Prompt photon photoproduction at HERA in the k_T-factorization approach

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Outline

1. Motivation
2. k_T-factorization approach
   - unintegrated parton distributions
   - off-shell matrix elements
3. Parameters
4. Numerical results
5. Conclusion

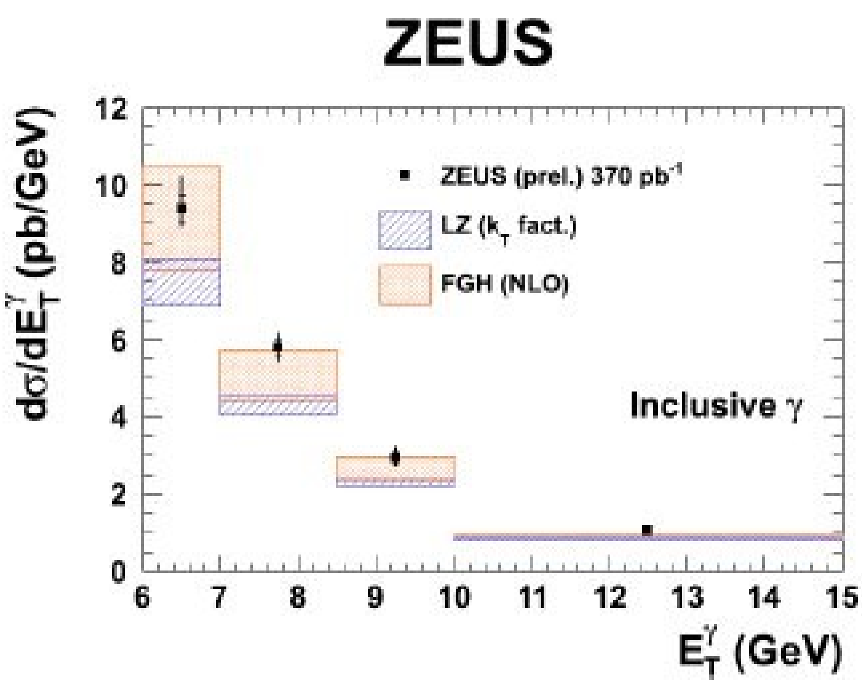
Motivation

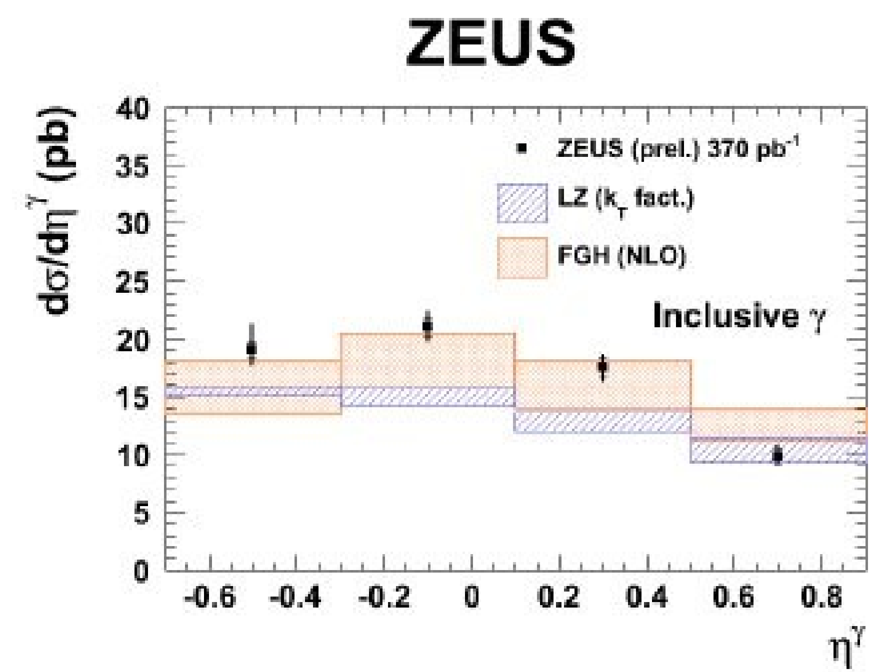
The prompt photon production in *ep* collisions at HERA is a direct probe of the hard subrocess dynamics, since produced photons are largely insensitive to the effect of final-state hadronization.

In the present work we have studied the prompt photon photoproduction in the k_T-factorization approach, which was successfully used before to describe other various high energy processes. In particular, it was used to describe the prompt photon production at HERA [A.V. Lipatov, N.P. Zotov, Phys.Rev. **D 72**, 054002 (2005); **D 81**, 094027 (2007)].

Recently new experimental data on prompt photon photoproduction have been presented by the ZEUS collaboration. Here we present the theoretical description of these and also previously published HERA data with taking into account additional contributions which are important for a better understanding of the evolution dynamics of the process.

Motivation





Graphs from the presentation by A. Iudin at DIS'13

The results obtained with with $O(\alpha^2)$ matrix elements [Lipatov, Zotov, 2005, 2007] tend to underestimate the new ZEUS data. In the NLO collinear approximation results also the box contributions were taken into account. This demands a reconsidering with the including higher order matrix elements in the k_T-factorization calculation.

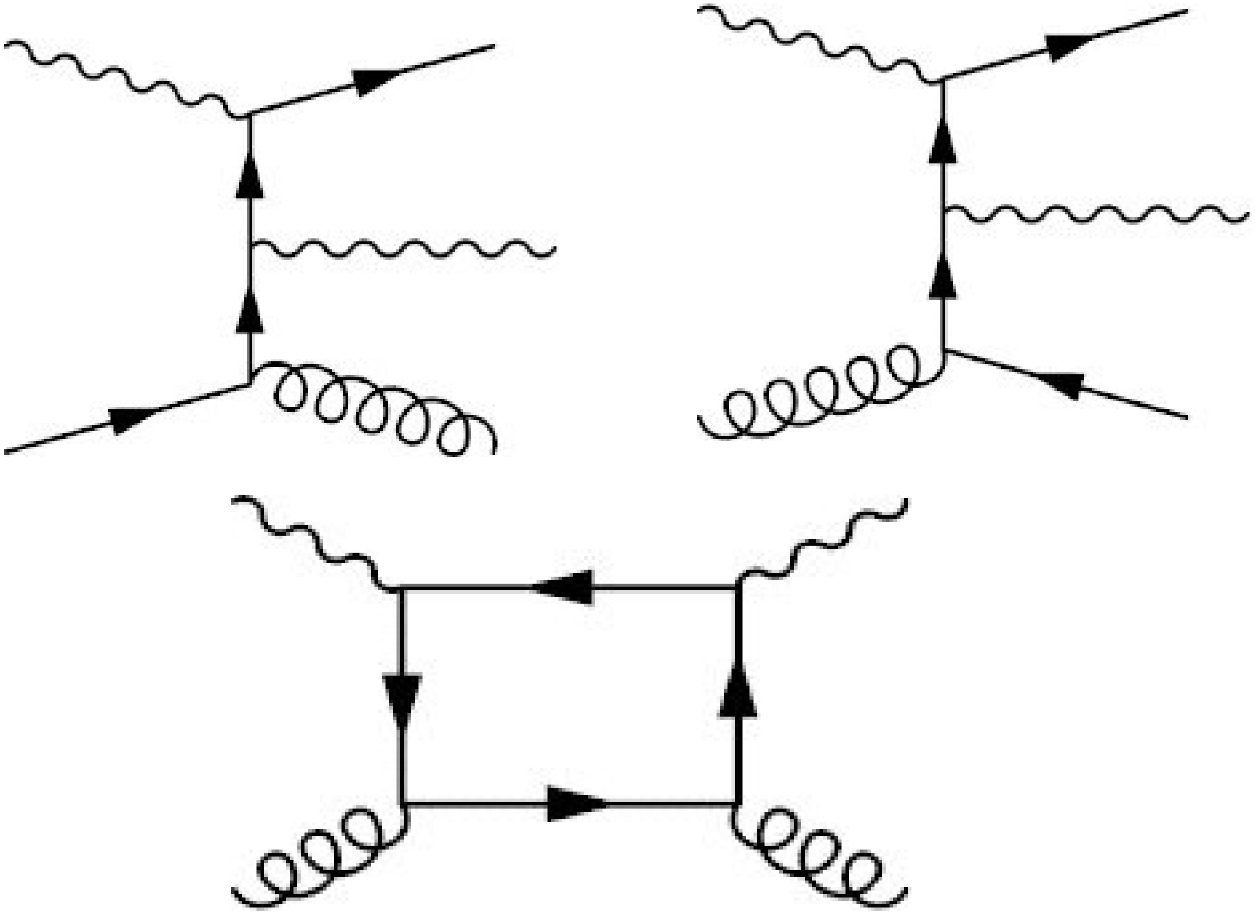
k_T-factorization approach

1. Matrix elements which depend on the transverse momenta of incoming gluons.
2. Unintegrated parton distributions

Considered subprocesses

We extend our consideration to the $O(\alpha^2\alpha_S)$ and $O(\alpha^2\alpha_S{}^2)$ subprocesses:

1. $\gamma q \to \gamma q g$
2. $\gamma g^* \to \gamma q \bar{q}$
3. $\gamma g \to \gamma g$



Consequence for γ+jet

In the case of photon and associated jet production the considering of the $O(\alpha^2\alpha_S)$ and $O(\alpha^2\alpha_S{}^2)$ subprocesses allows us to take into account the kinematics of the accompanied jet more accurately as compared with the previous consideration.

Additional motivation of our study is that similar consideration, based on the off-shell 2 → 3 subprocesses, results to a better description of the Tevatron data on the associated photon and heavy (b or c) quark jet as compared to the NLO pQCD predictions.

Cross section

$$\sigma(\gamma p \to \gamma X) = \sum \int \frac{E_T^\gamma}{128\pi^3 y (x_2 S)^2} \overline{|\mathcal{M}(\gamma q(g) \to \gamma q g(\bar{q}))|^2} \times$$
$$\times f_{q(g)}(x_2, \mathrm{k}_{2T}^2, \mu^2) dy_1\, dy_2\, dy^\gamma\, dE_T^\gamma\, d\mathrm{k}_{2T}^2 \frac{d\phi_2}{2\pi} \frac{d\psi_1}{2\pi} \frac{d\psi_2}{2\pi} \frac{d\psi^\gamma}{2\pi}$$

$$\sigma(\gamma p \to \gamma X) = \int \frac{E_T^\gamma}{8\pi\, y (x_2 s)^2} \overline{|\mathcal{M}(\gamma g \to \gamma g)|^2} f_g(x_2, \mathrm{k}_{2T}^2, \mu^2) \times$$
$$\times dy^\gamma\, dE_T^\gamma\, d\mathrm{k}_{2T}^2 \frac{d\phi_2}{2\pi} \frac{d\psi^\gamma}{2\pi},$$

where E_T^γ, y^γ, ψ^γ are the transverse energy, rapidity and azimuthal angle of the produced photon, and ψ_1, ψ_2, y_1 and y_2 are the azimuthal angles and the rapidities of the outcoming partons. The matrix elements are convoluted with the unintegrated (i.e. depending on the transverse momenta) parton densities, which were taken in the KMR form.

Unintegrated parton distributions

KMR approach(Kimber, Martin, Ryskin) [M.A. Kimber, A.D. Martin, M.G. Ryskin, Phys. Rev. D **63**, 114027 (2001); G. Watt, A.D. Martin, M.G. Ryskin, Eur. Phys. J. C 31, 73 (2003)]. Weakening of the strong ordering:

$$k_{1,T} \ll ... \ll k_{n-1,T} \ll k_T \sim \mu$$

Unintegrated parton distributions

In the KMR approach the distribution functions start to depend on the transverse momenta of the partons, and $f_a(x,\mathbf{k}_T^2)=const$, if $\mathbf{k}_T^2<\mu_0^2\sim 1\ \mathrm{GeV}^2$, otherwise they take the form:

$$f_q(x,\mathbf{k}_T^2,\mu^2) = T_q(\mathbf{k}_T^2,\mu^2)\frac{\alpha_s(\mathbf{k}_T^2)}{2\pi}\times$$

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

$$f_g(x,\mathbf{k}_T^2,\mu^2) = T_g(\mathbf{k}_T^2,\mu^2)\frac{\alpha_s(\mathbf{k}_T^2)}{2\pi}\times$$

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

Parameters

- Theoretical uncertainties are connected with the choice of the factorization and renormalization scales. We took $\mu_R = \mu_F = \mu = \xi E_T^{\gamma}$. We varied the scale parameter ξ between 1/2 and 2 about the default value $\xi = 1$.

- We neglected the quark masses.

- For completeness, we use LO formula for the strong coupling constant $\alpha_s(\mu^2)$ with $n_f = 4$ active quark flavors at $\Lambda_{QCD} = 200$ MeV.

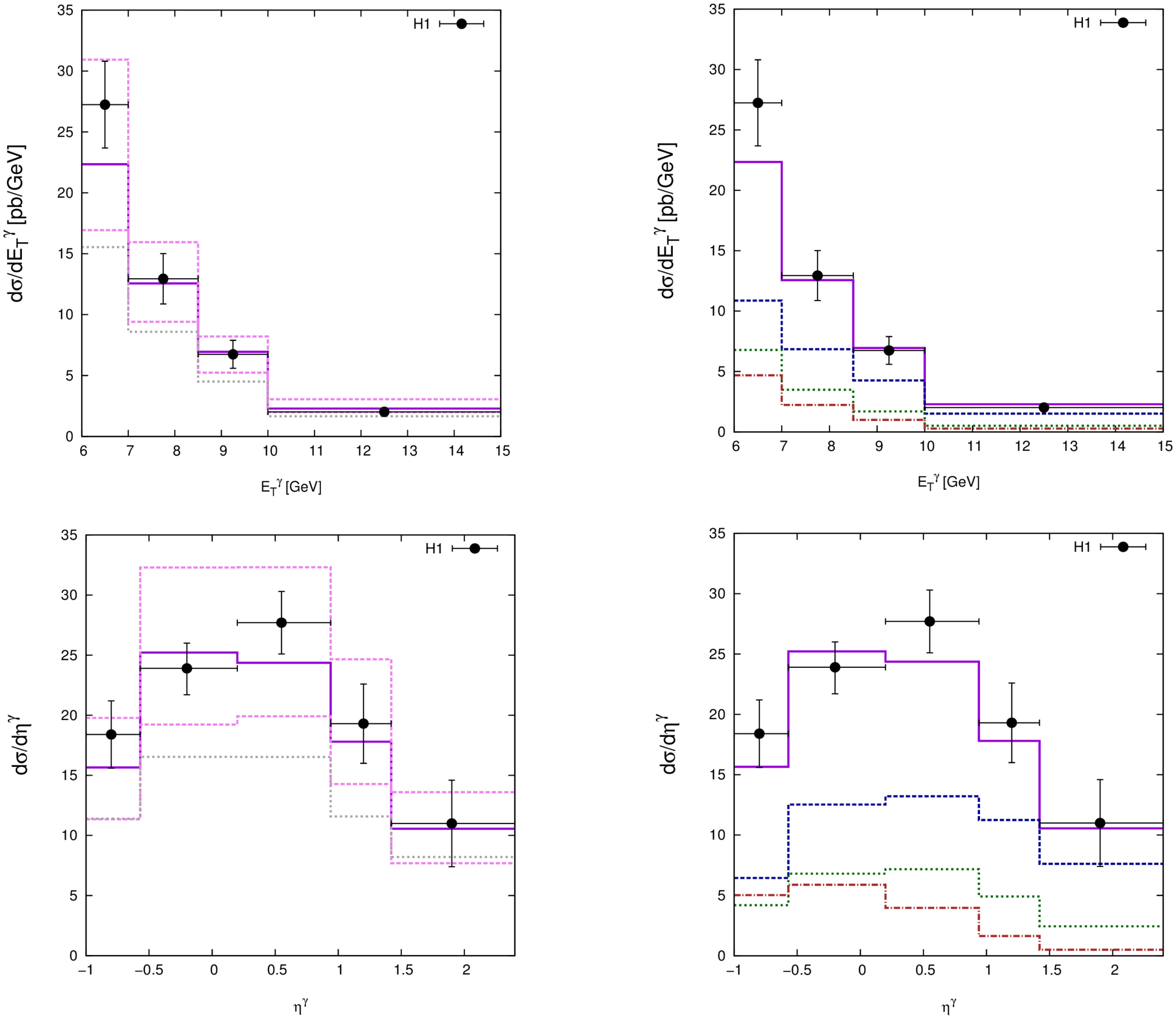
- We used the standard isolation experimental cuts:

$$E_T^{had} \leq E^{max}$$

$$(\eta^{had} - \eta)^2 + (\varphi^{had} - \varphi)^2 \leq R^2.$$

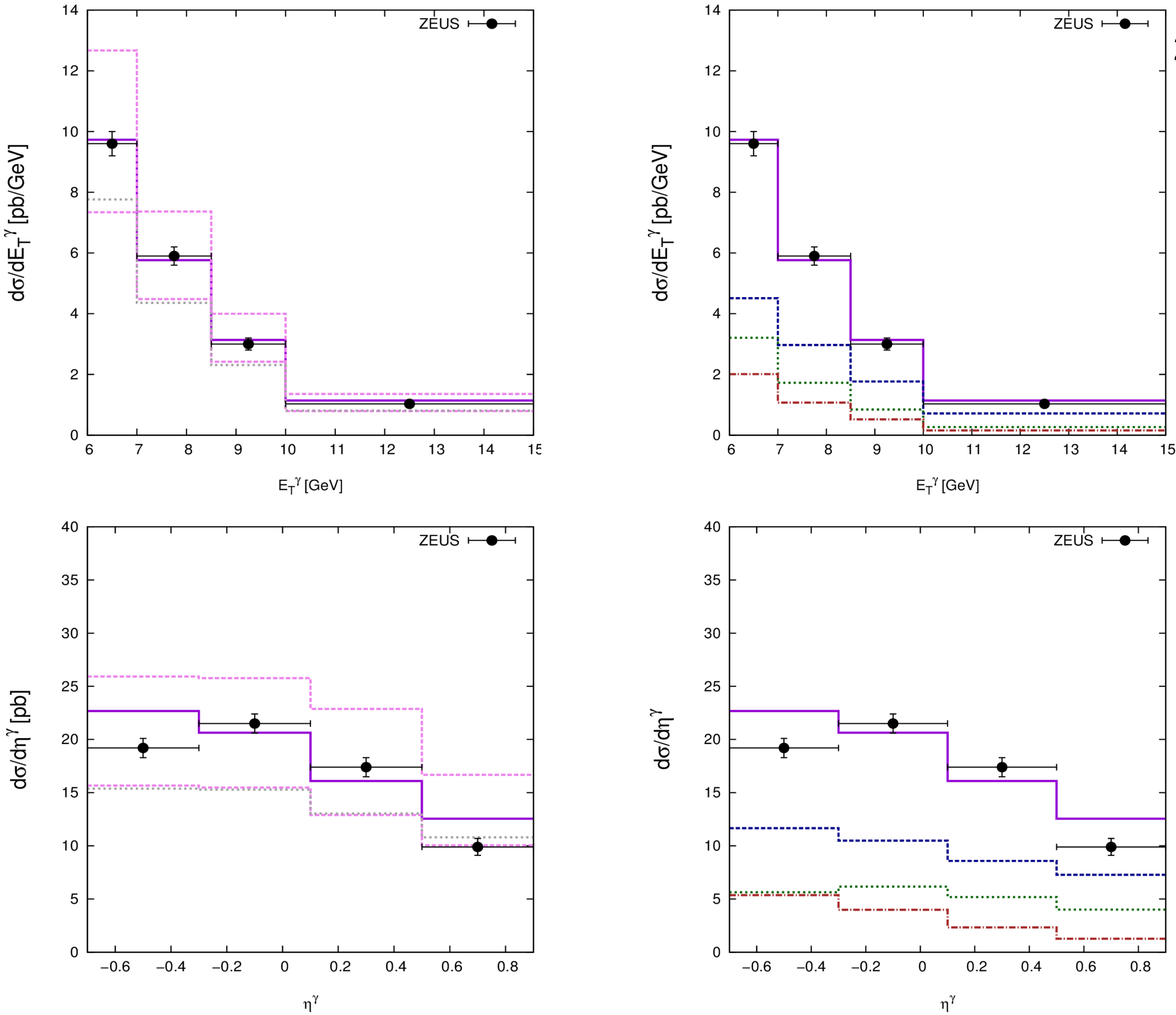
  The isolation not only reduces the background but also significantly reduces the so called fragmentation components, connected with collinear photon radiation (10%). Both H1 and ZEUS collaborations take R=1 and $E^{max} = 0.1\, E_T^{\gamma}$.

Numerical results — inclusive γ, H1-2009



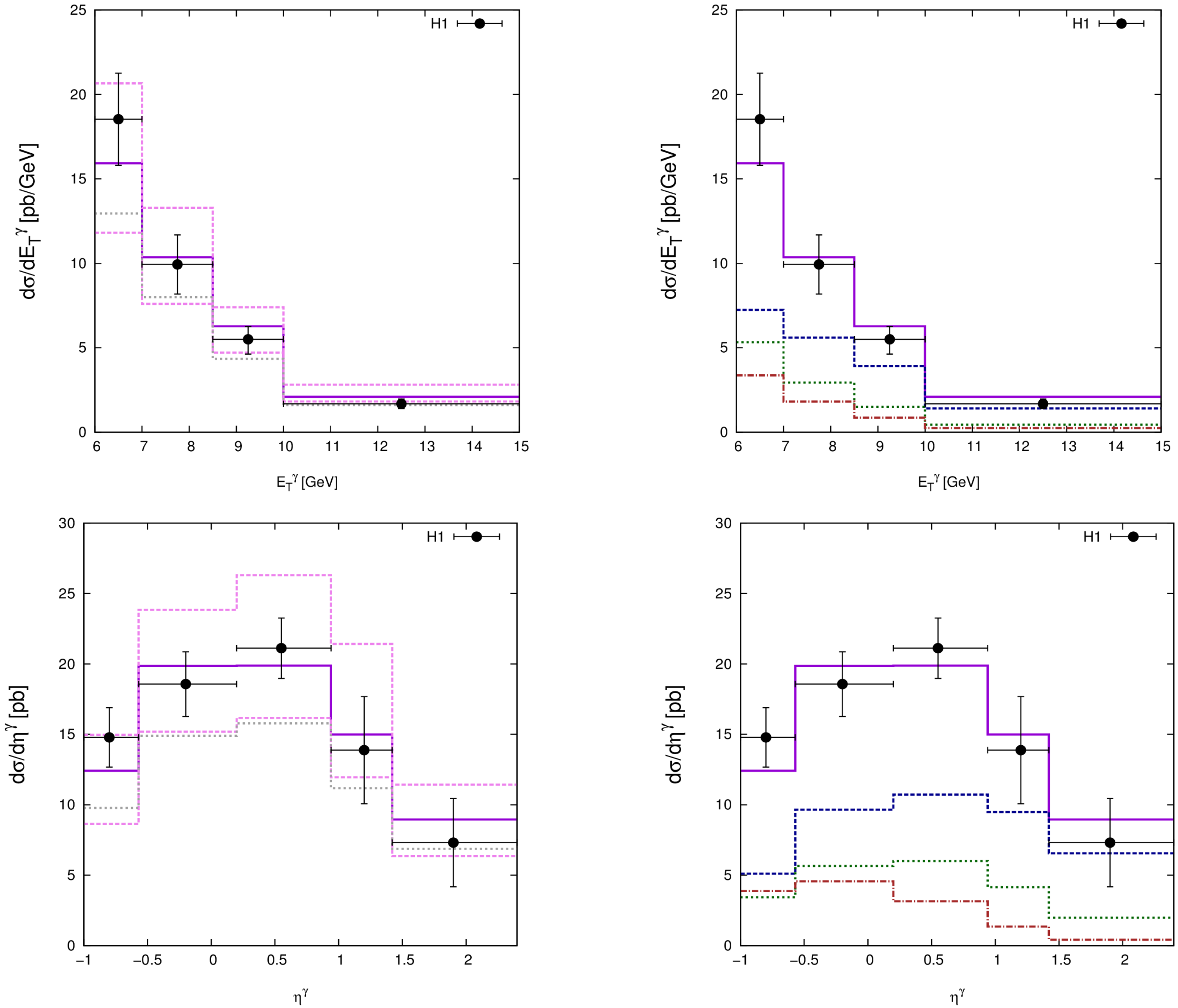
1. Differential cross section of the inclusive prompt photon photoproduction production $ep \to \gamma X$ at HERA as a function of the prompt photon transverse energy E_T^γ and pseudo-rapidity η^γ.
   Left: the solid line — the predictions; the dashed line — the uncertainties; dotted line — the predictions based on method of [Lipatov, Zotov, 2005, 2007]. Right: different contributions to the total cross-section (solid line): $\gamma q \to \gamma qg$ (dash-dotted), $\gamma g^* \to \gamma q\bar{q}$ (dashed), box (dotted). The experimental data are of H1 (2009).

Numerical results — inclusive γ, ZEUS-2013



2. Differential cross section of the inclusive prompt photon photoproduction production $ep\to\gamma X$ at HERA as a function of the prompt photon transverse energy $E_T{}^\gamma$ and pseudo-rapidity η^γ.
   Left: the solid line — the predictions; the dashed line — the uncertainties; dotted line — the predictions based on method of [Lipatov, Zotov, 2005, 2007]. Right: different contributions to the total cross-section (solid line): $\gamma q\to\gamma qg$ (dash-dotted), $\gamma g^*\to\gamma qq$ (dashed), box (dotted). The experimental data are of ZEUS (2013).

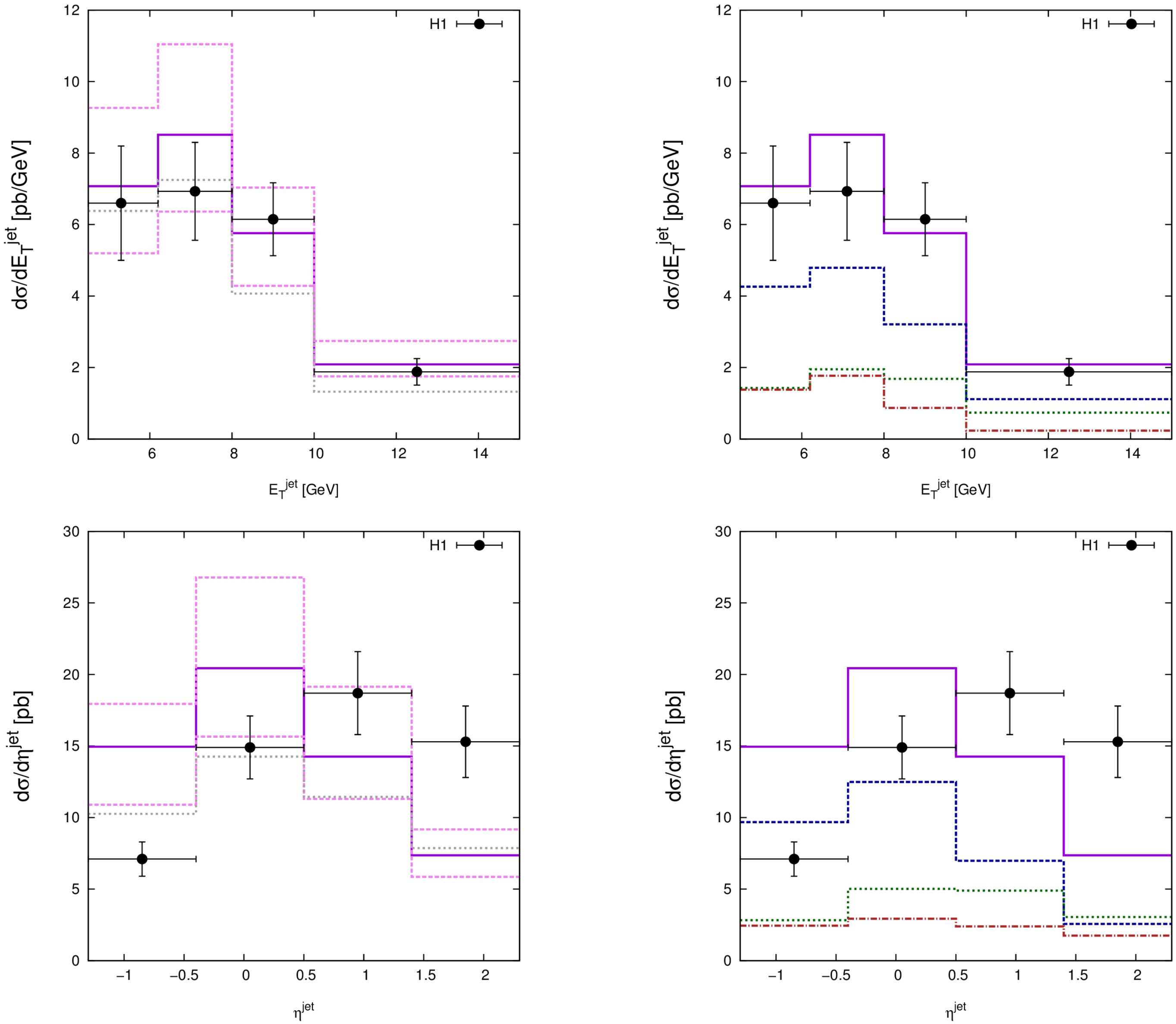
Numerical results — γ+jet, H1-2009



3. Differential cross section of the associated with a jet prompt photon photoproduction production $ep \to \gamma X$ at HERA as a function of the prompt photon transverse energy E_T^γ and pseudo-rapidity η^γ.

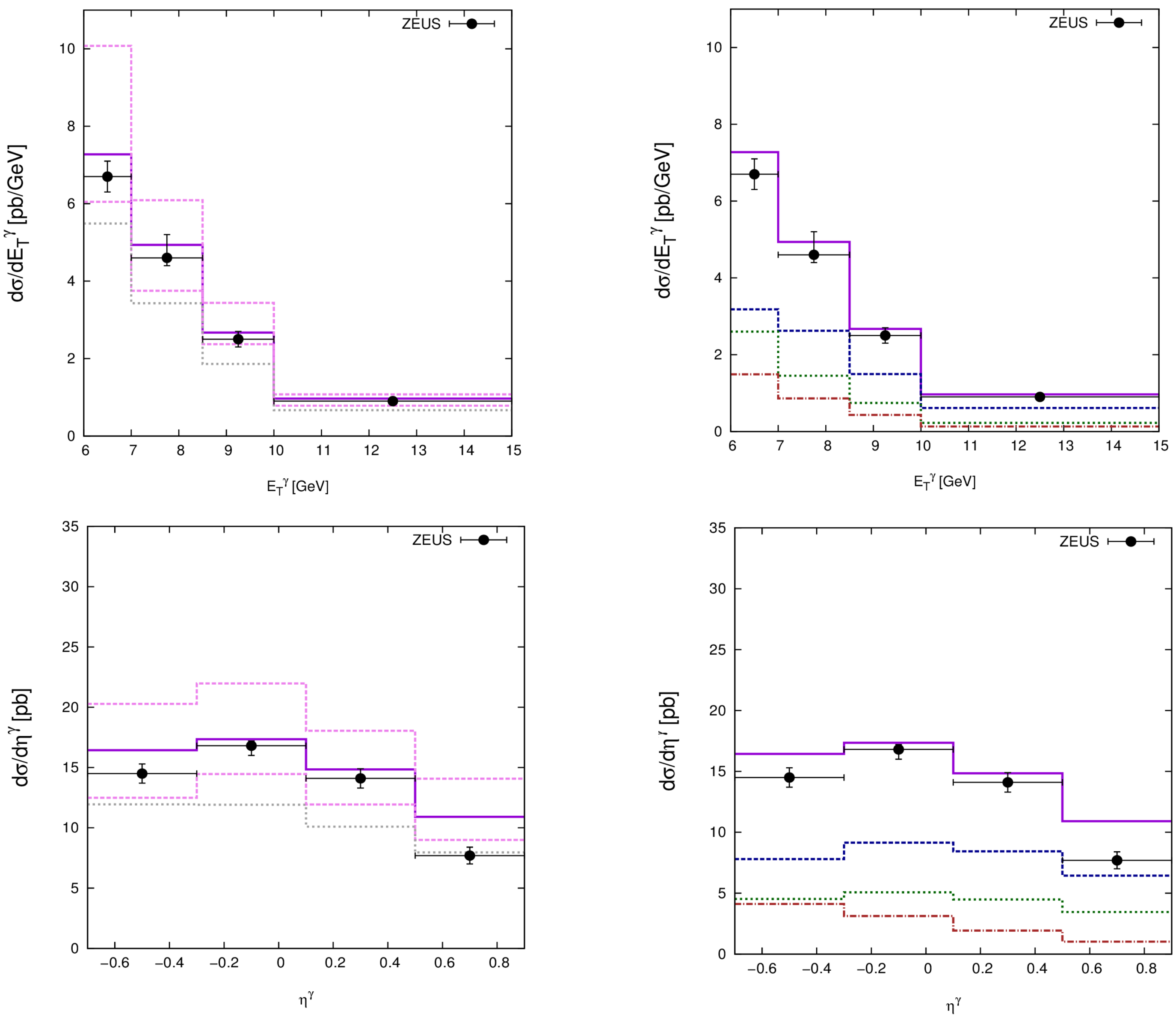
Left: the solid line — the predictions; the dashed line — the uncertainties; dotted line — the predictions based on method of [Lipatov, Zotov, 2005, 2007]. Rightt: different contributions to the total cross-section (solid line): $\gamma q \to \gamma qg$ (dash-dotted), $\gamma g^* \to \gamma q\bar{q}$ (dashed), box (dotted). The experimental data are of H1 (2009).

Numerical results — γ+jet, H1-2009



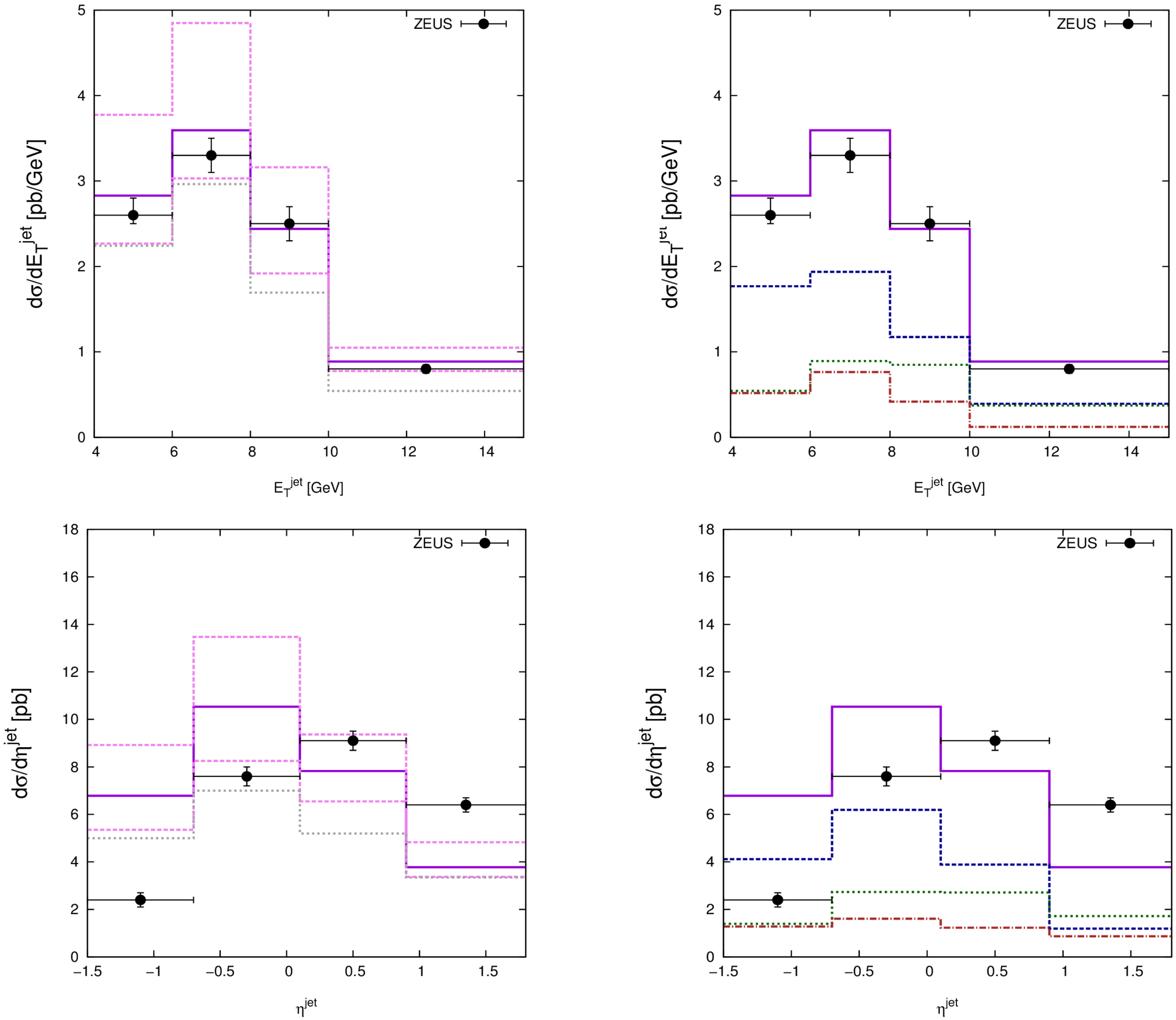
3. Differential cross section of the associated with a jet prompt photon photoproduction production $ep \to \gamma X$ at HERA as a function of the jet transverse energy E_T^{jet} and pseudo-rapidity η^{jet}.
Left: the solid line — the predictions; the dashed line — the uncertainties; dotted line — the predictions based on method of [Lipatov, Zotov, 2005, 2007]. Right: different contributions to the total cross-section (solid line): $\gamma q \to \gamma q g$ (dash-dotted), $\gamma g^* \to \gamma q \bar{q}$ (dashed), box (dotted). The experimental data are of H1 (2009).

Numerical results — γ+jet, ZEUS-2013



4. Differential cross section of the associated with a jet prompt photon photoproduction production $ep \to \gamma X$ at HERA as a function of the prompt photon transverse energy E_T^{γ} and pseudo-rapidity η^{γ}. Leftt: the solid line — the predictions; the dashed line — the uncertainties; dotted line — the predictions based on method of [Lipatov, Zotov, 2005, 2007]. Right: different contributions to the total cross-section (solid line): $\gamma q \to \gamma q g$ (dash-dotted), $\gamma g^* \to \gamma q \bar{q}$ (dashed), box (dotted). The experimental data are of ZEUS (2013).

Numerical results — γ+jet, ZEUS-2013



4. Differential cross section of the associated with a jet prompt photon photoproduction production $ep \to \gamma X$ at HERA as a function of the jet transverse energy E_T^{jet} and pseudo-rapidity η^{jet}.
Left: the solid line — the predictions; the dashed line — the uncertainties; dotted line — the predictions based on method of [Lipatov, Zotov, 2005, 2007]. Right: different contributions to the total cross-section (solid line): $\gamma q \to \gamma q g$ (dash-dotted), $\gamma g^* \to \gamma q \bar{q}$ (dashed), box (dotted). The experimental data are of ZEUS (2013).

x-variables

Important variables for testing the structure of the colliding proton and photon are the longitudinal momenta fractions of the partons in these particles.

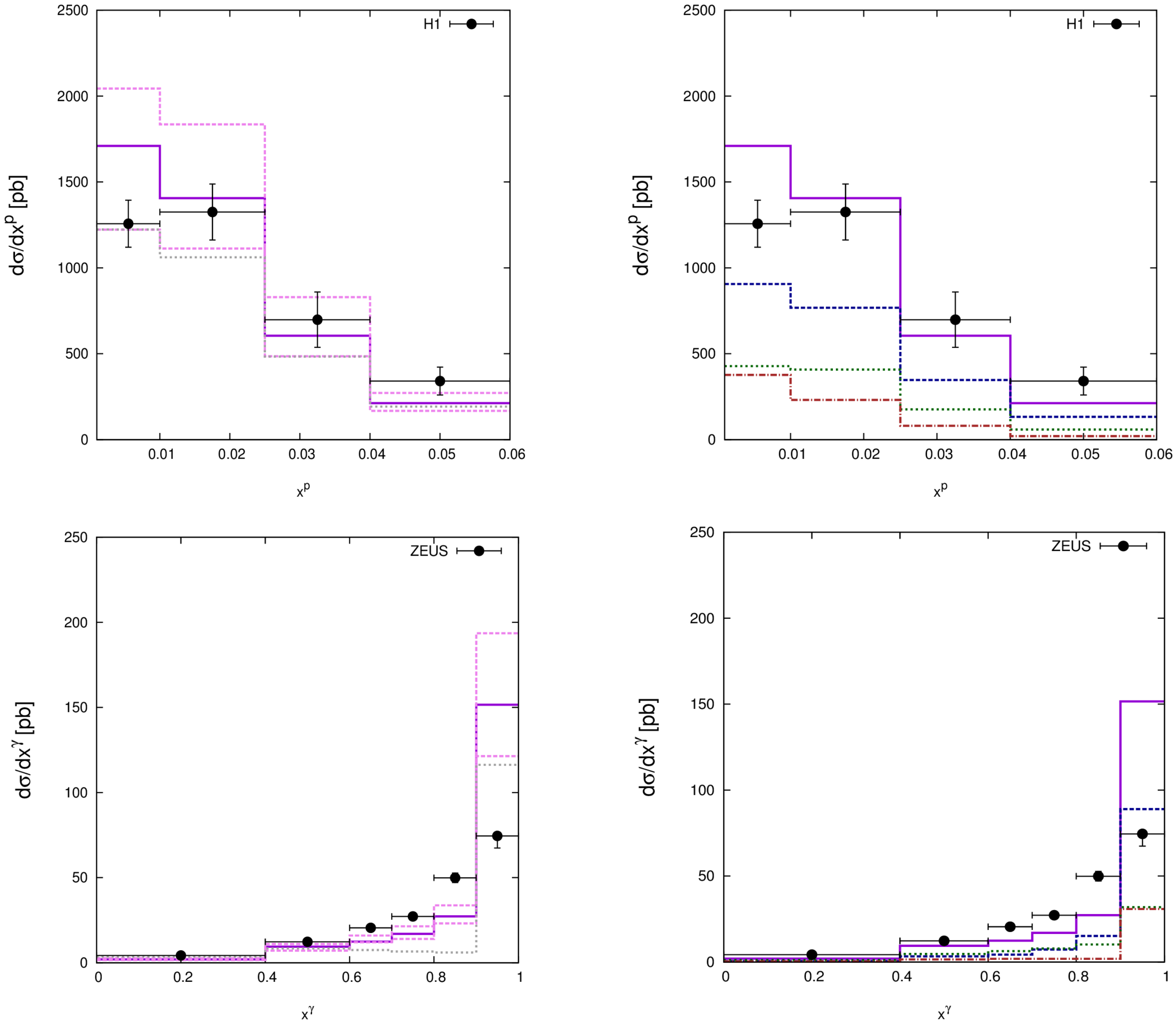
The ZEUS collaboration measures cross sections with the dependence from the following variable:

$$x_\gamma^{obs} = \frac{E_T^\gamma e^{-\eta^\gamma} + E_T^{jet} e^{-\eta^{jet}}}{2yE_e}$$

The H1 collaboration introduces the following observables:

$$x_\gamma^{LO} = \frac{E_T^\gamma (e^{-\eta^\gamma} + e^{-\eta^{jet}})}{2yE_e}, x_p^{LO} = \frac{E_T^\gamma (e^{-\eta^\gamma} + e^{\eta^{jet}})}{2E_p}$$

Numerical results - x-variables



5. Differential cross section of the associated with a jet prompt photon photoproduction production $ep \to \gamma X$ at HERA as a function of the longitudinal momentum of a parton from the initial photon x_γ^{obs} and of a parton from the initial proton in the leading order x_p^{LO}. Left: the solid line — the predictions; the dashed line — the uncertainties; dotted line — the predictions based on method of [Lipatov, Zotov, 2005, 2007]. Right: different contributions to the total cross-section (solid line): $\gamma q \to \gamma q g$ (dash-dotted), $\gamma g^* \to \gamma q \bar{q}$ (dashed), box (dotted). The experimental data are of H1 (2009) and ZEUS (2013).

Conclusion

In the presented talk the process of the the prompt photon photoproduction in the k_T-factorization QCD approach at HERA has been studied.

The matrix elements for $\gamma q \to \gamma q g$ and $\gamma g^* \to \gamma q \bar{q}$ have been calculated. Also the 'box' matrix element for $\gamma g \to \gamma g$ has been included into the consideration. The transverse momenta of the incoming quarks and gluons have been taken into account.

A reasonably good description of the experimental data of the ZEUS and H1 collaborations for the prompt photon photoproduction at HERA has been obtained.

Back up

Divergencies

- We do not use the concept of fragmentation functions obviously. In our approach the effect of final state radiation is already included in calculations at the level of partonic subprocess matrix elements (we have a 2 → 3 rather than 2 → 2 subprocesses). But as in the traditional approach the calculated cross sections can be split into two pieces: the direct and fragmentation contributions. They depend from fragmentation scale μ^2.
- In our calculations μ is the invariant mass of the produced photon and any final quark and we restrict direct contribution to $\mu \geq M$ = 1GeV in order to eliminate the collinear divergences in the direct cross section. Then the mass of light quark m_q can be safely to zero. The numerical effects of M is really small. It is less important than other theoretical uncertainties (connected with choice of renormalization and factorization scales).

Off-shell quarks

In the presented work we used a method, described in the article [S.P. Baranov, A.V. Lipatov, N.P. Zotov, Phys. Rev **D 81**, 094034 (2010)]. According to this method, the off-shell quark spin density matrix has the form (in the limit of zero masses):

$$\sum_s u^s(k)\bar{u}^s(k) = x\hat{P}$$

Here *P* is the momentum of the incoming proton.