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# Double transverse-spin asymmetries in Drell–Yan processes with antiprotons

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**Abstract**

We present next-to-leading order predictions for double transverse-spin asymmetries in Drell–Yan dilepton production initiated by proton–antiproton scattering. The kinematic region of the proposed PAX experiment at GSI: $30 \lesssim s \lesssim 200\ \text{GeV}^2$ and $2 \lesssim M \lesssim 7$ GeV is examined. The Drell–Yan asymmetries turn out to be large, in the range 20–40%. Measuring these asymmetries would provide the cleanest determination of the quark transversity distributions.


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*Keywords:* Drell–Yan; Transversity

**1.** The experiments with antiproton beams planned for the next decade in the High-Energy Storage Ring at GSI will provide a variety of perturbative and non-perturbative tests of QCD [1]. In particular, the possible availability of *transversely polarised* antiprotons opens the way to direct investigation of transversity, which is currently one of the main goals of high-energy spin physics [2]. The quark transversity (i.e., transverse polarisation) distributions $\Delta_T q$ were first introduced and studied in the context of transversely polarised Drell–Yan (DY) production [3]; this is indeed the cleanest process probing these quantities. In fact, whereas in semi-inclusive deep-inelastic scattering transversity couples to another unknown quantity, the Collins fragmentation function [4], rendering the extraction of $\Delta_T q$ a not straightforward task, the DY double-spin asymmetry

$$A_{TT}^{\text{DY}} \equiv \frac{\mathrm{d}\sigma^{\uparrow\uparrow} - \mathrm{d}\sigma^{\uparrow\downarrow}}{\mathrm{d}\sigma^{\uparrow\uparrow} - \mathrm{d}\sigma^{\uparrow\downarrow}} = \frac{\Delta_T\sigma}{\sigma_{\text{unp}}} \tag{1}$$

only contains combinations of transversity distributions. At leading order, for instance, for the process $p^\uparrow p^\uparrow \to \ell^+\ell^- X$ one has

$$A_{TT}^{\text{DY}} = a_{TT} \sum_q e_q^2 \big[\Delta_T q(x_1, M^2)\Delta_T \bar{q}(x_2, M^2) + \Delta_T \bar{q}(x_1, M^2)\Delta_T q(x_2, M^2)\big] \times \Big[\sum_q e_q^2 \big[q(x_1, M^2)\bar{q}(x_2, M^2) + \bar{q}(x_1, M^2)q(x_2, M^2)\big]\Big]^{-1}, \tag{2}$$

where $M$ is the invariant mass of the lepton pair, $q(x, M^2)$ is the unpolarised distribution function, and $a_{TT}$ is the spin asymmetry of the QED elementary process $q\bar{q} \to \ell^+\ell^-$. In the dilepton centre-of-mass frame, integrating over the production angle $\theta$, one has

$$a_{TT}(\varphi) = \frac{1}{2}\cos 2\varphi, \tag{3}$$

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where $\varphi$ is the angle between the dilepton direction and the plane defined by the collision and polarisation axes.

Measurement of $p^\uparrow p^\uparrow$ DY is planned at RHIC [5]. It turns out, however, that $A_{TT}^{\mathrm{DY}}(pp)$ is rather small at such energies [6–8], no more than a few percent (similar values are found for double transverse-spin asymmetries in prompt-photon production [9] and single-inclusive hadron production [10]). The reason is twofold: (1) $A_{TT}^{\mathrm{DY}}(pp)$ depends on antiquark transversity distributions, which are most likely to be smaller than valence transversity distributions; (2) RHIC kinematics ($\sqrt{s} = 200$ GeV, $M < 10$ GeV and $x_1 x_2 = M^2/s \lesssim 3 \times 10^{-3}$) probes the low-$x$ region, where QCD evolution suppresses $\Delta_T q(x, M^2)$ as compared to the unpolarised distribution $q(x, M^2)$ [11,12]. The problem may be circumvented by studying transversely polarised proton–*anti*proton DY production at more moderate energies. In this case a much larger asymmetry is expected [6,13,14] since $A_{TT}^{\mathrm{DY}}(p\bar{p})$ is dominated by valence distributions at medium $x$. The PAX Collaboration has proposed the study of $p^\uparrow \bar{p}^\uparrow$ Drell–Yan production in the High-Energy Storage Ring (HESR) at GSI, in the kinematic region $30 \lesssim s \lesssim 200$ GeV$^2$, $2 \lesssim M \lesssim 10$ GeV and $x_1 x_2 \gtrsim 0.1$ [15]. An antiproton polariser for the PAX experiment is currently under study [16]: the aim is to achieve a polarisation of 30–40%, which would render the measurement of $A_{TT}^{\mathrm{DY}}(p\bar{p})$ very promising.

Leading-order predictions for the $p\bar{p}$ asymmetry at moderate $s$ were presented in [13]. It was also suggested there to access transversity in the $J/\psi$ resonance production region, where the production rate is much higher. The purpose of this Letter is to extend the calculations of [13] to next-to-leading order (NLO) in QCD.[1] This is a necessary check of the previous conclusions, given the moderate values of $s$ in which we are interested. We shall see that the NLO corrections are actually rather small and double transverse-spin asymmetries are confirmed to be of order 20–40%.

**2.** The kinematic variables describing the Drell–Yan process are (1 and 2 denote the colliding hadrons)

$$\xi_1 = \sqrt{\tau} e^{y}, \qquad \xi_2 = \sqrt{\tau} e^{-y}, \qquad y = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}, \tag{4}$$

with $\tau = M^2/s$. We denote by $x_1$ and $x_2$ the longitudinal momentum fractions of the incident partons. At leading order, $\xi_1$ and $\xi_2$ coincide with $x_1$ and $x_2$, respectively. The QCD factorisation formula for the transversely polarised cross-section for the proton–antiproton Drell–Yan process is

$$\frac{\mathrm{d}\Delta_T\sigma}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}\varphi} = \sum_q e_q^2 \int_{\xi_1}^{1} \mathrm{d}x_1 \int_{\xi_2}^{1} \mathrm{d}x_2 \big[\Delta_T q\big(x_1, \mu^2\big)\Delta_T q\big(x_2, \mu^2\big) + \Delta_T \bar{q}\big(x_1, \mu^2\big)\Delta_T \bar{q}\big(x_2, \mu^2\big)\big] \frac{\mathrm{d}\Delta_T\hat{\sigma}}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}\varphi}, \tag{5}$$

[1] The results presented here were communicated at the QCD–PAC meeting at GSI (March 2005) and reported by one of us (M.G.) at the Int. Workshop “Transversity 2005” (Como, September 2005) [17].

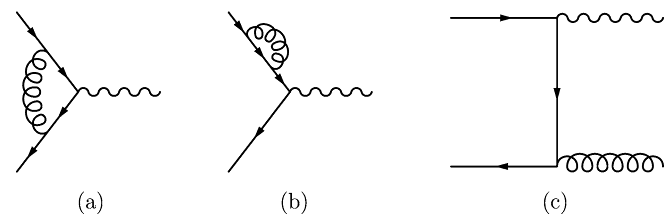


Fig. 1. Elementary processes contributing to the transverse Drell–Yan cross-section at NLO: (a), (b) virtual-gluon corrections and (c) real-gluon emission.

where $\mu$ is the factorisation scale and we take the quark (antiquark) distributions of the antiproton equal to the antiquark (quark) distributions of the proton. Note that, since gluons cannot be transversely polarised (there is no such thing as a gluon transversity distribution for a spin one-half object like the proton), only quark–antiquark annihilation subprocesses (with their radiative corrections) contribute to $\mathrm{d}\Delta_T\sigma$. In Eq. (5) we use the fact that antiquark distributions in antiprotons equal quark distributions in protons, and vice versa. At NLO, i.e., at order $\alpha_s$, the hard-scattering cross-section $\mathrm{d}\Delta_T\hat{\sigma}^{(1)}$, taking the diagrams of Fig. 1 into account, is given by [7]

$$\begin{aligned}
&\frac{\mathrm{d}\Delta_T\hat{\sigma}^{(1),\overline{\mathrm{MS}}}}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}\varphi} \\
&\quad = \frac{2\alpha^2}{9sM} C_F \frac{\alpha_s(\mu^2)}{2\pi} \frac{4\tau(x_1x_2+\tau)}{x_1x_2(x_1+\xi_1)(x_2+\xi_2)} \cos(2\varphi) \\
&\qquad \times \bigg\{ \delta(x_1-\xi_1)\delta(x_2-\xi_2) \\
&\qquad \times \left[\frac{1}{4}\ln^2\frac{(1-\xi_1)(1-\xi_2)}{\tau} + \frac{\pi^2}{4} - 2\right] \\
&\qquad + \delta(x_1-\xi_1)\left[\frac{1}{(x_2-\xi_2)_+}\ln\frac{2x_2(1-\xi_1)}{\tau(x_2+\xi_2)}\right. \\
&\qquad \left. + \left(\frac{\ln(x_2-\xi_2)}{x_2-\xi_2}\right)_+ + \frac{1}{x_2-\xi_2}\ln\frac{\xi_2}{x_2}\right] \\
&\qquad + \frac{1}{2[(x_1-\xi_1)(x_2-\xi_2)]_+} + \frac{(x_1+\xi_1)(x_2+\xi_2)}{(x_1\xi_2+x_2\xi_1)^2} \\
&\qquad - \frac{3\ln\big(\frac{x_1x_2+\tau}{x_1\xi_2+x_2\xi_1}\big)}{(x_1-\xi_1)(x_2-\xi_2)} \\
&\qquad + \ln\frac{M^2}{\mu^2}\bigg[\delta(x_1-\xi_1)\delta(x_2-\xi_2) \\
&\qquad \times \left(\frac{3}{4} + \frac{1}{2}\ln\frac{(1-\xi_1)(1-\xi_2)}{\tau}\right) + \frac{\delta(x_1-\xi_1)}{(x_2-\xi_2)_+}\bigg]\bigg\} \\
&\qquad + [1 \leftrightarrow 2],
\end{aligned} \tag{6}$$

where we have taken the factorisation scale $\mu$ equal to the renormalisation scale. In our calculations we set $\mu = M$.

The unpolarised Drell–Yan differential cross-section can be found, for instance, in [18]; besides the diagrams of Fig. 1, it also includes the contribution of quark–gluon scattering processes.

**3.** To compute the Drell–Yan asymmetries we need an assumption for the transversity distributions, which as yet are completely unknown. We might suppose, for instance, that transversity equals helicity at some low scale, as suggested by confinement models [11] (this is exactly true in the non-relativistic limit). Thus, one possibility is

$$\Delta_T q\left(x, \mu_0^2\right) = \Delta q\left(x, \mu_0^2\right), \tag{7}$$

where typically $\mu_0 \lesssim 1$ GeV. Another possible assumption for $\Delta_T q$ is the saturation of Soffer's inequality [19], namely

$$\left|\Delta_T q\left(x, \mu_0^2\right)\right| = \frac{1}{2}\left[q\left(x, \mu_0^2\right) + \Delta q\left(x, \mu_0^2\right)\right], \tag{8}$$

which represents an upper bound on the transversity distributions.

Since Eqs. (7) and (8) make sense only at very low scales, in practical calculations one has to resort to radiatively generated helicity and number densities, such as those provided by the GRV fits [20]. The GRV starting scale is indeed (at NLO) $\mu_0^2 = 0.40\ \text{GeV}^2$. We should however bear in mind that in the GRV parametrisation there is a sizeable gluon contribution to the nucleon's helicity already at the input scale ($\Delta g$ is of order 0.5). On the other hand, as already mentioned, gluons do not contribute to the nucleon's transversity. Thus, use of Eq. (7) with the GRV parametrisation may lead to substantially underestimating the quark transversity distributions and hence is a sort of "minimal bound" for transversity. Incidentally, the experimental verification or otherwise of the theoretical predictions of $A_{TT}$ based on the low-scale constraints (7), (8) would represent an indirect test of the "valence glue" hypothesis behind the GRV fits. Note too that, although the assumption (7) may, in principle, violate the Soffer inequality, we have explicitly checked that this is not the case with all the distributions we use.

After setting the initial condition (7) or (8), all distributions are evolved at NLO according to the appropriate DGLAP equations (for transversity, see [21]; the numerical codes we use to solve the DGLAP equations are described in [22]). The $u$ sector of transversity is displayed in Fig. 2 for the minimal bound (7) and for the Soffer bound (8).

The transverse Drell–Yan asymmetry $A_{TT}^{\text{DY}}/a_{TT}$, integrated over $M$ between 2 and 3 GeV (i.e., below the $J/\psi$ resonance region), for various values of $s$ is shown in Fig. 3. As can be seen, the asymmetry is of order of 30% for $s = 30\ \text{GeV}^2$ (fixed-target option) and decreases by a factor two for a centre-of-mass energy typical of the collider mode ($s = 200\ \text{GeV}^2$). The corresponding asymmetry obtained by saturating the Soffer bound, that is by using Eq. (8) for the input distributions, is displayed in Fig. 4. As expected, it is systematically larger, rising to over 50% for fixed-target kinematics.

Above the $J/\psi$ peak $A_{TT}^{\text{DY}}/a_{TT}$ appears as shown in Fig. 5, where we present the results obtained with the minimal bound (7). Comparing Figs. 3 and 5, we see that the asymmetry increases at larger $M$ (recall though that the cross-section falls rapidly with growing $M$).

The importance of NLO QCD corrections may be appreciated from Fig. 6, where one sees that the NLO effects hardly modify the asymmetry since the $K$ factors of the transversely polarised and unpolarised cross-sections are similar to each other and therefore cancel out in the ratio. As for the dependence on the factorisation scale $\mu$ (we recall that the results presented in all figures are obtained setting $\mu = M$), we have

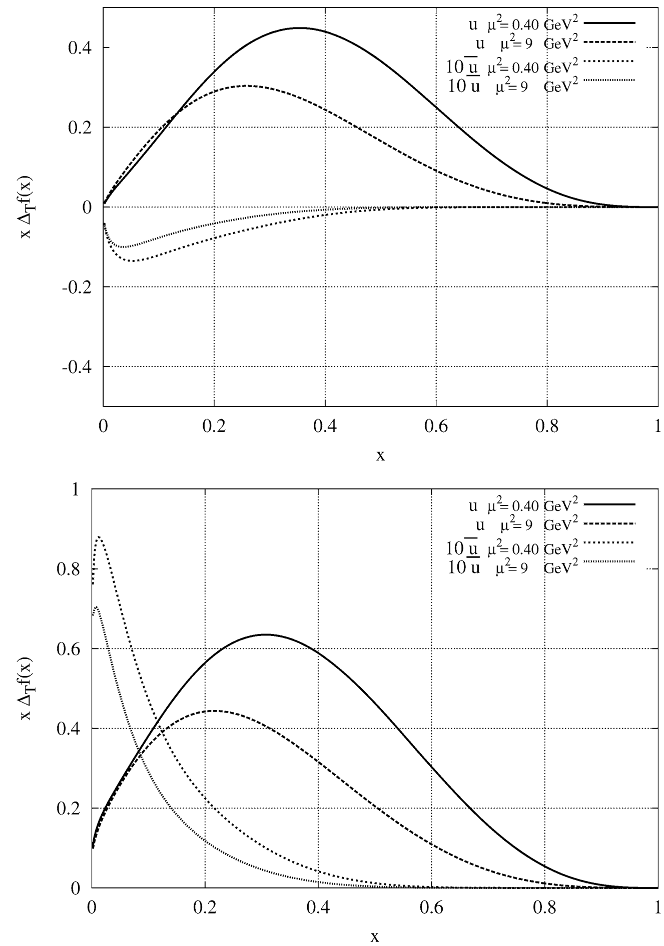


Fig. 2. The $u$ and $\bar{u}$ transversity distributions, as obtained from the GRV parametrisation and Eq. (7), top panel, or Eq. (8), bottom: $x\Delta_T u$ at $\mu^2 = \mu_0^2 = 0.40\ \text{GeV}^2$ (dashed curve) and $\mu^2 = 9\ \text{GeV}^2$ (solid curve); $x\Delta_T \bar{u}$ at $\mu^2 = \mu_0^2 = 0.40\ \text{GeV}^2$ (dotted curve) and $\mu^2 = 9\ \text{GeV}^2$ (dot-dashed curve). Note that the $\bar{u}$ transversity distributions have been multiplied by a factor of 10.

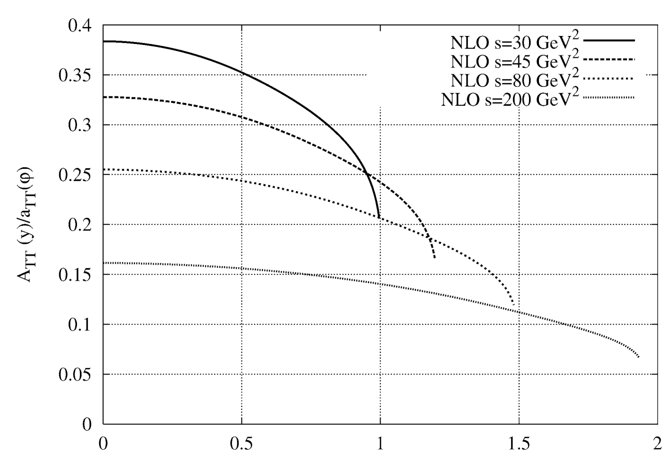


Fig. 3. The NLO double transverse-spin asymmetry $A_{TT}(y)/a_{TT}$, integrated between $M = 2$ GeV and $M = 3$ GeV, for various values of $s$; the minimal bound (7) is used for the input distributions.

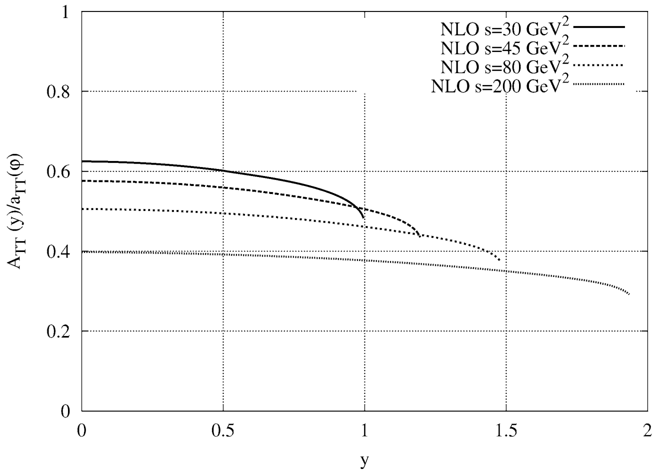


Fig. 4. As Fig. 3, but with input distributions corresponding to the Soffer bound (8).

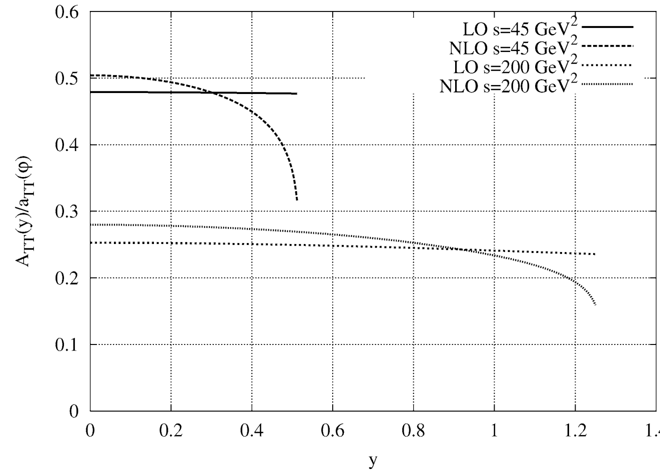


Fig. 6. NLO vs. LO double transverse-spin asymmetry $A_{TT}(y)/a_{TT}$ at $M = 4$ GeV for $s = 45\ \text{GeV}^2$ and $s = 200\ \text{GeV}^2$; the minimal bound (7) is used for the input distributions.

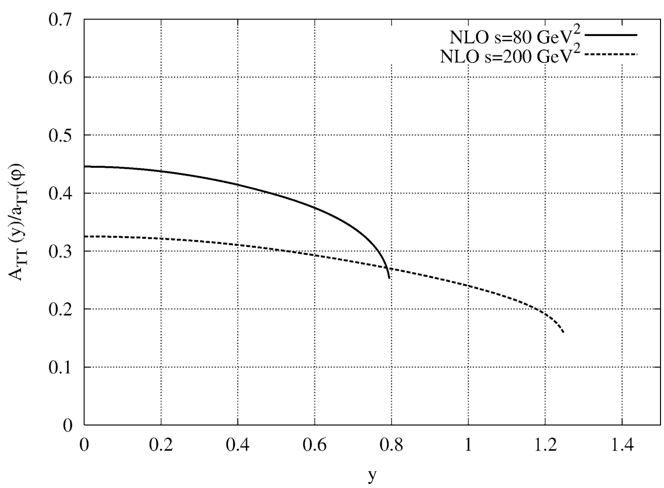


Fig. 5. The NLO double transverse-spin asymmetry $A_{TT}(y)/a_{TT}$, integrated between $M = 4$ GeV and $M = 7$ GeV, for various values of $s$; the minimal bound (7) is used for the input distributions.

repeated the calculations with two other choices ($\mu = 2M$ and $\mu = M/2$). In all cases in the $x$ and $y$ ranges considered the variation was less than 2–3%.

A *caveat* is in order at this point. The GSI kinematics is dominated by the domain of large $\tau$ and large $z = \tau/x_1x_2$, where real-gluon emission is suppressed and where there are powers of large logarithms of the form $\ln(1-z)$, which need to be resummed to all orders in $\alpha_s$ [23]. It turns out that the effects of threshold resummation on the asymmetry $A_{TT}^{\text{DY}}$ in the regime we are considering, although not irrelevant, are rather small (about 10%) if somewhat dependent on the infrared cutoff for soft-gluon emission.

The feasibility of the $A_{TT}$ measurement at GSI has been thoroughly investigated by the PAX Collaboration (see Appendix F of [15]). In collider mode, with a luminosity of $5 \times 10^{30}\ \text{cm}^{-2}\,\text{s}^{-1}$, a proton polarisation of 80%, an antiproton polarisation of 30% and considering dimuon invariant masses down to $M = 2$ GeV, after one year's data taking one expects a few hundred events per day and a statistical accuracy on $A_{TT}$ of 10–20%.

**4.** Before concluding, we briefly comment on the possibility of accessing transversity via $J/\psi$ production in $p\bar{p}$ scattering. It is known that the dilepton production rate around $M = 3$ GeV, i.e., at the $J/\psi$ peak, is two orders of magnitude higher than in the region $M \simeq 4$ GeV. Thus, with a luminosity of $5 \times 10^{30}\ \text{cm}^{-2}\,\text{s}^{-1}$, one expects a number of $p\bar{p} \to J/\psi \to \ell^-\ell^+$ events of order $10^5$ per year at GSI collider energies. This renders the measurement of $A_{TT}$ in the $J/\psi$-resonance region extremely advantageous from a statistical point of view.

As explained in [13], if $J/\psi$ formation is dominated by the $q\bar{q}$ annihilation channel, at leading order the double transverse-spin asymmetry at the $J/\psi$ peak has the same structure as the asymmetry for Drell–Yan continuum production, since the $J/\psi$ is a vector particle and the $q\bar{q}J/\psi$ coupling has the same helicity structure as the $q\bar{q}\gamma^*$ coupling. The CERN SPS data [24] show that the $p\bar{p}$ cross-section for $J/\psi$ production at $s = 80\ \text{GeV}^2$ is about ten times larger than the corresponding $pp$ cross-section, which is a strong indication that the $q\bar{q}$-fusion mechanism is indeed dominant. Therefore, at the $s$ values of interest here ($s \lesssim 200\ \text{GeV}^2$) dilepton production in the $J/\psi$ resonance region can be described in a manner analogous to Drell–Yan continuum production, with the elementary subprocess $q\bar{q} \to \gamma^* \to \ell^-\ell^+$ replaced by $q\bar{q} \to J/\psi \to \ell^-\ell^+$ [25]. Using this model, which successfully accounts for the SPS $J/\psi$ production data at moderate values of $s$, it was found in [13] that the transverse asymmetry at the $J/\psi$ peak is of the order of 25–30%.

At next-to-leading order, due to QCD radiative corrections, one cannot use a point-like $q\bar{q}J/\psi$ coupling, and therefore it is not possible to extend in a straightforward way the model used to evaluate $A_{TT}$ at leading order. Were NLO effects not dominant, as is the case for continuum production, one could still expect the $J/\psi$ asymmetry to be quite sizeable, but this is no more than an educated guess. What we wish to emphasise, however, is the importance of experimentally investigating the $J/\psi$ double transverse-spin asymmetry, which can shed light both on the transversity content of the nucleon and on the mechanism of $J/\psi$ formation (since gluon-initiated hard processes do not contribute to the transversely polarised scattering, the study of $A_{TT}$ in the $J/\psi$ resonance region may give information on the relative weight of gluon and quark–antiquark subprocesses in $J/\psi$ production).

**5.** In conclusion, experiments with polarised antiprotons at GSI will represent a unique opportunity to investigate the transverse polarisation structure of hadrons. The present Letter, which confirms the results of [13], shows that the double transverse-spin asymmetries are large enough to be experimentally measured and therefore represent the most promising observables to directly access the quark transversity distributions.

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