Charmonium-like (exotic) XYZ states at BESIII

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Outline

• Introduction
  ➢ Motivation

• Studies of XYZ states
  ➢ Latest, selected results
  ➢ Further plans

• Summary
Hadron spectroscopy – a highlight

Meson Spectroscopy

BESIII, arXiv:1303.5949

\[Z_c(3900)\]

American Physical Society:

Viewpoint: New Particle Hints at Four-Quark Matter → Highlight 2013!

[http://physics.aps.org/articles/v6/139]
Mesons and (Spin) Exotic States

Quark model
• Mesons: Color neutral q\bar{q} systems

QCD: Meson states beyond q\bar{q}
• Nowadays definition: Meson = Hadron with B = 0
• In contrast to simple q\bar{q} allows for huge variety of states:

- Hybrid (q\bar{q})_{8g}
- Tetraquark (q\bar{q}q\bar{q})_{1}
- Glue-ball (gg)_{1} or (ggg)_{1}

Further 4-quark-configurations:
- Molecule (q\bar{q})_{1}(q\bar{q})_{1}
- Hadro-quarkonium (Q\bar{Q})_{1}(q\bar{q})_{1}
- Di-quarkonium (qq)_{3}(q\bar{q})_{3}

[e.g. Braaten, PRD 90 (2014) 014044]
BESIII at BEPCII

- Symmetric $e^+e^-$ collider:
  - $\sqrt{s} = 2.0 - 4.6$ GeV
- Design luminosity:
  - $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$ (at $\psi(3770)$, achieved in 04/2016)

- Multi-purpose $4\pi$ detector with
  - good tracking
  - calorimetry
  - PID and muon detection
- Operating since March 2008
Unique BESIII data set
(collected so far ...)

- XYZ region: 3.8 ~ 4.6 GeV, integrated luminosity: ~ 5 fb⁻¹
- 104 energy points between 3.85 and 4.59 GeV (*R scan*)
- ~20 energy points between 2.0 and 3.1 GeV
The puzzle of XYZ states

- Below open charm threshold:
  - Good agreement theory vs. experiment

- Above open charm threshold:
  - Many predicted states not discovered
  - Many unexpected states observed

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**BESIII**: Study conventional as well as charmonium-like (exotic) XYZ states

- Direct access to Y states (1−) in direct formation (e+e− annihilation)
- Study X states in radiative decays
- Study (charged & neutral) Z states
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Some history

- Discovery of the Y(4260) by BarBar
- Discovery of the Y(4360) in ψ(2S)π−π+
The Y states, $e^+e^-$ production of $J/\psi\pi\pi$, $\psi(2S)\pi\pi$ and $h_c\pi\pi$

Some newer history

- An asymmetric shape?

- A low mass peak, "Y(4008)"?
The Y states, $e^+e^-$ production of $J/\psi\pi\pi$, $\psi(2S)\pi\pi$ and $h_c\pi\pi$

NEW: BESIII result, meanwhile published

- Cross-section in-consistent with a single peak for the $Y(4260)$!
  - two peaks favoured over one by $>7\sigma$

- The "$Y(4008)$" not needed to describe data
  - Fit I (wide low mass BW) identical to Fit II (interfering non-resonant exp. shape)
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NEW: BESIII preliminary result vs. Belle

- Clear indication of the $Y(4360)$ and $Y(4660)$ in $\psi(2S)\pi^-\pi^+$
- Significance of $Y(4260) < 3\sigma$

- BESIII confirms $Y(4360)$ lineshape
- More data for thorough study of mass region 4.2 - 4.3GeV (current data taking)
NEW: BESIII preliminary result vs. Belle

- The $h_c\pi^\mp\pi^\pm$ differs in shape from $J/\psi\pi\pi^\mp\pi^\pm$
- Based on more data, the $h_c\pi^-\pi^+$ shape appears to be consistent with two peaks

NEW: BESIII preliminary result vs. Belle

- The $h_c \pi^- \pi^+$ differs in shape from $J/\psi \pi^- \pi^+$
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More work is needed to sort out these exclusive cross-sections ...

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First observation of $e^+e^- \rightarrow \gamma X(3872)$

- $X(3872)$ is the first-discovered and best-studied of the XYZ states
- BESIII: First observation of $e^+e^- \rightarrow \gamma X(3872) \rightarrow \gamma \pi^+\pi^- J/\psi$
  - Analysed at $\sqrt{s} = 4009, 4229, 4260, 4360$ MeV


- $m = (3871.9 \pm 0.7 \pm 0.2)$ MeV/c$^2$
- $\Gamma < 2.4$ MeV (90% CL)

- Cross-section shape hints to production via a Y state – more data needed!
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Cross-section

Radiative transitions provide another route to access XYZ ...

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Upper limit on $e^+e^- \rightarrow \gamma J/\psi \phi$

- First evidence for $X(4140) \rightarrow J/\psi \phi$ (3.6$\sigma$) by CDF (or "$Y(4140)$")
  

- Recently confirmed by LHCb in B decays:
  - $B \rightarrow K(J/\psi \phi)$ ($J^{PC} = 1^{++}$)
  
  [PRD 95 (2017) 012002]

BESIII:

- Upper limit on $\sigma \times BR$:
  - $e^+e^- \rightarrow \gamma Y(4140)$, with $Y(4140) \rightarrow K(J/\psi \phi)$
  - UL = ~0.3 pb CL(90)
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The charged $Z_c(3900)$

- **Discovery of $Z_c(3900)^\pm \rightarrow J/\psi \pi^\pm$**
  - $e^+e^- \rightarrow J/\psi \pi^+\pi^-$
  - at $\sqrt{s} = 4.26$ GeV (525 pb$^{-1}$, >8$\sigma$)

- **Mass close to D$\bar{D}$* threshold**
  - \[ m = (3899.0 \pm 3.6 \pm 4.9) \text{ MeV}/c^2 \]
  - \[ \Gamma = (46 \pm 10 \pm 20) \text{ MeV} \]

- **Manifestly exotic:**
  - decays to $J/\psi$ => contains $c\bar{c}$
  - electrical charged => contains $u\bar{d}$
  - => First 4-quark state observation (?!)

- **Confirmed by Belle and CLEO-c**

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[Ref: PRL 110 (2013) 252001]
The neutral partner of the $Z_c(3900)$

- Observation of $Z_c(3900)^0 \rightarrow J/\psi \pi^0$
  - in $e^+e^- \rightarrow J/\psi \pi^0\pi^0$ GeV (2.8 fb$^{-1}$, 10.4$\sigma$)
  - confirms earlier evidence in CLEO-c data

- Parameters consistent with those of $Z_c(3900)^\pm$
  - $m = 3894.8 \pm 2.3 \pm 2.7$ MeV/$c^2$
  - $\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV

$\Rightarrow$ Establishes an isospin triplet $Z_c(3900)$

- Confirmed by Belle and consistent with CLEO-c data

[PRL 115 (2015) 112003]
Two $Z_c$ triplets established

- $e^+e^- \rightarrow \pi^-\pi^0J/\psi$
- $e^+e^- \rightarrow \pi^-\pi^+J/\psi$
- $e^+e^- \rightarrow \pi^-\pi^+h_c$
- $e^+e^- \rightarrow \pi^-\pi^0h_c$

- $e^+e^- \rightarrow \pi^- (D\bar{D}^*)^+$
- $e^+e^- \rightarrow \pi^- (D^*\bar{D}^*)^+$

$Z_c(3900)^{\pm,0}$?
$Z_c(4020)^{\pm,0}$?

- Nature of these states?
  - two isospin triplets of charmonium-like exotic states established
- Different decay modes (*hidden vs. open charm*) of same state observed?
  - further decay channels?
Summary & outlook

• BESIII successfully operating since 2008
  ➢ World largest data sets in tau-charm mass region
  ➢ Unique data for XYZ studies

• BESIII ideally suited to explore transitions and decays of Y states
  ➢ Investigate the XYZ-spectrum
  ➢ First two isospin triplet states Zc (3900), Zc (4020) established
  ➢ Precise measurement of the cross-section in the Y energy range

Outlook:

• More XYZ (energy scan) data just taken while talking (4.2-4.3 GeV)
• Detailed, further data taking proposal under preparation ....
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Stay tuned for more BESIII results, helping to solve the XYZ puzzle ... !
The BESIII Collaboration

11 countries
58 institutions
~ 450 members