

HEAVY QUARK JET PRODUCTION AT TEVATRON IN THE REGGE LIMIT OF QCD

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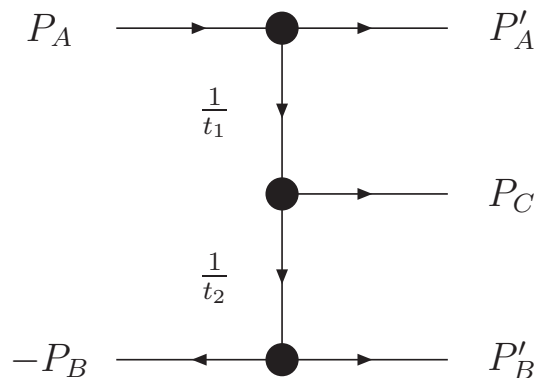
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Outlook

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

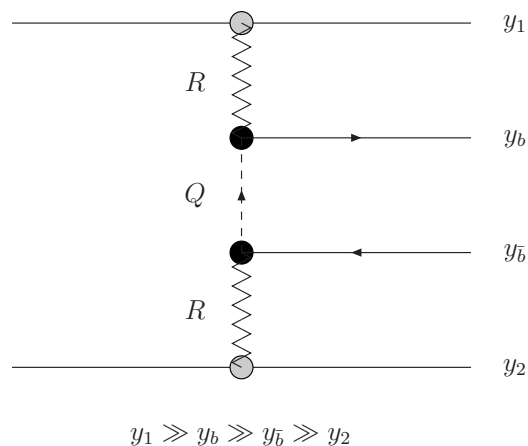
V. S. Fadin and V. E. Sherman, **1976**

Quon Reggeization in QCD:

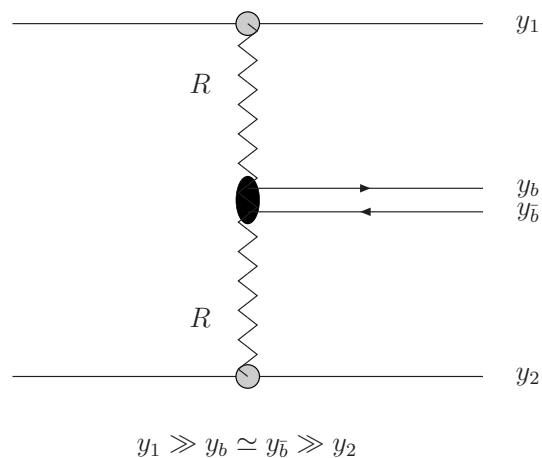
E. A. Kuraev, L. N. Lipatov, and V. S. Fadin, **1975**

I. I. Balitsky and L. N. Lipatov, **1978**

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



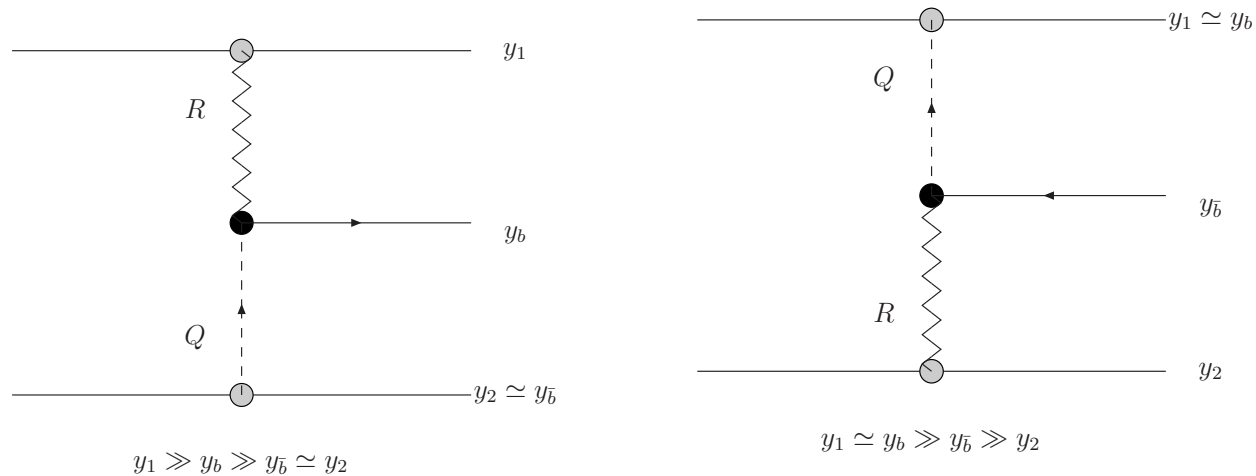
$$\mathcal{A}^{MRK} \sim \Gamma_{PP}^R \times \left(\frac{s_1}{t_1}\right)^{\omega_R(t_1)} \times \Gamma_{RQ}^b \times \left(\frac{s}{t}\right)^{\omega_Q(t)} \times \Gamma_{QR}^{\bar{b}} \times \left(\frac{s_2}{t_2}\right)^{\omega_R(t_2)} \times \Gamma_{PP}^R$$

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


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

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

b -jet production in the multi-Regge kinematics



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

$$\sigma(P P \rightarrow b X) = \Phi_Q \otimes \hat{\sigma}(Q_b R \rightarrow b) \otimes \Phi_R$$

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

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

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

Vertex functions:

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

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

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**

RR → *g*

$$C_{RR}^{g,\mu}(q_1, q_2) = -g_s f^{abc} \frac{q_1^+ q_2^-}{2\sqrt{t_1 t_2}} \left[(q_1 - q_2)^\mu + \frac{(n^+)^\mu}{q_1^+} (q_2^2 + q_1^+ q_2^-) - \frac{(n^-)^\mu}{q_2^-} (q_1^2 + q_1^+ q_2^-) \right]$$

Q \bar{Q} → γ

$$C_{Q\bar{Q}}^{\gamma,\mu}(q_1, q_2) = -ie e_q \left[\gamma^\mu - \hat{q}_1 \frac{(n^-)^\mu}{q_1^- + q_2^-} - \hat{q}_2 \frac{(n^+)^\mu}{q_1^+ + q_2^+} \right]$$

RQ → *q*

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

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

$RQ \rightarrow \gamma q$

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

$$\overline{|\mathcal{M}(RR \rightarrow g)|^2} = \frac{3}{2}\pi\alpha_s \vec{k}_T^2.$$

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

$$\overline{|\mathcal{M}(Q\bar{Q} \rightarrow \gamma)|^2} = \frac{4}{3}\pi\alpha e_q(\vec{q}_{1T}^2 + \vec{q}_{2T}^2).$$

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.

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

where

$$\begin{aligned} \mathcal{M}_A &= \frac{t_1 t_2}{\tilde{t}\tilde{u}} - \left(1 + \frac{\alpha_1 \beta_2 S}{\tilde{u}} + \frac{\alpha_2 \beta_1 S}{\tilde{t}} \right)^2, \\ \mathcal{M}_{NA} &= \frac{2}{S^2} \left(\frac{\alpha_1 \beta_2 S^2}{\tilde{u}} + \frac{S}{2} + \frac{\Delta}{\hat{s}} \right) \left(\frac{\alpha_2 \beta_1 S^2}{\tilde{t}} + \frac{S}{2} - \frac{\Delta}{\hat{s}} \right) \\ &\quad - \frac{t_1 t_2}{x_1 x_2 \hat{s}} \left[\left(\frac{1}{\tilde{t}} - \frac{1}{\tilde{u}} \right) (\alpha_1 \beta_2 - \alpha_2 \beta_1) + \frac{x_1 x_2 \hat{s}}{\tilde{t}\tilde{u}} - \frac{2}{S} \right], \\ \Delta &= \frac{S}{2} \left[\tilde{u} - \tilde{t} + 2S(\alpha_1 \beta_2 - \alpha_2 \beta_1) + t_1 \frac{\beta_1 - \beta_2}{\beta_1 + \beta_2} - t_2 \frac{\alpha_1 - \alpha_2}{\alpha_1 + \alpha_2} \right], \end{aligned}$$

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

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

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

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

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

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

$$w_0 = -t_1 t_2 (t_1 + t_2) + \hat{t} \hat{u} (\hat{t} + \hat{u}),$$

$$w_1 = x_2 t_1 (a_1 \hat{t} + a_2 \hat{u}) + x_1 t_2 (b_2 \hat{t} + b_1 \hat{u}) + t_1 t_2 (a_1 - a_2)(b_1 - b_2) + \hat{t} \hat{u} (2a_1 b_2 + x_1 b_1 + x_2 a_2)$$

$$w_2 = x_2^2 a_1 a_2 t_1 + x_1^2 b_1 b_2 t_2 + a_1 b_2 \hat{t} (x_2 a_1 + a_2 b_2) + a_2 b_1 \hat{u} (x_1 b_1 + a_2 b_2),$$

$$w_3 = a_1 a_2 b_1 b_2 \left[\frac{a_1 b_2 \hat{t}}{\hat{u}} + \frac{a_2 b_1 \hat{u}}{\hat{t}} \right].$$

$$\overline{|\mathcal{M}(Q_r \bar{Q}_r \rightarrow q_f \bar{q}_f)|^2} = -\frac{64\pi^2 \alpha_s^2}{9x_1 x_2 \hat{s}^2} (w_0 + w_1 S + w_2 S^2),$$

$$w_0 = x_1 x_2 \hat{s} (\tilde{t} + \tilde{u}),$$

$$w_1 = -2x_2^2 \alpha_1 \alpha_2 t_2 - 2x_1^2 \beta_1 \beta_2 t_1 + x_1 x_2 \{(\alpha_1 \beta_2 + \alpha_2 \beta_1)(\hat{s} + t_1 + t_2) + x_1 x_2 (\hat{s} - 2m^2) + x_1 [\beta_1(t_1 + \tilde{u}) + \beta_2(t_1 + \tilde{t})] + x_2 [\alpha_1(t_2 + \tilde{t}) + \alpha_2(t_2 + \tilde{u})]\},$$

$$w_2 = -2x_1 x_2 (\alpha_1 \beta_2 - \alpha_2 \beta_1)^2.$$

$$\overline{|\mathcal{M}(Q_r \bar{Q}_r \rightarrow q_r \bar{q}_r)|^2} = \frac{64\pi^2 \alpha_s^2}{27x_1 x_2 a_2 b_1 \hat{s}^2 \hat{t}^2} (w_0 + w_1 S + w_2 S^2)$$

$$w_0 = x_1 x_2 \hat{s} \hat{t} \left[t_1 \hat{t} (3a_2 b_1 - x_1 b_2) + t_2 \hat{t} (3a_2 b_1 - x_2 a_1) + t_1 t_2 (x_2 a_2 - x_1 b_2) - x_1 x_2 \hat{t}^2 + \right. \\ \left. + \hat{s} \hat{t} (6(a_1 b_1 + a_2 b_2) + 5(2a_2 b_1 + a_1 b_2)) \right]$$

$$w_1 = \hat{t} \left[t_1 x_1 a_2 b_2 (6b_1 \hat{t} (a_2 b_1 - a_1 b_2) - x_2 \hat{s} (x_1 b_1 + a_2 b_1 - a_1 b_2)) + \right. \\ \left. + t_2 x_2 a_1 b_1 (6a_2 \hat{t} (a_2 b_1 - a_1 b_2) - x_1 \hat{s} (x_2 a_2 + a_2 b_1 - a_1 b_2)) + \right. \\ \left. + 6x_1 x_2 a_2 b_1 (a_2 b_1 - a_1 b_2) \hat{t}^2 + x_1 x_2 a_2 b_1 \hat{s}^2 (a_2 b_1 - a_1 b_2 + 6x_1 x_2) + \right. \\ \left. + x_1 x_2 \hat{s} \hat{t} ((a_1 b_2 - a_2 b_1)^2 + a_1 b_2 (a_1 b_1 + a_2 b_2) - 2a_2 b_1 (2a_2 b_1 + x_1 b_2 + x_2 a_1)) \right]$$

$$w_2 = x_1 x_2 a_2 b_1 \left[6\hat{t}^2 (a_2 b_1 - a_1 b_2)^2 + 3x_1 x_2 a_2 b_1 \hat{s}^2 + \hat{s} \hat{t} (x_1 b_1 + x_2 a_2) (a_1 b_2 - a_2 b_1) \right]$$

High-energy factorization

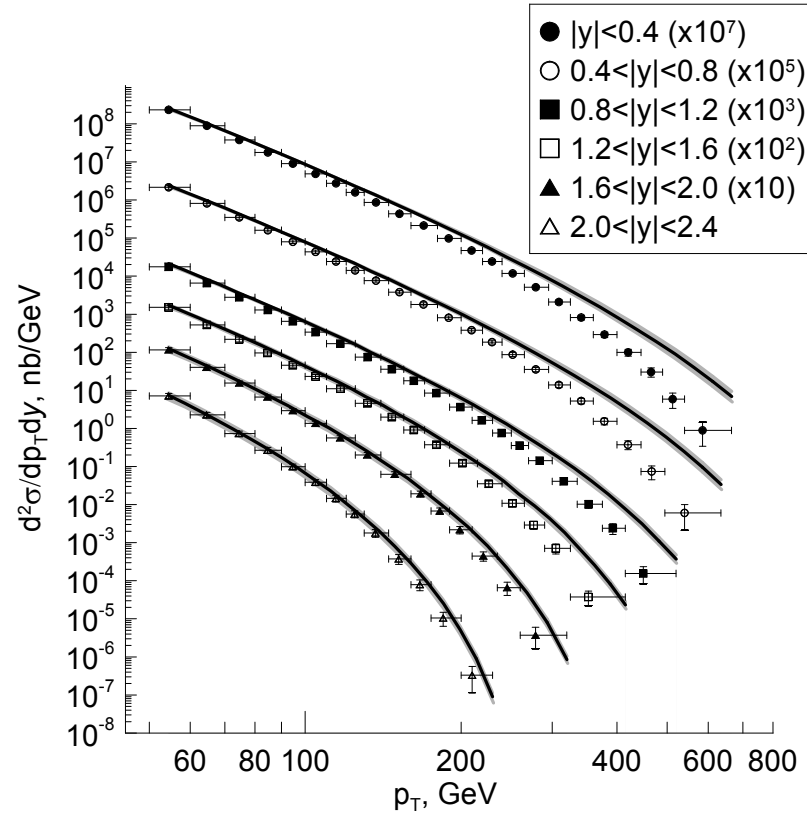
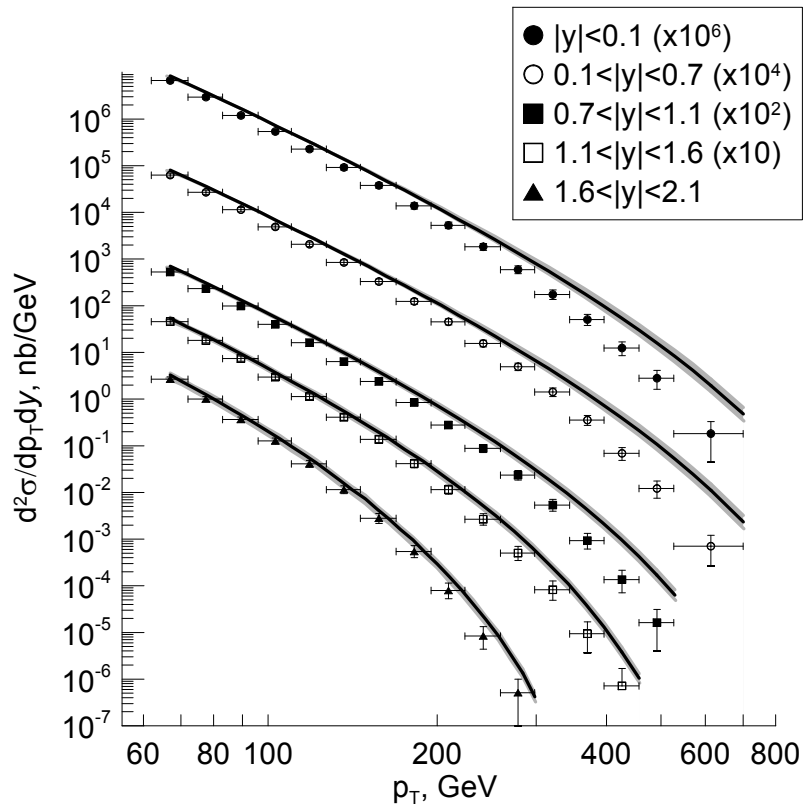
$$d\sigma(p\bar{p} \rightarrow X) = \sum_{i,j} \int \frac{dx_1}{x_1} \int \frac{d^2q_{1T}}{\pi} \int \frac{dx_2}{x_2} \int \frac{d^2q_{2T}}{\pi} \Phi_i^p(x_1, t_1, \mu^2) \Phi_j^{\bar{p}}(x_2, t_2, \mu^2) d\hat{\sigma}(ij \rightarrow X)$$

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

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.

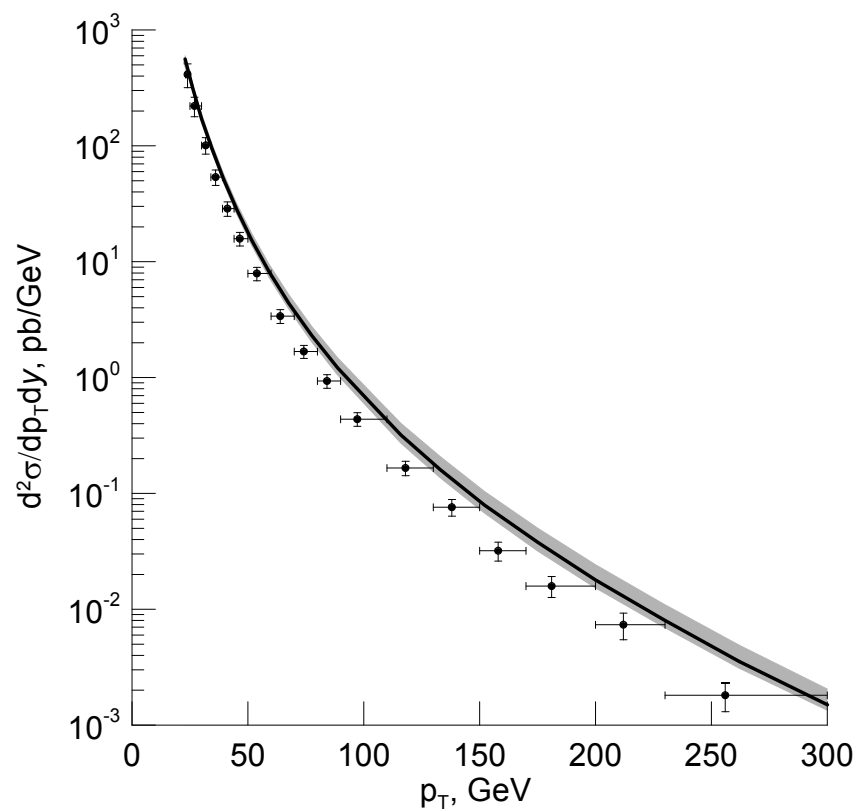
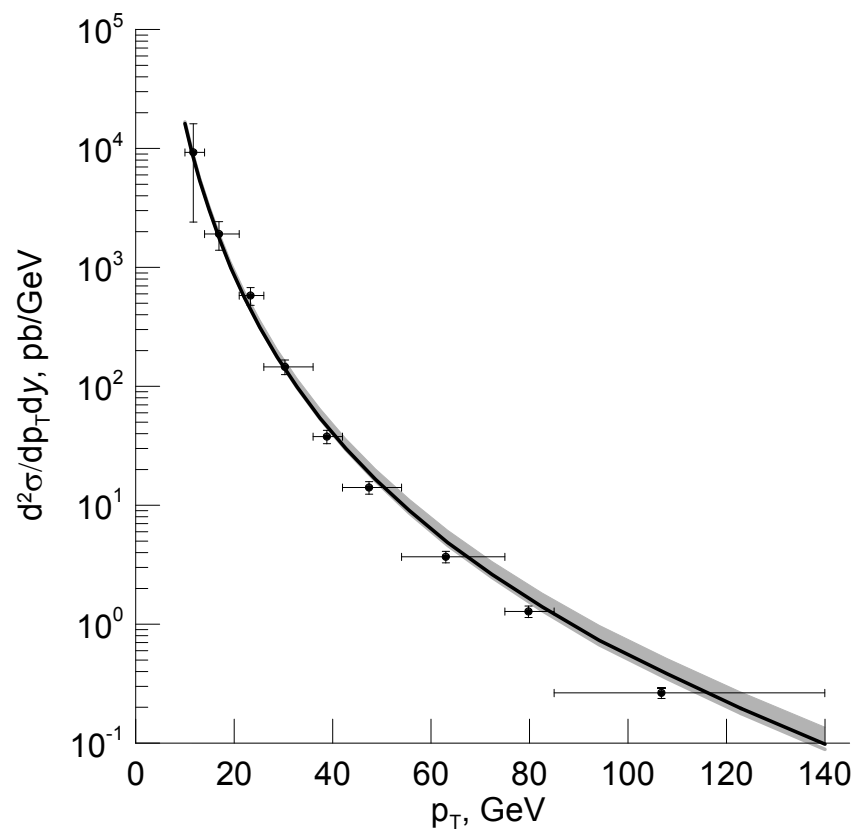
Inclusive jet production at Tevatron, CDF and D0

$$R + R \rightarrow g$$



Inclusive prompt photon production at Tevatron,
 $\sqrt{S} = 1.8 \text{ TeV}$ and $\sqrt{S} = 1.96 \text{ TeV}$, $|y| < 0.9$, D0

$$Q + \bar{Q} \rightarrow \gamma$$



Inclusive b -jet production at Tevatron

$$\sqrt{S} = 1.96 \text{ GeV}, \quad |y_b| < 0.7$$

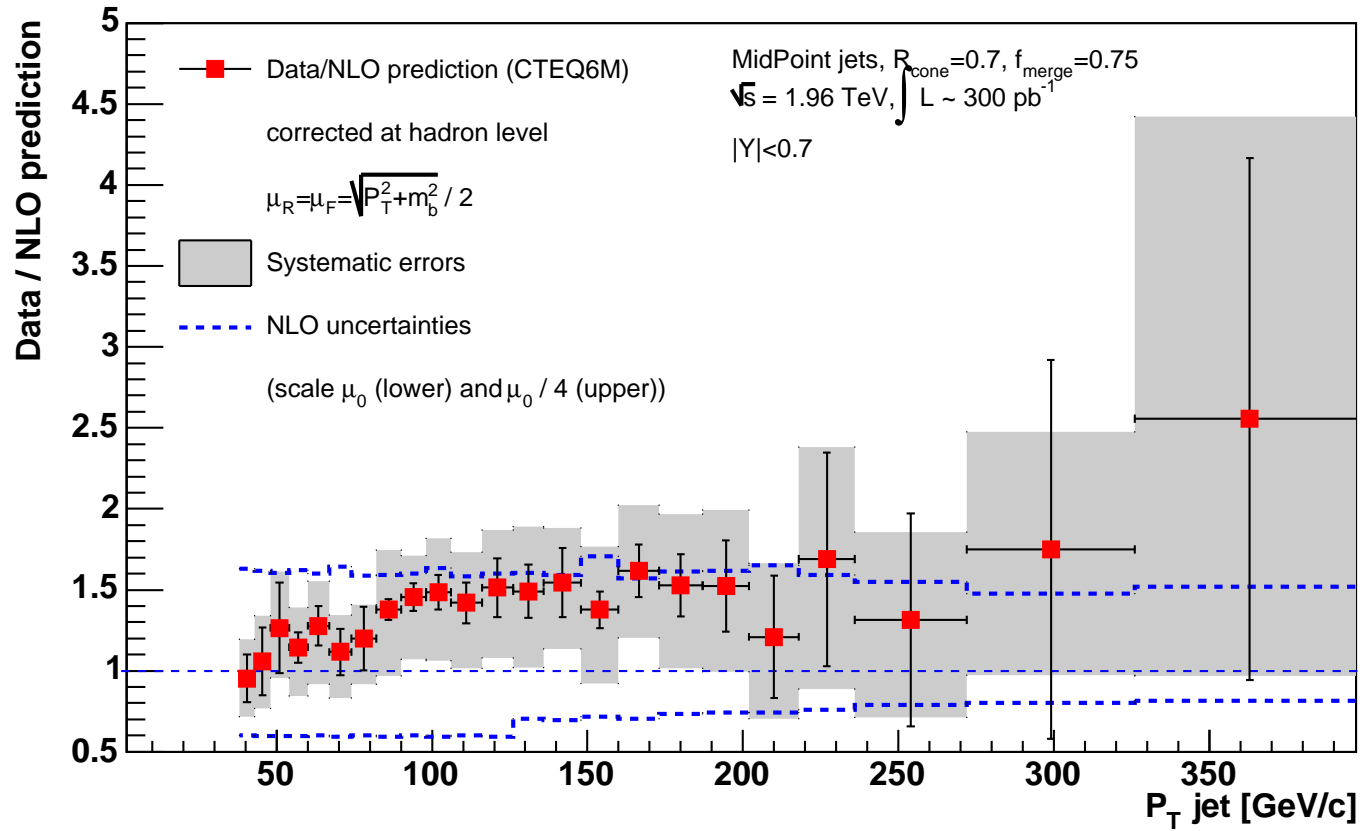
$$R_{cone} = \sqrt{(y_b - y_{\bar{b}})^2 - (\phi_b - \phi_{\bar{b}})^2} > 0.4$$

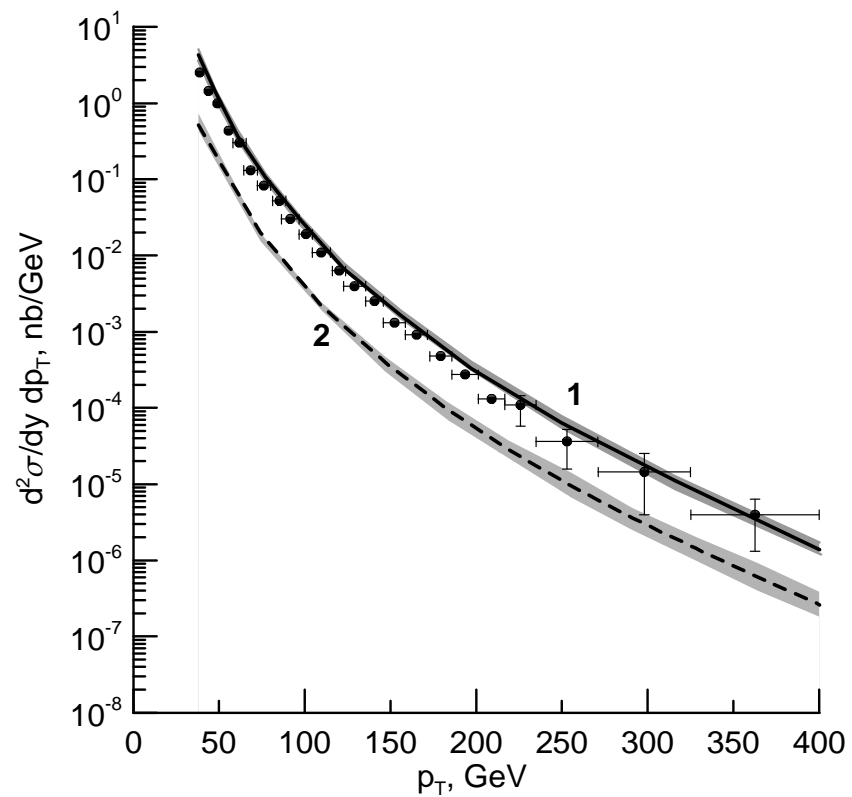
CDF note 8418, 2006, URL: <http://www-cdf.fnal.gov/physics/new/qcd/QCD.html>

Inclusive b -jet production

Ratio Data/NLO prediction

CDF RunII Preliminary





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

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

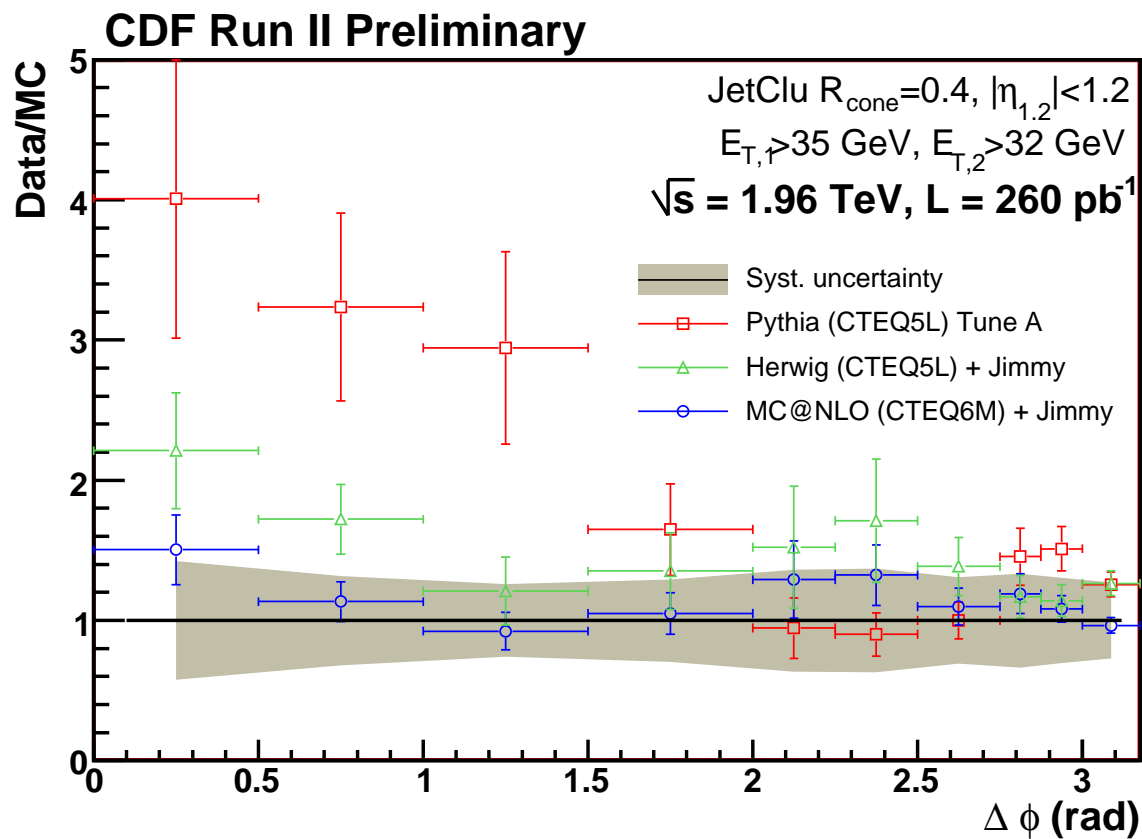
$$\sqrt{S} = 1.96 \text{ GeV}, \quad |y_{b,\bar{b}}| < 1.2, \quad E_{bT} > 35 \text{ GeV}, \quad E_{\bar{b}T} > 32 \text{ GeV},$$

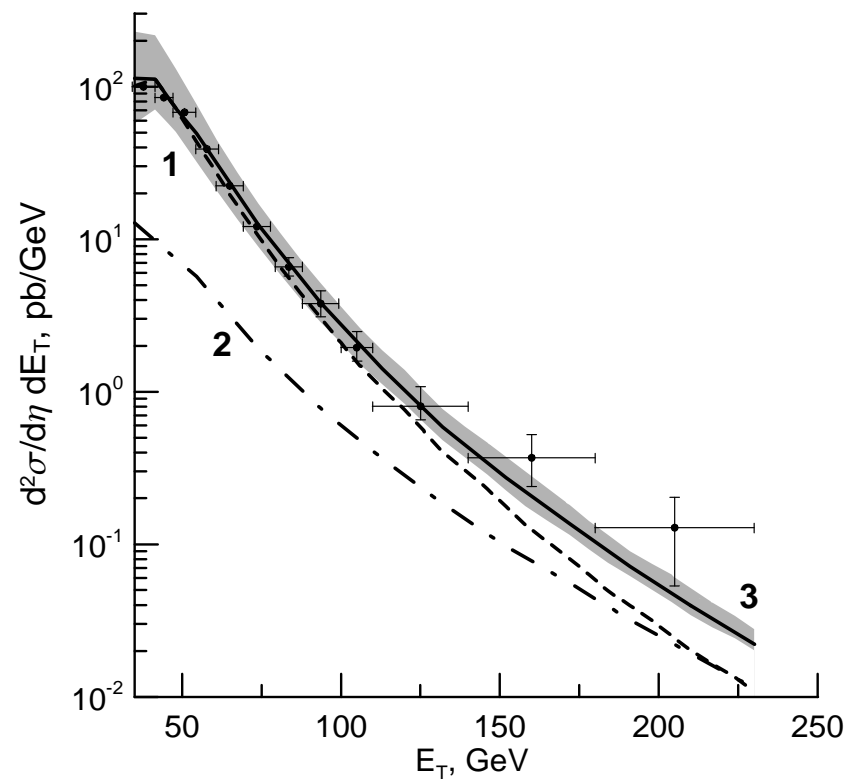
$$R_{cone} = \sqrt{(y_b - y_{\bar{b}})^2 - (\phi_b - \phi_{\bar{b}})^2} > 0.4$$

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

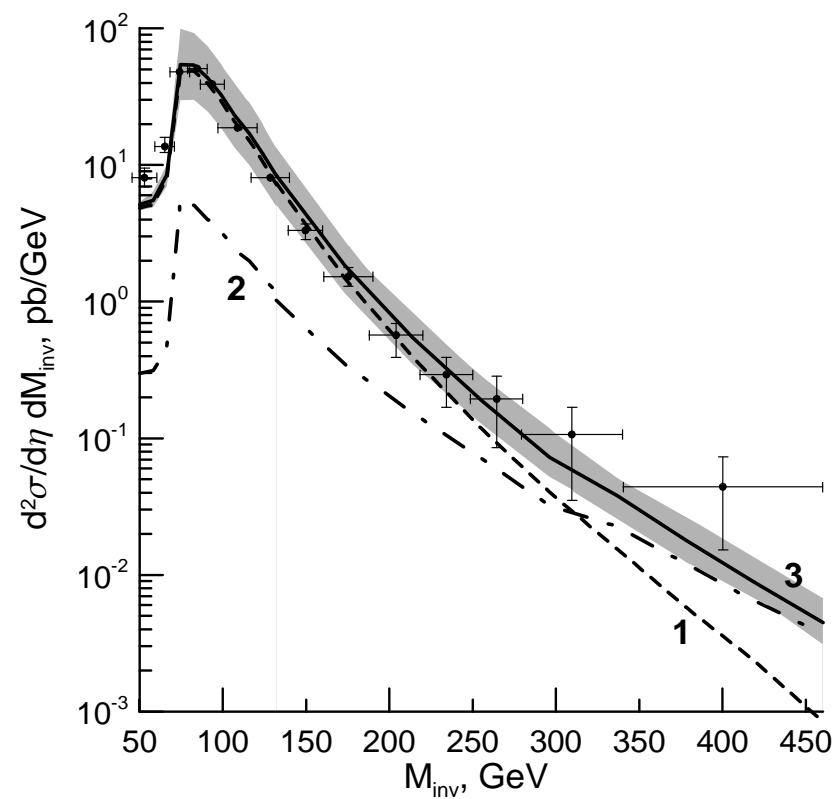
$b\bar{b}$ -pair production

Ratio Data/NLO prediction

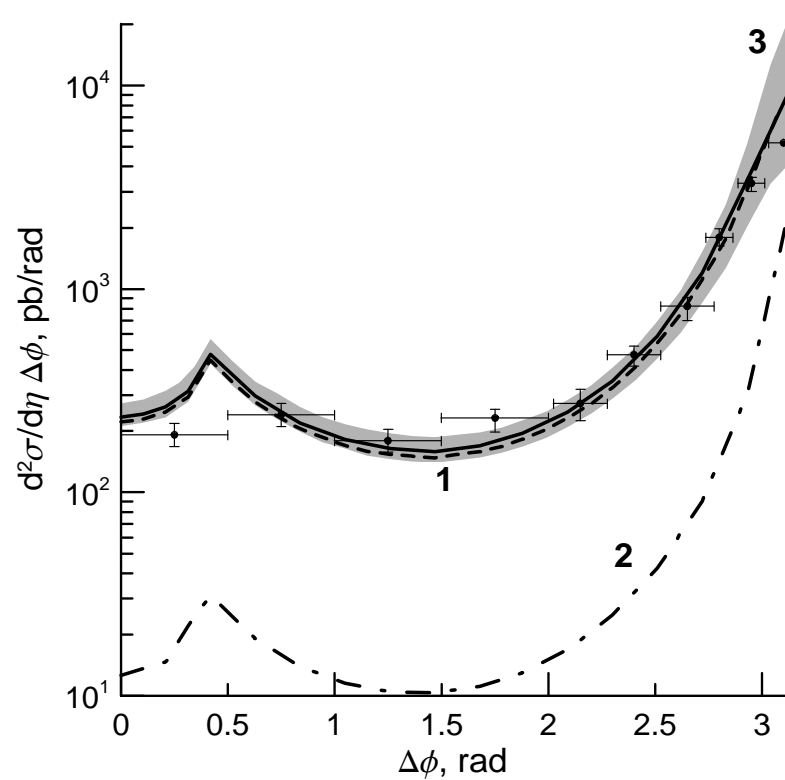




1 - $RR \rightarrow b\bar{b}$, 2 - $Q\bar{Q} \rightarrow b\bar{b}$, 3 - 1+2



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



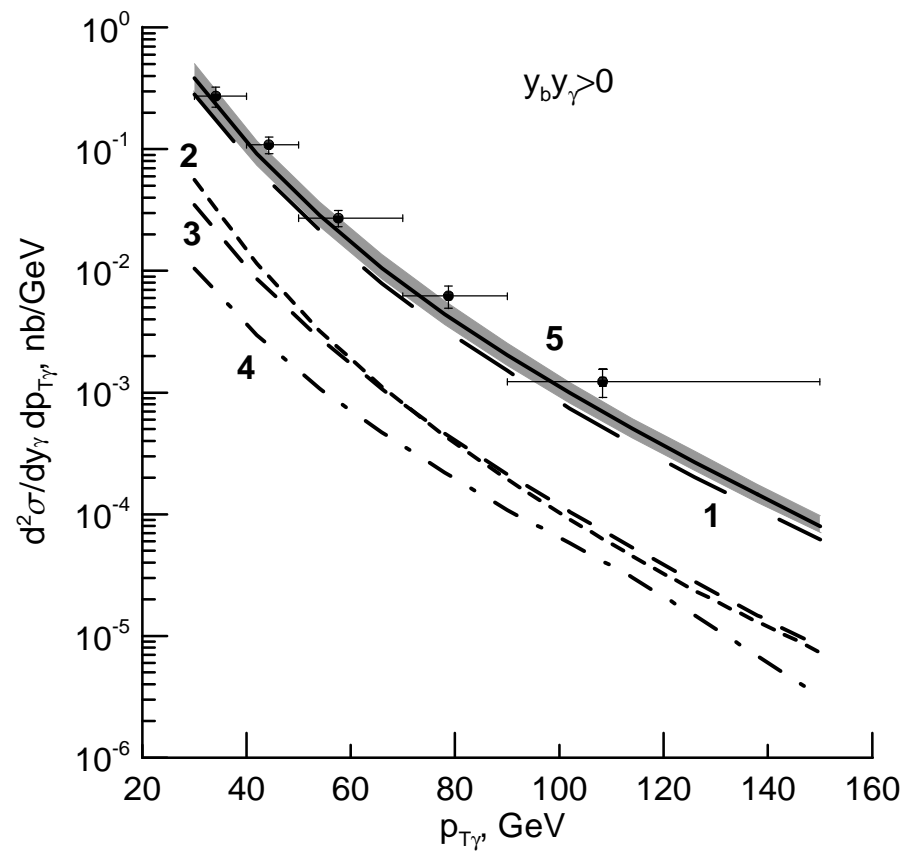
1 - $RR \rightarrow b\bar{b}$, 2 - $Q\bar{Q} \rightarrow b\bar{b}$, 3 - 1+2

Associated $b + \gamma$ production at Tevatron

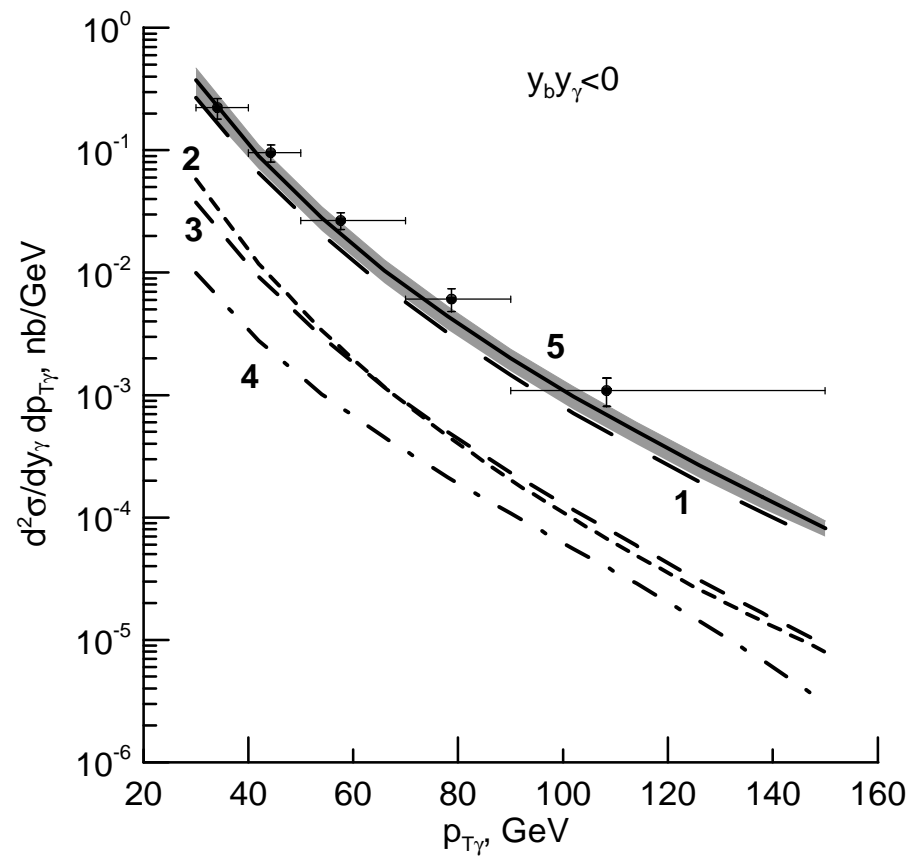
$$\sqrt{S} = 1.96 \text{ GeV}, \quad |y_\gamma| < 1.0, \quad |y_b| < 0.8,$$
$$30 < E_{T\gamma} < 150 \text{ GeV}, \quad E_{Tb} > 15 \text{ GeV},$$

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

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



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



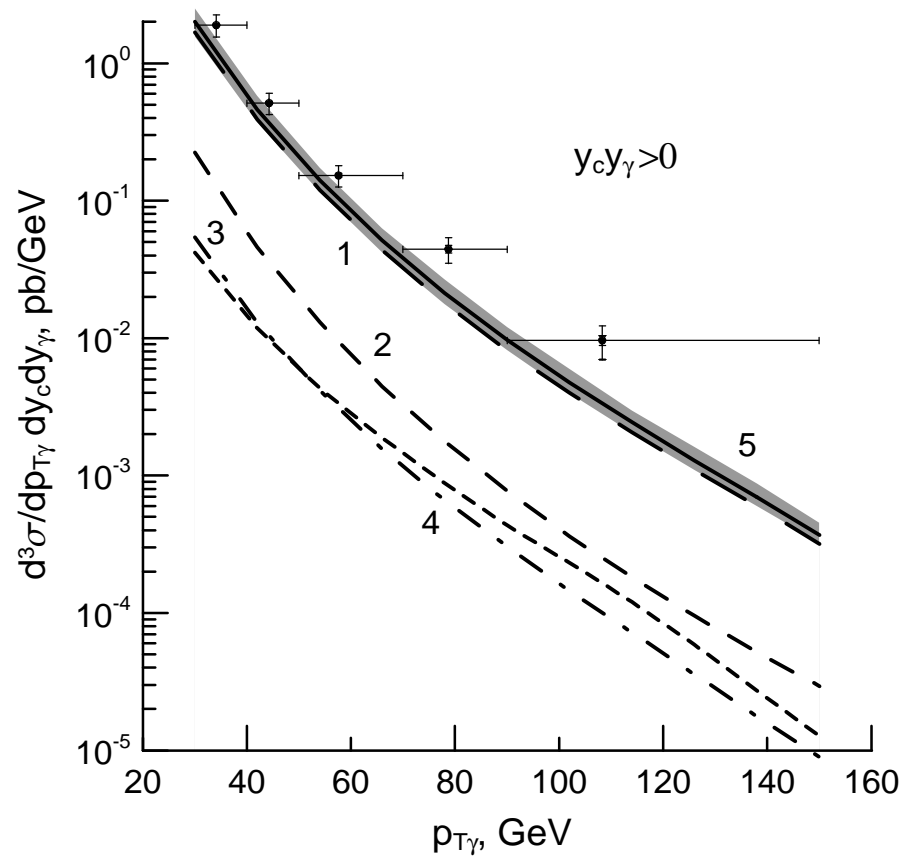
1 - $RQ_b \rightarrow b\gamma$, 2 - $RR \rightarrow b\bar{b}(\gamma)$, 3 - $QQ_b \rightarrow bq(\gamma)$, 4 - $Q\bar{Q} \rightarrow b\bar{b}(\gamma)$, 5 - sum

Associated $c + \gamma$ production at Tevatron

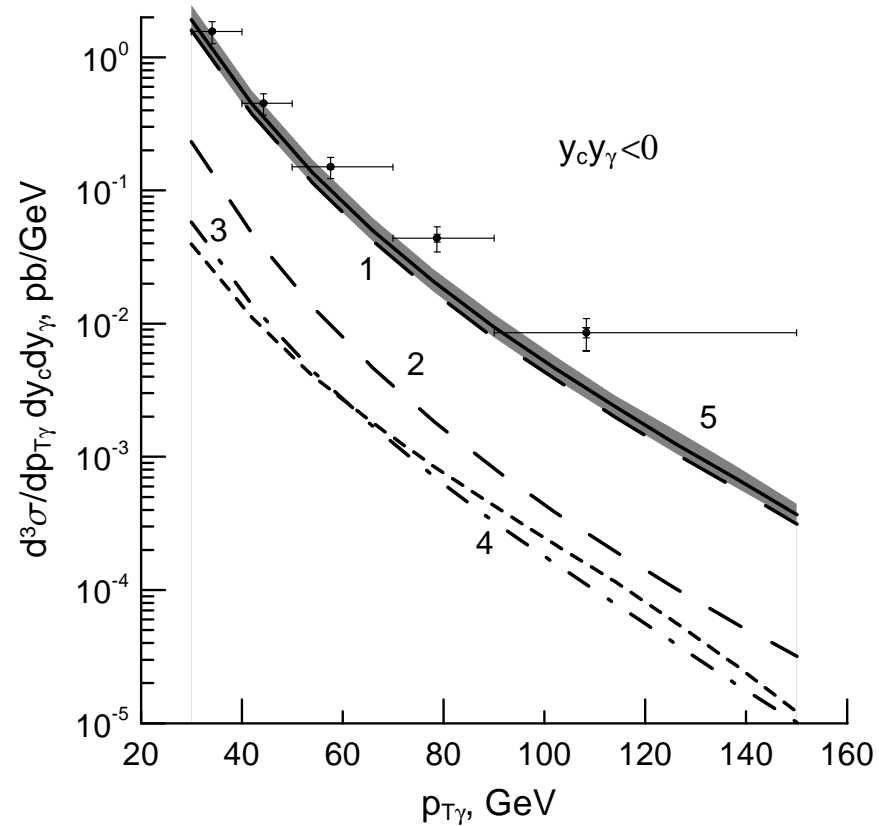
$$\sqrt{S} = 1.96 \text{ GeV}, \quad |y_\gamma| < 1.0, \quad |y_c| < 0.8,$$
$$30 < E_{T\gamma} < 150 \text{ GeV}, \quad E_{Tc} > 15 \text{ GeV},$$

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

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



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



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

Conclusions

1. Within the framework of LO QMRK approach, we have obtained good description for the inclusive production of single jets, prompt photons, 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 ($x \geq 0.1$)
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

1. **Charmonium production:** B. A. Kniehl, D. V. Vasin, and V. A. Saleev, Phys. Rev. D **73**, 074022 (2006) [arXiv:hep-ph/0602179];
2. **Botomonium production:** B. A. Kniehl, V. A. Saleev and D. V. Vasin, Phys. Rev. D **74**, 014024 (2006) [arXiv:hep-ph/0607254];
3. **D meson production:** B. A. Kniehl, A. V. Shipilova, and V. A. Saleev, Phys. Rev. D **79**, 034007 (2009) [arXiv:0812.3376 [hep-ph]];
4. **Prompt photon production:** V. A. Saleev, Phys. Rev. D **78**, 034033 (2008) [arXiv:0807.1587 [hep-ph]]; V. A. Saleev, Phys. Rev. D **78**, 114031 (2008) [arXiv:0812.0946 [hep-ph]]. V. A. Saleev, Phys. Rev. D **80**, 114016 (2009) [arXiv:0812.0946 [hep-ph]].
5. **b and $b + \bar{b}$ production:** B. A. Kniehl, A. V. Shipilova, and V. A. Saleev, Phys. Rev. D **81**, 094010 (2010) [arXiv:1003.0346 [hep-ph]];
6. **$\gamma + jet$ production:** V. A. Saleev, A. V. Shipilova, to be published.