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Measurement of the B Meson Differential Cross-Sections in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.8 TeV Using the Exclusive Decays $B^{\pm}\rightarrow J/\psi K^{\pm}$ and $B^0\rightarrow J/\psi K^{*0}$

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Measurement of the B Meson Differential Cross-Sections in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV Using the Exclusive Decays $B^{\pm} \rightarrow J/\psi K^{\pm}$ and $B^{0} \rightarrow J/\psi K^{*0}$

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This paper presents the first measurement of the differential $B^{\pm}$ and B^{0} cross-sections, $d\sigma/dp_T$, in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The data sample used represents an integrated luminosity of 19.3 ± 0.8 pb^{-1} accumulated by the Collider Detector at Fermilab(CDF). The cross-sections are measured over the p_T range 6-15 GeV/c in the central pseudorapidity region $|\eta| < 1$ by fully reconstructing the B meson decays $B^{\pm} \rightarrow J/\psi K^{\pm}$ and $B^{0} \rightarrow J/\psi K^{*0}$, where the J/ψ is required to decay to two muons, and the K^{*0} is required to decay to $K^{\pm}\pi^{\mp}$. The measured absolute normalization and shape of the cross-section as a function of p_T are compared to the theoretical QCD prediction calculated at next-to-leading order.

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QCD theory predicts that the b quark cross-section is large at high energy hadron colliders. The predictions were in agreement with the first cross-section measurements at $\sqrt{s}$= 630 GeV reported by UA1 [1], which interpreted the spectrum of inclusive leptons in terms of bottom and charm production. Similar measurements at $\sqrt{s}$= 1.8 TeV were made more recently at the Collider Detector at Fermilab (CDF) [2]. The measurements at this energy cast doubt on whether QCD correctly predicted either the absolute rate or the shape of the distribution in transverse momentum, p_T [3–6]. We present the first direct measurement of the differential B meson cross-section in p_T in hadronic collisions by measuring the mass and momentum of the B mesons decaying into final states in which the decay particle momenta are well measured. Such a measurement is free of the model-dependant procedures used to determine the b content and infer the b quark p_T from an inclusive lepton sample and thus provides a better test of the QCD prediction. These differential cross-sections will be available for the design of experiments to detect CP violation in the decays of B mesons produced at hadron colliders.

The measurement of the B meson cross-sections in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV uses the fully reconstructed decay channels $B^{\pm} \rightarrow J/\psi K^{\pm}$ and $B^{0} \rightarrow J/\psi K^{*0}$, with $J/\psi \rightarrow \mu^{+}\mu^{-}$ and $K^{*0} \rightarrow K^{+}\pi^{-}$, and their charge conjugates. By triggering on dimuons, we obtain a sample of J/ψ of which more than 15% comes from B decays [11]. The data sample represents $19.3 \pm 0.8\ pb^{-1}$ collected by CDF during the 1992-93 run. CDF has previously made measurements of the integrated cross-sections using these decay channels [4,5], but greatly increased statistics now allows measurement of the differential cross-section as a function of p_T.

Detailed descriptions of the CDF detector have been provided elsewhere [12]. A brief description of the components used in this analysis is presented here. The z-axis of the detector coordinate system is along the beam direction. The Central Tracking Chamber (CTC) is a drift chamber in a 1.4T axial magnetic field, consisting of nine superlayers, of which five give information on the track in the $r-\phi$ transverse plane and four give z information. A particle must have pseudorapidity $|\eta| < 1$ to pass through all nine superlayers, which motivates the choice of rapidity range for the cross-section measurement.

A newly-installed Silicon Vertex Detector (SVX) provides high-resolution $r-\phi$ tracking information near the interaction region [7]. The SVX detector is 51 cm long and consists of four layers of silicon microstrip detectors with an innermost radius of 2.9 cm. Pattern recognition is done by extrapolating CTC tracks to the outermost layer of SVX, and by using the errors on the tracking parameters to define roads in which to search for SVX hits. The distribution of the primary vertices in z can be described by a Gaussian with a width of 27 cm, so SVX information is available for about 60% of all tracks. If SVX information is added to the track, the momentum resolution, $\delta p_T/p_T$, after applying a vertex constraint is improved from $[(0.0014 p_T)^2 + (0.0066)^2]^{1/2}$ to $[(0.0009 p_T)^2 + (0.0066)^2]^{1/2}$.

Surrounding the CTC are electromagnetic and hadronic calorimeters. Outside the calorimeters are the central muon chambers, segmented into 72 modules which provide about 85% coverage in ϕ in the pseudorapidity range $|\eta| < 0.6$.

The selection of B candidates begins by identifying J/ψ candidates which decay to two muons. There are three levels of trigger requirements that must be passed for a muon pair to be included in the J/ψ data sample. At the first trigger level, they must have been detected in the central muon chambers (separated by at least 0.09 radians in ϕ), where a cut is made on the slope of the track in the $r-\phi$ plane, which corresponds to a cut in transverse momentum. Prompt muons with momentum below ~1.4 GeV/c range out in the calorimeters. The efficiency for this trigger is 90% at p_T = 3.8 GeV/c. At the second trigger level, at least one of the muon chamber tracks must match a track found in the CTC by a hardware track processor. The efficiency for the track processor rises from 10% at 2.3 GeV/c to 90% at 3.4 GeV/c. At the third trigger level, CTC pattern recognition and tracking are done. The CTC track is projected to the muon chamber and the intersection point is required to be within 4σ of its associated muon chamber track segment in the $r-\phi$ and z directions. The dimuon invariant mass is required to be within 300 MeV/c^2 of the J/ψ mass.

After offline event reconstruction is performed, additional cuts are imposed to improve the purity of the J/ψ sample. The matching requirement between the CTC track and its associated muon chamber track segment is tightened to 3σ in $r-\phi$ and 3.5σ in z. To match the trigger efficiencies, each muon is required to have $p_T \geq$ 1.8 GeV/c, and at least one muon is required to have $p_T \geq$ 2.8 GeV/c. The muons are required to have opposite charge and to come from a common vertex. The fitted number of J/ψ reconstructed after all the cuts have been applied is 61,700. Any dimuon pair with an invariant mass which differs from the average J/ψ mass by more than 4 times the error in the mass determination is excluded from the sample.

Kaons from $B^{\pm}$ decays have a p_T distribution that is considerably harder than that for particles from the underlying event, and thus $K^{\pm}$ candidates are required to have $p_T >$ 1.25 GeV/c. For the decay channel $B^{0} \rightarrow J/\psi K^{*0}$, $K^{*0} \rightarrow K^{+}\pi^{-}$, any pair of oppositely charged tracks are considered to be candidates for the K^{*0} decay products. The transverse momentum of the K^{*0} candidate is also required to be greater than 1.25 GeV/c. Given the above requirements, and those of the dimuon trigger, the B meson transverse momentum is required to be greater than 6.0 GeV/c. Due to the high combinatoric background, a K^{*0} mass peak is not observable, but since the detector resolution is much better than the natural width of the K^{*0}(49.8 MeV/c^2), m($K\pi$) is required to be withing 50 MeV/c^2 of the K^{*0} mass(896.1 MeV/c^2). Unlike purely combinatoric background, K^{*0} candidates formed by exchanging the kaon and pion mass assignments from a real K^{*0} decay give background that peaks at the B mass. So only the K^{*0} candidate with the mass closest to the world average mass of 896.1 MeV/c^2 is used, to avoid double counting.

The confidence level of a fit made by simultaneously constraining the decay tracks to come from a common vertex and the invariant mass of the dimuon tracks to equal the J/ψ mass is required to be greater than 0.5%. For each B candidate, the proper decay length, $c\tau \equiv L_{xy} m_B / p_T$, is calculated, where L_{xy} is the projection of the B vertex displacement onto the B transverse momentum. About 75% of the background that occurs when a prompt J/ψ is combined with other tracks from the primary vertex is removed by requiring $c\tau$ to be greater than 100 μm.

The B candidates are divided into subsamples according to their transverse momenta. For the $B^\pm$ candidates, the subsamples cover momentum ranges 6-9, 9-12, 12-15, and > 15 GeV/c. For the B^0 candidates, the subsamples cover momentum ranges 7-11, 11-15, and > 15 GeV/c. For each of these subsamples, the invariant mass distribution is fitted to a Gaussian plus a linear background over the signal region 5.2-5.6 GeV/c^2. The mass range below 5.2 GeV/c^2 is excluded from the fit since it can include contributions from higher multiplicity B decay modes. The slope of the background is determined from a sample of candidate events which fail the vertex χ^2 confidence level cut. The widths are fixed to the Monte Carlo predictions, scaled by the ratio of the J/ψ width observed in the data to that predicted by the Monte Carlo. The $B^\pm(B^0)$ invariant mass distributions for the four momentum ranges are shown in figure 1(2), and the fitted numbers of events are given in table I.

The differential cross-section is calculated from the following equation:

$$\frac{d\sigma}{dp_T} = \frac{N/2}{\mathcal{L} \cdot A \cdot e \cdot F \cdot \Delta p_T} \quad (1)$$

where N is the number of events observed, $\mathcal{L}$ is the integrated luminosity, A is the detector acceptance (including the efficiency of the kinematic cuts), e is the combined tracking and track-matching efficiency, F is the branching fraction, and Δp_T is the width of the p_T bin. The factor of 1/2 is included because decays involving both B and $\overline{B}$ mesons have been reconstructed, but the quoted cross-sections are for B mesons only. Integrated cross-sections are calculated for B $p_T > 15$ GeV/c.

In order to determine the acceptance, a sample of Monte Carlo events was generated, where b quarks were produced using the next-to-leading order QCD calculation [8,9], and the MRSD_-' [10] structure functions. The b quarks were then fragmented to B mesons according to the Peterson parameterization [13], using a value of $\epsilon_b = 0.006 \pm 0.001 \pm 0.002$ [14]. The events were run through a full detector simulation and a parameterization of the first and second trigger level efficiencies. Then all the selection requirements were applied. The detector acceptance, which is the fraction of events in the original sample which passed all the requirements, is given in table I for each of the momentum ranges.

The third level trigger efficiency for the muon pairs was determined to be 93 ± 2%, and the offline tracking efficiency for other decay particles was found to be 98.9 ± 1%. The efficiency of the matching requirement between the CTC track and the muon chamber track segment was measured to be 98.7 ± 1%. The resulting combined tracking and track-matching efficiency for the B^+ and B^0 decays are 90.8 ± 2.4 % and 89.8 ± 2.5%, respectively.

Branching fractions of $(1.12 \pm 0.17) \times 10^{-3}$ and $(1.53 \pm 0.37) \times 10^{-3}$ [15] were used for the $B^\pm \to J/\psi K^\pm$ and $B^0 \to J/\psi K^{*0}$ decays, respectively, and a branching fraction of 0.0597 ± 0.0025 was used for the $J/\psi \to \mu^+\mu^-$ decay [16]. This gives a combined branching fraction of $(6.7 \pm 1.1) \times 10^{-5}$ for the B^+ decay and $(6.1 \pm 1.5) \times 10^{-5}$ for the B^0 decays, including the 2/3 branching fraction for the $K^{*0} \to K^+\pi^-$ decay.

A major source of systematic uncertainty in the measurement of the reconstruction efficiency comes from uncertainty in the Monte Carlo model used for event generation and detector simulation. Estimates of the systematic error are determined by varying the Monte Carlo parameters used to generate the events. To measure the effect of changing the shape of the assumed production cross-section, the QCD mass scale, μ, is varied between the value $\mu_0 = \sqrt{m_b{}^2 + p_T{}^2}$ and $\mu_0/4$, where the b quark mass, m_b, is taken to be 4.75 GeV/c^2. In addition, the QCD parameter, Λ_4, is varied by 1σ from the central value, as determined from the calculations of the parton distribution functions [10]. We note that this variation causes the predicted cross-section to increase by a factor of 2.5. The resulting systematic error associated with the quark production model is 5%. The effect of varying the fragmentation parameter, ϵ_b, between 0.004 and 0.008 implies a systematic uncertainty of 7%.

The systematic uncertainty in the J/ψ trigger efficiency parameterization was determined to be ±4% by varying the level 1 and level 2 trigger efficiency fit parameters by $\pm 1\sigma$. Additionally, a systematic uncertainty of ±4% is associated with the reconstruction of kaons which decay inside the CTC volume. This is based on simulation results in which about 7% of the kaons decay in flight and half of these are successfully reconstructed. The 4% error represents the maximum discrepancy between the ability to reconstruct such tracks in the simulation and the data. An additional 10% uncertainty is associated with the pseudorapidity dependence of the tracking efficiency.

The efficiency of the $100\mu m$ cut on $c\tau$ depends on the lifetime of the meson, and on the resolution of the $c\tau$ measurement [17]. The $c\tau$ resolution is determined from sideband regions of the B invariant mass distribution, and it varies from 50 to 300 μm, depending on whether or not SVX information has been used in the vertex fit. The effect on the efficiency due to varying the lifetimes by $\pm 1\sigma$ and varying the resolution between 0 and 350 μm indicates a systematic uncertainty of $\pm 4\%$.

To determine the efficiency of the vertex fit confidence level cut, each pair of dimuons in the J/ψ data sample is refitted to a common vertex, and the invariant mass distribution is fitted before and after the cut on the confidence level of 0.5%. The efficiency is determined to be 98.6% with a systematic uncertainty of $\pm 1\%$, due to the deviation from the nominal value of 99.5%.

Recent measurements by CLEO have determined the polarization (Γ_L/Γ) of the decay products from the $B^0 \to J/\psi K^{*0}$ decay to be $(84 \pm 10)\%$ [15], which is consistent with a preliminary measurement made at CDF [18]. Varying the polarization within these limits changes the calculated acceptance by $\pm 7\%$.

Combining these effects in quadrature, the reconstruction efficiency has overall systematic errors of 17.6% for the B^+ decay and 19.0% for the B^0 decay. The branching fractions contribute additional uncertainties of 15% and 24%, respectively.

The differential B meson cross-section measurements are given in table I and are plotted in figure 3. The integrated cross-sections for $p_T > 15$ GeV/c are given in the table but not plotted. Each measurement is quoted at the mean p_T, $\langle p_T \rangle$, of its momentum range, as determined from the data. The branching fraction uncertainty of 15%(24%) for the $B^+(B^0)$ mesons has been removed from the error bars shown. The solid curve shows the differential B meson cross-sections predicted by the Monte Carlo, which uses next-to-leading order QCD for production and the Peterson parameterization for fragmentation, and includes the assumption that 75% [19] of $\bar{b}$ quarks fragment in equal amounts to B^+ and B^0 mesons. While this theory correctly predicts the shape, as measured here, the predicted rate using the natural choice for the renormalization scale, $\mu = \sqrt{m_b^2 + {p_T}^2}$, remains low.

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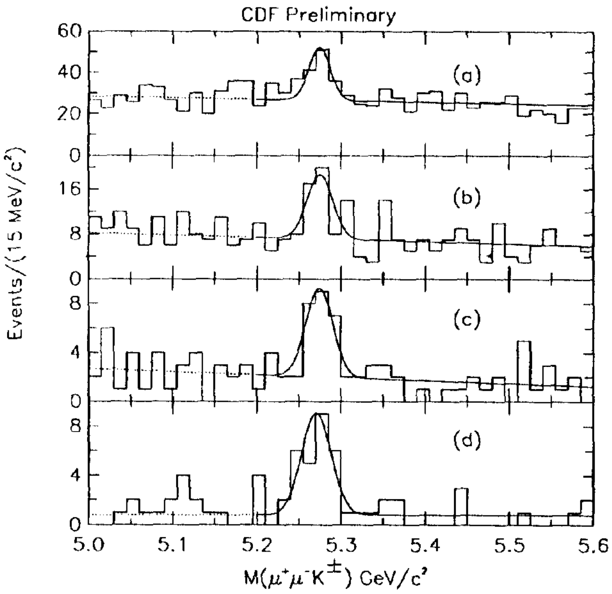

FIG. 1. $B^{\pm}$ meson invariant mass from the decay $B^{\pm} \to J/\psi K^{\pm}$ for the following momentum ranges: (a) 6-9 GeV/c, (b) 9-12 GeV/c, (c) 12-15 GeV/c, and (d) >15 GeV/c.

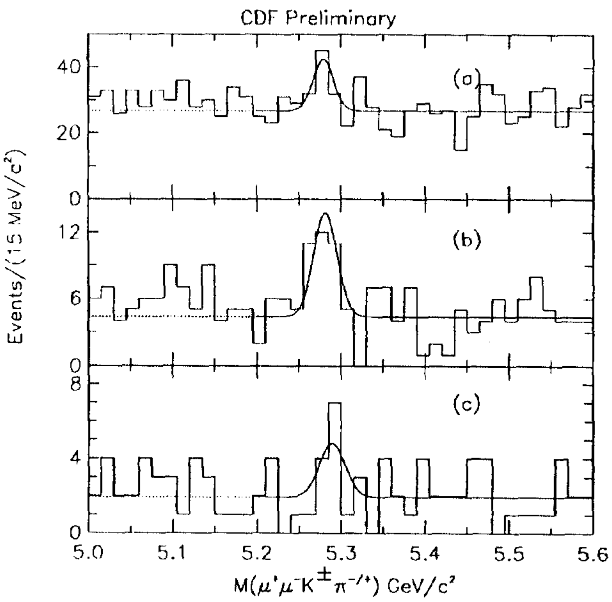

FIG. 2. B^0 meson invariant mass from the decay $B^0 \to J/\psi K^{*0}$ for the following momentum ranges: (a) 7-11 GeV/c, (b) 11-15 GeV/c, and (c) >15 GeV/c.

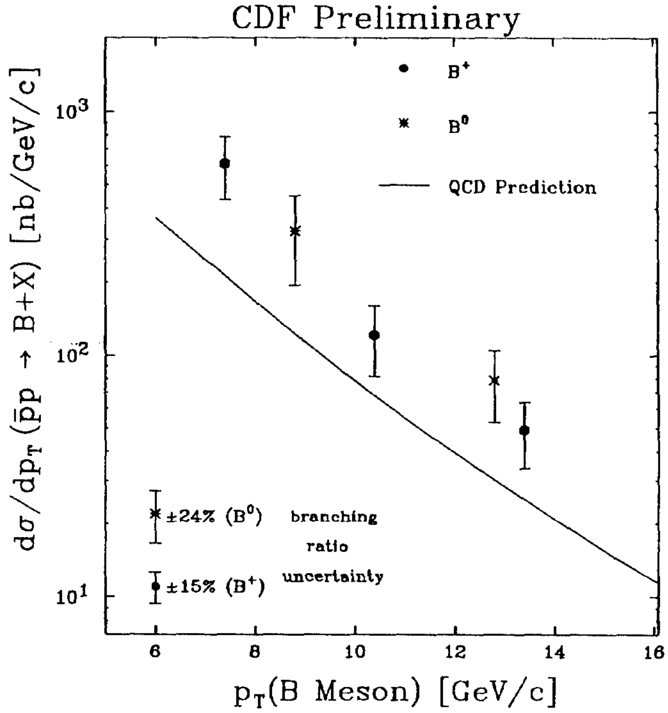

FIG. 3. B meson differential cross-sections compared to the QCD prediction. Branching ratio uncertainties are shown separately.

TABLE I. Differential B meson cross-sections, $d\sigma(|y| < 1.0)/dp_T$ (nb/GeV/c), for the p_T range 6-15 GeV/c and integrated cross-sections (nb) for $p_T > 15$ GeV/c.

	$p_T(B)$ GeV/c	$\langle p_T \rangle$ GeV/c	Acceptance %	No. of Events	Cross-section
B^+	6-9	7.4	1.29 ± 0.01	53 ± 12	610 ± 138 ± 141
	9-12	10.4	3.58 ± 0.04	29 ± 8	121 ± 33 ± 28
	12-15	13.4	5.71 ± 0.07	19 ± 5	49 ± 13 ± 11
	>15	19.7	9.03 ± 0.08	25 ± 6	12 ± 3 ± 3
B^0	7-11	8.8	1.18 ± 0.01	31 ± 11	324 ± 115 ± 99
	11-15	12.8	3.46 ± 0.04	22 ± 6	79 ± 22 ± 24
	>15	20.5	6.54 ± 0.06	8 ± 4	15 ± 8 ± 5