Heavy quark production at Teavatron and LHC in the k_T-factorization approach

Nikolai Zotov

Skobeltsyn Institute of Nuclear Physics,
Lomonosov Moscow State University

in collaboration with
S.P. Baranov (Lebedev Physics Institute),
A.V. Lipatov (Skobelsyn Inst. of Nucl. Phys., MSU)

OUTLINE

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Introduction

Why k_T-factorization or semi-hard **approach** (SHA)?

- **At Tevatron and LHC energies the** H.Q. **production - SH process.**

By definition **in these processes we have a hard scale** μ

$$\mu^2 \sim p_T^2 \sim M_T^2 = M^2 + p_T^2,\ M \sim M_Q,$$

which is large as compared to the Λ_{QCD} **but** μ **is much less than the total c.m.s. energy** $\sqrt{S}$ **of a process:**

$$\Lambda_{QCD} \ll \mu \ll \sqrt{S}.$$

In such case $M^2/S \sim x << 1$ and we have deal with hard processes in small x region.

2) It means the pQCD expansion any observable quantity in α_s contains large coefficients $(\ln^n(S/M^2)) \sim (\ln^n(1/x))$ (besides the usual R.G. ones $(\ln^n(\mu^2/\Lambda^2_{QCD}))$).
The resummation of these terms $(\alpha_s(\ln(1/x))^n$ (~ 1 at $x \to 0$) results in the so called unintegrated parton distribution $F_i(x, \vec{k}^2_T)$ - the probability to find a parton i carring the longitudinal momentum fraction x and transverse momentum $\vec{k}_T$.

If the terms $(\alpha_s \ln(\mu^2/\Lambda^2_{QCD}))^n$ and DL terms $(\alpha_s \ln(\mu^2/\Lambda^2_{QCD}) \ln(1/x))^n$ are also resummed, then the unintegrated parton distributions (u.p.d.) depends on the probing scale μ: $A(x, \vec{k}_T^2, \mu^2)$.

The (u.p.d.) obey certain evolution equations:

- **BFKL:** E.A. Kuraev, L.N. Lipatov, V.S. Fadin (1976, 1977); Y.Y. Balitskii, L.N. Lipatov (1978).
- **CCFM:** M. Ciafaloni (1988); S. Catani, F. Fiorani,G. Marchesini (1990); G. Marchesini (1995).

The u.p.d. are related to the conventional DGLAP densities once the k_T dependence is integrated out. For example, the u.p.d. reduce to the conventional gluon density by $\int_0^{Q^2} F_g(x, \vec{k}_T^2) d\vec{k}_T^2 \sim xG(x, Q^2)$.

LO + NLO calculations for $b\bar{b}$ quark production at HERA and Tevatron energies are O.K. now.

But

there is the very large discrepancy (by more than an order of magnitude) between the pQCD predictions (with CSM) and exiting exp. data for quarkonium **production at Tevatron.**

What will be at LHC?

Will we need LO + NLO + NNLO +... **or the better to have a** resummation **procedure?**

- to produce the H.Q. transverse momentum spectra: one usually intoduces the promordial k_T of initial partons;
  the size of that k_T cannot be predicted within model itself and is required to be $k_T \sim$1 - 2 GeV (instead k_T of the order $\Lambda_{QCD} \sim$ 300 MeV) to fit the data.

$->$ We need the semi-hard (SHA)
L. Gribov, E. Levin, M. Ryskin (1983); E. Levin, M. Ryskin, Y. Shabelski, Shuvaev (1991)
or k_T-factorization approach
J. Collins, R. Ellis (1991);
S. Catani, M. Ciafaloni, F. Hautmann (1991).

We have used SHA to discribe exp. data on:

- heavy quark photoproduction at HERA
- J/ψ production in photo- and electroproduction at HERA with CSM and COM
- D^* production in DIS
- charm contribution to the s.f. $F_2^c(x, Q^2)$, F_L^c, F_L
- $b\bar{b}$ production at TEVATRON

Here I want to present the results:

Phys. Atom. Nucl. 67(04) 824

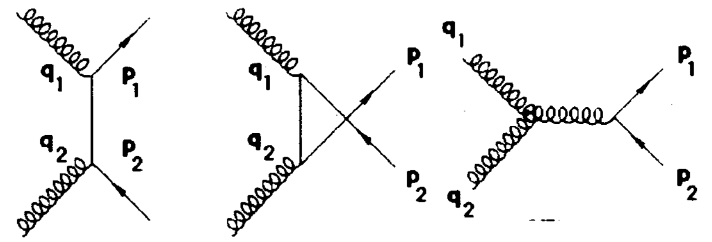
- $b\bar{b}$: S.P. Baranov, A.V. Lipatov, N. Z., hep-ph/0302171

N.Z, A.V. Lipatov, V.A. [illegible], Phys. Atom. Nucl. [illegible] (03) 755
hep-ph/0112114

LRSS, P. Hägler et al., BS, H. Jung

1. Partonic subprocess off-mass shell matrix elements.

The hard partonic subprocess $g^* g^* \to Q\bar{Q}$ amplitude is described by three Feynman's diagrams:



Ingredients of the SHA

which corresponds:

$$M_A = \bar{u}(p_1)(-ig\gamma^{\mu})\varepsilon_{\mu}(q_1)\, i\, \frac{\hat{p}_1 - \hat{q}_1 + m}{(p_1 - q_1)^2 - m^2} (-ig\gamma^{\nu})\varepsilon_{\nu}(q_2) v(p_2),$$

$$M_B = \bar{u}(p_1)(-ig\gamma^{\nu})\varepsilon_{\nu}(q_2)\, i\, \frac{\hat{p}_1 - \hat{q}_2 + m}{(p_1 - q_2)^2 - m^2} (-ig\gamma^{\mu})\varepsilon_{\mu}(q_1) v(p_2),$$

$$M_C = \bar{u}(p_1) C^{\mu\nu\lambda}(-q_1, -q_2, q_1 + q_2) \frac{g^2 \varepsilon_{\mu}(q_1)\varepsilon_{\nu}(q_2)}{(q_1 + q_2)^2} \gamma_{\lambda} v(p_2),$$

where

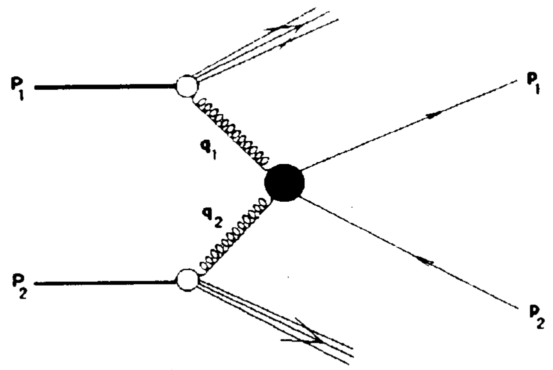
$$\underline{C^{\mu\nu\lambda}(q_1, q_2, q_3)} = i((q_2 - q_1)^{\lambda} g^{\mu\nu} + (q_3 - q_2)^{\mu} g^{\nu\lambda} + (q_1 - q_3)^{\nu} g^{\lambda\mu}).$$

The calculation of $|\bar{M}|^2$ was performed with the help of REDUCE program. The results will be numerically compared with ones obtained by S. Catani, M. Ciafaloni, F. Hautmann, NP., **B366** (1991) 135.

SHA QCD heavy quark production cross section.

The Sudakov decomposition for $p\bar{p} \to Q\bar{Q}\,X$ has form:

$p_1 = \alpha_1 P_1 + \beta_1 P_2 + p_{1T}$,
$p_2 = \alpha_2 P_1 + \beta_2 P_2 + p_{2T}$,
$q_1 = x_1 P_1 + q_{1T}$,
$q_2 = x_2 P_2 + q_{2T}$,



where $p_1^2 = p_2^2 = m^2$, $q_1^2 = q_{1T}^2$, $q_2^2 = q_{2T}^2$. In the c.m.s. of colliding particles we can write following expressions:

$$P_1 = \left(\frac{\sqrt{s}}{2},0,0,\frac{\sqrt{s}}{2}\right),\ P_2 = \left(\frac{\sqrt{s}}{2},0,0,-\frac{\sqrt{s}}{2}\right),\ P_1^2 = P_2^2 = 0;$$

$$\alpha_1 = \frac{m_{1T}}{\sqrt{s}}\exp(y_1^*),\ \alpha_2 = \frac{m_{2T}}{\sqrt{s}}\exp(y_2^*),$$

$$\beta_1 = \frac{m_{1T}}{\sqrt{s}}\exp(-y_1^*),\ \beta_2 = \frac{m_{2T}}{\sqrt{s}}\exp(-y_2^*);$$

$$x_1 = \alpha_1 + \alpha_2,\ x_2 = \beta_1 + \beta_2$$

Differential cross section in the semihard QCD approach can be written as:

$$d\sigma(p\bar{p} \to Q\bar{Q}\,X) = \frac{1}{16\pi(x_1x_2s)^2}\Phi(x_1, q_{T1}^2, \mu^2)\Phi(x_2, q_{T2}^2, \mu^2)\left|\bar{M}\right|_{SHA}^2(g^*g^* \to Q\bar{Q})\times$$
$$\times dy_1^*\, dy_2^*\, dp_{1T}^2\, dq_{1T}^2\, dq_{2T}^2\, \frac{d\varphi_1}{2\pi}\frac{d\varphi_2}{2\pi}\frac{d\varphi_3}{2\pi} \qquad (*)$$

In limit $q_{1T}^2 \to 0$, $q_{2T}^2 \to 0$ we have Parton Model expression:

$$d\sigma(p\bar{p} \to Q\bar{Q}\,X) = \frac{1}{16\pi(x_1x_2s)^2}x_1G(x_1, \mu^2)x_2G(x_2, \mu^2)\left|\bar{M}\right|_{PM}^2(gg \to Q\bar{Q})\times \qquad (*)$$
$$\times dy_1^*\, dy_2^*\, dp_{1T}^2$$

2. Unintegrated gluon distributions

- JB parametrization
  J. Blumlein, DESY 95-121

$$\Phi\left(x,q_T^2,\mu^2\right)=\int_x^1 \phi\left(\eta,q_T^2,\mu^2\right)\frac{x}{\eta}G\left(\frac{x}{\eta},\mu^2\right)d\eta,$$

where

$$\phi\left(\eta,q_T^2,\mu^2\right)=\begin{cases}\dfrac{\overline{\alpha}_s}{\eta\, q_T^2}J_0\left(2\sqrt{\overline{\alpha}_s \ln(1/\eta)\ln\left(\mu^2/q_T^2\right)}\right), & q_T^2\le\mu^2\\ \dfrac{\overline{\alpha}_s}{\eta\, q_T^2}I_0\left(2\sqrt{\overline{\alpha}_s \ln(1/\eta)\ln\left(q_T^2/\mu^2\right)}\right), & q_T^2\ge\mu^2\end{cases},$$

and $\overline{\alpha}_S=3\alpha_S/\pi$. $\Delta=j-1=\overline{\alpha}_S 4\ln 2\sim 0.53$ in LO and $\Delta=\overline{\alpha}_S 4\ln 2-N\overline{\alpha}_S^2$ in NLO, $N\sim 18$. However, some resummation procedures proposed in the last years
G. Salam, JHEP **9807:019** (1998), hep-ph/9806482, S. Brodsky, V. Fadin, V. Kim, L. Lipatov, G. Pivovarov, JETP lett., **70** (1999) 155, hep-ph/9901229
leads to positive value $\Delta\sim 0.2-0.3$. We will use $\Delta\sim 0.35$.

- KMS parametrization
  J. Kwiecinski, A. Martin, A. Stasto, Phys. Rev. **D56** (1997) 3991
  is obtained from a unified BFKL and DGLAP description of F_2 data and includes the so called consistency constraint
  J. Kwiecinski, A. Martin, A. Sutton, Phys. Rev. **D52** (1995) 1445, Z. Phys. **C71** (1996) 585
  The consistency constraint introduce a large correction to the LO BFKL equation: about 70 % of the full NLO corrections to the BFKL exponent Δ are effectively included in this costraint, as is declared in J. Kwiecinski, A. Martin, J. Outhwaite, Eur. Phys. J. **C9** (2001) 611.

- Frequently also used in literature the parametrization
  BFKL: N. Nikolaev, B. Zakharov, PL., **B333** (1994) 250
  which obtained from conventional gluon density $xG(x,Q^2)$ (by taking the Q^2-derivative):

$$\Phi\left(x,q_T^2,\mu^2\right)=\left.\frac{\partial xG(x,Q^2)\big|_{\mathrm{GRV}}}{\partial Q^2}\right|_{Q^2=q_T^2}.$$

DGRV parametrization

These u.g.d. resummed <u>different logs</u>: JB – $\ln^n(1/x)$; KMS – $\ln(1/x)\ln(\mu^2/\Lambda^2)$; DGRV – $\ln(\mu^2/\Lambda^2)$

$\Rightarrow$ different behaviour

- **GBW** parametrization
  K. Golec-Biernat, M. Wusthoff, PR., **D59** (1999) 014017, K. Golec-Biernat, M. Wusthoff, PR., **D60** (1999) 114023.

$$\Phi\left(x, q_T^2, \mu^2\right) = \frac{3\sigma_0}{4\pi^2}\frac{1}{\alpha_S} R_0^2(x) q_T^2 \exp\left(-R_0^2(x) q_T^2\right),$$

where

$$R_0^2(x) = \frac{1}{\text{GeV}^2}\left(\frac{x}{x_0}\right)^{\lambda/2},$$

and $\sigma_0 = 23\,\text{mb}$, $\lambda = 0.288$, $x_0 = 3{,}04 \cdot 10^{-4}$.

From Figs. 7–9 in Small x Collab.
B. Andersson et al. { DESY 02-041 (hep-ph/0204115) Eur. Phys. J. C25 ([illegible]) [illegible]

Fig. 7: KMR ≈ JB u.g.d.

Fig. 8: KMS ≈ KMR ≈ DGRV

Fig. 9: RS ≈ KMS

GBW → GRV ⟺ F_L

Exhaustive discussion of the u.pdf's was done by J.C. Collins, hep-ph/0304122

So far as to define the u.pdf's the extra cutoff needed on gluon rapidity one should not expect that the integral over trans. momentum of an u.g.d. should be exactly the corresponding integrated g.d.

In our paper

A. Lipatov, L. Lönnblad, N.Z.,
JHEP 0401:010 (2004)

we have been studied the three different versions of LDC **u.g.d., namely** standard, gluonic **and** leading **ones proposed in**

G. Gustafson, L. Lönnblad, G. Miu,
Phys. Rev. D67 (2003) 034020

The standard version includes non-leading **contributions and** non-singular **terms in the splitting functions.**

The gluonic and leading u.g.d. not take into account quark links in the evolution.

The gluoniic u.g.d. includes non-singular **terms in the splitting functions.**

The leading u.g.d. includes only singular **ones.**

For all versions non-perturbative input parton densities of the form

$$xf_i(x, k_{T0}^2) = A_i x^{a_i} (1-x)^{b_i}$$

were used, with all parameteres A_i, a_i, b_i **and the perturbative cutoff** k_{T0}^2 **fitted to reproduce the measured data on** $F_2(x, Q^2)$. **In all cases we used** $\mu^2 = m_T^2$.

The integration limits in SHA(*) **and SPM(*) are given by the kinematic conditions of the D0 and CDF exps.**

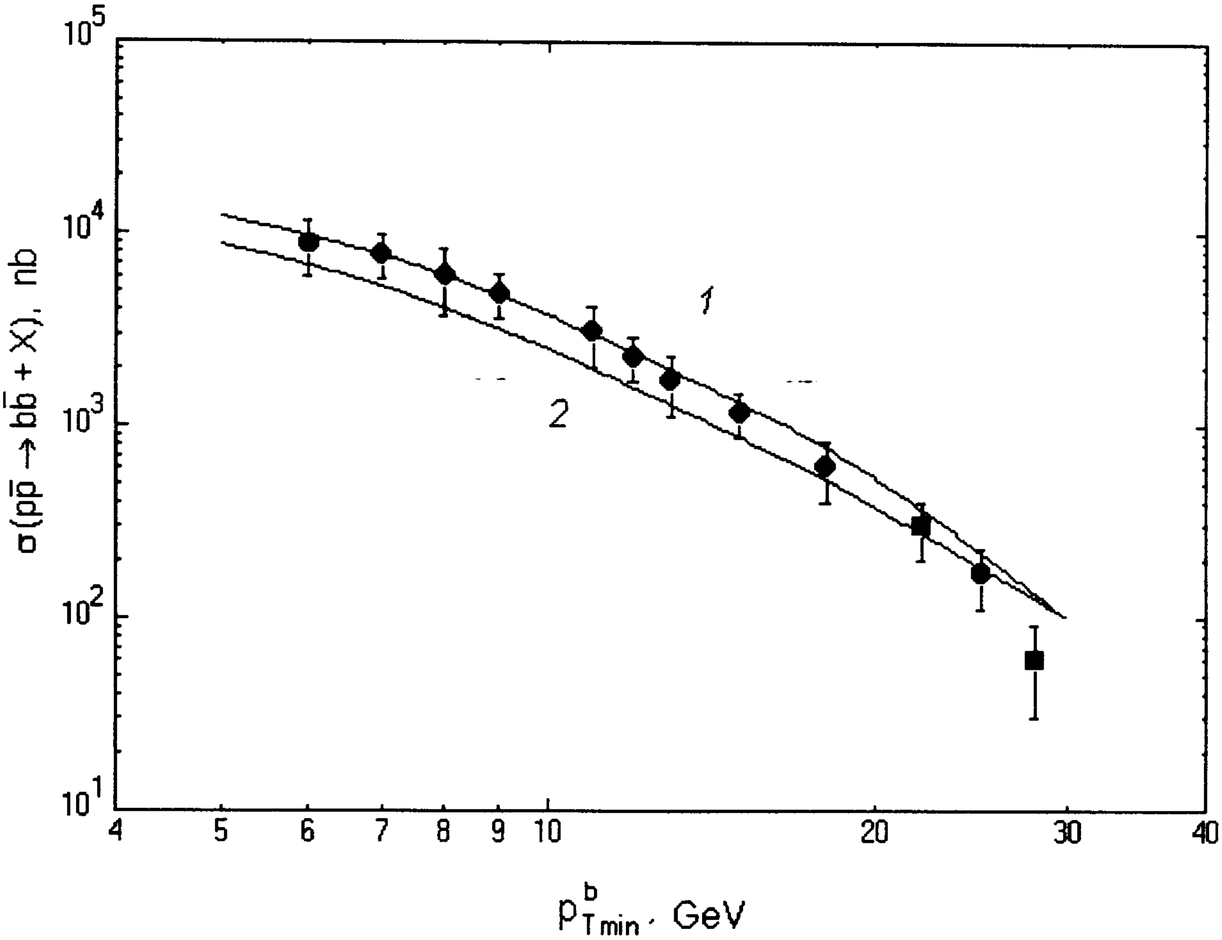
The calculation of H.Q. production c.s. in the SHA with JB u.g.d. have been done according to (*) **at** $q^2_{1T,2T} > Q^2_0$.

At $q^2_{1T,2T} \leqslant Q^2_0$ **we take** $q^2_{1T,2T} = 0$ **in m.e. and** $\Sigma|M_{SPM}(gg \to Q\bar{Q})|^2$ **instead** $\Sigma|M_{SHA}(g^*g^* \to Q\bar{Q})|^2$ **and use (*). We take** $Q^2_0 = 1$ **GeV**^{2}.

Our theor. results depend on m_b, μ **and** $b \to B$**-meson fragmentation f.**

For latter we use Peterson f.f. **with** $\epsilon = 0.006, m_B = 4.75$ **GeV and** $\mu^2 = q^2_{1T,2T}$ **(or** m^2_T**).**

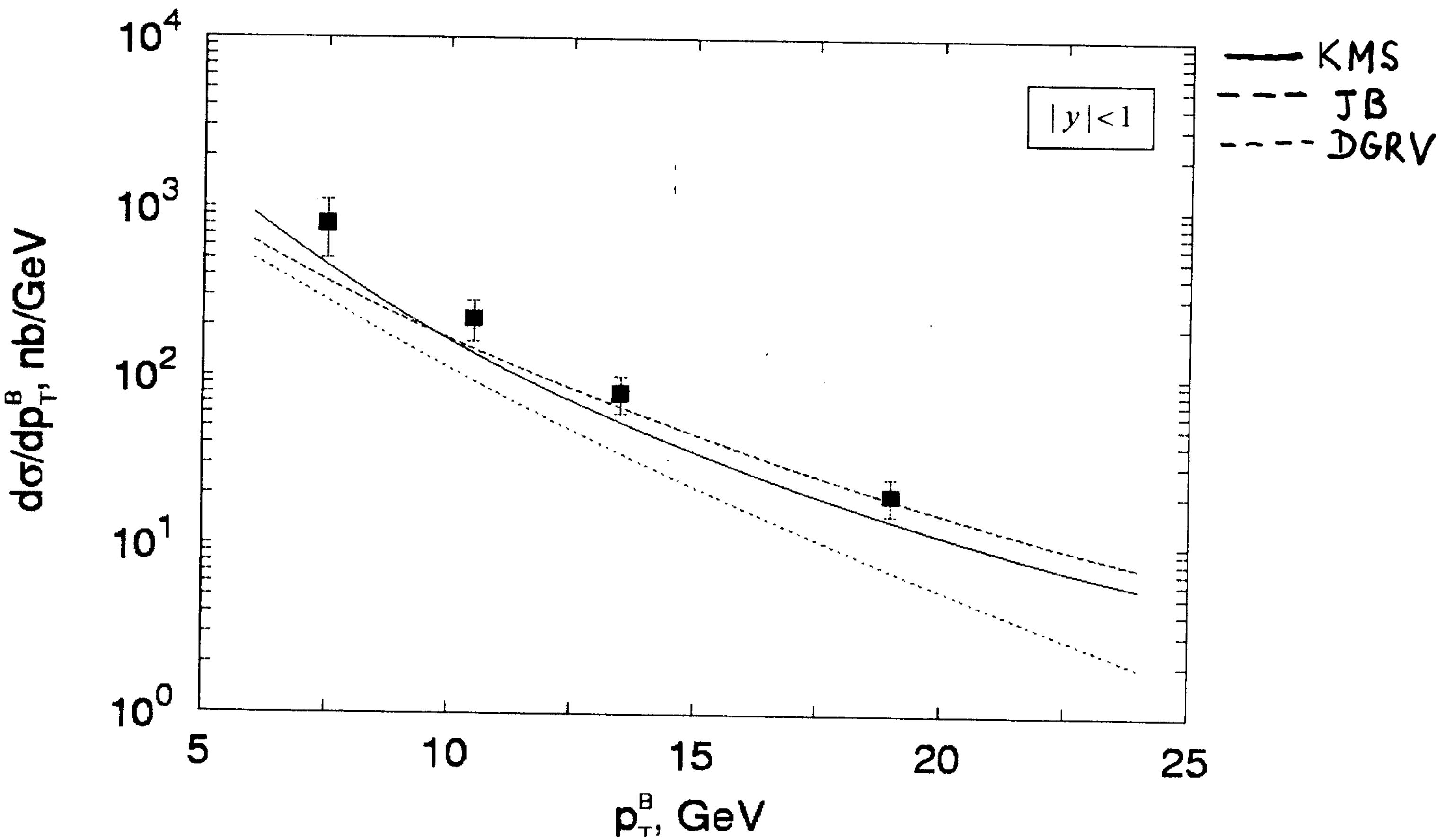
H. Q. production at Tevatron



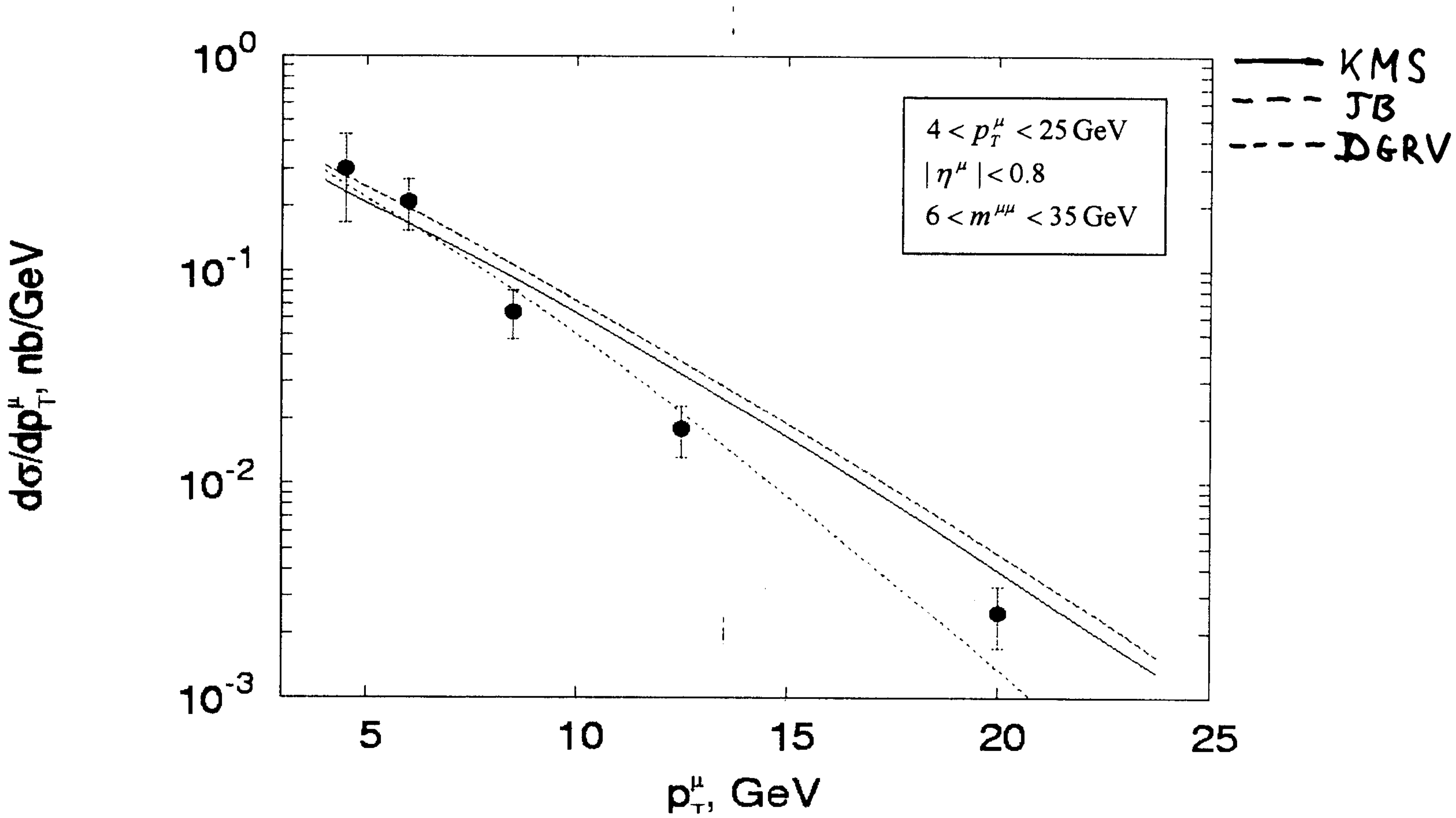
$1 - \mu^2 = \vec{q}_T^{\,2}$ $\quad 2 - \mu^2 = m_T^2 \equiv m_Q^2 + \vec{p}_T^{\,2}$

● ■ DØ, CDF

Numerical results

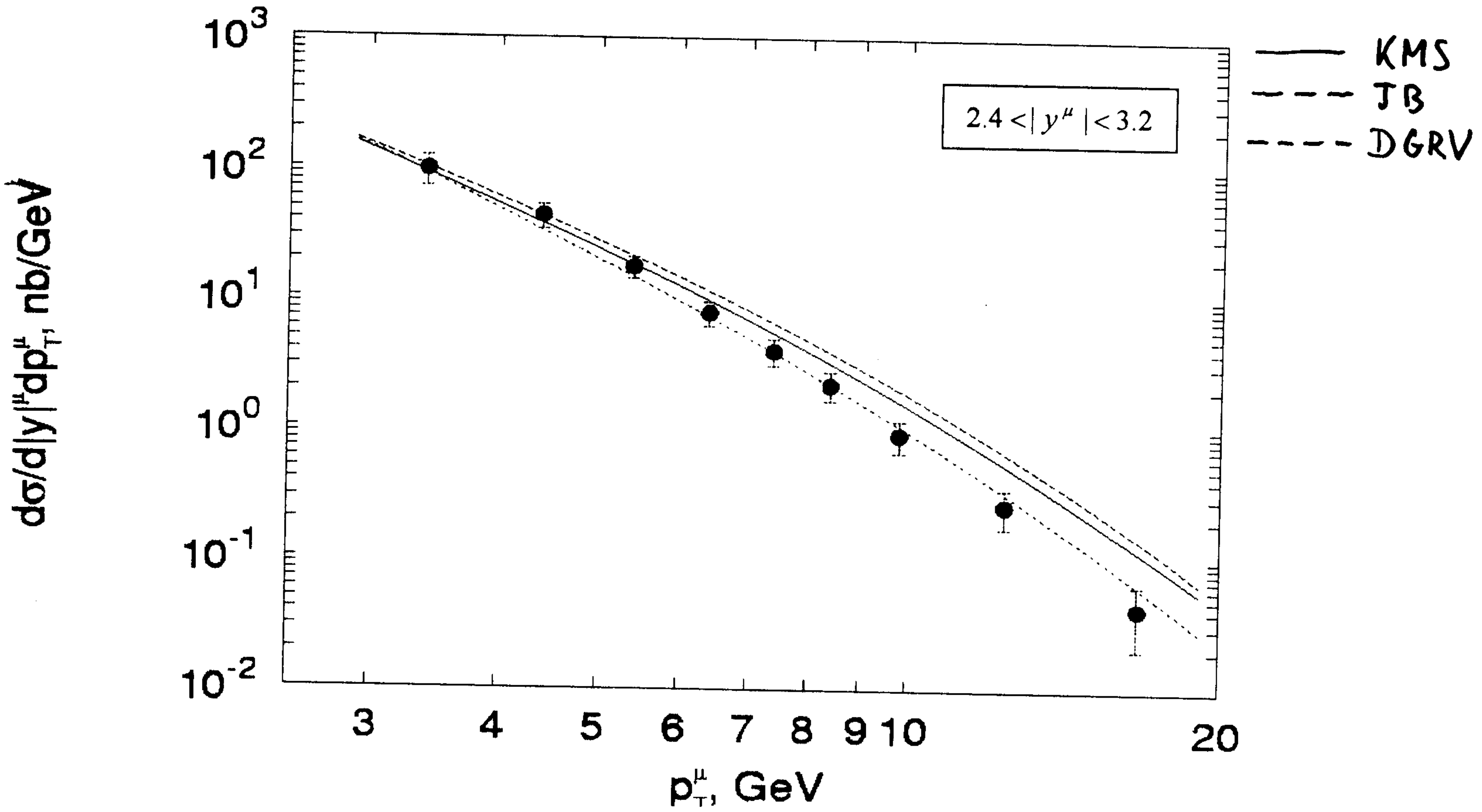


Experimental data are from CDF D. Acosta et al, hep-ex/0206019



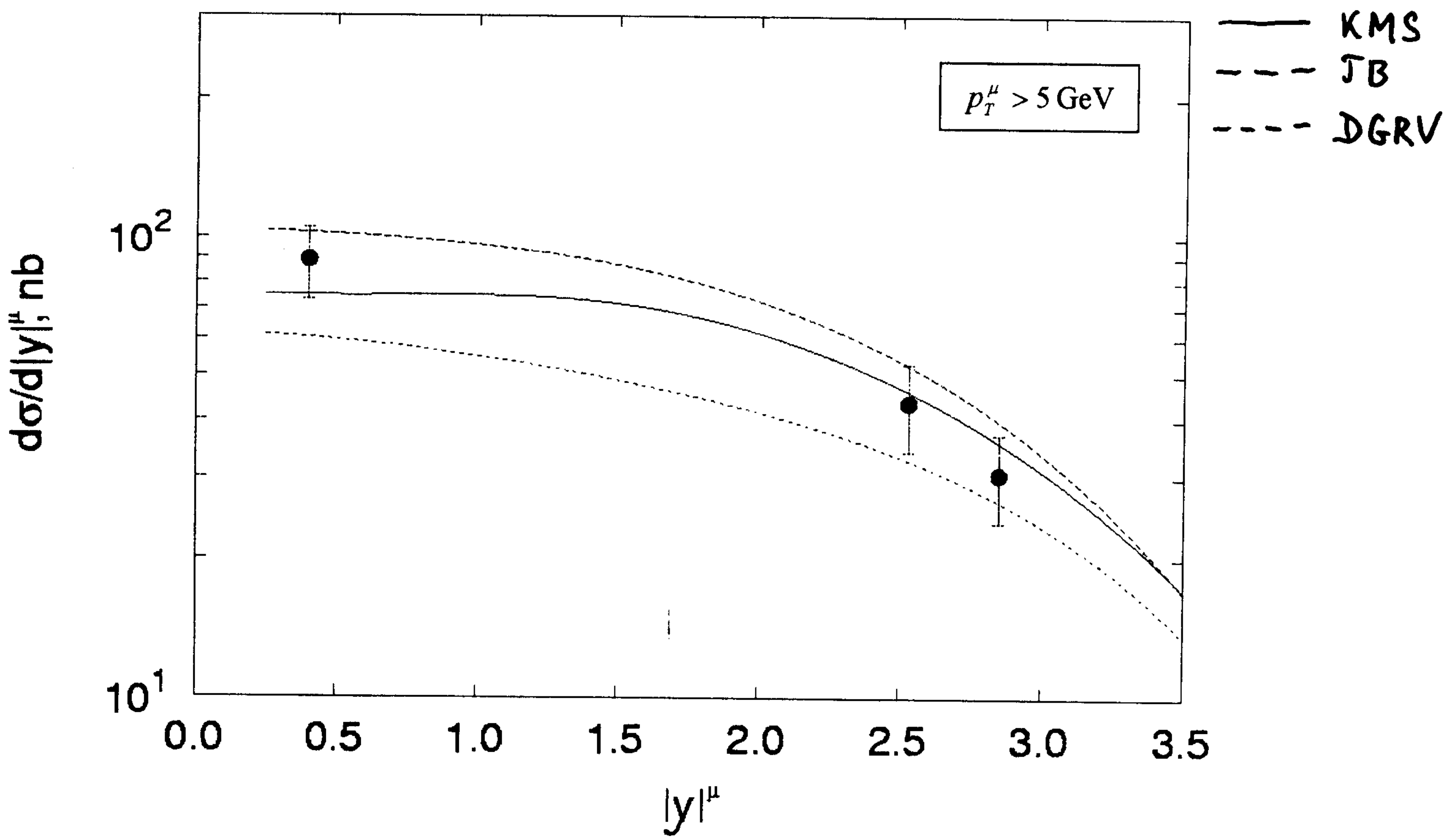
Experimental data are from D0 B. Abbott et al, Phys. Lett. B 487, 264 (2000)

Numerical results

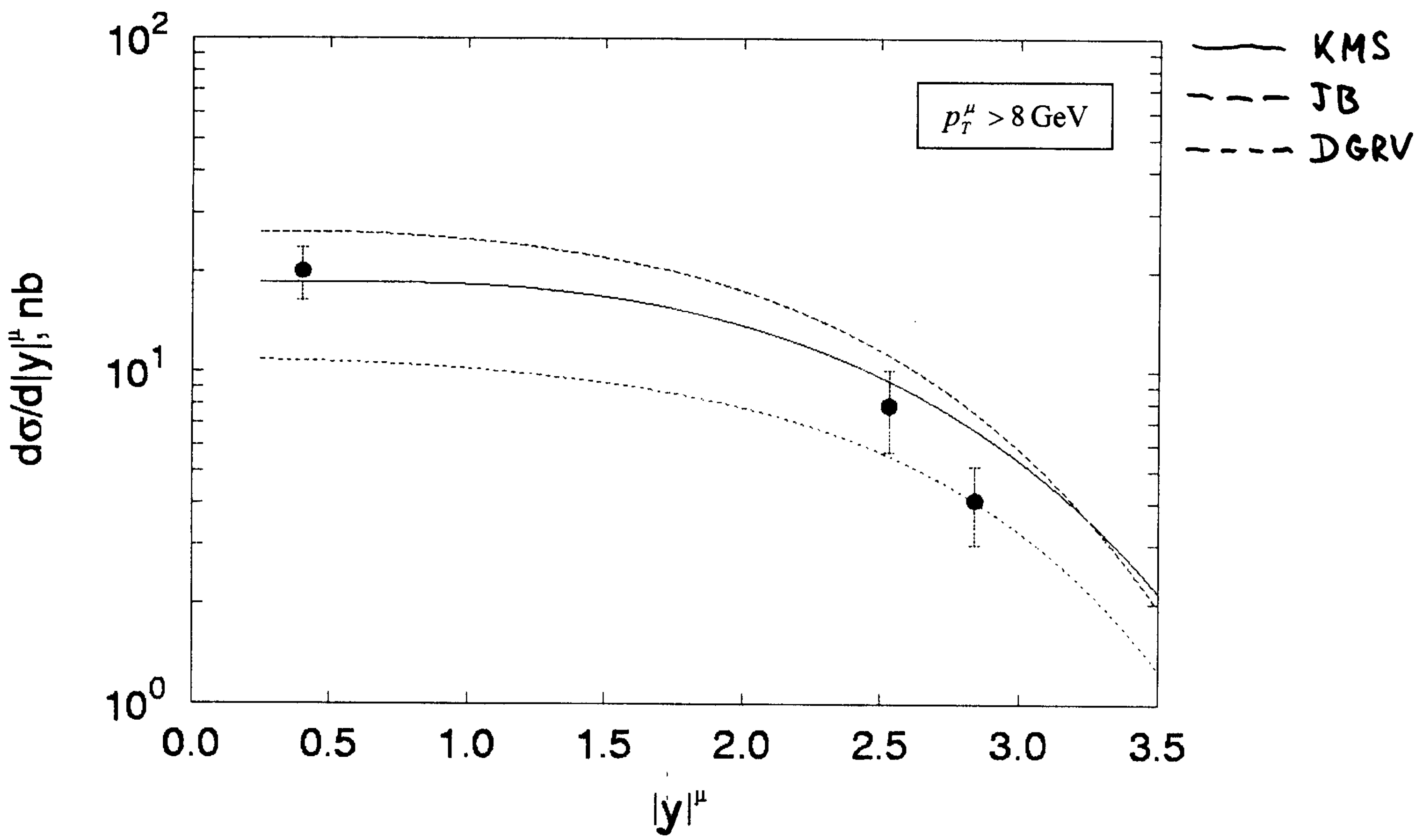


Experimental data are from D0 B. Abbott et al, hep-ex/9907029

Numerical results



Experimental data are from D0 B. Abbott et al, hep-ex/9907029



Experimental data are from D0 B. Abbott et al, hep-ex/9907029

A. Lipatov, L. Lönnblad, N.Z.
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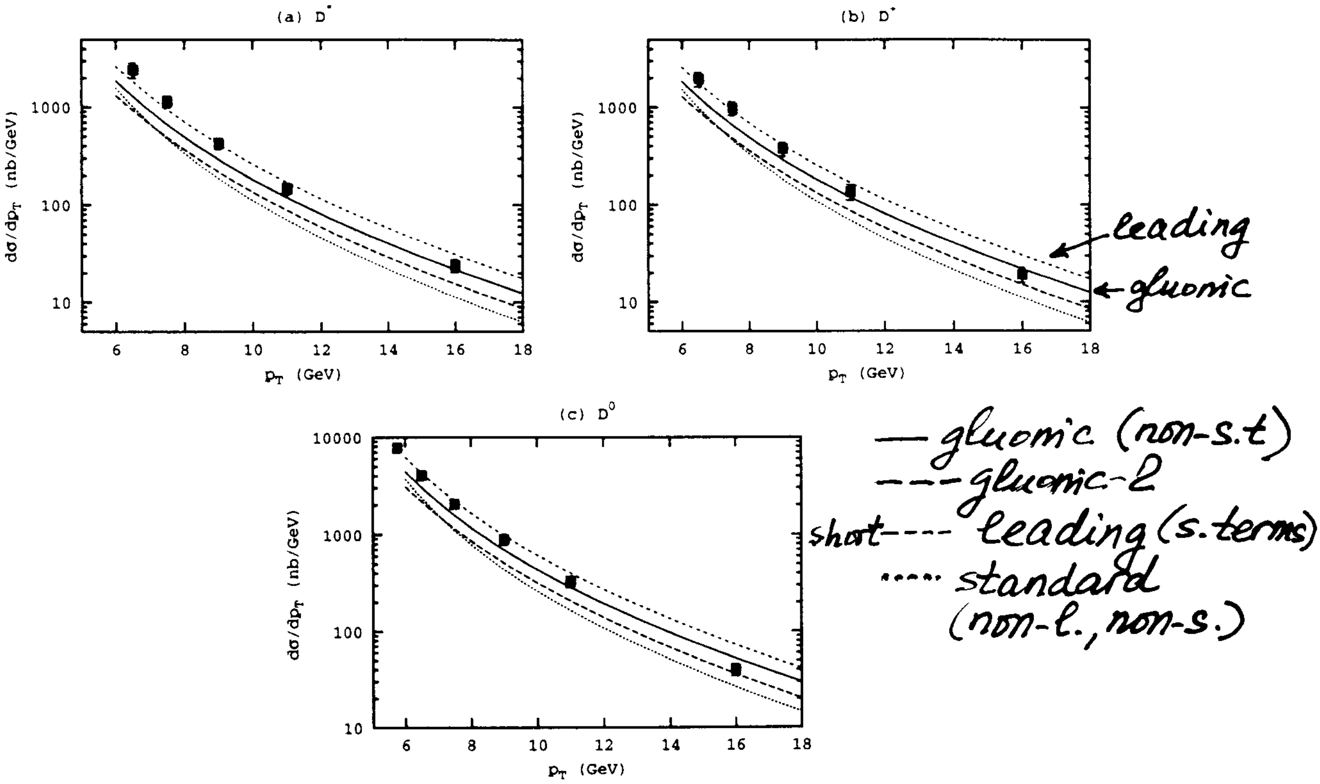


Figure 8: The prediction for the p_T spectrum of D^* (a), D^+ (b) and D^0 (c) mesons with $|y^D| < 1$ at $\sqrt{s} = 1960$ GeV compared to the CDF data. All curves are the same as in figure 3. Experimental data are from CDF [24].

leading version agree with data at $\Delta\phi^{\mu\mu} \sim \pi$ but overesimate data at $\Delta\phi^{\mu\mu} < 2\,\text{rad}$. The *gluonic* version agree with data within experimental errors everywhere but also tends to overestimate data in the small $\Delta\phi^{\mu\mu}$ region. Also we can conclude that effects connected with inclusion of non-singular terms in the gluon splitting function appears at $\Delta\phi^{\mu\mu} < 2.5\,\text{rad}$ only because at $\Delta\phi^{\mu\mu} > 2.5\,\text{rad}$ the *leading* and *gluonic* versions practically coinside.

Very recently CDF collaboration have reported preliminary experimental data [24] on charm production at the Tevatron Run II. These data found to be about a factor of 1.5 larger than NLO pQCD theoretical predictions [34]. In this paper we also will apply the LDC model for the description of CDF data [24].

The results of our calculations of transverse momenta spectra for D^*, D^+ and D^0 mesons with $|y^D| < 1$ at $\sqrt{s} = 1960$ GeV are shown in figure 8. One can see that *leading* version overestimate data at high $p_T > 10$ GeV but *gluonic* one are more or less in agreement with data within experimental errors except the small p_T region for D^* production. We would like to note that such observable overestimation data at high p_T could be connected with the importance of the transverse momentum logarithms resummation in this kinematical region, as it argued in [31, 34]. However for B meson production such resummation are not needed because the CDF experimental data [19] can be described well within the k_T-factorization formalism with the usual Peterson fragmentation function

Azimuthal $b\bar{b}$-correlations

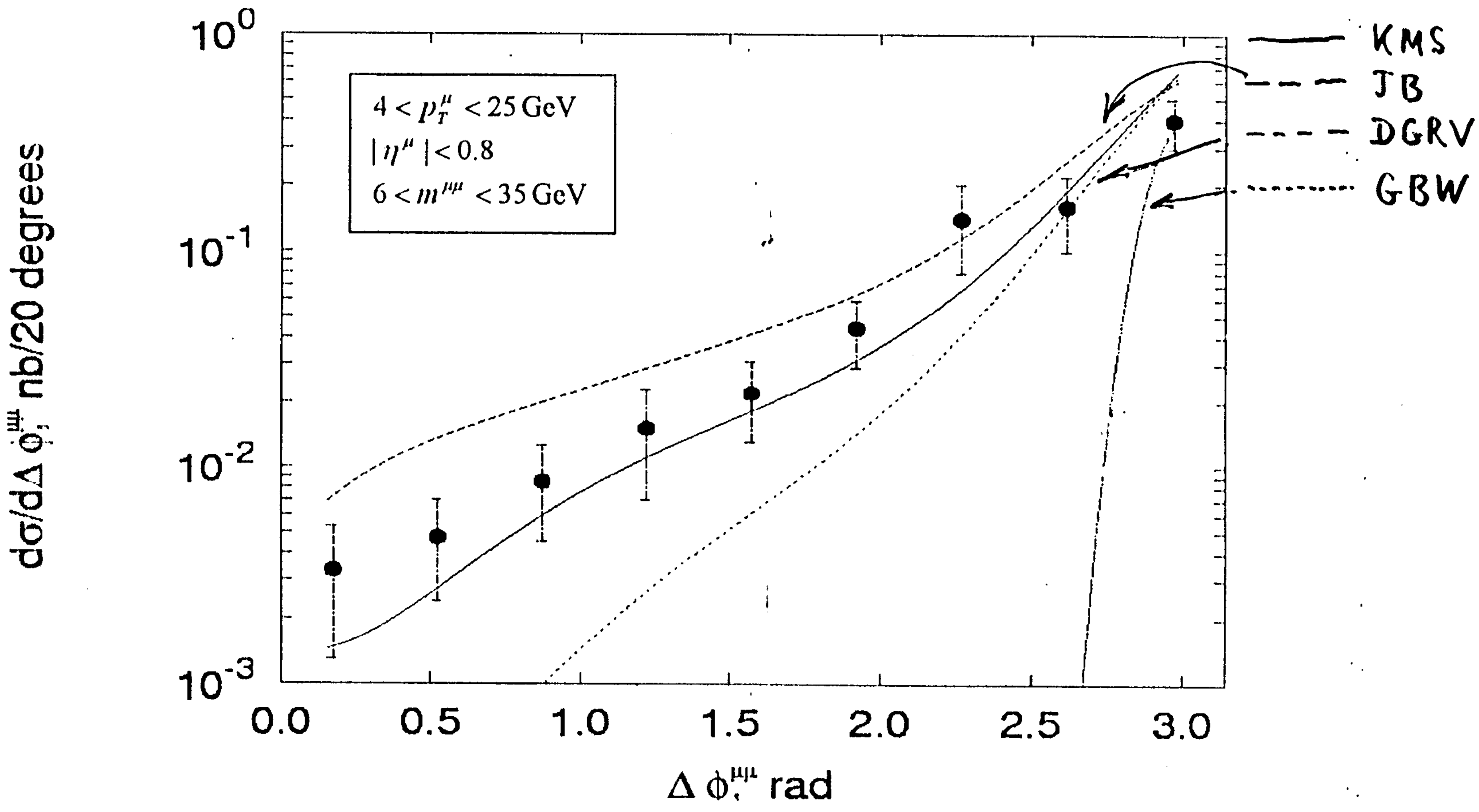
In the LO gg-fusion mechanism the distribution over the azimutal angle difference $\Delta\phi^{b\bar{b}}$ must be $\delta(\Delta\phi^{b\bar{b}} - \pi)$.

Taking into account the non-vanishing initial gluon t. m. q_{1T} and q_{2T} leads to the violation of this back-to-back symmetry in the k_T-factorization approach. Fig.

The shape of DGRV curve strongly differs from JB and KMS. At $\Delta\phi^{\mu\mu} \sim 0$ DGRV underestimates the D0 exp. data.

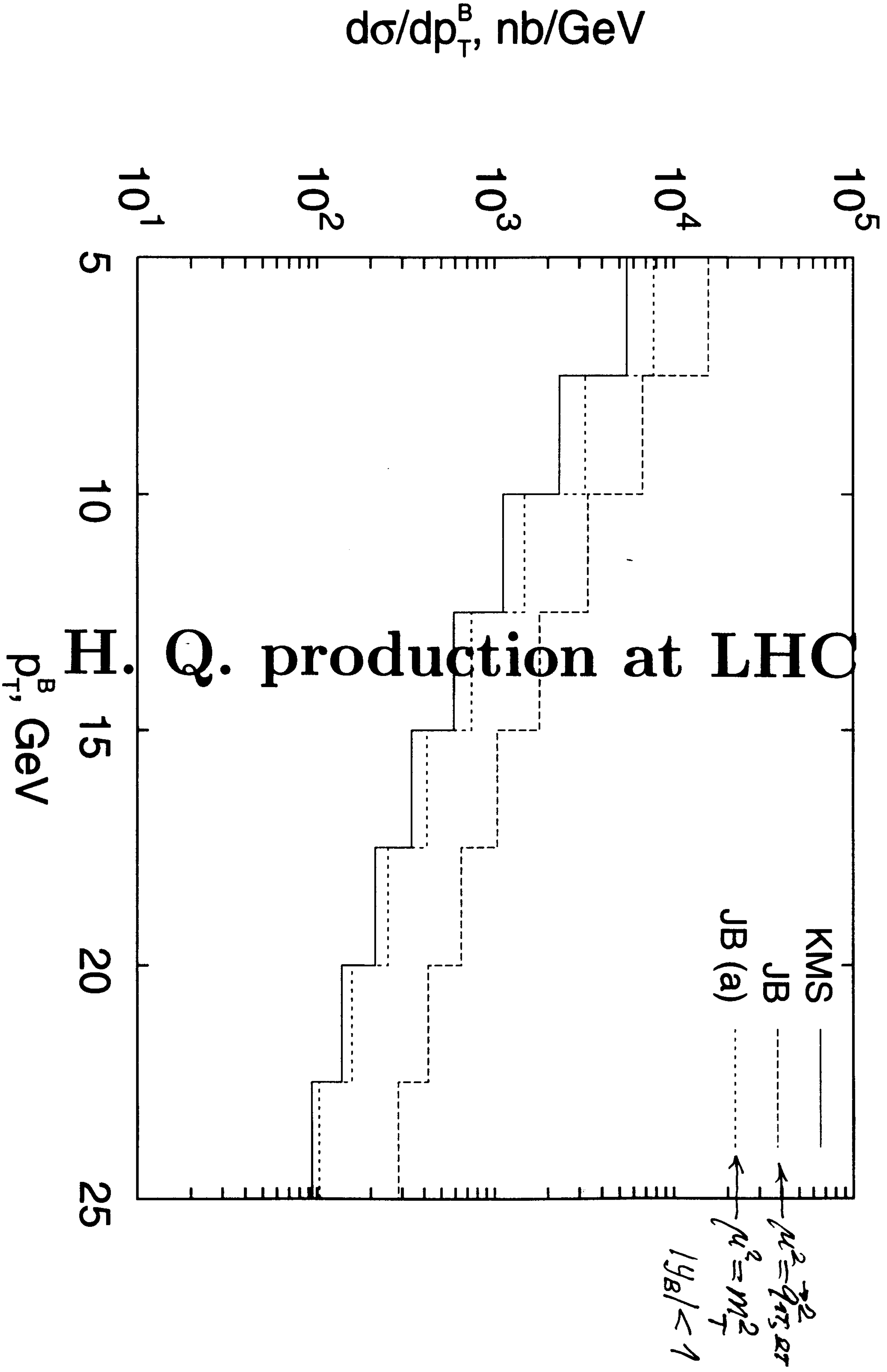
$\rightarrow$ **This fact indicates the importance of the large $\alpha_s^n \ln^n(1/x)$ contributions.**

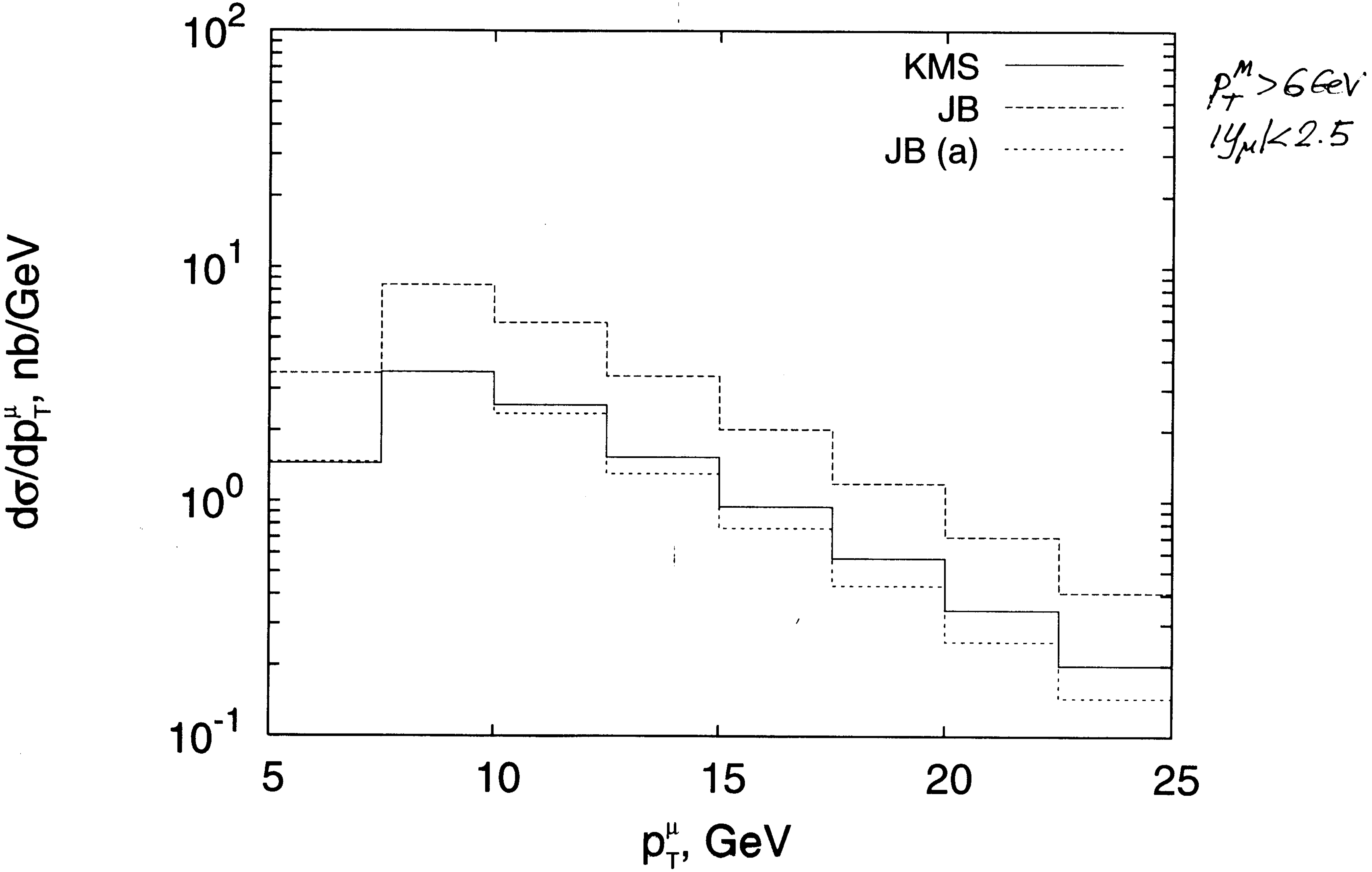
LO pQCD gives a peak at $\Delta\phi^{\mu\mu} \sim \pi$.



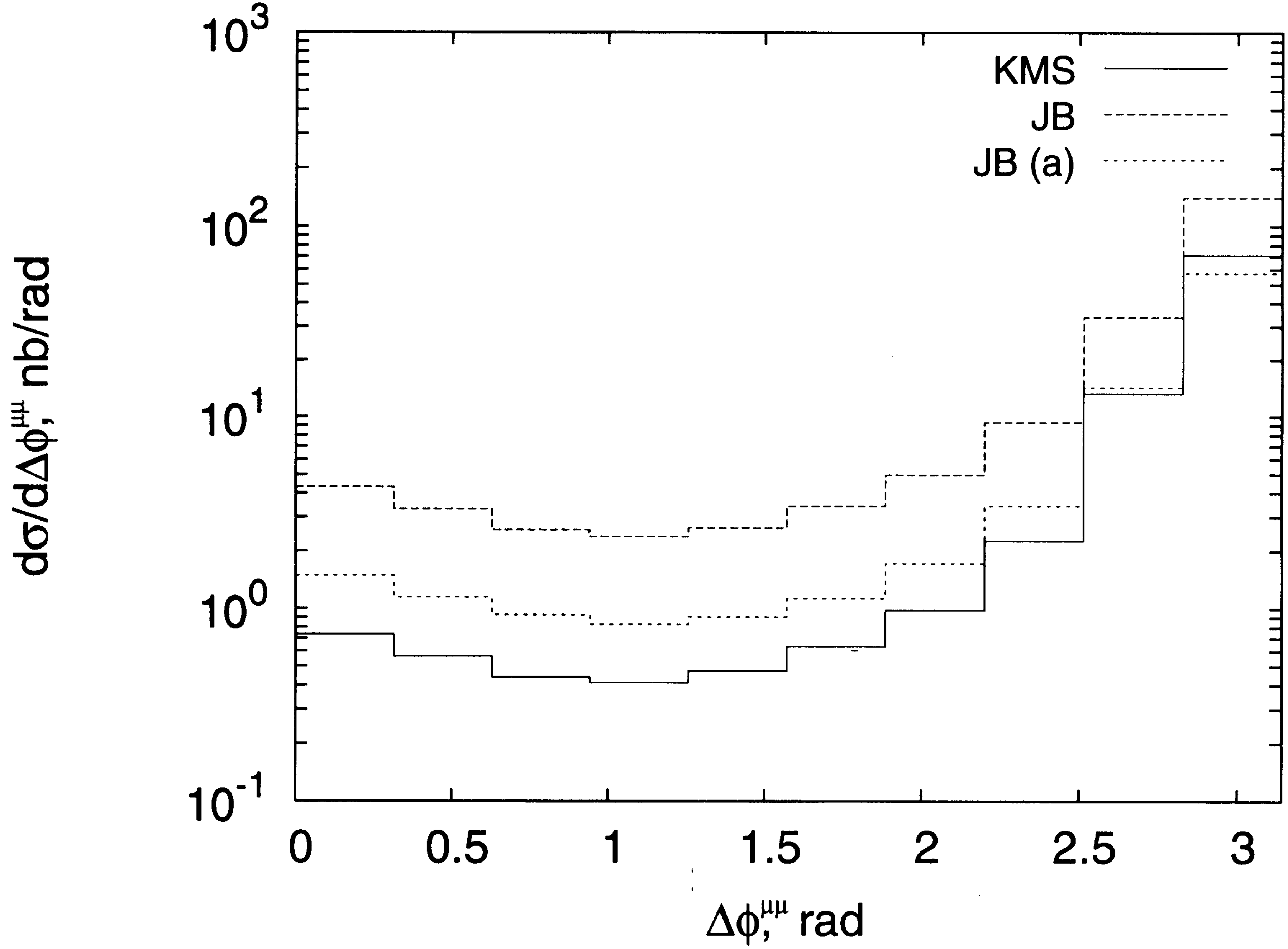
Experimental data are from D0 B. Abbott et al, Phys. Lett. B 487, 264 (2000)

H. Q. production at LHC

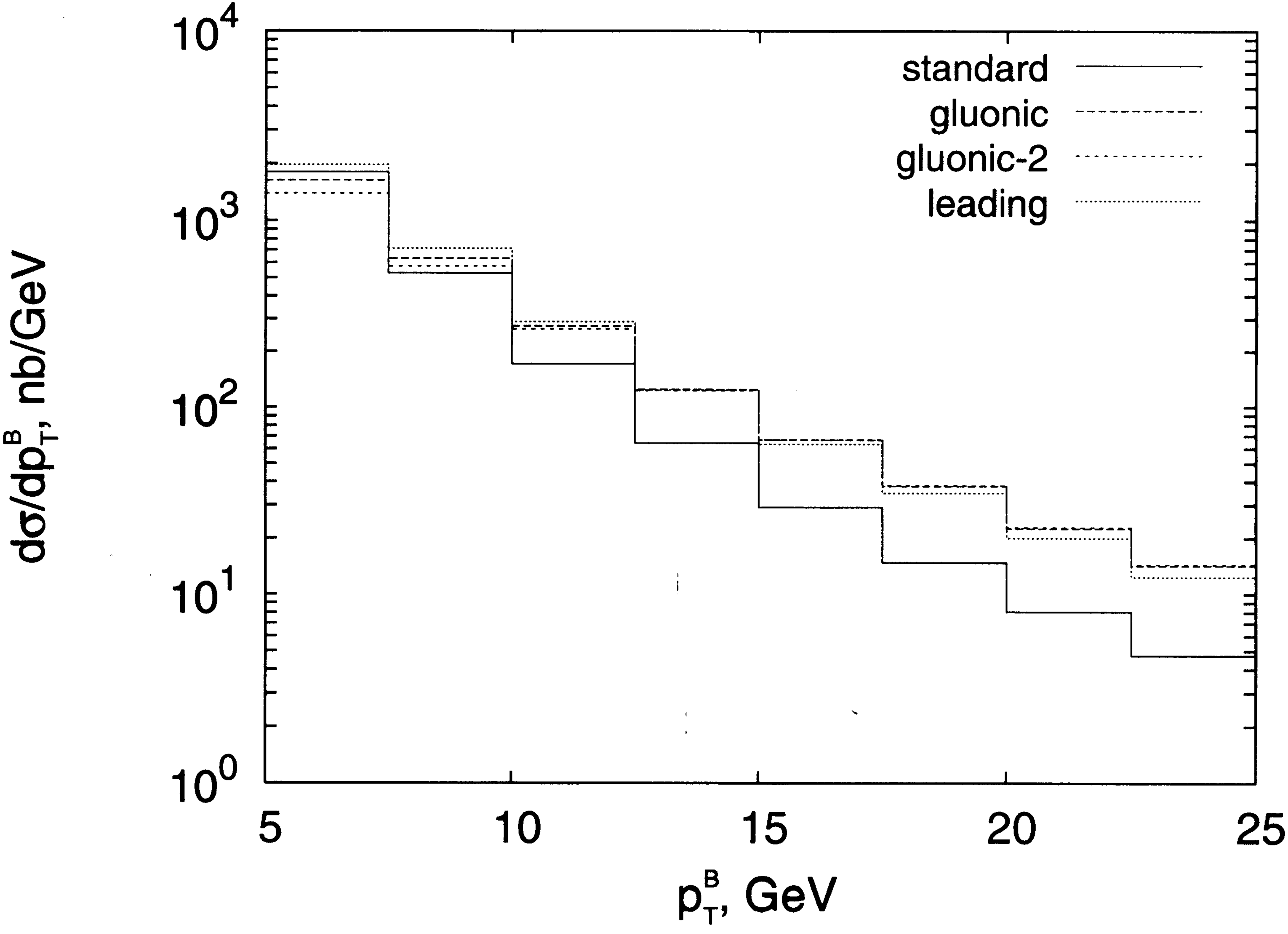




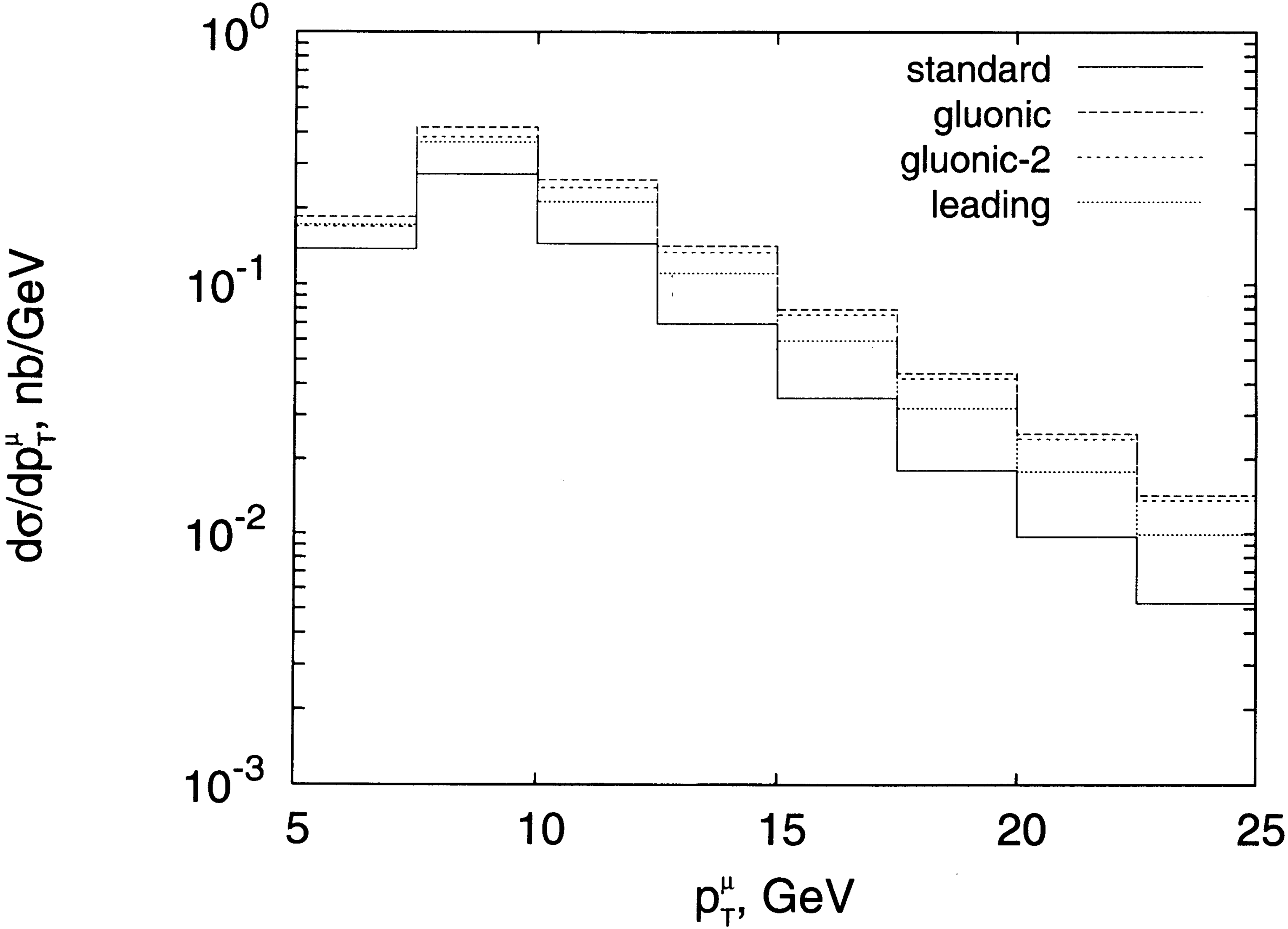
$d\sigma/dp_T^\mu$, nb/GeV
10^2
10^1
10^0
10^{-1}
KMS
JB
JB (a)
$p_T^\mu > 6$ GeV
$|y_\mu| < 2.5$
5
10
15
20
25
p_T^μ, GeV



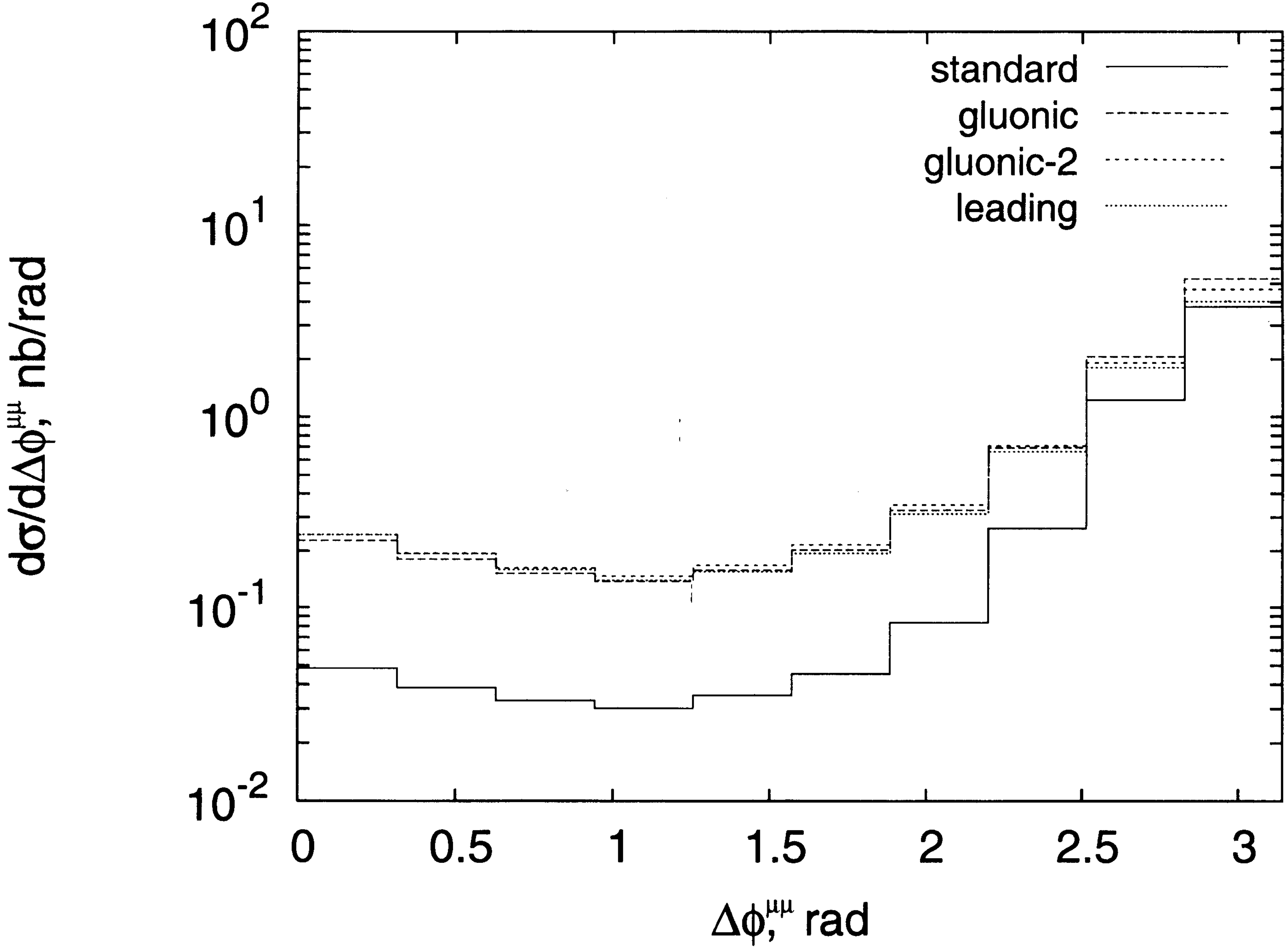
KMS
JB
JB (a)
10^3
10^2
10^1
10^0
10^-1
dσ/dΔφ,^μμ nb/rad
0
0.5
1
1.5
2
2.5
3
Δφ,^μμ rad



$d\sigma/dp_T^B$, nb/GeV
10^4
10^3
10^2
10^1
10^0
5
10
15
20
25
p_T^B, GeV
standard
gluonic
gluonic-2
leading



standard
gluonic
gluonic-2
leading
10^0
10^{-1}
10^{-2}
10^{-3}
5
10
15
20
25
$d\sigma/dp_T^\mu$, nb/GeV
p_T^μ, GeV



standard
gluonic
gluonic-2
leading
10^2
10^1
10^0
10^{-1}
10^{-2}
0
0.5
1
1.5
2
2.5
3
$d\sigma/d\Delta\phi_{,}^{\mu\mu}$ nb/rad
$\Delta\phi_{,}^{\mu\mu}$ rad

4. Summary

- **We studied H.Q. hadroproduction at Tevatron and LHC with k_T-factorization.**
- **JB and KMS u.g.d. describe the all exp. data. LDC:** *leading* **and** *gluonic.*
- **Azimuthal correlation in H.Q. production is a powerful test for u.g.d. (KMS).**
- **We obtained the predictions at LHC.**

We hope that H.Q. production at LHC
— very nice tool for study of
the k_T-factorization effects