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1. Introduction

Why k_T-factorization or semihard approach (SHA)?

1) At HERA energy and beyond 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 $\int\limits_0^{Q^2} F_g(x, \vec{k}_T^2) d\vec{k}_T^2 \sim xG(x, Q^2)$.

3) LO+NLO calculations for H.Q. production have some problems:

- all pQCD calculations underestimate the cross sections of D^* production at intermediate p_T and forward η at HERA
- all pQCD calculations underestimate the cross sections of $b\bar{b}$ production at TEVATRON and HERA
- there is the very large discrepancy (by more than an order of magnitude) between the pQCD predictions (with CSM) and existing exp. data for quarkonium production at TEVATRON.

- 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. Saleev; Phys. Atom. Nucl. 66(03) 755 hep-ph/0112114

"Ingredients" of k_T-factorization approach:

- Unintegrated gluon distribution $\Phi(x, q_T^2, \mu^2)$ obey BFKL equation which involve resummation of the terms $\alpha_S^n \ln^n \mu^2/\Lambda^2$, $\alpha_S^n \ln^n \mu^2/\Lambda^2 \ln^n 1/x$, $\alpha_S^n \ln^n 1/x$.

  <u>BFKL</u>: E. Kuraev, L. Lipatov, V. Fadin, Sov. Phys. JETP, **44** (1976) 443;
  E. Kuraev, L. Lipatov, V. Fadin, Sov. Phys. JETP, **45** (1977) 199;
  Yu. Balitsky, L. Lipatov, Sov. J. NP., **28** (1978) 822

  <u>CCFM</u>: S. Catani, F. Fiorani, G. Marchesini, NP., **B336** (1990) 18;
  M. Ciafaloni, NP., **B296** (1988) 49;
  G. Marchesini, NP., **B445** (1995) 49.

- Off-mass shell matrix elements of partonic subprocesses
  Virtual gluon polarization tensor $L^{\mu\nu}(q)$ is taken in BFKL form:

$$L^{\mu\nu}(q) = \frac{q_T^\mu q_T^\nu}{q_T^2}$$

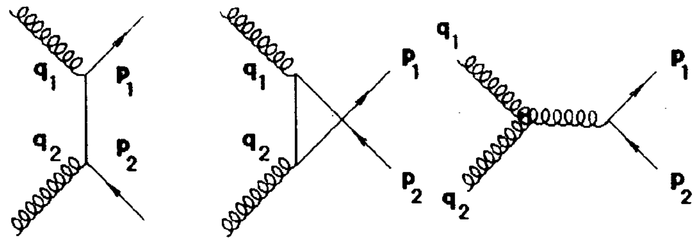
Therefore cross sections can be k_T-factorized into an off-shell (k_T dependent) partonic c.s. $\hat{\sigma}(x, k_T^2)$ and k_T-unintegrated parton d.f. $\mathcal{F}$

$$\sigma = \int \frac{dz}{z} d^2k_T \, \hat{\sigma}\left(\frac{x}{z}, k_T^2\right) \mathcal{F}(z, k_T^2)$$

We have k_T factorization instead standard collinear factorization

4. 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:



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

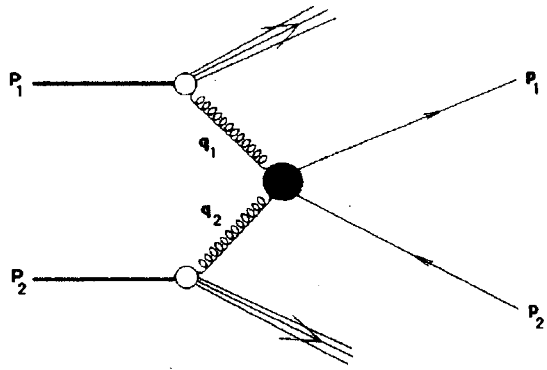
$$C^{\mu\nu\lambda}(q_1,q_2,q_3) = i((q_2-q_1)^\lambda g^{\mu\nu} + (q_3-q_2)^\mu g^{\nu\lambda} + (q_1-q_3)^\nu g^{\lambda\mu}).$$

The calculation of $|M|^2$ 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:

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

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

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

The integration limits in $\overset{SHA}{(*)}$ and $\overset{SPM}{(*)}$ are given by the kinematic conditions of the DØ and CDF exps.

The calculation of H.Q. production c.s. in the SHA have been done according to $(*)$ at $q^2_{1T,2T} \geq Q_0^2$

At $q^2_{1T,2T} \leq Q_0^2$ we take $q^2_{1T,2T} = 0$ in m.e. and $\sum |M_{SPM}|^2 (gg \to Q\bar{Q})$ instead of $|M_{SHA}(g^* g^* \to Q\bar{Q})$ and use $(*)$

The choice $Q_0^2 = 1\ GeV^2$ is determined by the requirement that $\alpha_s(\mu^2)$ at $q^2_{1T,2T} \geq Q_0^2$ should be small $(\alpha_s(\mu^2) < 0.26)$

Our theor. results depend on m_b, μ_F^2 and $b \to B$ fragmentation f.

For letter we use <u>Peterson f.f.</u> with $\epsilon = 0.006$

$m_b = 4.75$ GeV. and $\mu^2 = q^2_{1T,2T}$ (or m_T^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

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

and $\bar{\alpha}_S=3\alpha_S/\pi$. $\Delta=j-1=\bar{\alpha}_S 4\ln 2\sim 0.53$ in LO and $\Delta=\bar{\alpha}_S 4\ln 2-N\bar{\alpha}_S^2$ 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 – $\ln(1/x)\ln(\mu^2/k^2)$; DGRV – $\ln(\mu^2/k^2)$

$\Rightarrow$ 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.
R. Andersson et al. {DESY 02-041 (hep-ph/0204115) Eur. Phys. J. C25 (20[illegible]

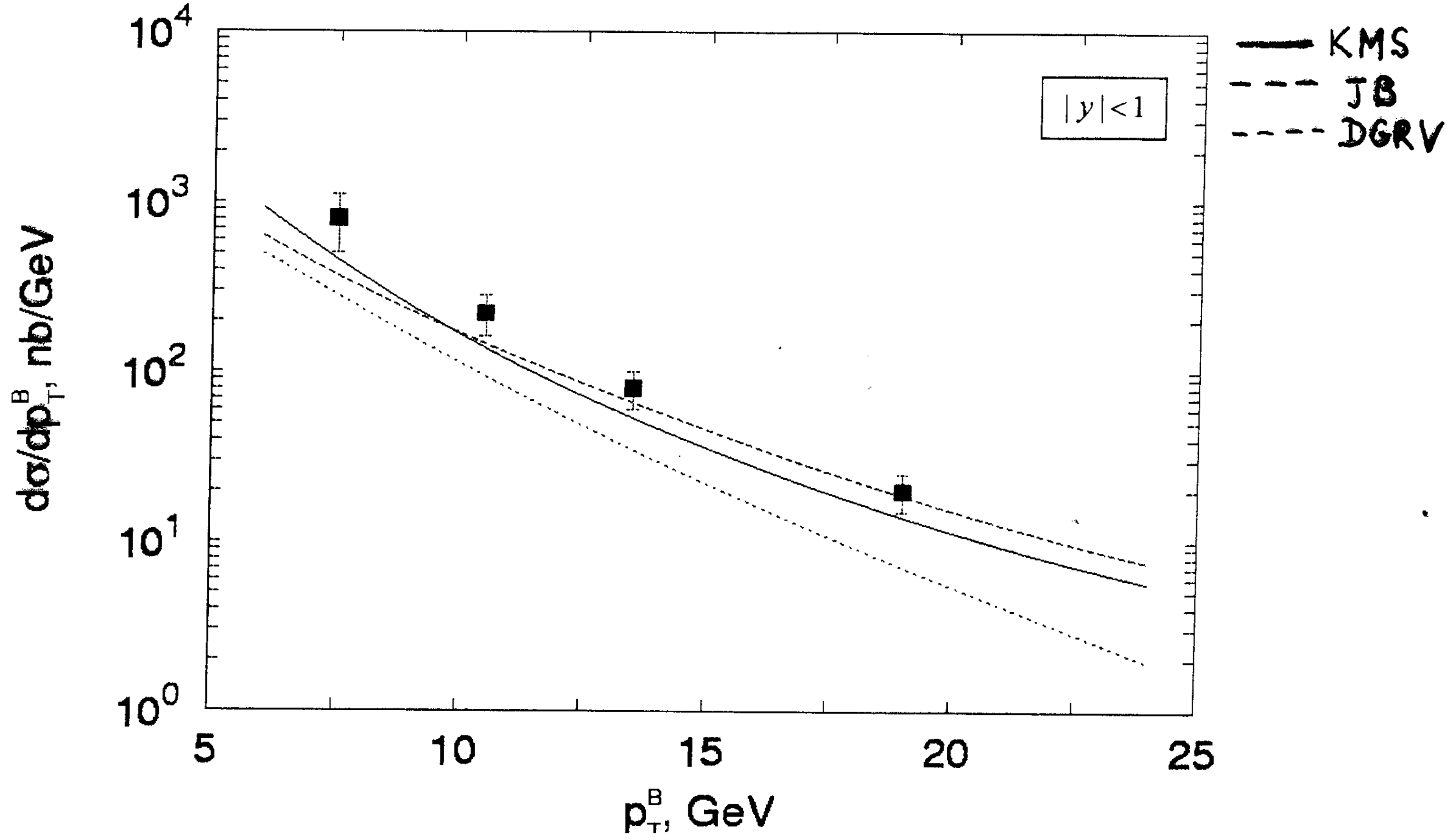
Fig. 7: KMR ≈ JB u.g.d.
Fig. 8: KMS ≈ KMR ≈ DGRV
Fig. 9: RS ≈ KMS

GRW → GRV ⟺ F_L

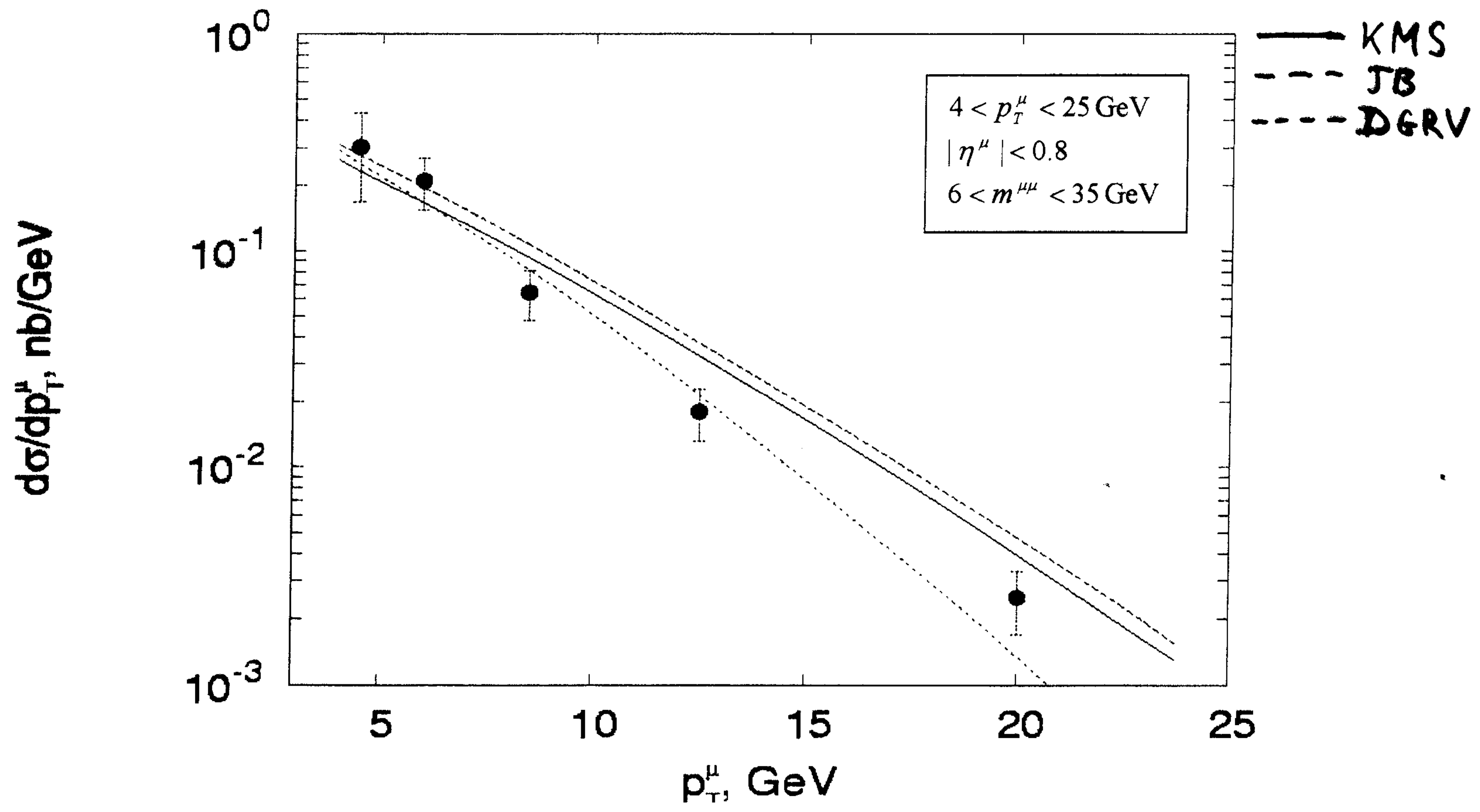
Exhaustive discussion of the u.pdf's was done by
J.C. Collins, hep-ph/0304122

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.

Numerical results

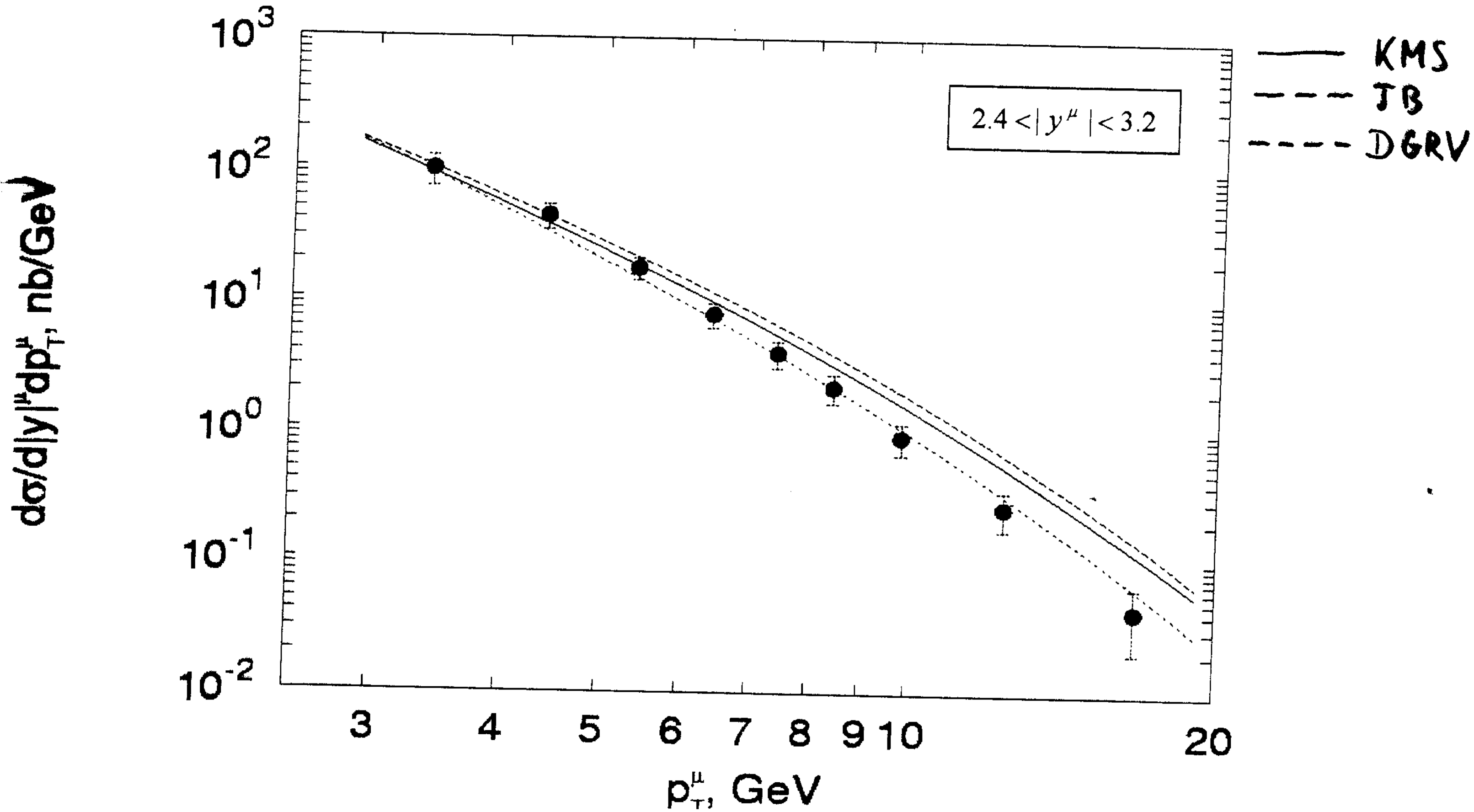


Experimental data are from CDF D.Acosta et al, hep-ex/0206019

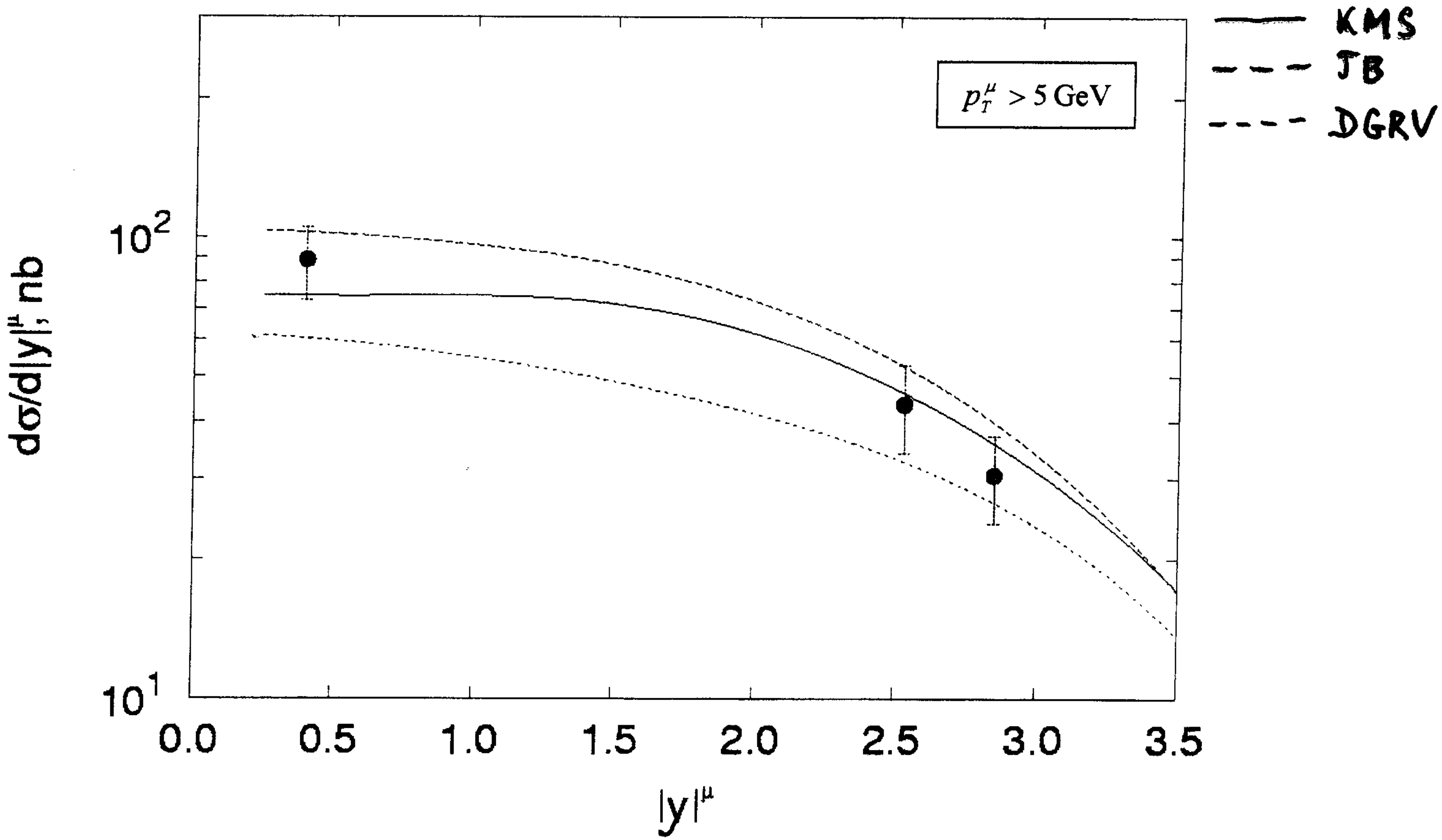


Experimental data are from D0 B. Abbott et al, Phys. Lett. B 487, 264 (2000)

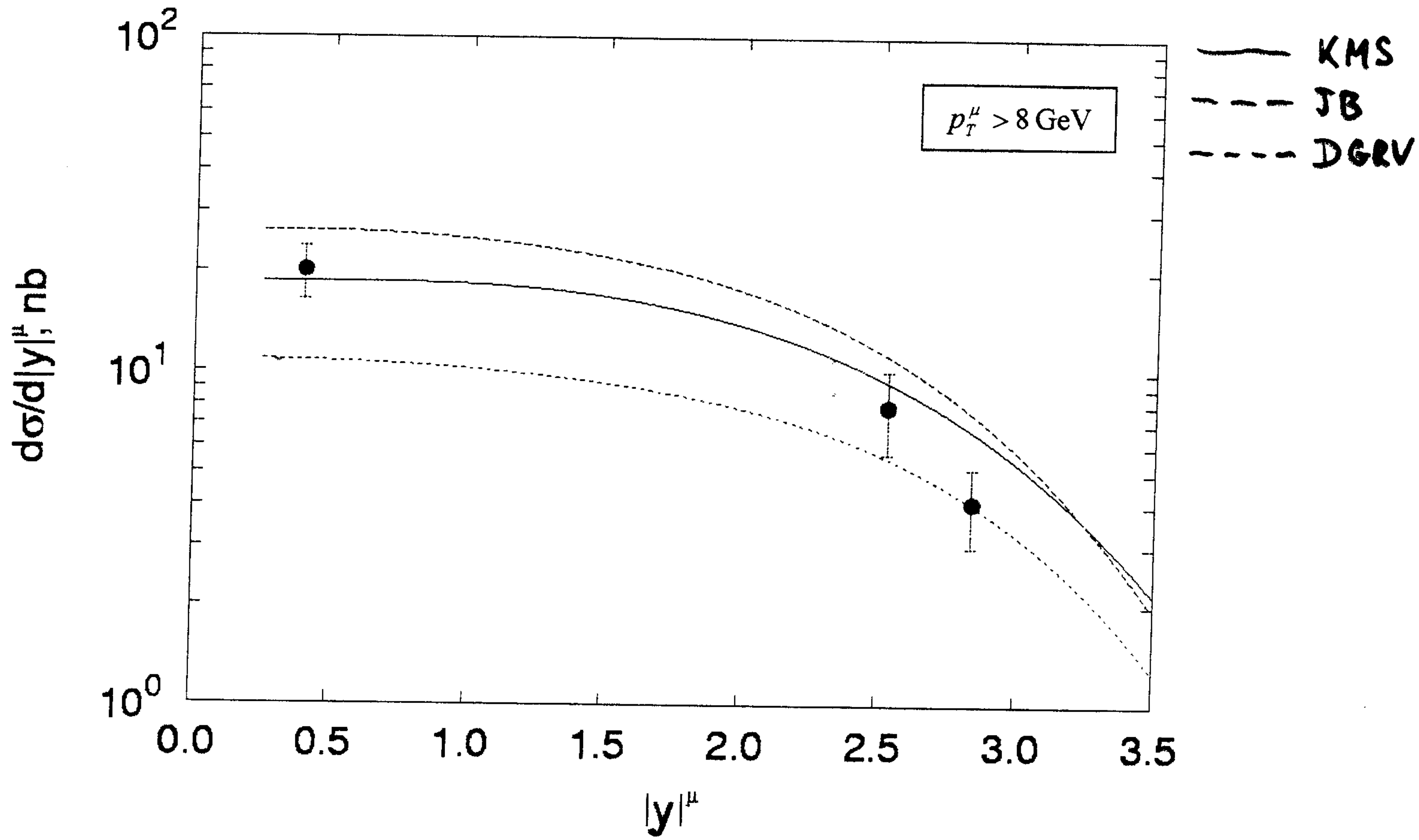
Numerical results



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



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



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

Azimuthal $b\bar{b}$-correlations

The investigations of $b\bar{b}$-correlations such as the azimuthal opening angle between b and $\bar{b}$ quarks (or their decay μ) allow additional details of $b\bar{b}$ production to be tested since these quantities are sensitive to the relative contributions of the different production mechanisms

LRSS, Yad. Fiz 53 (91) 1059

In the naive gg-fusion mechanism, the distr. over the azimuthal angle difference $\Delta\varphi^{b\bar{b}}$ must be $\delta(\Delta\varphi^{b\bar{b}} - \pi)$.

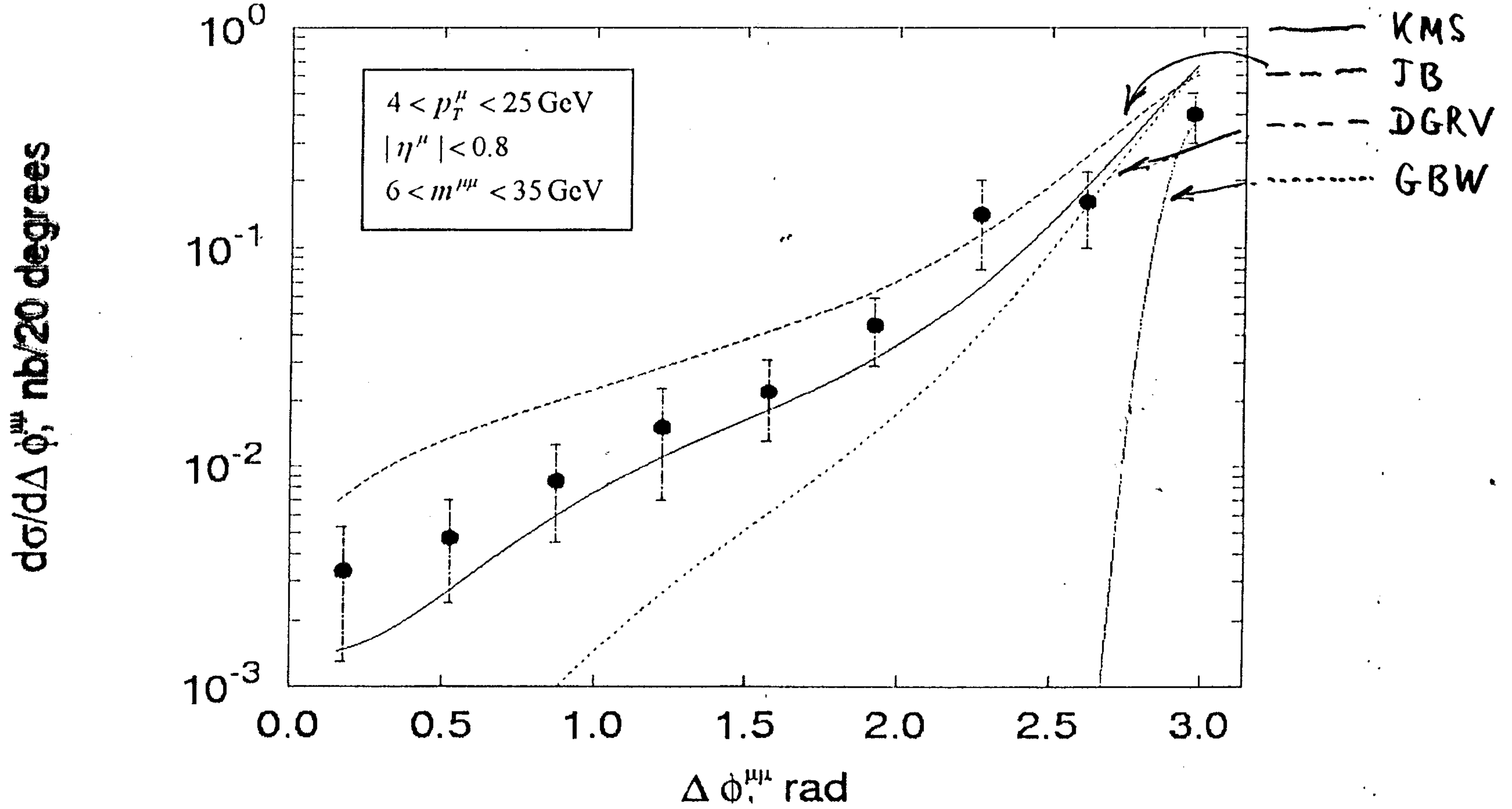
Taking into account the non-vanishing initial gluon t. m. q_{1T} and q_{2T} leads to the violation of this back-to-back symmetry in k_T factorization approach

The shape of DGRV curve strongly differs from JB and KMS

At $\Delta\varphi^{\mu\mu} \sim 0$ DGRV underestimates the DØ exp. d

$\Rightarrow$ this fact indicates the importance of the large $\alpha_s^n \ln^n(1/x)$ contributions

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



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

Summary:

- We study Heavy Quark Hadroproduction at Tevatron with k_T-factorization.
- JB and KMS unintegrated gluon distributions describes well all experimental data.
- Azimuthal correlation in Heavy Quark Production is a powerful test for unintegrated gluon distributions.
- GBW saturation model failed for Heavy Quark Hadroproduction at Tevatron.
- We give predictions for $\mu\mu$ and μ+jet c.s. at LHC