Connecting the XYZ at BESIII

Ryan Mitchell
Indiana University
Bormio 2014
January 31, 2014

Beijing, China
(I) The quark model describes most of charmonium remarkably well. \((c\bar{c})\)

Connecting the XYZ at BESIII

- \(\eta_c(4^1S_0)\)
- \(\psi(4^3S_1)\)
- \(h_c(3^1P_1)\)
- \(X_c(3^3P_2)\)
- \(\psi(2^3D_1)\)
- \(X_c(2^3P_1)\)
- \(\psi(3^3S_1)\)
- \(X_c(3^3P_0)\)
- \(\eta_c(3^1S_0)\)
- \(\psi'(2^3S_1)\)
- \(h_c(1^1P_1)\)
- \(X_c(1^3P_2)\)
- \(\psi''(1^3D_1)\)
- \(X_c(2^3P_0)\)
- \(\eta_c'(2^1S_0)\)
- \(h_c(1^3P_1)\)
- \(X_c(1^3P_0)\)
- \(J/\psi(1^3S_1)\)
- \(\eta_c(1^1S_0)\)

\(2M_0\)

\[\text{MASS} \quad \text{[GeV/c}^2\text{]}\]

\[\text{JPC}\]

Predicted, discovered

Predicted, undiscovered
Connecting the XYZ at BESIII

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**Example potential from Barnes, Godfrey, Swanson:**

\[
V^{(c\bar{c})}(r) = -\frac{4}{3} \frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2} \tilde{\delta}(r) \hat{S}_c \cdot \hat{S}_{\bar{c}}
\]

(Coulomb + Confinement + Contact)

\[
V_{\text{spin-dep}} = \frac{1}{m_c^2} \left[ \left( \frac{2\alpha_s}{r^3} - \frac{b}{2r} \right) \hat{L} \cdot \hat{S} + \frac{4\alpha_s}{r^3} T \right]
\]

(Spin-Orbit + Tensor)

PRD72, 054026 (2005)
Connecting the XYZ at BESIII

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Crystal Ball at SLAC
(discovery of \(\eta_c\))

PRL45, 1150 (1980)

\[
\begin{align*}
\text{MASS [GeV/c}^2\text{]} &= \begin{cases} 
\eta_c(4^1S_0) & \psi(4^3S_1) \\
\eta_c(3^1S_0) & \psi(3^3S_1) \\
h_c(3^1P_1) & \psi(2^3D_1) \\
x_{c1}(3^3P_2) & x_{c2}(3^3P_0) \\
x_{c1}(3^1P_1) & x_{c2}(3^3P_0) \\
x_{c1}(2^3P_1) & x_{c2}(2^3P_2) \\
x_{c1}(1^3P_1) & x_{c2}(1^3P_2) \\
x_{c1}(1^3P_0) & x_{c2}(1^3P_0) \\
\end{cases} \\
\end{align*}
\]
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Connecting the XYZ at BESIII

(I) The quark model describes most of charmonium remarkably well. \((c\bar{c})\)

(II) But the “XYZ” states point beyond the quark model. \((c\bar{c}g, c\bar{q}q\bar{c}, (c\bar{q})(q\bar{c}), c\bar{c}\pi\pi)\)
Connecting the XYZ at BESIII

Example lattice QCD calculation:

Hadron Spectrum Collaboration
JHEP 1207, 126 (2012)
Connecting the XYZ at BESIII

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HYBRID CHARMONIUM

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

![Diagram showing B decay](image)
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For example in B decays...

\[ B^\pm \rightarrow K^\pm (\pi^+\pi^- J/\psi) \text{ at Belle} \]

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\[ \psi(2S) \]

\[ X(3872) \]
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...

\[ B^\pm \rightarrow K^\pm (\pi^+ \pi^- J/\psi) \text{ at Belle} \]

\[ \text{X(3872)} \]

\[ M = 3871.68 \pm 0.17 \text{ MeV} \]

\[ \Gamma < 1.2 \text{ MeV (PDG 2012)} \]
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...

**X(3872) Properties:**
* very narrow ($< 1.2$ MeV)
* has $J^{PC} = 1^{++}$ (LHCb)
* too light to be the $\chi_{c1}(2P)$
* confirmed by many experiments
* mass is right at $D^{*0}D^0$ mass

---

**$D^*D$ molecule?**
Connecting the XYZ at BESIII

Most XYZ states were discovered at **Belle** and **BaBar** using \(\text{e}^+\text{e}^-\) collisions in the bottomonium region...

For example in B decays...

Other B decays:

\[ B^\pm \rightarrow K^\pm (\pi^+ \pi^- J/\psi) \]
\[ B \rightarrow K(\omega J/\psi) \]
\[ B \rightarrow K(\pi^+ \chi_{c1}(1P)) \]
\[ B \rightarrow K(\pi^+ \psi(2S)) \]
Most XYZ states were discovered at Belle and BaBar using $e^+e^-$ collisions in the bottomonium region...

For example in B decays...

\[ B \rightarrow K(\pi^+\psi(2S)) \text{ at Belle} \]
Most XYZ states were discovered at Belle and BaBar using e^+e^- collisions in the bottomonium region...

For example in B decays...

**Z(4430) Properties:**
* has an electric charge

⇒ needs at least four quarks!

* (not confirmed by BaBar)
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)...
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And in Initial State Radiation (ISR)...

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

[Graph showing the mass spectrum with peaks for different mass states such as Y(4260) and Z(4430)]

**PRD 86, 051102(R) (2012)**
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⁻(γ_ISR) → π⁺π⁻ψ(2S) at BaBar

PRL 98, 212001 (2007)
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)...

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

arXiv:1211.6271 and CHARM 2012
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

Theoretical Ideas on \(Y(4260), Y(4360):\)

- DD* bound states \((Y(4360) = D_sD_s^*)\)
  - (NPA815, 53 (2009))
- J/ψf₀ bound state (with KK \(\rightarrow\) ππ)
  - (PRD80, 094012 (2009))
- Tetraquarks (or two diquarks)
  - (PRD72, 031502(R) (2005))
- Hadrocharmonium
  - (PLB666, 344 (2008))
- Hybrid Charmonium
  - (PLB628, 215 (2005), PRD78, 094504 (2008), PLB625, 212 (2005))
Connecting the XYZ at BESIII

BESIII can produce the $\bf{Y(4260)}$ and $\bf{Y(4360)}$ directly by tuning the BEPCII center of mass energies…

\begin{align*}
\text{predicted, discovered} & \\
\text{predicted, undiscovered} & \\
\text{unpredicted, discovered} & 
\end{align*}
Connecting the XYZ at BESIII.
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\[ \eta_c(1^1S_0) \]
\[ \psi(1^3S_1) \]
\[ \psi'(1^3S_1) \]
\[ \psi(2^3D_1) \]
\[ \psi(3^3S_1) \]
\[ \psi'(2^3S_1) \]
\[ \eta_c(2^1S_0) \]
\[ \eta_c(3^1S_0) \]
\[ \eta_c(4^1S_0) \]
\[ \psi(3^3S_1) \]
\[ \psi(4^3S_1) \]
\[ \psi(2^3D_1) \]
\[ \psi(3^3S_1) \]
\[ \psi'(1^3D_1) \]
\[ X(3872) \]
\[ X(4260) \]
\[ X(4360) \]
\[ Y(3872) \]
\[ Y(4360) \]
\[ Z(4430)? \]

\[ 0^+ \quad 1^- \quad 1^+ \quad 0^+ \quad 1^+ \quad 2^+ \]

\[ J/\psi(1^3S_1) \]
\[ \chi_c(1^3P_1) \]
\[ \chi_c(2^3P_2) \]
\[ \chi_c(3^3P_2) \]
\[ \chi_c(3^3P_0) \]
\[ \chi_c(2^3P_0) \]
\[ \chi_c(2^3P_2) \]
\[ \chi_c(1^3P_1) \]

\[ \eta_c(1^1S_0) \]
\[ \eta_c(3^1S_0) \]
\[ \eta_c(4^1S_0) \]

\[ \text{predicted, discovered} \]
\[ \text{predicted, undiscovered} \]
\[ \text{unpredicted, discovered} \]
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\[ η_c^{(4^1 S_0)} \]
\[ η_c^{(3^1 S_0)} \]
\[ η_c^{(3^3 S_1)} \]
\[ ψ(3^3 S_1) \]
\[ ψ(3^3 D_1) \]
\[ ψ(2^3 D_1) \]
\[ ψ(2^3 S_0) \]
\[ ψ''(1^3 D_1) \]
\[ χ_c^{(2^3 P_0)} \]
\[ χ_c^{(2^3 P_1)} \]
\[ χ_c^{(3^3 P_0)} \]
\[ χ_c^{(3^3 P_1)} \]
\[ χ_c^{(3^3 P_2)} \]
\[ χ_c^{(3^1 P_1)} \]
\[ χ_c^{(3^1 P_2)} \]
\[ χ_c^{(1^3 P_1)} \]
\[ χ_c^{(1^3 P_2)} \]
\[ χ_c^{(1^3 P_0)} \]
\[ h_c^{(2^1 P_1)} \]
\[ h_c^{(1^1 P_1)} \]
\[ h_c^{(3^1 P_1)} \]
\[ J/ψ(1^3 S_1) \]
\[ X(3872) \]
\[ X(3872)? \]
\[ χ_c^{(3^3 S_0)} \]
\[ χ_c^{(4^3 S_1)} \]

\[ Z(4430)? \]

**MASS** [GeV/c²]

**JPC**

predicted, discovered
predicted, undiscovered
unpredicted, discovered

BEPCII, IHEP, Beijing, China

BESIII
Connecting the XYZ at BESIII

\[ \eta_c \left( 1^{1S_0} \right) \]

\[ \psi \left( 1^{3S_1} \right) \]

\[ \psi' \left( 2^{3S_1} \right) \]

\[ \psi'' \left( 1^{3D_1} \right) \]

\[ \chi_c \left( 1^{3P_1} \right) \]

\[ \chi_c \left( 2^{3P_2} \right) \]

\[ \chi_c \left( 3^{3P_2} \right) \]

\[ \eta_c' \left( 2^{1S_0} \right) \]

\[ \eta_c' \left( 3^{1S_0} \right) \]

\[ h_c \left( 2^{1P_1} \right) \]

\[ h_c \left( 3^{1P_1} \right) \]

\[ \chi_c \left( 2^{3P_0} \right) \]

\[ \chi_c \left( 3^{3P_0} \right) \]

\[ \chi_c \left( 4^{3P_1} \right) \]

\[ \psi \left( 3^{3S_1} \right) \]

\[ \psi \left( 4^{3S_1} \right) \]

\[ \psi \left( 2^{3D_1} \right) \]

\[ \chi_c \left( 4^{3P_2} \right) \]

\[ \chi_c \left( 3^{3P_2} \right) \]

\[ Y(4260) \]

\[ Y(4430) \]

\[ X(3872) \]

\[ 2M_0 \]

\[ 3.0 \]

\[ 3.2 \]

\[ 3.4 \]

\[ 3.6 \]

\[ 3.8 \]

\[ 4.0 \]

\[ 4.2 \]

\[ 4.4 \]

\[ \text{mass} \ [\text{GeV/c}^2] \]

\[ \text{JPC} \]

\[ 0^- \quad 1^- \quad 1^+ \quad 0^{++} \quad 1^{++} \quad 2^{++} \]

Google satellite image of BEPC-II

BEPCII, IHEP, Beijing, China

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Connecting the XYZ at BESIII

**Graphical Content**
- Mass spectrum with various particles labeled:
  - $\eta_c$, $J/\psi$, $\gamma$, $\chi_{c0}$, $\chi_{c1}$, $\chi_{c2}$, $\eta_c'$
- $\eta_c(1^1S_0)$, $J/\psi(1^3S_1)$
- Predicted, discovered, predicted, undiscovered, unpredicted, discovered

**Additional Information**
- BEPCII, IHEP, Beijing, China
- BESIII
Connecting the XYZ at BESIII

BEPCII, IHEP, Beijing, China

Google satellite image of BEPC-II

predicted, undiscovered

unpredicted, discovered
Connecting the XYZ at BESIII

\[ \eta_{c}(1^{S_{0}}) \]
\[ J/\psi(1^{S_{1}}) \]
\[ \psi(2^{S_{1}}) \]
\[ \psi'(1^{D_{1}}) \]
\[ \chi_{c0}(2^{P_{0}}) \]
\[ \chi_{c1}(2^{P_{1}}) \]
\[ \chi_{c2}(3^{P_{2}}) \]

\[ 0^{-} \quad 1^{-} \quad 1^{-} \quad 0^{+} \quad 1^{+} \quad 2^{+} \]

Mass [GeV/c^2]

predicted, discovered
predicted, undiscovered
unpredicted, discovered

Y(4260)
Y(4360)
X(3872)
Z(4430)

BEPCII, IHEP, Beijing, China

Google satellite image of BEPC-II
Connecting the XYZ at BESIII

\[ \eta_c(1^{1}S_0) \quad \psi(4^{3}S_1) \quad \psi(1^{3}P_1) \quad \psi(2^{3}D_1) \quad \psi(2^{3}S_1) \quad \psi'(2^{3}S_1) \quad \psi''(1^{3}D_1) \quad \eta_c'(2^{1}S_0) \quad J/\psi(1^{3}S_1) \quad \eta_c(3^{1}S_0) \quad \eta_c(4^{1}S_0) \]

\[ \chi_{c0}(2^{3}P_0) \quad \chi_{c1}(1^{3}P_1) \quad \chi_{c2}(3^{3}P_2) \quad \chi_{c}(1^{3}P_1) \quad \chi_{c}(2^{3}P_2) \quad \chi_{c}(3^{3}P_2) \quad X(3872) \quad X(3872) \quad X(4260) \quad X(4360) \quad Y(3872) \quad Y(3872) \quad Y(4360) \quad Y(4360) \quad Z(4430) \quad Z(4430) \]

\[
\begin{align*}
\text{JPC:} & \quad 0^- & \quad 1^- & \quad 0^+ & \quad 1^+ & \quad 2^+ \\
\text{MASS [GeV/c^2]:} & \quad 3.0 & \quad 3.2 & \quad 3.4 & \quad 3.6 & \quad 3.8 & \quad 4.0 & \quad 4.2 & \quad 4.4 \\
\end{align*}
\]
Connecting the XYZ at BESIII

BEPC-II $e^+e^-$ Collider

$e^+e^-$ collisions in the charmonium region

(about 2 – 5?? GeV center of mass energies)
Connecting the XYZ at BESIII

Select data samples (2008-present):
* more than a billion J/ψ decays
* 106 million ψ(2S) decays (+ more)
* ~2.9 fb⁻¹ at ψ''
* ~500 pb⁻¹ at 4.009 GeV
* XYZ data
Connecting the XYZ at BESIII

![BESIII Detector Diagram]

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**Connecting the XYZ at BESIII**

**BESIII** can produce the Y(4260) and Y(4360) directly by tuning the BEPCII center of mass energies…

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**Diagram:**

- **Z(4430)?**
- **ψ(4S1)**
- **ηc(4S0)**
- **Y(4360)**
- **ψ(2D1)**
- **ηc(3S1)**
- **h_c(1P1)**
- **χc1(3P1)**
- **X(3872)**
- **ψ'(3S1)**
- **ψ'(1D1)**
- **η_c'(2S0)**
- **χc2(1P0)**
- **ψ(3S1)**
- **Y(4260)**
- **h_c(2P1)**
- **χc1(3P0)**
- **h_c(3P1)**
- **χc1(3P1)**
- **χc2(3P1)**
- **χc0(3P0)**

---

**Table:**

<table>
<thead>
<tr>
<th>Mass [GeV/c^2]</th>
<th>JPC</th>
</tr>
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<tbody>
<tr>
<td>3.0</td>
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</tr>
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</tr>
</tbody>
</table>

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**Legend:**

- **predicted, discovered**
- **predicted, undiscovered**
- **unpredicted, discovered**

---

**Equations:**

\[ e^- \rightarrow c \]
\[ e^+ \rightarrow \bar{c} \]
\[ Y \]
Connecting the XYZ at BESIII

BESIII Initial Round of Data-taking

January 2013

February 2013

4260 (515 pb⁻¹)
(world’s largest sample of $Y(4260)$ by $\sim$2x)

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$4x)

4390 (53 pb⁻¹)
4420 (43 pb⁻¹)
Connecting the XYZ at BESIII

**BESIII Initial Round of Data-taking**

- **140 pb**
- **100 pb**
- **60 pb**
- **20 pb**

- **4260** (515 pb$^{-1}$)
- **4360** (523 pb$^{-1}$)
- **4390** (53 pb$^{-1}$)
- **4420** (43 pb$^{-1}$)
- **4190** (42 pb$^{-1}$)

- January 2013
- February 2013
Connecting the XYZ at BESIII

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at BESIII

- 595 events for $J/\psi \rightarrow e^+e^-$
- 882 events for $J/\psi \rightarrow \mu^+\mu^-$

PRL 110, 252001 (2013)

(cross section consistent with Belle and BaBar)

Ryan Mitchell — Indiana University
Connecting the XYZ at BESIII

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

PRD 86, 051102(R) (2012)

BESIII

(cross section consistent with Belle and BaBar)

[Diagram showing mass spectrum and JPC assignments for various particles, including predicted, discovered, predicted, undetected, and unpredicted, discovered states.]

\[ \sigma(e^+e^- \rightarrow J/\psi\pi^+\pi^-)(pb) \]

\[ E_{cm}(GeV) \]

Ryan Mitchell — Indiana University
Connecting the XYZ at BESIII

\[ e^+e^-(\gamma_{\text{ISR}}) \rightarrow \pi^+\pi^- J/\psi \text{ at Belle} \]

\[ \sigma(\pi^+\pi^- J/\psi) \text{ (pb)} \]

(cross section consistent with Belle and BaBar)

**Figure 1 (color online).** (a) Invariant mass distributions of $1e^+e^-$ collected at or near the $B^+$ peak with a mass between 3.8 and 5.5 GeV, and a large peak around 4 GeV. 

The event selection is described in Ref. [C25].

After the initial observations of the $J/\psi'(3686)$, we investigate the existence of similar states as the $J/\psi$. Connecting the XYZ at BESIII, wherein a subset of the unexplained states was not confirmed. Instead, they attributed the structure to exponentially falling non-resonant production.

Connecting the XYZ at BESIII, we report cross section measurements for the $e^+e^- (\gamma_{\text{ISR}}) \rightarrow \pi^+\pi^- J/\psi$ process at Belle with a peak around 4 GeV. The large peak around 4 GeV, which is attributed to the $\psi'$ resonance, is consistent with the results from Belle and BaBar.

**Figure 2** shows the invariant mass distribution of $1e^+e^-$ collected at or near the $B^+$ peak with a mass between 3.8 and 5.5 GeV. The peak around 4 GeV is attributed to the $\psi'$ resonance. The large peak around 4 GeV is attributed to the $\psi'$ resonance, which is consistent with the results from Belle and BaBar.

**Figure 3** illustrates the invariant mass distribution of $1e^+e^-$ collected at or near the $B^+$ peak with a mass between 3.8 and 5.5 GeV. The peak around 4 GeV is attributed to the $\psi'$ resonance. The large peak around 4 GeV is attributed to the $\psi'$ resonance, which is consistent with the results from Belle and BaBar.
Connecting the XYZ at BESIII

\[ \eta_c(1S_0) \rightarrow \psi(1S_0) \rightarrow J/\psi(2S_1) \rightarrow h_c(3P_1) \rightarrow X_c(3P_0) \rightarrow X_c(3P_2) \]

\[ \eta_c(2S_0) \rightarrow \psi'(2S_0) \rightarrow h_c(1P_1) \rightarrow X_c(1P_1) \rightarrow X_c(1P_2) \]

\[ \eta_c(3S_0) \rightarrow \psi(3S_1) \rightarrow h_c(3P_1) \rightarrow X_c(3P_0) \rightarrow X_c(3P_2) \]

\[ \psi(4S_1) \rightarrow Y(4360) \rightarrow h_c(3P_1) \rightarrow X_c(3P_0) \rightarrow X_c(3P_2) \]

\[ \psi(2D_1) \rightarrow X(3872) \rightarrow h_c(3P_1) \rightarrow X_c(3P_0) \rightarrow X_c(3P_2) \]

\[ \psi''(1D_1) \rightarrow \eta_c(2S_0) \rightarrow \psi'(2S_0) \rightarrow h_c(1P_1) \rightarrow X_c(1P_1) \rightarrow X_c(1P_2) \]

\[ Z(4430)? \]

**Study $Y(4260)$ at BESIII**

- Dec, 2012 to Jan, 2013, BESIII accumulate 525 pb$^{-1}$ data
- Study $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at BESIII

1. Very simple and straightforward analysis.
2. The produced vector charmonium(like) state almost in rest frame.
3. Y(4260) → π$^+\pi^-$ J/ψ, four charged track detected.

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

$\psi(2S) \rightarrow \pi^+\pi^- J/\psi$

at SLAC

PRL34, 1181 (1975)
Connecting the XYZ at BESIII

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

non-trivial substructure in \pi^+\pi^- J/\psi
Connecting the XYZ at BESIII

Connecting the XYZ at BESIII

\[ e^+ e^- \rightarrow \pi^+ \pi^- J/\psi \]

\[ M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV} \]
\[ \Gamma = 46 \pm 10 \pm 20 \text{ MeV} \]

\[ \Rightarrow \text{“Charged Charmoniumlike Structure”} \]

(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
Connecting the XYZ at BESIII

Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics 6, 139 (2013) | DOI: 10.1103/Physics.6.139

Physics looks back at the standout stories of 2013.

As 2013 draws to a close, we look back on the research covered in Physics that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the Physics staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed \( Z_c(3900) \), are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.
BESII Initial Round of Data-taking

Connecting the XYZ at BESIII

- 4260 (515 pb$^{-1}$)
  (world’s largest sample of $Y(4260)$ by ~2x)
- 4190 (42 pb$^{-1}$)
- 4230 (43 pb$^{-1}$)
- 4310 (44 pb$^{-1}$)

- 4360 (523 pb$^{-1}$)
  (world’s largest sample of $Y(4360)$ by ~4x)
- 4390 (53 pb$^{-1}$)
- 4420 (43 pb$^{-1}$)

January 2013
February 2013
Connecting the XYZ at BESIII

BESIII Additional Round of Data-taking

**Integrated Luminosity**

- March 2013
- April 2013
- May 2013

**BESIII meeting**

- 4260 (291 pb$^{-1}$)
- 4210 (52 pb$^{-1}$)
- 4220 (52 pb$^{-1}$)
- 4245 (53 pb$^{-1}$)

4230 (1011 pb$^{-1}$)
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$^{-1}$)
Connecting the XYZ at BESIII

\[ e^+e^- \text{ at } 4260 \text{ MeV} \rightarrow \pi^+\pi^- h_c(1P) \text{ at BESIII} \]

Exclusively reconstruct the process:

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

\[ h_c(1P) \rightarrow \gamma \eta_c(1S) \]

\[ \eta_c(1S) \rightarrow 16 \text{ decay channels} \]
Connecting the XYZ at BESIII

\[ e^+e^- (\text{at } 4260 \text{ MeV}) \rightarrow \pi^+\pi^- h_c(1P) \text{ at BESIII} \]

\[
\begin{align*}
\text{Exclusively reconstruct the process:} \\
&\quad e^+e^- \rightarrow \pi^+\pi^- h_c(1P) \\
&\quad h_c(1P) \rightarrow \gamma \eta_c(1S) \\
&\quad \eta_c(1S) \rightarrow 16 \text{ decay channels}
\end{align*}
\]

\[ \text{PRL 111, 242001 (2013)} \]
Connecting the XYZ at BESIII

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

Exclusively reconstruct the process:

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

\[ h_c(1P) \rightarrow \gamma \eta_c(1S) \]

\[ \eta_c(1S) \rightarrow 16 \text{ decay channels} \]
Connecting the XYZ at BESIII

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

Exclusively reconstruct the process:

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\[ \eta_c(1S) \rightarrow 16 \text{ decay channels} \]
Connecting the XYZ at BESIII

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

PRL 111, 242001 (2013)

\[ M = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV} \]

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

⇒ “Charged Charmoniumlike Structure”

\[ (this \ time \ close \ to \ D^*D^* \ threshold) \]
Connecting the XYZ at BESIII

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

The cross section shape requires more data…
Is it a combination of the \textbf{Y(4260)} and \textbf{Y(4360)}?
Or something completely different?
The $Z_c(3900)$ is close to $DD^*$ threshold...
Connecting the XYZ at BESIII

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

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

\[ M = 3883.9 \pm 1.5 \pm 4.2 \ MeV \]
\[ \Gamma = 24.8 \pm 3.3 \pm 11.0 \ MeV \]

PRL 112, 022001 (2014)

... 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.)
Connecting the XYZ at BESIII

The $Z_{c}'(4020)$ is close to $D^*D^*$ threshold...

![Graph showing the mass of $Z_{c}'(4020)$ 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 $D^*$. 

Ryan Mitchell — Indiana University
Connecting the XYZ at BESIII

Search for $Y(4260) \rightarrow \gamma X(3872)$...
Connecting the XYZ at BESIII

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

⇒ “Observation of the X(3872)”

significance = 6.3\sigma

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

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

Γ consistent with resolution
Connecting the XYZ at BESIII

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

-Hints that this is $Y(4260) \rightarrow \gamma X(3872)$!?
(I) The quark model describes most of charmonium remarkably well. \((c\bar{c})\)

(II) But the “XYZ” states point beyond the quark model. \((c\bar{c}g, c\bar{q}q\bar{c}, (c\bar{q})(q\bar{c}), c\bar{c}\pi\pi)\)

(III) Most of the XYZ states were discovered by Belle and BaBar.

(IV) But BESIII can directly produce the \(Y(4260)\) and \(Y(4360)\) in e\(^+\)e\(^-\) annihilation.

(V) BESIII has observed “charged charmoniumlike structures” — the \(Z_c(3900)\) and the \(Z_c'(4020)\).

(VI) BESIII has also observed a transition to the \(X(3872)\).

(VII) We are building connections.
Connecting the XYZ at BESIII

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Connecting the XYZ at BESIII

(1) The quark model describes most of charmonium remarkably well. \((c\bar{c})\)

Crystal Ball at SLAC
(discovery of \(\eta_c\))

PRL45, 1150 (1980)
Connecting the XYZ at BESIII

(I) The quark model describes most of charmonium remarkably well. \((c\bar{c})\)

(II) But the “XYZ” states point beyond the quark model. \((c\bar{c}g, c\bar{q}q\bar{c}, (c\bar{q})(q\bar{c}), c\bar{c}\pi\pi)\)

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(VI) BESIII has also observed a transition to the \(X(3872)\).

(VII) We are building connections.

(VIII) But there is much left to do… and a new running period has begun…
Connecting the XYZ at BESIII

(I) The quark model describes most of charmonium remarkably well. \((c\bar{c})\)

(II) But the “XYZ” states point beyond the quark model. \((c\bar{c}g, c\bar{q}q\bar{c}, (c\bar{q})(q\bar{c}), c\bar{c}\pi\pi)\)

(III) Most of the XYZ states were discovered predicted, discovered

(IV) But BESIII can directly produce the predicted, undiscovered \(Y(4260)\) and \(Y(4360)\) in e\(^{+}\)e\(^{-}\) annihilation.

(V) BESIII has observed “charged charmoniumlike structures” — unpredicted, discovered \(Z_{c}(3900)\) and \(Z'_{c}(4020)\).

(VI) BESIII has also observed a transition to predicted, discovered the \(X(3872)\).

(VII) We are building connections.

(VIII) But there is much left to do… \(and\ a\ new\ running\ period\ has\ begun\…\)

Look forward to many new results from BESIII!

Thanks!