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Open b production at LHC and Parton Shower Effects

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Abstract

We present hadron-level predictions from the Monte Carlo generator CASCADE and numerical level calculations of beauty quark and inclusive b -jet production in the framework of the k_T -factorization QCD approach for CERN LHC energies. The unintegrated gluon densities in a proton are determined using the CCFM evolution equation and the Kimber-Martin-Ryskin (KMR) prescription. We study the theoretical uncertainties of our calculations and investigate the effects coming from parton showers in initial and final states. Our predictions are compared with the recent data taken by the CMS collaboration.

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1 Introduction

Beauty production at high energies is subject of intense studies from both theoretical and experimental points of view since events containing b quarks present an important background to many of the searches at the LHC. From the theoretical point, the dominant production mechanism is believed to be quark pair production through the gluon-gluon fusion subprocess and therefore these processes provide an opportunity to test the different predictions based on Quantum Chromodynamics (QCD). The present note is motivated by the recent measurements [1, 2] b production performed by the CMS collaboration. The b -quark cross sections have been presented [1] as a function of the muon transverse momentum and pseudorapidity at $\sqrt{s} = 7$ TeV. It was observed that the data tend to be higher than the MC@NLO [3, 4] predictions. On the other hand the measurements of inclusive b -jet

production cross sections [2] are reasonably well described by MC@NLO. In addition to the comparison of CASCADE with data in [1] we present here further studies.

In the framework of the k_T -factorization approach of QCD [5], which is of primary consideration in this note, a study of the heavy quark production has been done (for previous results see [6–12]). In our previous study [12] we show a good agreement between the Tevatron data on the b quarks, $b\bar{b}$ di-jets, B^+ and several D mesons (or rather muons from their semileptonic decays) production with the predictions coming from k_T -factorization and we investigated the role of initial and final state parton showers. Based on these results, we give here a systematic analysis of the recent CMS measurements [1, 2] in the framework of k_T -factorization. As done in [12], we produce the calculations in two ways: we will perform numerical parton-level calculations (labeled as LZ) as well as calculations with the full hadron level Monte Carlo event generator CASCADE [13] and compare both with the measured cross sections of heavy quark production. In this way we will investigate the influence of parton showers in initial and final states for the description of the data. Additionally we study different sources of theoretical uncertainties, i.e. uncertainties connected with the gluon evolution scheme, heavy quark mass, hard scale of partonic subprocess and the heavy quark fragmentation functions.

The outline of our paper is the following. In Section 2 we recall very shortly the basic formulas of the k_T -factorization approach with a brief review of calculation steps. In Section 3 we present the numerical results of our calculations and a discussion. Section 4 contains our conclusions.

2 Theoretical framework

In the present analysis we follow the approach described in the earlier publication [12]. For the reader's convenience, we only briefly recall here main points of the theoretical scheme.

The cross section of heavy quark hadroproduction at high energies in the k_T -factorization approach is calculated as a convolution of the off-shell (i.e. k_T -dependent) partonic cross section $\hat{\sigma}$ and the unintegrated gluon distributions in a proton. It can be presented in the following form:

$$\begin{aligned} \sigma(p\bar{p} \rightarrow Q\bar{Q} X) = & \int \frac{1}{16\pi(x_1 x_2 s)^2} \mathcal{A}(x_1, \mathbf{k}_{1T}^2, \mu^2) \mathcal{A}(x_2, \mathbf{k}_{2T}^2, \mu^2) |\bar{\mathcal{M}}(g^* g^* \rightarrow Q\bar{Q})|^2 \times \\ & \times d\mathbf{p}_{1T}^2 d\mathbf{k}_{1T}^2 d\mathbf{k}_{2T}^2 dy_1 dy_2 \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi}, \end{aligned} \quad (1)$$

where $\mathcal{A}(x, \mathbf{k}_T^2, \mu^2)$ is the unintegrated gluon distribution in a proton, $|\bar{\mathcal{M}}(g^* g^* \rightarrow Q\bar{Q})|^2$ is the off-shell (i.e. depending on the initial gluon virtualities \mathbf{k}_{1T}^2 and \mathbf{k}_{2T}^2) matrix element squared and averaged over initial gluon polarizations and colors, and s is the total center-of-mass energy. The produced heavy quark Q and anti-quark \bar{Q} have the transverse momenta \mathbf{p}_{1T} and \mathbf{p}_{2T} and the center-of-mass rapidities y_1 and y_2 . The initial off-shell gluons have a fraction x_1 and x_2 of the parent protons longitudinal momenta, non-zero transverse momenta \mathbf{k}_{1T} and \mathbf{k}_{2T} ($\mathbf{k}_{1T}^2 = -k_{1T}^2 \neq 0$, $\mathbf{k}_{2T}^2 = -k_{2T}^2 \neq 0$) and azimuthal angles ϕ_1 and ϕ_2 . The analytic expression for the $|\bar{\mathcal{M}}(g^* g^* \rightarrow Q\bar{Q})|^2$ can be found, for example, in [5, 9].

The unintegrated gluon distribution in a proton $\mathcal{A}(x, \mathbf{k}_T^2, \mu^2)$ in (1) can be obtained from the analytical or numerical solution of the Balitsky-Fadin-Kuraev-Lipatov (BFKL) [14] or

Ciafaloni-Catani-Fiorani-Marchesini (CCFM) [15] equations. As in [12], in the numerical calculations we have tested a few different sets, namely CCFM A0 (B0) [16] and KMR [17] ones. The input parameters in both CCFM-evolved gluon densites have been fitted [16] to describe the proton structure function $F_2(x, Q^2)$. 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 [16] by both these sets. To evaluate the unintegrated gluon densities in a proton $\mathcal{A}(x, \mathbf{k}_T^2, \mu^2)$ we apply also the Kimber-Martin-Ryskin (KMR) approach [17]. The KMR approach is a formalism to construct the unintegrated parton (quark and gluon) distributions from the known conventional parton distributions. For the input, we have used the standard GRV 94 (LO) [18] (in LZ calculations) and MRST 99 [20] (in CASCADE) sets.

3 Numerical results

The unintegrated gluon distributions to be used in the cross section (1) depend on the renormalization and factorization scales μ_R and μ_F . Following [12], in the numerical calculations 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 $\Lambda_{\text{QCD}} = 200$ MeV, such that $\alpha_s(M_Z^2) = 0.1232$.

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 [1] 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 in the LZ calculations, 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. The branching of $b \rightarrow \mu$ as well as the cascade decay $b \rightarrow c \rightarrow \mu$ are taken into account with the relevant branching fractions taken from [22]. The predictions of the LZ and CASCADE calculations are shown in Figs. 1 and 2 in comparison with the CMS data. We find a good description of the data when using the CCFM-evolved (A0) gluon distribution in LZ calculations although the CASCADE curves tend to lie slightly below the data at central rapidities. The predictions between the LZ and CASCADE calculations agree well at parton level. The observed difference between them in Figs. 1 and 2 is due to missing parton shower effects in the LZ calculations. The influence of such effects is demonstrated in Fig. 3, where we show separately the results of our CASCADE calculations without parton shower, with only initial state, with only final state and with both initial and final state parton showers. One can see that without initial and final state parton showers, the CASCADE predictions are very close to the LZ ones. The similar situation was pointed out in [12] at the Tevatron energies.

To investigate the dependence of our predictions on the quark-to-hadron fragmentation function, we repeated our calculations with the shifted value of the Peterson shape parameter $\epsilon_b = 0.003$, which is often used in the NLO pQCD calculations. Additionally, we have applied the non-perturbative fragmentation functions which have been proposed in [23–25].

Source	$\sigma(pp \rightarrow b + X \rightarrow \mu + X', p_T^\mu > 6 \text{ GeV}, \eta^\mu < 2.1)$
CMS data [μb]	$1.32 \pm 0.01 \text{ (stat)} \pm 0.30 \text{ (syst)} \pm 0.15 \text{ (lumi)}$
A0 (LZ/CASCADE)	1.31/0.96
B0 (LZ/CASCADE)	0.98/0.72
KMR (LZ/CASCADE)	0.91/0.59
MC@NLO [1]	0.95
PYTHIA [1]	1.9

Table 1: The inclusive b-quark production cross section in pp collisions at $\sqrt{s} = 7 \text{ TeV}$.

The input parameters were determined [24, 25] by a fit to LEP data. The results of our calculations are shown in Fig. 4. For illustration, we used here the CCFM A0 gluon density. We find that the predicted cross sections in the considered kinematic region are larger for smaller values of the parameter ϵ_b or if the fragmentation function from [23–25] is used. Thus, the CMS data points lie within the band of theoretical uncertainties. The results obtained here (see Fig. 1) with the CCFM B0 and KMR gluon densities (but also with A0 density as shown in the CMS paper) are rather close to the MC@NLO ones (not shown) and underestimate the data by a factor of 1.6.

The visible cross sections of decay muons from b -decays are listed in Table 1 in comparison with the CMS data [1]. In Table 2 the systematic uncertainties of our calculations are summarized. To estimate the uncertainty coming from the renormalization scale μ_R , we used the CCFM set A0+ and A0– instead of the default density function A0. These two sets represent a variation of the scale used in α_s in the off-shell matrix element. The A0+ stands for a variation of $2\mu_R$, while set A0– reflects $\mu_R/2$. We observe a deviation of roughly 13% for set A0+. The uncertainty coming from set A0– is generally smaller and negative. The dependence on the b -quark mass is investigated by variation of b -quark mass of $m_b = 4.75 \text{ GeV}$ by $\pm 0.25 \text{ GeV}$. The calculated b -quark cross sections vary by $\sim \pm 6\%$.

The CMS collaboration has measured [2] the double differential cross sections $d\sigma/dy dp_T$ of inclusive b -jet production at the $\sqrt{s} = 7 \text{ TeV}$. The measurements have been determined in four b -jet rapidity regions, namely $|y| < 0.5$, $0.5 < |y| < 1$, $1 < |y| < 1.5$ and $1.5 < |y| < 2$. Our predictions are shown in Figs. 5 and 6 and compared to the CMS data. In the CASCADE calculations the b -jets are reconstructed with the anti- k_t cone algorithm [26] (using the FASTJET package [27, 28]) with radius $R > 0.5$. In contrast with the decay muon cross sections, the predictions based on the CCFM and KMR gluons are very similar to each

Source	$\sigma(pp \rightarrow b + X \rightarrow \mu + X', p_T^\mu > 6 \text{ GeV}, \eta^\mu < 2.1)$
CCFM set A0	0.96 μb
CCFM set A0+	+13%
CCFM set A0-	-2%
$m_b = 5.0 \text{ GeV}$	-7%
$m_b = 4.5 \text{ GeV}$	+6%
$\epsilon_b = 0.003$	+9%
Total	$\pm^{17\%}_{7\%}$

Table 2: Systematic uncertainties for beauty total cross section in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ obtained with CASCADe.

other. The reasonable description of the data is obtained by all unintegrated gluon densities under consideration.

Finally, we would like to point out the role of non-zero gluon transverse momentum k_T in the off-shell matrix elements (see Figs. 7 and 8). In these Figs, the solid histograms correspond to the results obtained according to the master formula (1). The dotted histograms are obtained by using the same formula but without virtualities of the incoming gluons in partonic amplitude and with the additional requirement $\mathbf{k}_{1,2T}^2 < \mu_R^2$. We find that the non-zero gluon transverse momentum in the hard matrix element is important for the description of data. The similar situation was pointed out in [12] at the Tevatron energies. It means, that the high \mathbf{k}_T region is important, and only when including the high \mathbf{k}_T tail the results are similar to NLO predictions.

4 Conclusions

In this note we analyzed the first data on the beauty production in pp collisions at LHC taken by the CMS collaboration. Our consideration is based on the k_T -factorization approach supplemented with the CCFM-evolved unintegrated gluon densities in a proton. The analysis covers the total and differential cross sections of muons originating from the semileptonic decays of beauty quarks as well as the double differential cross sections of inclusive b -jet production. Using the full hadron-level Monte Carlo generator CASCADe, we investigated

the effects coming from the parton showers in initial and final states. Different sources of theoretical uncertainties have been studied.

Our LZ predictions with the default set of parameters agree with the data. The CASCADE predictions tend to slightly underestimate the data at central rapidities but the data points still lie within the band of theoretical uncertainties. In this case the overall description of the data at a similar level of agreement as in the framework of NLO collinear QCD factorization.

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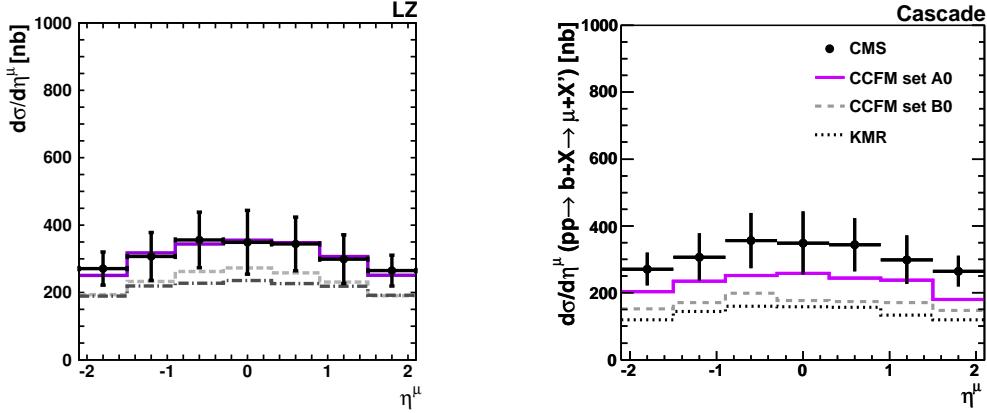


Figure 1: The pseudorapidity distributions of muons arising from the semileptonic decays of beauty quarks. The first column shows the LZ numerical results while the second one depicts the CASCADE predictions. The solid, dashed and dotted histograms correspond to the results obtained with the CCFM A0, B0 and KMR unintegrated gluon densities. The kinematic cuts applied are described in the text. The experimental data are from CMS [1].

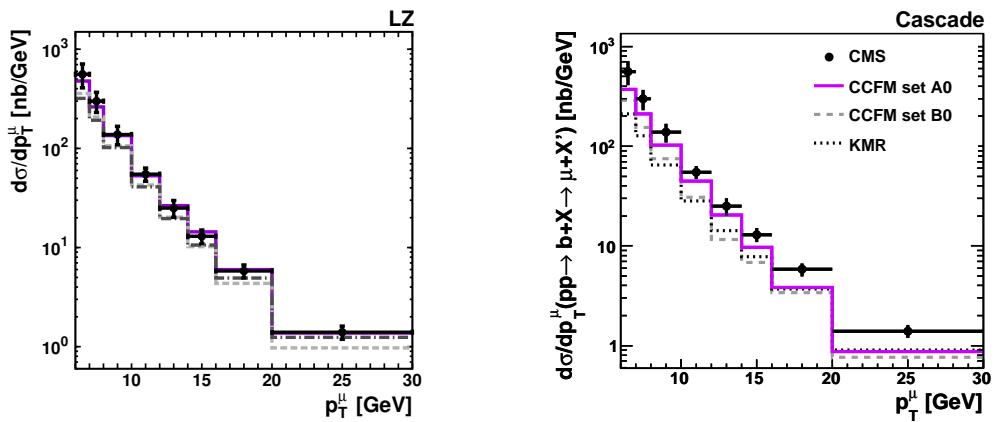


Figure 2: The transverse momentum distributions of muons arising from the semileptonic decays of beauty quarks. The first column shows the LZ numerical results while the second one depicts the CASCADE predictions. Notation of all histograms is the same as in Fig. 1. The kinematic cuts applied are described in the text. The experimental data are from CMS [1].

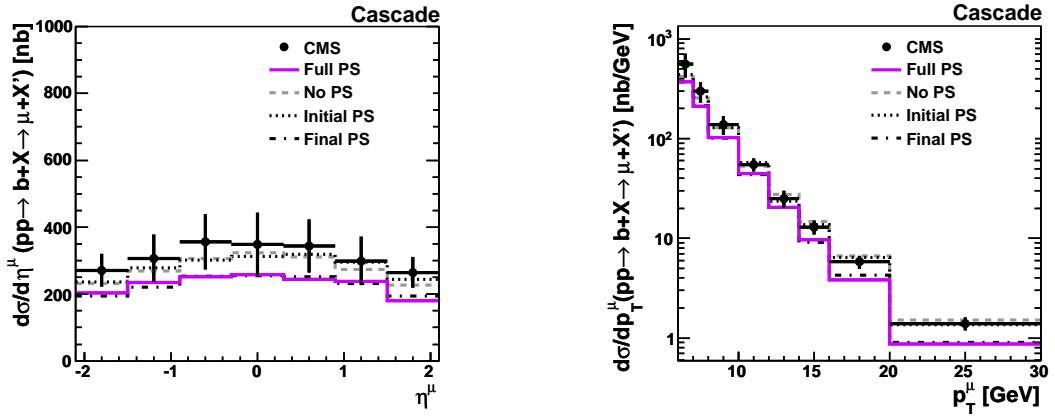


Figure 3: Parton shower effects in the pseudo-rapidity and transverse momentum distributions of the muons. The four lines represent full parton shower (solid line), no parton shower (dashed line), initial state parton shower (dashed dotted line) and final state parton shower (dotted line). The experimental data are from CMS [1].

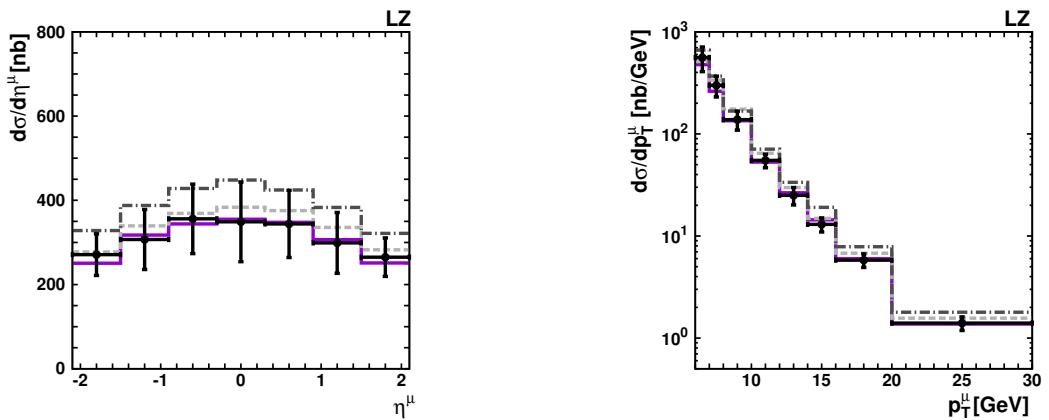


Figure 4: The dependence of our predictions on the fragmentation scheme. The solid, dashed and dash-dotted histograms correspond to the results obtained using the Peterson fragmentation function with $\epsilon_b = 0.006$, $\epsilon_b = 0.003$ and the non-perturbative fragmentation functions from [23–25], respectively. We use CCFM-evolved (A0) gluon density for illustration. The experimental data are from CMS [1].

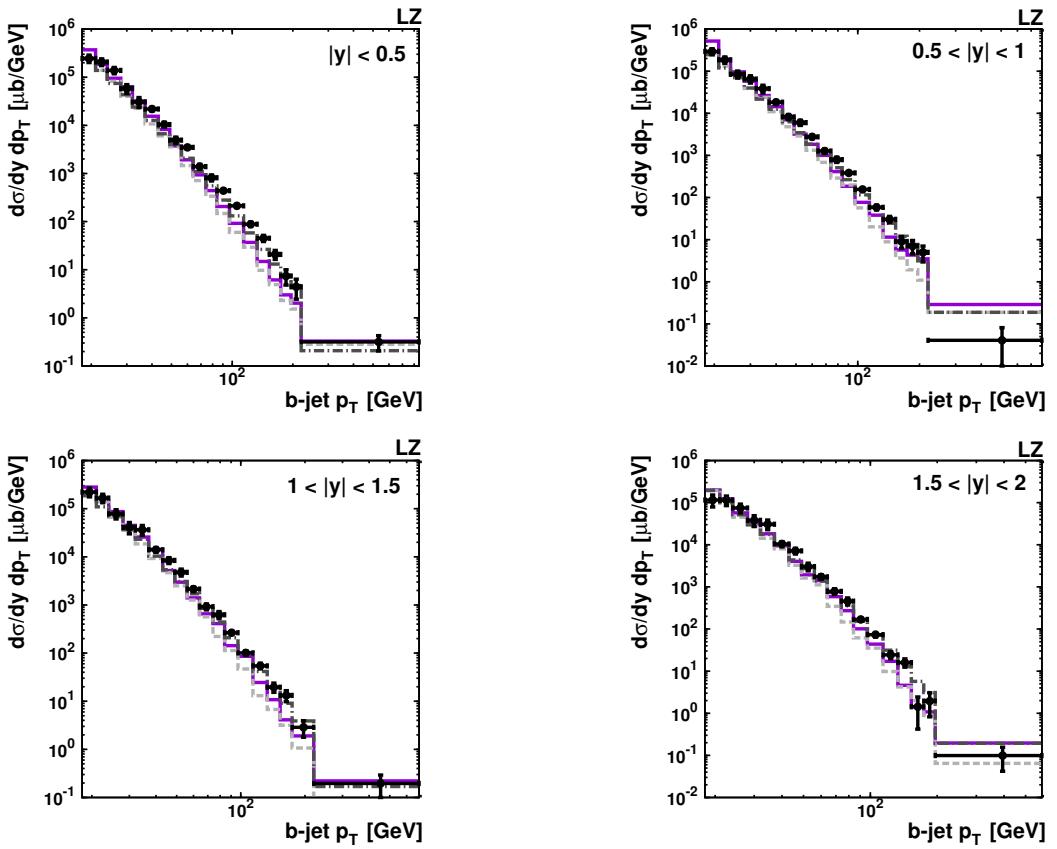


Figure 5: The double differential cross sections $d\sigma/dy dp_T$ of inclusive b -jet production as a function of p_T in different y regions calculated at $\sqrt{s} = 7$ TeV (LZ predictions). Notation of all histograms is the same as in Fig. 1. The experimental data are from CMS [2].

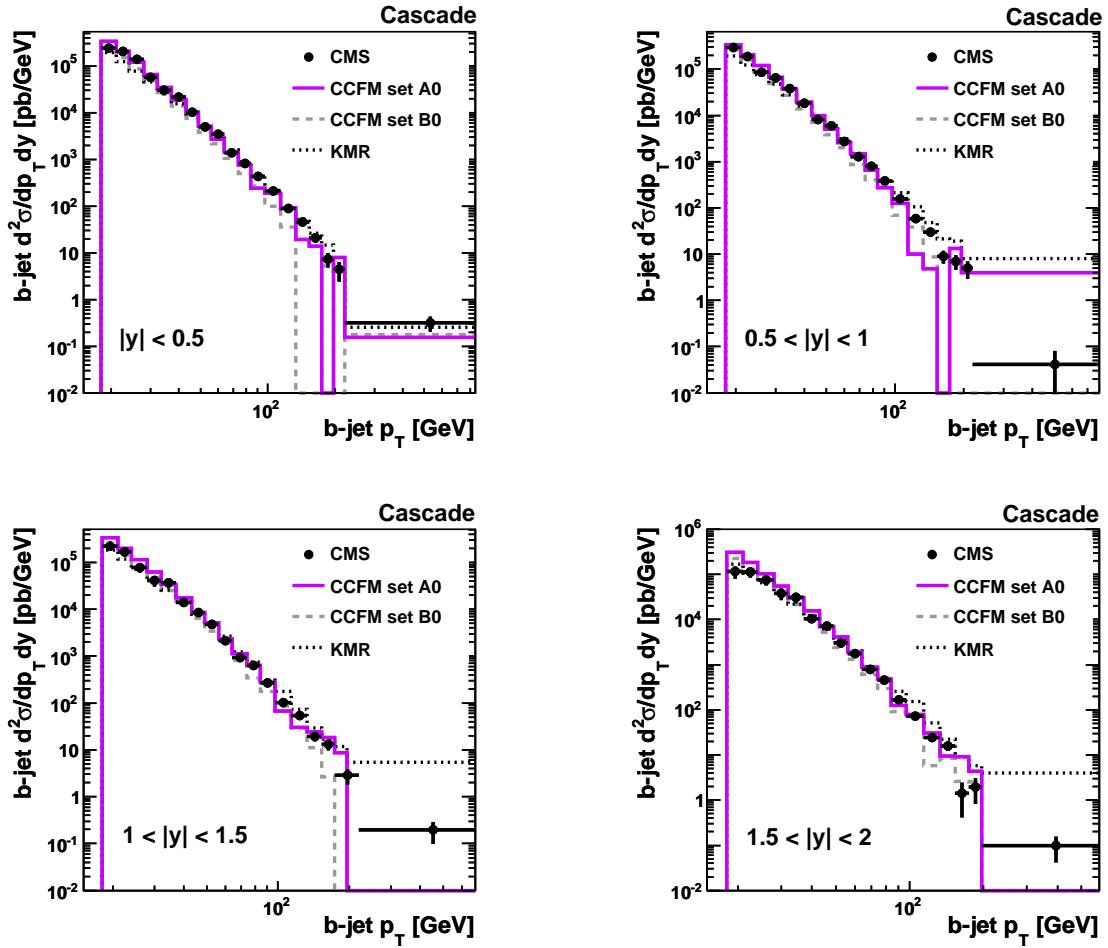


Figure 6: The double differential cross sections $d\sigma/dy dp_T$ of inclusive b -jet production as a function of p_T in different y regions calculated at $\sqrt{s} = 7$ TeV (CASCADE predictions). Notation of all histograms is the same as in Fig. 1. The experimental data are from CMS [2].

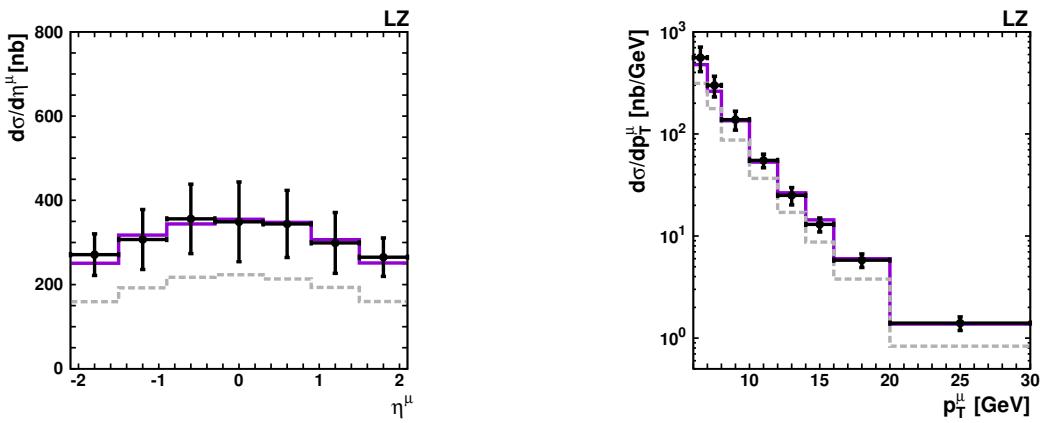


Figure 7: Importance of non-zero transverse momentum of incoming gluons in open b quark production at the LHC. The solid histograms correspond to the results obtained according to the master formula (1). The dotted histograms are obtained by using the same formula but now we switch off the virtualities of both incoming gluons in partonic amplitude and apply an additional requirement $k_{1,2T}^2 < \mu_R^2$. We have used here the CCFM A0 gluon for illustration. The experimental data are from CMS [1].

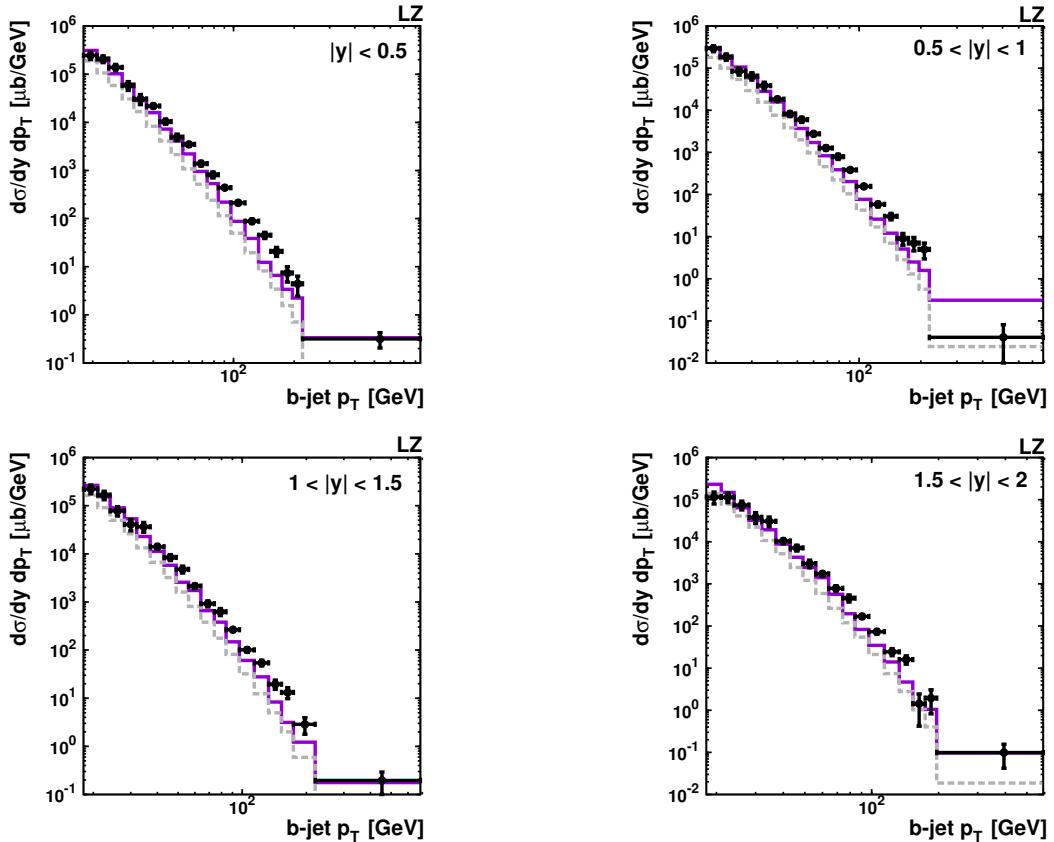


Figure 8: Importance of non-zero transverse momentum of incoming gluons in b -jet production at the LHC. Notation of all histograms is the same as in Fig. 7. The experimental data are from CMS [2].