BESIII experimental status

Chengping Shen
(for the BESIII Collaboration)
Beihang University, Beijing

3rd BelleII Theory Interface Platform (B2TiP) Workshop

Oct. 28 – 29, 2015
Beijing Electron Positron Collider (BEPC)

**Satellite view of IHEP, Beijing**

- **LINAC**
- **BEPCII** (Beijing electron-positron collider)
- **BESIII detector**
- **My previous office**
- **Main entrance to IHEP**

- Founded: 1984, $Ecm=2$-5 GeV
- 1989-2005 (BEPC): $L_{peak}=1.0 \times 10^{31} / \text{cm}^2 \text{s}$
- 2008-now (BEPCII): $L_{peak}=8.5 \times 10^{32} / \text{cm}^2 \text{s}$
**BEPC II**: a double-ring machine

Beam energy: 1-2.3 GeV
Luminosity: $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$
Optimum energy: 1.89 GeV
Energy spread: $5.16 \times 10^{-4}$
No. of bunches: 93
Bunch length: 1.5 cm
Total current: 0.91 A
SR mode: 0.25 A @ 2.5 GeV

Compton back-scattering for high precision beam energy measurement

BESIII is here

8 ns
2.5 m
22 mrad
1.5 cm
0.1 cm
The BESIII Detector

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

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

**Europe (13)**
- Germany: Univ. of Bochum, Univ. of Giessen, GSI, Univ. of Johannes Gutenberg, Helmholtz Ins. in Mainz
- Russia: JINR Dubna; BINP Novosibirsk
- Italy: Univ. of Torino, Univ. of Ferrara, Frascati Lab
- Netherlands: KVI/Univ. of Groningen
- Sweden: Uppsala Univ.
- Turkey: Turkey Accelerator Center

**Pakistan (2)**
- Univ. of Punjab
- COMSAT CIIT

**China (31)**
- IHEP, CCAST, GUCAS, Shandong Univ., Univ. of Sci. and Tech. of China, Zhejiang Univ., Huangshan Coll.
- Huazhong Normal Univ., Wuhan Univ.
- Zhengzhou Univ., Henan Normal Univ.
- Peking Univ., Tsinghua Univ., Zhongshan Univ., Nankai Univ.
- Shanxi Univ., Sichuan Univ., Univ. of South China, Hunan Univ., Liaoning Univ.
- Nanjing Univ., Nanjing Normal Univ.
- Guangxi Normal Univ., Guangxi Univ.
- Suzhou Univ., Hangzhou Normal Univ.
- Lanzhou Univ., Henan Sci. and Tech. Univ.
- Beihang Univ., Beijing Petrol Chemical Univ.

**Korea (1)**
- Seoul Nat. Univ.

**Japan (1)**
- Tokyo Univ.

~400 members
53 institutions from 11 countries
BESIII Collaborators

… a photo I can find myself in 10s!
Note that luminosity is lower at J/ψ, and machine is optimal near ψ'' peak.

Integrated lum.: Jan. 2009–June 2014 about 9 fb⁻¹ @ different energies.
Note increase in slopes!
ψ'': 2.9 fb⁻¹
ψ': 0.5 B
J/ψ: 1.3 B
XYZ: 5.0 fb⁻¹ [2013–14]

2010: ψ''
2011: ψ'' & ψ(4040)
2012: ψ' & J/ψ [0.35B & 1.0B]
BESIII data samples for XYZ study (5/fb)
Outline

• Exotic states
• The X states
• The Y states
• The $Z_c$ states
• Summary & Outlook
The heavy quarkonium system

- At short distance, the Cornell model works pretty well:
  \[ V(r) = -4\alpha_s/3r + kr \]
The quarkonium system

- When distance becomes larger
  - Theory 1: let there be screened potential
  - Theory 2: let there be hybrids with excited gluons
  - Theory 3: let there be tetraquark states
  - Theory 4: let there be meson molecules
  - Theory 5: let there be cusps
  - Theory 6: let there be final state interaction
  - Theory 7: let there be coupled-channel effect
  - Theory 8: let there be mixing
  - Theory 9: let there be mixture of all these effects
  - Theories …

**QCD is another least understood part of the SM.**

“The absence of exotics is one of the most obvious features of QCD” – R. L. Jaffe, 2005

“The story of pentaquark shows how poorly we understand QCD” – F. Wilczek, 2005
All these happen in 4.0-4.7 GeV

- Need data to develop theory.

Hybrids ~ 4.2-4.5 GeV
Tetraquarks ~ 3.9-4.7 GeV
DD*/D*D*/D_s*D_s/DD_1 molecule ~ 3.9-4.4 GeV

QCD just require hadrons to be colorless, and allow exotics.

Such exotic states exist?
Thanks B-factories!

- Discovery of X(3872) and other many XYZ states etc.
- Unexpected bonus of the B-factories

New resonances discovered at B-Factories

- X(3872)
- D_{sJ}(2317/2460)
- Y(4260)
- Y(4320)
- Z(4050), Z(4250)
- Z(4430)
- Zb(10610), Zb(10650)
- Zb^0
- η_b(2S)
- Z(3885)

Observed >15 Exotic resonances

Tetraquark

Neutral

Hybrid

Cluster
The X states
X(1835) review

- Observed in $J/\psi \to \gamma \eta' \pi^+\pi^-$ at BESII in 2005
- Nature unclear, interpretations include $p\bar{p}$ bound state, excited $\eta'$, glueball
- Confirmed in $J/\psi \to \gamma \eta' \pi^+\pi^-$ at BESIII
- Angular distribution consists with pseudoscalar, but other spin-parity assignments not excluded

225 million $J/\psi$ events

PRL 106, 072002 (2011)
X(1835) review

- Simulated by p\bar{p} threshold enhancement X(p\bar{p}) in J/\psi \rightarrow \gamma p\bar{p}
- Results in the observations of X(1870) in J/\psi \rightarrow \omega(\eta\pi^+\pi^-) and X(1840) in J/\psi \rightarrow \gamma 3(\pi^+\pi^-)
- Are these states observed around 1.8 GeV/c^2 from the same origin?
- Further investigations on different production and decay mechanisms, precise physical parameters measurement are necessary

Possible channels: J/\psi \rightarrow \gamma / \omega / \phi + \eta(\pi\pi) / K\bar{K}\eta / K\bar{K}\pi
Observation of X(1835) in J/ψ → γK_sK_sη

Why this channel?
- Unlike J/ψ → γK^+K^−η, no background from two potential but forbidden channels of J/ψ → K_sK_sη and J/ψ → K_sK_sηπ^0

Clear structure on mass spectrum of K_sK_sη around 1.85 GeV/c^2

Strong correlation with the enhancement near K_sK_s mass threshold (interpreted as f_0(980))

Structure is enhanced for M(K_sK_s) < 1.1 GeV/c^2

1.3 billion J/ψ events

PRL 115, 091803 (2015)
Observation of X(1835) in J/ψ→γK_sK_sη

- PWA for $M(K_sK_s) < 1.1$ GeV/c^2
- Two resonant pseudoscalar components are required in nominal solution

$X(1835) \rightarrow K_sK_s\eta \ (> 12.9 \sigma$)
dominated by $f_0(980)$ production

$m = 1844 \pm 9^{+16}_{-25}$ MeV/c^2

$\Gamma = 192^{+20+62}_{-17-43}$ MeV

$\mathcal{B}(J/ψ→γX(1835)) \times \mathcal{B}(X(1835)→K_sK_s\eta)$

$= (3.31^{+0.33+1.96}_{-0.30-1.29}) \times 10^{-5}$

---

<table>
<thead>
<tr>
<th>State</th>
<th>J^p</th>
<th>Decay Mode</th>
<th>Mass (MeV/c^2)</th>
<th>Width (MeV)</th>
<th>Product Branching Ratio</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(1835)</td>
<td>0^+</td>
<td>$K_sK_s\eta$</td>
<td>$1844 \pm 9^{+16}_{-25}$</td>
<td>$192^{+20+62}_{-17-43}$</td>
<td>$(3.31^{+0.33+1.96}_{-0.30-1.29}) \times 10^{-5}$</td>
<td>&gt; 12.9 σ</td>
</tr>
<tr>
<td>X(1835)</td>
<td>---</td>
<td>$\pi^+\pi^0\eta'$</td>
<td>$1836.5 \pm 3.0^{+5.6}_{-2.1}$</td>
<td>$190 \pm 9^{+38}_{-36}$</td>
<td>$(2.87 \pm 0.09^{+0.49}_{-0.52}) \times 10^{-4}$</td>
<td>&gt; 20 σ</td>
</tr>
<tr>
<td>X(p̅p)</td>
<td>0^+</td>
<td>p̅p</td>
<td>$1832^{+19+18}_{-5-17} \pm 19$</td>
<td>&lt;76@90%C.L.</td>
<td>$(9.0^{+4.4+1.5}_{-1.1-5.0} \pm 2.3) \times 10^{-5}$</td>
<td>&gt; 30 σ</td>
</tr>
</tbody>
</table>

ISR $\psi'$ signal is used for mass, and mass resolution calibration.

$N=1818; \ \Delta M=0.34\pm0.04$ MeV; $\Delta \sigma_M=1.14 \pm 0.07$ MeV

$N(X(3872)) = 20.1\pm4.5 \quad 6.3\sigma$

$M(X(3872)) = 3871.9\pm0.7\pm0.2$ MeV \hspace{1cm} [PDG: 3871.68 $\pm 0.17$ MeV]
Production mechanics

- Central-of-mass energy dependent cross section peaks at 4.26 GeV
- Strongly suggest the decay \( Y(4260) \rightarrow \gamma X(3872) \)
- The ratio of \( B[Y(4260) \rightarrow \gamma X(3872)] \)~10%

Fit with different shapes
- \( Y(4260): \chi^2/\text{ndf} = 0.49/3 \)
- E1 PHSP: \( \chi^2/\text{ndf} = 8.7/3 \)
- Linear: \( \chi^2/\text{ndf} = 5.5/2 \)

For the first time, bring connections between exotic hadrons (X and Y)!

- Central-of-mass energy dependent cross section peaks at 4.26 GeV
- Strongly suggest the decay \( Y(4260) \rightarrow \gamma X(3872) \)
- The ratio of \( B[Y(4260) \rightarrow \gamma X(3872)] \)~10%.
Evidence for the X(3823) at Belle


The measured mass and width are consistent with the missing Ψ(2(1D)) state.

BESIII may search for it!

M_{X(3823)} = M_{X(3823)}^{meas} - M_{\psi'}^{meas} + M_{\psi'}^{PDG}

= 3823.1 ± 1.8 ± 0.7 MeV

FIG. 4: 2D UML fit projection of M_{Xc1\gamma} distribution for the simultaneous fit of B^± → (Xc1\gamma)K^± and B^0 → (Xc1\gamma)K_S^0 decays for M_{bc} > 5.27 GeV/c^2. The curves used in the fits are described in [31].

1. Potential model: $1^3D_2 \rightarrow \gamma \chi_{c1}, \gamma \chi_{c2}$ with large width.
2. Use $\pi^+\pi^-$ transition to produce $1^3D_2$ with $J^{PC} = 2^- -$; D-wave (L=2) transition is expected.

- Event Selection:
  - Two charged pions and two leptons from $J/\psi$.
  - Two photons from charmonium transitions.
  - Using missing mass of $\pi^+\pi^-$ pair to identify signal (good resolution).

$\Box$ $\pi^+\pi^-\psi(2S)$ can be good reference channel.
Observation of $X(3823)$ at BESIII

- Simultaneous fit to data sets at different central-of-mass energies.
- $M[X(3823)]=3821.7 \pm 1.3 \pm 0.7$ MeV (calibrate by $\psi(2S)$).
- Statistical significance: $6.2\sigma (>5.9\sigma$ including sys.), observation!
- Good candidate of $\psi(1^3D_2)$, confirms $X(3872) \neq \psi(1^3D_2)$
Production mechanics of X(3823)

- Whether from Y(4360) or $\psi(4415)$ decay
- Favor the Y(4360)? [M. B. Voloshin, PRD 91, 114029 (2015)]
- $Y(4360) \rightarrow \pi^+\pi^-X(3823)$? New decay model of Y(4360)?

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>$\mathcal{L}$ (pb$^{-1}$)</th>
<th>$N^{\text{obs}}$</th>
<th>$\epsilon$</th>
<th>$1 + \delta$</th>
<th>$\frac{1}{(1-\Pi)^2}$</th>
<th>$\sigma^{B}_{X} \cdot B_1$ (pb)</th>
<th>$\sigma^{B}_{X} \cdot B_2$ (pb)</th>
<th>$\sigma^{B}_{\psi'}$ (pb)</th>
<th>$R_{\psi'}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.230</td>
<td>1092</td>
<td>$0.7^{+1.4}_{-0.7}$ ($&lt; 3.7$)</td>
<td>0.168</td>
<td>0.755</td>
<td>1.056</td>
<td>$0.12^{+0.24}_{-0.12} \pm 0.02$ ($&lt; 0.73$)</td>
<td>-</td>
<td>$34.1 \pm 8.1 \pm 4.7$</td>
<td>-</td>
</tr>
<tr>
<td>4.260</td>
<td>826</td>
<td>$1.1^{+1.8}_{-1.2}$ ($&lt; 4.5$)</td>
<td>0.178</td>
<td>0.751</td>
<td>1.054</td>
<td>$0.23^{+0.38}_{-0.24} \pm 0.04$ ($&lt; 1.11$)</td>
<td>-</td>
<td>$25.9 \pm 8.1 \pm 3.6$</td>
<td>-</td>
</tr>
<tr>
<td>4.360</td>
<td>540</td>
<td>$3.9^{+2.3}_{-1.7}$ ($&lt; 7.9$)</td>
<td>0.196</td>
<td>0.795</td>
<td>1.051</td>
<td>$1.10^{+0.47}_{-0.24} \pm 0.15$ ($&lt; 2.54$)</td>
<td>($&lt; 2.05$)</td>
<td>$58.6 \pm 14.2 \pm 8.1$</td>
<td>$0.20^{+0.13}_{-0.10}$</td>
</tr>
<tr>
<td>4.420</td>
<td>1074</td>
<td>$7.5^{+3.6}_{-2.8}$ ($&lt; 12.9$)</td>
<td>0.145</td>
<td>0.967</td>
<td>1.053</td>
<td>$1.23^{+0.59}_{-0.46} \pm 0.17$ ($&lt; 2.45$)</td>
<td>($&lt; 0.60$)</td>
<td>$33.4 \pm 7.8 \pm 4.6$</td>
<td>$0.39^{+0.21}_{-0.17}$</td>
</tr>
<tr>
<td>4.600</td>
<td>567</td>
<td>$1.9^{+1.8}_{-1.1}$ ($&lt; 5.2$)</td>
<td>0.157</td>
<td>1.075</td>
<td>1.055</td>
<td>$0.47^{+0.44}_{-0.27} \pm 0.07$ ($&lt; 1.48$)</td>
<td>-</td>
<td>$10.4^{+6.4}_{-4.7} \pm 1.5$</td>
<td>-</td>
</tr>
</tbody>
</table>
1. Assume $\pi\pi$ system is dominant by $f_0(500)$
2. Scattering angle distribution of $\psi(2S)$ and $X(3823)$ in $e^+e^-$ CM frame.
3. Kolmogorov-Smirnov test $p$-value is given.
4. (Left) $\pi^+\pi^-\psi(2S)$: S-wave ($p=0.791$), D-wave ($p=0.451$) $\rightarrow$ S-wave seems to be better.
5. (right) $\pi^+\pi^-X(3823)$: S ($p=0.928$), D ($p=0.978$) $\rightarrow$ Can’t distinguish
Good candidate for $\psi(1^3D_2)$

- Mass: D-wave $\sim$3.810-3.840 GeV by potential model.
- $X(3823)$ mass agree with $\psi(1^3D_2)$ prediction.

- Width: narrow
- $X(3823)$ should be narrow (<16 MeV @ 90% C.L.).

- Production ratio:
  - $R=\frac{B[X(3823)\rightarrow \gamma\chi_{c2}]}{B[X(3823)\rightarrow \gamma\chi_{c1}]}<0.43$ @ 90% C.L.
  - Agree with prediction $R \sim 0.2$.

- Exclusions: $1^1D_2 \rightarrow \gamma\chi_{c1}$ forbidden; $1^3D_3 \rightarrow \gamma\chi_{c1}$ amplitude=0.
Search $X(4140) \rightarrow \phi J/\psi$

- The $X(4140)$ was reported by CDF with Mass=$\left(4143.0 \pm 2.9 \pm 1.2\right)$ MeV and Width=$\left(11.7^{+8.3}_{-5.0} \pm 3.7\right)$ MeV
- Controversial: CMS (Yes), Belle (No), LHCb (No), BaBar (no)
- BESIII: different process $e^+e^- \rightarrow \gamma \phi J/\psi$
- No signal, cross section $\gamma X(4140)/\gamma X(3872) < 10\%$
The Y states
(vectors)
BaBar+Belle: Initial-State-Radiation (ISR)

$J^{PC} = 1^{-}$

$\psi'$, $\psi''$, $Y$...
Study of $J/\psi \rightarrow \eta \phi \pi^+ \pi^-$

based on 0.225 billion $J/\psi$ events

- $Y(2175)$ was observed by BABAR, then confirmed by BESII, BELLE and BABAR;

- Different interpretations have been proposed:
  ss'-gluon hybrid? excited $\phi$ state?
  tetraquark state? $\Lambda\Lambda$ bound state?
  an ordinary $\phi f_0(980)$ resonance produced by FSI?

- Confirmation and study of the $Y(2175)$ with a large data sample is necessary for clarifying its nature.

**Product branching fraction of** $J/\psi \rightarrow \eta Y(2175)$, $Y(2175) \rightarrow \phi f_0(980)$, $f_0(980) \rightarrow \pi \pi$ is measured to be: $(1.20 \pm 0.14 \pm 0.37) \times 10^{-4}$

**Mass and width are in agreement with previous measurements**

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Process</th>
<th>$M$ (MeV/$c^2$)</th>
<th>$\Gamma$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABAR [2]</td>
<td>$e^+e^- \rightarrow \phi f_0$ (ISR)</td>
<td>$2175 \pm 10 \pm 15$</td>
<td>$58 \pm 16 \pm 20$</td>
</tr>
<tr>
<td>BESII [3]</td>
<td>$J/\psi \rightarrow \eta \phi f_0(980)$</td>
<td>$2186 \pm 10 \pm 6$</td>
<td>$65 \pm 23 \pm 17$</td>
</tr>
<tr>
<td>BELLE [4]</td>
<td>$e^+e^- \rightarrow \phi f_0$ (ISR)</td>
<td>$2079 \pm 13^{+29}_{-28}$</td>
<td>$192 \pm 33^{+25}_{-26}$</td>
</tr>
<tr>
<td>BABAR (updated) [5]</td>
<td>$e^+e^- \rightarrow \phi f_0$ (ISR)</td>
<td>$2172 \pm 10 \pm 8$</td>
<td>$96 \pm 19 \pm 12$</td>
</tr>
<tr>
<td>BESIII</td>
<td>$J/\psi \rightarrow \eta \phi f_0(980)$</td>
<td>$2200 \pm 6 \pm 5$</td>
<td>$104 \pm 15 \pm 15$</td>
</tr>
</tbody>
</table>
Using scan data over 4.21 and 4.42 GeV, $e^+e^-\rightarrow\omega\chi_{c0}$ are significant @ $E_{\text{cm}}=4.23$ & 4.26 GeV.

Cross section peak near 4.23 GeV, fit with BW yields Mass=$(4230\pm8\pm6)$ MeV, Width=$(38\pm12\pm2)$ MeV.

A new structure? Tetraquark [PRD 91, 117501 (2015)]? Threshold effect?
Fits to $e^+e^- \rightarrow \pi^+\pi^- h_c$ and $\omega\chi_{c0}$

PRD91, 117501(2015)

A tetraquark? (arXiv: 1412.7196)

$\psi(4S)$? (arXiv: 1405.3831)

Threshold effect? ...

- Fit with two different scenarios :
  - Three body PHSP + a narrow resonance
  - Two resonances

Very likely a narrow structure around 4.23GeV
Observation of $e^+e^- \rightarrow \eta J/\psi$

- Agree with previous results with improved precision
- The cross section peaks around 4.2 GeV
- Analysis of high energy points underway at BESIII

$\Psi(4040)$ and $\Psi(4160)$ with interference
Observation of $e^+e^- \rightarrow \eta' J/\psi$
Observation of $e^+e^-\rightarrow \eta'J/\psi$

First observation, cannot tell the line shape due to statistics

- $4.23 \text{ GeV: } \sigma = 3.1 \pm 0.6 \pm 0.3 \text{ pb}$
- $4.26 \text{ GeV: } \sigma = 3.9 \pm 0.8 \pm 0.4 \text{ pb}$
Isospin violation $Y(4260) \rightarrow \pi^0 \eta J/\psi$

No significant signal observed with current BESIII data!
Can not provide effective constraint to models...

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>$L$ (pb$^{-1}$)</th>
<th>$(1+\delta^e)$</th>
<th>$(1+\delta^\mu)$</th>
<th>$(\epsilon^{ee} B_{ee} + \epsilon^{\mu\mu} B_{\mu\mu})$ (%)</th>
<th>$N^{obs}$</th>
<th>$N^{bkg}$</th>
<th>$N^{up}$</th>
<th>$\sigma^{Born}_{UL}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.009</td>
<td>482</td>
<td>0.838</td>
<td>1.044</td>
<td>$2.1 \pm 0.1$ (sys.)</td>
<td>5</td>
<td>1</td>
<td>598.1</td>
<td>3.6</td>
</tr>
<tr>
<td>4.230</td>
<td>1007</td>
<td>0.844</td>
<td>1.036</td>
<td>$2.2 \pm 0.1$ (sys.)</td>
<td>12</td>
<td>11</td>
<td>592.9</td>
<td>1.7</td>
</tr>
<tr>
<td>4.260</td>
<td>804</td>
<td>0.837</td>
<td>1.054</td>
<td>$2.2 \pm 0.1$ (sys.)</td>
<td>12</td>
<td>8</td>
<td>654.1</td>
<td>2.4</td>
</tr>
<tr>
<td>4.360</td>
<td>522</td>
<td>0.942</td>
<td>1.051</td>
<td>$2.2 \pm 0.1$ (sys.)</td>
<td>5</td>
<td>4</td>
<td>283.2</td>
<td>1.4</td>
</tr>
<tr>
<td>4.420</td>
<td>1023</td>
<td>0.951</td>
<td>1.053</td>
<td>$2.3 \pm 0.1$ (sys.)</td>
<td>5</td>
<td>6</td>
<td>342.7</td>
<td>0.9</td>
</tr>
<tr>
<td>4.600</td>
<td>567</td>
<td>0.965</td>
<td>1.055</td>
<td>$2.4 \pm 0.1$ (sys.)</td>
<td>6</td>
<td>3</td>
<td>418.4</td>
<td>1.9</td>
</tr>
</tbody>
</table>
What are the Y states?

- Between 4 and 4.7 GeV, at most 5 states expected (3S, 2D, 4S, 3D, 5S), 7 observed
- Hybrids are expected in this mass region
- Molecular states?
- Cannot rule out threshold effect/FSI/…
- The Ys are all narrow and similar
- $\pi^+\pi^-h_c$, $\omega\chi_c$, … add complexity
Belle II is very promising with ISR method

At 4.26 GeV for $\pi^+\pi^- J/\psi$

$\varepsilon_{\text{BES III}} = 46\%$

$\varepsilon_{\text{Belle}} = 10\%$

**BES III level**
The $Z_c$ states
Discovery of $Z_c(3900)^\pm$

$Z_c(3900)^+:$

$m = (3899.0 \pm 3.6 \pm 4.9) \text{ MeV}/c^2$

$\Gamma = (46 \pm 10 \pm 20) \text{ MeV}$

Mass close to $D\bar{D}^*$ threshold

Decays to $J/\psi \rightarrow$ contains $c\bar{c}$

Electric charge $\rightarrow$ contains $u\bar{d}$

$$\sigma[e^+e^- \rightarrow \pi^+\pi^-J/\psi] = 62.9 \pm 1.9 \pm 3.7 \text{ pb at } 4.26 \text{ GeV}$$

$$\frac{\sigma[e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^-J/\psi]}{\sigma[e^+e^- \rightarrow \pi^+\pi^-J/\psi]} = (21.5 \pm 3.3 \pm 7.5)$\% at 4.26 GeV

Belle with ISR data (PRL 110, 252002)

CLEOc data at 4.17 GeV (PLB 727, 366)
Neutral isospin partner: $Z_c(3900)^0$

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

A neutral structure on $\pi^0 J/\psi$ invariant mass is observed! An isospin triplet is established!

$M = 3894.8 \pm 2.3 \pm 3.2$ MeV
$\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV
Significance = 10.4$\sigma$

Mass near DD* threshold
Molecules? Tetraquark?

CLEO's data @ 4.17 GeV

PLB 727(2013) 366

$3.5\sigma$
\( e^+e^- \rightarrow (D\bar{D}^*)^+\pi^- + c.c. \) ?

**Single \( \pi^+D^0 \) tag @ 4.26 GeV**

**Double tag @ 4.23 GeV**

**Double tag @ 4.26 GeV**

**Single \( \pi^-D^+ \) tag @ 4.26 GeV**

**Single tag**

\[ M = 3883.9 \pm 1.5 \pm 4.2 \text{ MeV} \]

\[ \Gamma = 24.8 \pm 3.3 \pm 11.0 \text{ MeV} \]

\( J^P = 1^+ \)

**Double tag**

\[ M = 3881.7 \pm 1.6 \pm 2.1 \text{ MeV} \]

\[ \Gamma = 26.6 \pm 2.0 \pm 2.3 \text{ MeV} \]

\( J^P = 1^+ \)

Good agreement between ST & DT method

\( Z_c(3900) \) vs. \( Z_c(3885) \) -> Same resonance ?!
Neutral iso-spin $e^+e^- \rightarrow (DD^*)^0\pi^0 + c.c.$

Partial reconstruction method - Single tag

$M = 3885.7^{+4.3}_{-5.7} \pm 8.4$ MeV
$\Gamma = 35^{+11}_{-12} \pm 15$ MeV
Significance: $>10\sigma$

- Good agreement between neutral state and charged state
- An iso-spin triplet established in DD* channel
- Might be same as $Z_c(3900)$
- Molecule state? Tetraquark?
\[ e^+e^- \rightarrow \pi^+\pi^-h_c \text{ & } \pi^0\pi^0h_c \]

**Charged Z\(_c\)(4020)\(^\pm\)**
- Mass = \((4022.9 \pm 0.8 \pm 2.7)\) MeV
- Width = \((7.9 \pm 2.7 \pm 2.6)\) MeV
- Significance: >8.9\(\sigma\)

**Neutral Z\(_c\)(4020)\(^0\)**
- Mass = \((4023.9 \pm 2.2 \pm 3.8)\) MeV
- Width: fixed to charged partner
- Significance: 5\(\sigma\)

An spin triplet is established!
$e^+e^- \rightarrow \pi^-(D^*D^*)^+/\pi^0(D^*D^*)^0 + c.c.$

**Charged $Z_c(4025)$:**
- $M = (4026.3 \pm 2.6 \pm 3.7)$ MeV
- $\Gamma = (24.8 \pm 5.6 \pm 7.7)$ MeV
- Significance: $>10\sigma$

**Neutral $Z_c(4025)^0$:**
- $M = (4025.5^{+2.0}_{-4.7} \pm 3.1)$ MeV
- $\Gamma = (23.0 \pm 6.0 \pm 1.0)$ MeV
- Significance: $>5.9\sigma$

$Z_c(4025)$ and $Z_c(4020)$ have similar mass, but different width.

New isospin triplet?
What’s the nature of these Z 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
- FSI?
- Cusp?
- …
We found more questions to answer

• In the X sector
  – Where the X(3872) & X(3823) come from? Resonance decays or continuum production?
  – May other X states be produced and where?

• In the Y/ψ sector
  – Is the Y(4260) a single resonance? Is Y(4008) a real structure?
  – Does the Y(4360) decay only to $\pi\pi\psi$’? Not to $\eta J/\psi$?
  – What is hidden behind $\pi\pi h_c$? Large coupling to spin-singlet, is a hybrid state observed?
  – Correlation between charm production & charmonium transitions?
  – May we observe the charmonium $3^3D_1$ state at ~4.5 GeV?

• In the Z sector
  – Are the $Z_c$ and $Z_c'$ from resonance decays or continuum prod.?
  – Are there excited $Z_c$ states and $Z_{cs}$ states [$D^*D_s$ or $D\bar{D}_s^*$]?

• In the C sector
  – Charm spectroscopy: $D^*$, $D_0$, $D_1$, $D_2$, $D_{s0}$, $D_{s1}$, $D_{s2}$, ...
  – Charm decays: $D_s$ and $\Lambda_c$ samples are too small …
Summary

• BESIII produces significant XYZ results…
• X & Y states are difficult to distinguish from normal meson, charged $Z_c$ states provide solid evidence.
• Quark composition is still puzzling.
• More results are coming, we would finally understand them.

Thank you (谢谢)!