Exotics and Charmonium (-like) states at BESIII

Yutie Liang
On behalf of the BESIII Collaboration

JLU Giessen, Germany
Yutie.liang@physik.uni-giessen.de

CHARM 2016, Bologna, Italy, July 5-9, 2016

* Supported by DFG, Collaborative Research Group Grand # KU 1596/2-1
Outline

- Introduction
  Exotic states, XYZ, BESIII

- Selected results:
  X states: $X(3823), X(3872), X(4140)$
  Y states: Cross section of $e^+e^- \rightarrow \pi^+\pi^-J/\psi, \pi^+\pi^-\psi(2S)$,
  $\pi^+\pi^-h_c, \omega\chi_{cJ}, \eta/\eta'J/\psi$.
  Z states: $Z_c(3900)/Z_c(3885), Z_c(4020)/Z_c(4025)$

- Summary
What are exotic states?

- Conventional hadrons consist of 2 or 3 quarks:

  Naive Quark Model:

  - *Meson*: \(\, q\bar{q}\,\)
  - *Baryon*: \(\, q\,\, q\,\, q\,\)

- QCD allows for the existence of exotic states:

  - Multi-quark states: \(N \geq 4\)
  - Hybrids: \(qqg, qqqg\ldots\)
  - Glueballs: \(gg, ggg\)
The BESIII Experiment

First physics run starts from 2009!

Double ring:
Symmetric collider

CMS energy:
2.0~4.6 GeV

Design Luminosity @$\psi(3770)$
$1 \times 10^{-33} \text{cm}^{-2} \text{s}^{-1}$ Achieved!
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 for XYZ physics at BESIII

- Luminosity ~ 5/fb.
- Large data samples around $\psi(4040)$, $Y(4260)$, $Y(4360)$, $\psi(4415)$, $Y(4660)$. 

<table>
<thead>
<tr>
<th>CM energy (GeV)</th>
<th>$L$ (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.81</td>
<td>50.5±0.03</td>
</tr>
<tr>
<td>3.90</td>
<td>52.6±0.03</td>
</tr>
<tr>
<td>4.009</td>
<td>481.96±0.01</td>
</tr>
<tr>
<td>4.09</td>
<td>52.6±0.03</td>
</tr>
<tr>
<td>4.19</td>
<td>43.0±0.03</td>
</tr>
<tr>
<td>4.21</td>
<td>54.5±0.03</td>
</tr>
<tr>
<td>4.22</td>
<td>54.1±0.03</td>
</tr>
<tr>
<td>4.26$^1$</td>
<td>523.7±0.10</td>
</tr>
<tr>
<td>4.26$^2$</td>
<td>301.9±0.08</td>
</tr>
<tr>
<td>4.31</td>
<td>44.9±0.03</td>
</tr>
<tr>
<td>4.36</td>
<td>539.8±0.10</td>
</tr>
<tr>
<td>4.39</td>
<td>55.1±0.04</td>
</tr>
<tr>
<td>4.42$^1$</td>
<td>44.6±0.03</td>
</tr>
<tr>
<td>4.42$^2$</td>
<td>1028.8±0.13</td>
</tr>
<tr>
<td>4.47</td>
<td>109.9±0.04</td>
</tr>
<tr>
<td>4.53</td>
<td>109.98±0.04</td>
</tr>
<tr>
<td>4.575</td>
<td>47.6±0.03</td>
</tr>
<tr>
<td>4.60</td>
<td>566.9±0.11</td>
</tr>
</tbody>
</table>
X States at BESIII
\[ e^+e^- \rightarrow \pi^+\pi^- X(3823) \rightarrow \pi^+\pi^- \gamma \chi_{c1} \]

- \( M = 3821 \pm 1.3 \pm 0.7 \) 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 $Y(4260)$:

$$\frac{B(Y(4260) \rightarrow \gamma X(3872))}{B(Y(4260) \rightarrow \pi^+\pi^- J/\psi)} \sim 0.1$$
\(e^+e^- \rightarrow \gamma X(4140) \rightarrow \gamma \phi J/\psi\)

The X(4140) (or “Y(4140)”) seen by CDF, [PRL 102, 242002 (2009)]

[BESIII PRD 91, 032002 (2015)]

BESIII sets upper limit for \(e^+e^- \rightarrow \gamma X(4140)\) with \(X(4140) \rightarrow \phi J/\psi\)
Y States at BESIII
Y states

Exclusive measurements of the line shapes of the cross sections to search for Y states:

1. Cross section of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$
2. Cross section of $e^+e^- \rightarrow \pi^+\pi^- \psi(2S)$
3. Cross section of $e^+e^- \rightarrow \pi^+\pi^- h_c$
4. Cross section of $e^+e^- \rightarrow \omega\chi_{cJ}$
5. Cross section of $e^+e^- \rightarrow \eta/\eta' J/\psi$
Cross section of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$

The cross section is inconsistent with a single peak for the Y(4260)!

Two peaks are favored over one peak by $> 7 \sigma$

Peak 1: $4223.7 \pm 3.2$ (4222.4 ± 3.0)
43.1 ± 4.1 (43.1 ± 3.7)

Peak 2: $4318.6^{+9.4}_{-10.2}$ (4325.5 ± 9.4)
95.7$^{+23.2}_{-18.0}$ (92.5$^{+23.2}_{-18.1}$)

Asymmetric shape? Low-mass Y(4008)?
Cross section of $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$

- $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ using ISR at BaBar
  - PRL 98, 212001 (2007)
  - Y(4360)

- $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ using ISR at Belle
  - PRD 91, 112007 (2015)
  - Y(4660)
  - No evidence for Y(4260)

- Y(4360) confirmed by BESIII
- More data will be taken soon to thoroughly study the region 4.2 ~ 4.3 GeV.
- An analysis of the $\pi^\pm\psi(2S)$ substructure will be released soon.
Cross section of $e^+e^- \rightarrow \pi^+\pi^- h_c$

Previous measurements on line shape of $\pi^+\pi^- h_c$ and comparison with $\pi^+\pi^- J/\psi$.

BESIII new preliminary result on the line shape of $\pi^+\pi^- h_c$.

The $\pi^+\pi^- h_c$ shape is different from the $\pi^+\pi^- J/\psi$.

With more data, the $\pi^+\pi^- h_c$ shape appears to be consistent with two peaks:

<table>
<thead>
<tr>
<th>$M$ (MeV)</th>
<th>$\Gamma_{tot}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4218.4±4.0±0.9</td>
<td>66.0±9.0±0.4</td>
</tr>
<tr>
<td>4391.6±6.3±1.0</td>
<td>139.5±16.1±0.6</td>
</tr>
</tbody>
</table>
Cross section of $e^+e^- \to \omega \chi_{cJ}$

- $e^+e^- \to \omega \chi_{c0}$ significant at 4.23 and 4.26 GeV
- Cross section peak near 4.23 GeV
  
  $M=(4230 \pm 8 \pm 6)$ MeV, $\Gamma=(38 \pm 12 \pm 2)$ MeV

- A new structure?
- $\Psi(4S)$ EPJC 74:3208(2014)
- Threshold effect?

$e^+e^- \to \omega \chi_{c2}$ is fitted with the coherent sum of the $\psi(4415)$ BW function and a phase-space term.
Cross section of $e^+e^- \rightarrow \eta/\eta'J/\psi$

- Agrees with previous results with improved precision
- Structure around 4.2 GeV possibly from $\Psi(4160) \rightarrow \eta J/\psi$

$\sigma(\eta'J/\psi)$ much lower than $\sigma(\eta J/\psi)$, lower than NRQCD calculation [1].

Z States at BESIII
$Z_c(3900)^{±/0}$ in $e^+e^-\rightarrow\pi\pi J/\psi$

- $Z_c(3900)^{±}$, 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>$Z_c(3900)^{±}$</td>
<td>$3899.0\pm3.6\pm4.9$</td>
<td>$46\pm10\pm20$</td>
</tr>
<tr>
<td>$Z_c(3900)^0$</td>
<td>$3894.8\pm2.3\pm2.7$</td>
<td>$29.6\pm8.2\pm8.2$</td>
</tr>
</tbody>
</table>

An iso-spin triplet established!
$Z_c(3885)^{\pm/0}$ in $e^+e^- \rightarrow \pi(D\bar{D}^*)$
$Z_c(4020)^{\pm/0}$ 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.
**$Z_c(4025)^\pm/0$ in $e^+e^-\rightarrow\pi^\pm/0(D^*\overline{D}^*)^{-+/0}$**

**Table:**

<table>
<thead>
<tr>
<th>$Z_c(4025)$</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_c(4025)^\pm$</td>
<td>$4026.3\pm2.6\pm3.7$</td>
<td>$24.8\pm5.6\pm7.7$</td>
</tr>
<tr>
<td>$Z_c(4025)^0$</td>
<td>$4025.5^{+2.0}_{-1.7}\pm3.1$</td>
<td>$23.0\pm6.0\pm1.0$</td>
</tr>
</tbody>
</table>

- 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 $\pi h_c$ if $Z_c(4025)$ and $Z_c(4020)$ are the same state.

- $Z_c(4025)^0$, observed
Overview of $Z_c$ states

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

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

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

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

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

$Z_c(3885)^0$

$M(DD^*) (\text{GeV}/c^2)$

$Z_c(3900)^\pm$ ?

$Z_c(3900)^0$ ?

$Z_c(4020)^\pm$ ?

$Z_c(4020)^0$ ?
Lots of progress in charmonium-like studies recently.

X(3823), X(3872) observed, X(4140) not found.

Y states are studied with line shapes of exclusive channels.

Z states, charged and neutral, have been observed.

X, Y, Z particles are connected via transitions.

More experimental effort is needed.
Backup
Figure 15: Distribution of $m_{J/\psi \phi}$ for the data and the fit results with a model containing only $K^{*+} \rightarrow \phi K^+$ contributions.

A near-threshold $J/\psi \phi$ structure in our data is the most significant (8.4σ) exotic contribution to our model. We determine its quantum numbers to be $J^{PC} = 1^{++}$ at 5.7σ significance (Appendix C). When fitted as a resonance, its mass $(4146.5 \pm 4.5^{+4.6}_{-2.8}$ MeV) is in excellent agreement with previous measurements for the $X(4140)$ state, although the width $(83 \pm 21^{+21}_{-14}$ MeV) is substantially larger. The upper limit which we previously set for production of a narrow ($\Gamma = 15.3$ MeV) $X(4140)$ state based on a small subset of our present data [21] does not apply to such a broad resonance, i.e. the present results are consistent with our previous analysis.
Search for $Z_c(3900)^\pm$ in $\omega\pi^\pm$

- Searching for new decay of $Z_c(3900)$ can provide useful information on its internal structure.
- No significant signals observed.

$\sigma(e^+e^-\rightarrow Z_c\pi, Z_c\rightarrow\omega\pi) < 0.27$ pb @ 4.23 GeV
$\sigma(e^+e^-\rightarrow Z_c\pi, Z_c\rightarrow\omega\pi) < 0.18$ pb @ 4.26 GeV
From the line shapes of \( \pi^+\pi^- J/\psi, \pi^+\pi^- h_c, \omega\chi_{cJ} \) in the left plot, we may conclude the \( Y(4260) \) has a lower mass and narrower width than previous measurements.
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
Compared with the Born cross section of $e^+e^- \rightarrow \eta J/\psi$ [11], the measured Born cross section of $e^+e^- \rightarrow \eta' J/\psi$ is much smaller, which is in contradiction to the calculation in Ref. [13]. There are two possible reasons contributing to this discrepancy. The cross section of $e^+e^- \rightarrow \eta' J/\psi$ is investigated at an order of $O(\alpha_s^4)$; therefore, higher order corrections might need to be considered; additionally, the proportion of gluonic admixture in $\eta'$ needs to be further studied to make certain the contribution of a gluonium component on the results.