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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: $30 \lesssim s \lesssim 200~\mathrm{GeV}^2$ 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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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

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

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

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

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 θ, one has

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

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where φ 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 $A_{TT}^{\rm DY}(pp)$ 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) $A_{TT}^{\rm DY}(pp)$ 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 $x_1x_2 = M^2/s \lesssim 3\times 10^{-3}$) 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 $A_{TT}^{\rm DY}(p\bar p)$ 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 $30 \lesssim s \lesssim 200\ \mathrm{GeV}^2$, $2 \lesssim M \lesssim 10$ GeV and $x_1x_2 \gtrsim 0.1$ [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 $A_{TT}^{\rm DY}(p\bar p)$ 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/ψ 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, ξ_1 and ξ_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

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

[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].

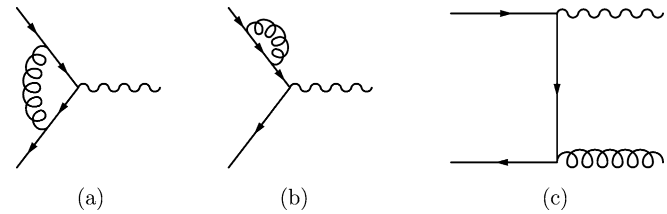

Fig. 1. Elementary processes contributing to the transverse Drell–Yan cross-section at NLO: (a), (b) virtual-gluon corrections and (c) real-gluon emission.

where μ 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 α_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]

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

where we have taken the factorisation scale μ 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