JET AND DIJET PRODUCTION AT TEVATRON IN THE REGGE LIMIT OF QCD

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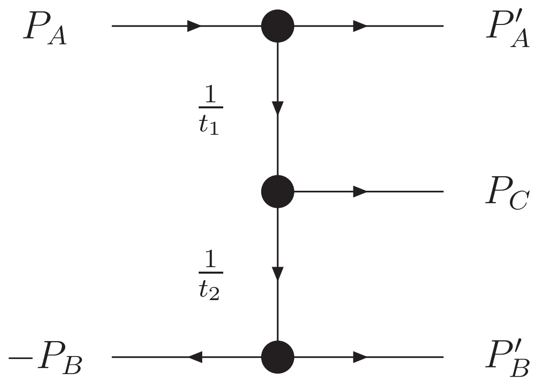
Outlook

1. Introduction
2. Particle production in the Regge kinematics
3. Effective vertices in the QMRK approach and high-energy factorization
4. Inclusive b and $b + \bar{b}$ production at Tevatron
5. Associated $b + \gamma, c + \gamma$ production at Tevatron
6. $\gamma + \gamma$ production at Tevatron
7. Conclusions

Particle production in the Regge kinematics



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

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

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

Electron Reggeization in QED:

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

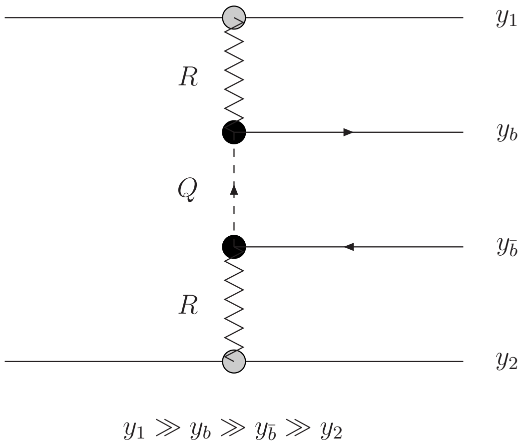
Quark Reggeization in QCD:

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

Qluon Reggeization in QCD:

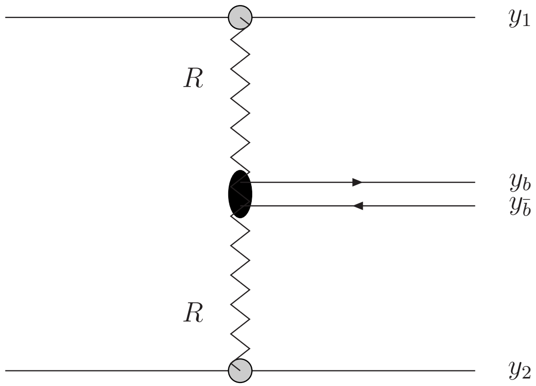
E. A. Kuraev, L. N. Lipatov, and V. S. Fadin, **1975**
I. I. Balitsky and L. N. Lipatov, **1978**

$b\bar{b}-$jet production in the multi-Regge kinematics



$$\mathcal{A}^{MRK} \sim \Gamma^{R}_{PP} \times \left(\frac{s_1}{t_1}\right)^{\omega_R(t_1)} \times \Gamma^{b}_{RQ} \times \left(\frac{s}{t}\right)^{\omega_Q(t)} \times \Gamma^{\bar{b}}_{QR} \times \left(\frac{s_2}{t_2}\right)^{\omega_R(t_2)} \times \Gamma^{R}_{PP}$$

$b\bar{b}$–jet production in the quasi-multi-Regge kinematics

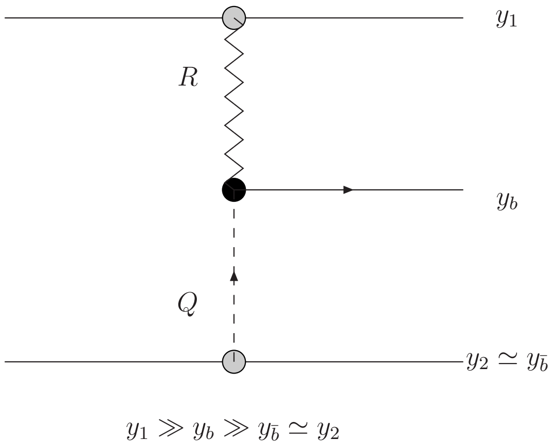


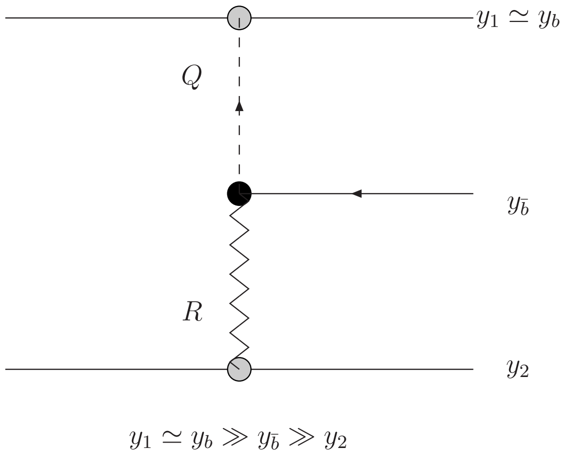
$y_1 \gg y_b \simeq y_{\bar{b}} \gg y_2$

$$\mathcal{A}^{QMRK} \sim \Gamma^R_{PP} \times \left(\frac{s_1}{t_1}\right)^{\omega_R(s_1)} \times \Gamma^{b\bar{b}}_{RR} \times \left(\frac{s_2}{t_2}\right)^{\omega_R(t_2)} \times \Gamma^R_{PP}$$

$$\sigma(PP \to b\bar{b}X) = \Phi_R \otimes \hat{\sigma}(RR \to b\bar{b}) \otimes \Phi_R$$

$b-$jet production in the multi-Regge kinematics





$$\mathcal{A}^{QMRK} \sim \Gamma^{Q}_{PP} \times \left(\frac{s_1}{t_1}\right)^{\omega_R(t_1)} \times \Gamma^{b}_{QR} \times \left(\frac{s_2}{t_2}\right)^{\omega_Q(t_2)} \times \Gamma^{R}_{PP}$$

$$\sigma(PP \to bX) = \Phi_Q \otimes \hat{\sigma}(Q_b R \to b) \otimes \Phi_R$$

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

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

$$q_1 = x_1 P_1 + q_{1T}, \qquad q_2 = x_2 P_2 + q_{2T}, \qquad t_1 = -q_1^2 = -q_{1T}^2, \qquad t_2 = -q_2^2 = -q_{2T}^2$$

Vertex functions:

$$g(k) + Q(q) \to q(k+q): \qquad \gamma_\mu^{\pm}(q,k) = \gamma_\mu + \hat{q}\frac{n^{\pm}}{k^{\pm}},$$

$$Q(q_1) + \bar{Q}(q_2) \to g(q_1+q_2): \qquad \gamma_\mu^{+-}(q_1,q_2) = \gamma_\mu - \frac{\hat{q}_1 n_\mu^-}{q_2^-} - \frac{\hat{q}_2 n_\mu^+}{q_1^+}$$

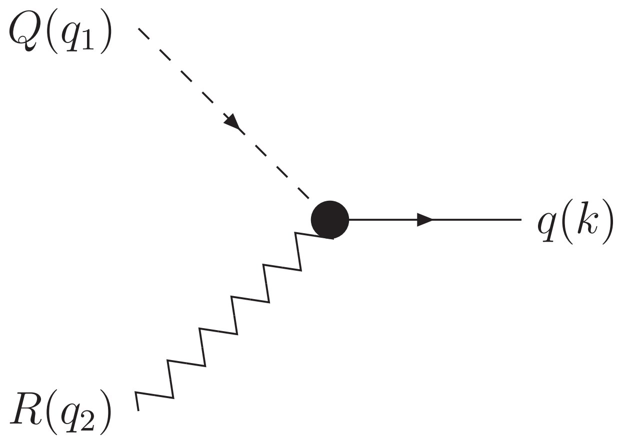
Effective vertices in the QMRK approach

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**

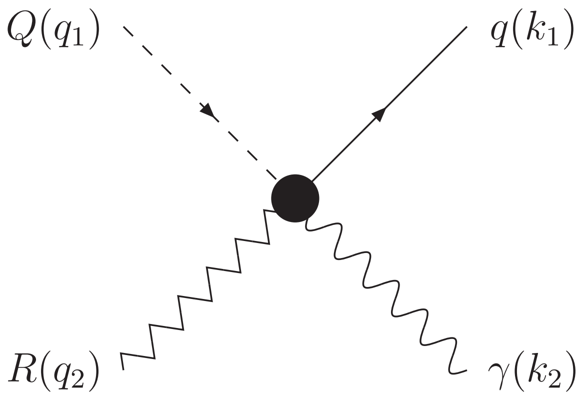
Feynman rules for the effective theory:

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



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

$$\Pi_T^{(+)\mu}(q_2)=\frac{q_{2T}^\mu}{|\vec{q}_{2T}|},\qquad \Pi_T^{(+)\mu}(q_2)=-\frac{x_2E_2(n^+)^\mu}{|\vec{q}_{2T}|}.$$



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

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

$$\overline{|\mathcal{M}(Q_b R \to b)|^2} = \frac{2}{3}\pi\alpha_s \vec{k}_T^2.$$

We have $\vec{k}_T^2 = \vec{q}_{1T}^2 + \vec{q}_{2T}^2 + 2|\vec{q}_{1T}||\vec{q}_{2T}|\cos\phi_{12}$, where $\vec{q}_{1T}$ and $\vec{q}_{2T}$ are the transverse momenta of the Reggeized quark and gluon, respectively, and ϕ_{12} is the azimuthal angle enclosed between them.

$$\overline{|\mathcal{M}(R+R\to b+\bar{b})|^2}=256\pi^2\alpha_s^2\left[\frac{1}{2N_c}\mathcal{M}_{\rm A}+\frac{N_c}{2(N_c^2-1)}\mathcal{M}_{\rm NA}\right],$$

where

$$\begin{aligned}
\mathcal{M}_{\rm A} &= \frac{t_1t_2}{\tilde{t}\tilde{u}}-\left(1+\frac{\alpha_1\beta_2 S}{\tilde{u}}+\frac{\alpha_2\beta_1 S}{\tilde{t}}\right)^2,\\
\mathcal{M}_{\rm NA} &= \frac{2}{S^2}\left(\frac{\alpha_1\beta_2 S^2}{\tilde{u}}+\frac{S}{2}+\frac{\Delta}{\hat{s}}\right)\left(\frac{\alpha_2\beta_1 S^2}{\tilde{t}}+\frac{S}{2}-\frac{\Delta}{\hat{s}}\right)\\
&\quad -\frac{t_1t_2}{x_1x_2\hat{s}}\left[\left(\frac{1}{\tilde{t}}-\frac{1}{\tilde{u}}\right)(\alpha_1\beta_2-\alpha_2\beta_1)+\frac{x_1x_2\hat{s}}{\tilde{t}\tilde{u}}-\frac{2}{S}\right],\\
\Delta &= \frac{S}{2}\left[\tilde{u}-\tilde{t}+2S(\alpha_1\beta_2-\alpha_2\beta_1)+t_1\frac{\beta_1-\beta_2}{\beta_1+\beta_2}-t_2\frac{\alpha_1-\alpha_2}{\alpha_1+\alpha_2}\right],
\end{aligned}$$

$\tilde{t}=\hat{t}-m^2$, $\tilde{u}=\hat{u}-m^2$, $t_1=-q_1^2$, $t_2=-q_2^2$, $\alpha_1=2(k_1\cdot P_2)/S$, $\alpha_2=2(k_2\cdot P_2)/S$, $\beta_1=2(k_1\cdot P_1)/S$, and $\beta_2=2(k_2\cdot P_1)/S$. Here, the Mandelstam variables are defined as $\hat{s}=(q_1+q_2)^2$, $\hat{t}=(q_1-k_1)^2$, $\hat{u}=(q_2-k_1)^2$, $S=(P_1+P_2)^2$.

$$\overline{|M(QR \to q\gamma)|^2} = -\frac{16}{3}\pi^2\alpha\alpha_s e_q^2 \frac{x_1 S}{b_2 \hat{s}\hat{u} t_2}\Big(w_0 + w_1 S + w_2 S^2\Big),$$

$$w_0 = b_1^2 t_2(t_1 - \hat{u}) - b_1 b_2(t_2\hat{t} + 2t_2\hat{u} + \hat{t}\hat{u}) - b_2^2\big(t_1 t_2 + t_2(\hat{t} + \hat{u}) + t_1\hat{u} + \hat{u}\hat{t}\big),$$

$$w_1 = -b_2 x_2\Big[2a_1 b_2(t_1 + \hat{t}) + a_1 b_1(t_2 + \hat{t}) + a_2 b_1(t_2 + \hat{u})\Big],$$

$$w_2 = a_1 b_2 x_2^2\Big[a_1 b_2\Big(1 + \frac{\hat{s}}{\hat{u}}\Big) - a_2 b_1\Big],$$

$$\overline{|M(Q\bar{Q} \to g\gamma)|^2} = -\frac{128}{9S}\pi^2\alpha\alpha_s e_q^2 \frac{x_1 x_2}{a_1 a_2 b_1 b_2 \hat{t}\hat{u}}\Big(w_0 + w_1 S + w_2 S^2 + w_3 S^3\Big),$$

$$\begin{aligned}
w_0 &= -t_1 t_2(t_1 + t_2) + \hat{t}\hat{u}(\hat{t} + \hat{u}),\\
w_1 &= x_2 t_1(a_1\hat{t} + a_2\hat{u}) + x_1 t_2(b_2\hat{t} + b_1\hat{u}) + t_1 t_2(a_1 - a_2)(b_1 - b_2) + \hat{t}\hat{u}(2a_1 b_2 + x_1 b_1 + x_2 a_2)\\
w_2 &= x_2^2 a_1 a_2 t_1 + x_1^2 b_1 b_2 t_2 + a_1 b_2 \hat{t}(x_2 a_1 + a_2 b_2) + a_2 b_1 \hat{u}(x_1 b_1 + a_2 b_2),\\
w_3 &= a_1 a_2 b_1 b_2\left[\frac{a_1 b_2 \hat{t}}{\hat{u}} + \frac{a_2 b_1 \hat{u}}{\hat{t}}\right].
\end{aligned}$$

$$\overline{|\mathcal{M}(Q_r\bar{Q}_r \to q_f\bar{q}_f)|^2} = -\frac{64\pi^2\alpha_s^2}{9x_1x_2\hat{s}^2}\left(w_0 + w_1 S + w_2 S^2\right),$$

$$\begin{aligned}
w_0 &= x_1x_2\hat{s}\left(\tilde{t} + \tilde{u}\right), \\
w_1 &= -2x_2^2\alpha_1\alpha_2 t_2 - 2x_1^2\beta_1\beta_2 t_1 + x_1x_2\{(\alpha_1\beta_2 + \alpha_2\beta_1)(\hat{s} + t_1 + t_2) + x_1x_2(\hat{s} - 2m^2) + \\
&\quad + x_1[\beta_1(t_1 + \tilde{u}) + \beta_2(t_1 + \tilde{t})] + x_2[\alpha_1(t_2 + \tilde{t}) + \alpha_2(t_2 + \tilde{u})]\}, \\
w_2 &= -2x_1x_2(\alpha_1\beta_2 - \alpha_2\beta_1)^2.
\end{aligned}$$

$$\overline{|\mathcal{M}(Q_r\bar{Q}_r \to q_r\bar{q}_r)|^2} = \frac{64\pi^2\alpha_s^2}{27x_1x_2a_2b_1\hat{s}^2\hat{t}^2}(w_0 + w_1 S + w_2 S^2)$$

$$\begin{aligned}
w_0 &= x_1x_2\hat{s}\hat{t}\Big[t_1\hat{t}(3a_2b_1 - x_1b_2) + t_2\hat{t}(3a_2b_1 - x_2a_1) + t_1t_2(x_2a_2 - x_1b_2) - x_1x_2\hat{t}^2 + \\
&+ \hat{s}\hat{t}\big(6(a_1b_1 + a_2b_2) + 5(2a_2b_1 + a_1b_2)\big)\Big] \\
w_1 &= \hat{t}\Big[t_1x_1a_2b_2\big(6b_1\hat{t}(a_2b_1 - a_1b_2) - x_2\hat{s}(x_1b_1 + a_2b_1 - a_1b_2)\big) + \\
&+ t_2x_2a_1b_1\big(6a_2\hat{t}(a_2b_1 - a_1b_2) - x_1\hat{s}(x_2a_2 + a_2b_1 - a_1b_2)\big) + \\
&+ 6x_1x_2a_2b_1(a_2b_1 - a_1b_2)\hat{t}^2 + x_1x_2a_2b_1\hat{s}^2(a_2b_1 - a_1b_2 + 6x_1x_2) + \\
&+ x_1x_2\hat{s}\hat{t}\big((a_1b_2 - a_2b_1)^2 + a_1b_2(a_1b_1 + a_2b_2) - 2a_2b_1(2a_2b_1 + x_1b_2 + x_2a_1)\big)\Big] \\
w_2 &= x_1x_2a_2b_1\Big[6\hat{t}^2(a_2b_1 - a_1b_2)^2 + 3x_1x_2a_2b_1\hat{s}^2 + \hat{s}\hat{t}(x_1b_1 + x_2a_2)(a_1b_2 - a_2b_1)\Big]
\end{aligned}$$

High-energy factorization

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

$$d\hat{\sigma}(ij \to X) = \frac{1}{2x_1 x_2 S} \times \overline{|\mathcal{M}(ij \to X)|^2} \times d\Phi_X$$

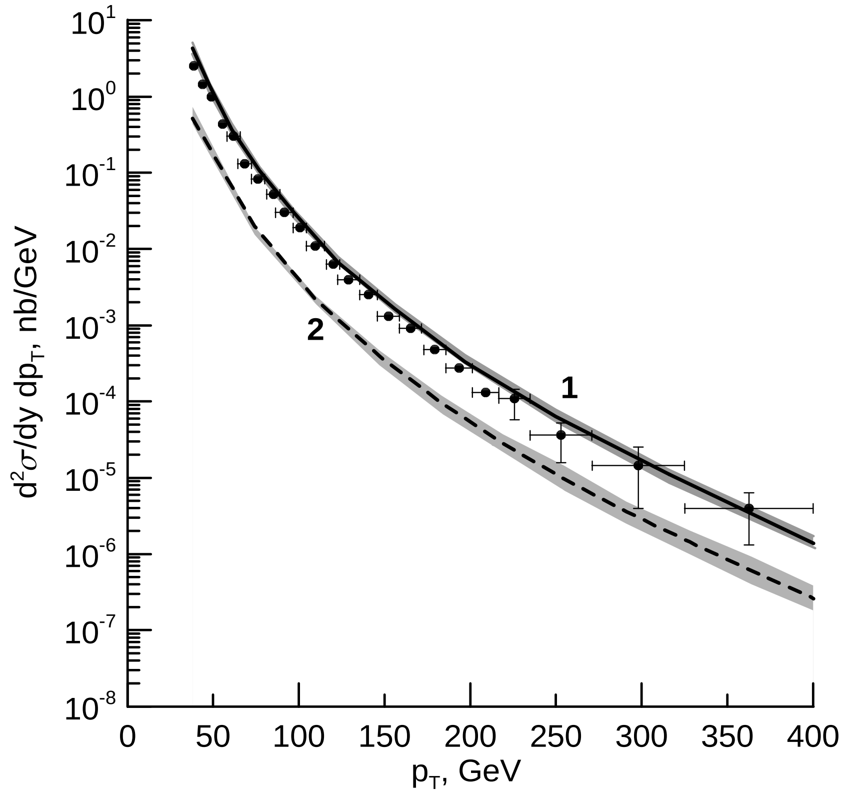
At the stage of numerical calculations we use the Kimber-Martin-Ryskin (KMR) prescription for unintegrated quark and gluon distribution functions $\Phi_{q,g}^{p,\bar{p}}(x, |\mathbf{q}_T|^2, \mu^2)$, with the Martin-Roberts-Stirling-Thorne (MRST) collinear densities as input.

Inclusive b–jet production at Tevatron

$$\sqrt{S} = 1.96\ \mathrm{GeV}, \qquad |y_b| < 0.7$$

$$R_{cone} = \sqrt{(y_b - y_{\bar{b}})^2 - (\phi_b - \phi_{\bar{b}})^2} > 0.4$$

CDF note 8418, 2006, URL: `http://www-cdf.fnal.gov/physics/new/qcd/QCD.html`



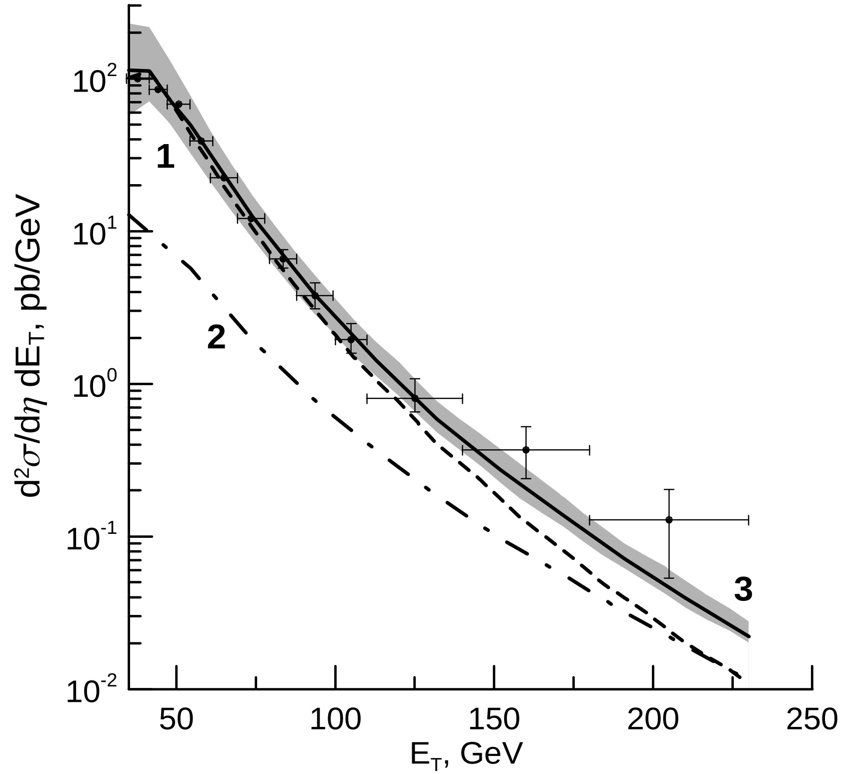
$$1 \text{ - } RQ_b \to b,\ 2 \text{ - } RR \to b\bar{b}$$

Associated $b\bar{b}$–jet production at Tevatron

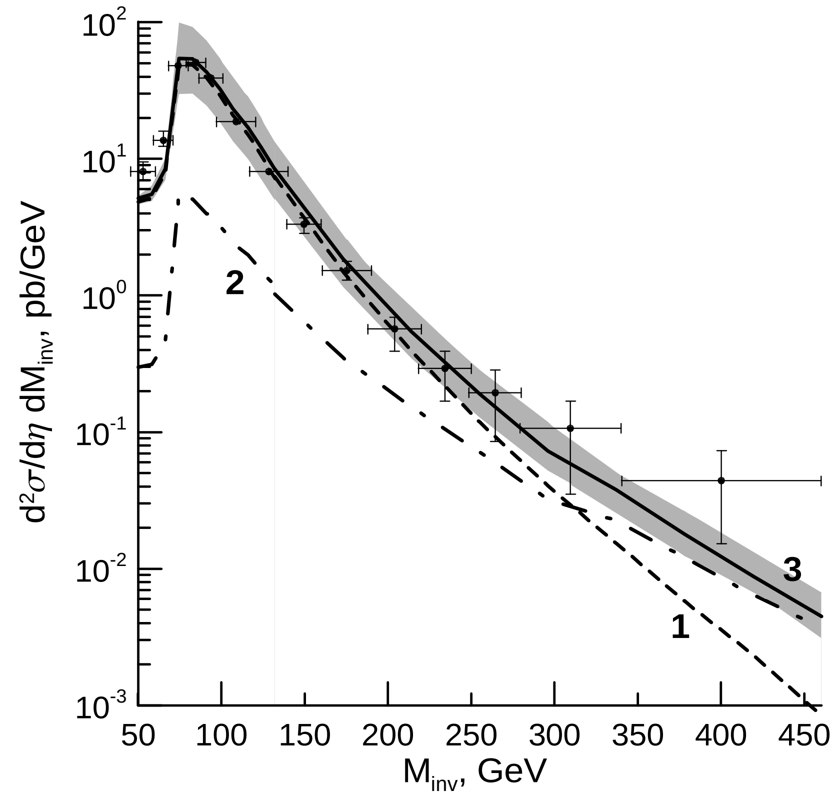
$$\sqrt{S} = 1.96 \text{ GeV}, \qquad |y_{b,\bar{b}}| < 1.2,\ E_{bT} > 35 \text{ GeV},\ E_{\bar{b}T} > 32 \text{ GeV},$$

$$R_{cone} = \sqrt{(y_b - y_{\bar{b}})^2 - (\phi_b - \phi_{\bar{b}})^2} > 0.4$$

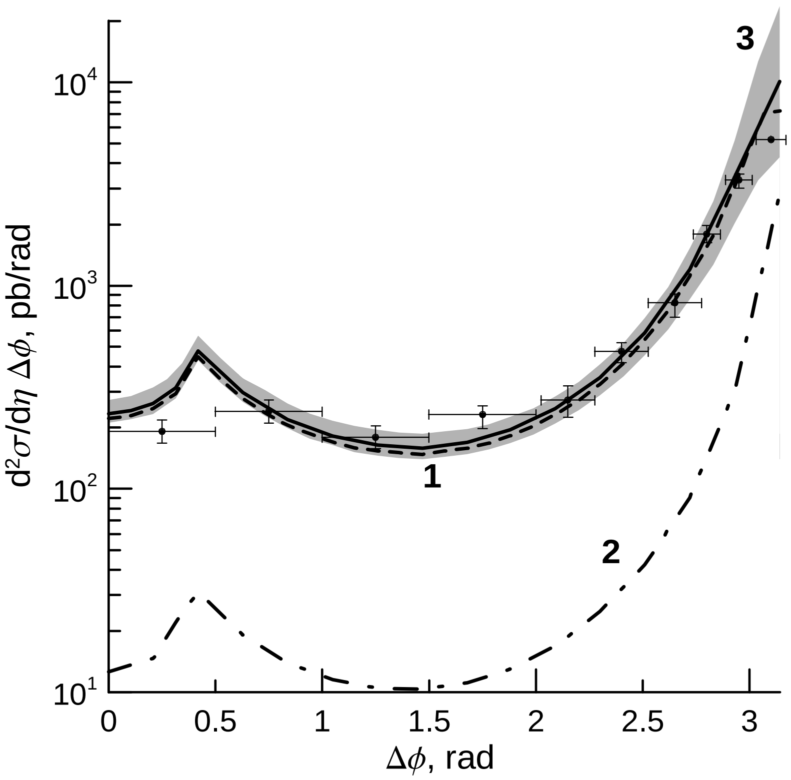
CDF note 8939, 2007, URL: `http://www-cdf.fnal.gov/physics/new/qcd/QCD.html`.



$$1 \text{ - } RR \to b\bar{b},\ 2 \text{ - } Q\bar{Q} \to b\bar{b},\ 3 \text{ - } 1{+}2$$



1 - $RR \to b\bar{b}$, 2 - $Q\bar{Q} \to b\bar{b}$, 3 - $1{+}2$



1 - $RR \to b\bar{b}$, 2 - $Q\bar{Q} \to b\bar{b}$, 3 - 1+2

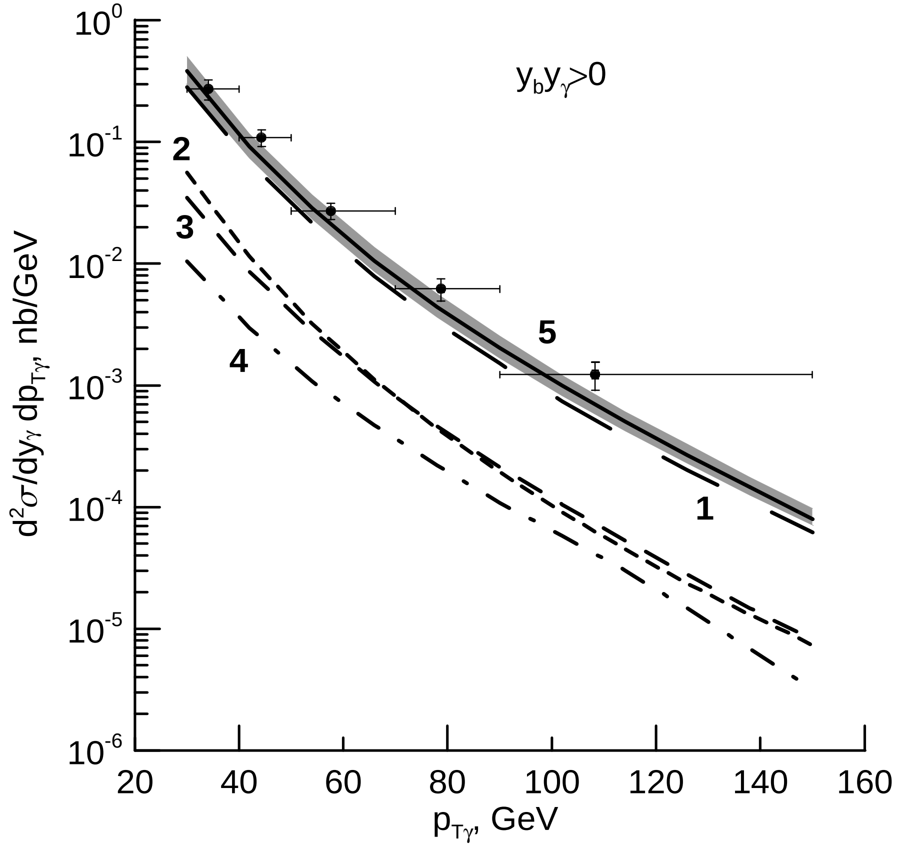
Associated $b + \gamma$ production at Tevatron

$$\sqrt{S} = 1.96 \text{ GeV}, \qquad |y_\gamma| < 1.0, \qquad |y_b| < 0.8,$$

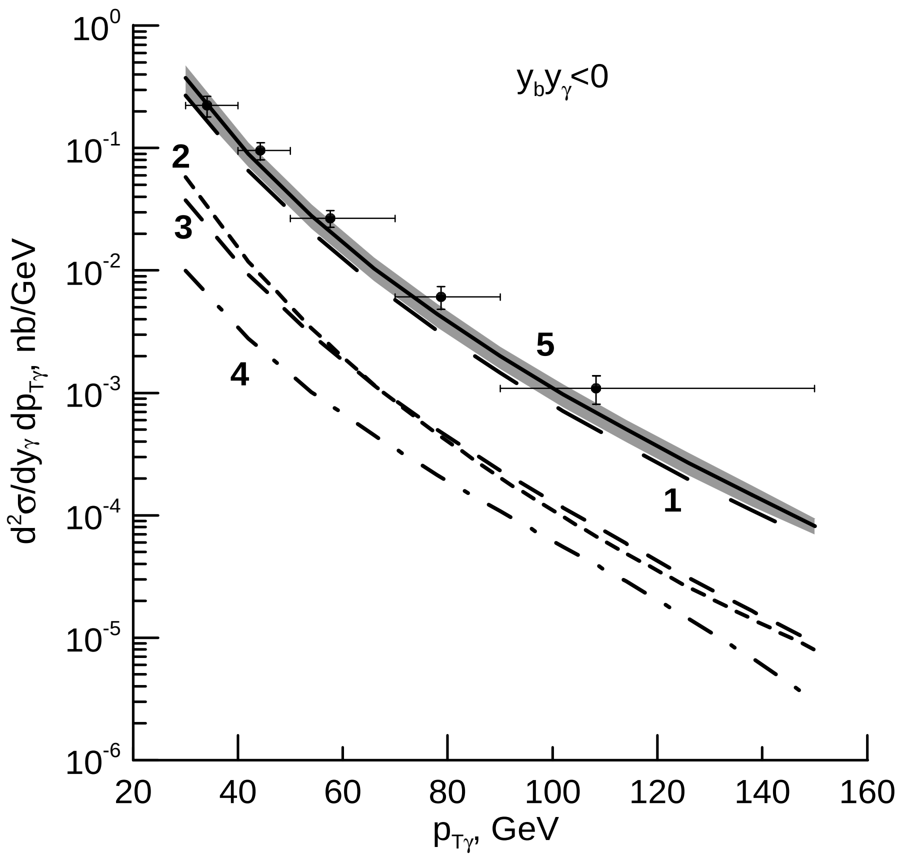
$$30 < E_{T\gamma} < 150 \text{ GeV}, \; E_{Tb} > 15 \text{ GeV},$$

$$R_{cone} = \sqrt{(y_b - y_\gamma)^2 - (\phi_b - \phi_\gamma)^2} > 0.7$$

D0 Collaboration, Phys. Rev. Lett. **102**, 192002 (2009).



1 - $RQ_b \to b\gamma$, 2 - $RR \to b\bar{b}(\gamma)$, 3 - $QQ_b \to bq(\gamma)$, 4 - $Q\bar{Q} \to b\bar{b}(\gamma)$, 5 - sum



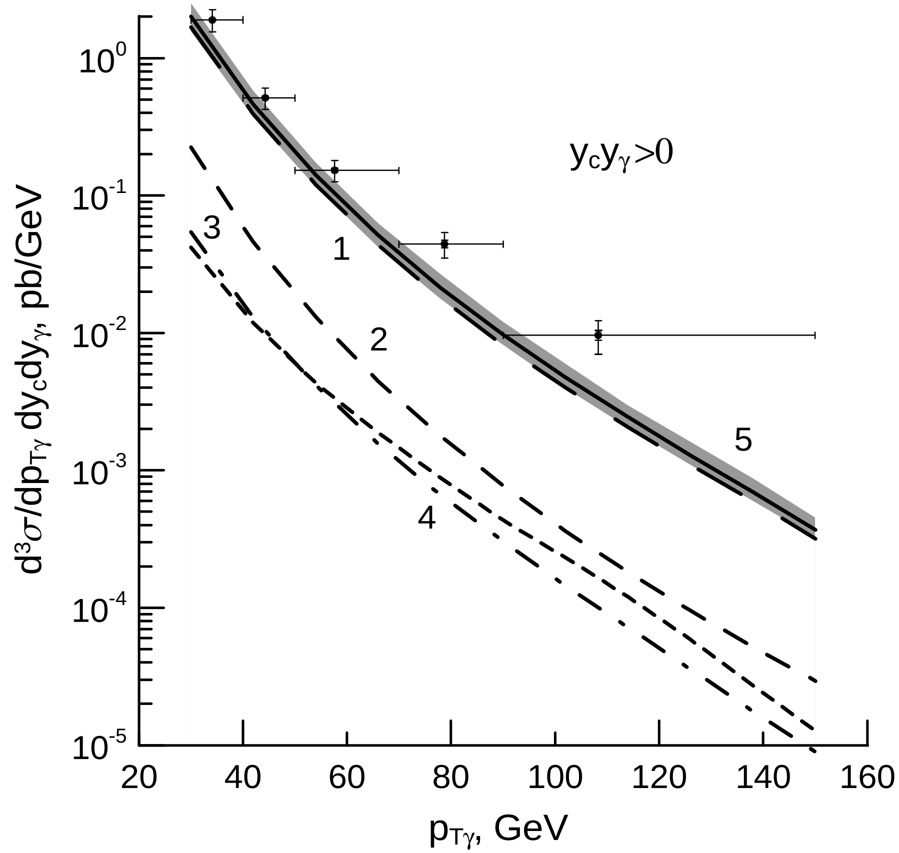
1 - $RQ_b \to b\gamma$, 2 - $RR \to b\bar{b}(\gamma)$, 3 - $QQ_b \to bq(\gamma)$, 4 - $Q\bar{Q} \to b\bar{b}(\gamma)$, 5 - sum

Associated $c + \gamma$ production at Tevatron

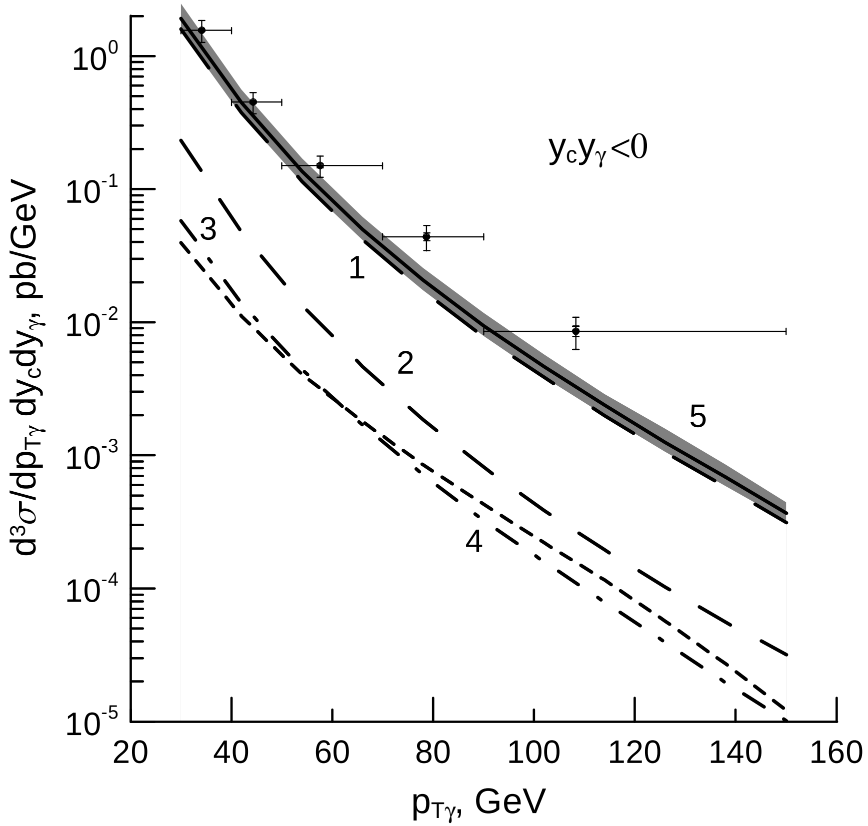
$$\sqrt{S} = 1.96 \text{ GeV}, \qquad |y_\gamma| < 1.0, \qquad |y_c| < 0.8,$$
$$30 < E_{T\gamma} < 150 \text{ GeV}, \; E_{Tc} > 15 \text{ GeV},$$

$$R_{cone} = \sqrt{(y_c - y_\gamma)^2 - (\phi_c - \phi_\gamma)^2} > 0.7$$

D0 Collaboration, Phys. Rev. Lett. **102**, 192002 (2009).



1 - $RQ_c \to c\gamma$, 2 - $RR \to c\bar{c}(\gamma)$, 3 - $QQ_c \to cq(\gamma)$, 4 - $Q\bar{Q} \to c\bar{c}(\gamma)$, 5 - sum



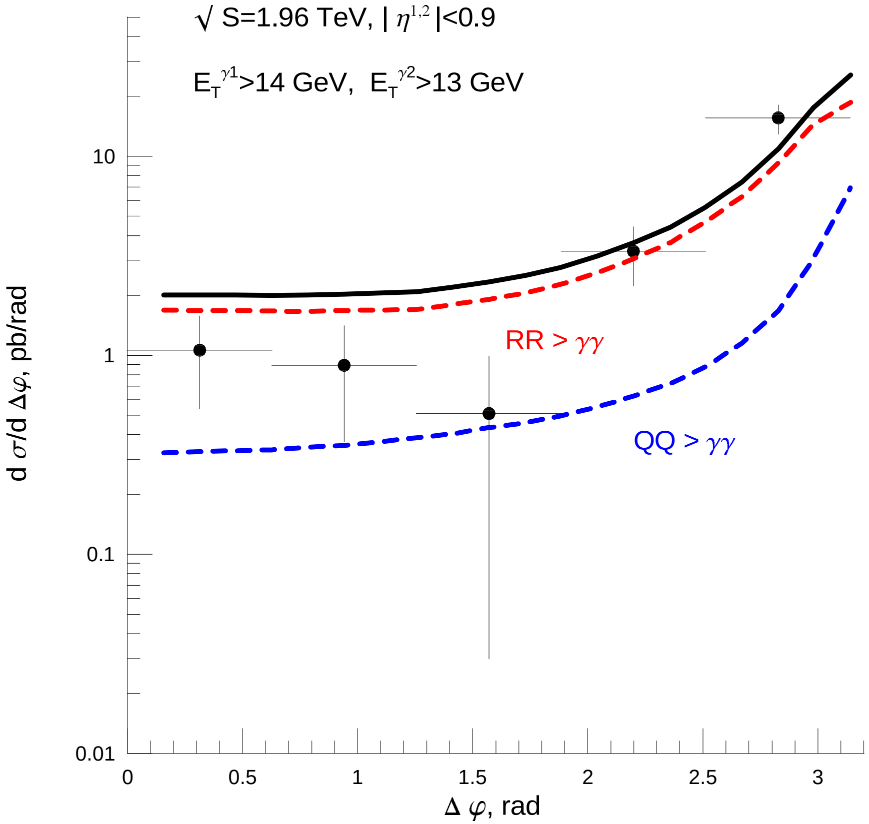
1 - $RQ_c \to c\gamma$, 2 - $RR \to c\bar{c}(\gamma)$, 3 - $QQ_c \to cq(\gamma)$, 4 - $Q\bar{Q} \to c\bar{c}(\gamma)$, 5 - sum

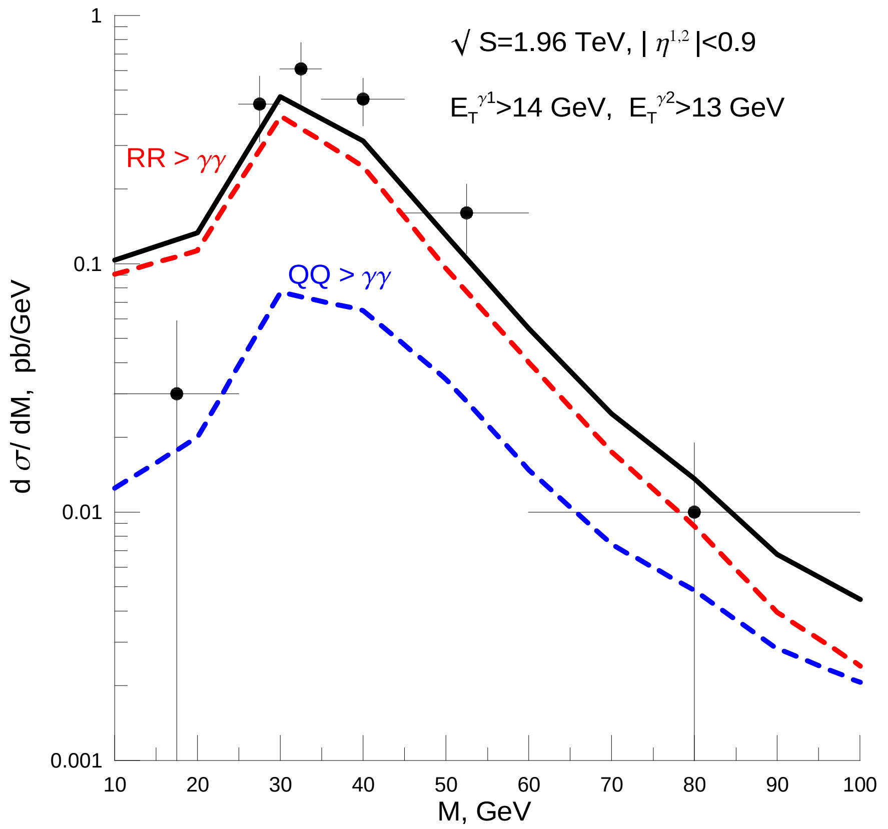
Associated $\gamma + \gamma$ production at Tevatron

$$\sqrt{S} = 1960 \text{ GeV}, \ |\eta^{\gamma}_{1,2}| < 0.9, \ k^{\gamma}_{1T} > 14 \text{ GeV and } k^{\gamma}_{2T} > 13 \text{ GeV}.$$

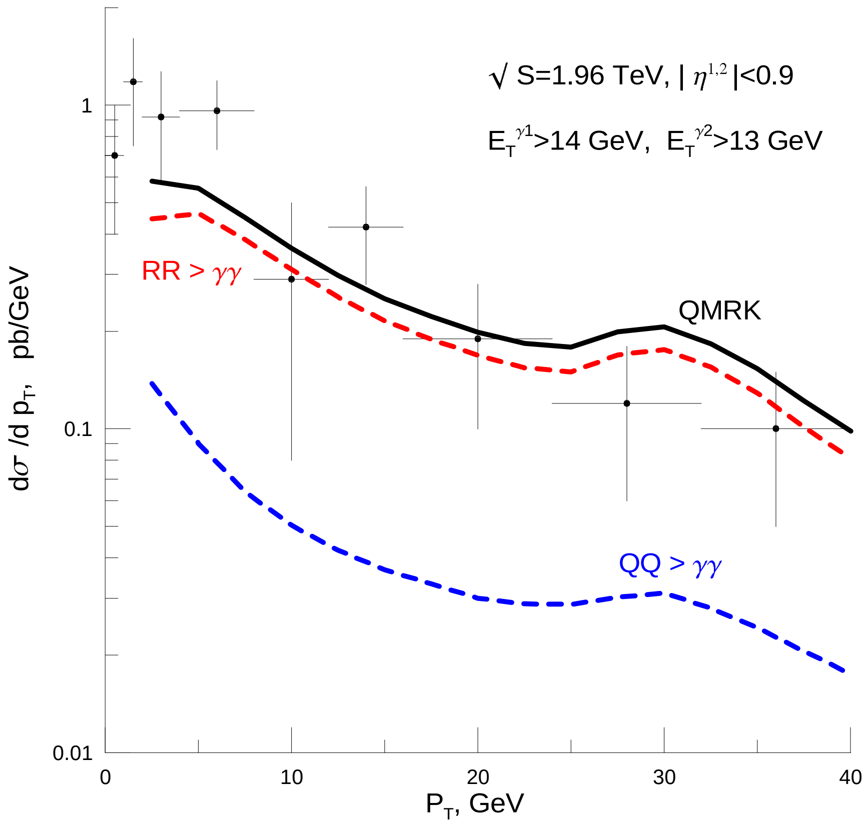
$$R_{cone} = \sqrt{(y^{\gamma}_1 - y^{\gamma}_2)^2 - (\phi^{\gamma}_1 - \phi^{\gamma}_2)^2} > 0.4$$

CDF Collaboration, D. Acosta et al. Phys. Rev. Lett. **95**, 022003 (2005).


√ 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/d Δφ, pb/rad
Δ φ, rad
10
1
0.1
0.01
0
0.5
1
1.5
2
2.5
3



√ S=1.96 TeV, | $\eta^{1,2}$ |<0.9
$E_T^{\gamma 1}$>14 GeV, $E_T^{\gamma 2}$>13 GeV
RR > $\gamma\gamma$
QQ > $\gamma\gamma$
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

Conclusions

1. Within the framework of LO QMRK approach, we have obtained good description for the inclusive production of single jets and dijets, containing heavy quarks and photons, in the central rapidity region at Tevatron, without any ad-hoc adjustments of input parameters.

2. The disagreement with the data at the large $p_T(E_T)$ or M_{inv} should be explain that the assumptions of our model don't work in this kinematical region $(x > 0.2)$

3. The QMRK approach is once again (*) proven to be a powerful tool for the theoretical description of QCD processes in the high-energy limit.

Recent relevant publications

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2. **Botomonium production:** B. A. Kniehl, V. A. Saleev and D. V. Vasin, Phys. Rev. D **74**, 014024 (2006) [arXiv:hep-ph/0607254];

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