Hadron Spectroscopy: Experiment

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Outline

• Introduction
• Light hadron spectroscopy
• Recent experimental results on X states
• Recent experimental results on Y states
• Recent experimental results on Z states
• Others (pentaquark, glueball, …)
• Summary
Hadrons: normal & exotic

- Quark model: hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks

- QCD does not forbid hadrons with $N_{\text{quarks}} \neq 2, 3$
  - Glueball: $N_{\text{quarks}} = 0$ (gg, ggg, ...)
  - Hybrid: $N_{\text{quarks}} = 2$ (or more) + excited gluon
  - Multiquark state: $N_{\text{quarks}} > 3$
  - Molecule: bound state of more than 2 hadrons
  - ...
Hadron spectra: normal

Charmonium

Bottomonium

Strange

$J^{PC}$ Quantum Numbers
- Parity = $(-1)^{L+1}$
- Charge Conjugation = $(-1)^{L+S}$
- Spin = $J = |L - S|, L, L + S$
- Vacuum = $^3P_0 \cong 0^{++}$

Quark Degrees of Freedom ONLY

0++ 0--
1-- 1++ 1+-
2-- 2++ 2+-
3-- 3++ 3+-
4-- 4++ 4+-
5-- 5++ 5+-

Experimental observation!!
Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

M. Gell-Mann, Phys. Lett. 8, 214 (1964)

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from anti-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means
Main Suppliers of Exotics
XYZ particles

Charmonium-like (XYZ) particles
New type of hadron (multi-quark ...)?

Particle “Zoo” again!
Too many models!

– Theory 1: screened potential
– Theory 2: hybrids with excited gluons
– Theory 3: tetraquark states
– Theory 4: meson molecules
– Theory 5: cusps effect
– Theory 6: final state interaction
– Theory 7: coupled-channel effect
– Theory 8: mixing of normal quarkonium and exotics
– Theory 9: mixture of all these effects
– Theories ...
Light hadron spectroscopy

$X(18??), Y(2175), ...$
- Any relations?
- What is the role of the ppbar threshold (and other thresholds)?
- Patterns in the production and decay modes
**Y(2175)**

**PRD 80, 031101 (2009)**

**Belle**

**PRD 74, 091103 (2006)**

**BaBar**

**PRD 91, 052017 (2015)**

**BESIII**

BaBar: $\Gamma=58 \pm 16 \pm 20$ MeV  
Belle: $\Gamma=211 \pm 14 \pm 19$ MeV  
BESIII: $\Gamma=104 \pm 15 \pm 15$ MeV

- A strangeonium analogue of the Y(4260)?  
- More strangeonium states?
X States

$X(3872), X(5568), X_b \ldots$
$X(3872) \to J/\psi\pi^+\pi^-$

Belle’s most cited paper: 1200+

first observed by Belle in $B \to K J/\psi\pi^+\pi^-$  

PRL91, 262001 (2003)

- $M_X$ close to $D^0D^{*0}$ threshold $M = 3871.68 \pm 0.17$ MeV  
  (not clear below or above: $\Delta m = -0.16 \pm 0.32$ MeV)
- surprisingly narrow: $\Gamma_{\text{tot}} < 1.2$ MeV at 90% CL

Angular analysis:

Belle 2006: $J^{PC} = 1^{++}$ or $\geq 2$

CDF 2008: $J^{PC} = 1^{++}$ or $2^{-+}$

Belle 2011: $J^{PC} = 1^{++}$ or $2^{-+}$

LHCb 2013: $J^{PC} = 1^{++}$
X(3872) → J/ψπ⁺π⁻ at COMPASS

- Various targets, "exclusive" reaction \( \mu^+ N \rightarrow \mu^+ X^0 \pi^\pm N' \rightarrow \mu^+ (J/ψ π^+ π^-) \pi^\pm N' \)
- Significance > 6 \( \sigma \) for large missing masses (\( M_{\text{miss}} > 3 \text{ GeV/c}^2 \))
- \( \pi\pi \) spectrum differs from previous observations
  \[
  M_{\text{miss}}^2 = (P_\mu + P_N - P_{\mu'} - P_{X^0})^2
  \]

160 or 200 GeV/c \( \mu \)

\( ^6\text{LiD} \) or \( \text{NH}_3 \) targets

**Diagram for exclusive muoproduction of \( X^0 \pi^\pm \)**

\[\sigma_{\gamma N \rightarrow X(3872) \pi N'} \times B_{X(3872) \rightarrow J/ψ \pi\pi} = 71 \pm 28 \text{ (stat)} \pm 39 \text{ (syst)} \text{ pb.} \]

\( N \) denotes the target nucleon and \( N' \) the unobserved recoil system.
\[ \pi\pi = \rho \text{ means Isospin violation!} \]

\[ X(3872) \rightarrow J/\psi\omega \text{ is seen: confirms isospin violation} \]

\[ B(X(3872) \rightarrow J/\psi\omega)/B(X(3872) \rightarrow J/\psi\pi\pi) = 0.8 \pm 0.3 \]

\[ \text{Radiative decays: Belle&Babar good agreement for } X \rightarrow J/\psi\gamma; \text{ not consistent for } X \rightarrow \psi(2S)\gamma. \]

LHCb confirms BaBar’s not vanishing \( X \rightarrow \psi(2S)\gamma. \)

\[ X(3872) \rightarrow DD^* - \text{ dominant mode} \]

\[ B \rightarrow X(3872)K\pi \text{ non-resonant } K\pi \text{ dominates!} \]
X(3872) decay channels

\[ \Gamma_{\text{tot}} \approx 15 \Gamma(X(3872) \rightarrow \pi^+\pi^- J/\psi) \]
\[ \Gamma(X(3872) \rightarrow \pi^+\pi^- J/\psi) < 80 \text{ keV} \]

D\text{\textsuperscript{0}}-\overline{D}\text{\textsuperscript{*0}} molecule?

Lots of literature about this

Impossible to produce such an fragile extended object in prompt high energy hadron colliders at the rates reported by CDF & CMS

QCD diquark-diantiquark?

Maiani et al. PRD 71, 014028 (2005)

Predicts partner states (e.g., a nearby state with u \rightarrow d) that have yet be seen.

no charged partners of the X(3872)

no nearby neutral X(3872) partners
Probably a mixture of D̄D* & a c̄c “core”

Specific model by Takizawa & Takeuchi, PTEP 9, 093D01

Most of the time looks like a D̄0B*0 molecule

Produced in pp via this component

“Core” state

\[ d_{\text{rms}} \approx \frac{1}{\sqrt{2\mu_D|BE|}} \]

Reduced mass

\[ |m_D + m_{D^*} - m_{X3872}| \]

\[ M_{X(3872)} - m_{D^0} - m_{D^{*0}} - \frac{q^2}{2\mu_0} \]

\[ |BE| < 0.2 \text{ MeV} \]

\[ d_{\text{rms}}^{D^0D^{*0}} > 10 \text{ fm} \]

\[ \frac{1}{M_{X(3872)} - m_{D^+} - m_{D^{*-}} - \frac{q^2}{2\mu_0}} \]

\[ |BE| \approx 8 \text{ MeV} \]

\[ d_{\text{rms}}^{D^+D^{*-}} \approx 1.5 \text{ fm} \]
Search for $X_b$ in $e^+e^- \to \gamma\pi^+\pi^-\pi^0 Y(1S)$ at 10.867 GeV

- The $X(3872)$ counterpart in the bottomonium sector $X_b$, NOT observed decay channel $\pi^+\pi^- Y(1S)$.
- As $X_b$ is above $\omega Y(1S)$ threshold, this Isospin-conserving process should be a more promising decay mode. [PRD88, 054007].

- Large Brs of $Y(5S)$ to $\pi^+\pi^-\pi^0\chi_{b1/b2}$, $\omega\chi_{b1/b2}$ are observed for the first time and their ratios are measured:
  hadronic loop effect?

  arXiv:1406.6763

PLB 727, 57 (2013).

PRL 113, 142001 (2014)

Assuming $X_b$ is narrow, the upper limit on the product branching fraction was given.
**X*(3860) (χ_{c0}(2P))**

A 6D amplitude analysis was done to $e^+e^- \rightarrow J/\psi D\bar{D}$

$$\Phi = (M_D\bar{D}, \theta_{\text{prod}}, \theta_{J/\psi}, \theta_{X^*}, \varphi_{\ell^-}, \varphi_D),$$

where $\theta_{\text{prod}}$ is the production angle, $\theta_{J/\psi}$ and $\theta_{X^*}$ are the $J/\psi$ and $X^*$ helicity angles, respectively, and $\varphi_{\ell^-}$ and $\varphi_D$ are the $\ell^-$ and $D$ azimuthal angles, respectively.

**Theory**

- $\chi_{c0}(2P)$ production in two body B decays is suppressed
- $\chi_{c0}(2P) \rightarrow DD$ should be dominant, but not seen
- a better candidate for $\chi_{c0}(2P)$ seen in $e^+e^- \rightarrow J/\psi DD$

**PDG 2016**: $X(3915) \neq \chi_{c0}(2P)$

**PDG: Y(3940)=X(3915)=\chi_{c0}(2P)**

**X*(3915):** $8.5\sigma$, $0^{++}$, $M=3862^{+26}_{-21}^{+40}_{-32}$ MeV/$c^2$

$\Gamma=201^{+154}_{-67}^{+88}_{-67}$ MeV

The parameters of $X*(3915)$ are $<2.7\sigma$ difference from the predicted $\chi_{c0}(2P)$

Confirmed by BaBar, prefer $J^P=0^+$

**Fit results**

Without $X^*$

$0^{++}$ is favored over the $2^{++}$ at $2.5\sigma$
If $X(3915) \neq \chi'_{c0}$, what is it?

It remains an intriguing puzzle

$X(3915) \rightarrow \omega J/\psi$ violates OZI-rule unless it’s a 4-quark state

Mass is near $2m_{D_s}$ threshold: $M(X(3915)) = 2m_{D_s} - 18$ MeV

$X(3915) \rightarrow D\bar{D}$ decays are suppressed: $\Gamma(X(3915) \rightarrow D\bar{D}) < 1$ MeV

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**$D_s\bar{D}_s$ molecule?**

Li & Voloshin, PRD 91, 114014

**$[\bar{c}s][cs]$ tetraquark?**

Lebed & Polosa, PRD 93, 094024

**$c\bar{c}$-gluon hybrid?**

---

what binds it?

no plausible nuclear-physics-type force can bind $D_s\bar{D}_s$ into a “molecule”

why not $X \rightarrow \eta \eta_c$?

too light for $0^{++}$ $c\bar{c}$-hybrid
X(5568) at D0

Structure in $B_s \pi$ spectrum?

- D0 collaboration claimed state decaying to $B_s \pi^+$
- LHCb has large data sample to check it
  - 112600 $B_s$ events (LHCb) vs. 5582 (D0)
- No state seen in place of D0 state

PRL117, 152003 (2016)

Statistical significance of signal (including systematics and LEE)

$$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3$$

With $\Delta R$ Cut: 5.1 $\sigma$, Without $\Delta R$ Cut: 3.9 $\sigma$

Not seen at LHCb and CMS

$X(5568)$

$M_X = 5567.8 \pm 2.9 \text{ (stat)} ^{+0.9}_{-1.9} \text{ (syst)} \text{ MeV}/c^2$

$\Gamma_X = 21.9 \pm 6.4 \text{ (stat)} ^{+5.0}_{-2.5} \text{ (syst)} \text{ MeV}/c^2$

$\rho = [8.6 \pm 1.9 \text{ (stat)} \pm 1.4 \text{ (syst)}] \%$

LHCb $p_T(B^0_s) > 10 \text{ GeV}$

PRL117, 152003 (2016)
$X(5568)$ at D0

**D0 Conference Note 6494**

$B_s \rightarrow D_s \mu \nu$

- **Data**
- **Fit with background shape fixed**
- **Background**
- **Signal**

$\chi^2/\text{ndf} = 0.7$

$m (B^0_s \pi^\pm)$ vs $[\text{GeV}/c^2]$

- **Local Significance**
  \[ \sqrt{ -2 \ln \frac{\mathcal{L}_0}{\mathcal{L}_{\text{max}}} } \]

- Statistical Significance 4.5 $\sigma$.
- Including Systematics 3.2 $\sigma$.

- $N_X = 139^{+51}_{-63}$
- $M_X = 5566.7^{+3.6}_{-3.4}$ MeV/$c^2$
- $\Gamma_X = 6.0^{+9.5}_{-6.0}$ MeV/$c^2$
Y States

Y(4260), Y(4360), Y(4660)…
Y(4260) in $e^+e^- \rightarrow \pi^+\pi^-J/\psi$

$J^{PC} = 1^-$

$\psi', \psi'', Y...$

- No Y(4260) to $D^{(*)}\bar{D}^{(*)}$
- If Y(4260) is $c\bar{c}$, the $\Gamma$ to $\pi^+\pi^-J/\psi$ should be small
$e^+e^- \to \pi^+\pi^- J/\psi$ cross section at BESIII

- Most precise cross section measurement to date from BESIII
- Fit I = $|BW_1 + BW_2 \cdot e^{i\phi_2} + BW_3 \cdot e^{i\phi_3}|^2$ or Fit II = $|\exp + BW_2 \cdot e^{i\phi_2} + BW_3 \cdot e^{i\phi_3}|^2$ (other fits ruled out)
- $M = 4222.0 \pm 3.1 \pm 1.4$ MeV (lower)
- $\Gamma = 44.1 \pm 4.3 \pm 2.0$ MeV (narrower)
- A 2nd resonance $Y_2$ with $M = 4320.0 \pm 10.4 \pm 7.0$ MeV/$c^2$
  $\Gamma = 101.4^{+25.3}_{-19.7} \pm 10.2$ MeV
- Observed for the first time, significance $> 7.6\sigma$
Updated $e^+e^- \to \pi^+\pi^- \psi(2S)$

Unbinned simultaneous maximum likelihood fit for $Y(4360)$ and $Y(4660)$.

$\text{Amp} = BW_1 + e^{i\phi} \cdot BW_2$

- Consistent with previous measurement
- No obvious signal above $Y(4660)$.
- Some events accumulate at $Y(4260)$, especially the $\pi^+\pi^- J/\psi$ mode.
- If $Y(4260)$ is included in the fit, ...

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solution I</th>
<th>Solution II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{Y(4360)}$ (MeV/c$^2$)</td>
<td>4347 ± 6 ± 3</td>
<td>4652 ± 10 ± 11</td>
</tr>
<tr>
<td>$\Gamma_{Y(4360)}$ (MeV)</td>
<td>103 ± 9 ± 5</td>
<td>68 ± 11 ± 5</td>
</tr>
<tr>
<td>$\mathcal{B} \cdot \Gamma_{Y(4360)}^{e^+e^-}$ (eV)</td>
<td>9.2 ± 0.6 ± 0.6</td>
<td>10.9 ± 0.6 ± 0.7</td>
</tr>
<tr>
<td>$M_{Y(4660)}$ (MeV/c$^2$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{Y(4660)}$ (MeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B} \cdot \Gamma_{Y(4660)}^{e^+e^-}$ (eV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\phi$ (°)</td>
<td>32 ± 18 ± 20</td>
<td>272 ± 8 ± 7</td>
</tr>
</tbody>
</table>

$\chi^2/\text{ndf} = 18.7/21$.  

PRD 91, 112007 (2015)
M(π⁺π⁻ψ(2S)) with Y(4260,4360,4660)

Unbinned simultaneous maximum likelihood fit for Y(4260), Y(4360) and Y(4660). $Amp = BW_1 + e^{i\phi_1} \cdot BW_2 + e^{i\phi_2} \cdot BW_3$.

<table>
<thead>
<tr>
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<th>Solution II</th>
<th>Solution III</th>
<th>Solution IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \cdot \Gamma_{Y(4260)}^{e^+e^-}$ (eV)</td>
<td>1.5 ± 0.6 ± 0.4</td>
<td>1.7 ± 0.7 ± 0.5</td>
<td>10.4 ± 1.3 ± 0.8</td>
<td>8.9 ± 1.2 ± 0.8</td>
</tr>
<tr>
<td>$M_{Y(4360)}$ (MeV/$c^2$)</td>
<td></td>
<td></td>
<td>4365 ± 7 ± 4</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{Y(4360)}$ (MeV)</td>
<td></td>
<td></td>
<td>74 ± 14 ± 4</td>
<td></td>
</tr>
<tr>
<td>$B \cdot \Gamma_{Y(4360)}^{e^+e^-}$ (eV)</td>
<td>4.1 ± 1.0 ± 0.6</td>
<td>4.9 ± 1.3 ± 0.6</td>
<td>21.1 ± 3.5 ± 1.4</td>
<td>17.7 ± 2.6 ± 1.5</td>
</tr>
<tr>
<td>$M_{Y(4660)}$ (MeV/$c^2$)</td>
<td></td>
<td></td>
<td>4660 ± 9 ± 12</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{Y(4660)}$ (MeV)</td>
<td></td>
<td></td>
<td>74 ± 12 ± 4</td>
<td></td>
</tr>
<tr>
<td>$B \cdot \Gamma_{Y(4660)}^{e^+e^-}$ (eV)</td>
<td>2.2 ± 0.4 ± 0.2</td>
<td>8.4 ± 0.9 ± 0.9</td>
<td>9.3 ± 1.2 ± 1.0</td>
<td>2.4 ± 0.5 ± 0.3</td>
</tr>
<tr>
<td>$\phi_1$ (°)</td>
<td>304 ± 24 ± 21</td>
<td>294 ± 25 ± 23</td>
<td>130 ± 4 ± 2</td>
<td>141 ± 5 ± 4</td>
</tr>
<tr>
<td>$\phi_2$ (°)</td>
<td>26 ± 19 ± 10</td>
<td>238 ± 14 ± 21</td>
<td>329 ± 8 ± 5</td>
<td>117 ± 23 ± 25</td>
</tr>
</tbody>
</table>

Significance of Y(4260) is 2.4σ—low, but affects Y(4360) and Y(4660) masses and widths.
FOUR solutions with equally good fit quality, which is $\chi^2/ndf = 14.8/19$. 
Comparsion of $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ cross section

BESIII (16 energy points; $L_{\text{tot}} = 5.1\, \text{fb}^{-1}$)

ψ(2S) Reconstructed modes:

Mode I: $\psi(3686) \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow l^+l^- (l=e/\mu)$

Mode II: $\psi(3686) \rightarrow \text{neutrals} + J/\psi, \text{neutrals} = (\pi^0\pi^0, \pi^0, \eta \text{ and } \gamma\gamma) \ J/\psi \rightarrow l^+l^- (l=e/\mu)$

The measured Born cross sections of two modes are combined by considering the correlated and uncorrelated uncertainties.
Updated $e^+e^- \rightarrow K^+K^-J/\psi$

Event selections are almost the same as in Phys. Rev. D 77, 011105(R) (2008)

Shaded hist.: $J/\psi$ mass sidebands

- +one resonance.
- Fit with $\psi(4415)$

$\chi^2/\text{ndf}=30/11$
- $M=4747\pm117\text{MeV}$
- $\Gamma=671\pm86\text{ MeV}$

4-6 GeV: 213 events
35 bkg, 178±16 signal

$\sigma_i = \frac{n_i^{\text{obs}} - f \times n_i^{\text{bkg}}}{\mathcal{L} \cdot \epsilon_i \cdot \mathcal{B}(J/\psi \rightarrow \ell^+\ell^-)}$

7.8% sys. error was not included.
$e^+e^- \rightarrow \pi^+\pi^- h_c$ cross section at BESIII

**PRL118, 092002 (2017)**

- $h_c \rightarrow \gamma \eta_c$, $\eta_c \rightarrow$ hadrons [16 exclusive decay modes]

- First precise cross section measurement from threshold to 4.6 GeV

- Fit with $|BW_1 + BW_2 * e^{i\phi_2}|^2$, two resonant structures are evident

- $M_1 = 4218.4^{+5.5}_{-4.5} \pm 0.9$ MeV/c$^2$, $\Gamma_1 = 66.0^{+12.3}_{-8.3} \pm 0.4$ MeV $\rightarrow Y(4220)$

- $M_2 = 4391.5^{+6.3}_{-6.8} \pm 1.0$ MeV/c$^2$, $\Gamma_2 = 139.5^{+16.2}_{-20.6} \pm 0.6$ MeV $\rightarrow Y(4390)$
$e^+ e^- \rightarrow \pi^+ D^0 D^{*-} + \text{c.c.}$ cross sections

- Reconstruct $D^0 \rightarrow K^- \pi^+$
- Select events with closest to $m(D^0)$
- Find an additional $\pi^+$;
- $1.9 < M(D^{*-}) < 2.1$ GeV/$c^2$
- select the candidate closest to $m(D^{*-})$

- Fit with a constant and two BW functions with interference
- Statistical significance is greater than $10\sigma$.
- Consistent with those of $Y(4220)$ and $Y(4390)$ in $e^+ e^- \rightarrow \pi^+ \pi^- h_c$.

<table>
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<th>SolutionII</th>
<th>SolutionIII</th>
<th>SolutionIV</th>
</tr>
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<tbody>
<tr>
<td>$c \times 10^{-4}$</td>
<td></td>
<td></td>
<td></td>
<td>$5.5\pm0.6$</td>
</tr>
<tr>
<td>$M_1$ (MeV/$c^2$)</td>
<td></td>
<td></td>
<td>$4224.8\pm5.6$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_1$ (MeV)</td>
<td></td>
<td></td>
<td>$72.3\pm9.1$</td>
<td></td>
</tr>
<tr>
<td>$M_2$ (MeV/$c^2$)</td>
<td></td>
<td></td>
<td>$4400.1\pm9.3$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_2$ (MeV)</td>
<td></td>
<td></td>
<td>$181.7\pm16.9$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_1^0$ (eV)</td>
<td>$62.9\pm11.5$</td>
<td>$7.2\pm1.8$</td>
<td>$81.6\pm15.9$</td>
<td>$9.3\pm2.7$</td>
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<tr>
<td>$\Gamma_2^0$ (eV)</td>
<td>$88.5\pm15.8$</td>
<td>$55.3\pm8.7$</td>
<td>$551.9\pm85.3$</td>
<td>$344.9\pm70.6$</td>
</tr>
<tr>
<td>$\phi_1$ (eV)</td>
<td>$-2.1\pm0.1$</td>
<td>$2.8\pm0.3$</td>
<td>$-0.9\pm0.1$</td>
<td>$-2.3\pm0.2$</td>
</tr>
<tr>
<td>$\phi_2$ (eV)</td>
<td>$1.9\pm0.3$</td>
<td>$2.3\pm0.2$</td>
<td>$2.3\pm0.1$</td>
<td>$-1.9\pm0.1$</td>
</tr>
</tbody>
</table>

The error are statistical only.
More precise measurements are helpful! “**(Y(4260))**” in different channels?

**PRL 118, 092002 (2017)**

\[ e^+ e^- \rightarrow \pi^+ \pi^- h_c \]

**PRD 93, 011102(R) (2016)**

\[ e^+ e^- \rightarrow \omega \chi_{c0} \]

**PRL118, 092001 (2017)**

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

**PRD 93, 011102(R) (2016)**

\[ e^+ e^- \rightarrow D^0 D^{*-} \pi^+ \] c. c.

**All above four channels show a structure at around 4.22 GeV/c^2.**
A combined fit is performed to extract the resonant parameters of the Y(4220) assuming it decays dominantly to the above four modes and their isospin symmetric modes.

\[ M = 4219.6 \pm 3.3\,\text{(stat)} \pm 5.1\,\text{(sys)} \,\text{MeV/c}^2 \]
\[ \Gamma = 56.0 \pm 3.6\,\text{(stat)} \pm 6.9\,\text{(sys)} \,\text{MeV} \]
$Y(4260)$: mass \rightarrow lower \& width \rightarrow narrower

pre-2017

Belle

PDG-2016:
$M(Y(4260)) = 4251 \pm 9 \text{ MeV}/c^2$
$\Gamma(Y(4260)) = 120 \pm 12 \text{ MeV}$.

post-2017

BESIII

$M_1 = 4220 \pm 4 \text{ MeV}/c^2$
$\Gamma_1 = 44 \pm 5 \text{ MeV}$

what is the 2nd peak?

$M_2 = 4320 \pm 13 \text{ MeV}/c^2$
$\Gamma_2 = 101^{+27}_{-22} \text{ MeV}$

$M(Y(4360)) = 4346 \pm 6 \text{ MeV}/c^2$
$\Gamma(Y(4360)) = 102 \pm 12 \text{ MeV}$.

$Y(4220)$ decay modes:
- $\pi^+\pi^0 J/\psi$
  - $nZ_c(3900)$
  - $f_0(980) J/\psi$
- $\pi^+\pi^0 h_c$
- $\omega X_c$
- $\eta J/\psi$
- $\gamma X(3872)$
- $\pi D\bar{D}^*$

$Y(4320)$ decay modes:
- $\pi^+\pi^- J/\psi$
- $\pi^+\pi^- \psi'$
What is the Y(4260)?

The Y(4260) mass is lower and width narrower than previously thought

“Y(4260)” → Y(4220)?

If it is a $D\bar{D}_{1}(2420)$ molecule:

B.E. ≈ 66 MeV  ⇐ too large??

“affinity” to $D\bar{D}_{1}(2420)$ should be high

If it is a $c\bar{c}$-gluon hybrid:

its mass is ~65 MeV below current ($m_{\pi} ≈ 400$ MeV) LQCD predictions  ⇐ not so bad?

“affinity” to $D\bar{D}_{0}(2400)$ should be high

If it is a QCD diquark–diantiquark tetraquark:

it should have Isospin- & SU$_c$(3)-multiplet partner states  ⇐ not seen

Maiani et al. PRD89,114010

If it is hadrocharmonium:

decays to non-J/$\psi(h_c)$ charmonium states should be suppressed  ← they aren't

Dubynskiy & Voloshin, PLB 666, 344

Li & Voloshin, Mod. Phys. Lett. A29, 1450060

BESIII is well suited to further investigate this intriguing puzzle  ← a "Y(4260)" factory

2012 LQCD calc. ($m_{\pi} ≈ 400$ MeV):

“Lowest 1- c\bar{c}-gluon hybrid: M=4285 ± 14 MeV”

pre-2017: too high by ~35 MeV

post-2017: too high by ~65 MeV

Had. Spectr. Collab. JHEP07, 126
Z States

\(Z_c(3900), Z_c(4020), \ Z_b(10610), \ Z_b(10650), \ ...\)
The $Z(4430)^+ \rightarrow \pi^+ \psi'$

“smoking gun” evidence for a 4-quark meson

- decays to $\psi'$ $\Rightarrow$ must contain $c\bar{c}$ pair
- electrically charged $\Rightarrow$ must contain $u\bar{d}$ pair

S-K Choi et al. Belle: PRL 100 142001
LHCb 4-dim analysis of $B \rightarrow K^+ \pi^- \psi'$

$J^P = 1^+$

$M = 4475 \pm 7^{+15}_{-25}$ MeV

$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

Good agreement with Belle, (with smaller errors)

$Bf(B^0 \rightarrow Z(4430)^- K^+) \times Bf(Z(4430)^- \rightarrow \pi^- \psi') \approx (3.4^{+1.1}_{-2.3}) \times 10^{-5}$
What is the Z(4430)?

Kinematic effect due to D*\bar{D} rescattering?

D*(2S)\bar{D} molecule?
Binding energy = 20 \pm 30 \text{ MeV}

D*(2620)\text{ molecule?}

Tetraquark formed with a radially excited diquark

"bad" diquark

"good" diquark

One of the diquarks is in an n_f=2, radially excited state.

Pakhlov & Uglov, PLB 183 (2015)
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ “Dalitz plot”

$Y(4260) \rightarrow f_0(980) J/\psi$  
$\rightarrow \pi^+\pi^-$

$Z_c \rightarrow \pi J/\psi$
“signal”

$Y_{4260}$

“reflection”

$Y(4260) \rightarrow \pi^\pm Z_c^\mp(3900)$
$\rightarrow \pi^\pm J/\psi$
Z_c(3900) State

Observed in e^+e^- \rightarrow (\gamma)\Upsilon(4260) \rightarrow J/\psi\pi^+\pi^-


Charged charmonium-like structure (>10 \sigma)
Decay to J/\psi (c\bar{c}) and electric charge (u\bar{u} or d\bar{d})
M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}/c^2, \Gamma = 46 \pm 10 \pm 20 \text{ MeV}
\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = 62.9 \pm 1.9 \pm 3.7 \text{ pb at 4.26 GeV}
\frac{\sigma(e^+e^- \rightarrow \pi^+Z_c(3900)^{\pm} \rightarrow \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} = 21.5 \pm 3.3 \pm 7.5 \%

The first Z_c state observed by more than one experiment (Belle and CLEO-c)!
Z_c(3900) State


Z_c(3900)\pm

BES III

\[ Z_c(3900) \]

\[ M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV/c}^2, \Gamma = 46 \pm 10 \pm 20 \text{ MeV} \]

\[ \sigma(e^+ e^- \rightarrow \pi^+ \pi^- J/\psi) = 62.9 \pm 1.9 \pm 3.7 \text{ pb at 4.26 GeV} \]

\[ \frac{\sigma(e^+ e^- \rightarrow \pi^+ Z_c(3900) \rightarrow \pi^+ \pi^- J/\psi)}{\sigma(e^+ e^- \rightarrow \pi^+ \pi^- J/\psi)} = 21.5 \pm 3.3 \pm 7.5 \% \]

The first Z_c state observed by more than one experiment (Belle and CLEO-c)!


Z_c(3900)^0

BES III

\[ M = 3894.8 \pm 2.3 \pm 3.2 \text{ MeV/c}^2, \Gamma = 29.6 \pm 8.2 \pm 8.2 \text{ MeV} \]

\[ \text{Neutral charmonium-like structure (10.4 \sigma)} \]

\[ \text{Using 3 data samples (~2.5 fb}^{-1}) \]

\[ \text{Evidence with 3.7\sigma by using CLEO-c data} \]

\[ \text{An iso-spin triplet is established!} \]
Search for exclusive photoproduction of $Z_c^{\pm}(3900)$ at COMPASS

$BR(Z_c^{\pm}(3900) \to J/\psi \pi^{\pm}) \times \sigma_{\gamma N \to Z_c^{\pm}(3900) N} \left|_{\sqrt{s_{\gamma N}}=13.8 \text{ GeV}} \right. < 52 \text{ pb}$.

Assuming $\Gamma_{\text{tot}} = 46 \text{ MeV}/c^2$, we obtain an upper limit $\Gamma_{J/\psi \pi} < 2.4 \text{ MeV}/c^2$. 
PWA on Zc(3900) state

**Amplitude analysis with helicity formalism**

- Zc line shape parameterized with Flatte-like formula
- $\pi^+\pi^-$ spectrum is described by $\sigma$, $f_0(980)$, $f_2(1270)$ and $f_0(1370)$
- $J^P$ of Zc favors $1^+$ with Significance larger than $7.3\sigma$ over other quantum numbers

Born cross sections: $\sigma(e^+e^-\rightarrow\pi^+Zc^- + c.c.) = (21.8 \pm 1.0 \pm 4.4) \text{ pb} @ 4.23 \text{ GeV}$

(11.0 ± 1.2 ± 5.4) pb @ 4.26 GeV.

No significant Zc(4020) signals; $\sigma(e^+e^-\rightarrow\pi^+Zc(4020)^- + c.c.) < 0.9 \text{ pb} @ 4.23 \text{ GeV}$

< 1.4 pb@4.26 GeV

**PRL119, 072001 (2017)**

1092 pb$^{-1}$

4.23 GeV

827 pb$^{-1}$

4.26 GeV
$Z_c(3900)$ State


Single D tag (ST)

$BES^\text{III}$

4.26 GeV


Double D tag (DT)

$BES^\text{III}$

4.23 GeV

$Z_c(3885)^\pm$ (ST)  
$3883.9^{+1.5}_{-1.2} \pm 4.2$  
$24.8^{+3.3}_{-3.0} \pm 11.0$

$Z_c(3885)^\pm$ (DT)  
$3881.7^{+1.6}_{-1.4} \pm 1.6$  
$26.6^{+2.0}_{-1.7} \pm 2.1$

Weighted average  
$3882.2^{+1.1}_{-1.7} \pm 1.5$  
$26.5^{+1.7}_{-1.2} \pm 2.1$

$Z_c(3885)^0$ (DT)  
$3885.7^{+4.3}_{-4.6} \pm 8.4$  
$35^{+14}_{-12} \pm 15$

- Good agreement between ST and DT method
- Good agreement between charged state and neutral state
- Another iso-spin triplet is established!
- $Z_c(3885) = Z_c(3900)$?
- Tetraquark? Molecule state?
Z_c(4020) & Z_c(4025) States

- Z_c(4020)^±/0 observed
- Another iso-spin triplet is established!
- No significant Z_c(3900)^± → π^± h_c is observed

<table>
<thead>
<tr>
<th>State</th>
<th>Mass (MeV/c^2)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z_c(4020)^±</td>
<td>4022.9±0.8±2.7</td>
<td>7.9±2.7±2.6</td>
</tr>
<tr>
<td>Z_c(4020)^0</td>
<td>4023.9±2.2±3.8</td>
<td>7.9 (fixed)</td>
</tr>
</tbody>
</table>

- Z_c(4025)^±/0 observed
- Another iso-spin triplet is established!
Summary on $Z_c$ States by BESIII

<table>
<thead>
<tr>
<th>State</th>
<th>Mass (MeV/c²)</th>
<th>Width (MeV)</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_c(3900)^\pm$</td>
<td>3899.0±3.6±4.9</td>
<td>46±10±20</td>
<td>$e^+e^-\rightarrow\pi^+\pi^-J/\psi$</td>
</tr>
<tr>
<td>$Z_c(3900)^0$</td>
<td>3894.8±2.3±3.2</td>
<td>29.6±8.2±8.2</td>
<td>$e^+e^-\rightarrow\pi^0\pi^0J/\psi$</td>
</tr>
<tr>
<td>$Z_c(3885)^\pm$ (ST)</td>
<td>3883.9±1.5±4.2</td>
<td>24.8±3.3±11.0</td>
<td></td>
</tr>
<tr>
<td>$Z_c(3885)^\pm$ (DT)</td>
<td>3881.7±1.6±1.6</td>
<td>26.6±2.0±2.1</td>
<td>$e^+e^-\rightarrow\pi^+(DD^*)^\pm$</td>
</tr>
<tr>
<td>Weighted average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_c(3885)^0$ (DT)</td>
<td>3885.7^{+4.3}_{-3.7}±8.4</td>
<td>35^{+11}_{-12}±15</td>
<td>$e^+e^-\rightarrow\pi^0(DD^*)^0$</td>
</tr>
<tr>
<td>$Z_c(4020)^\pm$</td>
<td>4022.9±0.8±2.7</td>
<td>7.9±2.7±2.6</td>
<td>$e^+e^-\rightarrow\pi^+\pi^-h_c$</td>
</tr>
<tr>
<td>$Z_c(4020)^0$</td>
<td>4023.9±2.2±3.8</td>
<td>7.9 (fixed)</td>
<td>$e^+e^-\rightarrow\pi^0\pi^0h_c$</td>
</tr>
<tr>
<td>$Z_c(4025)^\pm$</td>
<td>4026.3±2.6±3.7</td>
<td>24.8±5.6±7.7</td>
<td>$e^+e^-\rightarrow\pi^+(D^<em>D^</em>)^\pm$</td>
</tr>
<tr>
<td>$Z_c(4025)^0$</td>
<td>4025.5^{+2.0}_{-4.7}±3.1</td>
<td>23.0±6.0±1.0</td>
<td>$e^+e^-\rightarrow\pi^0(D^<em>D^</em>)^0$</td>
</tr>
</tbody>
</table>

$Z_c(3885)^\pm$ mass is about $2.6\sigma$ lower and the width $1.5\sigma$ lower than $Z_c(3900)^\pm$ value. If $Z_c(3885) = Z_c(3900)$, \( \frac{\Gamma(Z_c(3885)^\pm \rightarrow (DD^*)^\pm)}{\Gamma(Z_c(3900)^\pm \rightarrow \pi^\pm J/\psi)} = 6.2^{±1.1}_{±2.7} \), coupling to $D\overline{D}^*$ is larger than to $\pi J/\psi$;

$Z_c(4020)^\pm$ and $Z_c(4025)^\pm$ mass and width are consistent within $1.5\sigma$. If $Z_c(4020) = Z_c(4025)$, \( \frac{\Gamma(Z_c(4025)^\pm \rightarrow (D^*D^*)^\pm)}{\Gamma(Z_c(4020)^\pm \rightarrow \pi^\pm h_c)} = 12^{±5}_{±5} \), coupling to $D^*\overline{D}^*$ is larger than to $\pi h_c$. 
**Z_c(4050) at Belle**

**Observed by Belle in ISR**

\[ e^+e^- \rightarrow \Upsilon(4360) \rightarrow \psi(2S)\pi^+\pi^- \]

- No clear signal found in the \( \Upsilon(4660) \) region

**M = 4054 \pm 3 \pm 1 \text{ MeV}/c^2**

**\( \Gamma = 45 \pm 11 \pm 6 \text{ MeV} \)**

**Another Z_c state? Need confirmation**
Not like $\pi J/\psi$, the structures in $\pi \psi(2S)$ vs. $E_{cm}$ are much more complicated!

- $M = (4032.1 \pm 2.4) \text{ MeV}/c^2$
- $\Gamma = (26.1 \pm 5.3) \text{ MeV}$
$Z_c^{\pm} (4200)$ in $\Lambda^0_b \rightarrow J/\psi p\pi^-$ at LHCb

Cabibbo suppressed mode (less statistics)

Can be exotic Z contributions in $J/\psi p$

Fit with 2 pentaquarks + $Z_c(4200)$ favoured by 3σ compared to no exotic contributions

$N^*_{\Xi_c} (4200)$ in $\Lambda_0 \rightarrow J/\psi p\pi^-$ at LHCb

$m_{p\pi} > 1.8$ GeV

PRL 117, 082003(2016)
Search for $Z_{cs}$ states at Belle

No evident structure in $K^+J/\psi$ mass distribution under current statistics
Search for $Z_s$ states at BESIII

- ISPE predicts two $Z_s$ structures near the $K^* \bar{K}$ (narrow width) and $K^* \bar{K}^*$ (broad width), respectively, in $\phi(2170) \rightarrow \phi \pi^+ \pi^-$ decay.
- The $\phi$ paired with low-momentum $\pi$ is expected to be sensitive to $Z_s$ around 1.4 GeV/$c^2$.

- PWA is applied on $\phi \pi \pi$ candidates, no $Z_s$ observed.
- The upper limit of $Z_s$ production is obtained with different width hypothesis.

<table>
<thead>
<tr>
<th>Mass (GeV/$c^2$)</th>
<th>1.380</th>
<th>1.400</th>
<th>1.420</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width (MeV)</td>
<td>NUL</td>
<td>UL</td>
<td>NUL</td>
</tr>
<tr>
<td></td>
<td>(%)</td>
<td>(pb)</td>
<td>(%)</td>
</tr>
<tr>
<td>$\phi \pi^+ \pi^-$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>22.2</td>
<td>47.3</td>
<td>16.6</td>
</tr>
<tr>
<td>5</td>
<td>37.8</td>
<td>47.5</td>
<td>29.8</td>
</tr>
<tr>
<td>10</td>
<td>49.6</td>
<td>47.5</td>
<td>40.2</td>
</tr>
<tr>
<td>$\phi \pi^0 \pi^0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>25.6</td>
<td>13.8</td>
<td>25.2</td>
</tr>
<tr>
<td>5</td>
<td>28.0</td>
<td>13.8</td>
<td>28.6</td>
</tr>
<tr>
<td>10</td>
<td>31.2</td>
<td>13.8</td>
<td>32.4</td>
</tr>
</tbody>
</table>

ECM=2.125GeV, $\mathcal{L} = 108pb^{-1}$
Resonant structure of $\Upsilon(5S) \rightarrow (b\bar{b})\pi^+\pi^-$

Two peaks are observed in all modes!


$Z_b(10610)$ and $Z_b(10650)$ should be multiquark states.

$\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^+\pi^-$

$\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-$

$\Upsilon(5S) \rightarrow \Upsilon(3S)\pi^+\pi^-$

Note different scales.

Dalitz plot analysis.
$Z^+_b \rightarrow \text{Open Beauty}$

$$S(m) = |A_{Z_b(10610)} + A_{Z_b(10650)} + A_{nr}|^2$$
Assuming that $Z_b$ decays are saturated by the $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and $B^{(*)}B^*$ channels, one can calculate a table of relative branching fractions:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Fraction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(1S)\pi^+$</td>
<td>$0.60 \pm 0.17 \pm 0.07$</td>
</tr>
<tr>
<td>$\Upsilon(2S)\pi^+$</td>
<td>$4.05 \pm 0.81 \pm 0.58$</td>
</tr>
<tr>
<td>$\Upsilon(3S)\pi^+$</td>
<td>$2.40 \pm 0.58 \pm 0.36$</td>
</tr>
<tr>
<td>$h_b(1P)\pi^+$</td>
<td>$4.26 \pm 1.28 \pm 1.10$</td>
</tr>
<tr>
<td>$h_b(2P)\pi^+$</td>
<td>$6.08 \pm 2.15 \pm 1.63$</td>
</tr>
<tr>
<td>$B^+\bar{B}^{*0} + \bar{B}^0B^{**}$</td>
<td>$82.6 \pm 2.9 \pm 2.3$</td>
</tr>
<tr>
<td>$B^{*+}\bar{B}^{*0}$</td>
<td>$-2.3 \pm 2.2 \pm 2.3$</td>
</tr>
</tbody>
</table>

\[
\frac{\text{Br}(Z_b(10610)^{+}\rightarrow B\bar{B}^*)}{\text{Br}(Z_b(10610)^{+}\rightarrow b\bar{b})} = 5.93+0.99/-0.59+1.01/-0.73
\]

\[
\frac{\text{Br}(Z_b(10650)^{+}\rightarrow B^*\bar{B}^*)}{\text{Br}(Z_b(10650)^{+}\rightarrow b\bar{b})} = 2.80+0.69/-0.40+0.54/-0.36
\]

**B^{(*)}B^* channels dominate the Z_b decays**
Charmonium(like) spectroscopy

arXiv:1708.04012
Bottomonium (like) spectroscopy

arXiv:1708.04012
Others ...

Pentaquarks, Glueballs, ...
Observation of Pc states at LHCb


FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \rightarrow J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \rightarrow P_c^+ K^-$ decay.
Search for Pc states at GlueX

$J/\psi$ cross section as function of $E_{\gamma \text{beam}}$

Spring 2016: 12 GeV Engineering run

- Electron Beam Energy: 12.05 GeV
- Commissioning complete: Detector, Beamline, DAQ
- Data taken for early physics results:
  - $\sim$26 billion events, $\sim$7 billion with good quality
Search for Ps states at Belle


![Feynman diagram](image)

FIG. 1. Feynman diagram for the decay (a) \( \Lambda_c^+ \to \phi p \pi^0 \) and (b) \( \Lambda_c^+ \to P_s^+ \pi^0 \).

- \( \Sigma^+ \to p \pi^0 \) vetoed
- No significant Ps signal
- Best fit yields a peak at \( M = (2025 \pm 5) \text{ MeV}/c^2 \) and \( \Gamma = (22 \pm 12) \text{ MeV} \)

Number of candidate \( \Lambda_c \to P_s \pi^0 \to \phi p \pi^0 \) events: \( 77.6 \pm 28.1 \)

\[ \mathcal{B}(\Lambda_c \to P_s \pi^0) \times \mathcal{B}(P_s \to \phi p) < 8.3 \times 10^{-5} \text{ @90\% C.L.} \]
Glueballs are allowed by QCD
- The predicted $0^-$ glueball masses are 2.80, 3.81 and 4.33 GeV/c$^2$. [PRL113, 221601 (2014)], [JHEP 1510 (2015) 137]
- No signals in Y(1S,2S) and $\chi_{b1}$ decays: $\chi_{b1}\rightarrow J/\psi+$Glueball, Y(1S,2S) $\rightarrow \chi_{c1}+$ G$_{0^-}$, Y(1S,2S) $\rightarrow f_1(1285)+$ G$_{0^-}$ and $\chi_{b1}\rightarrow \omega+G_{0^-}$ at Belle [PRD 95, 012001 (2017)]
- Some multi-quark states with exotic quantum numbers are predicted in low mass region, for example, $0^{--}$ tetraquark with m=1.66 ± 0.14 GeV/c$^2$ and $1^{+-}$ with m=[1.18, 1.43] GeV/c$^2$ [PRD 95, 076017 (2017)].
Summary

A new field of exotic physics was discovered in the last decade; new information is still coming from both completed (Belle & BaBar) and currently ongoing (BESIII, D0, LHCb, CMS, …) experiments.

However (much) more data is required for a better understanding (BelleII, BESIII, LHCb, …)

BESIII, LHCb …are getting more data; start of the Belle II is approaching. Inputs from them are important to understand quarkonium(-like) spectra.

Common features between charmonium and bottomonium sectors is gradually emerging. No direct identity however.

Bottomonium spectra are less well studied compared to charmoniua. Input from Belle II is crucial to push exotic studies into bottomonium sector.

No clear understanding of the nature of new states yet. Let’s work harder.
X(3940) and X(4160) (Exotic ? Standard ?)

Mass of X(3940) & X(4160) are \(~100-150\) (250-300) MeV lower than the masses predicted by the potential models for $\eta_c (3S)$ and $\eta_c (4S)$

Theory probably needs more elaborate models to take into account charmonia couplings to meson pairs
Not all Y states are new?

- Opinion: Y(4320) and Y(4390) are not needed, not genuine resonances
- Fit method: ψ(4160), ψ(4415), Y(4220) with interference
- Conclusions: ψ(4160) and ψ(4415) can replace Y(4320) and Y(4390); Y(4220) is possible ψ(4S) state

Dian-Yong Chen, Xiang Liu, Takayuki Matsuki, arXiv:1708.01954

The authors’ suggestion: In study of XYZ, we should also focus on on-resonance mechanism, which may provide a unique perspective beyond XYZ.
Z(4430) = radial excitation of Z_c(3900)?

\[
\frac{\mathcal{B}(Z_c(4430)^+ \to \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+)} \sim 10
\]

Radial Wave Functions

The $c\bar{c}$ part of the wave function of the Z(4430) likely has a node $\Rightarrow$ a radial excitation of the ground state: the Z_c(3900)?

\[
M(Z_c(4430)) - M(Z_c(3900)) = 589 \pm 30 \text{ MeV}
\]

\[
M(\psi') - M(J/\psi) = 589 \text{ MeV}
\]
Charm vs. Beauty: I

What is in common?

- $\Upsilon(10860)/\Upsilon(4260)$ demonstrates anomalously large coupling to $\Upsilon\pi^+\pi^-/\psi\pi^+\pi^-$ and $h_b\pi^+\pi^-/h_c\pi^+\pi^-$ final states.

$Z_c(3900)$ is produced in $\Upsilon(4260) \rightarrow Z_c\pi \rightarrow \psi\pi^+\pi^-$

$Z_b(10610)$ is produced in $\Upsilon(10860) \rightarrow Z_b\pi \rightarrow \Upsilon(nS)\pi^+\pi^-$

$\Rightarrow Z_c\pi \rightarrow DD^*$

$\Rightarrow Z_b\pi \rightarrow BB^*$

MISSING PLOT
Charm vs. Beauty: II

What is difference?

• Both $Z_b(10610)$ and $Z_b(10650)$ isotriplets are observed in the $\Upsilon(nS)\pi$, $(n=1,2,3)$ and $h_b\pi$ final states.

• $\Upsilon(10860) \to h_b\pi^+\pi^-$ is saturated by the intermediate two-body $Z_b\pi$ production.

• Only $Z_c(3900)$ is observed in the $J/\psi\pi$ while both $Z_c(3900)$ and $Z_c(4020)$ are observed in the $h_c\pi$ final state. None of them is observed in the $\psi(2S)\pi$ final state (instead, another $Z_c(4430)$ is found).

• Large non $Z_c\pi$ component is observed in the $\Upsilon(4260) \to h_c\pi^+\pi^-$ amplitude.
Exotic mesons

**Masses (lattice QCD)**
- $1^{-+} \sim 2.0 - 2.4$ GeV
- $0^{+-} \sim 2.3 - 2.5$ GeV
- $2^{+-} \sim 2.4 - 2.6$ GeV

**Decay widths (from Models)**
- $\Gamma \sim 0.1 - 0.5$ GeV

**$J^{PC}$ Quantum Numbers**
- Parity $= (-1)^{L+1}$
- Charge Conjugation $= (-1)^{L+S}$
- Spin $= J = |L - S|$, $L$, $L + S$
- Vacuum $= ^3P_0 \cong 0^{++}$

Quark Degrees of Freedom ONLY

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>0--</th>
<th>0++</th>
<th>0--</th>
<th>0++</th>
</tr>
</thead>
<tbody>
<tr>
<td>1--</td>
<td>1--</td>
<td>1++</td>
<td>1--</td>
<td>1++</td>
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<tr>
<td>2--</td>
<td>2++</td>
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<td>5++</td>
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<td>5++</td>
<td>5--</td>
</tr>
</tbody>
</table>

$J^{PC}$ Exotic quantum numbers
$X(3872)$-J/$\psi$ relative sizes

$\text{d}_{\text{rms}}(^{64}\text{Zn nucleus}) \approx 8 \text{ fm}$

$\text{Volume}(J/\psi) / \text{Volume}(X_{3872}) \approx 10^{-4}$

$\text{d}_{\text{rms}}(X_{3872}) \sim 10 \text{ fm}$

$\text{d}_{\text{rms}}(J/\psi) \approx 0.4 \text{ fm}$

- How can such a fragile object be produced in H.E. pp collisions?

C. Bignamini et al, PRL 103, 162001:

$\sigma_{\text{CDF (meas)}} > 3.1 \pm 0.7 \text{nb}$ vs $\sigma_{\text{theory (molecule)}} < 0.11 \text{nb}$

after 14 years, we still don't know
Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold: connection between $X(1835)$ and $X(p\bar{p})$

$X(1835)$ observed in $J/\psi\rightarrow\gamma\eta'\pi^+\pi^-$


$X(1835)$ $J^{PC}=0^{-+}$

$M = 1844 \pm 9^{+19}_{-22}$ MeV/c$^2$

$\Gamma = 192^{+29+62}_{-17-43}$ MeV/c$^2$

$X(p\bar{p})$ observed in $J/\psi\rightarrow\gamma p\bar{p}$

PRL 108, 112003 (2012)

PRL 115, 091803 (2015)

$X(p\bar{p})$ $J^{PC}=0^{--}$

$M = 1832^{+19+18}_{-5-17} \pm 19$ MeV/c$^2$

$\Gamma = 13 \pm 19$ MeV/c$^2$

(< 76 MeV/c$^2$ @ 90\% C.L.)

Connection is emerging

PRL 117, 042002 (2016)

Model 1:

Flatte lineshape with strong coupling to $p\bar{p}$ and one additional, narrow Breit-Wigner at $\sim 1920$ MeV/c$^2$

Model 2:

Coherent sum of X(1835), Breit-Wigner and one additional, narrow Breit-Wigner at $\sim 1870$ MeV/c$^2$

- Suggest the existence of a state, either a broad one with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass thresh.
- Support the existence of a $p\bar{p}$ molecule-like state or bound state