Next-to-leading order QCD corrections
to one hadron-production
in polarized \( pp \) collisions at RHIC

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We calculate the next-to-leading order QCD corrections to the spin-dependent cross section for single-inclusive hadron production in hadronic collisions. This process will be soon studied experimentally at RHIC, providing a tool to unveil the polarized gluon distribution \( \Delta g \). We observe a considerably improvement in the perturbative stability for both unpolarized and polarized cross sections. The NLO corrections are found to be non-trivial, resulting in a reduction of the asymmetry.

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I. INTRODUCTION

In the last years measurements of the spin asymmetries \( A_1^N \) \((N = p, n, d)\) in longitudinally polarized deep-inelastic scattering (DIS) have provided much new information on the spin structure of the nucleon \([1]\). Recent theoretical leading order (LO) and next-to-leading order (NLO) \([2, 3, 4, 5, 6, 7, 8, 9]\) analyses of the data sets demonstrate, however, that these are not sufficient to accurately extract the spin-dependent quark \((\Delta q = q^+ - q^-)\) and gluon \((\Delta g = g^+ - g^-)\) densities of the nucleon. This is true in particular for \( \Delta g \) which could not yet be accurately studied experimentally.

As a result of this, it turns out that the \( x \)-shape of \( \Delta g \) seems to be hardly constrained at all by the DIS data, even though a tendency towards a fairly large positive total gluon polarization, \( \int_0^1 \Delta g(x, Q^2 = 10 \text{ GeV}^2) dx \sim 1 \), was found \([2, 3, 4, 5, 6, 7, 8, 9]\). The measurement of \( \Delta g \) thus remains one of the most interesting challenges for future spin physics experiments. In selecting suitable processes for a determination of \( \Delta g \), it is crucial to pick those that, unlike DIS, have a direct gluonic contribution already at the lowest order. Here, one thinks first in the place of high-\( p_T \) reactions in nucleon–nucleon collisions, which have been tremendously important in the unpolarized case to constrain the unpolarized gluon density.

At the moment, the most eagerly awaited experimental tool for the 'spin physics' community is the RHIC\([10]\) collider at BNL, at which first runs in a proton–proton mode with longitudinally polarized beams are expected to be accomplished this year. The center-of-mass energy for these \( pp \) collisions will be ranging between 200 and 500 GeV, with luminosities (rising with energy) between 320 and 800 \( \text{pb}^{-1} \), respectively. One expects about 70% polarization for each beam. Such conditions look extremely favorable for studying the spin asymmetries for all kinds of high-\( p_T \) \( pp \) processes that are sensitive to the gluon density, such as hadron, jet, prompt-photon, or heavy-flavor production. Hadrons and jets could be the key to \( \Delta g \): at \( \sqrt{S} = 200(500) \text{ GeV} \), hadrons (and jets) will be extremely copiously produced, and the corresponding cross-sections will show a strong sensitivity to \( \Delta g \) thanks to the dominance of the \( gg \) and \( qg \) initiated subprocesses in some kinematical ranges. While the STAR detector permits a clear determination of jets, in the case of PHENIX, where the limited coverage in rapidity does not allow to observe jets, hadrons (and especially pions) can be used as jet surrogates \([1, 2]\).

In order to make reliable quantitative predictions for a high-energy process, it is crucial to determine the NLO QCD corrections to the Born approximation. Quite in general, the key issue here is to check the perturbative stability of the process considered, i.e. to examine the extent to which the NLO corrections affect the cross sections and (in spin physics) the spin asymmetries relevant for experimental measurements. Only if the corrections are under control can a process that shows good sensitivity to, say, \( \Delta q \) at the lowest order be regarded as a genuine probe of the polarized gluon distribution and be reliably used to extract it from future data. Furthermore, the inclusion of extra partons in the NLO perturbative calculation also allows to improve the matching between the theoretical calculation and the realistic experimental conditions.

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The calculation of the NLO QCD corrections to hadron production by polarized hadrons is the purpose of this paper. Such a calculation needs the one-loop $2 \to 2$ and tree-level $2 \to 3$ polarized amplitudes as input. Fortunately, these amplitudes are already known \cite{[12],[13]}. Furthermore, several independent methods to calculate any infrared-safe quantity in any kind of hard unpolarized collision are at present available in the literature \cite{[14],[15],[16]}. The formalism of Ref. \cite{[16]} has been used in Ref. \cite{[18]} to construct a Monte Carlo code that can calculate any jet infrared-safe observable in hadron–hadron unpolarized collisions and extended, in Ref. \cite{[13]}, to the polarized case (photo-production of jets has been studied in \cite{[20]}). In the present paper, we extend the method of Refs. \cite{[16],[18]} to the case of one single hadron inclusive observables. As a result, we will present a customized code, with which it will be possible to calculate any infrared-safe quantity corresponding to one-hadron production to NLO accuracy, for both polarized and unpolarized collisions. It is worth noticing that the code presented here can be used to compute the ‘resolved’ contribution to hadron photo-production as well. This complements the calculation of the ‘direct’ component presented in Ref. \cite{[21]}.

This paper is organized as follows: in section II we describe the formalism and the main ingredients of the calculation. In section III we study the perturbative stability of the NLO results by looking at the scale dependence and $K$-factors. In section IV we present the results for the asymmetries at RHIC and study the possibility of extracting $\Delta g$ from $pp \to \pi$ data. Section V contains the conclusions.

II. FORMALISM AND MAIN INGREDIENTS

The factorization theorem \cite{[22]} allows to write the cross section for the one hadron production in hadronic collisions as

$$d\sigma_{pp \to hX} = \sum_{f_1, f_2, f} \int dx_1 dx_2 dz f_{1f_1}^H(x_1, \mu_F^2) f_{2f_2}^H(x_2, \mu_F^2) \times d\hat{\sigma}^{f_1 f_2 \to f X'}(x_1 p_1, x_2 p_2, p_h/z, \mu_F, \mu_R) \times D_H^f(z, \mu_R^2),$$

where $H_1$ and $H_2$ are the colliding particles with momentum $p_1$ and $p_2$, respectively, $h$ is the outgoing hadron with momentum $p_h$ and the sum in Eq. (1) runs over all possible initial and final partonic states. The parton distributions $f_{if_i}^H$ are evaluated at the factorization scale $\mu_F$, the fragmentation functions at the scale $\mu_F$ and the coupling constant, appearing explicitly in the perturbative expansion of the partonic cross section, at the renormalization scale $\mu_R$. The analogous of Eq. (1) for the polarized cross section is obtained by replacing the parton distributions and the partonic cross section by its polarized expressions, $\Delta f_{if_i}^H$, and $d\Delta \hat{\sigma}^{f_1 f_2 \to f X'}$, respectively.

As usual, the (longitudinally polarized) asymmetry is defined by the ratio between the polarized and unpolarized cross sections

$$A_{LL}^A = \frac{d\Delta \sigma}{d\sigma}.$$

The method we have used for computing the NLO corrections and implementing the results in a Monte-Carlo like code has been introduced and extensively discussed in Refs. \cite{[16],[18]}, and in Ref. \cite{[13]}. We refer the reader to those references for details. It is worth noticing that with one single code we can compute unpolarized and polarized cross sections, since the structure of the corrections is the same in both cases.

As stated in the introduction, there is hardly any experimental information on the spin-dependent gluon density $\Delta g$ at present. In contrast, the quark densities are far better constrained by the existing data from inclusive polarized DIS. This is particularly true for the polarized $u$ and $d$ quark densities, which come out rather similar in all theoretical analyses performed so far. The spin-dependent sea-quark distributions seem less well constrained; however, they are of minor importance for our studies.

In our phenomenological analysis we will try to cover as much as possible of the wide range of polarized parton densities allowed by the present DIS data: this is especially relevant for the gluon density, as we will discuss below. For the polarized parton densities, we will use the six sets of Ref. \cite{[4]} (DS1±, DS2±, DS3±), obtained by constraining the first moment of the polarized gluon densities in three different ways. The first moment of the gluon of DS3 is the largest and about three times larger than for DS1, which has the smallest gluon. The index ± refers to the different extremes assumptions done on the sea quark densities $\Delta \bar{u} = \pm \Delta \bar{d}$. Furthermore, we will also use the ‘standard’ set of Ref. \cite{[6]} (from now on, referred
to as GRV98, for comparison. All these distributions are available at both LO and NLO, the latter corresponding to the \( \overline{\text{MS}} \) scheme used also in our calculation of the NLO partonic cross section.

In this work, we will mostly concentrate on the phenomenology of pion production at RHIC with a center-of-mass energy of \( \sqrt{\mathcal{S}} = 200 \text{ GeV} \) and transverse momenta in the region of 4 GeV < \( p_T < 20 \text{ GeV} \). This implies that the polarized parton distributions will mainly be probed in the \( x \)-range 0.05 ≤ \( x \) ≤ 0.3 and at typical scales \( Q^2 \) of the order of 25 GeV². Figure 1 shows the NLO polarized quark and gluon densities of the different sets we are going to use. It becomes clear that there is indeed a wide range of possible gluon distributions compatible with present polarized DIS data. As mentioned earlier, in the quark sector, most of the distributions are very similar. The spin-dependent sea-quark densities (not shown in Fig. 1) differ more strongly among the various sets, but have a small impact on the cross sections in this kinematical region. In conclusion, since the variations in the quark sector are much smaller than the ones for gluons, we can expect that any differences between predictions for the polarized cross sections (or asymmetries) that are found when using different polarized parton density sets, are to be attributed to the sensitivity of the observable to \( \Delta g \).

The size of radiative QCD corrections to a given unpolarized hadronic process is often displayed in terms of a ‘\( K \)-factor’ which represents the ratio of the NLO over LO results. In the calculation of the numerator of \( K \) one obviously has to use NLO-evolved parton densities. As far as the denominator is concerned, a natural definition requires the use of LO-evolved parton densities. In the polarized case, a problem arises for such a definition. This is particularly true when the cross section is dominated by the gluon distribution: Since the data hardly constrain the gluon density, very different results for \( \Delta g \) can emerge if the fit is performed at LO or at NLO. Therefore, the ‘\( K \)-factor’ for one hadron production, defined using LO parton densities in the denominator could be artificially large or small merely from the fact that the gluon is at present so ill-constrained, and not because of a ‘genuine’ effect from higher order partonic corrections.

In order to avoid this problem, we will follow the definition introduced to perform the analysis of the results for jet production in polarized collisions at NLO [19], i.e., by defining the ‘\( K \)-factor’ as the ratio between the NLO and the ‘Born’ cross section, where the latest corresponds to the use of NLO-evolved parton densities (and 2-loop expression for \( \alpha_s \)) when evaluating the lowest-order partonic cross sections in the denominator. Nevertheless, it is important to remember that the ‘\( K \)-factor’ is not a physical quantity and just provides a number to ‘quantify’ the effect of the higher order corrections.

In the unpolarized case, we will use the GRV98 parton distributions [23]. Differences of the order of 10% in the cross section are observed when the more recent CTEQ [24] or MRST [25] distributions are used. Nevertheless, since both DS and GRV sets of polarized distributions used GRV98 as the reference set in the unpolarized case, either to impose positivity constraints or to define the measured asymmetries, we will restrict the analysis to the GRV98 set.

The other input needed in Eq. (1) corresponds to the fragmentation functions (FF). Several sets of FF have been released in the last years [26, 27, 28, 29], as the result of QCD analyses of all \( e^+e^- \rightarrow h \) available data. As it is well known, \( e^+e^- \) data can provide information on the combination \( D_q + D_{\bar{q}} \) in the quark sector and only a weak constrain on the gluon fragmentation function, which enters at NLO or through the \( Q^2 \) evolution. A comparison of two different analysis can be found in [27]. In particular, large differences are observed between the BKK [25] and Kretzer [28] distributions for the gluon in the whole range of \( z \) and in the quark case at large \( z \) (see Fig. 7 of [27] for details).

The lack of separation between ‘favored’ and ‘unfavored’ quark fragmentation functions, and the large uncertainties on the distributions result on the reduction of the predictive power of pQCD calculations in hadronic collisions. Besides the large differences than can arise in the computed cross section when different sets of FF are used, it is not possible to compute observables separately for, say, \( \pi^+ \) and \( \pi^- \): only cross sections for the sum \( \pi^+ + \pi^- \) can be computed with the FF obtained from fits to \( e^+e^- \) data.

An approach to solve the last problem is attempted in Kretzer’s FF: a \((1-z)\) suppression for the ‘unfavored’ fragmentation functions, with respect to the ‘favored’ ones, is assumed at the low initial scale \( \mu_0^2 = 0.4 \text{ GeV}^2 \). Within this assumption, a full separation between quark flavors is provided, showing a good agreement with the available semi-inclusive DIS data. Furthermore, the fit by Kretzer relies on the same values of \( \lambda_{QC} \) used by the GRV98, DS and GRV sets, allowing to perform a fully consistent analysis in the case of hadronic collisions. Therefore, we will present results for hadron production at RHIC using the set of fragmentation functions presented in Ref. [27].

Finally, it should be noticed that an analytical NLO calculation exists for the case of unpolarized hadronic collisions [30] since long time. We have compared numerically to the code presented in [30] finding excellent agreement. This provides a very important test on our calculation and, furthermore, on the structure of the code that we will also use to compute the polarized cross section.

III. PERTURBATIVE STABILITY

A reliable error estimate on our NLO results requires some knowledge on the size of the uncalculated higher-order terms. The best we can do, before higher-order terms are computed, is to study the dependence of the full NLO results on the renormalization and factorization
FIG. 2: Scale dependence of NLO and Born unpolarized cross sections. The scales are varied around the default value \( p_T \) as indicated in the text. The LO results have been rescaled by a factor 0.1.

FIG. 3: Scale dependence of NLO and Born polarized cross sections. The scales are varied around the default value \( p_T \) as indicated in the text. The LO results have been rescaled by a factor 0.1.

scales.

Although physical observables are obviously independent of \( \mu \), theoretical predictions do have such a dependence, arising from the truncation of the perturbative expansion at a fixed order in the coupling constant \( \alpha_s \). A large dependence on the scales, therefore, implies a large theoretical uncertainty. In order to show how the scale dependence is substantially reduced once the next-to-leading order corrections are included we will compare to the Born result (with a very similar scale dependence to the LO one). For some observables it might occur that there is a partial cancellation in the scale dependence when all scales are varied simultaneously, either at NLO or at the Born level, and a larger dependence is observed when the scales are varied independently. Therefore, we will look at the scale dependence of the cross section when the scales are varied either simultaneously or independently, with the others fixed at a default value in the last case.

We begin by presenting the results for the production of \( \pi^+ + \pi^- \) in unpolarized collisions at RHIC with \( \sqrt{s} = 200 \) GeV. The kinematics limits of the PHENIX detector (\(|\eta| < 0.35\)) have been imposed, but very similar results, concerning the perturbative stability, are obtained for the case of STAR (with \(|\eta| < 1\)).

In Figure 2 we show both NLO and Born unpolarized cross sections computed at different scales. We take as the default scales \( \mu_R = \mu_F = \mu_F = \mu = p_T \) and compare to the cases when the renormalization and factorization scales are varied by a factor of 2 (up and down when the scales are varied independently, and up when they are varied simultaneously) with respect to the default one. As can be observed there is a considerable reduction in the scale dependence, showing an improvement in the perturbative stability for all the scales relevant to this process.

Nevertheless, even though of the considerable improvement, it is worth noticing that the scale dependence is still rather large at NLO, of the order of 30% or more, and certainly larger than for jet production [19]. Actually, the scale dependence can be much larger for other choices of parton distributions and fragmentation functions. This issue will be studied in more detail in a future publication [34].

We move now to the polarized cross section. To avoid the proliferation of curves, we concentrate here on the case of the DS2+ set of polarized pdfs. Similar results are obtained with other distributions.

As can be observed in Figure 3, the reduction is the scale dependence is even more noticeable than in the unpolarized case. A similar situation has been already observed for other observables in hadron collisions, like jets [10], prompt-photon [31] and heavy quark production [32], and should be attributed to the less singular behavior of both polarized parton densities and partonic cross sections.

We finish by presenting the \( K \)-factors for both polarized and unpolarized collisions in Fig. 4. As discussed in the previous section, \( K \)-factors are defined by the ratio of the NLO and Born cross sections, with all scales fixed to \( \mu = p_T \). As can be observed, the corrections are larger for the unpolarized cross section than for the polarized, resulting in (about) a 30% reduction of the asymmetry, for both PHENIX and STAR. The situation is very similar to what has been observed in the case of jet production in polarized hadronic collisions [19].
All scales have been fixed to \( \mu = p_T \) for parton densities are reasonably well known. Partonic initial states in the unpolarized case, where the distribution by looking at the relevance of the different variables, as shown in Figure 6. The results correspond to the ratio between the contribution of the cross section of the gluon distribution in the unpolarized cross section, where the parton densities are reasonable well known.

This is shown on the left-hand side of Figure 5 again for \( \pi^+ + \pi^- \) production at PHENIX with \( \sqrt{s} = 200 \) GeV. All scales have been fixed to \( \mu = p_T \) and \( R \) corresponds to the ratio between the contribution of the cross section by a given partonic initial state and the full one, both computed to NLO accuracy. As can be observed, the cross section is dominated by the \( qg \) initial state at low \( p_T \), with an increasing contribution of the \( gg \) channel for larger transverse momentum. Considering the relevance of the gluon distribution in the unpolarized cross section, we can expect a large sensitivity on \( \Delta g \) in the polarized case. The right-hand side of Figure 5 corresponds to a similar ratio, but in this case, to compare the relevance of the contribution of the final state (fragmenting) partons. Except at very low \( p_T \), the quark fragmentation completely dominates the cross section. It is worth noticing that the situation can change considerably when other sets of fragmentation functions are used.

Before moving to the results for the asymmetries it is interesting to find out the range in \( x \) and \( z \) covered by RHIC measurement. This can be studied by looking at the dependence of the unpolarized cross section on those variables, as shown in Figure 3. The results correspond to the NLO integrated cross section for \( p_T \) larger than 4 GeV and 10 GeV. As can be observed, at \( \sqrt{s} = 200 \) GeV, the cross section is mostly sensitive to the parton distributions in the range \( 0.05 < x < 0.3 \) and to the fragmentation functions at large \( 0.2 < z < 0.8 \). It should be noticed that, unfortunately, this is the region where the uncertainties on both fragmentation and (unpolarized) parton distributions are considerably large.

We thus turn to the study of the dependence of the asymmetries on the polarized parton densities, as a way to determine the sensitivity on the polarized gluon distribution.

We begin with the asymmetry for \( \pi^+ + \pi^- \) production at PHENIX with \( \sqrt{s} = 200 \) GeV. Since the coverage in rapidity is rather small, we just concentrate on the \( p_T \) distribution. The NLO results, obtained using the sets of distributions enumerated in Section 2, are shown in Fig. 7.

To estimate the minimum value of the asymmetry observable at RHIC, we use the well-known formula

\[
(A_{LL}^*)_{\min} = \frac{1}{P} \frac{1}{\sqrt{\sigma L \epsilon}}
\]

where \( L \) is the integrated luminosity, \( P \) is the polarization of the beam, and the factor \( \epsilon \leq 1 \) accounts for experimental efficiencies; \( \sigma \) is the unpolarized cross section integrated over a small range in transverse momentum (\( p_T \) bin). The quantity defined in Eq. (2) is plotted as ‘error-bars’ in Fig. 7 for \( \epsilon = 1 \), \( P = 0.7 \), a \( p_T \)-bin size of 2 GeV and two scenarios for the integrated luminosities \( L = 7 \text{ pb}^{-1} \) and \( 100 \text{ pb}^{-1} \). From the figure we see that the asymmetry defined in Eq. (2) is measurable if the polarized parton densities are as described by all of the sets considered here. Furthermore, it is clear that even with the low integrated luminosity expected to be collected during the first run of RHIC with longitudinally polarized beams (\( \sim 7 \text{ pb}^{-1} \)), it will be possibly to reasonably estimate the size of the asymmetries \( \Delta g \) from the first \( p_T \) bins. Notice that the pattern of the asymmetries computed with different polarized distributions follows closely the one showed in Fig. 7 indicating an almost linear dependence on the gluon density and confirming the relevance of the \( gg \) partonic initial state also for the polarized cross section.
FIG. 6: Unpolarized cross section distributions in $x \equiv \sqrt{x_1 x_2}$ and $z$.

Smaller asymmetries are obtained for the $\sqrt{s} = 500$ GeV scenario. Nevertheless, the reduction in the asymmetry is compensated by a large increase in the cross section, allowing the measurement of the asymmetry up to larger values of $p_T$.

Using charged hadrons as jets surrogates allows to investigate whether searching for particular hadron in the final state provides a larger asymmetry. In this paper we concentrate in the cases of $\pi^+$ and $\pi^-$, within the approximation for the fragmentation functions discussed before.

In Fig. 8 we show the NLO asymmetries computed with the DS sets for PHENIX with $\sqrt{s} = 200$ GeV. The estimate for the minimum observable asymmetry has been obtained assuming an integrated luminosity of $L = 100 \text{ pb}^{-1}$. As can be observed, the asymmetries are considerably increased (about a factor of 2) with respect to the case of $\pi^+ + \pi^-$, while the minimum observable asymmetry only increases by, roughly, a $\sqrt{2}$ factor. The measurement of $\pi^+$ production could provide an even more powerful tool to extract the polarized gluon distributions, after the uncertainties on flavor separation of the fragmentation functions are reduced.

Finally, we move to the case of $\pi^-$ production presented in Fig. 9. The asymmetries turn out to be much smaller than in the other cases, reaching a zero around $p_T = 10 \text{ GeV}$ and becoming negative for larger values of the transverse momentum of the pions. Furthermore, the sensitivity of the asymmetry on $\Delta g$ is also considerably reduced, becoming very difficult to extract it from such a measurement.

It is possible to understand the differences between the asymmetries for $\pi^+$ and $\pi^-$ production on simple physical basis. The main contribution to the polarized cross section, at least regarding the terms depending on the gluon density, appears with the following combination of parton distributions and fragmentation functions

$$\Delta g \left( \Delta u D_u^u + \Delta d D_d^u \right).$$

In the kinematical range relevant for RHIC measurements, $\Delta u$ is found to be positive, while $\Delta d$ negative, with $|\Delta d/\Delta u| < 1$. Furthermore, for $\pi^+$ the ‘favored’ and ‘unfavored’ fragmentation functions obey $D_u^u > D_d^u$, while the opposite occurs for $\pi^-$. In the case of the $\pi^+ + \pi^-$ production, both fragmentation functions are the same. Therefore, for $\pi^+$ the combination $(\Delta u D_u^u + \Delta d D_d^u)$ reaches its maximum, thus increasing the dependence of the asymmetry on the polarized gluon density, while for $\pi^-$ can be zero, becoming the asymmetry dominated by other initial states, like $qq$.

Finally, it should be remarked that there are still large uncertainties on the estimates presented in this paper, mostly due to the lack of precise knowledge on the fragmentation functions. Nevertheless, those uncertainties could be considerably reduced by using the data on hadron production collected at RHIC running with unpolarized beams. Including these data on a global fit allows to define a safe procedure to extract the fragmentation functions needed to compute the measurable asymmetries in the polarized case.
V. CONCLUSIONS

We have computed the next-to-leading order QCD corrections to the spin-dependent cross section for single-inclusive hadron production in hadronic collisions. The calculation is implemented in a Monte-Carlo like code that allows to compute any infrared-safe quantity corresponding to one-hadron production to NLO accuracy, for both polarized and unpolarized collisions.

Using the code, we have investigated the phenomenological implications for pion production at RHIC. We find that the scale dependence is considerably reduced when the NLO corrections are included. Also the corrections are found to be non-trivial: $K$ factors are larger for the unpolarized cross section than for the polarized one, resulting in a reduction of the asymmetry at NLO. The possibility of looking at charged pions in the final state is also studied, finding that $\pi^+$ and $\pi^0$ are the most convenient channels for the determination of the polarized gluon density at values of $x$ between 0.05 and 0.3. One hadron production at RHIC provides an excellent tool for the extraction of $\Delta g$, being possible to obtain a reasonable estimate of the size of the polarized gluon distribution just from the first run with longitudinally polarized beams to be performed in the next few months.

Note Added

As we completed this manuscript, we became aware of a calculation for the same process being performed by B. Jäger, M. Stratmann and W. Vogelsang. We have compared our results numerically finding good agreement.

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