Charmonium study at BESIII

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Charmonium spectroscopy

S and D-wave spin-triplets have the same quantum number as the photon!

Godfrey & Isgur, PRD32, 189 (1985)

n radial quantum number
S total spin of c & cbar
L orbital angular momentum
L = 0, 1, 2 ... correspond to S, P, D, ...

J = S + L
P = (−1)^{L+1} parity
C = (−1)^{L+S} charge conj.
Charmonium(like) spectroscopy

- Charmonium-like (XYZ) particles
- New type of hadron (multi-quark ...)?
- Too many vector states! Exotics?

- **Charged**

- **Unpredicted, discovered**
- **Predicted, discovered**

2015 BESIII

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.660</td>
<td>Y(4660)</td>
</tr>
<tr>
<td>4.415</td>
<td>ψ(4415)</td>
</tr>
<tr>
<td>4.360</td>
<td>Y(4360)</td>
</tr>
<tr>
<td>4.260</td>
<td>Y(4260)</td>
</tr>
<tr>
<td>4.160</td>
<td>ψ(4160)</td>
</tr>
<tr>
<td>4.040</td>
<td>ψ(4040)</td>
</tr>
<tr>
<td>3.770</td>
<td>ψ(3770)</td>
</tr>
<tr>
<td>3.007</td>
<td>J/ψ</td>
</tr>
<tr>
<td>2.800</td>
<td>ηc(1S)</td>
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- **2005**

<table>
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<th>Mass (GeV)</th>
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<tbody>
<tr>
<td>3.872</td>
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<tr>
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<td>ηc(2S)</td>
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<tr>
<td>3.010</td>
<td>ψ(2S)</td>
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- **1974**

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Zc(3900)

charged
Beijing Electron Positron Collider (BEPC)

Beam energy: 1.0 – 2.3 GeV

BESIII detector

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

- Magnet yoke
- SC magnet, 1T
- MUC (RPC)
- TOF, 90 ps (120 ps)
- Be Beam pipe
- MDC, 120 mm
- EMC (CsI(Tl) calorimeter), 2.5 %@ 1 GeV

A total weight of 730 t, ~40,000 readout channels, data rate 6,000 Hz ~50 Mb/s
BESIII data samples

Note that luminosity is lower at $J/\psi$, and machine is optimal near $\psi''$ peak

Int. lum.: Jan. 2009–Mar. 2017
about 17 fb$^{-1}$ @ different energies
Note increase in slopes!

$\psi(4160)$: 3.2 fb$^{-1}$ [2016]
$\psi(3770)$: 2.9 fb$^{-1}$
$\psi'$: 0.5 B
$J/\psi$: 1.3 B

XYZ: 11 fb$^{-1}$ [2013-17]

2009: $\psi'$ & $J/\psi$

2010: $\psi''$

2011: $\psi''$ & $\psi(4040)$

2012: $\psi'$ & $J/\psi$
[0.35B & 1.1B]
Study of $e^+ e^- \rightarrow \pi^+ \pi^- D \bar{D}$

- The topology of $e^+ e^- \rightarrow \pi^+ \pi^- D \bar{D}$:
Motivation

\[ e^+ e^- \rightarrow \pi^+ \pi^- J/\psi \]
at 4.26 GeV

BESIII, PRL 110, 252001 (2013)
525 pb\(^{-1}\) at 4.26 GeV

Charged charmonium-like structure

\[ M = (3899.0 \pm 3.6 \pm 4.9) \text{ MeV/c}^2 \]
\[ \Gamma = (46 \pm 10 \pm 20) \text{ MeV} \]

Confirmed by Belle PRL 110, 252002
and with CLEOc data PLB 727, 366

Close to DD\(^*\) threshold
Interpretation?
Motivation

- BESIII also observed a charged charmonium-like structure $Z_c(4020)$ in $e^+e^- \rightarrow \pi^+\pi^- h_c$.

- $\psi(3770)$ is also a member of charmonium like $J/\psi$ and $h_c$, so is there any similar $Z_c$ structure in $\pi^\pm \psi(3770)$ system?

- Through precision measurement, BESIII observed $Y(4220)$ and $Y(4320)$ in the line-shape of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$, observed $Y(4220)$ and $Y(4390)$ in the line-shape of $e^+e^- \rightarrow \pi^+\pi^- h_c$. Is there any similar $Y$ states in the line-shape of $e^+e^- \rightarrow \pi^+\pi^- \psi(3770)$?

Inconsistent with a signal peak for the $Y(4260)$ (significance>$7\sigma$)
Motivation

- $1^3D_2$ charmonium $X(3823)$ has been observed by BESIII in $e^+e^- \rightarrow \pi^+\pi^- X(3823)$, $X(3823) \rightarrow \gamma \chi_{c1}$.
- $\sigma[e^+e^- \rightarrow \pi^+\pi^- \psi(3770)/\psi(1^3D_3)]$ may have the same level with $\sigma[e^+e^- \rightarrow \pi^+\pi^- X(3823)]$.
Motivation

- $X(3872)$: First charmonium-like states been observed.
- Under the $D\bar{D}^*$ molecular description of the $X(3872)$, can predict a $D^*\bar{D}^*$ bund state $X_2(4013)$ according to heavy quark spin symmetry.

$X_2(4013)$ decay dominantly into $D\bar{D}$ and $D\bar{D}^*$.

$\Gamma \sim 2-8$ MeV
Motivation

- Y(4260) is the first vector charmonium-like states been found.
- The peculiar characteristics of Y(4260) initiate many discussions about the nature of Y(4260). Some theory suggest that the Y(4260) is a $\bar{D}D_1$ molecule.
- This interpretation can accommodate nearly all the present observations for Y(4260). Such as its absence in various open charm decay channels and the observation of $Z_c(3900)$ in $Y(4260) \to \pi^+\pi^- J/\psi$.
- If Y(4260) is a $\bar{D}D_1$ molecule. The cross-section will rise fast near the threshold.
Method

- The processes we studied:
  - $e^+e^- \rightarrow \pi^+\pi^-\psi(3770) \rightarrow \pi^+\pi^-D\bar{D}$
  - $e^+e^- \rightarrow \pi^+\pi^-X(4013) \rightarrow \pi^+\pi^-D\bar{D}$
  - $e^+e^- \rightarrow \bar{D}D_1 \rightarrow \pi^+\pi^-D\bar{D}$

- Reconstructed method
  - 5 fb$^{-1}$ data at 4.09-4.60 GeV.
  - Full reconstruction, tag $D$ and $\bar{D}$, extra $\pi^+$ and $\pi^-$. 
  - Combine the final states $\pi^+\pi^-D\bar{D}$ to get the Intermediate states.

<table>
<thead>
<tr>
<th>$D^0$ channel</th>
<th>$D^+$ channel</th>
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<tbody>
<tr>
<td>$K^-\pi^+$</td>
<td>$K^-\pi^+\pi^+$</td>
</tr>
<tr>
<td>$K^-\pi^+\pi^0$</td>
<td>$K^-\pi^+\pi^+\pi^0$</td>
</tr>
<tr>
<td>$K^-\pi^+\pi^-\pi^+$</td>
<td>$K_S^0\pi^+$</td>
</tr>
<tr>
<td>$K^-\pi^+\pi^-\pi^0$</td>
<td>$K_S^0\pi^+\pi^0$</td>
</tr>
<tr>
<td></td>
<td>$K_S^0\pi^+\pi^-\pi^+$</td>
</tr>
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</table>
\[ e^+ e^- \rightarrow \pi^+ \pi^- \psi(3770) \]

- Observed the process \( e^+ e^- \rightarrow \pi^+ \pi^- \psi(3770) \).
- No \( \psi(1^3D_3) \) signal and no significant signal of \( Z_c \) in the \( \pi^\pm \psi(3770) \) system.
- Clear structure in the line-shape of \( \pi^+ \pi^- \psi(3770) \).
\[ e^+ e^- \rightarrow \pi^+ \pi^- X_2(4013) \]

- No significant signal of \( X_2(4013) \) was observed in the \( D\bar{D} \) invariant distribution.
- Maybe we can search for this process at higher energy points.
- Also we can search for \( X_2(4013) \) via \( e^+ e^- \rightarrow \gamma X_2(4013) \) (on going).
$e^+ e^- \rightarrow \overline{D}D_1$

- Observed the process $e^+ e^- \rightarrow \overline{D}D_1$.
- Clear structure in the line-shape of $e^+ e^- \rightarrow \overline{D}D_1$. 
Summary

- The process $e^+e^- \rightarrow \pi^+\pi^-\psi(3770)$ was observed with significance 5.2 $\sigma$.
- No obvious $Z_c$ signal was observed.
- The process $e^+e^- \rightarrow \bar{D}D_1$ was observed with significance 6.2 $\sigma$.
- $X_2(4013)$ was searched via $e^+e^- \rightarrow \pi^+\pi^-X_2(4013)$, no obvious signal.

On-going analysis

- Search for $\chi_{c0,2}(2P)$ via $e^+e^- \rightarrow \gamma\chi_{c0,2}(2P) \rightarrow \gamma D\bar{D}$
- Search for $X_2(4013)$, via $e^+e^- \rightarrow \gamma X_2(4013), \rightarrow \gamma D\bar{D}$

With more data above 4.0 GeV at BESIII, more information of charmonium(-like) particles will be uncovered. Hopefully we may understand the natures of them.

Thanks for your attention.