Recent Progress on the Charmonium and XYZ states at BESIII

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Beijing Electron Positron Collider (BEPCII)

- $E_{\text{beam}}$: 1.0-2.3 GeV
- $\sigma_E$: $5.16 \times 10^{-4}$
- L: $1.0 \times 10^{33}$ cm$^{-2}$s$^{-1}$ @3.773 GeV
**BESIII detector**

**Main Drift Chamber**
- Small cell, 43 layers
- \( \sigma_{xy} = 130 \, \mu m, \, dE/dx \sim 6\% \)
- \( \sigma_p/p = 0.5\% \) at 1 GeV

**Time Of Flight**
- Plastic scintillator
  - \( \sigma_T \) (barrel): 80 ps
  - \( \sigma_T \) (endcap): 110 ps
  - (endcap update with MRPC \( \sigma_T:65 \) ps)

**Electromagnetic Calorimeter**
- CsI(Tl): \( L=28 \, cm \) (15\( X_0 \))
- Energy range: 0.02-2 GeV
- Barrel \( \sigma_E = 2.5\% \), \( \sigma_l = 6 \, mm \)
- Endcap \( \sigma_E = 5.0\% \), \( \sigma_l = 9 \, mm \)

**Muon Counter**
- Resistive plate chamber
- Barrel: 9 layers
- Endcaps: 8 layers
- \( \sigma_{\text{spatial}} = 1.48 \, cm \)
Data sets for Charmonium and XYZ study

- World largest data samples on $J/\psi$ (~10 billion), $\psi(3686)$ (~0.45 billion)
- XYZ data:
  - 5 fb$^{-1}$ $e^+e^-$ collision data event in open charm region from 3.8 to 4.6 GeV in 2013
  - totally ~13 fb$^{-1}$ data taken in 4.0~4.60 GeV, more data samples are being taken this year (~3.8 fb$^{-1}$)
- R-scan data: 104 energy points from 3.85 to 4.59 GeV, integrated luminosity~0.79 fb$^{-1}$
The Charmonium System

- $c\bar{c}$ bound states can be described using potential models
- All predicted states below the $D\bar{D}$ threshold have been found!
- Properties are in agreement with predictions
- Many unpredicted states were reported above the $D\bar{D}$ threshold, called “XYZ” states

“XYZ” states
- “X”: Neutral, $J^{pc} \neq 1^{--}$
  - Observed in radiative or hadronic transitions from Y.
- “Y”: Neutral, $J^{pc} = 1^{--}$
  - Direct access in $e^+e^-$ annihilation.
- “Z”: isospin triplets
  - Observed in hadronic transitions from Y.
Recently highlight results in Charmonium and XYZ

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

✓ Observation of $X(3872) \rightarrow \omega J/\psi$  
  arXiv:1903.04695(accepted by PRL)

✓ Open charm and radiative decay transitions of $X(3872)$  
  (BESIII preliminary)

✓ Resonant structure in $e^+ e^- \rightarrow \pi^+ D^0 D^{*-}$  

✓ Resonant structure in $e^+ e^- \rightarrow \omega \chi_{c0}$  

✓ Observation of $e^+ e^- \rightarrow \pi^+ \pi^- \psi(3770)$ and $D_1(2420)\bar{D}$  
  arXiv: 1903.08126v1(submit to PRD)

✓ Evidence for $Z_c(3900) \rightarrow \rho^+ \eta_c$  
  (BESIII preliminary)  [in BACKUP]
The $X(3872)$ state

**Discovery of $X(3872)$ ($J^{PC} = 1^{++}$)**
- First observed by Belle in $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ decay
- Observed in $X(3872) \rightarrow \gamma J/\psi$ process by Babar and Belle
- Evidence of $X(3872) \rightarrow \omega J/\psi$ reported by Belle and Babar
- $M(X(3872)) = 3871.69 \pm 0.17 \text{ MeV}/c^2$
- $\Gamma < 1.2 \text{ MeV} \ (90\% \text{ C.L.})$
- At BESIII, $X(3872)$ is observed via $e^+ e^- \rightarrow \gamma X(3872) \rightarrow \gamma \pi^+ \pi^- J/\psi$

**Possible configuration for $X(3872)$**
- Conventional Charmonium state? $\chi'_{c1}$?
- Molecule-like $X(3872) = (D^{*0}\bar{D}^0 + D^0\bar{D}^{*0})/\sqrt{2}$
- Tetraquark
- …

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**Molecule**

\[ \text{d} \hat{\text{u}} \text{\ldots} \pi^-,\ldots \]

**Tetraquark**

\[ d\bar{d}u\bar{s} \]

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PRL. 92, 262001 (2003)

PRL. 112, 092001 (2014)
**$X(3872) \rightarrow \pi^0 \chi_{c1}(1P)$**

- **Data sample:** 9.0 fb$^{-1}$ data from 4.15 to 4.30 GeV
- **Reconstructed processes:**
  - **Signal channel:** $e^+e^- \rightarrow \gamma X(3872), \ X(3872) \rightarrow \pi^0 \chi_{cJ}$ (with $\chi_{cJ} \rightarrow \gamma J/\psi, J/\psi \rightarrow l^+l^-$)

\begin{align*}
\text{Clear signal of } X(3872) \text{ in } Y(4260) \text{ zone, } N_{X(3872)} &= 16.9^{+5.2}_{-4.9} \\
\text{No } X(3872) \text{ events outside of } Y(4260) \text{ zone} \\
\text{Clear cluster of } \chi_{c1}(1P) \text{ events in } X(3872) \text{ mass window} \\
\text{First observation of } X(3872) \rightarrow \pi^0 \chi_{c1}(1P) \text{ with significance } >5\sigma.
\end{align*}
In conventional $c\bar{c}$ hypothesis, $\Gamma(X(3872) \rightarrow \pi^0\chi_{c1}) \sim 0.06$ keV \textit{PRD 77, 014013(2008)}

In tetraquark/molecular state hypothesis, the decay width could be sizeable. \textit{PRD 92, 034019 (2015)}

Using $3.3\% < \mathcal{B}(X(3872) \rightarrow \pi^+\pi^-J/\psi) < 6.4\%$: $\mathcal{B}(X(3872) \rightarrow \pi^0\chi_{c1}) \sim 3$-$6\%$. 

If $X(3872)$ interpret as $\chi_{c1}(2P)$: $\Gamma(X(3872)) \sim 1.0$-$2.0$ keV, which is orders of magnitude smaller than all other observed charmonium states.

This measurement disfavors the $c\bar{c}$ interpretation of $X(3872)$
$X(3872) \rightarrow \omega J/\psi$

- Data sample: 11.6 fb$^{-1}$ data from 4.008 to 4.600 GeV
- Signal process: $e^+e^- \rightarrow \gamma X \rightarrow \gamma \omega J/\psi$, with $\omega \rightarrow \pi^+\pi^-\pi^0$, $J/\psi \rightarrow l^+l^-$

- An unbinned maximum-likelihood fit performed to $\omega J/\psi$.
- Signal PDF:
  - Three resonances hypothesis: (X(3872), X(3915) and X(3960))
    \[ N_{\text{sig}}(X(3872)) = 45 \pm 9 \pm 3 \]
  - Two resonance hypothesis: (X(3872), X(3915))
    \[ N_{\text{sig}}(X(3872)) = 40 \pm 8 \pm 2 \]

Hard to distinguish the two hypotheses since only 2.5$\sigma$ difference.
The production cross section of $e^+e^- \rightarrow \gamma X(3872)$ ($\sigma \cdot B(X(3872) \rightarrow \omega J/\psi)$) is calculated at each energy point.

The line-shape can be described by a single BW resonance $Y(4200)$.

A simultaneous fit to the $X(3872) \rightarrow \omega J/\psi$ and $\pi^+\pi^- J/\psi$ cross section gives

\[
M(Y(4200)) = 4200.6^{+7.9}_{-13.3} \pm 3.0 \text{ MeV}/c^2
\]
\[
\Gamma(Y(4200)) = 115^{+38}_{-26} \pm 12 \text{ MeV}
\]

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

(0.8\pm0.3 from Babar)
$X(3872) \rightarrow \gamma J/\psi, \gamma \psi(3686), D^0 \overline{D}^{*0}, \gamma D^+ D^-$

- Data sample: 8.5 fb$^{-1}$ from $\sqrt{s} = 4.178$ to 4.278 GeV

$X(3872) \rightarrow \gamma J/\psi$

$J/\psi \rightarrow \mu\mu/ee$

$X(3872) \rightarrow \gamma \psi(3686)$

$\psi(3686) \rightarrow \pi^+ \pi^- J/\psi$

$\psi(3686) \rightarrow \mu\mu$

$\frac{B[X(3872)\rightarrow \gamma \psi(3686)]}{B[X(3872)\rightarrow \gamma J/\psi]} < 0.59$ at 90% C.L.

- Simultaneous fit; significance $> 3.5 \sigma$

- Simultaneous fit; no evident signal

Expectation strength
$X(3872) \rightarrow \gamma J/\psi, \gamma \psi(3686), D^0 \bar{D}^*0, \gamma D^+D^-$

$X(3872) \rightarrow D^0 \bar{D}^*0 + c.c.$  

$D^0 \rightarrow \gamma D^0, \pi^0 D^0$

$D^0 \rightarrow K\pi, K\pi\pi, K\pi\pi\pi$

$X(3872) \rightarrow \gamma D^+D^-$

$D^\pm \rightarrow K\pi\pi, K\pi\pi\pi$

$N_{\gamma D^+D^-} = 0.0^{+0.5}_{-0.0}$

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

- Relative branching ratio compared with $X(3872) \rightarrow \pi^+\pi^- J/\psi$

<table>
<thead>
<tr>
<th>mode</th>
<th>$D^*0 \bar{D}^0 + c.c.$</th>
<th>$\gamma J/\psi$</th>
<th>$\gamma \psi'$</th>
<th>$\gamma D^+D^-$</th>
<th>$\omega J/\psi$</th>
<th>$\pi^0 \chi_{c1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ratio</td>
<td>$14.81 \pm 3.80$</td>
<td>$0.79 \pm 0.28$</td>
<td>$&lt; 0.42$</td>
<td>$&lt; 0.99$</td>
<td>$1.7^{+0.4}_{-0.3} \pm 0.2$ [27]</td>
<td>$0.88^{+0.33}_{-0.27} \pm 0.10$ [37]</td>
</tr>
</tbody>
</table>
The Y states

- **Y(4260)** in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$
  - Discovery in ISR process by BaBar
  - Confirmed by Belle.

<table>
<thead>
<tr>
<th>Y(4260)</th>
<th>PDG2018</th>
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</thead>
<tbody>
<tr>
<td>$M[Y(4260)]$</td>
<td>$4230 \pm 8$ (MeV/c$^2$)</td>
</tr>
<tr>
<td>$\Gamma_{tot}[Y(4260)]$</td>
<td>$55 \pm 19$ (MeV)</td>
</tr>
</tbody>
</table>

- At BESIII, two resonant structures are observed in the energy region of Y(4260).
  - Y(4320) observed for the first time with $7.6\sigma$ significance.
  - No hint of Y(4008) which is seen in Belle.

$$M_1 = 4222.5 \pm 3.1 \pm 1.4 \text{ MeV/c}^2, \Gamma_1 = 44.1 \pm 4.3 \pm 2.0 \text{ MeV}$$

$$M_2 = 4320.0 \pm 10.4 \pm 7.0 \text{ MeV/c}^2, \Gamma_2 = 101.4^{+25.3}_{-19.7} \pm 10.2 \text{ MeV}$$

References:
- PRD 86, 051102 (R) (2012)
- PRL 110, 252002 (2013)
- PRL 118, 092001 (2017)
- PDG2018
The Y states

- $Y(4360)$, $Y(4660)$ in $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$
  - Discovery in ISR process by Belle
  - Confirmed by Babar.
  - No evidence for the $Y(4260)$

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<tr>
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<th>PDG2018</th>
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<tbody>
<tr>
<td>$\Gamma_{\text{tot}}[Y(4260)]$</td>
<td>$55 \pm 19$(MeV)</td>
</tr>
<tr>
<td>$M[Y(4360)]$</td>
<td>$4368 \pm 13$ (MeV/c$^2$)</td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}[Y(4360)]$</td>
<td>$96 \pm 7$(MeV)</td>
</tr>
<tr>
<td>$M[Y(4660)]$</td>
<td>$4643 \pm 9$ (MeV/c$^2$)</td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}[Y(4660)]$</td>
<td>$72 \pm 11$(MeV)</td>
</tr>
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</table>

- At BESIII, two resonant structures observed in energy region 4.2-4.4 GeV
  - $Y(4220)$ observed for the first time in this process with significance of $5.8\sigma$

$$M_1 = 4209.5 \pm 7.4 \pm 1.4 \text{ MeV/c}^2, \quad \Gamma_1 = 80.1 \pm 24.6 \pm 2.9 \text{ MeV}$$
$$M_2 = 4383.8 \pm 4.2 \pm 0.8 \text{ MeV/c}^2, \quad \Gamma_2 = 84.2 \pm 12.5 \pm 2.1 \text{ MeV}$$
The Y states

**Some more Y states** observed at BESIII

- Y(4220), Y(4390) observed in $\pi^+\pi^- h_c$
- Y(4220) observed in $\omega \chi_{c0}$

**Why “exotic”**

- No natural place within quark model.
- Strongly coupling to $\pi^+\pi^- J/\psi$ rather charm decay modes.
- Dip on R-value

**Theoretical interpretation**

- Hybrid charmonium
- Tetraquark
- Hadronic molecule
- ...
Using data sample from 4.05 to 4.60 GeV

Reconstructed channel: $D^0 \rightarrow K^- \pi^+$

Using $RM(D^0 \pi^+) + M(D^0) - m(D^0)$ to select $D^{*-}$ signal

Peaking background comes from isospin partner $e^+e^- \rightarrow \pi^+D^-D^{*0}$

Fit with a coherent sum of three-body PHSP and two BW functions

Significance of two structures greater than $10\sigma$ over one structure assumption

$M_1 = 4228.6 \pm 4.1 \pm 6.3$ MeV/$c^2$, $\Gamma_1 = 77.1 \pm 6.8 \pm 6.8$ MeV

The resonance parameters around 4.40 GeV strongly depend on the model and need further studies

$e^+ e^- \rightarrow \omega \chi_{c0}$

Data sample: 7 fb$^{-1}$ from 4.178 to 4.278 GeV

The $\chi_{c0}$ is reconstructed from $\pi^+\pi^-$ and $K^+K^-$

This observation confirms and improves the previous result

$M = (4218.5 \pm 1.6 \pm 4.0)$ MeV/c$^2$

$\Gamma = (28.2.0 \pm 3.9 \pm 1.6)$ MeV
\[ e^+ e^- \rightarrow \pi^+ \pi^- \psi(3770), \ D_1(2420) \bar{D} \]

- Study the intermediate states of \[ e^+ e^- \rightarrow \pi^+ \pi^- D^0 \bar{D}^0 \], \[ e^+ e^- \rightarrow \pi^+ \pi^- D^+ D^- \]
  - \[ D^0 \rightarrow K^- \pi^+ \], \[ K^- \pi^+ \pi^0 \], \[ K^- \pi^+ \pi^+ \pi^- \] and \[ K^- \pi^+ \pi^+ \pi^- \pi^0 \]
  - \[ D^+ \rightarrow K^- \pi^+ \pi^+ \], \[ K^- \pi^+ \pi^+ \pi^0 \], \[ K_S^0 \pi^+ \], \[ K_S^0 \pi^+ \pi^0 \], and \[ K_S^0 \pi^+ \pi^+ \pi^- \]

- \[ e^+ e^- \rightarrow \pi^+ \pi^- \psi(3770) \] is observed for the first time at 4.42 GeV.
- Hints in \( \pi^\pm \psi(3770) \) mass spectrum at 4.04 and 4.13 GeV/c^2 in \( \sqrt{s} = 4.42 \) GeV data
- Clear structure in line-shape of \( \pi^+ \pi^- \psi(3770) \)
Three different decay channels ($D^0\pi^+\pi^−$, $D^{*+}\pi^−$, and $D^+\pi^+\pi^−$) are used to search for $D_1(2420)$

Clear structure in the line-shape of $e^+e^− \rightarrow D_1(2420)\bar{D}$
The Y states

Parameters of the Peaks in $e^+e^-$ Cross Sections

```
\begin{align*}
\psi(4160)_R & \\
\psi(4415)_R & \\
"Y(4220)"_{\pi\pi\psi} & \\
"Y(4320)"_{\pi\pi\psi} & \\
"Y(4220)"_{\pi\pi\psi(2S)} & \\
"Y(4390)"_{\pi\pi\psi(2S)} & \\
"Y(4220)"_{\pi\pi h_c} & \\
"Y(4390)"_{\pi\pi h_c} & \\
"Y(4220)"_{\pi\pi DD} & \\
"Y(4390)"_{\pi\pi DD} & \\
\end{align*}
```
Summary

BESIII has achieved great progress recently in Charmonium system, especially in XYZ studies, which help discriminate different theoretical interpretation.

- New decay mode $X(3872) \rightarrow \pi^0 \chi_{c1}$ is observed
- First firm observation of $X(3872) \rightarrow \omega J/\psi$
- Exclusive decays of $X(3872)$ is searched
- Two enhancement observed in the lineshape of $e^+e^- \rightarrow \pi^+D^0D^{*-}$
- Improved measurement of process $e^+e^- \rightarrow \omega \chi_{c0}$
- Line-shape measured for process $e^+e^- \rightarrow \pi^+\pi^-\psi(3770), D_1(2420)\bar{D}$

There are still many remain unanswered questions.

BESIII continues taking data and increasing the beam energy, more results in Charmonium system are foreseen.

Thanks
Backup
The Z states

- Discovery of a resonant structure decaying to $J/\psi \pi^\pm$ in $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$ by BESIII, and observed via ISR in Belle.

- Absolutely exotic!
  - Decays to $J/\psi \Rightarrow$ contain $c \bar{c}$
  - Electrically charged $\Rightarrow$ contains $u \bar{d}$
  - Very close to the $D D^*$ threshold

- Z states at BESIII
$Z_c(3900)^{\pm} \rightarrow \rho^{\pm}\eta_c$

The ratio of $\mathcal{B}(Z_c \rightarrow \rho\eta_c) / \mathcal{B}(Z_c \rightarrow \pi J/\psi)$ can be used to discriminate between the molecule and tetraquark scenarios.

The green band and yellow band show the $1\sigma$ and $2\sigma$ confidence range of the corresponding theoretical model.

A. Esposito et al., PLB 746(2015), 194-201
$Z_c(3900)^\pm \rightarrow \rho^\pm \eta_c$

- $\pi^+\pi^-\pi^0\eta_c$ final state is studied with $\eta_c$ reconstructed from 9 hadronic decay modes: ($p\bar{p}$, $2(K^+K^-)$, $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0$, $p\bar{p}\pi^0$, $K_sK\pi$, $\pi^+\pi^-\eta$, $K^+K^-\eta$ and $\pi^+\pi^-\pi^0\pi^0$)

- First evidence for the $Z_c(3900)^\pm \rightarrow \rho^\pm \eta_c$ is observed with 3.9$\sigma$ significance at 4.226 GeV.

- No significant signal is observed in $Z_c(4020)^\pm \rightarrow \rho^\pm \eta_c$
The production Born cross section is calculated at 4.226 GeV:

\[ \sigma(e^+e^- \to \pi^+\pi^-\pi^0\eta_c) = (46 \pm 12 \pm 10) \text{ pb} \]

\[ \sigma(e^+e^- \to \pi Z_c, Z_c \to \rho \eta_c) = (47 \pm 11 \pm 11) \text{ pb} \]

This measurement doesn't agree with both molecular Zc and tetraquark Zc Type-1 assumptions.