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Evidence for the exclusive decay $B_c^\pm \to J/\psi\pi^\pm$ and measurement of the mass of the B_c meson

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We report the first evidence of a fully reconstructed decay mode of the $B_c^{\pm}$ meson in the channel $B_c^{\pm} \to J/\psi\pi^{\pm}$, with $J/\psi \to \mu^+\mu^-$. The analysis is based on an integrated luminosity of 360 pb^{-1} in $p\bar{p}$ collisions collected by the Collider Detector at Fermilab. We observe 18.9 $\pm$ 5.7 signal events on a background of 10.0 $\pm$ 1.4 events and the fit to the $J/\psi\pi^{\pm}$ mass spectrum yields a $B_c^{\pm}$ mass of 6287.0 $\pm$ 4.8(stat) $\pm$ 1.1(syst) MeV/c^2.

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Within the standard model of elementary particles, five of the six different kinds of quarks combine in quark-antiquark pairs to make mesons. The $B_c^{\pm}$ meson is the combination of the two heaviest of these quarks, and is made of a bottom-charm antiquark-quark pair. Although it has been observed in semileptonic decay modes [1, 2], up to now it has not been observed in any fully reconstructed decay mode. Consequently, its mass $M(B_c)$ has not been measured with good precision.

Nonrelativistic potential models predict the $\bar{b}$ and c quarks to be tightly bound with a ground state mass in the approximate range 6200-6300 MeV/c^2 [3–5]. Recent

QCD-based perturbative computations up to $\mathcal{O}(\alpha_s^4)$ predict $M(B_c)$ to be 6307 ± 17 MeV/c^2 [6, 7]. Most recently, a three-flavor lattice QCD calculation obtains $M(B_c) = 6304 \pm 12(\text{stat} \oplus \text{syst})\ ^{+18}_{-0}(\text{cutoff effects})$ MeV/c^2 [8].

Several of the $B_c^\pm$ decay modes are predicted to contain a J/ψ meson [9]. These are among the most easily reconstructed $B_c^\pm$ decays at CDF, owing to an efficient dimuon trigger giving high purity $J/\psi \to \mu^+\mu^-$ reconstruction. The CDF collaboration made the first observation of the $B_c^\pm$ meson in the semileptonic decay channels $B_c^\pm \to J/\psi l^\pm \nu_l X$, in a sample of 110 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV in Run I at the Tevatron [1]. With a signal of $20.4^{+6.2}_{-5.5}$ events, the $B_c^\pm$ mass was measured to be $6.40 \pm 0.39(\text{stat}) \pm 0.13(\text{syst})$ GeV/c^2. Recently, the D0 Collaboration reported a preliminary observation of a $B_c^\pm$ signal in the decay channel $B_c^\pm \to J/\psi \mu^\pm \nu_\mu X$ in a sample of 210 pb^{-1} of Run II data [2]. The symbol X denotes possible unobserved particles.

In this paper we report first evidence for the $B_c^\pm$ meson in the fully reconstructed decay channel $B_c^\pm \to J/\psi\pi^\pm$, with $J/\psi \to \mu^+\mu^-$. The analysis is based on a dataset of 360 pb^{-1} in $p\bar{p}$ collisions collected at $\sqrt{s} = 1.96$ TeV by CDF at the Tevatron during Run II.

The CDF II detector consists of a magnetic spectrometer surrounded by calorimeters and muon chambers and is described in detail elsewhere [10]. The components relevant to this analysis are briefly described here. The tracking system is in a 1.4 T axial magnetic field and consists of a silicon microstrip detector (L00, SVX, ISL, in increasing order of radius) [11–13] surrounded by an open-cell wire drift chamber (COT) [14]. The muon detectors used for this analysis are the central muon drift chambers (CMU), covering the pseudorapidity range $|\eta| < 0.6$ [15, 16], and the extension muon drift chambers (CMX), covering $0.6 < |\eta| < 1.0$.

This measurement uses events containing muon pairs with $|\eta| < 1.0$, recorded with a three-level trigger. At the first trigger level, muon-candidate track segments in CMU and CMX are matched to COT tracks obtained with a hardware processor [17]. Dimuon triggers use combinations of CMU-CMU and CMU-CMX muons with $p_T >$1.5 (2.0) GeV/c for CMU (CMX) muons, where p_T is the momentum transverse to the beamline. At the second level, opening angle and opposite-charge cuts are imposed on the muon pairs. At the third level, three dimensional (3-D) tracking is performed to select muon pairs with invariant mass, $M(\mu^+\mu^-)$, between 2700 and 4000 MeV/c^2.

To reconstruct the $B_c^\pm \to J/\psi\pi^\pm$ decay offline, we make several requirements on the quality of the tracks and the J/ψ candidate. To ensure good vertex resolution, each track must have an $r - \phi$ position measurement on at least three of five SVX layers. For J/ψ identification, we require good matching between the COT muon tracks and the muon chamber track segments. In addition, we require that $3042 < M(\mu^+\mu^-) < 3152$ MeV/c^2, the average J/ψ mass resolution in our sample being 14 MeV/c^2. Each other charged particle track with $p_T > 400$ MeV/c^2 is treated as a pion candidate to be combined with the J/ψ. The pion and the two muons are then fitted to a common 3-D vertex, with $M(\mu^+\mu^-)$ constrained to the world average J/ψ mass value [18]. Track combinations that fail the vertex fit are rejected. The primary vertex position is calculated from the tracks in each event.

The $B_c^\pm$ search was performed using a "blind" analysis method. The mass values of the $J/\psi\pi^\pm$ combinations in the search window $5600 < M(J/\psi\pi^\pm) < 7200$ MeV/c^2, referred to as $B_c^\pm$ candidates, were temporarily hidden. The search window was chosen to correspond to the ± 2 standard deviation region around the CDF Run I measurement of the $B_c^\pm$ mass [1], and is approximately 100 times wider than the expected $B_c^\pm$ mass resolution.

In order to optimize the significance of a possible $B_c^\pm$ signal, we varied the selection criteria to maximize the function $S_F/(1.5 + \sqrt{B})$ [19]. 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 $B_c^\pm$ candidates scaled to correspond to a mass range of 63 MeV/c^2, based on the average mass resolution of a $B_c^\pm$ candidate within the search window. The term 1.5 is appropriate for optimizing a search for signal at least 3σ above background fluctuations. The distributions of the selection variables for the signal events were evaluated using samples of simulated $B_c^\pm \to J/\psi\pi^\pm$ decays. These were generated with a $B_c^\pm$ mass of 6400 MeV/c^2 and a lifetime of 0.46 ps [1], and p_T and rapidity distributions according to a leading order perturbative QCD calculation [20]. A harder p_T spectrum [21] was used as an alternative to check the stability of the optimal selection criteria; these were not very sensitive to variations of the p_T spectrum or the assumed lifetime within its experimental uncertainty. The Monte Carlo $B_c^\pm$ decays were processed with full detector simulation and the same trigger and reconstruction criteria as the data. The distributions of the selection variables for the background were taken from the data in the search window, in which the contribution from a signal is expected to be small.

The following optimized selection criteria were used: a quality requirement on the $J/\psi\pi^\pm$ three-track 3-D vertex fit ($\chi^2 < 9$ for four degrees of freedom), a requirement on the pion track contribution to the vertex fit ($\chi^2_\pi < 2.6$), the impact parameter of the $B_c^\pm$ candidate with respect to the primary vertex (< 65 μm), the maximum ct where t is the proper decay time of the $B_c^\pm$ candidate ($<$ 750 μm), the transverse momentum of the pion ($>$ 1.8 GeV/c), the 3-D angle between the momentum of the $B_c^\pm$ candidate and the vector joining the primary to the secondary vertex ($\beta < 0.4$ rad), and the significance of the projected decay length of the $B_c^\pm$ candidate onto its transverse momentum direction ($L_{xy}/\sigma(L_{xy}) > 4.4$). After these selection requirements, 390 candidates remain

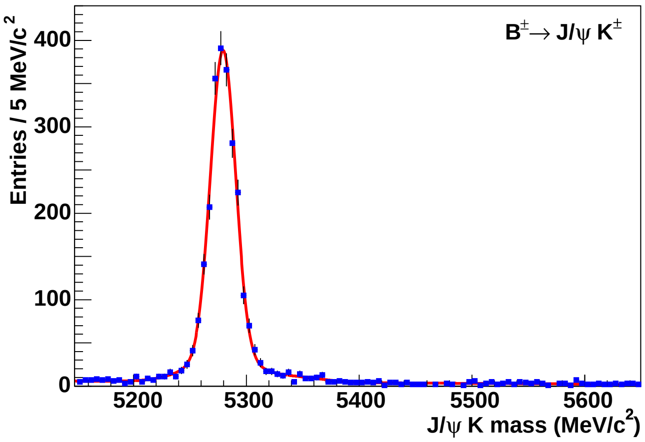

FIG. 1: The invariant mass distribution of the $B^{\pm} \to J/\psi K^{\pm}$ candidates.

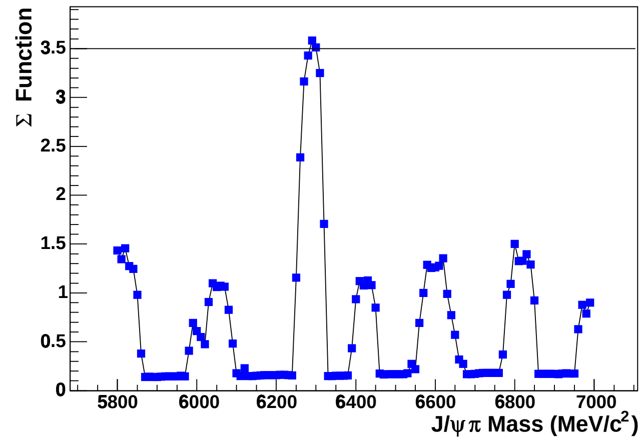

FIG. 2: The Σ function at different values of the invariant mass corresponding to the nominal mass peak position.

in the search window.

A sample of $B^{\pm}$ mesons, reconstructed in the decay mode $B^{\pm} \to J/\psi K^{\pm}$, was analyzed as a control sample in order to check our understanding of the reconstruction of the relevant variables in the simulation. The $B^{\pm} \to J/\psi K^{\pm}$ decay topology is the same as that of $B_c^{\pm} \to J/\psi\pi^{\pm}$, apart from the different masses and lifetimes. The $B^{\pm}$ mass distribution, shown in Fig. 1, was obtained using the same selection requirements as optimized for the $B_c^{\pm}$ candidates, but without the cut on maximum ct. A total of 2378 $\pm$ 57 $B^{\pm} \to J/\psi K^{\pm}$ signal events are found with a fitted mass of 5279.0 $\pm$ 2.6 MeV$/c^2$. The fit takes into account a small contribution from the Cabbibo-suppressed decay $B^{\pm} \to J/\psi\pi^{\pm}$. The average mass resolution is 11.5 $\pm$ 0.3 MeV$/c^2$, in agreement with the simulation, which can thus be used with confidence to evaluate the expected mass resolution for $B_c^{\pm}$ decays. The $B^{\pm}$ yield is used to calculate the expected $B_c^{\pm}$ yield. The relative reconstruction efficiency, $\epsilon_{B^{\pm}}/\epsilon_{B_c^{\pm}}$, is in the range 35%-85%, with uncertainties arising from the $B_c^{\pm}$ p_T spectrum and the $B_c^{\pm}$ lifetime. On the basis of the $B^{\pm}$ yield, previous CDF cross section measurements [1], and theoretical calculations [9, 22–27] of the branching fractions of the $B_c^{\pm} \to J/\psi\pi^{\pm}$ and $B_c^{\pm} \to J/\psi l^{\pm}\nu$ decay modes, a $B_c^{\pm}$ yield in the range of 10 to 50 events is expected.

Before unblinding the $J/\psi\pi^{\pm}$ mass distribution, a procedure to search for a signal peak was defined. This was based on a scan of the search region in intervals of 10 MeV$/c^2$, with a sliding fit window extending from -100 MeV$/c^2$ to $+200$ MeV$/c^2$ in mass around each nominal peak position, m. The fit window was chosen to minimize possible contributions from partially reconstructed $B_c^{\pm}$ decays below the peak position (e.g. into J/ψ and more than one meson). For each peak value, a fit function was defined as a Gaussian signal component with mean m, combined with a linear background term. The Gaussian resolution was a linear function of m based on Monte Carlo simulation, and varied from 13 to 19 MeV$/c^2$ over the search region. The number of signal (S) and background (B) events and the linear background slope were the parameters of the fit function. The output of a scan was defined to be the largest value of $\Sigma = S/(1.5 + \sqrt{B})$, Σ_{max}, obtained from the 121 fits performed in the mass interval $5800 \leq M(J/\psi\pi^{\pm}) \leq 7000$ MeV$/c^2$.

A set of Monte Carlo experiments was performed to determine the expected distribution of Σ_{max} for pure background samples [28]. This distribution was used as a decision criterion, before unblinding the mass distribution, as to whether the data would be used to establish a signal. The background in the search window is expected to consist of two components: a combinatorial background arising from random associations of a J/ψ with a track, and a "physical" background at masses below $M(B_c)$, arising from partially reconstructed $B_c^{\pm}$ decays. The mass distribution for the latter was modeled as a fixed broad Gaussian centered below 6400 MeV$/c^2$, based on Monte Carlo simulations of inclusive $B_c^{\pm} \to J/\psi X$ decays, with branching ratios taken from Ref. [9]. The mass distribution for the combinatorial background was modeled as a linear function. The number of combinatorial and physical background events was randomly varied in each experiment, according to the statistics in the data. From 1000 such Monte Carlo scans, one gave $\Sigma_{max} \geq 3.5$ and this value was chosen as the threshold for measuring the $B_c^{\pm}$ mass after unblinding the search window.

We applied the fitting procedure to the 390 candidates in the unblinded $J/\psi\pi^{\pm}$ mass distribution. Figure 2 shows the variation of Σ obtained from the scan over the search window. A maximum value of 3.6 is found at

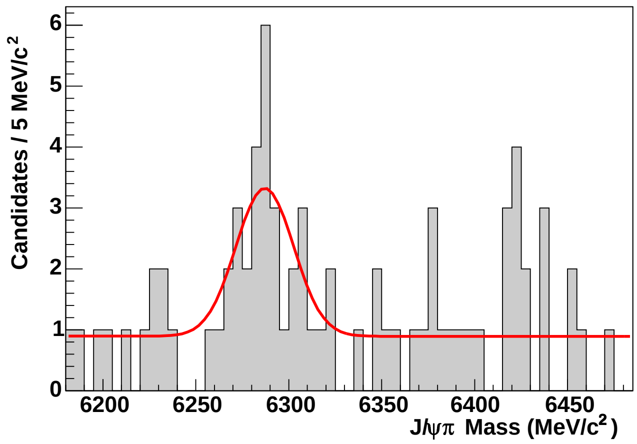

FIG. 3: The invariant mass distribution of the $J/\psi\pi^{\pm}$ candidates and results of an unbinned likelihood fit in the 300 MeV/c^2 region indicated by the Σ scan in Fig. 2.

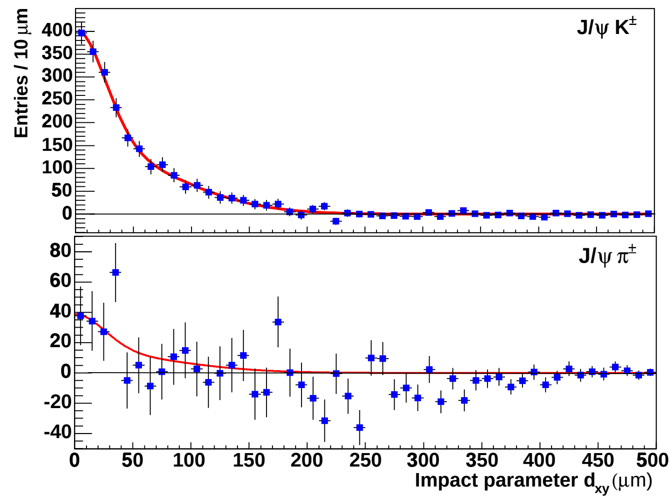

FIG. 4: Impact parameter distribution of the third track with respect to the J/ψ vertex for the lower sideband region, after subtraction of the same distribution for the upper side band: (top) in the $B^{\pm}$ data sample with an overlaid double Gaussian fit; (bottom) in the $B_c^{\pm}$ candidate sample with the above curve, rescaled. In both cases the selection criteria were relaxed.

a mass ≈6290 MeV/c^2, passing our predefined threshold criterion. Other maxima with magnitude ≈1 are consistent with random background fluctuations. Although the shape of the background mass distribution was not precisely known before the unblinding, it was subsequently found to be consistent with the shape assumed in the Monte Carlo scans. With a more accurate model and high statistics, the data value of Σ_{max} was found to be exceeded in 0.27% of Monte Carlo scans.

We now perform a separate unbinned likelihood fit to the mass region containing the peak. As before, we fit the distribution to a Gaussian plus a linear background. The mean of the Gaussian is now a free parameter of the fit, while the standard deviation is a linear function of the mean as found in the Monte Carlo simulation. A signal of 18.9 ± 5.7 events centered at a mass of 6287.0 ± 4.8 MeV/c^2 is observed, as shown in Fig. 3, with a background of 10.0 ± 1.4 events within a region of ±2 standard deviations from this central value. The standard deviation of the Gaussian at the central value is 15.5 MeV/c^2. Within the signal region, the distributions of the selection variables agree within statistics with those of the Monte Carlo simulation.

Systematic uncertainties on the $B_c^{\pm}$ mass determination due to measurement uncertainties on the track parameters (±0.3 MeV/c^2) and the momentum scale (±0.6 MeV/c^2) are evaluated from the corresponding uncertainties on the $B^{\pm}$ mass analysis [29]. Further uncertainties are due to the possible differences in the p_T spectra of the $B^{\pm}$ and $B_c^{\pm}$ 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.

In view of the limited statistics of the observed mass peak, it is desirable to establish an independent consistency check. If the mass peak is due to $B_c^{\pm} \to J/\psi\pi^{\pm}$ decays, we should also detect partially reconstructed $B_c^{\pm}$ decays in the mass region below the peak but not in the region above. The pion candidate in partially reconstructed decays should have a small impact parameter d_{xy} relative to the J/ψ vertex, consistent with being physically associated with it, whereas the pion candidate in combinatorial background events should have a broad d_{xy} distribution reflecting random association with the J/ψ vertex.

To perform this investigation, we relax the cuts on β, the impact parameter of the $B_c^{\pm}$ candidate, and the 3-D χ^2 vertex fit, so as to be able to see the signal in the d_{xy} distribution over the broader combinatorial background. We compare the distribution of d_{xy} of the pion candidate in the region 5600 < M(B_c) < 6187 MeV/c^2 (lower side band) to that in the region 6387 < M(B_c) < 7200 MeV/c^2 (upper side band), where the main contribution should be combinatorial.

Figure 4 (top) shows the difference between the lower and upper sidebands for the d_{xy} distribution in the $B^{\pm}$ data sample, with a large excess of events visible at small d_{xy} values. Figure 4 (bottom) shows the corresponding plot obtained using the $B_c^{\pm}$ candidate sample. An enhancement is visible with a shape compatible with that seen in the $B^{\pm}$ sample. The $B^{\pm}$ curve, rescaled to fit the $B_c^{\pm}$ data, provides a good description of this distribution. The excess of low d_{xy} events in the $B_c^{\pm}$ sample is evaluated to be 172 ± 49(stat) ± 15(syst), where the systematic uncertainty is evaluated by varying the fitting method. This result is consistent with Monte Carlo expectations based on the calculations of [9], and supports the hypothesis that the lower sideband in this sample contains a component of partially reconstructed $B_c^{\pm}$ decays.

In conclusion, we observe a peak in the $J/\psi\pi^{\pm}$ mass spectrum at a mass of $6287.0 \pm 4.8(\mathrm{stat}) \pm 1.1(\mathrm{syst})$ MeV/c^2. This peak is consistent with a narrow particle state which decays weakly, and is interpreted as the first evidence for fully reconstructed decays of the $B_c^{\pm}$ meson. The probability that a random background fluctuation would generate such a peak anywhere in the search window is calculated to be 0.27%. The mass value agrees with the much less precise mass values found in $B_c^{\pm}$ semileptonic decays. There is also good agreement with recent theoretical predictions for the $B_c^{\pm}$ mass around 6300 MeV/c^2 [6–8].

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