Prompt-photon plus jet photoproduction with ZEUS at DESY HERA in the parton Reggeization approach

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Abstract

We study the photoproduction of isolated prompt photons associated with hadron jets in the framework of the parton Reggeization approach. The main improvements with respect to previous studies in the $k_T$-factorization framework include the application of the Reggeized-quark formalism, the generation of exactly gauge-invariant amplitudes with off-shell initial-state quarks, and the exact treatment of the $\gamma R \rightarrow \gamma g$ box contribution with off-shell initial-state gluons. In this proceedings, the new data set, published recently by ZEUS collaboration is analyzed, were the distributions in photon and jet rapidity, transverse energy, azimuthal angle between photon and jet and proton momentum fraction are presented for different values of measured photon momentum fraction $x_{\text{meas}} < 0.7$, $0.8$ and $x_{\text{meas}} > 0.8$. The good agreement of measured distributions with our predictions is observed for the direct-dominating part of the data set. The comparison with the previous calculations in $k_T$-factorization, role of nonfactorizable higher-order and hadronization corrections is discussed.

Keywords: photoproduction, prompt-photons, jets, higher-order corrections in QCD, proton unintegrated PDFs, photon PDFs

1. Introduction.

The photoproduction of prompt photons with large transverse momenta provides a formidable laboratory for precision tests of perturbative quantum chromodynamics (QCD) and a useful source of information on the parton content of the proton and the real photon. The initial-state photon may interact with the partons inside the proton either directly (direct photoproduction) or via its partonic content (resolved photoproduction).

The inclusive photoproduction of prompt photons, singly and in association with jets, received a lot of attention, both experimentally and theoretically. On the experimental side, the H1 \cite{H1} and ZEUS \cite{ZEUS} collaborations measured the cross section distributions in the parton content of the proton and the real photon. The initial-state photon may interact with the partons inside the proton either directly (direct photoproduction) or via its partonic content (resolved photoproduction).

In azimuthal-decorrelation parameters such as the azimuthal angle enclosed between the prompt-photon and jet transverse momenta ($\Delta \phi$) and the component of the prompt-photon transverse momentum orthogonal to the direction of the jet transverse momentum ($p_{\perp}$). Also, the distributions in the variables estimating the momentum fractions of the initial-state partons, $x_{p}^{\text{LO}}$, $x_{\gamma}^{\text{LO}}$, and $x_{\text{obs}}^{\text{ebe}}$, were measured. This rich set of observables allows one to perform a detailed study of the underlying partonic processes and to assess the relevance of different perturbative corrections.

On the theoretical side, attempts to describe this data where made both at next-to-leading order (NLO) in the conventional collinear parton model (CPM) \cite{CPM} and in approaches accommodating off-shell initial-state partons, such as the $k_T$-factorization approach (KFA) \cite{KFA} and $k_T$-factorization approach with Reggeized partons, which we refer to as the parton Reggeization approach (PRA) \cite{PRA}.
For prompt-photon plus jet associated photoproduction, NLO CPM predictions generally agree with the measured $\eta$ distributions, slightly underestimate the $E_T$ distributions, and provide a poor description of the azimuthal decorrelation observables [2], due to the fact that these distributions collapse to delta functions in the LO CPM and, therefore, strongly depend on the radiation of additional partons. The available KFA predictions provide a better description of the measured $E_T$ distributions and azimuthal decorrelation observables, but are implemented with matrix elements that manifestly violate gauge invariance, which renders the quantitative improvements of the predictions questionable. Furthermore, in the early studies [9, 10], the partonic subprocess pertaining to the scattering of a photon and an off-shell gluon, $\gamma g' \rightarrow \gamma q g$, was not taken into account. Later, this contribution was found to be numerically significant [11], due to the large gluon luminosity under HERA conditions. But the treatment of this contribution was approximate because the virtuality of the initial-state gluon was not taken into account at the amplitude level, but only in the kinematics of the process [11].

In view of the shortcomings of the previous calculations mentioned above, the improved analysis of prompt-photon plus jet associated photoproduction in the LO of PRA was performed in [13]. In this work, the contributions of the following partonic subprocesses were taken into account:

\begin{align*}
Q(q_1) + \gamma(q_2) & \rightarrow q(q_3) + \gamma(q_4), \quad (1) \\
R(q_1) + \gamma(q_2) & \rightarrow g(q_3) + \gamma(q_4), \quad (2) \\
R(q_1) + q[\gamma](q_2) & \rightarrow q(q_3) + \gamma(q_4), \quad (3)
\end{align*}

where the four-momenta of the partons are denoted in the brackets. The parton coming from the proton is taken to be off-shell ($q_1^2 = -q_7^2_1 = -t_1$), and carries one large light-cone component of momentum $q_1^\perp = 2x_1E_p \ll q_1^\parallel$. This special (Multi-Regge) kinematics allows us to use the formalism of Reggeized gluons [14], denoted by $R$ in (3), and quarks [15], denoted by $Q$, to define the gauge-invariant amplitude of the hard subprocess. See Ref. [13] for further explanations and references.

The subprocess (2) is loop-induced, but due to the large gluon luminosity in the HERA kinematical conditions it’s contribution is comparable to the contribution of the resolved subprocess (3). The full $t_1$-dependence of the amplitude of the subprocess (2) was calculated in [13], and the suppression of this contribution up to 30% w. r. t. LO CPM result was observed as a consequence of this dependence.

The contributions of other resolved subprocesses was found to be numerically negligible as well as the contribution of the parton to photon fragmentation, which is suppressed by the photon isolation condition, applied in the experimental analysis, see the discussion in [13] for the further details.

In our numerical analysis we use the Kimber-Martin-Ryskin (KMR) [16] procedure to obtain the unintegrated PDF (unPDF) $\Phi_{i/p}(x_i, t_i, \mu_F^2)$ of the parton $i = g, q, \bar{q}$ in proton from the conventional (integrated) PDF of the CPM $f_{i/p}(x_i, \mu_F)$. As a collinear input for the KMR procedure we have used the LO proton PDF set by Martin et. al. [17] with $n_F = 4$ active quark flavors. To calculate the resolved contributions we have used the LO photon PDF set $f_{i/\gamma}(x_i, \mu_F)$ by Glück et al. [18].

In this proceedings we compare our predictions for the prompt photon+jet associated photoproduction at HERA with recently published dataset [6], which we will refer to as ZEUS-2014.

2. Numerical results for the ZEUS-2014 dataset.

The kinematical conditions for the ZEUS-2014 dataset are the following: the proton and electron energies where equal to $E_p = 920$ GeV and $E_e = 27.5$ GeV, and the photoproduction events are characterized by the range of inelasticity $0.2 < \gamma < 0.7$ and invariant squared momentum transfer $Q^2 < 1$ GeV$^2$. The kinematical cuts applied on the photon and jet in the ZEUS-2013 dataset [3] and ZEUS-2014 dataset [6] are the same: $6.0$ GeV $< E_T^\gamma < 15.0$ GeV; $0.7 < \eta^\gamma < 0.9$, $4.0$ GeV $< E_T^{\text{jet}} < 35.0$ GeV; $-1.5 < \eta^{\text{jet}} < 1.8$. But in the ZEUS-2014 dataset the kinematic distributions where presented in a different ranges of the measured photon momentum fraction transferred to the photon and the jet:

$$x_{gamma}^{\text{meas}} = \frac{E_T^\gamma + E_T^{\text{jet}} - p_T^{\text{jet}}}{E^{\text{all}} - p_T^{\text{all}}},$$

where all denotes all particles observed in the event. In the LO PRA, as well as in the LO CPM, the contributions of the direct subprocesses (1) to the cross section is proportional to $\delta(x_{gamma}^{\text{meas}} - 1)$, because the Reggeized parton do not carry the $q_1^\perp$ momentum component. Resolved contributions lead to the non-trivial dependence on the $x_1$ already in the LO. In the Ref. [6], the cross sections differential in $\eta^\gamma$, $\eta^{\text{jet}}$, $E_T^\gamma$, $E_T^{\text{jet}}$, $x_{gamma}$ and $\Delta\phi$ are presented for the direct-dominated region $x_{gamma}^{\text{meas}} > 0.8$ as well as for resolved-dominated regions $x_{gamma}^{\text{meas}} < 0.8$.
and $\chi^2_{\text{meas}} < 0.7$, which allows one to perform the very detailed tests of the quality of the model.

As it was shown in [13], the dependence of the cross section on the variable $x^2_{\text{obs}}$, defined in this paper, is well reproduced by our model for $x^2_{\text{obs}} \leq 0.6$. The region $x^2_{\text{obs}} > 0.6$ seems to be direct-dominated, and the shape of the $x^2_{\text{obs}}$-distribution is not reproduced there in the LO PRA (see Fig. 13 [13]). To smear the direct-$x^2_{\text{obs}}$ distribution, the NLO $2 \rightarrow 3$ processes with the production of the additional parton in the central region of rapidity should be included.

The authors of Ref. [11] claim to do this, but the treatment of the double counting of the additional radiation between different perturbative orders of the hard process and between the hard process and unPDF is a serious issue in $k_T$-factorization. Including the $2 \rightarrow 3$ processes they are forced to throw away their analogues of the LO $2 \rightarrow 2$ processes [1] and [3], and the question of the double counting with the unPDF is not addressed in the Ref [11] at all. As a result, they reproduce well the $x^2_{\text{obs}}$ distribution of Ref. [5], but fail to reproduce the shape of $\eta^\gamma$ distribution for $x^\gamma_{\text{meas}} < 0.8$ (see Fig. 4(b) of the Ref. [6]), which is well described in the NLO CPM and LO PRA, as it will be shown below.

In the figures [1]–[4] the predictions of our model for the cross sections differential in $\eta^\gamma$, $\eta^\gamma$, $E_T^\gamma$, $E_T^{\text{jet}}$ and $\Delta\phi$ are shown for $x^\gamma_{\text{meas}} < 0.8<(0.7)$ and $\chi^2_{\text{meas}} > 0.8$, also on the Fig. 4 the differential cross section $d\sigma/d\Delta\phi$ for all values of $\chi^2_{\gamma}$ is presented.

The theoretical uncertainty shown in the figures is only due to variation of the renormalization scale $\mu_R$ and two factorization scales $\mu_F^\gamma$ and $\mu_F^\text{jet}$ in $2^{\pm1}$ times around their common central value $\text{max}(E_T^\gamma, E_T^{\text{jet}})$. In the present analysis we have varied each of these three scales separately, keeping the other two fixed, and we have taken the largest variation of the cross section in the each bin as an estimate for the uncertainty.

Also we have studied the effect of hadronization corrections, which where calculated in Ref. [6] as a ratio of the detector-level and parton-level differential cross sections obtained from PYTHIA Monte-Carlo Event Generator. These corrections where applied in [6] both to the NLO CPM and $k_T$-factorization theoretical predictions.

In the case of our model, the application of the hadronization corrections improves the description of the data for the direct-dominated part of the phase-space, especially for the $\eta^\gamma$ distribution of the bottom-right panel of the Fig. [1]. Hadronization corrections to this distribution are significant, and change the form of the distribution, improving the agreement with data.

Figure 1: $\eta^\gamma$ and $\eta^\gamma$ distributions of $pe \rightarrow \gamma + j + X$ under ZEUS-2014 [6] kinematic conditions. The experimental data are compared with LO PRA predictions at the parton level (boldfaced solid blue lines and the grey scale-uncertainty band) and with the hadronization corrections of the Ref. [6] applied (boldfaced dotted magenta lines). The LO PRA predictions are decomposed into the contributions due to the subprocesses in Eqs. (1) (solid green lines), (2) (dashed red lines), and (3) (dot-dashed blue lines), and only the last one contributes for $x^\gamma_{\text{meas}} < 0.8$.

Figure 2: $E_T^\gamma$ and $E_T^{\text{jet}}$ distributions of $pe \rightarrow \gamma + j + X$ under ZEUS-2014 [6] kinematic conditions. The notations on the plots are the same as on the Fig. [1].
On the contrary, for the \( \gamma_{\text{meas}} < 0.8 \) part of the data, hadronization corrections lead to the systematic underestimation of the data. This is probably a consequence of the fact, that the variable \( \gamma_{\text{meas}} \) by construction is very sensitive to the additional(subleading) hard and soft radiation in the event, which is not taken into account in our LO computation. The variable \( \gamma_{\text{LO}} \), used by H1 collaboration in \([1,2]\), and the variable \( \gamma_{\text{obs}} \) used by ZEUS in the analysis \([3]\) depends only on the photon and jet momenta, so they should be less sensitive to the soft-radiation/hadronization effects, and the latter one is as good in separating between direct and resolved contributions as \( \gamma_{\text{meas}} \), since in the LO of PRA and CPM the direct contributions are proportional to the \( \delta(\gamma_{\text{obs}} - 1) \).

As it was stated above, we reproduce the shape of \( \eta^{\gamma} \) distribution (bottom-left panel of the Fig. 1) rather well already at the LO. The \( \eta^{\gamma} \) distribution is underestimated, as well as \( E_T^{\gamma}, E_T^{\gamma \gamma} \) (Fig. 2) and \( \Delta \phi \) (Fig. 4) distributions for the \( \gamma_{\text{meas}} < 0.8 \), probably due to the lack of direct contribution in this region.

In the resolved-dominating region \( \gamma_{\text{meas}} < 0.7 \) we reproduce the \( \eta^{\gamma}, \eta^{\gamma \gamma}, E_T^{\gamma}, E_T^{\gamma \gamma} \) rather well within experimental and theoretical uncertainties (Fig. 3). The \( \Delta \phi \) distribution for the \( \gamma_{\text{meas}} < 0.7 \) (Fig. 4 top-left panel) is also reproduced slightly better than for \( \gamma_{\text{meas}} < 0.8 \) (Fig. 4 bottom-left panel). This probably shows, that we have found a good LO approximation both for the direct and resolved subprocesses in the framework of \( k_T \)-factorization.

All the distributions in the direct-dominated region \( \gamma_{\text{meas}} > 0.8 \) are described on a same level of quality as in the Ref. \([13]\). As it can be observed form the right panels of the Fig. 4, the shape of the \( \Delta \phi \) spectra in the region \( 130^\circ < \Delta \phi < 180^\circ \) is well reproduced for the \( \gamma_{\text{meas}} > 0.8 \) and also for the all-\( \gamma_{\text{meas}} \) spectra. The same result was obtained in the Ref. \([13]\) for the normalized \( \Delta \phi \) distributions in H1-2010 kinematics, but for ZEUS-2014 data, we are able to reproduce the normalization of the cross section.

3. Conclusions.

In this proceedings contribution, we have compared theoretical predictions of our LO PRA model of Ref. \([13]\) with the recent experimental data \([6]\) on the prompt photon associated with jet photoproduction, measured by the ZEUS Collaboration at DESY HERA. The reasonable quantitative agreement of our predictions with experiment in the direct-dominated part of the dataset, as well as a good qualitative agreement in with the resolved-dominated data provides a new test of
$k_T$-factorization framework with Reggeized quarks and gluons.

References

[1] A. Aktas et al. (H1 Collaboration), Eur. Phys. J. C 38, 437 (2005) [hep-ex/0407018].
[2] F. D. Aaron et al. (H1 Collaboration), Eur. Phys. J. C 66, 17 (2010) [arXiv:0910.5631 [hep-ex]].
[3] J. Breitweg et al. (ZEUS Collaboration), Phys. Lett. B 472, 175 (2000) [hep-ex/0010045].
[4] S. Chekanov et al. (ZEUS Collaboration), Eur. Phys. J. C 49, 511 (2007) [hep-ex/0608028].
[5] H. Abramowicz et al. (ZEUS Collaboration), Phys. Lett. B 730, 293 (2014) [arXiv:1312.1539 [hep-ex]].
[6] H. Abramowicz et al. (ZEUS Collaboration), JHEP 1408, 023 (2014) [arXiv:1405.3127 [hep-ex]].
[7] M. Fontannaz, J. Ph. Guillet, and G. Heinrich, Eur. Phys. J. C 21, 303 (2001) [hep-ph/0105121]; M. Fontannaz and G. Heinrich, Eur. Phys. J. C 34, 191 (2004) [hep-ph/0312009].
[8] A. Zembrzuski and M. Krawczyk, Phys. Rev. D 64, 114017 (2001) [hep-ph/0105166]. Report No. IFT-2003-27 [hep-ph/0309338].
[9] A. V. Lipatov and N. P. Zotov, Phys. Rev. D 72, 054002 (2005) [hep-ph/0506044].
[10] A. V. Lipatov and N. P. Zotov, Phys. Rev. D 81, 094027 (2010) [arXiv:0907.3303 [hep-ph]].
[11] A. V. Lipatov, M. A. Malyshchev, and N. P. Zotov, Phys. Rev. D 88, 074001 (2013) [arXiv:1307.3644 [hep-ph]].
[12] V. A. Saleev, Phys. Rev. D 78, 114031 (2008) [arXiv:0812.0946 [hep-ph]].
[13] B. A. Kniehl, M. A. Nefedov and V. A. Saleev, Phys. Rev. D 89, 114016 (2014) [arXiv:1404.3513 [hep-ph]].
[14] L. N. Lipatov, Nucl. Phys. B452, 369 (1995) [hep-ph/9502308].
[15] L. N. Lipatov and M. I. Vyazovsky, Nucl. Phys. B597, 399 (2001) [hep-ph/0009340].
[16] M. A. Kimber, A. D. Martin, and M. G. Ryskin, Eur. Phys. J. C 12, 655 (2000) [hep-ph/9911379]; Phys. Rev. D 63, 114027 (2001) [hep-ph/0103438]; G. Watt, A. D. Martin, and M. G. Ryskin, Eur. Phys. J. C 31, 73 (2003) [hep-ph/0306169]. Phys. Rev. D 70, 014012 (2004); 70, 079902(E) (2004) [hep-ph/0309096].
[17] A. D. Martin, W. J. Stirling, and R. S. Thorne, Phys. Lett. B 636, 259 (2006) [hep-ph/0603143].
[18] G. Gluck, E. Reya, and A. Vogt, Phys. Rev. D 46, 1973 (1992).