# Prompt photon production at HERA with $k_T$-factorization

A. V. Lipatov[a*], S. P. Baranov[b†], N. P. Zotov[a‡]
[a]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University*
*119991, Leninskie Gory, 1, Moscow, Russia*
[b]*P.N. Lebedev Physical Institute*
*119991, Leninskii Prospekt, 53, Moscow, Russia*

**Abstract**

We investigate the prompt photon production at HERA within the framework of $k_T$-factorization QCD approach. The unintegrated parton densities in a proton and in a photon are determined using the CCFM equation and the Kimber-Martin-Ryskin (KMR) prescription. The theoretical results are compared with the recent experimental data taken by the H1 and ZEUS collaborations.

In the present talk we give a short summary of our results obtained in [1, 2]. As it is known, the H1 and ZEUS collaborations data [3–8] on the inclusive and associated (with the hadronic jet) prompt photon photo- and lepto-production at HERA are typically 30 or 40% above than the NLO pQCD predictions. It was shown that the observed discrepancy can be reduced by introducing some additional intrinsic transverse momentum $k_T$ of the incoming partons. The ZEUS fit to the data gaves a $k_T$ value of about 1.7 GeV, and a similar situation is observed also at Tevatron energies.

However, the transverse momentum $k_T$ of incoming partons naturally occurs in the framework of $k_T$-factorization approach of QCD [9]. In this approach, $k_T$ is generated perturbatively in the course of non-collinear parton evolution via the corresponding (usually BFKL or CCFM) evolution equations. A detailed description of the $k_T$-factorization can be found, for example, in review [10]. As it was demonstrated in the recent ZEUS and H1 studies [7, 8], the $k_T$-factorization predictions [11] are in better agreement with the data than the NLO pQCD calculations. In the present note we improve our previous predictions [11] by taking into account the transverse momentum of incoming quarks in a proper way. Also we extend our consideration to the DIS region [2]. Our main goal is to give a systematic analysis of all available experimental data [3–8] in the framework of the $k_T$-factorization formalism.

Prompt photons at HERA can be produced by one of three mechanisms: a direct production ($\gamma q \to \gamma q$ or $eq \to e\gamma q$), a single resolved production ($qg \to \gamma q$, $gq \to \gamma q$, $q\bar{q} \to \gamma g$) and via parton-to-photon fragmentation processes. However, the isolation criteria (see [3–8]) significantly reduces the fragmentation components and therefore in our further analysis we will neglect the this contribution. In DIS events, the resolved photon contribution is negligible but the observed final-state photon can be emitted by a quark or by a lepton (the so-called QQ and LL mechanisms, respectively). According to the $k_T$-factorization theorem, the cross section of "resolved photon" processes can be written as a convolution of the relevant off-shell partonic cross section $d\hat{\sigma}$ and unintegrated ($k_T$-dependent) parton distributions in a proton $f_p(x, \mathbf{k}_T^2, \mu^2)$

*e-mail: lipatov@theory.sinp.msu.ru
†e-mail: baranov@lebedev.ru
‡e-mail: zotov@theory.sinp.msu.ru

and in a photon $f_p^\gamma(x, \mathbf{k}_T^2, \mu^2)$:

$$\sigma = \sum_{p=q,\,g} \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} f_p^\gamma(x_1, \mathbf{k}_{1T}^2, \mu^2) f_p(x_2, \mathbf{k}_{2T}^2, \mu^2)\, d\mathbf{k}_{1T}^2 d\mathbf{k}_{2T}^2\, d\hat{\sigma}, \quad (1)$$

where initial off-shell partons have fractions $x_1$ and $x_2$ of a initial photon and proton longitudinal momenta and non-zero transverse momenta $\mathbf{k}_{1T}$ and $\mathbf{k}_{2T}$. The expressions for the direct contribution and for the DIS cross sections are given in [1, 2]. We use the Weizacker-Williams approximation to calculate $ep$ cross sections in the photo-production case. Evaluation of the corresponding off-shell matrix elements is a straightforward and the analytical expressions have been also listed in [1, 2]. Here we would like to only mention two technical points. First, in according to the $k_T$-factorization prescription [9], the summation over the incoming off-shell gluon polarizations is carried with $\sum \epsilon^\mu \epsilon^\nu = \mathbf{k}_T^\mu \mathbf{k}_T^\nu / \mathbf{k}_T^2$, where $\mathbf{k}_T$ is the gluon transverse momentum. Second, when we calculate the matrix element squared, the spin density matrix for all off-shell spinors is taken in the form $u(p)\bar{u}(p) = x\hat{p}_p$ [1, 2].

Concerning the unintegrated parton densities, we take them in the KMR form [12]. The KMR approach is a formalism to construct the unintegrated parton distributions from the known conventional ones and it can be applied to the proton as well as the photon[1]. Since the KMR procedure is based on the DGLAP equations, it gives $k_T$-dependent densities for both quarks and gluons. The solution for the unintegrated gluon distributions have been obtained also from the CCFM evolution equation in [15]. All input parameters have been fitted to describe the proton structure function $F_2(x, Q^2)$. The proposed gluon densities (namely, sets A0 and B0) have been applied to the number of QCD processes (see, for example, review [10] and references therein). However, the problem of calculation of unintegrated quark densities framework of the CCFM formalism is still open. Our idea to calculate them is connected with the separation of the unintegrated quark distributions into several parts which correspond to the interactions of valence quarks $f_q^{(v)}$, sea quarks appearing at the last step of the gluon evolution $f_q^{(g)}$ and sea quarks coming from the earlier gluon splittings $f_q^{(s)}$. The valence quark densities $f_q^{(v)}$ have been obtained recently [16] from the numerical solution of the CCFM-like equation. To calculate the $f_q^{(g)}$ we convolute the CCFM-evolved gluon distribution with the LO DGLAP splitting function $P_{qg}(z)$. Finally, to estimate the contributions from the $f_q^{(s)}$ we use the specific properties of the KMR formalism, as it was described in [1]. Note that we apply the calculation scheme above to the unintegrated parton densities in a proton only.

To calculate the semi-inclusive production rates we apply the following procedure [1, 2]. As an approximation, we assume that the parton $k'$ emitted in the last evolution step compensates the whole transverse momentum of the parton participating in the hard subprocess, i.e. $\mathbf{k}'_T \simeq -\mathbf{k}_T$. All the other emitted partons are collected together in the proton remnant, which is assumed to carry only a negligible transverse momentum compared to $\mathbf{k}'_T$. This parton gives rise to a final hadron jet with $E_T^{\rm jet} = |\mathbf{k}'_T|$ in addition to the jet produced in the hard subprocess. From these hadron jets we choose the one carrying the largest transverse energy, and then compute the cross section of prompt photon with an associated jets.

Numerically, we choose the renormalization and factorization scales to be $\mu^2 = \xi E_T^2$ (photoproduction) and $\mu^2 = \xi Q^2$ (DIS). In order to estimate the theoretical uncertainties of our calculations we vary the scale parameter $\xi$ between 1/2 and 2 about the default value $\xi = 1$. We use the LO formula for the strong coupling constant $\alpha_s(\mu^2)$ with $n_f = 4$ active (massless) quark flavours and $\Lambda_{\rm QCD} = 200$ MeV, such that $\alpha_s(M_Z^2) = 0.1232$. Also we use massless approximation.

Our typical numerical results for prompt photon photoproduction are shown in Fig. 1 in comparison with the HERA data [3, 5]. One can see that the data can be reasonably well described by using the KMR unintegrated parton densities. Concerning the predictions with

[1]Numerically, we have used the MSTW-2008 [13] and GRV-92 [14] sets as an input, respectively.

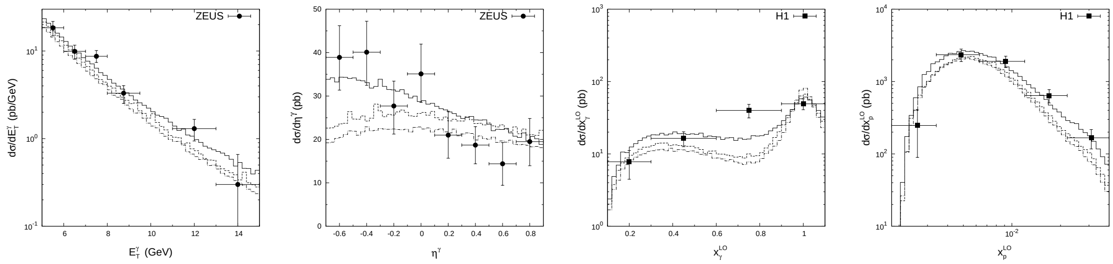

Figure 1: The prompt photon photoproduction cross sections at HERA. The solid, dash-dotted and dotted histograms correspond to the results obtained using the KMR, CCFM A0 and B0 parton densities. The experimental data are from ZEUS [3] and H1 [5].

the CCFM partons, we find the some underestimation of the HERA data in the rear pseudo-rapidity $\eta^\gamma$ region. One of the possible reasons of such disagreement can be connected with the absence of $f_q^{(s)}$ contributions in the calculation scheme. Our rough numerical estimation in [1] of this component gives 15 or 20% contribution to the calculated cross sections. However, to avoid double counting we do not sum predictions with the CCFM partons and the estimated $f_q^{(s)}$ contribution since it can be already partially included into the quark induced subprocesses (via relevant input densities for the CCFM-evolved gluons). For the DIS regime, we find again that the predicted inclusive cross sections agree well with the H1 and ZEUS data [4, 6] both in the normalization and shape (see Fig. 2, two left panels). However, concerning the $\gamma$ + jet cross sections, one can see that the we reproduce well the distributions measured by the H1 collaboration but our results overshoot the ealier ZEUS data (see Fig. 2, right panel). A possible reason for that can be connected with the jet selection and fragmentation algorithms, being the consequence of the used approximations.

In conclusion, we have investigated the production of prompt photons at HERA in the $k_T$-factorization approach. Our study is based on the relevant off-shell partonic amplitudes where the transverse momenta of both quarks and gluons are properly taken into account. We have found a reasonable agreement between our predictions and the available data (except the ZEUS ). Additionally we demonstrated that the quarks should be included into the non-collinear evolution cascade.

*Acknowledgements.* A.V.L. is very grateful to the Organization Comitee for the financial support. The authors have been supported by MSU — DESY project on MC implementation for HERA — LHC, RF FASI grant NS-4142.2010.2 and RF FASI state contract 02.740.11.0244. A.V.L. was supported in part by the HRJRG funds.

# References

[1] A.V. Lipatov and N.P. Zotov, Phys. Rev. D **81**, 094027 (2010).

[2] S.P. Baranov, A.V. Lipatov and N.P. Zotov, Phys. Rev. D **81**, 094034 (2010).

[3] J. Breitweg *et al.* (ZEUS Collaboration), Phys. Lett. B **472**, 175 (2000).

[4] S. Chekanov *et al.* (ZEUS Collaboration), Phys. Lett. B **595**, 86 (2004).

[5] A. Aktas *et al.* (H1 Collaboration), Eur. Phys. J. C **38**, 437 (2005).

[6] F.D. Aaron *et al.* (H1 Collaboration), Eur. Phys. J. C **54**, 371 (2008).

[7] S. Chekanov *et al.* (ZEUS Collaboration), Eur. Phys. J. C **49**, 511 (2007).

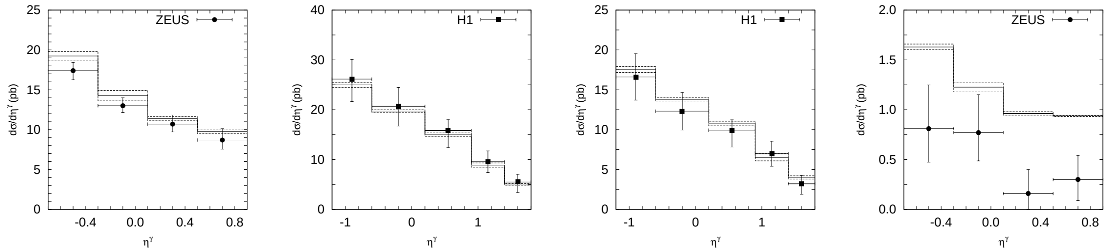


Figure 2: The inclusive deep inelastic prompt photon production (two left panels) and $\gamma$ + jet (two right panels) production as a function of $\eta^\gamma$. The solid and dashed histograms corresponds to the KMR predictions with the scale variations described in the text. The experimental data are from ZEUS [4] and H1 [6].

[8] F.D. Aaron *et al.* (H1 Collaboration), Eur. Phys. J. C **66**, 17 (2010).

[9] L.V. Gribov, E.M. Levin, and M.G. Ryskin, Phys. Rep. **100**, 1 (1983);
E.M. Levin, M.G. Ryskin, Yu.M. Shabelsky and A.G. Shuvaev, Sov. J. Nucl. Phys. **53**, 657 (1991);
S. Catani, M. Ciafoloni and F. Hautmann, Nucl. Phys. B **366**, 135 (1991);
J.C. Collins and R.K. Ellis, Nucl. Phys. B **360**, 3 (1991).

[10] J. Andersen *et al.* (Small-$x$ Collaboration), Eur. Phys. J. C **48**, 53 (2006).

[11] A.V. Lipatov and N.P. Zotov, Phys. Rev. D **72**, 054002 (2005).

[12] M.A. Kimber, A.D. Martin, and M.G. Ryskin, Phys. Rev. D **63**, 114027 (2001);
G. Watt, A.D. Martin, and M.G. Ryskin, Eur. Phys. J. C **31**, 73 (2003).

[13] A.D. Martin, W.J. Stirling, R.S. Thorne, and G. Watt, Eur. Phys. J. C **63**, 189 (2009).

[14] M. Glück, E. Reya, and A. Vogt, Phys. Rev. D **46**, 1973 (1992).

[15] H. Jung, arXiv:hep-ph/0411287.

[16] M. Deak, H. Jung, and K. Kutak, Proceedings of DIS'2008.