Prompt Photon Production in $\gamma\gamma$ Collisions and the Gluon Content of the Photon

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Abstract

We calculate the cross section for inclusive prompt photon production in $\gamma\gamma$ collisions, i.e. the reaction $e^+e^- \rightarrow \gamma\gamma \rightarrow \gamma X$, in next-to-leading order QCD. We show that at LEP2 energies this cross section is measurable and is sensitive to the gluon distribution of the photon, $g_\gamma$, which is currently very poorly constrained by data.
I. INTRODUCTION

The quark parton distribution functions (pdfs) of various particles, such as the proton and photon, are mainly determined by structure function measurements. This is because in leading order (LO) the structure function $F_2(x, Q^2)$ is directly proportional to the quark and anti-quark distributions:

$$F_2(x, Q^2) = \sum_{i=1}^{N_f} x e_i^2 \left( q_i(x, Q^2) + \bar{q}_i(x, Q^2) \right)$$

(1.1)

However gluon distributions are poorly constrained by such analyses because of the relatively weak coupling between the Altarelli-Parisi equations for the singlet quark and gluon sectors and so less direct methods must be used. In the case of hadrons, in particular the proton, the momentum sum rule provided the initial evidence for the existence of gluons and remains a very powerful tool in constraining the gluon distribution, particularly when combined with theoretical constraints on the $x$-dependence of the distributions as provided by counting rules and Regge theory. The application of perturbative QCD (PQCD) to phenomena at large momentum transfers provides invaluable further constraints on the pdfs. In particular, prompt photon production at large momentum transfer ($p_T$) is particularly useful, as it is very sensitive to the gluon distributions of the colliding particles as the dominant hard subprocess here is $gq \rightarrow \gamma q$. However, a meaningful analysis of existing data \cite{1,2} on $\bar{p}p$ collisions is highly non-trivial: in particular, isolation criteria on the photon signal must be imposed in order to reduce the background to the subprocess of interest produced by non-prompt photons from $\pi^0$s produced at large $p_T$ and subsequently decaying into two photons and prompt photons produced by fragmentation from the final state partons \cite{3,4}.

For the case of the photon, the situation is much worse than for the proton and the pdfs relatively poorly known for various reasons. Firstly, the structure function data on $F_2^\gamma(x, Q^2)$ are much less precise than that for protons and so the knowledge of the quark distributions is correspondingly worse. In addition, the gluon pdf, $g^\gamma$, is even less well determined. Most importantly, it is not constrained by a momentum sum rule \cite{5,6}. Also jet studies
in photon induced reactions are in their infancy. However jet cross-section measurements at TRISTAN \[7,8\] have recently established that \( g^\gamma \neq 0 \), a result confirmed at HERA \[9\].

The result of all this is that the available parametrizations of the photon have considerably different gluon distributions \[10,11\]. The input gluon distributions in the evolution equations, whilst not completely arbitrary, are currently just theoretically motivated guesses. Further PQCD studies of large \( p_T \) jets in photoproduction at HERA and in \( \gamma \gamma \) collisions with better data than are currently available will improve this situation but it seems worth investigating whether the production of prompt photons at large \( p_T \) in photon initiated reactions can be used to extract information on \( g^\gamma \). There have been several studies of prompt photon production at HERA \[12–14\]. The more realistic analyses \[13,14\], which work in the HERA lab frame with a spectrum of initial photon energies given by the equivalent photon approximation (EPA) \[15\], find slightly discouraging results in the sense that the competing subprocesses are hard to disentangle and the signal due specifically to \( g^\gamma \) difficult to isolate.

In this letter we investigate prompt photon production in \( \gamma \gamma \) collisions as a means of constraining \( g^\gamma \). This process was first investigated by Drees and Godbole \[16\]: their work must be regarded as a preliminary effort for several reasons. Firstly, it was a LO calculation of prompt photon plus opposite side jet. The reason for the latter condition was to suppress the contribution of fragmentation processes by requiring a kinematic balance (in \( p_T \)) between the photon and opposite side jet: because of the difficulty in measuring the ‘true’ \( p_T \) of the jet it is not clear how efficient this requirement would be. Also the photon pdfs they used have been superseded \[11\]. In our study we consider the inclusive prompt photon cross section including fragmentation contributions. We calculate in next-to-leading order (NLO) QCD using up-to-date NLO photon pdfs and NLO photon fragmentation functions (FFs).

II. BASIC MECHANISMS

To answer the question as to whether this cross section will be useful in constraining \( g^\gamma \), there are various points we need to consider:
1. Firstly in LO, the process is $O(\alpha_{em}^3/\alpha_s)$ where $\alpha_{em}$ and $\alpha_s$ are the electromagnetic and strong coupling respectively, so we need to know whether the cross section will be large enough to measure, at least at LEP2.

2. There are many subprocesses contributing to the cross section which we shall list below. For the purpose of extracting $g^\gamma$, the most important subprocesses are the ones involving two resolved photons in the initial state. We need to know whether there are any accessible kinematic regions where these processes contribute significantly.

3. As we shall soon see, there are many subprocesses where the prompt photon is produced via fragmentation off a final state parton. These involve the photon FFs, which are not well known at present. Thus it is important that the contribution of these background processes is not very significant.

4. Finally, we need to determine how important the NLO corrections are in order to decide whether conclusions drawn from the LO study are valid when HO corrections are taken into account. The only way to determine this is to calculate the cross section fully in NLO.

**A. Contributing Subprocesses: LO**

We begin by discussing the different contributions in the LO case. We divide the contribution into the seven types shown in fig.1(a)-(g) and classified in Table 1. They are classified according to the initial state, i.e. whether one (1-res), both (2-res), or neither (D), of the initial state photons are resolved, the final state, i.e. whether the prompt photon is produced directly in the hard subprocess (NF) or by the subsequent fragmentation from one of the partons produced in the hard subprocess(F), and by the type of hard subprocess. The notation for resolved photons and photon fragmentation is described in fig.1(h). All of these contributions in fig.1(a-g) are $O(\alpha_{em}^3/\alpha_s)$ because both the photon pdfs and photon FFs are $O(\alpha_{em}/\alpha_s)$. To take an example we consider the contribution shown in fig.1(c). This involves
one photon pdf and one photon FF which when convoluted with the subprocess cross section $\gamma q \rightarrow gq$ which is $O(\alpha_{em}\alpha_s)$ yields a contribution of $O(\alpha_{em}^3/\alpha_s)$. The 2-res fragmentation processes generically shown in fig.1(e) contain many type of subprocess, namely:

\begin{align*}
q + q &\rightarrow q + q \\
q + q' &\rightarrow q + q' \\
q + \bar{q} &\rightarrow q + \bar{q} \\
q + \bar{q} &\rightarrow q' + \bar{q}' \\
q + \bar{q} &\rightarrow g + g \\
g + g &\rightarrow q + \bar{q} \\
q + g &\rightarrow q + g \\
g + g &\rightarrow g + g 
\end{align*}

and we sum over them all. The total is still small.

Note that as regards a clean signal from the gluon content of the photon, not involving fragmentation, it is mostly the NF 2-res process of fig.1(g) that is relevant, corresponding to the subprocess $gq \rightarrow \gamma q$. Fortunately it is very significant, as we shall see.

**B. Contributing Subprocesses: NLO**

When it comes to the NLO calculation, then there are four types of corrections to the basic mechanisms:

1. NLO corrections to photon pdfs,

2. NLO corrections to the photon FFs,

3. NLO corrections to the matrix elements for the 1-res and 2-res processes,

4. NLO corrections to the direct contribution.
For (1) and (2), we simply use pdfs and FFs valid in NLO, as they are available. For (3), the matrix elements for these are available [18–20] and have previously been used in calculations of prompt photon production at HERA [14]. Finally for (4), we need to evaluate the gluonic radiative corrections (both real and virtual) to the LO process of fig.1(a). Examples of these are shown in figs. 2(a) and 2(b). At NLO the $O(\alpha^3_{em})$ process $\gamma\gamma \rightarrow q\bar{q}\gamma$ also contributes. We did not need to recalculate the matrix elements for this contribution since it can be simply obtained from the real gluon radiative process $\gamma\gamma \rightarrow q\bar{q}g$ [19] (depicted in fig.2(a) but before convolution with the fragmentation function) by adjusting couplings and color factors. All these NLO processes contribute up to $O(\alpha^3_{em})$.

III. RESULTS

For our calculations we use the EPA with the anti-tagging angle set at 35 milliradians, relevant to the LEP2 detectors. For the photon pdfs we use those of refs [5,21–23]: for the FFs we use those of ref [24]. For the scale of the hard scattering, $Q^2 = (p_T^\gamma)^2$ is chosen throughout. In fig.3 we show the cross section vs $p_T^\gamma$ integrated over the rapidities in the range $-2 \leq y^\gamma \leq 2$ at the $e^+e^-$ CMS energy $\sqrt{s} = 180$ GeV. This rapidity cut is relevant for the LEP2 detectors in the sense that to distinguish between electrons and photons the track must pass through the central tracking detector. In fig.3(a) we show the LO and NLO results using the new GS photon distributions and the NLO result using the GRV distributions. The K-factor in not very different from 1 even at low $p_T^\gamma$ values, indicating perturbative stability of the result. If one compares the LO and NLO results using the GRV distributions one finds significantly larger K-factors, as the LO GRV distributions give very similar results to the LO GS distributions. The reason for this difference is not completely clear, but it could be due to the fact that the LO and NLO GRV photon pdf parametrizations [23] were fitted to the $F_2^\gamma$ data independently and no attempt was made to connect them, whereas in the GS case $F_2^\gamma$ was required to be the same in LO and NLO at the input scale $Q^2 = Q^2_0 = 3$ GeV$^2$: hence they are essentially obtained by the same fit to the data [5,21,22]. The cross section
is less than 2 pb/GeV at $p_T^\gamma = 2$ GeV, indicating that the full planned luminosity of LEP2 of 500 $pb^{-1}$ will be necessary to properly measure the cross section.

In fig.3(b) we compare the full cross section to the contributions from fragmentation processes only in LO and NLO. The fragmentation contributions are most significant in the lower $p_T^\gamma$ region and have a very significant K-factor, but they are still not large enough in NLO to dominate the cross section. So while conclusions drawn from the LO analysis do not need to be completely revised, we note an important increase in the fragmentation background in this region when the NLO corrections are included.

In fig.4(a) we show the $p_T^\gamma$ distribution $d\sigma/dp_T^\gamma$ evaluated in NLO for the 2-res, 1-res and D contributions to the cross section. As would be expected, the 2-res contribution is most significant at low $p_T^\gamma$ but falls off most steeply with $p_T^\gamma$, whereas the D contribution is least significant at low $p_T^\gamma$ but increases in importance as $p_T^\gamma$ is increased. The 1-res contribution is intermediate between these two. The physical explanation for this is simply that all the initial photon’s energy goes into the hard process for the direct contributions whereas only some of it is available for the hard scattering in the resolved processes, making them correspondingly less efficient at producing high $p_T^\gamma$ final state photons. We would thus expect most of the sensitivity to the photon pdfs to be in the lower $p_T^\gamma$ region.

The last point made above is tested in fig.4(b) where we compare the full NLO cross section with and without gluon initiated processes included in the hard scattering cross section. There is a very significant fall in the cross section when we set $g^\gamma = 0$. We thus expect that this cross section could definitely yield important information on $g^\gamma$ at LEP2, given the planned high luminosities.

In fig.4(c) we show the cross section at the higher CMS energy of $\sqrt{s} = 500$ GeV. We also show the 2-res, 1-res and D contributions to the cross section for comparison with LEP2 energies. As might be expected the cross section is significantly larger at these energies, by a factor of 3 at $p_T^\gamma = 2$ GeV. The relative importance of the once-, twice-resolved and direct processes as a function of $p_T^\gamma$ has not altered significantly. Thus the main advantage of a machine at this CMS energy would be an increase in the cross section and thus the possibility.
of more accurate measurements assuming the luminosities and anti-tagging conditions are the same as in the LEP2 case.

**IV. CONCLUSIONS**

This study of prompt photon production in $\gamma\gamma$ collisions indicates that the cross section will be measurable at LEP2. The energy of the machine turns out to be ideal in the sense that it is high enough for there to be a significant contribution from resolved photon processes, particularly those involving $g\gamma$, and low enough that we do not expect a dominant contribution from fragmentation processes. Hence a measurement of the cross section should yield useful information on $g\gamma$. The relatively small contribution from the fragmentation processes also means that the inclusive as opposed to the isolated prompt photon cross section will be measurable here, although the need to remove the hadronic background from $\pi^0$s will mean that some isolation criterion will be imposed. We intend to address the issue of isolation in future work.

We concede that the cross section for this interesting process is small. However, the cross section for other interesting processes at LEP2, such as $e^+e^- \rightarrow W^+W^-$, are also very small: that it is why it imperative for LEP2 to achieve its design luminosity.

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### TABLE I. Classification of the contributions of fig.(1) according to initial state (D, 1-res., 2-res.), final state (F or NF), and subprocess type.

| Figure | Initial State | Final State | Subprocess               |
|--------|---------------|-------------|--------------------------|
| 1(a)   | D             | F           | $\gamma\gamma \to q\bar{q}$ |
| 1(b)   | 1-res         | F           | $\gamma g \to q\bar{q}$  |
| 1(c)   | 1-res         | F           | $\gamma q \to gq$        |
| 1(d)   | 1-res         | NF          | $\gamma q \to \gamma q$  |
| 1(e)   | 2-res         | F           | $qq \to qq$ etc.         |
| 1(f)   | 2-res         | NF          | $q\bar{q} \to g\gamma$  |
| 1(g)   | 2-res         | NF          | $qq \to \gamma q$        |
Figure Captions

Fig. 1: (a)-(g) Different contributions to the process $\gamma\gamma \rightarrow \gamma X$, classified in Table 1. (h) Notation used for resolved photons and photons produced by fragmentation.

Fig. 2: NLO corrections to the direct process 1(a).

Fig. 3: The cross section $d\sigma/dp_T^\gamma$ vs $p_T^\gamma$ integrated over rapidity $|y^\gamma| \leq 2$ at CMS energy $\sqrt{s} = 180$ GeV. (a) The cross section calculated in LO (dashed line) and NLO (full line) for the GS photon distributions and (dotted line) for the GRV NLO photon distributions. (b) The cross section showing the full results in LO and NLO and the corresponding contributions from the fragmentation processes.

Fig. 4: (a) $p_T^\gamma$ distribution for the direct, once-resolved and twice resolved contributions to the cross section in NLO. (b) The cross section in NLO with and without contributions from subprocesses initiated by gluons included. (c) Same as (a) but at CMS energy $\sqrt{s} = 500$ GeV, and including the sum of all contributions.
(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

resolved photon

photon fragmentation

Fig. 1

13
Fig. 2
$\sqrt{s} = 180 \text{ GeV}$

$-2 < y^\gamma < 2$

- Full (HO)
- Full (LO)
- Frag. (HO)
- Frag. (LO)

$\frac{d\sigma}{dp_T^\gamma} \text{ [pb/GeV]}$

$\log_{10}$

$2, 3, 4, 5, 6, 7, 8$

$p_T^\gamma \text{ [GeV]}$

Fig. 3b
$\sqrt{s} = 180 \text{ GeV}$
$-2 < y^\gamma < 2$

Fig. 4a
\[ \sqrt{s} = 180 \text{ GeV} \]
\[-2 < y^\gamma < 2 \]

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Full

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\[ g^\gamma = 0 \]

Fig. 4b
$\sqrt{s} = 500 \text{ GeV}$
$-2 < y^\gamma < 2$

Fig. 4c