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Prompt photon photoproduction at HERA in the k_T-factorization approach

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We present the results of the numerical calculations of inclusive and associated with a jet prompt photon photoproduction at HERA in the framework of the k_T-factorization approach. The proposed method is based on the $\mathcal{O}(\alpha^2\alpha_s)$ amplitudes for $\gamma q \to \gamma g q$ and $\gamma g^* \to \gamma q\bar{q}$ partonic subprocesses. Additionally, we take into account the $\mathcal{O}(\alpha^2\alpha_s^2)$ box contributions $\gamma g \to \gamma g$ to the production cross sections. Our predictions are compared with the ZEUS experimental data.

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The prompt (or direct) photon production[1] in ep-collisions is a direct probe of the hard subprocess dynamics, since produced photons are largely insensitive to the effects of the final state hadronization. It is a subject of a special interest since, in particular, measurements of total and differential cross sections of prompt photons can be used to constrain the parton densities in a proton.

In this work we have implemented the k_T-factorization approach for the prompt photon photoproduction process, where the virtuality of the exchanged photon Q^2 is lower than 1 GeV^2. The k_T-factorization approach was used to describe the prompt photon photoproduction at HERA in papers [1, 2]. That consideration was based on the off-shell $\mathcal{O}(\alpha^2)$ partonic amplitudes for direct ($\gamma q^* \to \gamma q$) and resolved photon ($q^* g^* \to \gamma q$, $g^* q^* \to \gamma q$ and $q^* \bar{q}^* \to \gamma g$) contributions to the photon cross section, where the non-zero transverse momenta of initial quarks and gluons were properly taken into account. A reasonably good description for HERA data [3, 4] was obtained whereas the traditional next-to-leading order (NLO) collinear pQCD calculations [5 – 7] underestimate these data by 30—40%, especially in rear pseudo-rapidity (electron direction) region, and the observed disagreement is difficult to explain within conventional theoretical uncertainties connected with scale dependence and parametrizations of the parton densities.

Recently new experimental data on prompt photon photoproduction have been presented by the ZEUS collaboration [8]. The results obtained with $\mathcal{O}(\alpha^2)$ matrix elements [1, 2] tend to underestimate the new ZEUS data. Also in the NLO collinear approximation results the box contributions were taken into account. This demands a reconsidering with the including higher order matrix elements in the k_T-factorization calculation. So, in this work we take into account $\mathcal{O}(\alpha^2 \alpha_s)$ subprocesses, namely $\gamma g^* \to \gamma q \bar{q}$ and $\gamma q \to \gamma g q$. These subprocesses effectively include the LO contributions of $\gamma q \to \gamma q$, $qg \to \gamma q$ and $q\bar{q} \to \gamma g$ in the k_T-factorization approach. Also in the case of photon and associated jet production, the considering of $2 \to 3$ subprocesses allows us to take into account the kinematics of the accompanied jet more accurately as compared with the previous consideration (see [9] for details). Additional motivation for such study is that similar consideration [10], based on the off-shell $2 \to 3$ subprocesses, results in better description of the Tevatron data on the associated photon and heavy (b or c) quark jet as compared to the NLO pQCD predictions. Moreover, we take into account $\mathcal{O}(\alpha^2 \alpha_s^2)$ contributions from the box $\gamma g \to \gamma g$ subprocess, which is known to be sizeable[7] since the high gluon density region is partially reached.

According to the k_T-factorization prescription, to calculate the cross section of the prompt photon photoproduction with the incoming direct photon one should convolute off-shell partonic cross sections with the relevant unintegrated (transverse momentum dependent) quark and/or gluon distributions in a proton:

$$\sigma = \sum_{a=q,g} \int \hat{\sigma}^*_{\gamma a}(x, \mathbf{k}_T^2)\, f_a(x, \mathbf{k}_T^2, \mu^2)\, dx\, d\mathbf{k}_T^2, \tag{1}$$

where $\hat{\sigma}^*_{\gamma a}(x, \mathbf{k}_T^2)$ is the relevant partonic cross section. The initial off-shell parton has fractions x of the initial proton longitudinal momentum, non-zero transverse momentum $\mathbf{k}_T$ and the azimuthal angle ϕ.

As the unintegrated parton dictrutions we use the KMR uPDFs [11, 12]. The KMR approach is the formalism to construct the unintegrated parton distributions $f_a(x, \mathbf{k}_T^2, \mu^2)$ from the known

[1]Usually the photons are called "prompt" if they are coupled to the interacting quarks.

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conventional parton distributions $xa(x,\mu^2)$, where $a = g$ or $a = q$. In this approximation, the unintegrated quark and gluon distributions are given by [11, 12]

$$f_q(x,\mathbf{k}_T^2,\mu^2) = T_q(\mathbf{k}_T^2,\mu^2)\frac{\alpha_s(\mathbf{k}_T^2)}{2\pi}\times \\ \times\int\limits_x^1 dz\left[P_{qq}(z)\frac{x}{z}q\left(\frac{x}{z},\mathbf{k}_T^2\right)\Theta(\Delta - z) + P_{qg}(z)\frac{x}{z}g\left(\frac{x}{z},\mathbf{k}_T^2\right)\right], \tag{2}$$

$$f_g(x,\mathbf{k}_T^2,\mu^2) = T_g(\mathbf{k}_T^2,\mu^2)\frac{\alpha_s(\mathbf{k}_T^2)}{2\pi}\times \\ \times\int\limits_x^1 dz\left[\sum_q P_{gq}(z)\frac{x}{z}q\left(\frac{x}{z},\mathbf{k}_T^2\right) + P_{gg}(z)\frac{x}{z}g\left(\frac{x}{z},\mathbf{k}_T^2\right)\Theta(\Delta - z)\right], \tag{3}$$

where $P_{ab}(z)$ are the usual unregulated LO DGLAP splitting functions. The theta functions which appear in (2) and (3) imply the angular-ordering constraint $\Delta = \mu/(\mu + |\mathbf{k}_T|)$ specifically to the last evolution step to regulate the soft gluon singularities. For other evolution steps, the strong ordering in transverse momentum within the DGLAP equations automatically ensures angular ordering[2]. The Sudakov form factors $T_q(\mathbf{k}_T^2,\mu^2)$ and $T_g(\mathbf{k}_T^2,\mu^2)$ which appear in (2) and (3) enable us to include logarithmic loop corrections to the calculated cross sections.

The calculation of the off-shell matrix elements for $\gamma g^* \to \gamma q\bar{q}$ and $\gamma q \to \gamma g q$ subprocesses is straightforward. The only difference comes from the modification of the polarization sum rules. In the k_T-factorization approach the gluon polarization density matrix takes so called BFKL form: $\sum \varepsilon^\mu \varepsilon^{*\nu} = k_T^\mu k_T^\nu/\mathbf{k}_T^2$. For the photons and outgoing on-shell gluon the summation over their polarizations can be performed with the usual covariant formula: $\sum \varepsilon^\mu \varepsilon^{*\nu} = -g^{\mu\nu}$. In other respects we follow the standard QCD Feynman rules. The evaluation of the emerging traces was done using the algebraic manipulation system FORM [14]. Concerning the box contribution $\gamma g \to \gamma g$, the corresponding amplitude squared was calculated a long time ago in the on-shell limit $\mathbf{k}_{2T}^2 \to 0$. The simple analytical expression can be found, for example, in [15]. In our phenomenological study, we apply this expression, however we keep the exact off-shell kinematics (see [16] for more details).

We neglect the contributions from the so-called fragmentation mechanisms since the the isolation cut application [8] reduces these contributions to less than 10% of the visible cross section. Note that the isolation cuts and additional conditions which preserve our calculations from divergences were specially discussed in [2].

Finally, since experimental data [8] refer to the prompt photon production in ep collisions, where the electron emits a quasi-real ($Q^2 \sim 0$) photon, γp cross section (1) should be weighted with the photon flux in the electron:

$$d\sigma(ep \to e' + \gamma + X) = \int f_{\gamma/e}(y)d\sigma(\gamma p \to \gamma + X)dy, \tag{4}$$

where y is the fraction of the initial electron energy carried by the photon in the laboratory frame. We use here the Weizacker-Williams approximation for the bremsstrahlung photon distribution from the electron:

$$f_{\gamma/e}(y) = \frac{\alpha}{2\pi}\left(\frac{1+(1-y)^2}{y}\ln\frac{Q^2_{\max}}{Q^2_{\min}} + 2m_e^2 y\left(\frac{1}{Q^2_{\max}} - \frac{1}{Q^2_{\min}}\right)\right), \tag{5}$$

[2]Numerically, in (2) and (3) we applied the MSTW2008 parton distributions [13].

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where m_e is the electron mass, $Q^2_{\min} = m_e^2 y^2/(1-y)^2$ and $Q^2_{\max} = 1$ GeV^2, which is a typical value for the recent photoproduction measurements at the HERA collider.

In our numerical calculations we took the renormalization and factorization scales $\mu_R^2 = \mu_F^2 = \xi^2 E_T^{\gamma 2}$. In order to evaluate theoretical uncertainties, we varied ξ between 1/2 and 2 about the default value $\xi = 1$. We used the LO formula for the strong coupling constant $\alpha_s(\mu^2)$ with $n_f = 4$ active quark flavours at $\Lambda_{QCD} = 200$ MeV, so that $\alpha_S(M_Z) = 0.1232$.

In Figs. 1 — 4 some results of our calculation [9] for the inclusive and associated with a jet photoproduction of the prompt photon are shown. The results are compared with the data taken by the ZEUS collaboration at the electron energy $E_e = 27.6$ GeV and the proton energy $E_p = 920$ GeV [8]. We also show the results, obtained with $2 \to 2$ matrix elements [1, 2]. We find that our predictions reasonably well describe the most of the available experimental data. Moreover, the shape and absolute normalization of the measured cross sections are adequately reproduced within the theoretical and experimental uncertainties. However, the distributions for $\eta^{\rm jet}$ and x_γ show some disagreement in the shape. The same shape disagreement in the $\eta^{\rm jet}$ distributions is observed in the predictions based on the $2 \to 2$ subprocesses. The possible reason of such discrepancy can be connected with the approximation for the jet determination [1, 2] and which was used in both type of calculations. Note that the predictions based on the former scheme give the results tending to underestimate the data, while the approach based on the $2 \to 3$ subprocesses shows better agreement.

The relative contributions of different subprocesses to the prompt photon cross section are shown on the right panels of Figs. 1 — 4. We find that while the subprocess $\gamma q \to \gamma q g$ dominates, the box subprocess $\gamma g \to \gamma g$ contributes significantly to the predicted cross section, specially at negative photon pseudorapidities. In this region, the box contribution is comparable with the contribution from the subprocess $\gamma g^* \to \gamma q \bar{q}$, and it amounts up to $\sim 15\%$ of the total cross section of inclusive prompt photon production.

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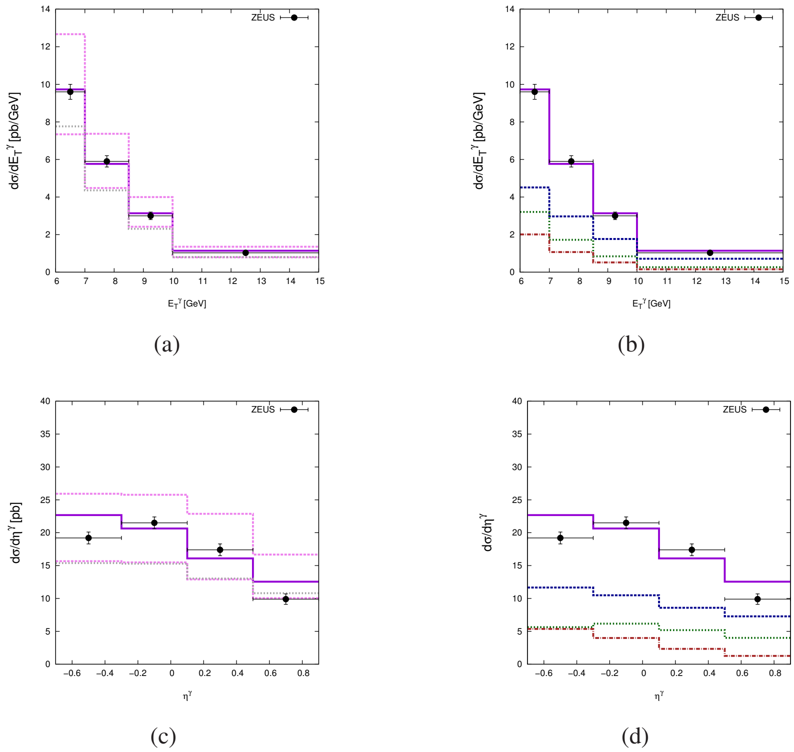

Figure 1: The inclusive prompt photon photoproduction cross section as a function of photon transverse energy E_T^γ and pseudo-rapidity η^γ at HERA. The left panel: the solid histograms correspond to the KMR predictions at the default scale $\mu = E_T^\gamma$, whereas the upper and lower dashed histograms correspond to scale variations described in the text; the dotted histograms represent the results obtained in previous papers [1, 2]. The right panel: the solid histograms represent the total cross section; dashed, dotted and dash-dotted histograms correspond to the contributions from $\gamma q \to \gamma g q$, $\gamma g^* \to \gamma q \bar{q}$ and $\gamma g \to \gamma g$ respectively. The experimental data are from ZEUS [8].

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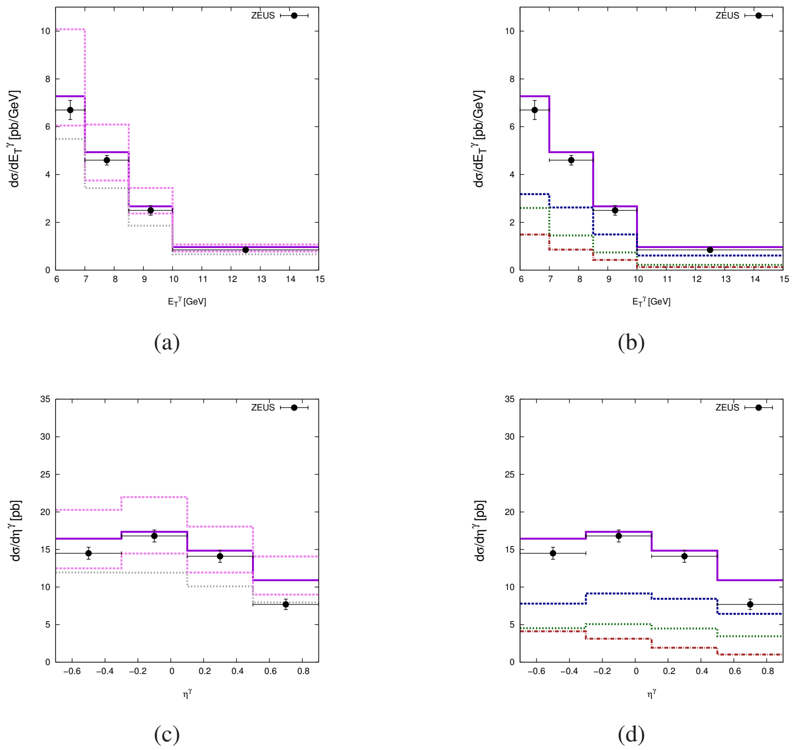

Figure 2: The associated with a jet prompt photon photoproduction cross section as a function of photon transverse energy E_T^γ and pseudo-rapidity η^γ at HERA. The notations of the histograms are the same as in Fig. 1. The experimental data are from ZEUS [8].

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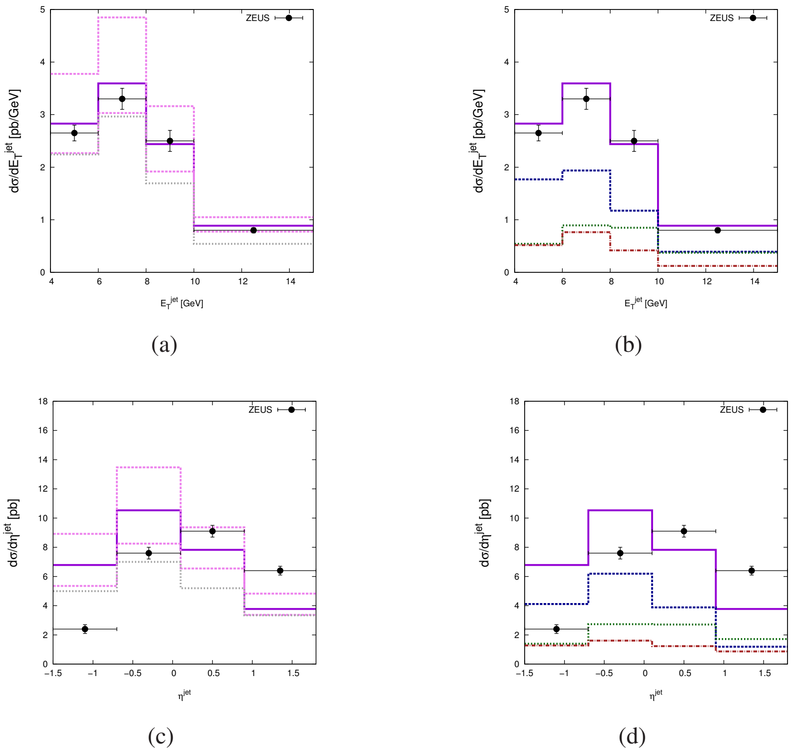

Figure 3: The associated with a jet prompt photon photoproduction cross section as a function of jet transverse energies $E_T^{\rm jet}$ and pseudo-rapidities $\eta^{\rm jet}$ at HERA. The notations of the histograms are the same as in Fig. 1. The experimental data are from ZEUS [8].

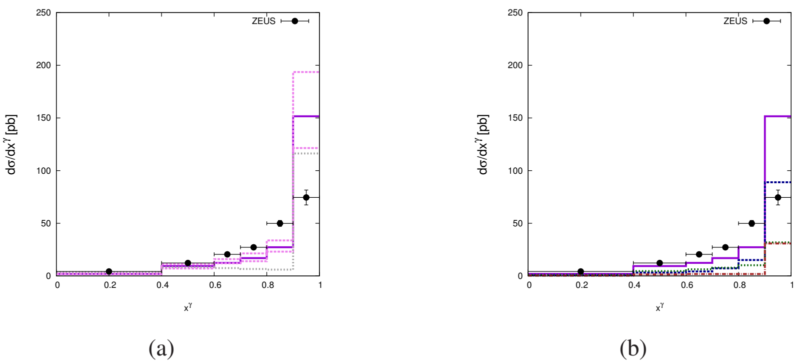

Figure 4: The associated with a jet prompt photon photoproduction cross section as a function of the longitudinal momentum of a parton from the initial photon $x_\gamma^{\rm obs}$ at HERA The notations of the histograms are the same as in Fig. 1. The experimental data are from ZEUS [8].