Beauty quark and quarkonium production at LHC: $k_T$-factorization and CASCADE versus data

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Abstract. We present hadron-level predictions from the Monte-Carlo generator CASCADE and numerical calculations of beauty quark and quarkonium production in the framework of the $k_T$-factorization approach for LHC energies. Our predictions are compared with the CMS experimental data.

Keywords: QCD, quarkonium production, $k_T$-factorization
PACS: 13.85 Qk, 12.38.Bx

Our study is motivated by very recent measurement of open beauty quark and $b$-jet production performed by the CMS Collaboration. It was observed that the data tends to be higher than the MC@NLO predictions and that the shape of the pseudo-rapidity distribution is not well described by MC@NLO. The $p_T$-spectra of b-jets are not well described too [1, 2].

Recently we have demonstrated reasonable agreement between the $k_T$-factorization predictions [3] and the Tevatron data on the $b$-quark, $b\bar{b}$ di-jets, $B^+$- and $D$-meson production and also agreement with total set of HERA data for $J/\psi$-mesons [4]. Based on these results, here we give the 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 perform 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 [5].

The basic dynamical quantity of the $k_T$-factorization approach is the unintegrated ($k_T$-dependent) gluon distribution (UGD) $\mathcal{A}(x, k_T^2, \mu^2)$ obtained from the analytical or numerical solution of the BFKL or CCFM evolution equations.

The cross section of any physical process is calculated as a convolution of the partonic cross section $\hat{\sigma}$ and the UGD $\mathcal{A}_g(x, k_T^2, \mu^2)$, which depend on both the longitudinal momentum fraction $x$ and transverse momentum $k_T$:

$$\sigma_{pp} = \int \mathcal{A}_g(x_1, k_{1T}^2, \mu^2) \mathcal{A}_g(x_2, k_{2T}^2, \mu^2) \hat{\sigma}_{gg}(x_1, x_2, k_{1T}^2, k_{2T}^2, \ldots) dx_1 dx_2 dk_{1T}^2 dk_{2T}^2.$$ 

The partonic cross section $\hat{\sigma}$ has to be taken off mass shell ($k_T$-dependent).

It also assumes a modification of their polarization density matrix. It has to be taken in...
so called BFKL form:

$$\sum_{\varepsilon, \varepsilon'} k_{\varepsilon}^\mu k_{\varepsilon'}^\nu \frac{k_F^2}{k_T^2}.$$  

Concerning the UPD in a proton, we used two different sets. First of them is the KMR one [6]. The KMR approach represents an approximate treatment of the parton evolution mainly based on the DGLAP equation and incorporating the BFKL effects at the last step of the parton ladder only, in the form of the properly defined Sudakov formfactors $T_q(k_T^2, \mu^2)$ and $T_g(k_T^2, \mu^2)$, including logarithmic loop corrections.

Second UGD is the CCFM one. The CCFM evolution equation have been solved numerically using Monte-Carlo method [7]. In this case UGD are determined by a convolution of the non-perturbative starting distribution $A_0(x)$ and CCFM evolution denoted by $\bar{A}(x, k_T^2, \mu^2)$. The parameters of $A_0(x)$ were determined in the fit to $F_2$ data.

It is known that the hard partonic subprocess of gluon-gluon fusion $gg \rightarrow Q\bar{Q}$ amplitude is described by three Feynman’s diagrams.

In the numerical calculations in the case CCFM UGD we have used two different sets, namely $A_0$ and $B_0$. The difference between these sets is connected with the different values of soft cut and width of the intrinsic $k_T$ distribution.

For KMR we have used as the standard GRV 94 (LO) [8] as MSTW [9] (in LZ calculations) and MRST 99 [10] (in CASCADE) sets. The UGD depends on the renormalization and factorization scales $\mu_R$ and $\mu_F$. We set $\mu_R^2 = m_Q^2 + (p_{1T}^2 + p_{2T}^2)/2$, $\mu_F^2 = \hat{s} + Q_T^2$, where $Q_T$ 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 $\Lambda_{QCD} = 200$ 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 $b$-quarks (Fig. 1). To produce muons from $b$-quarks, we first convert $b$-quarks into $B$-mesons using the Peterson fragmentation function with

![Image](image_url)

**FIGURE 1.** 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. Solid, dashed and dash-dotted, dotted histograms correspond to the results obtained with the CCFM A0, B0 and KMR UPD. The experimental data are from CMS.
default value $\varepsilon_b = 0.006$ [11] and then simulate their semileptonic decay according to the standard electroweak theory taking into account the decays $b \rightarrow \mu$ as well as the cascade decay $b \rightarrow c \rightarrow \mu$. In CASCADE calculations also Peterson fragmentation function is used but with full PYTHIA fragmentation. In Fig. 2 we show our description of the $b$-jet distributions at LHC.

In the case quarkonium production we used Color-Singlet (CS) photon-gluon or gluon-gluon fusion in the framework of the $k_T$-factorization approach. In Fig. 3 we show our results for $J/\psi$ production at HERA and in Fig. 4 we present comparison of our results with LHC data on the $J/\psi$ production in framework of the MC generator CASCADE.

In summary we have analysed the first data on the beauty and $J/\psi$ production in $pp$ collisions at LHC taken by the CMS collaboration. Our study is based on a semi-analytical parton level calculations and a full hadron level MC generator CASCADE. The overall description of the data is reasonable. In most of the distributions it is simi-

**FIGURE 2.** The double differential cross sections $d\sigma/dyd\,p_T$ 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.

**FIGURE 3.** Differential cross sections $J/\psi$ mesons at HERA. The solid, dashed and dash-dotted histograms correspond to the results obtained using the CCFM A0, BO and KMR gluon densities. The upper and lower dashed histograms represent the scale variations.
lar to MC@NLO except in some particular distributions where the $k_T$-factorization approach does describe the data better, like in $b$-jet. $J/\psi$ production in the $k_T$-factorization approach with CS model comes much closer to the data than the collinear calculations. The reason is the off-shell ME, which includes even higher order contributions than the NLO collinear calculations.

The authors were supported by MSU–DESY project on MC implementation for HERA–LHC, RF FASI grant NS-4142.2010.2 and RF FASI state contract 02.740.11.0244. A.L. was supported in part by the grant of President of Russian Federation (MK-3977.2011.2) and the HRJRG fund. N.Z. is very grateful to the Organization Committee, in particular R. Ent, for the financial support.

REFERENCES

1. CMS Collaboration, JHEP 1103, 090 (2011)
2. V. Chiochia, arXiv:1011.5212 [hep-ex].
3. H. Jung, M. Krämer, A.V. Lipatov, and N.P. Zotov, JHEP 1101, 085 (2011).
4. S.P. Baranov, A.V. Lipatov, and N.P. Zotov, Eur. Phys. J. C 71, 1631 (2011).
5. A. Bertolin, these Proceedings.
6. H. Jung, Comp. Phys. Comm. 143, 100 (2002); H. Jung, S. Baranov, M. Deak at al., Eur. Phys. J. C 70, 1237 (2010).
7. M. Kimber, A. Martin, and M. Ryskin, Phys. Rev. D 63, 114027 (2001); G. Watt, A.D. Martin, and M.G. Ryskin, Eur. Phys. C 31, 73 (2003).
8. M. Glück, E. Reya, and A. Vogt, Phys. Rev. D 46, 1973 (1992).
9. A.D. Martin, W.J. Stirling, R.S. Thorne, and G. Watt, Eur. Phys. J. C 63, 189 (2009).
10. A.D. Martin, R. G. Roberts, W.J. Stirling, and R.S. Thorne, Eur. Phys. J. C 14, 133 (2000).
11. C. Peterson, D. Schlatter, I. Schmitt, and P.M. Zerwas, Phys. Rev. D 27, 105 (1983).

FIGURE 4. Differential cross sections $J/\psi$ mesons at LHC in CASCADE. The experimental data are from CMS.