DIRECT PHOTON PRODUCTION IN $\bar{p}p$ COLLISIONS
AT COLLIDER AND ISR ENERGIES

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ABSTRACT

Predictions are presented for large $p_T$ direct photon production in $\bar{p}p$ collisions at collider and ISR energies in perturbative QCD. They are based on recently determined gluon and other parton distributions. Higher order ($O(\alpha_s^2)$) corrections (K factors) are taken into account. Comparison is also made with ISR data on $pp \rightarrow \gamma + X$.

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Direct photon production in hadronic collisions at large transverse momenta ($p_T$) \(^1\)-\(^2\) has been an important success of QCD, at least at ISR energies.

With the remarkable operation of the CERN collider, one may anticipate that direct γ data will soon be available at a much higher energy ($\sqrt{s} = 540$ GeV) and larger $p_T$. It is therefore important to present detailed theoretical predictions at such $s$ and $p_T$.

For one reason, particular interest arises from the fact that direct γ production provides important tests or constraints on the gluon distribution. Recently, the CERN-Dortmund-Heidelberg-Saclay-Beijing collaboration \(^4\) (CDHSB), by analyzing deep inelastic neutrino data, has produced a new form of the gluon distribution in the nucleon, and in fact a detailed set of parton distributions. Our calculations are based on these distributions, thus offering a test of the CDHSB gluon.

In recent years there has been much work on large corrections of higher orders of perturbative QCD (\(\Lambda\) factors). Here corrections to $O(\alpha_s^2)$ are approximately taken into account.

QCD studies of direct γ production are based on the subprocesses

\[\begin{align*}
q + q &\rightarrow q + γ \\
q + \bar{q} &\rightarrow q + γ
\end{align*}\]

Their lowest order differential cross-sections [Born, of \(O(\alpha_s^2)\), to be denoted by $d\sigma/dt$, are well known \(^5\),\(^6\)] and the contribution to the inclusive cross-section of $A + B \rightarrow γ + X$ for γ production at c.m. angle $\theta$ is

\[
E \frac{d\sigma}{d^3p} (s, p_T, \theta) = \frac{2}{\pi} \int_0^1 \frac{dx_a}{2x_a - x \cot \frac{\theta}{2}} \frac{F_{A/A} (x_a, Q^2)}{F_{B/B} (x_b, Q^2)} d\sigma_{\gamma} + A \rightarrow B
\]

where $x_T = 2p_T/\sqrt{s}$ and

\[
\begin{align*}
x_b &= x_T \frac{\tan \frac{\theta}{2}}{2x_a - x \cot \frac{\theta}{2}} \\
x_1 &= x_T \frac{\cot \frac{\theta}{2}}{2 - x_T \tan \frac{\theta}{2}}
\end{align*}
\]
\( F_{g/p}(x, Q^2 = 5 \text{ GeV}^2) = 2.616 (1 + 3.5x)(1-x)^{5.9} \) 

References 6) used a strong gluon distribution of the form \( F_{g/p}(x, Q^2=4)= 0.866(1+9x)(1-x)^4 \); this is stronger than (5). Still, it was found that ISR \( pp \rightarrow \gamma + X \) data require a \( K \) factor, roughly \( K \sim 2 \) \(^8\),\(^9\),\(^1\). Such \( K \) factors are known to arise from perturbative corrections due to virtual and real gluon emission. Unfortunately, for the subprocesses (1) and (2), no complete calculation of the \( O(\alpha_s^2) \) corrections is yet available. Such calculations are quite lengthy, and the final results very complicated and often non-transparent. However, for several large transfer processes, \( \pi^2 \) terms similar to those of Drell-Yan dilepton production (from loop graphs in the soft gluon limit) as well as certain collinear gluon bremsstrahlung (Brems) configurations were found responsible for the bulk of the correction \(^9\),\(^10\). In particular, for the subprocess (1), which dominates large \( p_T \) \( pp \rightarrow \gamma + X \), the techniques of Ref. 8) have led to an appropriate \( K \) factor. Also for the subprocess \( q\bar{q} \rightarrow \gamma + X \), which is closely related with (2) (and is important in large \( p_T \) \( \pi^+ \pi^- \rightarrow e^+e^- + X \) and \( \bar{p}N \rightarrow e^+e^- + X \)), a \( K \) factor has been determined again in agreement with the data as well as with complete theoretical calculations \(^10\),\(^11\).

We thus proceed with the results of Refs. 8) and 10). To \( O(\alpha_s^2) \) these amount to cross-sections of the form

\[
\frac{d\sigma}{d\mathbf{k}^2} = \left(1 + \frac{\alpha_s(Q^2)}{2\pi} C_{\pi^2} \right) \frac{d\sigma_{0}}{d\mathbf{k}^2} \tag{6}
\]

where \( C \) is a colour factor. For the subprocesses (1) and (2) \(^8\),\(^10\):

\[
C_{\gamma\pi^2} = N_c - C_F \quad C_{\gamma\bar{q}q} = C_F \tag{7}
\]

with \( N_c = 3 \) and \( C_F = 4/3 \) in colour SU(3). Note that (7) imply comparable corrections to (1) and (2).

At ISR energies, effects due to partons' intrinsic transverse momentum \( (k_T) \) are not very important for direct \( \gamma \) production [see Ref. 6) for a detailed calculation]; they are even less important at the collider where,
as functions of $p_T$, the cross-sections are less steep. Nevertheless we take them into account using a modest $\langle k_T^2 \rangle = 0.5$ GeV. Also, we use $\alpha_s(Q^2) = \frac{12\pi/25}{\ln(Q^2/\Lambda^2)}$ with $\Lambda = 0.2$ GeV.

There is a well-known ambiguity in the choice of the large variable $Q^2$. To decide, we have carried out calculations of $pp \to \gamma + X$ at $\sqrt{s} = 63$ GeV with $Q^2 = 2p_T^2$ and $Q^2 = p_T^2$, and compared with data (see below). We found that the choice $Q^2 = p_T^2$ (leading to a somewhat larger cross-section) gives better agreement, and we proceed with it.

Our predictions for $E\sigma/d^3p$ of $\bar{p}p \to \gamma + X$ at collider energy and $\theta = 90^\circ$ are given in Fig. 1, upper part. The dashed line corresponds to the sum of Born contributions of (1) and (2); the solid line includes the $O(\alpha_s^2)$ corrections (6) and (7) and $k_T$ effects. Figure 1 also shows separately the Born contributions of (1) and (2) denoted by $qg$, $q\bar{q}$, respectively.

To compare direct $\gamma$ with $\pi^0$ yields, we introduce the ratio

$$
\frac{\frac{\gamma}{\pi^0}}{AB} = \frac{E\sigma(AB \to \gamma X)/d^3p}{E\sigma(AB \to \pi^0 X)/d^3p} \tag{8}
$$

Regarding $\bar{p}p \to \pi^0 + X$ we proceed as follows: for $p_T \lesssim 4.5$ GeV we use an interpolation through available data; for $p_T > 4.5$ we use the theoretical calculation of Ref. 7) with the over-all normalization slightly adjusted to fit well the data at $p_T \lesssim 4.5$. Anyway, our $E\sigma(\bar{p}p \to \pi^0 X)/d^3p$ is also shown in Fig. 1, upper part. Then Fig. 1, lower part, shows our prediction for $(\gamma/\pi^0)_{pp}$ using the solid line of the upper part. At $p_T \approx 50$ GeV ($x_T \approx 0.2$) we predict $(\gamma/\pi^0)_{pp} \approx 1$. It is, perhaps, significant that Ref. 13) has a similar prediction, although it uses a different set of parton distributions ($P_{E/p}(x,Q_0^2=1.8) \sim (1-x)^5$).

In the range $15 \lesssim p_T \lesssim 30$ GeV there are some preliminary data for $\bar{p}p \to$ neutral + $X$, where neutral = $\gamma$, $\pi^0$ or $\eta$. Regarding $\gamma$ they can be summarized by stating: $(\gamma/jet)_{\bar{p}p} \lesssim 10^{-3}$. Our predictions (Fig. 1) are consistent with this result.

Note that in all the $p_T$ range of Fig. 1, the contribution of subprocess (1) well exceeds that of (2). The reason is that the corresponding $x_T (\lesssim 0.2)$ is small, so that $P_{E/p}(x,Q^2)$ is bigger than $P_q/p(x,Q^2)$. Of course, as $x_T$ increases, the subprocess (2) becomes more and more important.
Figure 2, upper part, shows our results for $pp \to \gamma X$ and $\bar{p}p \to \gamma X$ at $\sqrt{s} = 63$ GeV (with $K$ factors and $k_T$ effects included). Together, we present data on $pp \to \gamma X$ 1); at the lower $p_T$ they somewhat exceed our result. It is then possible that at such $p_T$ also our collider prediction is an underestimate. Note that at low $p_T$ ($\lesssim 4$ GeV), $\bar{p}p \to \gamma X$ is only slightly above $pp \to \gamma X$, but as $p_T$ increases, the former exceeds the latter more and more. This is because $\bar{p}$ contains valence antiquarks, so as $p_T$ increases ($x_T$ increases) the contribution of subprocess (2) to $\bar{p}p \to \gamma X$ becomes more and more important. Regarding the ratio $r = E_d(\bar{p}p \to \gamma X)/d_\gamma^3p/E_d(pp \to \gamma X)/d_\gamma^3p$ we predict that at $p_T = 6$ GeV $r \approx 1.4$ and at $p_T = 8$ $r \approx 1.65$. These ratios are fairly stable against various uncertainties of our calculation (form of $F_{E/p}$, choice of $Q^2$ and $\Lambda$) since they mainly depend on the increasing importance of subprocess (2) in $\bar{p}p \to \gamma X$.

Finally, Fig. 2, lower part, presents our ratios $(\gamma/n^0)_{\bar{p}p}$ (solid line) and $(\gamma/n^0)_{pp}$ (dash-dot-dotted line) at $\sqrt{s} = 63$. For $pp \to n^0 X$ we use an interpolation through the presented data 1). For $\bar{p}p \to n^0 X$ we assume $E_d/d_\gamma^3p$ the same as for $pp \to n^0 X$; this is supported by recent data 15), as well as by our theoretical calculations 7). We predict $(\gamma/n^0)_{\bar{p}p} \approx 1$ at $p_T \sim 9$ GeV.

Certain comments are now in order.

First, at a fixed $p_T$, the predicted direct $\gamma$ yields at collider energy are significantly higher than those at ISR energies. For example, at $p_T = 10$ GeV, $\bar{p}p \to \gamma X$ at $\sqrt{s} = 540$ exceeds $pp \to \gamma X$ at $\sqrt{s} = 63$ by almost two orders of magnitude, and $\bar{p}p \to \gamma X$ at $\sqrt{s} = 63$ by a factor of 40.

On the other hand, at a fixed relatively low $p_T$ ($\lesssim 10$) our predicted collider ratios $(\gamma/n^0)_{\bar{p}p}$ are well below the corresponding ISR ratios. This is because at such $p_T$ the $n^0$ cross-sections increase even more. The reason is that at the collider relatively low $p_T$ corresponds to very small $x_T$ ($\lesssim 0.04$); then $\bar{p}p \to n^0 X$ (and $p^* \to \gamma X$) receives a strong contribution from the subprocess $gg \to \gamma$ 13),7); there is no such contribution to $\bar{p}p \to \gamma X$.

Figures 1 and 2 include no contributions from the photon Brems subprocesses $qq \to qg\gamma$ studied in the second of Ref. 6), $gg \to qg\gamma$ and $gg \to q\bar{q}\gamma$. They can be estimated on the basis of the fragmentation function for $q \to \gamma$ 16)

$$D_{\gamma/q}(x, Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \left( \frac{1.14}{1 - 0.72 \log(1 - x)} \right) \log \frac{Q^2}{\Lambda^2}$$  \hspace{1cm} (9)

or of the lowest order probability function 6)
\[ P_{\gamma^*q}(x) = \frac{1 + (1-x)^2}{x} \] (10)

The result is an increase of the predicted cross-sections by 25% - 50%.

Finally, we remark that the \( O(\alpha_s^2) \) corrections [Eqs. (6) and (7)] are positive and large, as in Drell-Yan and other large transfer processes. However, their magnitude (as well as of the photon Brems contribution) is comparable to that of various uncertainties, like the exact form of the gluon distribution and the choice of the large variable \( Q^2 \) or of \( \Lambda \).

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Notice that use of the forms (9) and (10) is justified at not too small
\( x_\tau \).
**FIGURE CAPTIONS**

**Figure 1** : $\bar{p}p \rightarrow \gamma + X$ at collider energy. Upper part: dashed line: sum of lowest order (Born) contributions; solid line: including $O(\alpha_s^2)$ corrections and $k_T$ effects. The Born contributions (divided by 10) of the subprocesses $qg \rightarrow q\gamma$ and $q\bar{q} \rightarrow g\gamma$ are indicated by $qg$ and $q\bar{q}$. Lower part: the ratio $\sqrt{n^0}$ corresponding to the solid line of the upper part and to the indicated $\bar{p}p \rightarrow n^0 + X$ cross-section.

**Figure 2** : $pp \rightarrow \gamma + X$ and $\bar{p}p \rightarrow \gamma + X$ at ISR energy. Solid lines (corresponding to $pp \rightarrow \gamma + X$) and dash-dot-dotted lines (corresponding to $\bar{p}p \rightarrow \gamma + X$) include $O(\alpha_s^2)$ corrections and $k_T$ effects.
\( \bar{p}p \rightarrow \gamma + X \)

\( \sqrt{s} = 540 \text{ GeV} \)

\( \theta = 90^\circ \)

Figure 1
Fig. 2