Highlights on XYZ (charmonium-like) states and recent results on light hadron spectroscopy from BESIII

Hao Cai

Wuhan University, P. R. China

2014 Flavour Physics Conference, Quy Nhon, Vietnam

July 29th, 2014
Outline

- Introduction
  - BEPCII
  - BESIII
  - Data set
- XYZ Physics
- Light hadron spectroscopy
- Summary
# BEPCII

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy range</td>
<td>1-2.3 GeV</td>
</tr>
<tr>
<td>Optimized beam energy region</td>
<td>1.89 GeV</td>
</tr>
<tr>
<td>Current of each beam in collision</td>
<td>0.93 A</td>
</tr>
<tr>
<td>Luminosity achieved</td>
<td>$0.7 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>Beam lifetime</td>
<td>2.7 hrs</td>
</tr>
<tr>
<td>SR mode</td>
<td>0.25 A@2.5 GeV</td>
</tr>
</tbody>
</table>
**Main Drift Chamber (MDC):**

\[
\sigma_{xy} = 135 \, \mu m \\
\Delta P/P = 0.5\% @ 1 \, GeV \\
\sigma_{dE/dx} = 6\sim7\% 
\]

**TOF System:**

\[
\sigma_T = 80 \, ps @ \text{barrel} \\
110 \, ps @ \text{endcap} 
\]

**EM Calorimeter (EMC):**

\[
\Delta E/E = 2.5\% @ 1 \, GeV \\
\sigma_{Z,\phi} = 0.6 \, cm @ 1 \, GeV 
\]

Barrel and endcap have different performance

**1.0 Tesla Super-conducting Magnet**

**Muon Chamber (MUC):**

RPC based
BESIII Collaboration

~350 members
11 countries
53 institutions
22 outside China
**BESIII started data taking for physics since 2009**

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>Mass (GeV)</th>
<th>Year(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.3 \times 10^9$</td>
<td>$J/\Psi$ @ 3.097 GeV</td>
<td>2009 ($0.225 \times 10^9$) + 2012</td>
</tr>
<tr>
<td>$0.5 \times 10^9$</td>
<td>$\Psi'$ @ 3.686 GeV</td>
<td>2009 ($0.106 \times 10^9$) + 2012</td>
</tr>
<tr>
<td>2.9 fb$^{-1}$</td>
<td>$\Psi(3770)$ @ 3.773 GeV</td>
<td>2010 + 2011</td>
</tr>
<tr>
<td>0.5 fb$^{-1}$</td>
<td>$\Psi(4040)$ @ 4.009 GeV</td>
<td>2011</td>
</tr>
<tr>
<td>0.024 fb$^{-1}$</td>
<td>$\tau$ mass scan at around 3.554 GeV</td>
<td>2011</td>
</tr>
<tr>
<td>1.9 fb$^{-1}$</td>
<td>$Y(4260)$ @ 4.23 and 4.26 GeV</td>
<td>2013</td>
</tr>
<tr>
<td>0.5 fb$^{-1}$</td>
<td>$Y(4360)$ @ 4.36 GeV</td>
<td>2013</td>
</tr>
<tr>
<td>0.5 fb$^{-1}$</td>
<td>$Y(4260)$ and $Y(4360)$ scan</td>
<td>2013</td>
</tr>
<tr>
<td>0.8 fb$^{-1}$</td>
<td>R scan, 104 energy points between 3.85 and 4.59 GeV</td>
<td>2014</td>
</tr>
<tr>
<td>1.0 fb$^{-1}$</td>
<td>@ 4.42 GeV</td>
<td>2014</td>
</tr>
<tr>
<td>0.1 fb$^{-1}$</td>
<td>@ 4.47 GeV</td>
<td>2014</td>
</tr>
<tr>
<td>0.1 fb$^{-1}$</td>
<td>@ 4.53 GeV</td>
<td>2014</td>
</tr>
<tr>
<td>0.04 fb$^{-1}$</td>
<td>@ 4.575 GeV</td>
<td>2014</td>
</tr>
<tr>
<td>0.5 fb$^{-1}$</td>
<td>@ 4.60 GeV</td>
<td>2014</td>
</tr>
</tbody>
</table>
XYZ (charmonium-like) physics at BESIII
The Landscape

- All states below $D\bar{D}$ threshold have been observed
- Many missing states above $D\bar{D}$ threshold
- Pattern of masses
- Transitions between states

Prediction: Barnes, Swanson, and Godfrey, PRD 72, 054026 (2005)
**Y(4260)**

- $J^{PC} = 1^{--}$ state produced in $e^+e^- \rightarrow \gamma_{ISR} \pi^+ \pi^- J/\Psi$
- OZI favored decay is expected, but no obvious enhanced open-charm channel is observed

<table>
<thead>
<tr>
<th>Final state ($X$)</th>
<th>$\sigma(Y(4260) \rightarrow X)$ (mb)</th>
<th>$\sigma(Y(4260) \rightarrow \pi^+\pi^- J/\Psi)$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D\bar{D}$</td>
<td>&lt;4.0</td>
<td></td>
</tr>
<tr>
<td>$D^*\bar{D}$</td>
<td>&lt;45</td>
<td></td>
</tr>
<tr>
<td>$D^<em>\bar{D}^</em>$</td>
<td>&lt;11</td>
<td></td>
</tr>
<tr>
<td>$D^*\bar{D}\pi$</td>
<td>&lt;15</td>
<td></td>
</tr>
<tr>
<td>$D^<em>\bar{D}^</em>\pi$</td>
<td>&lt;8.2</td>
<td></td>
</tr>
<tr>
<td>$D^+_sD^-_s$</td>
<td>&lt;1.3</td>
<td></td>
</tr>
<tr>
<td>$D^+_sD^-_s$</td>
<td>&lt;0.8</td>
<td></td>
</tr>
<tr>
<td>$D^+_sD^-_s$</td>
<td>&lt;0.5</td>
<td></td>
</tr>
</tbody>
</table>

*CLEO-c*  
*PRD 80, 072001 (2009)*

*PRD 86, 051102 (2012)*

*PRL 110, 252002 (2013)*
Y(4360)

- Similar to Y(4260), $1^{-+}$ state produced in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-\Psi'$
- Additional state at 4660 MeV
- Nature of Y states is unknown
- The interference effect among them is large
- Dedicated running at BESIII starting in 2013 winter
$e^+e^- \rightarrow \pi^+\pi^- J/\Psi$ at $E_{cm} = 4260$ MeV

- $\pi\pi J/\Psi$ is the only firmly established decay mode of $Y(4260)$
$e^+e^- \rightarrow \pi^+\pi^- J/\Psi$ at $E_{cm} = 4260$ MeV

- Lum = 525 pb$^{-1}$
- Born cross section is $(62.9 \pm 1.9 \pm 3.7)\ \text{pb}$
- Analysis is valid and unbiased
Discovery of $Z_C^\pm(3900)$

- $Z_C^\pm(3900) \to \pi^\pm J/\Psi$
- First confirmed particle made of four quarks
- More data is needed

$M = (3899.0 \pm 3.6 \pm 4.9)\text{MeV}$
$\Gamma = (46 \pm 10 \pm 20)\text{MeV}$

$M = (3894.5 \pm 6.6 \pm 4.5)\text{MeV}$
$\Gamma = (63 \pm 24 \pm 26)\text{MeV}$

$M = (3886 \pm 6 \pm 4)\text{MeV}$
$\Gamma = (33 \pm 6 \pm 7)\text{MeV}$

Viewpoint: New Particle Hints at Four-Quark Matter
http://physics.aps.org/articles/v6/69
Evidence of neutral iso-spin partner is observed in \(e^+e^- \rightarrow \pi^0\pi^0J/\psi\)

Production correlated with \(Y(4260)\) is suggestive

**Preliminary results**

\[M = (3894.8 \pm 2.3 \pm 2.6)\text{MeV}\]
\[\Gamma = (29.6 \pm 8.2 \pm 7.3)\text{MeV}\]
\[ e^+ e^- \rightarrow \pi^\pm (D\bar{D}^*)^\mp \] at 4260 MeV

- \( Z_c(3885) \) is observed in the \( D\bar{D}^* \) invariant mass
- If \( Z_c(3885) \) is \( Z_c(3900) \)
  \[
  \frac{\Gamma(Z_c(3900) \rightarrow D\bar{D}^*)}{\Gamma(Z_c(3900) \rightarrow \pi J/\Psi)} = 6.2 \pm 2.9
  \]
  much smaller than that of conventional charmonium states
- \( \pi \) angular distribution favors \( j^P = 1^+ \)

\[
\begin{align*}
M[Z_c(3900)] &= (3899.0 \pm 3.6 \pm 4.9)\text{MeV} \\
\Gamma[Z_c(3900)] &= (46 \pm 10 \pm 20)\text{MeV}
\end{align*}
\]

\[
\begin{align*}
M[Z_c(3885)] &= 3884 \pm 4 \text{ MeV} \\
\Gamma[Z_c(3885)] &= 25 \pm 11 \text{ MeV}
\end{align*}
\]
$e^+ e^- \rightarrow \pi^+ \pi^- h_c$

- Significant $\pi^+ \pi^- h_c$ production at $E_{cm} = 4170$ MeV
- $h_c$ is spin singlet (S=0) state different from $J/\psi$
- Correlated with $Y(4260)$?
- $\sigma(\pi^+ \pi^- h_c)$ cross sections are comparable to $\sigma(\pi^+ \pi^- J/\psi)$
- Search for $\pi^\pm h_c$ states
- $e^+ e^- \rightarrow \pi^0 \pi^0 h_c$ is also interesting

PRL 107, 041803 (2011)

CLEO-c

$e^+ e^- \rightarrow \pi^+ \pi^- h_c @ 4170$ MeV

Events / 3 MeV/c

 EVENTS / 3 MeV/c

CLEO-c

$e^+ e^- \rightarrow \eta h_c @ 4170$ MeV

CLEO-c

$e^+ e^- \rightarrow \pi^0 h_c @ 4260$ MeV

CLEO-c

$\sigma(e^+ e^- \rightarrow \pi^+ \pi^- h_c)$ (scan data)

$\sigma(e^+ e^- \rightarrow \pi^+ \pi^- h_c)$ (4170 data)

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

CLEO-c

$\sigma(e^+ e^- \rightarrow \pi^0 \pi^0 h_c)$ (4260 data)

CLEO-c

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

CLEO-c

$\sigma(e^+ e^- \rightarrow \pi^+ \pi^- (h_c, J/\psi)) (pb)$

$\sigma(e^+ e^- \rightarrow \pi^0 \pi^0 (h_c, J/\psi)) (pb)$

CLEO-c

$\sigma(e^+ e^- \rightarrow \pi^+ \pi^- (h_c, J/\psi)) (pb)$
Discovery of $Z_c^{\pm}(4020)$

- No sharp structure in $\pi^+\pi^-h_c$ section, correlation with $Y(4260)$ or $Y(4360)$ unclear
- Narrow $\pi^\pm h_c$ structure observed
- No significance for $Z_c(3900) \rightarrow \pi^\pm h_c$

@ 4260 MeV

$\sigma(e^+e^- \rightarrow \pi^\pm Z_c^{\pm}(3900) \rightarrow \pi^+\pi^-h_c) < 11 \text{ pb @90}\% \text{ C.L.}$

$M[Z_c(4020)] = 4023 \pm 3 \text{ MeV}$

$\Gamma[Z_c(4020)] = 8 \pm 4 \text{ MeV}$
$Z_c^0(4020)$

- Using data collected at 4.23, 4.26 and 4.36 GeV to study $e^+e^- \rightarrow \pi^0\pi^0 h_c$
- The Born cross sections are found to be about half of those of $e^+e^- \rightarrow \pi^+\pi^- h_c$
- Evidence of neutral iso-spin partner of $Z_c^\pm(4020)$

$M = (4023.6 \pm 2.2 \pm 3.9)\text{MeV}$
\[ e^+ e^- \rightarrow \pi^\pm (D^*\overline{D}^*)^\mp \] at \( E_{\text{cm}} = 4260 \text{ MeV} \)

- Deviation from phase space decay; Described by a charged state \( Z_c^{\pm}(4025) \) decaying to \( D^*\overline{D}^* \)
- If \( Z_c^{\pm}(4025) \) is the \( Z_c^{\pm}(4020) \) observed in the \( \pi^\pm h_c \) spectrum
  \[
  \frac{\Gamma(Z_c(4020) \rightarrow D^*\overline{D}^*)}{\Gamma(Z_c(4020) \rightarrow \pi h_c)} = 12 \pm 5
  \]

\[
M[Z_c(4025)] = 4026 \pm 3 \text{ MeV} \quad \Gamma[Z_c(4025)] = 25 \pm 6 \text{ MeV}
\]

\[
M[Z_c(4020)] = 4023 \pm 3 \text{ MeV} \quad \Gamma[Z_c(4020)] = 8 \pm 4 \text{ MeV}
\]
\( Z_C^{\pm,0} (4020) \) and \( Z_C^{\pm,0} (3900) \)

- Qualitatively similar to each other
- Correlation with Y(4360) or Y(4260) is clear or not?
\( Z_c^{\pm,0}(4020) \) and \( Z_c^{\pm,0}(3900) \)

- Qualitatively similar to each other
- Correlation with \( Y(4360) \) or \( Y(4260) \) is clear or not?
$Z_{c}^{\pm,0}(4020)$ and $Z_{c}^{\pm,0}(3900)$

- Qualitatively similar to each other
- Correlation with $Y(4360)$ or $Y(4260)$ is clear or not?
- More interesting results

$\pi^\pm \pm \pi^\pm$

$D^* D^*$

$DD^*$

$\eta_c(1^3S_0)$

$\eta_c(4^1S_0)$

$\eta_c(3^1S_0)$

$\eta_c(2^3S_1)$

$\eta_c(2^1S_1)$

$\eta_c(1^1S_0)$

$\psi(4^3S_1)$

$\psi(3^3S_1)$

$\psi(2^1D_1)$

$\psi(1^3D_1)$

$\psi(2^3P_1)$

$\psi(3^1P_1)$

$\chi_{c0}(1^3P_0)$

$\chi_{c0}(2^3P_2)$

$\chi_{c0}(3^3P_2)$

$\chi_{c0}(1^3P_2)$

$\chi_{c0}(2^3P_2)$

$\chi_{c0}(3^3P_2)$

$\chi_{c2}(1^3P_2)$

$\chi_{c2}(2^3P_2)$

$\chi_{c2}(3^3P_2)$

$\gamma$

$\omega$

$\pi^0$

$\pi^+$

$\pi^-$

$\eta_c(1^3S_0)$

$\eta_c(4^1S_0)$

$\eta_c(3^1S_0)$

$\eta_c(2^3S_1)$

$\eta_c(2^1S_1)$

$\eta_c(1^1S_0)$

$\psi(4^3S_1)$

$\psi(3^3S_1)$

$\psi(2^1D_1)$

$\psi(1^3D_1)$

$\psi(2^3P_1)$

$\psi(3^1P_1)$

$\chi_{c0}(1^3P_0)$

$\chi_{c0}(2^3P_2)$

$\chi_{c0}(3^3P_2)$

$\chi_{c0}(1^3P_2)$

$\chi_{c0}(2^3P_2)$

$\chi_{c0}(3^3P_2)$

$\chi_{c2}(1^3P_2)$

$\chi_{c2}(2^3P_2)$

$\chi_{c2}(3^3P_2)$

$\gamma$

$\omega$

$\pi^0$

$\pi^+$

$\pi^-$

$\eta_c(1^3S_0)$

$\eta_c(4^1S_0)$

$\eta_c(3^1S_0)$

$\eta_c(2^3S_1)$

$\eta_c(2^1S_1)$

$\eta_c(1^1S_0)$

$\psi(4^3S_1)$

$\psi(3^3S_1)$

$\psi(2^1D_1)$

$\psi(1^3D_1)$

$\psi(2^3P_1)$

$\psi(3^1P_1)$

$\chi_{c0}(1^3P_0)$

$\chi_{c0}(2^3P_2)$

$\chi_{c0}(3^3P_2)$

$\chi_{c0}(1^3P_2)$

$\chi_{c0}(2^3P_2)$

$\chi_{c0}(3^3P_2)$

$\chi_{c2}(1^3P_2)$

$\chi_{c2}(2^3P_2)$

$\chi_{c2}(3^3P_2)$
$X(3872)$

- Mass: Very close to $D^0 D^{*0}$ threshold
- Width: Very narrow (< 1.2 MeV)
- $J^{PC} = 1^{++}$
- Radiative transition to $J/\Psi$ is observed
- Nature:
  - Bound $D^0 D^{*0}$ “molecular” state?
  - Mixture of excited $\chi_{c1}$ and $D^0 D^{*0}$ bound state?
  - If it is not $\chi_{c1}'$, where is $\chi_{c1}'$?

References:
- PRL 110, 222001 (2013)
- arXiv:1404.0275
Observation of $e^+e^- \rightarrow \gamma X(3872)$

- Search for $\gamma X(3872)$ with $X(3872) \rightarrow \pi^+\pi^- J/\Psi$ at $E_{cm} = 4.23, 4.26$ and $4.36$ GeV
- $6.3\sigma$ over all data
- Production in $Y(4260)$ is suggestive, but not conclusive
  \[ \frac{B(Y(4260) \rightarrow \gamma X(3872))}{B(Y(4260) \rightarrow \pi^+\pi^- J/\Psi)} \approx 0.1 \]
- Measuring transitions between states is essential
$e^+ e^- \rightarrow \omega \chi_{c0}$

- Using data collected at 4.23 and 4.26 GeV
- Fit with a single BW assumption, mass lower than 4.26 GeV
- No signal of $\omega \chi_{c1}$ or $\omega \chi_{c2}$ found between 4.19 and 4.42 GeV
- Disfavor $Y(4260)$ is a $\omega \chi_{c1}$ molecule

---

Preliminary results

---

Preliminary results
Light hadron spectroscopy at BESIII
Overview of light hadron spectroscopy

- Constituent Quark Model (CQM) has two types of hadrons
  - Mesons: $q\bar{q}$
  - Baryons: $qqq$
- QCD allows hadrons of other types
  - Multi-quark states: (more than 3 quarks)
  - Hybrids: $q\bar{q}g$
  - Glueballs: $gg$, $ggg$, ...
- BESIII has collected the largest $J/\psi$ and $\psi(2S)$ data sample in the world
  - 1.3 billion $J/\psi$ events taken in 2009 and 2012
  - 0.5 billion $\psi(2S)$ events taken in 2009 and 2012
- Over the past few years, many new particles have been found or confirmed at BESIII
  - $X(p\bar{p})$, $X(1835)$, $X(1870)$, $X(1810)$, $X(1840)$, $X(2120)$, $X(2370)$, ...
\( \omega \phi \) threshold enhancement in \( J/\psi \to \gamma \omega \phi \)

- \( J/\psi \to \gamma \omega \phi \) is a DOZI process, but has a similar branch ratio compared to that of \( J/\psi \to \gamma \phi \phi \), an OZI process
- Dynamical effect arising from intermediate meson rescattering
- A manifestation of \( f_0(1710) \)
- Hadrons of new types: tetraquark, hybrid, glueball, ...

<table>
<thead>
<tr>
<th>Resonance</th>
<th>( J^{PC} )</th>
<th>( M(\text{MeV}/c^2) )</th>
<th>( \Gamma(\text{MeV}/c^2) )</th>
<th>Events</th>
<th>( \Delta S )</th>
<th>( \Delta \text{ndf} )</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X(1810) )</td>
<td>0^{--}</td>
<td>1795 ± 7</td>
<td>95 ± 10</td>
<td>1319 ± 52</td>
<td>783</td>
<td>4</td>
<td>&gt;30σ</td>
</tr>
<tr>
<td>( f_2(1950) )</td>
<td>2^{++}</td>
<td>1944</td>
<td>472</td>
<td>665 ± 40</td>
<td>211</td>
<td>2</td>
<td>20.4σ</td>
</tr>
<tr>
<td>( f_0(2020) )</td>
<td>0^{--}</td>
<td>1992</td>
<td>442</td>
<td>715 ± 45</td>
<td>100</td>
<td>2</td>
<td>13.9σ</td>
</tr>
<tr>
<td>( \eta(2225) )</td>
<td>0^{-+}</td>
<td>2226</td>
<td>185</td>
<td>70 ± 30</td>
<td>23</td>
<td>2</td>
<td>6.4σ</td>
</tr>
<tr>
<td>Coherent nonresonant component</td>
<td>0^{--}</td>
<td>⋯</td>
<td>⋯</td>
<td>319 ± 24</td>
<td>45</td>
<td>2</td>
<td>9.1σ</td>
</tr>
</tbody>
</table>
Analysis of $J/\psi \to \gamma \eta \eta$

- Lattice QCD predicts the lowest lying $0^{++}$ glueball occurs in 1.5 to 1.7 GeV, and the lightest $2^{++}$ glueball has mass around 2.2 GeV

- $\eta \eta$ system: Even $^{++}$ states (mainly $0^{++}$ and $2^{++}$), ideal place for search of scalar and tensor glueballs
  - Crystal Ball observed $f_0(1710)$ in $J/\psi \to \gamma \eta \eta$
  - Crystal Barrel observed $f_0(1500)$ in $p\bar{p} \to \pi^0 \eta \eta$
  - Comparison to $\pi \pi$, $KK$, $\eta \eta'$ system

- $J/\psi \to \gamma \eta \eta$ at BESIII
  - High statistics
  - EMC: CsI(T1) crystals, high performance
  - Low background
Partial Wave Analysis of $J/\psi \rightarrow \gamma \eta \eta$

- $f_0(1710)$ and $f_0(2100)$ are dominant scalars, $f_0(1500)$ exists
- $f_2'(1525)$ is the dominant tensor, $f_2(1810)$ and $f_2(2340)$ exist
- Production rate of $f_0(1500)$ is approximately one order smaller than that of $f_0(1710)$ and $f_0(2100)$
- Production rate of $f_0(1710)$ in radiative $J/\psi$ decays is compatible with LQCD's prediction on that of a pure gauge scalar glueball.
- Large overlap between $f_0(1710)$ and a glueball?

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$B(J/\psi \rightarrow \gamma X \rightarrow \gamma \eta \eta)$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(1500)$</td>
<td>$(1.65^{+0.36}<em>{-0.21} ^{+0.51}</em>{-1.49}) \times 10^{-5}$</td>
<td>8.2σ</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>$(2.35^{+0.13}<em>{-0.11} ^{+1.24}</em>{-0.74}) \times 10^{-4}$</td>
<td>25.0σ</td>
</tr>
<tr>
<td>$f_0(2100)$</td>
<td>$(1.13^{+0.10}<em>{-0.10} ^{+0.64}</em>{-0.39}) \times 10^{-4}$</td>
<td>13.9σ</td>
</tr>
<tr>
<td>$f_2'(1525)$</td>
<td>$(3.42^{+0.43}<em>{-0.31} ^{+1.17}</em>{-1.36}) \times 10^{-5}$</td>
<td>11.0σ</td>
</tr>
<tr>
<td>$f_2(1810)$</td>
<td>$(5.40^{+0.60}<em>{-0.69} ^{+1.42}</em>{-2.35}) \times 10^{-5}$</td>
<td>6.4σ</td>
</tr>
<tr>
<td>$f_2(2340)$</td>
<td>$(5.60^{+0.62}<em>{-0.65} ^{+1.27}</em>{-2.03}) \times 10^{-5}$</td>
<td>7.6σ</td>
</tr>
<tr>
<td>0** PHSP</td>
<td>$(1.47^{+0.01}_{-0.02}) \times 10^{-4}$</td>
<td>12.4σ</td>
</tr>
</tbody>
</table>

$\chi^2$/ndf = 1.72
Observation of $\eta' \rightarrow \pi^+\pi^-\pi^+\pi^-(\pi^+\pi^-\pi^0\pi^0)$

- First observation the branching ratios
- Clearly support the model: Chiral perturbation and Vector-meson dominance

\[ B(\eta' \rightarrow \pi^+\pi^-\pi^+\pi^-) = (8.53 \pm 0.69 \pm 0.64) \times 10^{-5} \]
\[ B(\eta' \rightarrow \pi^+\pi^-\pi^0\pi^0) = (1.82 \pm 0.35 \pm 0.18) \times 10^{-4} \]

PRL 112, 251801 (2014)
Two new baryonic excited states are observed in PWA:

- \( N(2300) \left[ J^P = 1/2^+ \right] \),
- \( N(2570) \left[ J^P = 5/2^- \right] \),

- \( N(1885) \) or \( N(2065) \) has not been found

<table>
<thead>
<tr>
<th>Resonance</th>
<th>( M(\text{MeV}/c^2) )</th>
<th>( \Gamma(\text{MeV}/c^2) )</th>
<th>( \Delta S )</th>
<th>( \Delta N_{\text{fit}} )</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N(1440) )</td>
<td>( 1390^{+11}_{-21}^{+21} )</td>
<td>( 340^{+30}_{-40}^{+40} )</td>
<td>72.5</td>
<td>4</td>
<td>11.5σ</td>
</tr>
<tr>
<td>( N(1520) )</td>
<td>( 1510^{+4}_{-9}^{+11} )</td>
<td>( 115^{+20}_{-15}^{+40} )</td>
<td>19.8</td>
<td>6</td>
<td>5.0σ</td>
</tr>
<tr>
<td>( N(1535) )</td>
<td>( 1535^{+12}_{-22}^{+15} )</td>
<td>( 120^{+20}_{-20}^{+40} )</td>
<td>49.4</td>
<td>4</td>
<td>9.3σ</td>
</tr>
<tr>
<td>( N(1650) )</td>
<td>( 1650^{+13}_{-30}^{+11} )</td>
<td>( 150^{+21}_{-22}^{+14} )</td>
<td>82.1</td>
<td>4</td>
<td>12.2σ</td>
</tr>
<tr>
<td>( N(1720) )</td>
<td>( 1700^{+13}_{-32}^{+15} )</td>
<td>( 450^{+190}_{-149}^{+190} )</td>
<td>55.6</td>
<td>6</td>
<td>9.6σ</td>
</tr>
<tr>
<td>( N(2300) )</td>
<td>( 2300^{+40}_{-36}^{+49} )</td>
<td>( 340^{+30}_{-30}^{+40} )</td>
<td>120.7</td>
<td>4</td>
<td>15.0σ</td>
</tr>
<tr>
<td>( N(2570) )</td>
<td>( 2570^{+19}_{-16}^{+34} )</td>
<td>( 280^{+14}_{-14}^{+49} )</td>
<td>78.9</td>
<td>6</td>
<td>11.7σ</td>
</tr>
</tbody>
</table>
PWA of $\psi(2S) \rightarrow p\bar{p}\eta$

- $\psi(2S) \rightarrow N(1535)\bar{p}$ is dominant
- $J^P = 1/2^-$
- No evidence for a $p\bar{p}$ resonance that was observed by BESII and CLEO-c without PWA

\[ M = 1524 \pm 5^{+10}_{-4} \text{ MeV} \]
\[ \Gamma = 130^{+27}_{-24}^{+57}_{-10} \text{ MeV} \]
**X(1840) in \( J/\psi \rightarrow \gamma 3(\pi^+\pi^-) \)**

- A distinct enhancement can be clearly seen on mass spectrum of \( 3(\pi^+\pi^-) \) around 1.84 GeV
- Mass is consistent with that of \( X(1835) \), but the width is much smaller
- A new decay modes of \( X(1835) \)?
  - \( X(1835) \) is likely to have similar properties as \( \eta_c \). \( 3(\pi^+\pi^-) \) is a relatively large decay mode of \( \eta_c \), also for \( X(1835) \)?

\[
M = 1842.2 \pm 4.2^{+7.1}_{-2.6} \text{ MeV} \\
\Gamma = 82 \pm 14 \pm 11 \text{ MeV}
\]
X(1840) in $J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$

- $X(1835)$ is likely to have similar properties as $\eta_c$.
  - $3(\pi^+\pi^-)$ is a relatively large decay mode of $\eta_c$, also for $X(1835)$?
- A distinct enhancement can be clearly seen on mass spectrum of $3(\pi^+\pi^-)$ around 1.84 GeV
- Mass is consistent with that of $X(1835)$, but the width is much smaller
- A new decay modes of $X(1835)$?

$$M = 1842.2 \pm 4.2^{+7.1}_{-2.6} \text{ MeV}$$
$$\Gamma = 82 \pm 14 \pm 11 \text{ MeV}$$

Who are they?
Need more study: more data, PWA…
Summary of Observations

- Lots of XYZ results at BESIII
  - Charged Z particles are observed, very close to the DD* and D*D* threshold, at least four quark exotics
  - New production mode of $X(3872)$
  - Y resonances are very likely related to these particles’ production
  - Observation of $e^+e^- \rightarrow \omega \chi_0$, no $\omega \chi_1$ or $\omega \chi_2$ @ [4.19, 4.42 GeV]

- By using huge data samples collected for charmonium decays at BESIII, a lot of results have been obtained
- $X(1810)$ is confirmed
- First observation of $X_{1840}$
- Study of $\eta\eta$ system
- Observation of $\eta' \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$
- Study of $N^*_b$ baryons in $\phi_{2S} \rightarrow p p \eta$

- With more data sample accumulated at BESIII, exciting future is ahead!
Summary of Observations

- Lots of XYZ results at BESIII
  - Charged Z particles are observed, very close to the DD* and D*D* threshold, at least four quark exotics
  - New production mode of $X(3872)$
  - Y resonances are very likely related to these particles’ production
  - Observation of $e^+e^- \rightarrow \omega \chi_{c0}$, no $\omega \chi_{c1}$ or $\omega \chi_{c2}$ @ [4.19, 4.42 GeV]

- By using huge data samples collected for charmonium decays at BESIII, a lot of results have been obtained,
  - $X(1810)$ is confirmed
  - First observation of $X(1840) \rightarrow 3(\pi^+\pi^-)$
  - Study of $\eta\eta$ system
  - Observation of $\eta' \rightarrow \pi^+\pi^-\pi^+\pi^- (\pi^+\pi^-\pi^0\pi^0)$
  - Study of $N^*$ baryons in $\psi(2S) \rightarrow p\bar{p}\eta^0, p\bar{p}\eta$
Summary of Observations

- Lots of XYZ results at BESIII
  - Charged Z particles are observed, very close to the DD* and D*D* threshold, at least four quark exotics
  - New production mode of $X(3872)$
  - $Y$ resonances are very likely related to these particles’ production
  - Observation of $e^+e^- \rightarrow \omega \chi_{c0}$, no $\omega \chi_{c1}$ or $\omega \chi_{c2}$ @ [4.19, 4.42 GeV]
- By using huge data samples collected for charmonium decays at BESIII, a lot of results have been obtained,
  - $X(1810)$ is confirmed
  - First observation of $X(1840) \rightarrow 3(\pi^+\pi^-)$
  - Study of $\eta\eta$ system
  - Observation of $\eta' \rightarrow \pi^+\pi^-\pi^+\pi^- (\pi^+\pi^-\pi^0\pi^0)$
  - Study of $N^*$ baryons in $\psi(2S) \rightarrow p\bar{p}\pi^0, p\bar{p}\eta$
- With more data sample accumulated at BESIII, exciting future is ahead!
Thanks a lot!