Production of massless bottom jets in $p\bar{p}$ and pp collisions at next-to-leading order of QCD

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Abstract

We present predictions for the inclusive production of bottom jets in proton-antiproton collisions at 1.96 TeV and proton-proton collisions at 7 TeV. The bottom quark is considered massless. In this scheme, we find that at small transverse momentum (p_T) the ratio of the next-to-leading order to the leading-order cross section (K factor) is smaller than one. It increases with increasing p_T and approaches one at larger p_T at a value depending essentially on the choice of the renormalization scale. Adding non-perturbative corrections obtained from PYTHIA Monte Carlo calculations leads to reasonable agreement with experimental b-jet cross sections obtained by the CDF and the CMS collaborations.

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I. INTRODUCTION

The cross section for producing jets in proton-proton collisions at the Large Hadron Collider (LHC) constitutes an important testing ground of perturbative Quantum Chromodynamics (QCD) and offers information for the proton parton distribution functions (PDFs). So far, all predictions for LHC experiments, and also for Tevatron experiments, have been found in very good agreement with the measurements. In these predictions, the contributions of heavy quarks (charm and bottom) are included. Since they are usually only a few percent of the total jet production cross sections and considering the experimental error, it is not clear, whether the heavy quark jets are satisfactorily described by perturbative QCD (pQCD) calculations.

To test these heavy quark contributions, it is necessary to compare to cross sections for the production of particular heavy quark jets. Such measurements have been done recently by the CDF collaboration [1] at the Tevatron and the CMS [2] and ATLAS [3] collaborations at the LHC. The CDF measurement of the inclusive b-jet production cross section in $p\bar{p}$ collisions is performed for jets with rapidity y in the range $|y| \leq 0.7$ and for transverse momenta p_T in the region $38 < p_T < 400$ GeV, for events, in which the decay vertex of the b-hadron is directly reconstructed. For this, the cone-based-iterative MidPoint algorithm is applied. This algorithm is used for jet reconstruction in the $y - \phi$ space, assuming a cone radius of 0.7. Further details on b-jet identification through secondary vertex reconstruction can be found in Ref. [1].

As a first step in a perturbative approach, one can, roughly speaking, describe the data by a leading order (LO) calculation plus parton shower plus hadronization, where the latter two are non-perturbative effects. In this sense, next-to-leading order (NLO) calculations are part of the parton shower, which has to be treated accordingly, when higher-order calculations are explicitly included and multiplicative factors for the correct treatment of the non-perturbative effects have to be identified.

The measured b-jet production cross section from CDF is compared to the leading-order PYTHIA-TUNE A Monte Carlo [21] program predictions with the CTEQ5L PDF, finding reasonably good agreement between data and PYTHIA predictions [1], and to NLO pQCD predictions by Frixione and Mangano [4]. This theoretical NLO prediction is based on the massive quark scheme or fixed flavor number scheme (FFNS), in which bottom quarks ap-

pear in the final state only, but not as partons in the initial state. Here, the comparison is done applying a b-quark pole mass $m_b = 4.75$ GeV, the CTEQ6M PDF, renormalization and factorization scales μ_R and μ_F set to $\mu_0 = \sqrt{p_T^2 + m_b^2}/2$, and with a cone-based algorithm using cone size $R = 0.7$ and $R_{sep} = 1.3$. Furthermore, it includes an additional correction factor for non-perturbative contributions, i.e., contributions from underlying event and hadronization processes equal to 1.2 at low p_T and equal to 1.0 for $p_T > 140$ GeV. The data and theoretical cross sections are found in approximate agreement, most of the data points lie above the theoretical predictions by nearly 50%.

At the LHC, two collaborations, CMS [2] and ATLAS [3], have measured inclusive b-jet cross sections at 7 TeV center-of-mass (c.m.) energy. In this work, we shall concentrate on the comparison with the CMS data [2]. The jet transverse momentum in the cross sections presented by CMS lies between $18 < p_T < 200$ GeV for several rapidity intervals in the range $0.0 < |y| < 2.2$. To obtain the bottom jets, the anti-k_T algorithm [5] with R=0.5 is used experimentally, as well as in the theoretical NLO calculations [4]. In the CMS experiment, b-jets are identified by finding the secondary decay vertex of the b-hadrons. The measured cross sections have been compared to the PYTHIA Monte Carlo generator [6], and to the MC@NLO [7, 8] Monte Carlo generator which is essentially based on the FFNS NLO cross sections [4] with the subsequent Monte Carlo HERWIG generator [9] which contains shower and hadronic corrections. The MC@NLO predictions are below the data in the central region ($|y| < 1.0$) for low p_T by approximately a factor of 1.5 to 2.0. The predictions from the PYTHIA generator agree with the data at high p_T, but overestimate the cross section in the p_T region below 50 GeV.

It is clear that the PYTHIA and also the MC@NLO prediction depend on the amount of hadron corrections contained in these two Monte Carlo generators and it is not known which amount originates from the underlying leading-order or next-to-leading order hard perturbative QCD cross sections, the parton shower and the hadronic corrections.

It is the purpose of this work to find out the NLO perturbative QCD cross section for inclusive b-jet production at the Tevatron and the LHC center-of-mass energies and to supplement the NLO predictions with estimates of the hadronic corrections. In our calculation, the bottom quark is considered massless, like all other quarks u, d, s and c. So the calculations are performed in the zero-mass variable-flavor-number scheme (ZM-VFNS) as in our work on charm jets [10]. Such a framework has also been considered previously

by Banfi et al. [11, 12]. They started from the NLOJET [13, 14] program, which is an alternative to calculate jet cross sections in hadron-hadron collisions, where one sums over all flavors of outgoing partons. This program was modified in such a way that only b quarks (or c quarks) appear in the final state. In addition, they changed the jet algorithm for b quarks. Unfortunately, this new jet algorithm for heavy quarks has not been used in the analysis of the experimental data yet. It is not clear whether this can be realized.

In Sec. 2, we shall describe the theoretical framework and outline the PDF input for the initial state. Section 3 contains our results for the bottom-jet cross section. In this section, we also show a comparison with the single-inclusive jet cross section measured by the CDF collaboration at the Tevatron. Conclusions and summary are presented in Sec. 4.

II.   THEORETICAL FRAMEWORK AND PDF INPUT

As in our publication on charm jets [10], we rely on previous work on dijet production in the reaction $\gamma + p \to jet + X$ [15, 16], in which cross sections for inclusive one-jet and two-jet production up to NLO for both, the direct and the resolved contributions are calculated. The resolved part of this cross section routine can be used for $p\bar{p}$ or pp collisions replacing the photon PDF by the (anti)proton PDF. The routine [15, 16] contains quarks of all flavours up to and including the bottom quark, as well as the gluon. This routine has been modified in such a way that at least one bottom quark appears in the final state, in the same way as we did for the charm quark for charm jets in [10].

The routine [15, 16] is written for massless quarks, i.e. also the bottom quark is considered massless. This is justified as long as the transverse momentum p_T of the produced jets is large enough, i.e. for $p_T^2 \gg m_b^2$.

For our prediction of the inclusive b-jet cross section, we employ the MSTW2008NLO [17] PDF (central value) of the Durham collaboration. The chosen asymptotic scale parameter $\Lambda_{\overline{MS}}^{(5)} = 0.262$ GeV corresponds to $\alpha_s^{(5)}(m_Z) = 0.118$. We choose the renormalization scale $\mu_R = \xi_R p_T$ and the factorization scale $\mu_F = \xi_F p_T$, where p_T is the largest transverse momentum of the two or three final state jets. ξ_R and ξ_F are dimensionless scale factors, which are varied around $\xi_R = \xi_F = 1$ in a manner to be specified later. The center-of-mass energy of the proton-proton collisions is taken as $\sqrt{s} = 7$ TeV as for the data of CMS [2], and as $\sqrt{s} = 1.96$ TeV for the $p\bar{p}$ collisions as for the data of CDF [1].

The experimental data of CDF have been read off from the publications in Ref. [1]. Since the bin size in p_T was not specified there, we did our calculation with a bin size of $\Delta p_T = 10$ GeV and plotted the CDF data for fixed p_T values. The bin size in p_T for the CMS data is taken from Ref. [18]. The CMS data [2] appear for five bin sizes in $|y|$ between $0 < |y| < 2.2$. In our comparison with these data, we shall limit ourselves to the two most central bin sizes: $0 < |y| < 0.5$ and $0.5 < |y| < 1.0$, where the discrepancy with the MC@NLO [7, 8] predictions is the largest.

III.   RESULTS

A.   Comparison with CDF data

We start with the predictions for and the comparison to the inclusive b-jet production data obtained by the CDF Collaboration at the Tevatron [1]. In order to check our program, we have first calculated the cross section $d\sigma/dp_T dy$ for $p + \bar{p} \rightarrow single\ jet + X$ in the p_T range $54 < p_T < 700$ GeV and with rapidity $|y| < 0.1$ in p_T bins as chosen by CDF [19] for their measurement. Correction factors that approximately account for non-perturbative contributions from the underlying event and fragmentation of partons into hadrons as given in Ref. [19] were multiplied to the theoretical results. These non-perturbative correction factors are estimated using the PYTHIA-TUNE A Monte Carlo routine [20, 21]. The correction factors decrease with increasing p_T and lie below 1.2. The jets in the CDF analysis, as in our calculations, are defined with the k_T algorithm [22, 23] with the radius R=0.7.

Our results are shown in Fig. 1, and compared to the CDF data [19]. The agreement is satisfactory. Deviations occur for small p_T and for the largest p_T bin. The scales are $\mu_R = \mu_F = p_T/2$ and the theoretical error in our calculations has been estimated by varying $\mu_R = \mu_F$ by a factor of 2 up and down as usual. As seen in Fig. 1, most of the data points lie inside the theoretical error band. Our results can also be compared to the theoretical curves in Ref. [19] which have been calculated with the JETRAD routine [24] and the PDF set CTEQ6.1M [25] instead of the more modern PDF CT10 [26] used in our work. These different choices of PDFs may explain small differences in the NLO predictions in [19] as compared to our calculation.

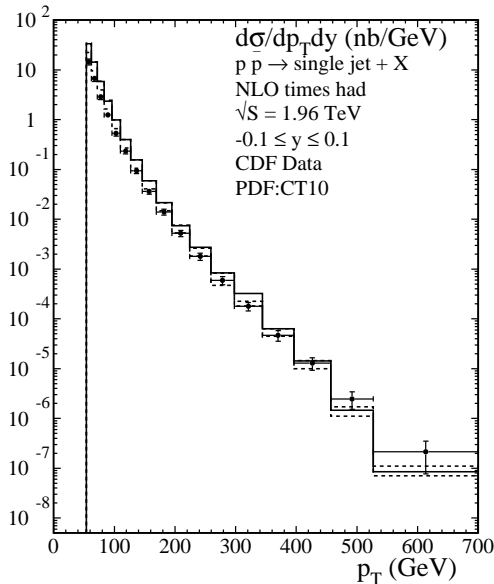The results for the inclusive b-jet cross sections at $\sqrt{s} = 1.96$ TeV are shown in Fig. 2

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FIG. 1. Single-inclusive jet cross sections $d\sigma/dp_T dy$ as a function of p_T compared to the data from CDF [19]. The NLO theoretical predictions are corrected for non-perturbative effects via multiplicative factors. The theoretical error is obtained by independent scale variations given as the dashed curves. The solid curve indicates the default scale choice.

in LO pQCD and as K factors, where K is the ratio of the NLO to the LO cross section $K = (d\sigma/dp_T dy)_{NLO}/(d\sigma/dp_T dy)_{LO}$ as a function of p_T. The scales for the LO cross sections are chosen as in [1], namely $\xi_R = \xi_F = 0.5$ (default, full line), $\xi_R = \xi_F = 0.25$ (upper broken line) and $\xi_R = \xi_F = 1.0$ (lower broken line). In Fig. 2, we have also plotted the data for the inclusive b-jet cross section as measured by CDF [1]. These data in numerical form have been read from the publication in [1]. As we can see, the corresponding LO cross sections are smaller than the experimental data by approximately a factor of 2 for low p_T and 4 for the largest p_T bin. The LO cross sections are multiplied with the hadronization correction factor 1.2 as reported in [1].

If as usual, i.e. for jet cross sections of all flavors, the NLO corrections would increase the b-jet cross sections by factors 2 to 3, we would have approximate agreement with the data. Unfortunately, this is not the case as we can see from Fig. 2 in the right frame. The K factors are smaller than 1 for small p_T and approach values of 1 for larger values of p_T depending on the choice of scales. For the scale choice $\xi_R = 2.0$, $\xi_F = 1.0$ (full line) this occurs at $p_T = 250$ GeV and for the larger scale $\xi_R = 4.0$, $\xi_F = 2.0$ at $p_T = 150$ GeV (upper
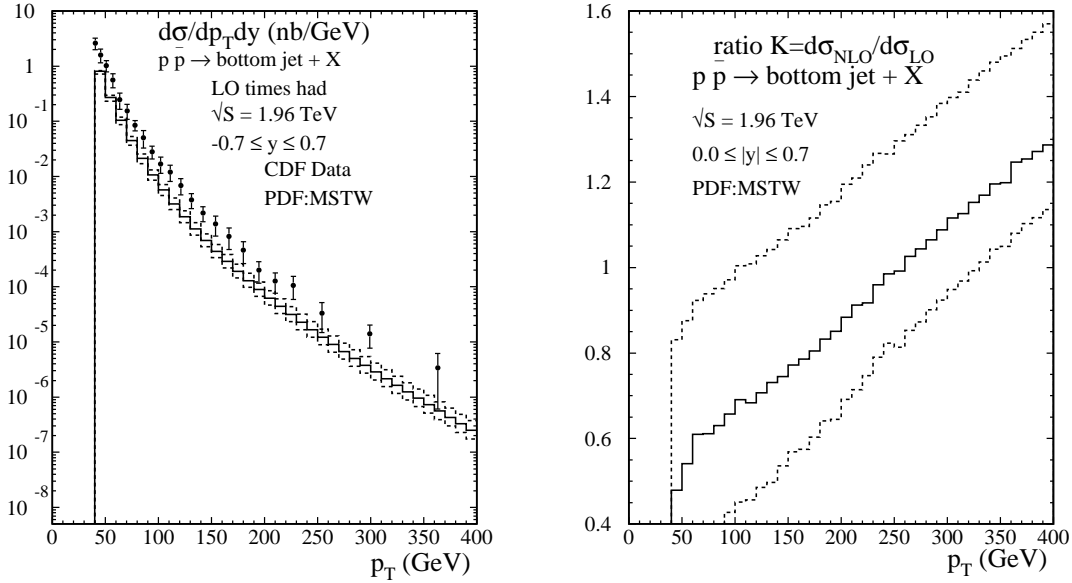
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FIG. 2. Left-hand side: single-inclusive b-jet cross section in LO as a function of p_T for the rapidity region $0.0 \leq |y| \leq 0.7$ compared to CDF data [1]. The LO theoretical predictions are corrected by non-perturbative effects via a multiplicative factor. The theoretical error (dashed lines) is obtained by scale variation as given in the text. The solid line indicates the default scale choice. Right-hand side: Ratio of single-inclusive b-jet cross section in NLO and LO for the rapidity region $0.0 \leq |y| \leq 0.7$ as a function of p_T, for three scale choices as given in the text.

broken line). For the usual scale choice $\xi_R = \xi_F = 1.0$ the K factor is smaller than 1 in the whole considered p_t range up to $p_T = 300$ GeV (lower broken line). The reason for the K factor to be smaller than 1 at small p_T lies in the fact that at these p_T values the jet cross section for all flavors as in Fig. 1 has large contributions from the hard scattering cross sections for light quarks as for example $gg \rightarrow q\bar{q}g$, where q stands for u, d, s, c quarks. Of course, these contributions are missing in the b-jet cross section. At larger p_T, these light quark contributions are presumably less important.

These results can be compared to the b-jet cross sections obtained in the FFNS, which can be found in Ref. [1] and which have been calculated with the NLO routine in Ref. [4]. These theoretical results show the expected scale dependence, i.e. smaller scales for $\mu_R = \mu_F$ lead to larger cross sections. The scale $\mu_R = \mu_0/2$ is chosen as the default scale, $\mu_R = \mu_0/4$ for the maximal and $\mu_R = \mu_0$ for the minimal cross section. In our case with massless b

quarks, it is just the opposite, increasing the scale μ_R leads to larger b-jet cross sections, since the NLO corrections are reduced with increasing μ_R. Second, the agreement between theory and data in Ref. [1] is best for $\mu_R = \mu_0/4$ in the range of $p_T > 80$ GeV and for $\mu_R = \mu_0/2$ if $p_T < 80$ GeV, whereas in our case for all considered scales the data lie above the predicted cross sections.

Our NLO cross sections are shown in Fig. 3, now for the scale choices: $\xi_R = 4.0$, $\xi_F = 2.0$ (full line), $\xi_R = 8.0$, $\xi_F = 4.0$ (upper broken line) and $\xi_R = 2.0$, $\xi_F = 1.0$ (lower broken line). The first and the last of these scale choices agree with those made for the K factor calculation in Fig. 2 (right frame). The choice of a larger renormalization scale, of course, has the effect that the NLO corrections to the cross section are reduced. At large p_T, the b-jet cross section for all three scales is almost the same as in the LO approximation (see Fig. 2, left frame) as to be expected from the K factors in Fig. 2 (right frame). For these results, the jet algorithm is the cone algorithm with $R = 0.7$ and $R_{sep} = 1.3$ which is considered best to represent the cone choice in the experimental analysis [4]. As PDF we have chosen the MSTW2008NLO version [17]. The NLO curves in Fig. 3 are compared to the data for inclusive b-jet cross sections as measured by CDF [1]. The agreement is similar as for the LO cross sections (see Fig. 2 left).

The cross-section calculations in the FFNS and in the ZM-VFNS behave quite differently, which follows already from the different scale dependence. The reason for this though is not known yet and would require a more detailed investigation, which is beyond this work. One possible reason might be that in our approach with massless bottom quarks, there are additional NLO contributions to the b-jet cross section originating from the b-quark PDF of the proton (antiproton) not present in the FFNS, since there it would amount to a NNLO contribution.

The unusual behaviour of the theoretical NLO prediction in comparison with the CDF data might be explained by missing non-perturbative hadronic and underlying event contributions. The CDF data have been compared in Ref. [1] also with the PYTHIA-TUNE A [21, 27] predictions and good agreement has been found up to $p_T = 200$ GeV. The PYTHIA Monte Carlo routines are based on LO hard production matrix elements and LO PDFs. Our LO predictions have been done with the same PDF [17] as for our NLO predictions and the results are shown in Fig. 2 left frame. The different choice of PDFs should have only little influence in this case. We saw in that figure that the LO cross section is nearer to the CDF
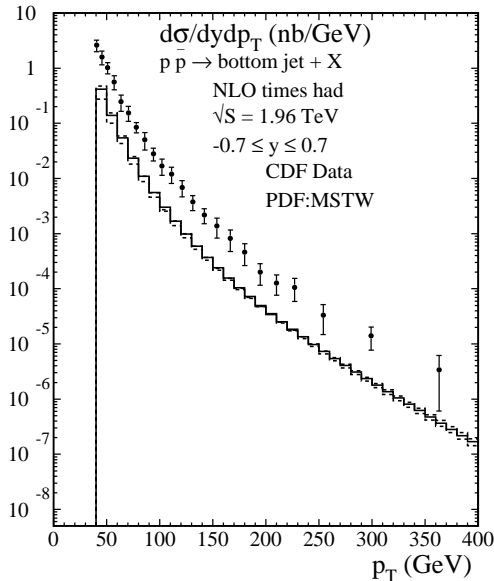
FIG. 3. Single-inclusive b-jet cross section in NLO as a function of p_T for the rapidity region $0.0 \leq |y| \leq 0.7$ compared to CDF data [1]. The NLO theoretical predictions are corrected by non-perturbative effects via a multiplicative factor. The theoretical error (dashed lines) is obtained by scale variation as given in the text. The solid line indicates the default scale choice.

data and similar to the NLO cross section. According to Ref. [1], the PYTHIA prediction and the CDF data agree more or less, so that the difference between PYTHIA and LO predictions would give a correction factor which brings the LO prediction into agreement and the NLO prediction, which is somewhat smaller at low p_T than the LO prediction, much closer to the data than the NLO curve plotted in Fig. 3. In other words, for NLO, the data of CDF need a much larger non-perturbative correction factor than the factor 1.2 which we applied in our plot of the NLO cross section in Fig. 3. The correction factor 1.2 originates from the same PYTHIA calculation, but with the difference that the contributions from multiple parton interactions and string fragmentation are subtracted from the PYTHIA result, because they are usually considered already to be part of the NLO corrections. This means that a correction factor that contains besides the non-perturbative hadronization corrections and contributions from the underlying event also the parton showers must be applied to come closer to the experimental cross section. As is well known, this implies some double counting since the parton showers contain some NLO corrections which are already contained in the perturbative NLO contributions.

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We shall see in the next subsection that the same pattern also follows from the comparison with the b-jet production cross section as measured by CMS [2]. Since we do not have the PYTHIA predictions at our disposal, we cannot be more quantitative concerning the comparison of the CDF data with our NLO calculations. It seems, however, that a much larger part of the b-jet cross section originates from the non-perturbative contribution and not just from the perturbative NLO contribution as it is the case for the single-jet cross section of all flavors.

At this point, we want to mention that the non-perturbative corrections are applied to the NLO b-jet cross section in form of a factor 1.2, taken from [1] and obtained from the PYTHIA Monte Carlo routine which is based on LO b-jet cross section with massive b and c quarks and only u-, d-, s- and g-PDFs of the proton and antiproton. From earlier studies we know that the b-jet and c-jet production cross section in LO differs only at rather small $p_T \simeq m_b, m_c$ from the massless LO cross sections. How finite values of m_b and m_c influence the parton shower contributions is not known. In addition, it is also not known how much the non-perturbative corrections are changed, if one adds b- and c-quark PDFs of the in-going hadrons in the LO cross section.

B. Comparison with CMS data

The CMS Collaboration has also measured the $p + p \rightarrow single\ jet + X$ cross section for all flavors in the range $18 < p_T < 1684$ GeV [28]. This has been compared to our calculations using the same routine as in this work in Fig. 1 of Ref. [10], with the result that good agreement between predictions and data has been found. In the following, we show the comparison of our prediction to the cross section measurements for single bottom production $p + p \rightarrow bottom\ jet + X$ published in Ref. [2]. We do this for two rapidity regions $|y| \leq 0.5$ and $0.5 \leq |y| \leq 1.0$, and for the jet transverse momenta in the range between $18 < p_T < 200$ GeV.

In Ref. [2], the CMS data have been compared to PYTHIA predictions [6] with the result that for $p_T > 50$ GeV good agreement had been found, whereas for $p_T < 50$ GeV the PYTHIA prediction was much larger than the data. This also occurred for the other three rapidity ranges not considered in this work. In addition, the CMS data have been compared to the MC@NLO predictions. For the two lowest $|y|$-regions, the MC@NLO values are below
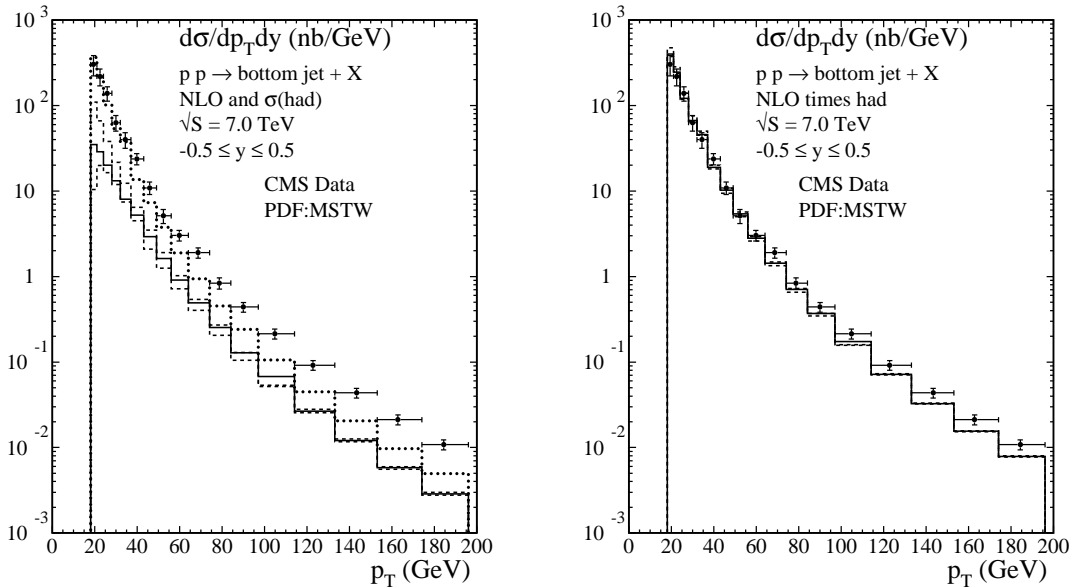
FIG. 4. Left-hand side: Single-inclusive b-jet cross section in NLO as a function of p_T for the rapidity region $0.0 \leq |y| \leq 0.5$ and compared to CMS data [2]. The NLO theoretical prediction is not corrected by non-perturbative effects via multiplicative factors. The theoretical error (dashed histograms) is obtained by scale variation as given in the text. The solid histogram indicates the default scale choice. The dotted histogram is the PYTHIA minus LO prediction. Right-hand side: Single-inclusive b-jet cross section in NLO plus the PYTHIA minus LO prediction as a function of p_T for the rapidity region $0.0 \leq |y| \leq 0.5$, compared to CMS data [2].

the data by a factor of 1.5 to 2.0 almost over the whole range of p_T values.

Next, we want to see how well our NLO predictions describe the CMS b-jet cross section data. For this purpose, we need to know the non-perturbative corrections. As an estimate for these corrections, we take the PYTHIA predictions made available to us in numerical form as they were plotted in Ref. [2] by R. Kogler and M.A. Voutilainen from the CMS Collaboration [29]. From the PYTHIA cross section, we subtracted the LO predictions as we proposed already for the comparison with the CDF data. The PYTHIA minus LO predictions are plotted in Fig. 4 and Fig. 5 for both rapidity regions $|y| \leq 0.5$ (dotted line in the left frame of Fig. 4) and for $0.5 \leq |y| \leq 1.0$ (dotted line in the left frame of Fig. 5). As can be seen form these two figures, for $p_T \leq 35$ GeV the CMS experimental data almost agree with these non-perturbative contributions. For $p_T > 35$ GeV the data points deviate from

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the dotted histogram and at the largest p_T bin, the dotted histogram yields approximately 50% of the experimental cross section for both $|y|$ regions.

In Fig. 4 (left frame) and Fig. 5 (left frame), we have also plotted our prediction for the NLO cross section (full line histogram) together with the scale variation (dashed line histograms). These NLO cross sections are obtained with the scale factors $\xi_R = 4.0$, $\xi_F = 1.0$ (default prediction), $\xi_R = 8.0$, $\xi_F = 2.0$ (upper broken line) and $\xi_R = 2.0$, $\xi_F = 1.0$ (lower broken line). The value $\xi_R = 4.0$ for the default prediction has been chosen in order to reduce the coupling constant to obtain a reasonably large NLO cross section for the smaller p_T, where the NLO cross section is still smaller than the LO prediction, giving rise to a K factor smaller than one, as we observed already for the prediction of the CDF data. At very small p_T, our prediction in NLO is approximately a factor 10 smaller than the data points so that the non-perturbative part alone produces the b-jet cross section. For the larger p_T this factor reduces to 3. This means that for all p_T our NLO prediction is below the measured cross section data. The scale dependencies of the NLO prediction decrease towards larger p_T and have, except for the first five p_T bins, no large effect.

In Fig. 4 (right frame) and Fig. 5 (right frame), the NLO cross sections and the non-perturbative contributions PYTHIA minus LO cross section have been added and compared to the CMS data. We find reasonable agreement between this prediction and the data inside the experimental errors up to approximately $p_T \simeq 100$ GeV. For larger p_T, the difference between prediction and data increases. But even at the largest p_T bin, the difference between the predicted and the measured cross section is not more than 20%, while the measured cross section is throughout larger than the theoretical cross section.

As already mentioned in connection with the comparison to the CDF cross section data, the PYTHIA predictions contain not only the hadronization corrections, but also additional parton shower corrections, which on the other hand are also part of NLO corrections. Of course, not all parton shower corrections would be equivalent to our NLO corrections, since they contain additional higher order contributions not contained in our NLO corrections. The numerical data given to us contain both contributions, hadronization corrections and parton shower corrections, together.

Usually the parton shower corrections contribute at small p_T and diminish for increasing p_T. Suppose they would be negligible at the highest p_T bin, then the hadronic corrections would still be larger than our NLO prediction in this bin (see Fig. 4 and 5, left frames). Since
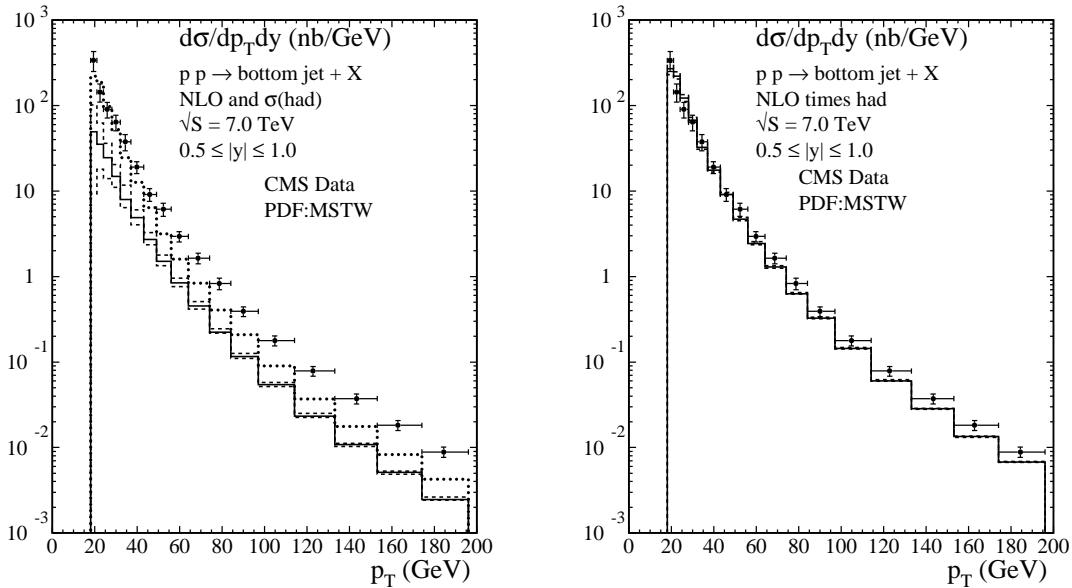
FIG. 5. The same caption as in Fig. 4, except for the rapidity region $0.5 \leq |y| \leq 1.0$.

we have no information on the details of the "non-perturbative" PYTHIA corrections, we cannot subtract the contribution originating from the parton shower corrections to obtain the purely hadronic corrections, etc, which are usually added to the perturbative NLO cross sections. We expect that after subtraction of the parton shower corrections, the agreement between our results and the CMS data would deteriorate and we would obtain similar results as for the MC@NLO result in Ref. [2], although these results have an appreciable error [2, 29] due to varying the renormalization scale, from variation of the parameters of the CTEQ PDF and from changing the b-quark mass.

IV.   SUMMARY AND CONCLUSIONS

We have calculated the inclusive bottom-jet cross section at NLO of QCD in the ZM-VFN scheme, i.e., with active bottom quarks in the proton and antiproton at $\sqrt{s} = 1.96$ TeV for $p\bar{p}$ and $\sqrt{s} = 7$ TeV for pp collisions. Both heavy quarks are considered massless. Our results are compared to experimental jet cross section measurements by the CDF collaboration at the Tevatron and the CMS collaboration at the LHC. To our surprise, the NLO cross section for both $\sqrt{s}$ energies are much smaller than the measured cross sections. The NLO cross sections are for most of the considered p_T range even smaller than the LO cross sections, i.e. the K

factors are smaller than one. This means that the total NLO contribution, i.e., without the LO contribution, is negative. There exist several possibilities to increase this contribution. Examples are: contributions originating from intrinsic b-quark contribution to the hadron PDF, as has been considered recently by Lyonnet et al. in Ref. [30], or contributions from NNLO, which might become known in the future. Another possibility are non-perturbative hadronic corrections which then must be much larger than have been estimated with the PYTHIA Monte Carlo routine in Ref. [1]. This approach has been followed in this work. It turns out that if the PYTHIA predictions minus the LO perturbative cross section is added to our NLO predictions, reasonable agreement with the measured b-jet cross sections can be achieved for the CDF data as well as for the CMS data. This approach has the problem of double counting due to the parton shower contributions in the PYTHIA Monte Carlo approach, a topic which we leave for investigations in the future.

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[1] M. D'Onofrio [CDF and D0 Collaborations], hep-ex/0505036;

M. D'Onofrio [CDF and D0 Collaborations], FERMILAB-CONF-06-224-E;

CDF Collaboration, CDF note 8418, July 25, 2006.

[2] S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1204** (2012) 084, doi:10.1007/JHEP04(2012)084 [arXiv:1202.4617 [hep-ex]].

[3] G. Aad *et al.* [ATLAS Collaboration], Eur. Phys. J. C **71** (2011) 1846, doi:10.1140/epjc/s10052-011-1846-4 [arXiv:1109.6833 [hep-ex]].

[4] S. Frixione and M. L. Mangano, Nucl. Phys. B **483** (1997) 321, doi:10.1016/S0550-3213(96)00577-9 [hep-ph/9605270].

[5] M. Cacciari, G. P. Salam and G. Soyez, JHEP **0804** (2008) 063, doi:10.1088/1126-6708/2008/04/063 [arXiv:0802.1189 [hep-ph]].

[6] T. Sjöstrand, S. Mrenna and P. Z. Skands, JHEP **0605** (2006) 026, doi:10.1088/1126-6708/2006/05/026 [hep-ph/0603175].

[7] S. Frixione and B. R. Webber, JHEP **0206** (2002) 029, doi:10.1088/1126-6708/2002/06/029, [hep-ph/0204244].

[8] S. Frixione, P. Nason and B. R. Webber, JHEP **0308** (2003) 007, doi:10.1088/1126-6708/2003/08/007 [hep-ph/0305252].

[9] G. Marchesini, B. R. Webber, G. Abbiendi, I. G. Knowles, M. H. Seymour and L. Stanco, Comput. Phys. Commun. **67** (1992) 465. doi:10.1016/0010-4655(92)90055-4

[10] I. Bierenbaum and G. Kramer, Int. J. Mod. Phys. A **30** (2015) 18n19, 1550111, doi:10.1142/S0217751X15501110 [arXiv:1412.5470 [hep-ph]].

[11] A. Banfi, G. P. Salam and G. Zanderighi, Eur. Phys. J. C **47** (2006) 113, doi:10.1140/epjc/s2006-02552-4 [hep-ph/0601139].

[12] A. Banfi, G. P. Salam and G. Zanderighi, JHEP **0707** (2007) 026, doi:10.1088/1126-6708/2007/07/026 [arXiv:0704.2999 [hep-ph]].

[13] Z. Nagy, Phys. Rev. Lett. **88** (2002) 122003, doi:10.1103/PhysRevLett.88.122003 [hep-ph/0110315].

[14] Z. Nagy, Phys. Rev. D **68** (2003) 094002, doi:10.1103/PhysRevD.68.094002 [hep-ph/0307268].

[15] M. Klasen and G. Kramer, Z. Phys. C **72** (1996) 107, doi:10.1007/s002880050229 [hep-ph/9511405].

[16] M. Klasen and G. Kramer, Z. Phys. C **76** (1997) 67, doi:10.1007/s002880050528 [hep-ph/9611450].

[17] A. D. Martin, W. J. Stirling, R. S. Thorne and G. Watt, Eur. Phys. J. C **63** (2009) 189, doi:10.1140/epjc/s10052-009-1072-5 [arXiv:0901.0002 [hep-ph]].

[18] http://hepdata.cedar.ac.uk/view/ins1089835

[19] A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. D **75** (2007) 092006 [Phys. Rev. D **75** (2007) 119901] doi:10.1103/PhysRevD.75.119901, 10.1103/PhysRevD.75.092006 [hep-ex/0701051].

[20] T. Sjöstrand, P. Eden, C. Friberg, L. Lonnblad, G. Miu, S. Mrenna and E. Norrbin, Comput. Phys. Commun. **135** (2001) 238, doi:10.1016/S0010-4655(00)00236-8 [hep-ph/0010017].

[21] The PYTHIA-TUNE A parameters are given in Ref. [34] of Ref. [19].

[22] S. Catani, Y. L. Dokshitzer, M. H. Seymour and B. R. Webber, Nucl. Phys. B **406** (1993) 187. doi:10.1016/0550-3213(93)90166-M

[23] S. D. Ellis and D. E. Soper, Phys. Rev. D **48** (1993) 3160, doi:10.1103/PhysRevD.48.3160 [hep-ph/9305266].

[24] W. T. Giele, E. W. N. Glover and D. A. Kosower, Nucl. Phys. B **403** (1993) 633, doi:10.1016/0550-3213(93)90365-V [hep-ph/9302225].

[25] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. M. Nadolsky and W. K. Tung, JHEP **0207** (2002) 012, doi:10.1088/1126-6708/2002/07/012 [hep-ph/0201195].

[26] H. L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin and C.-P. Yuan, Phys. Rev. D **82** (2010) 074024, doi:10.1103/PhysRevD.82.074024 [arXiv:1007.2241 [hep-ph]].

[27] T. Affolder *et al.* [CDF Collaboration], Phys. Rev. D **65** (2002) 092002. doi:10.1103/PhysRevD.65.092002

[28] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **107** (2011) 132001, doi:10.1103/PhysRevLett.107.132001 [arXiv:1106.0208 [hep-ex]].

[29] R. Kogler and M.A. Voutilainen, private communication

[30] F. Lyonnet, A. Kusina, T. Ježo, K. Kovařík, F. Olness, I. Schienbein and J. Y. Yu, JHEP **1507** (2015) 141, doi:10.1007/JHEP07(2015)141 [arXiv:1504.05156 [hep-ph]].