# CALCULATIONS OF SINGLE-INCLUSIVE CROSS SECTIONS AND SPIN ASYMMETRIES IN PP SCATTERING\*

WERNER VOGELSANG

Physics Department and RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, U.S.A. E-mail: wvogelsang@bnl.gov

We present calculations of cross sections and spin asymmetries in single-inclusive reactions in pp scattering. We discuss next-to-leading order predictions as well as all-order soft-gluon threshold resummations.

#### 1. Introduction

Single-inclusive reactions in pp scattering, such as  $pp \to \gamma X$ ,  $pp \to \pi X$ ,  $pp \rightarrow \text{jet } X$ , play an important role in QCD. At sufficiently large produced transverse momentum,  $p_T$ , QCD perturbation theory (pQCD) can be used to derive predictions for these reactions. Since high  $p_T$  implies large momentum transfer, the cross section may be factorized at leading power in  $p_T$  into convolutions of long-distance pieces representing the structure of the initial hadrons, and parts that are short-distance and describe the hard interactions of the partons. The long-distance contributions are universal, that is, they are the same in any inelastic reaction, whereas the shortdistance pieces depend only large scales and, therefore, can be evaluated using QCD perturbation theory. Because of this, single-inclusive cross sections offer unique possibilities to probe the structure of the initial hadrons in ways that are complementary to deeply-inelastic scattering. At the same time, they test the perturbative framework, for example, the relevance of higher orders in the perturbative expansion and of power-suppressed contributions to the cross section.

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Of special interest is the case when the initial protons are polarized. At RHIC, one measures spin asymmetries for single-inclusive reactions, in order to investigate the spin structure of the nucleon <sup>1</sup>. A particular focus here is on the gluon polarization in the nucleon,  $\Delta g \equiv g^{\uparrow} - g^{\downarrow}$ .

In the following, we will present some theoretical predictions for cross sections and spin asymmetries for single-inclusive reactions. We will first discuss the double-longitudinal spin asymmetries  $A_{\rm LL}$  for pion and jet production at RHIC and their sensitivities to  $\Delta g^{2,3}$ . In the second part, we will give results for new calculations <sup>4</sup> of the unpolarized cross section for  $pp \to \pi^0 X$  in the fixed-target regime, which show a greatly improved description of the available experimental data.

## 2. Spin asymmetries for $pp \to (\pi^0, \text{ jet}) X$ at RHIC

We consider the double-spin asymmetry

$$A_{\rm LL} \equiv \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \equiv \frac{d\Delta\sigma}{d\sigma} , \qquad (1)$$

where the superscripts denote the helicities of the initial protons. According to the factorization theorem the spin-dependent cross section  $\Delta\sigma$  can be written in terms of the spin-dependent parton distributions  $\Delta f$  as

$$\frac{d\Delta\sigma}{dp_T d\eta} = \sum_{a,b} \Delta f_a(x_a,\mu) \otimes \Delta f_b(x_b,\mu) \otimes \frac{d\Delta\hat{\sigma}_{ab}}{dp_T d\eta}(x_a,x_b,p_T,\eta,\mu) , \quad (2)$$

where the symbols  $\otimes$  denote convolutions and where the sum is over all contributing partonic channels. We have written Eq. (2) for the case of jet production; for pion production there is an additional convolution with a pion fragmentation function. As mentioned above, the parton-level cross sections may be evaluated in QCD perturbation theory:

$$d\Delta\hat{\sigma}_{ab} = d\Delta\hat{\sigma}_{ab}^{(0)} + \frac{\alpha_s}{\pi} d\Delta\hat{\sigma}_{ab}^{(1)} + \dots \quad , \tag{3}$$

corresponding to "leading order" (LO), "next-to-leading order" (NLO), and so forth. The NLO corrections for the spin-dependent cross sections for inclusive-hadron and jet production were published in  $^{2,5}$  and  $^{3,6}$ , respectively. They are crucial for making reliable quantitative predictions and for analyzing the forthcoming RHIC data in terms of spin-dependent parton densities. The corrections can be sizable and they reduce the dependence on the factorization/renormalization scale  $\mu$  in Eq. (2). In case of jet production, NLO corrections are also of particular importance since it is only at NLO that the QCD structure of the jet starts to play a role.

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Figure 1. NLO spin asymmetry  $^2$  for  $\pi^0$  production, using several GRSV polarized parton densities  $^7$  with different gluon polarizations.

Figure 1 shows NLO predictions for the spin asymmetry  $A_{\rm LL}$  for high  $p_T$  pion production for collisions at  $\sqrt{S} = 200$  GeV at RHIC. We have used various sets of polarized parton densities of <sup>7</sup>, which mainly differ in  $\Delta g$ . As one can see, the spin asymmetry strongly depends on  $\Delta g$ , so that measurements of  $A_{\rm LL}$  at RHIC should give direct and clear information. The "error bars" in the figure are uncertainties expected for measurements with an integrated luminosity of 3/pb and beam polarization P=0.4. We note that PHENIX has already presented preliminary data <sup>8</sup> for  $A_{\rm LL}$ . We also mention that the figure shows that at lower  $p_T$  the asymmetry is not sensitive to the sign of  $\Delta g$ . This is related to the dominance of the gg scattering channel which is approximately quadratic in  $\Delta g$ . In fact it can be shown that  $A_{\rm LL}$  in leading-power QCD can hardly be negative at  $p_T$ of a few GeV <sup>9</sup>. One may obtain better sensitivity to the sign of  $\Delta g$  by expanding kinematics to the forward rapidity region.

Figure 2 shows predictions for the spin asymmetry  $A_{LL}$  for high- $p_T$  jet production. The gross features are rather similar to the pion asymmetry, except that everything is shifted by roughly a factor two in  $p_T$ . This is due to the fact that a pion takes only a certain fraction of ~  $\mathcal{O}(50\%)$  of the outgoing parton's momentum, so that the hard scattering took place at roughly twice the pion transverse momentum. A jet, however, will carry the full transverse momentum of a produced parton.

We emphasize that PHENIX and STAR have presented measurements <sup>10</sup> of the unpolarized cross section for  $pp \to \pi^0 X$ . These are well described by the corresponding NLO QCD calculations <sup>2,5</sup>, providing con-

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Figure 2. Same as Fig. 1, but for inclusive jet production <sup>3</sup> at RHIC.

fidence that the NLO pQCD hard-scattering framework is indeed adequate in the RHIC domain. This is in contrast to what was found in comparisons <sup>11</sup> between NLO theory and data for inclusive-hadron production taken in the fixed-target regime. We will turn to this issue next.

#### 3. Threshold resummation for inclusive-hadron production

One may further improve the theoretical calculations by an all-order resummation of large logarithmic corrections to the partonic cross sections <sup>4</sup>. At partonic threshold, when the initial partons have just enough energy to produce a high-transverse momentum parton (which subsequently fragments into the observed pion) and a massless recoiling jet, the phase space available for gluon bremsstrahlung vanishes, resulting in large logarithmic corrections to the partonic cross section. For the rapidity-integrated cross section, partonic threshold is reached when  $\hat{x}_T \equiv 2\hat{p}_T/\sqrt{\hat{s}} = 1$ , where  $\sqrt{\hat{s}}$ is the partonic center-of-mass (c.m.) energy, and  $\hat{p}_T$  is the transverse momentum of the produced parton fragmenting into the hadron. The leading large contributions near threshold arise as  $\alpha_s^k \ln^{2k} \left(1 - \hat{x}_T^2\right)$  at the kth order in perturbation theory. Sufficiently close to threshold, the perturbative series will be only useful if such terms are taken into account to all orders in  $\alpha_s$ , which is achieved by threshold resummation <sup>12</sup>. This resummation has been derived for a number of cases of interest, to next-to-leading logarithmic (NLL) order, in particular also for jet production  $^{13}$  which proceeds through the same partonic channels as inclusive-hadron production.

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The larger  $\hat{x}_T$ , the more dominant the threshold logarithms will be. Since  $\hat{s} = x_a x_b S$ , where  $x_{a,b}$  are the partonic momentum fractions and  $\sqrt{S}$  is the hadronic c.m. energy, and since the parton distribution functions fall rapidly with increasing  $x_{a,b}$ , threshold effects become more and more relevant as the hadronic scaling variable  $x_T \equiv 2p_T/\sqrt{S}$  goes to one. This means that the fixed-target regime with 3 GeV  $\leq p_T \leq 10$  GeV and  $\sqrt{S}$  of 20–30 GeV is the place where threshold resummations are expected to be particularly relevant and useful.

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The resummation is performed in Mellin-N moment space, where the logarithms  $\alpha_s^k \ln^{2k} (1 - \hat{x}_T^2)$  turn into  $\alpha_s^k \ln^{2k}(N)$ , which then exponentiate. For inclusive-hadron production, because of the color-structure of the underlying Born  $2 \rightarrow 2$  QCD processes, one actually obtains a *sum* of exponentials in the resummed expression. Details may be found in <sup>4</sup>. Here, we only give a brief indication of the qualitative effects resulting from resummation. For a given partonic channel  $ab \rightarrow cd$ , the leading logarithms exponentiate in N space as

$$\hat{\sigma}_{ab\to cd}^{(res)}(N) \propto \exp\left[\frac{\alpha_s}{\pi} \left(C_a + C_b + C_c - \frac{1}{2}C_d\right) \ln^2(N)\right] , \qquad (4)$$

where

$$C_g = C_A = N_c = 3$$
,  $C_q = C_F = (N_c^2 - 1)/2N_c = 4/3$ . (5)

This exponent is clearly positive for each of the partonic channels, which means that the soft-gluon effects will lead to an enhancement of the cross section. Indeed, as may be seen from Fig. 3, resummation dramatically increases the cross section in the fixed-target regime. The example we give is a comparison of NLO and NLL resummed predictions at  $\sqrt{S} = 31.5$  GeV with the data of E706 <sup>14</sup> at that energy. We have used the "KKP" set of pion fragmentation functions <sup>15</sup>, and the parton distributions of <sup>16</sup>. We finally note that the results shown in Fig. 3 are also interesting with respect to the size of power corrections to the cross section. Resummation may actually suggest the structure of nonperturbative power corrections. For a recent study of this for single-inclusive cross sections, see <sup>17</sup>.

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Figure 3. NLO and NLL resummed <sup>4</sup> results for the cross section for  $pp \to \pi^0 X$  for E706 kinematics. Results are given for three different choices of scales,  $\mu = \zeta p_T$ , where  $\zeta = 1/2, 1, 2$ . Data are from <sup>14</sup>.

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