Observation and Properties of the X(3872) Decaying to J/ψ π⁺π⁻ in pp Collisions at √s = 1.96 TeV


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We report the observation of the X(3872) in the $J/\psi \pi^+\pi^-$ channel, with $J/\psi$ decaying to $\mu^+\mu^-$, in $pp$ collisions at $\sqrt{s} = 1.96$ TeV. Using approximately 230 pb$^{-1}$ of data collected with the Run II D0 detector, we observe 522 ± 100 $X(3872)$ candidates. The mass difference between the $X(3872)$ state and the $J/\psi$ 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.


A new particle, the X(3872), was recently discovered by the Belle Collaboration [1] in the decay mode $B^\pm \rightarrow X K^\mp$ ($X \rightarrow J/\psi \pi^+\pi^-$) 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 $pp$ 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 $pp$ 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 characteristics to $\psi(2S)$ as a function of the transverse momentum, 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 $pp$ collisions at $\sqrt{s} = 1.96$ TeV between April 2002 and January 2004, and corresponds to an integrated luminosity of approximately $230 \text{ pb}^{-1}$. 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 $\theta$ 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 $\approx 50 \mu$m for tracks with $p_T \approx 1 \text{ GeV}/c$, improving asymptotically to $15 \mu$m for tracks with $p_T \geq 10 \text{ GeV}/c$.

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 $\pm 3^\circ$ 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.

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 $J/\psi$ 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. $J/\psi$ 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 $J/\psi$ 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, $\Delta R$, 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 $\Delta R$ is defined as $\sqrt{\Delta\phi^2 + \Delta\eta^2}$, with $\phi$ being the azimuthal angle. The invariant mass of the two pairs, $M(\pi^+\pi^-)$, is required to be greater than 0.52 GeV/$c^2$, and the $\chi^2$ 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 \( 17 \pm 3 \text{ MeV/c}^2 \), which is consistent with detector resolution. The results of the Gaussian fit yield \( 522 \pm 100 \ X(3872) \) candidates with \( \Delta M = 771.9 \pm 3.1 \text{ (stat)} \ \text{MeV/c}^2 \). 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\( \pm \)98, 336\( \pm \)78 and 170\( \pm \)54 events, respectively.

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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 \( \Delta M \) 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, \( \Delta \ell \), is defined as the distance in the transverse plane from the primary vertex to the decay vertex of the \( J/\psi \) scaled by the mass of the \( \mu^+\mu^-\pi^+\pi^- \) system divided by the mass of the \( \mu^+\mu^-\pi^+\pi^- \) system \( p_T \).

The isolation is defined as the ratio of the \( \mu^+\mu^-\pi^+\pi^- \) system 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 \( \pi^+\pi^- \) (or muons) can be inferred by measuring the angles \( \theta_\mu \) 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 form. For example, we compare the event yield fraction:

\[
\frac{N(X(3872))}{N(\psi(2S))} |y| < 1
\]

\[
\frac{N(X(3872))}{N(\psi(2S))} |y| < 2
\]

From the ratios of isolation and decay lengths, it appears 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 \( X(3872) \) and the \( J/\psi \) is \( \Delta M = 774.9 \pm 3.1 \text{ (stat)} \pm 3.0 \text{ (syst)} \ \text{MeV/c}^2 \). When the data are separated according to production and decay variables, we find no significant differences between the \( X(3872) \) and the \( \psi(2S) \).

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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.

<table>
<thead>
<tr>
<th>Regions</th>
<th>Number of ( \psi(2S) )</th>
<th>Number of ( X(3872) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial selection</td>
<td>1192 ± 55</td>
<td>522 ± 100</td>
</tr>
<tr>
<td>(a) ( p_T(J/\psi \pi^+\pi^-)&gt;15 \text{ GeV}/c )</td>
<td>396 ± 26</td>
<td>179 ± 39</td>
</tr>
<tr>
<td>( p_T(J/\psi \pi^+\pi^-)\leq15 \text{ GeV}/c )</td>
<td>796 ± 41</td>
<td>358 ± 64</td>
</tr>
<tr>
<td>(b) (</td>
<td>y</td>
<td>&lt;1 )</td>
</tr>
<tr>
<td>( 1&lt;</td>
<td>y</td>
<td>&lt;2 )</td>
</tr>
<tr>
<td>(c) ( \cos(\theta_x)&lt;0.4 )</td>
<td>589 ± 34</td>
<td>288 ± 53</td>
</tr>
<tr>
<td>( \cos(\theta_x)&gt;0.4 )</td>
<td>606 ± 34</td>
<td>244 ± 53</td>
</tr>
<tr>
<td>(d) ( d\ell&lt;0.01 \text{ cm} )</td>
<td>838 ± 41</td>
<td>351 ± 66</td>
</tr>
<tr>
<td>( d\ell&gt;0.01 \text{ cm} )</td>
<td>359 ± 26</td>
<td>164 ± 41</td>
</tr>
<tr>
<td>(e) isolation = 1</td>
<td>257 ± 20</td>
<td>85 ± 22</td>
</tr>
<tr>
<td>isolation &lt; 1</td>
<td>942 ± 44</td>
<td>438 ± 72</td>
</tr>
<tr>
<td>(f) ( \cos(\theta_\rho)&lt;0.4 )</td>
<td>593 ± 33</td>
<td>232 ± 46</td>
</tr>
<tr>
<td>( \cos(\theta_\rho)&gt;0.4 )</td>
<td>602 ± 35</td>
<td>288 ± 60</td>
</tr>
</tbody>
</table>

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

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[†] Visitor from Institute of Nuclear Physics, Krakow, Poland.
[3] F. E. Close, P. R. Page, “The \( D^{*0} \bar{D}^{0} \) threshold reso-