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New Results in k_T-Factorization for *ep*-Processes

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Abstract—We report on newest results in k_T-factorization approach for *ep*-processes. We describe HERA data on longitudinal structure function measurements as well as on associated prompt photon and jet photoproduction. The calculations include first application of the new LLM-2022 transverse momentum dependent gluon distribution developed by the authors. The study includes also the first implementation of parton showers for photoproduction processes in k_T-factorization. The data are described well with the simulations. The *ep*-processes are included to the new version of Monte-Carlo generator pegasus.

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INTRODUCTION

In recent years, the high energy, or k_T-factorization approach (see, for instance, [1] and references therein) has become a frequently used tool to describe various processes in collider phenomenology. The k_T-factorization is based on the Balitsky–Fadin–Kuraev–Lipatov (BFKL) or Catani–Ciafaloni–Fiorani–Marchesini (CCFM) evolution equations, which resum $\log^n 1/x$ enhanced terms in the perturbative series, important at high energies (or small longitudinal momentum fractions x). This is in contrast with the conventional collinear factorization based on the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) equations, where only $\log^n Q^2/\Lambda^2_{QCD}$ are taken into account. An advantage of the k_T-factorization approach is that it effectively takes into account a number of higher-order perturbative corrections into the calculations with unintegrated (transverse momentum dependent, TMD) parton distributions. The k_T-factorization is implemented in TMD-based Monte-Carlo generators CASCADE [2], KaTie [3] and PEGASUS [4].

As it has been mentioned, the essential ingredient of the k_T-factorization approach is the unintegrated TMD parton density in the proton. Recently we proposed a new TMD—LLM'2022 [5], the parameters of which were determined from the best fit on low transverse momenta p_T LHC data on soft hadron production spectra as well as on higher scales results of HERA and LHC, including heavy quark structure functions and Higgs boson production cross sections[1]. The new LLM TMD has been recently used to describe HERA data on longitudinal structure function $F_L(x,Q^2)$ [7] and prompt photon photoproduction [8]. In this proceeding we briefly review these results.

LONGITUDINAL STRUCTURE FUNCTION $F_L(x,Q^2)$

The longitudinal structure function measurements are of a special interest since $F_L(x,Q^2)$ probes mainly the gluon content of the proton and thus can give us more information about gluon TMDs. One can calculate $F_L(x,Q^2)$ in the k_T-factorization approach with the following formula:

$$F_L(x,Q^2) = \int\limits_x^1 \frac{dz}{z}\int d\mathbf{k}_T^2 \times \sum e_f^2 \hat{C}_L^g(x/z, Q^2, m_f^2, \mathbf{k}_T^2) f_g(z, \mathbf{k}_T^2, \mu^2), \quad (1)$$

where the summation is performed over flavors f of quarks with electric charges e_f and masses m_f. The hard coefficient function $C_L^g(x/z, Q^2, m_f^2, \mathbf{k}_T^2)$ corre-

[1] Recently we have found that low Q^2 HERA data on the proton structure function $F_2(x,Q^2)$ suggest that the parameters of the LLM TMD have to be altered [6]. We plan to estimate the impact of such a variation on higher Q^2 data in our future works.

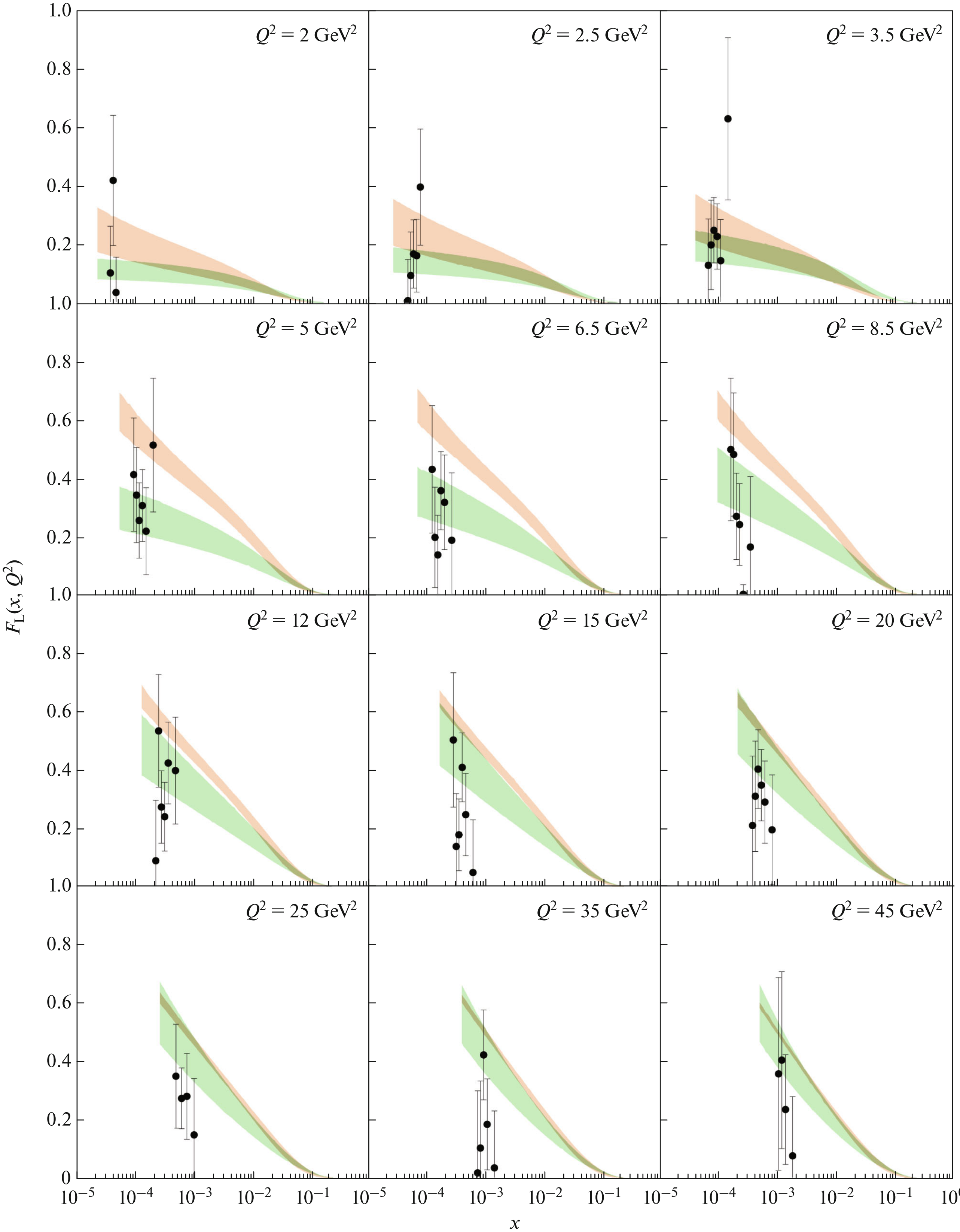

Fig. 1. $F_L(x,Q^2)$ calculated at different Q^2. The green band corresponds to the result obtained with the LLM'2022 gluon density with scale uncertainties; the red line represents results calculated with the JH'2013 set 2 TMD. The experimental data are from H1 [10].

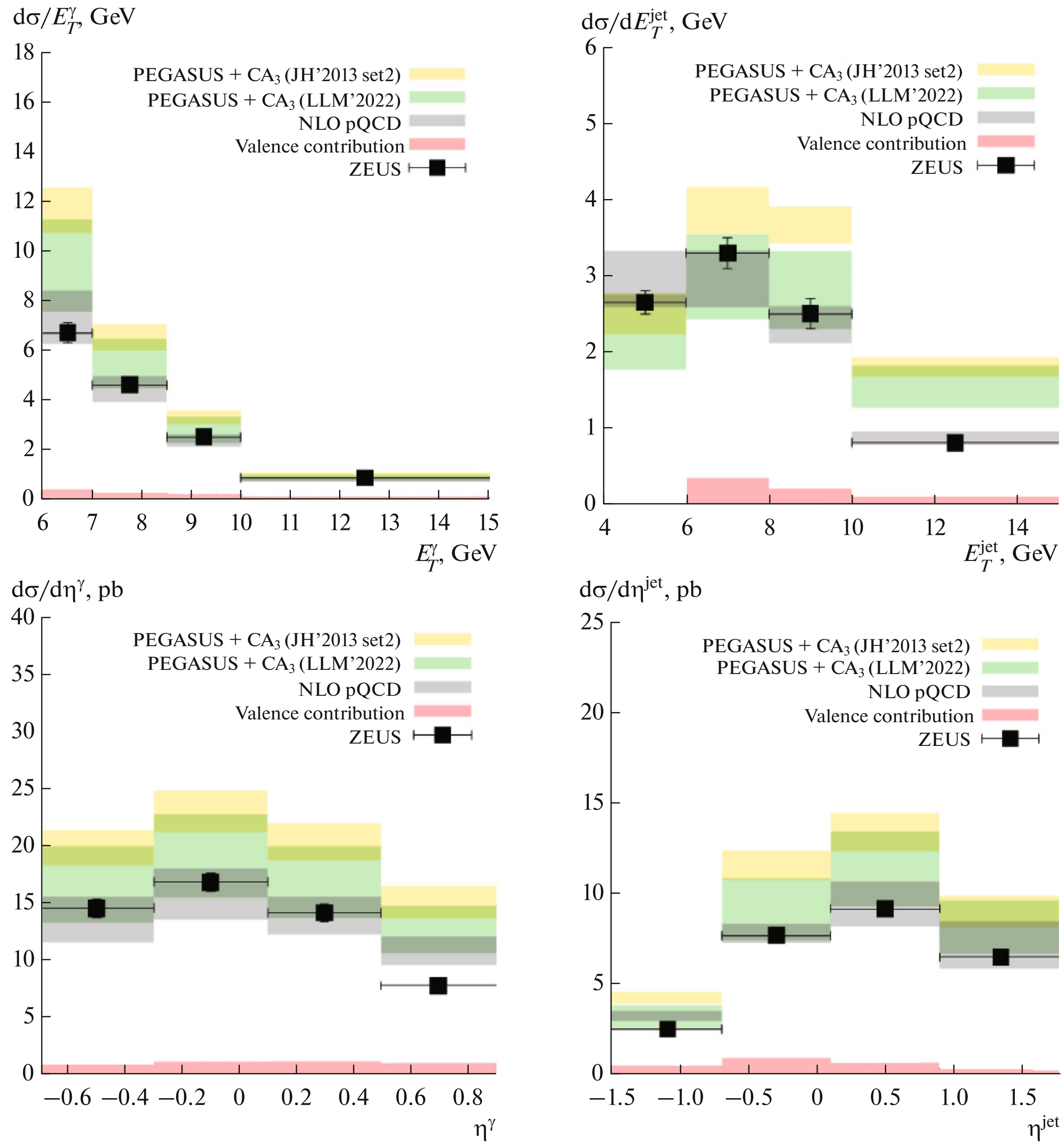

Fig. 2. The associated prompt photon and jet photoproduction cross section as functions of photon and jet transverse energies and pseudorapidities. The green histograms and shaded bands correspond to the predictions obtained with LLM'2022 gluon density and estimated scale uncertainties of these calculations. The yellow histograms represent the JH'2013 set 2 predictions. Separately shown the contributions from $\gamma + q_{val} \to \gamma + q$ subprocess and conventional NLO pQCD results (taken from [14]). The experimental data are from ZEUS [14].

sponds to the quark-box diagram for off-shell photon-gluon fusion subprocess and was calculated earlier [9]. We set the charm and beauty masses to $m_c = 1.67$ GeV and $m_b = 4.75$ GeV and use the massless limit to evaluate the corresponding contributions from the light quarks. Also, we apply the 2-loop formula for the strong coupling constant α_s with $N_f = 4$ quark flavours at $\Lambda_{QCD} = 200$ MeV. Results of our calculations are shown in Fig. 1 in comparison with available HERA data taken by the H1 [10] Collaboration. As a reference, we also show the results obtained with another popular CCFM gluon TMD—JH'2013 set 2 gluon density [11]. The shaded bands correspond to theoretical uncertainties of our calculations connected with the choice of hard scales. Note that in the case of the JH'2013 set 2 gluon density we use auxiliary "+" and "–" distributions corresponding to the variated renormalization scales. So,

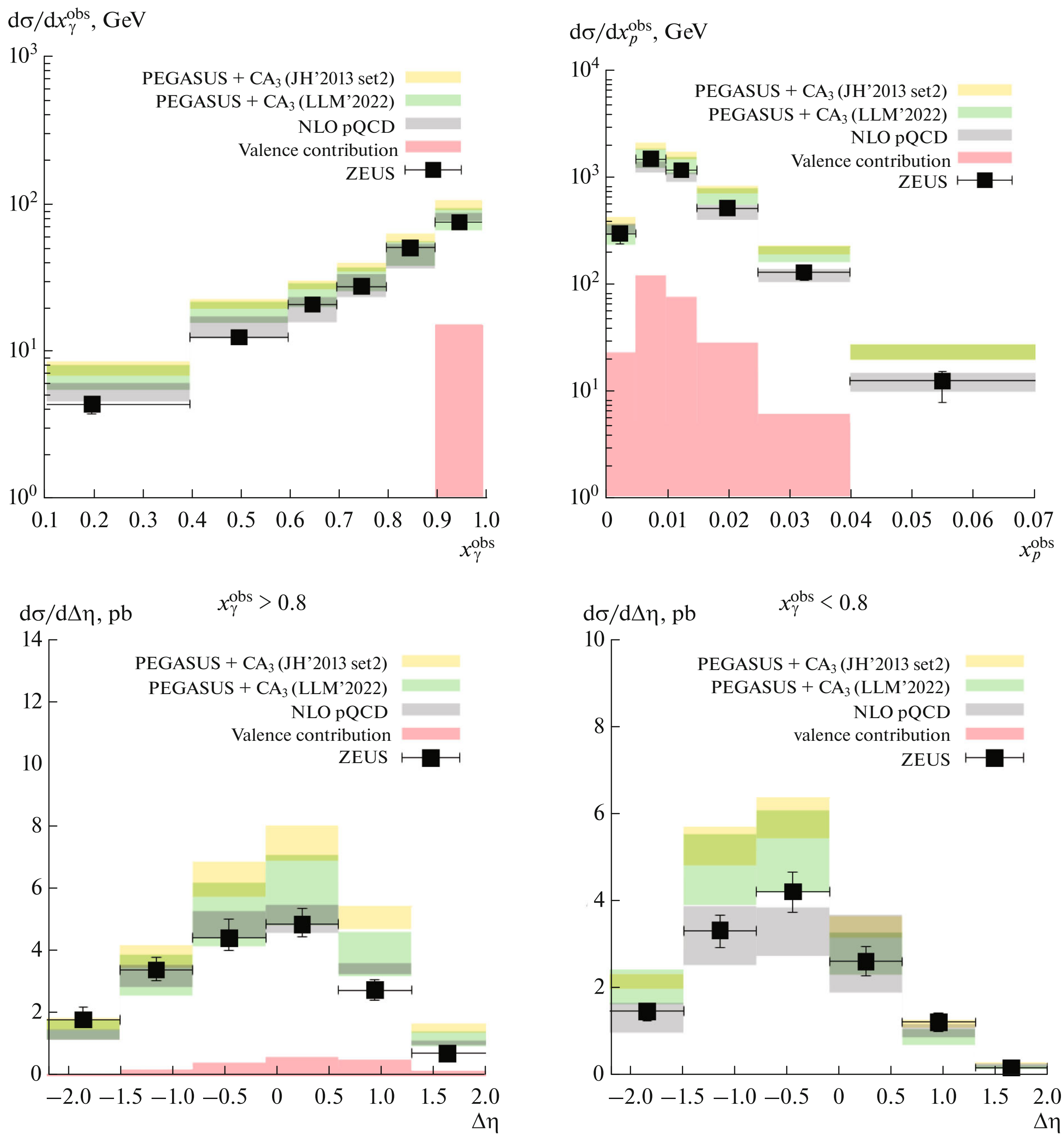

Fig. 3. The associated prompt photon and jet photoproduction cross section as functions of x_γ^{obs}, x_p^{obs} (upper panels) variables and $\Delta\eta$ at $x_\gamma^{obs} > 0.8$ (left panels) and $x_\gamma^{obs} < 0.8$ (lower panels). The notations are the same as in Fig. 2. The experimental data are from ZEUS [14, 15].

we find that the LLM'2022 gluon density describes the HERA data quite well within the estimated theoretical and experimental uncertainties. In addition, our calculations demonstrate that the available experimental data for the proton structure function $F_L(x, Q^2)$ are sensitive to the TMD gluon densities, especially at low Q^2.

PROMPT PHOTON PHOTOPRODUCTION

Prompt photon[2] is a clear probe of the proton structure since it is not affected by hadronization effects. Additional investigation of associated jets allows one to study also jet observables and photon-jet

[2] Photons are prompt if they originate from the interacting quarks rather than from hadron decays.

correalations. This made the jet associated prompt photon photoproduction an important subject of studies within the k_T-factorization [12, 13]. They revealed some problems with description of HERA data, in particular, a qualitatively incorrect behaviour of jet pseudorapidity $\eta_{\rm jet}$ distribution was predicted. So we reconsidered this process in [8]. We concentrated on leading direct off-shell gluon-initiated subprocesses giving the main contribution at small x: $\gamma g^* \to \gamma q\bar{q}$ and the "box" $\gamma g^* \to \gamma g$. Valence quark contribution, important at large x, was taken in the collinear approach at LO as $\gamma q \to \gamma q$. Resolved contributions bear effectively higher perturbative order, so we neglect them. For the first time in the k_T-factorization we implement parton showering and hadronization using the new version of CASCADE [2], which now includes DIS processes. The parameters of calculations are essentially the same as for $F_L(x, Q^2)$; the renormalization scale was taken as the prompt photon transverse energy $\mu_R = E_T^\gamma$ and factorization scale was calculated as $\mu_F = s + \mathbf{k}_T^2$, with $\mathbf{k}_T$ being the initial off-shell gluon transverse momentum. This unusual choice is dictated by the CCFM evolution. Some of our results compared with ZEUS data [14] are presented in Fig. 2. We show the histograms obtained with LLM'2022 and JH'2013 set 2 TMDs. As a comparison we also depict collinear NLO results taken from [14]. One can see that good description of data is achieved with LLM TMD. It is notable that now the $\eta_{\rm jet}$ distribution follows the observed behavior.

Other important variables are the longitudinal momenta fractions carried by the colliding partons. The momentum fractions of the initial photon and proton are introduced in the ZEUS analyses [14, 15] as the following:

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

The $x_\gamma > 0.8$ corresponds to the 'direct' region, while $x_\gamma < 0.8$—to the "resolved" one. Our results for these observables are shown in Fig. 3. One can see good agreement with the data, which was not achieved in [12, 13]. Also we show results for the pseudorapidity difference $\Delta\eta = \eta^\gamma - \eta^{\rm jet}$ in different x_γ regions. One can see that we describe the data well in both regions.

CONCLUSIONS

We have evaluated longitudinal structure function $F_L(x, Q^2)$ and the cross section of associated prompt photon + jet photoproduction within the k_T-factorization approach. Good description of H1 and ZEUS data has been achieved with the new LLM'2022 TMD gluon distribution. For the first time TMD parton showers have been included for photoproduction processes. Finally, a long standing problem of a qualitatively correct description of jet-related observables in γ + jet photoproduction in k_T-factorization has been solved. The prompt photon photoproduction process is now available in the newest version of the Monte-Carlo generator PEGASUS [4].

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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