Fermi National Accelerator Laboratory

FERMILAB-Conf-98/291-E
D0 and CDF

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October 1998

Published Proceedings of the *International Conference on High Energy Physics (ICHEP 98)*, Vancouver, British Columbia, Canada, July 23-30, 1998

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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PROPERTIES OF b-QUARK PRODUCTION AT THE TEVATRON

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We report on results obtained by the DØ and CDF collaborations on the properties of b-quark production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The DØ experiment has measured the inclusive production cross section for muons originating from b-quark decays in the forward region, corresponding to the rapidity range $2.4 <| y^{\mu} |< 3.2$. Combined with previous measurements in the central region, these results permit a comparison of the rapidity dependence of the b-quark production cross section with the predictions of next-to-leading order QCD. The CDF experiment has achieved the first direct measurement of $b\bar{b}$ rapidity correlations at a hadron collider, with the ratio of the cross sections obtained in two rapidity bins. This measurement is a direct probe of the high-x gluon content of the proton.

1 Introduction

The production of b quarks in $p\bar{p}$ collisions provides a benchmark process for the study of perturbative QCD. Predictions of the QCD theory at the next-to-leading order (NLO) have been available for a decade [1]. They describe the production of heavy flavors by three major mechanisms: flavor creation, with s-channel gluon or t-channel quark exchange, t-channel gluon exchanges with subsequent gluon splitting, and, flavor excitation. The latter two mechanisms dominate the $\mathcal{O}(\alpha_s^3)$ contribution to the cross section and are of about the same size as the leading order (LO) contribution.

The NLO QCD predictions show a large dependence on the choice of the renormalization and factorization scale, μ. This scale is usually choosen as $\mu = \mu_o \equiv \sqrt{m_b^2 + (p_T^b)^2}$, where p_T^b is the transverse momentum of the b-quark and m_b its mass. The theoretical uncertainties are obtained by varying μ between $\mu_0/2$ and $2\mu_0$. This large scale dependence is a symptom of large next-to-NLO (NNLO) corrections. The theoretical predictions are also affected by the choice of m_b, with a central value set to 4.75 GeV/c^2, and varied between 4.5 and 5.0 GeV/c^2 for the uncertainties.

In the last few years, the inclusive b-quark production cross section has been measured in the central rapidity region $| y |< 1$ by CDF [2] and DØ [3] using various data samples. These measurements were found to agree in shape with the NLO QCD predictions over the studied transverse momentum range, $6 < p_T^b < 40$ GeV/c, but to be a factor 2 to 3 larger than the central value obtained with $m_b = 4.75$ GeV/c^2 and $\mu = \mu_0$.

The DØ experiment has now measured the differential muon cross section due to b-quark decays in the forward region, $2.4 <| y^{\mu} |< 3.2$, as a function of the muon transverse momentum, p_T^{μ}. This analysis is presented in section 2.

The study of $b\bar{b}$ correlations is a fundamental test of QCD at the next-to-leading order. It allows the comparison of the shapes of kinematic distributions rather than their more uncertain normalizations. Previous studies of the $b\bar{b}$ correlations performed by CDF [4] and DØ [5] focused on the difference in azimuthal angle between the two muons coming from $b\bar{b}$ decays. These results show consistently higher values than the prediction of the NLO QCD theory. The shape of the opening angle between the two muons is found to be consistent with the theory within the uncertainties. However, another CDF analysis [6] of the correlations between the b and $\bar{b}$ quarks in μ–jet events shows discrepancies between the predicted and observed shape of the azimuthal opening angle between the two quarks, indicating that a simple K factor is insufficient to explain the difference between data and theory.

Recently, CDF has extended its correlation studies to the forward region, measuring the $b\bar{b}$ production cross section when one quark is produced in the forward region ($1.8 <| \eta^b |< 2.6$), and the other in the central pseudorapidity range ($| \eta^b |< 1.5$). This measured cross section was found to be higher than the QCD prediction by a factor $2.4^{+0.6}_{-0.5}$, with the uncertainty reflecting the experimental error only. In order to reduce the systematic uncertainties affecting both the data and the theory, they now measure the cross section in two rapidity bins and take the ratio. This analysis is described in section 3.

2 Forward μ and b-Quark Production

The DØ analysis of the b-quark production in the forward region is based on the small angle muon spectrometer [7] consisting of magnetized iron toroids and drift tube stations on each side of the interaction region with pseudorapidity coverage of $2.2 <| \eta^{\mu} |< 3.3$ for a single muon.

The data were collected in special runs during the 1994-95 Tevatron run. Using only events corresponding to a single interaction, the effective integrated luminosity for these runs is 82 ± 7 nb^{-1}.

Muons are selected in the rapidity range $2.4 <| y^\mu |< 3.2$, with momentum $p^\mu < 150$ GeV/c and transverse momentum $p_T^\mu > 2$ GeV/c. Additional cuts are applied to ensure a good momentum measurement and an energy deposition in the calorimeter consistent with that from a minimum ionizing particle, leading to a final sample of 6709 events. The contamination due to cosmic rays and hadronic punch-through are estimated to be less than 1%. The contribution from W and Z decays is determined by both DØ data and ISAJET[8] Monte Carlo (MC) simulation and is also negligible. The muon detection efficiency is obtained from MC events with full detector simulation. It is cross-checked with muon unbiased data.

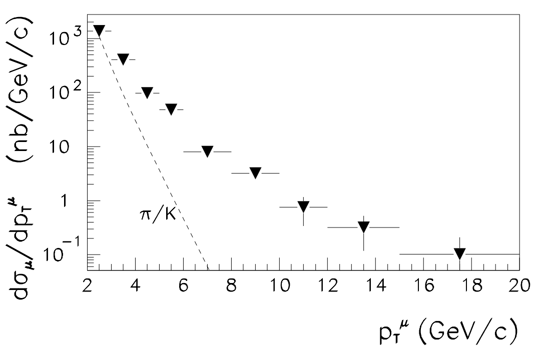

Figure 1: The inclusive muon cross section, per unit of rapidity, in the forward region as a function of p_T^μ. The dashed line represents the expected contributions from π/K decays.

The measured inclusive muon cross section is shown in Fig. 1 as a function of p_T^μ. It is computed per unit of rapidity and only the statistical errors are shown. The systematic uncertainties vary between 14 and 18%, the major error sources being the limited MC statistics and the momentum unfolding.

The two major contributions to the inclusive muon cross section consist of in-flight decays of pions and kaons, and, b- and c-quark decays. The expected π/K contribution is obtained using ISAJET. The p_T spectrum of charged particles predicted by ISAJET was found to be in agreement with the CDF measurement in the central region. As shown in Fig. 1, this contribution dominates the inclusive muon cross section for low p_T^μ but falls more rapidly than the data, the excess being attributed to the heavy flavors decays. After subtraction of the π/K contribution, the muon cross section is multiplied by the b-quark fraction, f_b, defined as the ratio of the muon yield due to b-quark decays to the total muon yield from b- and c-quark decays. This ratio is determined using NLO QCD predictions for b- and c-quark production cross sections. DØ uses events containing a muon associated to a jet to compare the b-quark fraction obtained from the data against the MC predictions. The presence of the jet allows the determination of the origin of the muon by looking at its transverse momentum relative to that of the jet. From a sample of 31,000 events collected during the entire 1994-95 Tevatron run ($\int \mathcal{L} dt = 90$ nb^{-1}), they find an excellent agreement between data and MC simulation for the b-quark fraction *vs.* p_T^μ.

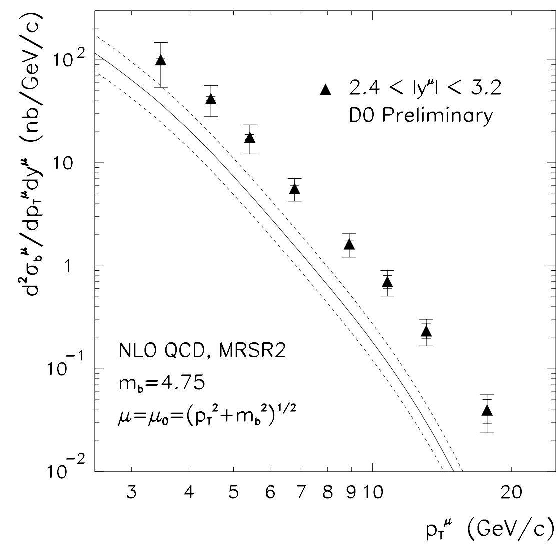

Figure 2: p_T spectrum of forward muons from b decays compared to NLO QCD prediction.

The differential muon cross section from b-quark production and decay is presented in Fig. 2. The systematic uncertainties on this measurement include those of the inclusive muon cross section together with uncertainties due to the f_b estimation $(10-3)$% and the π/K subtraction $(14-1)$%. In Fig. 2, the data are compared to the NLO QCD prediction obtained using the Monte Carlo simulation HVQJET[9]. This MC relies on MNR calculations[1] for the production of the $b/\bar{b}$ partons and ISAJET for the fragmentation to B mesons and the decay of these mesons to muons. The "partonic events" are generated with $m_b = 4.75$ GeV/c, $\mu = \mu_0$, and the MRSR2[10] parton distribution functions. The theoretical uncertainty is determined by varying the parameters m_b and μ from 4.5 and 5.0 GeV/c^2 and from $\mu_0/2$ to $2\mu_0$, respectively. The disagreement between the data and the model prediction is patent and increases with p_T^μ, from around 2.5 at low p_T^μ to more than 5 when $p_T^\mu > 8$ GeV/c. A slightly better agreement in shape is obtained when using the MRSA′[11] parton distribution functions but the data remain larger than the theory by a factor close to 4.

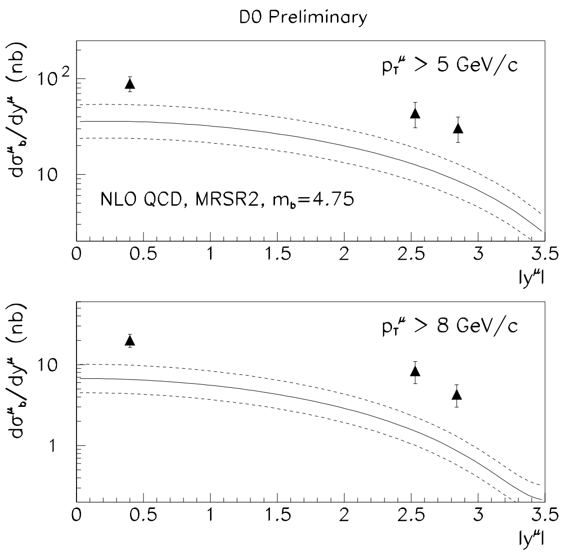

Figure 3: b-produced muon cross section *vs.* rapidity compared to the NLO QCD prediction.

These measurements can be combined with previous DØ results [3] obtained in the central region ($|y^\mu| < 0.8$) to study the rapidity dependence of the b-produced muon cross section. The differential muon cross section from b decay as a function of rapidity is shown in Fig. 3 for two p_T^μ ranges, $p_T^\mu > 5$ GeV/c and $p_T^\mu > 8$ GeV/c. The NLO QCD prediction obtained with HVQJET does not exhibit the same rapidity dependence as the data: for $p_T^\mu > 5$ GeV/c, the ratio data/theory is equal to 2.5 ± 0.5 in the central region and increases to 3.6 ± 0.6 in the forward region. The uncertainty on these ratios only reflects the experimental errors. For $p_T^\mu > 8$ GeV/c, these numbers become 3.1 ± 0.6 and 5.1 ± 1.1 in the central and forward regions, respectively.

3 $b\bar{b}$ Rapidity Correlations

Using their forward muon data set collected during the 1994–95 Tevatron run, CDF recently measured the production cross section for $b\bar{b}$ pairs with one quark in the forward region ($1.8 < |\eta^{b_1}| < 2.6$), and the other in the central pseudorapidity range ($|\eta^{b_2}| < 1.5$) [12]. The resulting cross section

$$\sigma(p\bar{p} \to b_1 b_2 X) = 6.49 \pm 0.63(\text{stat})^{+1.43}_{-1.23}(\text{syst}) \text{ nb},$$

valid for $p_T^{b_1,b_2} > 25$ GeV/c, is a factor $2.4^{+0.6}_{-0.5}$ larger than the NLO QCD prediction (2.7 nb) obtained with the standard parameter values and the MRSA′ [11] parton distribution functions.

In order to reduce the systematic uncertainties on both the data and the theory, CDF now measures the cross section in two rapidity bins and takes the ratio. In this way, several of the large uncertainties affecting the absolute measurement of the forward-central cross section cancel in the ratio. Moreover, the dependence of the theory prediction on the choice of the μ scale is reduced.

The event selection requires a central b-quark jet with $E_T > 26$ GeV and $|\eta^{\text{jet}}| < 1.5$, accompanied by a second b-quark decaying into a muon and a jet. This jet must have an $E_T > 15$ GeV and the events are classified as central-central or forward-central depending upon the muon pseudorapidity range, $|\eta^\mu| < 0.6$ or $2.0 < |\eta^\mu| < 2.6$, respectively. For the μ-jet combination, the b-quark decay is identified on the basis of the muon momentum transverse to the μ-jet direction, p_T^{rel}. The central b-quark jet is identified through a secondary vertex tag. A minimal azimuthal opening angle of 60° between the two tags is required to remove events from the region of poor acceptance. Based on 80 pb^{-1} of data collected in 1994-1995, the final data sample contains 382 forward-central and 7544 central-central events.

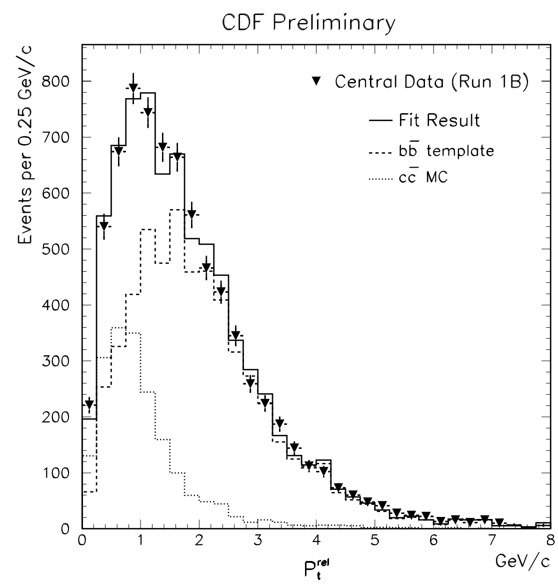

Figure 4: p_T^{rel} distribution for the muons in central-central events together with the fit result.

To extract the signal fraction in each sample, the p_T^{rel} of the muon and the pseudo-$c\tau$ of the b-jet are fitted simultaneously using a binned maximum likelihood method. The template histograms for the signal and the dominant background sources ($c\bar{c}$ production and $b\bar{b}$ production where one b tag is a fake) are obtained either from MC simulation or directly from the data. The p_T^{rel}

distribution obtained for central-central events is shown in Fig. 4, together with the fit result. The results of the fits are summarized in Table 1. The signal fraction is about 75% in the forward-central events and 60% in the central-central events.

Table 1: Composition of the data samples.

Source (b-tag/μ-tag)	forward-central	central-central
Real b / Real b	0.739 ± 0.073	0.582 ± 0.021
c / $\bar{c}$	0.123 ± 0.089	0.169 ± 0.021
Real b / Fake	$0.034^{+0.087}_{-0.034}$	0.085 ± 0.026
Fake / Real b	0.104 ± 0.030	0.165 ± 0.009

The ratio of the cross sections is obtained with the relation:

$$R_{\rm data} = \frac{\sigma(p\bar{p} \rightarrow b_1 b_2 X;\ 2.0 <\mid y_{b_1} \mid< 2.6)}{\sigma(p\bar{p} \rightarrow b_1 b_2 X;\ \mid y_{b_1} \mid< 0.6)} \qquad (1)$$

where $p_T(b_1, b_2) > 25$ GeV/c, $\mid y_{b_2} \mid< 1.5$, and, $\delta\phi(b\bar{b}) > 60°$. It is calculated using the number of signal events in both samples and the ratio of the total efficiency for central-central and forward-central events. Due to the much smaller kinematic acceptance of the forward toroids relative to the central detector, this ratio is equal to 5.4. The result is

$$R_{\rm data} = 0.361 \pm 0.041({\rm stat})^{+0.011}_{-0.023}({\rm syst}),$$

in good agreement with the NLO QCD prediction obtained with MRSA$'$:

$$R_{\rm theory} = 0.338^{+0.014}_{-0.097}.$$

The dominant systematic errors on $R_{\rm data}$ come from uncertainty in the energy scale (3%), acceptance (3%), fragmentation (3%), and background assumption (5%). The uncertainty on $R_{\rm theory}$ results from changing the μ scale between $2\mu_0$ and $\mu_0/2$. The evolution of the cross section ratio with the rapidity range of the muon coming from the b-quark semileptonic decay is shown in Fig. 5. The measurement is in agreement with both the LO and NLO QCD predictions.

With the cross section definition given in (1), the forward-central events arise from collisions between one parton with an average $x \approx 0.025$ and a second parton at $x \approx 0.25$. The cross section ratio should thus be sensitive to the gluon distribution in the proton at high x values, i.e. in a region where this gluon distribution is not very well known [13].

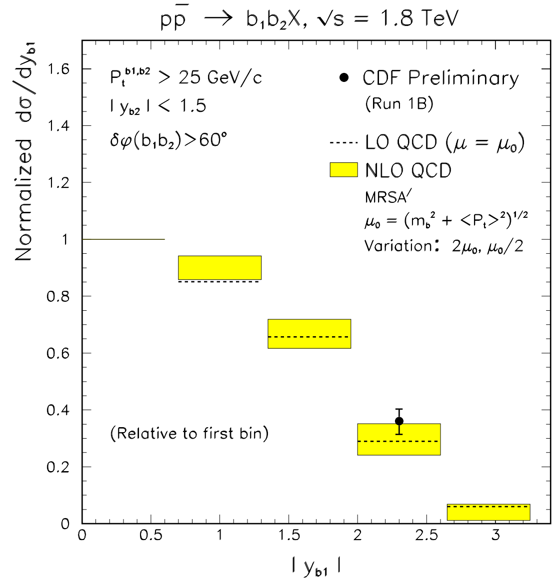

Figure 5: Evolution with rapidity of the cross section ratio.

Figure 6 shows a comparison of the $R_{\rm data}$ measurement with $R_{\rm theory}$ obtained using the parton distribution sets MRSR1(2) [10] and CTEQ4HJ [14]. The data point and theory curves are normalized to MRSA$'$ and are presented as a function of the rapidity of the b-quark decaying to μ-jet. The data point is in good agreement with the MRS sets and slightly disfavors the CTEQ4HJ distribution.

4 Summary

DØ has measured the b-produced muon cross section as a function of the muon rapidity. Compared with the NLO QCD calculations, the data are a factor 2.5 ± 0.5 larger than the central prediction in the region $\mid y^\mu \mid< 0.8$ for $p_T^\mu > 5$ GeV/c. This discrepancy increases to a factor 3.6 ± 0.6 in the forward region, $2.4 <\mid y^\mu \mid< 3.2$. Recent theoretical developments attempt to account for this increase of the data/theory discrepancy with rapidity. New calculations based on a variable flavor number scheme [15] predict an increase of the forward b-quark production cross section by a factor of 1.2 - 1.5 with respect to the standard NLO QCD calculations corresponding to a fixed flavor number scheme. A stiffer b-quark fragmentation function would result in a 30 to 50% increase of the B-meson production cross section for transverse momentum larger than 10 GeV/c when compared to that obtained with the usual Peterson fragmentation function [16].

CDF has measured the ratio of the forward-central to the central-central cross sections. This ratio $R_{\rm data} = 0.361 \pm 0.041({\rm stat})^{+0.011}_{-0.023}({\rm syst})$ is in good agreement with

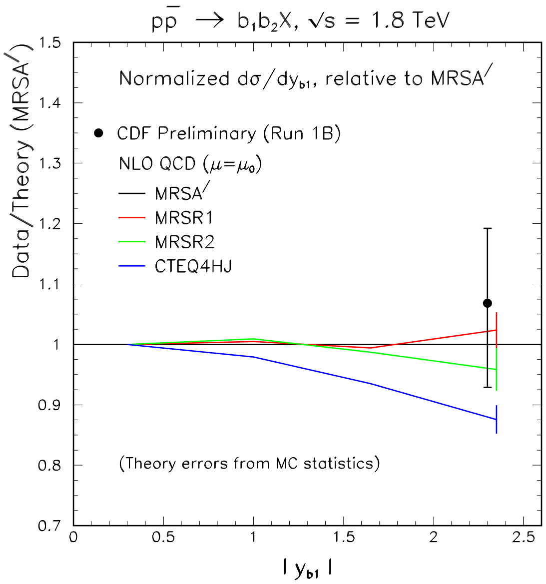

Figure 6: Comparison of the cross section ratio with various parton distribution functions.

the NLO QCD prediction. Although this measurement should show some sensitivity to the gluon distribution in the proton at large x values, more data are needed before being able to distinguish between various parton distributions.

Acknowledgements

I would like to thank the organizers for inviting me to this very pleasant conference.

References

1. M. Mangano, P.Nason and G. Ridolfi, *Nucl. Phys.* B **373**, 295 (1992).
2. F. Abe *et al.*, *Phys. Rev. Lett.* **71**, 500, 2396, 2537 (1993); *Phys. Rev. Lett.* **75**, 1451 (1995); *Phys. Rev. Lett.* **79**, 572 (1997).
3. S. Abachi *et al.*, *Phys. Rev. Lett.* **74**, 3548 (1995).
4. F. Abe *et al.*, *Phys. Rev.* D **55**, 2546 (1997).
5. D. Fein, FERMILAB-Conf-97/008-E (1997).
6. F. Abe *et al.*, *Phys. Rev.* D **53**, 1051 (1996).
7. DØ Collaboration, S. Abachi *et al.*, *Nucl. Instrum. Methods* **A338**, 185 (1994).
8. F. Paige and S.D. Protopopescu, BNL-Report BNL-38034 (1986).
9. M. Baarmand, private communication.
10. A.D. Martin, R.G. Roberts and W.J. Stirling, *Phys. Lett.* B **387**, 419 (1996).
11. A.D. Martin, R.G. Roberts and W.J. Stirling, *Phys. Rev.* D **47**, 867 (1993).
12. D. Zieminska, in: Proceedings of the XXXIIIrd Rencontres de Moriond '98, QCD and Hadronic Interactions.
13. J. Huston *et al.*, the CTEQ Collaboration, hep-ph/9801444.
14. H. L. Lai *et al.*, the CTEQ Collaboration, *Phys. Rev.* D **55**, 1280 (1997).
15. F.I. Olness, R.J. Scalise, and Wu-Ki Tung, FERMILAB-Pub-97/428-T, hep-ph/9712494.
16. M.L. Mangano, hep-ph/9711337.