New Hadronic States at BESIII

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Baltimore, Maryland
April 14, 2015
BESIII at BEPCII

- The physics goals of BESIII cover a diverse range:
  - Light hadron spectroscopy, charm physics, τ physics, charmonium physics
  - $e^+e^-$ collisions in the charmonium region
  - Use the properties and decays of charmonium states to study QCD
BESIII at BEPCII

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\[ J/\psi \rightarrow \eta \phi \pi^+\pi^- \]

- Observed $Y(2175)$: possible strangeonium counterpart of $Y(4260)$
- Observed $\eta(1295)$: existence is questionable

Partial wave analysis of $J/\psi \rightarrow \gamma \eta \eta$

- $f_0(1710)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2σ)
- $f_2'(1525)$ is the dominant tensor
- $f_2(1810)$ and $f_2(2340)$ exist (6.4 and 7.6σ)
- No evidence for $f_J(2220)$

Spin-Parity Analysis of $p\bar{p}$ Mass Threshold Structure in $J/\psi$ and $\psi'$ Radiative Decays

- $0^+$ structure observed in $p\bar{p}$ spectra
- Not apparent in $J/\psi \rightarrow \omega p\bar{p}$
BESIII at BEPCII

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  - Light hadron spectroscopy, **charm physics, τ physics**, charmonium physics

**Precision measurements of** $B(D^+ \to \mu^+\nu_\mu)$

$B(D^+ \to \mu^+\nu_\mu) = [3.71 \pm 0.19\text{(stat)} \pm 0.06\text{(sys)}] \times 10^{-4}$

- Using $|V_{cd}|$ from global SM fit, $f_{D^+} = (203.2 \pm 5.3 \pm 1.8)\text{ MeV}$
- Using lattice QCD prediction for $f_{D^+}$, $|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$
- In either case, these are the most precise results for these quantities

**Measurement of the relative strong-phase**

- Model independent measurement of the strong phase difference between $D^0$ and $\bar{D}^0$ decays to $K^0\pi^+\pi^-$
- Significant improvement in a previously statistically limited measurement

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**Precision Measurement of the Mass of the τ Lepton**

BESIII: PRD 90, 012001 (2014)
**BESIII at BEPCII**

- The physics goals of BESIII cover a diverse range:
  - Light hadron spectroscopy, charm physics, $\tau$ physics, **charmonium physics**

- **XYZ physics:**
  - $Z_c(3900)^\pm$ to $\pi^+\pi^-J/\psi$ (2013)
  - $Z_c(3900)^0$ to $\pi^0\pi^0J/\psi$ (Prelim.)
  - $Z_c(3885)\pm$ to $(D\bar{D}^*)^\pm$ (2014, Prelim.)
  - $Z_c(4020)^\pm$ to $\pi^+\pi^-h_c$ (2013)
  - $Z_c(4020)^0$ to $\pi^0\pi^0h_c$ (2014)
  - $Z_c(4025)^\pm$ to $(D^*\bar{D}^*)^\pm$ (2014)
  - Observation of $X(3823)$ (2015)
  - $Y(4260)$ to $\gamma X(3872)$ (2014)
  - $e^+e^-$ to $\pi^+\pi^-\omega$ (Prelim.)
  - $Y(4260)$ to $\omega \chi_{c0}$ (2015)
  - $e^+e^-$ to $(\eta/\pi^0)J/\psi$ (2015)
  - $e^+e^-$ to $\eta'J/\psi$ (Prelim.)
The charmonium spectrum

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- Below D̅D̅ threshold, all states have been observed
- Charm anti-charm potential model describes these states well
- Goal: Obtain a better understanding of charmonium and charmonium-like states
- Method: Study pattern of masses, transitions between states, etc.

Predictions from: Barnes, Swanson, and Godfrey, PRD 72 054026 (2005)
The charmonium spectrum

More than a decade ago, unconventional charmonium-like states began appearing
- Unexpectedly small decay widths to open charm
- $Y(4260)$
  - $\sigma(D\bar{D}) : \sigma(\pi\pi J/\psi) \sim 4:1$
  - Compare with $\sim 500:1$ for $\psi(3770)$!
- Quantum numbers $1^{--}$
  - Perfect for study at BESIII
- Similarly for $Y(4360)$
  - Decays dominantly to $\pi\pi\psi'$

Predictions from: Barnes, Swanson, and Godfrey, PRD 72 054026 (2005)
The charmonium spectrum

- Study $e^+e^-$ annihilation to $\pi^+\pi^-J/\psi$ at $E_{CM} = 4.260$ GeV
  - $M = (3899.0 \pm 3.6 \pm 4.9)$ MeV$/c^2$
  - $\Gamma = (46 \pm 10 \pm 20)$ MeV
  - Significance $>8\sigma$

- Charged charmonium-like structure, $Z_c(3900)^\pm$
The charmonium spectrum

\( j_{PC} = 0^+ \quad 1^- \)

Viewpoint: New Particle Hints at Four-Quark Matter

Eric Swanson, University of Pittsburgh, Pittsburgh, PA 15260, USA

Published June 17, 2013 | Physics 6, 69 (2013) | DOI: 10.1103/Physics.6.69

- Charged charmonium-like structure, \( Z_c(3900)^\pm \)
The charmonium spectrum

- More than a decade ago, unconventional charmonium-like states began appearing

- Y states:
  - Unexpectedly small decay widths to open charm
    - $R(DD):R(\pi\pi\psi') \sim 4:1$
    - Compared with $\sim 500$ for $\psi(3770)$

- Quantum numbers
  - Perfect for study at BESIII!
  - Only well established decay mode of $Y(4260)$ is $\pi\pi\psi'$
  - $Y(4360)$ decays dominantly to $\pi\pi\psi'$

<table>
<thead>
<tr>
<th>$L_J = 0$</th>
<th>$L_J = 1$</th>
<th>$L_J = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J^{PC} = 0^+$</td>
<td>$1^+$</td>
<td>$1^-$</td>
</tr>
<tr>
<td>$J^{PC} = 1^-$</td>
<td>$0^+$</td>
<td>$1^+$</td>
</tr>
</tbody>
</table>

X states
- Isospin $I = 0$
- $J^{PC} \neq 1^-$
- Narrow resonance

Y states
- Isospin $I = 0$
- $J^{PC} = 1^-$
- No corresponding enhancement of open-charm production

Z states
- Isospin $I \neq 0$
- Cannot consist of a quark-antiquark pair

$\chi^2/d.o.f=1.08$

$2S+1L_J = 1S_0, 3S_1, 1P_1, 3P_0, 3P_1, 3P_2, 1D_2, 3D_1, 3D_2, 3D_3$
The charmonium spectrum

BESIII can produce Y states directly in $e^+e^-$ annihilation
Search for new exotic states Y decays
Investigate the hidden and open charm decays of XYZ states
Search for neutral $Z_c(3900)$ isospin partner

- Study $e^+e^-$ to $\pi^0\pi^0 J/\psi$
  - 2.5 fb$^{-1}$ at $E_{CM} = 4.23, 4.26$ and $4.36$ GeV
  - Simultaneous fit to $\pi^0 J/\psi$ spectrum

$M = (3894.8 \pm 2.3 \pm 2.7)\text{ MeV}/c^2$

$\Gamma = (29.6 \pm 8.2 \pm 8.2)\text{ MeV}$

Significance = 10.4$\sigma$

Consistent with CLEO-c evidence with 586 pb$^{-1}$ at $E_{CM} = 4.17$

PLB 727, 366 (2013)
The charmonium spectrum

Isospin triplet $Z_c(3900)$ is established!

$Z_c(3900)^\pm$

$M = (3899.0 \pm 3.6 \pm 4.9)$ MeV/$c^2$

$\Gamma = (46 \pm 10 \pm 20)$ MeV

Significance > 8$\sigma$

$Z_c(3900)^0$

$M = (3894.8 \pm 2.3 \pm 2.7)$ MeV/$c^2$

$\Gamma = (29.6 \pm 8.2 \pm 8.2)$ MeV

Significance > 10$\sigma$
The charmonium spectrum

What about other reactions?

- CLEO-c saw hint of a rising cross section near 4.26 GeV for $\pi^+\pi^- h_c$
Observation of charged charmonium-like structure in $\pi^+\pi^-h_c$

- Study $e^+e^-$ annihilation to $\pi^+\pi^-h_c$
  - $h_c$ decaying to $\gamma\eta_c$; $\eta_c$ reconstructed through 16 hadronic decay modes
- Simultaneous fit to $M(\pi^\pm h_c)$ at $E_{\text{CM}} = 4.23$, 4.26, and 4.36 GeV

- Visible $Z_c(4020)^\pm$
  - $M = (4022.9 \pm 0.8 \pm 2.7) \text{ MeV/c}^2$
  - $\Gamma = (7.9 \pm 2.7 \pm 2.6) \text{ MeV}$
  - Significance = $8.9\sigma$

- No evidence for $Z_c(3900)^\pm$
  - Significance = $2.1\sigma$
  - Upper limits determined
Observation of neutral charmonium-like structure in $\pi^0\pi^0 h_c$

- Study $e^+e^-$ annihilation to $\pi^0\pi^0 h_c$
  - $h_c$ decaying to $\gamma\eta_c$; $\eta_c$ reconstructed through 16 hadronic decay modes
- Simultaneous fit to $M(\pi^0 h_c)$ at $E_{CM} = 4.23$, 4.26, and 4.36 GeV

- $Z_c(4020)^0$
  - $M = (4023.9 \pm 2.2 \pm 3.8)$ MeV/c$^2$
  - $\Gamma$ fixed to $\Gamma(Z_c(4020)^\pm)$
  - Significance $> 5\sigma$
- Born cross sections agree with expectations from isospin symmetry

$$\frac{\sigma(e^+e^- \rightarrow \pi^0\pi^0 h_c)}{\sigma(e^+e^- \rightarrow \pi^+\pi^- h_c)} = 0.63 \pm 0.9$$
(expect 0.5)
The charmonium spectrum

\[ J^{PC} = 0^+ 1^- 1^+ \]

Isospin triplet \( Z_c(4020) \) is established!

\[ Z_c(4020)^\pm \]
M = \( 4022.9 \pm 0.8 \pm 2.7 \) MeV/c²
\[ \Gamma = (7.9 \pm 2.7 \pm 2.6) \text{ MeV} \]
Significance > 8σ


\[ Z_c(4020)^0 \]
M = \( 4023.9 \pm 2.2 \pm 3.8 \) MeV/c²
\[ \Gamma \text{ fixed to } \Gamma(Z_c(4020)^\pm) \]
Significance > 5σ

BESIII: PRL 111, 242001 (2013)
The charmonium spectrum

... but the cross section seems complicated

- Correlation of $\pi\pi h_c$ with $Y(4260)$ and $Y(4360)$ is unclear
- Is it a combination of both or something else altogether?
The charmonium spectrum

- **Z states** appear near open charm thresholds

  - $Z_c(3900)$ mass is $\sim 20$ MeV above $D\bar{D}* \text{ threshold}$
  - $Z_c(4020)$ mass is $\sim 5$ MeV above $D*\bar{D}* \text{ threshold}$

- Neither measurement considers interference with a coherent non-resonant background (may shift the results)

- Natural question: Do the Z states decay to open charm?
Observation of a charged structure in \((D\bar{D}^*)^\pm\)

- Study \(e^+e^-\) to \((D\bar{D}^*)^\pm\pi^\mp\) at \(E_{CM} = 4.26\) GeV (525 pb\(^{-1}\))
- Single tag analysis
  - Reconstruct bachelor \(\pi^+\) and \(D^0\) (to \(K^-\pi^+\)) or \(D^-\) (to \(K^+\pi^-\pi^-\))
  - Require \(D^*\) in missing mass
  - Veto \(e^+e^-\) to \((D^*\bar{D}^*)^0\)
  - apply kinematic fit: look in mass recoiling against \(\pi^+\)

BESIII: PRL 112, 022001 (2014)
Observation of a charged structure in \((D\bar{D}^*)^\pm\)

- Study \(e^+e^-\) to \((D\bar{D}^*)^\pm\pi^\pm\) at \(E_{\text{CM}} = 4.26\) GeV (525 pb\(^{-1}\))
- Single tag analysis
- Structure apparent in \((D\bar{D}^*)^\pm\)
  - \(M = 3883.9 \pm 1.5 \pm 4.2\) MeV/c\(^2\)
  - \(\Gamma = 24.8 \pm 3.3 \pm 11.0\) MeV
  - Significance > 18\(\sigma\)
  - Favors \(J^P = 1^+\) (disfavors 0\(^-\) and 1\(^-\))

![Graph showing the distribution of events and fractional yield](image-url)
Observation of a charged structure in \((D\bar{D}^*)^\pm\)

- Study \(e^+e^-\) to \((D\bar{D}^*)^\pm\pi^\mp\) at \(E_{CM} = 4.26\) GeV (525 pb\(^{-1}\))
- Double tag analysis
  - Reconstruct bachelor \(\pi^+, D^0\) (4 decay modes) and \(D^-\) (6 decay modes)
  - Improved statistics, systematics; better control over background shape
  - Apply kinematic fit: look in mass recoiling against \(\pi^+\)

![Graph of events vs mass recoiling against \(\pi^+\)]
Observation of a charged structure in \((D\bar{D}^*)^\pm\)

- Study \(e^+e^-\) to \((D\bar{D}^*)^\pm\pi^\mp\) at \(E_{CM} = 4.23\) (1090 pb\(^{-1}\)) and 4.26 GeV (827 pb\(^{-1}\))
- Double tag analysis
- Structure apparent in \((D\bar{D}^*)^\pm\)
  - \(M = 3884.3 \pm 1.2 \pm 1.8\) MeV/c\(^2\)
  - \(\Gamma = 23.8 \pm 2.1 \pm 2.6\) MeV
  - Significance > 10\(\sigma\)
  - Favors \(J^P = 1^+\) (disfavors 0\(^-\) and 1\(^-\))

Compatible with, but more precise than, the single tag analysis results:
\(M = 3883.9 \pm 1.5 \pm 4.2\) MeV/c\(^2\)
\(\Gamma = 24.8 \pm 3.3 \pm 11.0\) MeV
The charmonium spectrum

Comparisons between $Z_c(3900)$ and $Z_c(3885)$

<table>
<thead>
<tr>
<th></th>
<th>$Z_c(3900) \rightarrow DD^*$</th>
<th>$Z_c(3900) \rightarrow \pi J/\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass / MeV/c$^2$</td>
<td>3884.3 $\pm$ 1.2 $\pm$ 1.5</td>
<td>3899.0 $\pm$ 3.6 $\pm$ 4.9</td>
</tr>
<tr>
<td>Width / MeV</td>
<td>23.8 $\pm$ 2.1 $\pm$ 2.6</td>
<td>46 $\pm$ 10 $\pm$ 20</td>
</tr>
<tr>
<td>$\sigma \times B$ / pb</td>
<td>88.0 $\pm$ 6.1</td>
<td>13.5 $\pm$ 2.1</td>
</tr>
</tbody>
</table>

Masses and widths are consistent within $\sim$2$\sigma$, but...

If the $Z_c(3900)$ and $Z_c(3885)$ are the same state, the ratio of partial widths is reduced relative to typical charmonium decays.

$$\frac{\Gamma(Z_c(3885) \rightarrow DD^*)}{\Gamma(Z_c(3900) \rightarrow \pi J/\psi)} = 6.5 \pm 1.1$$

$$\frac{\Gamma(\psi(4040) \rightarrow D^* D^*)}{\Gamma(\psi(4040) \rightarrow \eta J/\psi)} \approx 283$$

Open charm decays are suppressed!

Dynamics of $Y(4260) - Z_c(3900)$ system are different than conventional charmonium
Observation of a charged structure in $({D^*\overline{D}^*})^\pm$

- Study $e^+e^-$ to $({D^*\overline{D}^*})^\pm\pi^\mp$ at $E_{CM} = 4.26$ GeV ($827$ pb$^{-1}$)
- Structure apparent in $({D^*\overline{D}^*})^\pm$

**Z$_c$(4025)$^\pm$**
- $M = 4026.3 \pm 2.6 \pm 3.7$ MeV/c$^2$
- $\Gamma = 24.8 \pm 5.6 \pm 7.7$ MeV
- Significance = $13\sigma$
- Assuming $J^P = 1^+$ (others not ruled out)
- Cross section = $83.5 \pm 6.6 \pm 22.0$ pb
The charmonium spectrum

Comparisons between $Z_c(4020)$ and $Z_c(4025)$

<table>
<thead>
<tr>
<th></th>
<th>$Z_c(4025) \rightarrow D^<em>\bar{D}^</em>$</th>
<th>$Z_c(4020) \rightarrow \pi h_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass / MeV/$c^2$</td>
<td>4026.3 ± 2.6 ± 3.7</td>
<td>4022.9 ± 0.8 ± 2.7</td>
</tr>
<tr>
<td>Width / MeV</td>
<td>24.8 ± 5.6 ± 7.7</td>
<td>7.9 ± 2.7 ± 2.6</td>
</tr>
<tr>
<td>$\sigma \times B / \text{pb}$</td>
<td>89.0 ± 12.3</td>
<td>7.4 ± 1.7 (at 4260 MeV)</td>
</tr>
</tbody>
</table>

Masses and widths are consistent within ~2\sigma, but...

If the $Z_c(4020)$ and $Z_c(4025)$ are the same state, the ratio of partial widths is reduced relative to typical charmonium decays.

$$\frac{\Gamma(Z_c(4025) \rightarrow D^*\bar{D}^*)}{\Gamma(Z_c(4020) \rightarrow \pi h_c)} = 12.0 \pm 3.2$$

$$\frac{\Gamma(\psi(4040) \rightarrow D^*\bar{D}^*)}{\Gamma(\psi(4040) \rightarrow \eta J/\psi)} \approx 283$$

Open charm decays are suppressed!

Dynamics of $Y(4260) – Z_c(4020)$ system are different than conventional charmonium
Observation of $X(3823)$

- $e^+e^- \to \pi^+\pi^-\gamma\chi_{c1}$ from 4.19 to 4.6 GeV
  - $M = 3821.7 \pm 1.3 \pm 0.7$ MeV/$c^2$
  - $\Gamma < 16$ MeV
  - Significance = $6.7\sigma$
- Measurements in good agreement with potential model prediction of the $X(3823)$ as the $1^{3}D_{2}$ charmonium state

$$\frac{\mathcal{B}(X \to \gamma\chi_{c1})}{\mathcal{B}(X \to \gamma\chi_{c2})} < 0.43$$

Consistent with prediction $\sim 0.2$
Observation of $X(3823)$

- Line shape consistent with both $Y(4360)$ and $\psi(4415)$
- Not enough statistics to distinguish between S and D wave
Making connections

• Decay properties provide useful information
• Three important decay modes for charmonium-like states
  • fall-apart to open charm mesons
  • cascade to hidden charm mesons
  • decays to light hadrons via intermediate gluons
e\textsuperscript{+}e\textsuperscript{-} to $\gamma X(3872)$ at energies between 4.009 and 4.42 GeV

- Decay properties provide useful information
- Three important decay modes for charmonium-like states
  - fall-apart to open charm mesons
  - cascade to hidden charm mesons
  - decays to light hadrons via intermediate gluons

- Y(4260) and Y(4360) only observed in final states with charmonium plus $\pi^+\pi^-$
  - Couple with other exotic states like $Z_c$
- $e^+e^- \to \gamma X(3872)$; $X(3872)$ to $\pi^+\pi^- J/\psi$ at energies between 4.009 and 4.42 GeV
  - Previously only observed in B decays and hadronic collisions

\[ M = 3871.9 \pm 0.7 \pm 0.2 \text{ MeV/c}^2 \]
Significance = 6.3\sigma
$e^+e^- \rightarrow \gamma X(3872)$ at energies between 4.009 and 4.42 GeV

- Decay properties provide useful information
- Three important decay modes for charmonium-like states
  - fall-apart to open charm mesons
  - cascade to hidden charm mesons
  - decays to light hadrons via intermediate gluons

- Y(4260) and Y(4360) only observed in final states with charmonium plus $\pi^+\pi^-$
- Couple with other “exotic” states like $Z_c$
- $e^+e^- \rightarrow \gamma X(3872)$; $X(3872) \rightarrow \pi^+\pi^- J/\psi$ at energies between 4.009 and 4.42 GeV
- Previously only observed in B decays and hadronic collisions
- Cross section consistent with expectations for radiative transition from Y(4260)

\[ M = 3871.9 \pm 0.7 \pm 0.2 \text{ MeV}/c^2 \]
Significance = 6.3$\sigma$
e^+e^- to \pi^+\pi^-\omega at 4.23 and 4.26 GeV

- Decay properties provide useful information
- Three important decay modes for charmonium-like states
  - fall-apart to open charm mesons
  - cascade to hidden charm mesons
  - decays to light hadrons via intermediate gluons

- Rescattering in hidden and open charm final states could enhance the D\overline{D}^* threshold*
  - Z_{c}(3900) decays to light hadrons will play a unique role in distinguishing a resonance from threshold effects

*PRL 111, 78 132003 (2013), PRL 80 110, 232001 (2013)
**e^+e^- to π^+π^-ω at 4.23 and 4.26 GeV**

- Decay properties provide useful information
- Three important decay modes for charmonium-like states
  - fall-apart to open charm mesons
  - cascade to hidden charm mesons
  - decays to light hadrons via intermediate gluons

- **e^+e^- to π^+π^-ω at 4.23 and 4.26 GeV**
  - A typical decay mode of a 1^{+-} resonance
  - No significant signal for Z_c(3900)

May indicate that c\bar{c} annihilation in Z_c(3900) decays is suppressed
Making connections

- Coupling of Y(4260) to $\omega \chi_{c0}$ predicted to be sizeable – ratio of Y(4260) decays to $\omega \chi_{cJ}$ ($J = 0:1:2$) predicted to be $4:3:5^*$
- $e^+ e^- \to \omega \chi_{cJ}$ between 4.21 and 4.42 GeV
  - Only $\omega \chi_{c0}$ observed!
  - $M = 4230 \pm 8 \pm 6$ MeV/$c^2$; $\Gamma = 38 \pm 12 \pm 2$ MeV
  - Inconsistent with Y(4260) production!


- $e^+ e^- \to \eta \ J/\psi$ (No significant signal for $\pi^0 \ J/\psi$)
- Hadronic transitions (by an $\eta$ or $\pi^0$) to lower charmonia are regarded as sensitive probes to study the properties of Y-states
- Cross sections for these reactions are predicted to have line shapes that are strongly affected by open charm effects

- Cross section to $\eta' \ J/\psi$ is lower than that of $\eta \ J/\psi$ and theoretical predictions
  - Significance of 9σ at 4.23 GeV, $\sigma_B = 3.1 \pm 0.6 \pm 0.3$ pb
  - Significance of 7.7σ at 4.26, $\sigma_B = 3.9 \pm 0.8 \pm 0.4$ pb
  - Higher order effects may be significant, or gluonium component contributions may affect the results significantly
Summary

- Below D\overline{D} threshold, all states have been observed
- Spectroscopy above open charm threshold less clear
- New charmonium-like states with properties that point beyond conventional charmonium
  - Suspiciously close to thresholds
  - Dynamically generated structure or new type of QCD state?
- More experimental measurements and theory calculations are needed to clarify spectrum
  - Making connections between the XYZ states
  - Look forward to more detailed studies from BESIII