Vector states above open charm threshold

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6th International Conference on New Frontiers in Physics
17 - 26 August 2017, Kolymbari, Creta, Greece
New charmonium-like states, i.e. “XYZ” states, are observed in experiment.
Charmnonium spectrum (2)

- Below the open charm threshold the spectrum is well understood
  - very good agreement between predicted and discovered states
- Above the threshold the situation is more complex
  - only few of the predicted states have been found
  - in the last decades many new states have been observed with properties that are not consistent with expectations for charmonium: X, Y, Z

what I mainly focus on: Y states
What are the Y states?

- A bit similar to $c\bar{c}$ states with $J^{PC} = 1^{--}$, but they are charmonium-like states
- Observed in direct $e^+e^-$ annihilation or in ISR.
- Possible final state: $\pi\pi(KK)J/\psi$, $\pi\pi(KK)\psi(2S)$, $\pi\eta_c$, $\pi\pi X$, $\eta J/\psi$, $\eta'J/\psi$, $\eta\psi(2S)$, $\omega\chi_c$, $\pi DD^*$, $\gamma X$ ...
- Cannot rule out threshold effect/FSI/....
• \( e^+e^-\rightarrow \gamma_{\text{ISR}} \pi^+\pi^- J/\psi (\psi(2S)) : Y(4260) & Y(4008) & Y(4360) & Y(4660) \)
• \( e^+e^-\rightarrow \pi^0\pi^0 \psi(2S) : Y(4360) ? \)
• \( e^+e^-\rightarrow \pi^+\pi^- (\pi^0\pi^0, KK) J/\psi : Y(4260) & Y(4222) & Y(4320) \)
• \( e^+e^-\rightarrow \pi^+\pi^- (\pi^0\pi^0) J/\psi \)
• \( e^+e^-\rightarrow \pi^0\eta J/\psi : \text{No} \ Y(4260) \)
• \( e^+e^-\rightarrow \pi^+\pi^- h_c : Y(4218) \& Y(4391) \text{ or } Y(4360) ? \)
• \( e^+e^-\rightarrow \pi^+\pi^- X(3823) : Y(4360) \text{ or } \psi(4415) ? \)
• \( e^+e^-\rightarrow \gamma X(3872) : Y(4260) ? \)
• \( e^+e^-\rightarrow \omega \chi_{c0,1,2} : Y(4230) \text{ or more} ? \)
• \( e^+e^- \rightarrow \pi^+D^0D^{*-} \ (Y(4220) \& Y(4440) ?) \)
• \( \text{Search for } Y(4140) \text{ in } \phi J/\psi \text{ mass spectrum} \)
• \( e^+e^-\rightarrow PJ/\psi \ (P=\eta, \eta') : \psi(4040) \& \psi(4160) \& \psi(4415) ? \)
• \( \text{summary} \)
\[ e^+e^- \rightarrow \gamma_{\text{ISR}} \pi^+\pi^- J/\psi \ (Y(4260)) \]

**Babar:**
- First observation of $Y(4260)$ in $\pi^+\pi^- J/\psi$ mass spectrum via ISR events. $M=4259^{+8}_{-6} \ MeV/c^2$, $\Gamma=88^{+23}_{-4} \ MeV/c^2$

**Belle:**
- Confirm $Y(4260)$ in $\pi^+\pi^- J/\psi$ mass spectrum
- Observe a new structure $Y(4008)$

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solution I</th>
<th>Solution II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(R1)$</td>
<td>$4008 \pm 40^{+114}_{-28}$</td>
<td>$226 \pm 44 \pm 87$</td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}(R1)$</td>
<td>$5.0 \pm 1.4^{+6.1}_{-0.9}$</td>
<td>$12.4 \pm 2.4^{+14.8}_{-1.1}$</td>
</tr>
<tr>
<td>$M(R2)$</td>
<td>$4247 \pm 12^{+17}_{-13}$</td>
<td>$108 \pm 19 \pm 10$</td>
</tr>
<tr>
<td>$\Gamma_{\text{tot}}(R2)$</td>
<td>$6.0 \pm 1.2^{+4.7}_{-0.5}$</td>
<td>$20.6 \pm 2.3^{+9.1}_{-1.7}$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$12 \pm 29^{+7}_{-98}$</td>
<td>$-111 \pm 7^{+28}_{-31}$</td>
</tr>
</tbody>
</table>

Babar: PRL95, 142001 (2005)

\[ e^+e^- \rightarrow \gamma_{\text{ISR}} \pi^+\pi^-\psi(2S) \ (Y(4360)\&Y(4660)) \]

**Babar:**
- First observation of \( Y(4360) \) in \( \pi^+\pi^-\psi(2S) \) mass spectrum. \( M=4324\pm24 \text{ MeV}/c^2 \), \( \Gamma=172\pm33 \text{ MeV}/c^2 \)

**Belle:**
- Confirm \( Y(4360) \) in \( \pi^+\pi^-\psi(2S) \) mass spectrum
- Observe a new \( Y(4660) \) state

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<tr>
<td>( M(Y(4360)) )</td>
<td>4361 ( \pm 9 \pm 9 )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_{\text{tot}}(Y(4360)) )</td>
<td>74 ( \pm 15 \pm 10 )</td>
<td></td>
</tr>
<tr>
<td>( \mathcal{B}\Gamma_{e^+\ell^-}(Y(4360)) )</td>
<td>10.4 ( \pm 1.7 \pm 1.5 )</td>
<td>11.8 ( \pm 1.8 \pm 1.4 )</td>
</tr>
<tr>
<td>( M(Y(4660)) )</td>
<td>4664 ( \pm 11 \pm 5 )</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_{\text{tot}}(Y(4660)) )</td>
<td>48 ( \pm 15 \pm 3 )</td>
<td></td>
</tr>
<tr>
<td>( \mathcal{B}\Gamma_{e^+\ell^-}(Y(4660)) )</td>
<td>3.0 ( \pm 0.9 \pm 0.3 )</td>
<td>7.6 ( \pm 1.8 \pm 0.8 )</td>
</tr>
<tr>
<td>( \phi )</td>
<td>39 ( \pm 30 \pm 22 )</td>
<td>(-79 \pm 17 \pm 20 )</td>
</tr>
</tbody>
</table>


\[ e^+e^- \rightarrow \pi^0\pi^0\psi(2S) \] (Y(4360)?)

- BESIII measured the Born cross section of \( e^+e^- \rightarrow \pi^0\pi^0\psi(2S) \) at 8 energies. Our results agree with the previous experiments.

- There is a bump near 4.36 GeV. Is it Y(4360)?
\[ e^+e^- \rightarrow \pi^+\pi^- J/\psi \] (Y(4260), or Y(4220) & Y(4320)?)

**CLEO:**
- Confirm Y(4260) via the missing momentum (\(\sqrt{s}=4.26 \text{ GeV}\))

\[ A(\sqrt{s}) = \frac{M}{\sqrt{s}} \frac{12\pi e^+e^- \Gamma_{\text{tot}} B_R}{s-M^2+iM\Gamma_{\text{tot}}} \sqrt{\frac{\Phi(\sqrt{s})}{\Phi(M)}} e^{i\phi}. \]

**BESIII:**
- Resonance 1: \(M=4222.0^{+3.1}_{-1.4} \pm 1.4 \text{ MeV}/c^2\), \(\Gamma=44.1^{+4.3}_{-2.0} \pm 2.0 \text{ MeV}/c^2\). Its mass is similar to Y(4260), but its width is much less than that of average Y(4260)
- Resonance 2: \(M=4320^{+10.4}_{-7.0} \pm 7.0 \text{ MeV}/c^2\), \(\Gamma=101.4^{+25.3}_{-19.7} \pm 10.2 \text{ MeV}/c^2\) (new!)
- Rule out only one resonance with 5.4\(\sigma\)


BESIII: PRL118, 092001 (2017)
$e^+e^- \rightarrow \pi^0\pi^0 J/\psi$ (Y(4260)?)

- **CLEO**: a weak evidence of Y(4260) signal
- **BESIII**: hard to determine any clear structure around 4.26 GeV


\( e^+e^- \rightarrow KKJ/\psi \) (Y(4260)?)

• CLEO: a weak evidence of Y(4260) signal in \( K^+K^-J/\psi \)

• BESIII(\textit{preliminary}): inconclusive as to whether Y(4260) decays to \( K\bar{K} (K^+K^-, K^0_S K^0_S)J/\psi \).
Search for the isospin violation decay of \( Y(4260) \)

- No signal is observed
- Can not provide effective constraint to models……

**BESIII: PRD92,012008 (2015)**
\[ \sigma(m) = \left| B_1(m) \frac{P(m)}{P(M_1)} + e^{i\phi} B_2(m) \frac{P(m)}{P(M_2)} \right|^2 \]

\[ B_j(m) = \sqrt{12\pi} \Gamma_{ee} B_j \Gamma_j \left( m^2 - M_j^2 + i M_j \Gamma_j \right) : \text{constant width BW function} \]

\[ P(m) : 3\text{-body phase space factor} \]

\[ \phi : \text{relative phase between two resonances} \]

- Significance of two resonant structures over that of one structure is 10\(\sigma\)
- The parameters of these two structures are different from those of \(\psi(4260)\) and \(\psi(4360)\), and \(\psi(4415)\)

<table>
<thead>
<tr>
<th>(\psi(4220))</th>
<th>(4218.4^{+5.5}_{-4.5} \pm 0.9)</th>
<th>(66.0^{+12.3}_{-8.3} \pm 0.4)</th>
<th>(4.6^{+2.9}_{-1.4} \pm 0.8)</th>
<th>--</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\psi(4390))</td>
<td>(4391.5^{+6.3}_{-1.4} \pm 1.0)</td>
<td>(139.5^{+16.2}_{-20.6} \pm 0.6)</td>
<td>(11.6^{+5.0}_{-4.4} \pm 1.9)</td>
<td>(3.1^{+0.7}_{-0.9} \pm 0.2)</td>
</tr>
</tbody>
</table>
\[ e^+e^- \rightarrow \pi^+\pi^-X(3823) \ (Y \text{ or } \psi?) \]

- Clear \( X(3823) \) is seen in \( \chi_{c1} \) mass region
- Line-shape of \( \pi^+\pi^-X(3823) \)
  - \( Y(4360)? \)
  - \( \psi(4415)? \)
  - Both?
  - More?

Kolmogorov test:
\[ D_{5, obs}^{H1} = 0.151 \text{ for } Y(4360), \quad D_{5, obs}^{H2} = 0.169 \text{ for } \psi(4415) \]
Considering \( D_{5,0.1} \) = 0.509, we accept both \( Y \) and \( \psi \) hypothesis at the 90% C.L.

PRL115,011803 (2015)
Clear $X(3872)$ is seen in $\pi^+\pi^-J/\psi$ mass spectrum via $e^+e^-\rightarrow\gamma\pi^+\pi^-J/\psi$

Try to fit $\sigma^B(\gamma X(3872) \rightarrow \gamma\pi^+\pi^-J/\psi)$ with $Y(4260)$, linear and phase-space shape

$Y(4260) \rightarrow \gamma X(3872)$? Need to be confirmed
Using scan data over 4.23 and 4.6 GeV, \( e^+e^- \rightarrow \omega \chi_{c0} \) are significant.

- Cross section peak near 4.23 GeV, fit with BW yields Mass = \((4230 \pm 8 \pm 6)\) MeV, Width = \((38 \pm 12 \pm 2)\) MeV.
  - A new structure?
  - Tetraquark [PRD 91, 117501 (2015)]?
  - Threshold effect?
  - Similar to the first structure \( Y(4220) \) in \( e^+e^- \rightarrow \pi^+\pi^- h_c \) line-shape.
Clear $\chi_{c2}, \chi_{c1}$ are observed at $\sqrt{s}=4.42, 4.6$ GeV, respectively.

The Born cross section have been measured for $e^+e^- \rightarrow \omega \chi_{c1,2}$.

$\sigma(e^+e^- \rightarrow \omega \chi_{c2})$ is fitted with the coherent sum of the $\psi(4415)$ BW function and a phase-space term. Two solutions are obtained: ......constructive, --- destructive.
The statistical significance of two resonances assumption over one resonance is greater than 10σ.

The resonant parameters of Y(4220) and Y(4390) states are consistent with the structures observed in $e^+e^- \rightarrow \pi^+\pi^- h_c$. The resonant parameters of Y(4220) are also consistent with those of the resonance observed in $e^+e^- \rightarrow \omega \chi_{c0}$ and $e^+e^- \rightarrow \pi^+\pi^- J/\psi$. 

$$\sigma_{dress}(m) = \frac{N^{obs}}{\mathcal{L}(1 + \delta r) B(D^0 \rightarrow K^-\pi^+)\epsilon}$$
Y(4140) & Y(4330) & more?

• First observation in CDF via $B^+ \rightarrow \phi J/\psi K^+$ with 6.0 fb$^{-1}$ data (an evidence with 2.7 pb$^{-1}$ data)
• CMS and D0 confirm with the same process
• Belle and Babar failed to confirm with the same process
• LHCb hasn’t observed any structure firstly, but observed 4 structures with a large sample
• Belle hasn’t confirmed with two-photon process, either
• BESIII hasn’t observed Y(4140) via $e^+e^- \rightarrow \gamma \phi J/\psi$
Belle observed two structures in Born cross section of $e^+e^- \rightarrow \eta J/\psi$ and fit them using $\psi(4040) & \psi(4160)$ line-shapes.

BESIII’s results agree with Belle’s results with improved precision in some points.

The cross section also peaks around 4.2 GeV.
Significant signals are observed at $\sqrt{s} = 4.23$ and 4.26 GeV

The measured cross section support the hypothesis that signal events of $\eta’J/\psi$ come from $\psi(4160)$ decay; not from $\psi(4415)$
Summary

• Many candidates of charmonium-like vector states are observed above open charm threshold.

• They are difficult to distinguish from the traditional charmonium states.

• Some potential new structures need to be further confirmed.

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