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Observation of the Narrow State $X(3872) \to J/\psi\pi^+\pi^-$ in $\bar{p}p$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report the observation of a narrow state decaying into $J/\psi\pi^+\pi^-$ and produced in 220 pb^{-1} of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV in the CDF II experiment. We observe 730 ± 90 decays. The mass is measured to be $3871.3 \pm 0.7\,(stat) \pm 0.4\,(syst)$ MeV/c^2, with an observed width consistent with the detector resolution. This is in agreement with the recent observation by the Belle Collaboration of the $X(3872)$ meson.

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The study of bound states of charm-anticharm quarks revolutionized our understanding of hadrons beginning with the discovery of the J/ψ meson in 1974 [1]. Although numerous charmonium ($c\bar{c}$) states are now known, others should be observable. Recently, the Belle Collaboration reported a new particle, $X(3872)$, observed in exclusive decays of B mesons produced in e^+e^- collisions [2]. This particle has a mass of 3872 MeV/c^2 and decays into $J/\psi\pi^+\pi^-$. A natural interpretation of this particle would be a previously unobserved charmonium state, but there are no such states predicted to lie at or near the observed mass with the right quantum numbers to decay into $J/\psi\pi^+\pi^-$ [3, 4]. Within the framework of QCD there are other possibilities [5]. The near equality of the $X(3872)$ mass to the sum of the D^0 and D^{*0} masses suggests that the $X(3872)$ may be a deuteron-like "molecule" composed of a D and $\overline{D}^*$. Another possibility is that the $X(3872)$ is a $c\bar{c}g$ hybrid meson—a $c\bar{c}$ system possessing a valence gluon. These novel possibilities have excited great interest in the $X(3872)$ [6]. Whether it is a new form of hadronic matter or a conventional $c\bar{c}$-state in conflict with theoretical models, the $X(3872)$ is an important object of study. Here we report the observation of a $J/\psi\pi^+\pi^-$ resonance produced inclusively in $\bar{p}p$ collisions and which is consistent with the $X(3872)$.

The analysis uses a data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV with an integrated luminosity of 220 pb^{-1} collected between February 2002 and August 2003 with the upgraded Collider Detector (CDF II) at the Fermilab Tevatron. The important components of the CDF II detector for this analysis include a tracking system composed of a silicon strip vertex detector (SVX II) [7] surrounded by an open cell drift chamber system called the Central Outer Tracker (COT) [8]. The SVX II detector comprises five concentric layers of double-sided sensors located at radii between 2.5 and 10.6 cm. On one side of the sensors axial strips measure positions in the plane transverse to the beamline. Strips on the other side are used for stereo measurements. One layer has strips tilted by $+1.2°$, another by $-1.2°$, and three layers by 90° with respect to the axial strips. The active volume of the COT is a 3.1 m long cylinder covering radii from 43 to 132 cm with 8 superlayers of 12 wires each. Superlayers of axial wires alternate with superlayers of $+2°$ stereo angle wires and superlayers of $-2°$ stereo angle wires to provide three-dimensional tracking. The central tracking system is immersed in a 1.4 T solenoidal magnetic field for the measurement of charged particle momenta transverse to the beamline, p_T. The outermost detection system consists of planes of multi-layer drift chambers for detecting muons [9]. The Central Muon system (CMU) covers $|\eta| \leq 0.6$, where $\eta \equiv -\ln[\tan(\theta/2)]$ and θ is the angle of the particle with respect to the direction of the proton beam. Additional muon chambers (CMX) extend the rapidity coverage to $|\eta| = 1.0$.

In this analysis $J/\psi \to \mu^+\mu^-$ decays are recorded using a dimuon trigger. The CDF II detector has a three-level trigger system. The Level-1 trigger uses tracks in the muon chambers with a clear separation in azimuth from neighboring tracks. The eXtremely Fast Tracker (XFT) [10] uses information from the COT to select tracks based on p_T. XFT tracks with $p_T \geq 1.5$ GeV/c ($p_T \geq 2.0$ GeV/c) are extrapolated into the CMU (CMX) muon chambers and compared with the positions of muon tracks. If there are two or more XFT tracks with matches to muon tracks, the event passes the Level-1 trigger. Dimuon triggers have no requirements at Level 2. At Level 3, the full tracking information from the COT is used to reconstruct a pair of opposite sign muon candidates in the mass range from 2.7 to 4.0 GeV/c^2. Events passing the Level-3 trigger are recorded for further analysis.

The offline analysis makes use of the best available calibrations of the tracking system for reconstructing events. Well reconstructed tracks are selected by accepting only those with ≥ 3 axial SVX II hits, and > 20 axial and > 16 stereo COT hits. Tracks are refit to take into account the ionization energy loss appropriate for the particle hypotheses under consideration [11]. Dimuon candidates are selected in the mass range from 2.8 to 3.2 GeV/c^2 after being constrained to originate from a common point in a three-dimensional vertex fit. Pairs of oppositely charged tracks, both having $p_T \geq 0.35$ GeV/c and assumed to be pions, are then fit with the dimuon candidates to a common vertex. In this three-dimensional vertex fit the dimuon mass is constrained to be the world average J/ψ mass [12]. We require that the χ^2 for the $J/\psi\pi^+\pi^-$ vertex fit must be less than 40.

Due to the large multiplicity of charged tracks in some events, there can be a large number of $J/\psi\pi^+\pi^-$ candidates in one event that satisfy the pre-selection cuts discussed above, especially for larger $J/\psi\pi^+\pi^-$ masses. These events contribute a large amount of combinatoric background relative to a small potential signal. We reject events with 12 or more pre-selection candidates that have masses below 4.5 GeV/c^2. Although a large number of candidates are accepted at this stage, after the final selection the average number of $J/\psi\pi^+\pi^-$ candidates within the mass window of interest (3.65-4.0 GeV/c^2) is fewer than 1.2 per event for events with at least one such candidate. The specific number of pre-selection candidates allowed per event is determined by the optimization procedure described below.

We apply the following tighter cuts to suppress $J/\psi\pi^+\pi^-$ backgrounds: $\chi^2 < 15$ for the dimuon vertex fit, dimuon invariant mass within 60 MeV/c^2 (~ 4

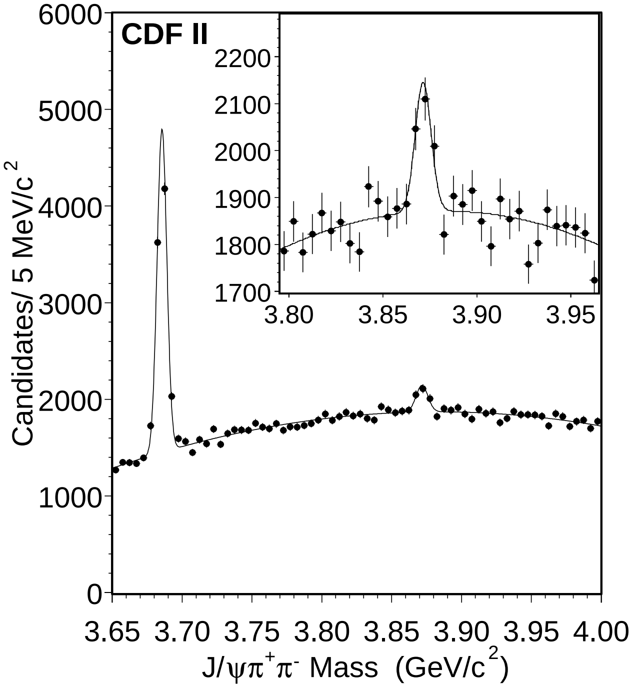

FIG. 1: The mass distribution of $J/\psi\pi^+\pi^-$ candidates passing the selection described in the text. A large peak for the $\psi(2S)$ is seen and a signal near a mass of 3872 MeV/c^2 is visible (enlargement shown in the inset). The curve is a fit using two Gaussians and a quadratic background to describe the data.

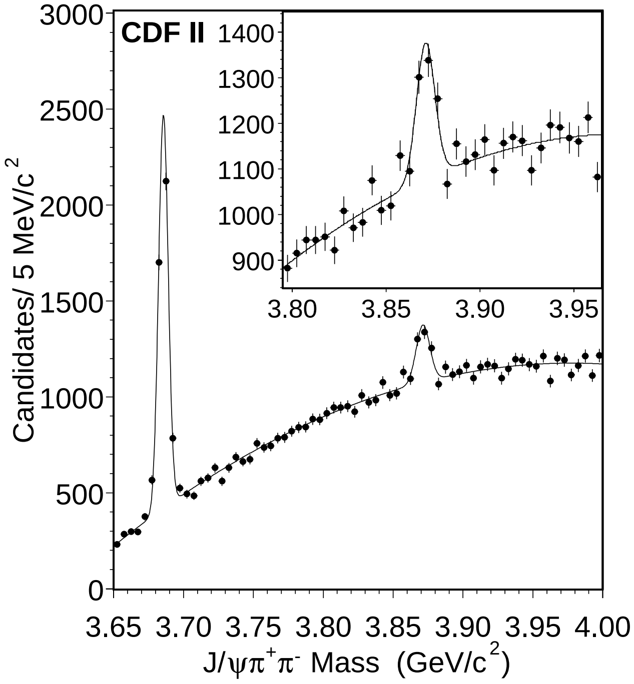

FIG. 2: The mass distribution of $J/\psi\pi^+\pi^-$ candidates requiring $m(\pi^+\pi^-) > 500$ MeV/c^2. The curve is a fit with two Gaussians and a quadratic background.

standard deviations) of the world average J/ψ mass, $p_T(J/\psi) \geq 4$ GeV/c, $\chi^2 < 25$ for the $J/\psi\pi^+\pi^-$ vertex fit, $p_T(\pi) \geq 0.4$ GeV/c, and $\Delta R \leq 0.7$ for both pions. Here ΔR is defined as $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ where $\Delta\phi$ and $\Delta\eta$ are the azimuthal angle and pseudorapidity of the pion with respect to the $J/\psi\pi^+\pi^-$ candidate.

The values of these cuts are determined by an iterative optimization procedure in which the significance $S/\sqrt{S+B}$ is maximized, where S and B respectively represent the numbers of signal and background candidates. B is obtained from a background fit to the data in a window around 3872 MeV/c^2. The dependence of the X-yield on the cuts is modeled by using the observed $\psi(2S)$ signal. The value used for S is obtained by rescaling the $\psi(2S)$-yield to reflect the much smaller $X(3872)$ signal. The rescaling factor is determined such that S matches the observed X-yield for a set of reference cuts. Since the denominator of the significance ratio is dominated by the much larger background the optimization is not sensitive to the precise value of the rescaling.

The $J/\psi\pi^+\pi^-$ mass distribution of the selected candidates is displayed in Figure 1. A large peak for the $\psi(2S)$ is seen, and in addition, a small peak at a $J/\psi\pi^+\pi^-$ mass around 3872 MeV/c^2 is observed. To fit the mass distribution, we model each peak by a single Gaussian and use a quadratic polynomial to describe the background. A binned maximum likelihood fit of the mass spectrum between 3.65 and 4.0 GeV/c^2 is also shown in Figure 1. The fit yields signals of 5790 ± 140 $\psi(2S)$ candidates and 580 ± 100 $X(3872)$ candidates.

The $X(3872)$ signal reported by the Belle Collaboration favors large $\pi^+\pi^-$ masses. Our data support this conclusion as well. Figure 2 shows the $J/\psi\pi^+\pi^-$ mass distribution after requiring the $\pi^+\pi^-$ invariant mass to be above 500 MeV/c^2, a value large enough to probe the high mass behavior of the $X(3872)$ candidates and yet not eliminate all the $\psi(2S)$ reference signal. Fitting the mass spectrum between 3.65 and 4.0 GeV/c^2 gives 3530 ± 100 $\psi(2S)$ candidates and 730 ± 90 $X(3872)$ candidates. The fitted mass and width of the $\psi(2S)$ are $3685.65 \pm 0.09\,(stat)$ MeV/c^2 and $3.44 \pm 0.09\,(stat)$ MeV/c^2, respectively. For the $X(3872)$ we obtain a mass of $3871.3 \pm 0.7\,(stat)$ MeV/c^2 and a width of 4.9 ± 0.7 MeV/c^2. The latter value is consistent with detector resolution. Our mass is in good agreement with the Belle result of $3872.0 \pm 0.6\,(stat) \pm 0.5\,(syst)$ MeV/c^2 [2].

Imposing the dipion mass cut reduces the background by almost a factor of two, and apparently increases the amount of fitted $X(3872)$ signal. A significant part of the increase is attributable to a larger fitted width. The original fit without the 500 MeV/c^2 cut returns a smaller but consistent width of 4.2 ± 0.8 MeV/c^2. We conclude that the $X(3872)$ signal yield after the dipion cut is unchanged within statistics, and thus there is little signal with dipion masses below 500 MeV/c^2. We use the selection with the dipion mass cut for measuring the $X(3872)$ mass as the improved signal-to-noise ratio reduces the statistical uncertainty.

The fit displayed in Figure 2 has a χ^2 of 74.9 for 61 degrees of freedom, which corresponds to a probability of 10.9%. To estimate the significance of the signal, we first count the number of candidates in the 3 bins centered on the peak, i.e. 3893. The 3-bin background is estimated from the fit to be 3234 candidates, leaving a signal of 659 candidates. In a Gaussian approach, this corresponds to a significance of $659/\sqrt{3234} = 11.6$ standard deviations. The Poisson probability for 3234 to fluctuate up to or above 3893 is in good agreement with the Gaussian estimate, considering the approximations of each method.

The systematic uncertainty on the mass scale is related to the momentum scale calibration, the various tracking systematics, and the vertex fitting. These effects were studied in detail for our measurement of the mass difference $m(D_s^+) - m(D^+)$ [11], where the systematic uncertainty was ±0.21 MeV/c^2. A larger systematic uncertainty arises for our $X(3872)$ mass determination because it is an absolute measurement. We use the $\psi(2S)$ mass to gauge our systematic uncertainty. With the dipion mass cut, the $\psi(2S)$ mass is measured to be 0.3 MeV/c^2 below the world average mass of 3685.96 ± 0.09 [12], a difference substantially larger than the statistical uncertainty of 0.1 MeV/c^2. Studies of the stability of the $\psi(2S)$ mass for different selection requirements indicate a slightly larger systematic uncertainty of 0.4 MeV/c^2 should be assigned. Variations of the fit model and fit range have negligible effect on the mass.

In summary, we report the observation of a state consistent with the $X(3872)$ decaying into $J/\psi\pi^+\pi^-$. From a sample of 730 ± 90 candidates we measure the $X(3872)$ mass to be $3871.3 \pm 0.7\,(stat) \pm 0.4\,(syst)$ MeV/c^2, and find that the observed width is consistent with the detector resolution. This is in agreement with the measurement by the Belle Collaboration using $B^\pm$ decays [2]. The average mass from the two experiments, assuming uncorrelated systematic uncertainties, is 3871.7 ± 0.6 MeV/c^2. Our large sample of this new particle opens up avenues for future investigations, such as production mechanisms, the dipion mass distribution, and spin-parity analysis.

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