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Prompt photon and associated heavy quark production in the k_T-factorization approach

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We present the results of the numerical calculations of prompt photon and associated heavy quark production at Tevatron and LHC in the framework of the k_T-factorization approach with KMR parton distributions. Our predictions are compared with the D∅ and CDF experimental data. Also we make predictions for LHC

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Prompt photon and associated heavy (b, c) quark production has been a subject of pointed theoretical and experimental investigations up to now since it is highly sensitive to parton distribution in the hadron. So it provides a test of hard subprocess dynamics. Also this process contributes to the background for the physics beyound the Standard Model processes.

In this work the k_T-factorization approach is used to make the calculations. It was used to describe the production of prompt photons associated with the charm or beauty quark in paper [1]. The consideration was based on the $\mathcal{O}(\alpha\alpha_s^2)$ amplitude for the gluon fusion subprocess $g^*g^* \to \gamma Q\bar{Q}$. A reasonably good agreement between the numerical predictions and the Tevatron data [2, 3] was obtained in the region of relatively low p_T^γ where the off-shell gluon fusion dominates. However, the quark-induced subprocesses become more important at moderate and large p^γ and therefore should be taken into account. Here we extend the previous analysis by including into the consideration two additional $\mathcal{O}(\alpha\alpha_s^2)$ subprocesses: $q\bar{q} \to \gamma Q\bar{Q}$ and $qQ \to \gamma qQ$, where Q is the charm or beauty quark.

The essential ingredient of the k_T-factorization approach is unintegrated (transeverse momentum dependent) parton distribution functions (uPDFs). One of the aims of the presented study was to test these parton densities. This is important as a step in the search of universal universal uPDFs.

According to the k_T-factorization theorem, to calculate the cross section of the prompt photon and associated heavy quark production one should convolute the off-shell partonic cross sections with the relevant unintegrated quark and/or gluon distributions in a proton:

$$\sigma = \sum_{a,b=q,g} \int \hat{\sigma}^*_{ab}(x_1, x_2, \mathbf{k}_{1T}^2, \mathbf{k}_{2T}^2)\, f_a(x_1, \mathbf{k}_{1T}^2, \mu^2)\, f_b(x_2, \mathbf{k}_{2T}^2, \mu^2)\, dx_1 dx_2\, d\mathbf{k}_{1T}^2 d\mathbf{k}_{2T}^2 \frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi},$$

where $\hat{\sigma}^*_{ab}(x_1, x_2, \mathbf{k}_{1T}^2, \mathbf{k}_{2T}^2)$ is the relevant partonic cross section. The initial off-shell partons have fractions x_1 and x_2 of initial protons longitudinal momenta, non-zero transverse momenta $\mathbf{k}_{1T}$ and $\mathbf{k}_{2T}$ and azimuthal angles ϕ_1 and ϕ_2.

In this work we test the KMR uPDFs [4, 5]. The KMR approach is the formalism to construct the unintegrated parton distributions $f_a(x, \mathbf{k}_T^2, \mu^2)$ from the known 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 [4, 5]

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

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

where $P_{ab}(z)$ are the usual unregulated LO DGLAP splitting functions. The theta functions which appear in (1) and (2) 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[1]. The Sudakov form factors $T_q(\mathbf{k}_T^2,\mu^2)$ and $T_g(\mathbf{k}_T^2,\mu^2)$ which appear in (1) and (2) enable us to include logarithmic loop corrections to the calculated cross sections.

The calcuation of the matrix elements generally follows the standard Feynman rules. 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: $\sum \varepsilon^\mu \varepsilon^{*\nu} = k_T^\mu k_T^\nu / \mathbf{k}_T^2$. The spin density matrix for the off-shell quark with the momentum $k = xP + k_T$ in massless limit is [7] $\sum_s u^s(k)\bar{u}^s(k) = x\hat{P}$, where P is the momentum of the incoming proton (or antiproton). Since the expression was obtained in the massless approximation, we neglected the light quarks masses.

In our numerical calculations we took the renormalization and factorization scales $\mu_R^2 = \mu_F^2 = \xi^2 p_T^2$. 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 $\alpha_S(M_Z) = 0.1232$. We set the charm and beauty quark masses to $m_c = 1.5$ GeV and $m_b = 4.75$ GeV.

In order to reduce the huge background from the secondary photons produced by the decays of π^0 and η mesons the isolation criterion is introduced in the experimental analyses. This criterion is the following. A photon is isolated if the amount of hadronic transverse energy E_T^{had} deposited inside a cone with aperture R centered around the photon direction in the pseudo-rapidity and azimuthal angle plane, is smaller than some value E_{max}.

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

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

The isolation not only reduces the background but also significantly reduces the so called fragmentation components, connected with collinear photon radiation (10%). We took $R = 0.4$ and $E^{max} = 1$ GeV.

In Figs. 1—5 the results of our calculation [8] for the production of the prompt photon with the associated heavy quark are shown. The results are compared with the data taken by the D0 and CDF collaborations at $\sqrt{s} = 1960$ GeV [9–12]. For comparison we also plot the NLO QCD predictions [13]. We find that the full set of experimental data is reasonably well described by the k_T-factorization approach. One can see that the shape and absolute normalization of measured cross sections are adequately reproduced. However, in the case of $\gamma + c$-jet production, the situation is a bit worse: we find a substantial disagreement between our predictions and early D0 data [10] at high p^γ (see Fig. 4). Note, however, that very recent CDF data [11] for $\gamma + c$-jet production are well described by the k_T-factorization in a whole p_T range (see Fig. 5). This problem remained open before recent time, but new D0 experimental data [14] are in a good agreement with the k_T-factorization predictions.

In Fig. 6 the results of the calculation for associated production of the prompt photon and the muon originated from the semileptonic decays of charm or beauty quarks is presented. The experimental data are from CDF [3]. To produce muons from charmed and beauty quarks, we first convert them into D or B hadrons using the Peterson fragmentation function [15] and then simulate

[1]Numerically, in (1) and (2) we applied the MSTW2008 parton distributions [6].

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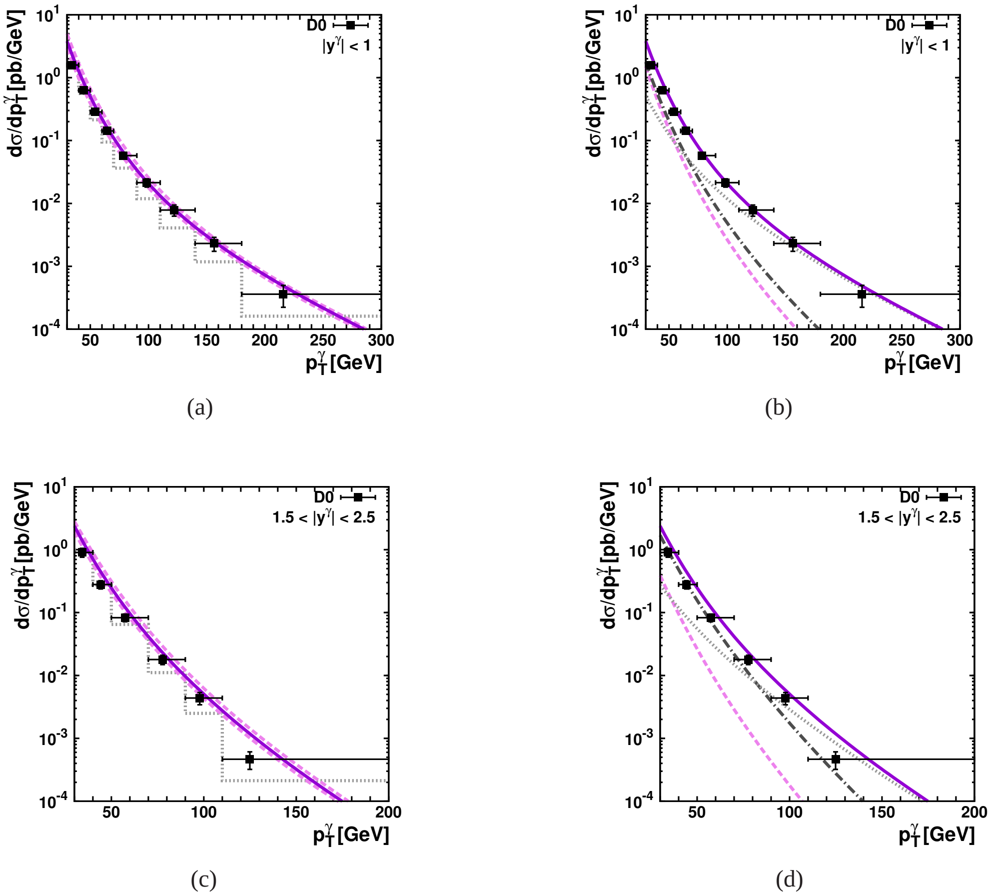
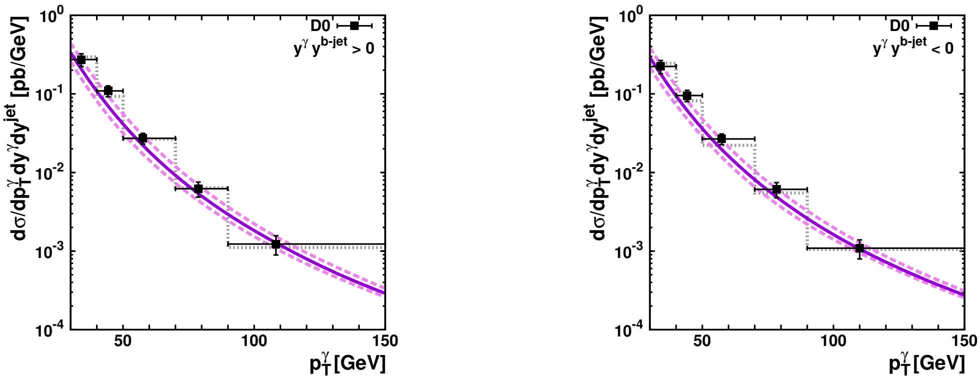


Figure 1: *The associated $\gamma + b$-jet cross section as a function of photon transverse momentum p_T^γ in the kinematical region defined by $|y^{jet}| < 1.5$ and $p_T^{jet} > 15$ GeV at $\sqrt{s} = 1960$ GeV. Left panels: the solid curve corresponds to the KMR predictions at the default scale $\mu = E_T$, whereas the upper and lower dashed curves correspond to scale variations described in the text. The dotted histogram represents the NLO pQCD predictions [13] listed in [9]. Right panels: the different contributions to the $\gamma + b$-jet cross section. The dashed, dotted and dash-dotted curves correspond to the contributions from the $g^*g^* \to \gamma Q\overline{Q}$, $q^*\overline{q}^* \to \gamma Q\overline{Q}$ and $q^*Q \to \gamma qQ$ subprocesses, respectively. The solid curve represents their sum. The experimental data are from D0 [9].*

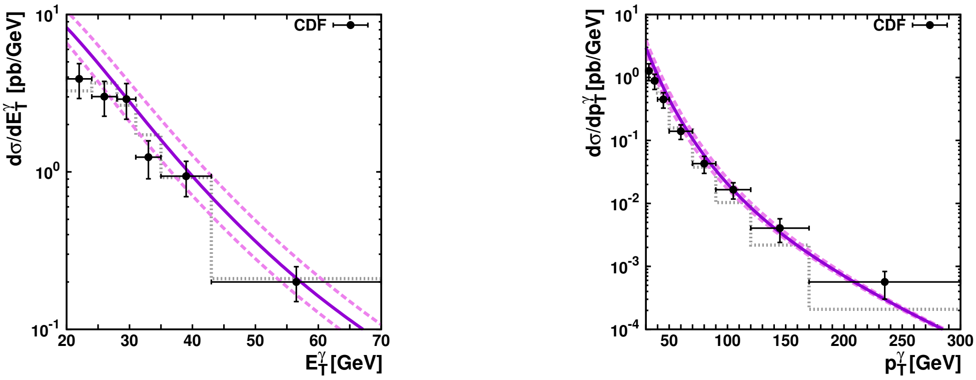
their semileptonic decay according to the standard electroweak theory. Additionally, the cascade decays $b \to c \to \mu$ have been taken into account. We set the fragmentation parameters $\varepsilon_c = 0.06$ and $\varepsilon_b = 0.006$ and corresponding branching fractions to $f(c \to \mu) = 0.0969$, $f(b \to \mu) = 0.1071$ and $f(b \to c \to \mu) = 0.0802$ [16]. We find that the k_T-factorization predictions describe the data very well. One can see that the CDF data clearly favor the k_T-factorization results.

In the present work we also make some predictions for LHC energies. We define the kinematical region by the following requirements: $|y^\gamma| < 2.5$, $25 < p_T^\gamma < 400$ GeV, $|y^{jet}| < 2.2$ and $18 < p_T^{jet} < 200$ GeV. Our predictions for differential $\gamma + b$-jet cross sections as a function of photon transeverse momentum p_T^γ and rapidity y^γ are shown in Fig. 7.



(a) (b)

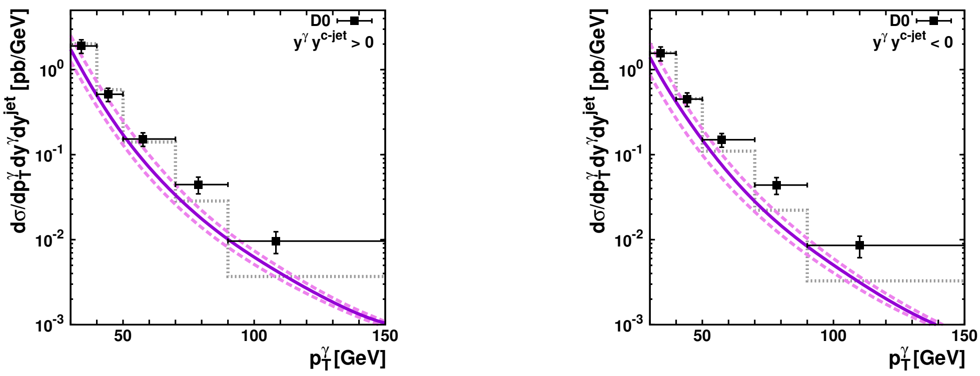
Figure 2: *The associated* $\gamma + b$*-jet cross section as a function of photon transverse momentum* p_T^γ *in the kinematical region defined by* $|y^\gamma| < 1.0$, $|y^{jet}| < 0.8$ *and* $p_T^{jet} > 15$ *GeV at* $\sqrt{s} = 1960$ *GeV. The notations are the same as for the left panel of Fig. 1. The experimental data are from D0 [10].*



(a) (b)

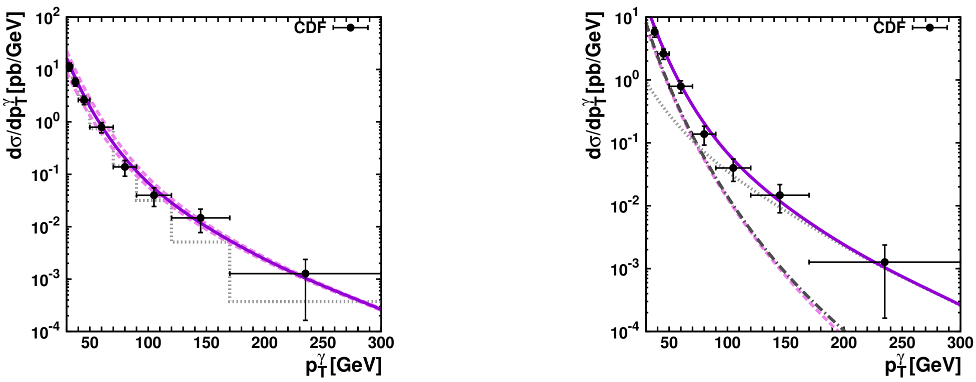
Figure 3: *The associated* $\gamma + b$*-jet cross section as a function of photon transverse momentum* p_T^γ *in the kinematical region defined by* $|y^\gamma| < 1.0$, $|y^{jet}| < 1.5$ *and* $p_T^{jet} > 20$ *GeV (a) and* $|\eta^\gamma| < 1.1$, $|\eta^{jet}| < 1.5$ *and* $p_T^{jet} > 20$ *GeV (b) at* $\sqrt{s} = 1960$ *GeV. The notations are the same as for Fig. 2. The experimental data are from CDF [11, 12].*

In summary, we have studied the process of the prompt photon production with the associated heavy (b, c) quark in the k_T-factorization QCD approach at Tevatron and LHC energies. A reasonably good description of D0 and CDF data for the associated prompt photon and heavy quark production has been obtained. Also the associated prompt photon and μ-meson production has been studied. A theoretical uncertainties investigation has been studied and a predictive power of the used approach has been shown. The obtained results prove the applicability of the KMR unintegrated parton distribution for the description of such processes.



(a) (b)

Figure 4: *The associated* $\gamma + c$*-jet cross section as a function of photon transverse momentum* p_T^γ *in the kinematical region defined by* $|y^\gamma| < 1.0$, $|y^{jet}| < 0.8$ *and* $p_T^{jet} > 15$ *GeV at* $\sqrt{s} = 1960$ *GeV. The notations are the same as for Fig. 2. The experimental data are from D0 [10].*



(a) (b)

Figure 5: *The associated* $\gamma + c$*-jet cross section as a function of photon transverse momentum* p_T^γ *in the kinematical region defined by* $|y^\gamma| < 1.0$, $|y^{jet}| < 1.5$ *and* $p_T^{jet} > 20$ *GeV at* $\sqrt{s} = 1960$ *GeV. The notations are the same as for Fig. 1. The experimental data are from CDF [11].*

Acknowledgments

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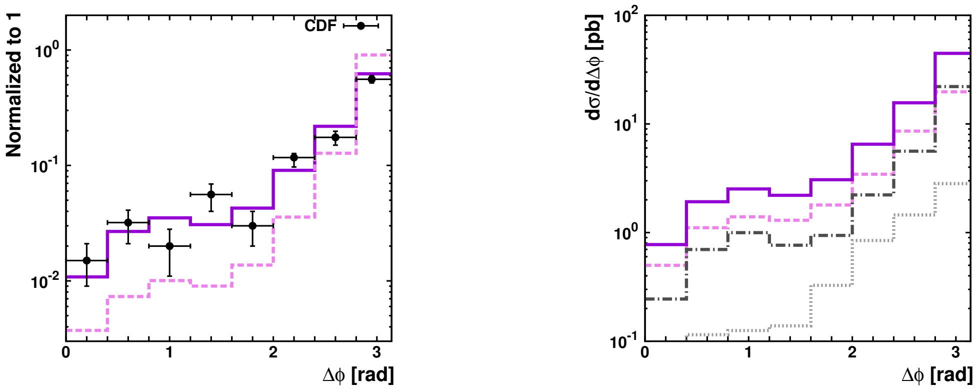
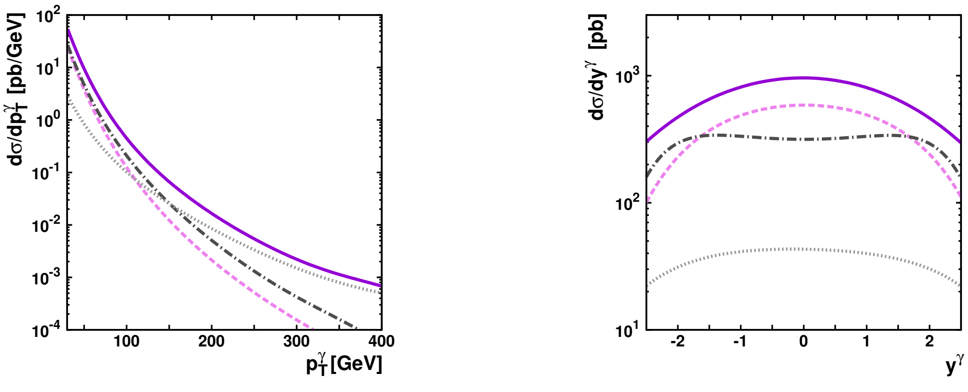


(a) (b)

Figure 6: *The associated $\gamma + \mu$ cross section as a function of the azimuthal angle difference between the produced prompt photon and muon in the kinematical region defined by $|\eta^{\gamma}| < 0.9$, $|\eta^{\mu}| < 1.0$ and $p_T^{\mu} > 4$ GeV at $\sqrt{s} = 1800$ GeV. Panel (a): the solid line corresponds to the k_T-factorization calculation, the dashed line corresponds to the collinear QCD factorization results. The notations on the panel (b) are the same as for Fig. 1. The experimental data are from CDF [3].*



(a) (b)

Figure 7: *The associated $\gamma + b$-jet cross section as a function of photon transverse momentum p_T^{γ} (a) and rapidity y^{γ} (b) in the kinematical region defined by $|y^{\gamma}| < 2.5$, $25 < p_T^{\gamma} < 400$ GeV, $|y^{jet}| < 2.2$ and $18 < p_T^{jet} < 200$ GeV at $\sqrt{s} = 7000$ GeV. The notations are the same as for the right panel of Fig. 1.*

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