Small x physics and hard QCD processes at LHC

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1. Introduction

The so-called small x regime of QCD is the kinematic region, where the characteristic hard scale of the process μ

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

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

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

In this sense, HERA was the first small x machine, and LHC is more of a small x collider.
Typical x values probed at the LHC in the central rapidity region are almost two orders of magnitude smaller than x values probed at HERA at the same scale.
Hence, small x corrections start being relevant even for a final state with a characteristic electroweak scale $M \sim 100$ GeV.

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 gluon distribution $\mathcal{F}(x, \mathbf{k}_T^2)$. The (u.g.d.) obey certain evolution equations:

- **BFKL: E.A. Kuraev, L.N. Lipatov, V.S. Fadin, Sov. Phys. JETP 44 (1976) 443, 45 (1977) 199; Y.Y. Balitskii, L.N. Lipatov, Sov. J. Nucl. Phys. 28 (1978) 822.**
- **CCFM: M. Ciafaloni, Nucl. Phys. B296 (1988) 49;**
  S. Catani, F. Fiorani, G. Marchesini, Nucl. Phys. B336 (1990) 18;
  G. Marchesini, Nucl. Phys. B445 (1995) 49.

  In last case the u.g.d. depend additionaly on the probing scale μ: $A(x, \mathbf{k}_T^2, \mu^2)$.

The BFKL evolution equation predict more rapid growth of gluon disity ($\sim x^{-\Delta}$, where $1 + \Delta$ is the intercept of so-called hard BFKL Pomeron).
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-Kovchgov (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 $Q_s(x)$. This equilibrium-like system is the so called Color Glass Condesate (CGC):

M. Gyulassy, L. McLerran, nucl-th/0405013;

A.V. Leonidov, UFN 175 (2005) 345.

Since the saturation scale increases with decreasing of x: $Q_s^2(x, A) \sim x^{-\lambda} A^{\delta}$ with $\lambda \sim 0.3, \delta \sim 1/3$:

E. Iancu, arXiv:0901.0986 [hep-ph],

J.P. Blaizot, arXiv:1101.0260 [hep-ph]

one may expect that the saturation effect will be more clear at LHC energies.

2. Unintegrated parton distributions (uPDF or TMD)

The basic dynamical quantity in the small x physics is transverse-momentum-dependent (TMD) ($\mathbf{k}_T$-dependent) or unintegrated parton distribution (uPDF) $\mathcal{A}(x, \mathbf{k}_T^2, \mu^2)$.
To calculate the cross sections of any physical process the uPDF $\mathcal{A}(x, \mathbf{k}_T^2, \mu^2)$ has to be convoluted with the relevant partonic cross section $\hat{\sigma}$:

$$\sigma = \int \frac{dz}{z} \int d\mathbf{k}_T^2 \, \hat{\sigma}(x/z, \mathbf{k}_T^2, \mu^2) \mathcal{A}(x, \mathbf{k}_T^2, \mu^2).$$

For the uPDF there is no unique definition, and as a cosequence it is for the phenomenology of these quantities very important to identify uPDF which are used in description of h.e. processes. For a general introduction to small x physics and the small x evolution equations, as well as tools for calculation in terms of MC programs, we refer to the reviews:

B. Andersson *et al.* (Small-x Collaboration), Eur. Phys. J. C25 (2002) 77;
J. Andersen *et al.* (Small-x Collaboration), Eur. Phys. J. C35 (2004) 67; C48 (2006) 53.

During roughly the last decade, there has been steady progress toward a better understanding of the k_T-factorization (high energy factorization) and the uPDF (for example):

F. Dominguez *et al.*, Phys. Rev. D83 (2011) 105005;

S.M. Aybat, T.C. Rogers, Phys. Rev. D83 (2011) 114042;

I.O. Cherednikov, arXiv:1102.0892; I.O. Cherednikov, N.G. Stefanis, arXiv:1108.0811.

Workshop on Transvere Momentum Distributions (TMD 2010), which was held in Trento (Italy), was dedicated to the recent developments in small x physics, based on the k_T-factorization and the uPDF:

http://www.pv.infn.it/ bacchett/TMDprogram.htm.

Recently the definition for the TMDs determined by the requirement of factorization, maximal universality and internal consistency have been done by J.C. Collins:

J.C. Collins, *Foundations of Perturbative QCD* (Cambridge University Press, Cambridge, 2011);

J.C. Collins, arXiv:1107.4123 [hep-ph].

The results obtained in previous works are reduced to the following: k_T(TMD)-factorization is valid in

- **Back-to-back hadron or jet production in e^+e^--annihilation,**
- **Drell-Yan process ($P_A + P_B \to (\gamma^*, W/Z) + X$),**
- **Semi-inclusive DIS ($e + P \to e + h + X$).**

In hadroproduction of back-to-back jets or hadrons ($h_1 + h_2 \to H_1 + H_2 + X$) TMD-factorization is problematic.
For expample, partonic picture gives the following q_T-dependent hadronic tensor for DY cross section (Collins, 2011):

$$W^{\mu\nu} = \Sigma_f |H_f(Q;\mu)|^{\mu\nu} \quad (1)$$

$$\int d^2\mathbf{k}_{1T} d^2\mathbf{k}_{2T} F_{f/P_1}(x_1, k_{1T};\mu;\zeta_1)\overline{F}_{\overline{f}/P_2}(x_2, k_{2T};\mu;\zeta_2)\delta(\mathbf{k}_{1T} + \mathbf{k}_{2T} - \mathbf{q}_T) + Y(Q, q_T).$$

The hard part $H_f(Q;\mu)$ is calculable to arbitrary order in α_s, μ - the renormalization scale. The term $Y(Q, q_T)$ describes the matching to large q_T where the approximations of TMD-factorization break down.

The scales ζ_1, ζ_2 are related to the regulation of light-cone divergences and $\zeta_1 . \zeta_2 = Q^4$. The soft factors connected with soft gluons are contained in the definitions of the TMDs, which cannot be predicted from the theory and must be fitted to data.

3. The k_T-factorization approach in hadroproduction

The k_T-factorization approach in hadroproduction is based on the work by Catani, Ciafaloni and Hautman (CCH).
The factorization formula for pp-collision in physical gauge ($n.A = 0, n^\mu = aP_1^\mu + bP_2^\mu$) is

$$\sigma = \frac{1}{4M^2}\int d^2\mathbf{k}_{1T}\int\frac{dx_1}{x_1}\int d^2\mathbf{k}_{2T}\int\frac{dx_2}{x_2}\mathcal{F}(x_1,\mathbf{k}_{1T})\hat{\sigma}_{gg}(\rho/(x_1x_2),\mathbf{k}_{1T},\mathbf{k}_{2T})\mathcal{F}(x_2,\mathbf{k}_{2T}), \quad (2)$$

where $\rho = 4M^2/s$, M is the invariant mass of heavy quark, and $\mathcal{F}$'s are the unintegrated gluon distributions, defined by the BFKL equation:

$$\mathcal{F}(x,\mathbf{k};Q_0^2) = \frac{1}{\pi}\delta(1-x)\delta(\mathbf{k}^2-Q_0^2) + \quad (3)$$

$$+\overline{\alpha}_s\int\frac{d^2\mathbf{q}}{\pi\mathbf{q}^2}\int\frac{dz}{z}[\mathcal{F}(x/z,\mathbf{k}+\mathbf{q};Q_0^2) - \Theta(k-q)\mathcal{F}(x/z,\mathbf{k};Q_0^2)],$$

were $\overline{\alpha}_s = \alpha_s N_c/\pi$. It means that the rapidity divergencies are cut off since there are an implicit cuts in the BFKL formalism.

Effectively one introduces a cuts ζ_1, ζ_2, and then sets $\zeta_1 = x_1, \zeta_2 = x_2$ in (2).
The declaration that $\mathcal{F}$ is defined via the BFKL equation (3) means that the BFKL unintegrated gluon distribution reduces to the dipole gluon distribution:

V. Barone, M. Genovese, N.N. Nikolaev,
E. Predazzi, B.G. Zakharov, Phys. Lett. B326 (1994) 161
A. Bialas, H. Navelet, R. Peschanski, Nucl. Phys. B593 (2001) 438.

The connections between different uPDF recently were analyzed in

E. Avsar, arXiv:1108.1181 [hep-ph].

The procedure for resumming inclusive hard cross-sections at the leading non-trivial order through k_T-factorization was used for an increasing number of processes: photoproduction ones, DIS ones, DY and vector boson production, direct photon production, gluonic Higgs production both in the point-like limit, and for finite top mass m_t. Please look (for example)

S. Marzani, arXiv:1006.2314 [hep-ph].

The hadroproduction of heavy quarks was considered in

R.D. Ball, R.K. Ellis, JHEP 0105 (2001) 053,

and recently in

R.D. Ball, Nucl. Phys. B796 (2008) 137.

In last paper it was shown that when the coupling runs the dramatic enhancements seen at fixed coupling, due to infrared singularities in the partonic cross-sections, are substantially reduced, to the extent that they are largely accounted for by the usual NLO and NNLO perturbative corrections.
It was found that resummation modifies the B-production c.s. at the LHC by at most 15%, but that the enhancement of gluonic W-production may be as large 50% at large rapidities.

4. Ingredients of our k_T-factorization numerical calculations

We have used the k_T-factorization approach to discribe exp. data on:

- **heavy quark photo- and electroproduction at HERA**
- **J/ψ production in photo- and electroproduction at HERA with CSM and COM**
- **D^*, $D^* + jet$, $D^* + 2jet$ photoproduction and D^* production in DIS**
- **charm contribution to the s.f. $F_2^c(x, Q^2), F_L^c, F_L$**
- **B-meson and $b\bar{b}$ production at Tevatron**
- **charm, beauty, D^* and J/ψ production in two-photon collisions at LEP2**
- **Higgs production at Tevatron and LHC**
- **prompt photon production at HERA and Tevatron**
- **W/Z production at Tevatron**

The main motivations of our study

- **to demonstrate the possibilities of the k_T-factorization approach**
- **search the "universal" unintegrated gluon distribution**
- **search the effects of BFKL and CCFM dynamics**
- **possible saturation effects**
- **to use this the BFKL- and CCFM-based unintegrated gluon distribution to predict cross sections for different processes at LHC.**

Here I want to present the results of b-quark and J/ψ production at LHC in comparison with first exp. data obtained by ATLAS, CMS and LHCb Collaborations:

H. Jung, M. Krämer, A.V. Lipatov, N. Z., DESY 11-086, arXiv:1105.6276 [hep-ph];

S.P. Baranov, A.V. Lipatov, N.Z., DESY 11-143, arXiv:1108.2856.

The description of prompt photon production and DY pairs was done by

M.A. Malyshev, talk at this Workshop.

According to the k_T-factorization approach to calculate the cross sections of any physical process the unintegrated gluon distribution $\mathcal{A}(x, \mathbf{k}_T^2, \mu^2)$ has to be convoluted with the relevant partonic cross section $\hat{\sigma}$:

$$\sigma = \int \frac{dz}{z} \int d\mathbf{k}_T^2 \, \hat{\sigma}(x/z, \mathbf{k}_T^2, \mu^2) \mathcal{A}(x, \mathbf{k}_T^2, \mu^2).$$

- **The partonic cross section $\hat{\sigma}$ has to be taken off mass shell ($\mathbf{k}_T$-dependent).**
- **It also assumes a modification of their polarization density matrix. It has to be taken in so called BFKL form:**

$$\sum \epsilon^{\mu} \epsilon^{*\,\nu} = \frac{k_T^{\mu} k_T^{\nu}}{\mathbf{k}_T^2}.$$

- **Concerning the uPDF in a proton, we used two different sets.**

First of them is the KMR one. The KMR approach represent an approximate treatment of the parton evolution mainly based on the

DGLAP equation and incorpotating the BFKL effects at the last step of the parton ladder only, in the form of the properly defined Sudakov formfactors $T_q(\mathbf{k}_T^2, \mu^2)$ and $T_g(\mathbf{k}_T^2, \mu^2)$, including logarithmic loop corrections.

M. Kimber, A. Martin, M. Ryskin, Phys. Rev. D63 (2001) 114027.

$$\mathcal{A}_q(x, \mathbf{k}_T^2, \mu^2) = T_q(\mathbf{k}_T^2, \mu^2) \frac{\alpha_s(\mathbf{k}_T^2)}{2\pi} \times$$
$$\times \int\limits_x^1 dz \left[P_{qq}(z) \frac{x}{z} q\left(\frac{x}{z}, \mathbf{k}_T^2\right) \Theta\left(\Delta - z\right) + P_{qg}(z) \frac{x}{z} g\left(\frac{x}{z}, \mathbf{k}_T^2\right) \right], \tag{4}$$

$$\mathcal{A}_g(x, \mathbf{k}_T^2, \mu^2) = T_g(\mathbf{k}_T^2, \mu^2) \frac{\alpha_s(\mathbf{k}_T^2)}{2\pi} \times$$
$$\times \int\limits_x^1 dz \left[\sum_q P_{gq}(z) \frac{x}{z} q\left(\frac{x}{z}, \mathbf{k}_T^2\right) + P_{gg}(z) \frac{x}{z} g\left(\frac{x}{z}, \mathbf{k}_T^2\right) \Theta\left(\Delta - z\right) \right]. \tag{5}$$

Θ-functions imply the angular-ordering constraint $\Delta = \mu/(\mu + k_T)$ specifically to the last evalution step (to regulate the soft gluon singularities). For other evolution steps the strong ordering in transverse

momentum within DGLAP eq. automatically ensures angular ordering.
$T_a(\mathbf{k}_T^2, \mu^2)$ **- the probability of evolving from** $\mathbf{k}_T^2$ **to** μ^2 **without parton emission.** $T_a(\mathbf{k}_T^2, \mu^2) = 1$ **at** $\mathbf{k}_T^2 > \mu^2$**.**
Such definition of the $\mathcal{A}_a(x, \mathbf{k}_T^2, \mu^2)$ **is correct for** $\mathbf{k}_T^2 > \mu_0^2$ **only, where** $\mu_0 \sim 1$ **GeV is the minimum scale for which DGLAP evolution of the collinear parton densities is valid.**
We use the last version of KMRW uPDF obtained from DGLAP eqs.:

G. Watt, A.D. Martin, M.G. Ryskin, Eur. Phys. C31 (2003) 73.

In this case ($a(x, \mu^2) = xG$ **or** $a(x, \mu^2) = xq$**): The normalization condition**

$$a(x, \mu^2) = \int_0^{\mu^2} \mathcal{A}_a(x, \mathbf{k}_T^2, \mu^2) d\mathbf{k}_T^2,$$

is satisfied, if

$$\mathcal{A}_a(x, \mathbf{k}_T^2, \mu^2)|_{\mathbf{k}_T^2 < \mu_0^2} = a(x, \mu_0^2) T_a(\mu_0^2, \mu^2),$$

where $T_a(\mu_0^2, \mu^2)$ **are the quark and gluon Sudakov form factors.**
The UPD $\mathcal{A}_a(x, \mathbf{k}_T^2, \mu^2)$ **is defined in all** $\mathbf{k}_T^2$ **region.**

The other uPDF was obtained using the CCFM ev. eq. The CCFM ev. eq. have been solved numerically using a Monte-Carlo method:

H. Jung, heph/9908497;

H. Jung, G. Salam, EPJ C19 (2001) 359;

H. Jung, S.P. Baranov, M. Deak at al., EPJ C70 (2010) 1237.

According to the CCFM ev. eq., the emission of gluons during the initial cascade is only allowed in an angular-ordered region of phase space. The maximum allowed angle Ξ related to the hard quark box sets the scale μ: $\mu^2 = \hat{s} + \mathbf{Q}_T^2 (= \mu_f^2)$.
The unintegrated gluon distribution are determined by a convolution of the non-perturbative starting distribution $\mathcal{A}_0(x)$ and CCFM evolution denoted by $\bar{\mathcal{A}}(x, \mathbf{k}_T^2, \mu^2)$:

$$x\mathcal{A}(x, \mathbf{k}_T^2, \mu^2) \;=\; \int dz \mathcal{A}_0(z) \frac{x}{z} \bar{\mathcal{A}}(\frac{x}{z}, \mathbf{k}_T^2, \mu^2),$$

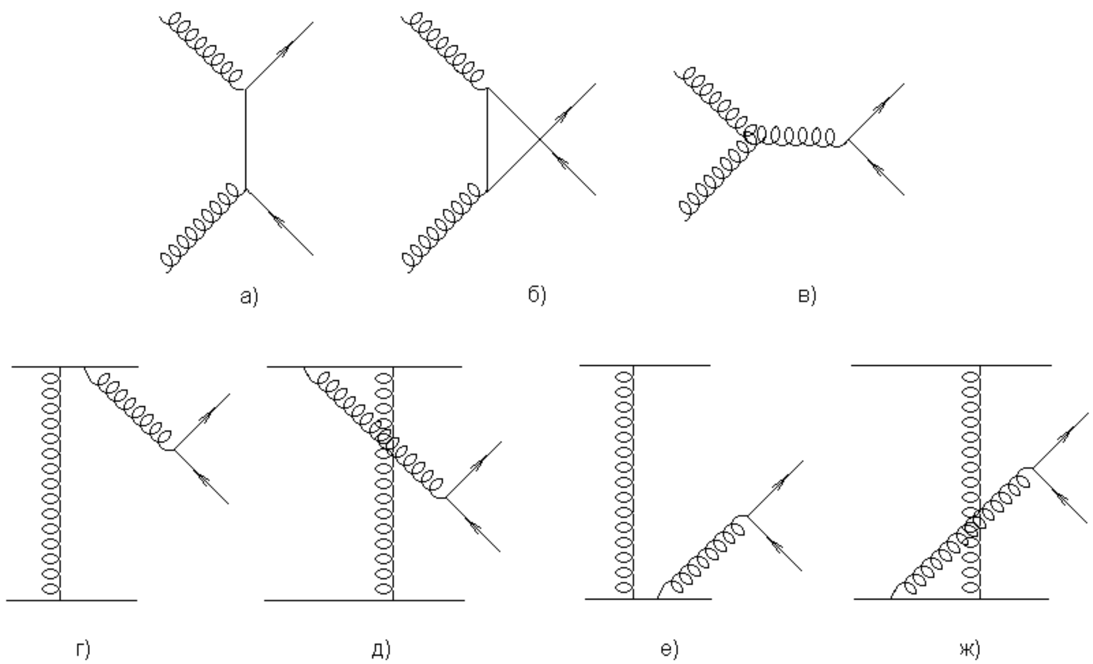
where

$$x\mathcal{A}_0(x) \;=\; N x^{p_0} (1-x)^{p_1} \exp(-\mathbf{k}_T^2 / k_0^2).$$

The parameters were determined in the fit to F_2 data.

Heavy quark production in pp-interaction

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



which correspond to m.e.

$$M_1 = \bar{u}(p_1)(-ig\gamma^\mu)\varepsilon_\mu(q_1)i\frac{\hat{p}_1 - \hat{q}_1 + M}{(p_1 - q_1)^2 - M^2}(-ig\gamma^\nu)\varepsilon_\nu(q_2)v(p_2),$$

$$M_2 = \bar{u}(p_1)(-ig\gamma^\nu)\varepsilon_\nu(q_2)i\frac{\hat{p}_1 - \hat{q}_2 + M}{(p_1 - q_2)^2 - M^2}(-ig\gamma^\mu)\varepsilon_\mu(q_1)v(p_2),$$

$$M_3 = \bar{u}(p_1)C^{\mu\nu\lambda}(-q_1, -q_2, q_1 + q_2)\,\frac{g^2\varepsilon_\mu(q_1)\varepsilon_\nu(q_2)}{(q_1 + q_2)^2}\gamma_\lambda\,v(p_2),$$

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 Sudakov decomposition for the process $pp \to Q\bar{Q}X$ has form:

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

$p_1^2 = p_2^2 = M^2, \;\; q_1^2 = q_{1T}^2, \;\; q_2^2 = q_{2T}^2$.

In the center of mass frame of colliding particles

$$P_1 = (E, 0, 0, E), \; P_2 = (E, 0, 0, -E), \; E = \sqrt{s}/2, \; P_1^2 = P_2^2 = 0,$$
$$(P_1 P_2) = s/2.$$

Sudakov variables:

$$\alpha_1 = \frac{M_{1T}}{\sqrt{s}} \exp(y_1^*), \;\; \alpha_2 = \frac{M_{2T}}{\sqrt{s}} \exp(y_2^*),$$
$$\beta_1 = \frac{M_{1T}}{\sqrt{s}} \exp(-y_1^*), \;\; \beta_2 = \frac{M_{2T}}{\sqrt{s}} \exp(-y_2^*),$$

$$q_{1T} + q_{2T} = p_{1T} + p_{2T}, \;\; x_1 = \alpha_1 + \alpha_2, \;\; x_2 = \beta_1 + \beta_2.$$

The cross section of the process $pp \to Q\bar{Q}X$ is

$$\sigma(p\bar{p} \to Q\bar{Q}\,X) = \frac{1}{16\pi(x_1x_2s)^2} \int \mathcal{A}(x_1, \mathbf{k}_{1T}^2, \mu^2)\mathcal{A}(x_2, \mathbf{k}_{2T}^2, \mu^2)|\bar{\mathcal{M}}(g^*g^* \to Q\bar{Q})|^2 \times$$
$$\times d\mathbf{p}_{1T}^2 d\mathbf{k}_{1T}^2 d\mathbf{k}_{2T}^2 dy_1^* dy_2^* \frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi}.$$

In the numerical calculations we have used three different sets, namely CCFM A0 (B0) and KMR ones. The difference between A0 and B0 sets is connected with the different values of soft cut and width of the intrinsic $\mathbf{k}_T$ distribution. A reasonable description of the F_2 data can be achieved by both these sets.
For the input, we have used the standard MSTW'2008 (LO) (in LZ calculations) and MRST 99 (in CASCADE) sets.
The unintegrated gluon distributions depend on the renormalization and factorization scales μ_R and μ_F. We set $\mu_R^2 = m_Q^2 + (\mathbf{p}_{1T}^2 + \mathbf{p}_{2T}^2)/2$, $\mu_F^2 = \hat{s} + \mathbf{Q}_T^2$, where $\mathbf{Q}_T$ is the transverse momentum of the initial off-shell gluon pair, $m_c = 1.4 \pm 0.1$ GeV, $m_b = 4.75 \pm 0.25$ GeV. We use the LO formula for the coupling $\alpha_s(\mu_R^2)$ with $n_f = 4$ active quark flavors at $\Lambda_{\rm QCD} = 200$ MeV, such that $\alpha_s(M_Z^2) = 0.1232$.

5. Numerical results

Recently we have demonstrated reasonable agreement between the k_T-factorization predictions and the Tevatron data on the b-quarks, $b\bar{b}$ di-jets, B^+- and D-mesons:

H. Jung, M. Krämer, A.V. Lipatov, N.Z., JHEP 1101 (2011) 085.

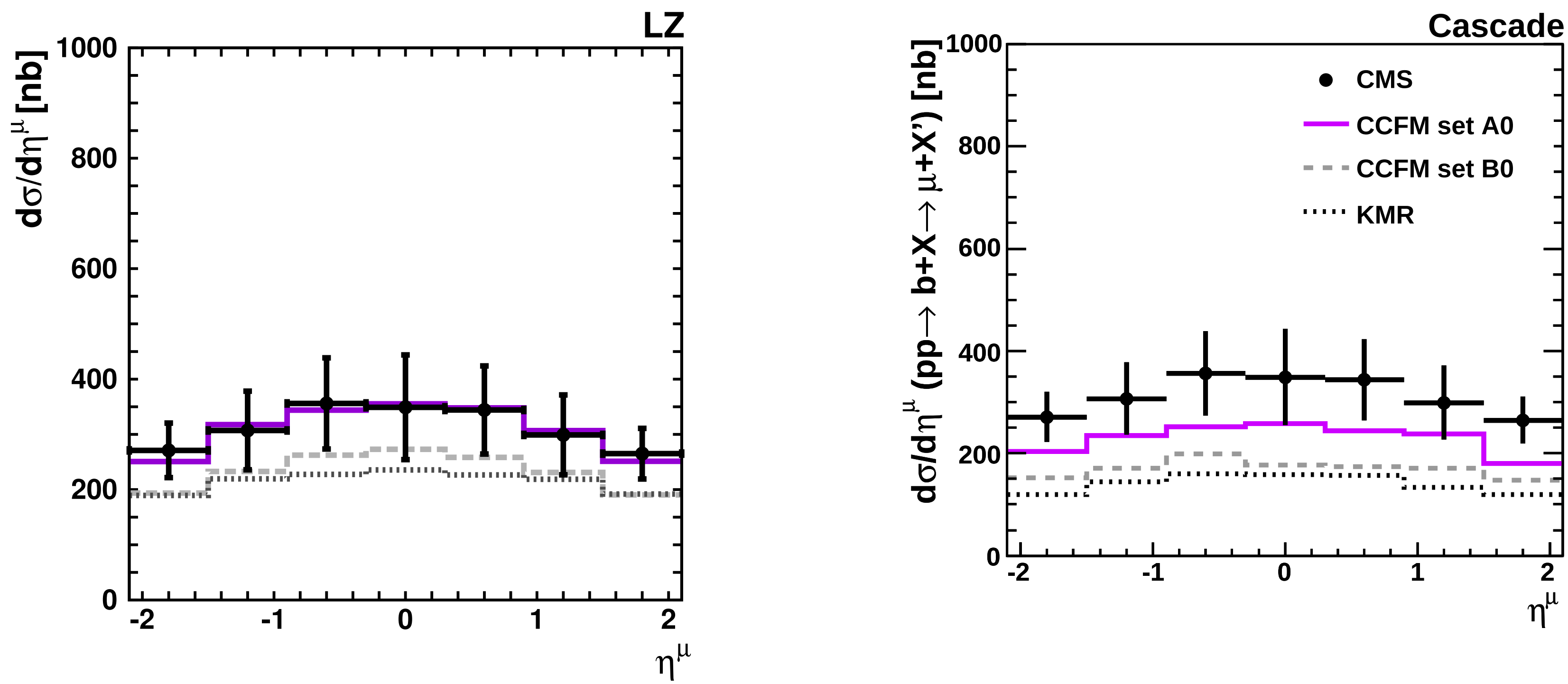
Based on these results, here we give here analysis of the CMS data in the framework of the k_T-factorization approach.
We produce the relevant numerical calculations in two ways:

- **We will performe analytical parton-level calculations (which are labeled as LZ).**
- **The measured cross sections of heavy quark production will be compared also with the predictions of full hadron level Monte Carlo event generator CASCADE:**

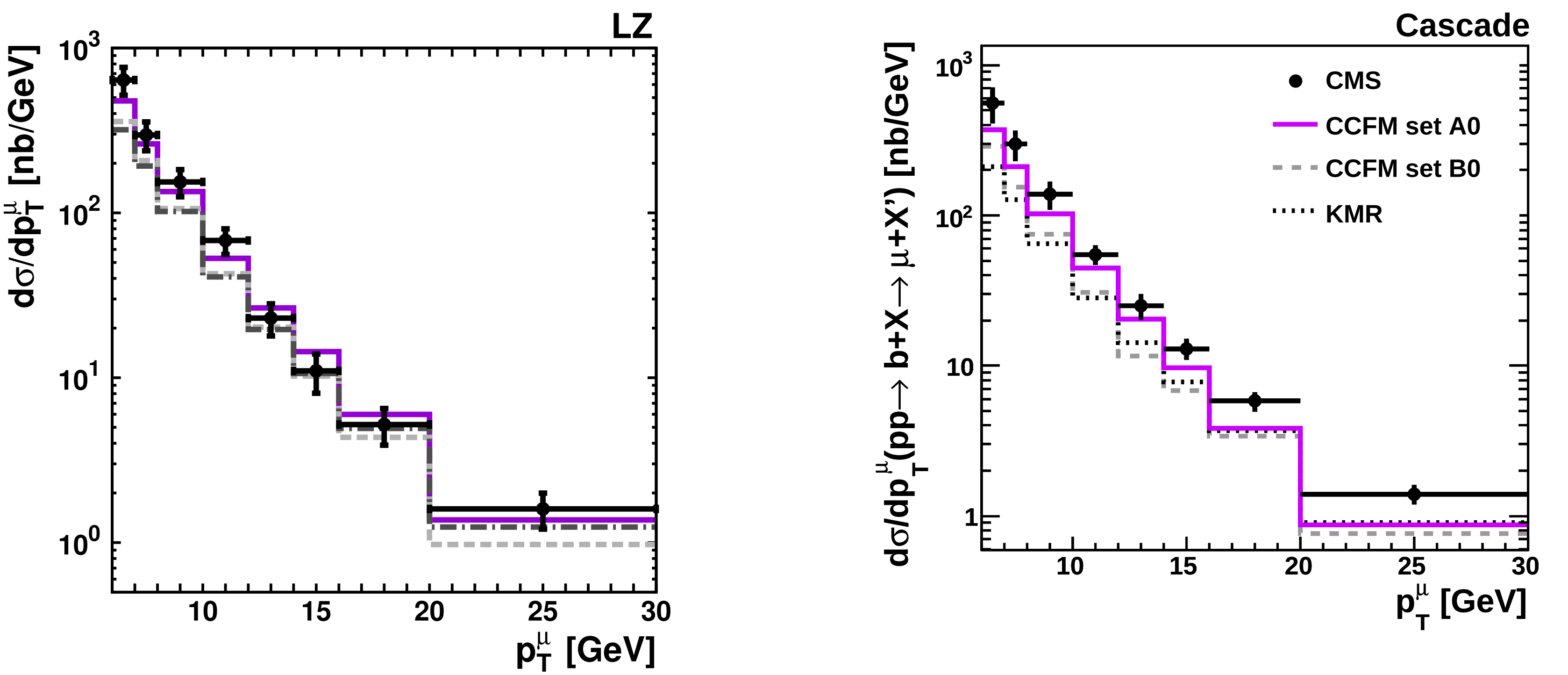
H. Jung, Comp. Phys. Comm. 143 (2002) 100;
H. Jung, S. Baranov, M. Deak at al. Eur. Phys. J. C70 (2010) 1237.

We begin the discussion by presenting our results for the muons originating from the semileptonic decays of the b quarks. The CMS collaboration has measured the transverse momentum and pseudorapidity distributions of muons from b-decays. The measurements have been performed in the kinematic range $p_T^\mu > 6$ GeV and $|\eta^\mu| < 2.1$ at the total center-of-mass energy $\sqrt{s} = 7$ TeV.

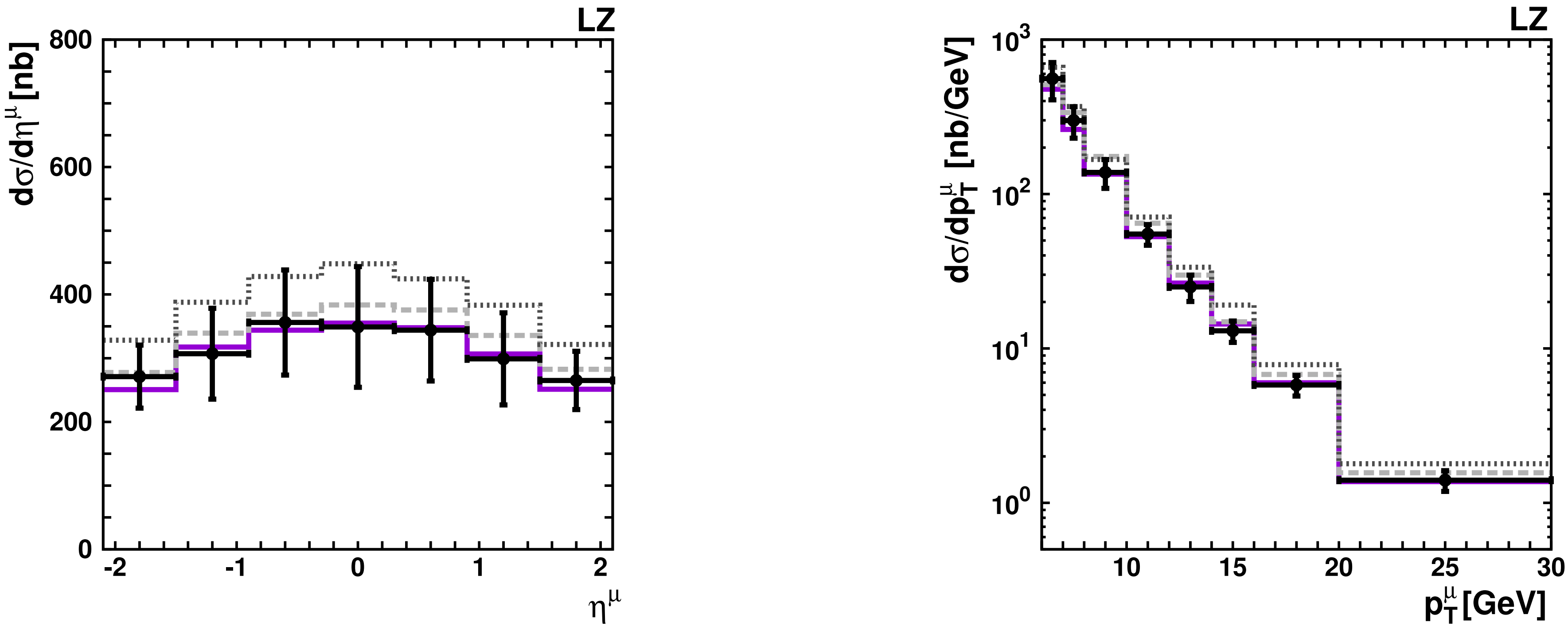
To produce muons from b-quarks, we first convert b-quarks into B mesons using the Peterson fragmentation function with default value $\epsilon_b = 0.006$ and then simulate their semileptonic decay according to the standard electroweak theory taking into account the decays $b \to \mu$ as well as the cascade decay $b \to c \to \mu$.



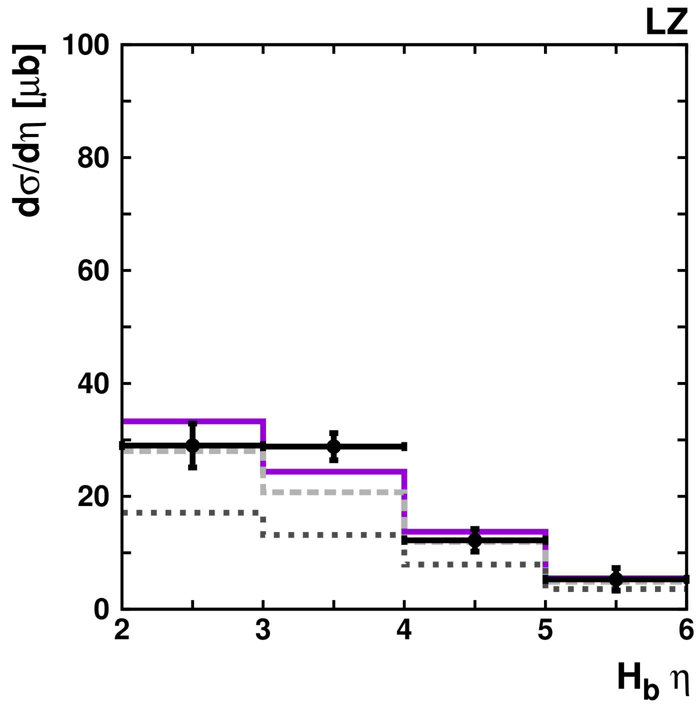
The pseudo-rapidity distributions of muons arising from the semileptonic decays of beauty quarks. The first column shows the LZ numerical results while the second one depicts the CASCADE *predictions. The solid, dashed and dash-dotted, dotted histograms correspond to the results obtained with the CCFM A0, B0 and KMR unintegrated gluon densities. The experimental data are from CMS.*



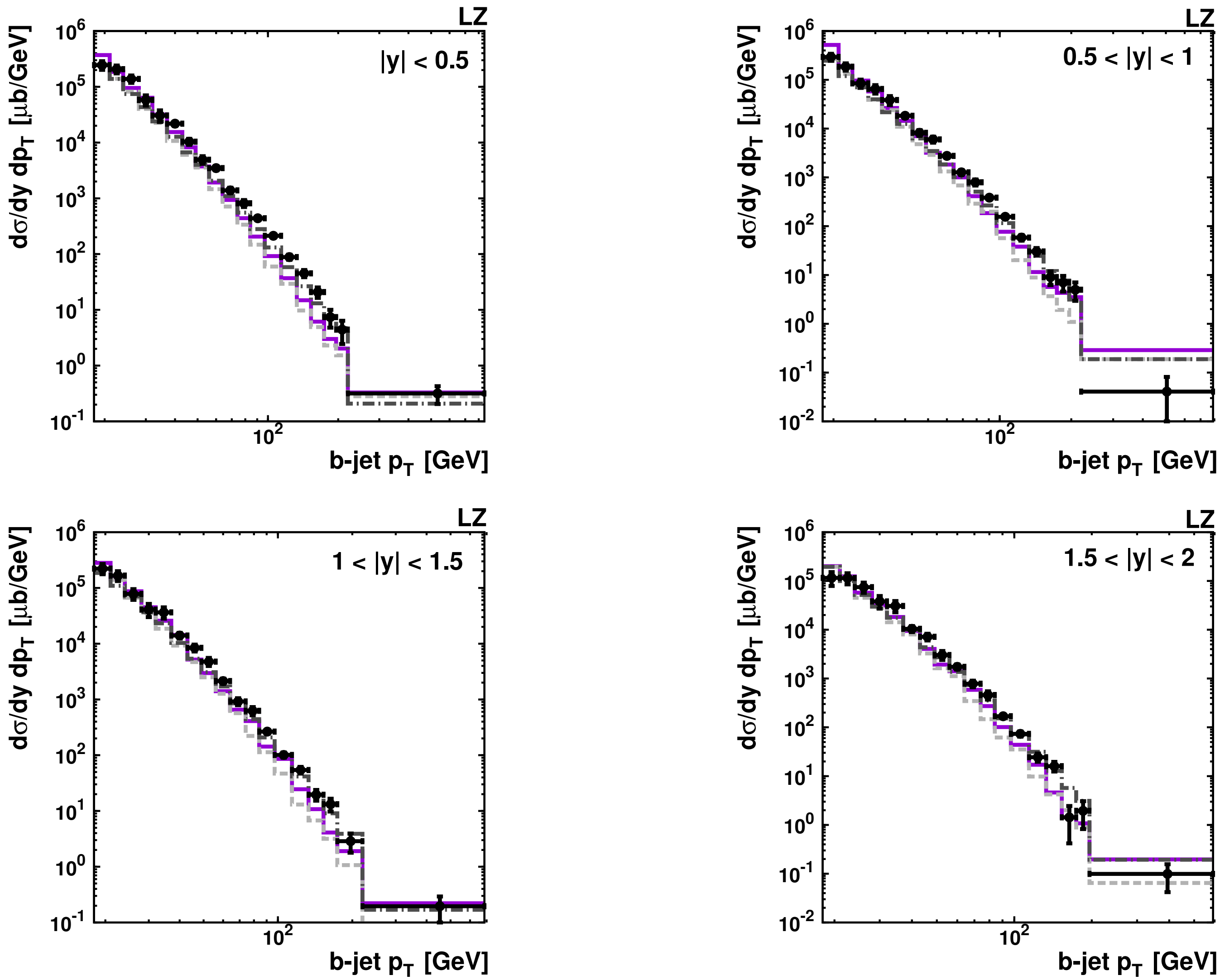
The transverse momentum distributions of muons arising from the semileptonic decays of beauty quarks. The first column shows the LZ numerical results while the second one depicts the CASCADE *predictions. Notation of all histograms is the same as on previous slide. The experimental data are from CMS.*



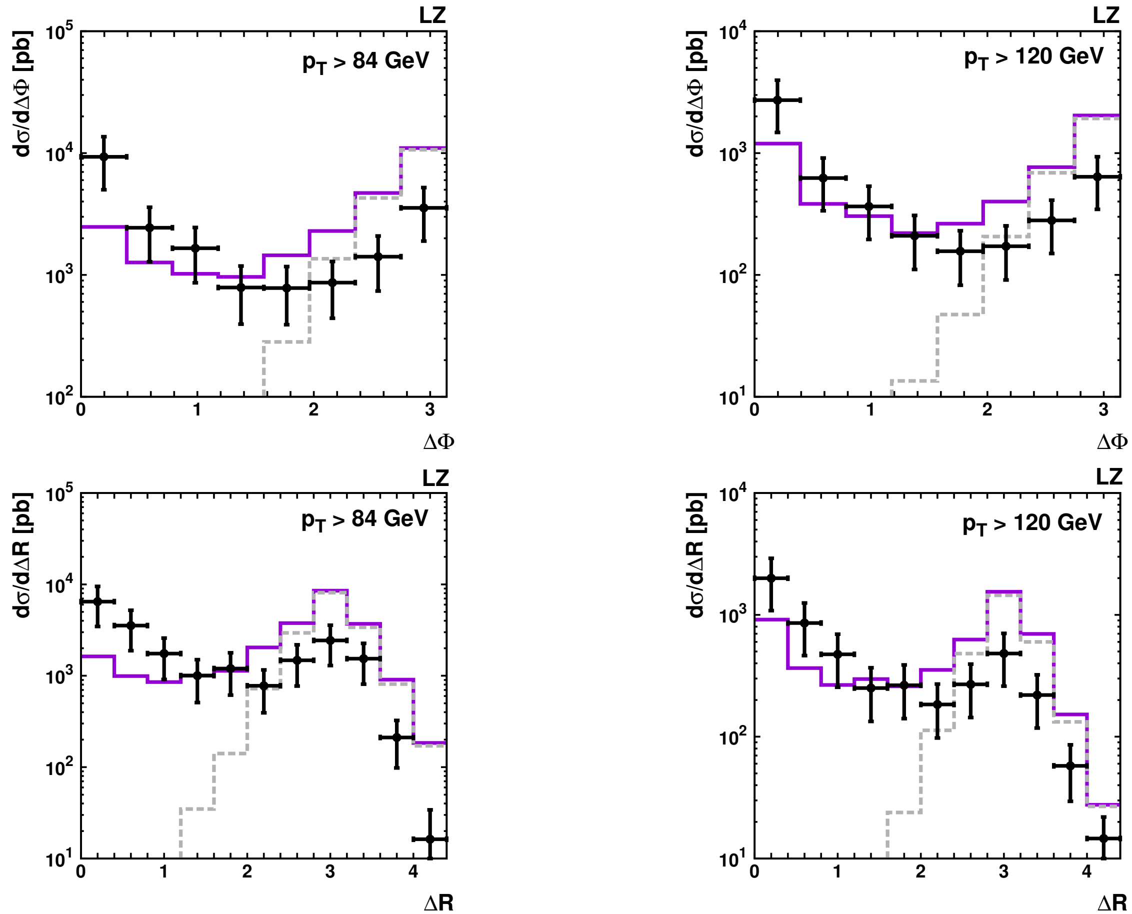
The dependence of our predictions on the fragmentation scheme. The solid, dashed and dash-dotted histograms correspond to the results obtained using the Peterson fragmentation function with $\epsilon_b = 0.006$, $\epsilon_b = 0.003$ *and the non-perturbative fragmentation functions respectively. We use CCFM (A0) gluon density for illustration. The experimental data are from CMS.*



The pseudorapidity distributions of b-flavored hadrons at LHC. The histograms - LZ results with the CCFM AO, BO and KMR u.g.d. The exp. data are from LHCb collaboration.



The double differential cross sections $d\sigma/dy\,dp_T$ *of inclusive* b*-jet production.*

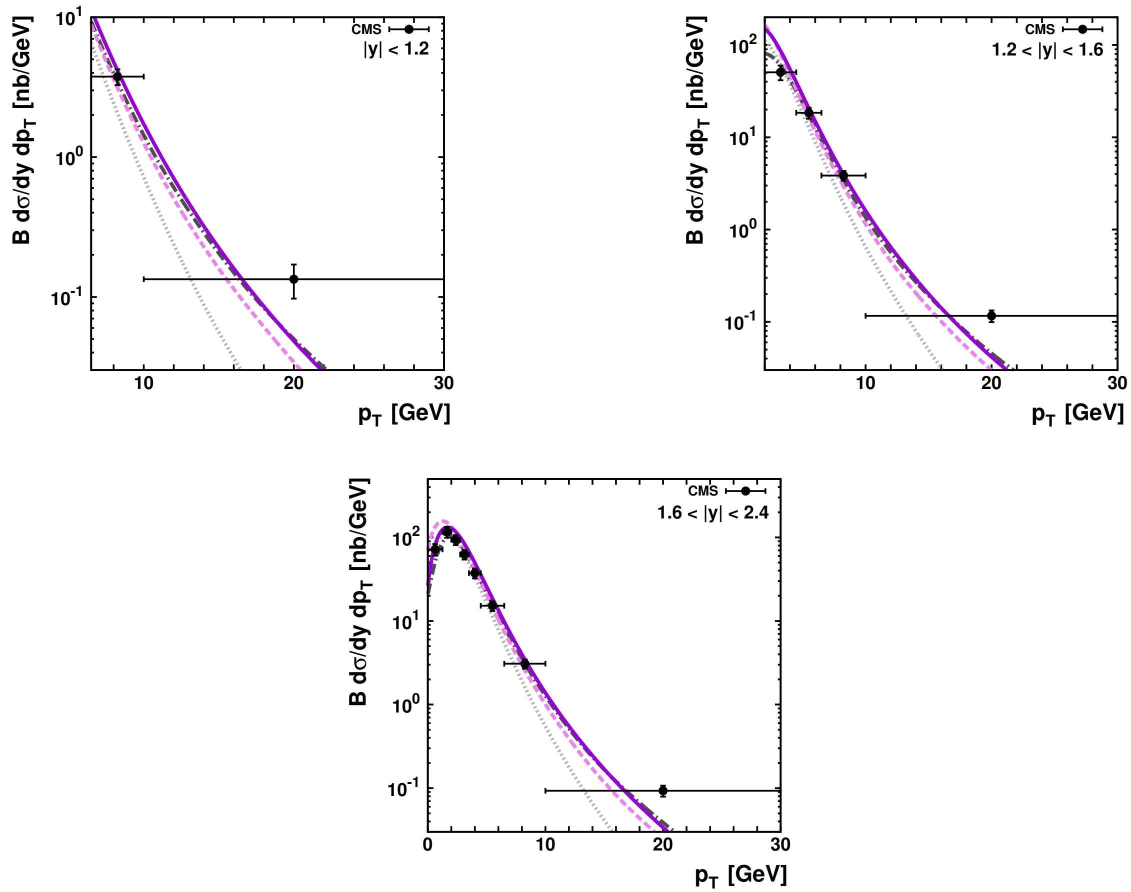


Importance of non-zero $\mathbf{k}_T$ *of incoming gluons. Ditted histograms - the results obtained without the virtualities gluons and with* $\mathbf{k}_T^2 < \mu_R^2$ *in m.e.. The CMS data.*

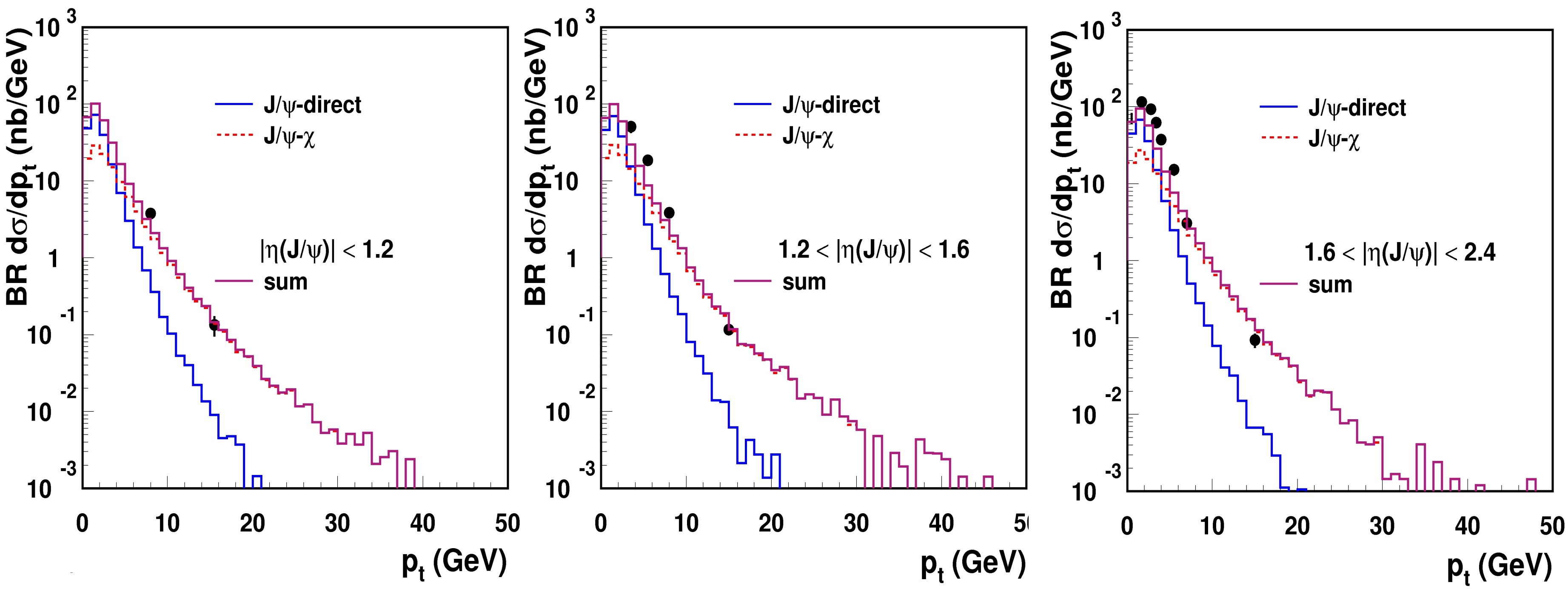
Quarkonium production in pp-interaction

The production of prompt $J/\psi(\Upsilon)$ mesons in pp collisions can proceed via either direct gluon-gluon fusion or the production of P-wave states χ_c (χ_b) and S-wave state ψ' followed by their radiative decays $\chi_c(\chi_b) \to J/\psi(\Upsilon) + \gamma$.
In the CS model the direct mechanism corresponds to the partonic subprocess $g^* + g^* \to J/\psi(\Upsilon) + g$. The production of P-wave mesons is given by $g^* + g^* \to \chi_c(\chi_b)$, and there is no emittion of any additional gluons. The feed-down contribution from S-wave state ψ' is described by $g^* + g^* \to \psi' + g$.
The cross sections charmonium states depend on the renormalization and factorization scales μ_R and μ_F. We set $\mu_R^2 = m^2 + \mathbf{p}_T^2$ and $\mu_F^2 = \hat{s} + \mathbf{Q}_T^2$, where $\mathbf{Q}_T^2$ is the tr. momentum of initial off-shell gluon pair. Following to PDG, we set $m_{J/\psi} = 3.097$ GeV, $m_{\chi c1} = 3.511$ GeV, $m_{\chi c2} = 3.556$ GeV, $m_{\psi'} = 3.686$ GeV and use the LO formula for the coupling constant $\alpha_s(\mu^2)$ with $n_f = 4$ quark flavours at $\Lambda_{QCD} = 200$ Mev, such that $\alpha(M_Z^2) = 0.1232$.

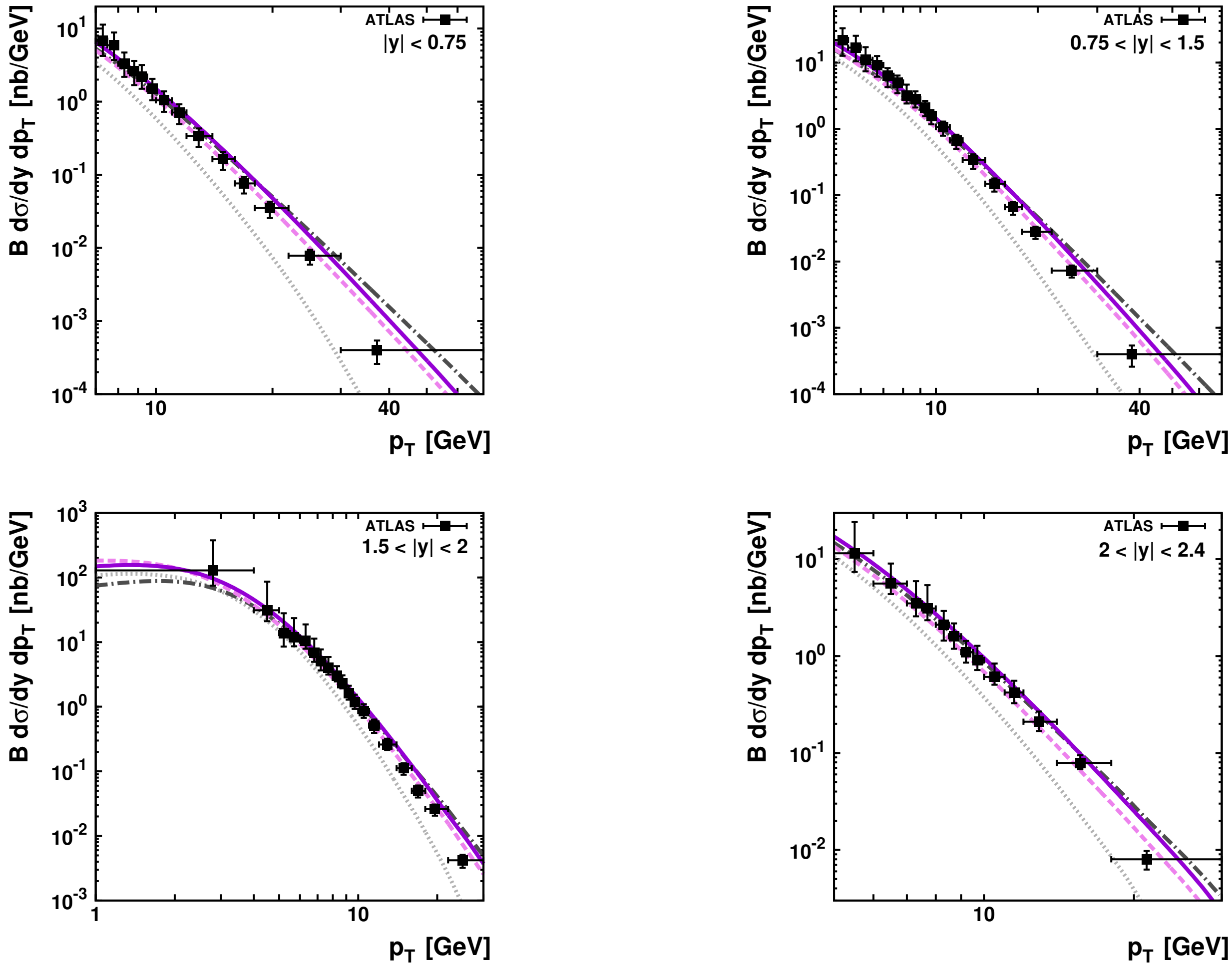
The charmonium wave functions are taken to be equal to $|R_{J/\psi}(0)|^2 = 0.0876$ **GeV**^{3}**,** $|R'_{\chi}(0)|^2 = 0.075$ **GeV**^{5}**,** $|R_{\psi'}(0)|^2 = 0.0391$ **GeV**^{3} **and the following branching fractions are used** $B(\chi_{c1} \to J/\psi{+}\gamma) = 0.356, B(\chi_{c2} \to J/\psi + \gamma) = 0.202, B(\psi' \to J/\psi + X) = 0.561$ **and** $B(J/\psi \to \mu^+\mu^-) = 0.0593$**. Since the branching fraction for** $\chi_{c0} \to J/\psi + \gamma$ **decay is more than an order of magnitide smaller than for** χ_{c1} **and** χ_{c2}**, we neglect its contribution to** J/ψ **production. As** $\psi' \to J/\psi + X$ **decay m.e. are unknown, these events were generated according to the phase space.**



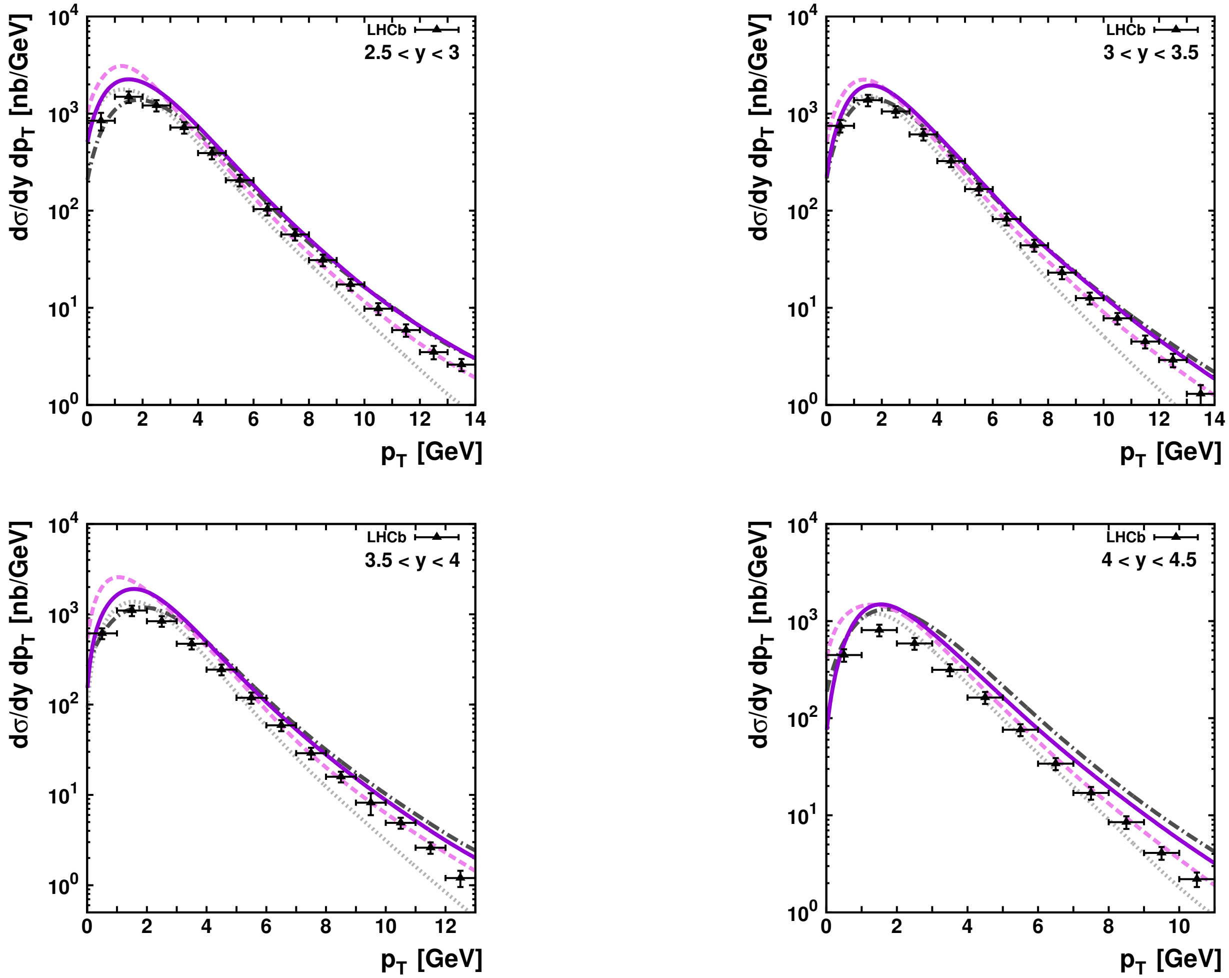
Double differential cross section $d\sigma/dydp_T$ of prompt J/ψ production at LHC. Solid, dashed and dashed-dotted curves correspond to the results obtained using the CCFM A0, B0 and KMR u.p.d.. Dotted curves represent the contribution from sole direct production mechanism calculated with the CCFM A0 u.g.d..



Differential cross section J/ψ mesons at LHC in CASCADE. The experimental data are from CMS



Double differential cross section $d\sigma/dydp_T$ of the J/ψ production at LHC compared to the ATLAS data.



Double differential cross section $d\sigma/dydp_T$ of the J/ψ production at LHC compared to the LHCb data.

Conclusions

- **There is steady progress toward a better understanding of the k_T-factorization (high energy factorization) and the uPDF (TMD).**
- **We have described the first exp. data of b-quark and J/ψ production at LHC in the k_T-factorization approach.**
- **We have obtained reasonable agreement of our calculations and the first experimental data taken by the CMS and ATLAS Collaborations.**
- **The dependence of our predictions on the u.g.d. appears at small transverse momenta and at large rapidities in H_b and J/ψ-production covered by the LHCb experiment.**
- **Our study has demonstrated also that in the framework of the k_T-factorization approach is no room for a CO contributions for the charmonium production at the LHC.**

- **The future experimental analyses of quarkonium polarization at LHC turend out to be very important and informative for discriminating the different theoretical models.**

Back up

Considering the polarization properties of $J/\psi(\Upsilon)$ mesons originating from radiative decays of P-wave states we rely upon the dominance of electric dipole $E1$ transitions. The corresponding invariant amplitides can be written as

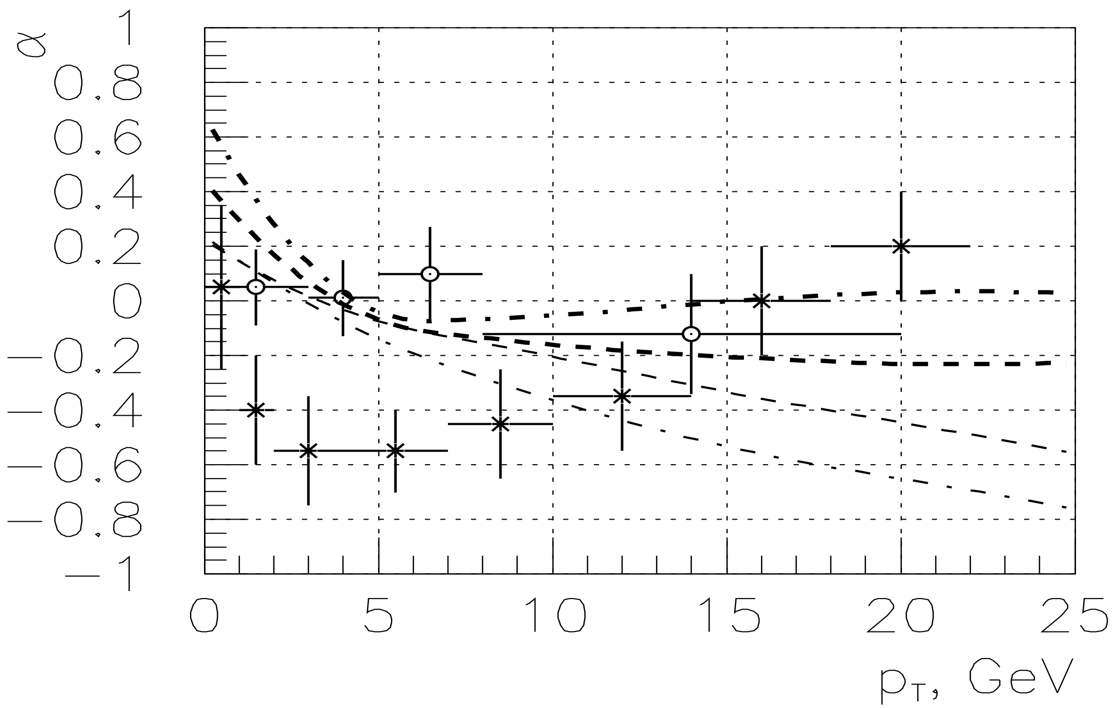
$$i\mathcal{A}(\chi_{c1} \to J/\psi + \gamma) = g_1\, \epsilon^{\mu\nu\alpha\beta} k_\mu \epsilon_\nu^{(\chi_{c1})} \epsilon_\alpha^{(J/\psi)} \epsilon_\beta^{(\gamma)},$$

$$i\mathcal{A}(\chi_{c2} \to J/\psi + \gamma) = g_2\, p^\mu \epsilon^{\alpha\beta}_{(\chi_{c2})} \epsilon_\alpha^{(J/\psi)} \left[k_\mu \epsilon_\beta^{(\gamma)} - k_\beta \epsilon_\mu^{(\gamma)}\right].$$

Polarization of the decay products

$$\begin{aligned}
\sigma_{V(h=0)} &= B(\chi_1 \to V\gamma)\left[(1/2)\,\sigma_{\chi_1(|h|=1)}\right] \\
&+ B(\chi_2 \to V\gamma)\left[(2/3)\,\sigma_{\chi_2(h=0)} + (1/2)\,\sigma_{\chi_2(|h|=1)}\right] \\
\sigma_{V(|h|=1)} &= B(\chi_1 \to V\gamma)\left[\sigma_{\chi_1(h=0)} + (1/2)\,\sigma_{\chi_1(|h|=1)}\right] \\
&+ B(\chi_2 \to V\gamma)\left[(1/3)\,\sigma_{\chi_2(h=0)} + (1/2)\,\sigma_{\chi_2(|h|=1)} + \sigma_{\chi_2(|h|=2)}\right].
\end{aligned}$$

$\Upsilon(1S)$ Spin alignement at the TEVATRON



Dash-dotted lines – JB gluons; dashed – dGRV gluons;
Thin lines – direct Υ only; thick lines – with χ_b decays added.
Theor. predictions are from S.P. Baranov, N.Z. Pis'ma v ZhETF, **88** *(2008) 825;*

∘ *D.Acosta et al.(CDF), Phys. Rev. Lett.* **88** *(2002) 161802;*

× *V.M.Abazov et al.(DO), Phys. Rev. Lett.***101** *(2008) 182004.*