Recent results on charmonium from BESIII

LIU Beijiang
Institute of High Energy Physics, Beijing
(for BESIII collaboration)
Beijing Electron Positron Collider (BEPC)

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):
\[ L_{\text{peak}} = 100 \times 10^{33} \text{ cm}^2/\text{s} \]
Features of the BEPC Energy Region

- Rich of resonances: charmonia and charmed mesons
- Threshold characteristics (pairs of $\tau$, D, $D_s$, ...)
- Transition between continuum and resonances, perturbative and non-perturbative QCD
- Energy location of the gluonic excitations and multi-quark states
For the XYZ states study, BESIII has accumulated about 5 fb\(^{-1}\) data. Around \(\psi\) (4040), \(Y(4260)\), and \(Y(4360)\) peaks, we collected the largest data sample in the world so far for the study of their decays. Data samples with small statistics at other energy points are collected for the line-shape study.
Hadron spectroscopy is a key tool to investigate QCD.

- testing QCD in the confinement regime
- providing insights into the fundamental degrees of freedom

Not unambiguously established yet
XYZ states:
Cannot fit in the spectrum of conventional heavy quarkonia

Additional degree of freedom from light quarks and gluons?

Open charm threshold

c- and b-quark are heavy
Non-relativistic QM applies

NRQCD approach is a spectacular success, validated by the consistency between \((c\bar{c})\)
and \((b\bar{b})\)
X States at BESIII
Observation of $e^+e^- \rightarrow \gamma X(3872)$

Strong evidence for $X(3872) \rightarrow \pi\pi J/\psi$

$M = 3871.9 \pm 0.7 \pm 0.2$ MeV/c$^2$

PRL 112, 092001 (2014)

Suggestive of $Y(4260) \rightarrow \gamma X(3872)$

* New mode of production of $X(3872)$ and $Y(4260)$ decay?

If we take $\mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi) \sim 5\%$, ( $>2.6\%$ in PDG)

$$\frac{\sigma(e^+e^- \rightarrow \gamma X(3872))}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} \sim : 10\%$$

Large transition ratio!
$e^+e^- \rightarrow \pi^+\pi^-X(3823) \rightarrow \pi^+\pi^-\gamma\chi_{c1}$

Reconstruct $\chi_c \rightarrow \gamma J/\psi \rightarrow \gamma l^+l^-$
look for $\pi^+\pi^-$ recoil

Simultaneous fit of $\gamma\chi_{c1}$ (left) and $\gamma\chi_{c2}$ (right) events
$M(X(3823)) = (3821.7 \pm 1.3 \text{ (stat)} \pm 0.7 \text{ (syst)}) \text{ MeV/c}^2$
$\Gamma(X(3823)) < 16 \text{ MeV at 90% C.L. consist with Belle}$

$B(X(3823) \rightarrow \gamma\chi_{c2})$
$B(X(3823) \rightarrow \gamma\chi_{c1}) < 0.42$ at 90% C.L.

Good candidate of $\Psi(1^3D_2)$.

$X(3823)$ scattering angle distribution
D-wave is expected.
Limited statistics

Cross section VS energy
Both $Y(4360)$ and $\Psi(4415)$ line shape give reasonable description
Search for $\phi J/\psi$ structure in $e^+e^- \rightarrow \gamma \phi J/\psi$

No evidence for $X(4140) \rightarrow \phi J/\psi$ using BESIII data
Y States at BESIII
Cross sections of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$

Inconsistent with a single BW of Y(4260)

significance of an additional narrow structure $> 7 \sigma$

**TABLE I**: The measured masses and widths of the resonances from the fit to the $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ cross section with three coherent Breit-Wigner functions. The numbers in the brackets correspond to a fit by replacing $R_1$ with an exponential continuum. The errors are statistical only.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Fit result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(R_1)$</td>
<td>$3815.9^{+59.6}_{-89.1} \ (\cdots)$</td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}(R_1)$</td>
<td>$467.9^{+74.4}_{-62.7} \ (\cdots)$</td>
</tr>
<tr>
<td>$M(R_2)$</td>
<td>$4223.7 \pm 3.2 \ (4222.4 \pm 3.0)$</td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}(R_2)$</td>
<td>$43.1 \pm 4.1 \ (43.1 \pm 3.7)$</td>
</tr>
<tr>
<td>$M(R_3)$</td>
<td>$4318.6^{+9.4}_{-10.2} \ (4325.5 \pm 9.4)$</td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}(R_3)$</td>
<td>$95.7^{+22.7}<em>{-18.0} \ (92.5^{+23.2}</em>{-18.1})$</td>
</tr>
</tbody>
</table>
Search for the isospin violating decay $Y(4260) \rightarrow J/\psi \eta \pi^0$

- Considerable decay width expected in hadrocharmonium model and tetra quark model of $Y(4260)$ [PRD 86 034013, PRD 87 111102]

- Measured upper limit is well above the prediction of $D_1 D$ molecule model (0.05 pb at 4.260 GeV) [PRD 89, 054038]
Cross sections of $e^+e^-\rightarrow\pi^+\pi^-\psi(2S)$

- BESIII confirms the lineshape for the Y(4360).
- More data will be taken soon to thoroughly study the region between 4.2 and 4.3 GeV.
- An analysis of the $\pi^\pm\psi(2S)$ substructure will be released soon.
Cross sections of $e^+e^- \rightarrow \pi^+\pi^- h_c$

$e^+e^- \rightarrow \pi^+\pi^- h_c$ at BESIII (direct)

Clearly different from $\pi\pi J/\psi$

significance of two structures assumption over one structure $> 10\sigma$

<table>
<thead>
<tr>
<th>$M$ (MeV)</th>
<th>$\Gamma_{\text{tot}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4218.4±4.0±0.9</td>
<td>66.0±9.0±0.4</td>
</tr>
<tr>
<td>4391.6±6.3±1.0</td>
<td>139.5±16.1±0.6</td>
</tr>
</tbody>
</table>
Cross sections of $e^+e^- \rightarrow \omega \chi_{cJ}$ ($J=0,1,2$)

$e^+e^- \rightarrow \omega \chi_{c0}$:
Fit with a single BW
Mass = $4226 \pm 8 \pm 6$ MeV
Width = $39 \pm 12 \pm 2$ MeV
Significance $> 9\sigma$

$e^+e^- \rightarrow \omega \chi_{c2}$:
Agree with from $\psi(4415)$ with
BR = $(1.4 \pm 0.5) \times 10^{-3}$ (sol. I), or
BR = $(6 \pm 1) \times 10^{-3}$ (sol. II)

Need data beyond 4.6 GeV to check structure in $\omega \chi_{c1}$.

The triangle black data points are from

Other data points are from
Cross sections of $e^+e^- \rightarrow \eta/\eta'J/\psi$

Agree with previous results with improved precision
Narrow structure around 4.2GeV possible from $\psi(4160) \rightarrow \eta J/\psi$?

Fit with $\psi(4160)$ and $\psi(4415)$ resonances
$\psi(4415)$ is not significant
$\sigma(\eta'J/\psi)$ much lower than $\sigma(\eta J/\psi)$, lower than NRQCD calculation

arXiv:1605.03256
Revisit the $Y(4260)$ -- with improved cross section measurements

Not a single/simple BW?

Is there any connection to $\bar{D}_s^*D_s^*$ threshold (4224 MeV).

$\bar{D}_1D$ threshold (4293 MeV)?

Different in $\bar{b}b$, see S.Elderman’s talk
### $Z_c$’s at BESIII

<table>
<thead>
<tr>
<th>$Z_c$</th>
<th>Reaction</th>
<th>Journal</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(3900)^\pm$</td>
<td>$e^+e^- \rightarrow \pi^+ \pi^- J/\psi$</td>
<td>PRL 110, 252001 (2013)</td>
<td></td>
</tr>
<tr>
<td>$(3900)^0$</td>
<td>$e^+e^- \rightarrow \pi^0 \pi^0 J/\psi$</td>
<td>PRL 115, 112003 (2015)</td>
<td></td>
</tr>
<tr>
<td>$(3885)^\pm$</td>
<td>$e^+e^- \rightarrow \pi^+ (D\bar{D}^*)^-$</td>
<td>PRL 112, 022001 (2014)</td>
<td></td>
</tr>
<tr>
<td>$(3885)^0$</td>
<td>$e^+e^- \rightarrow \pi^0 (D\bar{D}^*)^0$</td>
<td>PRL 115, 222002 (2015)</td>
<td></td>
</tr>
<tr>
<td>$(4020)^\pm$</td>
<td>$e^+e^- \rightarrow \pi^+ \pi^- h_c$</td>
<td>PRL 111.242001 (2013)</td>
<td></td>
</tr>
<tr>
<td>$(4020)^0$</td>
<td>$e^+e^- \rightarrow \pi^0 \pi^0 h_c$</td>
<td>PRL 113, 212002 (2014)</td>
<td></td>
</tr>
<tr>
<td>$(4025)^\pm$</td>
<td>$e^+e^- \rightarrow \pi^+ (D^<em>\bar{D}^</em>)^-$</td>
<td>PRL 112,132001 (2013)</td>
<td></td>
</tr>
<tr>
<td>$(4025)^0$</td>
<td>$e^+e^- \rightarrow \pi^0 (D^<em>\bar{D}^</em>)^0$</td>
<td>PRL 115, 182002 (2015)</td>
<td></td>
</tr>
</tbody>
</table>
$e^+e^- \rightarrow \pi^0 Z_c(3900) \rightarrow \pi(\pi J/\psi)$

PRL 110, 252001 (2013)

$e^+e^- \rightarrow \pi^+ Z_c(3900)^- (\pi^- J/\psi)$ @ 4.26 GeV

PRL 115, 112003 (2015)

$\sigma(e^+e^- \rightarrow \pi^0 Z_c(3900)^0(\pi^0 J/\psi))$

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

More data is needed for the line shape of $\sigma(e^+e^- \rightarrow \pi^0 Z_c(3900)^0)$
\[ e^+ e^- \rightarrow \pi Z_c(3885) \rightarrow \pi (\bar{D} D^*) \]

### $Z_c(3885)$

<table>
<thead>
<tr>
<th>$Z_c(3885)$</th>
<th>Mass(MeV)</th>
<th>Width(MeV)</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_c(3885)^\pm$ (single D-tag)</td>
<td>$3883.9 \pm 1.5 \pm 4.2$</td>
<td>$24.8 \pm 3.3 \pm 11.0$</td>
<td>PRL 112, 022001 (2014)</td>
</tr>
<tr>
<td>$Z_c(3885)^\pm$ (double D-tag)</td>
<td>$3881.7 \pm 1.6 \pm 2.6$</td>
<td>$26.6 \pm 2.0 \pm 2.3$</td>
<td>PRD 92, 092006 (2015)</td>
</tr>
<tr>
<td>$Z_c(3885)^0$ (single D-tag)</td>
<td>$3885.7^{+4.3}_{-5.7} \pm 8.4$</td>
<td>$35^{+11}_{-12} \pm 15$</td>
<td>PRL 115, 222002 (2015)</td>
</tr>
</tbody>
</table>
Search for light hadron decays of Zc in $e^+e^- \rightarrow \pi Z_c(3900) \rightarrow \pi(\omega\pi)$

- Searching for new decays of $Zc(3900)$ to light hadrons: distinguish a resonance from threshold effects
- No significant $Zc \rightarrow \omega\pi$ is observed:
  $\sigma(e^+e^- \rightarrow Zc\pi, Zc \rightarrow \omega\pi) < 0.26 \text{ pb} @ 4.23 \text{ GeV}$
  $\sigma(e^+e^- \rightarrow Zc\pi, Zc \rightarrow \omega\pi) < 0.18 \text{ pb} @ 4.26 \text{ GeV}$
\[ e^+e^- \rightarrow \pi Z_c(4020) \rightarrow \pi \pi h_c \]

\[ e^+e^- \rightarrow \pi^+\pi^- h_c \text{ and } \pi^0\pi^0 h_c \]

\( h_c \) reconstructed through E1 transition \( h_c \rightarrow \gamma \eta_c \), reconstructed from 16 exclusive hadronic modes.

\[ \sqrt{s} = 4.23, 4.26, \text{ and } 4.36 \text{ GeV} \]

**Z_c(4020)**

\[ Z_c(4020)^+ \]

2.1\( \sigma \)

\[ Z_c(4020)^0 \]

>5\( \sigma \)


\[ M = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV}/c^2 \]

\[ \Gamma = 7.9 \pm 2.7 \pm 2.6 \text{ MeV} \]

**Phys.Rev.Lett.113.212002(201)

\[ M = 4023.9 \pm 2.2 \pm 3.8 \text{ MeV}/c^2 \]

Fixed \( \Gamma \)

Close to D\(^*\)D\(^*\) threshold
$e^+e^- \rightarrow \pi Z_c(4025) \rightarrow \pi (D^*\overline{D}^*)$


$e^+e^- \rightarrow (D^*\overline{D}^*)^+\pi^- + \text{c.c.}$

0.8 fb$^{-1}$ @ 4.26 GeV

Partial reconstruction technique

$M = 4026.3 \pm 2.6 \pm 3.7$ MeV/c$^2$

$\Gamma = 24.8 \pm 5.6 \pm 7.7$ MeV


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

1.1 fb$^{-1}$ @ 4.23 and 0.8 fb$^{-1}$ @ 4.26 GeV

Partial reconstruction technique

$M = (4025.5^{+2.0}_{-4.7} \pm 3.1)$ MeV/c$^2$

$\Gamma = (23.0 \pm 6.0 \pm 1.0)$ MeV
Observations of $Z_c$

\[ e^+e^- \rightarrow \pi^+ \pi^- J/\Psi \]
\[ e^+e^- \rightarrow \pi^0 \pi^0 J/\Psi \]
\[ e^+e^- \rightarrow \pi^+ \pi^- h_c \]
\[ e^+e^- \rightarrow \pi^0 \pi^0 h_c \]

\[ Z_c(3900) \pm \]
\[ Z_c(3900)^0? \]
\[ Z_c(4020) \pm \]
\[ Z_c(4020)^0? \]

Tetraquark? Hadroquarkonium? Molecule? Threshold effect?
# Summary of the $Z_c$ at BESIII

<table>
<thead>
<tr>
<th>$Z_c^\pm(3900)$</th>
<th>$Z_c^\pm(4020)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^-\rightarrow \pi^+\pi^-J/\psi$</td>
<td>$e^+e^-\rightarrow \pi^+\pi^-h_c$</td>
</tr>
<tr>
<td>$M = 3899.0 \pm 3.6 \pm 4.9\text{ MeV}$</td>
<td>$M = 4022.9 \pm 0.8 \pm 2.7\text{ MeV}$</td>
</tr>
<tr>
<td>$\Gamma = 46 \pm 10 \pm 20\text{ MeV}$</td>
<td>$\Gamma = 7.9 \pm 2.7 \pm 2.6\text{ MeV}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$Z_c^0(3900)$</th>
<th>$Z_c^0(4020)$</th>
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<tbody>
<tr>
<td>$e^+e^-\rightarrow \pi^0\pi^0J/\psi$</td>
<td>$e^+e^-\rightarrow \pi^0\pi^0h_c$</td>
</tr>
<tr>
<td>$M = 3894.8 \pm 2.3\text{ MeV}$</td>
<td>$M = 4023.9 \pm 2.2 \pm 3.8\text{ MeV}$</td>
</tr>
<tr>
<td>$\Gamma = 29.6 \pm 8.2\text{ MeV}$</td>
<td>$\Gamma$ Fixed at $Z_c^\pm(4020)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$Z_c^\pm(3885)$</th>
<th>$Z_c^\pm(4025)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^-\rightarrow \pi(D\bar{D}^*)^\pm$</td>
<td>$e^+e^-\rightarrow \pi(D^<em>\bar{D}^</em>)^\pm$</td>
</tr>
<tr>
<td>$M = 3882.2 \pm 1.1 \pm 1.5\text{ MeV}$</td>
<td>$M = 4026.3 \pm 2.6 \pm 3.7\text{ MeV}$</td>
</tr>
<tr>
<td>$\Gamma = 26.5 \pm 1.7 \pm 2.1\text{ MeV}$</td>
<td>$\Gamma = 24.8 \pm 5.6 \pm 7.7\text{ MeV}$</td>
</tr>
</tbody>
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<thead>
<tr>
<th>$Z_c^0(3885)$</th>
<th>$Z_c^0(4025)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^-\rightarrow \pi(D\bar{D}^*)^0$</td>
<td>$e^+e^-\rightarrow \pi(D^<em>\bar{D}^</em>)^0$</td>
</tr>
<tr>
<td>$M = 3885.7 \pm 5.7 \pm 8.4\text{ MeV}$</td>
<td>$M = 4025.5 \pm 4.7 \pm 3.1\text{ MeV}$</td>
</tr>
<tr>
<td>$\Gamma = 35 \pm 12 \pm 15\text{ MeV}$</td>
<td>$\Gamma = 23.0 \pm 6.0 \pm 1.0\text{ MeV}$</td>
</tr>
</tbody>
</table>

- $J^P$ of $Z_c(3900)=1^+$ determined from PWA
- DD* dominates $Z_c(3900)$ decays, D*D* dominates $Z_c(4025)$ decays
- No significant $Z_c(3900) \rightarrow h_c\pi$, $Z_c(4020) \rightarrow J/\psi\pi$
States or/and interactions

Multiquark Hybrid
Hadrocharmonium Molecule Threshold effects
Cusps...

What is the role of threshold

--Many new observations near thresholds: D*D,D*D*, D₁D, ...

See reviews by Swanson (Hadron2015), Eichten (QWG2016), Zhao(MENU2016) and ref. within

* Phase variations appear in many process: not unique for resonance

To have a complete picture, more clues are needed

- Energy-dependence
- Patterns in productions and decays

World-wide experimental efforts

Pole properties For XYZ, the picture is still unclear

Models

LQCD
Prospects of hadron spectroscopy at BESIII

- BESIII collected world’s largest samples of J/ψ, ψ(2S), ψ(3770), Y(4260), ... from e+e− production.
- It will continue to run a few years.

<table>
<thead>
<tr>
<th></th>
<th>BESIII</th>
<th>Goal</th>
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</thead>
<tbody>
<tr>
<td>J/ψ</td>
<td>1.3*10^9</td>
<td>10*10^9</td>
</tr>
<tr>
<td>ψ'</td>
<td>0.6*10^9</td>
<td>3*10^9</td>
</tr>
<tr>
<td>ψ(3770)</td>
<td>2.9 fb⁻¹</td>
<td>20 fb⁻¹</td>
</tr>
<tr>
<td>Above open charm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>threshold</td>
<td>0.5 fb⁻¹ @ψ(4040), 1.9 fb⁻¹ @~4260, 0.5 fb⁻¹ @4360, 1.0 fb⁻¹ @4420, 0.5 fb⁻¹ @4600</td>
<td>5-10 fb⁻¹</td>
</tr>
<tr>
<td>R scan and tau</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>3.8-4.6 GeV at 105 energy points</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0-3.1 GeV at 20 energy points</td>
<td></td>
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<tr>
<td>Y(2175)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 pb⁻¹ (2015)</td>
<td></td>
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<tr>
<td>ψ(4170)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 fb⁻¹ (2016)</td>
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</tr>
</tbody>
</table>

**Opportunities for both heavy and light hadron spectroscopy**
Thank you