Exotic hadrons from BESIII

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Outline

• The BESIII experiment
• charmoniumlike states
  – The Y states — $J^{PC} = 1^{--}$
  – The $Z_c$ states — $I=1$ & decays into $\bar{c}c$
• Summary
Where is the BESIII experiment

We are here!

IHEP, Beijing
12km west from the Forbidden City
Beijing Electron Positron Collider (BEPC)

- Founded: 1984
  - $E_{cm} = 2-4.6$ GeV
- 1989-2005 (BEPC):
  - $L_{peak} = 1.0 \times 10^{31} / \text{cm}^2 \text{s}$
- 2008-now (BEPCII):
  - $L_{peak} = 1.0 \times 10^{33} / \text{cm}^2 \text{s}$
  - (Apr. 5, 2016)
BESIII Detector

Magnet yoke

SC magnet, 1T

RPC

Be beam pipe

MDC, 120 μm 0.5% at 1 GeV/c

TOF, 80ps

CsI(Tl) calorimeter, 2.5% @ 1 GeV

Total weight 730 ton, ~40,000 readout chnls, Data rate: 5kHz, 50Mb/s

Has been in full operation since 2008, all subdetectors are in very good status!
BESIII Collaboration

14 countries
64 institutions
~500 members
Can cover 0-4.6 GeV from direct annihilation or ISR
Charmonium spectroscopy

S and D-wave spin-triplets have the same quantum number as the photon!

\[ \text{Mass (GeV)} \]

\[ \begin{array}{cccc}
2^3D_1(4.19) & 2^3D_1(4.52) & 2^3D_1(4.21) & 2^3D_2(4.21) & 2^3D_3(4.22) \\
3^3S_1(4.10) & 3^3S_1(4.06) & 3^3S_1(4.09) & 3^3S_1(4.10) & 3^3S_1(4.09) \\
2^3P_0(3.92) & 2^3P_0(3.96) & 2^3P_0(3.98) & 2^3P_0(3.95) & 2^3P_0(3.98) \\
2^3P_1(3.95) & 2^3P_1(3.98) & 2^3P_1(3.98) & 2^3P_1(3.98) & 2^3P_1(3.98) \\
1^3P_1(3.52) & 1^3P_1(3.51) & 1^3P_1(3.51) & 1^3P_1(3.51) & 1^3P_1(3.51) \\
1^3S_1(3.10) & 1^3S_1(3.06) & 1^3S_1(3.06) & 1^3S_1(3.06) & 1^3S_1(3.06) \\
\end{array} \]

Godfrey & Isgur, PRD32, 189 (1985)

\[ n^{(2S+1)\text{L}_J} \]

- **n**: radial quantum number
- **S**: total spin of c & cbar
- **L**: orbital angular momentum
- **J**: \( S + L \)
- **P**: \((-1)^{L+1}\) parity
- **C**: \((-1)^{L+S}\) charge conj.
Charmonium(like) spectroscopy

- Charmonium-like (XYZ) particles
- New type of hadron (multi-quark ...)?
- Too many vector states! Exotics?

Godfrey & Isgur, PRD32, 189 (1985)
The Y states
measurements of more final states for the
Y and $\psi$ states
The Y states

Belle: PRL99, 142002, 670/fb
BaBar: PRD89, 111103, 520/fb

May BESIII help?
e^+e^- → π^+π^-J/ψ at 4.26 GeV

- Select 4 charged tracks and reconstruct J/ψ with lepton pair.
- Very clean sample, very high efficiency (~45%).
- \( \sigma(e^+e^- → π^+π^-J/ψ) = (62.9 ± 1.9 ± 3.7) \text{ pb} \)

PRL110, 252001 (2013)
Most precise cross section measurement to date from BESIII

Fit I = |BW_1 + BW_2 e^{i\phi_2} + BW_3 e^{i\phi_3}|^2 or Fit II = |\exp + BW_2 e^{i\phi_2} + BW_3 e^{i\phi_3}|^2 (other fits ruled out)

\[ M = 4222.0 \pm 3.1 \pm 1.4 \text{ MeV (lower)} \]
\[ \Gamma = 44.1 \pm 4.3 \pm 2.0 \text{ MeV (narrower)} \]
Most precise cross section measurement to date from BESIII

Fit I = $|BW_1 + BW_2 \times e^{i\theta_2} + BW_3 \times e^{i\phi_3}|^2$ or Fit II = $|\exp + BW_2 \times e^{i\phi_2} + BW_3 \times e^{i\phi_3}|^2$ (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 $> 7.6\sigma$
$e^+e^- \rightarrow \pi^+\pi^-h_c(1P)$

- $h_c \rightarrow \gamma\eta_c$, $\eta_c \rightarrow$ hadrons [16 exclusive decay modes]
  - $pp$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-pp$, $2(K^+K^-)$, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$
  - $2(\pi^+\pi^-)K^+K^-$, $K_S^0K^+\pi^-+c.c.$, $K_S^0K^+\pi^-\pi^+\pi^-+c.c.$, $K^+K^-\pi^0$
  - $pp\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)\eta$, $2(\pi^+\pi^-\pi^0)$

Method same as in PRL111, 242001 (2013)
$e^+e^- \rightarrow \pi^+\pi^- h_c$ cross section

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

~6 fb$^{-1}$
$e^+e^- \rightarrow \pi^+\pi^- h_c$ cross section

BESIII: R-scan data sample
- BESIII: XYZ data sample
- Fit curve: Total
- Fit curve: $Y(4220)$
- Fit curve: $Y(4390)$

$\sqrt{s}$ (GeV)

Dressed Cross section (pb)

- $M_1 = 4218.4^{+5.5}_{-4.5} \pm 0.9$ 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 $\rightarrow Y(4390)$

~6 fb$^{-1}$
$e^+ e^- \rightarrow \pi^+ D^0 D^{*-} + c.c.$

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

- An un-binned maximum likelihood fit
- Signal shape: MC convolved with a Gaussian;
- The isospin partner background (dotted line) is parameterized with MC;
- A linear function for other bkg
Fit to the dressed X-section of
\[ e^+ e^- \rightarrow \pi^+ D^0 D^{*-} + \text{c.c.} \]

\[
\sigma_{dress} = \frac{N^{obs}}{\mathcal{L}(1 + \delta_r) B(D^0 \rightarrow K^- \pi^+) \epsilon}
\]

\[
\sigma_{dress}(m) = |c \cdot \sqrt{P(m)} + e^{i\phi_1}B_1(m) \sqrt{\frac{P(m)}{P(M_1)}} + e^{i\phi_2}B_2(m) \sqrt{\frac{P(m)}{P(M_2)}}|^2
\]

Fit with a constant (pink dashed triple-dot line) and two constant width relativistic BW functions (green dashed double-dot line and aqua dashed line).
Resonant parameters

| Parameters       | SolutionI       | SolutionII      | SolutionIII      | SolutionIV      |
|------------------|-----------------|-----------------|------------------|-----------------|
| $c \times 10^{-4}$ | 5.5±0.6         |                 |                  |                 |
| $M_1$ (MeV/$c^2$) | 4224.8±5.6      |                 |                  |                 |
| $\Gamma_1$ (MeV) | 72.3±9.1        |                 |                  |                 |
| $M_2$ (MeV/$c^2$) | 4400.1±9.3      |                 |                  |                 |
| $\Gamma_2$ (MeV) | 181.7±16.9      |                 |                  |                 |
| $\Gamma_1^{el}$ (eV) | 62.9±11.5     | 7.2±1.8         | 81.6±15.9        | 9.3±2.7         |
| $\Gamma_2^{el}$ (eV) | 88.5±15.8     | 55.3±8.7        | 551.9±85.3       | 344.9±70.6      |
| $\phi_1$         | -2.1±0.1        | 2.8±0.3         | -0.9±0.1         | -2.3±0.2        |
| $\phi_2$         | 1.9±0.3         | 2.3±0.2         | 2.3±0.1          | -1.9±0.1        |

- Statistical significance is greater than 10σ.
- Consistent with those of Y(4220) and Y(4390) in $e^+e^- \rightarrow \pi^+\pi^- h_c$. 

The error are statistical only.

Preliminary
Improvement of $e^+e^- \rightarrow \pi^+\pi^-\psi'$

**Data samples:**
- 16 energy points from $\sqrt{s}=4.008$ to 4.600 GeV.
- The total integrated luminosity ($L_{\text{int}}$) is 5.1 fb$^{-1}$.

**Reconstructed modes:**

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

**Mode II:** $\Psi(3686) \rightarrow$ neutrals+$J/\psi$,
neutrals=$(\pi^0\pi^0, \pi^0, \eta$ and $\gamma\gamma$) $J/\psi \rightarrow l^+l^-$ (l=e/\mu)
• Number of signals are extracted from $\pi^+\pi^-J/\psi$ invariant mass (mode I) and $\pi^+\pi^-$ recoiled mass spectrum (mode II).
• Signals are described with MC simulated shape convolved with a Gaussian function.
The Ys in $e^+e^- \rightarrow \pi^+\pi^-\psi'$

The Y(4220) is necessary (significance = 5.8$\sigma$)

Fix parameters of the Y(4660) to Belle results

| Parameters                        | Solution I          | Solution II         |
|-----------------------------------|---------------------|---------------------|
| $M(Y_{4220})$ (MeV/$c^2$)         | 4209.5 ± 7.4        |                     |
| $\Gamma(Y_{4220})$ (MeV)          | 80.1 ± 24.6         |                     |
| $\mathcal{B}\Gamma^{e^+e^-}(Y_{4220})$ (eV) | 0.8 ± 0.7           | 0.4 ± 0.3           |
| $M(Y_{4390})$ (MeV/$c^2$)         | 4383.8 ± 4.2        |                     |
| $\Gamma(Y_{4390})$ (MeV)          | 84.2 ± 12.5         |                     |
| $\mathcal{B}\Gamma^{e^+e^-}(Y_{4390})$ (eV) | 3.6 ± 1.5           | 2.7 ± 1.0           |
| $\phi_1$ (rad)                    | 3.3 ± 1.0           | 2.8 ± 0.4           |
| $\phi_2$ (rad)                    | 0.8 ± 0.9           | 4.7 ± 0.1           |
Y(4260) → Y(4220): what is it?

Y(4220) appeared in $\omega \chi_{c0}, \pi^+ \pi^- J/\psi, \pi^+ \pi^- \psi', \pi^+ \pi^- h_c, D^0 D^{*-} \pi^+$

Mass~4220 MeV, Width~60 MeV!
Leptonic width of Y(4220)

For an isospin-zero charmoniumlike state, we expect

\[
\mathcal{B}(Y \rightarrow \pi \pi h_c) = \frac{3}{2} \times \mathcal{B}(Y \rightarrow \pi^+ \pi^- h_c), \\
\mathcal{B}(Y \rightarrow \pi \pi J/\psi) = \frac{3}{2} \times \mathcal{B}(Y \rightarrow \pi^+ \pi^- J/\psi), \\
\mathcal{B}(Y \rightarrow \pi \pi \psi(3686)) = \frac{3}{2} \times \mathcal{B}(Y \rightarrow \pi^+ \pi^- \psi(3686)), \\
\mathcal{B}(Y \rightarrow \pi D \bar{D}^*) = 3 \times \mathcal{B}(Y \rightarrow \pi^+ D^0 D^{*-} + c.c.),
\]

\[
\Gamma_{e^+e^-} = \sum_i \mathcal{B}_i \times \Gamma_{e^+e^-} \\
= \mathcal{B}_{\omega_{Xc0}} \times \Gamma_{e^+e^-} + \mathcal{B}_{\pi \pi h_c} \times \Gamma_{e^+e^-} + \mathcal{B}_{\pi \pi J/\psi} \times \Gamma_{e^+e^-} + \mathcal{B}_{D D^{*-} \pi} \times \Gamma_{e^+e^-} + \ldots
\]

Taking Solutions with the smallest \( B \times \Gamma_{e^+e^-} \),

\[
\Gamma_{e^+e^-} > \left( 36.4 \pm 2.0\,(\text{stat}) \pm 4.2\,(\text{sys}) \right) \text{eV}
\]

More modes being measured:

- charmed meson pairs, light hadrons+$\eta_c$

J. Zhang et al., arXiv:1805.03565
What is Y(4220)?

• Hybrid?
  – Mass agrees with LQCD
  – Couples to $e^+e^-$ weaker than conventional charmonium
  – Couples to spin-singlet strongly

• $\bar{D}_1 D$ molecule?
  – S-wave open threshold [BESIII will release $\sigma(e^+e^-\rightarrow \bar{D}_1 D)$ soon]

• $\psi(4S)$ state?
  – Screened potential reduces 4S mass

• $\bar{D}_s^* D_s^*$ molecule?

• $\omega \chi_{c0}$ molecule?

⇒ more data and more theoretical efforts
The $Z_c$ states
**BES III** $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ at $E_{cm} = 4.26$ GeV

**PRL110, 252001 (2013)**

525 pb$^{-1}$ data at 4.260 GeV

1595 events in J/ψ signal region, purity~90%

$M^2(\pi^+ J/\psi) (\text{GeV}/c^2)^2$ vs $M^2(\pi^+ J/\psi) (\text{GeV}/c^2)^2$

$M(\pi^+ J/\psi) (\text{GeV}/c^2)$ vs $M(\pi^+ J/\psi) (\text{GeV}/c^2)$

$M(\pi^- J/\psi) (\text{GeV}/c^2)$ vs $M(\pi^- J/\psi) (\text{GeV}/c^2)$
Spin-parity of $Z_c(3900)$

- Asymmetric line shape
- JP=1+ preferred over 0-, 1-, 2-, 2+ by at least 7$\sigma$.
- Significant $f_0(980)$ contribution
- $\pi\pi$ D-wave fraction increases as $E_{cm}$ increases

May any model calculate the s-dependent Dalitz plot?

[large data samples at 4.18-4.28 every 0.01 GeV, 4.36, and 4.42 GeV]
Spin-parity of $Z_c(3900)$

- $Z_c$ enhanced events show clear JP=1+ preference!
### Improved res. param. of $Z_c(3900)$

\[
BW(s, M, g_1', g_2') = \frac{1}{s - M^2 + i[g_1'\rho_1(s) + g_2'\rho_2(s)]}
\]

| parameter       | value                                      |
|-----------------|--------------------------------------------|
| Mass            | $$(3901.5 \pm 2.7 \pm 38.0) \text{ MeV}$$ |
| $g_1'$          | $$(0.075 \pm 0.006 \pm 0.025) \text{ GeV}^2$$ |
| $g_2'/g_1'$     | $$27.1 \pm 2.0 \pm 1.9$$                 |
| $M_{\text{pole}}$ | $$(3881.2 \pm 4.2 \pm 52.7) \text{ MeV}$$ |
| $\Gamma_{\text{pole}}$ | $$(51.8 \pm 4.6 \pm 36.0) \text{ MeV}$$ |
| $E_{\text{cm}}$ | $\sigma(e^+e^-\rightarrow\pi^+Z_c+c.c.)$  |
| $4.23 \text{ GeV}$ | $$(21.8 \pm 1.0 \pm 4.4) \text{ pb}$$ |
| $4.26 \text{ GeV}$ | $$(11.0 \pm 1.2 \pm 5.4) \text{ pb}$$ |

PRL 119, 072001 (2017)
Dalitz plot of $e^+e^- \rightarrow \pi^+\pi^- h_c(1P)$

- Obvious structure around 4.02 GeV
- Hints of $Z_c(3900)$
- ~1500 events in $h_c$ signal region at 4.230, 4.260 and 4.360 GeV, purity about 65%

PRL111, 242001 (2013)
Observation of $Z_c(4020)^+$

Simultaneous fit to 4.23/4.26/4.36 GeV data, 16 $\eta_c$ decay modes. 8.9σ

$M(Z_c(4020)) = 4022.9\pm0.8\pm2.7$ MeV;

$\Gamma(Z_c(4020)) = 7.9\pm2.7\pm2.6$ MeV

Close to $\bar{D}^*D^*$ threshold

$\sigma(e^+e^-\rightarrow \pi Z_c \rightarrow \pi^+\pi^- h_c)$:

8.7±1.9±2.8±1.4 pb @ 4.230 GeV

7.4±1.7±2.1±1.2 pb @ 4.260 GeV

10.3±2.3±3.1±1.6 pb @ 4.360 GeV

Significance: 8.9σ [$Z_c(4020)$]

No significant $Z_c(3900)$ (2.1σ)
**Z_c in e^+e^- → π^+π^-ψ’ ?**

- A prominent narrow structure is observed in πψ(3686) mass spectrum for data at $\sqrt{s} = 4.416$ GeV.

- An S-wave Breit-Wigner fit function is performed on the Dalitz plot of $M^2(\pi^+\psi(3686))$ versus $M^2(\pi^-\psi(3686))$

$$\frac{p \cdot q/c^2}{(M_R^2 - x)^2 + M_R^2 \cdot \Gamma^2/c^4} + \frac{p \cdot q/c^2}{(M_R^2 - y) + M_R^2 \cdot \Gamma^2/c^4}$$

- The fit yields a mass of $M=4032.1 \pm 2.4$ MeV/c$^2$ and a width of $\Gamma=26.1 \pm 5.3$ MeV, with a significance of 9.2σ

**Stat. err. ONLY!**

**Different behavior between high and low $M^2(\pi^+\pi^-)$!**
Fit of intermediate state

Interference not considered & fits cannot describe data well!

PRD 96, 032004 (2017)
Search for $Z_c \rightarrow \rho \eta_c$

- Search for new decay mode of $Z_c(3900)$ and $Z_c(4020)$
- The ratios of $Z_c^{(r)} \rightarrow \rho \eta_c$ to $Z_c^{(r)} \rightarrow \pi J/\psi(\pi h_c)$ may discriminate the tetra-quark and molecule models.

$$R_z = \frac{B(Z_c \rightarrow \rho \eta_c)}{B(Z_c \rightarrow \pi J/\psi)}$$

$$R_{z'} = \frac{B(Z_c' \rightarrow \rho \eta_c)}{B(Z_c' \rightarrow \pi h_c)}$$

A. Esposito, A. L. Guerrieri, A. Pilloni, Phys. Lett. B 746, 194 (2015)

Type II tetraquark model:

- neglect the spin-spin interaction outside the diquarks
Evidence for $Z_c \rightarrow \rho \eta_c$

- $e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta_c$
- $\eta_c \rightarrow 9$ hadronic decays

| Decay mode     | BR    |
|----------------|-------|
| $\eta_c \rightarrow p\bar{p}$ | $\sim 0.13\%$ |
| $\eta_c \rightarrow 2(K^+K^-)$ | $\sim 0.15\%$ |
| $\eta_c \rightarrow \pi^+\pi^-K^+K^-$ | $\sim 1.50\%$ |
| $\eta_c \rightarrow \pi^+\pi^-\pi^0\eta$ | $\sim 1.60\%$ |
| $\eta_c \rightarrow K^+K^-\pi^0$ | $\sim 1.20\%$ |
| $\eta_c \rightarrow K^+K^-\pi^0$ | $\sim 1.20\%$ |
| $\eta_c \rightarrow K^0S\eta$ | $\sim 1.80\%$ |
| $\eta_c \rightarrow K^0S\pi\pi$ | $\sim 0.57\%$ |
| $\eta_c \rightarrow \pi^+\pi^-\pi^0\pi^0$ | $\sim 2.40\%$ |

- Strong evidence of $e^+e^- \rightarrow \pi Z_c$, $Z_c \rightarrow \rho \eta_c$ at $\sqrt{s} = 4.23$, statistical significance is $4.3\sigma$ (3.9$\sigma$ including systematics)
- $e^+e^- \rightarrow \pi Z'_c$, $Z'_c \rightarrow \rho \eta_c$ not seen.

$e^+e^- \rightarrow \pi Z_c, Z_c \rightarrow \rho \eta_c$ @ 4.23 GeV
Evidence for $Z_c \to \rho \eta_c$

- Measure Born cross section at 4.23 GeV:

\[ \sigma^B(e^+e^- \to \pi^+\pi^-\pi^0\eta_c) = (46 \pm 12 \pm 10) \text{ pb} \]

\[ \sigma^B(e^+e^- \to \pi Z_c, Z_c \to \rho \eta_c) = (47 \pm 11 \pm 11) \text{ pb} \]

| $\sqrt{s} = 4.23 \text{ GeV}$ | $\sqrt{s} = 4.26 \text{ GeV}$ | $\sqrt{s} = 4.36 \text{ GeV}$ | Tetra-quarks-I | Tetra-quarks-II | Molecule |
|--------------------------------|--------------------------------|--------------------------------|----------------|----------------|----------|
| $R_{Z_c}(3900)$                | 2.1 ± 0.8                      | < 6.4                         | ...            | $230^{+330}_{-140}$ | $0.27^{+0.40}_{-0.17}$ | $0.046^{+0.025}_{-0.017}$ |
| $R_{Z_c}(4020)$                | < 1.9                          | < 1.2                         | < 1.0          | $6.6^{+56.8}_{-5.8}$ | $0.010^{+0.006}_{-0.004}$ |

\[ R_z = \frac{B(Z_c \to \rho \eta_c)}{B(Z_c \to \pi J/\psi)} \]

\[ R_{Z'} = \frac{B(Z'_c \to \rho \eta_c)}{B(Z'_c \to \pi h_c)} \]

A. Esposito, A.L. Guerrieri, A. Pilloni, Phys. Lett. B 746, 194 (2015)
### Summary of the $Z_c$ states at BESIII

| Decay Modes | $Z_c$(3900) | $Z_c$(4020) |
|-------------|-------------|-------------|
| $I^G(J^{PC})$ | $1^+(1^{+-})$ | $1^+(??^-)$ |
| $\pi J/\psi$ | Discovery mode | No |
| $\pi h_c$ | $2.1\sigma$ | Discovery mode |
| $\bar{D}^*D$ | Yes | No |
| $\bar{D}^*D^*$ | No | Yes |
| $\pi \psi'$ | No | Yes? |
| $\rho h_c$ | $4.3\sigma$ | No |
Summary

• Lots of progress in the study of charmoniumlike states at BESIII
• Measurements of many hidden charm final states, \( Y(4260) \rightarrow Y(4220) \) with more decay modes now
• \( J^P=1^+ \) for \( Z_c(3900) \), evidence for \( Z_c(3900) \rightarrow \rho \eta_c \) a new \( Z_c \) structure in \( \pi \psi' \)?
• BESIII will take more data and continue the study.

Thanks a lot!
Thanks a lot!

谢谢！
Belle II vs. BESIII

ISR produces events at all CM energies BESIII can reach

At 4.26 GeV for $\pi^+\pi^- J/\psi$

$\varepsilon_{\text{BESIII}} = 46\%$

$\varepsilon_{\text{Belle}} = 10\%$