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Inclusive B-Meson Production at the LHC in the GM-VFN Scheme

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Abstract

We calculate the next-to-leading-order cross section for the inclusive production of B mesons in pp collisions in the general-mass variable-flavor-number scheme, an approach which takes into account the finite mass of the b quarks. We use realistic evolved nonperturbative fragmentation functions obtained from fits to e^+e^- data and compare our results for the transverse-momentum and rapidity distributions at a center-of-mass energy of 7 TeV with recent data from the CMS Collaboration at the CERN LHC. We find good agreement, in particular at large values of p_T.

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1 Introduction

Since the late eighties there has been much interest in the study of B-meson production in $p\bar{p}$ and pp collisions at hadron colliders, both experimentally and theoretically. The first measurements were performed more than two decades ago by the UA1 Collaboration at the CERN $S\bar{p}pS$ collider [1] operating at a center-of-mass energy of $\sqrt{S} = 0.63$ TeV. More recent measurements were made by the CDF and D0 Collaborations at the Fermilab Tevatron running at $\sqrt{S} = 1.8$ TeV [2, 3] and 1.96 TeV [4]. Just recently, the CMS Collaboration at the CERN LHC collider published first results for inclusive B^+- [5], B^0- [6], and B_s-meson [7] production in pp collisions at $\sqrt{S} = 7$ TeV. B^+ mesons were reconstructed via their decay $B^+ \to J/\psi K^+$ followed by $J/\psi \to \mu^+\mu^-$, whereas B^0 mesons were identified through the observation of $J/\psi K_s^0$ final states with the subsequent decays $J/\psi \to \mu^+\mu^-$ and $K_s^0 \to \pi^+\pi^-$. In the case of B_s mesons, the reconstructed final states were generated by the decay chain $B_s \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, and $\phi \to K^+K^-$. From all these measurements the differential cross sections $d\sigma/dp_T$ and $d\sigma/dy$ as well as the integrated cross section for $p_T \geq 5$ GeV (for B^+ and B^0 mesons) or $p_T \geq 8$ GeV (for B_s mesons) were reported.

The general-mass variable-flavor-number (GM-VFN) scheme provides a rigorous theoretical framework for the description of the inclusive production of single heavy-flavored hadrons, combining the fixed-flavor-number (FFN) [8] and zero-mass variable-flavor-number (ZM-VFN) [9] schemes, which are valid in complementary kinematic regions, in a unified approach that enjoys the virtues of both schemes and, at the same time, is bare of their flaws. Specifically, it resums large logarithms by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution of nonperturbative fragmentation functions (FFs), guarantees the universality of the latter as in the ZM-VFN scheme, and simultaneously retains the mass-dependent terms of the FFN scheme without additional theoretical assumptions. It was elaborated at next-to-leading order (NLO) for photoproduction [10] and hadroproduction [11] of charmed hadrons as well as for their production by e^+e^- annihilation [12]. It was also applied to obtain predictions for B-meson hadroproduction [13], which could be compared with recent CDF data [4]. An earlier implementation of such an interpolating scheme is the so-called fixed-order-next-to-leading-logarithm (FONLL) approach, in which the conventional cross section in the FFN scheme is linearly combined, with the help of a p_T-dependent weight function, with a suitably modified cross section in the ZM-VFN scheme implemented with perturbative FFs [14].

In Ref. [13], nonperturbative FFs for the transitions $a \to B$, where a is any parton, including b and $\bar{b}$ quarks, were extracted at NLO in the $\overline{\mathrm{MS}}$ factorization scheme with $n_f = 5$ flavors from the scaled-energy (x) distributions $d\sigma/dx$ of $e^+e^- \to B + X$ measured by the ALEPH [15] and OPAL [16] Collaborations at the CERN LEP1 collider and by the SLD Collaboration [17] at the SLAC SLC collider. As explained in Ref. [13], these FFs may be consistently used in our GM-VFN framework. Working at NLO in the GM-VFN scheme with these B-meson FFs, we found excellent agreement with recent CDF measurements of $d\sigma/dp_T$ for $p\bar{p} \to B + X$ [4], especially in the upper p_T range, $p_T \gtrsim 10$

GeV [13].

The content of this paper is as follows. In Sec. 2, we summarize our input choices of PDFs and B-meson FFs. In Sec. 3, we compare the predictions of the GM-VFN scheme with the CMS data from the recent LHC run at $\sqrt{S} = 7$ TeV [5, 6, 7]. Our conclusions are given in Sec. 4.

2 Input PDFs and B-meson FFs

As PDFs for the proton, we choose one of the most recent parametrizations of the CTEQ Collaboration, set CTEQ6.6M [18], which provides an improvement over the earlier version CTEQ6.5M. Both sets were obtained in the framework of a general-mass scheme using the input values $m_c = 1.3$ GeV, $m_b = 4.5$ GeV, and $\alpha_s(m_Z) = 0.118$. In both set, the b-quark PDF has its starting scale at $\mu_0 = m_b$.

The nonperturbative FFs describing the transition of the b and $\bar{b}$ quarks into a B meson can be obtained only from experiment. In our earlier work on inclusive B-meson production at the Tevatron [13], we constructed such FFs using as input recent precise measurements of the cross section of inclusive B-meson production in e^+e^- annihilation obtained by the ALEPH [15], OPAL [16], and SLD [17] Collaborations.[1] These data were taken on the Z-boson resonance, so that finite-m_b effects, being of relative order m_b^2/m_Z^2, are strongly suppressed, which means that we are in the asymptotic regime where the GM-VFN scheme is equivalent to the ZM-VFN scheme. The combined fit to the three data sets was performed using the NLO value $\Lambda^{(5)}_{\overline{MS}} = 227$ MeV corresponding to $\alpha_s^{(5)}(m_Z) = 0.1181$, values adopted from Ref. [18]. The renormalization and factorization scales were chosen to be $\mu_R = \mu_F = m_Z$. In accordance with the chosen PDFs, the starting scale of the $b \to B$ FF was taken to be $\mu_0 = m_b$, while the $g, q \to B$ FFs, where q denotes the light quarks including the charm quark, were taken to vanish at $\mu_F = \mu_0$.

For fitting the data, we actually employed two different parametrizations for the $b \to B$ FF at $\mu_0 = m_b$, namely the Peterson ansatz [20] and the simple power ansatz [21]. It turned out that the Peterson ansatz led to a very poor fit. Therefore, we shall use in this work only the FFs obtained with the power ansatz, whose parameters at the starting scale are listed in Table 1 of Ref. [13]. A comparison of the fit performed using this ansatz with the three input data sets may be found in Fig. 1 of that reference.

We note that the data from OPAL and SLD included all B-hadron final states, in particular those with Λ_b hadrons, while, in the ALEPH analysis, only final states with identified $B^\pm$ and B^0 mesons were taken into account. Our fit was based on the assumption that the FFs of all b hadrons had the same shape. The branching fraction of $b \to B^+$ was taken equal to that of $b \to B^0$ and fixed to 0.397. In our calculations for B_s-meson production to be presented below, we shall use the same FFs and rescale them by the factor

[1] Recently, similar data became available also from the DELPHI Collaboration [19].

0.113/0.401, which uses the up-to-date values for the $b \to B^+$ and $b \to B_s$ branching fractions quoted by the Particle Data Group [22].

We should emphasize that, in the analysis of the available e^+e^- annihilation data, the charged and neutral B mesons were not separated. Furthermore, the charged states B^+ and B^- could not be distinguished. The FFs obtained in Ref. [13] are, therefore, valid for the average of B^+ and B^- and, similarly, for the average of B^0 and $\overline{B^0}$.

The factorization scales related to the initial- and final-state singularities entering the PDFs and FFs, respectively, can in principle be chosen independently. We checked, however, that when estimating theoretical error bands by varying these scales by factors of 2 up and down, the extreme values are indeed obtained when the initial- and final-state factorization scales are identified. Our default choice of renormalization and factorization scales is $\mu_R = \mu_F = m_T = \sqrt{p_T^2 + m_b^2}$. Theoretical uncertainties will be estimated by setting $\mu_R = \xi_R m_T$ and $\mu_F = \xi_F m_T$, and varying ξ_R and ξ_F about their default values $\xi_R = \xi_F = 1$ by factors of 2 up and down, restricting the ratio to the range $1/2 \leq \xi_R/\xi_F \leq 2$.

3 Theoretical Predictions for $pp \to B + X$ and Comparisons with CMS Data

To obtain an overview of the p_T dependence of $d\sigma/dp_T$, we first show results for this observable, integrated over $|y| \leq 2.4$, for the case of B^+ production in the GM-VFN scheme as described above. This differential cross section is shown in Fig. 1 (left) for p_T values between 5 and 30 GeV and in Fig. 1 (right) for larger p_T values, up to 100 GeV, where we expect data to come in the near future when the LHC experiments are accumulating more statistics.

In the p_T range between 5 and 30 GeV, the cross section falls off by three orders of magnitude. This is essentially due to the behavior of the PDFs as a function of the scaling variable x and less so from the behavior of the partonic cross sections. Towards low p_T values, both the upper edge of the error band and the cross section for the default choice of scales rise steadily with decreasing p_T value, down to $p_T = 5$ GeV. This is caused by the scale dependence of the b-quark PDF and the FFs. With our choice of scales, they fade out and quench the cross section, leading to a turn-over of the p_T distributions only at $p_T = 0$ and not already at some finite p_T value. The lower edge of the error band is obtained for $\xi_F = 0.5$. Here, both the b-quark PDF and the FFs vanish at $p_T \approx 8$ GeV, corresponding to $\mu_F = m_b = 4.5$ GeV. The line representing the lower edge of the error band therefore stops at this point.

The CMS Collaboration measured the differential cross section $d\sigma/dp_T$ for the production of B^+ mesons [5] (actually the average of B^+ and B^- mesons), integrated over the y range $|y| \leq 2.4$, as a function of p_T. The measurement covered the p_T range from 5 GeV to