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Transverse single spin asymmetries in photon production

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Abstract

Transverse single spin asymmetries (SSA) in inclusive reactions are now considered to be directly related to the transverse momentum \mathbf{k}_T of the fundamental partons involved in the process. We find that the ideal probe to extract information on the gluon Sivers function is the transverse SSA of prompt photon production $pp^\uparrow \rightarrow \gamma X$, at large p_T . The following related processes, $pp^\uparrow \rightarrow \gamma + \text{jet} + X$, $pp^\uparrow \rightarrow \gamma^* + X \rightarrow \mu^+ \mu^- + X$ and $\bar{p}p^\uparrow \rightarrow \gamma + X$ are also briefly discussed.

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At present there is a wealth of experimental observations of single spin asymmetries (SSA) in many different processes. Large SSA have been measured in $pp^\uparrow \rightarrow \pi X$, where one proton is transversely polarized, and in which the produced pion prefers to come out, either to the right or to the left of the plane formed by the beam direction and the proton polarization vector, depending on its charge. This effect was first observed at FNAL more than ten years ago, in experiments done by the E704 Collaboration [1],

at center-of-mass (c.m.) energy $\sqrt{s} \sim 20$ GeV. It occurs also at $\sqrt{s} = 200$ GeV, as observed recently for π^0 production by the STAR Collaboration [2], in the first spin run at BNL-RHIC. Although the data appear to have very little energy dependence, a careful study of the unpolarized cross section leads to conclude that the SSA, in these two energy regimes, may have two different dynamical origins [3]. Several SSA have been also measured in hyperon (and antihyperon) inclusive production $pN \rightarrow Y^\uparrow X$, at various energies [4], but a suitable detailed interpretation of these rich polarization data is still missing. Moreover, recently an azimuthal asymmetry has been also observed in semi-inclusive deep-inelastic scattering (SIDIS) $lp^\uparrow \rightarrow l\pi X$, for targets polarized transversely (A_{UT}) and longitudinally (A_{UL}) relative to the direction of the unpolarized incoming lepton beam direction [5,6].

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Although these SSA are not yet fully understood, they are expected to give valuable information on the orbital angular momenta of quarks and gluons inside the hadron. Furthermore, they provide us with an understanding of QCD at the amplitude level, which comes from the fact that the SSA is proportional to the interference of a spin flip and a non-spin flip amplitude, out of phases. Therefore in perturbation theory such an interference effect, which requires an imaginary part, is generated at the one loop level. The interference is between wave functions with angular momenta $J_z = \pm 1/2$ and hence contains information on the partons orbital angular momenta [7]. Moreover, the required matrix element measures the spin–orbit correlation $\vec{S} \cdot \vec{L}$ within the target hadrons wave function, the same matrix element which produces the anomalous magnetic moment of the proton, the Pauli form factor, and the generalized parton distribution E which is measured in deeply virtual Compton scattering.

In practice, essentially two mechanisms have been proposed in order to explain the SSA. The first one is to generalize the parton distribution functions by considering distributions that depend on the transverse momenta \mathbf{k}_T of these partons, and the second is to take into account higher twist operators [8]. Recently it was shown that there is a direct relation between these two approaches, so in fact they are expected to produce very similar effects. In the case of the \mathbf{k}_T dependent distribution functions, the SSA can be produced either by quark distributions, which is called the Sivvers effect [9], proposed long time ago, or by quark fragmentation functions, which is called the Collins effect [10]. For some time it was thought that the Sivvers function vanished, but this was shown not to be the case in an explicit simple model calculation [7].

In general both the Sivvers and the Collins effects will be present in a specific reaction, although there are some cases in which only one of them contributes. For example, the Collins effect is the only mechanism that can lead to asymmetries A_{UT} and A_{UL} , defined above. On the other hand, it does not appear in some electroweak interaction processes, where there is only the Sivvers effect. In this Letter we will concentrate on the Sivvers function, whose existence was proved by considering final state interactions in a diquark model [7,11]. The diquark model can only predict the Sivvers function for the valence quarks, and it is also of interest to calculate it for sea quarks or for gluons.

In fact, the gluon Sivvers function was mentioned for the first time in Ref. [12], and only recently it was also considered in jet correlations [13] and in D meson production [14] in $p^\uparrow p$ collisions. Just as the quark Sivvers function is related to the hadrons anomalous magnetic moment, the gluon Sivvers function is connected with the gluons contribution to the same anomalous magnetic moment, a quantity which in general is difficult to obtain.

The direct photon production in pp collisions can provide a clear test of shortdistance dynamics as predicted by perturbative QCD, because the photon originates in the hard scattering subprocess and does not fragment, which immediately means that the Collins effect is *not* present. This process is very sensitive to the gluon structure function, since it is dominated by the quark–gluon Compton subprocess in a large photon transverse momentum range. Prompt-photon production, $pp(p\bar{p}) \rightarrow \gamma X$, has been a useful tool for the determination of the unpolarized gluon density and it is considered one of the most reliable reactions for extracting information on the polarization of the gluon in the nucleon [15]. Some years ago, the E704 Collaboration [16] at FNAL measured single spin asymmetries for direct photon production in pp collisions at 200 GeV/c. Although the single spin asymmetry for the direct photon production was found consistent with zero, within the experimental uncertainty, there is nowadays a real possibility to increase the precision of the measurement. In this Letter, we show how to relate the transverse SSA to the gluon Sivvers function.

There are only two hard scattering processes for the direct photon production in high p_T collisions. One is the lowest-order Compton subprocess, $qg \rightarrow \gamma q$ and the other one is the lowest-order annihilation subprocess, $q\bar{q} \rightarrow \gamma g$. However, since the first subprocess is dominant in $pp \rightarrow \gamma X$ collisions, the unpolarized cross section for producing a photon of transverse momentum p_T and rapidity y can be written approximately as

$$d\sigma = \sum_i \int_{x_{\min}}^1 dx_a \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} \frac{x_a x_b}{x_a - (p_T/\sqrt{s})e^y} \times \left[q_i(x_a, \mathbf{k}_{Ta}) G(x_b, \mathbf{k}_{Tb}) \frac{d\hat{\sigma}}{d\hat{t}}(q_i G \rightarrow q_i \gamma) + G(x_a, \mathbf{k}_{Ta}) q_i(x_b, \mathbf{k}_{Tb}) \frac{d\hat{\sigma}}{d\hat{t}}(G q_i \rightarrow q_i \gamma) \right], \quad (1)$$

where $q_i(x, \mathbf{k}_T)$ [$G(x, \mathbf{k}_T)$] is the quark [gluon] distribution function with specified \mathbf{k}_T . A priori k_T , the magnitude of \mathbf{k}_T , is expected to be small compared to \sqrt{s} , where s is the center-of-mass energy of the reaction $pp \rightarrow \gamma X$. Therefore in order to simplify our discussion, we will use the following expressions

$$\begin{aligned} x_b &= \frac{x_a(p_T/\sqrt{s})e^{-y}}{x_a - (p_T/\sqrt{s})e^y}, \\ x_{\min} &= \frac{(p_T/\sqrt{s})e^y}{1 - (p_T/\sqrt{s})e^{-y}}, \end{aligned} \quad (2)$$

which are valid only in the collinear approximation. The subprocess cross section is

$$\frac{d\hat{\sigma}}{d\hat{t}}(q_i G \rightarrow q_i \gamma) = -\frac{\pi e_q^2 \alpha \alpha_s}{3\hat{s}^2} \left[\frac{\hat{u}}{\hat{s}} + \frac{\hat{s}}{\hat{u}} \right], \quad (3)$$

and by replacing \hat{u} by \hat{t} , one obtains the other internal cross section occurring in Eq. (1). Here α is the fine structure constant, α_s is the strong coupling constant, e_q denotes the quark charge and \hat{s} , \hat{t} , \hat{u} stand for the Mandelstam variables for the parton subprocess

$$\begin{aligned} \hat{s} &= x_a x_b s, & \hat{u} &= -x_a p_T \sqrt{s} e^{-y}, \\ \hat{t} &= -x_b p_T \sqrt{s} e^y. \end{aligned} \quad (4)$$

According to the general definition of the \mathbf{k}_T -dependent parton distributions $f(x, \mathbf{k}_T)$ ($f = q, G$) inside a transversely polarized proton, where spin-up is labeled with \uparrow and down with \downarrow , it is clear that

$$\begin{aligned} f(x, \mathbf{k}_T) &= \frac{1}{2} [f_{\uparrow}(x, \mathbf{k}_T) + f_{\downarrow}(x, \mathbf{k}_T)] \\ &= \frac{1}{2} [f_{\uparrow}(x, \mathbf{k}_T) + f_{\uparrow}(x, -\mathbf{k}_T)] \\ &= f(x, k_T), \end{aligned} \quad (5)$$

whereas for the Sivvers functions [9] we have

$$\begin{aligned} \Delta f_N(x, \mathbf{k}_T) &= f_{\uparrow}(x, \mathbf{k}_T) - f_{\downarrow}(x, \mathbf{k}_T) \\ &= f_{\uparrow}(x, \mathbf{k}_T) - f_{\uparrow}(x, -\mathbf{k}_T) \\ &= \Delta f_N(x, k_T) \mathbf{S}_p \cdot \hat{\mathbf{p}} \times \mathbf{k}_T. \end{aligned} \quad (6)$$

Here \mathbf{S}_p denotes the transverse polarization of the proton of three-momentum \mathbf{p} and $\hat{\mathbf{p}}$ is a unit vector in the direction of \mathbf{p} . The correlation proposed by Sivvers corresponds to a time-reversal odd triple vector product. Now we can define the SSA as

$$A_N^\gamma = \frac{d\Delta_N\sigma}{d\sigma}, \quad (7)$$

where $d\Delta_N\sigma = d\sigma^\uparrow - d\sigma^\downarrow$, whereas $d\sigma = d\sigma^\uparrow + d\sigma^\downarrow$ and we have

$$\begin{aligned} d\Delta_N\sigma &= \sum_i \int_{x_{\min}}^1 dx_a \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} \frac{x_a x_b}{x_a - (p_T/\sqrt{s})e^y} \\ &\times \left[q_i(x_a, \mathbf{k}_{Ta}) \Delta_N G(x_b, \mathbf{k}_{Tb}) \frac{d\hat{\sigma}}{d\hat{t}}(q_i G \rightarrow q_i \gamma) \right. \\ &\left. + G(x_a, \mathbf{k}_{Ta}) \Delta_N q_i(x_b, \mathbf{k}_{Tb}) \frac{d\hat{\sigma}}{d\hat{t}}(G q_i \rightarrow q_i \gamma) \right]. \end{aligned} \quad (8)$$

A priori the \mathbf{k}_T -dependence of all these parton distributions is unknown, but as an approximation one can assume a simple factorized form for the distribution functions and take for example, as in Ref. [12],

$$f(x, k_T) = f(x) \lambda(k_T), \quad (9)$$

where $\lambda(k_T)$ is flavor independent, and a similar expression for the corresponding Sivvers functions

$$\Delta_N f(x, k_T) = \Delta_N f(x) \eta(k_T). \quad (10)$$

In such a situation,² it is clear that the SSA will also factorize and then it reads

$$A_N^\gamma f(s, x_F, \mathbf{p}_T) = H(p_T) A^\gamma(s, x_F) \mathbf{S}_p \cdot \hat{\mathbf{p}} \times \mathbf{p}_T, \quad (11)$$

where \mathbf{p}_T is the transverse momentum of the photon produced at the c.m. energy \sqrt{s} , and $H(p_T)$ is a function of p_T , the magnitude of \mathbf{p}_T . We also recall the well-known relation between y and x_F , namely $x_F = 2 \sinh y(p_T/\sqrt{s})$.

Both Sivvers functions for quarks and gluons are involved in $A^\gamma(s, x_F)$, and therefore we want to identify a kinematic region where the gluon Sivvers function dominates. To achieve that it is necessary to determine in Eqs. (1) and (8), the range of integration over x_a and to study the relative magnitude of x_a and x_b . As an example, using Eq. (2) with $\sqrt{s} = 200$ GeV and $p_T = 20$ GeV, the results for x_{\min} versus x_F are shown in Fig. 1(a) and we find that $x_{\min} \approx x_F$ in the region

² The simplifying assumptions used above for the kinematics in the collinear approximation (see Eq. (2)), is justified by taking Gaussian expressions for $\lambda(k_T)$ and $\eta(k_T)$.

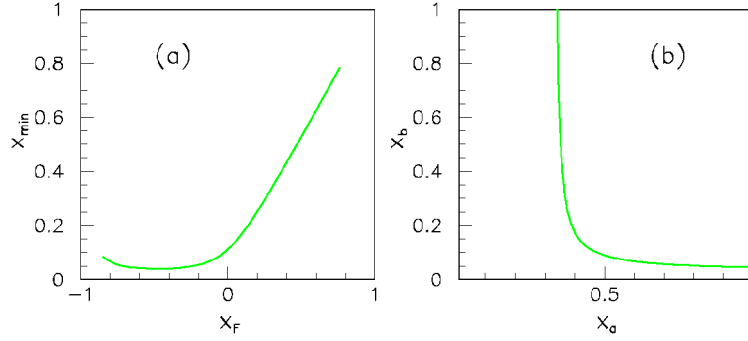


Fig. 1. For $\sqrt{s} = 200$ GeV, $p_T = 20$ GeV: (a) x_{\min} versus x_F and (b) x_b versus x_a .

$x_F > 0.3$. On the other hand, x_b versus x_a is shown in Fig. 1(b) and we see that when x_a is integrated over the range $[x_{\min}, 1]$, the main contribution comes from the low x_b values. Therefore, when we look at the large x_F region, where x_a is large but x_b is small, the asymmetry can be approximately expressed as

$$A^\gamma(s, x_F) = \frac{\langle \Delta_N G \rangle}{\langle G \rangle}, \quad (12)$$

where $\langle \Delta_N G \rangle$ and $\langle G \rangle$ mean the corresponding values over an appropriate integrating range. Unlike the quark Sivers functions, for which several theoretical calculations have been performed, for example in a spectator model with axial-vector diquarks (see Ref. [11] and references therein), the gluon Sivers function has not been really investigated, so we will not try to use a numerical estimate for $\Delta_N G$. On the experimental side the inaccurate result of Ref. [16] is anyway irrelevant for our purpose, because it concerns the central region $x_F \sim 0$. On the other hand it is worth mentioning the measurement of the SSA in the forward production of photons in pp collisions at $\sqrt{s} = 200$ GeV, with $p_T \ll 0.5$ GeV, consistent with zero [17]. The fact that they measure *all* photons and not only direct photons, makes these data irrelevant. This kinematic region is indeed quite accessible at RHIC, since the PHENIX Collaboration has already released the unpolarized cross section for $pp \rightarrow \gamma X$ at $\sqrt{s} = 200$ GeV, in the central region for p_T up to 18 GeV [18], in fair agreement with NLO pQCD calculations. The same calculation predicts for $p_T \sim 8$ GeV and $x_F \sim 0.3$, a cross section of about 40 pb/GeV².³ We hope this

will be a good motivation to undertake the measurement of the SSA, but we know that the extraction of the gluon Sivers function, even if it turns out to be large, will not be straightforward. Among the various effects which might dilute the SSA, it is important to mention the effects of QCD gluon resummation [19,20] and Sudakov effects have been shown to lead to significant suppression of the SSA considered in Ref. [13].

Other similar processes are $pp^\dagger \rightarrow \gamma + \text{jet} + X$, muon pair production $pp^\dagger \rightarrow \gamma^* + X \rightarrow \mu^+ \mu^- + X$ and $\bar{p}p^\dagger \rightarrow \gamma + X$. The first reaction is certainly very interesting also, because by detecting simultaneously the photon and the jet, one has both rapidities to consider and Eq. (12) becomes simpler, with no integrations. For muon pair production, the outgoing photon is monitored by its conversion to muon pairs and this process is more difficult to study experimentally. Finally, in the case of $\bar{p}p^\dagger \rightarrow \gamma + X$, the quark annihilation process $\bar{q}q \rightarrow \gamma g$ dominates, which makes it unpractical. Therefore, the ideal probe to extract the gluon Sivers function is the transverse single spin asymmetry of prompt photon production at high p_T , and RHIC is obviously very suitable to realize this important measurement with good precision.

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