Prompt photon production in photoproduction, DIS
and hadronic collisions

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Abstract

Recent results on prompt photon production in photoproduction, deeply inelastic scattering and hadronic collisions are reviewed and the importance of photons for LHC experiments is briefly discussed.

1 Introduction

Photons have always played a very important role in particle physics, historically to develop the quantum theory of electrodynamics (QED) and experimentally due to their omnipresence and clean signature. Another interesting aspect is their “dual nature” with respect to the strong interactions: On one hand, the photon acts like a pointlike particle described by QED, on the other hand, photons also have a “hadronic face”: energetic partons can “fragment” into a large-\(p_T\) photon and hadronic energy, this process being described by photon fragmentation functions \[2, 3\]. Similarly, initial state photons also can be “resolved” into their hadronic structure by a hard interaction, leading to the concept of photon structure functions, see e.g. \[4, 5\] for recent reviews. Making use of this dual nature, reactions involving photons are an ideal tool to study QCD in various aspects (for recent literature, see e.g. \[6, 7\]).

Furthermore, final state photons play an important role in the search for a Higgs boson with mass below ~ 140 GeV, where the decay into two photons is a very prominent channel. In addition, they are important signatures for various scenarios of Physics Beyond the Standard Model, as they appear e.g. in the decay chain of SUSY particles or Kaluza-Klein excitations.

Therefore it is very important to understand the Standard Model physics involving photons. For that matter we can learn a lot from past and present experiments. In the following, we will highlight some of the results obtained recently involving large-\(p_T\) (“prompt”) photons in the final state. Due to the limited scope of this article, we only cover HERA and hadron collider kinematics.

2 Photoproduction of prompt photons

High energy electron-proton scattering, as it has been carried out at the DESY \(e p\) collider HERA, is dominated by so-called photoproduction processes, where the electron is scattered at small angles, emitting a quasi-real photon which scatters with the proton. The spectrum of these photons can be described by the Weizsäcker-Williams approximation \[8, 9\]. The \(\gamma - p\) scattering processes are of special interest since they are sensitive to both the partonic structure of the photon as well as of the proton. As will be explained below, they offer the possibility to constrain the (presently poorly known) gluon distributions in the photon, since in a certain kinematic region the subprocess \(qg \rightarrow \gamma q\), where the gluon is stemming from a resolved photon, is dominating \[10\].

The cross section for \(e p \rightarrow \gamma X\) can symbolically be written as a convolution of the par-
ton densities for the incident particles (resp. fragmentation function for an outgoing parton fragmenting into a photon) with the partonic cross section $\hat{\sigma}$:

$$d\sigma^{ep\rightarrow\gamma X}(P_P, P_e, P_\gamma) = \sum_{a,b,c} \int dx_e \int dx_p \int dz F_{a/e}(x_e, M) F_{b/p}(x_p, M_p) D_{c/e}(z, M_F) \, \hat{\sigma}^{ab\rightarrow cX}(x_P, x_e P_e, P_\gamma/z, \mu, M, M_p, M_F) ,$$

where $M, M_p$ are the initial state factorisation scales, $M_F$ the final state factorisation scale, $\mu$ the renormalisation scale and $a, b, c$ run over parton types.

The subprocesses contributing to the partonic reaction $ab \rightarrow cX$ can be divided into four categories, as depicted in Fig. 1.

The “resolved” contributions are characterised by a resolved photon in the initial state where a parton stemming from the photon instead of the photon itself participates in the hard subprocess. In these cases, $F_{a/e}(x_e, M)$ is given by a convolution of the Weizsäcker-Williams spectrum $f_e(y)$ with the parton distributions in the photon:

$$F_{a/e}(x_e, M) = \int_0^1 dy \, f_e(y) \, F_{a/\gamma}(x_\gamma, M) \, \delta(x_\gamma y - x_e).$$

The cases with “direct” attributed to the initial state photon correspond to $a = \gamma$, so $F_{a/\gamma} = \delta(1 - x_\gamma)$ and $F_{a/e}$ in eq. 2 collapses to the Weizsäcker-Williams spectrum.

If additional jets are measured, eq. (1) also contains a jet function, which defines the clustering of the final state partons other than the photon into jets.

**Photon isolation**

In order to single out the prompt photon events from the background of secondary photons produced by the decays of $\pi^0, \eta, \omega$ mesons, isolation cuts have to be imposed on the photon signals in the experiment. A widely used isolation criterion is the following: A photon is isolated if, inside a cone centered around the photon direction in the rapidity and azimuthal angle plane, the amount of hadronic transverse energy $E_T^{had}$ deposited is smaller than some value $E_T^{max}$:

$$E_T^{had} \leq \epsilon \, E_T^{max}.$$  

For $(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R$,

$$E_T^{had} \leq \epsilon \, E_T^{max}.$$  

HERA experiments mostly used $E_T^{max} = \epsilon \, p_T^\gamma$, with $\epsilon = 0.1$ and $R = 1$. Isolation not only reduces the background from secondary photons, but also substantially reduces the fragmentation components. It is important to note that the isolation parameters must be carefully fixed in order to allow a comparison between data and perturbative QCD calculations. Indeed a part of the hadronic
energy measured in the cone may come from the underlying event; therefore even the direct contribution can be cut by the isolation condition if the latter is too stringent.

2.1 Inclusive prompt photons

Inclusive prompt photons in photoproduction processes have been measured by ZEUS \cite{11} and H1 \cite{12}, and compared to PYTHIA \cite{13} and HERWIG \cite{14} as well as NLO perturbative QCD calculations \cite{15, 16}. Interestingly, the data are above the NLO QCD prediction after corrections for hadronisation and multiple interactions (see Fig. 2). This feature is seen in both, ZEUS and H1 data, and also persists in the comparison to PYTHIA 6.1 and HERWIG 6.1, as shown in Fig. 3. The K&Z \cite{15} curve being below the

\[
\begin{align*}
\text{Inclusive prompt photon} \\
\text{Figure 2: H1 data} \text{[12] compared to NLO QCD} \text{[15, 16]. The NLO results are corrected for hadronisation and multiple interaction (h.c.+m.i.) effects. The light blue (outer) error bands show the estimated uncertainties on these corrections for the FGH result, the dark blue (inner) bands show the scale uncertainty. The } \eta^\gamma \text{ distribution is based on } E^\gamma_{T, \text{min}} = 5 \text{ GeV.}
\end{align*}
\]

FGH \cite{16} curve in Fig. 2 can be explained by the fact that the K&Z calculation does not contain the NLO corrections to the resolved part.

\[
\begin{align*}
\text{Figure 3: H1 and ZEUS data on inclusive prompt photon production compared to PYTHIA and HERWIG. The blue histogram \text{“without multiple interactions (m.i.)” as well as the “direct only (dir)” histogram refer to the PYTHIA prediction. The figure is taken from ref. [12].}
\end{align*}
\]

2.2 Prompt photon + jet

Prompt photon production in association with a jet offers more possibilities to probe the underlying parton dynamics, as it allows to define observables which give information about the momentum fractions \(x^\gamma, x^p\) the partons are carrying with respect to the photon respectively proton they are originating from. The partonic \(x^\gamma, x^p\) are not observable, but one can define the observables

\[
\begin{align*}
x^\gamma_{\text{obs}} &= \frac{p_T^\gamma e^{-\eta^\gamma} + p_T^{\text{jet}} e^{-\eta^{\text{jet}}}}{2E^\gamma}, \\
x^p_{\text{obs}} &= \frac{p_T^\gamma e^{\eta^\gamma} + p_T^{\text{jet}} e^{\eta^{\text{jet}}}}{2E^p},
\end{align*}
\]

which, for direct photons in the final state, coincide with the partonic \(x^\gamma, x^p\) at leading order. Unique to photoproduction processes is the possibility to “switch on/off” the resolved photon by suppressing/enhancing large \(x^\gamma\). As \(x^\gamma = 1\) corresponds to direct photons in the initial state, one can obtain e.g. resolved photon enriched data samples by placing a cut \(x^\gamma_{\text{obs}} \leq 0.9\). Another possibility to enhance or suppress the resolved photon component is to place cuts on \(p_T\) and
rapidity. From eq. (4) one can easily see that $x_\text{obs}^\gamma$ is small at low $p_T^\text{jet}$ values and large negative rapidities. Small $x_\gamma^\gamma$-enriched data samples could be used to further constrain the parton distributions in the real photon, in particular the gluon distribution, as investigated e.g. in [10]. Similarly, one can suppress the contribution from the resolved photon to probe the proton at small $x_p$ by direct $\gamma - p$ interactions [10].

As the hadronisation corrections are smaller for $\gamma + \text{jet}$ than for dijet photoproduction [17], $\gamma + \text{jet}$ final states in principle offer the possibility for highly accurate comparisons of perturbative QCD predictions to the data, once the issues about photon isolation are well under control. For example, a study of the effective transverse momentum $\langle k_T \rangle$ of partons in the proton has been made by ZEUS [18]. Comparing the shapes of normalised distributions for $\langle k_T \rangle$-sensitive observables to a NLO calculation, it was found that the data agree well with NLO QCD without extra intrinsic $\langle k_T \rangle$ [19].

Detailed analyses for $\gamma + \text{jet}$ measurements in photoproduction have been carried out by both ZEUS [17, 20] and H1 [12], where the ZEUS collaboration has also compared with the $k_T$-factorisation approach of Lipatov and Zotov [21]. Sample plots are shown in Figs. 4 and 5.

Figure 4: ZEUS $\gamma + \text{jet}$ data [17] for $E_T^\gamma \geq 5 \text{ GeV}$ compared to different theory predictions (see text).

Figure 5: H1 $\gamma + \text{jet}$ data [12] compared to NLO QCD predictions [15, 19]. The labelling of the histograms is the same as in Fig. 2.
light it would be interesting to reconsider the inclusive prompt photon data with increased $E_{T,\gamma}^{\text{min}}$.

3 Prompt photons in DIS

Some time ago, the ZEUS collaboration performed a measurement [22] of the inclusive prompt photon cross section in deeply inelastic scattering (DIS), where rather large discrepancies to the predictions of PYTHIA6.206 [23] and HERWIG6.1 [14] were found. This motivated a dedicated partonic calculation [24] where both the radiation of photons off leptons and off quarks was taken into account. The result is in fair agreement with the experimental data, which shows the importance of both subprocesses, as well as the inclusion of large-angle photon radiation [24]. In particular, the shapes of the individual contributions in Fig. 7 suggest that PYTHIA seems to underestimate the photon radiation off leptons.

Very recently, H1 also presented data on prompt photon production in DIS [25–28], where the measurement range could be extended considerably as compared to previous measurements, thus increasing the cross section by almost an order of magnitude. The $\eta^\gamma$ distribution, again compared to the calculation of ref. [24], is shown in Fig. 8.

Prompt photon plus jet production in DIS also has been measured by ZEUS [22] and H1 [20], and compared to parton-level calculations. In this case, NLO predictions are available [27, 28, 29], which describe the shape of the $\eta^\gamma$ distribution reasonably well, but still underestimate the data [22, 20].

Based on the above mentioned partonic calculations, it is suggested in [30] that the photon fragmentation functions can be
measured at HERA from $\gamma^+(0+1)$-jet and $\gamma^+(1+1)$-jet data samples in DIS.

4 Prompt photons in hadronic collisions

As already mentioned, prompt photon production in hadronic collisions is of particular importance these days for various reasons, e.g. photons play a major role in performing luminosity/calibration measurements at the LHC, and, at a later stage, measuring the gluon pdfs at the LHC. Further, (di-)photons are important in connection with the background to $H \rightarrow \gamma\gamma$ for $m_H \lesssim 140$ GeV, pair-production of SUSY-particles decaying to lower mass states, radiative decays of excited states in various New Physics scenarios, etc. Covering all these subjects is far beyond the scope of this short review, therefore we focus on calculations related to recent experimental measurements.

It should be noted that at high energies, the electroweak corrections from virtual weak boson exchange increase strongly. This fact motivated the calculation of the complete one-loop electroweak corrections to large-$p_T$ photon production in hadronic collisions [31, 32]. Indeed it was found that at the LHC, where photon transverse momenta in the range of 2 TeV are within reach, these corrections amount to up to -17% [32].

4.1 Diphoton production in hadronic collisions

Two publicly available parton level calculations which include various types of higher order corrections are available, DIPHOX [33] and ResBos [34, 35, 36, 37]. ResBos has recently seen an important update [34], where $O(\alpha_3^3)$ corrections to $gg$-scattering [38, 39, 40, 41] have been included. In addition, it contains NNLL resummation of initial-state singularities at small $q_T$. Although a complete treatment of resummation would require joint initial- and final state resummation, which is quite difficult because of the interplay with photon isolation, the resummation done in [34] certainly improves the theoretical prediction in the region sensitive to initial state multiple gluon emission. On the other hand, ResBos uses an approximation for the fragmentation contributions which is effectively leading order, while in DIPHOX the fragmentation contributions are included fully at next-to-leading order.

Figure 9: CDF diphoton data compared to DIPHOX [33], ResBos [37] and PYTHIA6.216 [23]. The figure is taken from ref. [42].

CDF has performed a recent measurement of diphoton production [44]. The comparison to the data reflects the features of the different theoretical descriptions, as can be seen from Fig. 9. DIPHOX diverges at low $q_T$ because this region requires resummation of large logarithms. ResBos underestimates the tail because its fragmentation contribution is effectively at leading order. In particular, the shoulder seen in the data at $q_T \gtrsim 28$ GeV can be understood as arising from an increase in phase space for $\Delta \phi_{\gamma\gamma} < \pi/2$, which is particularly enhanced in the fragmentation contribution due to an interplay with isolation. Detailed studies can be found in [43]. Note that Fig. 9 has been obtained with the ResBos version of ref. [37], but the most recent version shows basically the same features with respect to this plot [34].
4.2 Inclusive prompt photon production

D0 has measured the cross section for the inclusive production of isolated photons in the range $23 < p_T^\gamma < 300\text{ GeV}$ [45]. This extends previous measurements [46, 47, 48] to significantly higher values of $p_T^\gamma$. In fact, the $p_T^\gamma$ range is the widest ever tested. As can be seen from Fig. 10, the data agree quite well with NLO QCD calculations [49, 50].

![Figure 10: D0 data on inclusive prompt photon production for $23\text{ GeV} < p_T^\gamma < 300\text{ GeV}$, $|\eta^\gamma| < 0.9$ compared to JET-PHOX [49]. The figures are taken from [51].](image)

4.3 Prompt photon + jet production

Measurements of $p\bar{p} \rightarrow \gamma + \text{jet} + X$ for $30\text{ GeV} < p_T^\gamma < 300\text{ GeV}$ are just being performed by D0 [52]. The NLO partonic Monte Carlo program JETPHOX [49] is used to compare to theory at next-to-leading order. The comparison is done separately for different regions in rapidity of the photon and the jet. The preliminary data show a discrepancy to the theory prediction in some regions [52, 53] which still needs to be understood, as it is not always at low $p_T^\gamma$, where it could be explained by non-perturbative effects.

Understanding prompt photon plus jet production in hadronic collisions is certainly very important in view of the LHC, where the process $gq \rightarrow q\gamma$ dominates in a wide kinematic range and thus offers the possibility to constrain the gluon distribution in the proton [54, 55, 56, 57]. Further, $\gamma$+jet events can be used to set the absolute jet energy scale, as shown e.g. in dedicated CMS studies [58, 59]. It is also a good channel to study photon selection criteria in view of searches for New Physics [54, 57].

4.4 Prompt photon production at RHIC

RHIC pp collisions at $\sqrt{s} = 200\text{ GeV}$ [60, 61] cover the intermediate energy range between fixed target and Tevatron collider energies and are therefore of major importance to bridge a gap which allows a revisited interpretation of all of these data. Further, the PHENIX experiment at RHIC uses different photon isolation methods [60], which allows to study systematics related to isolation. An interesting possibility is also the measurement of photon-hadron azimuthal correlations as presented in [62] and studied from the theory side in [63, 64].

The PHENIX prompt photon data have been compared to NLO QCD calculations by JETPHOX [49] and W. Vogelsang et al [50] and show very good agreement, as can be seen from Fig. 11.

5 The overall picture

Looking at Figs. 10 and 11, one may wonder why prompt photons in hadronic collisions had the bad reputation of exhibit-
The discrepancies were mainly seen in prompt photon production on fixed targets, but also at Tevatron $p\bar{p}$ collider energies (for a review, see e.g. [49, 65]). It was suspected that there are large effects from multiple soft gluon emission, and the necessity for large intrinsic $\langle k_T\rangle$ to account for soft gluon- and nonperturbative effects was claimed.

As a consequence, various theory efforts to quantify these effects have been undertaken, e.g. threshold resummation for $x_T=2p_T/\sqrt{s} \rightarrow 1$ and joint resummation of threshold and recoil effects [72, 73, 74, 75]. It has been shown that the effect of resummation extends down to $x_T \gtrsim 10^{-1}$, thus covering the fixed target range, and that scale dependences are considerably reduced by resummation. Further, it turned out that, as to be expected, recoil effects in inclusive prompt photon production are relatively small, and that agreement with almost all prompt photon data can be achieved. A detailed collection and analysis of prompt photon results at different energies has been performed in [49], where Fig. 12 has been taken from. One can see that, with the new data from the Tevatron and from PHENIX, we cover a very wide range in $x_T$. More importantly, the picture emerges that, apart from the E706 data, the agreement with NLO theory is quite impressive.

In conclusion, we have learnt a lot (and still do!) from prompt photon production at HERA. Further, thanks to recent RHIC and Tevatron measurements, the reputation of prompt photons in hadronic collisions is rising again: NLO QCD in general does a pretty good job where it is expected to do so. Therefore we are looking forward to further exploiting the advantageous features of photons in future measurements and calculations.

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