Experimental Aspects of Heavy Quark Exotica: A Brief Tour of the XYZ

Ryan Mitchell
Indiana University
XIIIth Quark Confinement and the Hadron Spectrum
Maynooth, Ireland, August 2, 2018

e^+e^- \rightarrow Y(4260) \rightarrow \pi^+\pi^- J/\psi
Q: What are heavy quark exotica?
A: Phenomena in the heavy quark sector that do not easily fit into the naive quark model picture of mesons and baryons.

Q: Why are they interesting?
A: They can be used to explore novel phenomena in QCD:

\[\text{hybrid mesons, tetraquarks, pentaquarks, molecules, hadroquarkonium, thresholds}\]

Q: Why are they called XYZ?
A: Mostly historical reasons.

But now there are patterns:

- **Z**: electrically charged (I = 1).
- **Y**: \( J^{PC} = 1^{--} \), made directly in e^+e^-.
- **X**: whatever is leftover.

But there are many exceptions!

[And the PDG has now renamed them by \(IJ^{PC}\).]

Q: How many have been found?
A: Many.
Table 8.1: Symbols for mesons with strangeness and heavy-flavor quantum numbers equal to zero. States that do not yet appear in the RPP are listed in parentheses.

\[
J^{PC} = \begin{cases} 
0^+ & 1^- & 1^{--} & 0^{++} \\
2^- & 3^- & 2^{--} & 1^{++} 
\end{cases}
\]

Minimal quark content

\[
\begin{align*}
\{u \bar{d}, u \bar{u} - d \bar{d}, d \bar{u}\} & \quad (I = 1) \\
\{d \bar{d} + u \bar{u}\} & \quad (I = 0)
\end{align*}
\]

and/or \( s \bar{s} \)

\[
\begin{align*}
c \bar{c} & \quad \eta_c, h_c, \psi^\dagger, \chi_c \\
b \bar{b} & \quad \eta_b, h_b, \Upsilon, \chi_b
\end{align*}
\]

\( I = 1 \) with \( c \bar{c} \)

\( (\Pi_c) \quad Z_c, R_c, (W_c) \)

\( I = 1 \) with \( b \bar{b} \)

\( (\Pi_b) \quad Z_b, (R_b), (W_b) \)

\( \dagger \)The \( J/\psi \) remains the \( J/\psi \).

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**Introduction to Heavy Quark Exotica**

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(1) The hidden-charm pentaquark and tetraquark states
Hua-Xing Chen, Wei Chen, Xiang Liu, Shi-Lin Zhu

(2) Heavy-Quark QCD Exotica
Richard F. Lebed, Ryan E. Mitchell, Eric S. Swanson
*Progress in Particle and Nuclear Physics* 93, 143–194 (2017) [arXiv:1610.04528]

(3) Multiquark Resonances
A. Esposito, A. Pilloni, A.D. Polosa
*Physics Reports* 668, 1-97 (2017) [arXiv:1611.07920]

(4) Hadronic Molecules
Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meißenner, Qian Wang, Qiang Zhao, and Bing-Song Zou

(5) Exotics: Heavy Pentaquarks and Tetraquarks
Ahmed Ali, Jens Sören Lange, Sheldon Stone
*Progress in Particle and Nuclear Physics* 97, 123–198 (2017) [arXiv:1706.00610]

(6) Nonstandard Heavy Mesons and Baryons: Experimental Evidence
Stephen Lars Olsen, Tomasz Skwarnicki, Daria Zieminska
## 2016-2018 Review Articles on Heavy Quark Exotica

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<tbody>
<tr>
<td>$X(3823) \ (\psi_2(ID))$</td>
<td>0+2−</td>
<td>3822.2 ± 1.2 [176]</td>
<td>&lt; 16</td>
<td>$B \rightarrow K\pi; X \rightarrow \gamma X_1$ $e^+e^- \rightarrow \pi^+\pi^-\pi^0; X \rightarrow \gamma X_1$</td>
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<tr>
<td>$X(3872)$</td>
<td>0+1++</td>
<td>3871.69 ± 0.17 [176]</td>
<td>&lt; 1.2</td>
<td>$B \rightarrow K\pi; X \rightarrow \gamma J/\psi$ $B \rightarrow K\pi; X \rightarrow \gamma J/\psi$ $B \rightarrow K\pi; X \rightarrow \gamma J/\psi$ $B \rightarrow K\pi; X \rightarrow \gamma J/\psi$ $e^+e^- \rightarrow \gamma X; X \rightarrow \pi^+\pi^-J/\psi$ $pp \rightarrow X + \text{any}; X \rightarrow \pi^+\pi^-J/\psi$</td>
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<tr>
<td>$Z_c(3900)$</td>
<td>1+1++</td>
<td>3886.6 ± 2.4 [176]</td>
<td>28.1 ± 2.6</td>
<td>$e^+e^- \rightarrow \pi Z; Z \rightarrow J/\psi$ $e^+e^- \rightarrow \pi Z; Z \rightarrow D^<em>D^</em>$</td>
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<td>$X(3915)$</td>
<td>0+0++</td>
<td>3918.4 ± 1.9 [176]</td>
<td>20 ± 5</td>
<td>$e^+e^- \rightarrow \pi Z; Z \rightarrow \rho \rho$ $e^+e^- \rightarrow \pi Z; Z \rightarrow D^<em>D^</em>$</td>
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<td>$X(3940)$</td>
<td>0+0++</td>
<td>3932.7 ± 2.6 [176]</td>
<td>24 ± 6</td>
<td>$e^+e^- \rightarrow \gamma Z; Z \rightarrow DD$ $e^+e^- \rightarrow \gamma Z; Z \rightarrow DD$</td>
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<tr>
<td>$Z(3990) \ (\gamma_3(2P))$</td>
<td>0+2++</td>
<td>3942.6 ± 6 [46]</td>
<td>37 ± 0.8</td>
<td>$B \rightarrow K\pi; X \rightarrow \omega J/\psi$</td>
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<tr>
<td>$Y(4008)$</td>
<td>1−−</td>
<td>3891 ± 41 ± 12 [23]</td>
<td>255 ± 40 ± 14</td>
<td>$e^+e^- \rightarrow \gamma Y; Y \rightarrow \pi^+\pi^-J/\psi$</td>
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<tr>
<td>$Z_c(4020)$</td>
<td>1+?−</td>
<td>4024.1 ± 1.9 [176]</td>
<td>13 ± 5</td>
<td>$e^+e^- \rightarrow \pi Z; Z \rightarrow \rho \rho$ $e^+e^- \rightarrow \pi Z; Z \rightarrow D^<em>D^</em>$</td>
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<td>$Z(4050)$</td>
<td>1−−?+</td>
<td>4051 ± 14.2 ± 13 [133]</td>
<td>82 ± 1.7</td>
<td>$B \rightarrow K\pi; Z \rightarrow \pi^0\pi^0$</td>
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<tr>
<td>$Z_c(4055)$</td>
<td>1+?−</td>
<td>4054 ± 3 ± 1 ± 148</td>
<td>45 ± 11 ± 6</td>
<td>$e^+e^- \rightarrow \pi Z; Z \rightarrow \pi^0\pi^0(2S)$</td>
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<td>$Y(4140)$</td>
<td>0+1++</td>
<td>4146 ± 4.5 ± 2 ± 8 [125]</td>
<td>83 ± 21 ± 14</td>
<td>$B \rightarrow K\pi; Y \rightarrow \phi J/\psi$ $pp \rightarrow Y + \text{any}; Y \rightarrow \phi J/\psi$</td>
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<tr>
<td>$X(4160)$</td>
<td>1+1++</td>
<td>4156 ± 29 ± 15 [46]</td>
<td>139 ± 9 ± 21</td>
<td>$e^+e^- \rightarrow \gamma J/\psi + X; \rightarrow D^<em>D^</em>$</td>
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<tr>
<td>$Z_c(4200)$</td>
<td>1+1−</td>
<td>4196 ± 29 ± 15 [46]</td>
<td>370 ± 9 ± 12</td>
<td>$B \rightarrow K\pi; Z \rightarrow \pi^0\pi^0$</td>
</tr>
<tr>
<td>$Y(4230)$</td>
<td>0+1</td>
<td>4230 ± 8 ± 6 [149]</td>
<td>38 ± 12 ± 2</td>
<td>$e^+e^- \rightarrow \gamma Y; Y \rightarrow \phi J/\psi$</td>
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<tr>
<td>$Z(4240)$</td>
<td>0+?−</td>
<td>4251 ± 9 [176]</td>
<td>120 ± 12</td>
<td>$e^+e^- \rightarrow \gamma Y; Y \rightarrow \phi J/\psi$</td>
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<tr>
<td>$X(4274)$</td>
<td>0+1++</td>
<td>4273.3 ± 8.3 ± 1.6 [125]</td>
<td>52 ± 11 ± 11</td>
<td>$B \rightarrow K\pi; Y \rightarrow \phi J/\psi$</td>
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<td>$X(4350)$</td>
<td>0+1?+</td>
<td>4356 ± 0.3 ± 0.7 [170]</td>
<td>131 ± 9 ± 4</td>
<td>$e^+e^- \rightarrow \gamma Y; Y \rightarrow \phi J/\psi$</td>
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<td>$X(4360)$</td>
<td>1−−</td>
<td>4366 ± 6 [176]</td>
<td>102 ± 10</td>
<td>$B \rightarrow K\pi; Z \rightarrow \pi^0\pi^0(2S)$</td>
</tr>
<tr>
<td>$Z_c(4430)$</td>
<td>1+1−</td>
<td>4478 ± 15 [176]</td>
<td>181 ± 31</td>
<td>$B \rightarrow K\pi; Z \rightarrow \pi^0\pi^0$</td>
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<tr>
<td>$X(4500)$</td>
<td>0+0?+</td>
<td>4500 ± 11.4 ± 12 [125]</td>
<td>92 ± 21 ± 20</td>
<td>$B \rightarrow K\pi; X \rightarrow \phi J/\psi$</td>
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<tr>
<td>$X(4630)$</td>
<td>1−−</td>
<td>4634 ± 12.4 ± 13 [150]</td>
<td>92 ± 21 ± 20</td>
<td>$e^+e^- \rightarrow \gamma X; X \rightarrow \phi J/\psi$</td>
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<tr>
<td>$Y(4660)$</td>
<td>0+1</td>
<td>4643 ± 9 [176]</td>
<td>72 ± 11</td>
<td>$e^+e^- \rightarrow \gamma Y; Y \rightarrow \pi^0\pi^0(2S)$</td>
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<tr>
<td>$X(4700)$</td>
<td>0+0?+</td>
<td>4704 ± 10.8 ± 12 [125]</td>
<td>120 ± 31 ± 14</td>
<td>$B \rightarrow K\pi; X \rightarrow \phi J/\psi$</td>
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<tr>
<td>$P_c(4380)$</td>
<td></td>
<td>4380 ± 8 ± 29 [35]</td>
<td>205 ± 18 ± 86</td>
<td>$\Lambda_b \rightarrow KP_c; P_c \rightarrow \phi J/\psi$</td>
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<td>$P_c(4450)$</td>
<td></td>
<td>4494.8 ± 8.7 ± 2.5 [35]</td>
<td>39 ± 5 ± 19</td>
<td>$\Lambda_b \rightarrow KP_c; P_c \rightarrow \phi J/\psi$</td>
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<tr>
<td>$X(5568)$</td>
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<td>5567.8 ± 29 ± 1.0 [175]</td>
<td>21.9 ± 6.4 ± 2.5</td>
<td>$pp \rightarrow X + \text{anything}; X \rightarrow B_s\pi^+$</td>
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<tr>
<td>$Z(10601)$</td>
<td>1+1−</td>
<td>10607.2 ± 2.0 [176]</td>
<td>18.4 ± 2.4</td>
<td>$e^+e^- \rightarrow \pi Z; Z \rightarrow \phi T(1S,2S,3S)$ $e^+e^- \rightarrow \pi Z; Z \rightarrow \phi h_0(1P,2P)$ $e^+e^- \rightarrow \pi Z; Z \rightarrow \phi B^0$</td>
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<td>$Z(10650)$</td>
<td>1+1−</td>
<td>10652.2 ± 1.5 [176]</td>
<td>11.5 ± 2.2</td>
<td>$e^+e^- \rightarrow \pi Z; Z \rightarrow \phi h_0(1P,2P)$ $e^+e^- \rightarrow \pi Z; Z \rightarrow \phi B^0$</td>
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<td>$Y_c(10888)$</td>
<td>0−1−</td>
<td>10891 ± 4 [176]</td>
<td>54 ± 7</td>
<td>$e^+e^- \rightarrow \gamma Y; Y \rightarrow \pi^0\pi Y(1S,2S,3S)$ $e^+e^- \rightarrow \gamma Y; Y \rightarrow \pi^0\pi h_0(1P,2P)$</td>
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### 2016-2018 Review Articles on Heavy Quark Exotica

**B and Λ_b Decays**

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<th>Process</th>
<th>Production</th>
<th>Decay</th>
<th>Particle</th>
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</thead>
<tbody>
<tr>
<td>$B \to K + X$</td>
<td>$X \to \pi^+\pi^-J/\psi$ [4, 109, 110, 111, 112, 113, 114]</td>
<td>$X(3872)$</td>
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<tr>
<td></td>
<td>$X \to D^{(*)}D^0$ [115, 116, 117]</td>
<td></td>
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<tr>
<td></td>
<td>$X \to \gamma J/\psi$ [118, 119, 120, 121]</td>
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<tr>
<td></td>
<td>$X \to \gamma\psi(2S)$ [118, 120]</td>
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<tr>
<td>$B \to K + Z$</td>
<td>$Z \to \pi^\pm\chi_{c1}$ [133, 134]</td>
<td>$Z_1(4050)$, $Z_2(4250)$</td>
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<td>$Z \to \pi^\pm J/\psi$ [133, 140]</td>
<td>$Z_1(4200)$, $Z_2(4430)$</td>
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<td>$Z \to \pi^\pm\psi(2S)$ [130, 135, 136, 137, 138, 139]</td>
<td>$Z_{1,2}(4430)$</td>
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<td>$B \to K\pi + X$</td>
<td>$X \to \pi^+\pi^-J/\psi$ [114]</td>
<td>$X(3872)$</td>
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<td>$\Lambda_b \to K + P_c$</td>
<td>$P_c \to pJ/\psi$ [35]</td>
<td>$P_{c1}(4380)$, $P_{c2}(4450)$</td>
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**$e^+e^- \to Y$**

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<th>Production</th>
<th>Decay</th>
<th>Particle</th>
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<tr>
<td>$e^+e^- \to Y$</td>
<td>$Y \to \pi\pi J/\psi$ [23, 29, 141, 142, 143, 144, 145]</td>
<td>$Y(4008)$, $Y(4260)$</td>
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<td>$Y \to \pi\pi\psi(2S)$ [108, 146, 147, 148]</td>
<td>$Y(4300)$, $Y(4660)$</td>
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<td>$Y \to \omega\chi_{c0}$ [149]</td>
<td>$Y(4230)$</td>
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<td>$Y \to \Lambda,\Lambda_c$ [150]</td>
<td>$X(4630)$</td>
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<td></td>
<td>$Y \to \pi\gamma(1S, 2S, 3S)$ [151, 152]</td>
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<td></td>
<td>$Y \to \pi\pi h_0(1P, 2P)$ [153]</td>
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<td>$e^+e^- \to \pi^\pm Z$</td>
<td>$Z \to \pi\pi\chi_{c1}$ [156, 157]</td>
<td>$Z_c(3900)$</td>
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<td>$Z \to D^<em>D^</em>$ [158, 159]</td>
<td>$Z_c(4020)$</td>
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<td></td>
<td>$Z \to \pi^\pm\psi(2S)$ [148]</td>
<td>$Z_c(4050)$</td>
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<td>$e^+e^- \to \gamma + X$</td>
<td>$X \to \pi^+\pi^-J/\psi$ [52]</td>
<td>$X(3872)$</td>
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<td></td>
<td>$X \to \gamma\chi_{c1}$ [164]</td>
<td>$X(3823)$</td>
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<td>$e^+e^- \to J/\psi + X$</td>
<td>$X \to D\pi^+$ [41, 165]</td>
<td>$X(3940)$</td>
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<td>$X \to D^*\pi^+$ [41]</td>
<td>$X(4100)$</td>
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<td>$\gamma\gamma$ Collisions</td>
<td>$\gamma\gamma \to X$</td>
<td>$X \to \omega J/\psi$ [166, 167]</td>
<td>$X(3915)$</td>
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<td></td>
<td>$X \to D\pi^+$ [168, 169]</td>
<td>$X(3930)$</td>
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<tr>
<td>Hadron Collisions</td>
<td>$pp$ or $p\bar{p} \to X +$ anything</td>
<td>$X \to \phi J/\psi$ [170]</td>
<td>$X(4350)$</td>
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<td>$X \to \omega J/\psi$ [171, 172, 173]</td>
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<td>$X \to D^*\pi^+$ [41]</td>
<td>$X(4100)$</td>
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<td>$X \to B_s\pi^+$ [175]</td>
<td>$X(4558)$</td>
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<td>BaBar</td>
<td>$Y(4260)$ [29], $Y(4360)$ [108]</td>
<td>PEP-II</td>
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<td>Belle</td>
<td>$X(3872)$ [4], $Y(3940)$ [106], $X(3915)$ [166], $Z_b(4430)$ [30, 136, 137], $Z_b(10650)$ [160, 162, 163], $Y(10888)$ [154, 152]</td>
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<td>Belle II</td>
<td>Upcoming continuation of Belle</td>
<td>SuperKEKB</td>
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<td>$Y(4260)$ [142], $\pi^+\pi^-\omega_c$ [177]</td>
<td>CESR-c</td>
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<td>BESIII</td>
<td>$Z_b(3900)$ [22, 154], $Z_b(4020)$ [156, 158], $Y(4220)$ [149], $X(3872)$ [52]</td>
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<td>2008–</td>
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<td>CDF</td>
<td>$X(3872)$ [174], $Y(4140)$ [126], $Y(4274)$ [132], $X(3872)$ [178, 179, 172]</td>
<td>Tevatron</td>
<td>1985–2011</td>
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<td>D0</td>
<td>$X(3872)$ [174], $Y(4140)$ [174], $X(5568)$ [175]</td>
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<td>LHCb</td>
<td>$Z_b(4430)$ [138, 139], $X(3872)$ [109], $P_{b,c}(4380)$, $P_{b,c}(4450)$ [35], $Y(4140)$, $Y(4274)$ [125, 131]</td>
<td>LHC</td>
<td>2010–</td>
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<td>COMPASS</td>
<td>photoproduction [181], $\alpha_1(1420)$ [182]</td>
<td>SPS</td>
<td>2002–2011</td>
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<td>CEBAF</td>
<td>2016–</td>
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<td>CLAS12</td>
<td>Beginning (searches for light quark hybrid mesons)</td>
<td>CEBAF</td>
<td>2016–</td>
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A. Glossary of Exotic States

A.1. \( X(3823) \) (or \( \psi_2(1D) \))

The \( X(3823) \) was discovered by the Belle Collaboration in 2013 in the reaction \( B \to KX \) with \( X \to \gamma \chi_{c1} \) \[124\]. The BESIII Collaboration later found a peak consistent with the \( X(3823) \) produced in \( e^+e^- \to \pi^+\pi^-X \), again with \( X \to \gamma \chi_{c1} \) \[164\]. The \( X(3823) \) is likely the \( \psi_2(1D) \) state of charmonium. See Sec. 2.6 for more detail.

A.2. \( X(3872) \)

Accidentally discovered by the Belle Collaboration in 2003 in the reaction \( B \to KX \) with \( X \to \pi^+\pi^-J/\psi \) \[4\], the \( X(3872) \) was both the first of the \( XYZ \) states to be discovered and is the one that has been most studied. Nevertheless, like most of the \( XYZ \) states, there is no interpretation that is universally agreed upon. It has been produced in decays of the \( B \) meson \[4, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 140\], in hadronic collisions \[27, 28, 171, 172, 173, 178\], and perhaps in radiative decays of the \( Y(4260) \) \[52\]. Besides \( \pi^+\pi^-J/\psi \), it has also been seen to decay to \( \omega J/\psi \) \[122\], \( D^*\bar{D} \) \[115, 116, 117\], \( \gamma J/\psi \) \[118, 119, 120, 121\], and \( \gamma\psi(2S) \) \[118, 120\]. Its unusual features include a mass that is currently indistinguishable from the \( D^{*0}\bar{D}^0 \) threshold (the current mass difference is \( 0.01 \pm 0.18 \text{ MeV} \)) and a narrow width (< 1.2 MeV). It has no isospin partners and has \( J^{PC} = 1^{++} \). See Sec. 2.3 for more discussion of its experimental properties.

A.3. \( Z_c(3900) \)

The \( Z_c(3900) \) was simultaneously discovered in 2013 by the BESIII and Belle Collaborations in the process \( e^+e^- \to \pi^\pm Z_c^\pm \) with \( Z_c^\pm \to \pi^\pm J/\psi \). For the BESIII observation \[22\], the center-of-mass energy was fixed to 4.26 GeV. Belle \[23\] used initial-state radiation to cover the energy region from 4.15 to 4.45 GeV, corresponding to the region of the \( Y(4260) \). It is not yet clear whether the production of the \( Z_c(3900) \) is associated with the \( Y(4260) \). The \( Z_c(3900) \) has since been seen in decays to \( \pi^0 J/\psi \) \[31, 32\] (\( Z_c^0 \)) and in \( D^*\bar{D} \) (both charged and neutral) \[33, 154, 155\]. It has only been produced in the reaction \( e^+e^- \to \pi Z_c \). See Sec. 2.5.4 for more experimental details.

A.4. \( X(3915) \) (or \( \chi_{c0}(2P) \))

The \( X(3915) \) was first seen by the Belle Collaboration in 2010 in the process \( \gamma \gamma \to X \) with \( X \to \omega J/\psi \) \[166\]. It was later confirmed by the BaBar Collaboration \[167\]. It appears as a clear peak with little background. Its \( J^{PC} \) is likely \( 0^{++} \), so there is some possibility that it is the \( \chi_{c0}(2P) \) state of charmonium, although this assignment is controversial. See Sec. 2.6 for more discussion.
[OUTLINE] A Tour through the XYZ

[PRELIM: Four foundational discoveries]
X(3872), Y(3940), Y(4260), Z_c(4430)

[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
Disentangling the \( \chi_cJ(2P) \).

[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in \( e^+e^- \) cross sections (“Y states”).
Peaks in their decays (“Z states”).

[Part IV: Z_c(4430)]
What happened to the Z_c(4430)?
Peaks in B decays.
Peaks in \( \Lambda_b \) decays.
B → KX; X → π⁺π⁻J/ψ at Belle
PRL91,262001 (2003)
Year: 2005  
Search for this: \( B \to KX(3872) \to \omega J/\psi \)  
Find this: \( B \to KY(3940) \to \omega J/\psi \)
Year: 2005

Search for this: $e^+e^- \rightarrow X(3872) \rightarrow \pi^+\pi^- J/\psi$

Find this: $e^+e^- \rightarrow Y(4260) \rightarrow \pi^+\pi^- J/\psi$

$e^+e^- \rightarrow Y; Y \rightarrow \pi^+\pi^- J/\psi$ at BaBar

PRL95,142001 (2005)
B → KZ; Z → π±ψ(2S) at Belle

PRL100,142001 (2008)
[PRELIM: Four foundational discoveries]
X(3872), Y(3940), Y(4260), Z_c(4430)

[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
Disentangling the χ_{cJ}(2P).

[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in e^+e^- cross sections (“Y states”).
Peaks in their decays (“Z states”).

[Part IV: Z_c(4430)]
What happened to the Z_c(4430)?
Peaks in B decays.
Peaks in Λ_b decays.
[OUTLINE] A Tour through the XYZ

[PRELIM: Four foundational discoveries]
X(3872), Y(3940), Y(4260), Zc(4430)

[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
Disentangling the $\chi_{cJ}(2P)$.

[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in $e^+e^-$ cross sections (“Y states”).
Peaks in their decays (“Z states”).

[Part IV: Zc(4430)]
What happened to the Zc(4430)?
Peaks in B decays.
Peaks in $\Lambda_b$ decays.
\[ B \to KX; X \to \pi^+\pi^- J/\psi \text{ at Belle} \]

*PRL*91,262001 (2003)

\[ B \to KX; X \to \pi^+\pi^- J/\psi \text{ at LHCb} \]

*PRD*92,011102 (2015)

More statistics!!
More experimental details.
Properties:
1. Its mass is \textit{really} close to the D^0D^{*0} threshold.
\[ M(X) - M(D^0\bar{D}^{*0}) = 0.01 \pm 0.18 \text{ MeV} \]
2. It’s narrow.
\[ \Gamma(X) < 1.2 \text{ MeV} \]
3. It has no isospin partners.
4. It has J^PC = 1^{++}.

Decays:
5. It decays to \(\omega J/\psi\).
6. It has radiative decays to \(J/\psi\) and \(\psi(2S)\).
\[ \frac{B(X \rightarrow \gamma \psi(2S))}{B(X \rightarrow \gamma J/\psi)} = 2.6 \pm 0.6 \]
7. It decays to \(\omega J/\psi\).
\[ \frac{B(X \rightarrow \omega J/\psi)}{B(X \rightarrow \pi^+ \pi^- J/\psi)} = 0.8 \pm 0.3 \]
8. It decays to \(D^0D^{*0}\).
\[ \frac{B(X \rightarrow D^0\bar{D}^{*0})}{B(X \rightarrow \pi^+ \pi^- J/\psi)} = 9.2 \pm 2.9 \]
9. There are lower limits on its branching fractions.
\[ B(X \rightarrow \pi^+ \pi^- J/\psi) > 3.2\% \]

Production:
10. It is produced in B decays.
11. It is produced in hadron collisions.
\[ \frac{\sigma(pp \rightarrow X + \text{anything}) \times B(X \rightarrow \pi^+ \pi^- J/\psi)}{\sigma(pp \rightarrow \psi(2S) + \text{anything}) \times B(\psi(2S) \rightarrow \pi^+ \pi^- J/\psi)} = 0.0656 \pm 0.0029 \pm 0.0065 \quad \text{(CMS)} \]
12. It’s produced in e^+e^- \(\rightarrow \gamma X(3872)\), maybe through the Y(4260).
13. It might be produced in photoproduction.

\[ B \rightarrow KX; X \rightarrow \pi^+ \pi^- J/\psi \] at LHCb
PRD92,011102 (2015)

\[ \Delta M = M(\pi^+ \pi^- J/\psi) - M(J/\psi) \text{ [MeV]} \]

Candidates per 1 MeV

\(X(3872)\)
**PART I: X(3872) | Experimental Details**

**Properties:**
1. Its mass is really close to the $D^0\bar{D}^{*0}$ threshold.
   \[ M(X) - M(D^0\bar{D}^{*0}) = 0.01 \pm 0.18 \text{ MeV} \]
2. It's narrow.
   \[ \Gamma(X) < 1.2 \text{ MeV} \]
3. It has no isospin partners.
4. It has $J^{PC} = 1^{++}$.

**Production:**
10. It is produced in B decays.
11. It is produced in hadron collisions.
   \[ \frac{\sigma(pp \rightarrow X + \text{anything}) \times B(X \rightarrow \pi^+\pi^-J/\psi)}{\sigma(pp \rightarrow \psi(2S) + \text{anything}) \times B(\psi(2S) \rightarrow \pi^+\pi^-J/\psi)} = 0.0656 \pm 0.0029 \pm 0.0065 \quad \text{(CMS)} \]
12. It’s produced in $e^+e^- \rightarrow \gamma X(3872)$, maybe through the Y(4260).
13. It might be produced in photoproduction.

**Decays:**
5. It decays to $\rho J/\psi$.
6. It has radiative decays to $J/\psi$ and $\psi(2S)$.
   \[ \frac{B(X \rightarrow \gamma\psi(2S))}{B(X \rightarrow \gamma J/\psi)} = 2.6 \pm 0.6 \]
7. It decays to $\omega J/\psi$.
   \[ \frac{B(X \rightarrow \omega J/\psi)}{B(X \rightarrow \pi^+\pi^- J/\psi)} = 0.8 \pm 0.3 \]
8. It decays to $D^0\bar{D}^{*0}$.
   \[ \frac{B(X \rightarrow D^0\bar{D}^{*0})}{B(X \rightarrow \pi^+\pi^- J/\psi)} = 9.2 \pm 2.9 \]
9. There are lower limits on its branching fractions.
   \[ B(X \rightarrow \pi^+\pi^- J/\psi) > 3.2\% \]
[PART I: X(3872)] Experimental Details

Properties:
1. Its mass is really close to the $D^0\bar{D}^{*0}$ threshold.
   
   \[ M(X) - M(D^0\bar{D}^{*0}) = 0.01 \pm 0.18 \text{ MeV} \]

2. It’s narrow.
   \[ \Gamma(X) < 1.2 \text{ MeV} \]

3. It has no isospin partners.
4. It has $J^{PC} = 1^{++}$.

Decays:
5. It decays to $qJ/\psi$.
6. It has radiative decays to $J/\psi$ and $\psi(2S)$.
   \[ \frac{B(X \rightarrow \gamma \psi(2S))}{B(X \rightarrow \gamma J/\psi)} = 2.6 \pm 0.6 \]

7. It decays to $\omega J/\psi$.
   \[ \frac{B(X \rightarrow \omega J/\psi)}{B(X \rightarrow \pi^+\pi^- J/\psi)} = 0.8 \pm 0.3 \]

8. It decays to $D^0\bar{D}^{*0}$.
   \[ \frac{B(X \rightarrow D^0\bar{D}^{*0})}{B(X \rightarrow \pi^+\pi^- J/\psi)} = 9.2 \pm 2.9 \]

9. There are lower limits on its branching fractions.
   \[ B(X \rightarrow \pi^+\pi^- J/\psi) > 3.2\% \]

Production:
10. It is produced in B decays.
11. It is produced in hadron collisions.
   \[ \frac{\sigma(pp \rightarrow X + \text{ anything}) \times B(X \rightarrow \pi^+\pi^- J/\psi)}{\sigma(pp \rightarrow \psi(2S) + \text{ anything}) \times B(\psi(2S) \rightarrow \pi^+\pi^- J/\psi)} = 0.0656 \pm 0.0029 \pm 0.0065 \quad \text{(CMS)} \]
12. It’s produced in $e^+e^- \rightarrow \gamma X(3872)$, maybe through the $Y(4260)$.
13. It might be produced in photoproduction.

\[ pp \rightarrow X + \text{ anything}; \quad X \rightarrow \pi^+\pi^- J/\psi \] at ATLAS

\[ \text{JHEP 01, 117 (2017)} \]
**Properties:**
1. Its mass is *really* close to the $D^0D^{*0}$ threshold.
   \[ M(X) - M(D^0D^{*0}) = 0.01 \pm 0.18 \text{ MeV} \]
2. It’s narrow.
   \[ \Gamma(X) < 1.2 \text{ MeV} \]
3. It has no isospin partners.
4. It has $J^{PC} = 1^{++}$.  

**Decays:**
5. It decays to $qJ/\psi$.
6. It has radiative decays to $J/\psi$ and $\psi(2S)$.
   \[ \frac{B(X \rightarrow \gamma \psi(2S))}{B(X \rightarrow \gamma J/\psi)} = 2.6 \pm 0.6 \]
7. It decays to $\omega J/\psi$.
   \[ \frac{B(X \rightarrow \omega J/\psi)}{B(X \rightarrow \pi^+ \pi^- J/\psi)} = 0.8 \pm 0.3 \]
8. It decays to $D^0D^{*0}$.
   \[ \frac{B(X \rightarrow D^0D^{*0})}{B(X \rightarrow \pi^+ \pi^- J/\psi)} = 9.2 \pm 2.9 \]
9. There are lower limits on its branching fractions.
   \[ B(X \rightarrow \pi^+ \pi^- J/\psi) > 3.2\% \]

**Production:**
10. It is produced in $B$ decays.
11. It is produced in hadron collisions.
   \[ \frac{\sigma(pp \rightarrow X + \text{anything}) \times B(X \rightarrow \pi^+ \pi^- J/\psi)}{\sigma(pp \rightarrow \psi(2S) + \text{anything}) \times B(\psi(2S) \rightarrow \pi^+ \pi^- J/\psi)} = 0.0656 \pm 0.0029 \pm 0.0065 \quad \text{(CMS)} \]
12. It’s produced in $e^+e^- \rightarrow \gamma X(3872)$, maybe through the $Y(4260)$.
13. It might be produced in photoproduction.

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**Figure 1 (color online):** The mass scale and to extract the resolution difference between is

**Figure 3 (color online):** The $\cos \theta$ distribution with

**PHYSICAL REVIEW LETTERS**

**PRL 112, 092001 (2014)**
**PART I: X(3872)**  Experimental Details

**Properties:**
1. Its mass is *really* close to the $D^0D^{*0}$ threshold.
   \[ M(X) - M(D^0D^{*0}) = 0.01 ± 0.18 \text{ MeV} \]
2. It’s narrow.
   \[ \Gamma(X) < 1.2 \text{ MeV} \]
3. It has no isospin partners.
4. It has $J^{PC} = 1^{++}$.

**Decays:**
5. It decays to $qJ/\psi$.
6. It has radiative decays to $J/\psi$ and $\psi(2S)$.
   \[ \frac{B(X\rightarrow \gamma\psi(2S))}{B(X\rightarrow \gamma J/\psi)} = 2.6 ± 0.6 \]
7. It decays to $\omega J/\psi$.
   \[ \frac{B(X\rightarrow \omega J/\psi)}{B(X\rightarrow \pi^+\pi^- J/\psi)} = 0.8 ± 0.3 \]
8. It decays to $D^0D^{*0}$.
   \[ \frac{B(X\rightarrow D^0D^{*0})}{B(X\rightarrow \pi^+\pi^- J/\psi)} = 9.2 ± 2.9 \]
9. There are lower limits on its branching fractions.
   \[ B(X \rightarrow \pi^+\pi^- J/\psi) > 3.2\% \]

**Production:**
10. It is produced in $B$ decays.
11. It is produced in hadron collisions.
    \[ \frac{\sigma(pp\rightarrow X + \text{anything}) \times B(X\rightarrow \pi^+\pi^- J/\psi)}{\sigma(pp\rightarrow \psi(2S) + \text{anything}) \times B(\psi(2S)\rightarrow \pi^+\pi^- J/\psi)} = 0.0656 ± 0.0029 ± 0.0065 \quad \text{(CMS)} \]
12. It’s produced in $e^+e^- \rightarrow \gamma X(3872)$, maybe through the $Y(4260)$.
13. It might be produced in photoproduction.

\[ e^+e^- \rightarrow \gamma X; \ X \rightarrow \pi^+\pi^- J/\psi \text{ at BESIII} \]
\[ \text{PRL 112, 092001 (2014)} \]

![Graph showing the production of $Y(4260) \rightarrow \gamma X(3872)$](image)
**Production:**

10. It is produced in B decays.
11. It is produced in hadron collisions.

\[
\frac{\sigma(pp \to X + \text{anything}) \times B(X \to \pi^+ \pi^- J/\psi)}{\sigma(pp \to \psi(2S) + \text{anything}) \times B(\psi(2S) \to \pi^+ \pi^- J/\psi)} = 0.0656 \pm 0.0029 \pm 0.0065 \quad \text{(CMS)}
\]

12. It's produced in \(e^+e^- \to \gamma X(3872)\), maybe through the \(Y(4260)\).
13. It might be produced in photoproduction.

**Experimental Details**

\[
e^+e^- \to \gamma X; \ X \to \pi^+\pi^- J/\psi \quad \text{at BESIII}
\]

**Fig. 4 (color online).** The fit to \(e^+e^- \to \gamma X(3872)\) events (including statistical uncertainty) measured ISR, the expected shape from the dominant background source (red solid curve), a linear continuum (blue dashed curve), or a phase space term (red dotted-dashed curve). Dots with error bars satisfy cos(\(\theta_{CM}\)) close to the \(D^0\) and \(\eta\) resonance (red solid curve). Points are data; lines are fits.
Production:
10. It is produced in B decays.
11. It is produced in hadron collisions.
\[
\frac{\sigma(pp \rightarrow X + \text{anything}) \times B(X \rightarrow \pi^+ \pi^- J/\psi)}{\sigma(pp \rightarrow \psi(2S) + \text{anything}) \times B(\psi(2S) \rightarrow \pi^+ \pi^- J/\psi)} = 0.0656 \pm 0.0029 \pm 0.0065 \quad \text{(CMS)}
\]
12. It’s produced in $e^+e^- \rightarrow \gamma X(3872)$, maybe through the $Y(4260)$.
13. It might be produced in photoproduction.

NEW:
\[
R_j = \frac{B(X \rightarrow \pi^0 \chi_{cJ})}{B(X \rightarrow \pi^+ \pi^- J/\psi)}:
\]
\[
R_0 < 19 \quad (90\% \ U.L.)
\]
\[
R_1 = 0.88^{+0.31}_{-0.26} \pm 0.14
\]
\[
R_2 < 1.0 \quad (90\% \ U.L.)
\]

[PRELIM: Four foundational discoveries]  
X(3872), Y(3940), Y(4260), Z_c(4430)

[Part I: X(3872)]  
What happened to the X(3872)?  
An accumulation of experimental details.

[Part II: Y(3940)]  
What happened to the Y(3940)?  
Disentangling the \( \chi_c J(2P) \).

[Part III: Y(4260)]  
What happened to the Y(4260)?  
Peaks in e^+e^- cross sections ("Y states").  
Peaks in their decays ("Z states").

[Part IV: Z_c(4430)]  
What happened to the Z_c(4430)?  
Peaks in B decays.  
Peaks in \( \Lambda_b \) decays.
[OUTLINE] A Tour through the XYZ

[PRELIM: Four foundational discoveries] 
X(3872), Y(3940), Y(4260), Z_c(4430)

[Part I: X(3872)] 
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)] 
What happened to the Y(3940)?
Disentangling the χcJ(2P).

[Part III: Y(4260)] 
What happened to the Y(4260)?
Peaks in e^+e^- cross sections (“Y states”).
Peaks in their decays (“Z states”).

[Part IV: Z_c(4430)] 
What happened to the Z_c(4430)?
Peaks in B decays.
Peaks in Λ_b decays.
It was confirmed.

Its mass shifted to ~3915 MeV/c^2.

It was found in γγ collisions with J^{PC} = 0^{++}

Its name changed to X(3915).

Does X(3915) = χ_c0(2P)??

B → KX; X → ωJ/ψ at BaBar
PRD82,011101 (2010)

γγ → X; X → ωJ/ψ at BaBar
PRD86,072002 (2012)
[PART II: Y(3940)] Where is the $\chi_{c0}(2P)$?

Studies of $\gamma\gamma \to DD$ show the $\chi_{c2}(2P)$, but where is the $\chi_{c0}(2P)$?

Problems with X(3915)/Y(3940) = $\chi_{c0}(2P)$:
* why isn’t it in DD?
* why is the $\chi_{c0}(2P)/\chi_{c2}(2P)$ mass splitting so small?

Possible partial solution: perhaps the $\chi_{c0}(2P)$ is broad.
[PART II: Y(3940)] Where is the $\chi_{c0}(2P)$?

Candidate $\chi_{c0}(2P)$ found in $e^+e^- \rightarrow J/\psi(D\bar{D})$ [0++ favored].

Mass and width makes sense.

But then what is the $X(3915)/Y(3940)$??

$X(3860) = \chi_{c0}(2P)$?

e$^+e^- \rightarrow J/\psi X; X \rightarrow D\bar{D}$ at Belle

PRD 95, 112003 (2017)
[PRELIM: Four foundational discoveries]
X(3872), Y(3940), Y(4260), Zc(4430)

[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
Disentangling the χcJ(2P).

[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in e+e− cross sections (“Y states”).
Peaks in their decays (“Z states”).

[Part IV: Zc(4430)]
What happened to the Zc(4430)?
Peaks in B decays.
Peaks in Λb decays.
[PRELIM: Four foundational discoveries]

X(3872), Y(3940), Y(4260), Z_c(4430)

[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
Disentangling the \( \chi_cJ(2P) \).

[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in e^+e^- cross sections (“Y states”).
Peaks in their decays (“Z states”).

[Part IV: Z_c(4430)]
What happened to the Z_c(4430)?
Peaks in B decays.
Peaks in \( \Lambda_b \) decays.
[PART III: Y(4260)]  What happened?

\[ e^+ e^- \rightarrow Y; Y \rightarrow \pi^+ \pi^- J/\psi \text{ at BaBar} \]

\[ Y(4260) \]

\[ e^+ e^- \rightarrow Y; Y \rightarrow \pi^+ \pi^- J/\psi \text{ at BESIII} \]

\[ Y(4220) \]

\[ Y(4320) \]

The Y(4260) is not a simple peak.

\textit{Important Note: Old and new data are consistent!!}
[PART III: Y(4260)] Peaks in $e^+e^-$ cross sections (“Y”)

$e^+e^- \rightarrow Y; Y \rightarrow \pi^+\pi^-\psi(2S)$ at BaBar

$Y(4360)$

The Y(4360) is not a simple peak.
[PART III: Y(4260)] Peaks in e⁺e⁻ cross sections ("Y")

Parameters of the Peaks in e⁺e⁻ Cross Sections

Important Note: Masses and widths (and numbers of peaks) depend on parametrization!! A global analysis is needed.
The $e^+e^-$ cross sections above open-bottom threshold are more orderly.
[PART III: Y(4260)] Peaks in “Y” decays (“Zc”)

*e+e− → π±Z; Z → π±J/ψ* at BESIII
PRL110,252001 (2013)

*e+e− → π±Z; Z → π±h_c(1P)* at BESIII
PRL111,242001 (2013)

*e+e− → π±Z; Z → (DD*)±* at BESIII
PRL112,022001 (2014)

*e+e− → π±Z; Z → (D*D*)± at BESIII
PRL112,132001 (2014)
[PART III: Y(4260)] Peaks in “Y” decays (“Z_b”)

\[ e^+ e^- \rightarrow \pi^\pm Z; Z \rightarrow \pi^\mp Y(1S, 2S, 3S) \] at Belle
PRL108,122001 (2012)

\[ e^+ e^- \rightarrow \pi^\pm Z; Z \rightarrow (B^*)B^* \mp \] at Belle
PRL116,212001 (2016)


[OUTLINE] A Tour through the XYZ

[PRELIM: Four foundational discoveries]
X(3872), Y(3940), Y(4260), Z_c(4430)

[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
Disentangling the $\chi_cJ$(2P).

[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in $e^+e^-$ cross sections (“Y states”).
Peaks in their decays (“Z states”).

[Part IV: Z_c(4430)]
What happened to the Z_c(4430)?
Peaks in B decays.
Peaks in $\Lambda_b$ decays.
[OUTLINE] A Tour through the XYZ

[PRELIM: Four foundational discoveries]
X(3872), Y(3940), Y(4260), Z_c(4430)

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What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
Disentangling the \( \chi_c J(2P) \).

[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in e^+e^- cross sections (“Y states”).
Peaks in their decays (“Z states”).

[Part IV: Z_c(4430)]
What happened to the Z_c(4430)?
Peaks in B decays.
Peaks in \( \Lambda_b \) decays.
[PART IV: $Z_c(4430)$] What happened?

$B \to KZ; Z \to \pi^\pm \psi(2S)$ at Belle
PRL100,142001 (2008)

$Z_c(4430)$

$B \to KZ; Z \to \pi^\pm \psi(2S)$ at LHCb
PRL112,222002 (2014)

It was confirmed by LHCb.

Its phase motion was measured.
[PART IV: \(Z_c(4430)\)] Peaks in B decays

\[B \rightarrow KZ; Z \rightarrow \pi^\pm \psi(2S)\] at LHCb
PRL112,222002 (2014)

\[B \rightarrow KX; X \rightarrow \phi J/\psi\] at LHCb
PRL118,022003 (2017)

\[B \rightarrow KZ; Z \rightarrow \pi^\pm J/\psi\] at Belle
PRD90,112009 (2014)

\[B \rightarrow KZ; Z \rightarrow \pi^\pm \chi_{c1}\] at Belle
PRD78,072004 (2008)
[PART IV: $Z_c(4430)$] Peaks in $\Lambda_b$ decays

$\Lambda_b \to KP; P \to pJ/\psi$ at LHCb
PRL115,072001 (2015)

$\Lambda_b \to \pi P; P \to pJ/\psi$ at LHCb
PRL 117, 082003 (2016)
[PRELIM: Four foundational discoveries]
X(3872), Y(3940), Y(4260), Z_c(4430)

[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
Disentangling the \( \chi_cJ(2P) \).

[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in e^+e^- cross sections (“Y states”).
Peaks in their decays (“Z states”).

[Part IV: Z_c(4430)]
What happened to the Z_c(4430)?
Peaks in B decays.
Peaks in \( \Lambda_b \) decays.
[OUTLINE] A Tour through the XYZ

[PRELIM: Four foundational discoveries]
X(3872), Y(3940), Y(4260), Z_c(4430)

[Part I: X(3872)]
What happened to the X(3872)?
An accumulation of experimental details.

[Part II: Y(3940)]
What happened to the Y(3940)?
Disentangling the \(\chi_c(2P)\).

[Part III: Y(4260)]
What happened to the Y(4260)?
Peaks in e^+e^- cross sections (“Y states”).
Peaks in their decays (“Z states”).

[Part IV: Z_c(4430)]
What happened to the Z_c(4430)?
Peaks in B decays.
Peaks in \(\Lambda_b\) decays.
(1) The field is characterized by:
* experimental results that are unexpected…
  … but robust.
* theoretical developments that are unsettled…
  … but productive.
* many avenues left to explore.

(2) The flow of experimental results will not end:
* BESIII and LHC experiments will continue.
* Belle II will soon be producing results.

(3) Further progress will require more interchange between experiment and theory.

(4) New production mechanisms need to be explored (e.g. PANDA, COMPASS).

(5) We should also test ideas beyond charmonium and bottomonium (e.g. GlueX, LHC).

We are making progress!