Higher order corrections to longitudinally polarized reactions^(†)

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Higher order corrections (HOC) are determined for (I) Large- p_T direct γ production in $\vec{p}\vec{p}$ collisions and (II) Polarized photoproduction of heavy $Q\bar{Q}$. For (I) detailed next-to-leading order corrections and for (II) the HOC to the dominant subprocess $\vec{\gamma}\vec{g} \rightarrow Q\bar{Q}$ are presented. In general, K -factors well exceed unit. For both (I) and (II), soft, collinear and virtual gluons dominate the HOC, at least for sufficiently large x_T .

1 Introduction

The central problem of Spin Physics is to determine the size and shape of $\Delta g(x)$. The best way is to study polarized reactions dominated by subprocesses with initial gluons. Two of the most important such reactions are:

(I) $\vec{p}\vec{p} \rightarrow \gamma(\text{large-}p_T) + X$ domin. by $\vec{q}\vec{g} \rightarrow \gamma q$

(II) $\vec{\gamma}\vec{p} \rightarrow Q(\bar{Q}) + X$ domin. by $\vec{\gamma}\vec{g} \rightarrow Q(\bar{Q})$

Experiments at various stages of proposal are: For (I) RHIC Spin, $\sqrt{s} = 100 - 500$ GeV and HERA, $\sqrt{s} = 40$ GeV; for (II) SLAC and COMPASS, $\sqrt{s_{\gamma p}} \simeq 10$ GeV and HERA, $\sqrt{s_{\gamma p}} \simeq 40$ GeV [1].

The importance of determining HOC cannot be overemphasized. Theoretically, in general, they enhance the stability of the predictions against changes of schemes and

scales. Phenomenologically, if HOC are large and of opposite sign to the Born, predicted cross sections are small and experiments hard.

Now polarized 2-loop split functions (anomalous dimensions) are available [2] and on their basis various groups have constructed sets of polarized parton distributions differing essentially in the size and shape of Δg . We use the sets of *one* group [3], which can be roughly characterized as follows:

Set A: $\Delta g(x) > 0$ and relatively large,

Set B: $\Delta g(x) > 0$ and small,

Set C: Δg changing sign; $\Delta g < 0$ for $x > 0.1$.

We present detailed next-to-leading order (NLO) predictions for (I) and preliminary ones for (II). Note that we aim at the *whole* of Δg , i.e. all its moments, and not just the first one.

^(†) Supported by the Secretariat of Research and Technology of Greece, by the Natural Science and Engineering Research Council of Canada and by the EU Human Capital and Mobility Program CHRX-CT93-0319.

2 Direct photon production

The contributing subprocesses, known from unpolarized $pp \rightarrow \gamma(\text{large-}p_T) + X$, have been calculated some time ago [4, 5]. At that time polarized 2-loop split functions were not available; also, the then existing data were permitting quite large Δg . So, the predictions of e.g. [4] have been reconsidered [6].

Treating HOC in polarized reactions via dimensional methods requires extension of the Dirac matrix γ_5 in $n = 4 - 2\epsilon$ dimensions. There are several schemes for this, and the scheme of [2] differs from those of [4]; so adding *conversion terms* is necessary.

In general the n -dimensional split functions have the form:

$$P_{ba}^n(x, \epsilon) = P_{ba}(x) + \epsilon P_{ba}^\epsilon(x). \quad (1)$$

The conversion terms are determined from the difference of $P_{ba}^\epsilon(x)$ in the various schemes [6].

Fig. 1 presents K -factors at $\sqrt{s} = 500$ GeV and 100 GeV (RHIC) as well as at 38 GeV ($\sim$ HERA), for set A and pseudorapidity $\eta = 1$; results for set B are very similar, and for C and other η 's are discussed in [4]. First, for $\bar{q}\bar{q} \rightarrow \gamma q$, denoting by $\sigma_B(qq) [\sigma_{HO}(qq)]$ the contribution of Born [HOC] to the cross section

Fig. 1

Fig. 2

$E\Delta d\sigma/d^3p$, Fig. 1(a) shows $K_{qg} \equiv [\sigma_B(qg) + \sigma_{HO}(qg)]/\sigma_B(qg)$. Next, Fig. 1(b) shows the corresponding K -factor for all $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$ contributions:

$$K \equiv [\sigma_B(qg) + \sigma_{HO}(qg) + \sigma_B(q\bar{q}) + \sigma_{HO}(q\bar{q}) + \sigma(gg) + \sigma(qq)]/[\sigma_B(qg) + \sigma_B(q\bar{q})].$$

Clearly K differs little from K_{qg} , i.e. $q\bar{q} \rightarrow \gamma q$ indeed dominates. This is further supported by Fig. 1(c), in which $K_{q\bar{q}} \equiv \sigma(q\bar{q})/\sigma_B(q\bar{q})$ is small. Finally, $\sigma(gg)/\sigma_B(qg)$ is even smaller, see [4].

The important point is that, in general, K well exceeds unit. Fig. 2 presents asymmetries A ; we see that they permit a clear distinction between sets A, B and C , in particular at RHIC.

3 Photoproduction of heavy Q (Open)

The contributing subprocesses are as follows:

At leading order ($\alpha\alpha_s$): (a1) The Born subprocesses of (II). (a2) The resolved γ via:

$$\bar{q}\bar{q} \rightarrow Q\bar{Q}, \quad g\bar{q} \rightarrow Q\bar{Q}. \quad (2)$$

These involve the polarized γ structure functions $\Delta F_{q/\gamma}$, $\Delta F_{g/\gamma}$ known only theoretically [7]; hopefully, some information will eventually come from the related experiments of Sect. 1.

At NLO ($\alpha\alpha_s$): (b1) The loop and Bremsstrahlung (Brems) subprocesses associated with (a1). This is the hardest part of the calculation due to $m_Q \neq 0$. (b2) The subprocess

$$\bar{\gamma}\bar{q} \rightarrow Q\bar{Q}q. \quad (3)$$

In what follows we present *preliminary* results for (a1) and (b1) only. Educated guesses [8], [4, 6] suggest that in the kinematic ranges below we account for the dominant part of the NLO corrections; however, everything should be accounted for. Also here, we present results only with sets A, B .

Notice that the Abelian part of (b1) provides the HOC to

$$\bar{\gamma}\bar{\gamma} \rightarrow Q\bar{Q}. \quad (4)$$

This is of interest in itself [9]: In Higgs searches, for $M_H < 2M_W$, in future $\gamma - \gamma$ colliders, the

dominant mode is:

$$\gamma\gamma \rightarrow H \rightarrow b\bar{b}. \quad (5)$$

With polarized γ 's the Born background to $\bar{\gamma}\bar{\gamma} \rightarrow b\bar{b}$ is suppressed, but HOC have important effects [9].

Regarding the determination of HOC, loop contributions (b1) were determined via Passarino-Veltman techniques and Brems contributions using the Gottfried-Jackson frame of the final $g + \bar{Q}$ [10, 9]. The singularities ($1/\epsilon^2, 1/\epsilon$) were eliminated via dimensional reduction. In general, this is problematic regarding the Ward identity. To satisfy it we had to add a vertex counterterm [9]:

$$\gamma^\mu \rightarrow \frac{-g^2}{(4\pi)^2} C_F (g^{\mu\nu} - g_n^{\mu\nu}) \gamma_\nu \frac{1}{\epsilon}. \quad (6)$$

where $g_n^{\mu\nu}$ the metric tensor in n dimensions. Also, to use polarized parton distributions of 2-loop split functions [3], we added proper conversion terms (Sect. 2).

The heavy Q mass and wave function renormalization are carried on shell [9]. Charge renormalization is carried in the following scheme: Let $g_0(g)$ denote the bare (renormalized) coupling and define the renormalization constant $Z_g \equiv g_0/g$. Also define

$$A_\epsilon(m) \equiv (g/4\pi)^2 (4\pi\mu^2/m^2)^\epsilon \Gamma(1+\epsilon). \quad (7)$$

Then, with N_{lf} = number of light flavors, $b = (11N_c - 2N_{lf})/6$ and m_R a regularization mass:

$$Z_g = 1 - \frac{1}{\epsilon} \left\{ A_\epsilon(m_R) b - \frac{1}{3} A_\epsilon(m) \right\}. \quad (8)$$

In this scheme the heavy Q is decoupled at low energy. In arriving at (8), we use Slavnov-Taylor identities; we also use them to fix the vertex $gQ\bar{Q}$ renormalization.

We consider $Q = c$ with $m_c = 1.5 \text{ GeV}$. Let p_T the transverse momentum of c and y its rapidity in the $\gamma - p$ c.m. The cross sections of interest are $\Delta d\sigma/dp_T$ and $\Delta d\sigma/dy$. We present results for the first, with the scales $\mu = M = (p_T^2 + m_c^2)^{1/2}$, at $\sqrt{s_{\gamma p}} = 10 \text{ GeV}$ (SLAC and COMPASS).

Denoting by $\Delta d\sigma_B/dp_T$ the contribution of (a1)(Born) and by $\Delta d\sigma_{HO}/dp_T$ that of (b1), Fig.

$$K \equiv \frac{\Delta d\sigma_B/dp_T + \Delta d\sigma_{HO}/dp_T}{\Delta d\sigma_B/dp_T} \quad (9)$$

We notice that: (i) K 's are sizable, a welcome result; this is not surprising since the corresponding p_T 's are rather small and $\alpha_s(\mu)$ fairly large, (ii) sets A and B lead to similar K 's since changing the set affects similarly the numerator and denominator of (9), and (iii) K 's vary little with x_T (excepting kinematic endpoints).

Finally we ask to what extent soft, collinear and virtual gluon terms dominates the HOC. To be specific, let $\bar{\gamma}(p_1) + \bar{g}(p_2) \rightarrow Q(p_3) + \bar{Q}$ the basic subprocess and define

$$s = 2p_1 \cdot p_2, \quad \bar{t} = -2p_1 \cdot p_3, \\ \bar{u} = -2p_2 \cdot p_3, \quad w = -\bar{u}/(s + \bar{t}).$$

The above terms correspond to HOC pieces proportional to the distributions $\delta(1-w)$, $1/(1-w)_+$ and $(\ln(1-w)/(1-w))_+$. Denoting by $\Delta d\sigma_s/dp_T$ the contribution of such pieces, Fig. 4 presents

$$L \equiv \frac{\Delta d\sigma_{HO}/dp_T - \Delta d\sigma_s/dp_T}{\Delta d\sigma_{HO}/dp_T}. \quad (10)$$

Clearly, L is small, i.e. soft, collinear and virtual gluons dominate the HOC. Moreover, as x_T increases, L decreases fast, a general feature for unpolarized, longitudinally polarized [4] and transversely polarized reactions.

One should keep in mind that, particularly at lower p_T , other effects (higher twist, nucleon mass etc.), left out in perturbative calculations like ours, may play an important role.

Fig. 3

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Fig. 4