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David K. Fein
For the D0 and CDF Collaborations

University of Arizona
Tucson, Arizona 85721

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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TEVATRON RESULTS ON b-QUARK CROSS SECTIONS AND CORRELATIONS

DAVID K. FEIN

(For the D0 and CDF Collaborations)

University of Arizona, Department of Physics, Tucson, AZ 85721, USA

E-mail: fein@uazhep.physics.arizona.edu

We report on recent results obtained by the DØ and CDF collaborations on the properties of b-quark production and correlations in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The DØ experiment has measured the angular correlations between the b- and $\bar{b}$-quarks using the azimuthal opening angle between their decay muons. This measurement is also used to extract the inclusive b-quark production cross section for $|y_b| < 1.0$ and is combined with previous Tevatron results. The CDF experiment has made the first direct measurement of $b\bar{b}$ rapidity correlations at a hadron collider, measuring the ratio of cross sections obtained in two different rapidity bins. DØ has also measured the inclusive production cross section for muons originating from b-quark decays in the forward region. These results are combined with previous measurements in the central region to obtain a rapidity dependence of the b-quark production cross section.

1 Introduction

The properties of b-quark production in $p\bar{p}$ collisions provide an important test of perturbative QCD at the next-to-leading order (NLO). Predictions of the QCD theory have been available for some time[1,2]. The theory describes the leading-order (LO) production of heavy flavor pairs through $q\bar{q}$ annihilation and gg fusion. The $q\bar{q}$ annihilation process proceeds through s-channel exchange while gg fusion proceeds through t-channel exchange. The NLO diagrams are dominated by two processes, gluon splitting and flavor excitation. The sum of the LO and NLO contributions has a magnitude of approximately twice that of the LO processes only.

Previous measurements of $b\bar{b}$ correlations at both $\sqrt{s} = 630$ GeV and 1.8 TeV have given inconsistent results as compared to the NLO QCD predictions. Two measurements using the azimuthal opening angle of muons from heavy quark decays showed qualitative agreement[3,4] with the NLO QCD predictions, while another measurement[5] utilizing the azimuthal opening angle between a muon from B-decay and $\bar{b}$-jet shows qualitative differences with the predictions. In all cases, the measurements show a systematic shift in the overall normalization of the cross section above the central values of the NLO QCD predictions. In addition, previous measurements of the inclusive b-quark production cross section in the central rapidity region, $|y| < 1$, by both DØ[6,7] and CDF[5,8], have been systematically above the central values of NLO QCD predictions.

The DØ experiment now reports on a new measurement of $b\bar{b}$ correlations using the semi-leptonic decay of the b-quark into a muon to tag the heavy quarks. In addition, this data sample is also used to provide another independent measurement of the inclusive b-quark production cross section in the central rapidity region. This analysis is presented in Section 2.

CDF[9] 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 region ($|\eta^b| < 1.5$). The measured cross section was once again found to lie above the central values of the NLO QCD predictions. In order to reduce systematic uncertainties affecting both the data and theory, CDF[10] now measures the cross section in each pseudorapidity region and takes the ratio. This analysis is described in Section 3.

Finally, Section 4 describes a recent analysis by DØ which measured the differential muon cross section due to b-quark decays in the forward region ($2.4 < |y^\mu| < 3.2$). The data from this analysis were combined with previous measurements of the muon cross section from b-quark decays to determine the differential cross section as a function of rapidity.

2 $b\bar{b}$ Angular Correlations and Inclusive b-Quark Production

The DØ analysis of $b\bar{b}$ correlations is based on 6.5 pb^{-1} of data collected during the 1992-1993 Tevatron run. The event selection required two muons with $p_T^\mu > 4$ GeV/c and pseudorapidity $|\eta^\mu| < 0.8$. Both muon candidates were also required to have an associated jet with $E_T > 12$ GeV within a cone of $\Delta\mathcal{R} = 0.8$. The invariant mass of the dimuons was restricted to the range $6 < M^{\mu\mu} < 35$ GeV/c^2 to enhance the sample originating from b-decays. A total of 397 events passed the selection criteria.

To extract the $b\bar{b}$ signal from other sources of dimuon events ($c\bar{c}$ production and heavy quark decay plus in-flight decay of π/K), DØ used a maximum likelihood fit with four input distributions. These included the transverse momentum of each muon with respect to the jet axis, p_T^{rel}, the longitudinal momentum of the jet carried by the higher p_T muon divided by the jet E_T, and the time of passage of the muon track through the muon chambers with respect to the beam crossing time. The first three variables were used to discriminate between background and $b\bar{b}$ production, while the last variable was used to identify the cosmic ray muon background. From the fit, DØ obtains a 45.3±5.8% contribution from $b\bar{b}$ production. Figure 1 shows the azimuthal correlation, $\Delta\phi^{\mu\mu}$, for $b\bar{b}$ production in the central region. Included in this figure is the NLO QCD prediction based on HVQJET[11]. The systematic errors on the data range from 25 to 31%. The data show an excess above the QCD prediction but agree with the overall shape. The agreement in shape is a clear indication for the presence of NLO subprocesses.

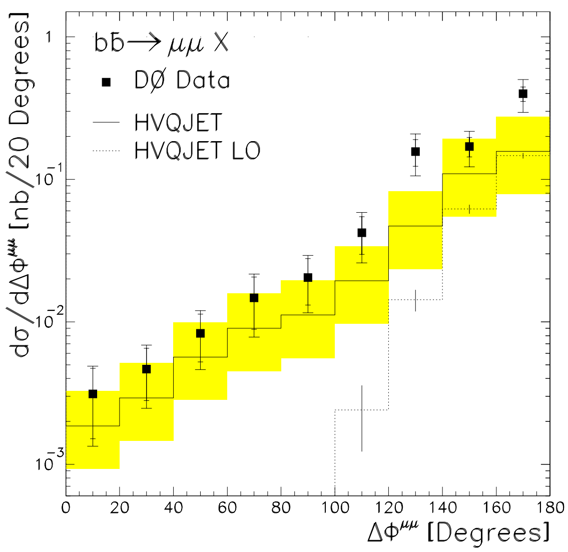

Figure 1: The $\Delta\phi^{\mu\mu}$ spectrum for $b\bar{b}$ production compared to the predicted spectrum. The DØ data are preliminary.

This data set can also be used to extract the inclusive b-quark cross section as a function of p_T^b for $|y^b| < 1.0$. Figure 2 shows this data combined with previous CDF[5,8] results and revised inclusive muon results from DØ[6]. Good agreement is found between the different measurements over the entire p_T^b range. The data are systematically larger than the NLO QCD prediction using MRSR2[12] parton distribution functions. The theoretical uncertainty of $^{+67}_{-38}$% results from varying the mass of the b-quark between 4.5 and 5.0 GeV/c^2 and the renormalization scale between $2\mu_0$ and $\mu_0/2$, where $\mu_0^2 = m_b^2 + \langle p_T^b \rangle^2$.

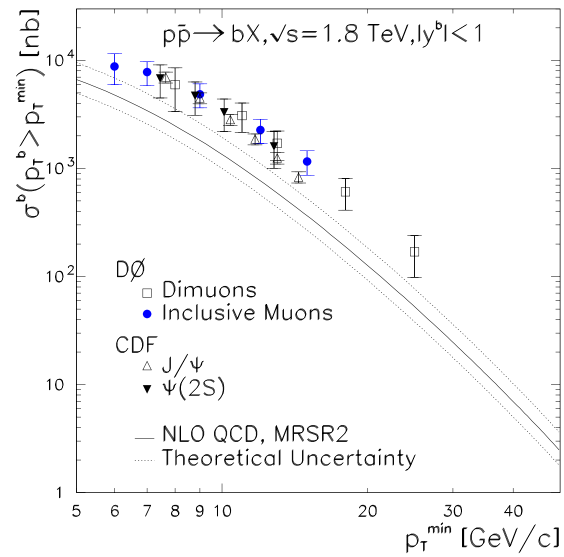

Figure 2: The inclusive b-quark production cross section for $|y^b| < 1.0$. The DØ data are preliminary.

3 $b\bar{b}$ Rapidity Correlations

Using their data set from the 1994-1995 Tevatron run, CDF has measured the ratio of the double differential cross section, $d^2\sigma/dy_1dy_2$, for two independent samples of b-quarks, a central-central topology, and a central-forward topology. By simultaneously measuring central and forward $b\bar{b}$ cross sections and taking their ratio, CDF is able to significantly reduce the experimental uncertainties associated with an absolute cross section measurement. In addition, the dependence of the theory prediction on the choice of the renormalization scale μ is reduced.

The analysis requires a central b-quark jet with $E_T >$ 26 GeV and $|\eta^{jet}| < 1.5$. This jet is identified as a b-quark jet through a secondary vertex tag. In addition, a second b-quark jet decaying into a muon must also be present. The second jet must have $E_T > 15$ GeV. The event is then classified as being either central-central or central-forward depending on the muon pseudorapidity range,$|\eta^\mu| < 0.6$ or $2.0 < |\eta^\mu| < 2.6$, respectively. For the μ-jet combination, the b-quark is identified using the muon momentum transverse to the μ-jet direction, p_T^{rel}. Finally, an azimuthal opening angle cut of 60° between the two tagged jets is required to explitly remove the contribution from the gluon splitting subprocess. This allows CDF to ignore this process in acceptance calculations. A total of 383 central-forward events and 7544 central-central events were collected based on 77 pb^{-1} of data.

To extract the signal fraction from each data sample, the p_T^{rel} of the muon and the pseudo-$c\tau$ of b-jet are fitted simultaneously using a binned maximum likelihood method, where pseudo-$c\tau$ is the transverse proper decay length of the secondary vertex. The input templates used for the signal and background sources ($c\bar{c}$ production and $b\bar{b}$ production where one b-tag is a fake) were obtained either from Monte Carlo simulations or from the data. Figure 3 shows the p_T^{rel} fit result for the central-central event sample, while Table 1 summarizes the fitted fractions to each data sample.

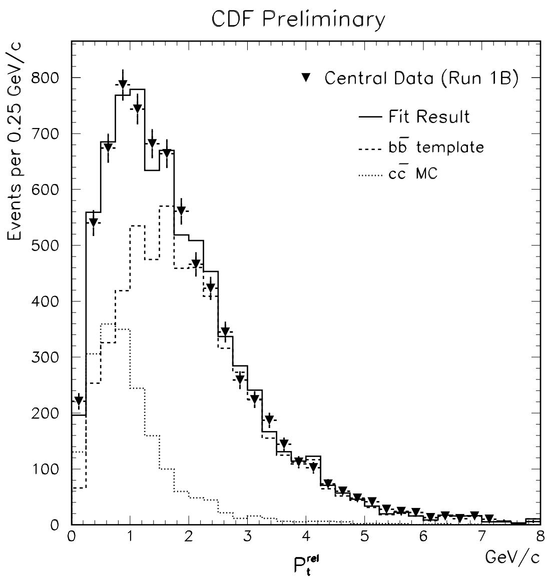

Figure 3: The p_T^{rel} distribution for the muons in the central-central data sample.

Table 1: Summary of fitted fractions to the forward-central and central-central data samples.

Source (b-tag/μ-tag)	Forward-central	Central-central
Real b / Real b	0.815 ± 0.060	0.617 ± 0.017
c / c	0.083 ± 0.051	0.148 ± 0.014
Real b / Fake	$0.000^{+0.059}_{-0.000}$	0.066 ± 0.021
Fake / Real b	$0.017^{+0.047}_{-0.017}$	0.070 ± 0.010
Fake / Real c	$0.086^{+0.035}_{-0.046}$	0.099 ± 0.010

The cross section ratio is then measured with the following relation:

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

where $p_T^{(b_1,b_2)} > 25$ GeV/c, $|y_{b_2}| < 1.5$, and $\Delta\phi > 60^\circ$. Included in this calculation are the efficiencies for the central-central and central-forward events which were determined using a combination of Monte Carlo and data samples. Due to the smaller kinematic acceptance of the forward toroids, the ratio of the central to forward acceptance is 5.24. The final result is

$$R_{\rm expt} = 0.361 \pm 0.033({\rm stat})^{+0.015}_{-0.031}({\rm syst}), \qquad (2)$$

in good agreement with the NLO QCD prediction obtained using the MRSA′[13] PDFs:

$$R_{\rm theory} = 0.338^{+0.014}_{-0.097}. \qquad (3)$$

The main systematic uncertainties associated with the experimental value of R come from the fitting procedure (7%), energy scale (4%), acceptance (4%), and fragmentation (3%). The uncertainty on $R_{\rm theory}$ arise from changing the renormalization scale between $2\mu_0$ and $\mu_0/2$.

4 Forward μ and b-Quark Production

The DØ analysis of the forward μ and b-quark production cross section is based on 82 ± 7 nb^{-1} of data collected during the 1994-1995 Tevatron run. The analysis primarily relies on the small angle muon spectrometer[14] which has a pseudorapidity coverage of $2.2 < |\eta^\mu| < 3.3$.

The event selection required a muon 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. In addition, cuts were applied to ensure good momentum measurement and energy deposition in the calorimeter matching the muon track. Only events with single interactions were accepted, leaving a total of 6709 events in the final data sample. The muon detection efficiency was obtained from Monte Carlo events with full detector simulation and is cross-checked with unbiased muon data.

The measured inclusive muon cross section, which includes both μ^+ and μ^-, is shown in Fig. 4 as a function of p_T^μ. The cross section was calculated per unit of rapidity, and only the statistical errors are shown. The contamination due to cosmic ray muons and hadronic punch-through were estimated to be less than 1%. The contribution from W and Z boson decays was determined using both DØ data and Monte Carlo and found to be negligible. The systematic uncertainties vary between 14 and 18%, and are dominated by Monte Carlo statistics and the muon momentum unfolding.

The two main sources of muons to the forward cross section consist of in-flight decays of pions and kaons and heavy quark decays. The expected π/K decay spectrum is also shown in Fig. 4. This spectrum was obtained using the ISAJET[15] Monte Carlo and was found to be in agreement with the charged particle spectrum measured by CDF[16] in the central region, $|\eta| < 1$. In addition, the π/K decay spectrum approximately matches the data spectrum in the first p_T^μ bin where these decays should dominate. The excess of the cross section is attributed to the heavy flavors decays.

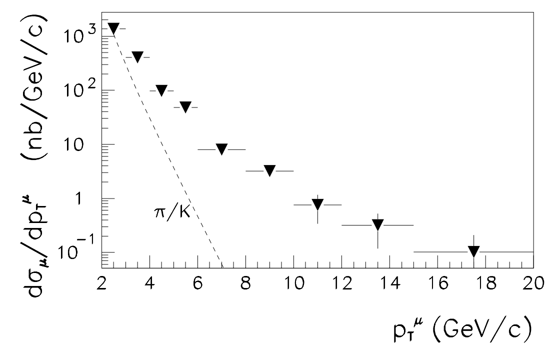

Figure 4: The inclusive muon cross section, per unit of rapidity, in the forward region as a function of p_T^μ. The dashed line represents the expected π/K decay contribution. The DØ data are preliminary.

After subtraction of the π/K contribution, the inclusive muon cross section is multiplied by the b-quark fraction, f_b, defined to be the ratio of the muon yield due to b-quark decays to the total muon yield from b- and c-quark decays. This ratio was determined using NLO QCD predictions for the b- and c-quark production cross sections. A check to this method was performed by using data events that had an associated jet with the muon. By requiring a jet, p_T^{rel} can be calculated and thus the origin of the muon can be determined on a statistical basis. From a sample of 31,000 events collected during the 1994-1995 Tevatron run, DØ finds excellent agreement between data and the Monte Carlo simulation for the b-quark fraction as a function of p_T^μ.

The differential muon cross section from b-quark production and decay is shown in Fig. 5. The systematic uncertainties of this measurement include those of the inclusive muon cross section with addition uncertainties due to the estimation of f_b (10-3%) and the π/K subtraction(14-1%). The NLO QCD prediction based on HVQJET are also shown in Fig. 5. The theoretical uncertainty is determined by varying the b-quark mass from 4.5 to 5.0 GeV/c^2 and the normalization scale from $2\mu_0$ to $\mu_0/2$. The predictions of this model match the overall shape of the measured cross section fairly well but are approximately a factor of four lower than the data.

Combining these results with previous DØ[6] measurements obtained in the central rapidity region ($|y^\mu| < 0.8$), the rapidity dependence of the b-produced muon cross

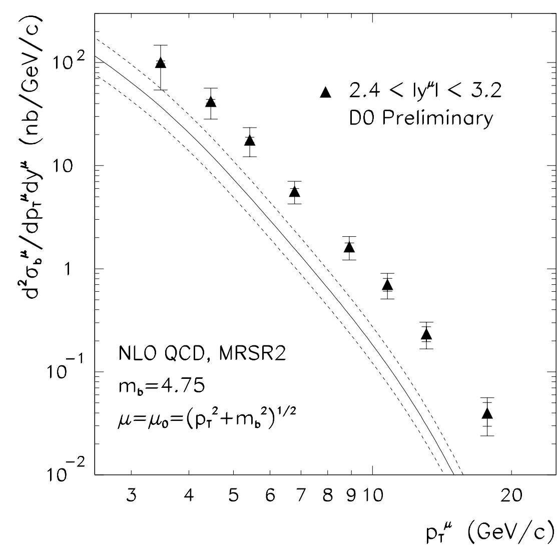

Figure 5: The p_T^μ spectrum of forward muons from b-decays along with the NLO QCD prediction.

section is obtained. This is shown in Fig. 6 for two p_T^μ ranges as a function of muon rapidity. For $p_T^\mu > 5$ GeV/c, the ratio of data/theory is 2.5$\pm$0.4 in the central region and increases to 3.6$\pm$0.8 in the forward region. The uncertainty in these ratios reflects the experimental error only. The data hint at some excess in the forward region.

5 Summary

DØ has recently measured the inclusive b-quark production cross section and the $b\bar{b}$ azimuthal angle correlations using dimuons to tag the presence of b-quarks. Both measurements are found to agree in shape with the NLO QCD calculations but lie above the central values of these predictions. The measurements for the inclusive b-quark production cross section are in good agreement with previous measurements by CDF. In addition, DØ has also 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 of 2.5$\pm$0.4 larger than the theory for $|y^\mu| < 0.8$ and increases to a factor of 3.6$\pm$0.8 in the forward region, $2.4 < |y^\mu| < 3.2$. Recent theoretical developments[17] attempt to account for the discrepancies between data and theory.

CDF has measured the ratio of the central-forward to the central-central cross sections. The value $R_{\rm expt} = 0.361 \pm 0.033({\rm stat})^{+0.015}_{-0.031}({\rm syst})$ is in good agreement with the NLO QCD prediction. This measurement represents the first direct experimental evidence supporting

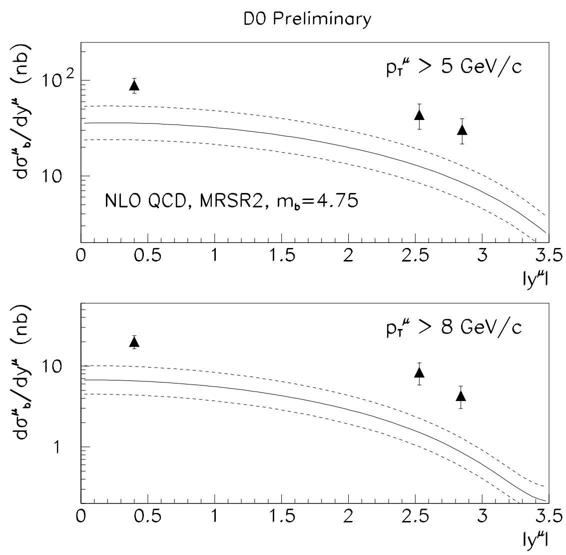

Figure 6: The b-produced muon cross section as a function of rapidity compared to the NLO QCD prediction. The top figure is for $p_T^\mu > 5$ GeV/c and the lower figure for $p_T^\mu > 8$ GeV/c.

the strong $b\bar{b}$ rapidity correlation predicted by theory.

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