Connecting the XYZ at BESIII

Ryan Mitchell
Indiana University
Hadron 2013
November 4, 2013

Beijing, China
Connecting the XYZ at BESIII

(I) The quark model describes most of charmonium remarkably well. \((c\bar{c})\)
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But the “XYZ” states point beyond the quark model. (c̅cg, c̅qqc̅, (c̅q)(q̅c), c̅cππ)
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We are building connections.
Most XYZ states were discovered at Belle and BaBar using e^+e^- collisions in the bottomonium region...
Most XYZ states were discovered at Belle and BaBar using $e^+e^-$ collisions in the bottomonium region...

For example in B decays...
Connecting the XYZ at BESIII

Most XYZ states were discovered at Belle and BaBar using e+e− collisions in the bottomonium region...

For example in B decays...

\[ B^\pm \rightarrow K^\pm (\pi^+\pi^- J/\psi) \text{ at Belle} \]
Most XYZ states were discovered at Belle and BaBar using $e^+e^-$ collisions in the bottomonium region...

And in Initial State Radiation (ISR)...
Connecting the XYZ at BESIII

Most XYZ states were discovered at Belle and BaBar using $e^+e^-$ collisions in the bottomonium region...

And in Initial State Radiation (ISR)...

$$e^+e^-(\gamma_{ISR}) \rightarrow \pi^+\pi^- J/\psi$$ at BaBar

PRL 95, 142001 (2005)
Connecting the XYZ at BESIII

Most XYZ states were discovered at Belle and BaBar using $e^+e^-$ collisions in the bottomonium region...

And in Initial State Radiation (ISR)...
Connecting the XYZ at BESIII

Most XYZ states were discovered at Belle and BaBar using e⁺e⁻ collisions in the bottomonium region...

And in Initial State Radiation (ISR)...

\[ e^+ e^- (\gamma_{\text{ISR}}) \rightarrow \pi^+ \pi^- \psi(2S) \] at BaBar and Belle

arXiv:1211.6271 and CHARM 2012
**BESIII** can produce the \(Y(4260)\) and \(Y(4360)\) directly by tuning the BEPCII center of mass energies…

**Diagram:**

- **Left Panel:**
  - Mass versus PC state diagram with various particles and their decay modes.
  - Particles: \(\eta_c(1^{1}S_0)\), \(\psi(1^{3}S_1)\), \(\psi(2^{3}D_1)\), \(\psi(3^{3}S_1)\), \(\eta_c'(1^{1}S_0)\), \(\eta_c(2^{1}S_0)\), \(h_c(1^{1}P_1)\), \(h_c(2^{1}P_1)\), \(X_{c1}(1^{3}P_1)\), \(X_{c0}(1^{3}P_0)\), \(X_{c2}(1^{3}P_2)\), \(X_{c2}(2^{3}P_2)\), \(X(3872)\), \(X(3872)\), \(\eta_c(3^{1}S_0)\), \(\eta_c(4^{1}S_0)\), \(\psi(4^{3}S_1)\), \(\psi(3^{3}S_1)\), \(\psi(2^{3}D_1)\), \(\psi' (3^{3}S_1)\), \(\psi'' (1^{3}D_1)\), \(Z(4430)?\), \(X(3872)\).
  - JPC states: \(0^+\), \(1^-\), \(1^+\), \(2^+\).

- **Right Panel:**
  - Diagram showing the reaction: \(e^- + c \rightarrow \bar{c} + Y\) with the particles and their decay modes indicated:
    - \(e^-\) enters, \(c\) interacts with \(\bar{c}\), resulting in \(Y\).
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BESIII Initial Round of Data-taking

BESIII Initial Round of Data-taking

January 2013
February 2013

4260 (515 pb\(^{-1}\))
(world’s largest sample of \(Y(4260)\) by \(\sim 2 \times\))

4190 (42 pb\(^{-1}\))
4230 (43 pb\(^{-1}\))
4310 (44 pb\(^{-1}\))

4360 (523 pb\(^{-1}\))
(world’s largest sample of \(Y(4360)\) by \(\sim 4 \times\))

4390 (53 pb\(^{-1}\))
4420 (43 pb\(^{-1}\))
Connecting the XYZ at BESIII

BESIII Initial Round of Data-taking

BESIII Initial Round of Data-taking

<table>
<thead>
<tr>
<th>Energy</th>
<th>Cross Section</th>
</tr>
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<tbody>
<tr>
<td>4260</td>
<td>(515 pb$^{-1}$)</td>
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<tr>
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January 2013
February 2013
Connecting the XYZ at BESIII

\[ e^+e^- (at \ 4260 \ MeV) \rightarrow \pi^+\pi^- J/\psi \ at \ BESIII \]

**J/ψ \rightarrow e^+e^-**

- **Data**
- **Fit**
- **Background**

595 events

**J/ψ \rightarrow μ^+μ^-**

- **Data**
- **Fit**
- **Background**

882 events

(PRL 110, 252001 (2013))

(cross section consistent with Belle and BaBar)
Connecting the XYZ at BESIII

$e^+e^- (at 4260 \, MeV) \rightarrow \pi^+\pi^- J/\psi$ at BESIII

non-trivial substructure in $\pi^+\pi^- J/\psi$

$M^2(\pi^+\pi^-) \, (GeV/c^2)^2$ vs $M^2(J/\psi) \, (GeV/c^2)^2$
Connecting the XYZ at BESIII

$e^+e^- (at\ 4260\ MeV) \rightarrow \pi^+\pi^-J/\psi$ at BESIII

PRL 110, 252001 (2013)

$Z_c(3900)$

$M = 3899.0 \pm 3.6 \pm 4.9\ MeV$

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

$\Rightarrow$ “Charged Charmonium-like Structure”

(Confirmed by Belle and CLEO data.)

(Many theoretical ideas -- close to $D^*D$ threshold.)
Connecting the XYZ at BESIII

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

Particle physicists seem to have a pretty good handle on the fundamental particles of the universe, but there are some glaring holes in this understanding. Quarks are a good example of this. We know that all nuclear matter is made up of quarks, and we have a pretty good understanding of how two quarks interact at close range. But our quark theory cannot tell us which quark combinations will result in a bound particle or a stable matter is made up of quarks, and we have a pretty good understanding of how two quarks interact at close range. But our quark theory cannot tell us which quark combinations will result in a bound particle or a stable matter is made up of quarks, and we have a pretty good understanding of how two quarks interact at close range. But our quark theory cannot tell us which quark combinations will result in a bound particle or a stable.
BESIII Initial Round of Data-taking

Connecting the XYZ at BESIII

**IV. A New Era of Discovery**

**BESIII Initial Round of Data-taking**

January 2013

February 2013

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<tr>
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</tr>
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<td>4420</td>
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Connecting the XYZ at BESIII

BESIII Additional Round of Data-taking

Integrated Luminosity

March 2013

April 2013

May 2013

4245 (53 pb$^{-1}$)

4220 (52 pb$^{-1}$)

4210 (52 pb$^{-1}$)

4260 (291 pb$^{-1}$)

4230 (1011 pb$^{-1}$)

BESIII meeting
Connecting the XYZ at BESIII

BESIII Additional Round of Data-taking

Integrated Luminosity

April 2013

May 2013

June 2013

91 pb$^{-1}$

4210 (52 pb$^{-1}$)

4220 (52 pb$^{-1}$)

4245 (53 pb$^{-1}$)

4230 (1011 pb$^{-1}$)

3810 (48 pb$^{-1}$)

3900 (50 pb$^{-1}$)

4090 (50 pb$^{-1}$)

April 2013

May 2013

June 2013

Ryan Mitchell — Indiana University
Connecting the XYZ at BESIII

\[ \eta_c(1S) \rightarrow 16 \text{ decay channels} \]

Exclusively reconstruct the process:

\[ e^+e^- \rightarrow \pi^+\pi^- h_c(1P) \]

\[ h_c(1P) \rightarrow \gamma \eta_c(1S) \]
Connecting the XYZ at BESIII

\[ e^{+}e^{-} \rightarrow \pi^{+}\pi^{-}h_c(1P) \] at BESIII

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**FIG. 4:** $M_{\pi^+\pi^-}$ distribution of $e^+e^-\rightarrow \pi^+\pi^-h_c(1P)$ candidate events in the $h_c$ signal region (dots with error bars) and the normalized $h_c$ sideband region (shaded histogram), summed over data at all energy points.

**FIG. 5:** Sum of the simultaneous fits to the $M_{\pi^+\pi^-}$ distributions at 4.23 GeV, 4.26 GeV, and 4.36 GeV as described in the text; the inset shows the sum of the simultaneous fit to the $M_{\pi^+h_c}$ distributions at 4.23 GeV and 4.26 GeV with $Z_c(3900)$ and $Z_c(4020)$. Dots with error bars are at data; shaded histograms are normalized sideband background; the solid curves show the total fit, and the dotted curves the backgrounds from the fit.

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$0^-$</th>
<th>$1^-$</th>
<th>$1^+$</th>
<th>$0^+$</th>
<th>$1^+$</th>
<th>$2^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c(1S_0)$</td>
<td>predicted, discovered</td>
<td></td>
<td></td>
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<tr>
<td>$\psi(2S_1)$</td>
<td>predicted, undiscovered</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\psi'(3S_1)$</td>
<td>unpredicted, discovered</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>$h_c(1P_1)$</td>
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<tr>
<td>$X(3872)$</td>
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<tr>
<td>$X_c(3P_2)$</td>
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</tbody>
</table>

**Exclusively reconstruct the process:**

$e^+e^- \rightarrow \pi^+\pi^-h_c(1P)$

$h_c(1P) \rightarrow \gamma\eta_c(1S)$

$\eta_c(1S) \rightarrow 16$ decay channels

*arXiv:1309.1896*
Connecting the XYZ at BESIII

$e^+e^- \rightarrow \pi^+\pi^- h_c(1P)$ at BESIII

$\Rightarrow$ “Charged Charmoniumlike Structure”

$(this \ time \ close \ to \ D^*D^* \ threshold)$

$M = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV}$

$\Gamma = 7.9 \pm 2.7 \pm 2.6 \text{ MeV}$
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The cross section shape requires more data…

Is it a combination of the Y(4260) and Y(4360)?

Or something completely different?
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The $Z_c(3900)$ is close to DD* threshold...

[Diagram showing mass and JPC states for various hadrons, such as $\eta_c(1S_0)$, $\psi(2S_1)$, $\psi(1S_0)$, and $Z_c(3900)$, with predicted, discovered, and unpredicted, discovered labels for some states.]
Connecting the XYZ at BESIII

The $Z_c(3900)$ is close to DD$^*$ threshold...

$e^+e^- \ (\text{at } 4.26 \text{ GeV}) \rightarrow \pi^+ D^0 D^{*-} \ at \ BESIII$

$M = 3883.9 \pm 1.5 \pm 4.2 \text{ MeV}$
$\Gamma = 24.8 \pm 3.3 \pm 11.0 \text{ MeV}$

arXiv:1310.1163

... and BESIII sees structure in DD$^*$.

Reconstruct the $\pi^+$ and $D^0 \rightarrow K^- \pi^+$ and infer the $D^{*-}$.
(Also analyze $\pi^+D^-D^{*0}$ with the same method.)
The $Z_c'(4020)$ is close to $D^*D^*$ threshold...
Connecting the XYZ at BESIII

The $Z_c'(4020)$ is close to $D^*D^*$ threshold...

$e^+e^- (at \, 4.26 \, GeV) \rightarrow \pi^\pm(D^*D^*)^\mp$ at BESIII

Reconstruct the $\pi^+$, $a \, D^+ \rightarrow K^-\pi^+\pi^+$, and a $\pi^0$ from a $D^*$. 
Connecting the XYZ at BESIII

Search for \( Y(4260) \rightarrow \gamma X(3872) \)...

\[
\begin{align*}
\chi_{c1}(2^3P_1) & \quad \eta_c(1^{1}S_0) \\
\psi(2^1D_1) & \quad h_c(2^1P_1) \\
\psi'(2^3S_1) & \quad \eta_c'(2^1S_0) \\
\psi''(1^3D_1) & \quad h_c(1^1P_1) \\
\chi_{c0}(2^3P_0) & \quad \chi_{c1}(1^3P_1) \\
X(3872) & \\
X_c(2^3P_2) & \\
Y(4360) & \quad \psi(4^3S_1) \\
Y(4260) & \\
\eta_c(4^1S_0) & \\
Z(4020) & \\
Z(3900) & \\
Z(4430)? &
\end{align*}
\]
Connecting the XYZ at BESIII

\[ e^+e^- \rightarrow \gamma(\pi^+\pi^- J/\psi) \text{ at BESIII} \]

\[ \text{significance} = 6.3\sigma \]

\[ N = 20.1 \pm 4.5 \text{ events} \]

\[ M = 3871.9 \pm 0.7 \pm 0.2 \text{ MeV} \]

\[ \Gamma \text{ consistent with resolution} \]
Connecting the XYZ at BESIII

$\sqrt{s}$ (GeV) $\sigma^B[e^+e^- \rightarrow \gamma X(3872)] \cdot B(X(3872) \rightarrow \pi^+\pi^- J/\psi)$ (pb)

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>&lt; 0.12</th>
<th>0.29 ± 0.10 ± 0.02</th>
<th>0.36 ± 0.13 ± 0.03</th>
<th>&lt; 0.39</th>
</tr>
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<tbody>
<tr>
<td>4.009</td>
<td></td>
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</tr>
<tr>
<td>4.230</td>
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</tr>
<tr>
<td>4.260</td>
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<td></td>
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<tr>
<td>4.360</td>
<td></td>
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Hints that this is $Y(4260) \rightarrow \gamma X(3872)$
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(VII) But there is much left to do… *and a new running period begins soon…*

Stay Tuned! Thank you…