Recent results of XYZ study at BESIII

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On behalf of BESIII Collaboration

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Outline

- Introduction
  
  Exotic states, XYZ, BESIII

- Selected recent results:
  
  X states, not covered in this talk
  
  $Z_c(3900)$ spin parity determination
  
  Y study via cross section line-shape

- Summary
What’s exotic state?

- Conventional hadrons consist of 2 or 3 quarks:
  
  Naive Quark Model:

  ![Meson](image1) ![Baryon](image2)

- QCD predicts the exotic state:

  Multi-quark states: \((N \geq 4)\)  
  Hybrids: \(\bar{q}qg, qqqg\ldots\)  
  Glueballs: \(gg, ggg\)
The BESIII Experiment

- Founded: 1984, $E_{cm}=2-4.6$ GeV
- 1989-2005 (BEPC):
  \[ L_{\text{peak}} = 1.0 \times 10^{31} \text{/cm}^2\text{s} \]
- 2008-now (BEPCII):
  \[ L_{\text{peak}} = 1.0 \times 10^{33} \text{/cm}^2\text{s} \]
  (Apr. 5, 2016)
BESIII Detector

MDC
- R inner: 63mm
- R outer: 810mm
- Length: 2582 mm
- Layers: 43

CsI(Tl) EMC
- Crystals: 28 cm (15 $X_0$)
- Barrel: $|\cos\theta| < 0.83$
- Endcap: $0.85 < |\cos\theta| < 0.93$

RPC MUC
- Inner chamber replaced by CGEM is ongoing

TOF
- BTOF: two layers
- ETOF: $\rightarrow$ MRPC
- Installation completed in Oct., 2015
- 60ps (120ps)

BMUC: 9 layers – 72 modules
EMUC: 8 layers – 64 modules
Charmonium Spectroscopy

- **Above open charm threshold:**
  - many expected states not observed
  - many unexpected observed

- **Below open charm threshold:**
  
  Good agreement between discovery and theoretical prediction.
Data samples

- Luminosity ~ 8/fb (above 4 GeV)
- Huge data samples around $\Psi(4040)$, $\Psi(4160)$, $Y(4260)$, $Y(4360)$, $\Psi(4415)$ and $Y(4660)$
$Z_c(3900)^{\pm/0}$ in $e^+e^-\rightarrow\pi\pi J/\psi$

- $Z_c(3900)^{\pm}$, BESIII, Belle, CLEOc data, in 2013
- $Z_c(3900)^0$, evidence with $3.7\sigma$ by CLEOc, observed with $>10\sigma$ by BESIII

<table>
<thead>
<tr>
<th>$Z_c(3900)$</th>
<th>Mass(MeV)</th>
<th>Width(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_c(3900)^{\pm}$</td>
<td>3899.0±3.6±4.9</td>
<td>46±10±20</td>
</tr>
<tr>
<td>$Z_c(3900)^0$</td>
<td>3894.8±2.3±2.7</td>
<td>29.6±8.2±8.2</td>
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</tbody>
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An iso-spin triplet established!
Determination of $J^p$ of $Z_c(3900)$

Amplitude analysis with helicity formalism
Simultaneous fit to data samples at 4.23 GeV and 4.26 GeV
$\pi\pi$ spectrum parameterized by $\sigma$, $f_0(980)$, $f_2(1270)$, $f_3(1370)$,
Determination of $J^p$ of $Z_c(3900)$

$J^p$ of $Z_c$ favor $1^+$ with statistical significance larger than 7 $\sigma$ over other quantum numbers.

$M_{\text{pole}} = (3881.2 \pm 4.2_{\text{stat}} \pm 52.7_{\text{syst}}) \text{ MeV}/c^2$

$\Gamma_{\text{pole}} = (51.8 \pm 4.6_{\text{stat}} \pm 36.0_{\text{syst}}) \text{ MeV}$
Cross section measurement of $e^+e^- \rightarrow \pi^+\pi^- J/\Psi$

- Coherent sum of two BW-like structures + one incoherent $\Psi(3770)$
  - $M = (4222.0 \pm 3.1 \pm 1.4) \text{ MeV}, \quad \Gamma = (44.1 \pm 4.3 \pm 2.0) \text{ MeV}$
  - Lower and narrower than previous $Y(4260)$ PDG values
  - $M = (4320.0 \pm 10.4 \pm 7) \text{ MeV}, \quad \Gamma = (101.4 \pm 25 \pm 10) \text{ MeV}$
  - A little bit lower than $Y(4360)$ PDG value
- Compared with one BW fit, the sig. of the second BW is 7.6 $\sigma$
- $Y(4260) + Y(4360)$? The first observation of $Y(4360) \rightarrow \pi^+\pi^- J/\Psi$?

PRL 118, 092001 (2017)
Cross section measurement of $e^+e^- \rightarrow \pi^+\pi^- h_c$

- Fitted with coherent sum of two BW-like structures
  - $M = (4218.4^{+5.5}_{-4.5} \pm 0.9) \text{ MeV}, \quad \Gamma = (66.0^{+12.3}_{-8.3} \pm 0.4) \text{ MeV}$
  - $M = (4391.5^{+6.3}_{-6.8} \pm 1) \text{ MeV}, \quad \Gamma = (139.5^{+16.2}_{-20.6} \pm 0.6) \text{ MeV}$
- The lower one is consistent with the state observed in $\pi^+\pi^- J/\Psi$ around 4222 MeV

PRL 118, 092002 (2017)
A clear peak around $Y(4360)$, consistent with the results from Belle and Babar, but with much improved precision.

A binned $\chi^2$ fit with 3 resonances: $Y(4220)$, $Y(4390)$, $\Psi(4660)$

The significance of $Y(4220)$ is 5.8 $\sigma$.

PRD 96, 032004 (2017)
Charged structures in $e^+ e^- \rightarrow \pi^+ \pi^- \Psi'$

**4.23 GeV**

**4.26 GeV**

**4.36 GeV**

**4.42 GeV**

Different structures at different energy points.

Structure @4.42 GeV
Significance of $9.2\sigma$
$M = 4032.1 \pm 2.4$ MeV
$\Gamma = 26.1 \pm 5.3$ MeV

New Zc? Need more Investigation!!!

Discrepancies between the fit model and data!

**PRD 96, 032004 (2017)**
Cross section measurement of $e^+e^- \rightarrow \pi^0\pi^0\Psi'$

- Cross section measured at 16 energy points from 4.008 to 4.6 GeV, consistent with $\frac{1}{2} \pi^+\pi^-\Psi'$
- Dalitz plots consistent with the $\pi^+\pi^-\Psi'$

arXiv: 1710.10740
Cross section measurement of $e^+e^- \rightarrow KKJ/\Psi$

Cross section measured at 14 energy points from 4.189 to 4.6 GeV

Energy dependence differ from $\pi^+\pi^-J/\Psi$

Evidence for a structure around 4.5 GeV

Neutral and charged kaons consistent with expectations from isospin conservation.

arXiv: 1802.01216
Cross section measurement of $e^+e^- \rightarrow \eta h_c$

- 16 channels searched.

- Clear signals at 4.226 and 4.358 GeV

- A fit with a coherent sum of 3 BW functions.

$M = (4204 \pm 6) \text{ MeV}$

$\Gamma = (32 \pm 22) \text{ MeV}$

arXiv: 1704.08033
Measurement of $e^+e^- \rightarrow \pi^+D^0D^{*-}+\text{c.c.}$

$\square$ Coherent sum of 3-body phase space and 2 Breit-Wigner functions

$\Rightarrow M = (4228.6 \pm 4.1 \pm 5.0) \text{ MeV}, \quad \Gamma = (77.1 \pm 6.8 \pm 2.7) \text{ MeV}$

$\Rightarrow M = (4404.6 \pm 7.4 \pm 4.8) \text{ MeV}, \quad \Gamma = (191.7 \pm 13.0 \pm 15.1) \text{ MeV}$

$\square$ Two structures are consistent with those in $\pi\pi h_c, \pi\pi \Psi'$

$\square$ Evidence of open charm production from Y states.
Y(4260) \rightarrow Y(4220): What is it?

Y(4220): Mass \sim 4220\,\text{MeV}, \quad \text{Width} \sim 60\,\text{MeV}
Summary

- Lots of progress in charmonium-like studies recently.
- $J^P$ of $Z_c(3900)$ is determined to be $1^+$.  
- Observation of $Z_c$ states, a new structure in $\pi \Psi'$.  
- Measurements of many final states, $Y(4260) \rightarrow Y(4220)$ with more decay modes now.  
- The nature of many $XYZ$ states are still not clear, more efforts are expected.

Thank You
Backup
Determination of $J^p$ of $Z_c(3900)$

TABLE I: Significance of the spin parity $1^+$ over other quantum numbers for \( Z_c^{\pm} \). The significance is obtained for given change in ndf, \( \Delta(\text{ndf}) \). In each case, \( \Delta(\text{ndf}) = 2 \times 4 + 5 \), where \( 2 \times 4 \) ndf account for the coupling strength for \( e^+e^- \rightarrow Z_c^{\pm}\pi^{\mp} \) at the two data sets, and the additional five ndf are the contribution of the common degrees of freedom for the \( Z_c \) resonant parameters and the coupling strength for \( Z_c^{\pm} \rightarrow J/\psi\pi^{\pm} \).

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>( \Delta(-2\ln L) )</th>
<th>( \Delta(\text{ndf}) )</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^+ \text{ over } 0^-$</td>
<td>94.0</td>
<td>13</td>
<td>7.6$\sigma$</td>
</tr>
<tr>
<td>$1^+ \text{ over } 1^-$</td>
<td>158.3</td>
<td>13</td>
<td>10.8$\sigma$</td>
</tr>
<tr>
<td>$1^+ \text{ over } 2^-$</td>
<td>151.9</td>
<td>13</td>
<td>10.5$\sigma$</td>
</tr>
<tr>
<td>$1^+ \text{ over } 2^+$</td>
<td>96.0</td>
<td>13</td>
<td>7.7$\sigma$</td>
</tr>
</tbody>
</table>

\[ e^+e^- \rightarrow Z_c(3900)^{\pm}\pi^{-} + c.c. \rightarrow J/\psi\pi^{+}\pi^{-} \]

\[
(21.8 \pm 1.0_{\text{stat}} \pm 4.4_{\text{syst}}) \text{ pb at } \sqrt{s} = 4.23 \text{ GeV}
\]

\[
(11.0 \pm 1.2_{\text{stat}} \pm 5.4_{\text{syst}}) \text{ pb at } \sqrt{s} = 4.26 \text{ GeV}
\]
A similar fit to data with the additional requirement $M^2(\pi^+\pi^-) > 0.3 \text{ (GeV/c}^2)^2$ is performed, which yields a mass of $M = 4030.3 \pm 0.1 \text{ MeV/c}^2$ and a width of $\Gamma = 5.1 \pm 0.2 \text{ MeV}$. The corresponding projection of the fit and data on the $M^2(\pi^+\psi(3686))$ distribution is shown in Fig. 4, and the fit C.L. is 50\%.
Measurement of $e^+e^- \rightarrow \pi^+D^0D^{*-}+c.c.$

\[ \sigma_{dress} = \frac{N^{obs}}{\mathcal{L}(1 + \delta r)B(D^0 \rightarrow K^-\pi^+) \epsilon} \]

\[ \sigma_{dress}(m) = |c \cdot \sqrt{P(m)} + e^{i\phi_1} B_1(m) \sqrt{\frac{P(m)}{P(M_1)}} + e^{i\phi_2} B_2(m) \sqrt{\frac{P(m)}{P(M_2)}}|^2 \]

BESIII Preliminary

Fit with a constant (pink dashed triple-dot line) and two constant width relativistic BW functions (green dashed double-dot line and aqua dashed line).
Overview of $Z_c$ states

$e^+e^- \rightarrow \pi^+\pi^0 J/\psi$

$e^+e^- \rightarrow \pi^0\pi^0 J/\psi$

$e^+e^- \rightarrow \pi^-\pi^+ h_c$

$e^+e^- \rightarrow \pi^0\pi^0 h_c$

$e^+e^- \rightarrow \pi^\pm(D\bar{D}^*)^{+/0}$

$Z_c(3900)^\pm$ ?

$Z_c(3900)^0$ ?

$Z_c(4020)^\pm$ ?

$Z_c(4020)^0$ ?

Preliminary

soon…
Summary

- Lots of progress in charmonium-like studies recently.
- Charged charmonium-like states ($Z_c$) has been observed.
- Neutral partners observed, make them isospin triplet states.
- No evidence of $Z_c(3900)$ in a light hadronic decay to $\omega\pi^\pm$.
- Observation of $e^+e^-\rightarrow\gamma X(3872) \& \pi^+\pi^-X(3823)$.
- X, Y, Z particles are correlated!
- More experimental effort is needed.

Thank You
NATURE of $Z_c$ STATES

- At least 4 quarks, not a conventional meson

- Tetraquark state?
  - Phys. Rev. D89, 054019 (2014); Phys. Rev. D90, 054009 (2014); etc

- $D^(*)\bar{D}^(*)$ molecule state?
  - Phys. Rev. D 89, 074029 (2014); Phys. Rev. D 88, 074506 (2013); etc

- Final States Interactions?
- ...
The nature of $Z_c(3900)$?

From SPIRE HEP Database (17th, May)

1. Tetraquarks
   arXiv: 1110.1333, 1303.6857
   arXiv: 1304. (0345, 1301, 6433, 7080, 7816)

2. Hadronic molecules
   arXiv: 1303.6608,
   arXiv: 1304. (2882, 1850, 5748, 7467)

3. Four quark state (1 or 2)
   arXiv: 1304.0380

4. Meson loop
   arXiv: 1303.6355, 1304.4458

5. Initial State Pion Emission (ISPE) model
   arXiv: 1303.6842, 1304.5845
\[ e^+e^- \rightarrow \pi^+\pi^- X(3823) \rightarrow \pi^+\pi^- \gamma \chi_{c1} \]

- \( M = 3821 \pm 1.3 \pm 0.7 \) MeV, \( \Gamma < 16 \) MeV, Significance: 6.2\( \sigma \)!
- \( R = B[X(3823) \rightarrow \gamma \chi_{c2}] / B[X(3823) \rightarrow \gamma \chi_{c1}] < 0.43 @ 90\% \) C.L.
- Both \( Y(4360) \) and \( \Psi(4415) \) line shape give reasonable description.
  - Potential Model: D wave. \( M \sim (3.810-3.840) \) GeV, narrow.
  - \( R \sim 0.2 \)

Agree with BELLE’s 3.7\( \sigma \) evidence (PRL111, 032001)

\( X(3823) \) : good candidate for \( \Psi(1^3D_2) \)
$e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma \pi^+\pi^- J/\psi$

- Search for $\gamma X(3872)$ with $X(3872) \rightarrow \pi^+\pi^- J/\psi$ at $E_{cm} = 4.23, 4.26, 4.36$ GeV.

- $X(3872)$ significance = $6.3\sigma$, summed over all data.

- Production in $Y(4260)$ decay suggestive, but not conclusive. If from $Y(4260)$:

$$\frac{B(Y(4260) \rightarrow \gamma X(3872))}{B(Y(4260) \rightarrow \pi^+\pi^- J/\psi)} \sim 0.1$$
$Z_c(3885)^\pm$ in $e^+e^- \rightarrow \pi^\pm (D\bar{D}^*)^{-/+}$

Mass $= 3883.9\pm1.5\pm4.2$ MeV
Width $= 24.8\pm3.3\pm11.0$ MeV
Fit to angular distribution favors $1^+$

Mass and width close to $Z_c(3900)$
$Z_c(4020)^{\pm/0}$ in $e^+e^- \rightarrow \pi\pi h_c$

- $h_c \rightarrow \gamma \eta_c$, $\eta_c \rightarrow 16$ hadronic channels
- $Z_c(4020)^{\pm}$, observed
- A weak evidence for $Z_c(3900) \rightarrow \pi^\pm h_c$
- $Z_c(4020)^0$, observed
- Another iso-spin triplet established!
- $Z_c(4020)$, near the threshold of $D^*D^*\bar{D}$. 

### Table: $Z_c(4020)$ Properties

<table>
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<tr>
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</tr>
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<tbody>
<tr>
<td>$Z_c(4020)^\pm$</td>
<td>$4022.9\pm0.8\pm2.7$</td>
<td>$7.9\pm2.7\pm2.6$</td>
</tr>
<tr>
<td>$Z_c(4020)^0$</td>
<td>$4023.8\pm2.2\pm3.8$</td>
<td>Fixed(=7.9)</td>
</tr>
</tbody>
</table>

- **BESIII PRL 111, 242001(2013)**
  - $8.9\sigma$
  - $2.1\sigma$

- **BESIII PRL 113, 212002(2014)**
  - $>5\sigma$
$Z_c(4025)^{\pm/0}$ in $e^+e^-\rightarrow \pi^{\pm/0}(D^*\overline{D}^*)^{-+/+0}$

- Tag a $D^+$ and a bachelor $\pi^-$, reconstruct one $\pi^0$ to suppress the background
- $Z_c(4025)^\pm$, observed
- Coupling to $D^*D^*$-bar is much larger than to $\pi\eta_c$ if $Z_c(4025)$ and $Z_c(4020)$ are the same state.
- $Z_c(4025)^0$, observed

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<tr>
<td>$Z_c(4025)^\pm$</td>
<td>4026.3±2.6±3.7</td>
<td>24.8±5.6±7.7</td>
</tr>
<tr>
<td>$Z_c(4025)^0$</td>
<td>4025.5$^{+2.0}_{-4.7}$±3.1</td>
<td>23.0±6.0±1.0</td>
</tr>
</tbody>
</table>