Recent results in (exotic) charmonium spectroscopy

Wenbiao Yan

University of Science and Technology of China
Hadrons

- **Hadrons:**
  - 2 quarks (meson) or 3 quarks (baryon)
  - described with quark model (QM)

- **QCD suggests:**
  - Molecule: bound state of two hadrons
  - Multiquark state: (qqqq, qqqqq, …)
  - Glueball: (gg, ggg, …)
  - Hybrid: (qqg, …)

**Search for these exotic hadrons**
Below charm threshold, all states have been observed

Charm anti-charm potential model described spectrum very well

Many missing states above charm threshold.

A number of new states above charm threshold that do not fit into $c\bar{c}$ slots

- Not all of them are charmonium
- What are they?
XYZ production

From PDG

ψ(4040)@4.008GeV
ψ(4260)@4.26GeV
ψ(4360)@4.36GeV
ψ(4415)@4.42GeV
ψ(4660)@4.6GeV

- Vector ψ/Y states can be produced directly
- ISR production
- B decay
Y(4260) and Y(4008)

Both Belle and Babar updated results, consistent with previous measurements.

Discrepancy between two experiments still exist: Belle observed additional Y(4008), BaBar updated with more data, no Y(4008) observed.

**BESIII data could clarify**
Y(4360)/Y(4660): $e^+e^- \rightarrow \gamma_{ISR} \psi'\pi^+\pi^-$

- BaBar and Belle observed Y(4360)
- Belle with additional Y(4660)
- BaBar updated results in good agreement with Belle

Y(4660) confirmed

- Belle preliminary results in good agreement with previous results, Y(4260) significance 2.1σ only.
\[ e^+e^- \rightarrow \pi^+\pi^-h_c \]

- \( \sigma(e^+e^- \rightarrow \pi^+\pi^-h_c) \sim \sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi) \), but different line shape.
- Local maximum \( \sim 4.23 \text{ GeV} \), broad structure at \( \sim 4.4 \text{ GeV} \)?
- More data around 4.23 GeV and above 4.4 GeV is very help.
Cross section of $e^+e^- \rightarrow \omega \chi_{c0}$

- Data samples at 9 energy points from 4.21 GeV to 4.42 GeV
- $\omega \rightarrow \pi^+\pi^-\pi^0$; $\chi_{c0} \rightarrow \pi^+\pi^-/K^+K^-$
- Signal observed at 4.23 MeV and 4.26 MeV
- Simultaneous fit performed

Cross section peaks around 4.23 GeV
Charged charmonium-like states

- Have electric charge, thus has two more light quarks
  - At least 4 quarks, not a conventional meson
- Could exist in $\pi^\pm J/\psi$, $\pi^\pm \psi(2S)$, $\pi^\pm h_c$, $\pi^\pm \chi_{cJ}$, …
  - Search for Neutral isospin partner
- Experimental search:
  - BESIII/CLEO-c: $e^+e^-\rightarrow \pi^\pm$ exotics,…
  - Belle/BaBar: $e^+e^-\rightarrow (\gamma_{ISR})\pi^\pm$ exotics,…
  - Belle/BaBar/LHCb: $B\rightarrow K$ exotics,…
Observation of Zc(3900)$^\pm$

$e^+e^- \rightarrow J/\psi \, \pi^+\pi^-$

**BESIII**

\[ M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV} \]
\[ \Gamma = 46 \pm 10 \pm 20 \text{ MeV} \]
\[ 307 \pm 48 \text{ events, } >8\sigma \]

**BELLE**

\[ M = 3894.5 \pm 6.6 \pm 4.5 \text{ MeV} \]
\[ \Gamma = 63 \pm 24 \pm 26 \text{ MeV} \]
\[ 159 \pm 49 \text{ events, } >5.2\sigma \]

**CLEO-c Data**

\[ M = 3886 \pm 4 \pm 2 \text{ MeV} \]
\[ \Gamma = 37 \pm 4 \pm 8 \text{ MeV} \]
\[ 81 \pm 16 \text{ events, } >5\sigma \]
**Zc(3900)^0 @ e^+e^- → π^0π^0J/ψ**

**BESIII Preliminary**

- $Z_c(3900)^0$ is observed clearly at $\sqrt{s} = 4.23, 4.26, 4.36$ GeV
- BESIII preliminary results:
  - $M = 3894.8 \pm 2.3$ MeV, $\Gamma = 29.6 \pm 8.2$ MeV
  - Significance = 10.4 $\sigma$

**Neutral isospin partner, Zc(3900)^0 observed**
\[ e^+e^- \rightarrow \pi^\pm (DD^*) \mp \ @ 4.26\text{GeV} \]

- Bachelor \(\pi\) angular distribution favors a \(J^p=1^+\) assignment

\[
\begin{align*}
M[D^0D^*^-] & \rightarrow 3883.9 \pm 1.5 \pm 4.2\text{MeV} \\
\Gamma[Z_c(3885)] & = 24.8 \pm 3.3 \pm 11.0\text{MeV} \\
\end{align*}
\]

\(2\sigma/1\sigma\) below those of \(Z_c(3900)\)

\[
\frac{\Gamma(Z_c(3900) \rightarrow D\bar{D}^*)}{\Gamma(Z_c(3900) \rightarrow \pi J/\psi)} = 6.2 \pm 2.9
\]

Large non-DDbar coupling
Observation of $Z_c(4020)$

$e^+e^-\rightarrow\pi^+\pi^-h_c$

- Narrow $\pi^+h_c$ structure observed
  - $M = 4022.9\pm0.8\pm2.7$ MeV;
  - $\Gamma = 7.9\pm2.7\pm2.6$ MeV
  - Significance : $8.9\sigma$

- No significant evidence for $Z_c(3900)\rightarrow\pi^+h_c$
  - Significance 2.1\sigma

$\sigma(e^+e^-\rightarrow\pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^-h_c) < 11$ pb

$\sigma(e^+e^-\rightarrow\pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^-J/\psi) = 13 \pm 5$ pb

$e^+e^-\rightarrow\pi^\pm(D^*D^*)^\mp$

- Deviation from phase space decay
  - $M = 4026.3\pm2.6\pm3.7$ MeV
  - $\Gamma = 24.8\pm5.6\pm7.7$ MeV
  - Significance : $10\sigma$

- If assume $Z_c(4025)$ is $Z_c(4020)$

$$\frac{\Gamma(Z_c(4020) \rightarrow D^*\bar{D}^*)}{\Gamma(Z_c(4020) \rightarrow \pi h_c)} = 12 \pm 5$$
Neutral partner of $Z_c(4020)$

- X-sec. is about half of charged process, agree with expectation of isospin symmetry
- Observe $Z_c(4020)^0$ structure in $\pi_0 h_c$ mass distribution
- Simultaneous fit to 4.23 /4.26/ 4.36 GeV data, BESIII preliminary Result:
  - $M[Z_c(4020)^0] = 4023.6\pm2.2\pm3.9$ MeV  [$M[Z_c(4020)^\pm] = 4022.9\pm0.8\pm2.7$ MeV]
  - Width fixed to charged $Z_c(4020)$
  - Interference neglect
Zc (4430) in $B^0 \to \psi(2S)K\pi$

- First charged charmonium-like particle, reported by Belle
- Babar: reflections of K* states, but not contradict to Belle
- Belle update results confirmed its existence, $J^P$ is favored $1^+$
  - Four dimensional analysis, $F$=($M_{K\pi}^2$, $M_{\psi'\pi}^2$, $\theta_{\psi'}$, $\varphi$)
  - Mass and width are higher than that of previous Belle results
- LHCb established its existence, $J^P$=1$^+$ unambiguously
  - Mass and width consistent with Belle latest result
B^0 \rightarrow J/\psi k\pi \ @ Belle

- New $Z_c (4200)$ is found ($J^P = 1^+$) with $7.2\sigma$:
  \[ M = 4196^{+31+17}_{-29-6} \text{ MeV/c}^2, \quad \Gamma = 370^{+70+70}_{-70-85} \text{ MeV}. \]
- Exclusion levels ($J^p=0^-, 1^-, 2^-, 2^+$): $6.7\sigma$, $7.7\sigma$, $5.2\sigma$, $7.6\sigma$
- $Z_c(4430)$ is also found ($4\sigma$),

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

A new charged charmonium-like particle, $Z_c(4200)$?  
A new $Z_c(4430)$ decay mode?  
Need confirmation!
Summary and outlook

● Y states
  ✓ New information on the Y’s from BaBar and Belle. Y(4660) confirmed, Y(4008) need confirmed
  ✓ $e^+e^-\rightarrow \pi^+\pi^- h_c$ and $\omega\chi_c^0$ cross section measured by BESIII
    □ different line shape observed at $\pi^+\pi^−h_c$ process, makes situation complicate

● Zc states
  ✓ Confirmed exotic state with at least four quarks, $Z_c(3900)$, at BESIII & Belle
  ✓ Observation of charged and neutral $Z_c'$ at BESIII
  ✓ $Z_c(4430)$ confirmed by LHCb, quantum number favor $1^+$
Summary and outlook

- Y(4260), Y(4360) and Y(4660) @ BESIII
  - All produced in $e^+e^-$ collisions
    - narrow structure above charm threshold
    - Strongly couple to charmonium states
  - No evidence in open-charm process and R-value scan
    Large BESIII R value data sample may confirm/improve
  - C-even states can be produced from radiative transitions

- ISR & B decay @ Belle, Babar and Belle II
  - Belle and Babar have remarkable success in quarkonium spectroscopy
  - No doubt for further success for Belle II with higher luminosities

- ATLAS/CMS/LHCb @ LHC
  - made great measurement improved results from B-Factory
  - Promise to be even more fruitful sources after a two-year shutdown for an upgrade