Prompt photon hadroproduction in off-shell gluon-gluon fusion

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arXiv: 0708.3560 [hep-ph]

O U T L I N E

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1. Introduction

The prompt (or direct) photon production in hadron-hadron collisions at Tevatron is a subject of intensive studies.

U. Baur *et al.*, hep-ph/ 0005226

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

The theoretical and experimental investigations of such processes have provided a direct probe of the hard subprocess dynamics, since the produced photons are largely insensitive to the effects of final-state hadronization (with the photon isoliation cuts).
At the leading order, prompt photons in hadron collisions can be produced via qg Compton scattering or $q\bar{q}$ annihilation.

$\Rightarrow$ **The cross sections of these processes are strongly sensitive to the parton (quark and gluon) content of a proton.**

Despite the fact that the NLO pQCD predictions agree with the recent high-p_T measurements

V.M. Abazov *et al.* (D∅ Collaboration), Phys. Lett. 639 (2006) 151

within uncertainties, there is still open questions.
The observed E_T distribution is steeper than the predictions of perturbative QCD.
These shape differences lead to a significant disagreement in the ratio of cross sections calculated at different center-of-mass energies $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1800$ GeV as a function of scaling variable $x_T = 2E_T^\gamma/\sqrt{s}$.
The origin of the disagreement can be attributed to the effect of initial-state soft-gluon radiation. The discrepancy can be reduced also by introducing (phenomenologicaly) some additional intrinsic transverse momentum k_T of the incoming partons.
But the average value of this k_T increases from $\langle k_T \rangle \sim 1$ GeV to more than $\langle k_T \rangle \sim 3$ GeV in hard-scattering processes as the $\sqrt{s}$ increases from UA6 to Tevatron energies:

L. Apanasevich *et al.*, Phys. Rev. D59 (1999) 074007
A. Kumar *et al.*, Phys. Rev. D68 (2003) 014017

The k_T-factorization approach gives us a chance to take into account both of these effects.
In this approach the transverse momentum of incoming partons is generated in the course of non-collinear parton evolution under control of relevant BFKL or CCFM evolution equations.
In the paper

M.A. Kimber, A.D. Martin, M.G. Ryskin, Eur. Phys. J. C12 (2000) 655

to study the effects of the transverse momentum k_T of the incoming partons on the observed E_T spectrum of prompt photon in pp collisions the k_T-factorization approach (in the DLA approximation) was applied. The usual on-shell m.e. of qg Compton and $q\bar{q}$ annihilation were evaluated with precise off-shell kinematics.
In our previous paper

A.V. Lipatov, N.Z., J. Phys. G34 (2007) 219

to analyse the previuos D$\oslash$ and CDF data we have used the proper off-shell expressions for m.e. of these partonic subprocesses and also the KMR-constructed u.p.d. (which were evaluated independently):

M.A. Kimber, A.D. Martin, M.G. Ryskin, Phys. Rev. D63 (2001) 114027;

G. Watt, A.D. Martin, M.G. Ryskin, Eur. Phys. J. C31 (2003) 73.

Our results for the inclusive prompt photon production agree well with available experimental data at Tevatron in both central and forward pseudo-rapidity regions. Perfect agreement was found also in the ratio of two cross sections calculated at $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1800$ GeV. This ratio shows specific effect connected with off-shell gluons in the k_T-factorization approach.

However, the important component of all above calculations was the using of u.q.d. in a proton. At present these densities are available in the framework of KMR formalism only. As result the dependence of calculated cross sections on the non-collinear evolution scheme has been not investigated yet.
This dependence in general can be significant and it is a special subject of study in the k_T-factorization approach. Therefore here we try a different and more systematic way. Instead the using of the u.q.d. and the corresponding qg Compton and/or $q\bar{q}$ annihilation cross sections we will calculate off-shell m.e. of the $g^*g^* \to q\bar{q}\gamma$ subprocess and then operate in terms of the u.g.d. only. In this way the different non-collinear evolution schemes can be applied and tested.

But in this case our approach covers only sea quark contribution from the qg Compton and/or $q\bar{q}$ annihilation and therefore the contribution from valence quarks is not taken into account. However, this contribution is significant only at large x and therefore can be safely accounted for in the collinear LO approximation as additional one.
In the numerical calculations we tested the different sets of u.g.d. which were obtained from the full CCFM equation as well as with KMR prescription.

2. Theoretical framework

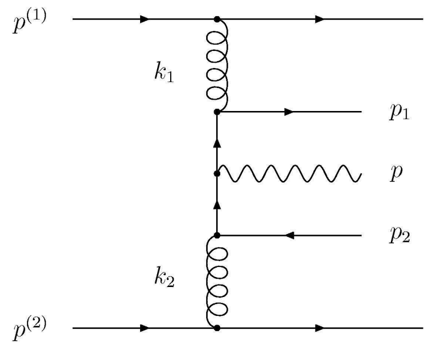

Figure 1: .

The kinematical variables are shown in Fig. 1. We used Sudakov decopmosition for them.

There are eight diagrams (see Fig. 2), which describe the partonic subprocess $g^* g^* \to q\bar{q}\gamma$ at the leading order in α_s and α.
If ϵ_1, ϵ_2, ϵ are the initial gluons and produced photon polarization vectors, respectively, then the summation on the produced photon polarization was carried out by covariant formula

$$\sum \epsilon^{\mu} \epsilon^{*\,\nu} = -g^{\mu\nu}.$$

In the case of initial off-shell gluon we used known now the BFKL prescription:

$$\epsilon_i^{\mu}(k) \epsilon_i^{*\,\nu}(k) = \frac{k_{iT}^{\mu} k_{iT}^{\nu}}{\mathbf{k}_{iT}^2}.$$

The last formula converges to the former after azimuthal angle averaging in the $k_T \to 0$ limit. The evaluation of the traces of eight m.e. was done using the algebraic manipulation system FORM. The usual method of squaring of m.e. results in enormously long output. This technical problem was solved by applying the method of so called orthogonal amplitudes:

R.E. Prange, Phys. Rev. **110** (1958) 240.

We used the finite values of light quark masses m_q in order to avoid the part of possible m.e. singularities.
The gauge invariance of matrix element is the special subject of study in the k_T-factorization approach. We have tested the gauge invariance of matrix element in the $k_T \to 0$ limit numerically.
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 $E_T^{\rm had}$, 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 $E_T^{\rm max}$:

$$E_T^{\rm had} \leq E_T^{\rm max},$$
$$(\eta^{\rm had} - \eta)^2 + (\phi^{\rm had} - \phi)^2 \leq R^2.$$

The both D$\oslash$ and CDF collaborations take $R \sim 0.4$ and $E_T^{\rm max} \sim 1$ GeV in the their experiments. The isolation not only reduces the background but also significantly reduces the so called fragmentation components, connected with collinear photon radiation (10%).

In the traditional approach the basic LO partonic subprocess is $2 \to 2$ one (for example $gg \to q\bar{q}$) and the corresponding m.e. are finite in the zero mass limit. The basic subprocess is then followed by the final state radiation (bremsstrahlung process), which is usually present in calculations in the form of quark fragmentation function. The latter shows the logarithmic dependence on quark mass. In summary the dependence on quark mass is canceled:

S. Catani, M. Fontannaz *et al.*, JHEP **0205** (2002) 028;
P. Aurenche, M. Fontannaz *et al.*, hep-ph/0602133.

In contrast with that, we do not use the concept of f.f. In our approach the effect of final state radiation is already included in calculations at the level of partonic subprocess m.e. (we have a $2 \to 3$ rather than $2 \to 2$ subprocesses, see Fig. 2). In the absence of photon isolation cuts our m.e. show logarithmic dependence on the light quark mass. Introducing the isolation cuts reduces the contributions from logarithmically divergent diagrams, accordingly reducing the sensitivity of the final results to the light quark mass. The numerical effect of mass variation (from $3 MeV$ to $5 MeV$) is really small. It is less important than other theoretical uncertainties (connected with choice of R. and F. scales).

The master formula for the cross section of prompt photon hadroproduction in the k_T-factorization approach is

$$\sigma(p\bar{p} \to \gamma\, X) = \sum_q \int \frac{1}{64\pi^3 (x_1 x_2 s)^2} |\bar{\mathcal{M}}(g^* g^* \to q\bar{q}\gamma)|^2 \times$$

$$\times \mathcal{A}(x_1, \mathbf{k}_{1T}^2, \mu^2) \mathcal{A}(x_2, \mathbf{k}_{2T}^2, \mu^2) d\mathbf{k}_{1T}^2 d\mathbf{k}_{2T}^2 d\mathbf{p}_{1T}^2 \mathbf{p}_{2T}^2 dy dy_1 dy_2 \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi} \frac{d\psi_1}{2\pi} \frac{d\psi_2}{2\pi},$$

where $\mathcal{A}(x, \mathbf{k}_T^2, \mu^2)$ is the u.g.d. in a proton, $|\bar{\mathcal{M}}(g^* g^* \to q\bar{q}\gamma)|^2$ is the off-mass shell m. e., ϕ_1, ϕ_2 are the azimuthal angles of the incoming gluons and ψ_1, ψ_2 are the azimuthal angles of the final state quark and antiquark, respectively.
Concerning the u.g.d. in a proton, we used two different sets of them. First u.g.d. has been obtained recently from the numerical solution of the full CCFM equation:

H. Jung, A.V. Kotikov, A.V. Lipatov, N.Z., Proceedings of ICHEP'2006 [hep-ph/0611093].

Function $\mathcal{A}(x, \mathbf{k}_T^2, \mu^2)$ is determined by a convolution of the non-perturbative starting distribution $\mathcal{A}_0(x)$ and the CCFM evolution denoted by $\tilde{\mathcal{A}}(x, \mathbf{k}_T^2, \mu^2)$:

$$\mathcal{A}(x, \mathbf{k}_T^2, \mu^2) = \int \frac{dx'}{x'} \mathcal{A}_0(x') \tilde{\mathcal{A}} \left(\frac{x}{x'}, \mathbf{k}_T^2, \mu^2 \right).$$

In the perturbative evolution the gluon splitting function $P_{gg}(z)$ including non-singular terms was applied:

H. Jung, Mod. Phys. Lett. A **19** (2004) 1.

The input parameters in $\mathcal{A}_0(x)$ were fitted to describe the proton structure function $F_2(x, Q^2)$. This distribution has been applied recently in the analysis of the deep inelastic proton structure functions F_2^c, F_2^b and F_L:

H. Jung,A.V. Kotikov, A.V. Lipatov, N.Z., Proceedings of DIS'2007, arXiv:0706.3793 [hep-ph].

Another u.g.d. is the so-called KMR distribution. The KMR-constructed parton distributions were used, in particular, to describe the prompt photon photoproduction at HERA also:

A.V. Lipatov, N.Z, Phys. Rev. **D72** (2005) 054002;
S. Chekanov *et al.* (ZEUS Coll.), Eur. Phys. J. **C49** (2007) 511.

Significant theoretical uncertainties are connected with the choice of the F. and R. scales. We took $\mu_R = \mu_F = \mu = \xi|\mathbf{p}_T|$**.**

We varied the scale parameter ξ **between** $1/2$ **and 2 about the default value** $\xi = 1$**.**

The masses of all light quarks were set to be equal to $m_q = 4.5$ **MeV and the charmed quark mass was set to** $m_c = 1.4$ **GeV. We have checked that uncertainties which come from these quantities are negligible in comparison to the uncertainties connected with the unintegrated gluon distributions.**

For completeness, we use LO formula for the strong coupling constant $\alpha_s(\mu^2)$ **with** $n_f = 3$ **active quark flavours at** $\Lambda_{\rm QCD} = 232$ **MeV, such that** $\alpha_s(M_Z^2) = 0.117$**.**

We used special choice $n_f = 4$ **and** $\Lambda_{\rm QCD} = 130$ **MeV in the case of CCFM gluon** $(\alpha_s(M_Z^2) = 0.118)$**.**

3. Numerical results

There are the following data sets at Tevatron:
D∅ (2000, '01) at $\sqrt{s} = 630$ **GeV and** $\sqrt{s} = 1800$ **GeV in the central pseudo-rapidity region** $|\eta| < 0.9$ **and the forward one** $1.6 < |\eta| < 2.5$**.**

CDF ('02, '04) at $\sqrt{s} = 630$ **GeV and** $\sqrt{s} = 1800$ **GeV in the central pseudo-rapidity region** $|\eta| < 0.9$**.**

D∅ ('06) at $\sqrt{s} = 1960$ **GeV and high** $p_T \sim 300$ **GeV.**

4. Conclusions

- **We have presented the results of calculations of inclusive prompt photon hadroproduction at high energies in the framework of k_T-factorization QCD approach based on the $g^*g^* \to q\bar{q}\gamma$ off-mass shell matrix element.**
  There are two important points:
  1) Initial parton k_T based on BFKL or CCFM equations,
  2) Off-shell quarks generated by gluon splitting.
- **We have calculated the total and differential cross sections and have made comparisons to the recent D⊘ and CDF experimental data.**
- **We have used the unintegrated gluon densities which are obtained from the full CCFM equation as well as from the Kimber-Martin-Ryskin prescription.**
- **In the central pseudo-rapidity region at low p_T the observed cross section is a strongly sensitive to the unintegrated gluon density.**

The cross section evaluated with the CCFM and KMR gluon distributions differs to each other by a factor of about 2. This is due to the fact that low-p_T measurements in the central pseudo-rapidity region probes immediately the small-x region, where shapes of unintegrated gluon densities under consideration are different.

- **In the forward pseudo-rapidity range the predictions from different gluon densities are practically coincide.**
- **We have made the prediction for prompt photon production at LHC.**
- **LHC experimental data can be applied in future to better constraint of the unintegrated gluon distribution. Especially it will useful in the case of the CCFM evolution (which is valid for both small and large values of x).**

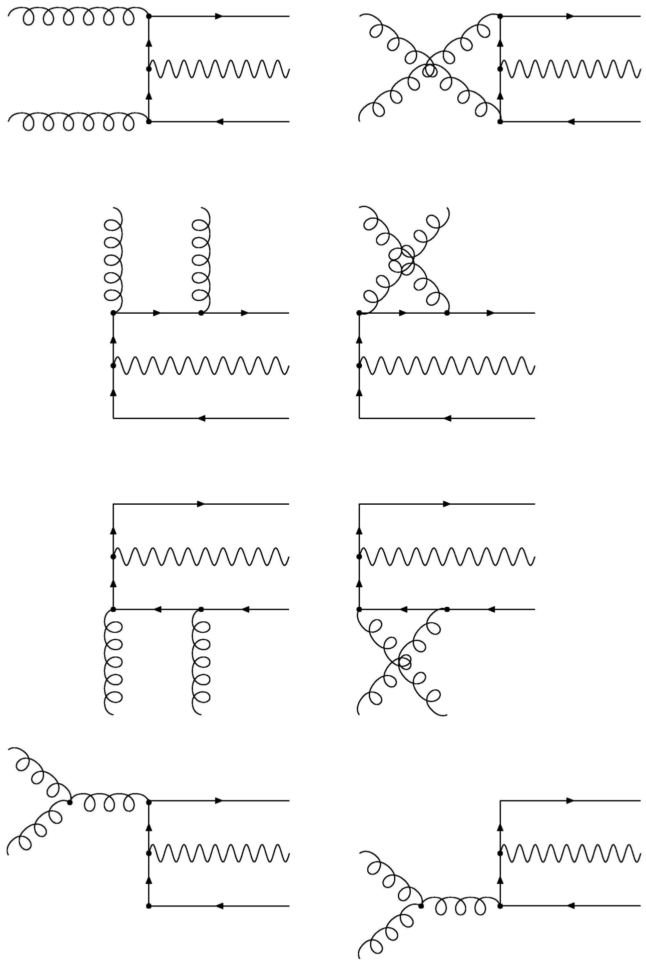

Figure 2: *Feynman diagrams of the partonic subprocess* $g^* g^* \to q\bar{q}\gamma$.

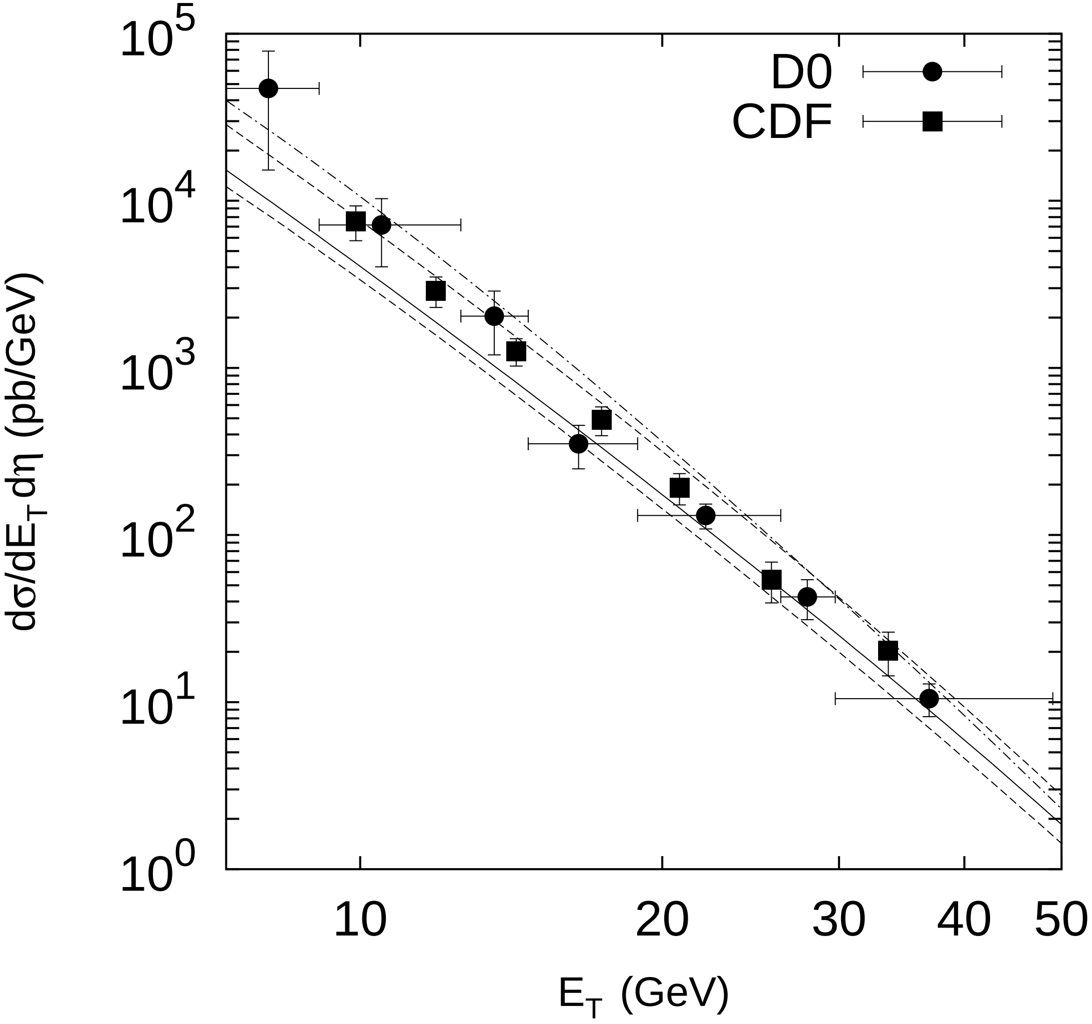

Figure 3: *The double d. c. s.* $d\sigma/dE_T d\eta$ *for inclusive prompt photon hadroproduction at* $|\eta| < 0.9$ *and* $\sqrt{s} = 630$ GeV*. The solid line corresponds to the KMR u.g.d. with the default scale* $\mu = E_T$*, the upper and lower dashed lines correspond to the usual scale variation in the KMR distribution, respectively. The dash-dotted line corresponds to the CCFM u.g.d.*

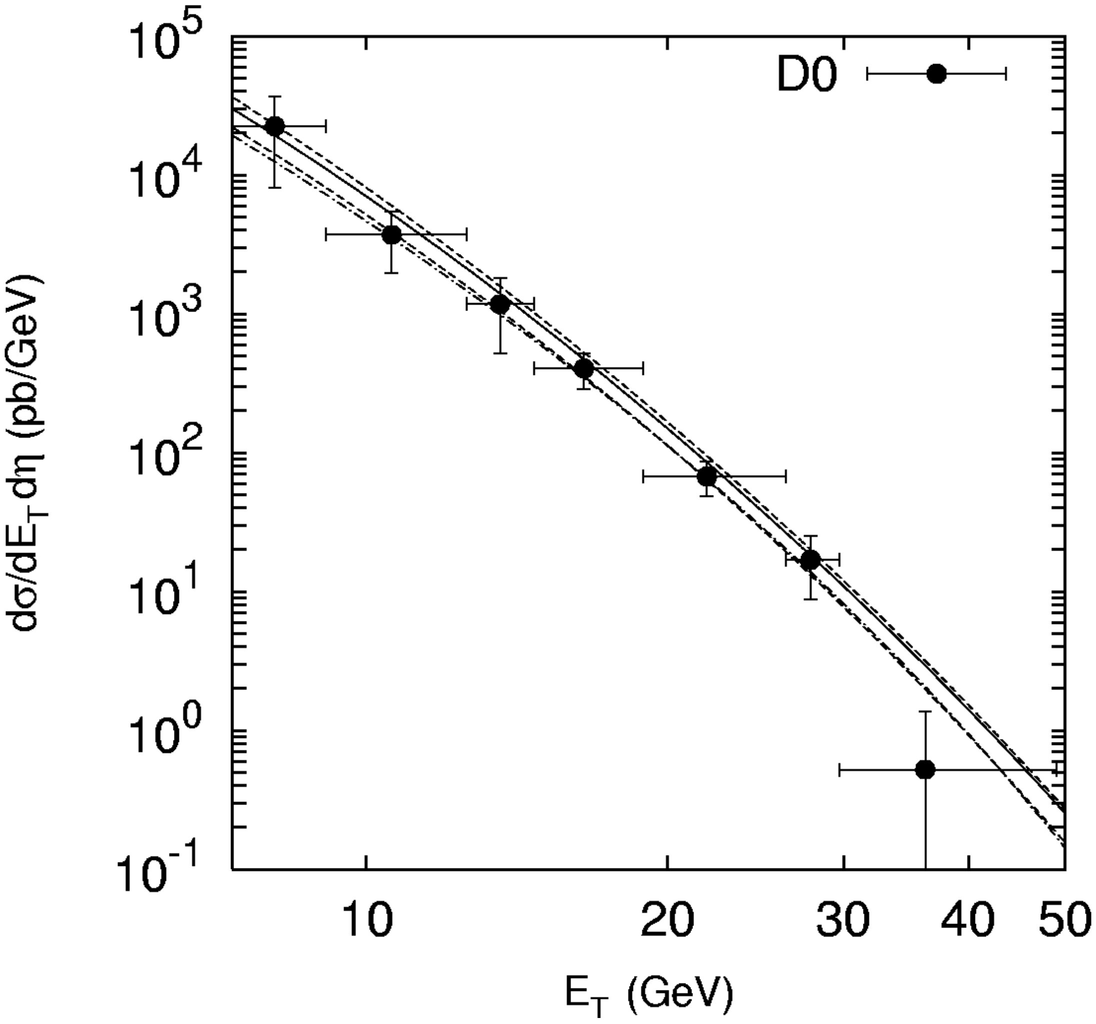

Figure 4: $d\sigma/dE_T d\eta$ *for inclusive prompt photon hadroproduction at* $1.6 < |\eta| < 2.5$ *and* $\sqrt{s} = 630\ GeV$. *The solid line corresponds to the KMR u.g.d. with the default scale* $\mu = E_T$, *the upper and lower dashed lines correspond to the usual scale variation in the KMR distribution, respectively. The dash-dotted line corresponds to the CCFM u.g.d.*

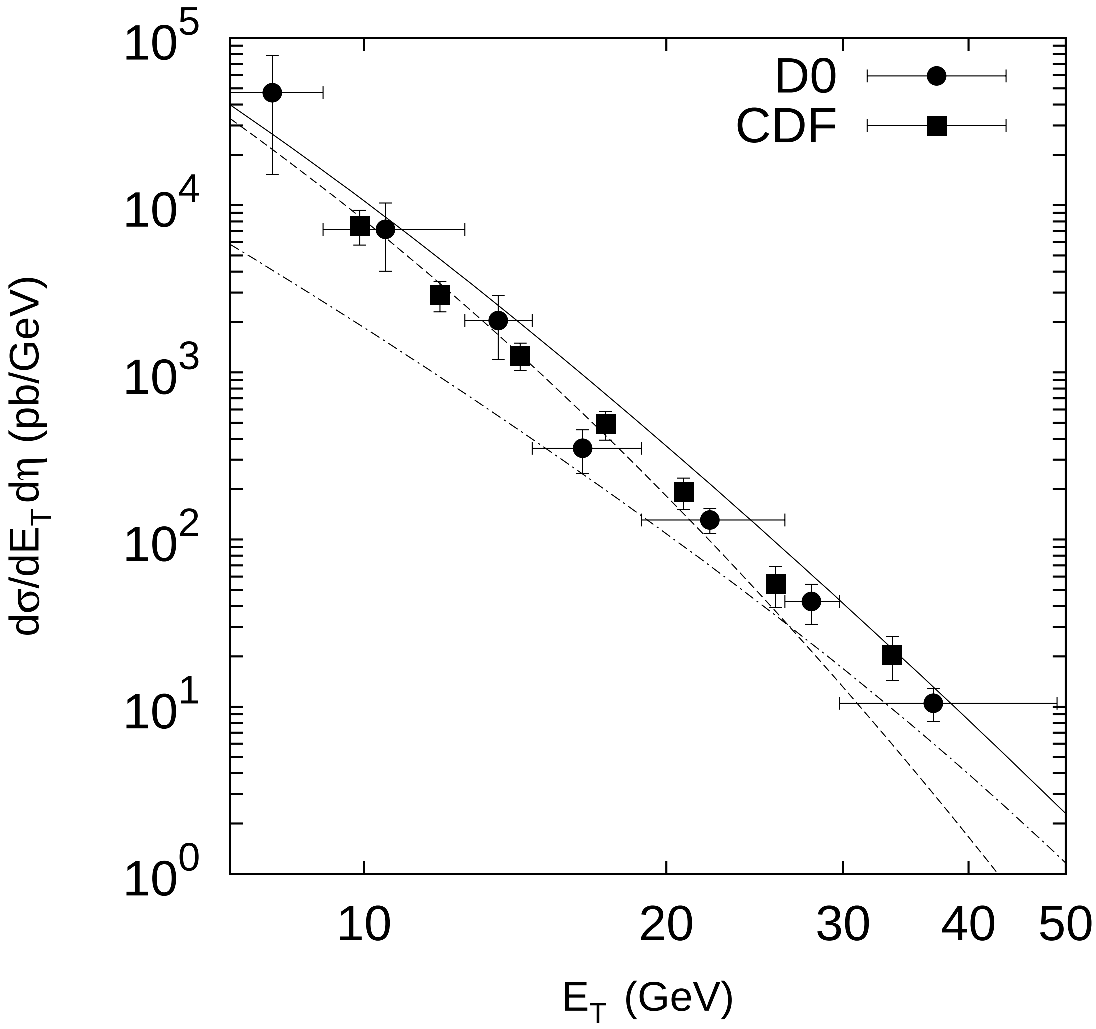

Figure 5: $d\sigma/dE_T d\eta$ *for inclusive prompt photon hadroproduction at* $|\eta| < 0.9$ *and* $\sqrt{s} = 630$ *GeV. The dashed and dash-dotted lines represent the gluon and valence quark contributions, respectively. The solid line - the sum of these contributions with the CCFM u.g.d.*

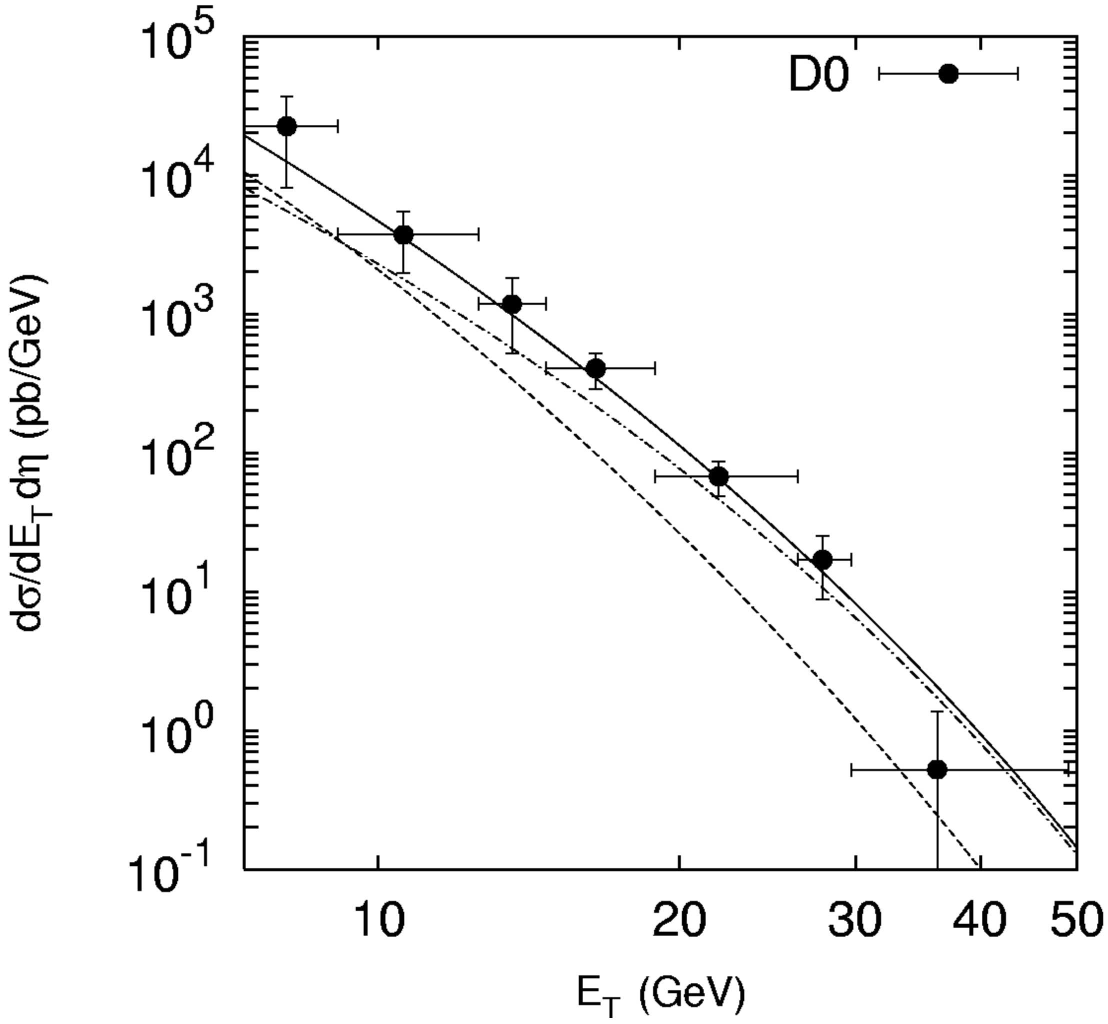

Figure 6: *$d\sigma/dE_T d\eta$ for inclusive prompt photon hadroproduction at $1.6 < |\eta| < 2.5$ and $\sqrt{s} = 630$ GeV. The dashed and dash-dotted lines represent the gluon and valence quark contributions, respectively. The solid line - the sum of these contributions with the CCFM u.g.d.*

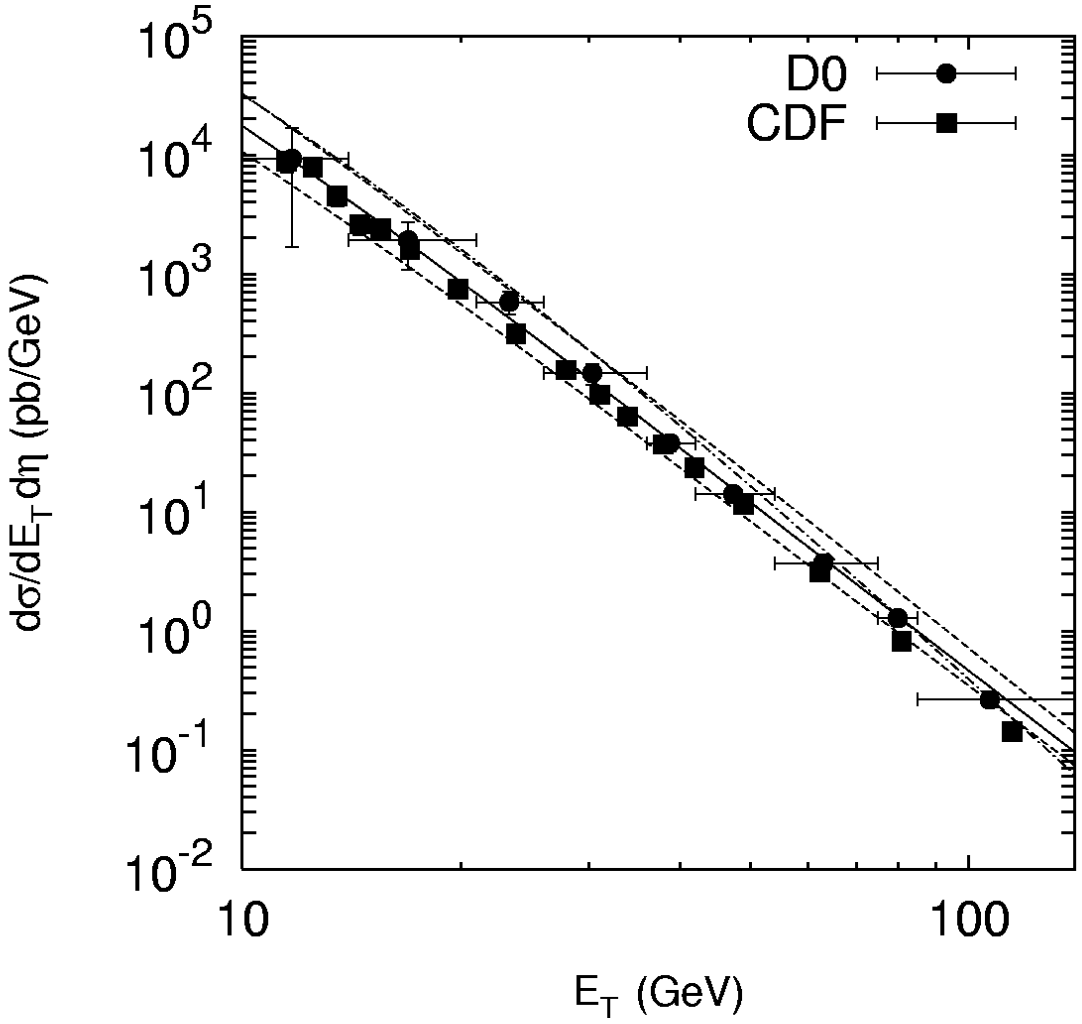

Figure 7: $d\sigma/dE_T d\eta$ *for inclusive prompt photon hadroproduction at* $|\eta| < 0.9$ *and* $\sqrt{s} = 1800$ *GeV. The solid line corresponds to the KMR u.g.d. with the default scale* $\mu = E_T$*, the upper and lower dashed lines correspond to the usual scale variation in the KMR distribution, respectively. The dash-dotted line corresponds to the CCFM u.g.d.*

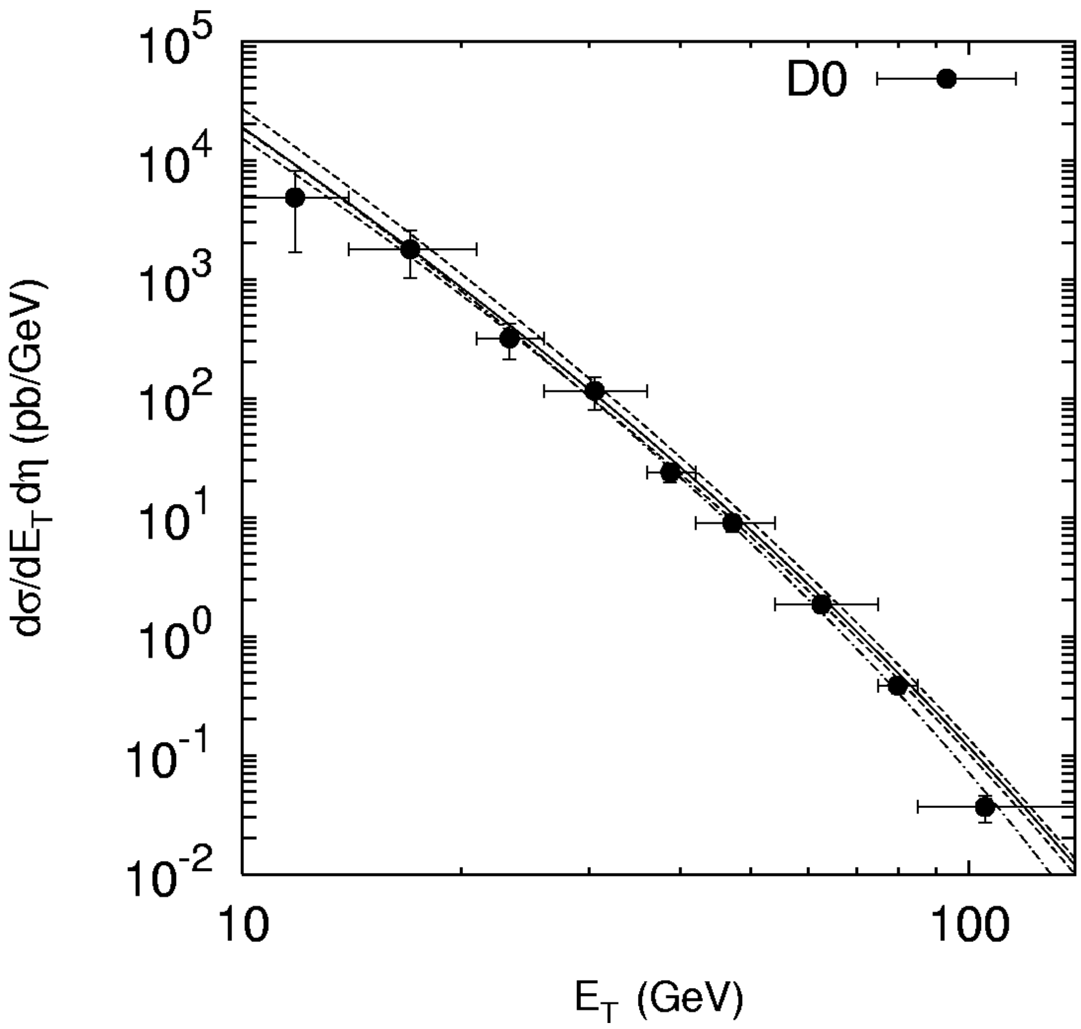

Figure 8: $d\sigma/dE_T d\eta$ *for inclusive prompt photon hadroproduction at* $1.6 < |\eta| < 2.5$ *and* $\sqrt{s} = 1800$ *GeV. The solid line corresponds to the KMR u.g.d. with the default scale* $\mu = E_T$*, the upper and lower dashed lines correspond to the usual scale variation in the KMR distribution, respectively. The dash-dotted line corresponds to the CCFM u.g.d.*

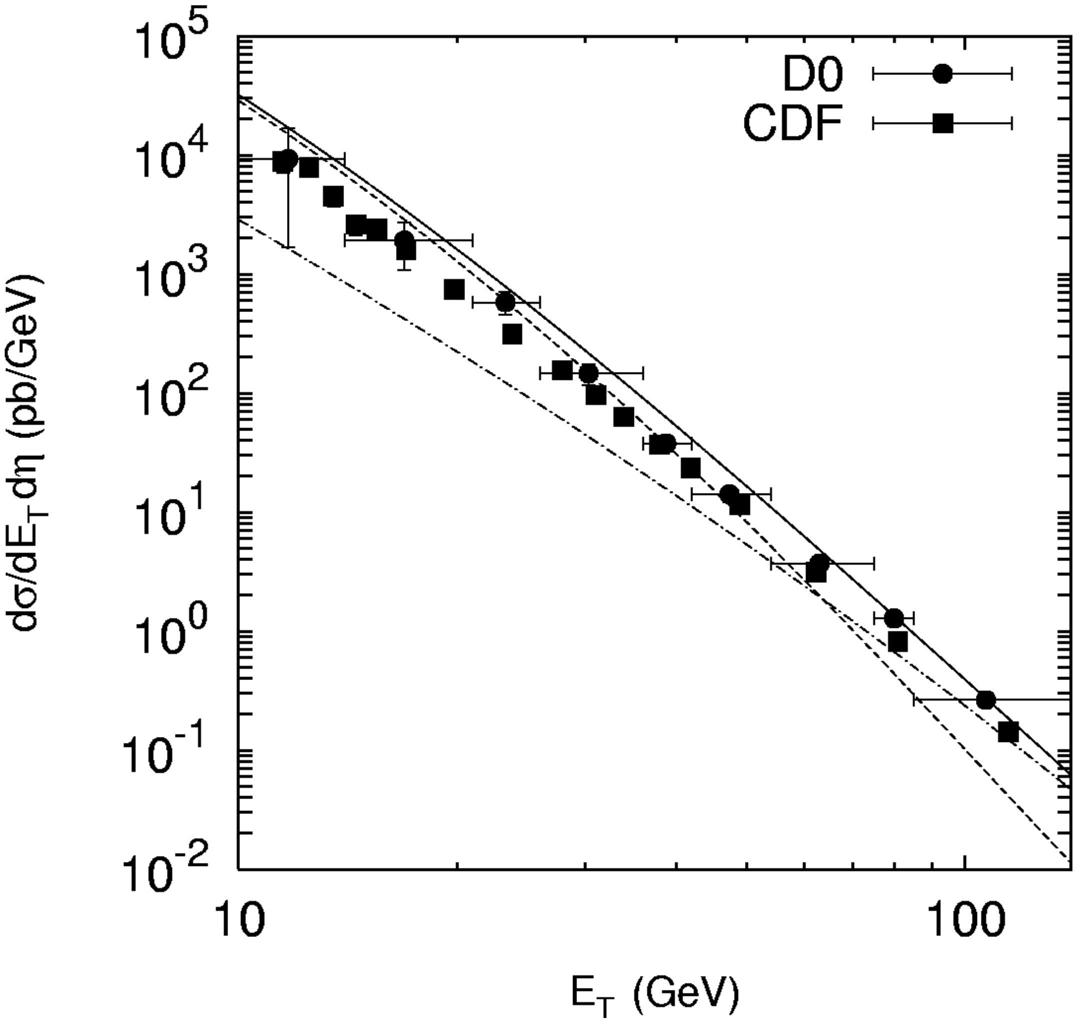

Figure 9: $d\sigma/dE_T d\eta$ *for inclusive prompt photon hadroproduction at* $|\eta| < 0.9$ *and* $\sqrt{s} = 1800$ *GeV. The dashed and dash-dotted lines represent the gluon and valence quark contributions, respectively. The solid line - the sum of these contributions with the CCFM u.g.d.*

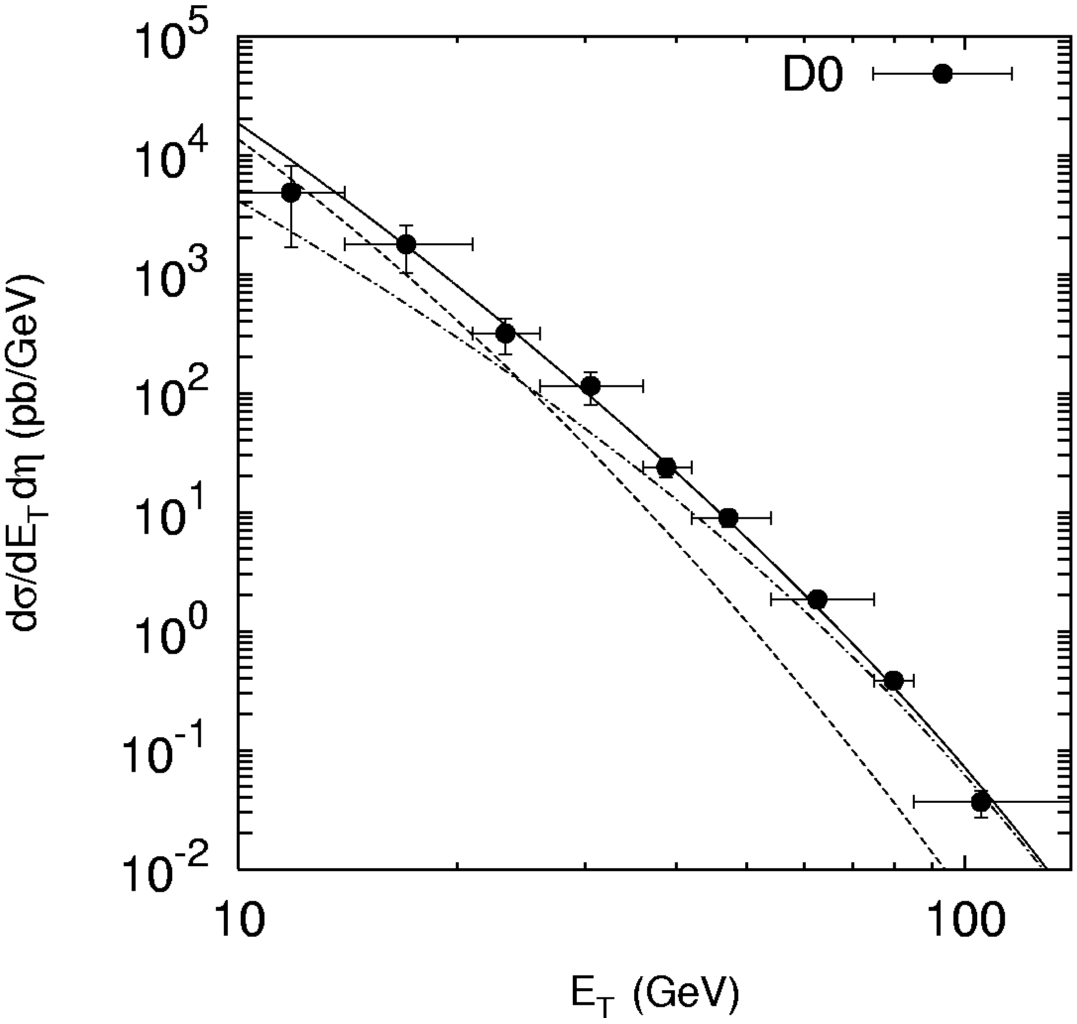

Figure 10: $d\sigma/dE_T d\eta$ *for inclusive prompt photon hadroproduction at* $1.6 < |\eta| < 2.5$ *and* $\sqrt{s} = 1800$ *GeV. The dashed and dash-dotted lines represent the gluon and valence quark contributions, respectively. The solid line - the sum of these contributions with the CCFM u.g.d.*

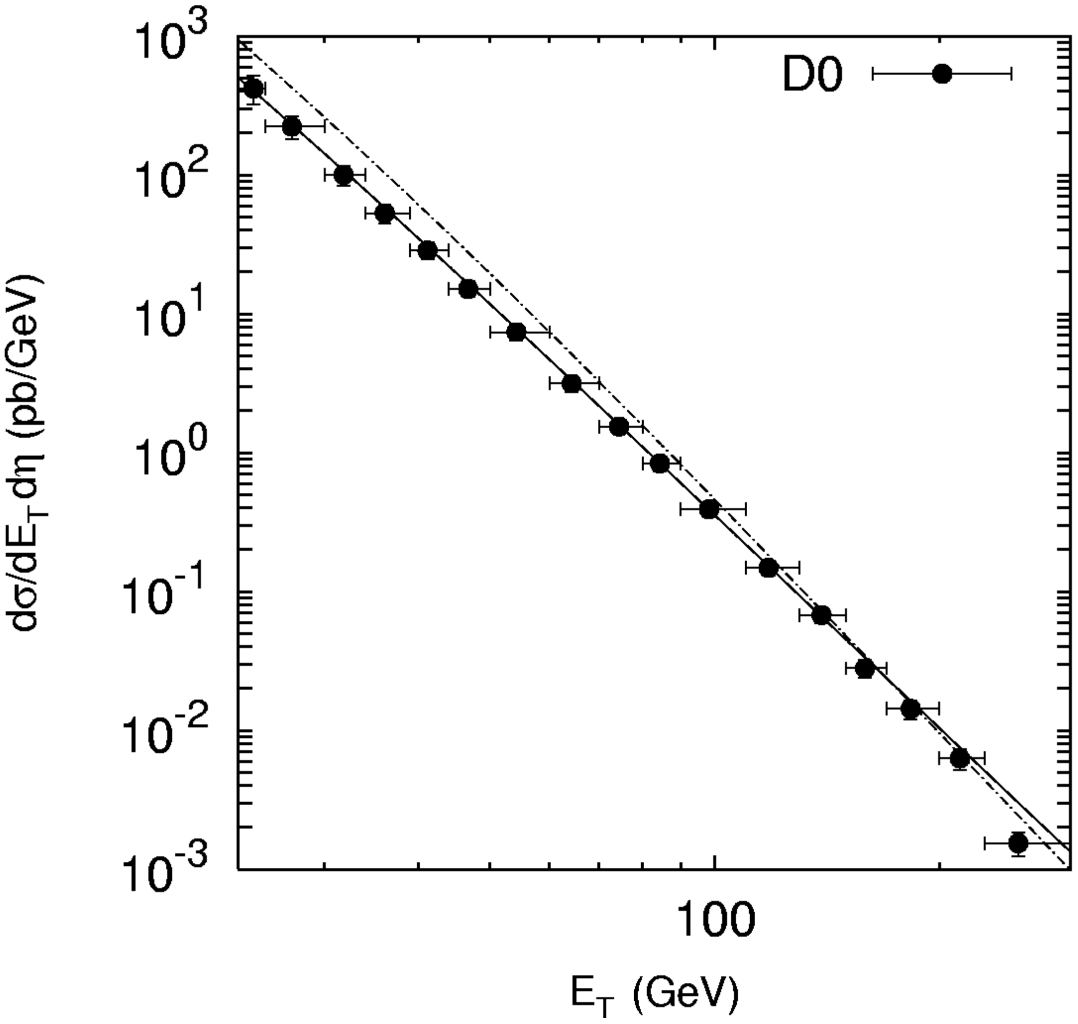

Figure 11: $d\sigma/dE_T d\eta$ *for inclusive prompt photon hadroproduction at* $|\eta| < 0.9$ *and* $\sqrt{s} = 1960$ *GeV. The solid and dash-dotted lines correspond to the KMR and CCFM u.g.d., respectively.*

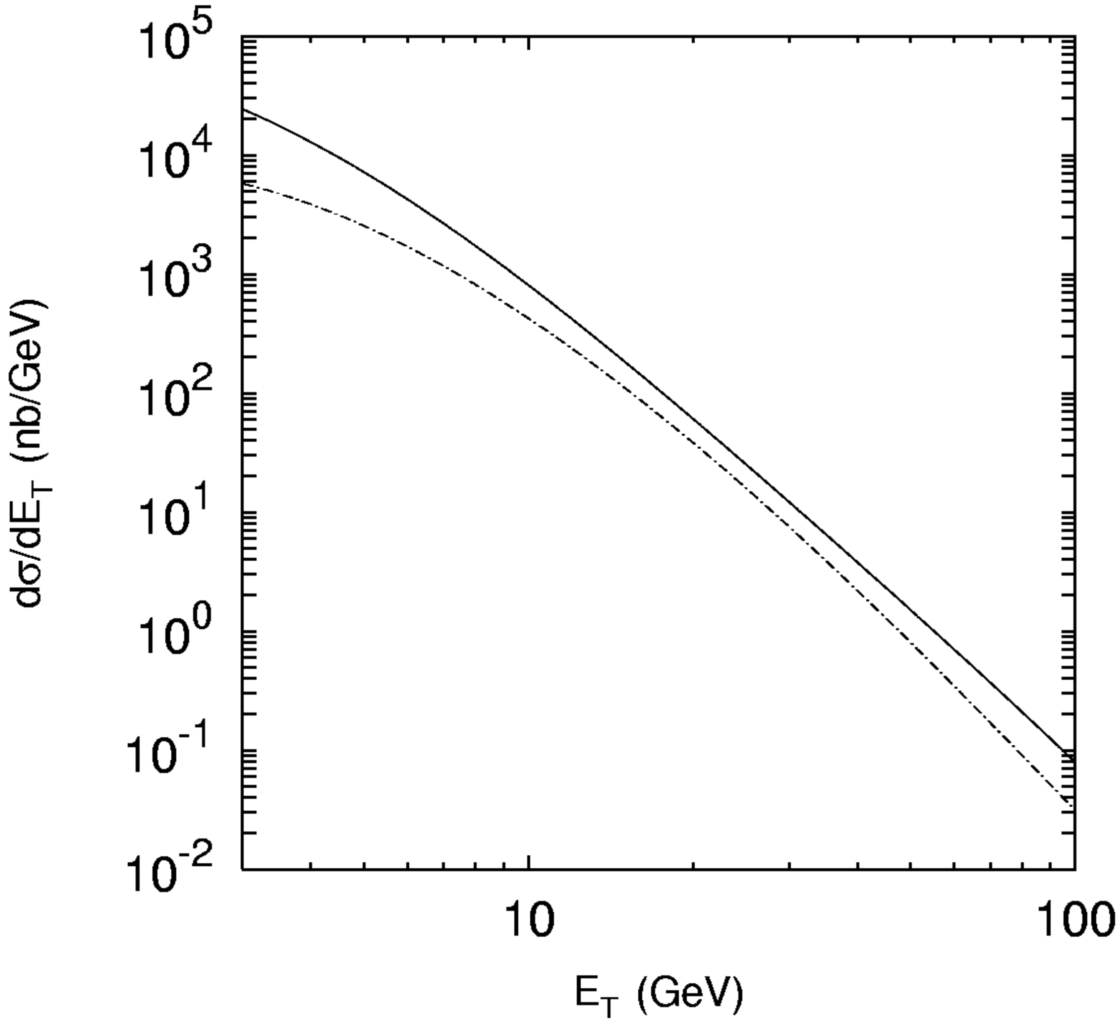

Figure 12: *The transverse enery E_T distribution of inclusive prompt photon hadroproduction calculated at $|\eta| < 2.5$ and $\sqrt{s} = 14$ TeV.The solid and dash-dotted lines correspond to the KMR and CCFM u.g.d., respectively.*