Inclusive μ and b-Quark Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We report a measurement of the inclusive muon and b-quark production cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the D0 detector at the Fermilab Tevatron collider. The inclusive muon spectrum extends over the kinematic range $|y^{\mu}| < 0.8$ and $3.5 < p_T^{\mu} < 60$ GeV/c, and is well described by the expected contributions from various known sources. The b-quark production cross section for $|y^b| < 1.0$ and $p_T^b > 6$ GeV/c is extracted, and agrees with next-to-leading order QCD predictions within the experimental and theoretical uncertainties.

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The study of b-quark production in high energy hadronic collisions is important for testing the perturbative QCD description of heavy quark production [1,2]. The cross section for b-quark production measured at $\sqrt{s} = 0.63$ TeV by UA1 [3] is in agreement with the next-to-leading order (NLO) theoretical predictions [1]. However, the Collider Detector at Fermilab (CDF) [4] published data at $\sqrt{s} = 1.8$ TeV are generally higher than these predictions.

We have measured the inclusive muon and b-quark production cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, using the D0 detector [5]. The data correspond to an integrated luminosity $\int \mathcal{L}\, dt = 73.3 \pm 8.8\ \mathrm{nb}^{-1}$ taken during the 1992–93 Fermilab Tevatron collider run.

The D0 central muon system consists of ten planes of proportional drift tubes arranged in three layers outside the calorimeter of, respectively, 4, 3, and 3 planes. Magnetized steel toroids between the first and second layer provide additional hadron filtering and muon momentum measurement. Typical drift tube resolution in the bend plane is 0.8 mm. The muon momentum resolution was measured using $J/\psi \to \mu\mu$ and $Z \to \mu\mu$ data and parametrized as $\sigma(1/p)/(1/p) = 0.18(p-2)/p \oplus 0.008p$, with p in GeV/c and the two terms added in quadrature.

The data sample was obtained by filtering the interactions through a multilevel trigger. The hardware muon trigger [6] required hits in the muon chambers to lie within 60 cm wide roads in the bend plane pointing to the interaction region. A subsequent software trigger required at least one reconstructed muon track with transverse momentum $p_T^\mu > 3$ GeV/c. The events were fully reconstructed off line and retained for further analysis if they contained at least one muon track with rapidity $|y^\mu| < 0.8$ and $p_T^\mu > 3.5$ GeV/c. Candidate muons had to deposit >1 GeV/c of energy in the calorimeter; the mean energy loss for a single muon is about 2.5 GeV. A match was required with a good track in the central tracking detector pointing back to the primary interaction vertex. To ensure the best possible muon momentum measurement, only tracks with hits in all three muon layers were selected, with a traversed field integral in the toroids ≥ 2 T m, reducing hadronic punchthrough to less than 0.5%. To minimize cosmic ray background, the reconstructed time of passage (t_0) through the muon chambers had to be within 100 ns of the beam crossing. A total of 15 995 muons passed all selections.

Possible sources of backgrounds to muons from heavy flavor decays consist of cosmic rays, muons from Drell-Yan and prompt J/ψ decays, and from π/K and W/Z decays. The residual cosmic ray contamination was estimated from the observed t_0 distribution to be $(9 \pm 3)\%$, almost independent of p_T^μ, and was subtracted from the data. Muons from Drell-Yan and J/ψ decays were estimated to contribute less than 2% of the data.

The efficiency for the trigger and muon reconstruction, including the geometrical acceptance, was determined with simulated events, and was found to agree closely with an analysis of cosmic ray muons. The trigger and reconstruction efficiency was 0.56 ± 0.05 for $p_T^\mu \geq 6$ GeV/c. The efficiency for a triggered and reconstructed track to pass each off-line selection criterion was measured using $J/\psi \to \mu\mu$ data. Using one muon to tag the presence of the other, the total off-line selection efficiency was found to be 0.50 ± 0.03 per muon, independent of p_T. The overall detection efficiency (ϵ) was averaged over y^μ and parametrized as a function of p_T^μ; it rises from 0.06 ± 0.01 at $p_T^\mu = 3.5$ GeV/c to 0.28 ± 0.03 for $p_T^\mu \geq 6$ GeV/c. The error is dominated by the uncertainty in the muon chamber efficiency.

For the simulation of the b/c-quark, π/K, and W/Z decays into muons, we used the ISAJET [7] Monte Carlo program. A sample of about 33 000 muon events was generated within the acceptance, and processed with a complete simulation of detector [8], trigger, and off-line selections.

The inclusive muon differential cross section, summing over both charges, and averaged over the muon rapidity range Δy, was calculated as follows:

$$\frac{d\sigma^\mu}{dp_T^\mu} = \frac{1}{\Delta y}\int_{-\Delta y/2}^{+\Delta y/2} dy^\mu \frac{d^2\sigma}{dp_T^\mu\, dy^\mu} = \frac{1}{\Delta y}\frac{N^\mu}{(\int \mathcal{L}\, dt)\epsilon}, \tag{1}$$

where N^μ is the number of muons per GeV/c passing all off-line selection cuts, with the cosmic ray background subtracted. The cross section, per unit of y, is shown in Fig. 1 as a function of the measured p_T^μ. The curves are the expected contributions from π/K and W/Z decays, folded with the muon momentum resolution. The excess is to be attributed to heavy flavor decays. The observed distribution is consistent with a large contribution from π/K decays at the lowest p_T and dominance by W/Z decays at high p_T. This consistency is an important cross-check on the absolute normalization of the data.

The π/K decay spectrum was estimated using ISAJET dijet events, with $E_T^{\mathrm{jet}} > 3$ GeV. The charged-hadron p_T distribution from ISAJET was checked against the measured inclusive spectrum [9], and a 15% systematic uncertainty was assigned to the calculated muon spectrum from π/K decays. The p_T^μ distributions from W/Z decays were simulated with ISAJET, with cross sections and systematic errors determined from our data [10]. The estimated contribution from W decays is in agreement with the result of a missing transverse energy analysis.

In obtaining the b-quark cross section we restricted our analysis to muons in the p_T^μ range 4–30 GeV/c. We estimated and subtracted the expected W/Z background ($N_{W/Z}^\mu$) as indicated above. The remainder is expected to come mainly from b- and c-quark decays, with a

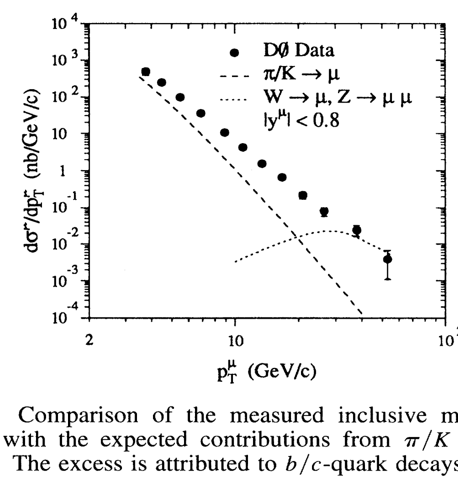

FIG. 1. Comparison of the measured inclusive muon cross section with the expected contributions from π/K and W/Z decays. The excess is attributed to b/c-quark decays.

significant background ($\sim$25%) from π/K decays only at low p_T^μ. To determine the fraction of muons from b-quark decays, f_b, we used the transverse momentum of the muon with respect to the associated jet axis ($p_T^{\rm rel}$). Jets are reconstructed for $E_T^{\rm jet} > 8$ GeV, using a cone algorithm with radius $R = 0.7$ in pseudorapidity–azimuthal-angle space. Because the accompanying jets tend to have low E_T, only 60% of the muons have a reconstructed jet nearby ($\Delta R^{\mu,\rm jet} < 1$). We have verified that this fraction is consistent with the reconstructed jet fraction in simulated events, and that all kinematic distributions for muons with and without jets are similar. The fraction f_b subsequently extracted from the subset of muons with jets was assumed to hold for the full sample.

The $p_T^{\rm rel}$ distributions for b-quark, c-quark, and π/K decays were modeled with ISAJET. The distribution for b-quark decays includes both direct ($b \to \mu$) and sequential ($b \to c \to \mu$) decays, with the appropriate branching fractions [11], and closely agrees in shape with the lepton spectrum measured by the OPAL collaboration [12] at the CERN Large Electron-Positron Collider (LEP). f_b was determined by fitting the b-quark, c-quark, and π/K $p_T^{\rm rel}$ distributions to the data in bins of p_T^μ. For illustration, Fig. 2(a) shows the $p_T^{\rm rel}$ distribution for the p_T^μ range 8–30 GeV/c. The errors on f_b ($\simeq$12%) were estimated by varying the fitted distributions within their errors and repeating the fits. We cross-checked this determination of f_b by subtracting the estimated W/Z and π/K decay contributions from our data, and using the expected ratio of the contributions from charm to bottom decays. We used the c/b ratio from ISAJET and estimated the error on f_b from this method by varying this input c/b ratio by 50%.

The muon cross section for inclusive b-quark decays was calculated as follows:

$$\frac{d\sigma_b^\mu}{dp_T^\mu} = \frac{1}{\Delta y}\,\frac{(N^\mu - N^\mu_{W/Z})f_b f_p}{(\int \mathcal{L}\, dt)\epsilon}\,, \qquad (2)$$

where f_b was determined from the $p_T^{\rm rel}$ technique, and f_p is a correction factor that accounts for the smearing due to the muon momentum resolution. To determine f_p as a function of p_T^μ an unfolding technique [13] was applied: f_p varies from 1 at low p_T^μ to $\simeq$0.7 at $p_T^\mu = 20$ GeV/c. The uncertainty of f_p ($\simeq$6%) was estimated by varying the resolution function within its errors.

The spectrum shown in Fig. 3(a), with systematic errors of $\simeq$21%, is extracted without assumptions concerning heavy flavor production cross sections, and represents our experimental result. The theoretical expectation was calculated using ISAJET for b-quark production, fragmentation, and decay, with the cross section normalized to the NLO QCD calculation [1]. The predicted b-quark production cross section from ISAJET, including higher-order processes, and using CTEQ 2L parton distributions [14], has a p_T shape similar to the NLO calculation with MRS D0 parton distributions [15], but is larger by almost a factor 2. We used the Peterson fragmentation function with

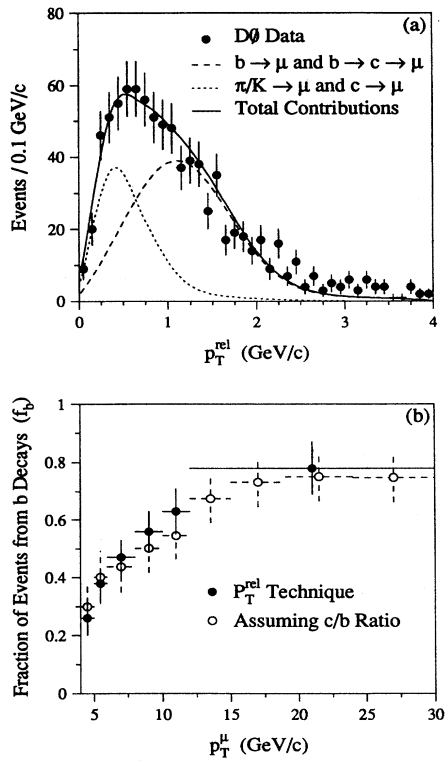

FIG. 2. (a) $p_T^{\rm rel}$ distribution for the subset of muons associated with jets in the p_T^μ range 8–30 GeV/c and for $|y^\mu| < 0.8$; (b) f_b as a function of p_T^μ. The solid points are from the $p_T^{\rm rel}$ fitting technique and the open circles are from the c/b ratio method.

$\epsilon_b = 0.006 \pm 0.003$ [16] and the average LEP inclusive branching ratio $B(B \to \mu) = 0.110 \pm 0.005$ [17].

To extract a b-quark cross section from the muon spectrum we followed the method used by UA1 [3] and CDF [4]. The relation between the b-quark cross section and the experimental muon spectrum is given by

$$\sigma^b(p_T^b > p_T^{\rm min}) = \tfrac{1}{2}\,\sigma_b^\mu(p_T^{\mu 1}, p_T^{\mu 2})\,\frac{\sigma^b_{\rm MC}}{\sigma^\mu_{\rm MC}}\,, \qquad (3)$$

where $\sigma_b^\mu(p_T^{\mu 1}, p_T^{\mu 2})$ is the muon cross section of Eq. (2) integrated over the interval $p_T^{\mu 1} < p_T^\mu < p_T^{\mu 2}$. For each consecutive p_T^μ interval, $p_T^{\rm min}$ was determined (using Monte Carlo simulation), such that 90% of the muons in the interval originated from b quarks with $p_T^b > p_T^{\rm min}$, $\sigma^b_{\rm MC}$ is the total inclusive b-quark cross section for $p_T^b > p_T^{\rm min}$, and $\sigma^\mu_{\rm MC}$ is the cross section for production of b quarks that decay to muons within the p_T^μ interval, both evaluated with ISAJET. The factor $\frac{1}{2}$ yields the cross section average for b and $\bar{b}$ production from our measurement of μ^+ and μ^- data. The ratio of the Monte Carlo cross sections depends on the shape of the p_T spectrum of the b quark, but not on its absolute normalization. The uncertainty due to the assumed p_T shape ($\simeq$12%) was estimated by replacing the MRS D0 parton distributions by MRS D- [15], which have a more singular gluon

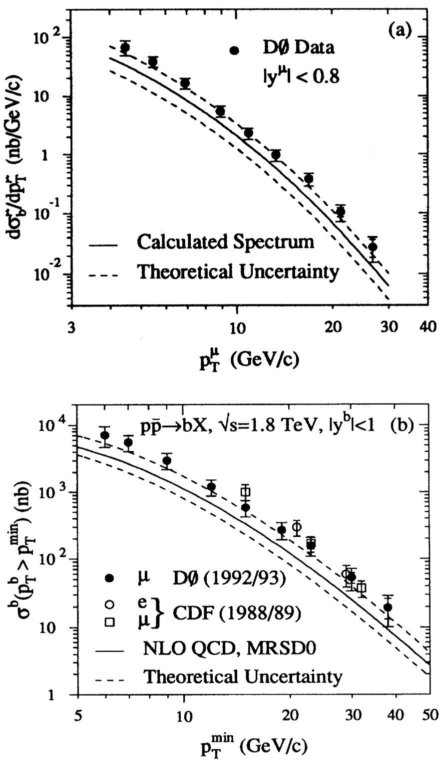

FIG. 3. (a) The unfolded muon spectrum for inclusive b-quark decays compared to the expected spectrum (see text); (b) b-quark production cross section compared to NLO QCD predictions (see text). Inner error bars indicate statistical uncertainties.

distribution. The error on ϵ_b, together with 1σ variations in B-hadron leptonic branching and decay parameters, lead to an additional 13% uncertainty. Together with the error on the muon cross section, we obtained a systematic uncertainty of $\simeq$27% on the b-quark cross section.

The resulting cross section for b-quark production as a function of $p_T^{\min}$, for $|y^b| < 1.0$, is shown in Fig. 3(b), where similar CDF [4] measurements using inclusive leptons are shown for comparison. The curves represent the NLO QCD predictions [1] using MRS D0 parton distribution functions. The QCD mass scale $\Lambda_{\overline{\rm MS}}^{(5)} = 140$ MeV ($\overline{\rm MS}$ denotes the modified minimal-subtraction scheme) and the renormalization and factorization scale $\mu = \mu_0$ [with $\mu_0^2 = m_b^2 + (p_T^b)^2$, and $m_b = 4.75$ GeV$/c^2$] were used for the solid curve, and customary variations of these parameters for the dashed curves: 187 MeV and $\mu_0/2$ (upper), and 100 MeV and $2\mu_0$ (lower).

In conclusion, we have presented a measurement of the inclusive muon and b-quark production cross sections. The inclusive muon cross section is well described by the expected contributions from various known sources. Within errors, our b-quark cross section agrees with that of CDF [4] for inclusive leptons. Other measurements of σ^b by CDF [4] are made at low p_T^b and use different final states such as J/ψ or semiexclusive $b \to c$ decays, which are thus not directly comparable because of theoretical uncertainties in the fraction of J/ψ due to b production. Our measurement indicates that, within theoretical uncertainties, the NLO QCD description [1] of heavy flavor production in $p\overline{p}$ at $\sqrt{s} = 1.8$ TeV is adequate for the kinematic range $|y^b| < 1.0$ and $p_T^b > 6$ GeV$/c$.

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