$X(3872)$ at BESIII

Speaker: Junhao Yin
on behalf of BESIII Collaboration
What have we known about $X(3872)$

- **Mass**
  - $3871.68 \pm 0.17$ MeV/$c^2$
  - $B_E = 0.01 \pm 0.20$ MeV/$c^2$
- **Width**
  - $< 1.2$ MeV
- **$J^{PC}$** $= 1^{++}$
- **Production**
  - In $pp/p\bar{p}$ collision
  - In B decays
  - In Y decays
- **Decay**
  - $\pi^+ \pi^- J/\psi$ and $\omega J/\psi$
  - $\gamma J/\psi$ and $\gamma\psi(3686)$
  - $D^0 \bar{D}^{*0} + c. c.$

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**What is it?**
- Loosely $D^0 \bar{D}^{*0}$ bound state?
- Mixture of $\chi_{c1}'$ and $D^0 \bar{D}^{*0}$?
- Cusp?
- Tetraquarks?

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QWG 2019, Junhao Yin
What BESIII have contributed

A new $X(3872)$ production mode
If we take $B(X(3872) \rightarrow \pi\pi J/\psi) \sim 5%$ (>3.2% in PDG)

$$\frac{\sigma(e^+e^-\rightarrow\gamma X(3872))}{\sigma(e^+e^-\rightarrow\pi\pi J/\psi)} \sim 10\% \text{ around } Y(4260)$$

Large production rate, low background level

[QWG 2019, Junhao Yin]
What BESIII now have

- Massive data sample around the $Y(4230)$ peak, with the total integrated luminosity larger than 9.0 fb$^{-1}$
- More data are being taken this year.
- Background is much lower than in other productions.
Observation of $X(3872) \rightarrow \pi^0 \chi_{c1}(1P)$

- In conventional $c\bar{c}$ hypothesis, $\Gamma(X(3872) \rightarrow \pi^0 \chi_{c1}(1P)) \sim 0.06$ keV
- In tetraquark/molecular state hypothesis, the decay width could be sizeable.

[PRD 77, 014013(2008)], [PRD 92, 034019(2015)]

- Very clear signal of $X(3872)$, $N_{X(3872)} = 16.9^{+5.2}_{-4.9}$
- Statistical significance is 4.8$\sigma$
- No $X(3872)$ events outside of $Y(4260)$ zone

arXiv:1901.03992
Observation of $X(3872) \rightarrow \pi^0 \chi_{c1}(1P)$

- After $X(3872)$ mass window cut applied, very clear cluster of $\chi_{c1}(1P)$ events
- $|M(\gamma_2 J/\psi) - M_0(\chi_{cJ})| < 25(20) \text{ MeV}/c^2$ for $J = 0(1,2)$
- Sum $J = 0,1,2$, $N_{X(3872)} = 15.1^{+4.8}_{-3.8}$
**Observation of $X(3872) \rightarrow \pi^0 \chi_{c1}(1P)$**

<table>
<thead>
<tr>
<th></th>
<th>$\pi^+\pi^-J/\psi$</th>
<th>$\pi^0 \chi_{c0}$</th>
<th>$\pi^0 \chi_{c1}$</th>
<th>$\pi^0 \chi_{c2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event yield</td>
<td>$84.1_{-9.4}^{+10.1}$</td>
<td>$1.9_{-1.3}^{+1.9}$</td>
<td>$10.8_{-3.1}^{+3.8}$</td>
<td>$2.5_{-1.7}^{+2.3}$</td>
</tr>
<tr>
<td>Significance ($\sigma$)</td>
<td>16.1</td>
<td>1.6</td>
<td>5.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Ratio to $\pi^+\pi^-J/\psi$</td>
<td>...</td>
<td>$6.6_{-4.5}^{+6.5} \pm 1.1$ (19)</td>
<td>$0.88_{-0.27}^{+0.33} \pm 0.10$</td>
<td>$0.40_{-0.27}^{+0.37} \pm 0.04$ (1.1)</td>
</tr>
</tbody>
</table>

*Numbers in the parentheses are upper limits at 90% C.L.*

- Using $\mathcal{B}(X(3872) \rightarrow \pi^+\pi^-J/\psi) > 3.2\%$ and $< 6.4\%$, it is found that $\mathcal{B}(X(3872) \rightarrow \pi^0 \chi_{c1}(1P)) \sim 3 - 6\%$

- Using $\Gamma_{X(3872)} \sim 1.2$ MeV, we get the predicted $\mathcal{B}(X(3872) \rightarrow \pi^0 \chi_{c1}(1P)) \sim 0.5\%$

- **Conclusion:** disfavor the $c\bar{c}$ interpretation of the $X(3872)$.

arXiv:1901.03992
Observation of $X(3872) \rightarrow \omega J/\psi$

- Belle and BABAR reported $4\sigma$ evidence for this decay, and give
  $$\frac{\mathcal{B}(X(3872) \rightarrow \pi^+\pi^0 J/\psi)}{\mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4 \pm 0.3$$

- BESIII is expected to find $\sim 70 \ X(3872) \rightarrow \omega J/\psi$ events with the data accumulated around $Y(4230)$.

Full reconstruction
Use $J/\psi \rightarrow e^+e^-/\mu^+\mu^-$

Significant $e^+e^- \rightarrow \gamma \omega J/\psi$ signal,
compared with $e^+e^- \rightarrow \gamma_{ISR}\psi(2S) [\psi(2S) \rightarrow \eta J/\psi]$
Observation of $X(3872) \rightarrow \omega J/\psi$

At least one additional BW-formed resonance expect $X(3872)$

- $X(3915)$ along with $X(3960)$.
- or $X(3930)$

Hard to distinguish the two hypotheses since only $2.5\sigma$ difference between them.

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Observation of $X(3872) \rightarrow \omega J/\psi$

<table>
<thead>
<tr>
<th></th>
<th>$X(3872)$</th>
<th>$X(3915)$</th>
<th>$X(3960)$</th>
<th>$X(3930)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (in MeV/c$^2$)</td>
<td>$3873.3 \pm 1.1 \pm 1.0$</td>
<td>$3926.4 \pm 2.2 \pm 1.2$</td>
<td>$3963.7 \pm 5.5 \pm 1.3$</td>
<td>$3932.6 \pm 8.7 \pm 4.7$</td>
</tr>
<tr>
<td>Width (in MeV)</td>
<td>$1.2$</td>
<td>$3.8 \pm 7.5 \pm 2.6$</td>
<td>$33.3 \pm 34.2 \pm 8.3$</td>
<td>$59.7 \pm 15.5 \pm 3.7$</td>
</tr>
</tbody>
</table>

By fitting the cross sections of $e^+e^- \rightarrow \gamma X(3872)$ with $X(3872) \rightarrow \omega J/\psi$ and $X(3872) \rightarrow \pi^+\pi^- J/\psi$, we give

$$\mathcal{R} \equiv \frac{B[X(3872) \rightarrow \omega J/\psi]}{B[X(3872) \rightarrow \pi^+\pi^- J/\psi]} = 1.6^{+0.4}_{-0.3} \pm 0.2, \text{ agree with the previous measurements.}$$

$0.8 \pm 0.3$ from BABAR
More measurements

Combined the BaBar, Belle, and LHCb

\[ \frac{\mathcal{B}[X(3872) \rightarrow \gamma \psi(2S)]}{\mathcal{B}[X(3872) \rightarrow \gamma J/\psi]} = 2.31 \pm 0.57 \]

\[ \begin{align*}
3.4 &\pm 1.4, \text{BABAR} & 3.6\sigma \text{ and } 3.5\sigma \\
\leq 2.1 \, (90\% \text{C.L.}), \text{Belle} & & 5.5\sigma \text{ and } 0.4\sigma \\
2.46 &\pm 0.64 \pm 0.29, \text{LHCb} & > 8\sigma \text{ and } 4.4\sigma 
\end{align*} \]

Also

\[ \frac{\mathcal{B}[X(3872) \rightarrow \gamma J/\psi]}{\mathcal{B}[X(3872) \rightarrow \pi^+\pi^- J/\psi]} = 0.24 \pm 0.05 \]

\~30 \, X(3872) \rightarrow \gamma J/\psi \text{ and } \~20 \, X(3872) \rightarrow \gamma \psi(2S) \text{ events expected on BESIII}

A good test for the existing measurements!
Datasets and decay chain

\[ X(3872) \rightarrow D^0 \bar{D}^{*0} + c.c. \]
\[ D^{*0} \rightarrow \gamma D^0, \pi^0 D^0 \]
\[ D^0 \rightarrow K\pi, K\pi\pi, K\pi\pi\pi \]

\[ X(3872) \rightarrow \gamma J/\psi \]
\[ J/\psi \rightarrow \mu\mu/ee \]

\[ X(3872) \rightarrow \gamma \psi(3686) \]
\[ \psi(3686) \rightarrow \pi^+\pi^- J/\psi \]
\[ \psi(3686) \rightarrow \mu\mu \]

\[ X(3872) \rightarrow \gamma D^+ D^- \]
\[ D^\pm \rightarrow K\pi\pi, K\pi\pi\pi \]

<table>
<thead>
<tr>
<th>( \sqrt{s} ) GeV</th>
<th>Luminosity (pb(^{-1}))</th>
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<tbody>
<tr>
<td>4.1783</td>
<td>3189.0</td>
</tr>
<tr>
<td>4.1888</td>
<td>521.9</td>
</tr>
<tr>
<td>4.1989</td>
<td>523.7</td>
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<tr>
<td>4.2092</td>
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<tr>
<td>4.2187</td>
<td>508.2</td>
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<tr>
<td>4.2263</td>
<td>1092</td>
</tr>
<tr>
<td>4.2357</td>
<td>528.9</td>
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<tr>
<td>4.2438</td>
<td>532.7</td>
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<tr>
<td>4.2580</td>
<td>826</td>
</tr>
<tr>
<td>4.2668</td>
<td>529.3</td>
</tr>
<tr>
<td>4.2777</td>
<td>174.5</td>
</tr>
</tbody>
</table>
Study of $X(3872) \to \gamma J/\psi, \gamma \psi(3686)$

Requirement:

$\cos \theta_\gamma \in [-0.7, 0.7]$ in $J/\psi \to e^+e^-$

$|M(\gamma L\gamma_H) - m_{\pi^0(\eta)}| > 0.02(0.03)$ GeV/$c^2$

$|M(\gamma L J/\psi) - m_{\chi_{c1,2}}| > 0.02$ GeV/$c^2$

Simultaneous fit; significance $> 3.5 \sigma$

Requirement:

$|M(\gamma L\gamma_H) - m_{\pi^0(\eta)}| > 0.02(0.03)$ GeV/$c^2$

$|M(\pi^+\pi^-)_{\text{recoil}} - m_{\psi(3686)}| > 0.01$ GeV/$c^2$

Simultaneous fit; no evident signal

\[
\frac{B[X(3872) \to \gamma \psi(3686)]}{B[X(3872) \to \gamma J/\psi]} < 0.59 \text{ at 90\% C.L.}
\]
Study of $X(3872) \rightarrow D^0 \bar{D}^{*0}$ and $\gamma D^+ D^-$

Simultaneous fit on $D^{*0} \rightarrow \gamma D^0$ and $\pi^0 D^0$

Significance > 7.4$\sigma$

No evident signal for $\gamma D^+ D^-$

Using the same way in Ref.[PRL 112, 092001(2014)] to reconstruct $X(3872) \rightarrow \pi^+ \pi^- J/\psi$ as the reference channel.
Summary and outlook

• Great progress achieved recently:
  • New decay mode of $X(3872)$ is observed, $X(3872) \to \pi^0 \chi_{c1}$
  • First firm observation of $X(3872) \to \omega J/\psi$
  • More decays are searched and measured

• BESIII provide essential test for the existing measurements

• BESIII is taking more data
Back up
Background suppression

• $\pi^0 / \eta$ suppression
  • In decays with two photons in final states
  • $|M(\gamma_{L,Y_H}) - m_{\pi^0}| > 0.02 \text{ GeV/c}^2, |M(\gamma_{L,Y_H}) - m_{\eta}| > 0.03 \text{ GeV/c}^2$

• $X(3872) \to \gamma J/\psi$
  • $\cos \theta_\gamma \in [-0.7, 0.7]$ in $J/\psi \to e^+ e^-$
  • $|M(\gamma_{L,J/\psi}) - m_{\chi_{c1,2}}| > 0.02 \text{ GeV/c}^2$

• $X(3872) \to \gamma \psi(3686)$
  • $|M(\pi^+ \pi^-)_{\text{recoil}} - m_{\psi(3686)}| > 0.01 \text{ GeV/c}^2$
Calculating the upper limits of the relative ratios

• In calculating the relative ratios, the statistical uncertainty of both denominator and numerator must be considered.

• For example, in calculating the \( \frac{B[X(3872) \to \gamma J/\psi]}{B[X(3872) \to \gamma \psi(3686) / \psi]} \), we sampling the likelihood distribution for \( \gamma J/\psi \) and \( \gamma \psi(3686) / \psi \) mode randomly.

• After thousands of sampling, the likelihood distribution of the ratio could be obtained, in which the statistical uncertainties from both channels are considered.

• Then a Gaussian presented the systematic uncertainty is smeared on the distribution.

• Thus the new distribution would be the distribution of the ratio considering the statistical and systematic uncertainties.