Next-to-leading order QCD corrections to single-inclusive hadron production in transversely polarized \( pp \) and \( \bar{p}p \) collisions

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We present a calculation of the next-to-leading order QCD corrections to the partonic cross sections contributing to single-inclusive high-\( p_T \) hadron production in collisions of transversely polarized hadrons. We use a recently developed projection technique for treating the phase space integrals in the presence of the \( \cos(2\Phi) \) azimuthal-angular dependence associated with transverse polarization. Our phenomenological results show that the double-spin asymmetry \( A_{TT} \) for neutral-pion production is expected to be very small for polarized \( pp \) scattering at RHIC and could be much larger for the proposed experiments with an asymmetric \( \bar{p}p \) collider at the GSI.

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I. INTRODUCTION

The partonic structure of spin-1/2 targets at the leading-twist level is characterized entirely by the unpolarized, longitudinally polarized, and transversely polarized distribution functions \( f, \Delta f, \) and \( \delta f \), respectively [1]. Of these, the “transversity” distributions \( \delta f \) remain virtually unknown. They are defined [1–4] as the differences of probabilities for finding a parton of flavor \( f \) at scale \( \mu \) and light-cone momentum fraction \( x \) with its spin aligned (\( \uparrow \uparrow \)) or anti-aligned (\( \downarrow \uparrow \)) with that of the transversely polarized nucleon:

\[
\delta f(x, \mu) = f_{\uparrow \uparrow}(x, \mu) - f_{\downarrow \uparrow}(x, \mu) . \tag{1}
\]

A program of polarized \( pp \) collisions is now underway at the BNL Relativistic Heavy Ion Collider (RHIC) [5], aiming at further unraveling the spin structure of the proton. Collisions of transversely polarized protons are hoped to give information on transversity through, e.g., the measurement of double-spin asymmetries

\[
A_{TT} = \frac{1}{2} \frac{d\sigma(\uparrow \uparrow) - d\sigma(\downarrow \downarrow)}{d\sigma(\uparrow \uparrow) + d\sigma(\downarrow \downarrow)} = \frac{d\delta\sigma}{d\sigma} \tag{2}
\]

for various reactions with observed produced high-transverse momentum (\( p_T \)) or invariant mass. The best-studied, and perhaps most promising among these, is the Drell-Yan process [2, 6, 7], which offers the largest spin asymmetries but whose main drawback is the rather moderate event rate. Other reactions, such as high-\( p_T \) prompt-photon, pion, or jet production, are much more copious, but suffer from fairly small spin asymmetries [3, 8–11], due to large contributions from gluon-gluon and quark-gluon scattering only present in the unpolarized cross section in the denominator of Eq. (2).

Very recently, it has also been proposed to extract transversity from measurements of \( A_{TT} \) in transversely polarized \( \bar{p}p \) collisions at the planned GSI-FAIR facility [12–14] near Darmstadt, Germany. For later stages of operations, there are plans to have an asymmetric \( \bar{p}p \) collider, with moderate proton and antiproton energies of 3.5 and 15 GeV, respectively. So far, theoretical work has focused on the Drell-Yan process. It was found that the expected spin asymmetries could be very large, possibly reaching several tens of per cents [14–16]. This can be readily understood, because for the GSI kinematics only partons with rather large momentum fractions scatter off each other, and in \( \bar{p}p \) collisions the relevant lowest order (LO) process, \( q\bar{q} \) annihilation, will receive large contributions from valence quarks, which are expected to carry strong polarization. This appears to make the proposed measurements at GSI particularly interesting for learning about transversity.

The theoretical framework for GSI kinematics is somewhat more involved than for RHIC, since perturbative all-order resummations of large logarithmic contributions to the partonic cross sections are particularly important. For the Drell-Yan process, these have been addressed in detail recently in [16]. In any case, information from RHIC and from GSI experiments will be complementary, due to the very different kinematics accessed, and very likely both will be needed to gain sufficient knowledge about the \( \delta f \) over a large range in \( x \).

In this paper, we perform a detailed study of high-\( p_T \) single-inclusive pion production in transversely polarized \( pp \) and \( \bar{p}p \) collisions. In particular, we derive the next-to-leading order (NLO) QCD corrections to the relevant partonic cross sections. In general, these are indispensable for arriving at a firmer theoretical framework for analyzing experimental data in terms of parton densi-
Neglecting all masses, one has the relations
\[ \text{partonic quantities are given by} \]
\[ \text{in obvious notation of the momenta. The corresponding} \]
\[ \text{those for a parent proton even for} \]
\[ \text{dependence associated with transverse polarization [11].} \]
\[ \text{As we shall see, the spin asymmetry for} \]
\[ \text{ties. For the calculation we employ a recently developed} \]
\[ \text{a recently developed} \]
\[ \text{from Drell-Yan and from} \]
\[ \text{are very significant at GSI energies, so that further} \]
\[ \text{that the size of the NLO corrections and the scale depen-} \]
\[ \text{is expected to be much smaller than that for the Drell-} \]
\[ \text{D} \]
\[ \text{is expected to be much smaller than that for the Drell-} \]
\[ \text{Finally,} \]
\[ \text{II. TECHNICAL FRAMEWORK} \]
\[ \text{According to the factorization theorem [18], the fully} \]
\[ \text{use the charge conjugation property} \]
\[ \text{The fact that we are observing a specific hadron in the} \]
\[ \text{Neglecting all masses, one has the relations} \]
\[ \text{The transversity densities in Eq. (3) always refer to} \]
\[ \text{use to regularize the ultraviolet, infrared, and collinear} \]
\[ \text{we will always take as equal for simplicity.} \]
\[ \text{We now give a few technical details of the NLO calcu-} \]
\[ \text{Projection on a definite polarization state for the initial} \]
\[ \text{in dimensional regularization, which we will} \]
\[ \text{Owing to the chirally odd nature of transversity, in our} \]
\[ \text{we will take as equal for simplicity.} \]
\[ \text{The transversity densities in Eq. (3) always refer to} \]
\[ \text{for the correctness of the calculation.} \]
The transverse polarization vectors of the initial hadrons give rise to a characteristic dependence of the cross section on the azimuthal angle $\Phi$ of the observed particle. In the hadronic center-of-mass system (c.m.s.) frame, taking the initial hadrons along the $\pm z$ axis and their spin vectors in $\pm x$ direction, the $\Phi$-dependence is of the form $\cos(2\Phi)$. Integration over $\Phi$ is therefore not appropriate. Keeping $\Phi$ fixed in the NLO calculation is however very cumbersome since standard techniques developed in the literature for performing NLO phase-space integrations rely on the choice of particular reference frames different from the one specified above. In [11] we developed a general projection method that involves integration over all $\Phi$, thereby allowing to keep the benefits of the standard phase space integration techniques.

The trick, and the virtue of our method, is to project out the dependence of the matrix elements on the spin vectors which satisfy $s_i \cdot p_i = s_i \cdot p_b = 0$ and $s_a^2 = s_b^2 = -1$. $\mathcal{F}(p,c,s_a,s_b)$ reduces to $\cos(2\Phi)$ in the hadronic c.m.s. frame. We may, therefore, use $\mathcal{F}(p,c,s_a,s_b)/\pi$ instead of the explicit $\cos(2\Phi)/\pi$ in the “projector” in the integrand of Eq. (7). For any contributing partonic channel we multiply the squared matrix element for transversely polarized initial partons, $\delta[M^2_{ab\rightarrow cX})$, by $\mathcal{F}(p,c,s_a,s_b)/\pi$. The resulting expression may then be integrated over the full azimuthal phase space in a covariant way without producing a vanishing result, unlike the case of $\delta[M^2$ itself; see Ref. [11] for further details. It is crucial here that the other observed (“fixed”) quantities, the hadron’s transverse momentum $p_T$ and pseudorapidity $\eta$, are determined entirely by scalar products $(p_a \cdot p_c)$ and $(p_b \cdot p_c)$, independently of the spin vectors $s_{a,b}$.

Our method becomes particularly convenient for treating the $2 \rightarrow 3$ scattering contributions arising at NLO where one has an additional phase space integral over the second unobserved parton in the final-state. After applying the projection method we can perform all phase space integrations by employing techniques familiar from the corresponding calculations in the unpolarized and longitudinally polarized cases [20, 21]. We note that as a non-trivial check on our calculation we have also integrated all squared matrix elements over the spin vectors without using any projector at all. This amounts to integrating $\cos(2\Phi)$ over all $0 \leq \Phi \leq 2\pi$, and, as expected, the final answer is zero.

The use of dimensional regularization is straightforward in all this. Ultraviolet poles in the virtual diagrams are removed by the renormalization of the strong coupling constant. Infrared singularities cancel in the sum between virtual and real-emission diagrams. After this cancellation, only collinear poles are left. From the factorization theorem it follows that these need to be factored into the parton distribution and fragmentation functions. This is a standard procedure which we have also described in quite some detail in [11, 21]. We use the MS scheme throughout.

After factorization, we arrive at the final result, the finite partonic NLO hard scattering cross sections. There are all in all five subprocesses that contribute for transverse polarization:

\[
qq \rightarrow qX, \\
\bar{q}q \rightarrow qX, \\
\bar{q}q \rightarrow q'X, \\
\bar{q}q \rightarrow qX, \\
qq \rightarrow gX, \\
\quad (9)
\]

where at NLO in each case $X$ denotes a one- or two-parton final state, summed over all possibilities and integrated over its phase space. The first four of these reactions are present at LO already. The corresponding LO transversity cross sections may be found in [8–10, 22]. The last subprocess appears for the first time at NLO. For each of the five subprocesses, the NLO expression for the transversely polarized cross section can be cast into the following form:

\[
\frac{d^3 \delta \sigma^{(1)}_{ab\rightarrow cX}(s, v, w, \mu)}{dv dw d\Phi} = \cos(2\Phi) \left( \frac{\alpha_s(\mu)}{\pi} \right)^2 \left[ \left( A_0 \delta(1 - w) + B_0 \frac{1}{(1 - w)_+} + C_0 \right) \ln \frac{\mu^2}{s} + A \delta(1 - w) + B \frac{1}{(1 - w)_+} + C + D \left( \ln \frac{1 - w}{1 - w} \right)_+ + E \ln w + F \ln v + G \ln(1 - v) \right]
\]
where the “plus”-distribution is defined in the usual way over the interval $[0, 1]$. All coefficients in Eq. (10) are functions of $v$ and $w$, except those multiplying the distributions $\delta(1-w), 1/(1-w), \ln(1-w)/(1-w)$, which may be written as functions just of $v$. Terms with distributions are present only for the subprocesses that already contribute at the Born level. The coefficients are available upon request as a FORTRAN code from the authors.

$$
+ H \ln(1 - w) + I \ln(1 - vw) + J \ln(1 - v + vw) + K \ln \frac{w}{1 - w} + L \ln \frac{1 - w}{1 - vw} + M \frac{\ln(1 - v + vw)}{1 - w},
$$

where the “plus”-distribution is defined in the usual way over the interval $[0, 1]$. All coefficients in Eq. (10) are functions of $v$ and $w$, except those multiplying the distributions $\delta(1-w), 1/(1-w), \ln(1-w)/(1-w)$, which may be written as functions just of $v$. Terms with distributions are present only for the subprocesses that already contribute at the Born level. The coefficients are available upon request as a FORTRAN code from the authors.

**III. PHENOMENOLOGICAL RESULTS**

We now present some phenomenological results for single-inclusive pion production in transversely polarized $pp$ collisions at RHIC ($\sqrt{s} = 200$ and $500$ GeV) and asymmetric $p\bar{p}$ collisions at the planned GSI-FAIR facility with proton and antiproton energies of $3.5$ GeV and $15$ GeV, respectively.

Since nothing is known experimentally about transversity so far, we need to model the $\delta f$ for our study. Guidance is provided by the Soffer inequality [23]

$$2|\delta q(x)| \leq q(x) + \Delta q(x) \quad (11)$$

which gives bounds for each $\delta f$. As in [10, 11] we utilize this inequality by saturating the bound at some low input scale $\mu_0 \approx 0.6$ GeV, choosing all signs to be positive, and using the NLO (LO) GRV [24] and GRSV (“standard scenario”) [25] densities $q(x, \mu_0)$ and $\Delta q(x, \mu_0)$, respectively. For $\mu > \mu_0$ the transversity densities $\delta f(x, \mu)$ are then obtained by evolving them at LO or NLO. We refer the reader to [7, 10] for more details on our model distributions. We note that we will always perform the NLO (LO) calculations using NLO (LO) parton distribution functions and the two-loop (one-loop) expression for $\alpha_s$. We use the pion fragmentation functions of Ref. [26] which has both a LO and an NLO set. They provide a very good description of the recent RHIC data on unpolarized neutral-pion production [27].

Figure 1 shows our estimates for the transversely polarized single-inclusive pion production cross sections in LO and NLO for $\sqrt{s} = 200$ and $500$ GeV collisions at RHIC. The LO results have been scaled by a factor of 0.01. The shaded bands represent the changes if the scale $\mu$ is varied in the range $p_T \leq \mu < 4p_T$. The lower panel shows the ratios of the NLO and LO results for both c.m.s. energies.

The lower part of the Figure 1 displays the so-called “$K$-factor”, defined as usual as the ratio of the NLO to the LO cross section, for the scale choice $\mu = 2p_T$. Except for small $p_T$, where the NLO corrections lead to a significant reduction of the cross section, the $K$-factor turns out to be rather moderate and close to unity. It is known that the $K$-factor for the unpolarized cross section is significantly larger than one at RHIC energies, see, e.g., Fig. 4 in Ref. [21] for $\sqrt{s} = 200$ GeV, mostly because of large corrections found for gluon-initiated partonic channels. Therefore, one expects that the double-spin asymmetry $A_{T}T$ at RHIC will decrease when going from LO to NLO. Indeed, as Fig. 2 shows, this is the case. Here we used the CTEQ6M (CTEQ6L1) [28] set of unpolarized parton distributions to calculate the corresponding NLO (LO) unpolarized cross section. We have chosen the scale $\mu = p_T$ which leads to the largest cross sections in Fig. 1. We also indicate in Fig. 2 an estimate of the statistical
where \( E_P, E_p \) are the antiproton and proton energies. The rapidity interval we use is roughly symmetric in c.m.s. pseudorapidities, \( |\eta| \lesssim 1.75 \).

Figure 3 shows our results for the unpolarized (left) and transversely polarized (right) cross sections at NLO and LO, as functions of \( p_T \). For the calculation in the unpolarized case we have chosen the GRV [24] parton distributions. This choice is motivated by our ansatz for the transversity distributions, for which we had also used the GRV densities when saturating the Soffer inequality, Eq. (11). Unlike at RHIC energies, at \( \sqrt{S} = 14.5 \) GeV and \( p_T \) of several GeV, rather large momentum fractions \( x_{a,b} \) of the partons are probed in Eq. (3), where the polarized and unpolarized parton densities for a given parton type are expected to become similar [29]. It then appears most sensible to use the same parton distributions in the unpolarized case that we used when modeling the transversity densities. In this way we avoid any artificial effects in the NLO corrections and \( A_{TT} \) induced by a mismatch in the \( x \to 1 \) behavior of the parton densities used in the calculation.

The shaded bands in the upper panels of Fig. 3 again indicate the uncertainties due to scale variation in the range \( p_T \lesssim \mu \lesssim 4p_T \). One can see that for both, the unpolarized and the polarized cross sections, the scale dependence does not really improve from LO to NLO. This is a characteristic feature in low-order perturbative calculations of cross sections for lower fixed-target energies, suggesting that corrections beyond NLO are still very significant. Indeed, it was recently shown [30] that for inclusive-hadron production in the fixed-target regime certain double-logarithmic corrections to the partonic cross sections are important at each order of perturbation theory, and need to be resummed to all orders to achieve an adequate theoretical description. Such a resummation will be required in particular in the case we are considering here and would be very desirable for the future, along with a study of power corrections. We emphasize that when the proposed measurements of \( A_{TT} \) will be performed, it will be crucial to have precise measurements also of the unpolarized cross section, in order to test the theoretical framework. Only if the theory is sufficiently understood will data on \( A_{TT} \) become useful for determining transversity. Similar comparisons of data [27] and theoretical calculations for the unpolarized neutral-pion cross section at RHIC have shown an excellent agreement even down to fairly low pion transverse momenta, which has indeed provided much confidence that the calculations based on partonic hard-scattering are adequate, so that spin asymmetries measured at RHIC determine the spin-dependent parton distributions of the proton.

The lower parts of Fig. 3 display the corresponding \( K \)-factors at scale \( \mu = 2p_T \). We note that these decrease as \( p_T \) increases, which is related entirely to the different behavior of the LO and NLO parton distributions at large \( x \). Had we chosen the same parton distributions at LO and NLO, the \( K \)-factors would actually slightly increase with \( p_T \), as a result of the large double-logarithmic cor-
FIG. 3: Unpolarized (left) and transversely polarized (right) single-inclusive neutral-pion production cross sections at LO and NLO at the GSI. The LO results have been scaled by a factor of 0.01. The shaded bands represent the theoretical uncertainty if the factorization/renormalization scale $\mu$ is varied in the range $p_T \leq \mu \leq 4p_T$. The lower panel shows the ratios of the NLO and LO results in each case, using $\mu = 2p_T$.

FIG. 4: Upper bounds for the transverse double-spin asymmetry $A_{TT}$ for single-inclusive neutral-pion production in LO and NLO at GSI-FAIR. The “error bars” indicate the expected statistical accuracy for bins in $p_T$ (see text).

IV. CONCLUSIONS

We have presented in this paper the complete NLO QCD corrections for the partonic hard-scattering cross sections relevant for the double-spin asymmetry $A_{TT}$ for single-inclusive high-$p_T$ pion production in collisions of transversely polarized hadrons. This asymmetry could be a tool to determine the transversity distributions of the nucleon. Our calculation is based on a largely analytical evaluation of the NLO partonic cross sections, and we have used a projection technique for treating the characteristic azimuthal-angle dependence introduced by the transverse spin vectors.

In our phenomenological studies we found that the spin asymmetry $A_{TT}$ is expected to be very small in $pp$ collisions at RHIC and even decreases when going from LO to NLO, due to a larger $K$-factor in the unpolarized case. We have also studied $A_{TT}$ for possibly forthcoming transversely polarized $\bar{p}p$ collisions in an asymmetric collider mode at the GSI-FAIR facility. Here, the spin asymmetry may be much larger, but it will be crucial in the future to investigate the effects of all-order resummations of large Sudakov logarithms. Detailed measurements of the unpolarized cross sections will be essential for testing the applicability of the theoretical framework at the moderate c.m.s. energies available at GSI-FAIR.

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