RBRC-295

BNL-69508

arXiv:hep-ph/0211248 v1 15 Nov 2002

NLO QCD Corrections to A_{LL}^{π}

Barbara Jäger*, Marco Stratmann* and Werner Vogelsang†

*Inst. for Theor. Physics, Univ. of Regensburg, D-93040 Regensburg, Germany
†RBRC and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, U.S.A.

Abstract. We present a calculation for single-inclusive large-p_T pion production in longitudinally polarized pp collisions in next-to-leading order QCD. The corresponding double-spin asymmetry A_{LL}^{π} for this process will soon be used at BNL-RHIC to measure Δg.

THEORETICAL FRAMEWORK

Very inelastic pp collisions with longitudinally polarized beams at the BNL-RHIC will open up unequaled possibilities to measure the so far elusive polarized gluon density Δg. RHIC has the advantage of operating at high energies ($\sqrt{S} = 200$ and 500 GeV), where the underlying theoretical framework, i.e., perturbative QCD, is expected to be under good control. In addition, it offers various different channels in which Δg can be studied, such as prompt-γ, heavy flavor, jet or inclusive-hadron production [1, 2]. In this way, RHIC will provide the best source of information on Δg for a long time to come.

The basic concept that underlies most of spin physics at RHIC is the factorization theorem. It states that large momentum-transfer reactions may be factorized at a scale μ_F into long-distance pieces that contain the desired information on the spin structure of the nucleon in terms of its *universal* parton densities, such as Δg, and parts that are short-distance and describe the hard interactions of the partons. The latter can be evaluated using perturbative QCD. The factorization scale μ_F is not further specified by the theory but usually chosen to be of the order of the hard scale in the reaction.

In the following, we consider the spin-dependent cross section

$$d\Delta\sigma \equiv \frac{1}{2}\left[d\sigma^{++} - d\sigma^{+-}\right] \ , \tag{1}$$

where the superscripts denote the helicities of the protons in the scattering, for the reaction $pp \to \pi X$, where the pion is at high transverse momentum p_T, ensuring large momentum transfer. The statement of the factorization theorem is then

$$\begin{aligned} d\Delta\sigma \ &= \ \sum_{a,b,c} \int dx_a \int dx_b \int dz_c \, \Delta f_a(x_a,\mu_F)\, \Delta f_b(x_b,\mu_F) D_c^{\pi}(z_c,\mu_F') \\ &\quad \times d\Delta\hat{\sigma}_{ab}^{c}(x_a P_A, x_b P_B, P_\pi/z_c, \mu_R, \mu_F, \mu_F') \ , \end{aligned} \tag{2}$$

where the sum is over all contributing partonic channels $a + b \to c + X$, with $d\Delta\hat{\sigma}_{ab}^{c}$ the associated partonic cross section, defined in complete analogy with Eq. (1). Besides

the factorization scale μ_F for the initial-state partons $\Delta f_{a,b}$, there is also a factorization scale μ_F' for the absorption of long-distance effects into the parton-to-pion fragmentation functions D_c^π. The renormalization scale μ_R in (2) is associated with the running of α_s.

It is planned for the coming RHIC run (early 2003) to attempt a first measurement of

$$A_{LL}^\pi = \frac{d\Delta\sigma}{d\sigma} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} \tag{3}$$

for high-p_T pion production. The main underlying idea here is that the spin asymmetry A_{LL}^π is very sensitive to Δg through the contributions from polarized quark-gluon and gluon-gluon scatterings. In general, a leading-order (LO) estimate of (2) or (3) merely captures the main features, but does not usually provide a quantitative understanding. For instance, the dependence on the unphysical scales μ_F, μ_F', and μ_R is expected to be much reduced when going to higher orders in the perturbative expansion. Hence, only with knowledge of the next-to-leading order (NLO) QCD corrections can one reliably extract information on the parton distribution functions from the reaction. A NLO calculation of A_{LL}^π has been completed very recently [3], and here we briefly sketch the results; for details, see [3]. We note that the PHENIX collaboration has recently presented first, still preliminary, results for the *un*polarized cross section for $pp \to \pi^0 X$ at $\sqrt{S} = 200$ GeV, which are well described by a NLO QCD calculation [4].

The partonic cross sections $d\Delta\hat{\sigma}_{ab}^c$ in (2) have to be summed over all final states (excluding c which fragments) and integrated over the entire phase space of X. The LO results, which have been known for a long time [5], are obtained from evaluating all tree-level $2 \to 2$ QCD scattering diagrams. At NLO, we have $\mathcal{O}(\alpha_s)$ corrections to the LO reactions, and also additional new processes, giving rise to 16 different channels in total, like $qq \to qX$, $qg \to gX$, etc. At intermediate stages the NLO calculation will necessarily show singularities that represent the long-distance sensitivity. In addition, for those processes that are already present at LO, real $2 \to 3$ and virtual one-loop $2 \to 2$ contributions will individually have infrared (IR) singularities that only cancel in their sum. Virtual diagrams will also produce ultraviolet (UV) poles that need to be removed by the renormalization of the strong coupling constant at a scale μ_R. We choose $n = 4 - 2\varepsilon$ dimensional regularization to make these singularities manifest. Subtractions of poles will generally be made in the $\overline{\text{MS}}$ scheme. We use the HVBM prescription [6] to describe polarizations of particles in n dimensions.

At $\mathcal{O}(\alpha_s^3)$, virtual corrections, which we have calculated adopting two different methods, only contribute through their interference with the Born diagrams. Firstly, one could make use of known $\overline{\text{MS}}$-renormalized one-loop vertex and self-energy insertions as given in [7]. Only the UV-finite box diagrams have to be calculated from scratch. The second approach makes use of the fact that helicity amplitudes for all one-loop $2 \to 2$ QCD scattering diagrams were presented in [8]. These results will not immediately yield the answer for the HVBM prescription but the transformation is straightforward.

In the $2 \to 3$ contributions, the two unobserved partons need to be integrated over their entire phase space which we perform *analytically*. In this way the final answer is much more amenable to a numerical evaluation, giving stable results in a short time. This may become important when experimental data will become available, and one is aiming to extract Δg from them within a "global analysis" [9]. Phase space integrations

are organized best in the rest frame of the two unobserved partons. Extensive partial fractioning of the matrix elements then always leads to a "master integral" which can be done analytically. Singularities when the invariant mass of the unobserved partons vanishes are made manifest with help of the usual "+"-distributions.

All genuine IR singularities cancel in the sum of all contributions. However, the limit $\varepsilon \to 0$ still cannot be taken as a result of collinear divergencies. These remaining poles need to be factored into the bare parton distribution and fragmentation functions, depending on whether their origin was in the initial or final state. This standard procedure introduces the factorization scales μ_F and μ_F' in Eq. (2). We note that we have simultaneously computed also the NLO corrections for the unpolarized case, where we fully agree at an *analytical level* with results available in the literature [10]. This provides an extremely powerful check on the correctness of all our calculations.

Finally, we note that the same NLO calculation was presented in [11] based on MC phase space integration techniques. Such an approach has the advantage of being very flexible as it may be used for any IR-safe observable, with any experimental cut. However, the numerical integrations are delicate and time-consuming. Early comparisons show very good agreement of the numerical results.

NUMERICAL RESULTS

For our numerical calculations we assume the same kinematic coverage as in the unpolarized PHENIX measurement mentioned above [4]: $\sqrt{S} = 200\,\text{GeV}$, pion transverse momenta in the range $2 \leq p_T \leq 13$ GeV, and pseudorapidities integrated over $|\eta| \leq 0.38$. We also always take into account that the pion measurement is at present possible only over half the azimuthal angle. To calculate the NLO/LO polarized cross section (2) we use the spin-dependent GRSV parton densities ("GRSV-std") and the pion fragmentation functions of [13]. To investigate the sensitivity of A_{LL}^{π} to Δg, we also use a set, for which Δg is assumed to be particularly large ("GRSV-max"). For the NLO (LO) unpolarized cross section, we use the CTEQ5M (CTEQ5L) [14] densities.

Figure 1 shows our results for the unpolarized and polarized cross sections at NLO and LO, where we have chosen the scales $\mu_R = \mu_F = \mu_F' = p_T$. The lower part of the figure displays the "K-factor", $K = d(\Delta)\sigma^{\text{NLO}}/d(\Delta)\sigma^{\text{LO}}$. One can see that in the unpolarized case the corrections are roughly constant and about 50% over the p_T-region considered. In the polarized case, we find generally smaller corrections which become of similar size as those for the unpolarized case only at the high-p_T end. The cross section for p_T-values smaller than about 2 GeV is outside the domain of perturbative calculations as indicated by rapidly increasing NLO corrections and, therefore, is not considered here.

Figure 2 shows the improvement in scale dependence of the spin-dependent cross section when going from LO to NLO. In each case the shaded bands indicate the uncertainties from varying the unphysical scales in the range $p_T/2 \leq \mu_R = \mu_F = \mu_F' \leq 2p_T$. The solid lines are for the choice where all scales are set to p_T. One can see that the scale dependence indeed becomes much smaller at NLO.

Results for A_{LL}^{π} are given in Fig. 3. We have again chosen all scales to be p_T. As expected from the larger K-factor for the unpolarized cross section shown in Fig. 1, the

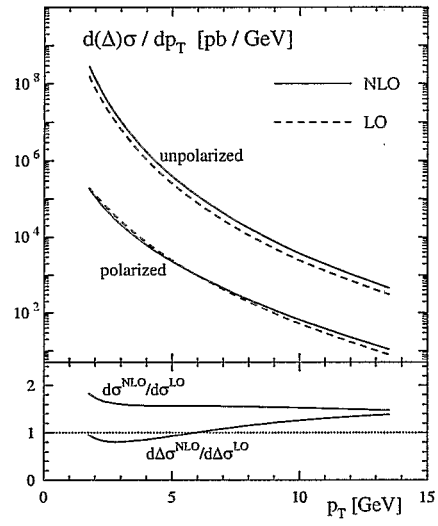

FIGURE 1. Unpolarized and polarized π^0 production cross sections in NLO (solid) and LO (dashed) at $\sqrt{S} = 200$ GeV. The lower panel shows the K-factor in each case. Figure taken from [3].

asymmetry is somewhat smaller at NLO than at LO, showing that inclusion of NLO QCD corrections is rather important for the analysis of the data in terms of Δg.

We also conclude from the figure that there are excellent prospects for determining $\Delta g(x)$ from A_{LL}^{π} measurements at RHIC: the asymmetries found for the two different sets of polarized parton densities, which mainly differ in the gluon density, show marked differences, much larger than the expected statistical errors in the experiment, indicated in the figure. The latter may be estimated by the formula $\delta A_{LL}^{\pi} = 1/(P^2\sqrt{\mathscr{L}\sigma_{\text{bin}}})$, where P is the polarization of one beam, $\mathscr{L}$ the integrated luminosity, and σ_{bin} the unpolarized

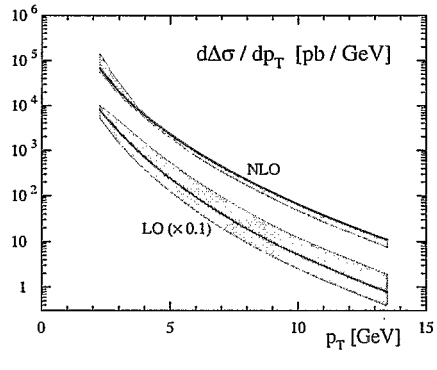

FIGURE 2. Scale dependence of the polarized cross section for π^0 production at LO and NLO [3] in the range $p_T/2 \leq \mu_R = \mu_F = \mu_F' \leq 2p_T$. We have rescaled the LO results by 0.1 to separate them better from the NLO ones. In each case the solid line corresponds to the choice where all scales are set to p_T.

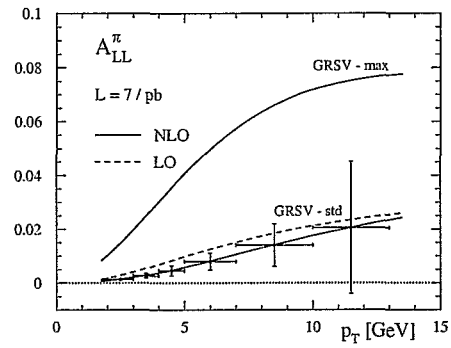

FIGURE 3. Spin asymmetry for π^0 production in NLO (solid lines). The dashed line shows the asymmetry at LO for the GRSV "standard" set. The "error bars" indicate the expected statistical accuracy targeted for the upcoming run of RHIC (see text). Figure taken from [3].

cross section integrated over the p_T-bin for which the error is to be determined. We have used very moderate values $P = 0.4$ and $\mathscr{L} = 7$/pb, which are targets for the coming run.

To conclude, we have presented the results of a largely analytical computation of the NLO partonic hard-scattering cross sections relevant for the spin asymmetry A^{π}_{LL} for high-p_T pion production in longitudinally polarized hadron-hadron collisions. The asymmetry turns out to be a promising tool to provide first information on Δg even for the rather moderate luminosities targeted for the coming run with polarized protons at RHIC.

B.J. is supported by the European Commission IHP program under contract HPRN-CT-2000-00130. W.V. is grateful to RIKEN, Brookhaven National Laboratory and the U.S. Department of Energy (contract number DE-AC02-98CH10886) for providing the facilities essential for the completion of this work.

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