration. « Observation of $t\bar{t}H$ Production ». In: *Phys. Rev. Lett.* **120**, 231801 (2018). DOI: [10.1103/PhysRevLett.120.231801](https://doi.org/10.1103/PhysRevLett.120.231801) (cit. on p. 16).
- [22] M.Benedikt et al. « Future Circular Colliders ». In: *Annual Review of Nuclear and Particle Science*, **69** In Press (2019). DOI: [10.1146/annurev-nucl-101918-023748](https://doi.org/10.1146/annurev-nucl-101918-023748) (cit. on pp. 16, 22).
- [23] K.Fujii et al. « Physics Case for the International Linear Collider ». In: *ILC-NOTE-2015-067* (2015). URL: <https://arxiv.org/abs/1506.05992v2> (cit. on p. 16).

- [24] M.McCullough. « Erratum: Indirect model-dependent probe of the Higgs self-coupling [Phys. Rev. D 90, 015001 (2014)] ». In: *Phys. Rev. D*, **90**, 015001 (2015). DOI: [10.1103/PhysRevD.92.039903](https://doi.org/10.1103/PhysRevD.92.039903) (cit. on p. 16).
- [25] ATLAS Collaboration. « Erratum to: Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector ». In: *Eur. Phys. J. C* **76**: 152 (2016). DOI: [10.1140/epjc/s10052-016-3934-y](https://doi.org/10.1140/epjc/s10052-016-3934-y) (cit. on p. 17).
- [26] CMS Collaboration. « Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV ». In: *Phys. Rev. D*, **92**, 012004 (2015). DOI: [10.1103/PhysRevD.92.012004](https://doi.org/10.1103/PhysRevD.92.012004) (cit. on p. 17).
- [27] D.d'Enterria et al. « High-precision α_S measurements from LHC to FCC-ee ». In: *CERN-PH-TH-2015-299, CoEPP-MN-15-13* (2015). URL: <https://arxiv.org/abs/1512.05194v1> (cit. on pp. 18, 21).
- [28] SLD Collaboration. « Measurement of the branching ratios of the Z^0 into heavy quarks ». In: *Phys. Rev. D*, **71**, 112004 (2005). DOI: [10.1103/PhysRevD.71.112004](https://doi.org/10.1103/PhysRevD.71.112004) (cit. on p. 18).
- [29] P.Janot. « Erratum to: Direct measurement of $\alpha_{QED}(m_Z^2)$ at the FCC-ee ». In: *J. High Energ. Phys.* **2017**: 164 (2017). DOI: [10.1007/JHEP11\(2017\)164](https://doi.org/10.1007/JHEP11(2017)164) (cit. on p. 18).
- [30] D.d'Enterria and M.Srebre. « α_S and $|V_{CS}|$ determination, and CKM unitarity test, from W decays at NNLO ». In: *Physics Letters B* **763** 465-471 (2016). DOI: [10.1016/j.physletb.2016.10.012](https://doi.org/10.1016/j.physletb.2016.10.012) (cit. on p. 18).
- [31] The Gfitter Group. « Update of the global electroweak fit and constraints on two-Higgs-doublet models ». In: *Eur. Phys. J. C* **78**: 675 (2018). DOI: [10.1140/epjc/s10052-018-6131-3](https://doi.org/10.1140/epjc/s10052-018-6131-3) (cit. on p. 17).
- [32] The Gfitter Group. « The global electroweak fit at NNLO and prospects for the LHC and ILC ». In: *Eur. Phys. J. C* **74**: 3046 (2014). DOI: [10.1140/epjc/s10052-014-3046-5](https://doi.org/10.1140/epjc/s10052-014-3046-5) (cit. on p. 17).
- [33] The ALEPH Collaboration; The DELPHI Collaboration; The L3 Collaboration; The OPAL Collaboration; The SLD Collaboration; The LEP Electroweak Working Group; The SLD Electroweak and Heavy Flavour Groups. « Precision electroweak measurements on the Z resonance ». In: *Physics Report*, **427**, 257-454 (2006). DOI: [10.1016/j.physrep.2005.12.006](https://doi.org/10.1016/j.physrep.2005.12.006) (cit. on p. 20).
- [34] ATLAS Collaboration. « Measurement of the top quark mass in the $t\bar{t} \rightarrow \text{lepton} + \text{jets}$ channel from $\sqrt{s} = 8$ TeV ATLAS data and combination with previous results ». In: *Eur. Phys. J. C* **79**: 290 (2019). DOI: [10.1140/epjc/s10052-019-6757-9](https://doi.org/10.1140/epjc/s10052-019-6757-9) (cit. on p. 20).
- [35] CMS Collaboration. « Measurement of the top quark mass using proton-proton data at $\sqrt{s} = 7$ and 8 TeV ». In: *Phys. Rev. D*, **93**, 072004 (2016). DOI: [10.1103/PhysRevD.93.072004](https://doi.org/10.1103/PhysRevD.93.072004) (cit. on p. 20).
- [36] G.Degrassi et al. « Higgs mass and vacuum stability in the Standard Model at NNLO ». In: *J. High Energ. Phys.* **2012**: 98 (2012). DOI: [10.1007/JHEP08\(2012\)098](https://doi.org/10.1007/JHEP08(2012)098) (cit. on p. 21).

- [37] D.d'Enterria et al. « Parton Radiation and Fragmentation from LHC to FCC-ee ». In: *CoEPP-MN-17-1* (2017). URL: <https://arxiv.org/abs/1702.01329v1> (cit. on p. 21).
- [39] Linear Collider Collaboration. « The International Linear Collider. A Global Project ». In: (2019). URL: <https://arxiv.org/abs/1901.09829v1> (cit. on p. 23).
- [40] LCLS-II Collaboration. « The Linac Coherent Light Source-II Project ». In: *IPAC-2014-TUOCA01* (2014). DOI: [10.18429/JACoW-IPAC2014-TUOCA01](https://doi.org/10.18429/JACoW-IPAC2014-TUOCA01) (cit. on p. 23).
- [41] R.Pöschl. « Future colliders - Linear and circular ». In: *Proceedings of Science* (2018). URL: <https://arxiv.org/abs/1809.10426v2> (cit. on pp. 23, 28).
- [42] CLIC and CLICdp Collaborations. « Updated Baseline for a staged Compact Linear Collider ». In: *CERN-2016-004* (2016). DOI: [10.5170/CERN-2016-004](https://doi.org/10.5170/CERN-2016-004) (cit. on p. 24).
- [43] CLIC and CLICdp Collaborations. « The Compact Linear Collider (CLIC) - 2018 Summary Report ». In: *CERN-2018-005 M* (2018). DOI: [10.23731/CYRM-2018-002](https://doi.org/10.23731/CYRM-2018-002) (cit. on p. 24).
- [44] G.Günther and A.Ghigo. « CTF3 Design Report ». In: *CERN-PS-2002-008-RF ; CTF3-NOTE-2002-047 ; LNF-2002-008-IR* (2019). URL: <https://cds.cern.ch/record/559331> (cit. on p. 24).
- [45] D.Schulte. « FCC-hh Design Highlights ». In: *ICFA Beam Dyn. Newslett.* **72**, 99 (2017). URL: http://cds.cern.ch/record/2315722/files/9999999_99-109.pdf (cit. on p. 25).
- [46] K.Oide et al. « Erratum: Design of beam optics for the future circular collider e^+e^- collider rings ». In: *Phys. Rev. Accel. Beams*, **20**, 049901 (2017). DOI: [10.1103/PhysRevAccelBeams.20.049901](https://doi.org/10.1103/PhysRevAccelBeams.20.049901) (cit. on p. 26).
- [47] P.Raimondi et al. « Beam-Beam Issues for Colliding Schemes with Large Piwinski Angle and Crabbed Waist ». In: *LNF-07/003 (IR)* (2007). URL: <https://arxiv.org/abs/physics/0702033v1> (cit. on p. 26).
- [48] P.Raimondi et al. « Beam-beam simulations for particle factories with crabbed waist ». In: *IEEE Part. Acc. Confe. (PAC)*, **C070625**, 1469-1471 (2007). DOI: [10.1109/PAC.2007.4440792](https://doi.org/10.1109/PAC.2007.4440792) (cit. on p. 26).
- [49] M.Boscolo et al. « Machine detector interface studies: Layout and synchrotron radiation estimate in the future circular collider interaction region ». In: *Phys. Rev. Accel. Beams*, **20**, 011008 (2017). DOI: [10.1103/PhysRevAccelBeams.20.011008](https://doi.org/10.1103/PhysRevAccelBeams.20.011008) (cit. on p. 26).
- [50] N.Alipour Tehrani et al. « CLICdet: The post-CDR CLIC detector model ». In: *CLICdp-Note-2017-001* (2017). URL: <https://cds.cern.ch/record/2254048> (cit. on p. 31).
- [51] CMS Collaboration. « The CMS magnet project: Technical Design Report ». In: *CERN-LHCC-97-010* (1997). URL: <https://cds.cern.ch/record/331056> (cit. on p. 32).
- [52] G.Chiarello et al. « A new construction technique of high granularity and high transparency drift chambers for modern high energy physics experiments ». In: *Nuclear Inst. and Methods in Physics Research, A* **824** 512-514 (2016). DOI: [10.1016/j.nima.2015.12.021](https://doi.org/10.1016/j.nima.2015.12.021) (cit. on p. 33).

- [53] A.M.Baldini et al. « Single-hit resolution measurement with MEG II drift chamber prototypes ». In: *JINST*, **11** P07011 (2016). DOI: [10.1088/1748-0221/11/07/P07011](https://doi.org/10.1088/1748-0221/11/07/P07011) (cit. on p. 34).
- [54] S.Panati et al. In: *IEEE-NSS Conf. record* (2017) (cit. on p. 34).
- [55] S.Lee M.Livan and R.Wigmans. « Dual-readout calorimetry ». In: *Review of Modern Physics*, **90**, 025002 (2018). DOI: [10.1103/RevModPhys.90.025002](https://doi.org/10.1103/RevModPhys.90.025002) (cit. on pp. 34, 36, 48, 50, 55, 67).
- [56] G.Bencivenni et al. « The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD ». In: *JINST*, **10** P02008 (2015). DOI: [10.1088/1748-0221/10/02/P02008](https://doi.org/10.1088/1748-0221/10/02/P02008) (cit. on p. 34).
- [57] ATLAS Collaboration. « The ATLAS Experiment at the CERN Large Hadron Collider ». In: *JINST*, **3** (2008). DOI: [10.1088/1748-0221/11/07/P07011](https://doi.org/10.1088/1748-0221/11/07/P07011) (cit. on p. 35).
- [58] H.H.J. Ten Kate. « FCC Week presentation (April, 2018) ». In: *Amsterdam* (2018). URL: https://indico.cern.ch/event/656491/contributions/2939122/attachments/1629705/2597192/20180409-TenKate_-_FCCee_IDEA_thin_2T_Solenoid.pdf (cit. on p. 35).
- [59] R.Wigmans. *Calorimetry, Energy Measurement in Particle Physics*. International Series of Monographs on Physics. Oxford University Press, 2017. ISBN: 9780198786351 (cit. on pp. 36, 39–41, 45, 47, 50).
- [60] K.Hagiwara et al.; PDG Collaboration. « Review of Particle Properties ». In: *Phys. Rev. D*, **66**, (1) 010001(R) (2002). DOI: [10.1103/PhysRevD.66.010001](https://doi.org/10.1103/PhysRevD.66.010001) (cit. on p. 37).
- [61] C.W.Fabjan and F.Gianotti. « Calorimetry for particle physics ». In: *Review of Modern Physics*, **75**, 1243 (2003). DOI: [10.1103/RevModPhys.75.1243](https://doi.org/10.1103/RevModPhys.75.1243) (cit. on pp. 37, 38, 40, 45, 46).
- [62] R.Wigmans and M.T.Zeyrek. « On the differences between calorimetric detection of electrons and photons ». In: *Nuclear Inst. and Methods in Physics Research, A* **485** 385-398 (2002). DOI: [10.1016/S0168-9002\(01\)02141-6](https://doi.org/10.1016/S0168-9002(01)02141-6) (cit. on p. 39).
- [63] R.Wigmans. « Calorimetry ». In: *Università degli Studi di Pavia, Scientifica Acta*, **2** 18-55 (2008). URL: http://siba.unipv.it/fisica/ScientificaActa/volume_2_1/Wigmans.pdf (cit. on pp. 39, 40, 48, 49).
- [64] A.Ferrari and P.R.Sala. *Calorimetry in High Energy Physics - Selected Topics in Sampling Calorimetry*. Proceedings of the 9th International Conference on Calorimetry in High Energy Physics, Annecy, France. Frascati Physics Series 21, edited by B. Aubert et al., p.31, 2001 (cit. on p. 42).
- [65] N.Akchurin et al. « Beam test results from a fine-sampling quartz fiber calorimeter for electron, photon and hadron detection ». In: *Nuclear Inst. and Methods in Physics Research, A* **399** 202-226 (1997). DOI: [10.1016/S0168-9002\(97\)00789-4](https://doi.org/10.1016/S0168-9002(97)00789-4) (cit. on pp. 41, 48, 51).
- [66] D.Green. *Calorimetry in High Energy Physics - Selected Topics in Sampling Calorimetry*. Proceedings of the 4th International Conference, La Biodola, Isola d'Elba, Italy. World

- Scientific, edited by A.Menzione and A.Scribano, p.1, 1994. ISBN: 978-981-4534-71-0. DOI: [10.1142/2273](#) (cit. on p. 42).
- [67] H.Abramowicz et al. « The response and resolution of an iron-scintillator calorimeter for hadronic and electromagnetic showers between 10 GeV and 140 GeV ». In: *Nuclear Inst. and Methods in Physics Research, A* **180** 429-439 (1981). DOI: [10.1016/0029-554X\(81\)90083-5](#) (cit. on p. 43).
- [68] D.Acosta et al. « Lateral shower profiles in a lead/scintillating fiber calorimeter ». In: *Nuclear Inst. and Methods in Physics Research, A* **316** 184-201 (1992). DOI: [10.1016/0168-9002\(92\)90901-F](#) (cit. on pp. 43, 47, 48).
- [69] D.Acosta et al. « Results of prototype studies for a spaghetti calorimeter ». In: *Nuclear Inst. and Methods in Physics Research, A* **294** 193-210 (1990). DOI: [10.1016/0168-9002\(90\)91833-W](#) (cit. on p. 43).
- [70] R.Wigmans M.Livan V.Vercesi. *Scintillating-fibre Calorimetry*. Detectors and Experimental Techniques. CERN Yellow Report: Monographs, No. CERN 95-02, 1995. ISBN: 9789290830702. DOI: [10.5170/CERN-1995-002](#) (cit. on p. 45).
- [71] T.A.Gabriel et al. « Energy dependence of hadronic activity ». In: *Nuclear Inst. and Methods in Physics Research, A* **338** 336-347 (1994). DOI: [10.1016/0168-9002\(94\)91317-X](#) (cit. on pp. 47, 50).
- [72] M.Livan and R.Wigmans. « Misconceptions about calorimetry ». In: *Instruments 1 (MDPI AG)*, **3** (2017). DOI: [10.3390/instruments1010003](#) (cit. on p. 48).
- [73] S.Lee et al. « On the limits of the hadronic energy resolution of calorimeters ». In: *Nuclear Inst. and Methods in Physics Research, A* **882** 148-157 (2018). DOI: [10.1016/j.nima.2017.10.087](#) (cit. on pp. 48, 52, 54).
- [74] D.Acosta et al. « Electron, pion and multiparticle detection with a lead/scintillating- fiber calorimeter ». In: *Nuclear Inst. and Methods in Physics Research, A* **308** 481-508 (1991). DOI: [10.1016/0168-9002\(91\)90062-U](#) (cit. on p. 49).
- [75] CALICE Collaboration. « Hadron shower decomposition in the highly granular CALICE analogue hadron calorimeter ». In: *JINST*, **11** P06013 (2016). DOI: [10.1088/1748-0221/11/06/P06013](#) (cit. on p. 49).
- [76] E.Bernardi et al. « Performance of a compensating lead-scintillator hadronic calorimeter ». In: *Nuclear Inst. and Methods in Physics Research, A* **262** 229-242 (1987). DOI: [10.1016/0168-9002\(87\)90861-8](#) (cit. on p. 50).
- [77] D.Acosta et al. « Electron, pion and multiparticle detection with a lead/scintillating-fiber calorimeter ». In: *Nuclear Inst. and Methods in Physics Research, A* **308** 481-508 (1991). DOI: [10.1016/0168-9002\(91\)90062-U](#) (cit. on pp. 50, 61).
- [78] T.Suzuki et al. « A systematic measurement of energy resolution and e/π ratio of a lead/plastic-scintillator sampling calorimeter ». In: *Nuclear Inst. and Methods in Physics Research, A* **432** 48-65 (1999). DOI: [10.1016/S0168-9002\(99\)00394-0](#) (cit. on p. 50).

- [79] U.Behrens et al.; The ZEUS Calorimeter Group. « Test of the Zeus forward calorimeter prototype ». In: *Nuclear Inst. and Methods in Physics Research, A* **289** 115-138 (1990). DOI: [10.1016/0168-9002\(90\)90253-3](https://doi.org/10.1016/0168-9002(90)90253-3) (cit. on p. 50).
- [80] R.Wigmans. « Energy measurement at the TeV scale ». In: *New Journal of Physics* **10** (2) 025003 (2008). DOI: [10.1088/1367-2630/10/2/025003](https://doi.org/10.1088/1367-2630/10/2/025003) (cit. on p. 50).
- [81] C.Patrignani et al.; PDG Collaboration. « Energy measurement at the TeV scale ». In: *Chinese Physics C* **40** 10 (2016). DOI: [10.1088/1674-1137/40/10/100001](https://doi.org/10.1088/1674-1137/40/10/100001) (cit. on p. 50).
- [82] A.Andresen et al.; The ZEUS Calorimeter Group. « Response of a uranium-scintillator calorimeter to electrons, pions and protons in the momentum range 0.5–10 GeV/c ». In: *Nuclear Inst. and Methods in Physics Research, A* **290** 95-108 (1990). DOI: [10.1016/0168-9002\(90\)90347-9](https://doi.org/10.1016/0168-9002(90)90347-9) (cit. on p. 50).
- [83] ATLAS Liquid Argon EMEC/HEC Collaboration. « Hadronic calibration of the ATLAS liquid argon end-cap calorimeter in the pseudorapidity region $1.6 < |\eta| < 1.8$ in beam tests ». In: *Nuclear Inst. and Methods in Physics Research, A* **531** 481-514 (2004). DOI: [10.1016/j.nima.2004.05.133](https://doi.org/10.1016/j.nima.2004.05.133) (cit. on p. 51).
- [84] C.Adloff et al. « Hadronic energy resolution of a highly granular scintillator-steel hadron calorimeter using software compensation techniques ». In: *JINST*, **7** P09017 (2012). DOI: [10.1088/1748-0221/7/09/p09017](https://doi.org/10.1088/1748-0221/7/09/p09017) (cit. on p. 51).
- [85] J.A.Bakken et al.; L3 Collaboration. « Performance of a prototype BGO calorimeter in an electron beam from 2 to 50 GeV ». In: *Nuclear Inst. and Methods in Physics Research, A* **254** 535-541 (1987). DOI: [10.1016/0168-9002\(87\)90025-8](https://doi.org/10.1016/0168-9002(87)90025-8) (cit. on p. 52).
- [86] G.D.Barr et al. « Performance of an electromagnetic liquid krypton calorimeter based on a ribbon electrode tower structure ». In: *Nuclear Inst. and Methods in Physics Research, A* **370** (2-3) 413-424 (1996). DOI: [10.1016/0168-9002\(95\)00800-4](https://doi.org/10.1016/0168-9002(95)00800-4) (cit. on p. 52).
- [87] F.Sefkow et al. « Experimental tests of particle flow calorimetry ». In: *Review of Modern Physics*, **88**, 015003 (2016). DOI: [10.1103/RevModPhys.88.015003](https://doi.org/10.1103/RevModPhys.88.015003) (cit. on p. 52).
- [88] N.Akchurin et al. « On the differences between high-energy proton and pion showers and their signals in a non-compensating calorimeter ». In: *Nuclear Inst. and Methods in Physics Research, A* **408** 380-396 (1998). DOI: [10.1016/S0168-9002\(98\)00021-7](https://doi.org/10.1016/S0168-9002(98)00021-7) (cit. on p. 54).
- [89] A.Sill V.Nagaslaev and R.Wigmans. « Beam tests of a thin dual-readout calorimeter for detecting cosmic rays outside the Earth's atmosphere ». In: *Nuclear Inst. and Methods in Physics Research, A* **462** 411-425 (2001). DOI: [10.1016/S0168-9002\(01\)00185-1](https://doi.org/10.1016/S0168-9002(01)00185-1) (cit. on p. 55).
- [90] N.Akchurin et al. « Muon detection with a dual-readout calorimeter ». In: *Nuclear Inst. and Methods in Physics Research, A* **533** 305-321 (2004). DOI: [10.1016/j.nima.2004.05.134](https://doi.org/10.1016/j.nima.2004.05.134) (cit. on pp. 55, 58, 117, 118).
- [91] N.Akchurin et al. « Hadron and jet detection with a dual-readout calorimeter ». In: *Nuclear Inst. and Methods in Physics Research, A* **537** 537-561 (2005). DOI: [10.1016/j.nima.2004.07.285](https://doi.org/10.1016/j.nima.2004.07.285) (cit. on pp. 55–58, 61).

- [92] N.Akchurin et al. « Lessons from Monte Carlo simulations of the performance of a dual-readout fiber calorimeter ». In: *Nuclear Inst. and Methods in Physics Research*, A **762** 100-118 (2014). DOI: [10.1016/j.nima.2014.05.121](https://doi.org/10.1016/j.nima.2014.05.121) (cit. on pp. 58, 65, 66).
- [93] N.Akchurin et al. « Contributions of Cherenkov light to the signals from lead tungstate crystals ». In: *Nuclear Inst. and Methods in Physics Research*, A **582** 474-483 (2007). DOI: [10.1016/j.nima.2007.08.174](https://doi.org/10.1016/j.nima.2007.08.174) (cit. on p. 59).
- [94] N.Akchurin et al. « Dual-readout calorimetry with a full-size BGO electromagnetic section ». In: *Nuclear Inst. and Methods in Physics Research*, A **610** 488-501 (2009). DOI: [10.1016/j.nima.2009.08.074](https://doi.org/10.1016/j.nima.2009.08.074) (cit. on pp. 59, 60).
- [95] N.Akchurin et al. « A comparison of BGO and BSO crystals used in the dual-readout mode ». In: *Nuclear Inst. and Methods in Physics Research*, A **640** 91-98 (2011). DOI: [10.1016/j.nima.2011.03.013](https://doi.org/10.1016/j.nima.2011.03.013) (cit. on p. 59).
- [96] N.Akchurin et al. « Optimization of crystals for applications in dual-readout calorimetry ». In: *Nuclear Inst. and Methods in Physics Research*, A **621** 212-221 (2010). DOI: [10.1016/j.nima.2010.05.063](https://doi.org/10.1016/j.nima.2010.05.063) (cit. on p. 60).
- [97] N.Akchurin et al. « Polarization as a tool for dual-readout calorimetry ». In: *Nuclear Inst. and Methods in Physics Research*, A **638** 47-54 (2011). DOI: [10.1016/j.nima.2011.02.077](https://doi.org/10.1016/j.nima.2011.02.077) (cit. on p. 60).
- [98] N.Akchurin et al. « Detection of electron showers in dual-readout crystal calorimeters ». In: *Nuclear Inst. and Methods in Physics Research*, A **686** 125-135 (2012). DOI: [10.1016/j.nima.2012.04.092](https://doi.org/10.1016/j.nima.2012.04.092) (cit. on p. 60).
- [99] N.Akchurin et al. « The electromagnetic performance of the RD52 fiber calorimeter ». In: *Nuclear Inst. and Methods in Physics Research*, A **735** 130-144 (2014). DOI: [10.1016/j.nima.2013.09.033](https://doi.org/10.1016/j.nima.2013.09.033) (cit. on pp. 61–63, 67, 68, 121, 131, 138).
- [100] R.Dinapoli S.Ritt and U.Hartmann. « Application of the DRS chip for fast waveform digitizing ». In: *Nuclear Inst. and Methods in Physics Research*, A **623** 486-488 (2010). DOI: [10.1016/j.nima.2010.03.045](https://doi.org/10.1016/j.nima.2010.03.045) (cit. on p. 61).
- [101] N.Akchurin et al. « Electron detection with a dual-readout calorimeter ». In: *Nuclear Inst. and Methods in Physics Research*, A **536** 29-51 (2005). DOI: [10.1016/j.nima.2004.06.178](https://doi.org/10.1016/j.nima.2004.06.178) (cit. on pp. 62, 138).
- [102] N.Akchurin et al. « Particle identification in the longitudinally unsegmented RD52 calorimeter ». In: *Nuclear Inst. and Methods in Physics Research*, A **735** 120-129 (2014). DOI: [10.1016/j.nima.2013.09.024](https://doi.org/10.1016/j.nima.2013.09.024) (cit. on pp. 63–65, 69, 70, 154–157, 160).
- [103] S.Lee et al. « Hadron detection with a dual-readout fiber calorimeter ». In: *Nuclear Inst. and Methods in Physics Research*, A **866** 76-90 (2017). DOI: [10.1016/j.nima.2017.05.025](https://doi.org/10.1016/j.nima.2017.05.025) (cit. on pp. 65, 67).
- [104] DREAM Collaboration. *Dual-Readout Calorimetry for High-Quality Energy Measurements*. Internal Report NO. CERN-SPSC-2013-012. CERN, 2013. URL: <https://cds.cern.ch/record/1536796/files/SPSC-SR-117.pdf> (cit. on pp. 65, 66).

- [105] R.Wigmans. « New results from the RD52 project ». In: *Nuclear Inst. and Methods in Physics Research, A* **824** 721-725 (2016). DOI: [10.1016/j.nima.2015.09.069](https://doi.org/10.1016/j.nima.2015.09.069) (cit. on p. 67).
- [106] R.Wigmans. « New results from the RD52 (DREAM) project ». In: *Nuclear Inst. and Methods in Physics Research, A* **718** 43-47 (2013). DOI: [10.1016/j.nima.2012.11.056](https://doi.org/10.1016/j.nima.2012.11.056) (cit. on p. 67).
- [107] A.Cardini et al. « The small-angle performance of a dual-readout fiber calorimeter ». In: *Nuclear Inst. and Methods in Physics Research, A* **808** 41-53 (2016). DOI: [10.1016/j.nima.2015.11.005](https://doi.org/10.1016/j.nima.2015.11.005) (cit. on p. 68).
- [108] V.Arosio. « Development of a Silicon Photomultiplier based innovative and low cost Positron Emission Tomography scanner ». PhD thesis. Università degli Studi dell'Insubria, 2016. URL: <http://hdl.handle.net/10277/753> (cit. on pp. 73, 80, 87, 88).
- [109] T.L.Jackson and T.E.Murphy. « Methods of fabrication of semiconductor dice having back side redistribution layer accessed using through-silicon vias and assemblies thereof ». Pat. U.S. Patent No. 6,962,867. 8 Nov. 2005 (cit. on p. 73).
- [111] C.Piemonte and A.Gola. « Overview on the main parameters and technology of modern Silicon Photomultipliers ». In: *Nuclear Inst. and Methods in Physics Research, A* **926** 2-15 (2019). DOI: [10.1016/j.nima.2018.11.119](https://doi.org/10.1016/j.nima.2018.11.119) (cit. on pp. 74, 75, 79, 82-86).
- [112] F.Acerbi and S.Gundacker. « Understanding and simulating SiPMs ». In: *Nuclear Inst. and Methods in Physics Research, A* **926** 16-35 (2019). DOI: [10.1016/j.nima.2018.11.118](https://doi.org/10.1016/j.nima.2018.11.118) (cit. on pp. 75, 80, 82, 85, 87).
- [113] B.Dolgoshein et al. « Status report on silicon photomultiplier development and its applications ». In: *Nuclear Inst. and Methods in Physics Research, A* **563** 368-376 (2006). DOI: [10.1016/j.nima.2006.02.193](https://doi.org/10.1016/j.nima.2006.02.193) (cit. on pp. 75, 78).
- [114] S.Gundacker et al. « SiPM time resolution: From single photon to saturation ». In: *Nuclear Inst. and Methods in Physics Research, A* **718** 569-572 (2013). DOI: [10.1016/j.nima.2013.01.047](https://doi.org/10.1016/j.nima.2013.01.047) (cit. on p. 76).
- [115] F.Acerbi et al. « Characterization of Single-Photon Time Resolution: From Single SPAD to Silicon Photomultiplier ». In: *IEEE Trans. Electron Devices* **61** (5) 2678-2686 (2014). DOI: [10.1109/TNS.2014.2347131](https://doi.org/10.1109/TNS.2014.2347131) (cit. on p. 76).
- [116] D.Renker. « Geiger-mode avalanche photodiodes, history, proprieties and problems ». In: *Nuclear Inst. and Methods in Physics Research, A* **567** 48-56 (2006). DOI: [10.1016/j.nima.2006.05.060](https://doi.org/10.1016/j.nima.2006.05.060) (cit. on pp. 76, 86).
- [117] V.Arosio et al. « An Educational Kit Based on a Modular Silicon Photomultiplier System ». In: *arXiv* (2014). URL: <https://arxiv.org/abs/1308.3622v2> (cit. on pp. 77, 78, 88, 103, 145, 165).
- [118] P.Eckert et al. « Characterisation Studies of Silicon Photomultipliers ». In: *Nuclear Inst. and Methods in Physics Research, A* **620** 217-226 (2010). DOI: [10.1016/j.nima.2010.03.169](https://doi.org/10.1016/j.nima.2010.03.169) (cit. on p. 78).

- [119] R.Klanner. « Characterization of SiPMs ». In: *Nuclear Inst. and Methods in Physics Research, A* **926** 36-56 (2019). DOI: [10.1016/j.nima.2018.11.083](https://doi.org/10.1016/j.nima.2018.11.083) (cit. on pp. 79, 88, 89).
- [120] M.A.Green. « Self-consistent optical parameters of intrinsic silicon at 300 K including temperature coefficients ». In: *Solar Energy Materials and Solar Cells*, **92** 1305-1310 (2008). DOI: [10.1016/j.solmat.2008.06.009](https://doi.org/10.1016/j.solmat.2008.06.009) (cit. on p. 81).
- [121] T. Pro et al. « New developments of Near-UV SiPMs at FBK ». In: *IEEE Trans. Nucl. Sci.*, **60** (3) 2247-2253 (2013). DOI: [10.1109/TNS.2013.2259505](https://doi.org/10.1109/TNS.2013.2259505) (cit. on p. 81).
- [122] G.Zappalá et al. « Study of the photo-detection efficiency of FBK High-Density silicon photomultipliers ». In: *JINST*, **11** P11010 (2016). DOI: [10.1088/1748-0221/11/11/p11010](https://doi.org/10.1088/1748-0221/11/11/p11010) (cit. on p. 81).
- [123] A.N.Otte et al. « Characterization of three high efficiency and blue sensitive silicon photomultipliers ». In: *Nuclear Inst. and Methods in Physics Research, A* **846** 106-125 (2017). DOI: [10.1016/j.nima.2016.09.053](https://doi.org/10.1016/j.nima.2016.09.053) (cit. on p. 81).
- [124] M.Ghioni et al. « Large-area low-jitter silicon single photon avalanche diodes ». In: *Proc. SPIE 6900, Quantum Sensing and Nanophotonic Devices V*, 69001D (2006). DOI: [10.1117/12.761578](https://doi.org/10.1117/12.761578) (cit. on p. 83).
- [125] F.Acerbi et al. « Cryogenic Characterization of FBK HD Near-UV Sensitive SiPMs ». In: *IEEE Trans. Electron Devices* **645** (2) 521-526 (2017). DOI: [10.1109/TED.2016.2641586](https://doi.org/10.1109/TED.2016.2641586) (cit. on p. 84).
- [126] A.N.Otte. « On the efficiency of photon emission during electrical breakdown in silicon ». In: *Nuclear Inst. and Methods in Physics Research, A* **610** 105-109 (2009). DOI: [10.1016/j.nima.2009.05.085](https://doi.org/10.1016/j.nima.2009.05.085) (cit. on p. 84).
- [127] S.Vinogradov. « Analytical models of probability distribution and excess noise factor of solid state photomultiplier signals with crosstalk ». In: *Nuclear Inst. and Methods in Physics Research, A* **695** 247-251 (2012). DOI: [10.1016/j.nima.2011.11.086](https://doi.org/10.1016/j.nima.2011.11.086) (cit. on p. 86).
- [128] V.Chmill et al. « On the characterisation of SiPMs from pulse-height spectra ». In: *Nuclear Inst. and Methods in Physics Research, A* **854** 70-81 (2017). DOI: [10.1016/j.nima.2017.02.049](https://doi.org/10.1016/j.nima.2017.02.049) (cit. on p. 86).
- [129] P.Buzhan et al. « Large area silicon photomultipliers: Performance and applications ». In: *Nuclear Inst. and Methods in Physics Research, A* **567** 78-82 (2006). DOI: [10.1016/j.nima.2006.05.072](https://doi.org/10.1016/j.nima.2006.05.072) (cit. on p. 86).
- [130] F.Acerbi et al. « NUV silicon photomultipliers with high detection efficiency and reduced delayed correlated-noise ». In: *IEEE Trans. Nucl. Sci.*, **62** (3) 1318-1325 (2015). DOI: [10.1109/TNS.2015.2424676](https://doi.org/10.1109/TNS.2015.2424676) (cit. on p. 86).
- [131] M.Ghioni et al. « Progress in silicon single-photon avalanche diodes ». In: *IEEE J. Sel. Top. Quantum Electron.*, **13** (4) 852-862 (2007). DOI: [10.1109/JSTQE.2007.902088](https://doi.org/10.1109/JSTQE.2007.902088) (cit. on p. 87).

- [132] Y.Musienko et al. « The gain, photon detection efficiency and excess noise factor of multi-pixel Geiger-mode avalanche photodiodes ». In: *Nuclear Inst. and Methods in Physics Research, A* **567** 57-61 (2006). DOI: [10.1016/j.nima.2006.05.214](https://doi.org/10.1016/j.nima.2006.05.214) (cit. on p. 88).
- [133] L.Gruber. « Over saturation behavior of SiPMs at high photon exposure ». In: *Nuclear Inst. and Methods in Physics Research, A* **737** 11-18 (2014). DOI: [10.1016/j.nima.2013.11.013](https://doi.org/10.1016/j.nima.2013.11.013) (cit. on p. 89).
- [134] A.Stoykov et al. « On the limited amplitude resolution of multipixel Geiger-mode APDs ». In: *JINST*, **2** P06005 (2016). DOI: [10.1088/1748-0221/2/06/P06005](https://doi.org/10.1088/1748-0221/2/06/P06005) (cit. on p. 89).
- [135] E.Garutti and Yu.Musienko. « Radiation damage of SiPMs ». In: *Nuclear Inst. and Methods in Physics Research, A* **926** 69-84 (2019). DOI: [10.1016/j.nima.2018.10.191](https://doi.org/10.1016/j.nima.2018.10.191) (cit. on p. 89).
- [136] T.Bretz et al. « Dynamic range measurement and calibration of SiPMs ». In: *JINST*, **11** P03009 (2016). DOI: [10.1088/1748-0221/11/03/P03009](https://doi.org/10.1088/1748-0221/11/03/P03009) (cit. on pp. 89, 90).
- [137] CALICE Collaboration. « Construction and commissioning of the CALICE analog hadron calorimeter prototype ». In: *JINST*, **5** P05004 (2010). DOI: [10.1088/1748-0221/5/05/P05004](https://doi.org/10.1088/1748-0221/5/05/P05004) (cit. on pp. 90, 91).
- [138] K.Abe et al; T2K Collaboration. « The T2K experiment ». In: *Nuclear Inst. and Methods in Physics Research, A* **659** 106-135 (2011). DOI: [10.1016/j.nima.2011.06.067](https://doi.org/10.1016/j.nima.2011.06.067) (cit. on p. 90).
- [139] F.Simon. « Silicon photomultipliers in particle and nuclear physics ». In: *Nuclear Inst. and Methods in Physics Research, A* **926** 85-100 (2019). DOI: [10.1016/j.nima.2018.11.042](https://doi.org/10.1016/j.nima.2018.11.042) (cit. on pp. 90, 91, 94).
- [140] CALICE Collaboration. « Construction and performance of a silicon photomultiplier/extruded scintillator tail-catcher and muon-tracker ». In: *JINST*, **7** P04015 (2012). DOI: [10.1088/1748-0221/7/04/P04015](https://doi.org/10.1088/1748-0221/7/04/P04015) (cit. on p. 91).
- [141] CALICE Collaboration. « Electromagnetic response of a highly granular hadronic calorimeter ». In: *JINST*, **6** P04003 (2011). DOI: [10.1088/1748-0221/6/04/P04003](https://doi.org/10.1088/1748-0221/6/04/P04003) (cit. on pp. 92, 105).
- [142] CALICE Collaboration. « Hadronic energy resolution of a highly granular scintillator-steel hadron calorimeter using software compensation techniques ». In: *JINST*, **7** P09017 (2012). DOI: [10.1088/1748-0221/7/09/P09017](https://doi.org/10.1088/1748-0221/7/09/P09017) (cit. on p. 92).
- [143] CALICE Collaboration. « Performance of the first prototype of the CALICE scintillator strip electromagnetic calorimeter ». In: *Nuclear Inst. and Methods in Physics Research, A* **763** 278-289 (2014). DOI: [10.1016/j.nima.2014.06.039](https://doi.org/10.1016/j.nima.2014.06.039) (cit. on p. 92).
- [144] CALICE Collaboration. « Construction and response of a highly granular scintillator-based electromagnetic calorimeter ». In: *Nuclear Inst. and Methods in Physics Research, A* **887** 150-168 (2018). DOI: [10.1016/j.nima.2018.01.016](https://doi.org/10.1016/j.nima.2018.01.016) (cit. on p. 92).

- [145] CALICE Collaboration. « Track segments in hadronic showers in a highly granular scintillator-steel hadron calorimeter ». In: *JINST*, **8** P09001 (2013). DOI: [10.1088/1748-0221/8/09/P09001](https://doi.org/10.1088/1748-0221/8/09/P09001) (cit. on p. 93).
- [146] CMS Collaboration. « The Phase-2 Upgrade of the CMS Endcap Calorimeter ». In: *Tech. Rep. CERN-LHCC-2017-023, CMS-TDR-019, CERN* (2017). URL: <http://cds.cern.ch/record/2293646> (cit. on p. 93).
- [147] CMS Collaboration. « CMS Technical Design Report for the Phase 1 Upgrade of the Hadron Calorimeter ». In: *Tech. Rep. CERN-LHCC-2012-015, CMS-TDR-010, CERN* (2012). DOI: [10.2172/1151651](https://doi.org/10.2172/1151651) (cit. on p. 93).
- [148] N. Strobbe et al.; CMS Collaboration. « The upgrade of the CMS hadron calorimeter with silicon photomultipliers ». In: *JINST*, **12** (01) C01080 (2017). DOI: [10.1088/1748-0221/12/01/C01080](https://doi.org/10.1088/1748-0221/12/01/C01080) (cit. on p. 93).
- [149] B.Beischer et al. « A high-resolution scintillating fiber tracker with silicon photomultiplier array readout ». In: *Nuclear Inst. and Methods in Physics Research, A* **622** 542-554 (2010). DOI: [10.1016/j.nima.2010.07.059](https://doi.org/10.1016/j.nima.2010.07.059) (cit. on p. 94).
- [150] LHCb Collaboration. « LHCb Tracker Upgrade Technical Design Report ». In: *Tech. Rep. CERN-LHCC-2014-001, LHCb-TDR-015, CERN* (2014). URL: <http://cds.cern.ch/record/1647400> (cit. on p. 94).
- [151] R.Greim et al.; LHCb Collaboration. « A large scintillating fibre tracker for LHCb ». In: *JINST*, **12** (02) C02053 (2017). DOI: [10.1088/1748-0221/12/02/C02053](https://doi.org/10.1088/1748-0221/12/02/C02053) (cit. on p. 94).
- [152] F.Sefkow et al. « Experimental tests of particle flow calorimetry ». In: *Rev. Mod. Phys.* **88** 015003 (2016). DOI: [10.1103/RevModPhys.88.015003](https://doi.org/10.1103/RevModPhys.88.015003) (cit. on p. 95).
- [153] N.Anfimov et al. « Shashlyk EM calorimeter prototype readout by MAPD with superhigh pixel density for COMPASS II ». In: *Nuclear Inst. and Methods in Physics Research, A* **718** 75-77 (2012). DOI: [10.1016/j.nima.2012.11.104](https://doi.org/10.1016/j.nima.2012.11.104) (cit. on p. 95).
- [154] GlueX Collaboration. « First results from the GlueX experiment ». In: *AIP Conference Proceedings* **1735**, 020001 (2016). DOI: [10.1063/1.4949369](https://doi.org/10.1063/1.4949369) (cit. on p. 95).
- [155] GlueX Collaboration. « Characterization of novel Hamamatsu Multi Pixel Photon Counter (MPPC) arrays for the GlueX experiment ». In: *Nuclear Inst. and Methods in Physics Research, A* **732** 431-436 (2013). DOI: [10.1016/j.nima.2013.06.071](https://doi.org/10.1016/j.nima.2013.06.071) (cit. on p. 95).
- [156] F.G.Hartjes and R.Wigmans. « Scintillating plastic fibres for hadron calorimetry ». In: *Nuclear Inst. and Methods in Physics Research, A* **277** 379-385 (1989). DOI: [10.1016/0168-9002\(89\)90766-3](https://doi.org/10.1016/0168-9002(89)90766-3) (cit. on pp. 98, 126).
- [157] V.Chmill et al. « Study of the breakdown voltage of SiPMs ». In: *Nuclear Inst. and Methods in Physics Research, A* **845** 75-77 (2017). DOI: [10.1016/j.nima.2016.04.047](https://doi.org/10.1016/j.nima.2016.04.047) (cit. on p. 98).
- [159] N.Dinu et al. « Temperature and bias voltage dependence of the MPPC detectors ». In: *IEEE Nuc. Sci. Sym. & Med. Imag. Conf.*, 1318-1325 (2010). DOI: [10.1109/NSSMIC.2010.5873750](https://doi.org/10.1109/NSSMIC.2010.5873750) (cit. on p. 104).

- [160] C.R.Crowell and S.M.Sze. « Temperature dependence of avalanche multiplication in semiconductors ». In: *Appl. Phys. Lett.*, **9** (1966) 242 (2004). DOI: [10.1063/1.1754731](https://doi.org/10.1063/1.1754731) (cit. on p. 104).
- [161] B.Dolgoshein. « Silicon Photomultipliers in Particle Physics: Possibilities and Limitations ». In: *The Science and Culture Series, Innovative Detectors for Supercolliders*, 442-456 (2004). DOI: [10.1142/9789812702951_0029](https://doi.org/10.1142/9789812702951_0029) (cit. on p. 109).
- [162] CERN. « Delay Wire Chambers: a users guide ». In: *SL-Note-98-023 (BI)* (1998). URL: <http://cds.cern.ch/record/702443/files/sl-note-98-023.pdf> (cit. on p. 110).
- [164] S.Agostinelli et al. « GEANT4 - a simulation toolkit ». In: *Nuclear Inst. and Methods in Physics Research, A* **506** 250-303 (2003). DOI: [10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8) (cit. on p. 135).
- [165] L.Pezzotti. « Dual readout calorimetry development for future collider experiments ». Master thesis. Università degli Studi di Pavia, 2016. URL: http://www.infn.it/thesis/thesis_dettaglio.php?tid=11792 (cit. on pp. 135, 143, 151).
- [166] R.Santoro. « International Conference on New Photo-Detectors (PD15) (July, 2015) ». In: *Moscow, Troitsk* (2015). URL: <http://indico.inr.ru/event/4/session/9/contribution/52/material/slides/0.pdf> (cit. on p. 145).
- [167] M.Backets et al. « TMVA 4, Toolkit for Multivariate Data Analysis with ROOT ». In: *CERN-OPEN-2007-007* (2009). URL: <https://arxiv.org/abs/physics/0703039v5> (cit. on p. 160).

Websites

- [38] Linear Collider Collaboration. 2019. URL: <http://linearcollider.org> (cit. on p. 22).
- [110] Hamamatsu. 2019. URL: <http://www.hamamatsu.com> (cit. on pp. 73, 98).
- [158] Nuclear Instruments. 2019. URL: <http://www.nuclearinstruments.eu/sipm.html> (cit. on pp. 99, 100).
- [163] Kodak Wratten 2 Filters. 2019. URL: https://www.kodak.com/IT/it/motion/products/lab_and_post_production/kodak_filters/wratten_2_filters/default.htm (cit. on p. 126).

