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B_c Results from CDF

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CDF Run II detector has accumulated about 360 pb^{-1} data using dimuon triggers in $p\bar{p}$ collisions collected at $\sqrt{s}$ = 1.96 TeV. We report a first evidence for the $B_c^{\pm}$ meson in the fully reconstructed decay channel $B_c \to J/\psi\pi$, and its mass measurement. In addition, we present ratio of branching fractions in $B_c \to J/\psi\ell$ modes, normalized to the $B_c \to J/\psi K$ mode.

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1. Introduction

The B_c is a ground state $\overline{b}c$ meson, composed of two heaviest quarks, within the standard model of particle physics. The first observation of B_c meson came from the CDF collaboration in the semileptonic decays, $B_c \to J/\psi\ell\nu_\ell X$, at the Run I of the Tevatron. In a data sample of 110 pb^{-1} at $\sqrt{s}$ = 1.8 TeV CDF observed $20.4^{+6.2}_{-5.5}$ signal events and measured a B_c mass of 6.40 $\pm$ 0.39(stat) $\pm$ 0.13(sys) GeV/c^2 [1]. Recently, the DØ collaboration reported a preliminary observation of a B_c signal in the decay channel $B_c \to J/\psi\mu\nu_\mu X$, in a sample of 210 pb^{-1} data collected in Run II [2]. Owing to lack of mass measurement in fully reconstructed decay modes, the B_c mass is less precise than the theoretical prediction. This leaves room for future measurements to test lattice QCD and potential models.

At the Tevatron energies B_c is produced via decays of excited states, whose observation would lead to test of competing models. In $p\overline{p}$ collisions gluon fusion $gg(q\overline{q}) \to (\overline{b}c)b\overline{c}$ is the dominant mechanism for B_c production, which involves diagrams at $O(\alpha_s^4)$. On the other hand, the B^+ production involves diagrams at $O(\alpha_s^2)$. Thus at Tevatron the production cross-section for B_c is predicted to be $\approx 10^{-3}$ smaller than that for B^+. Latest calculations suggest this number to be 7.4 *nb* [3]. The decay of B_c occurs via weak decays of *b*-quark (25%) and *c*-quark (65%) and the rest through weak annihilation decays [3, 4]. Since there is no annihilation decay channel for $B_c \to$ hadrons via gluons, its lifetime is large.

The CDF II detector consists of a magnetic spectrometer surrounded by calorimeters and muon chambers and is described in detail elsewhere [5]. The components relevant to the B_c measurements are briefly described here. The tracking system is immersed in a 1.4 Tesla axial magnetic field and consists of a silicon microstrip detector (L00, SVX, ISL, in increasing order of radius) [6 – 8] surrounded by an open-cell wire drift chamber (COT) [9]. The muon detectors used for this analysis are the central muon chambers (CMU), covering the pseudorapidity range $|\eta| < 0.6$ [10, 11], and the extension muon drift chambers (CMX), covering $0.6 < |\eta| < 1.0$. Soft electrons are identified as tracks associated to clusters in the Central Electromagnetic Calorimeter (CEM), with 2-dimensional position measurement provided by the Central Shower Maximum detector (CES), a proportional wire chamber placed roughly at a depth of 6 radiation lengths in the CEM, near shower maximum, and by the Central Preradiator (CPR), a plane of multi-wire proportional chambers situated in the gap between the solenoid coil and the CEM, used mainly for electron pion separation.

Signal control samples for these measurements were collected using CDF's di-muon trigger, a three-tiered trigger system requiring opposite charged muon pairs in $|\eta| < 1$, $p_T > 1.5$ GeV, azimuthal opening angle $< 2.5^\circ$ and invariant mass $2700 < \mathrm{M}_{pair} < 4000$ MeV/c^2. For particle identification studies $D^* \to D^0\pi$ and $\Lambda \to p\pi$ samples were collected using a two-track trigger and $\gamma \to e^+e^-$ sample was collected using a single electron trigger with $p_T > 8$ GeV.

2. Analysis

In the following subsections we present mass measurement of B_c in the fully reconstructed decay mode, $B_c \to J/\psi\pi$, and ratio of branching fractions in the semileptonic decays, $B_c \to J/\psi\ell\nu_\ell X$, with $\ell = \mu$ or e. Whereas the former decay mode has a lower rate and smaller background, suitable for a precise measurement of mass, the latter have larger statistics and depend on a careful determination of background for signal estimation.

2.1 Mass Measurement

The $B_c \rightarrow J/\psi\pi$ search was performed using a blind analysis method. The mass value of the $J/\psi\pi$ combinations in the search window 5600 < $M(J/\psi\pi)$ < 7200 MeV/c^2, referred to as B_c candidates, were temporarily hidden.

In order to optimize the significance of a possible signal, we varied the selection criteria to maximize the function $\Sigma = S_F/(1.5+\sqrt{B})$ [12]. Here, S_F is the accepted fraction of signal events, in this case taken from a Monte Carlo sample, and the background B is the number of accepted B_c candidates. The optimized selection criteria were:

- a quality requirement on the $J/\psi\pi$ three-track 3-D vertex fit (χ^2 < 9 for four degrees of freedom),
- a requirement on the pion track contribution to the vertex fit (χ^2_π < 2.6),
- the impact parameter of the B_c candidate with respect to the primary vertex (< 65 μm),
- the maximum $c\tau$ where t is the proper decay time of the B_c candidate (< 750 μm),
- the transverse momentum of the pion (> 1.8 GeV/c),
- the 3-D angle between the momentum of the B_c candidate and the vector joining the primary to the secondary vertex (β < 0.4 rad),
- and the significance of the projected decay length of the B_c candidate onto its transverse momentum direction ($L_{xy}/\sigma(L_{xy})$ > 4.4).

Because of the relatively long B_c lifetime, the 3-track vertexing is critical to this analysis for background rejection.

A sample of $B^\pm$ mesons, reconstructed in the decay mode $B \rightarrow J/\psi K$, was analyzed as a control sample in order to check our understanding of the reconstruction of the relevant variables in the simulation.

Before "unblinding" the $J/\psi\pi$ mass distribution, a procedure to search for a signal peak was defined. This was based on a scan of the search region with a sliding window. Using a set of Monte Carlo experiments of the expected distribution of maximum Σ (Σ_{max}), for pure background sample [13], a threshold of 3.5 is obtained which corresponds to $\approx$0.1% probability for background to fluctuate into signal. We then applied the fitting procedure to the 390 candidates in the unblinded $J/\psi\pi$ mass distribution. This provides a value of $\Sigma(m) = S/(1.5+\sqrt{B})$ as a function of the mass in the search window. A maximum value of Σ_{max} = 3.6 is found at a mass $\approx$ 6290 MeV/c^2. Probability for the background to give a peak at this value of Σ_{max} was estimated from the Monte Carlo experiments as 0.27%.

The final mass measurement was made with an unbinned likelihood fit, shown in Figure 1. Systematic uncertainties on the B_c mass determination are due to measurement uncertainties on the track parameters ($\pm$0.3 MeV/c^2), the momentum scale ($\pm$0.6 MeV/c^2), the possible differences in

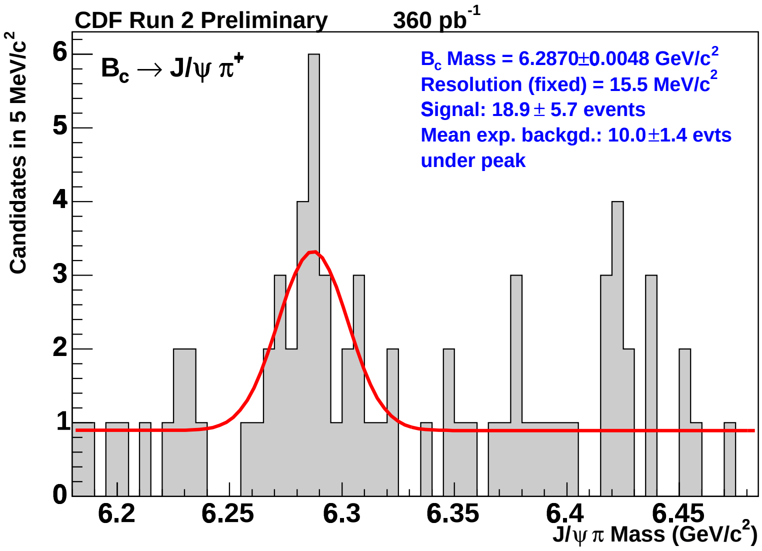

Figure 1: The invariant mass distribution of the $J/\psi\pi$ candidates and results from an unbinned likelihood fit.

the p_T spectra of the B and B_c mesons (± 0.5 MeV/c^2) and our limited knowledge of the background shape used in the final mass fit (± 0.8 MeV/c^2). The total systematic uncertainty is evaluated to be ± 1.1 MeV/c^2.

We observe 18.9 ± 5.7 signal events on a background of 10.0 ± 1.4 events and the fit to the $J/\psi\pi$ mass spectrum yields a B_c mass of $6287.0 \pm 4.8(\text{stat}) \pm 1.1(\text{syst})$ MeV/c^2.

2.2 Ratio of Branching Fraction Measurements

The kinematic region for $M(\mu\mu\ell)$ in the semileptonic decay of B_c lies between the J/ψ mass and the B_c mass. Assuming $M(B_c) = 6.4$ GeV/c^2 we find that most of the signal events lie between 4 and 6 GeV, which is defined as the search window. The search consists of counting the candidates in this window and comparing them with the expected background events. The sources of background are the following:

- Fake μ/e from $K/\pi/p$
- Conversion electrons (for the $J/\psi e$ channel)
- $b\bar{b}$ events, with $b \rightarrow J/\psi + X$ and $\bar{b} \rightarrow e/\mu + X$
- Fake J/ψ, *i.e.* unrelated muon pairs which appear to have a common vertex and invariant mass close to the J/ψ

The fake μ/e rate is estimated from the $D^{*+} \rightarrow D^0\pi^+ \rightarrow \pi^+K^-\pi^+$ and $\Lambda \rightarrow p\pi$ samples, where the π, K and p particles are identified with certainty and events are counted by fitting the D^0 and Λ invariant mass peaks. The probability for a π, K or p to be identified as a lepton is defined as the ratio between the number of events that passed all of the lepton identification cuts and the

	$B_c \to J/\psi\mu$	$B_c \to J/\psi e$
Fake μ/e	16.3 ± 2.9	15.43 ± 0.31
$b\bar{b}$	$12.7 \pm 1.7 \pm 5.7$	33.63 ± 2.20
Conversions	N/A	14.54 ± 4.38
Fake J/ψ	19.0 ± 3.0	negligible
Fake J/ψ & μ	-2.0 ± 0.5	negligible
Total background	46.0 ± 7.3	63.6 ± 4.9
Signal yield	60 ± 13	$115 \pm 16 \pm 14$
Significance	5.2σ	5.9σ

Table 1: Summary of backgrounds in the semileptonic analyses

total number of events in the sample. Once this rate has been measured, it is multiplied by the probability for the third track in the vertex to be a π, K or p. This number is extracted from a fit to the distribution of the time-of-flight and dE/dx data and from Monte Carlo simulation.

The background from conversion electrons, *i.e.* those $\gamma \to e^+e^-$ events where only one electron is identified and associated to the muon pair, is estimated by evaluating, from a full simulation of the CDF detector, the efficiency for identifying conversions. This efficiency is dependent on the momentum of electrons. It is then normalized to our data sample.

Pairs of b-quarks are produced through three parton level processes, namely flavour creation, gluon splitting and flavour excitation. These processes are generated with the Pythia program [14] and passed through the full CDF simulation to evaluate the background from $b\bar{b}$ events. Then the number of such events is normalized to data, using the $B \to J/\psi K$ sample. The relative contribution of the three processes in Pythia is checked with data, by fitting the azimuthal angle separation between the J/ψ and the μ/e.

Finally the number of fake J/ψ events is estimated from the sidebands of the invariant mass distribution of the J/ψ. Table 1 summarizes contribution of all background sources, signal event yield and their significance, defined as a poissonian probability for the background to fluctuate to reproduce the observed signal.

Figures 2 and 3 show the invariant mass distributions of signal and background events for, respectively, the $J/\psi\mu$ and $J/\psi e$ channels.

By carefully evaluating the detection efficiency for signal and reference channel, we obtain the main results of these measurements, which are the cross-section times branching fraction ratios:

$$\frac{\sigma(B_c) \times \mathrm{BR}(\mathrm{B_c} \to \mathrm{J}/\psi\mu)}{\sigma(B) \times \mathrm{BR}(\mathrm{B} \to \mathrm{J}/\psi\mathrm{K})} = 0.249 \pm 0.045(\mathrm{stat})^{+0.107}_{-0.076}(\mathrm{syst})$$

and

$$\frac{\sigma(B_c) \times \mathrm{BR}(\mathrm{B_c} \to \mathrm{J}/\psi\mathrm{e})}{\sigma(B) \times \mathrm{BR}(\mathrm{B} \to \mathrm{J}/\psi\mathrm{K})} = 0.282 \pm 0.038(\mathrm{stat}) \pm 0.074(\mathrm{syst})$$

3. Conclusion

We measured mass and ratio of branching fractions of the B_c meson using a 360 pb^{-1} data sample collected by the CDF II detector at the Tevatron Run II. These results are compatible with

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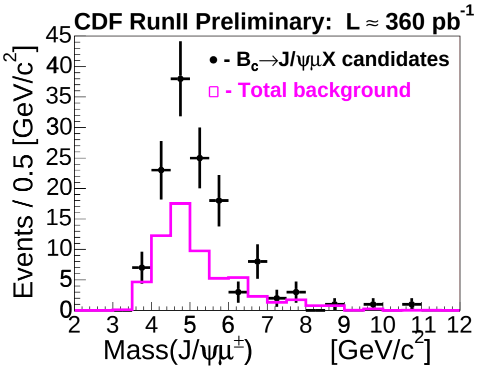

Figure 2: The invariant mass for the $J/\psi\mu$ signal data (points) and background Monte Carlo (histogram) candidates.

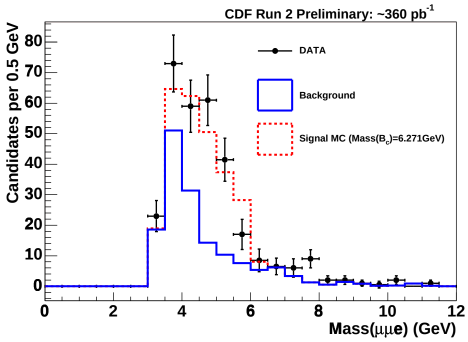

Figure 3: The invariant mass for the $J/\psi e$ signal data (points), signal Monte Carlo (dashed histogram) and estimated background (solid histogram).

theory and earlier measurements. The mass measurement, in particular, is performed in the fully reconstructed decay channel $B_c \to J/\psi\pi$ for the first time with unprecedented precision. With over 1 fb^{-1} of accumulated data on tape, we expect further improvements on these results in the near future.

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