Light hadron spectroscopy at BESIII

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( On behalf of BESIII Collaboration )

PANIC 2017
Outline

BEPCII and BESIII

Selected topics on Light Hadron spectroscopy

- Light Meson spectroscopy
  - $X(1835)$ and $X(p\bar{p})$
  - $J/\psi \rightarrow \gamma \eta K_S^0 K_S^0$
  - $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

- Glueball Searches
  - PWA of $J/\psi \rightarrow \gamma \eta \eta$
  - MIPWA of $J/\psi \rightarrow \gamma \pi^0 \pi^0$
  - PWA of $J/\psi \rightarrow \gamma \phi \phi$

- Exotic Search
  - $\chi_{c1} \rightarrow \eta \pi^+ \pi^-$

Summary
Beijing Electron Positron Collider II (BEPC II)

1989-2004 (BEPC I):
- $L_{\text{peak}} = 1.0 \times 10^{31} \text{ /cm}^2\text{s}$
- Beam energy: 1.0 – 2.3 GeV

2004:
- Started BEPCII upgrade, BESIII construction

2008:
- Test run

2009 - now:
- BESIII physics run

2015:
- $L_{\text{peak}} = 1 \times 10^{33} /\text{cm}^2\text{s}$
Detector

Main Drift Chamber (MDC)
$\sigma_p/P = 0.5\%$ (1 GeV)
$\sigma_{dE/dx} = 6\%$

Time of Flight (TOF)
$\sigma_T$: 90 ps (barrel)
60 ps (endcap)

Electromagnetic Calorimeter (EMC)
CsI (TI)
$\sigma_E/\sqrt{E} = 2.5\%$ (1 GeV)
$\sigma_{z,\phi} = 0.5 - 0.7$ cm/$\sqrt{E}$

$\mu$ Counter (MUC)
8 - 9 layers RPC
$\delta_{R\phi} = 1.4$ cm $\sim$ 1.7 cm

Data Collected at BESIII

World largest $J/\psi$, $\psi(3686)$, $\psi(3770)$, ... produced directly from $e^+e^-$ collision — ideal factory to study hadron spectroscopy
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- $X(1835)$ and $X(p\bar{p})$
- $J/\psi \rightarrow \gamma \eta K_S^0 K_S^0$
- $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

Glueball Searches

- PWA of $J/\psi \rightarrow \gamma \eta \eta$
- MIPWA of $J/\psi \rightarrow \gamma \pi^0 \pi^0$
- PWA of $J/\psi \rightarrow \gamma \phi \phi$

Exotic Search

- $\chi_c \rightarrow \eta \pi^+ \pi^-$

Summary
\(X(p\bar{p})\)

- Discovered by BESII in \(J/\psi \rightarrow \gamma pp\)
- Confirmed by BESIII and CLEO-c in \(\psi(3686) \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow \gamma pp\)
- Confirmed by BESIII in \(J/\psi \rightarrow \gamma pp\) and its \(J^{pc}\) determined by PWA
  - \(J^{pc} = 0^{-+}\)
  - \(M = 1832^{+19}_{-5} +18 \pm 19\ MeV/c^2\)
  - \(\Gamma = 13 \pm 39^{+10}_{-13} \pm 4\ MeV/c^2\)
  - \(B(J/\psi \rightarrow \gamma X) \cdot B(X \rightarrow pp) = 9.0^{+0.4}_{-1.1} +1.5 \pm 2.3 \times 10^{-5}\)

**X(1835)**

- Discovered by BESII in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$
- Confirmed by BESIII in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$ with two $\eta'$ decays
  - $M = 1836.5^{+19}_{-5} \pm 3.0^{+5.6}_{-2.1}$ MeV/c$^2$
  - $\Gamma = 190 \pm 9^{+38}_{-36}$ MeV/c$^2$
  - Angular distribution is consistent with $0^-$
  - Observed two additional structures $> 2$ GeV/c$^2$

| Resonance | $M$(MeV/c$^2$) | $\Gamma$(MeV/c$^2$) | $N_{\text{event}}$
|-----------|----------------|----------------|----------------|
| $f_1(1510)$ | $1522.7 \pm 5.0$ | $48 \pm 11$ | $230 \pm 37$
| X(1835) | $1836.5 \pm 3.0$ | $190.1 \pm 9.0$ | $4265 \pm 131$
| X(2120) | $2122.4 \pm 6.7$ | $83 \pm 16$ | $647 \pm 103$
| X(2370) | $2376.3 \pm 8.7$ | $83 \pm 17$ | $565 \pm 105$

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**Phys. Rev. Lett. 95, 262001 (2005)**


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Observation of $X(1835)$ in $J/\psi \rightarrow \gamma \eta K_S^0 K_S^0$

- $1.3 \times 10^9 J/\psi$ events collected in 2009 and 2012
- Clear structure on mass spectrum of $K_S^0 K_S^0 \eta$ around 1.85 GeV/$c^2$
- Strongly correlated to $f_0(980)$
- PWA for events:
  - $M(K_S^0 K_S^0) < 1.1$ GeV/$c^2$
  - $M(K_S^0 K_S^0 \eta) < 2.8$ GeV/$c^2$
Observation of $X(1835)$ in $J/\psi \rightarrow \gamma \eta K_S^0 K_S^0$

$X(1835)$
- $J^{pc}$ determined to be $0^{-+}$
- $X(1835) \rightarrow \eta K_S^0 K_S^0$ ($> 12.9 \sigma$), dominated by $f_0(980)$ production
  - $M = 1844 \pm 9^{+16}_{-25} \text{ MeV}/c^2$
  - $\Gamma = 192^{+20+62}_{-17-43} \text{ MeV}/c^2$
  - $B(J/\psi \rightarrow \gamma X(1835)) \cdot B(X(1835) \rightarrow \eta K_S^0 K_S^0) = (3.31^{+0.33+1.96}_{-0.30-1.29}) \times 10^{-5}$
- Consistent with $X(1835)$ parameters obtained from $J/\psi \rightarrow \gamma \eta \pi^+ \pi^-$

$X(1560)$
- $J^{pc} = 0^{-+}$; $X(1560) \rightarrow \eta K_S^0 K_S^0$ ($> 8.9 \sigma$)
  - $M = 1565 \pm 8^{+6}_{-63} \text{ MeV}/c^2$
  - $\Gamma = 45^{+14+21}_{-13-28} \text{ MeV}/c^2$
- Consistent with $\eta(1405)/\eta(1475)$ within 2.0 $\sigma$

X(1835) and X(p\bar{p})

- Any relations?
- What is the role of the p\bar{p} threshold (and other thresholds)?
- Patterns in the production and decay modes


Anomalous line shape of $\eta' \pi^+ \pi^-$ near the $p\bar{p}$ mass threshold in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

- Use $1.09 \times 10^9 J/\psi$ events collected by BESIII in 2012
- Two decay modes of $\eta'$
  - $\eta' \rightarrow \gamma \pi^+ \pi^-$
  - $\eta' \rightarrow \eta \pi^+ \pi^-$, $\eta \rightarrow \gamma \gamma$
- Clear peaks of $X(1835)$, $X(2120)$, $X(2370)$, $\eta_c$ and a structure near 2.6 GeV/$c^2$
- A significant distortion of the $\eta' \pi^+ \pi^-$ line shape near the $p\bar{p}$ mass threshold
Anomalous line shape of $\eta' \pi^+ \pi^-$ near the $p\bar{p}$ mass threshold in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

- **Model 1:** Flatté lineshape with strong coupling to $p\bar{p}$ and one additional, narrow Breit-Wigner at $\sim 1920 \text{ MeV}/c^2$

- **Model 2:** coherent sum of $X(1835)$ Breit-Wigner and one additional narrow Breit-Wigner at $\sim 1870 \text{ MeV}/c^2$

A simple Breit-Wigner function to describe the $X(1835)$ lineshape fails near the $p\bar{p}$ mass threshold.

*Phys. Rev. Lett. 117, 042002 (2016)*
Anomalous line shape of $\eta'\pi^+\pi^-$ near the $p\bar{p}$ mass threshold in $J/\psi \rightarrow \gamma\eta'\pi^+\pi^-$

Both models fit the data well with almost equally good quality

- Cannot distinguish them with current data
- Suggest the existence of a state, either a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold
- Support the existence of a $p\bar{p}$ molecule-like state or bound state

To understand the nature of the state(s)

- Take more data
- Study line shapes in other related decay channels
Outline

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Selected topics on Light Hadron spectroscopy

Light Meson spectroscopy

- X(1835) and X(p̅p)
- J/ψ → γηK_S^0 K_S^0
- J/ψ → γη'π^+π^−

Glueball Searches

- PWA of J/ψ → γηη
- MIPWA of J/ψ → γπ^0π^0
- PWA of J/ψ → γϕϕ

Exotic Search

- χc1 → ηπ^+π^−

Summary
Glueballs

- Formed by gluon-gluon interaction
  - Predicted by QCD
  - Lattice QCD prediction
    - $0^{++}$ ground state: 1~2 GeV/c$^2$
    - $2^{++}$ ground state: 2.3~2.4 GeV/c$^2$
    - $0^{-+}$ ground state: 2.3~2.6 GeV/c$^2$

- Experimentally, some candidates, but not established
  - $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, $f_1(2220)$, ...

- $J/\psi$ radiative decays are believed to be an ideal place to search for glueballs

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**PWA of $J/\psi \rightarrow \gamma\eta\eta$**

- Use $225 \times 10^6$ $J/\psi$ events collected by BESIII in 2009
- $f_0(1700)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2σ)
- $f_2^1(1525)$ is the dominant tensor
- $f_2(1810)$ and $f_2(2340)$ exist (6.4σ and 7.6σ)
- No evidence for $f_1(2220)$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV/$c^2$)</th>
<th>Width (MeV/$c^2$)</th>
<th>$B(J/\psi \rightarrow \gamma X \rightarrow \gamma\eta\eta)$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(1500)$</td>
<td>$1468^{+12+14}_{-15-12}$</td>
<td>$136^{+41+28}_{-26-100}$</td>
<td>$(1.65^{+0.25+0.31}_{-0.31-1.40}) \times 10^{-5}$</td>
<td>8.2σ</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>$1759 \pm 6^{+14}_{-25}$</td>
<td>$172 \pm 10^{+32}_{-16}$</td>
<td>$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$</td>
<td>25.0σ</td>
</tr>
<tr>
<td>$f_0(2100)$</td>
<td>$2081 \pm 13^{+3+24}_{-36}$</td>
<td>$273^{+27+30}_{-24-23}$</td>
<td>$(1.13^{+0.09+0.64}_{-0.10-0.06}) \times 10^{-4}$</td>
<td>13.9σ</td>
</tr>
<tr>
<td>$f_2^1(1525)$</td>
<td>$1513 \pm 5^{+5}_{-10}$</td>
<td>$75^{+12+16}_{-10-18}$</td>
<td>$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$</td>
<td>11.0σ</td>
</tr>
<tr>
<td>$f_2(1810)$</td>
<td>$1822^{+29+66}_{-24-57}$</td>
<td>$229^{+52+88}_{-42-155}$</td>
<td>$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$</td>
<td>6.4σ</td>
</tr>
<tr>
<td>$f_2(2340)$</td>
<td>$2362^{+31+140}_{-30-63}$</td>
<td>$334^{+62+165}_{-54-100}$</td>
<td>$(5.60^{+0.82+2.37}_{-0.65-2.07}) \times 10^{-5}$</td>
<td>7.6σ</td>
</tr>
</tbody>
</table>

- Br. of $f_0(1700)$ and $f_0(2100)$ are $\sim 10 \times$ larger than than of $f_0(1500)$
- Possible large overlap with LQCD predictions of $0^+$ Glueball (PRL 110 021601)
Model Independent PWA of $J/\psi \rightarrow \gamma \pi^0\pi^0$

- Use $1.3 \times 10^9 J/\psi$ events collected by BESIII in 2009 and 2012
- $\pi^0\pi^0$ system
  - Only significant $0^{++}$ and $2^{++}$ contributions
  - Larger statistics and more open channels than $\eta\eta$ system
  - Many broad and overlapping resonances (parameterization challenging)
- Model independent PWA

- More than 440,000 reconstructed events
- Background level $\sim 1.8\%$

Model Independent PWA of $J/\psi \rightarrow \gamma \pi^0 \pi^0$

- Extract amplitudes in each $M(\pi^0 \pi^0)$ mass bin
- Significant features of the scalar spectrum includes structures near 1.5, 1.7 and 2.0 GeV/c$^2$
- $2^{++}$ dominated by $f_2(1270)$
- Multi-solution problem in MIPWA is usually unavoidable.
- Model Dependent PWA of global PWA fit is still needed to extract resonance parameters.

Extracted Intensity

Relative Phase


- Nominal Solution
- Ambiguous Solution
**PWA of $J/\psi \rightarrow \gamma \phi \phi$**

- Besides $\eta(2225)$, little known on the pseduoscalar above 2 GeV
- New results help to map out the pseudoscalar excitations and search for $0^{-+}$ glueball
- Use $1.3 \times 10^9 J/\psi$ events collected by BESIII in 2009 and 2012
- PWA procedure
  - Covariant tensor formalism
  - Data-driven background subtraction
  - Resonances are parameterized by relativistic Breit-Wigner with constant width
  - Resonances with significance $> 5\sigma$ are selected as components in solution

*Phys. Rev. D 93, 112011 (2016)*
PWA of $J/\psi \rightarrow \gamma \phi \phi$

- Dominant contribution from pseudoscalars
  - $\eta(2225)$ is confirmed
  - $\eta(2100)$ and $X(2500)$ are observed with large sig.

- Three tensor states
  - $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ are observed
  - Strong production of $f_2(2340)$ is compatible with LQCD prediction for tensor glueball

- Well consistent with the results from Model Independent PWA
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  ■ Glueball Searches
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    ■ PWA of J/ψ → γϕϕ
■ Exotic Search
  ■ \( \chi_{c1} \rightarrow ηπ^+ π^- \)
■ Summary
Exotics ($J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{+-}, ...$)

- $J^{PC}$ exotic particles: beyond the naïve quark model
- Easily to distinguish from others due to the exotic $J^{PC}$
- Theoretically, LQCD predicts the lightest hybrid with exotic $1^{-+}$ is between 1.8 and 1.9 GeV, the Bag model also predicts an exotic $1^{-+}$ around or above 1.4 GeV
- Experimentally, $\pi_1(1400), \pi_1(1600)$ were observed in $\pi p$ reaction decay to $\eta / \eta' / \rho + \pi$
Amplitude Analysis of $\chi_{c1} \rightarrow \eta\pi^+\pi^-$

- $\chi_{c1}$ provides another suitable place to look for $1^{-+}$
  - $\pi_1(1600)$ studied in $\chi_{c1}$ decays by CLEO-c
  - Only $\pi_1(1400)$ reported decaying to $\eta\pi$

- World largest $\chi_{c1}$ sample (~ 35K) from $448.0 \times 10^6 \psi(3686)$ events
  - $\psi(3686) \rightarrow \gamma \chi_{c1} \rightarrow \gamma \eta\pi^+\pi^-$
  - Search for exotic meson with $1^{-+}$ in $\eta\pi, \eta'\pi$ and $\pi\pi$ final states

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Amplitude Analysis of $\chi_{c1} \rightarrow \eta \pi^+ \pi^-$

- Most dominant two-body structure is from $a_0(980)\pi$
- Observation of nonzero $a_0(980)$ coupling to the $\eta'\pi$
- Observed $\chi_{c1} \rightarrow a_2(1700)\pi$ for the first time ($>17\sigma$)
- Measured upper limits for $\pi_1(1^{-+})$ in 1.4-2.0 GeV/c$^2$ region
Summary

- Highlights of latest results in light hadron spectroscopy from BESIII
  - Observation of $X(1835)$ in $J/\psi \to \gamma \eta K^0_S K^0_S$
    - New decay mode of $X(1835) \to \eta K^0_S K^0_S$ and $J^{pc}$ determined to be $0^{-+}$
  - Observation of anomalous $\eta' \pi^+ \pi^-$ line shape near $p\bar{p}$ mass threshold
    - Support the existence of $p\bar{p}$ bound state or molecule-like state
  - Partial wave analysis of $J/\psi \to \gamma \eta\eta$
    - Strong production of $f_0(1700)$ and $f_0(2100)$
  - Model independent PWA of $J/\psi \to \gamma \pi^0\pi^0$
    - Useful information for $0^{++}$ and $2^{++}$ components
  - Partial wave analysis of $J/\psi \to \gamma \phi\phi$
    - Many $0^{-+}$, $2^{++}$ mesons observed
  - Amplitude Analysis of $\chi_{c1} \to \eta \pi^+\pi^-$
    - Clear evidence for $a_2(1700)$ in $\chi_{c1}$ decays and upper limit for $\pi_1$

- More results come soon with BESIII continuing data taking
Thanks for your attention!