Exotics in Leptonic Machines

Kai Zhu
Institute of High Energy Physics, Beijing
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Outline

- Introduction
- Selected topics on recent observations at leptonic machines
  - Enhancement/structure near 1.84 GeV
  - Charmonium–like particles (XYZ)
- Summary & Outlook

I apologize cannot cover all the topics in this interesting and charming field.
Exotic candidates because of self–coupling of gluons in QCD

- Bound gluons (glueball)
- $q\bar{q}$–pair with an excited gluon (hybrids)
- Multi–quark color singlet states
  - $q\bar{q}q\bar{q}$ (tetra–quark and molecular)
  - $q\bar{q}q\bar{q}q$ (penta–quark)
  - $q\bar{q}q\bar{q}q\bar{q}$ (six–quark and baryonium)

Figures from arXiv:1403.1254, S. Olsen

Exotics in leptonic machines 2014/5/25
Introduction—Leptonic machine

Charm factories
CLEOc and BESIII

B factories
BaBar and Belle

CLEOc

BESIII

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Structures near 1.84 GeV

- Recently observed or searched for structures near $p\bar{p}$ threshold
  - $X(p\bar{p}), X(1835), X(1840), X(1870), X(1810)$
- I have to give up lots of interesting topics such as
  - Scalar particles:
    - $a_0(980), f_0(980), f_0(1500), f_0(1710), f_0(2300)$, etc.
  - Tensors: $f_2'(1525), f_2(1810), f_2(2340)$
  - Enhancement near threshold of $p\Lambda$
  - More ...

For $f_0(1500), f_0(1710), f_0(2300)$, See T. Latham’s talk.
No obvious structure observed

$$J/\psi \rightarrow \gamma p\bar{p}$$

\[ M = 1832^{+19}_{-15} \text{ (stat.)}^{+18}_{-17} \text{ (syst.)} \pm 19 \text{ (model) } \text{MeV/c}^2 \]

\[ \Gamma = 13 \pm 39 \text{ (stat.)}^{+10}_{-13} \text{ (syst.)} \pm 4 \text{ (model) } \text{MeV/c}^2 \]

$$j^{PC} = 0^{-+}$$

$$\psi' \rightarrow \gamma p\bar{p}$$

exotics in leptonic machines
$p\bar{p}$ enhancement cont.

$J/\psi \rightarrow \omega p\bar{p}$

Disfavors the pure FSI interpretation for the $p\bar{p}$ threshold enhancement in the decay $J/\psi \rightarrow \gamma p\bar{p}$.

No obvious structure observed.
X(1835)

- Via $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$

To determine spin and parity, PWA is needed. X(1835) is consistent with a pseudo-scalar.
X(1835), cont

- Via $\gamma\gamma \rightarrow \pi^+\pi^-\eta'$

Interference between $X(1835)$ and $\eta(1760)$ is considered.
Search $X(1835)$ via $e^+e^- \rightarrow J/\psi + X(1835)$ at $\sqrt{s} \approx 10.6 \text{GeV}$

No significant evidence is found to support the hypothesis of the $X(1835)$ as a glueball produced in association with a $J/\psi$. 
Via $J/\psi \rightarrow \gamma \omega \phi$

**X(1810)**

**Phys. Rev. D 87 (2012) 032008**

**BES III**

**PWA**

**TABLE I.** Results from the best PWA fit solution.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$J^{PC}$</th>
<th>$M$(MeV/$c^2$)</th>
<th>$\Gamma$(MeV/$c^2$)</th>
<th>Events</th>
<th>$\Delta S$</th>
<th>$\Delta$ndf</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(1810)$</td>
<td>0$^{++}$</td>
<td>1795 ± 7</td>
<td>95 ± 10</td>
<td>1319 ± 52</td>
<td>783</td>
<td>4</td>
<td>&gt;30$\sigma$</td>
</tr>
<tr>
<td>$f_2(1950)$</td>
<td>2$^{++}$</td>
<td>1944</td>
<td>472</td>
<td>665 ± 40</td>
<td>211</td>
<td>2</td>
<td>20.4$\sigma$</td>
</tr>
<tr>
<td>$f_0(2020)$</td>
<td>0$^{++}$</td>
<td>1992</td>
<td>442</td>
<td>715 ± 45</td>
<td>100</td>
<td>2</td>
<td>13.9$\sigma$</td>
</tr>
<tr>
<td>$\eta(2225)$</td>
<td>0$^{-+}$</td>
<td>2226</td>
<td>185</td>
<td>70 ± 30</td>
<td>23</td>
<td>2</td>
<td>6.4$\sigma$</td>
</tr>
<tr>
<td>Coherent nonresonant component</td>
<td>0$^{-+}$</td>
<td>...</td>
<td>...</td>
<td>319 ± 24</td>
<td>45</td>
<td>2</td>
<td>9.1$\sigma$</td>
</tr>
</tbody>
</table>
Via $J/\psi \to \omega \eta \pi^+\pi^-$, where $J/\psi \to \omega X(1870)$, $X(1870) \to a^\pm(980)\pi^\mp$

PWA is needed to determine the spin and parity of $X(1870)$. 

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV/c²)</th>
<th>Width (MeV/c²)</th>
<th>$B \times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1(1285)$</td>
<td>$1285.1 \pm 1.0^{+1.6}_{-0.3}$</td>
<td>$22.0 \pm 3.1^{+2.0}_{-1.5}$</td>
<td>$1.25 \pm 0.10^{+0.19}_{-0.20}$</td>
</tr>
<tr>
<td>$\eta(1405)$</td>
<td>$1399.8 \pm 2.2^{+2.8}_{-0.1}$</td>
<td>$52.8 \pm 7.6^{+0.1}_{-7.6}$</td>
<td>$1.89 \pm 0.21^{+0.21}_{-0.23}$</td>
</tr>
<tr>
<td>$X(1870)$</td>
<td>$1877.3 \pm 6.3^{+4.4}_{-5.4}$</td>
<td>$57 \pm 12^{+19}_{-4}$</td>
<td>$1.50 \pm 0.26^{+0.72}_{-0.36}$</td>
</tr>
</tbody>
</table>
$J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$

PWA is needed to determine the spin and parity of X(1840).

No $\eta'$ signal is found.

Statistical significance: 7.6$\sigma$

$M = 1842.2 \pm 4.2^{+7.1}_{-2.6} \text{ MeV}/c^2$

$\Gamma = 83 \pm 14 \pm 11 \text{ MeV}$
A partial summary

Not like a glueball

Not found in $\psi'$ radiative decay
Not like a pure FSI

$J/\psi$ radiative decay

$p\bar{p}$ threshold

Same source or not?

Bayonia?
Glueball?
Hybrid?
Threshold effect?
Other possibilities?

PWA is needed.
Charmonium–like exotics

- New information on $X(3872)$
- New information on $Y$ states
  - Babar and Belle update $e^+e^- \rightarrow \gamma_{ISR} \pi^+\pi^- J/\psi$, $e^+e^- \rightarrow \gamma_{ISR} \pi^+\pi^- \psi(2S)$ with larger luminosities
  - BESIII: $\pi^+\pi^- h_c$
- Charged $Z$
  - $Z_c(3900)$ and its partners
  - $Z_{cs}$ search via $K^+K^- J/\psi$
  - $Z_b(10610)$ and $Z_b(10650)$

For $Z_c(4430)$, see Ye Chen’s talk
Overview of $X(3872)$

- First observed in $B \rightarrow K(\pi^+\pi^- J/\psi)$ 2003
  - mass: close to $D^*0 D^0$ threshold
  - width: very narrow
- $J^{PC}=1^{++}$  [CDF and LHCb]
- Decay BR:
  - open charm $\sim 50\%$, charmonium $\sim O(\%)$
- Nature (many possibilities)
  - Charmonium state: $\chi_{c1}(2P)$
  - $D^0D^{*0}$ module
  - Hybrid: mass too low
  - Tetra-quark: no charged partner be found
- Production
  - in pp collision and B decays
  - $e^+ e^- \rightarrow \gamma X(3872)$ [NEW, see next slide]
X(3872), new production mode

Phys. Rev. Lett. 112, 092001

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

From $Y(4260)$ decay?

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.01</td>
<td></td>
</tr>
<tr>
<td>4.23</td>
<td></td>
</tr>
<tr>
<td>4.26</td>
<td></td>
</tr>
<tr>
<td>4.36</td>
<td></td>
</tr>
</tbody>
</table>
**Y states: 1-- states from ISR**

Y(4260), PRL 95 142001

Y(4260) PRL 99 182004

Y(4630) = Y(4660) ?

Large partial width to $\pi^+\pi^- J/\psi$ and $\pi^+\pi^-\psi(2S)$

No sign of $Y \rightarrow D^{(*)}D^{(*)}$

Too many Y states!
Significant \( Y(4260) \) is found.

Not confirm \( Y(4008) \).

Fit method?

Still observe two resonances \( Y(4008) \) and \( Y(4260) \).

Agrees with Belle’s previous results.
Y states: update cont.

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

Fitted with $Y(4360)$, $Y(4660)$, two solutions.

Fitted with $Y(4260)$, $Y(4360)$, $Y(4660)$.

The significance of $Y(4260)$ is only 2.1$\sigma$, but its effect on others is large.

From C.P. Shen

arXiv:1211.6271

$520 \, fb^{-1}$

$980 \, fb^{-1}$
An individual work based on the combined BESIII and CLEOc data.

Fit with a narrow $Y(4220)$ and a wide $Y(4290)$.

C. Z. Yuan arXiv:1310.0280
$e^+e^- \rightarrow \omega \chi_{c0}$

Fit with a single BW assumption, mass lower than 4.26 GeV.

No signal of $\omega \chi_{c1}$ or $\omega \chi_{c2}$ found.
Disfavor $Y(4260)$ is a $\omega \chi_{c1}$ molecule.
$Z_c(3900)$: observed in BESIII and Belle

At 4.26 GeV: PRL. 110, 252001

- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV
- $\Gamma = 46 \pm 10 \pm 20$ MeV
- 307 ± 48 events
- $>8\sigma$

ISR: PRL 110, 252002

- $M = 3894.5 \pm 6.6 \pm 4.5$ MeV
- $\Gamma = 63 \pm 24 \pm 26$ MeV
- 159 ± 49 events
- $>5.2\sigma$
**Z_{c}(3900): confirmed by an analysis of CLEOc data**

- \( M = 3885 \pm 5 \pm 1 \) MeV
- \( \Gamma = 34 \pm 12 \pm 4 \) MeV
- 81 ± 20 events
- 6.1\( \sigma \)

- Couples to \( c\bar{c} \)
- Has electric charge
- At least 4-quarks

- **DD* molecule?**
- **Tetraquark?**
- **Cusp?**
- **Threshold effect?**
- ...
$Z_c(3885)$

- $e^+e^- \rightarrow \pi^\pm(D\bar{D}^*)^\mp$ at 4.26 GeV

$\sqrt{s}=4.26$ GeV
525 pb$^{-1}$
Favor $J^P = 1^+$

<table>
<thead>
<tr>
<th>$Z_c(3885) \rightarrow D\bar{D}^*$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV/$c^2$)</td>
<td>$3883.9 \pm 1.5 \pm 4.2$</td>
</tr>
<tr>
<td>$\Gamma$ (MeV)</td>
<td>$24.8 \pm 3.3 \pm 11.0$</td>
</tr>
<tr>
<td>$\sigma \times B$ (pb)</td>
<td>$83.5 \pm 6.6 \pm 22.0$</td>
</tr>
</tbody>
</table>
\( Z_c(4025) \)

- \( e^+ e^- \rightarrow \pi^\pm (D^* \bar{D}^*)^\mp \) at 4.26 GeV

\[ \sqrt{s} = 4.26 \text{ GeV} \]
\[ 827 \text{ pb}^{-1} \]
\[ M = (4026.3 \pm 2.6 \pm 3.7) \text{ MeV} \]
\[ \Gamma = (24.8 \pm 5.6 \pm 7.7) \text{ MeV} \]
\( Z_c(4020): \) charged

\[ e^+ e^- \rightarrow \pi^+ \pi^- h_c \] from 3.90 to 4.42 GeV (13 \cdot)

\[ M = (4022.9 \pm 0.8 \pm 2.7) \text{ MeV}/c^2 \]
\[ \Gamma = (7.9 \pm 2.7 \pm 2.6) \text{ MeV} \]
$Z_c(4020)$: neutral

Observation of $e^+e^\to\pi^0\pi^0h_c(1P)$

Summed results at $E_{cm} = 4.23, 4.26, 4.36\,\text{GeV}$

Preliminary

For $R_{\pi\eta h_c} = \frac{\sigma(\text{neutral})}{\sigma(\text{charged})}$,

- $R_{\pi\eta h_c} = 0.54 \pm 0.11 \pm 0.06$ at $\sqrt{S} = 4.23\,\text{GeV}$,
- $R_{\pi\eta h_c} = 0.64 \pm 0.14 \pm 0.10$ at $\sqrt{S} = 4.26\,\text{GeV}$,
- $R_{\pi\eta h_c} = 0.73 \pm 0.14 \pm 0.10$ at $\sqrt{S} = 4.36\,\text{GeV}$,
$Z_c(4020)$: neutral cont.

$e^+e^- \rightarrow \pi^0 Z^0_c(4020) \rightarrow \pi^0 \pi^0 h_c(1P)$

Summed results at $E_{cm} = 4.23, 4.26, 4.36 \text{GeV}$

Simultaneous fit to 4.23/4.26/4.36 GeV Data and 16 $\eta_c$ modes;
$\Gamma(Z_c^0(4020))$ is fixed to value of $\Gamma(Z_c^+ (4020))$;
Interference is neglected;
$M(Z_c^0(4020)) = 4023.6 \pm 2.2 \pm 3.9 \text{ MeV}/c^2$;
Significance : $> 5 \sigma$.
\(Z_{cs} \) search

- Belle update \(K^+K^-J/\psi\) to Dalitz Plot

No evident structure in \(K^{\pm}J/\psi\) mass distribution under current statistics
$Z_b(10610), Z_b(10650)$ : charged

$e^+ e^- \rightarrow \pi^+ \pi^- \Upsilon(nS)$

Phys. Rev. D 89, 72015

$\Upsilon(10860) \rightarrow Z_b(10610)^{\pm} \pi^\mp \rightarrow [B \bar{B}^*]^{\pm} \pi^\mp$

$\Upsilon(10860) \rightarrow Z_b(10650)^{\pm} \pi^\mp \rightarrow [B^* \bar{B}^*]^{\pm} \pi^\mp$

arXiv: 1209.6450
Partial summary of $Z$

- If we assume
  - $Z_c(3900)$ and $Z_c(3885)$ are a same state $Z_c$
  - $Z_c(4020)$ and $Z_c(4025)$ are a same state $Z_c'$

**More excited states?**
**Other prod. modes?**

- $Z_c(4430)$ or $Z_c(4470)$

**$Z_c$**
- $\pi J/\psi$
- $D \bar{D}^*$

**$Z_c'$**
- $D^* \bar{D}^*$
- $\pi h_c$

**$Z_b(10610)$**
- $\pi Y(nS)$
- $B \bar{B}^*$
- $\pi h_b(mP)$

**$Z_b(10650)$**
- $\pi Y(nS)$
- $B \bar{B}^*, B^* \bar{B}^*$
- $\pi h_b(mP)$

**Only coincidence?**

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Summary

- Leptonic machines produce exotics. These particles are unexpected, weird and strange, while also tantalizing, charming and interesting.

- Some structures are observed near $p\bar{p}$ threshold with similar masses.
  - Are they from same source? Are they baryonia, glueball or hybrid? For some cases, PWA is needed to determine the spin and parity. Search via more modes will help to reveal the veil.

- Lots of progress in XYZ studies in $e^+e^-$ experiments
  - Observation of $e^+e^- \rightarrow \gamma X(3872)$
  - New information on the Y’s from BaBar, Belle and BESIII.
  - Confirmed exotic state seems at least four quarks, $Z_c(3900)$
  - Observation of more $Z_c'$ at BESIII

- Exciting future!
Thanks a lot!