b-jet Production at High Energy Colliders in the Regge Limit of QCD

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Outline

1. **High-energy hadronic collisions**
2. **Parton Reggeization Approach**
3. **$b\bar{b}$-pair production at Tevatron and LHC**
4. **Inclusive b-jet production at Tevatron and LHC**
5. **Conclusions**

High-energy hadronic collisions - I

We consider a b-jet production in $p\bar{p}$ (Tevatron) and pp (LHC) collisions.

$m_T = \sqrt{m_b^2 + p_T^2} \sim \mu \gg \Lambda_{QCD}$, $\alpha_s \ll 1$: perturbative QCD series expansion.

Processes with hadrons in the initial state are described in terms of parton distribution functions $F_a^h(x, \mu^2)$.

The conventional model is **the collinear parton model:**

- DGLAP evolution equation, which sums large logarithms only of the type $\ln^n(\mu/\Lambda_{QCD})$;
- the collinear approximation is used: $\mathbf{q_T} = 0$ for the initial-state partons.

High-energy hadronic collisions - II

At the modern hadronic colliders **the Regge limit of QCD** $(\mathbf{S \gg \mu^2})$ is achieved, so that $x \simeq \mu/\sqrt{S} \ll 1$.

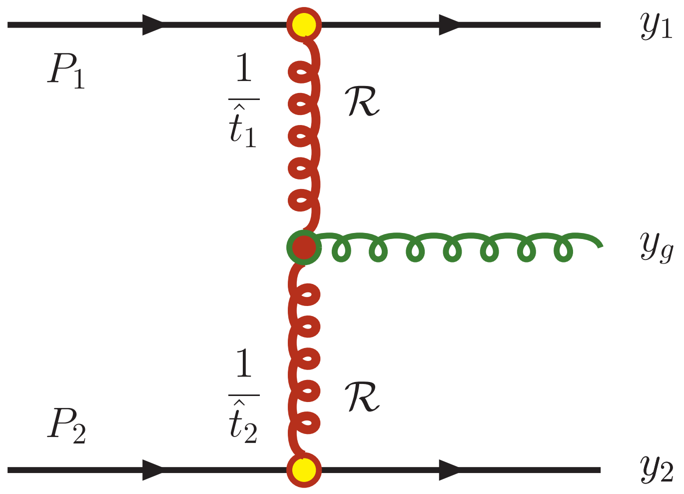
In the small-x region the large logarithms of the new type $\ln^n(1/x)$ arise in all orders of perturbative expansion.

To sum these logarithms: BFKL or BFKL-like (CCFM, ...) evolution equations.

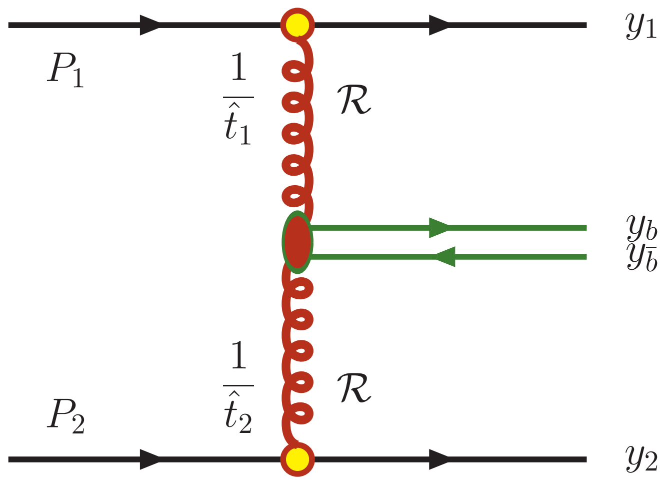
In small-x region the t-channel parton exchanges are to dominate, and one must take into account the transverse momenta of the initial-state partons and its off-shell properties $\mathbf{q_T} \neq 0$, $q^2 = q_T^2 = -|\mathbf{q_T}|^2 \neq 0$.

High-energy hadronic collisions - III

Processes with t-channel parton exchanges, the dominant types of kinematics: **multi-Regge kinematics (MRK)** and **quasi-multi-Regge kinematics (QMRK)**. MRK is a particular case of QMRK.



MRK: $y_1 \ll y_g \ll y_2$



QMRK: $y_1 \ll y_b \simeq y_{\bar{b}} \ll y_2$

Yellow-red — Reggeon-Particle-Particle (RPP) vertices; green-red — RRP(P)

Parton Reggeization Approach - I

is based on the property of **gluon Reggeization** and provides the most general and theoretically proved description of the considering processes.

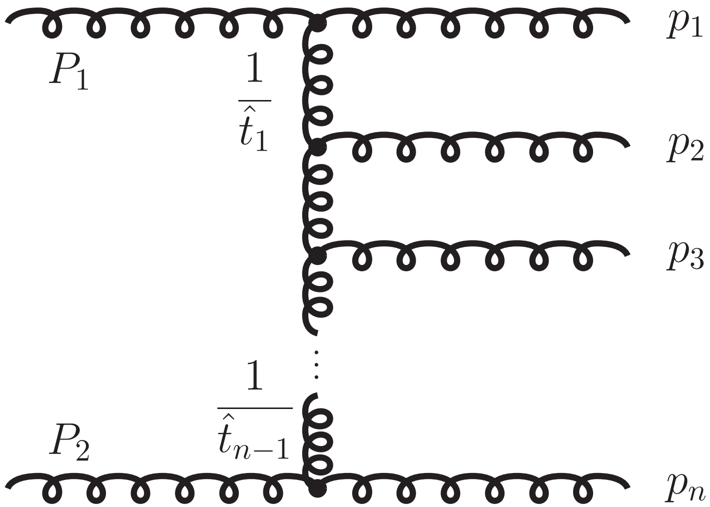
Reggeization — a quantum field theory effect: at large $\sqrt{S}$ and fixed momentum transfer $-\sqrt{t}$, the amplitude with exchange of given particle, including radiative corrections, has the same form as in the Born approximation but with spin depending on momentum transfer.

The first study of elementary particles Reggeization: electron Reggeization in QED, M. L. Gell-Mann *et al.* Elementary Particles of Conventional Field Theory as Regge Poles. III, Phys. Rev. B, 1964.

The gluon Reggeization in QCD: E. A. Kuraev, L. N. Lipatov, V. S. Fadin Multi-Reggeon Processes in the Yang-Mills Theory, Sov. Phys. JETP, 1976.

Parton Reggeization Approach - II

The gluon Reggeization provides a simple factorized form of particle production amplitudes in MRK and QMRK.



The contributions of ladder-type diagrams which appear in (N)NLO approximation of collinear parton model are taken into account already in the LO of Parton Reggeization Approach.

Parton Reggeization Approach - III

The induced and effective vertices of Reggeized particles and common particles interactions had been derived using methods based on the analiticity and unitarity of particle production amplitudes in the works of V. S. Fadin, E. A. Kuraev and L. N. Lipatov since 1976 year.

In 1995 **the effective quantum field theory with non-Abelian gauge invariant action** was stated by L. N. Lipatov, which allows to deduce the effective vertices directly from the Lagrangian (*V. S. Fadin, R. Fiore, Calculation of Reggeon vertices in QCD, Phys. Rev. D, 2001*), and the set of Feynman rules was derived (*E. N. Antonov, L. N. Lipatov, E. A. Kuraev, I. O. Cherednikov, Feynman rules for effective Regge action, Nucl. Phys. B, 2005.*)

Parton Reggeization Approach - IV

The effective $\mathcal{R}\mathcal{R}g$ vertex (V. S. Fadin, E. A. Kuraev, L. N. Lipatov, 1976):

$$C^{g,\mu}_{\mathcal{R}\mathcal{R}}(q_1,q_2) = -\sqrt{4\pi\alpha_s} f^{abc} \frac{q_1^+ q_2^-}{2\sqrt{t_1 t_2}} \left[(q_1-q_2)^\mu + \right.$$

$$\left. + \frac{(n^+)^\mu}{q_1^+}\left(q_2^2 + q_1^+ q_2^-\right) - \frac{(n^-)^\mu}{q_2^-}\left(q_1^2 + q_1^+ q_2^-\right) \right],$$

$(n^\pm)^\mu = (1,0,0,\pm 1)$, $k^\pm = k \cdot n^\pm$ for any four-vector k^μ.

$$q_{1,2} = x_{1,2} P_{1,2} + q_{1,2T}$$

$$t_1 = -q_1^2 = |\mathbf{q}_{1T}|^2, \quad t_2 = -q_2^2 = |\mathbf{q}_{2T}|^2$$

The factorization hypothesis

$$d\sigma\,(p+p(\bar p)\to g+X)=\int\frac{dx_1}{x_1}\int\frac{d^2q_{1T}}{\pi}\int\frac{dx_2}{x_2}\int\frac{d^2q_{2T}}{\pi}\times$$
$$\times\Phi_g^p(x_1,t_1,\mu^2)\Phi_g^{p(\bar p)}(x_2,t_2,\mu^2)d\hat\sigma(\mathcal{R}+\mathcal{R}\to g)$$

$\Phi_g^{p(\bar p)}(x,|\mathbf{q_T}|^2,\mu^2)$ — the unintegrated gluon distribution functions, are extracted from collinear ones:

- the KMR procedure (M. A. Kimber, A. D. Martin, M. G. Ryskin, G. Watt, 2001–2004)
- the Blümlein approach, (J. Blümlein, Preprint DESY 95–121, 1995).

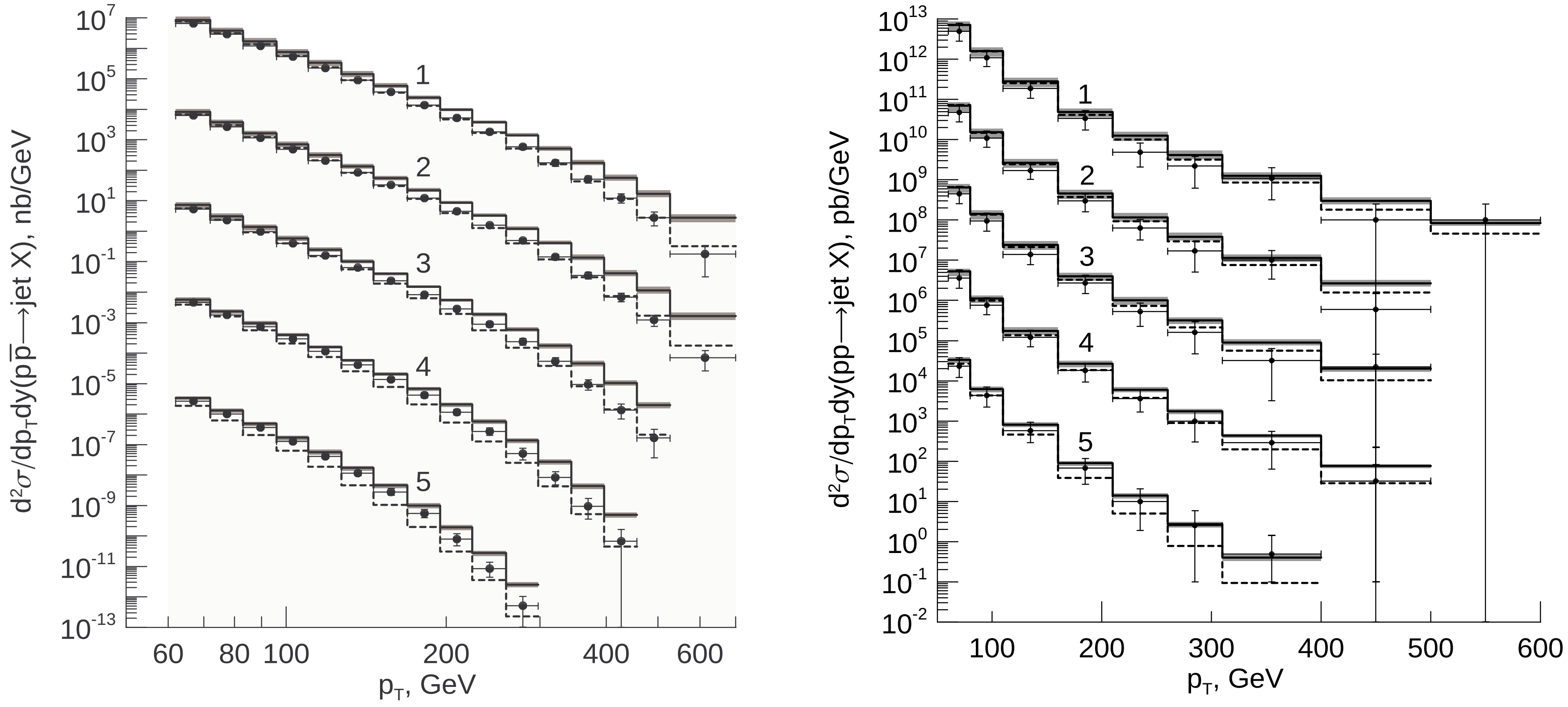
The normalization condition:

$$xF_g^{p,\bar p}(x,\mu^2)=\int^{\mu^2}\Phi_g^{p,\bar p}(x,t,\mu^2)dt$$

The initial collinear gluon distribution functions: A. D. Martin, R. G. Roberts , V. G. Stirling , R. S. Thorne, 2002

Inclusive jet production

B. A. Kniehl , V. A. Saleev , A. V. Shipilova , E. V. Yatsenko, Single jet and prompt-photon inclusive production with multi-Regge kinematics: From Tevatron to LHC, Phys. Rev. D84 (2011) 074017. Left fig. — Tevatron, right fig. — LHC.



$b\bar{b}$-pair production at high-energy colliders

Tevatron Run II, CDF Collaboration

$\sqrt{S} = 1.96$ TeV, 30 GeV$< p_T < 250$ GeV, $|y_{b,\bar{b}}| < 1.2$

Large Hadronic Collider, ATLAS Collaboration $\sqrt{S} = 7$ TeV,
50 GeV$< p_T < 700$ GeV, $|y_{b,\bar{b}}| < 1.1$

$$x_{1,2} \sim x_T = 2p_T/\sqrt{S} \lesssim 0.1$$

$b\bar{b}$-pair production in the QMRK - I

In the LO of Parton Reggeization Approach the dominant partonic subprocess reads

$$\mathcal{R}(q_1) + \mathcal{R}(q_2) \to b(k_1) + \bar{b}(k_2)$$

The effective $\mathcal{R}\mathcal{R}q\bar{q}$ vertex $C_{\mathcal{R}\mathcal{R}}^{q\bar{q}}(q_1, q_2) = C_{\hat{s}} + C_{\hat{t}} + C_{\hat{u}}$

$$\begin{aligned}
C_{\hat{s}} &= \frac{4\pi\alpha_s}{\hat{s}} f^{acb} T^c C_{\mathcal{R}\mathcal{R}}^{g,\mu}(q_1, q_2) \bar{U}(k_1)\gamma_\mu V(k_2), \\
C_{\hat{t}} &= i\frac{4\pi\alpha_s}{\hat{t}} T^a T^b \bar{U}(k_1)\gamma^\mu(\hat{k}_1 - \hat{q}_1)\gamma^\nu V(k_2)\Pi_\mu^{(-)}(q_1)\Pi_\nu^{(+)}(q_2), \\
C_{\hat{u}} &= i\frac{4\pi\alpha_s}{\hat{u}} T^b T^a \bar{U}(k_1)\gamma^\nu(\hat{k}_1 - \hat{q}_2)\gamma^\mu V(k_2)\Pi_\mu^{(-)}(q_1)\Pi_\nu^{(+)}(q_2).
\end{aligned}$$

The matrix element

$$\overline{|\mathcal{A}(\mathcal{R} + \mathcal{R} \to q + \bar{q})|^2} = 256\pi^2\alpha_s^2 \left(\frac{1}{2N_c}\mathcal{M}_{\mathrm{Ab}} + \frac{N_c}{2(N_c^2 - 1)}\mathcal{M}_{\mathrm{NAb}} \right)$$

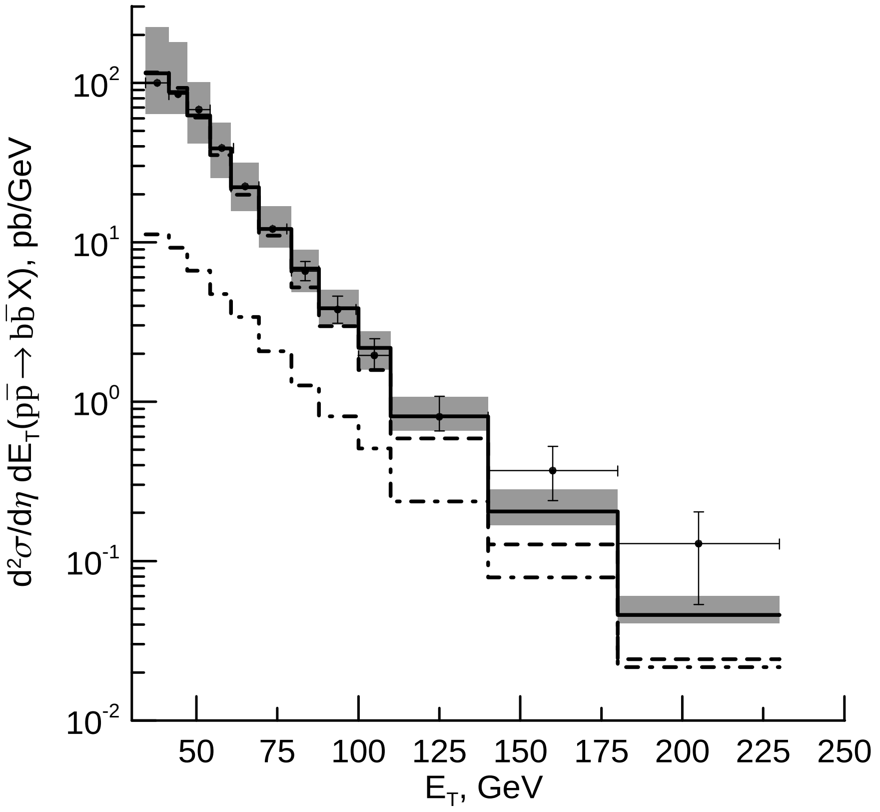
$b\bar{b}$-pair production in the QMRK - II

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

$\hat{s} = (q_1 + q_2)^2$, $\hat{t} = (q_1 - k_1)^2$, $\hat{u} = (q_2 - k_1)^2$, $\tilde{t} = \hat{t} - m^2$, $\tilde{u} = \hat{u} - m^2$

$\alpha_1 = 2(k_1 \cdot P_2)/S$, $\alpha_2 = 2(k_2 \cdot P_2)/S$, $\beta_1 = 2(k_1 \cdot P_1)/S$ и $\beta_2 = 2(k_2 \cdot P_1)/S$

$b\bar{b}$-pair production at the Tevatron Collider - I



$\sqrt{S} = 1.96$ TeV, $|\eta_{b,\bar{b}}| < 1.2$

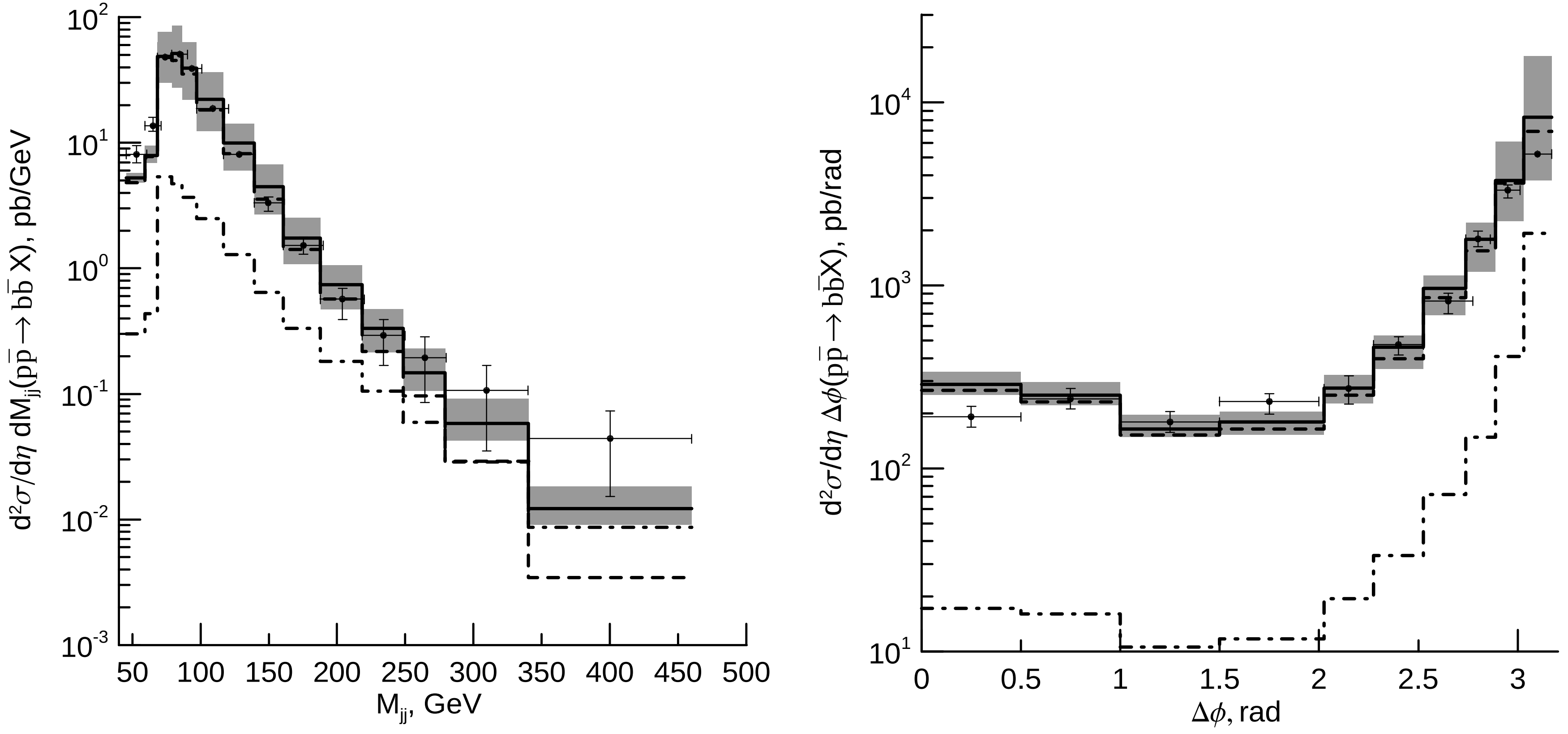
$\mu = \zeta k_T$, $1/2 < \zeta < 2$

$\mathcal{R} + \mathcal{R} \to b + \bar{b}$ (dash),

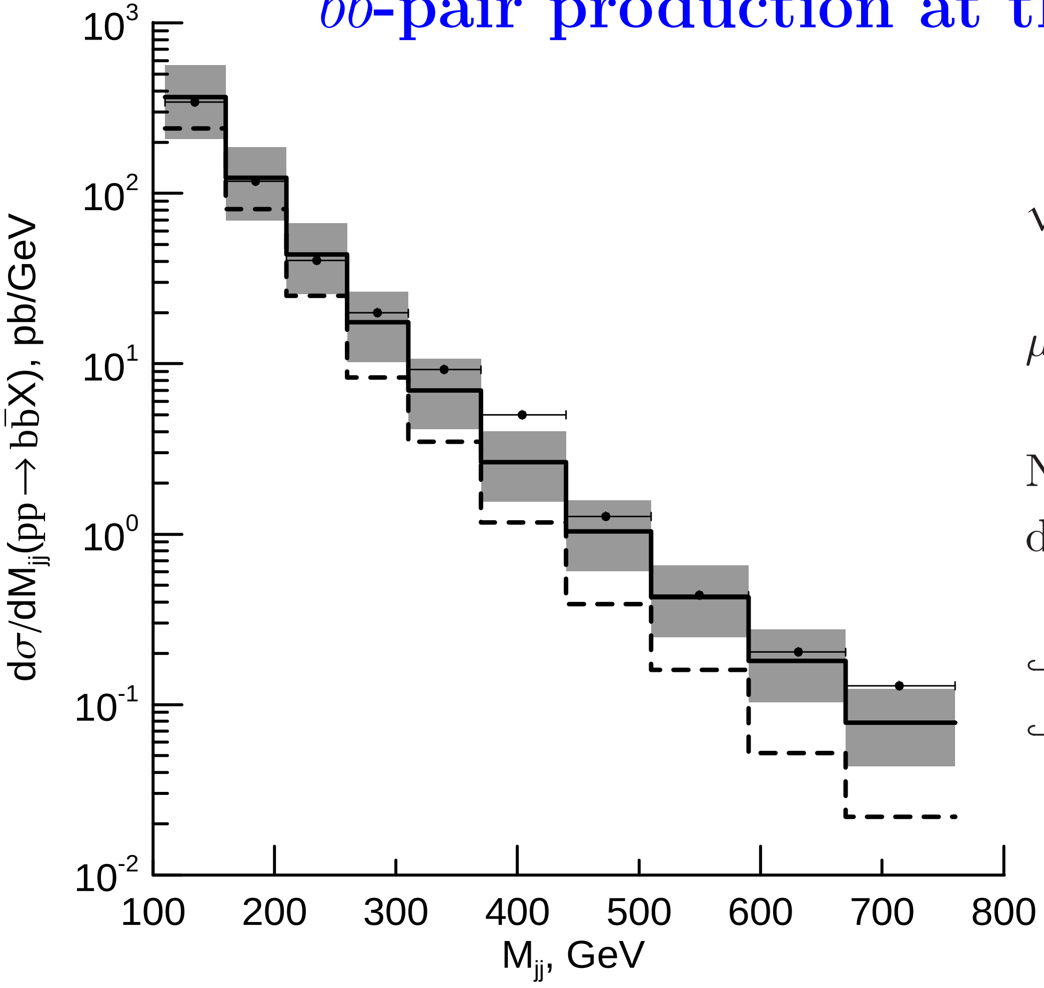
$\mathcal{Q}_q + \bar{\mathcal{Q}}_q \to b + \bar{b}$ (dash-dot),

sum of both them (solid)

$b\bar{b}$-pair production at the Tevatron Collider - II



$b\bar{b}$-pair production at the LHC - I



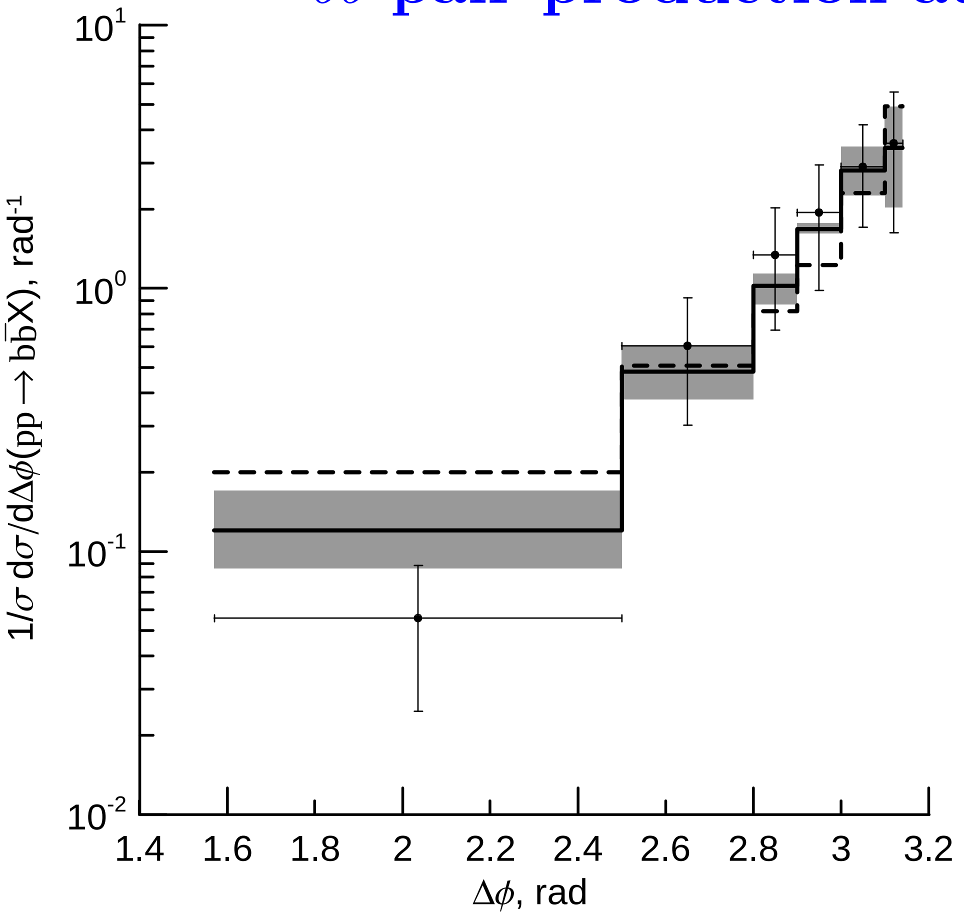
$\sqrt{S} = 7$ TeV, $|y_{b,\bar{b}}| < 1.12$

$\mu = \zeta k_T$, $1/2 < \zeta < 2$

Nonintegrated gluon
distribution functions

$\hookrightarrow$ KMR (solid line),
$\hookrightarrow$ Blümlein (dashed line)

$b\bar{b}$-pair production at the LHC - II



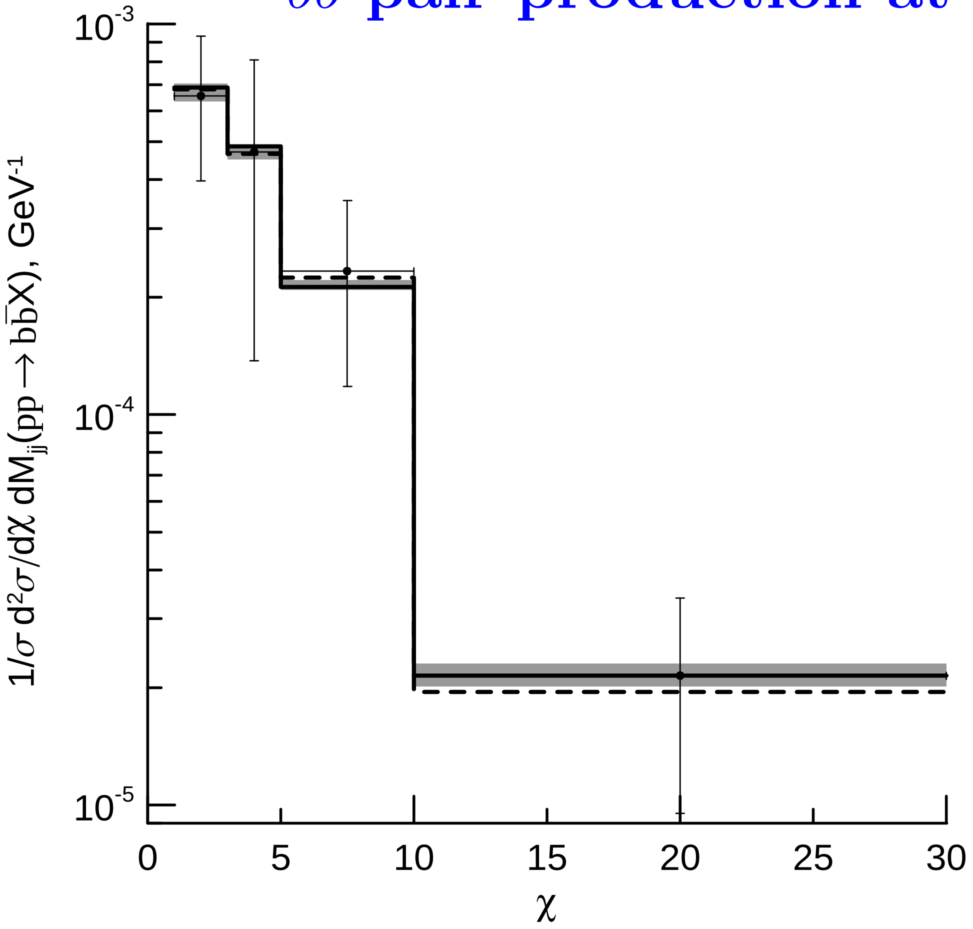
$\sqrt{S} = 7$ TeV, $|y_{b,\bar{b}}| < 1.12$

$\mu = \zeta k_T$, $1/2 < \zeta < 2$

Nonintegrated gluon distribution functions

$\hookrightarrow$ KMR (solid line),
$\hookrightarrow$ Blümlein (dashed line)

$b\bar{b}$-pair production at the LHC - III



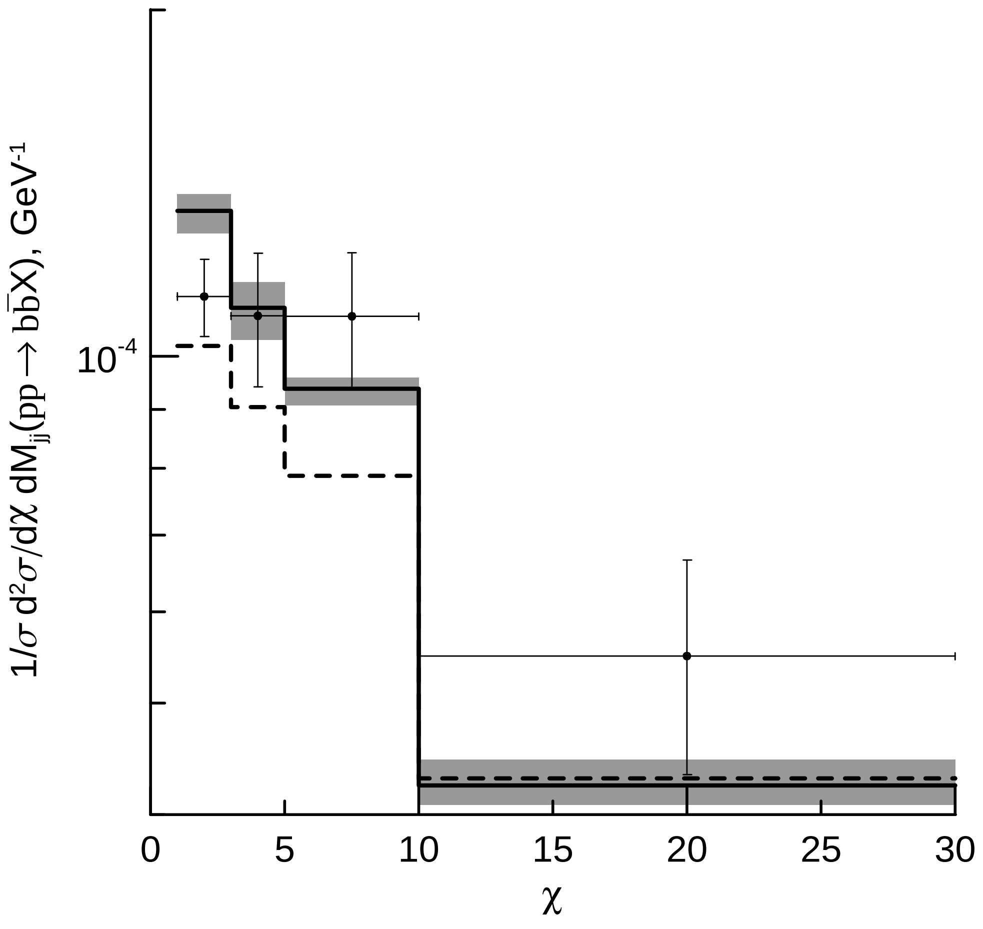
$\sqrt{S} = 7$ TeV, $|y_{b,\bar{b}}| < 1.12$

$\mu = \zeta k_T$, $1/2 < \zeta < 2$
$\chi = \exp|y_1 - y_2|$

Nonintegrated gluon distribution functions

$\hookrightarrow$ KMR (solid line),
$\hookrightarrow$ Blümlein (dashed line)

$b\bar{b}$-pair production at the LHC - IV



$\sqrt{S} = 7$ TeV, $|y_{b,\bar{b}}| < 1.12$

$\mu = \zeta k_T$, $1/2 < \zeta < 2$
$\chi = \exp|y_1 - y_2|$

Nonintegrated gluon
distribution functions

$\hookrightarrow$ KMR (solid line),
$\hookrightarrow$ Blümlein (dashed line)

Inclusive b-jet production at high-energy colliders

Tevatron, CDF Collaboration

$\sqrt{S} = 1.96$ TeV, 30 GeV$< p_T < 250$ GeV, $|y_b| < 0.7$

Large Hadronic Collider, ATLAS Collaboration

$\sqrt{S} = 7$ TeV, 50 GeV$< p_T < 700$ GeV, $|y_b| < 2.1$

Large Hadronic Collider, CMS Collaboration

$\sqrt{S} = 7$ TeV, 30 GeV$< p_T < 200$ GeV, $|y_b| < 2.4$

Inclusive b-jet production in MRK and QMRK

$$\frac{d\sigma^{bjet}}{dp_T} = \frac{d\sigma^{frag}}{dp_T} + \frac{d\sigma^{open}}{dp_T}$$

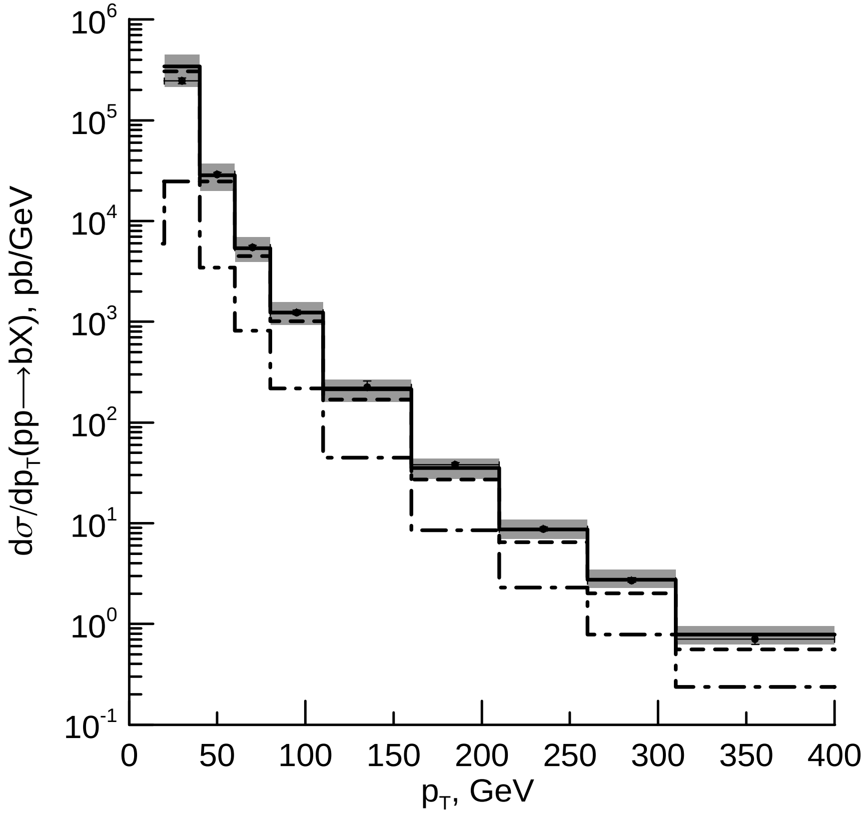
The subprocesses of Parton Reggeization Approach which give the LO contribution:

1. open b-quark production: $\mathcal{R} + \mathcal{R} \to b + \bar{b}$
2. b-quark production via gluon fragmentation: $\mathcal{R} + \mathcal{R} \to g \to b$;

$$\frac{d\hat{\sigma}^{frag}}{dp_T} = \frac{d\hat{\sigma}^{g}}{dp_T} n_g(\mu),$$

$n_g(\mu)$ — b-quark multiplicity in the gluon jet. We extract it from the comparison of our results with the ATLAS data.

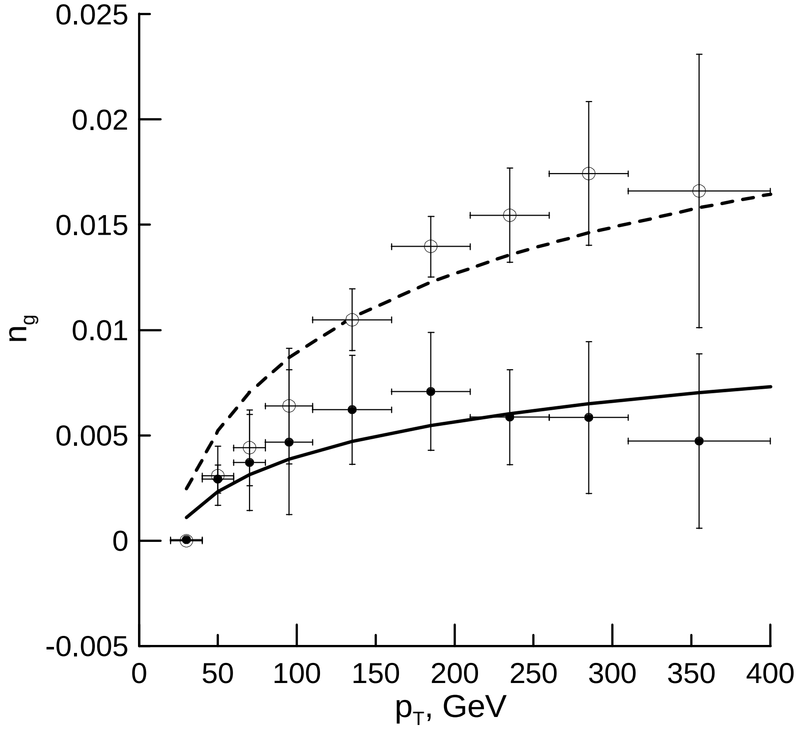
Inclusive b-jet production at the LHC - I



dash — open b-quark production, dash-dot — b-quark production via gluon fragmentation, solid — sum of both contributions.

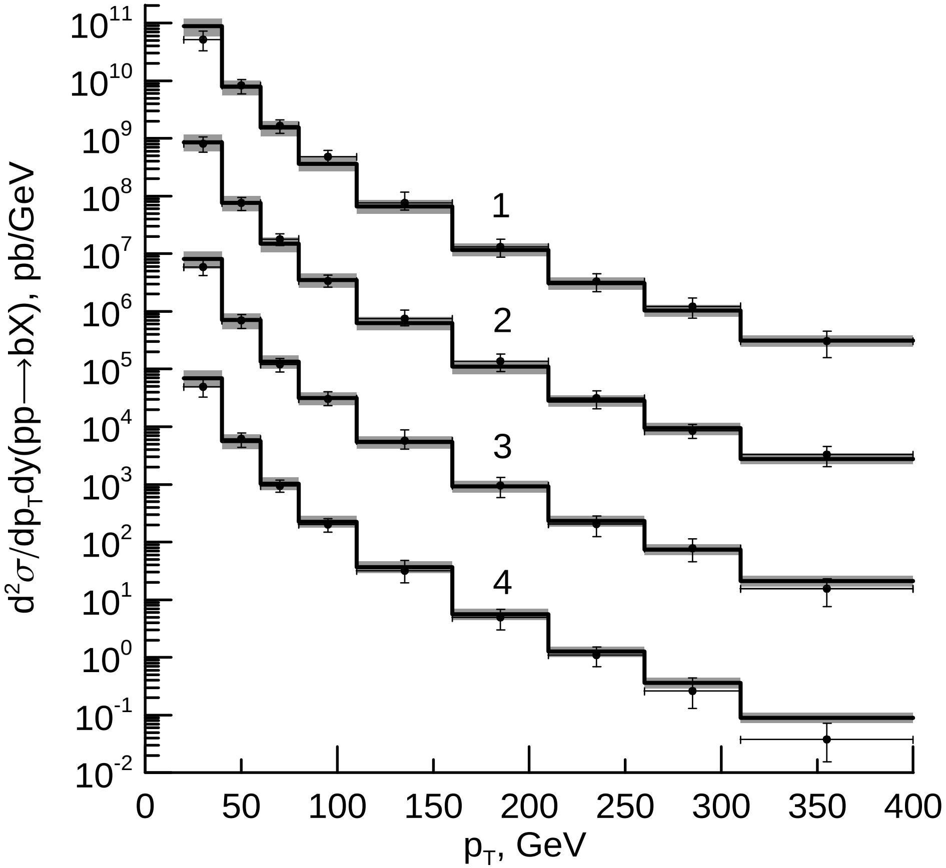
Inclusive b-jet production at the LHC - II

The extracted $b\bar{b}$-pair multiplicity in a gluon jet



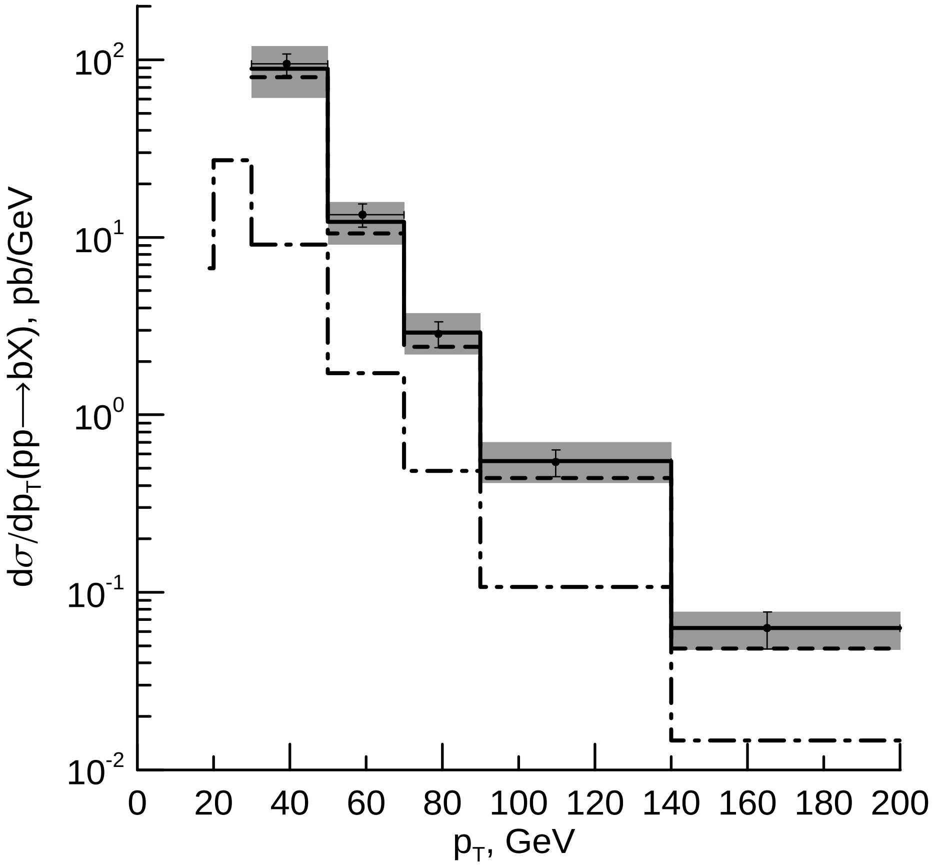
open circles, dashed fitting line — Blümlein unintegrated PDF,
the black circles, solid fitting line — KMR unintegrated PDF.

Inclusive b-jet production at the LHC - III



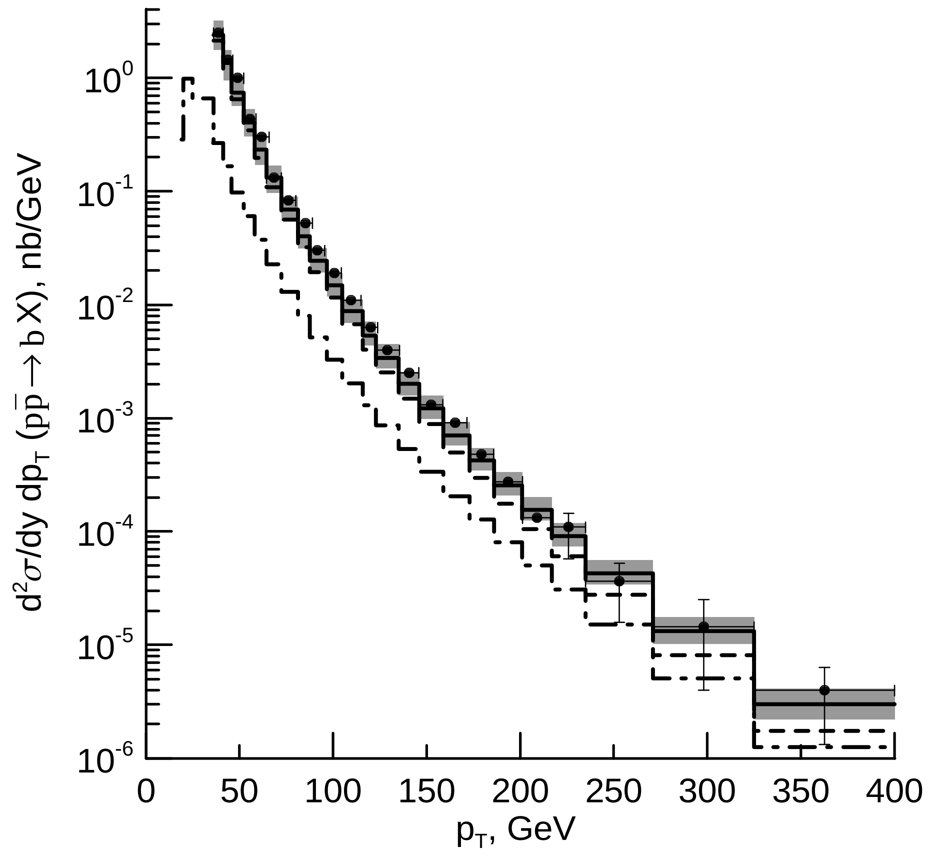
$\sqrt{S} = 7$ TeV, $|y| < 0.3$ (1), $0.3 < |y| < 0.8$ (2), $0.8 < |y| < 1.2$ (3), $1.2 < |y| < 2.1$ (4)

Inclusive b-jet production at the LHC - IV



$$\sqrt{S} = 7 \text{ TeV}, \ |y| < 2.1$$

Inclusive *b*-jet production at the Tevatron - V



$$\sqrt{S} = 1.96 \text{ TeV}, \ |y| < 0.7$$

Conclusions

1. Working in terms of Parton Reggeization Approach, we describe well the wide amount of data on $b\bar{b}$-pair correlations and inclusive b-jet production at Tevatron Collider and LHC.
2. We demonstrate, to reach the degree of agreement between theoretical predictions and the experimental data, achieved already in the LO of Parton Reggeization Approach, one needs to take into account (N)NLO contributions in the collinear parton model.
3. The extracted by our fit of data the $b\bar{b}$-pair multiplicity in the gluon jet is in agreement with the previous measurements at the LEP Collider.

Our recent works

- *V. A. Saleev and A. V. Shipilova.* Inclusive b-jet and $b\bar{b}$-dijet production at the LHC via Reggeized gluons, Accepted to publication to Phys. Rev. D.
- *M. A. Nefedov, V. A. Saleev, A. V. Shipilova.* Prompt J/psi production in the Regge limit of QCD: From Tevatron to LHC Phys. Rev. D **85**, 074013 (2012).
- *B. A. Kniehl, V. A. Saleev, A. V. Shipilova, E. V. Yatsenko.* Single jet and prompt-photon inclusive production with multi-Regge kinematics: From Tevatron to LHC. Phys. Rev. D **84**, 074017 (2011).
- *B. A. Kniehl, A. V. Shipilova and V. A. Saleev.* Inclusive b and b anti-b production with quasi-multi-Regge kinematics at the Tevatron. Phys. Rev. D **81**, 094010 (2010).

Thank you for attention.