Prompt photon production at high energies with k_T-factorization

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J. Phys. G **34**, 219 (2007)

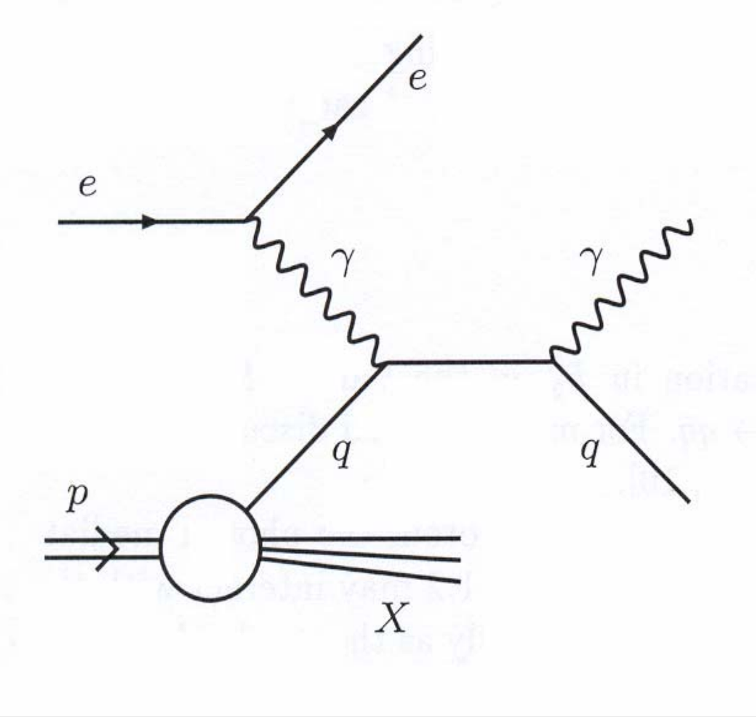
Content

- Introduction
- Formalism of the k_T-factorization
  - non-collinear parton evolution
  - off-shell matrix elements
  - unintegrated parton distributions
- Prompt photon production at HERA
  - inclusive, associated with hadronic jet
- Prompt photon production at Tevatron
  - inclusive, associated with muon
- Prompt photon prediction at LHC
- Conclusions

Introduction

Prompt photon's are:

- coupled to the interacting quarks
- provide a clear information about the QCD dynamics
- insensitive to the effects of final state hadronization
- sensitive to the parton distribution functions (PDFs)



Production mechanism at HERA

- **direct events**

  deep inelastic Compton scattering (DIC)

- **resolved events**

  $q+g \rightarrow \gamma+q$

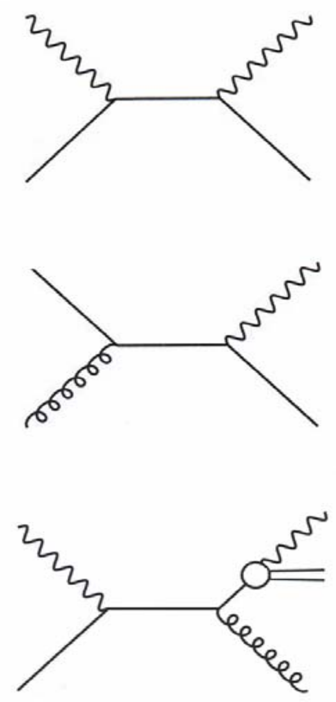
  $g+q \rightarrow \gamma+q$

  $q+\overline{q} \rightarrow \gamma+g$

- **fragmentation processes**

  described in terms of the parton-to-photon fragmentation functions

  $D_{p\rightarrow\gamma}(z,\mu^2)$



Isolation

- huge background from the secondary photons produced by the π, η and ω decays
- fragmentation functions $D_{p\to\gamma}(z,\mu^2)$ relatively poorly known

Isolation criterion is introduced:

$$E_T^{\rm had} \le E_T^{\rm max} = \varepsilon E_T^{\gamma}$$
$$(\eta-\eta^{\gamma})^2 + (\phi-\phi^{\gamma})^2 \le R^2$$

This criterion substantial (up to 5—6%) reduces the fragmentation contribution

M. Fontannaz, J.Ph. Guillet, G. Heinrich, EPJ C **21**, 303 (2001)

NLO pQCD calculations

- 30—40% below the HERA data (specially in the rear η^{γ} region)
- not describe the shape of transverse energy E_T^{γ} distribution at Tevatron
- not describe the ratio of cross sections $\sigma(630\,\mathrm{GeV})/\sigma(1800\,\mathrm{GeV})$ at Tevatron

These disagreements is hard to explain by the conventional theoretical uncertainties

M. Fontannaz, J.Ph. Guillet, G. Heinrich, EPJ C **21**, 303 (2001)
A. Zembrzuski, M. Krawczyk, PR D **64**, 114017 (2001)
H. Baier, J. Ohnemus, J.F. Owens, PR D **42**, 61 (1990)

k_T - smearing?

- additional intrinsic transverse momentum k_T of the incoming partons is introduced in NLO calculations
- it is assumed that this k_T have a Gaussian-like distribution
- $\langle k_T \rangle \sim 0.5\,\mathrm{GeV}$ at UA6 and $\langle k_T \rangle \sim 2\,\mathrm{GeV}$ at Tevatron
- such large partonic k_T must have a significant perturbative QCD component
- full kinematics of the subprocess is not taken into account

H.-L. Lai, H.-N. Li, PR D **58**, 114020 (1998)

L. Apanasevich *et al*, PR D **59**, 074007 (1999)

A. Kumar *et al*, PR D **68**, 014017 (2003)

Another possibility

Simple k_T-smearing picture can be modified in the framework of k_T-factorization (or semihard) approach of QCD

In this approach, the partonic transverse momentum is generated in the course of the non-collinear parton evolution

V.N. Gribov, E.M. Levin, M.G. Ryskin, Phys. Rep. **100**, 1 (1983)
E.M. Levin, M.G. Ryskin *et al*, Sov. J. Nucl. Phys. **53**, 657 (1991)
S. Catani, M. Ciafoloni, F. Hautmann, NP B **366**, 135 (1991)
J.C. Collins, R.K. Ellis, NP B **360**, 3 (1991)

k_T — factorization approach

- based on the BFKL or CCFM evolution equations
- can incorporate the leading $\ln 1/x$ terms
- can be used in the both large and small *x* regions
- takes into account true kinematics of the partonic subprocess even at leading order
- has been applied already to a number of different processes

Ph. Hagler, R. Kirschner *et al*, PR D **62**, 071502 (2000)

S.P. Baranov, PR D **66**, 114003 (2002)

A.V. Kotikov, A.V. Lipatov, N.P. Zotov, JETP **101**, 811 (2005)

A.V. Lipatov, N.P. Zotov, EPJ C **27**, 87 (2003); **41**, 163 (2005); **44**, 559 (2005)

Collinear evolution

- DGLAP equations

$$\frac{\partial q_i(x,\mu^2)}{\partial \ln(\mu^2/\Lambda^2)} = \frac{\alpha_S(\mu^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}^{(0)}(x/y)q_i(y,\mu^2) + P_{qg}^{(0)}(x/y)g(y,\mu^2)\right]$$

$$\frac{\partial g(x,\mu^2)}{\partial \ln(\mu^2/\Lambda^2)} = \frac{\alpha_S(\mu^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{gq}^{(0)}(x/y)q_i(y,\mu^2) + P_{gg}^{(0)}(x/y)g(y,\mu^2)\right]$$

take into account $\ln\mu^2$ terms only (in LLA)

V.N. Gribov, L.N. Lipatov, Yad. Fiz. **15**, 781 (1972)
L.N. Lipatov, Sov. J. Nucl. Phys. **20**, 94 (1975)
G. Altarelly, G. Parizi, NP B **126**, 298 (1977)
Y.L. Dokshitzer, JETP **46**, 641 (1977)

Non-collinear evolution

- BFKL equation

$$f_g(x,k_T^2) = f_g^{(0)}(x,k_T^2) + \overline{\alpha}_S k_T^2 \int_x^1 \frac{dy}{y} \int_{k_{T0}^2}^{\infty} \frac{dk'^2_T}{k'^2_T} \left[\frac{f_g(x/y,k'^2_T) - f_g(x/y,k_T^2)}{\left|k'^2_T - k_T^2\right|} + \frac{f_g(x/y,k_T^2)}{\sqrt{4k'^4_T + k_T^4}} \right]$$

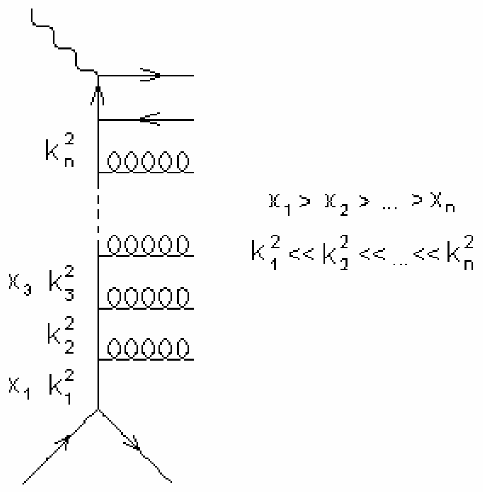
E.A. Kuraev, L.N. Lipatov, V.S. Fadin, JETP **44**, 443 (1976); **45**, 199 (1977); I.I. Balitsky, L.N. Lipatov, Sov. J. Nucl. Phys. **28**, 822 (1978)

- CCFM equation

$$A(x,k_T^2,\overline{q}^2) = A^{(0)}(x,k_T^2,\overline{q}^2) + \int_x^1 \frac{dy}{y} \int \frac{d^2q}{\pi q^2} \theta(\overline{q} - yq) \Delta_S(\overline{q}, yq) P(y,k_T^2,\overline{q}^2) A(x/y,k_T^2,q^2)$$

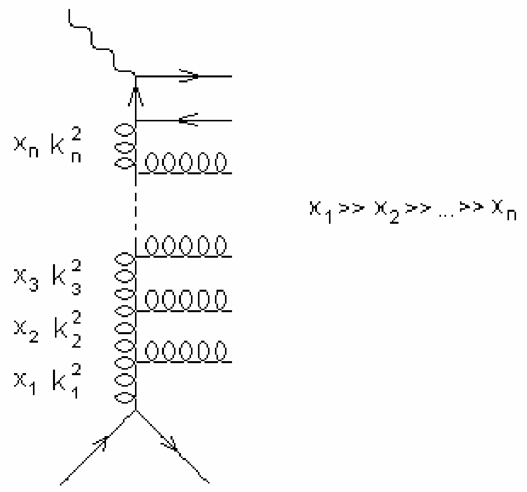
M. Ciafaloni, NP B **296**, 49 (1988); S. Catani, F. Fiorani, G. Marchesini, PL B **234**, 339 (1990); NP B **336**, 18 (1990); G. Marchesini, NP B **445**, 49 (1995)

Ladder diagrams



DGLAP

collinear evolution



BFKL

non-collinear evolution

Other properties

- off-shell partonic cross section

$$\varepsilon^{\mu\nu} = \frac{k_T^\mu k_T^\nu}{k_T^2}, \quad \frac{1}{2\pi}\int_0^{2\pi} \varepsilon^{\mu\nu} d\phi = \frac{1}{2} g^{\mu\nu}$$

- main part of the collinear high-order corrections is already included at LO level
- visible effects in predictions due to non-zero partonic k_T

B. Andersson *et al* (Small-x Collaboration), EPJ C **25**, 77 (2002)
J. Andersen *et al* (Small-x Collaboration), EPJ C **35**, 67 (2004)
J. Andersen *et al* (Small-x Collaboration), EPJ C 48, 53 (2006)

Unintegrated PDFs

- numerical or analytical solution of the non-collinear evolution equations

  JB (BFKL)

  KMS (unified DGLAP-BFKL)

  J2003 set 1 — 3 (CCFM)

- can be obtained from the conventional PDFs

  KMR approach

B. Andersson *et al* (Small-x Collaboration), EPJ C **25**, 77 (2002)
J. Andersen *et al* (Small-x Collaboration), EPJ C **35**, 67 (2004)
J. Andersen *et al* (Small-x Collaboration), EPJ C **48**, 53 (2006)

KMR approach

- provide us the unintegrated quark distribution
- valid for a proton as well as a photon
- accounts for the angular ordering which comes from coherence effect in gluon emission
- μ-dependence enters at the last step of the evolution
- single scale (DGLAP or unified BFKL-DGLAP) equations can be used up to last evolution step

M.A. Kimber, A.D. Martin, M.G. Ryskin, PR D **63**, 114027 (2001)

G. Watt, A.D. Martin, M.G. Ryskin, EPJ C **31**, 73 (2003)

KMR approach

Unintegrated quark and gluon distributions

$$f_g(x,k_T^2,\mu^2) = T_g(k_T^2,\mu^2)\frac{\alpha_S(k_T^2)}{2\pi}\int_x^1 dz\left[\sum_q P_{qg}(z)(x/z)q(x/z,k_T^2) + P_{gg}(z)(x/z)g(x/z,k_T^2)\theta(\Delta - z)\right]$$

$$f_q(x,k_T^2,\mu^2) = T_q(k_T^2,\mu^2)\frac{\alpha_S(k_T^2)}{2\pi}\int_x^1 dz\left[P_{qq}(z)(x/z)q(x/z,k_T^2)\theta(\Delta - z) + P_{qg}(z)(x/z)g(x/z,k_T^2)\right]$$

Sudakov form factors

$$\ln T_g(k_T^2,\mu^2) = -\int_{k_T^2}^{\mu^2}\frac{dp_T^2}{p_T^2}\frac{\alpha_S(p_T^2)}{2\pi}\left[n_f\int dz\,P_{qg}(z) + \int dz\,zP_{gg}(z)\right]$$

$$\ln T_q(k_T^2,\mu^2) = -\int_{k_T^2}^{\mu^2}\frac{dp_T^2}{p_T^2}\frac{\alpha_S(p_T^2)}{2\pi}\int dz\,P_{qq}(z)$$

Angular-ordering constraint $\Delta = \mu/(\mu + k_T)$ give possibility to extent the KMR parton densities into region $k_T^2 > \mu^2$

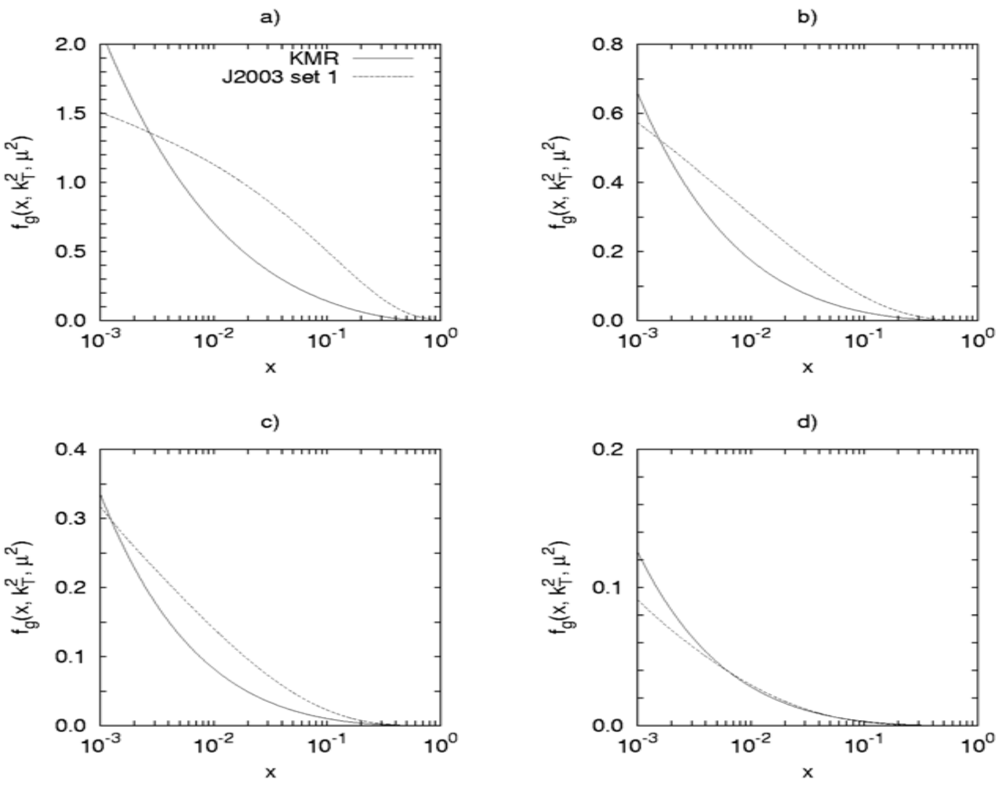
KMR u.g.d. as a function of *x*

a) $k_T^2 = 2\,\text{GeV}^2$

b) $k_T^2 = 10\,\text{GeV}^2$

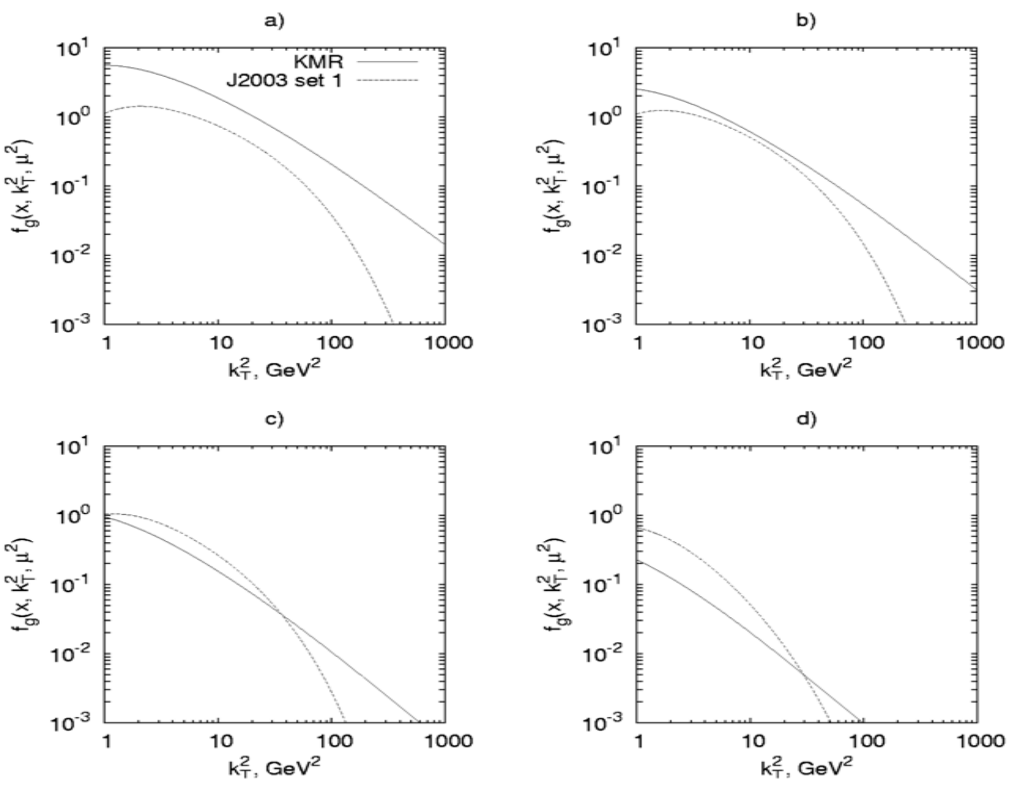
c) $k_T^2 = 20\,\text{GeV}^2$

d) $k_T^2 = 50\,\text{GeV}^2$



KMR u.g.d. as a function of k_T

a) $x = 1 \cdot 10^{-4}$
b) $x = 1 \cdot 10^{-3}$
c) $x = 1 \cdot 10^{-2}$
d) $x = 1 \cdot 10^{-1}$



Prompt photon production at HERA

- inclusive and associated with jet prompt photon photoproduction
- both direct and resolved photon contributions are taken into account
- gauge invariant partonic cross sections

  (off-shell gluons and on-shell quarks)
- conservative error analysis has been performed
- estimation of the fragmentation component (about 5%)
- contributions from the quark box diagram (which are formally NNLO level) are neglected

Cross sections

direct production

$$\sigma^{(\mathrm{dir})}(\gamma+p\to\gamma+X)=\sum_q\int\frac{E_T^\gamma}{8\pi(x_2s)^2(1-\alpha)}\left|\overline{M}\right|^2(\gamma+q\to\gamma+q)f_q(x_2,k_{2T}^2,\mu^2)dy^\gamma dE_T^\gamma dk_{2T}^2\frac{d\phi_2}{2\pi}\frac{d\phi^\gamma}{2\pi}$$

resolved photon production

$$\sigma^{(\mathrm{res})}(\gamma+p\to\gamma+X)=\sum_{a,b}\int\frac{E_T^\gamma}{8\pi(x_1x_2s)^2}\left|\overline{M}\right|^2(a+b\to\gamma+c)f_a^\gamma(x_1,k_{1T}^2,\mu^2)f_b(x_2,k_{2T}^2,\mu^2)$$

$$\times dk_{1T}^2dk_{2T}^2dE_T^\gamma dy^\gamma dy^c\frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi}\frac{d\phi^\gamma}{2\pi}$$

photon flux in the electron

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

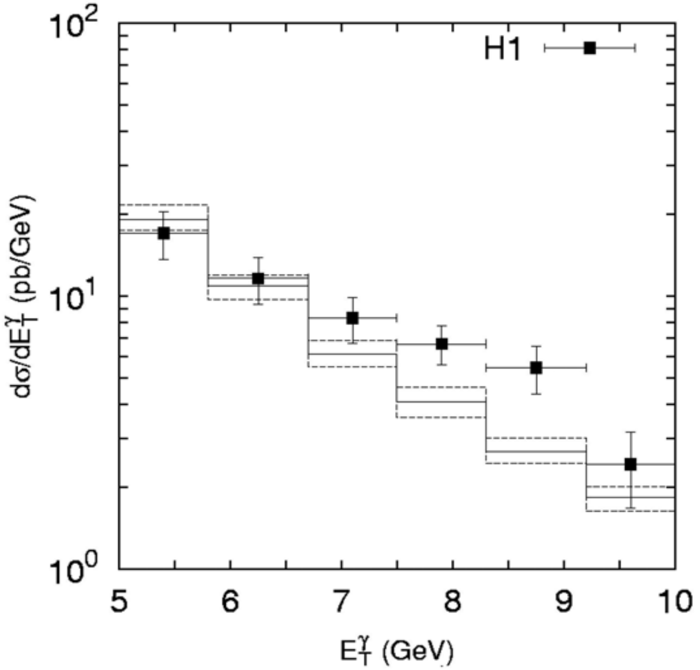
$$f_{\gamma/e}(y)=\frac{\alpha_{em}}{2\pi}\left(\frac{1+(1-y)^2}{y}\ln\frac{Q_{\max}^2}{Q_{\min}^2}+2m_e^2y\left(\frac{1}{Q_{\max}^2}-\frac{1}{Q_{\min}^2}\right)\right)$$

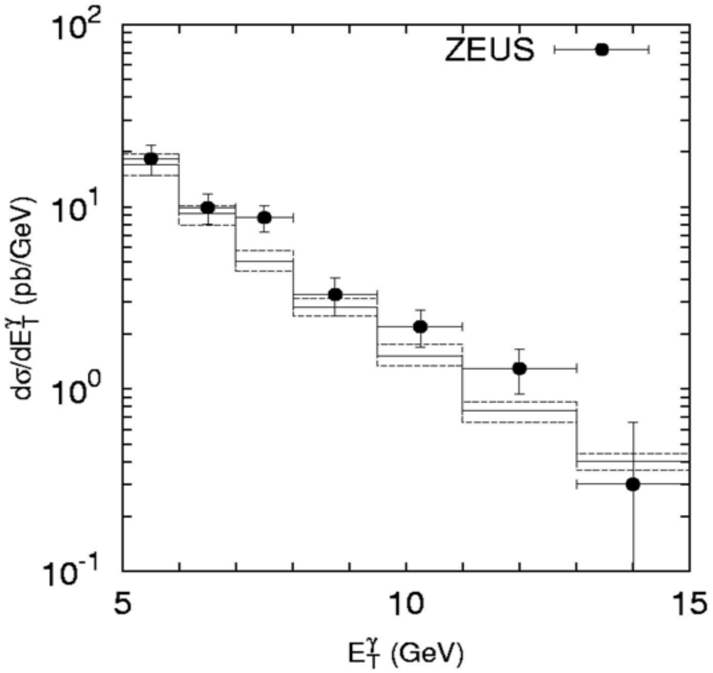
Numerical results

Set of parameters:

- factorization and renormalization scales $\mu = \xi E_T^\gamma$
  $\xi = 1/2$ ... $\xi = 2$ (default value $\xi = 1$)
- LO $\alpha_S(\mu^2)$ with $n_f = 3$ active (massless) quark flavours
- $\Lambda_{\mathrm{QCD}} = 232\,\mathrm{MeV}$, such that $\alpha_S(M_Z^2) = 0.1169$
- $m_c = 1.4\,\mathrm{GeV}$, $m_b = 4.75\,\mathrm{GeV}$

E_T^γ - distribution (inclusive)

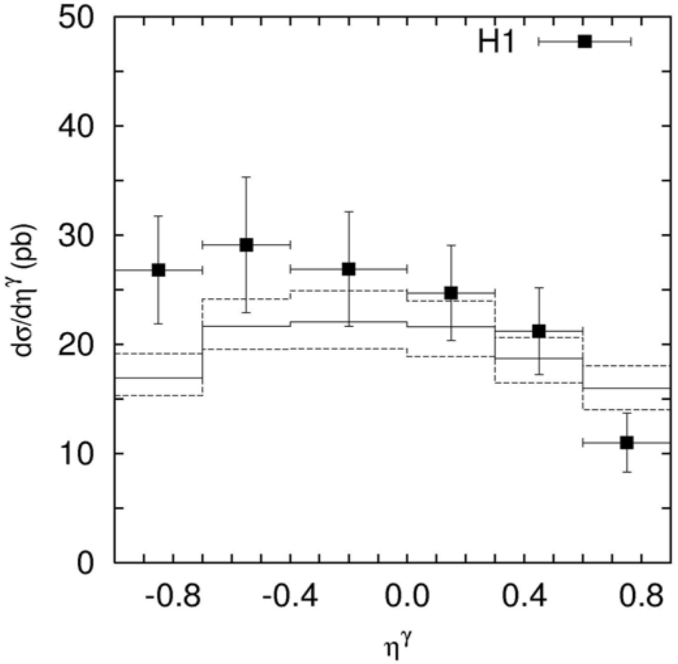




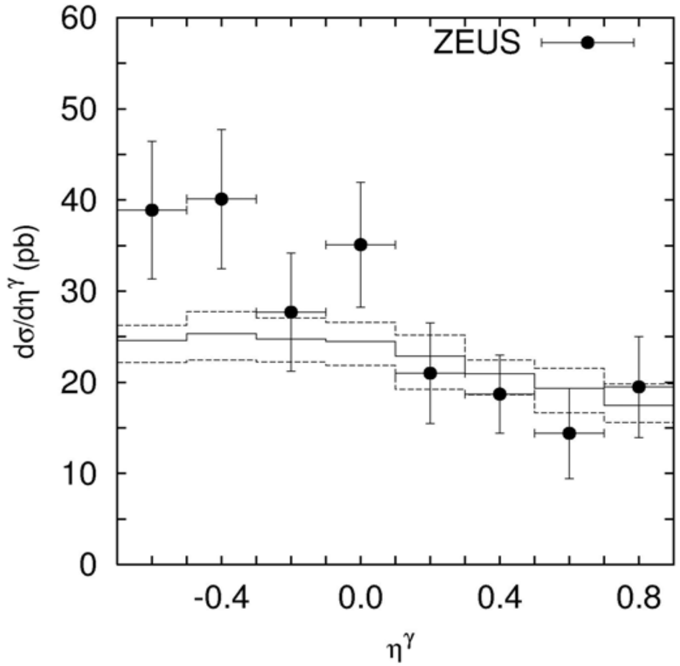
$E_T^\gamma > 5\,\mathrm{GeV},\quad -1 < \eta^\gamma < 0.9,\quad 0.2 < y < 0.7$

$E_T^\gamma > 5\,\mathrm{GeV},\quad -0.7 < \eta^\gamma < 0.9,\quad 0.2 < y < 0.9$

η^γ - distribution (inclusive)

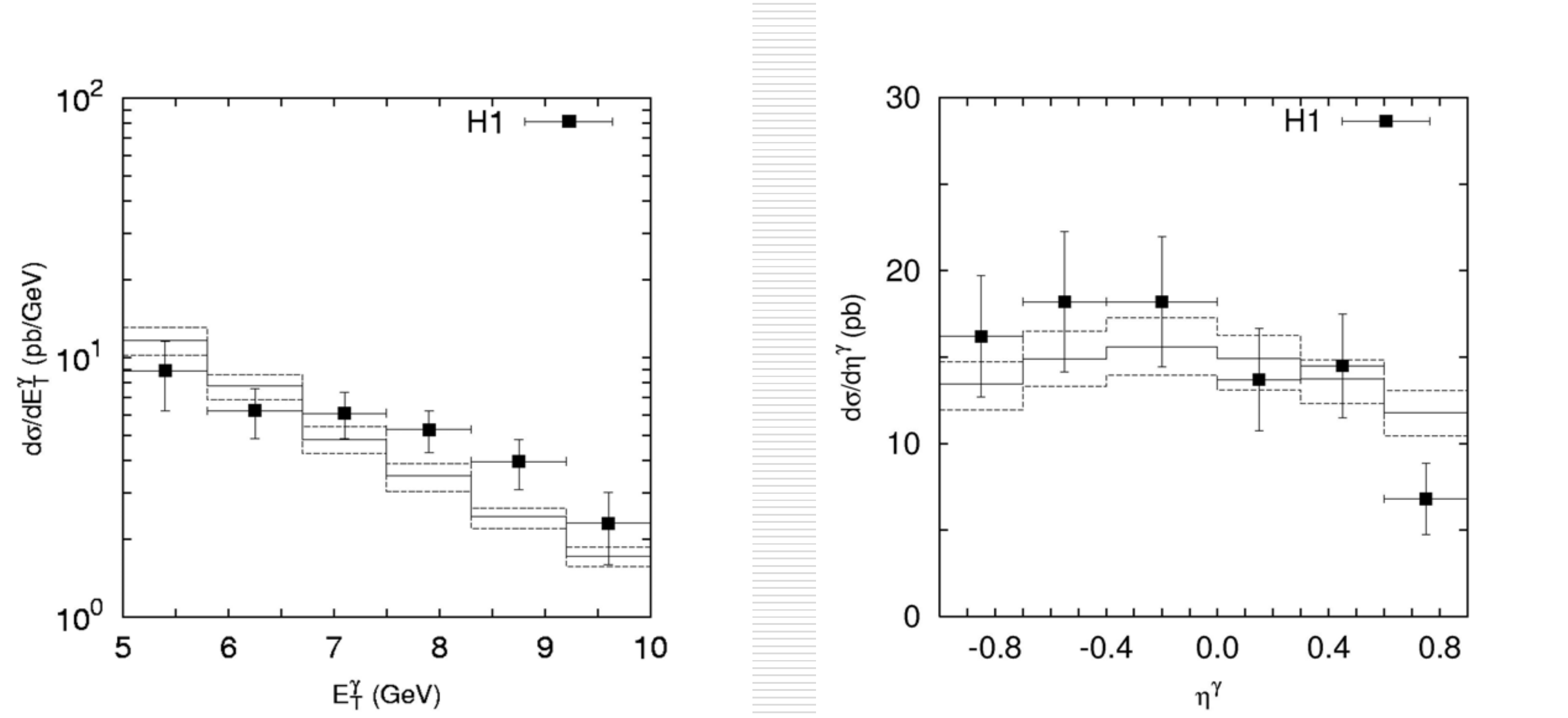


$E_T^\gamma > 5\,\mathrm{GeV}, \quad -1 < \eta^\gamma < 0.9, \quad 0.2 < y < 0.7$



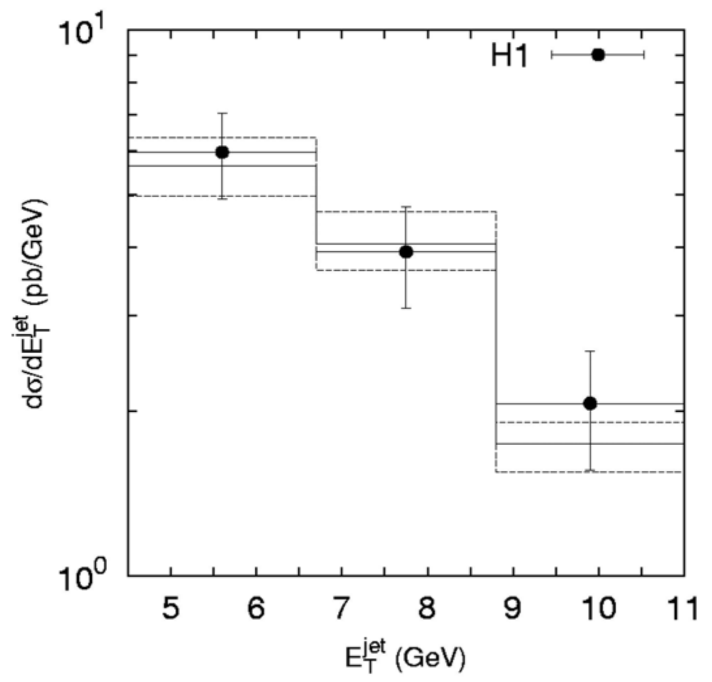
$E_T^\gamma > 5\,\mathrm{GeV}, \quad -0.7 < \eta^\gamma < 0.9, \quad 0.2 < y < 0.9$

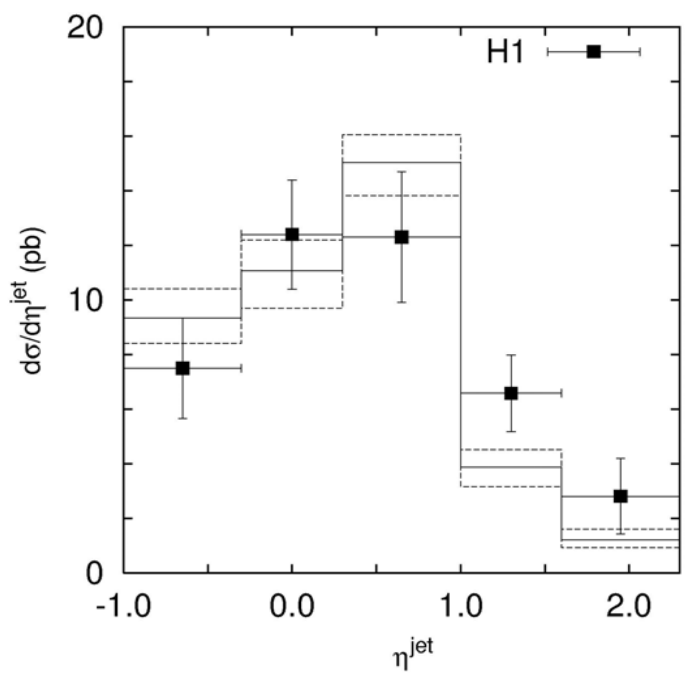
Associative γ + jet production



$$5 < E_T^\gamma < 10\,\text{GeV}, \quad -1 < \eta^\gamma < 0.9, \quad 0.2 < y < 0.7, \quad -1 < \eta^{\text{jet}} < 2.3, \quad E_T^{\text{jet}} > 4.5\,\text{GeV}$$

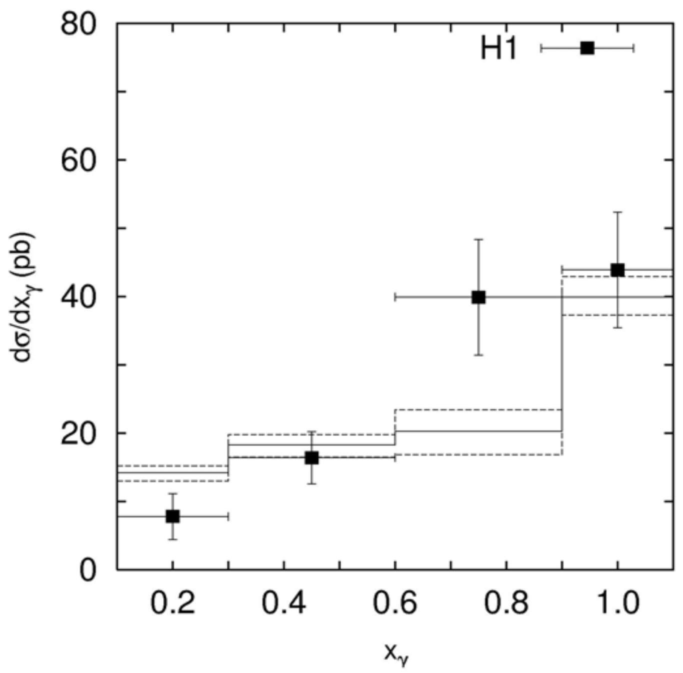
Associative γ + jet production

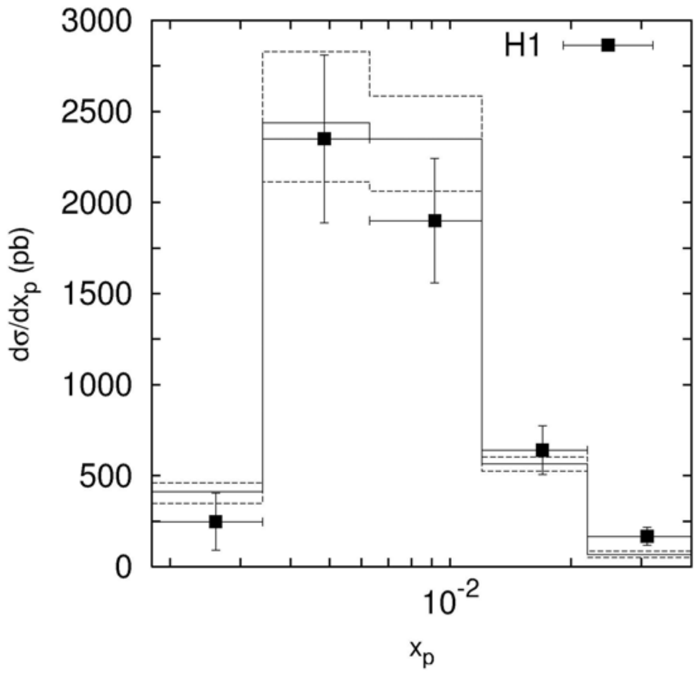




$$5 < E_T^{\gamma} < 10\,\text{GeV},\quad -1 < \eta^{\gamma} < 0.9,\quad 0.2 < y < 0.7,\quad -1 < \eta^{\text{jet}} < 2.3,\quad E_T^{\text{jet}} > 4.5\,\text{GeV}$$

Associative γ + jet production

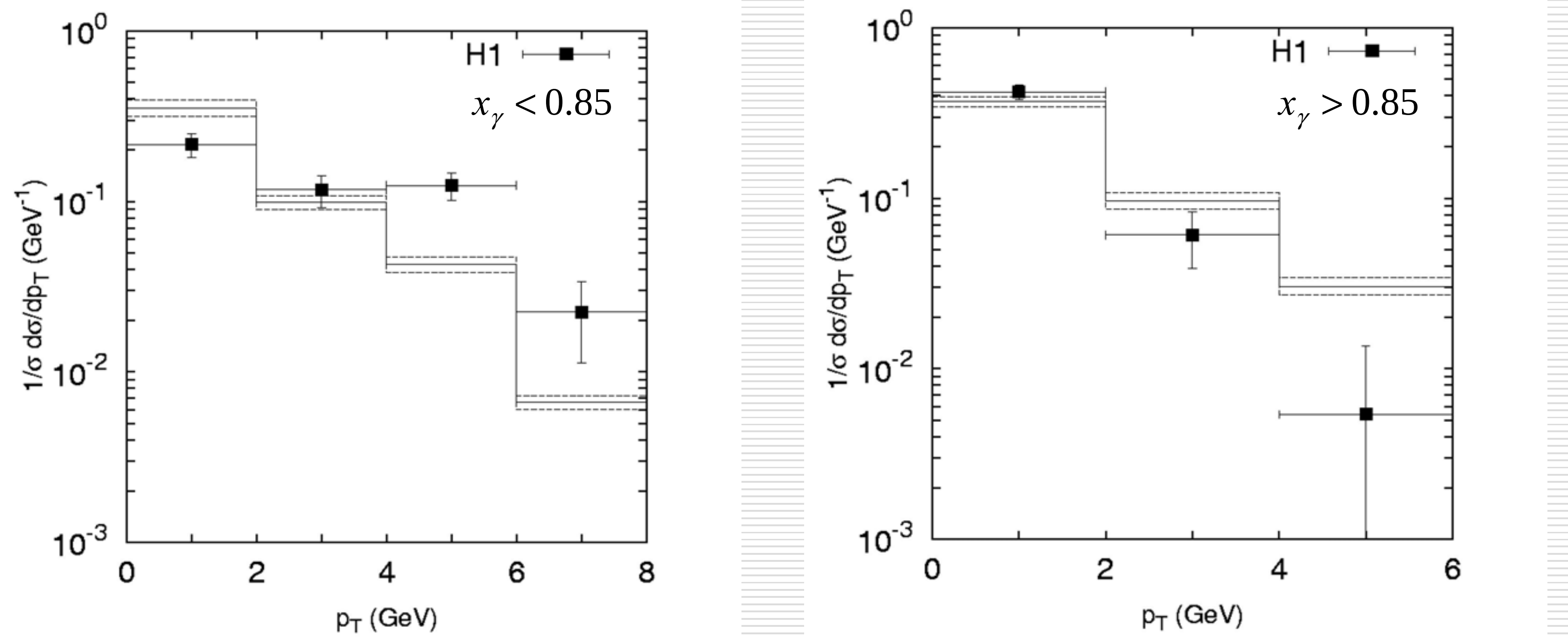




$$x_\gamma = \frac{E_T^\gamma(e^{-\eta^\gamma} + e^{-\eta^{\text{jet}}})}{2yE_e}$$

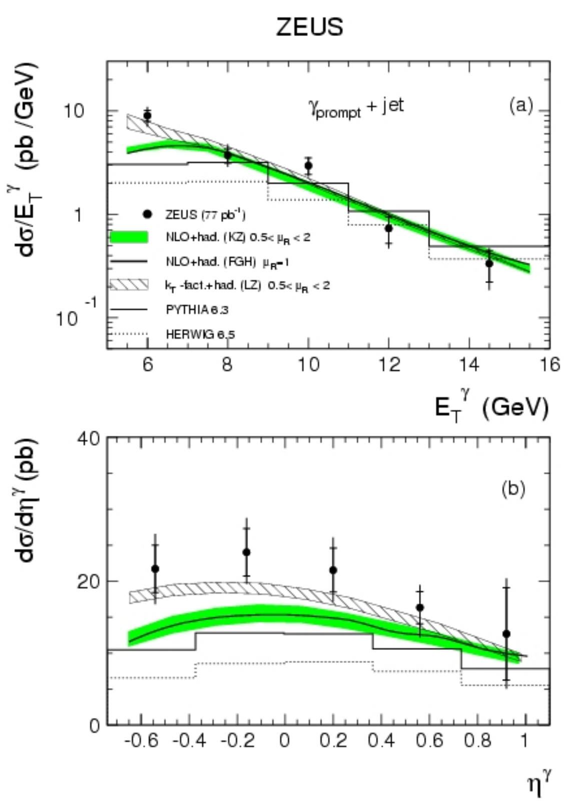
$$x_p = \frac{E_T^\gamma(e^{\eta^\gamma} + e^{\eta^{\text{jet}}})}{2E_p}$$

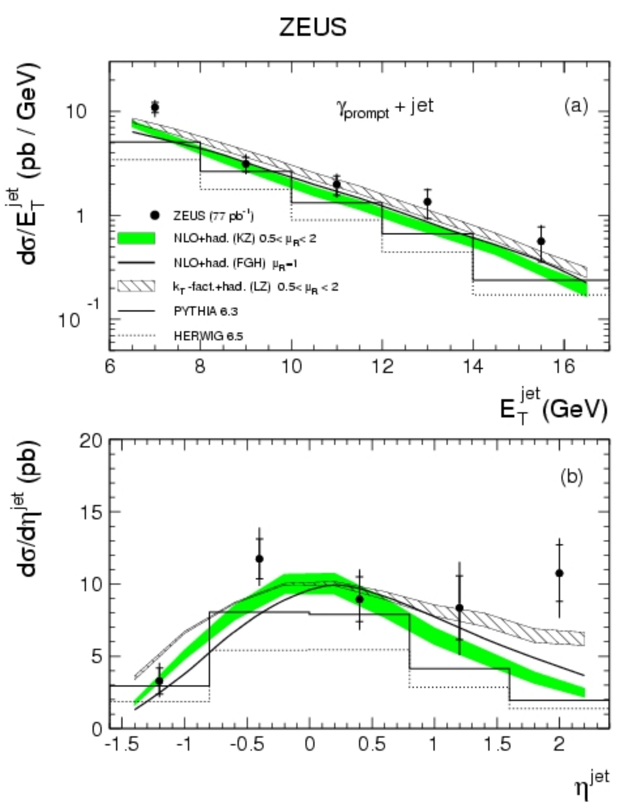
Associative γ + jet production



$$p_T = \left| p_T^\gamma \times p_T^{\mathrm{jet}} \right| / \left| p_T^{\mathrm{jet}} \right| = E_T^\gamma \sin \Delta\phi$$

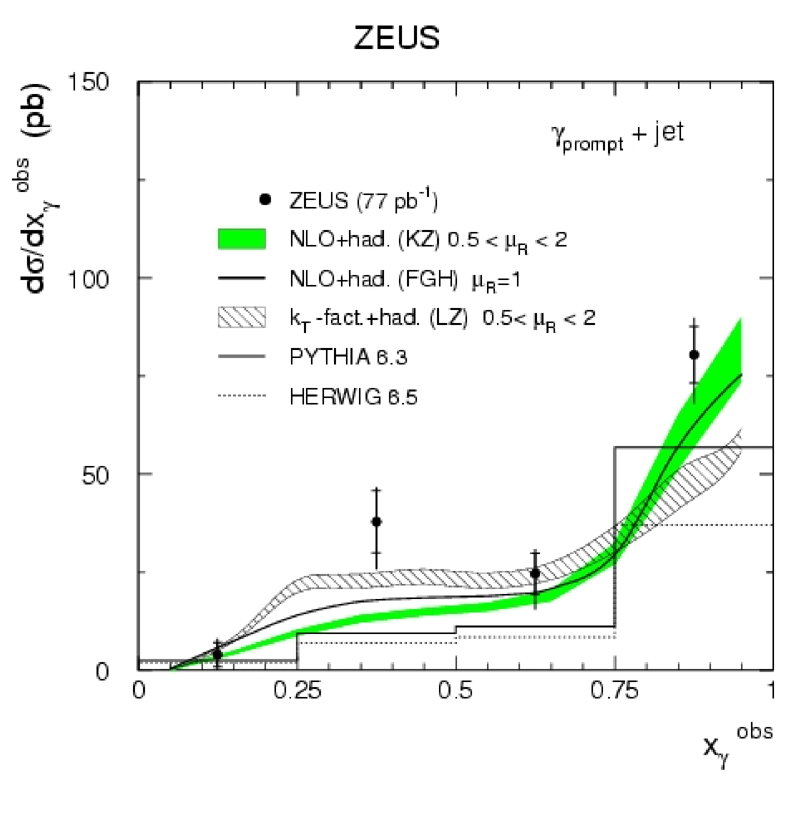
γ + jet production (ZEUS, EPJ C 49, 511 (2007), hep-ex/0608028)





$E_T^{\gamma} > 5\,\text{GeV}, E_T^{jet} > 6\,\text{GeV}$

γ + jet production (ZEUS, EPJ C 49, 511 (2007), hep-ex/0608028)



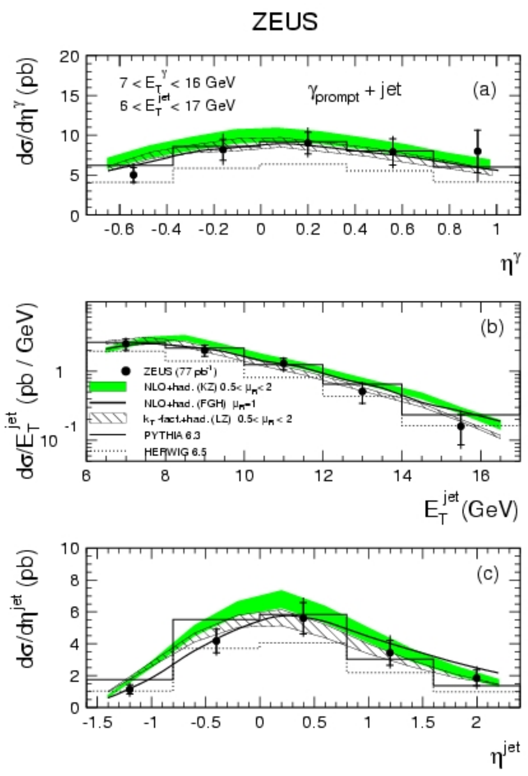
$E_T^\gamma > 5\,\text{GeV}, E_T^{jet} > 6\,\text{GeV}$

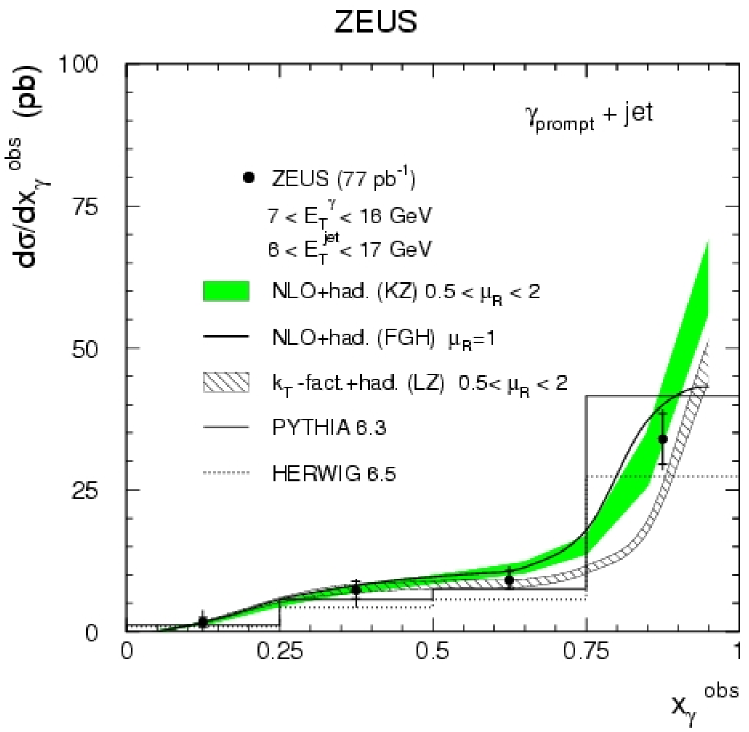
The k_T- factorization

- describes better the lowest E_T^{γ} region
- the shape η^{γ} of the c.s. is closer to the data
- the η^{jet} c.s. in forward region is better reproduced by our calculations

- However the observed c.s. is still above the k_T-factorization prediction due to the poor description of the low E_T^{jet} and large x_{γ}^{obs} region

γ + jet production (ZEUS, DESY 06-125, hep-ex/0608028)



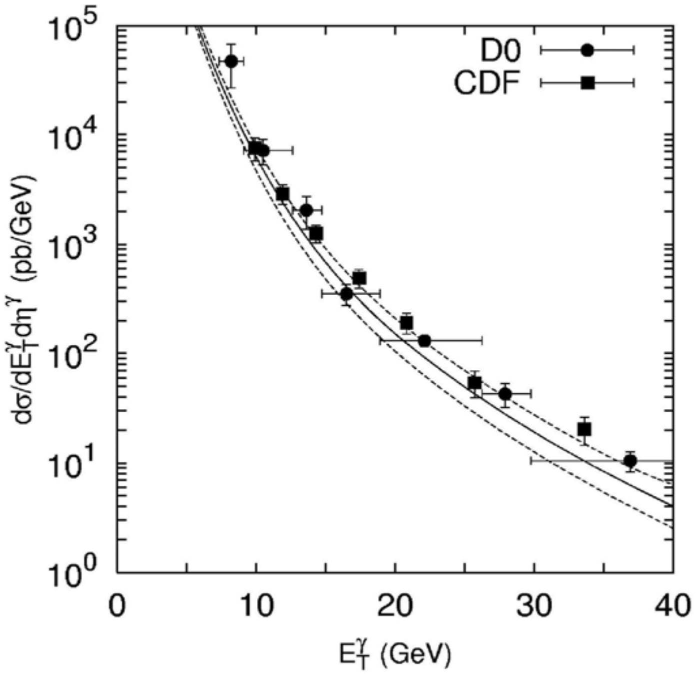


$E_T^{\gamma} > 7\,\mathrm{GeV}, E_T^{jet} > 6\,\mathrm{GeV}$

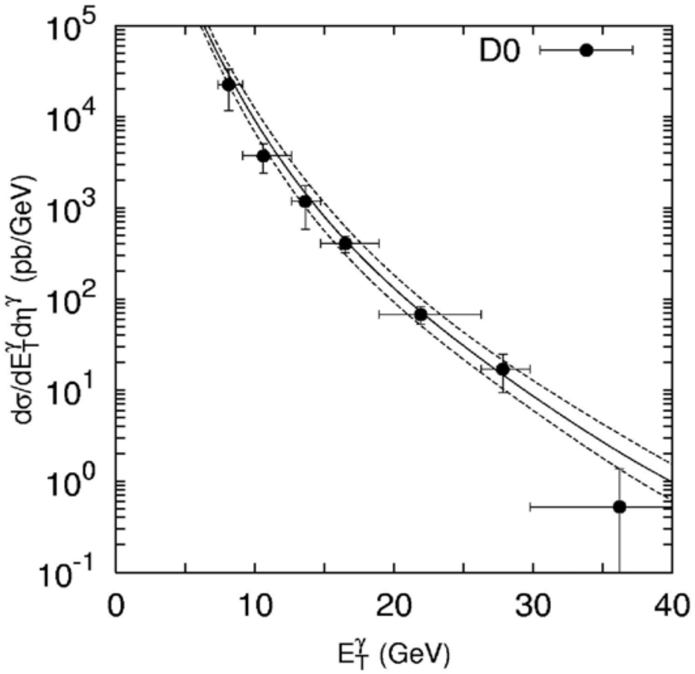
Prompt photon hadroproduction

- inclusive prompt photon hadroproduction at Tevatron at $\sqrt{s} = 630\,\mathrm{GeV}$ and $\sqrt{s} = 1800\,\mathrm{GeV}$
- prompt photon and associated muon production (due to Compton scattering where the final heavy quark produces a muon)
- comparison of our results with the recent D0 and CDF data
- same set of parameters which has been used in description of the HERA data
- extrapolation of our results to LHC energies

$\sqrt{s} = 630\,\mathrm{GeV}$ (inclusive)

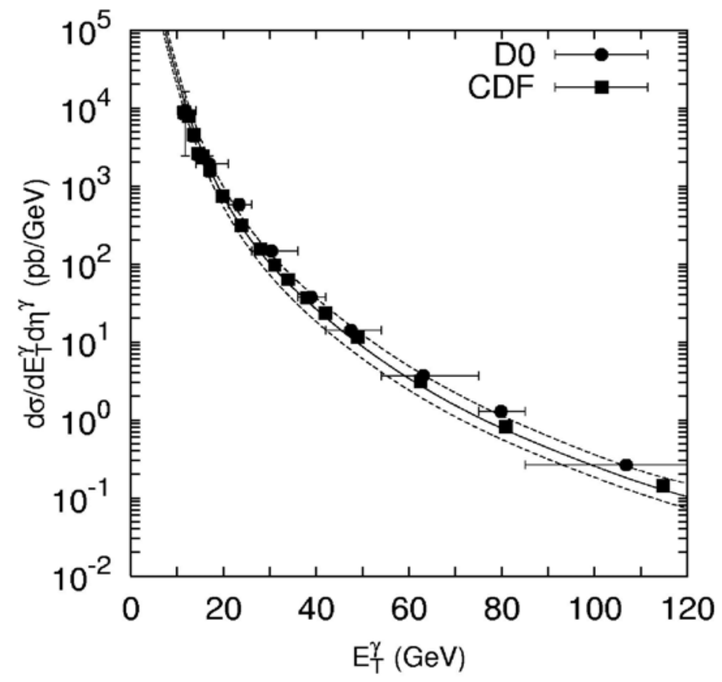


$|\eta^\gamma| < 0.9$

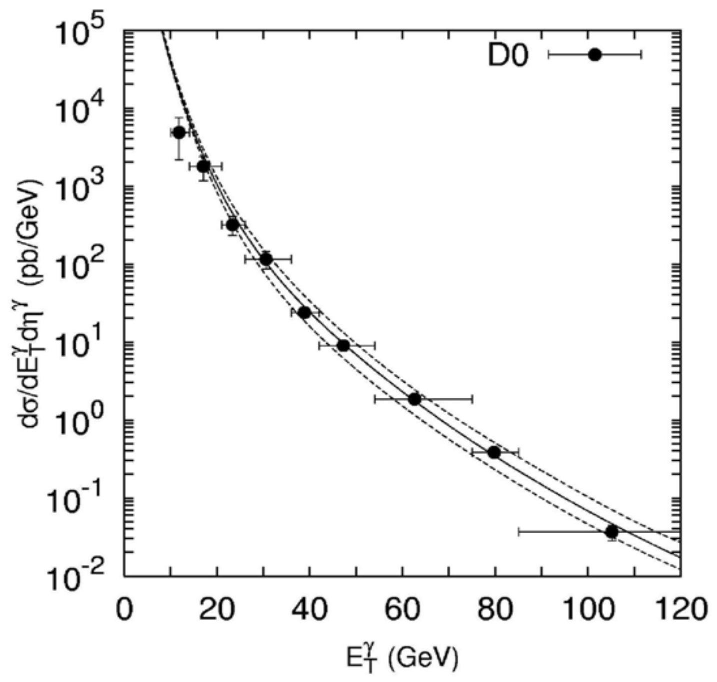


$1.6 < |\eta^\gamma| < 2.5$

$\sqrt{s} = 1800\,\mathrm{GeV}$ (inclusive)

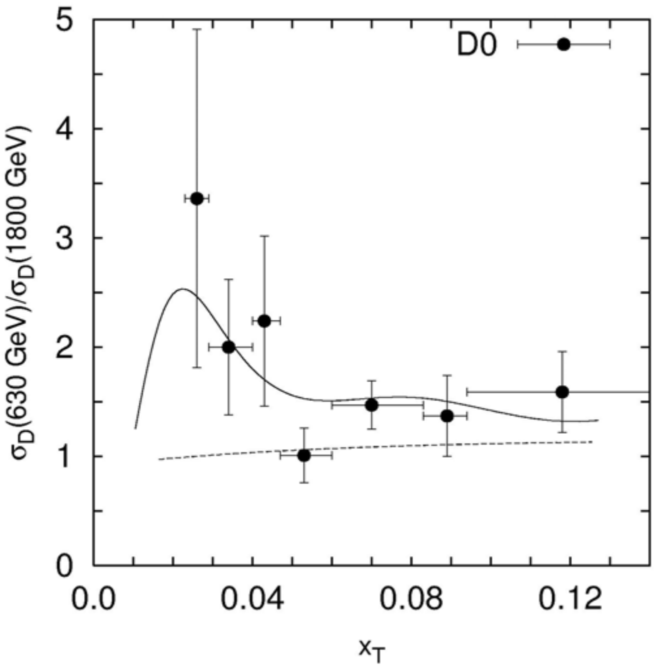


$|\eta^\gamma| < 0.9$

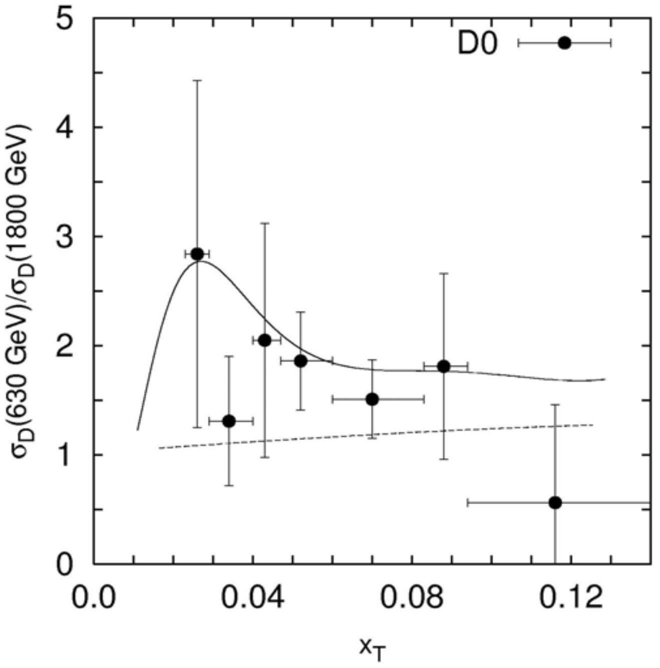


$1.6 < |\eta^\gamma| < 2.5$

Ratio of cross sections

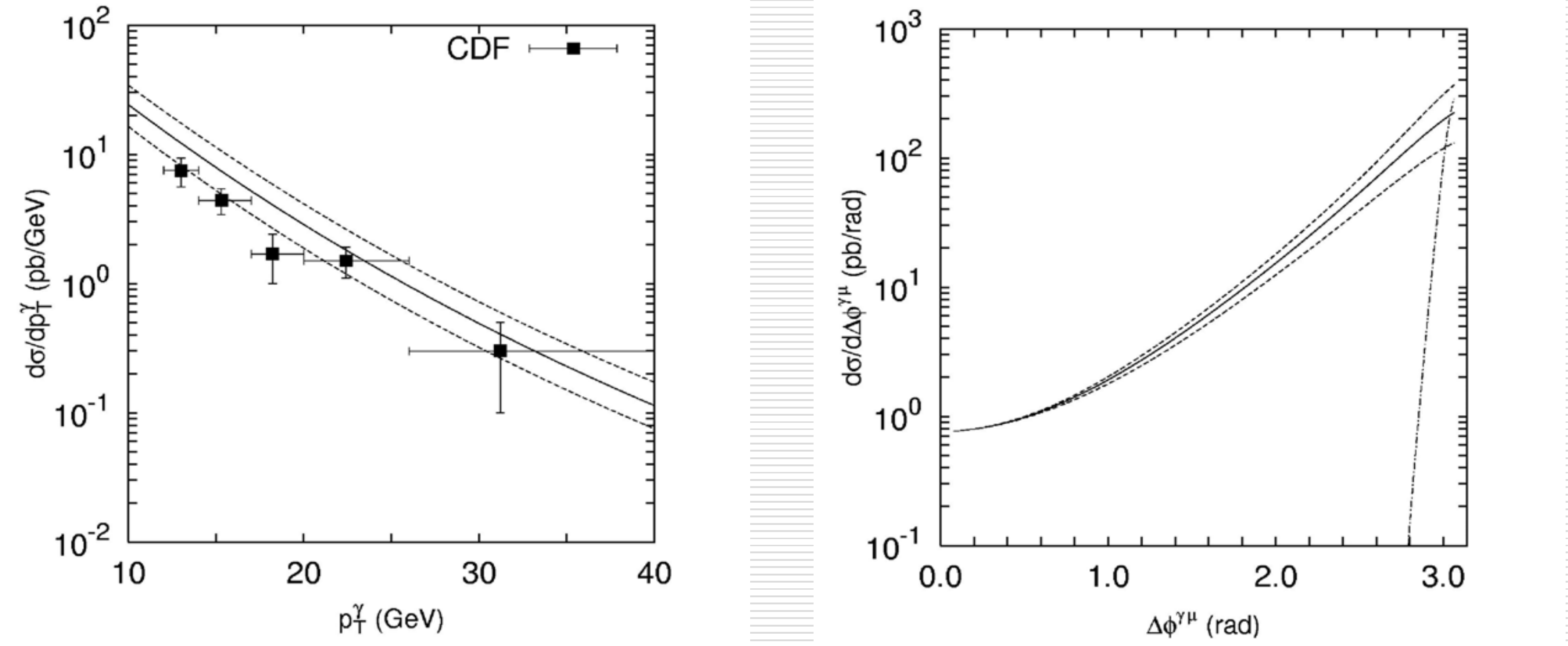


$|\eta^{\gamma}| < 0.9$



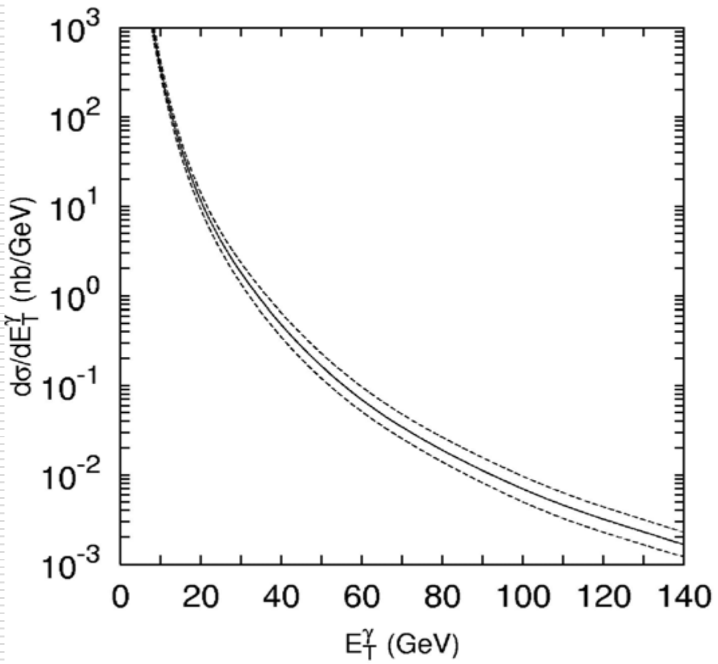
$1.6 < |\eta^{\gamma}| < 2.5$

Associated $\gamma + \mu$ production

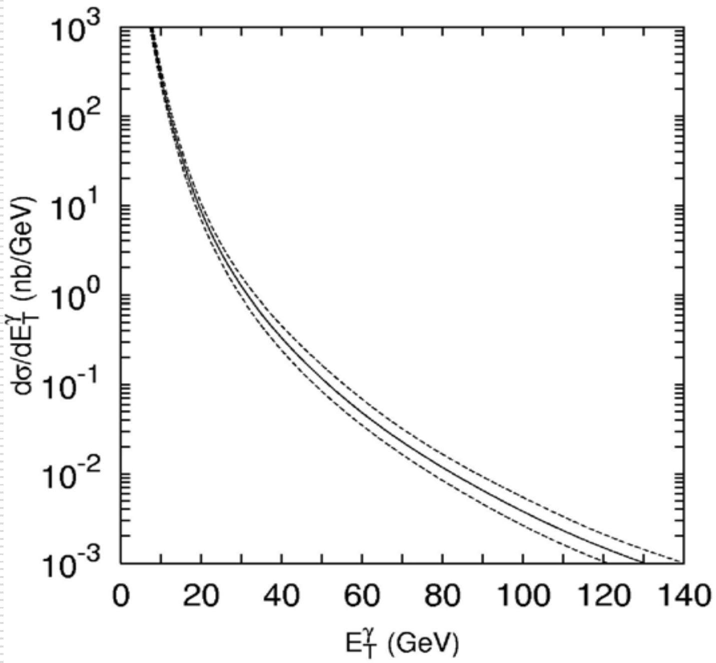


$$p_T^{\mu} > 4\,\mathrm{GeV},\quad |\eta^{\gamma}| < 0.9,\quad |\eta^{\mu}| < 1.0$$

Predictions for LHC



$|\eta^\gamma| < 0.9$



$1.6 < |\eta^\gamma| < 2.5$

Conclusions

- k_T -factorization approach of QCD gives a reasonable description of the recent HERA and Tevatron data
- we demonstrate that k_T-factorization effectively includes the main part of the collinear high-order corrections
- scale dependence of our results is about 10-15%
- Realistic predictions at LHC