Possible saturation effects in the k_T factorization at HERA and LHC

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3. **Structure function F_L at HERA**
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1. Motivation

Remarkable progress in study of DIS processes at HERA has resulted from the observation: the gluon density in a proton at small x grows as x decreases.

Both DGLAP and BFKL evolution equations predict this rapid growth of the parton densities, demonstrating the triumph of pQCD.

However it is clear that this growth cannot continue for ever, because it would violate the unitarity constraint

L.V. Gribov, E.M. Levin, M.G. Ryskin, Phys. Rep. 100 (1983) 1.

Consequently, the parton evolution dynamics must change at some point, and new phenomenon must come into play.

Indeed as the gluon density increases, non-linear parton interactions are expected to become more and more important, resulting eventually in the slowdown of the parton density growth (known as "saturation effect")

L.V. Gribov, E.M. Levin, M.G. Ryskin (1983); A.H. Mueller, J. Qiu, NP B268 (1986) 427;

L.McLerran, R. Venugopalan, PR D49 (1994) 2233, PR D49 (1994) 3352, D50 (1994) 2225, D53 (1996) 458, D59 (1999) 094002...
K. Golec-Biernat, M. Wusthoff, PR D59 (1999) 014017, D60 (1999) 114023.

The underlying physics can be described by the non-linear Balitsky-Kovchegov (BK) equation
I.I. Balitsky, NP B463 (1996) 99;
Y.V. Kovchegov, PR D60 (1999) 034008.

These nonlinear interactions lead to an equilibrium-like system of partons with some definite value of the average transverse momentum k_T and the corresponding saturation scale $Q_s(x)$
E. Levin, in *THERA Book*, DESY 01-123F vol 4, DESY-LC-REV-2001-062, p.160.

This equilibrium-like system is the so called Color Glass Condensate (CGC)
E. Iancu, L. McLerran, nucl-th/0405013

Since the saturation scale increases with decreasing of x: $Q_s^2(x, A) \sim x^{-\lambda} A^{\delta}$ with $\lambda \sim 0.3, \delta \sim 1/3$, one may expect that the saturation effects will be more clear at the LHC energies.

In preasymptotic region $k_T \geq Q_s$
the k_T-factorization approach is applicable:

F. Gelis, R. Venugopalan, PR D69 (2004) 014019;
D. Kharzeev, K. Tuchin, NP A735 (2004) 248;
R. Baier, A.H. Mueller, D. Schiff,
NP A741 (2004) 358.

At $k_T < Q_s$ the k_T-factorization approach may be will give a chance to account for saturation effects (if they are under control the BK equation) using scale properties of dipole model, which is equivalent the k_T-factorization:

V. Barone, M. Genovese, N.N. Nikolaev,
E. Predazzi, B.G. Zakharov, PL B326 (1994) 161
A. Bialas, H. Navelet, R. Peschanski,
hep-ph/0009248

We have used the semi-hard (SHA)

L. Gribov, E. Levin, M. Ryskin (1983),
E. Levin, M. Ryskin, Y. Shabelski, A. Shuvaev,
Sov. J. Nucl. Phys. 53 (1991) 657

or k_T-factorization approach

S. Catani, M. Ciafaloni, F. Hautmann,
Nucl. Phys. B366 (1991) 135;
J. Collins, R. Ellis, Nucl. Phys. B360 (1991) 3,

in order to describe exp. data on:

- **charm quark photoproduction at HERA**
- J/ψ **production in photo- and electroproduction at HERA (at Tevatron also)**
- D^* **photoproduction and DIS**
- **charm contribution to the s.f.** $F_2^c(x, Q^2), F_L^c, F_L$
- $b\bar{b}$ **production at Tevatron**
- **charm,** D^* **and** J/ψ **production in two-photon collisions at LEP2**
- **Higgs production at LHC**
- **prompt photon production at HERA at Tevatron**

A.V. Lipatov, N. Z., hep-ph/0506044,
hep-ph/0507243.

The main goals of our study

- **to investigate whether the inclusive heavy quark, D^*, and J/ψ production at HERA, Tevatron, LEP2 can be explained in the traditional CS model by using k_T-factorization and the BFKL- and CCFM-based u.g.d. in a proton and a photon**
- **to find the "universal" unintegrated gluon distribution**
- **to use this the BFKL- and CCFM-based unintegrated gluon distribution to predict cross sections for different processes at LHC.**

2. Ingredients of the k_T-factorization (SHA)

1) Off-mass shell matrix elements

Feynman diagrams are evaluated for the virtual incoming partons (gluons) with all possible polarizations, since there are no reason to neglect the gluon tr. momenta in initial state (q_{1T} and q_{2T} in pp processes, for example) in comparison with H.Q. mass and tr. momenta of final quarks

$\Longrightarrow$ QCD m.e. of the subprocesses become off-mass shell

2) Unintegrated parton distributions

- **JB parameterization:**

J. Blumlein, J.Phys. G19 (1993) 1623; DESY 95-121,hep-ph/9506403.

The u.g.d. is calculated as a convolution of collinear gluon density $G(x,\mu^2)$ with universal weight factors:

$$\Phi(x,\mathbf{q}_T^2,\mu^2)=\int\limits_x^1 \varphi(\eta,\mathbf{q}_T^2,\mu^2)\,\frac{x}{\eta}\,G\left(\frac{x}{\eta},\,\mu^2\right)\,d\eta,$$

where

$$\varphi=\begin{cases}\dfrac{\bar\alpha_S}{\eta\,\mathbf{q}_T^2}J_0\left(2\sqrt{\bar\alpha_S\ln(1/\eta)\ln(\mu^2/\mathbf{q}_T^2)}\right),\mathbf{q}_T^2\le\mu^2,\\ \dfrac{\bar\alpha_S}{\eta\,\mathbf{q}_T^2}I_0\left(2\sqrt{\bar\alpha_S\ln(1/\eta)\ln(\mathbf{q}_T^2/\mu^2)}\right),\mathbf{q}_T^2>\mu^2,\end{cases}$$

J_0 and I_0 are Bessel functions (of real and imaginary arguments, respectively), and $\bar\alpha_s=\alpha_s/3\pi$. The $\bar\alpha_S$ is connected with the Pomeron intercept: $\Delta=4\bar\alpha_S\ln 2=0.53$ in the LO, and $\Delta=4\bar\alpha_S\ln 2-N\bar\alpha_S^2$ in the NLO, where $N\sim 18$. However, some resummation procedures proposed in the last years lead to positive values: $\Delta\sim 0.2-0.3$.

G. Salam, JHEP 9807 (1998) 019
S. Brodsky, V. Fadin, V. Kim, L. Lipatov, G.Pivovarov, JETP Lett. 70 (1999) 155.

We used $\Delta = 0.35$, obtained from the description of the p_T spectrum of D^* electroproduction at HERA

S.P. Baranov, N.Z. PL B458 (1999) 389;

- **KMS parameterization**

  J. Kwiecinski, A. Martin, A. Stasto, PR D56 (1997) 3991

  was 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, PR D52 (1995) 1445, Z.Phys. C 71 (1996) 585.

  The consistency constraint introduces 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 constraint

  J. Kwiecinski, A. Martin, J. Outhwaite, EPJ C9 (2001) 611.

Here we are interested in the parameterizations which take into account saturation effects:

- **GBW parameterization**

  K. Golec-Biernat, M. Wusthoff (1999)

- **GLLM parameterization**

  E. Gotsman, E. Levin, M. Lublinsky, U. Maor, EPJ C27 (2003) 411.

The main ingredients are two QCD-based evolution equations:
BK nonlinear equation (which sums higher twists preserving unitarity) and the linear equation including the DGLAP kernel.
The solution is $N(\vec{\rho}, x, \vec{b}) + \Delta N$, where $N(\vec{\rho}, x, \vec{b})$ is imaginary part of e.s. amplitude of a dipole (of size $\vec{\rho}$).
The GLLM parameterization reproduces all existing low x data on the SF $F_2(x, Q^2)$ with $\Delta \sim (0.3 - 0.4)$ (hard Pomeron) at high Q^2 and $\Delta \sim (0.08 - 0.1)$ (soft Pomeron intercept) at $Q^2 < 1$ GeV^2 and $x \sim 10^{-6}$.
It provides a solution to the problem of soft-hard Pomeron transition.

3. F_L at fixed W with the k_T-factorization

In the k_T-factorization the SF $F_{2,L}(x, Q^2)$ are driven at small x primarily by gluons and are related in the following way to the unintegrated distribution $\Phi_g(x, k_\perp^2)$:

$$F_{2,L}(x, Q^2) = \int_x^1 \frac{dz}{z} \int^{Q^2} dk_\perp^2 \sum_{i=u,d,s,c} e_i^2 \cdot \hat{C}^g_{2,L}(x/z, Q^2, m_i^2, k_\perp^2) \Phi_g(z, k_\perp^2)$$

The functions $\hat{C}^g_{2,L}(x, Q^2, m_i^2, k_\perp^2)$ can be regarded as SF of the off-shell gluons with virtuality $k_\perp^2$ (hereafter we call them *hard structure functions* **). They are described by the sum of the quark box (and crossed box) diagram contribution to the photon-gluon interaction.**

To calculate the longitudinal SF $F_L(x, Q^2)$ we used: the hard SF $\hat{C}^g_{2,L}(x, Q^2, m^2, k_\perp^2)$

A.V. Kotikov, A.V. Lipatov and N.Z. Eur. Phys. J. C 27 (2003) 219.

and different u.g.d.

The $k_\perp^2$-integral in Eqs. can be divergent at lower limit, at least for some parameterizations of $\Phi_g(x, k_\perp^2)$.

To overcome the problem we change the low Q^2 asymptotic of the QCD coupling constant within hard structure functions.

We used the soft version of "frozen" procedure.

In the case the subject of the modification is the argument of the strong coupling constant: it is shifted $Q^2 \to Q^2 + M^2$.

For massless produced quarks $M = m_\rho$. In the case of massive quarks with mass m_Q, $M = 2m_Q$

SF F_L is the sum of two contributions: the light and the charm quark:

$F_L = F_L^l + F_L^c$.

For the F_L^l part we use the massless limit of our hard SF, and we restrict ourselves to the modification of the argument in the strong c. c. of the hard structure function only.

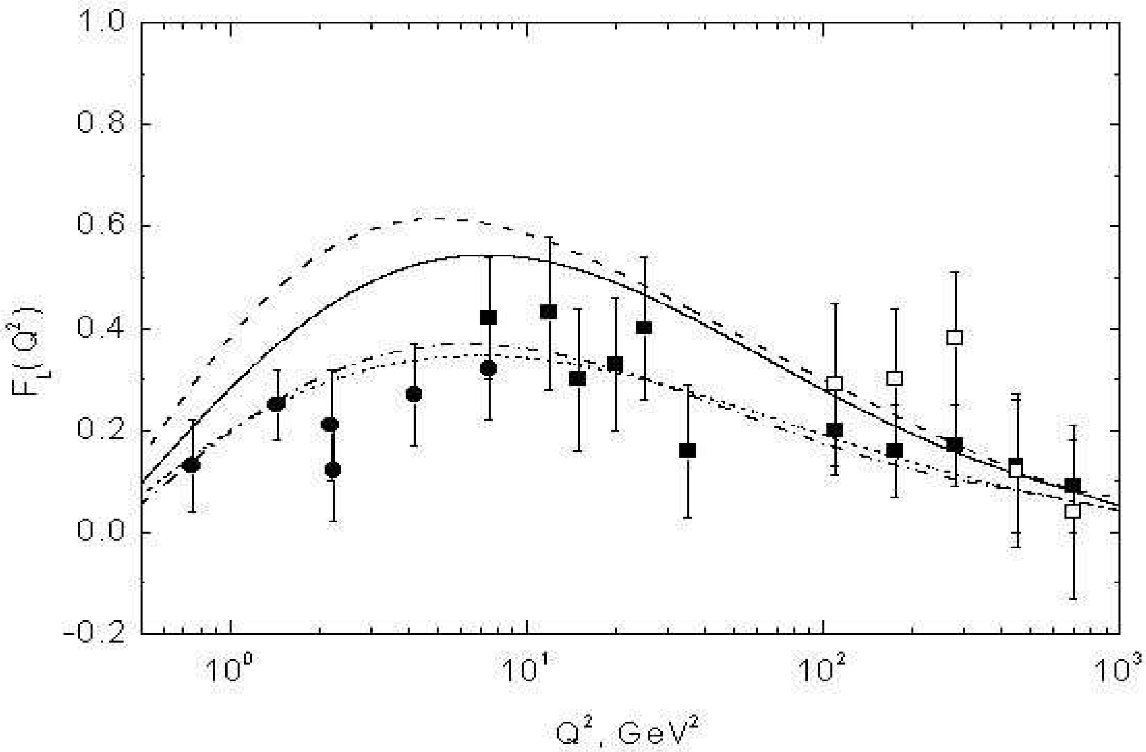

Figure 1: Q^2 dependence of $F_L(x, Q^2)$ (at fixed $W = 276$ GeV). Solid curve - the k_T-factorization approach with the JB u. g. d. and "frozen" c. c.. Dashed curve - the GRV LO calculations, dash-dotted curve - the GRV NLO calculations, dotted curve - the GRV LO calculations with $\mu^2 = 127Q^2$.

The k_T-factorization results lie between the collinear ones, that demonstrates clearly the particular resummation of high-order collinear contributions at small x values in the k_T-factorization approach.

We also see excellent agreement between the experimental data and collinear approach with GRV NLO approximation. The NLO corrections are large and negative and decrease the F_L value by an approximate factor of 2 at $Q^2 < 10$ GeV^2.

The k_T-factorization results are in good agreement with the data for large and small Q^2. There is some disagreement between the data and theoretical predictions at $Q^2 \sim 3$ GeV^2.

The disagreement origins from two possible reasons:
1) additional higher-twist contributions, which are important at low Q^2 (Some part of higher-twist contributions was took into account by the"freezing" procedure),
2) or/and NLO corrections.

It was shown that the saturation (non-linear QCD) approaches contain information of all orders in $1/Q^2$, they resum higher-twist contributions:

J. Bartels, K. Golec-Biernat, K.Peters, EPJ C17 (2001) 121,
E. Gotsman, E. Levin, U. Maor et al., NP A683 (2001) 383.

Analysis of the behavior of the longitudinal SF $F_L(x, Q^2)$ in different saturation models was done by

V.P. Goncalves, M.V.T. Machado, EPJ C37 (2004) 299.

In Fig. 2 we demonstrate our k_T-factorization description of $F_L(Q^2)$ at fixed W with the GLLM unintegrated gluon distribution including non-linear (saturation) effects:

E. Gotsman, E. Levin, M. Lublisky, U. Maor, EPJ C27 (2003) 411.

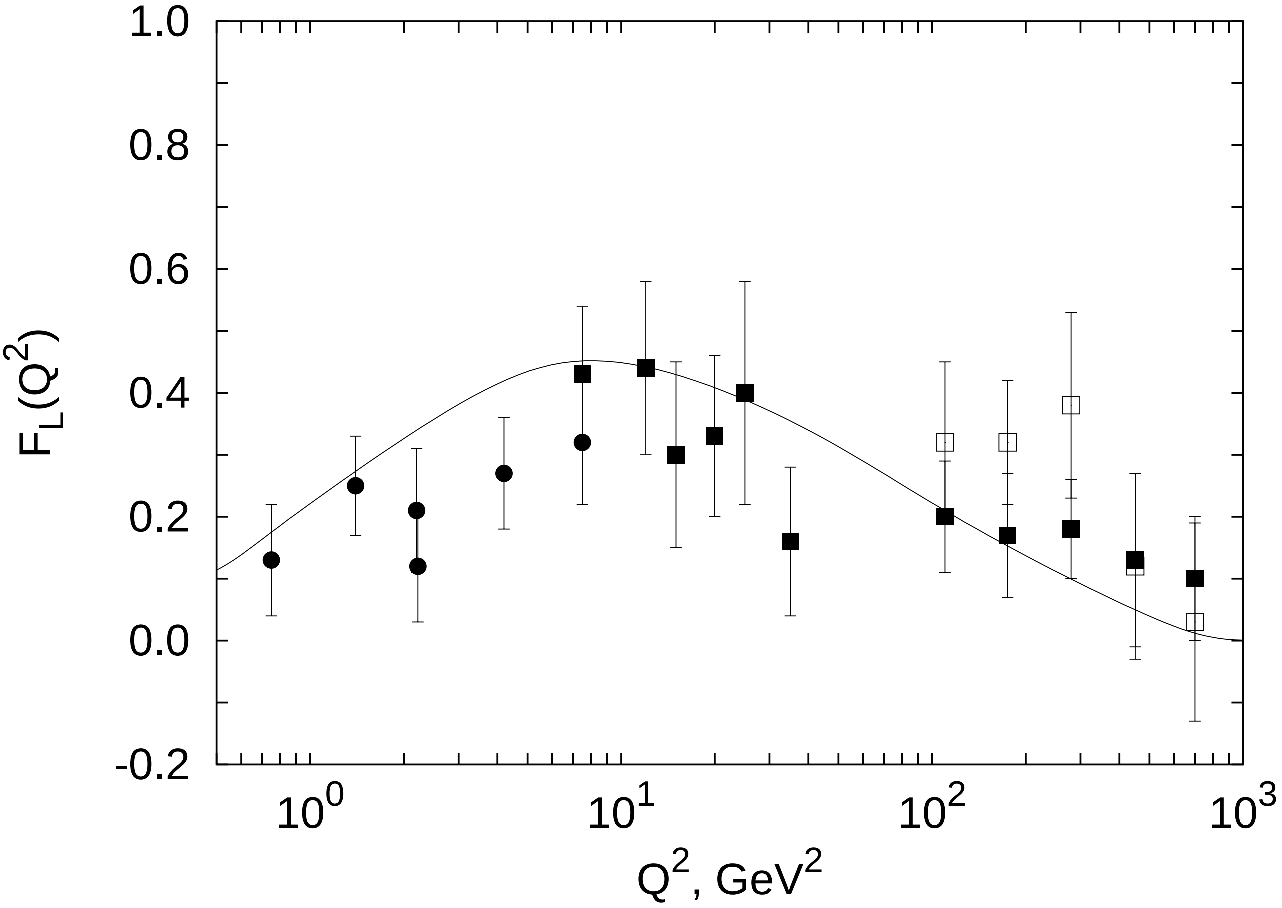

Figure 2: Q^2 dependence of $F_L(x, Q^2)$ (at fixed $W = 276$ GeV). The experimental points are as in Fig. 1. Solid curve is the result of the k_T-factorization approach with the GLLM unintegrated gluon distribution.

3. Saturation effects in $q\bar{q}$−production at LHC

It was shown the data on the $b\bar{b}$ azimuthal correlations at Tevatron (measured as the decay muon a.c., $d\sigma/d\Delta\phi_{\mu\mu}$) are much more informative to distinguish different u.g.d.

S.P. Baranov, A.V. Lipatov, N.P.Z., Yad. Fiz. 66 (2004) 859, hep-ph/0302171.

What you will wait at LHC?

Next Figs. display our predictions for $b\bar{b}$ a.c. at LHC obtained with different u.g.d.

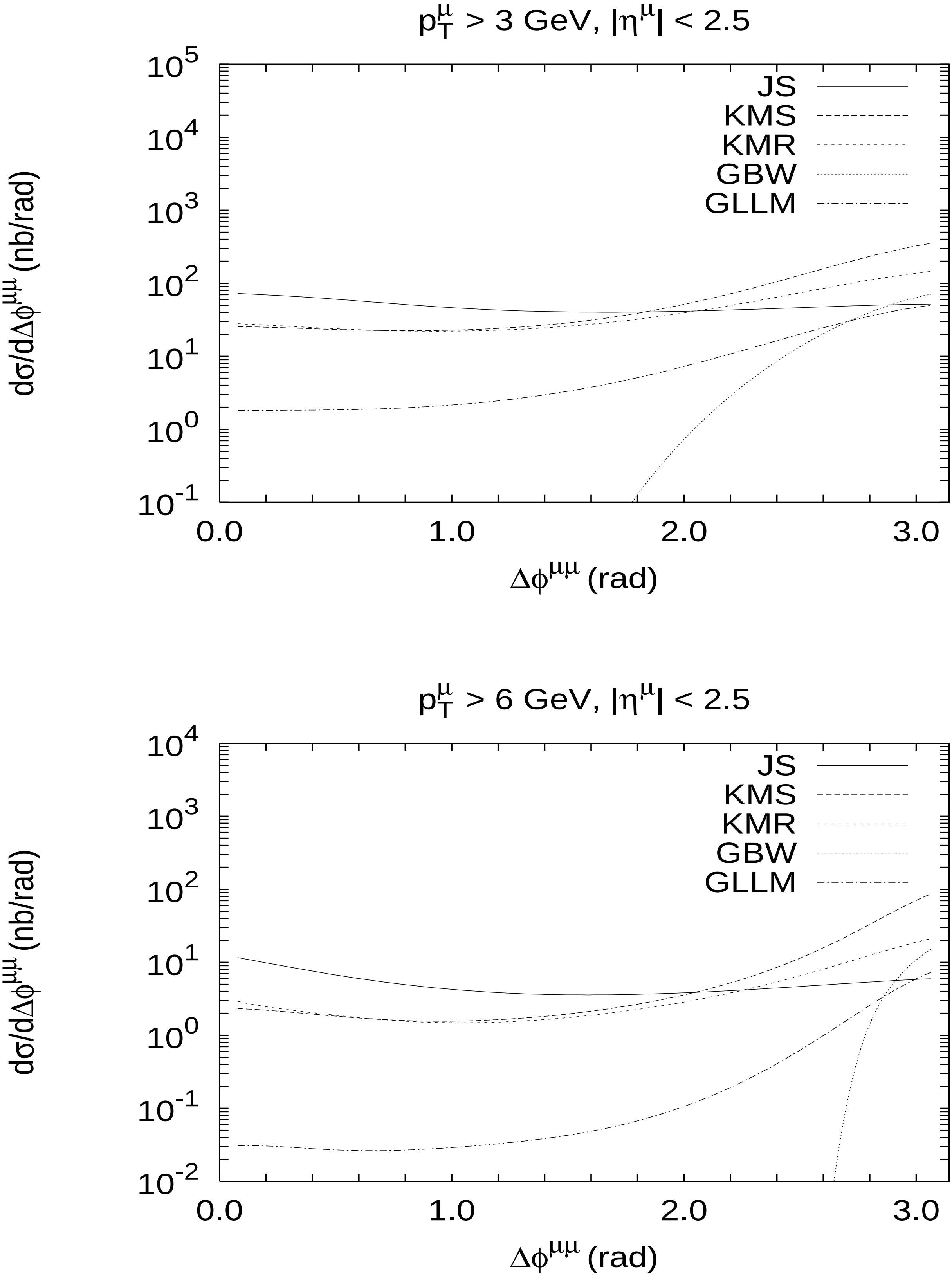

Figure 3: Azimuthal muon-muon correlations at LHC with different u.g.d.

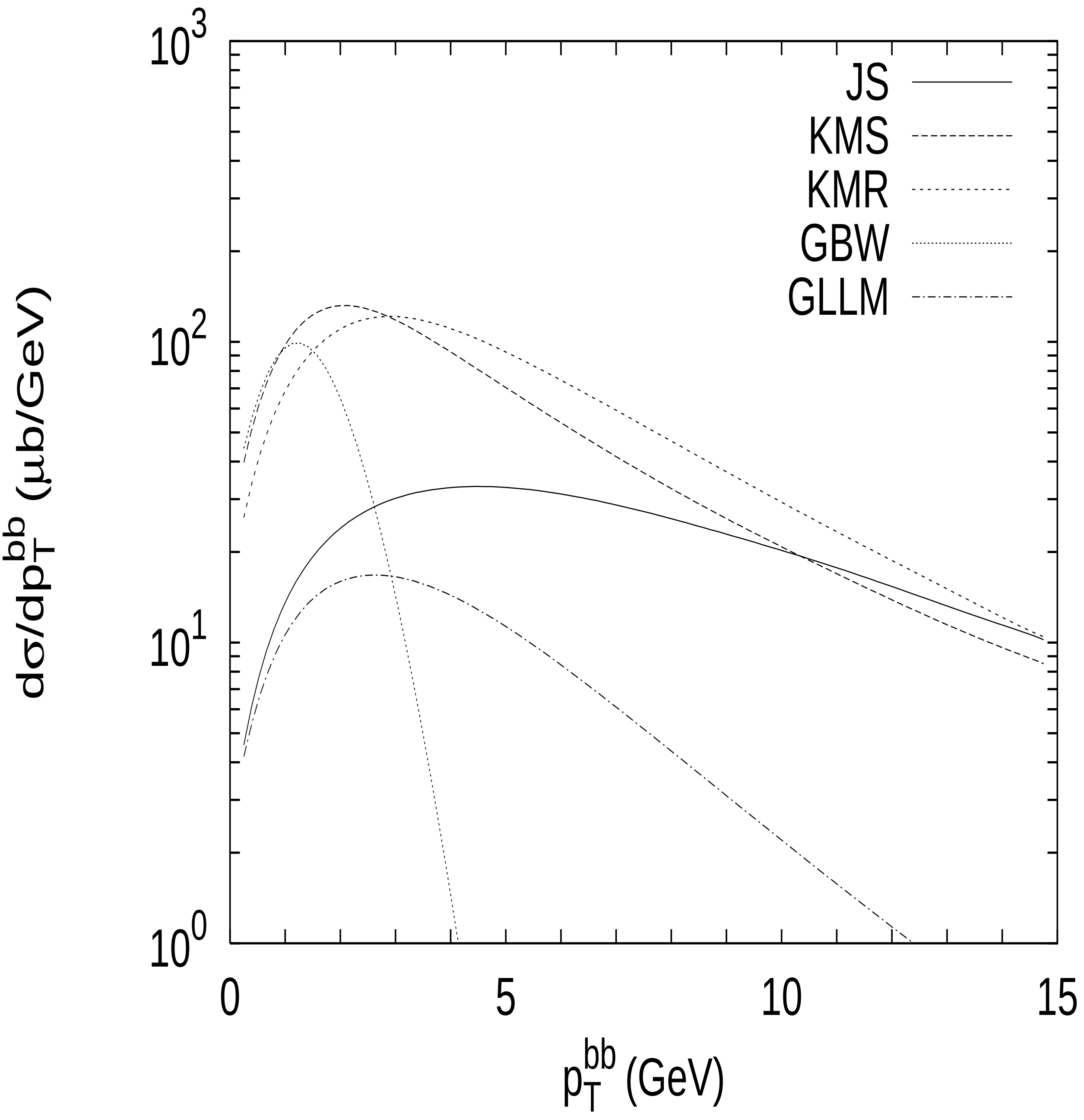

Figure 4: The total transverse momentum distribution ($\vec{p_T}^{b\bar{b}} = \vec{p_T}^{b} + \vec{p_T}^{\bar{b}}$) at LHC with different u.g.d.

4. Summary

- **We have considered in the k_T-factorization approach possible manifestation of the saturation effects at HERA and LHC.**
- **We have shown that the account of saturation effects (by the GLLM u.g.d.) improves to a marked degree description of the F_L data at low Q^2 (at HERA).**
- **We have demonstrated that the exp. data for the $b\bar{b}$ azimuthal correlations and the $p_T^{b\bar{b}}-$distribution at LHC will give us additional possibility to study saturation effects.**
- **We hope that the LHC exp. data will enable us to discriminate between the different u.g.d. (with saturation effects).**