STUDIES OF XYZ AT BESIII

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Outline

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  - Charmonium and XYZ spectrum
  - BEPCII and BESIII
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- Studies of XYZ states
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Charmonium and XYZ spectrum

- **Below open-charm threshold**
  - Good agreement between experimental measurements and theoretical predictions

- **Above open-charm threshold**
  - Many expected states not discovered
Charmonium and XYZ spectrum

- Below open-charm threshold
  - Good agreement between experimental measurements and theoretical predictions

- Above open-charm threshold
  - Many expected states not discovered
  - Many unexpected states observed:
    - charmonium final states
    - no conventional charmonium states assignment
    - called charmonium-like or XYZ states

- To do list
  - New decay modes of known charmonium(-like) states
  - New charmonium(-like) states
Beijing Electron and Positron Collider (BEPCII)

beam energy: 1.0 – 2.3 GeV

2004: started BEPCII upgrade, BESIII construction
2008: test run
2009 - now: BESIII physics run

- 1989-2004 (BEPC):
  \[ L_{\text{peak}} = 1.0 \times 10^{31} \text{ /cm}^2\text{s} \]
- 2009-now (BEPCII):
  \[ L_{\text{peak}} = 1.0 \times 10^{33} \text{ /cm}^2\text{s} \]
The BESIII detector

Magnet yoke

SC magnet, 1T

RPC

TOF, 80ps

Be beam pipe

MDC, 120 μm
0.5% at 1 GeV/c

CsI(Tl) calorimeter, 2.5% @ 1 GeV

Total weight 730 ton,
~40,000 readout chnls,
Data rate: 5kHz, 50Mb/s

Has been in full operation since 2008!
BESIII data Samples

2009: 106M $\psi(2S)$
        225M $J/\psi$
2010: 975 pb$^{-1}$ at $\psi(3770)$
2011: 2.9 fb$^{-1}$ at $\psi(3770)$ (total)
        482 pb$^{-1}$ at 4.01 GeV
2012: 0.45B $\psi(2S)$ (total)
        1.3B $J/\psi$ (total)
2013: 1092 pb$^{-1}$ at 4.23 GeV
        826 pb$^{-1}$ at 4.26 GeV
        540 pb$^{-1}$ at 4.36 GeV
        ~50 pb$^{-1}$ at 3.81, 3.90, 4.09, 4.19, 4.21
        4.22, 4.245, 4.31, 4.39, 4.42 GeV
2014: 1029 pb$^{-1}$ at 4.42 GeV
        110 pb$^{-1}$ at 4.47 GeV
        110 pb$^{-1}$ at 4.53 GeV
        48 pb$^{-1}$ at 4.575 GeV
        567 pb$^{-1}$ at 4.6 GeV
        0.8 fb$^{-1}$ R-scan from 3.85 to 4.59 GeV (104 points)
2015: R-scan from 2-3 GeV + 2.175 GeV data
2016: ~3fb$^{-1}$ at 4.18 GeV (for $D_s$)
2017: 500/pb each for 7 energy points between 4.19~4.28 GeV
        400/pb around chic c1
        200/pb around X(3872)

~ 130 points for R scan (~1.3 fb$^{-1}$)

~ 8 fb$^{-1}$ above 4.0 GeV in total
Studies of XYZ states

- The $Z_c$ states

  ---- Determination of $J^P$ of $Z_c(3900)$

  - $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$
  
  - $e^+e^- \rightarrow K\bar{K}J/\psi$
  
  - $e^+e^- \rightarrow \pi^+D^0D^{*-}$
    - Preliminary result
  
  - $e^+e^- \rightarrow \phi\chi_{c1,2}$
The $Z_c$ states

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

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

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

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

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

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

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

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

ST: PRL 112, 022001 (2014)
DT: PRD92, 092006 (2015)
Determination of $J^P$ of $Z_c(3900)$

Six contributions are considered in the amplitude:

- $\sigma(500), f_0(980), f_2(1270)$, and $f_0(1370)$ in the $\pi^+\pi^-$ mass spectrum;
- $Z_c(3900)^\pm$ in the $\pi^\pm J/\psi$ mass spectrum;
- The nonresonant process: $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$.

Five $J^P$ assumptions: $0^-, 1^-, 1^+, 2^-, \text{ and } 2^+$. 

![Graph showing data and fit for $M_{\pi^+\pi^-}$]
Determination of $J^P$ of $Z_c(3900)$

Simultaneous fit to data samples at 4.23 GeV and 4.26 GeV. $Z_c(3900)^+$ and $Z_c(3900)^-$ states are assumed as isospin partner, share the same mass and coupling constants;

$Z_c(3900)^\pm$ is parameterized with Flatte-like formula:

$$BW(s) = \frac{1}{s - M^2 + i(g'_1 \rho_{J/\psi}(s)) + (g'_2 \rho_{D^*D}(s))'}$$

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

$J^P$ of $Z_c$ favor to be $1^+$ with statistical significance larger than 7$\sigma$ over other quantum numbers;

$g'_2/g'_1$ is consistent with previous result 27.1$\pm$13.1, estimated based on the measured decay width ratio of $Z_c(3885)^\pm \to (D\bar{D}^*)^\pm$ and $Z_c(3900)^\pm \to \pi^\pm J/\psi$. 

<table>
<thead>
<tr>
<th>$Z_c$</th>
<th>Mass</th>
<th>$g'_1$ (GeV$^2$)</th>
<th>$g'_2/g'_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+</td>
<td>3901.5$\pm$2.7$\pm$38.0</td>
<td>0.075$\pm$0.006$\pm$0.025</td>
<td>27.1$\pm$2.0$\pm$1.9</td>
</tr>
</tbody>
</table>
$e^+ e^- \rightarrow \pi^0 \pi^0 \psi(3686)$

Y(4360) was observed and subsequently confirmed in $e^+ e^- \rightarrow (\gamma_{ISR}) \pi^+ \pi^- \psi(3686)$ by BABAR, Belle, and BESIII, it is interesting to study the Y(4360) in $\pi^0 \pi^0$ transition to $\psi(3686)$ and to examine the isospin symmetry;

A charmoniumlike structure observed in $\pi^\pm \psi(3686)$ invariant mass by BESIII and Belle measurements. We can search for its neutral isospin partner in $e^+ e^- \rightarrow \pi^0 \pi^0 \psi(3686)$.

The width of the intermediate state in BESIII measurement varies in a wide range for different kinematic region within the data set, more data and theoretical input are necessary.
Decay channel: $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$, $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow \ell^+\ell^-(\ell = e \text{ or } \mu)$;

16 energy points from $\sqrt{s} = 4.008$ to 4.600 GeV, the total luminosity is about 5.2 fb$^{-1}$;

The result of cross section measurement is consistent with the charged mode from isospin symmetry.
\[ e^+ e^- \rightarrow \pi^0 \pi^0 \psi(3686) \]

A neutral charmoniumlike structure is observed in \( \pi^0 \psi(3686) \) invariant mass;

A simple fit with S-wave Breit-Wigner function is performed, and yield a mass with mass \((4038.7 \pm 6.5) \text{ MeV}/c^2 \), which confirms the structure in the charged mode;

No obvious \( Z_c(3900)^0 \) state is observed in the fit.
Measure the cross section of $e^+e^- \rightarrow K\bar{K}J/\psi$ at c.m. energies from 4.189 to 4.600 GeV.

The energy dependence of the cross section for $e^+e^- \rightarrow K^+K^-J/\psi$ is shown to differ from that for $\pi^+\pi^-J/\psi$ in the region around the Y(4260);

The ratio of cross sections for $e^+e^- \rightarrow K^+K^-J/\psi$ and $e^+e^- \rightarrow K_S^0K_S^0J/\psi$ is consistent with expectations from isospin conservation.
Most precise cross section measurement for center-of-mass energy from 4.05 to 4.60 GeV;

Fit with a coherent sum of three-body phase space term (pink dashed triple-dot line) and two Breit-Wigner functions (green dashed double-dot line and aqua dashed line);

The statistical significance of two resonant assumption over one resonant assumption is greater than 10σ;

\[ M(Y(4220)) = (4224.8 \pm 5.6 \pm 4.0) \text{ MeV}/c^2, \Gamma(Y(4220)) = (72.3 \pm 9.1 \pm 0.9) \text{ MeV}. \]

\[ M(Y(4390)) = (4400.1 \pm 9.3 \pm 2.1) \text{ MeV}/c^2, \Gamma(Y(4390)) = (181.7 \pm 16.9 \pm 7.4) \text{ MeV}. \]
$e^+ e^- \rightarrow \phi \chi_{c1,2}$

- BESIII has measured the cross section of $e^+ e^- \rightarrow \omega \chi_{c0}$ and observed an intermediate resonance around 4226 MeV/c².
- Considering that $\omega$ and $\phi$ have the same spin, parity, and isospin, $\omega \chi_{cJ}$ and $\phi \chi_{cJ}$ may have a similar production mechanism.
- We study the $e^+ e^- \rightarrow \phi \chi_{c0,1,2}$ at $\sqrt{s} = 4.60$ GeV (567 pb⁻¹), where $\chi_{c0} \rightarrow \pi^+\pi^-, K^+K^-, K^+K^-\pi^+\pi^-$, and $\pi^+\pi^-\pi^+\pi^-$, $\chi_{c1,2} \rightarrow \gamma J/\psi, J/\psi \rightarrow \ell^+\ell^- (\ell = e \text{ or } \mu)$, and $\phi \rightarrow K^+K^-.$

- BESIII has searched for the Y(4140) in the process of $e^+ e^- \rightarrow \gamma \phi J/\psi$ with data samples at c.m. energies $\sqrt{s} = 4.23, 42.6, \text{ and } 4.36$ GeV, but no obvious signal has been observed. We also can repeat this analysis at $\sqrt{s} = 4.60$ GeV.
No obvious $e^+e^- \rightarrow \phi\chi_{c0}$ signals are observed, the production $\sigma(e^+e^- \rightarrow \phi\chi_{c0}) < 5.4$ pb @ 90% C.L.;

The first observation of $e^+e^- \rightarrow \phi\chi_{c1}$ and $\phi\chi_{c2}$, $\sigma(e^+e^- \rightarrow \phi\chi_{c1}) = 4.2^{+1.7}_{-1.0}$ pb and $\sigma(e^+e^- \rightarrow \phi\chi_{c2}) = 6.7^{+3.4}_{-1.7}$ pb;

No obvious $e^+e^- \rightarrow \gamma Y(4140)$ signals are observed, $\sigma(e^+e^- \rightarrow \gamma Y(4140)) \times \mathcal{B}(Y(4140) \rightarrow \phi J/\psi) < 1.2$ pb @ 90% C.L.
Summary & Outlook

• Recent results of XYZ states at BESIII are presented. BESIII is an active and successful experiment for charmonium(-like) spectroscopy study.

• A new $Z_c$ structure in $\pi\psi(3686)$?

• The $J^P$ of $Z_c(3900)$ is determined to be $1^+$. 

- Continue to take data and increase the beam energy;
- Provide cutting-edge results in charmonium spectroscopy.

Thank You!
Backup
Hadrons: naive and exotic

- Naive quark model:
  - 2 quarks: meson (q̅q)
  - 3 quarks: baryon (qqq)

- QCD predicts the exotic states:
  - Multiquark states: $N_{\text{quarks}} \geq 4$
  - Molecule: bound state of hadrons
  - Hybrid: $N_{\text{quarks}} \geq 2 + \text{gluon}$
  - Glueball: $N_{\text{quarks}} = 0$ (gg, ggg, ...)