Small-Angle Muon and Bottom-Quark Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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This Letter describes a measurement of the muon cross section originating from b-quark decay in the forward rapidity range $2.4 < |y^{\mu}| < 3.2$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The data used in this analysis were collected by the D0 experiment at the Fermilab Tevatron. We find that next-to-leading-order QCD calculations underestimate b-quark production by a factor of 4 in the forward rapidity region.

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Measurements of b-quark production at the Tevatron have provided valuable information in the study of perturbative QCD. Cross sections measured by both the D0 [1], and CDF [2] Collaborations in the central rapidity region ($|y^b| < 1.5$) are systematically higher (by a factor of 2 to 3) than the nominal values predicted by next-to-leading-order (NLO) QCD [3]. This measurement extends these studies to the previously unexplored rapidity region ($2.4 < |y^\mu| < 3.2$), and provides further insights into the discrepancy between b-quark production measurements and theoretical predictions.

Forward muons are measured by the D0 detector [4] using the small angle muon spectrometer (SAMUS) [5,6]. SAMUS consists of two identical systems, each with three drift tube stations and a 1.8 T magnetized iron toroid, on either side of the interaction region. The momentum resolution of this system varies from $\approx$19% at 20 GeV/c to $\approx$25% at 100 GeV/c. Muons reaching the SAMUS chambers traverse approximately 20 interaction lengths of material, reducing the hadronic punch-through background to a negligible level. This region does, however, face a large combinatoric background due to the flux of beam jet related particles. There are on average 6 to 14 hits per plane in a given bunch crossing, and the drift tubes near the beam axis have an approximate 5% occupancy.

The data used in this analysis come from special runs taken at low instantaneous luminosity during the 1994–1995 collider run. The integrated luminosity for these runs is 104 ± 6 nb^{-1}. The trigger required the presence of an inelastic collision near the center of the detector and at least one track in the SAMUS detector with an apparent $p_T^\mu > 3$ GeV/c pointing back to the interaction region. Muon candidates were also required to have an associated energy deposition in the calorimeter. The hit multiplicity in each layer was also required to fall below a maximum cutoff to improve background rejection and lower the trigger rates to an acceptable level.

Muons are selected offline in the rapidity range $2.4 < |y^\mu| < 3.2$, with $p^\mu < 150$ GeV/c and $p_T^\mu > 2$ GeV/c. Single interaction events are selected by requiring only one reconstructed vertex in an event, leaving an effective integrated luminosity of $\mathcal{L} = 75 \pm 7$ nb^{-1}. Muon tracks are required to have at least 15, out of an average of 18, hits. To ensure a good momentum measurement, we require muons to traverse a magnetic field integral of at least 1.2 T $\cdot$ m. Muons are also required to be associated with a tracklike object in the calorimeter with energy deposition consistent with that of a minimum ionizing particle. With these cuts, the combinatoric background is determined using both data and Monte Carlo (MC) to be less that 1%. The number of surviving muons in this sample is $N^\mu = 5106$.

The muon trigger and track reconstruction efficiencies are obtained using data and MC single muons, with detector simulation using GEANT [7], superimposed onto real minimum bias events. The trigger efficiencies for the hit multiplicity cut [(31 ± 2)%] and the calorimeter confirmation [(95 ± 1)%] are obtained from data, as are the offline cut efficiencies for energy deposition [(94 ± 3)%] and number of hits on a track [(96 ± 2)%]. The overall detection efficiency is 1% for $p_T^\mu = 2$ GeV/c and reaches a plateau of 10% for $p_T^\mu > 9$ GeV/c. The MC momentum scale and resolution are shown to be correct to within 2% by comparing the peak values and widths of the reconstructed J/ψ signal from data [6] and MC.

The muon cross section is calculated as follows:

$$\frac{d\sigma^\mu}{dp_T^\mu dy^\mu} = \frac{1}{\mathcal{L}\,\Delta y^\mu \Delta p_T^\mu}\,\frac{N^\mu f_{\rm smr}}{\epsilon}, \qquad (1)$$

where $f_{\rm smr}$ is a correction factor that accounts for momentum smearing, and ϵ is the detection efficiency. As there are high correlations between kinematic variables and cuts, $f_{\rm smr}$ and ϵ are determined by

$$\frac{N^\mu f_{\rm smr}}{\epsilon} = \frac{1}{\epsilon_{\rm data}}\,\frac{H(\text{data})H(\text{MCgen})}{H(\text{MCreco})}, \qquad (2)$$

where $\epsilon_{\rm data}$ is the combined data-based efficiency of the previously described cuts not simulated in the MC, and the H's are matrices with elements corresponding to two-dimensional histograms in the (p_T^μ, y^μ) plane. H(data) is the data distribution after all offline cuts; H(MCgen) is the generated Monte Carlo distribution, and H(MCreco) is the reconstructed MC distribution with full detector simulation and the same cuts as the data. The histograms are segmented with 25 bins in p_T^μ from 0 to 25 GeV/c, and 7 bins in rapidity from 2.0 to 3.4. The MC events are weighted in an iterative procedure to match the corrected p_T^μ and rapidity distributions of the data. This method is found to give consistent results (within 3%) regardless of the shape of the initial distribution. The resulting reconstructed MC distributions also agree quite well with those of the data for all kinematic variables of interest after the weighting procedure.

The inclusive muon cross section in the forward rapidity region (which includes both muon charges) is shown in Fig. 1 and Table I. The systematic errors in this measurement vary as a function of p_T^μ from 15 to 45%. They are dominated by uncertainties associated with the momentum

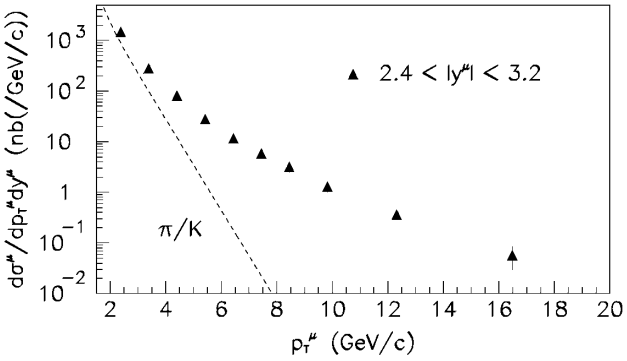

FIG. 1. The inclusive muon cross section in the forward region as a function of p_T^μ (per unit rapidity). The dashed line shows the expected contributions from π/K decays.

TABLE I. Forward muon cross sections (per unit rapidity).

p_T^μ (GeV/c)	$\langle p_T^\mu \rangle$ (GeV/c)	σ^μ [nb/(GeV/c)]	$\sigma^\mu(\pi/K)$ [nb/(GeV/c)]	f_b	σ_b^μ [nb/(GeV/c)]
2–3	2.4	1474 ± 33 ± 265	1091 ± 383		
3–4	3.4	282.5 ± 7.5 ± 45	92.2 ± 33.1	0.513 ± 0.087	97.6 ± 3.8 ± 25
4–5	4.4	81.4 ± 3.1 ± 12	10.4 ± 3.7	0.619 ± 0.086	43.9 ± 1.9 ± 9.2
5–6	5.4	28.2 ± 1.5 ± 4.2	1.3 ± 0.5	0.656 ± 0.078	17.6 ± 1.0 ± 3.4
6–7	6.4	11.72 ± 0.80 ± 1.9	0.17 ± 0.06	0.671 ± 0.080	7.75 ± 0.54 ± 1.6
7–8	7.4	5.86 ± 0.53 ± 1.1	0.02 ± 0.01	0.675 ± 0.081	3.94 ± 0.36 ± 0.83
8–9	8.4	3.17 ± 0.34 ± 0.63		0.685 ± 0.075	2.17 ± 0.23 ± 0.50
9–11	9.8	1.30 ± 0.13 ± 0.29		0.697 ± 0.070	0.906 ± 0.091 ± 0.22
11–15	12.4	0.367 ± 0.039 ± 0.11		0.718 ± 0.067	0.264 ± 0.028 ± 0.080
15–20	16.7	0.057 ± 0.011 ± 0.026		0.749 ± 0.062	0.043 ± 0.008 ± 0.020

smearing correction [(6–41)%], the single interaction luminosity (10%), and the trigger efficiency (8%).

The contributions to this cross section from cosmic rays, hadronic punch-through, and W/Z decay are negligible (determined using both data and MC). The pion and kaon decay contribution is obtained using ISAJET [8], which we find to be in agreement with the charged particle cross section measured in the central region [9]. The excess above the π/K contribution is attributed to b and c quark decay. The fraction of this excess due to b quark decay (f_b) can be obtained using the transverse momentum spectrum of the muons relative to that of an associated jet ($p_T^{\rm rel}$), but, because of our jet reconstruction threshold of $E_T > 10$ GeV, only (7.9 ± 0.8)% of the events in the forward region have a reconstructed associated jet. We must, therefore, rely on a NLO QCD MC to determine f_b.

In this Monte Carlo, b and c quarks are generated according to the p_T and rapidity distributions of NLO QCD calculations [3] using MRSR2 parton distribution functions [10], quark masses $m_b = 4.75$ GeV/c^2 and $m_c = 1.6$ GeV/c^2, with renormalization and factorization scales $\mu = \mu_0 = \sqrt{m_q^2 + p_T^2}$. The four momenta of the quarks are input to an ISAJET MC which simulates initial and final state radiation, as well as quark fragmentation and decay. The theoretical uncertainty is determined by varying the parameters m_b from 4.5 to 5.0 GeV/c^2, m_c from 1.3 to 1.9 GeV/c^2, and μ from $\mu_0/2$ to $2\mu_0$. The Peterson fragmentation parameters [11] ($\epsilon_b = 0.006$, $\epsilon_c = 0.06$) are also varied by 50%, as are the branching ratios within their errors [12]. This simulation predicts that 8.5% of the muons should have a reconstructed associated jet, which is consistent within errors with what is found in the data.

We check the validity of this MC by comparing its prediction for f_b to that determined from our entire 1994–1995 data set. 31 000 forward muons with an associated jet are selected from low p_T single muon and muon + jet triggers. The trigger requirements keep the physics content of this sample the same as that of the cross section sample. The full sample is unsuitable for a cross section determination, however, as there is a large uncertainty in its normalization due to the various trigger thresholds and prescales, and luminosities that the data were taken with.

The b-quark fraction is determined by fitting the $p_T^{\rm rel}$ distributions (in various ranges of p_T^μ) to the expected shapes from b-quark, c-quark, and π/K decay (see Fig. 2) as determined from ISAJET MC. The shape for π/K decays was found to agree with the data distribution sample in the p_T^μ range 0.5–1.0 GeV/c which is dominated by these decays. As is shown in Fig. 3, the NLO QCD Monte Carlo agrees quite well with the measured f_b obtained in the $p_T^{\rm rel}$ fits of both the entire data sample, and the subset of events from the cross section sample that have a jet associated with a muon. Having shown that the MC is reliable for events with muons with jets, we assume it is also reliable for inclusive muons.

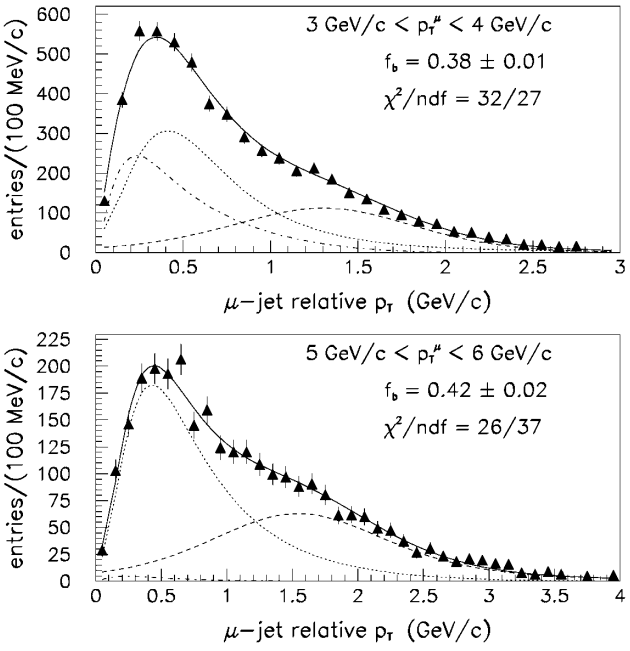

FIG. 2. Data $p_T^{\rm rel}$ distributions for two selected p_T^μ ranges. The solid line shows the fit to the data, with broken lines showing contributions from b-quark (dashed), c-quark (dotted), and π/K (dot-dashed) decay. f_b is the b-quark fraction after π/K subtraction (errors are statistical only).

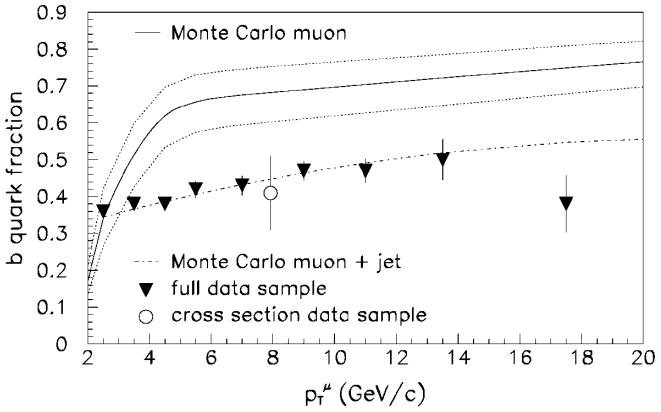

FIG. 3. f_b for muons with an associated jet as measured from data p_T^{rel} fits (triangles and circle) and as predicted by the NLO QCD MC (dot-dashed curve). The prediction of f_b for muons without the jet requirement is shown by the solid curve with uncertainties indicated by dotted curves.

Subtracting the π/K contribution from the inclusive muon cross section and multiplying the result by the QCD MC predictions for f_b gives the cross section for muons originating from b quark decay. Our measurement, which includes both muon charges, and sequential $b \to c \to \mu$ decays, is shown in Fig. 4 and Table I.

The systematic uncertainties of this measurement include those of the inclusive muon cross section, with additional uncertainties due to f_b and the π/K subtraction. The contribution to the muon cross section from π/K decay is predominantly in the low p_T^μ bins. Conservatively assuming that the data in the 2–3 GeV/c bin (see Fig. 1) is entirely due to π/K decay, we determine that the ISAJET normalization is correct to within a factor of 1.35. This factor is used to determine the uncertainty in the higher p_T^μ bins.

Also shown in the figure is a cross check of our measurement. We determine the cross section using the same events, but now require the muon to be associated with a jet, and use the values for f_b that were determined in the p_T^{rel} fits to the entire data sample. We obtain the same cross section (within statistical errors) as we do in the inclusive muon analysis.

The NLO QCD predictions for the forward muon cross section from b-quark decay are also shown in Fig. 4 as a function of p_T^μ. They match the shape of the measured cross section fairly well, but are approximately a factor of 4 lower than the data.

By combining the forward cross section with that of a previous D0 measurement in the central rapidity range ($|y^\mu| < 0.8$) [1] we can study the rapidity dependence of b quark production. Our measurement of the cross section for muons from b quark decay as a function of rapidity ($d\sigma_b^\mu/d|y^\mu|$) is shown in Fig. 5 for both $p_T^\mu > 5$ GeV/c and $p_T^\mu > 8$ GeV/c. The ratios between data and theory are shown in Table II. We find that next-to-leading order QCD calculations do not reproduce the measurements. There have been some recent theoretical attempts to account for this discrepancy [13,14], but none have been successful in bringing the predicted cross sections up to the measured values.

In summary, we have measured the inclusive muon cross section, and the cross section for muons originating from b quark decay, in the forward rapidity region of $2.4 < |y^\mu| < 3.2$. We find that next-to-leading order QCD calculations underestimate b quark production by a factor of 4 in this region.

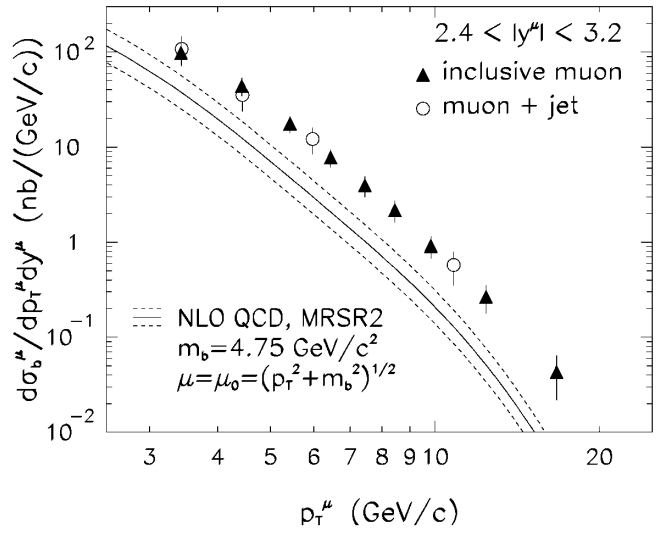

FIG. 4. The cross section for muons from b-quark decay as a function of p_T^μ (per unit rapidity) as measured with the inclusive muon sample (triangles) and its subsample of events that have a jet associated with the muon (circles). The solid curve is the NLO QCD prediction, with the dashed curves representing the theoretical uncertainties.

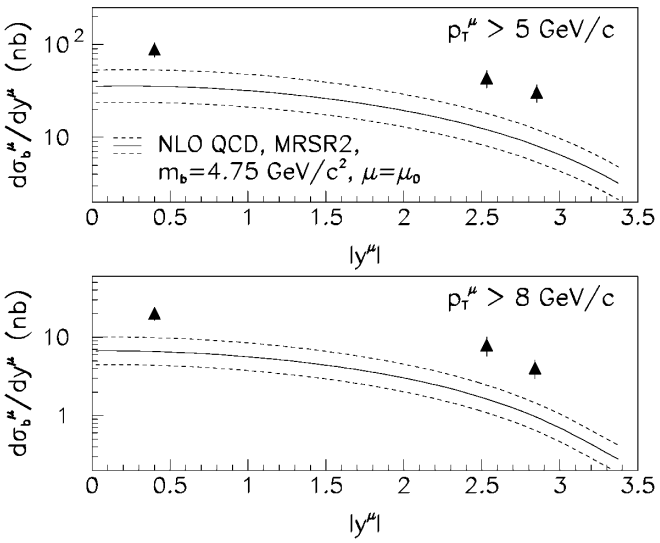

FIG. 5. The cross section of muons from b quark decay as a function of $|y^\mu|$ for $p_T^\mu > 5$ GeV/c, and $p_T^\mu > 8$ GeV/c. The solid curves are the NLO QCD predictions, with uncertainty bands shown by the dashed lines.

TABLE II. The cross section of muons from b-quark decay compared to NLO QCD. Errors are statistical and systematic added in quadrature.

$p_T^\mu > 5$ GeV/c

Rapidity	$\langle y \rangle$	Measured σ_b^μ (nb)	Theory σ_b^μ (nb)	Ratio
0.00–0.80	0.40	89 ± 16	36	2.5 ± 0.4
2.40–2.65	2.53	43.5 ± 9.4	12	3.6 ± 0.8
2.65–3.20	2.85	30.5 ± 6.6	8.4	3.6 ± 0.8

$p_T^\mu > 8$ GeV/c

Rapidity	$\langle y \rangle$	Measured σ_b^μ (nb)	Theory σ_b^μ (nb)	Ratio
0.00–0.80	0.40	20.1 ± 3.7	6.6	3.0 ± 0.6
2.40–2.65	2.53	7.9 ± 2.2	1.6	4.8 ± 1.3
2.65–3.20	2.84	4.1 ± 1.1	0.99	4.0 ± 1.1

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