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Evidence for the Exclusive Decay $B_c^{\pm} \rightarrow J/\psi\pi^{\pm}$ and Measurement of the Mass of the $B_c^{\pm}$ Meson

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We report the first evidence for a fully reconstructed decay mode of the $B_c^\pm$ meson in the channel $B_c^\pm \rightarrow J/\psi\pi^\pm$, with $J/\psi \rightarrow \mu^+\mu^-$. The analysis is based on an integrated luminosity of 360 pb^{-1} in $p\bar{p}$ collisions at 1.96 TeV center of mass energy collected by the Collider Detector at Fermilab. We observe 14.6 ± 4.6 signal events with a background of 7.1 ± 0.9 events, and a fit to the $J/\psi\pi^\pm$ mass spectrum yields a $B_c^\pm$ mass of $6285.7 \pm 5.3(\text{stat}) \pm 1.2(\text{syst})\ \text{MeV}/c^2$. The probability of a peak of this magnitude occurring by random fluctuation in the search region is estimated as 0.012%.

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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 combines the two heaviest of these quarks as a bottom-charm quark-antiquark pair. Although it has been observed in semileptonic decay modes [1,2], up to now no evidence for the $B_c^\pm$ has been found in fully reconstructed decay modes [3–6]. 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 [7–9]. Recent QCD-based perturbative computations up to $\mathcal{O}(\alpha_s^4)$ predict $M(B_c)$ to be $6307 \pm 17\ \text{MeV}/c^2$ [10,11]. Most recently, a three-flavor lattice QCD calculation obtains $M(B_c) = 6304 \pm 12(\text{stat} \oplus \text{syst})^{+18}_{-0}(\text{cutoff effects})\ \text{MeV}/c^2$ [12].

Several of the predicted $B_c^\pm$ decay modes contain a J/ψ meson [13]. These are among the most easily reconstructible $B_c^\pm$ 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]. The symbol X denotes possible undetected decay particles. 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].

In this Letter 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 data set 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 [14]. The components most 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) [15–17] surrounded by an open-cell wire drift chamber (COT) [18]. The muon detectors used for this analysis are the central muon drift chambers (CMU), covering the pseudorapidity range $|\eta| < 0.6$ [19,20], and the extension muon drift chambers (CMX), covering $0.6 < |\eta| < 1.0$. Cylindrical coordinates are used with the $+z$ axis in the proton beam direction.

This measurement uses events containing pairs of muons, each with $|\eta| < 1.0$, selected 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 [21]. 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 beam line. At the second level, opening angle and opposite-charge cuts are imposed on the muon pairs. At the third level, three-dimensional (3D) 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 primary and secondary 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 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$/c$ is treated as a pion candidate to be combined with the J/ψ. The pion candidate and the two muons are then fitted to a common 3D vertex, with $M(\mu^+\mu^-)$ constrained to the world average J/ψ mass value [22]. All combinations for which the vertex fit converged are retained. The primary vertex position is calculated from the other tracks in each event.

The $B_c^\pm$ search was performed using the following 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]; it 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 $Q = S_F/(1.5 + \sqrt{B_{\rm av}})$ [23]. Here, S_F is the accepted fraction of signal events, in this case taken from a Monte Carlo sample, and the background $B_{\rm av}$ is the number of selected $B_c^\pm$ candidates within the search window, 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 a 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$/c^2$, a lifetime of 0.46 ps [1], and p_T and rapidity distributions according to a leading order perturbative QCD calculation [24]. A harder p_T spectrum [25] 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.

Optimized cuts were determined for the following selection variables: the $J/\psi\pi^\pm$ three-track 3D vertex fit ($\chi^2 < 9$ for 4 degrees of freedom), the pion track contribution to the vertex fit ($\chi^2_\pi < 2.6$), the impact parameter in $r - \phi$ of the $B_c^\pm$ candidate with respect to the primary vertex ($<65\ \mu$m), the maximum ct where t is the proper decay time of the $B_c^\pm$ candidate ($<750\ \mu$m), the transverse momentum of the pion (>1.8 GeV$/c$), the 3D 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 selections, 390 candidates remain in the search window, with no two candidates from the same beam crossing.

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 ± 57 $B^{\pm} \to J/\psi K^{\pm}$ signal events is found, with a fitted mass of 5279.0 ± 0.3 MeV$/c^2$. The fit takes into account a small contribution from the Cabibbo-suppressed decay $B^{\pm} \to J/\psi\pi^{\pm}$. The average mass resolution is 11.5 ± 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 trigger and reconstruction efficiency, $\epsilon_{B_c^{\pm}}/\epsilon_{B^{\pm}}$, 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 [13,26–31] 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.

A search procedure was then defined to identify any possible signal in the data and to estimate its significance. This was based on a scan of the search region in 10 MeV$/c^2$ intervals, with a sliding fit window extending from -100 to $+200$ MeV$/c^2$ in mass around each nominal peak position, m. This 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 additional particle). For each value of m, a fit function was defined as a Gaussian signal with mean m, combined with a linear background term. The Gaussian resolution was fixed as a linear function of m based on Monte Carlo simulation, and varied from 13 to 19 MeV$/c^2$ over the search region. The three fit parameters were the number of signal (S) and background (B) events and the linear background slope. The output of a scan was defined to be the largest value of $\Sigma = S/(1.5 + \sqrt{B})$, $\Sigma_{\rm max}$, obtained from the 131 fits performed in the mass interval $5700 \leq M(J/\psi\pi^{\pm}) \leq 7000$ MeV$/c^2$.

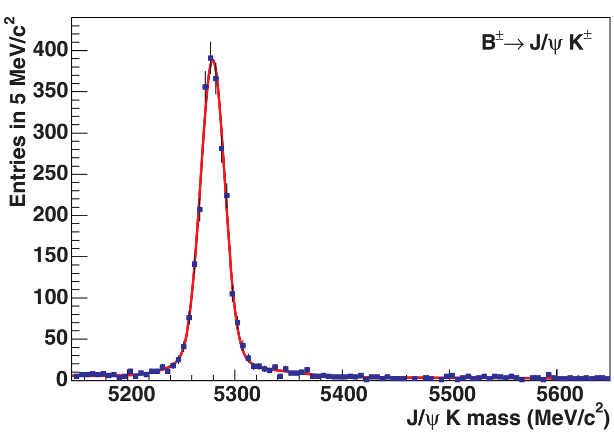

FIG. 1 (color online). The invariant mass distribution of the $B^{\pm} \to J/\psi K^{\pm}$ candidates. The curve is a fit to the data.

The distribution of $\Sigma_{\rm max}$ for the null hypothesis was obtained from Monte Carlo experiments [32], in which the mass spectra were derived from a smooth background model. This model was necessarily approximate owing to the initially hidden mass distribution. The model consisted of a linear background, to describe combinatoric events, and a "physical" background to describe partially reconstructed $B_c^{\pm}$ decays in the mass range below 6400 MeV$/c^2$. Studies showed that the main source of combinatoric background are events in which a genuine J/ψ is paired with an uncorrelated track. The shape of the physical background was based on Monte Carlo simulations of inclusive $B_c^{\pm} \to J/\psi X$ decays, with branching ratios taken from Ref. [13].

Applied to the 390 event data sample, the scan procedure found a $\Sigma_{\rm max}$ near $m = 6290$ MeV$/c^2$, which is compatible with a $B_c^{\pm}$ signal of 19 ± 6 events. Using a large set of Monte Carlo simulations, we modeled the shape of the observed background, and, analyzing it in the same way as the data, evaluated the probability that a random enhancement has a $\Sigma_{\rm max}$ value exceeding that of the data. This probability was found to be 0.17%.

After the above steps had been performed, further checks on the previously hidden events revealed that the existing pion selection allowed two classes of fitted tracks that were unsuitable for the $B_c^{\pm}$ search. The first class had insufficient number of COT hits to give good mass resolution and so was not compatible with a search for a narrow Gaussian signal; the second class had poor SVX resolution in the z direction and was dominated by combinatorial background. The above two classes of events contributed 10% to the $B^{\pm}$ signal; they would be expected to contribute fewer than two events to the $B_c^{\pm}$ signal, but they increase the combinatorial background by about 40% over the $J/\psi\pi^{\pm}$ mass range. After removal of both classes of poor quality tracks in addition to the original optimized cut selection, 220 candidates remained. These were required to have good SVX z resolution on both the pion track and at least one of the muon tracks. This final track selection, which maximizes Q, is therefore not fully blind; it is based also on the observed properties of the $B^{\pm}$ signal and the overall properties of the $B_c^{\pm}$ candidate sample.

Figure 2 shows the mass spectrum for the 220 event sample. The main features are the $B_c^{\pm} \to J/\psi\pi^{\pm}$ signal peak near 6290 MeV$/c^2$, a linear combinatorial background above this peak, and a broad enhancement below the peak which can be attributed to the physical background from partially reconstructed $B_c^{\pm}$ decays. We perform a global unbinned likelihood fit over the entire mass range to obtain the mass and yield for the $B_c^{\pm}$ signal. The fit included a Gaussian signal with a variable mass but with a resolution whose mass-dependent value was determined by

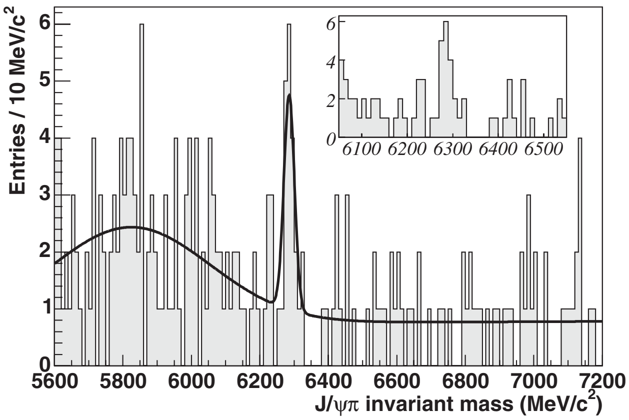

FIG. 2. The invariant mass distribution of the $J/\psi\pi^{\pm}$ candidates and results of an unbinned likelihood fit in the search window. The inset shows the peak section of the distribution. The broad enhancement below 6.2 GeV$/c^2$ is attributable to partially reconstructed $B_c^{\pm}$ mesons.

the Monte Carlo simulation, together with background modeled as a linear combinatorial term and a broad low-mass Gaussian contribution for the physical background. A signal of 14.6 ± 4.6 events is obtained centered at a mass of 6285.7 ± 5.3 MeV$/c^2$. The standard deviation of the Gaussian at the central value of the signal mass is 15.5 MeV$/c^2$. The background within a region of ± 2 standard deviations from this mass value is 7.1 ± 0.9 events. The statistical significance of the signal is discussed below. 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 [33]. 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 as well as uncertainty in the signal width (± 0.9 MeV$/c^2$) [34]. The total systematic uncertainty is evaluated to be ± 1.2 MeV$/c^2$.

The signal peak is robust under variations of the pion track quality selection. We have investigated several methods for determining the best figure of significance for such a peak over a broad mass range. The method that gives the best sensitivity to a real signal is based on the standard significance measure $S/\sqrt{B}$. We repeated the Monte Carlo scans for the new track selection to determine the null hypothesis distribution for $S/\sqrt{B}$. Applying to the Monte Carlo simulations the same global fit method as to the data, we find that the probability that a random enhancement anywhere in the range 5800–7000 MeV$/c^2$ exceeds the value of $S/\sqrt{B}$ for the experimental peak is 0.012%.

In view of the limited statistics of the observed mass peak, an independent consistency check was performed. If the mass peak is due to fully reconstructed $B_c^{\pm} \to J/\psi\pi^{\pm}$ decays, partially reconstructed $B_c^{\pm} \to J/\psi$ + track + X decays should be detectable 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 investigate this, we relax the cuts on β, the impact parameter of the $B_c^{\pm}$ candidate, and the χ^2 of the 3D vertex fit, so as to make a signal in the d_{xy} distribution visible over the broader combinatorial background. We compare the distribution of d_{xy} of the pion candidate in the region $5600 < M(B_c) < 6190$ MeV$/c^2$ (lower side band) to that in the region $6390 < M(B_c) < 7200$ MeV$/c^2$ (upper side band), where the main contribution should be combinatorial.

Figure 3 (top panel) shows the difference between the lower (4900–5100 MeV$/c^2$) and upper (5400–5700 MeV$/c^2$) 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 3 (bottom panel) 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 244 ± 59, where the uncertainty is statistical only. This result is consistent with Monte Carlo esti-

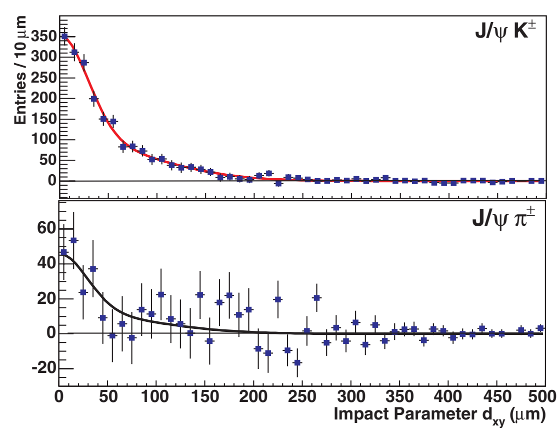

FIG. 3 (color online). Impact parameter of the third track relative to the J/ψ vertex for the lower sideband region, after subtraction of the same distribution for the upper side band: (top panel) the curve is the sum of two Gaussians, fitted to the $B^{\pm}$ data points; (bottom panel) the $B_c^{\pm}$ data points, overlaid with the above curve, rescaled. In both cases the selection criteria were relaxed.

mates based on the calculations of [13]. This supports the hypothesis that the broad physical background below the signal peak, evident in Fig. 2, is in fact associated with partially reconstructed $B_c^\pm$ decays.

In conclusion, we observe a peak in the $J/\psi\pi^\pm$ mass spectrum at a mass of $6285.7 \pm 5.3(\mathrm{stat}) \pm 1.2(\mathrm{syst})\ \mathrm{MeV}/c^2$. This peak is consistent with a narrow, weakly decaying particle state and is interpreted as the first evidence for fully reconstructed decays of the $B_c^\pm$ meson. The mass value has much improved precision over the results obtained in $B_c^\pm$ semileptonic decays [1,2]. There is also good agreement with recent theoretical predictions for the $B_c^\pm$ mass around 6300 MeV/c^2 [10–12].

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