Direct photon production in polarized hadron collisions at collider and fixed target energies

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\textbf{ABSTRACT}

Recently determined next-to-leading order sets of polarized parton distributions are used to study large-\(p_T\) \(\bar{p}p \to \gamma + X\) at \(\sqrt{s} = 38, 100\) and 500 GeV. Certain conversion terms, necessary to use the above sets, are determined. It is concluded that, to distinguish between the above sets, planned RHIC experiments should be successful, in particular at c.m. photon pseudorapidity \(\simeq 1\), and that a proposed HERA–\(\bar{N}\) fixed target experiment should have rather large accuracy at relatively large \(x_T (= 2p_T/\sqrt{s})\).

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I. INTRODUCTION

Polarized particle reactions have opened a new domain to test perturbative QCD. In this domain, in spite of extensive recent data on polarized deep inelastic scattering \[1\], the shape and the size of the polarized gluon distribution \(\Delta g(x)\) remains an open question. Important progress requires experiments on reactions with polarized initial hadrons, dominated by subprocesses with initial gluons, like those planned in \[2\] or proposed in \[3\].

Among such reactions, large-\(p_T\) direct photon production in longitudinally polarized proton-proton collisions occupies a prominent place, hence higher (next-to-leading) order corrections (HOC) have been determined \[4,5\]. The results, based on the then existing leading order polarized parton distributions, predicted large asymmetries.

Recently, however, there have been important developments in two respects. First, the two-loop longitudinally polarized splitting functions became known \[6\]. Second, making use of them as well as of the recent data \[1\], sets of new polarized parton distributions have been determined. As before, the sets differ essentially in the input \(\Delta g(x)\). In contrast, however, to older sets, due to \[1\], the new sets exclude very large values of the integral \(\Delta G \equiv \int_0^1 \Delta g(x) \, dx\). Thus the predictions of \[4,5\] must be reconsidered, and this is the main purpose of the present work.

Regarding the extension of the Dirac matrix \(\gamma_5\) in \(n = 4 - 2\varepsilon\) dimensions, in our work \[4\] we adopted an anticommuting \(\gamma_5\) (AC) scheme as well as dimensional reduction (see below). The two-loop splitting functions of \[6\] are determined in a different scheme, and one must calculate the terms to be added to the hard scattering cross section of \[4\] to convert to the scheme of \[6\] (conversion terms). An additional purpose of this work is to determine these terms.

In Sect. 2 we determine the conversion terms. In Sect. 3, using three new sets of polarized parton distributions, we present detailed results and compare them to \[4\]. Sect. 4 contains our conclusions.

II. CONVERSION TERMS

In a given scheme, the \(n\)-dimensional split function \(P_{ba}^n(z, \varepsilon)\) is written

\[
P_{ba}^n(z, \varepsilon) = P_{ba}(z) + \varepsilon P_{ba}^\varepsilon(z); \tag{2.1}
\]

the function \(P_{ba}^\varepsilon(z)\) will be termed \(\varepsilon\)-part. In the same scheme, at some factorization scale \(M\), let \(f_{a/A}(x, M)\) denote parton distribution. In a different scheme, the corresponding quantities are distinguished by primes. Then the parton distributions transform according to: \[6\]

\[
f_{a/A}'(x, M) = f_{a/A}(x, M) + \frac{\alpha_s(M)}{2\pi} \int_x^1 \frac{dy}{y} f_{a/A}(y, M) \left[ P_{ba}(x/y) - P_{ba}^\varepsilon\left(\frac{x}{y}\right)\right] + \mathcal{O}(\alpha_s^2), \tag{2.2}
\]
where $\mu$ is a renormalization scale. Polarized parton distributions, $\Delta f_{a/A}(x, M)$, transform in a similar manner in terms of the polarized $\varepsilon$-parts, $\Delta P_{ba}^\varepsilon(z)$.

In view of the multitude of schemes, in particular for problems of polarized particles, we specify those relevant to the present work.

The first is the anticommuting $\gamma_5$ scheme previously mentioned. This was introduced in [8] and was used to determine the HOC of [8] and most of the HOC of [4]. In this scheme, in addition to $\Delta P_{nqq}^n(z, \varepsilon)$ and $\Delta P_{nnqg}^n(z, \varepsilon)$, the complete expressions are:

\[
\Delta P_{nqq}^n(z, \varepsilon) = C_F \left\{ \frac{1 + z^2}{(1 - z)_+} - \varepsilon(1 - z) + \frac{3 + \varepsilon}{2} \delta(1 - z) \right\}
\]

\[
\Delta P_{nnqg}^n(z, \varepsilon) = 2N_F \left\{ \frac{1}{(1 - z)_+} - 2z + 1 \right\} + \left( b + \varepsilon \frac{N_F}{6} \right) \delta(1 - z)
\]

\[
\Delta P_{qgq}^n(z, \varepsilon) = C_F \left\{ 2 - z + 2\varepsilon(1 - z) \right\}
\]

where $C_F = 4/3$ and $N_C = 3$ (colour SU(3)), $N_F$ is the number of flavours and $b = (11N_C - 2N_F)/6$.

The second scheme is dimensional reduction (RD) [9], in which part of the HOC of [4] were determined. In RD, for all a,b:

\[
P_{ab}^\varepsilon(z) = \Delta P_{ab}^\varepsilon(z) = 0 \quad \text{(RD scheme)} \quad (2.4)
\]

The third is the t’Hooft–Veltman (HV) scheme [10], apart from the $\varepsilon$-part of $\Delta P_{qq}^n$, which is taken as in (2.3) to satisfy helicity conservation. Here we need all split functions, and the remaining ones are found to be (see also the second of [3]):

\[
\Delta P_{qq}^n(z, \varepsilon) = 2N_C \left\{ \frac{1}{(1 - z)_+} - 2z + 1 + 2\varepsilon(1 - z) \right\} + \left( b + \varepsilon \frac{N_F}{6} \right) \delta(1 - z)
\]

\[
\Delta P_{qgq}^n(z, \varepsilon) = 2N_F \left\{ \frac{z - 1}{2} - \varepsilon(1 - z) \right\}
\]

\[
\Delta P_{qgq}^n(z, \varepsilon) = C_F \left\{ 2 - z + 2\varepsilon(1 - z) \right\} \quad \text{(HV scheme)} \quad (2.5)
\]

It is this scheme to which we should convert our results.

The conversion terms are known to arise from differences in the $\varepsilon$-parts of the split functions and are completely determined from the factorization counterterms [7]. The form of the latter has been given in [8], and the determination of the conversion terms is straightforward.

Denoting a given subprocess by $a(p_1) + b(p_2) \to \gamma(p) + c + d$, where the quantities in parentheses are 4-momenta, we define:

\[
\hat{s} = (p_1 + p_2)^2 \quad \hat{t} = (p_1 - p)^2 \quad \hat{u} = (p_2 - p)^2
\]
and
\[ v = 1 + \hat{t}/\hat{s} \quad \quad w = -\hat{u}/(\hat{s} + \hat{t}) \] (2.6)

Below we give the terms to be added to \( \Delta f = \Delta f(v, w) \) defined by: \{Eq. (4.4) of [4(b)]\}

\[
E \frac{\Delta d\sigma}{d^3p} = \frac{\Phi}{\pi p_T^2} \int_{v_1}^{v_2} dv \frac{v(1-v)}{w} \Delta F_a/A(x_a) \Delta F_b/B(x_b) \{ \Delta B(v) \delta(1-w) + \frac{\alpha_s}{2\pi} \Delta f \} 
+ (A \leftrightarrow B, \eta \leftrightarrow -\eta) \] (2.7)

where \( v_1, v_2, w_1, x_a = x_a(v, w), x_b = x_b(v, w) \) and \( \Delta B \) are given in [4(b)]; \( \eta \) is the c.m. pseudorapidity of the photon and \( \Phi \) is also specified below.

First consider \( \vec{g}(p_1) + \vec{q}(p_2) \rightarrow \gamma(p) + q + g \). We need the conversion term from AC to HV scheme. With \( \Phi = \pi \alpha_s e_q^2/N_C \), writing

\[ A \equiv v(1-v)w/2, \]

and setting \( 2N_F \rightarrow 1 \) in the expressions of \( \Delta P_{n}^{g}(z, \varepsilon) \) we find:

\[
\Delta f_{gg} = -A^{-1}(1-w)\{C_F[v^2 + (1-v)^2] + 2N_C(1+v)(1-v)^2 \} \] (2.8)

For \( \vec{g} \rightarrow \gamma q\bar{q} \) we should also go from AC to HV scheme. With \( \Phi = \pi \alpha_s e_q^2/8 \):

\[
\Delta f_{gg} = 2C_F A^{-1}v^2(1-w)(3-v+w) \] (2.9)

Now consider \( \vec{q}_\alpha(p_1) + \vec{q}_\beta(p_2) \rightarrow \gamma(p) + q_\alpha + q_\beta \). We need the conversion term from RD to HV scheme. Here the \( \varepsilon \)-part of the split function \( P_{n}^{q}(z, \varepsilon) \) in the (conventional) dimensional regularization scheme is required. We find:

\[
P_{n}^{q}(z, \varepsilon) = [1 + (1-z)^2]/z - \varepsilon z \quad \quad \text{(dim. reg.)} \]

Then, with \( \Phi = \pi C_F \alpha_s/2N_C \), we find for \( \beta \neq \alpha \):

\[
\Delta f_{qq} = 2v\{e_\alpha^2[1 + \frac{2vw}{1-v} - \frac{1-w}{A} \frac{v^3w^2(2-vw)}{(1-vw)^2}] + e_\beta^2[1 + \frac{2(1-v)}{vw} - \frac{1-w}{vA} (1+v)(1-v)^2] \} \] (2.10)

and for \( \beta = \alpha \) and \( z = 1-v+wv \):

\[
\Delta f_{qq} = 2ve_\alpha^2\{2[1 + \frac{vw}{1-v} + \frac{1-v}{vw} - \frac{z^2}{N_C vw(1-v)}] - \frac{1-w}{A} \frac{v^3w^2(2-vw)}{(1-vw)^2} + \frac{(1+v)(1-v)^2}{v} \} \] (2.11)
Finally we consider $\bar{q}(p_1) + q(p_2) \rightarrow \gamma (p) + q + \bar{q}$ ($q, \bar{q}$ of identical flavour) and give the conversion term from RD $\rightarrow$ HV scheme. With $\Phi = \pi c_F \alpha_s / 2 N_C$:

$$\Delta f_{q\bar{q}} = 2 v e_q^2 \{ 1 + \frac{2v w}{1 - v} - \frac{(1 - v)^2 + v^2 w^2}{z^2} - \frac{2 v^2 w^2}{z} - \frac{1 - w}{A} \frac{v^3 w^2 (2 - v w)}{(1 - v w)^2}$$

$$+ \frac{(1 + v)(1 - v)^2}{v} \}$$  (2.12)

The contributions of $q\bar{q} \rightarrow \gamma gg$ and $\tilde{q}_\alpha \tilde{q}_\alpha \rightarrow \gamma q\bar{q}$ with $q\bar{q}$ produced via $g \rightarrow q\bar{q}$ are obtained from the corresponding unpolarized subprocesses by a change of sign. As in [4], we use unpolarized results in dimensional regularization (MS scheme) and in view of taking $\Delta P_{qq} = P_{qq}$ (see before Eq. (2.5)), conversion terms are absent.

Note that (2.9) is the same as the corresponding term of [11], a fact easily understood: The terms of [11] convert from the so-called MS$_P$ scheme, introduced in [5], to HV. The MS$_P$ scheme has $\Delta P_{qq}^g = C_F[-(1 - z) + \delta(1 - z)/2], \Delta P_{gg}^g = N_F \delta(1 - z)/6$ and $\Delta P_{ab}^g = 0$ for the rest. Thus, as far as we are concerned, it is equivalent to the AC scheme. Likewise, in (2.10)–(2.12), the parts $\sim 1/A$ are the same as the corresponding terms of [11]; they amount to converting from MS$_P$ to HV. Finally, with the transformation $v' = 1 - v w, w' = (1 - v)/(1 - v w)$ [i.e. $t \leftrightarrow \hat{t}$], and taking into account that the Jacobian $\partial(v', w') / \partial(v, w) = v/(1 - v w)$, we find that (2.3) becomes the same as the corresponding result of [11]; it should be so, since the latter interchanges $p_1$ and $p_2$ between initial partons.

Some doubts have been expressed about the possibility to convert from AC to HV scheme [11]. In view of the above, and as far as we can tell, the doubts are unfounded.

### III. RESULTS AND DISCUSSION

We use various sets of polarized parton distributions of one group (the next-to-leading order sets A, B, C of [12]); different groups proceed with different input assumptions, and this may obscure the degree of real difference in the gluon distribution.

Furthermore, in presenting asymmetries we always divide the polarized by unpolarized cross sections determined via one set of unpolarized parton distributions, of STEQ4M [13]; dividing by cross sections determined via distributions of different sets obscures to some extend the differences in $\Delta g(x)$. CTEQ4M has $\Lambda_4 = 0.296$ GeV, which we also use in our (two-loop) expression of $\alpha_s(\mu)$, varying it as we cross the $b$-quark threshold ($m_b = 4.5$ GeV).

An explanation of our attitude towards $\gamma$ Brems and the related $\gamma$ fragmentation is in order. First, the related effects are known to be important at rather small $x_T (= 2p_T / \sqrt{s})$. The RHIC experiment, being a colliding beam one, is expected to observe isolated $\gamma$'s. Then, unless isolation criteria are specified, a calculation of $\gamma$ Brems is of dubious value. The proposed HERA–$\bar{N}$ experiment [3], being a fixed–target one, may observe non-isolated $\gamma$'s. However, it’s energy ($\sqrt{s} = 39$ GeV) is relatively low and the values of $x_T$ for which $\gamma$
Brems is important correspond to $p_T$ rather small. At small $p_T$, other effects, like intrinsic parton’s $k_T$, higher twist etc also become important. In particular at lower $\sqrt{s}$, the cross sections are steeper and $k_T$ effects are stronger.

We thus prefer to leave out $\gamma$ Brems; as in [4], our calculations include only the factorization counterterms necessary to cancel the mass singularities of collinear $\gamma$ emission. The subsequent results correspond to $x_T > 0.08$.

We briefly comment on the input $\Delta g(x)$ of [12] ($Q_0^2 = 4\text{GeV}^2$). In sets A, B, $\Delta g(x) > 0$ throughout; in set C, $\Delta g(x)$ changes sign, and for $x > 0.1$ becomes negative. The integral $\Delta G$ has its largest value for A and its smallest for C; even for A, however, it is significantly smaller than the large $\Delta G$ of [14] used in [4].

As in [4], we present results for $\bar{p}p \rightarrow \gamma + X$ at $\sqrt{s} = 38, 100$ and $500$ GeV; the first value is relevant to the HERA–$\bar{N}$ experiment [3]. Also, we consider photon c.m. pseudorapidities $\eta = 0, 1$ and 1.6 and use $\mu = M = p_T$. As there are similarities in the pattern, in Figs. 1 and 2(a), (b), we present results for set A and $\eta = 1$, but we comment on the results for other sets and $\eta$'s.

Beginning with $q\bar{q} \rightarrow \gamma q$, denote by $\sigma_B(q\bar{q}) [\sigma_{HO}(q\bar{q})]$ the contribution of $\Delta B [\Delta f]$ to $E_\Delta d\sigma/d^3p$, Eq. (2.7). Compared to [4], in the considered range of $x_T$, for sets A, B the $K$–factor $K_{q\bar{q}} \equiv [\sigma_B(q\bar{q}) + \sigma_{HO}(q\bar{q})]/\sigma_B(q\bar{q})$, changes very little; this is clear in Fig. 1(a). For set C, at $\sqrt{s} = 38$ and 100 GeV and $\eta = 1.6$ and 1, $K_{q\bar{q}}$ is not smooth; at $\eta = 0$ and for $\sqrt{s} = 500$ at all $\eta$, it is similar to Fig. 1(a).

Next, for $g\bar{g} \rightarrow \gamma q\bar{q}$ consider the corresponding $\Delta f$ and denote by $\sigma(qg)$ its contribution to $E_\Delta d\sigma/d^3p$. The ratio $K_{gq} \equiv \sigma(qg)/\sigma_B(qg)$, used as a measure, for sets A, B is negative and in magnitude very small over all our kinematic range; Fig. 1(b) presents a typical $K_{gq}$. For C it is similar, except for $\sqrt{s} = 38$ and 100 GeV and small $x_T$, where $K_{gq} > 0$, but still very small.

For $\bar{q}q \rightarrow \gamma qq$, denoting by $\sigma(qq)$ the contribution of the corresponding $\Delta f$, we consider $K_{qq} \equiv \sigma(qq)/\sigma_B(qq)$. For all sets, $K_{qq}$ is negative. In magnitude, for sets A, B it is very small, for C somewhat larger. Fig. 1(c) shows a typical $K_{qq}$.

Now we consider the $K$-factor for all $O(\alpha_s)$ and $O(\alpha_s^2)$ contributions:

\begin{equation}
K \equiv [\sigma_B(qg) + \sigma_{HO}(qg) + \sigma_B(q\bar{q}) + \sigma_{HO}(q\bar{q}) + \sigma(qg) + \sigma(q\bar{q})]/[\sigma_B(qg) + \sigma_B(q\bar{q})] \quad (3.1)
\end{equation}

For sets A, B, due to smallness of $|K_{gq}|$ and $|K_{qq}|$, $K$ is almost the same as $K_{qg}$; Fig. 2(a) makes this clear. As for $K_{qg}$, for set C, $K$ is smooth only at $\sqrt{s} = 500$ GeV.

Turning to cross section $E_\Delta d\sigma/d^3p$, for sets A, B the shapes are similar to [4] but the magnitudes smaller; this is clear in Figs. 2(b) and 2(c). We remark [Fig. 2(c)] that, as in [4], the maximum of $E_\Delta d\sigma/d^3p$ is at $\eta > 0$, near $\eta = 1$ at the higher energies. For set C the behaviour is complicated: at $\sqrt{s} = 38$ GeV for $\eta = 0, 1$ and 1.6, at $\sqrt{s} = 100$ for $\eta = 0$ and 1 and at $\sqrt{s} = 500$ for $\eta = 0$, $E_\Delta d\sigma/d^3p$ changes sign as $x_T$ varies.

Figs. 3,4 present in detail asymmetries

\begin{equation}
A_{LL}(p_T, s, \eta) = E_\Delta d\sigma(p_T, s, \eta)/d^3p/Ed\sigma(p_T, s, \eta)/d^3p \quad (3.2)
\end{equation}
Considering first $\sqrt{s} = 38$ GeV, for $p_T \leq 6$ GeV, due to the smallness of $\Delta G$, $A_{LL}$ is small for all sets. It becomes larger at larger $p_T$, and for $x_T \geq 0.4$ there is a clear distinction, at least between set A and sets B, C. The cross sections, however, become smaller and the proposed HERA–$\bar{N}$ experiment \cite{3} will need high accuracy. At $\sqrt{s} = 100$ and 500 GeV (RHIC Spin), to distinguish between A and B, C should not be difficult at either $\eta \simeq 0$ or $\eta \simeq 1$; to distinguish between B and C, data near $\eta \simeq 1$ (Fig. 4) may be necessary.

Note that, in general, $A_{LL}$ determined with HOC and without (only Born) differ. Fig. 4 shows the latter for set A, $\sqrt{s} = 100$ and $\eta = 1$ (dash-dotted line); at the higher $p_T$, it differs by a factor $\sim 2$.

Finally we turn to the effect of changing the scales, and consider the ratio (Fig. 5, set A):

$$r = E \Delta d\sigma(M = p_T/2)/d^3p / E \Delta d\sigma(M = 2p_T)/d^3p$$

As one expects, with the evolution of the distributions determined via two-loop splitting functions, there is more stability than in \cite{4}. With set B, $r$ is even more stable. Set C leads to unstable $r$, ranging from negative to positive values.

One may wonder about the effect of the conversion terms (Sect. 2) on our results. For all quantities considered, the effect does not exceed 6%; of course, mathematical consistency requires the presence of the terms.

**IV. CONCLUSIONS**

Our essential conclusions, based on the next-to-leading order sets A, B, C of \cite{12}, are as follows:

In general, there is a marked difference between the predictions of sets A, B ($\Delta g(x) > 0$) and of set C ($\Delta g(x)$ changing sign).

For sets A, B, the $K$-factors \cite{3.1} exceed unity; thus the HOC enhance the Born cross sections. For set C, $K$-factors are more complicated and in several cases the HOC are of opposite sign to the Born.

Due to smaller $\Delta G$, the cross sections and asymmetries $A_{LL}$ are smaller than in \cite{4}. $A_{LL}$ become significant at relatively large $p_T$, and the differences between $A_{LL}$ of the above three sets are larger at $\eta \simeq 1$, where also polarized cross sections are larger, in general. Thus, to distinguish between A, B and C, RHIC, with its expected high luminosity, should be successful, in particular near $\eta = 1$; on the other hand, HERA–$\bar{N}$ will need rather high statistics at $x_T \geq 0.4$.

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FIGURE CAPTIONS

Fig. 1. Relative contributions of the basic subprocesses using the distributions of set A at
$\eta = 1$. Dashed lines: $\sqrt{s} = 38$ GeV, dotted: $\sqrt{s} = 100$, solid: $\sqrt{s} = 500$. (a) The
$K$-factor $K_{gg}$ for $\bar{g}g \rightarrow \gamma q$. (b) The factor $K_{gg} \equiv \sigma(gg)/\sigma_B(gg)$ for $\bar{g}g \rightarrow \gamma q\bar{q}$. (c) The
factor $K_{qq} \equiv \sigma(qq)/\sigma_B(gg)$ for $\bar{q}q \rightarrow \gamma qq$. 
Fig. 2. Results with set A: (a) The $K$-factor (3.4) for all $O(\alpha_s)$ and $O(\alpha_s^2)$ contributions at $\eta = 1$. (b) Inclusive cross sections for $p\bar{p} \rightarrow \gamma + X$ vs $x_T = 2p_T/\sqrt{s}$ for $\eta = 1$. Lines as in Fig. 2(a). (c) Inclusive cross sections for $p\bar{p} \rightarrow \gamma + X$ vs $\eta$.

Fig. 3. Asymmetries $A_{LL}$ for all three sets of distributions at pseudorapidity $\eta = 0$.

Fig. 4. As Fig. 3 for $\eta = 1$.

Fig. 5. Ratio $r \equiv [E\Delta d\sigma(M = \mu = p_T/2)/d^3p]/[E\Delta d\sigma(M = \mu = 2p_T)/d^3p]$ with set A. Solid lines: $\eta = 1.6$. Dotted: $\eta = 1$. Dashed: $\eta = 0$. 

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