Single spin asymmetries, unpolarized cross sections and
the role of partonic transverse momentum

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Abstract

Partonic intrinsic transverse momentum can be essential for the explanation of large single spin asymmetries in hadronic reactions in the framework of perturbative QCD. The status of an ongoing program investigating in a consistent way the role of intrinsic transverse momentum both in unpolarized and polarized processes is discussed. We compute inclusive cross sections for hadron and photon production in hadronic collisions and for Drell-Yan processes; the results are compared with available experimental data in several different kinematical situations.

In the last years a lot of experimental and theoretical activity has been devoted to the study of transverse single spin asymmetries (SSA) in hadronic collisions and in semi-inclusive DIS. In fact, perturbative QCD (pQCD) with ordinary collinear partonic kinematics leads to negligible values for these asymmetries, as soon as the relevant scale of the process under consideration becomes large. There are however several experimental results which seem to contradict this expectation; two well known examples are: the large transverse Λ polarization measured in unpolarized hadronic collisions; the large SSA observed in the process \( p^+ p \rightarrow π X \). A possible way out from this situation comes from extending the collinear pQCD formalism with the inclusion of spin and partonic intrinsic transverse momentum, \( k_∥ \), effects. This leads to the introduction of a new class of spin and \( k_∥ \) dependent partonic distribution (PDF) and fragmentation (FF) functions, describing fundamental properties of hadron structure.

The role of \( k_∥ \) effects in inclusive hadronic reactions has been extensively studied also in the calculation of unpolarized cross sections. It has been shown that, particularly at moderately large \( p_T \) (which is the region where SSA are measured to be large) these effects can be relevant and may help in improving the agreement between experimental results and pQCD (at LO and NLO) calculations, which often underestimate the data.

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Based on these considerations, in this contribution we present a preliminary account of an ongoing program which aims to describe consistently both polarized and unpolarized cross sections (and SSA) for inclusive particle production in hadronic collisions at large energies and moderately large $p_T$, using LO pQCD with the inclusion of intrinsic transverse momentum effects. Our main goal is not to fit the cross sections as well as possible (including NLO contributions, etc.), but rather to show that in our LO approach they are reproduced up to an overall factor of 2-3, compatible with expected NLO K-factors and scale dependences, which reasonably cancel out in SSA and are then out of our present interest.

In a pQCD approach at LO and leading twist with inclusion of spin and $k_\perp$ effects, the unpolarized cross section for the inclusive process $A B \rightarrow C X$ reads

$$d\sigma \propto \sum_{a,b,c} \hat{f}_{a/A}(x_a, k_{\perp a}) \otimes \hat{f}_{b/B}(x_b, k_{\perp b}) \otimes d\hat{\sigma}_{c\rightarrow d}^{ab-c\rightarrow d}(x_a, x_b, k_{\perp a}, k_{\perp b}) \otimes \hat{D}_{C/c}(z, k_{\perp c})$$

(1)

with obvious notations. A similar expression holds for the numerator of a transverse SSA (\propto d\Delta^N \sigma/d\sigma), substituting for the polarized particle involved the corresponding unpolarized PDF (or FF) with the appropriate polarized one, $\Delta^N f$ or $\Delta^N D$. At leading twist there are four new spin and $k_\perp$ dependent part functions to take into account:

$$\Delta^N f_{q/p}(x, k_\perp) = \hat{f}_{q/p}(x, k_\perp) - \hat{\sigma}_{q/p}(x, k_\perp); \quad \Delta^N f_{\bar{q}/p}(x, k_\perp) = \hat{f}_{\bar{q}/p}(x, k_\perp) - \hat{\sigma}_{\bar{q}/p}(x, k_\perp)$$

(2)

$$\Delta^N D_{h/q} (z, k_\perp) = \hat{D}_{h/q}(z, k_\perp) - \hat{\sigma}_{h/q}(z, k_\perp); \quad \Delta^N D_{\bar{h}/q} (z, k_\perp) = \hat{D}_{\bar{h}/q}(z, k_\perp) - \hat{\sigma}_{\bar{h}/q}(z, k_\perp)$$

(3)

two in the PDF, Eq. (2), and two in the FF, Eq. (3); the first functions in Eqs. (2),(3) are respectively the function introduced by Boer [3] and the so-called “polarizing” FF.

The unpolarized PDF and FF are given in a simple factorized form, and the $k_\perp$ dependent part is usually taken to have a Gaussian shape:

$$\hat{f}_{a/A}(x, k_{\perp a}) = f_{a/A}(x) \frac{\beta^2}{\pi} e^{-\beta^2 k_{\perp a}^2}; \quad \hat{D}_{q}(z, k_{\perp q}) = D_{q}(z) \frac{\beta^2}{\pi} e^{-\beta^2 k_{\perp q}^2}$$

(4)

where the parameter $\beta$ ($\beta'$) is related to the average partonic (hadronic) $k_\perp$ by the simple relation $1/\beta(\beta'') = \langle k_{\perp a(h)}^2 \rangle^{1/2}$. Similar expressions are adopted for the polarized PDF and FF of Eqs. (2),(3).

Using this approach, we have studied the unpolarized cross section for several hadronic processes, analyzing a large sample of available data in different kinematical situations: i) The Drell-Yan process $p p \rightarrow \ell^+ \ell^- X$; ii) Prompt photon production in $p p \rightarrow \gamma X$; iii) Inclusive pion production in $p p \rightarrow \pi X$. We find that an overall good reproduction of the corresponding unpolarized cross sections is possible (within the limits indicated above) by choosing, depending on the kinematical situation considered, $\beta = 1.0 - 1.25$ (GeV/c)$^{-1}$ (that is, $\langle k_{\perp a}^2 \rangle^{1/2} = 0.8 - 1.0$ GeV/c). The choice of $\beta$ is related to the set of $x$ dependent PDF utilized; throughout this paper
we use the GRV94 set. The optimal choice of $\beta'$ in case iii) (pion production) is commented in the following. We limit ourself to present few indicative results and comments regarding the processes considered and the SSA in pion production. A full account of this analysis will be presented elsewhere.

i) At LO and within collinear partonic configuration the final lepton pair produced in Drell-Yan processes cannot have any transverse momentum, $q_T$, with respect to the colliding beams. Experimental data show however that the lepton pair has a well defined $q_T$ spectrum. As an example, in Fig. 1a we show estimates of the invariant cross section at $E = 400$ GeV as a function of $q_T$, for several different invariant mass bins (in GeV) at fixed rapidity $y = 0.03$, and using $\beta = 1.11$ (GeV/c)$^{-1}$; data are from [7]. Theoretical curves are arbitrarily raised by a factor $K_{\text{fac}} = 1.6$, which could be well accommodated by NLO K-factors and scale dependences, an issue that as said above we do not address here. Notice how data are well reproduced by a Gaussian dependence up to $q_T = 2-2.5$ GeV/c; larger $q_T$ data show a power-law decrease well explained by pQCD corrections.

ii) Several data for the unpolarized cross section are available in the case of prompt photon production, mainly at central rapidities and moderately large $p_T$. As an example, in Fig. 1b we show estimates of the invariant cross section for the process $p p \rightarrow \gamma X$ at $E = 280$ GeV for two different values of $p_T$ vs. $x_F$, with $k_\perp$ effects (thick lines) and without them (thin lines), using $K_{\text{fac}} = 1$ and $\beta = 1.25$ (GeV/c)$^{-1}$; data are from [8].

iii) For inclusive pion production, $p p \rightarrow \pi X$, some experimental results for SSA are also available, and we can see how our approach works for SSA and unpolarized cross sections at the same time. This case is however more intricate, since we can have $k_\perp$ effects in the fragmentation process also. The $z$ and $k_\perp$ dependences in
the FF are chosen according to Eq. (4); a direct $z$ dependence of the $\beta'$ parameter seems to be favored, $1/\beta'(z) = \langle k^2_\perp(\pi)(z) \rangle^{1/2} = 1.4 z^{1.3} (1 - z)^{0.2}$ GeV/c.

Unpolarized FF are presently known with much less accuracy than nucleon PDF. In particular, all available sets of parameterizations for the pion FF are for neutral pions (or for the sum of charged pions), since $e^+e^-$ data do not allow to separate among $\pi^+$ and $\pi^-$ case; this can be made under further assumptions, which remain to be tested. In Fig. 2a we present estimates of the invariant cross section for the process $p p \to \pi X$ at $E = 200$ GeV vs. $x_F$ for different $p_T$ values. We use two sets of FF from Kretzer (K, thin lines) [9] and Kniehl, Kramer, and Pötter (KKP, thick lines) [10], $K_{fac} = 2.4(K), 1.9(KKP), \beta = 1.25$ (GeV/c)$^{-1}$. Data are from [11].

Let us now consider the SSA in $p^+ p \to \pi X$, within the same approach and assuming it is generated by the Sivers effect alone, that is from a spin and $k_\perp$ effect in the PDF inside the initial polarized proton, described by the Sivers function $\Delta^N f_{q/p^1}(x, k_\perp)$. There are other possible sources for SSA, and notably the so-called Collins effect, concerning the fragmentation of a polarized parton into the final observed pion. These effects are not considered here. Analogous studies have already been performed [12], using an effective averaging on $k_\perp$ and a simplified partonic kinematics. Here we show the first results with full treatment of $k_\perp$ effects and partonic kinematics. These results are in good qualitative agreement with previous work.

The numerator of the SSA, $d\sigma^+ - d\sigma^-$ can be expressed in the form of Eq. (4), with the substitution $\hat f_{A/A}(x, k_\perp) \rightarrow \Delta^N f_{q/p^1}(x, k_\perp)$. For the Sivers function we choose an expression similar to that of the unpolarized distribution, Eq. (4)

$$\Delta^N f_{q/p^1}(x, k_\perp) = \Delta^N f_{q/p^1}(x) h(k_\perp) \sin \phi_{k_\perp},$$

(5)

where $\phi_{k_\perp}$ is the angle between $k_\perp$ and the polarization vector of the proton; $\Delta^N f_{q/p^1}(x)$
and $h(k_\perp)$ are such to fulfill the general positivity bound $|\Delta^N f_{q/p}(x, k_\perp)|/2 f_{q/p}(x, k_\perp) \leq 1$:

$$\Delta^N f_{q/p}(x) = N_q x^{a_q}(1-x)^{b_q} \frac{(a_q + b_q)(a_q+b_q)}{a_q b_q} 2 f_{q/p}(x), \quad |N_q| \leq 1$$  \hspace{1cm} (6)

$$h(k_\perp) = \left(2 e^{\frac{1-2r}{r}} \right)^{1/2} \left( \frac{\beta^2}{\pi} \right) k_\perp \exp \left(-\beta^2 k_\perp^2/r \right), \quad 0 < r < 1.$$  \hspace{1cm} (7)

A choice of the parameters in Eqs. (6),(7) which allow to reasonably reproduce the experimental results for the pion SSA is the following (only valence quark contributions to the Sivers function are considered):

$$N_u = +0.5 \quad a_u = 2.0 \quad b_u = 0.3$$  \hspace{1cm} (8)

$$N_d = -1.0 \quad a_d = 1.5 \quad b_d = 0.2 , \quad r \approx 0.7.$$  

In Fig. 2b we show our preliminary estimates of $A_N$ with Sivers effect at $E = 200$ GeV and $p_T = 1.5$ GeV/c, vs. $x_F$, for three different choices of the pion FF: K, KKP and a modified version of K. Data are from [13]. The SSA for $\pi^+$ and $\pi^0$ is well reproduced independently of the FF set. Interestingly, the $\pi^-$ case shows a stronger sensitivity to the relation between the leading and non-leading contributions to the fragmentation process, which cannot be extracted from present experimental information on unpolarized pion cross sections. In fact, our results with the K(KKP) FF sets underestimate (overestimate) in magnitude the $\pi^-$ asymmetry, while a good agreement is recovered using a somehow fictitious set (K-mod) with an intermediate behavior.

In conclusion, we have presented here preliminary results of an ongoing program dedicated to the study of partonic transverse momentum effects both in unpolarized and polarized cross sections (and SSA) for inclusive particle production in hadronic collisions. These results show that it seems possible to reproduce reasonably well, within pQCD at LO and leading twist and up to a factor of 2-3, unpolarized cross sections for Drell-Yan processes, prompt photon and inclusive pion production in hadronic collisions, in several different kinematical situations. Within the same approach, we have reanalyzed the SSA for $p^+ p \rightarrow \pi X$ taking into account Sivers effect alone; we have found reasonable agreement with data and with previous theoretical results obtained with a simplified treatment of $k_\perp$ effects and partonic kinematics, whose main results are therefore confirmed by our analysis. The next steps of this program are the study of the pion SSA with Collins effect, of the SSA in photon production, and of the unpolarized cross section and the transverse polarization for $A$ production in unpolarized hadronic collisions. The extension of our analysis to RHIC kinematics, where a thorough program on SSA measurements is in progress, is of great interest. First estimates of the SSA in $p^+ p \rightarrow \pi X$ seem to be in reasonable agreement with preliminary results from RHIC [14].

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