Quark Reggeization and Prompt Photon Production at HERA and Tevatron

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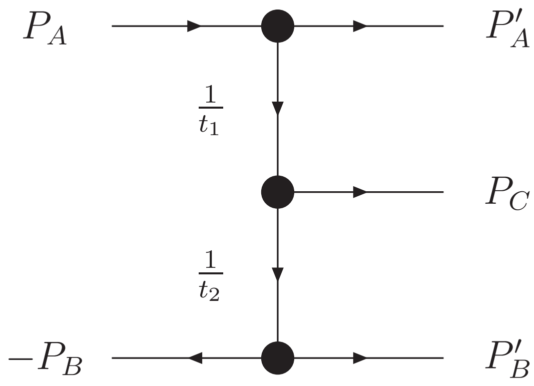
1. QMRK approach and the particle Reggeization hypothesis
2. Relevant effective vertices in the QMRK approach
3. Inclusive prompt photon production at Tevatron (**Phys.Rev.D78, 034033, 2008**)
4. Prompt diphoton production at Tevatron (**New**)
5. Associated prompt photon and jet production at HERA (**New**)
6. Inclusive prompt photon production at HERA (**Phys.Rev.D78, 114031, 2008; it is corrected in part**)
7. Conclusions

QMRK approach and the particle Reggeization hypothesis



$$S_{AB} = (P_A + P_B)^2, \quad S_{A'C} = (P_{A'} + P_C)^2, \quad S_{B'C} = (P_{B'} + P_C)^2$$

$$S_{A'C},\; S_{B'C}, P_C^2\;, P_{TC}^2 \;\ll S_{AB}, \quad (P_A \cdot P_{A'}) \ll (P_A \cdot P_C) \ll (P_A \cdot P_{B'})$$

$$y_{A'} \gg y_C \gg y_{B'}$$

Electron Reggeization in QED:

M. Gell-Mann, M. L. Goldberger, F. E. Low, E. Marx, and F. Zachariasen, **1964**.

Quark Reggeization in QCD:

V. S. Fadin and V. E. Sherman, **1976**

Qluon Reggeization in QCD:

E. A. Kuraev, L. N. Lipatov, and V. S. Fadin, **1975**
I. I. Balitsky and L. N. Lipatov, **1978**

$$P_1 = E_1(1,0,0,1), \qquad P_2 = E_2(1,0,0,-1), \qquad S = 4E_1E_2$$

$$(n^+)^\mu = P_2^\mu/E_2, \qquad (n^-)^\mu = P_1^\mu/E_1, \qquad k^\pm = k\cdot n^\pm = k^\mu n_\mu^\pm$$

$$q_1 = x_1P_1 + q_{1T}, \qquad q_2 = x_2P_2 + q_{2T}$$

$$t_1 = -q_1^2 = -q_{1T}^2, \qquad t_2 = -q_2^2 = -q_{2T}^2$$

$$x_1 \ll 1, \qquad x_2 \ll 1$$

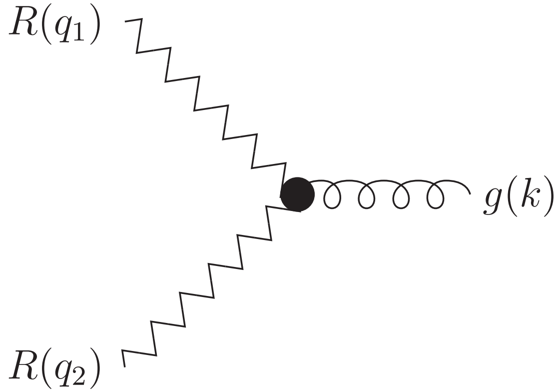
Effective vertices in the QMRK approach

The QMRK approach is based on effective quantum field theory implemented with the non-abelian gauge-invariant action:

Reggeized gluons (R), L. N. Lipatov, **1995**,
Reggeized quarks (Q), L. N. Lipatov and M. I. Vyazovsky, **2001**

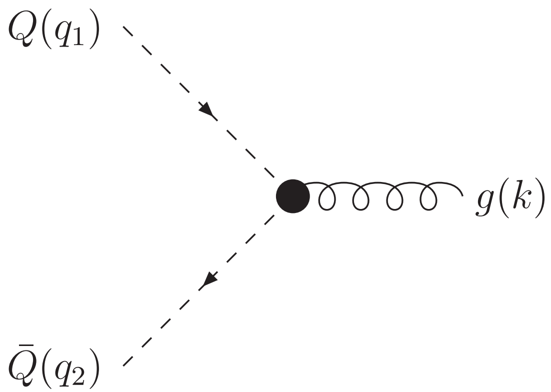
Feynman rules for the effective theory:

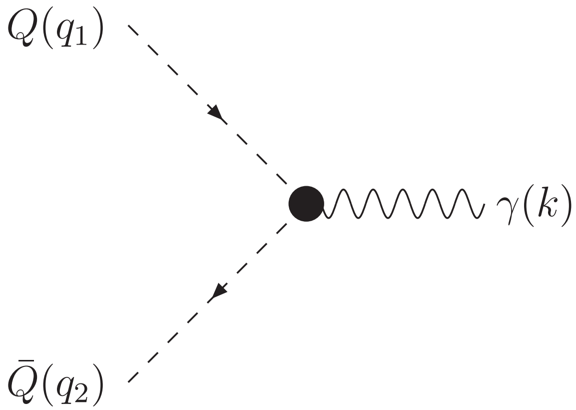
E. N. Antonov, L. N. Lipatov, E. A. Kuraev, and I. O. Cherednikov, **2005**
L. N. Lipatov and M. I. Vyazovsky, **2001**



$$C_\mu^{RR\to g}(q_1,q_2) = 2g_s f^{abc}\left((q_1-q_2)_\mu - (n^+)_\mu(q_1^- + \frac{q_1^2}{q_2^+}) + (n^-)_\mu(q_2^+ + \frac{q_2^2}{q_1^-})\right) \times \frac{x_1 x_2 E_1 E_2}{\sqrt{t_1 t_2}}$$

$$k = q_1 + q_2$$

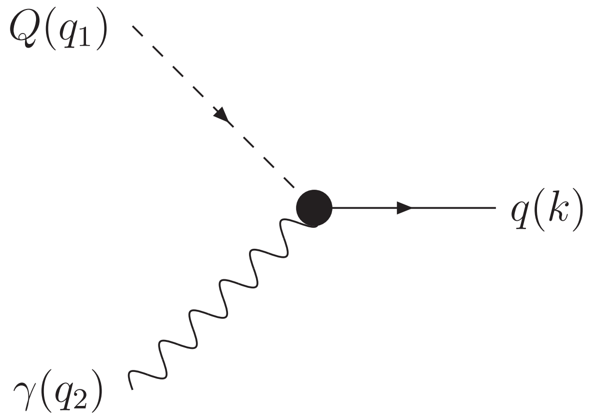




$$C_\mu^{Q\bar{Q}\to g}(q_1, q_2) = -ig_s T^a \gamma_\mu^{(+-)}(q_1, -q_2)$$

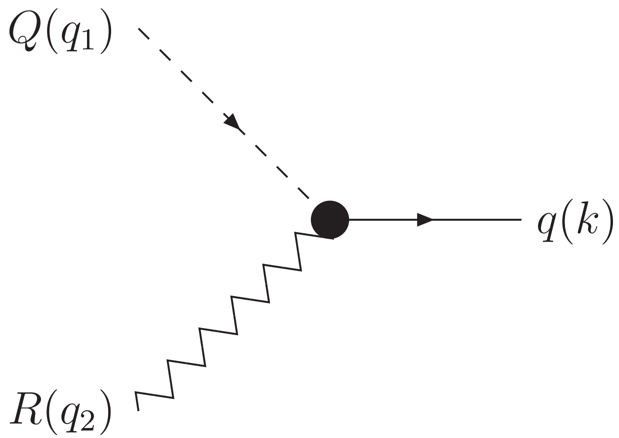
$$\gamma_\mu^{(+-)}(q_1, q_2) = \gamma_\mu - \hat{q}_1 \frac{(n^-)_\mu}{k^-} + \hat{q}_2 \frac{(n^+)_\mu}{k^+}$$

$$k = q_1 + q_2$$



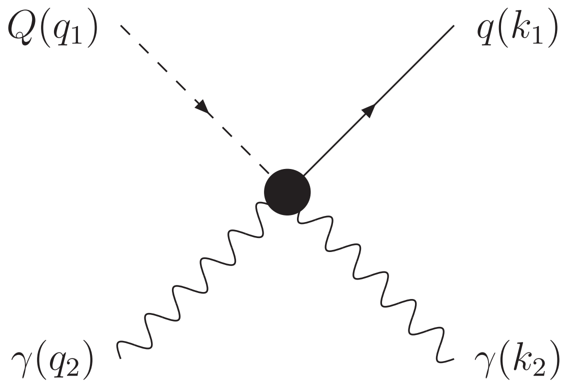
$$C_\mu^{\gamma Q\to q}(q_1,q_2) = -iee_q\gamma_\mu^{(-)}(q_1,q_2)$$

$$\gamma_\mu^{(+)}(q,k) = \gamma_\mu + \hat{q}\frac{n_\mu^+}{k^+} = \gamma_\mu + \hat{q}\frac{P_{2\mu}}{P_2\cdot k}, \qquad \gamma_\mu^{(-)}(q,k) = \gamma_\mu + \hat{q}\frac{n_\mu^-}{k^-} = \gamma_\mu + \hat{q}\frac{P_{1\mu}}{P_1\cdot k}.$$



$$C^{RQ\to q}(q_1,q_2) = -ig_s T^a \gamma_\mu^{(-)}(q_1,q_2)\Pi_T^{(+)\mu}(q_2)$$

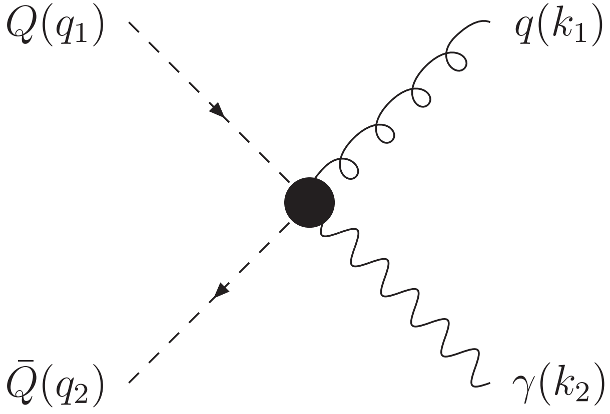
$$\Pi_T^{(+)\mu}(q_2) = \frac{q_{2T}^\mu}{|\vec{q}_{2T}|}, \qquad \Pi_T^{(+)\mu}(q_2) = -\frac{x_2 E_2 (n^+)^\mu}{|\vec{q}_{2T}|}.$$



$$C_{\mu\nu}^{\gamma Q\to\gamma q}(q_1, P_2, k_1, k_2) =$$

$$-e^2 e_q^2\Big[\gamma_\nu \frac{\hat{q}_1 - \hat{k}_2}{(q_1 - k_2)^2}\gamma_\mu^{(-)}(-k_2, q_1) + \gamma_\mu \frac{\hat{k}_1 + \hat{k}_2}{(k_1 + k_2)^2}\gamma_\nu^{(-)}(P_2, q_1) - \hat{q}_1 \frac{n_\mu^- n_\nu^-}{P_2^- k_2^-}\Big]$$

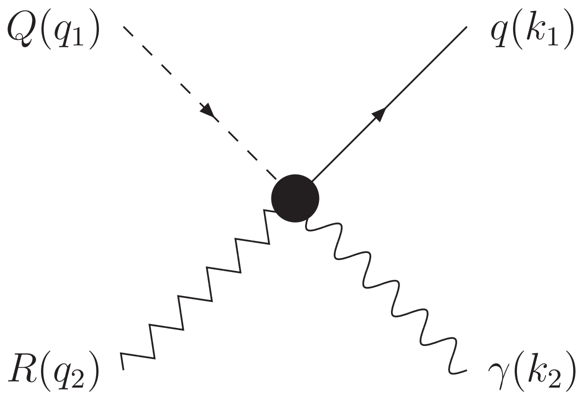
$$q_1 = x_1 P_1 + q_{1T}, \qquad q_2 = P_2$$



$$C_{\mu\nu}^{\bar{Q}Q\to\gamma g}(q_1,q_2,k_1,k_2) = -e_q e g_s T^b \Big[\gamma_\nu^{(+)}(k_2,q_2)\frac{\hat{q}_1-\hat{k}_1}{(q_1-k_1)^2}\gamma_\mu^{(-)}(-k_1,q_1)+$$

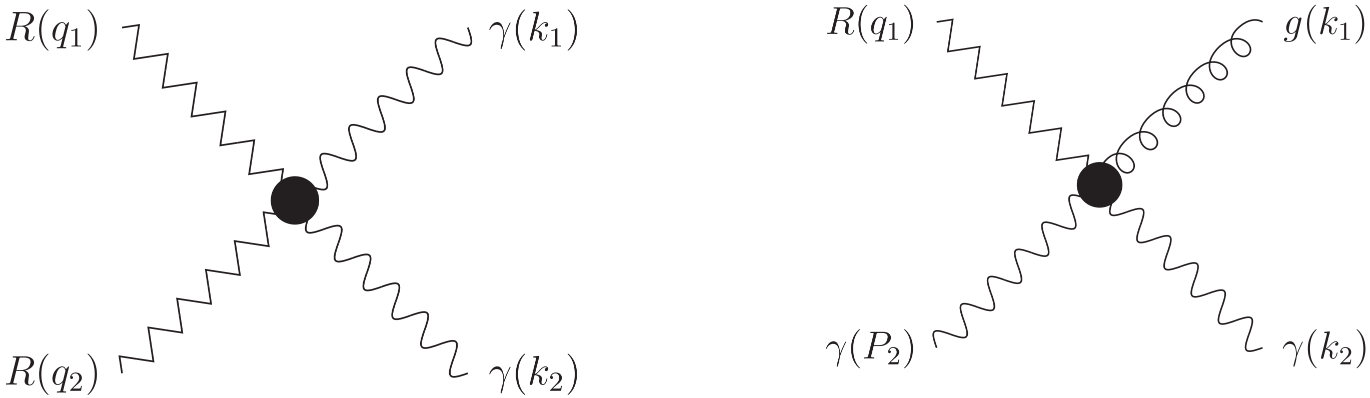
$$\gamma_\mu^{(+)}(k_1,q_2)\frac{\hat{q}_1-\hat{k}_2}{(q_1-k_2)^2}\gamma_\nu^{(-)}(-k_2,q_1)+\Delta_{\mu\nu}(q_1,-q_2)\Big]$$

$$\Delta_{\mu\nu}(q_1,q_2) = \hat{q}_1\frac{n_\mu^- n_\nu^-}{k_1^- k_2^-}+\hat{q}_2\frac{n_\mu^+ n_\nu^+}{k_1^+ k_2^+}$$



$$C_\mu^{RQ\to\gamma q}(q_1,q_2,k_1,k_2) = -ee_q g_s T^b \Pi_T^{(+)\nu}(q_2)\Big[\gamma_\nu \frac{\hat{q}_1-\hat{k}_2}{(q_1-k_2)^2}\gamma_\mu^{(-)}(-k_2,q_1)+$$

$$\gamma_\mu \frac{\hat{k}_1+\hat{k}_2}{(k_1+k_2)^2}\gamma_\nu^{(-)}(q_2,q_1) - \hat{q}_1 \frac{n_\mu^- n_\nu^-}{q_2^- k_2^-}\Big]$$



$$C_{\rho,\sigma}^{RR\to\gamma\gamma}(q_1,q_2,k_1,k_2) = \Pi_T^{(+)\mu}(q_1)\Pi_T^{(-)\nu}(q_2)G_{\mu\nu\rho\sigma}^{\text{box}}(q_1,q_2,k_1,k_2)$$

$$C_{\rho,\sigma}^{\gamma R\to\gamma g}(q_1,P_2,k_1,k_2) = \Pi_T^{(+)\mu}(q_1)\varepsilon^{\nu}(P_2)G_{\mu\nu\rho\sigma}^{\text{box}}(q_1,q_2,k_1,k_2)$$

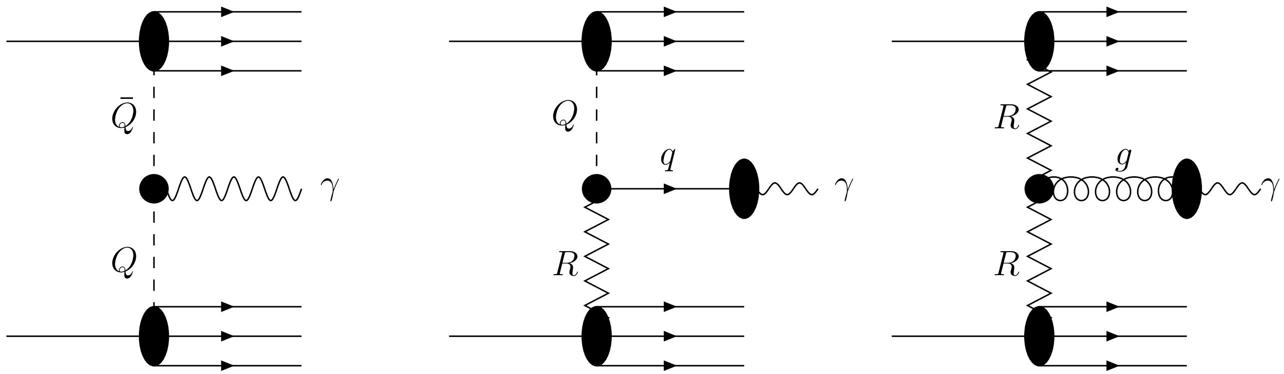
$$d\sigma(p\bar{p} \to X) = \sum_{i,j} \int \frac{dx_1}{x_1} \int \frac{d^2q_{1T}}{\pi} \int \frac{dx_2}{x_2} \int \frac{d^2q_{2T}}{\pi} \Phi_i^p(x_1, t_1, \mu^2) \Phi_j^{\bar{p}}(x_2, t_2, \mu^2) d\hat{\sigma}(ij \to X)$$

$$\sigma(ep \to X) = \int dy G_{\gamma/e}(y) \sigma(\gamma p \to X)$$

$$d\hat{\sigma}(ij \to X) = \frac{1}{2x_1x_2S} \times \overline{|\mathcal{M}(ij \to X)|^2} \times d\Phi_X$$

At the stage of numerical calculations we use the Kimber-Martin-Ryskin (KMR) prescription for unintegrated quark and gluon distribution functions $\Phi_{q,g}^{\gamma,p}(x, |\mathbf{q}_T|^2, \mu^2)$, with the following collinear densities as input: Martin-Roberts-Stirling-Thorne (MRST) for a proton and Glück-Reya-Vogt (GRV) for a photon.

Inclusive prompt photon production at Tevatron



D0 and CDF isolation cone conditions:

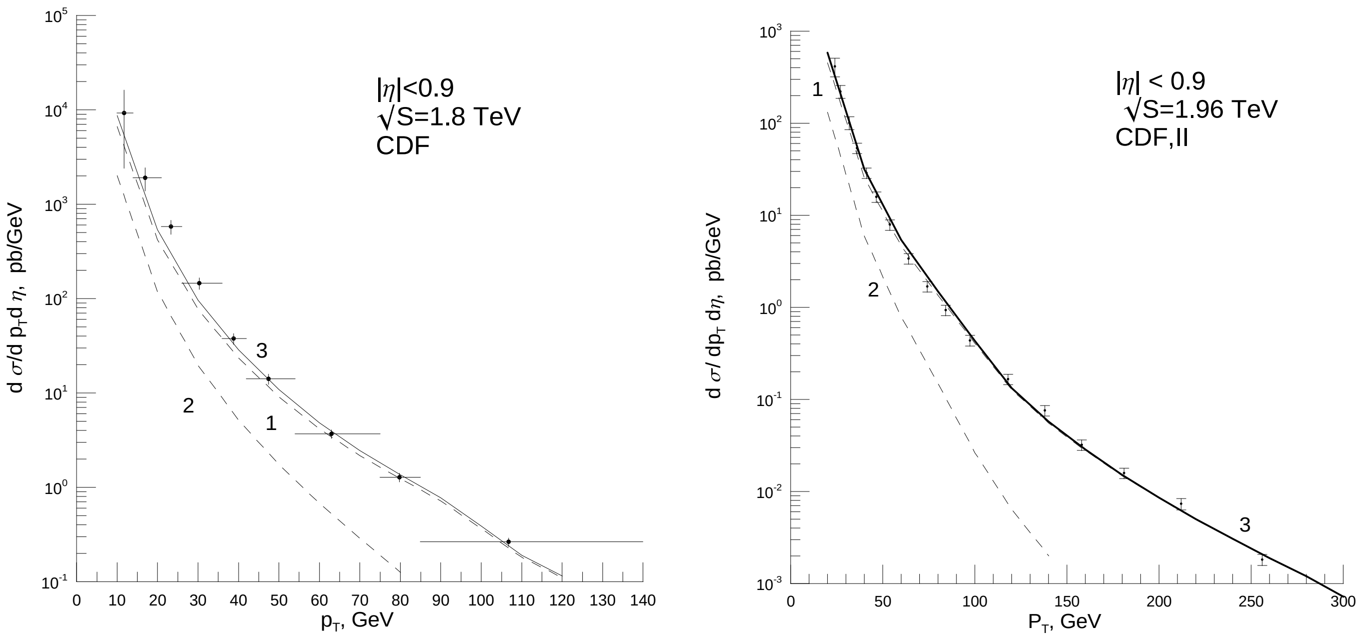
$$(\eta^{\gamma} - \eta^{jet})^2 + (\phi^{\gamma} - \phi^{jet})^2 \leq R^2, \qquad R \simeq 0.4$$

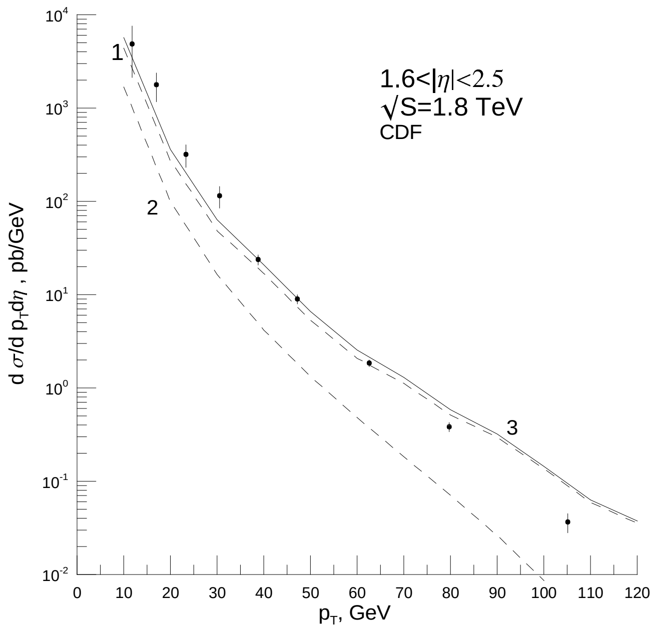
$$E_T^{jet} \leq E_T^{max}, \qquad E_T^{max} \simeq 1 \ \ \mathrm{GeV}$$

$$z = E_T^\gamma / E_T^{quark}, \qquad d\hat{\sigma}(ij \to \gamma X) = \int_{z_{min}}^{1} dz D_{q\to\gamma}(z,\mu^2) d\hat{\sigma}(ij \to qX)$$

$$E_T^{quark} = E_T^\gamma + E_T^{jet}, \qquad z_{min} = \frac{E_T^\gamma}{E_T^\gamma + E_T^{jet}} \simeq 1 - \frac{E_T^{jet}}{E_T^\gamma},$$

$$E_T^\gamma \geq 10 \ \ \mathrm{GeV}, \qquad \Rightarrow \quad z_{min} \geq 0.9$$

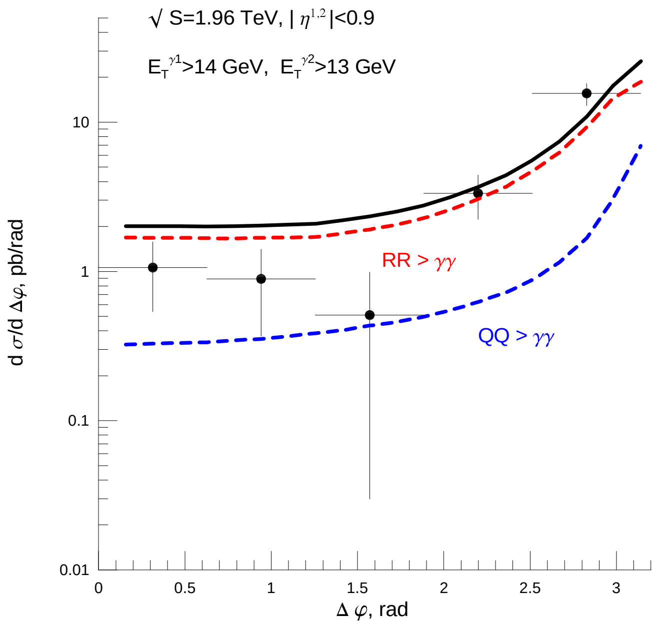

|η|<0.9
√S=1.8 TeV
CDF
d σ/d p_T d η, pb/GeV
p_T, GeV
1
2
3
|η| < 0.9
√S=1.96 TeV
CDF,II
d σ/ dp_T dη, pb/GeV
P_T, GeV

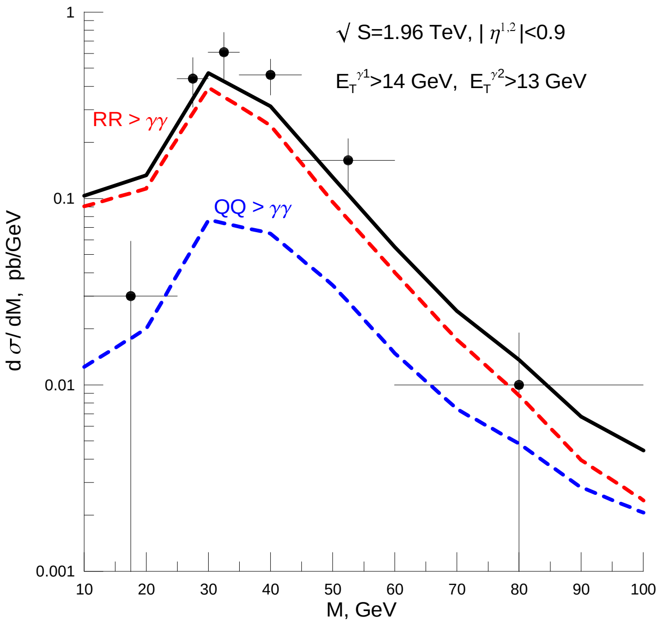


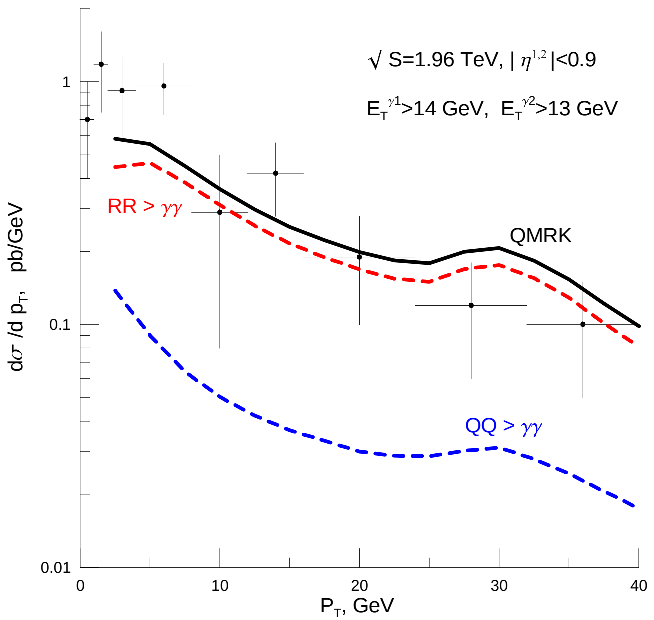
If $1.6 < \eta < 2.5$ then $x_1 \geq 0.2$ and $x_2 \ll 1$

$$\frac{d\sigma}{d\eta dp_T} = \frac{2\pi}{p_T^3} \sum_{q,\bar{q}} x_1 f_q^p(x_1, \mu^2) \Phi_{q,\bar{q}}^{\bar{p}}(x_2, p_T^2, \mu^2) \overline{|M|^2}, \qquad \overline{|M|^2} = \frac{4}{3}\pi\alpha e_q^2 p_T^2$$

Prompt diphoton production at Tevatron




√ S=1.96 TeV, | η^{1,2} |<0.9
E_T^{γ1}>14 GeV, E_T^{γ2}>13 GeV
RR > γγ
QQ > γγ
d σ/ dM, pb/GeV
M, GeV
1
0.1
0.01
0.001
10
20
30
40
50
60
70
80
90
100


√ S=1.96 TeV, | η^{1,2} |<0.9
E_T^{γ1}>14 GeV, E_T^{γ2}>13 GeV
RR > γγ
QMRK
QQ > γγ
dσ /d p_T, pb/GeV
P_T, GeV
1
0.1
0.01
0
10
20
30
40

Associated prompt photon and jet production at HERA

The kinematic region under consideration H1 is defined by

$$E_p = 920 \text{ GeV}, \quad E_e = 27.6 \text{ GeV},$$

$$0.2 < y < 0.7, \quad Q^2_{max} = 1 \text{ GeV}^2,$$

$$5 < E_T^\gamma < 10 \text{ GeV}, \quad -1 < \eta^\gamma < 0.9,$$

$$E_T^{jet} > 4.5 \text{ GeV}, \quad -1 < \eta^{jet} < 2.3,$$

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

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

H1 and ZEUS isolation cone conditions:

$$(\eta^\gamma - \eta^{jet})^2 + (\phi^\gamma - \phi^{jet})^2 \leq R^2, \qquad R \simeq 1$$

$$E_T^{jet} \leq E_T^{max}, \qquad E_T^{max} \simeq 0.1 \times E_T^\gamma$$

Direct production:

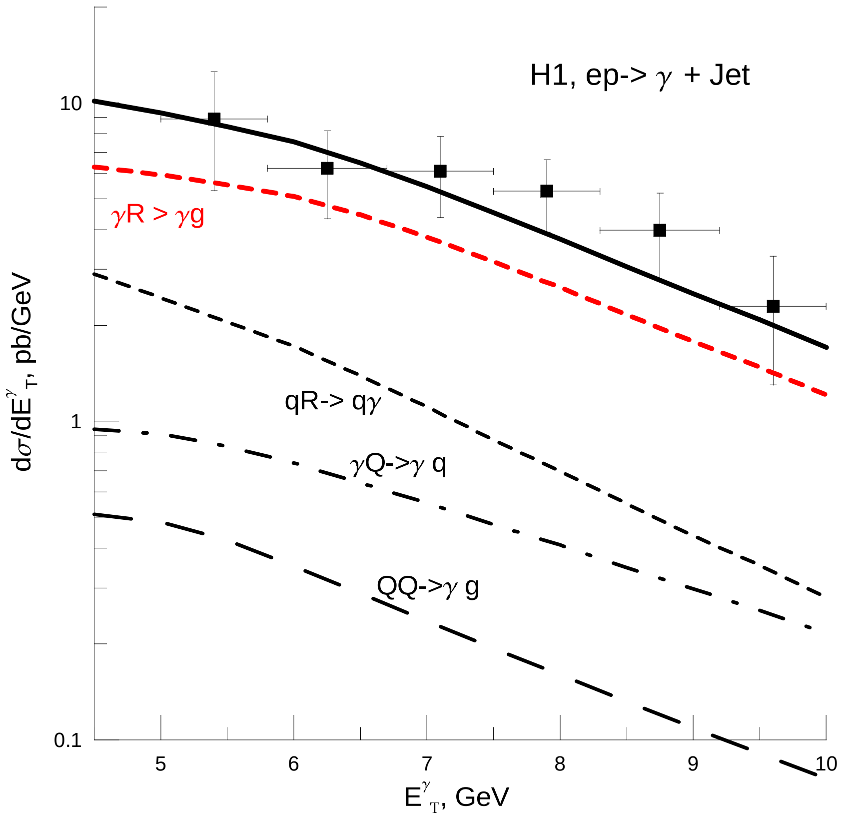
$$\underline{\gamma + Q_p \to \gamma + q} \quad (\alpha^2), \qquad \underline{\gamma + R_p \to \gamma + g} \quad (\alpha^2 \alpha_s^2)$$

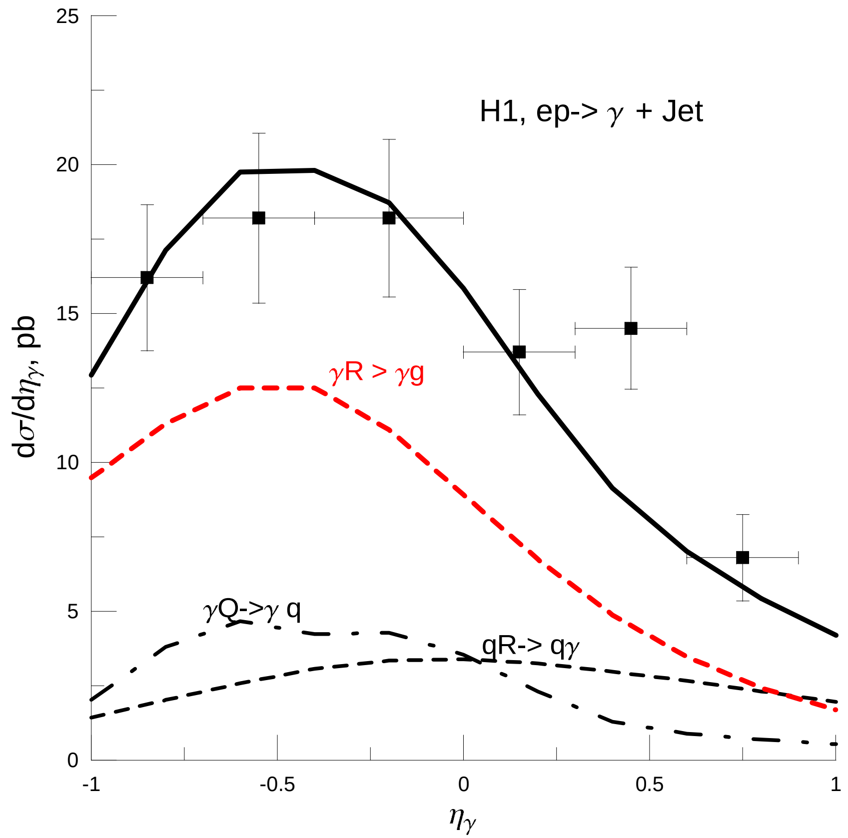
Resolved production:

$$x_\gamma = x_2 \geq 0.2, \qquad x_p = x_1 \leq 0.05$$

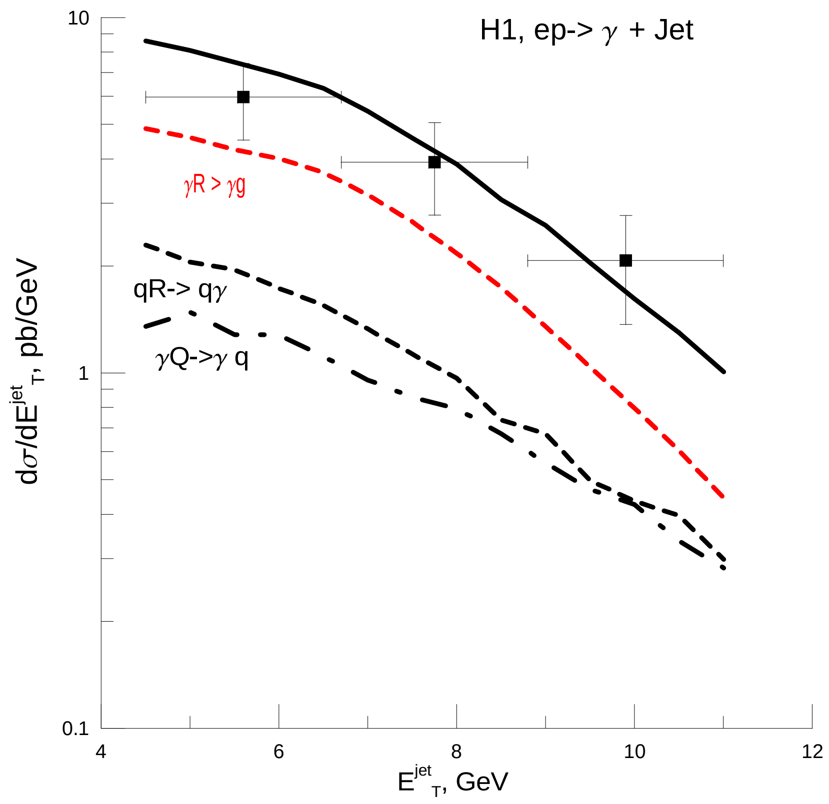
$$q_\gamma + \bar{Q}_p \to \gamma + g, \qquad \underline{q_\gamma + R_p \to \gamma + q,} \qquad g_\gamma + Q_p \to \gamma + q \quad (\alpha \alpha_s)$$

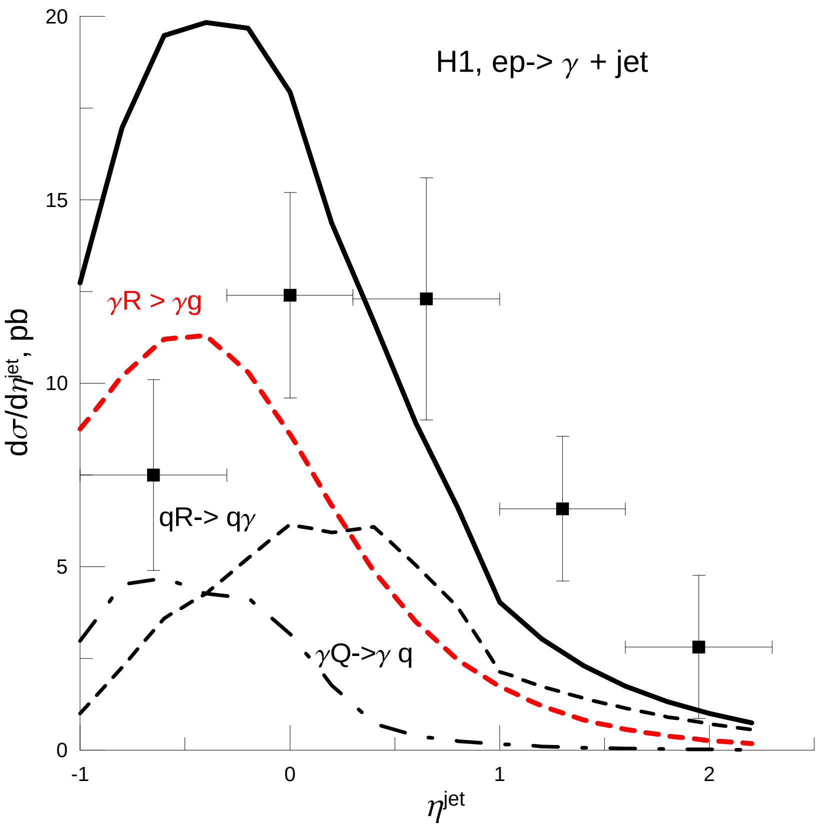
Note: the corrections for hadronization and multiple interactions are not applied.


H1, ep-> γ + Jet
10
1
0.1
γR > γg
qR-> qγ
γQ->γ q
QQ->γ g
dσ/dE^γ_T, pb/GeV
5
6
7
8
9
10
E^γ_T, GeV

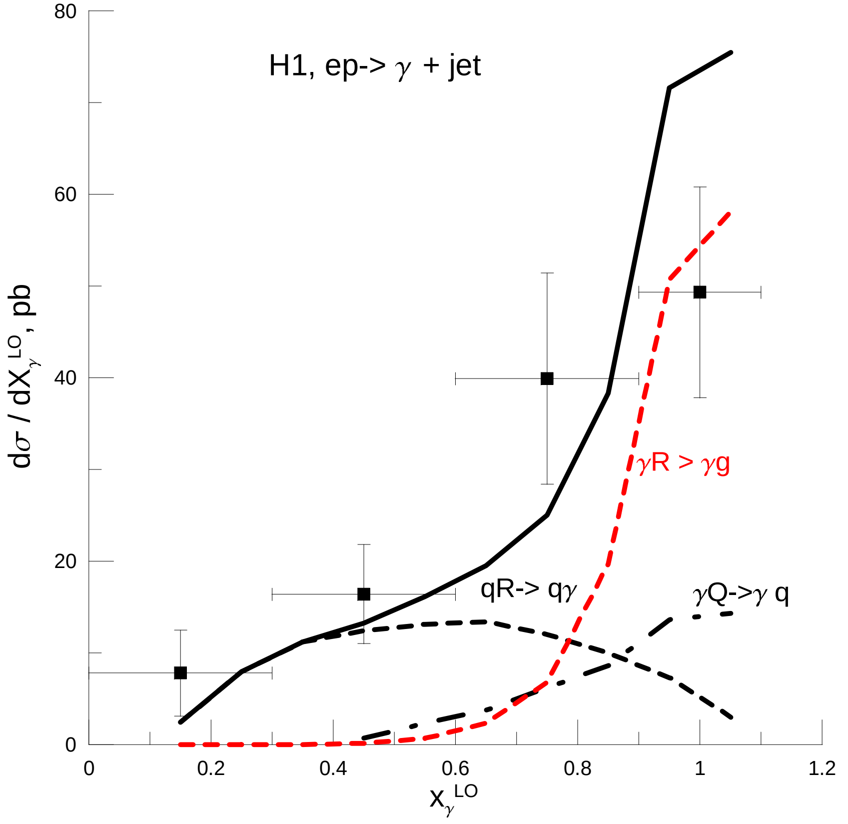


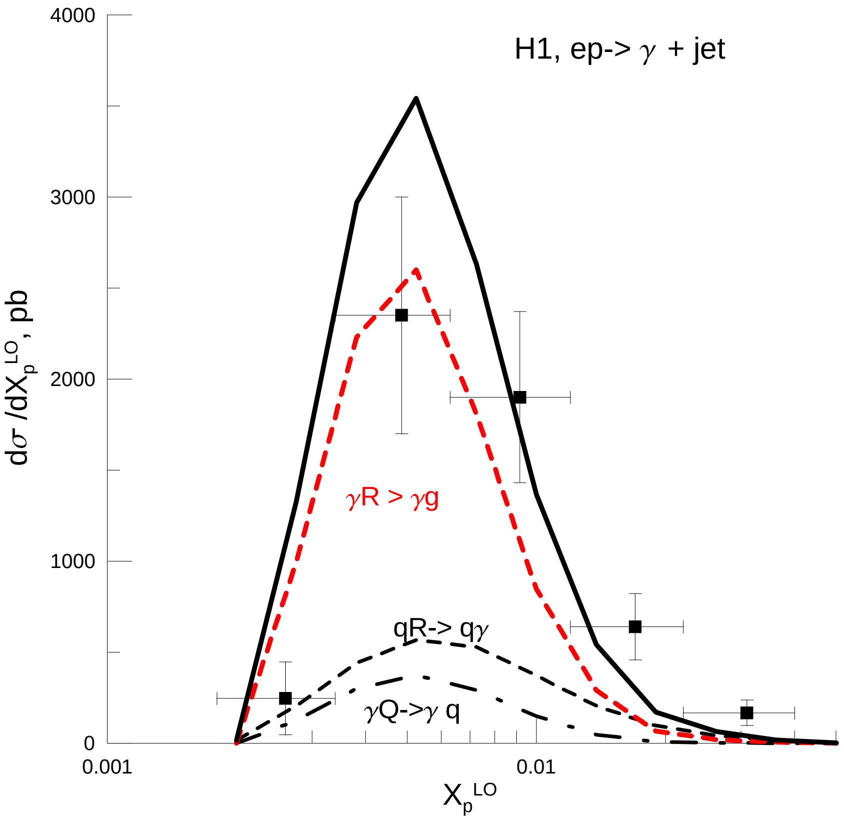
H1, ep-> γ + Jet
γR > γg
γQ->γ q
qR-> qγ
dσ/dη_γ, pb
η_γ
0
5
10
15
20
25
-1
-0.5
0
0.5
1


H1, ep-> γ + Jet
γR > γg
qR-> qγ
γQ->γ q
dσ/dE^jet_T, pb/GeV
E^jet_T, GeV
10
1
0.1
4
6
8
10
12

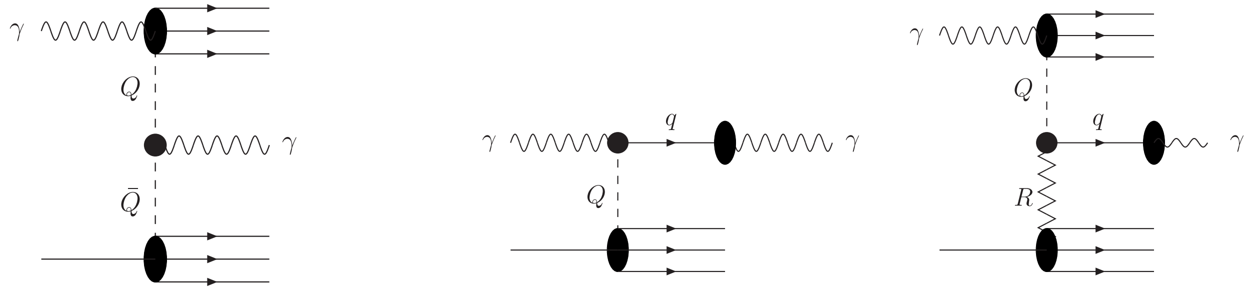


H1, ep-> γ + jet
γR > γg
qR-> qγ
γQ->γ q
dσ/dη^{jet}, pb
η^{jet}
20
15
10
5
0
-1
0
1
2


H1, ep-> γ + jet
dσ / dX_γ^LO, pb
x_γ^LO
γR > γg
qR-> qγ
γQ->γ q
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
1.2


4000
3000
2000
1000
0
0.001
0.01
H1, ep-> γ + jet
γR > γg
qR-> qγ
γQ->γ q
dσ /dX_p^LO, pb
X_p^LO

Inclusive prompt photon production at HERA



Direct-fragmentation production:

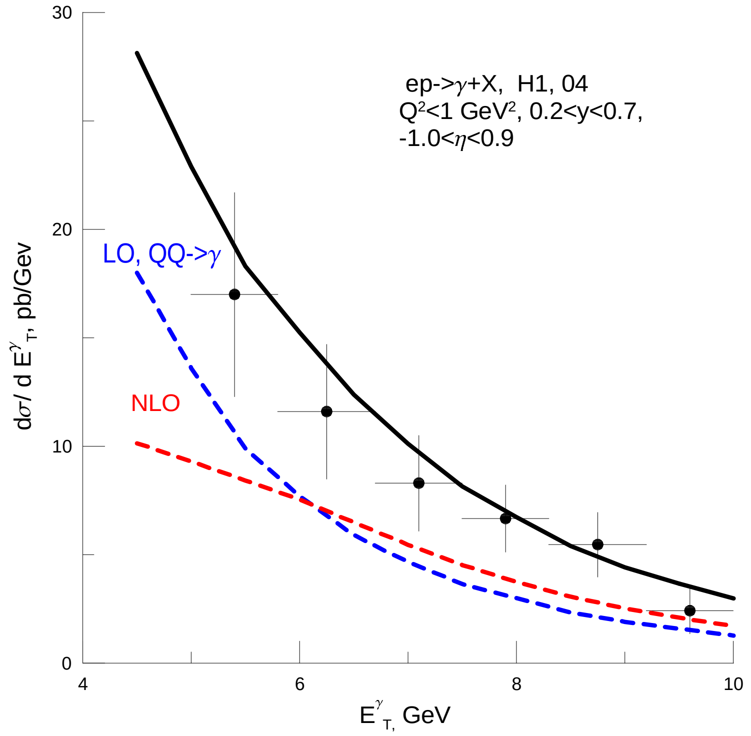
$$\gamma + Q_p \to q \to \gamma$$

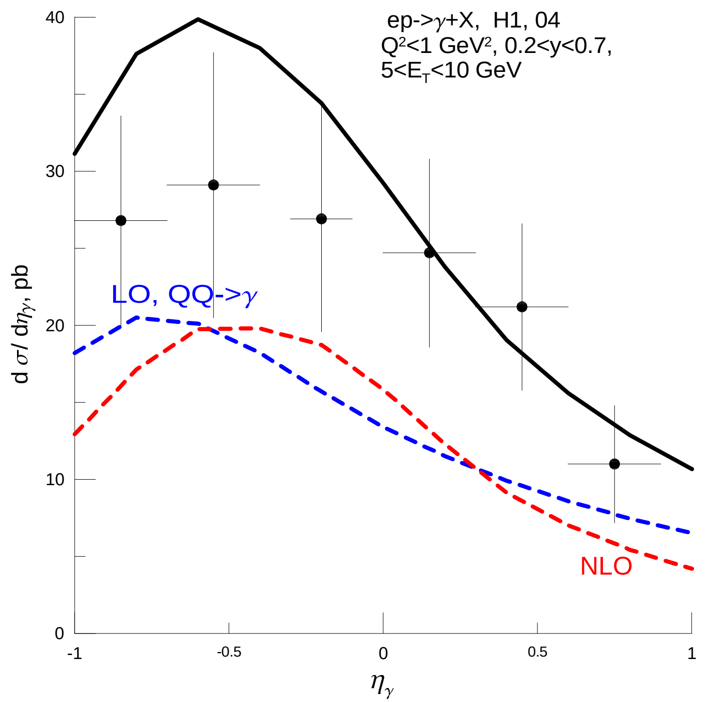
Resolved-direct production:

$$\underline{q_\gamma + \bar{Q}_p \to \gamma},$$

Resolved-fragmentation production:

$$q_\gamma + R_p \to q \to \gamma$$


ep->γ+X, H1, 04
Q²<1 GeV², 0.2<y<0.7,
-1.0<η<0.9
LO, QQ->γ
NLO
dσ/ d E^γ_T, pb/Gev
E^γ_T, GeV
0
10
20
30
4
6
8
10


ep->γ+X, H1, 04
Q²<1 GeV², 0.2<y<0.7,
5<E_T<10 GeV
LO, QQ->γ
NLO
d σ/ dη_γ, pb
η_γ
40
30
20
10
0
-1
-0.5
0
0.5
1

Conclusions

1. We describe data for the spectra of single prompt photons and prompt diphotons in the $p\bar{p}$ collisions at the Fermilab Tevatron.

2. We describe data for the spectra of inclusive prompt photons in the γp collisions at the DESY HERA.

3. We describe data for the associated prompt photon and jet production in the γp collisions at the DESY HERA.

4. We demonstrate the non-trivial role of the $\gamma R \to \gamma g$ and $RR \to \gamma\gamma$ processes in the photon and diphoton production.

We have shown that the QMRK approach, which is based on the quark-gluon Reggeizetion hypothesis, is a powerful tool for the theoretical description of QCD processes in the high energy limit, which accommodates an important class of correction that lie beyond the collinear parton model.