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We report the observation of the $X(3872)$ in the $J/\psi\,\pi^+\pi^-$ channel, with J/ψ decaying to $\mu^+\mu^-$, in $p\bar{p}$ collisions at $\sqrt{s}=$ 1.96 TeV. Using approximately 230 pb^{-1} of data collected with the Run II DØ detector, we observe 522 ± 100 $X(3872)$ candidates. The mass difference between the $X(3872)$ state and the J/ψ is measured to be 774.9 ± 3.1 (stat) ± 3.0 (syst) MeV/c^2. We have investigated the production and decay characteristics of the $X(3872)$, and find them to be similar to those of the $\psi(2S)$ state.

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A new particle, the $X(3872)$, was recently discovered by the Belle Collaboration [1] in the decay mode $B^\pm \to X K^\pm$ ($X \to J/\psi\,\pi^+\pi^-$) where the mass of the $X(3872)$ was measured to be 3872.0 ± 0.6 (stat) ± 0.5 (syst) MeV/c^2. The existence of the $X(3872)$ state has been confirmed (also decaying in the $J/\psi\,\pi^+\pi^-$ mode) in

$p\bar{p}$ collisions by the CDF Collaboration [2]. At this time, it is still unclear whether this particle is a $c\bar{c}$ state, or a more complex object. See for example [3, 4, 5, 6].

The charmonium state $\psi(2S)$, with mass $m_{\psi(2S)}=3685.96 \pm 0.09$ MeV/c^2 [7], has the same decay mode, providing a good benchmark for comparison with the

$X(3872)$. The $\psi(2S)$ mesons produced in $p\bar{p}$ collisions can originate either from decays of B hadrons or from direct production. The $\psi(2S)$ mesons from B decays have longer effective decay lengths and tend to be less isolated than directly produced $\psi(2S)$ mesons [8].

We examine the production rate of the $X(3872)$ relative to $\psi(2S)$ as a function of the transverse momentum with respect to the beam axis (p_T), isolation and decay length, as well as a function of rapidity ($y = \frac{1}{2}\log\frac{E+P_L}{E-P_L}$, where E is the energy and P_L is the longitudinal momentum with respect to the beam axis), to determine whether the production characteristics of the $X(3872)$ are similar to those of the $\psi(2S)$. We also compare the angular decay distributions of the $\pi^+\pi^-$ and $\mu^+\mu^-$ systems in $X(3872)$ decays with those from $\psi(2S)$, to check for any differences in helicities of these two states.

The data set used in this Letter was collected in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV between April 2002 and January 2004, and corresponds to an integrated luminosity of approximately 230 pb^{-1}. The DØ detector is described elsewhere [9]. The components most important to this analysis include the vertex, central tracking and muon systems. The DØ tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both within a 2 T solenoidal magnetic field.

The SMT has approximately $800,000$ individual strips, with typical pitch of 50–80 μm, and a design optimized for tracking and vertexing over the range $|\eta| < 3$, where $\eta = -\ln[\tan(\theta/2)]$ is the pseudorapidity and θ is the polar angle measured relative to the proton beam direction. The system has a six-barrel longitudinal structure, each with a set of four layers arranged axially around the beam pipe, and interspersed with 16 radial disks. The system provides a resolution, in the plane transverse to the beam axis, for the distance of closest approach of a charged particle relative to the primary vertex of ≈ 50 μm for tracks with $p_T \approx 1$ GeV/c, improving asymptotically to 15 μm for tracks with $p_T \geq 10$ GeV/c.

The CFT comprises eight thin coaxial barrels, each supporting two doublets of overlapping scintillating fibers of 0.835 mm diameter, one doublet being parallel to the collision axis, and the other alternating by $\pm 3°$ to provide information along the beam axis.

The muon system is located outside the calorimeters, and consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroidal magnets, followed by two similar layers behind the toroids. Tracking in the muon system in the range $|\eta| < 1$ relies on 10 cm wide drift tubes [10], while 1 cm mini-drift tubes are used for $1 < |\eta| < 2$.

$J/\psi \rightarrow \mu^+\mu^-$ decays are selected by triggering on dimuons using a three-tier trigger system. The first trigger level uses hardware to form roads defined by hits in two layers of the muon scintillator system. The second trigger level uses digital signal processors to form track stubs defined by hits in the muon drift-chamber and muon scintillator systems. The third level comprises a farm of computer processors with access to the entire

event. Events passing the third-level trigger are recorded for analysis.
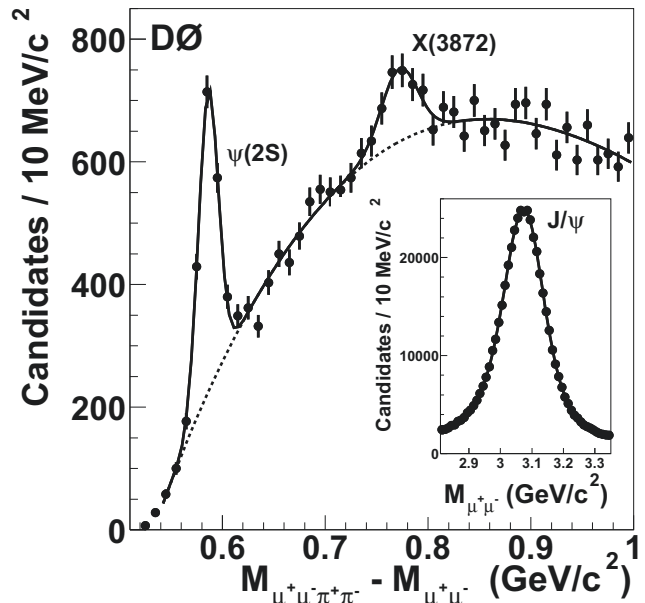

FIG. 1: $\Delta M = M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$ for all candidates satisfying the selection requirements. The solid curve is a fit to the data and the dashed curve represents the background under each peak. The insert shows the mass distribution of the J/ψ candidates used in the analysis.

Muons are identified by extrapolating charged particle tracks from the central tracking system that match with muon track segments formed from hits in the muon system. Oppositely charged muons are combined to form J/ψ candidates, which are then combined with two oppositely charged particles assumed to be pions. At least two of these four tracks are required to have at least one hit in the SMT. To reduce background from combinatorics, events are required to satisfy the following selection criteria. An event is required to have less than 100 tracks. J/ψ candidates are selected by requiring the invariant mass of the $\mu^+\mu^-$ system to be between 2.80 and 3.35 GeV/c^2, and the transverse momentum with respect to the beam axis (p_T) of the J/ψ is required to be greater than 5 GeV/c. In addition, the p_T of each of the two pions must be greater than 0.7 GeV/c, and the spatial separation, ΔR, between the momentum vector of the $J/\psi\,\pi^+\pi^-$ system and each pion momentum vector is required to have $\Delta R < 0.4$, where ΔR is defined as $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, with ϕ being the azimuthal angle. The invariant mass of the two pions, $M(\pi^+\pi^-)$, is required to be greater than 0.52 GeV/c^2, and the χ^2 of a fit to the $\mu^+\mu^-\pi^+\pi^-$ vertex is required to be less than 16 (for five degrees of freedom).

Figure 1 shows the distribution in the mass difference $\Delta M = M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$, after all selections.

Superimposed is a fit to the data, where Gaussians are used to describe the $\psi(2S)$ and the $X(3872)$, and a third-order polynomial is used to account for the background. The fitted width of the $X(3872)$ peak is 17 ± 3 MeV/c^2, which is consistent with detector resolution. The results of the Gaussian fit yield 522 ± 100 $X(3872)$ candidates with $\Delta M = 771.9 \pm 3.1$ (stat) MeV/c^2. The yield of the $X(3872)$ is dependent on the value of the $M(\pi^+\pi^-)$ requirement. When we tighten the requirement on $M(\pi^+\pi^-)$ to be greater than 0.60 GeV/c^2, 0.65 GeV/c^2 and 0.70 GeV/c^2 and fix the mean of the $X(3872)$ to its nominal value, we obtain yields of 433 ± 98, 336 ± 78 and 170 ± 54 events, respectively.

The position of the J/ψ mass in Fig. 1 is shifted relative to the currently accepted value [7]. This is within the uncertainties of our momentum scale, but we correct the measured ΔM by the ratio of the currently accepted mass difference between the $\psi(2S)$ and the J/ψ [7] and our corresponding measured mass difference. We assign a 100% systematic uncertainty to this mass scale correction, giving a final measurement of $\Delta M = 774.9 \pm 3.1$ (stat) $\pm$ 3.0 (syst) MeV/c^2. We investigated systematic effects by using different background parameterizations and bin widths in our fits, and found the largest change in the central value of the mass difference to be 0.6 MeV/c^2.

To investigate the characteristics of the $X(3872)$ state, we study its production and decay properties, and compare the signal yields of the $X(3872)$ to the $\psi(2S)$. For example, Fig. 2 shows the ΔM distribution in two separate regions of rapidity of the $X(3872)$. The data is also separated into regions of effective proper decay length, transverse momentum of the $X(3872)$ candidate, isolation, and decay angle.

The effective proper decay length, dl, is defined as the distance in the transverse plane from the primary vertex to the decay vertex of the J/ψ scaled by the mass of the $\mu^+\mu^-\pi^+\pi^-$ system divided by the $\mu^+\mu^-\pi^+\pi^-$ system p_T.

The isolation is defined as the ratio of the $X(3872)$ momentum to the sum of the momentum of the $X(3872)$ and the momenta of all other reconstructed charged particles within a cone of radius $\Delta R = 0.5$, about the direction of the $X(3872)$ momentum.

The helicity of the $\pi^+\pi^-$ ($\mu^+\mu^-$) system can be inferred by boosting one of the pions (or muons) and the $X(3872)$ into the dipion (dimuon) rest frame, and measuring the angle θ_π (θ_μ) between them. The cosine of this angle is used for the comparison between the $X(3872)$ and $\psi(2S)$.

The widths of the $\psi(2S)$ and $X(3872)$ are fixed to the values obtained in the fit to the full sample, and the fitted number of $\psi(2S)$ and $X(3872)$ candidates in each region of chosen variables is given in Table I. The data in all regions are well represented by our choice of fitting function, with fit probabilities all greater than 15%. In Fig. 3, we present the results of Table I in a graphical
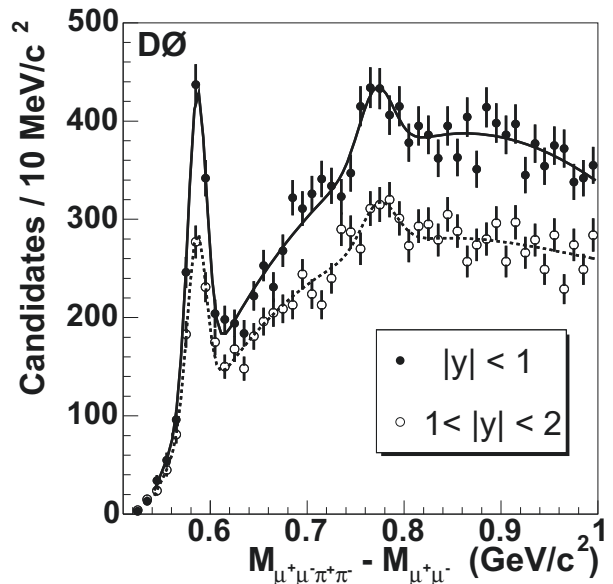

FIG. 2: ΔM distribution for two ranges of rapidity of the $\mu^+\mu^-\pi^+\pi^-$ system.

form. For example, we compare the event yield fraction:

$$f_{X(3872)} = \frac{N(X(3872))\ |y| < 1}{N(X(3872))\ |y| < 2},$$

to that for $\psi(2S)$:

$$f_{\psi(2S)} = \frac{N(\psi(2S))\ |y| < 1}{N(\psi(2S))\ |y| < 2}.$$

From the ratios of isolation and decay lengths, it is apparent that the production of the $X(3872)$ has a similar mixture of prompt and long-lived contributions as the $\psi(2S)$.

In summary, we observe the $X(3872)$ particle in approximately 230 pb^{-1} of data with a significance of 5.2 standard deviations. The mass difference between the $X(3872)$ particle and the J/ψ is $\Delta M = 774.9\pm3.1$ (stat) $\pm$ 3.0 (syst) MeV/c^2. When the data are separated according to production and decay variables, we find no significant differences between the $X(3872)$ and the $c\bar{c}$ state $\psi(2S)$.

TABLE I: Number of $\psi(2S)$ and $X(3872)$ candidates for different ranges of variables. The fitted widths of the $X(3872)$ and $\psi(2S)$ are not constrained in the initial selection, but in the different ranges they are fixed to the values obtained from the full sample. Apart from the full sample, uncertainties are only from the normalization of the fitted Gaussian function and do not include small contributions from uncertainties in the background.

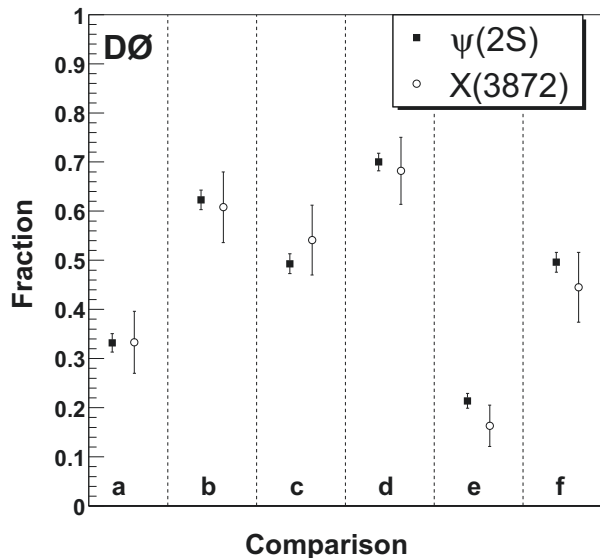| Regions	Number of $\psi(2S)$	Number of $X(3872)$
Initial selection	1192 ± 55	522 ± 100
(a) $p_T(J/\psi\,\pi^+\pi^-) > 15$ GeV/c	396 ± 26	179 ± 39
$p_T(J/\psi\,\pi^+\pi^-) \le 15$ GeV/c	796 ± 41	358 ± 64
(b) $|y| < 1$	741 ± 37	316 ± 57
$1 \le |y| \le 2$	449 ± 31	204 ± 49
(c) $\cos(\theta_\pi) < 0.4$	589 ± 34	288 ± 53
$\cos(\theta_\pi) \ge 0.4$	606 ± 34	244 ± 53
(d) $dl < 0.01$ cm	838 ± 41	351 ± 66
$dl \ge 0.01$ cm	359 ± 26	164 ± 41
(e) isolation $= 1$	257 ± 20	85 ± 22
isolation < 1	942 ± 44	438 ± 72
(f) $\cos(\theta_\mu) < 0.4$	593 ± 33	232 ± 46
$\cos(\theta_\mu) \ge 0.4$	602 ± 35	288 ± 60

FIG. 3: Comparison of event-yield fractions for $X(3872)$ and $\psi(2S)$ in the regions: (a) $p_T(J/\psi\,\pi^+\pi^-) > 15$ GeV/c; (b) $|y|$ of $J/\psi\,\pi^+\pi^- < 1$; (c) $\cos(\theta_\pi) < 0.4$; (d) effective proper decay length, $dl < 0.01$ cm; (e) isolation $= 1$; (f) $\cos(\theta_\mu) < 0.4$.

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