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DIRECT PHOTON PRODUCTION IN POLARIZED PP COLLISIONS

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ABSTRACT

We argue that inclusive direct photon production at large transverse momentum in proton-proton interactions with longitudinally polarized beam and target is an incisive probe of the polarized gluon distribution in a proton. We provide predictions of cross sections for a range of reasonable choices of the polarized gluon distribution. At current fixed target energies, the cross sections are small but measurable. At collider energies, such as the SSC energy, isolated direct photon production should be considered in order to minimize the nonperturbative contribution due to fragmentation.

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*Work supported by the U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38.

†SSC Fellow; Research at SUNY is supported in part by the National Science Foundation under grant No. PHY-89-08495.

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ABSTRACT

We argue that inclusive direct photon production at large transverse momentum in proton-proton interactions with longitudinally polarized beam and target is an incisive probe of the polarized gluon distribution in a proton. We provide predictions of cross sections for a range of reasonable choices of the polarized gluon distribution. At current fixed target energies, the cross sections are small but measurable. At collider energies, such as the SSC energy, isolated direct photon production should be considered in order to minimize the nonperturbative contribution due to fragmentation.

I. INTRODUCTION

Recent data on the polarization asymmetry in deeply inelastic scattering (DIS) of polarized muons on polarized protons have renewed interest in the relationship between the spin of a proton and the polarization of its constituents (quarks and gluons).^{1,2} This asymmetry measures the spin-dependent structure function $g_1^p(x, Q^2)$ of a proton.¹ Here x is the usual Bjorken scaling variable, and Q^2 is the square of the four-momentum transfer. The measurement of $g_1^p(x, Q^2)$ and its first moment, combined with the Bjorken sum rule and the F/D ratio obtained from semileptonic hyperon decays, permits a determination of the first moment of the SU(3)-singlet combination of the spin-dependent quark distributions, $\Delta\Sigma$. The result is that $\Delta\Sigma$ is consistent with zero.¹ This result has led to a good deal of discussion in the literature.³ At the core of the discussion is how to interpret (or to define) the "right" spin-dependent quark distributions, $\Delta q(x, Q^2)$, and whether there is a large gluonic contribution to the first moment of $g_1^p(x, Q^2)$. Of particular interest to us is the spin-dependent gluon distribution in a polarized proton and its independent experimental measurement.⁴

Direct access to the spin-dependent gluon distribution should be provided by processes in which the gluons contribute *dominantly* to the cross sections. In the case of unpolarized proton-proton scattering, direct photon production at large transverse momentum, p_T , is known to be dominated by the "Compton" subprocess $qg \rightarrow \gamma q$ at fixed target energies.⁵ Here q and g stand for quark and gluon constituents. Data, therefore, allow a direct determination of the (spin-averaged) gluon distribution $G(x, Q^2)$, provided the quark distributions are well-determined in other processes (e.g., in DIS). When both the beam and target protons are polarized, the cross section due to the "Compton" subprocess can be expressed directly in terms of the polarized gluon distribution $\Delta G(x, Q^2)$.⁶ Based on the DIS data and a range of reasonable choices of spin-dependent gluon distributions, we shall argue that the inclusive direct photon production in polarized pp collisions is also dominated by the "Compton" subprocess. As a result, such experiments will provide direct access to the spin-dependent gluon distribution in a polarized proton.

*Invited talk presented at the *Polarized Collider Workshop*, November 15-17, 1990, Pennsylvania State University, University Park, PA.

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In Sec. II we explain why the "Compton" subprocess dominates the cross section for unpolarized hadronic prompt photon production. We then argue that the same conclusion can be reached for the polarized case. In Sec. III we provide specific predictions for the cross sections and polarization asymmetries expected for direct photon production in polarized pp collisions at fixed target energies. We discuss our expectations for polarized direct photon production at collider energies in Sec. IV. As shown explicitly in Sec. IV, at leading order, our predictions are not very sensitive to what interpretation or definition one adopts for the spin-dependent quark distributions. Instead, our prediction is directly related to the experimentally measured structure function $g_1^p(x, Q^2)$ as a whole. Conclusions are also found in Sec. IV.

II. PROMPT PHOTONS AT LARGE p_T

Measurement of inclusive direct photon production at large p_T in pp collisions is known to be a clean probe of the (spin-averaged) gluon distribution in a proton at fixed target energies. However, at collider energies, *isolated* (instead of inclusive) direct photon production must be considered in order to minimize the large contribution from nonperturbative photon fragmentation.⁷ Many estimates are available of cross sections for direct photon production in *unpolarized* pp collisions.⁵ Data are generally in accord with the calculations. To understand how good direct photon production in *polarized* pp collisions may be in determining the spin-dependent gluon distribution, it is important to examine why the process is good for determining the gluon distribution in the case of unpolarized pp collisions.

At large p_T , a photon can be produced through a pointlike, perturbatively calculable hard scattering term, as well as through a nonperturbative fragmentation process (generalization of the bremsstrahlung process). Because of the nonperturbative nature of the fragmentation process, perturbative QCD alone cannot predict the actual size of the inclusive prompt photon cross section. In principle, whether in the case of unpolarized or polarized interactions, we can expect direct photon production to give good information on parton (gluon or quark) distributions only if the nonperturbative fragmentation process can be controlled.

With approximate leading logarithmic photon fragmentation functions, we estimate that the fragmentation contribution in the unpolarized case is only about a 10% effect at current fixed target energies. In contrast, it amounts to a 50% (or even larger) effect at collider energies.⁷ Because of the poorly known photon fragmentation function, we do not expect that inclusive direct photon production at high energy can yield clean information on gluon distributions. However, at fixed target energies, inclusive prompt photon is a relatively good probe of short-distance physics.

At leading order, short-distance prompt photon production is governed by the tree "Compton" $qg \rightarrow \gamma q$ and annihilation $q\bar{q} \rightarrow \gamma g$ subprocesses. The "Compton" (or annihilation) contribution to the cross section can be written in general as

$$\begin{aligned}\sigma_{\text{Com}} &= (q \otimes G) \otimes \hat{\sigma}_{\text{Com}} \quad \text{"Compton"} \\ \sigma_{\text{anni}} &= (q \otimes \bar{q}) \otimes \hat{\sigma}_{\text{anni}} \quad \text{Annihilation,}\end{aligned}\tag{1}$$

where $\hat{\sigma}$ is a parton level cross section – the short-distance hard scattering term, q ($\bar{q}$) and g are quark (antiquark) and gluon distributions, and $\otimes$ means a convolution between the distributions and the hard scattering term. The expression in parentheses ($\otimes$) can be thought of as the parton flux. The statement that inclusive direct photon production is a good probe of the gluon distribution for the unpolarized case is based on the fact that the net "Compton" contribution in pp interactions is *numerically* much larger than the annihilation contribution. At the parton level, the "Compton" contri-

Figure 1: The dot-dashed line is the contribution to $xg_1^p(x, Q^2)$ from the polarized valence quark distributions at $Q^2 = 10.7 \text{ GeV}^2$. The solid line is our parametrization of $xg_1^p(x, Q^2)$ including effective sea distributions (Ref. 4). The data are from EMC (Ref. 1).

bution is actually *smaller* than the annihilation contribution, $\hat{\sigma}_{\text{Com}} < \hat{\sigma}_{\text{anni}}$. The reason the net “Compton” contribution is larger than the annihilation contribution is that in a proton (spin-averaged) the gluon density is much larger than the antiquark density. Equivalently, the difference in the parton flux controls the answer. For example, if $x_T = 2p_T/\sqrt{s}$ and $x_a \sim x_b \sim x_T \sim 0.1$, $\hat{\sigma}_{\text{Com}} \sim (1/2)\hat{\sigma}_{\text{anni}}$; but $G(x) \sim 20 \bar{q}(x)$ for $x \sim 0.1$. Here x_a and x_b are momentum fractions carried by initial partons participating in the hard scattering. Because the observed cross section is dominated by the region where $x_a \sim x_b \sim x_T$, the above simple estimate suggests that $\sigma_{\text{Com}} \sim 10 \sigma_{\text{anni}}$, about the same as is obtained in a more precise numerical calculation.

In the case of polarized interactions, the hard part for the annihilation subprocess is the same as that for the unpolarized case up to a sign difference. But, the hard part for the “Compton” subprocess is even smaller than that in the unpolarized case. As a result, $\Delta\hat{\sigma}_{\text{Com}} \sim (1/4)|\Delta\hat{\sigma}_{\text{anni}}|$ for $x_a \sim x_b \sim x_T \sim 0.1$. Therefore, inclusive direct photon production in polarized pp collisions can yield useful information on ΔG iff ΔG is much bigger than $\Delta\bar{q}$, which is not a priori obvious. The spin-averaged gluon distribution is much larger than the antiquark distribution because the evolution kernel for gluons has a $1/x$ pole. In contrast, the evolution kernel for the spin-dependent gluon distribution does not have the $1/x$ pole. Consequently, ΔG is much smaller than G when x is small. The question is now whether $\Delta\bar{q}$ is even smaller.

To estimate the size of $\Delta\bar{q}$, we assume that the Carlitz and Kaur⁸ model is approximately valid for the spin-dependent valence quark distributions. We justify this assumption by noting that the valence quark part of the structure function $g_1^p(x, Q^2)|_{\text{val}}$, the dot-dashed curve in Fig. 1, fits the data in the large x region. Then, we use the difference between the data and $g_1^p(x, Q^2)|_{\text{val}}$ in the small x region to parametrize the effective spin-dependent sea and anti-quark distributions. From Fig. 1, for example,

we can estimate $\Delta\bar{q}(x)$ for $x \sim 0.1$ as follows:

$$xg_1^p(x, Q^2)|_{\text{data}} - xg_1^p(x, Q^2)|_{\text{val}} \approx 2 \left[2 \left(\frac{1}{3} \right)^2 + \left(\frac{2}{3} \right)^2 \right] x \Delta\bar{q}(x, Q^2) \quad (2)$$

where $xg_1^p(x, Q^2)|_{\text{data}}$ means the solid curve, and an SU(3) symmetric sea is assumed. Here the scale Q^2 is about 10.7 GeV². For $x \sim 0.1$, $xg_1^p(x, Q^2)|_{\text{data}} - xg_1^p(x, Q^2)|_{\text{val}} \approx 0.01$, and consequently, $\Delta\bar{q}(x, Q^2) \sim -0.075$ when $x \sim 0.1$.

Because $\Delta G(x, Q^2)$ should be much smaller than $G(x, Q^2)$ in the small x region, a conservative assumption is that $\Delta G(x, Q^2) \approx xG(x, Q^2)$. Taking $xG(x, Q^2) \sim 3(1-x)^5$, we have $\Delta G(x, Q^2) \sim 1.8$ for $x \sim 0.1$. Comparing with $|\Delta\bar{q}(x, Q^2)| \sim 0.075$, we observe that $\Delta G(x, Q^2)$ is much larger than $\Delta\bar{q}(x, Q^2)$ in the region where $x \sim 0.1$. We conclude that inclusive direct photon production in polarized pp collisions is a good probe of the spin-dependent gluon distribution, $\Delta G(x, Q^2)$, of a polarized proton.

III. NUMERICAL RESULTS

To obtain quantitative predictions for the cross sections for inclusive direct photon production in polarized pp collisions, we need parametrizations of spin-dependent quark and gluon distributions. The general procedure to obtain the spin-dependent parton distributions is first to parametrize the distributions at an arbitrary reference value $Q^2 = Q_0^2$, and then to use the spin-dependent Altarelli-Parisi evolution equations⁹ to obtain the distributions at any other scale Q^2 . To parametrize the spin-dependent input parton distributions, we adopt the Carlitz and Kaur model for spin-dependent valence quark distributions. With the assumption of an SU(3) symmetric sea, we parametrize the spin-dependent sea quark and antiquark distributions by fitting the difference between the data and the prediction from the Carlitz and Kaur model. For the spin-dependent gluon distribution $\Delta G(x, Q^2) = G^{(+)}(x, Q^2) - G^{(-)}(x, Q^2)$, the difference between the numbers of gluons with positive and negative helicity, we select a simple one-parameter function⁴

$$\Delta G(x, Q_0^2) = \begin{cases} G(x, Q_0^2), & x_c \leq x \leq 1, \\ \frac{x}{x_c} G(x, Q_0^2), & 0 \leq x \leq x_c. \end{cases} \quad (3)$$

The parameter x_c with $0 < x_c \leq 1$ determines the net helicity carried by gluons. When the value of x_c is adjusted, this simple parametrization covers a spectrum of reasonable choices of the polarized gluon distribution. The behavior of our polarized parton distributions is displayed numerically in Ref. 4.

In leading-order QCD perturbation theory, the cross section for prompt photon production in *polarized* pp reactions, $\vec{p}_A + \vec{p}_B \rightarrow \gamma + X$, is given by

$$E_\gamma \frac{d\Delta\sigma_{AB}}{d^3p_\gamma}(s, x_F, p_T) = \sum_{a,b} \int dx_a dx_b \Delta P_A^a(x_a, Q^2) \Delta P_B^b(x_b, Q^2) \times E_\gamma \frac{d\Delta\hat{\sigma}_{ab}}{d^3p_\gamma}(\hat{s}, x_F, p_T), \quad (4)$$

where a and b run over all possible quark flavors and the gluon; $\Delta\sigma_{pp} \equiv \frac{1}{2}[\sigma_{pp}(++) - \sigma_{pp}(+-)]$; and $\sigma_{pp}(++)$ denotes the cross section when the two incident protons have their spins oriented along the directions of motion of the protons in the overall pp center-of-mass system. Similarly, for the unpolarized case,

$$E_\gamma \frac{d\sigma_{AB}}{d^3p_\gamma}(s, x_F, p_T) = \sum_{a,b} \int dx_a dx_b P_A^a(x_a, Q^2) P_B^b(x_b, Q^2) E_\gamma \frac{d\hat{\sigma}_{ab}}{d^3p_\gamma}(\hat{s}, x_F, p_T). \quad (5)$$

Figure 2: Predicted cross sections for prompt photons as a function of p_T for $x_F = 0$ in pp interactions at $p_{\text{beam}} = 800$ GeV/c. The solid line shows the rate in unpolarized pp interaction, whereas the dashed and dot-dashed curves show a range of rates in the polarized case.

In Eq. (4), $\Delta P_A^a(x_a, Q^2)$ and $\Delta P_B^b(x_b, Q^2)$ are spin-dependent parton distributions, and in Eq. (5), $P_A^a(x_a, Q^2)$ and $P_B^b(x_b, Q^2)$ are spin-averaged parton distributions. The short-distance hard scattering terms $\Delta\hat{\sigma}$ and $\hat{\sigma}$ include the parton level “Compton” and annihilation subprocesses. Their analytical expressions can be found in Ref. 4.

Having the parton distributions and expressions for the cross sections, we can calculate rates for direct photon production at different energies.⁴ In Fig. 2 we plot the production rates as a function of the photon’s transverse momentum p_T for incoming beam energy equal to 800 GeV². The solid line represents the rate in unpolarized pp collisions. The dashed line represents the rate in polarized pp interactions with parameter $x_c = 1.0$ for the polarized input gluon distribution, and dot-dashed line for $x_c = 0.2$. These two lines in the polarized case represent roughly a reasonable range expected for the polarized cross section at fixed target energies. They correspond to values of the integral (integral of ΔG over all x) of 0.5 and 2.5 at $Q \sim 2$ GeV. The predicted energy dependence of the cross sections is shown in Fig. 3. Notice in Fig. 3 that when energy increases, the unpolarized cross section increases faster than the polarized one. At higher energies, smaller values of x contribute, and at small x , the unpolarized gluon distribution is much larger than its polarized counterpart. From Fig. 2, we notice that the cross section is small for direct photon production with transverse momentum $p_T > 4$ GeV, but it is still measurable.⁴

IV. DISCUSSION AND CONCLUSIONS

We have argued that at fixed target energies, inclusive direct photon production in polarized pp collisions is a good probe of the spin-dependent gluon distribution in a proton. At collider energies (e.g., SSC energy), the inclusive process is no longer ideal for measuring the gluon distribution because of the large nonperturbative contribution due to fragmentation processes. However, our experience with the treatment of the

Figure 3: Predicted cross sections for prompt photons as a function of beam energy p_{beam} for $x_F = 0$ and $p_T = 4$ GeV. The solid, dashed and dot-dashed lines are defined as in Fig. 2.

unpolarized case ⁷ at collider energies leads us to believe that isolated direct photon production in polarized pp interactions should be an appropriate process from which to extract the spin-dependent gluon distribution, as long as the isolation cut is imposed properly in both experimental measurements and theoretical calculations.

Our numerical predictions for the rate of direct photon production at large p_T depend on the polarized parton distributions. Experiments measure only a combination of the distributions, for example, the structure function $g_1^p(x, Q^2)$. One question of interest is how sensitively our predictions depend on the different parametrizations (or separations) of the valence and sea quark distributions. Our conclusion is that at leading order, the cross section is actually insensitive to the different choices of parametrizations of parton distributions, as long as these distributions fit the DIS data. This result is due to dominance of the “Compton” subprocess. To make our point more transparent, we rewrite the cross sections given in Eqs. (4) and (5) approximately as

$$E_\gamma \frac{d\Delta\sigma_{AB}}{d^3p_\gamma}(s, x_F, p_T) = \int dx_a dx_b \left[2g_1^p(x_a, Q^2) \Delta G(x_b, Q^2) E_\gamma \frac{d\hat{\sigma}_{qg}}{d^3p_\gamma}(\hat{s}, x_F, p_T) \right. \\ \left. + (x_a \leftrightarrow x_b) \right] + \text{“Annihilation term”} \quad (6)$$

and

$$E_\gamma \frac{d\sigma_{AB}}{d^3p_\gamma}(s, x_F, p_T) = \int dx_a dx_b \left[\frac{F_2(x_a, Q^2)}{x_a} G(x_b, Q^2) E_\gamma \frac{d\hat{\sigma}_{qg}}{d^3p_\gamma}(\hat{s}, x_F, p_T) \right. \\ \left. + (x_a \leftrightarrow x_b) \right] + \text{“Annihilation term”} \quad (7)$$

where $g_1^p(x, Q^2)$ and $F_2(x, Q^2)$ are the two proton structure functions measured in polarized and unpolarized DIS. Neglecting the annihilation terms, one sees immediately that the cross sections for direct photon production are proportional to measured structure

functions and are therefore not sensitive to the detailed parametrizations of the quark distributions of different flavors. More important is that Eqs. (6) and (7) show that large p_T direct photon production in pp interactions measures the gluon distribution directly, provided the proton structure functions are well measured in DIS.

The x range explored by fixed target experiments is limited. Based on fixed target data, it will be difficult to derive an accurate measurement of the *first moment* of the polarized gluon distribution, which we would like to know. Nevertheless the sign of the polarized gluon distribution as well as its magnitude in the large and intermediate x regions should be accessible experimentally. This information would be particularly interesting.

We conclude that inclusive direct photon production at large p_T in polarized pp collisions at fixed target energies is dominated by the gluon-induced "Compton" subprocess. Correspondingly, fixed target experiments with longitudinally polarized proton beams and targets would measure the sign and magnitude of the polarized gluon distribution in a proton in interesting regions of x . At fixed target energies, the cross section is small, but it should be measurable. The production rate will be greater at higher energies (such as the SSC energy), but at collider energies an isolation cut on the photon may be required to minimize the nonperturbative contribution due to fragmentation processes.

Acknowledgements

We have benefitted from discussions with J.C. Collins, G. Sterman, and W.K. Tung. The research was supported in part by the U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38; and by the National Science Foundation under grant No. PHY-89-08495.

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