Four Quark States?
Department of Physics and Astronomy Colloquium:
Notes from the Editors: Highlights of the Year

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*Physics* looks back at the standout stories of 2013.

Images from popular *Physics* stories in 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 $Z_0 (3900)$, are possible, the “tetraquark” interpretation may be gaining traction: BESIII has since *seen* a series of other particles that appear to contain four quarks.
OUTLINE

- BESIII experiment
- Charmonium
- XYZ states
  - $X(3872)$
  - $Y(4260)$
- BESIII does XYZ
  - $Z_c(3900)$
  - $Z_c(4020)$
  - $Z_c(4025)$
  - $Z_c(3885)$
  - $X(3872)$
- Where are we?
- Summary
Beijing Electron Positron Collider (BEPCII)

Design luminosity: $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
BEPCII: a high luminosity double-ring collider

CM Energy: 2 - 4.6 GeV
Luminosity: $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$ @ 1.89 GeV
BESIII Detector

- Magnet Yoke
- Be beam pipe
- TOF: 80 ps - barrel
- 1 T SC magnet
- RPC 9 layers
- MDC: $\delta p/p = 0.58\%$, $dE/dx \sim 6\%$ at 1 GeV
- CsI(Tl) calorimeter: $\delta E = 2.5\%$ at 1 GeV

References:
- NIM A614, 345 (2010)
The 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, Frascati Lab, Ferrara Univ.
- Netherlands: KVI/Univ. of Groningen
- Sweden: Uppsala Univ.
- Turkey: Turkey Accelerator Center

US (6)
- Univ. of Hawaii
- Univ. of Washington
- Carnegie Mellon Univ.
- Univ. of Minnesota
- Univ. of Rochester
- Univ. of Indiana

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

China (29)
- 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., Beihang 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.

Korea (1)
- Seoul Nat. Univ.

Japan (1)
- Tokyo Univ.

~350 members
52 institutions from
11 countries
BESIII

- **Hawaii members:**
  - Mihajlo Kornicer: $X_{c1} \rightarrow \eta\pi\pi, \eta'\pi\pi$ and $\tau$ mass studies
  - Tao Luo: $\tau$ mass studies
  - Gary Varner

- **Data sets (started from 2008):**
  - 1.25 B $J/\Psi$ events
  - 125 M $\Psi(3668)$ events
  - 2.9 fb$^{-1}$ at $\Psi(3770)$ for D physics
  - 500 pb$^{-1}$ at 4.009 GeV
  - XYZ - 2.4 fb$^{-1}$
  - Now doing R scan from 3.8 GeV to 4.6 GeV; then more XYZ running
Introduction to charmonium
Standard Model particles are made of quarks, leptons, and the force carriers.

Visible matter:

- \( p = uud \)  \( n = udd \)
- \( \pi^+ = u\bar{d} \)  \( \pi^- = \bar{u}d \)
- \( D^+ = c\bar{d} \)  \( D^- = \bar{c}d \)

Particles made of 2 or 3 quarks.

BEPCII operates in the 2 - 4.6 GeV energy region so it can study the lighter quarks (u, d, c, and s) and the leptons. “\( \tau - \)charm factory”
Charmonium

- Charmonium is one of the simplest bound states in QCD.
- Charge zero.
- Like positronium in QED.
- Classify using $J^{PC}$.
- Match to $n^{2S+1}L_J$ quark model states:
  - $J = L + S$
  - $P = (-1)^{L+1}$
  - $C = (-1)^{L+S}$

$J^P = \frac{1}{2}^+$

BESIII has studied these.
Introduction to Charmonium

How to predict masses?

Potential Models
(tuned using lowest mass states)

Example from Barnes, Godfrey, Swanson:

\[
V_0^{(c\bar{c})}(r) = -\frac{4}{3} \frac{\alpha_s}{r} + b r + \frac{32\pi \alpha_s}{9m_c^2} \tilde{\delta}_o(r) \vec{S}_c \cdot \vec{S}_{\bar{c}}
\]

(Coulomb + Confinement + Contact)

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

(Spin-Orbit + Tensor)

PRD72, 054026 (2005)
Introduction to Charmonium

A more fundamental approach: Lattice QCD

Charmonium

D $\bar{D}$ thresh.

Fermilab Lattice and MILC Collaborations
PRD81, 034508 (2010)
Charmonium spectrum below open charm

Only $J/\psi$ and $\psi'$ produced directly in $e^+e^-$ collisions, but states below $\psi'$ produced through radiative and hadronic transitions.
Many charmonium states predicted by potential models and LQCD. Many have been found.

XYZ states not predicted by potential models. What are they?
<table>
<thead>
<tr>
<th>State</th>
<th>$m$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>$J^{PC}$</th>
<th>Process (mode)</th>
<th>Experiment (#/$\sigma$)</th>
<th>Year</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3872)$</td>
<td>3871.52 ± 0.20</td>
<td>1.3 ± 0.6</td>
<td>1$^+$/2$^+-$</td>
<td>$B \rightarrow K (\pi^+ \pi^- J/\psi)$</td>
<td>Belle [85, 86] (12.8), BABAR [87] (8.6)</td>
<td>2003</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&lt;2.2)</td>
<td></td>
<td>$p\bar{p} \rightarrow (\pi^+ \pi^- J/\psi) + \cdots$</td>
<td>CDF [88–90] (np), DØ [91] (5.2)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K (\omega J/\psi)$</td>
<td>Belle [92] (4.3), BABAR [93] (4.0)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K (D^{*0} \bar{D}^{0})$</td>
<td>Belle [94, 95] (6.4), BABAR [96] (4.9)</td>
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<td></td>
<td>$B \rightarrow K (\gamma J/\psi)$</td>
<td>Belle [92] (4.0), BABAR [97, 98] (3.6)</td>
<td></td>
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<td></td>
<td>$B \rightarrow K (\gamma \psi(2S))$</td>
<td>BABAR [98] (3.5), Belle [99] (0.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X(3915)$</td>
<td>3915.6 ± 3.1</td>
<td>28 ± 10</td>
<td>0/2$^+$</td>
<td>$B \rightarrow K (\omega J/\psi)$</td>
<td>Belle [100] (8.1), BABAR [101] (19)</td>
<td>2004</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \rightarrow e^+e^- (\omega J/\psi)$</td>
<td>Belle [102] (7.7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X(3940)$</td>
<td>3942$^{+9}_{-8}$</td>
<td>37$^{+27}_{-17}$</td>
<td>?$^+$</td>
<td>$e^+e^- \rightarrow J/\psi (D\bar{D}^*)$</td>
<td>Belle [103] (6.0)</td>
<td>2007</td>
<td>NC!</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \rightarrow J/\psi (\ldots)$</td>
<td>Belle [54] (5.0)</td>
<td></td>
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</tr>
<tr>
<td>$G(3900)$</td>
<td>3943 ± 21</td>
<td>52 ± 11</td>
<td>1$^-$</td>
<td>$e^+e^- \rightarrow \gamma (D\bar{D})$</td>
<td>BABAR [27] (np), Belle [21] (np)</td>
<td>2007</td>
<td>OK</td>
</tr>
<tr>
<td>$Y(4008)$</td>
<td>4008$^{+121}_{-49}$</td>
<td>226 ± 97</td>
<td>1$^-$</td>
<td>$e^+e^- \rightarrow \gamma (\pi^+ \pi^- J/\psi)$</td>
<td>Belle [104] (7.4)</td>
<td>2007</td>
<td>NC!</td>
</tr>
<tr>
<td>$Z_1(4050)^+$</td>
<td>4051$^{+24}_{-43}$</td>
<td>82$^{+51}_{-55}$</td>
<td>?</td>
<td>$B \rightarrow K (\pi^+ \chi_c(1P))$</td>
<td>Belle [105] (5.0)</td>
<td>2008</td>
<td>NC!</td>
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<tr>
<td>$Y(4140)$</td>
<td>4143.4 ± 3.0</td>
<td>15$^{+11}_{-7}$</td>
<td>?$^+$</td>
<td>$B \rightarrow K (\phi J/\psi)$</td>
<td>CDF [106, 107] (5.0)</td>
<td>2009</td>
<td>NC!</td>
</tr>
<tr>
<td>$X(4160)$</td>
<td>4156$^{+29}_{-25}$</td>
<td>139$^{+113}_{-65}$</td>
<td>?$^+$</td>
<td>$e^+e^- \rightarrow J/\psi (D\bar{D}^*)$</td>
<td>Belle [103] (5.5)</td>
<td>2007</td>
<td>NC!</td>
</tr>
<tr>
<td>$Z_2(4250)^+$</td>
<td>4248$^{+185}_{-45}$</td>
<td>177$^{+321}_{-72}$</td>
<td>?</td>
<td>$B \rightarrow K (\pi^+ \chi_c(1P))$</td>
<td>Belle [105] (5.0)</td>
<td>2008</td>
<td>NC!</td>
</tr>
</tbody>
</table>
### XYZ States

**EPJ C71, 1534 (2011)**

- **Most discoveries by B factory experiments.**
- **Many states not confirmed.**
- **Produced indirectly by ISR production or B decay.**
- **Still a puzzle after 10 years.**
- **Much theoretical interest.**

<table>
<thead>
<tr>
<th>State</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>JPC</th>
<th>Decays</th>
<th>Experiment</th>
<th>Year</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y(4260)$</td>
<td>4263 ± 5</td>
<td>108 ± 14</td>
<td>1--</td>
<td>$e^+e^- \rightarrow \gamma (\pi^+\pi^- J/\psi)$</td>
<td><em>BABAR</em> [108, 109] (8.0)</td>
<td>2005</td>
<td>OK</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>$B \rightarrow K (\phi J/\psi)$</td>
<td><em>CDF</em> [107] (3.1)</td>
<td></td>
<td>NC!</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>$e^+e^- \rightarrow e^+e^- (\phi J/\psi)$</td>
<td><em>Belle</em> [112] (3.2)</td>
<td></td>
<td>NC!</td>
</tr>
<tr>
<td>$Y(4274)$</td>
<td>4274.4$^{+8.4}_{-6.7}$</td>
<td>32$^{+22}_{-15}$</td>
<td>?+</td>
<td>$B \rightarrow K (\phi J/\psi)$</td>
<td><em>CDF</em> [107] (3.1)</td>
<td>2010</td>
<td>NC!</td>
</tr>
<tr>
<td>$X(4350)$</td>
<td>4350.6$^{+4.6}_{-5.1}$</td>
<td>13.3$^{+18.4}_{-10.0}$</td>
<td>0.2++</td>
<td>$e^+e^- \rightarrow e^+e^- (\phi J/\psi)$</td>
<td><em>Belle</em> [112] (3.2)</td>
<td>2009</td>
<td>NC!</td>
</tr>
<tr>
<td>$Y(4360)$</td>
<td>4353 ± 11</td>
<td>96 ± 42</td>
<td>1--</td>
<td>$e^+e^- \rightarrow \gamma (\pi^+\pi^- J/\psi)$</td>
<td><em>BABAR</em> [113] (np), <em>Belle</em> [114] (8.0)</td>
<td>2007</td>
<td>OK</td>
</tr>
<tr>
<td>$Z(4430)^+$</td>
<td>4443$^{+24}_{-18}$</td>
<td>107$^{+113}_{-71}$</td>
<td>?</td>
<td>$B \rightarrow K (\pi^+\psi(2S))$</td>
<td><em>Belle</em> [115, 116] (6.4)</td>
<td>2007</td>
<td>NC!</td>
</tr>
<tr>
<td>$X(4630)$</td>
<td>4634$^{+9}_{-11}$</td>
<td>92$^{+41}_{-32}$</td>
<td>1--</td>
<td>$e^+e^- \rightarrow \gamma (\Lambda_c^+ \Lambda_c^-)$</td>
<td><em>Belle</em> [25] (8.2)</td>
<td>2007</td>
<td>NC!</td>
</tr>
<tr>
<td>$Y(4660)$</td>
<td>4664 ± 12</td>
<td>48 ± 15</td>
<td>1--</td>
<td>$e^+e^- \rightarrow \gamma (\pi^+\pi^- J/\psi(2S))$</td>
<td><em>Belle</em> [114] (5.8)</td>
<td>2007</td>
<td>NC!</td>
</tr>
<tr>
<td>$Y_b(10888)$</td>
<td>10888.4 ± 3.0</td>
<td>30.7$^{+8.9}_{-7.7}$</td>
<td>1--</td>
<td>$e^+e^- \rightarrow (\pi^+\pi^- \gamma (nS))$</td>
<td><em>Belle</em> [37, 117] (3.2)</td>
<td>2010</td>
<td>NC!</td>
</tr>
</tbody>
</table>
Charmonium Production Processes

- $e^+e^-$ annihilation
- B decay
- ISR
  - $e^+e^-$ radiate one or more photons.
  - Measure $\sigma$ over range of energies.
- 2 photon
  - even spin mesons
  - anti glueball filter.

High luminosities at B factories allow use of ISR and 2 photon processes.
Experiments

Belle (1998 - 2010)

BaBar (1998 - 2008)

Belle II (2016? - )

BESIII (2009 - )
X(3872)

• Observed first by Belle in 2003 in $B^\pm \rightarrow K^\pm (\pi^+\pi^-J/\Psi)$
• Confirmed by CDF, D0, and BaBar
• Belle and BaBar observe $X(3872) \rightarrow \gamma J/\Psi$: $C = +$
• CDF and LHCb determine $J^P = 1^+$
  
  $M = 3871.68 \pm 0.17 \text{ MeV/c}^2$
  $\Gamma < 1.2 \text{ MeV}$
X(3872)

Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \rightarrow K^{\pm} \pi^+ \pi^- J/\psi$ Decays


(Belle Collaboration)

Dec. 2003

Belle's most cited paper
$J^{PC} = 1^{--}$ since produced in ISR

BaBar, PRL 95, 142001 (2005)


BaBar, PRD 86, 051102 (2012)
X(3872) and Y(4260)

• Not only don’t X(3872) and Y(4260) fit in normal quark model, they decay to π⁺π⁻J/Ψ even though they are above DD-bar threshold.

• New XYZ era has generated much excitement and many, many theoretical papers. Some theoretical ideas for Y(4260):
  - DD* bound state [NPA815, 53 (2009)].
  - J/Ψ f0 bound state (with KK →ππ) [PRD80, 094012 (2009)].
  - Tetraquarks (or two diquarks) [PRD72, 031502 (2005)].
  - Hadrocharmonium [PLB666, 215 (2008)].

See Xiang Liu, arXiv:1312.7408 for a recent list of references.
BESIII does XYZ

Data collection continued around $Y(4260)$ and $Y(4360)$ until June. Much more data collected.

Provides excellent opportunities to understand XYZ particles.
Y(4260)

Data: 525 pb⁻¹ at 4260 MeV
Select $e^+e^- \rightarrow \pi^+\pi^- J/\Psi$, $J/\Psi \rightarrow l^+l^-$ events.

1477 events found.

Born cross section, $(62.9 \pm 1.9 \pm 3.7)$ pb, consistent with production of $Y(4260)$. 
$Z_c(3900)$

Structure observed in the $\pi^\pm J/\Psi$ mass spectrum:
\[e^+e^- \rightarrow \pi^+ Z_c(3900) \rightarrow \pi^- (\pi^+ J/\Psi) +c.c.\]

\[N(Z_c(3900)) = 307 \pm 48\]
\[M(Z_c(3900)) = 3899.0 \pm 2.8 \pm 1.4\text{ MeV; }\]
\[\Gamma(Z_c(3900)) = 46 \pm 10 \pm 20\text{ MeV; }\]

- Suggestive of a state containing more than just a C and C-bar quark. ($\pi^+ = ud, \ J/\psi = cc$)
- PRL 110, 252001 (2013) with > 100 citations
- Was on top of APS Physics Highlights of 2013
Studies at B factories found unconfirmed/controversial structures in $\pi^\pm\psi(3686)$, $Z^\pm(4430)$, [Belle, PRL 100, 142001 (2008); BaBar, PRD 79, 112001 (2009)] and $\pi^\pm X_{c1}$, $Z_1^\pm (4050)$ and $Z_2^\pm (4250)$, [Belle, PRD 78, 072004 (2008); BaBar, PRD 85, 052003 (2012)] systems.

Luckily, the $Z_c(3900)$ was confirmed by Belle [PRL 110, 252002 (2013)] in ISR $Y(4260)$ production and by Kam Seth [PLB 727, 366 (2013)] using 586 pb$^{-1}$ of CLEO data taken at a CM energy of 4170 MeV.

$Z_c(3900)$ first confirmed charged charmonium state.
**Z_c(4020)**

$e^+ + e^- \rightarrow \pi^+\pi^- h_c, \ h_c \rightarrow \gamma\eta_c, \ \eta_c \rightarrow 16\ exclusive\ states$

- Measure cross sections at 13 energies.
- Very different than $\pi^+\pi^- J/\Psi$ cross section.

- Narrow structure near $(D^*D^*)^+$ threshold in $\pi^\pm h_c$ mass:

$$e^+ e^- \rightarrow \pi^- Z_c(4020) \rightarrow \pi^- (\pi^+ h_c) + c.c.$$

$$M(Z_c(4020)) = 4022.9^{+0.8}_{-0.7} \pm 2.7\ MeV;$$

$$\Gamma(Z_c(4020)) = 7.9^{+2.7}_{-2.6} \pm 2.6\ MeV$$

$J^P = 1^+$ assumed

- No significant $Z_c(3900)$ observed.

PRL 111, 242001 (2013)

24 citations

1/23/2014
• Partial reconstruction: detect $\pi^-$, $D^+$, and one $\pi^0$
• 827 pb$^{-1}$ of data at 4.26 GeV
• Born cross section, $(137 \pm 9 \pm 15)$ pb

• Structure observed in mass recoiling from $\pi^-$:
  $e^+e^- \rightarrow \pi^- Z_c(4025)^+ \rightarrow \pi^- (D^*D^*)^+ + \text{c.c.}$

  $M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV/c$^2$;
  $\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7$ MeV
  $J^{P} = 1^+$ assumed

Loosely bound $D^*D^*$ system?

$\sigma(e^+e^- \rightarrow \pi^- Z_c(4025)^{+/+} \rightarrow \pi^- (D^*D^*)^{+/+})$

$\sigma(e^+e^- \rightarrow \pi^- (D^*D^*)^{+/+}) = (65 \pm 9 \pm 6)\%$

1/23/2014 Submitted to PRL; arXiv1308.2760
**Z_c(3885)**

- Partial reconstruction:
  - detect $\pi$ and final state D
- 525 pb^{-1} of data at 4.26 GeV
- Born cross section, (83.5 ± 6.6 ± 22) pb
- Structure observed near DD* threshold in mass recoiling from $\pi$:

$$e^+e^- \rightarrow \pi^+Z_c(3885)^- \rightarrow \pi^+(DD^*)^- + c.c.$$

- $M(Z_c(3885)) = 3883.9\pm1.5\pm4.2$ MeV/c²;
- $\Gamma(Z_c(3885)) = 24.8\pm3.3\pm11.0$ MeV
• Structure prefers $J^P = 1^+$

• Assuming $Z_c(3885)$ and $Z_c(3900)$ same:

\[
\frac{\Gamma(Z_c(3885) \rightarrow DD^*)}{\Gamma(Z_c(3900) \rightarrow \pi J/\Psi)} = 6.2 \pm 1.1 \pm 2.7
\]

PRL 112, 022001 (2014)
# Zc Summary

<table>
<thead>
<tr>
<th></th>
<th>Reaction</th>
<th>R (%)</th>
<th>( M(Z_c) ) (MeV/c²)</th>
<th>( \Gamma(Z_c) ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z_c(3885) )</td>
<td>( e^+ e^- \rightarrow \pi^{+/-} Z_c^{+/-} \rightarrow \pi^{+/-} (DD^*)^{+/-} )</td>
<td></td>
<td>3883.9 ± 1.5 ± 4.2</td>
<td>24.8 ± 3.3 ± 11</td>
</tr>
<tr>
<td>( Z_c(3900) )</td>
<td>( e^+ e^- \rightarrow \pi^{+/-} Z_c^{+/-} \rightarrow \pi^+ \pi^- J/\Psi )</td>
<td>21.5±3.3±7.5</td>
<td>3899 ± 3.6 ± 4.9</td>
<td>46 ± 10 ± 20</td>
</tr>
<tr>
<td>( Z_c(4020) )</td>
<td>( e^+ e^- \rightarrow \pi^{+/-} Z_c^{+/-} \rightarrow \pi^+ \pi^- h_c )</td>
<td>18</td>
<td>4022.9 ± 0.8 ± 2.7</td>
<td>7.9 ± 2.7 ± 2.6</td>
</tr>
<tr>
<td>( Z_c(4025) )</td>
<td>( e^+ e^- \rightarrow \pi^{+/-} Z_c^{+/-} \rightarrow \pi^{+/-} (D^<em>D^</em>)^{+/-} )</td>
<td>65 ± 9 ± 6</td>
<td>4026.3 ± 2.6 ± 3.7</td>
<td>24.8 ± 5.6 ± 7.7</td>
</tr>
</tbody>
</table>

\[
R = \frac{\Gamma(e^+e^- \rightarrow Z_c \pi \rightarrow \pi \text{ f.s.})}{\Gamma(e^+e^- \rightarrow \pi \text{ f.s.})}
\]

At least two states.
• So far X(3872) only observed in B decays and hadron collisions.
• Since $J^{PC} = 1^{++}$, should be able to see Y(4260) radiative decay to X(3872):

$$e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma \pi^+\pi^- J/\psi$$

• Combine data at 4.009, 4.229, 4.26, and 4.36 GeV:
  $M(X(3872)) = 3872.1 \pm 0.8 \pm 0.3$ MeV
  [PDG: 3871.68 ±0.17 MeV]
• X(3872) from radiative Y(4260) decay?
• Accepted by PRL; arXiv1310.4101
XYZ Transitions

Have measured a number of transitions. Many other analyses underway. More data at other energy points this year.
Where are we?
Theorists have been very busy, and many explanations have been offered for the X(3872), Y(4260), and now the Zc: tetraquarks, molecular states (DD* bound state), hadrocharmonium, hybrid charmonium, etc. I will only show a couple of results here.

1.) Actually the Zc states were predicted based on Zb structures observed by Belle at 10610 and 10650 MeV/c² in Υ decays and using the Initial Single Pion Emission mechanism (ISPE). Initial state here is charmonium.

D.Y. Chen and X. Liu, PRD 84, 034032 (2011).
ISPE mechanism:

Initial Single Pion Emission mechanism.

- intermediate $D\bar{D}^*$ states
- intermediate $D^*\bar{D}^*$ states

$Z_c(3900)$

$Z_c(4020)$

Initial Single Pion Emission mechanism.
Theory:

• Many of the states are near thresholds (DD*, D*D*, etc), so molecules and other 4-quark states popular.
2.) Voloshin proposes that $Y(4260)$ and $Y(4360)$ are mixtures of two states of hadrocharmonium, one containing a spin triplet heavy quark pair and the other containing a spin singlet pair.

- Predicts line shapes:

3.) Wang, Hanhart, and Zhao propose $Y(4260)$ is a $DD_1(2420) \overline{DD}_1(2420)$ molecule. Suggests $Z(3900)$ is a $DD^* + DD^*$ molecular state. Both box diagram and $Z_c(3900)$ contribute to peak.

See Xiang Liu, arXiv:1312.7408 for a recent list of references.
Where are we?

Do we understand everything now?

1.) What are X(3872), Y(4260), and Z_c states?
2.) Are they 4-quark states?
3.) Are they resonances? Cusps? Dynamic effects?
4.) Is there a universal explanation for XYZs?
Summary

• BESIII has begun XYZ physics running at and around the Y(4260).
• The $Z_c(3900)$ is the first confirmed charged charmonium-like state.
• Other processes have led to other narrow $Z_c$ states.
• These have generated a lot of theoretical interest.
• However more experimental results are needed to understand the physics.
• BESIII is working on this.
Thank you