Light quark spectroscopy at BESIII

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(on behalf of BESIII Collaboration)

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OUTLINE

- BESIII/BEPCII and BESIII physics
- Selected topics on light quark spectroscopy
  - $X(1835)$ and mass enhancement
  - Model independent PWA of $J/\psi \rightarrow \gamma \pi^0\pi^0$
  - PWA of $J/\psi \rightarrow \gamma \phi\phi$
  - Amplitude analysis of $\chi_{c1} \rightarrow \eta \pi^+\pi^-$
- Conclusion and outlook
Symmetric electron-positron collider BEPC II

- Energy range: $\sqrt{s} = 2.0$-4.6 GeV
- Design luminosity: $1\times10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (at $\psi(3770)$)
- Energy spread: $\sim5\times10^{-4}$
- Operating since March 2008
- Achieved luminosity: $1\times10^{33} \text{ cm}^{-2}\text{s}^{-1}$
BESIII Detector

RPC Muon Detector
8 layers (end caps), 9 layers (barrel)
\( \Delta R_\phi = 1.4 - 1.7 \text{ mm} \)

Electromagnetic
CsI(Tl) Calorimeter
\( \sigma_E / E < 2.5\% / \sqrt{E} \)
\( \sigma_{z,\phi} = 0.5 - 0.7 \text{ cm} / \sqrt{E} \)

Time of Flight System
\( \sigma_t = 80 \text{ ps} \) (barrel)
\( \sigma_t = 110 \text{ ps} \) (end caps)

Drift Chamber
\( \sigma_{(dE/dx)} = 6\% \)
\( \sigma_{p_t}/p_t = 0.5\% \)

The new BESIII detector is hermetic for neutral and charged particle with excellent resolution, PID, and large coverage.
BESIII Physics

- Light Hadrons
  - Meson and baryon spectroscopy
  - Search for exotic hadrons, e.g. glueballs, hybrids, tetraquarks
  - Light meson decays ($\eta^($, $\omega$)

- Charmonium Physics
  - X, Y, and Z states
  - Decays and transitions

- Open Charm Physics
  - D meson decays
  - D$\bar{D}$ mixing
  - CP violation in the charm sector

- And many further topics
  - e.g. tau and two-photon physics
Data samples

\[ R = \frac{\sigma(\text{hadrons})}{\sigma(\ell^+\ell^-)} \]

- 1.3 \times 10^9 J/\psi events
- 5 \times 10^8 \psi(2S) events
- 2.9 fb^{-1}
- 0.5 fb^{-1}
- 1 fb^{-1}
- \psi_{4040}
- \psi_{4415}
- 2.3 fb^{-1}
- 0.5 fb^{-1}
- @4600
- @4360
- 0.5 fb^{-1}

Scan: 2-3 GeV, 19 points, ~0.5 fb^{-1}; 3.85-4.59 GeV, 104 points, ~0.8 fb^{-1}

plus 24 pb at \tau mass threshold and 0.5/fb in the region 4100-4400 MeV
Enhancement of $p\bar{p}$ threshold

- Enhancement at $p\bar{p}$ threshold observed in $J/\psi \to \gamma p\bar{p}$ by BESII (2003) and confirmed by CLEOc (2010)
- Enhancement not observed in related channel: $Y(1S) \to \gamma p\bar{p}$
- Nature yet unclear
  - baryonium, multiquark state, FSI effect?
Radiative $J/\psi$ and $\psi'$ decays into $p\bar{p}$

- Partial Wave Analysis of $J/\psi \rightarrow \gamma p\bar{p}$ and $\psi' \rightarrow \gamma p\bar{p}$ in the mass region $m_{p\bar{p}} < 2.2$ GeV/c$^2$

$J/\psi \rightarrow \gamma p\bar{p}$: Significant contributions of $X(p\bar{p})$, $f_2(1920)$, $f_0(2100)$, and non-resonant $0^{++}$ $p\bar{p}$ wave

$\rightarrow$ Structure at threshold $X(p\bar{p})$: $J^{PC} = 0^{-+}$ Breit-Wigner parameterization:

$$M = 1832^{+19}_{-5}(\text{stat})^{+18}_{-17}(\text{syst}) \pm 19(\text{model}) \text{ MeV/c}^2$$

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

$$\text{BR}_{[J/\psi \rightarrow \gamma X] \times \text{BR}[X \rightarrow p\bar{p}]} = (9.0^{+0.4}_{-1.1}(\text{stat})^{+1.5}_{-0.5}(\text{syst}) \pm 2.3(\text{model})) \times 10^{-5}$$

- $\psi' \rightarrow \gamma p\bar{p}$: $X(p\bar{p})$ production is suppressed by a factor of $\sim 20$ over production in $J/\psi \rightarrow \gamma p\bar{p}$
Hadronic $J/\psi$ decays into $\omega\, p \, \bar{p}$ and $\phi\, p \, \bar{p}$

Study of $J/\psi \rightarrow \omega X(p\bar{p})$ and $J/\psi \rightarrow \Phi X(p\bar{p})$ may shed further light on the nature of $X(p\bar{p})$

- $J/\psi \rightarrow \omega\, p \, \bar{p}$
  
  $B(J/\psi \rightarrow \omega X(p\bar{p}) \rightarrow \omega p\bar{p}) < 3.7 \times 10^{-6}$ (95% CL)
  
  $>10x$ suppressed compared to $J/\psi \rightarrow \gamma X(p\bar{p}) \rightarrow \gamma p\bar{p}$

- $J/\psi \rightarrow \phi\, p \, \bar{p}$
  
  $B(J/\psi \rightarrow \Phi X(p\bar{p}) \rightarrow \Phi p\bar{p}) < 2 \times 10^{-7}$ (90% CL)
  
  $>100x$ suppressed compared to $J/\psi \rightarrow \gamma X(p\bar{p}) \rightarrow \gamma p\bar{p}$
X(1835) in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

- X(1835) previously observed at BES and BESII
- Nature unclear, interpretations include glueball, $\bar{p}p$ bound state, excited $\eta$ meson
- Confirmed at BESIII with two additional structures above 2 GeV/c$^2$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$M$(MeV/c$^2$)</th>
<th>$\Gamma$(MeV/c$^2$)</th>
<th>$&gt;\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$(1510)</td>
<td>$1522.7 \pm 5.0$</td>
<td>$48 \pm 11$</td>
<td>$&gt;5.7\sigma$</td>
</tr>
<tr>
<td>X(1835)</td>
<td>$1836.5 \pm 3.0$</td>
<td>$190.1 \pm 9.0$</td>
<td>$&gt;20\sigma$</td>
</tr>
<tr>
<td>X(2120)</td>
<td>$2122.4 \pm 6.7$</td>
<td>$83 \pm 16$</td>
<td>$&gt;7.2\sigma$</td>
</tr>
<tr>
<td>X(2370)</td>
<td>$2376.3 \pm 8.7$</td>
<td>$83 \pm 17$</td>
<td>$&gt;6.4\sigma$</td>
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</table>

X(1835) angular distribution consistent with pseudoscalar, but other spin-parity assignments not exclude

Systematic studies of X(1835) ongoing at BESIII
X(1835) in J/ψ → γK_{S}^{0}K_{S}^{0}\eta

- Structure in invariant K_{S}K_{S}\eta mass at ~1.85 GeV/c^{2}

- Strong correlation with enhancement at K_{S}K_{S} mass threshold (interpreted as f_{0}(980))

- Structure in K_{S}K_{S}\eta is enhanced for m(K_{S}K_{S})<1.1 GeV/c^{2}
X(1835) in J/ψ → γK_{S^0}K_{S^0}η

- Partial wave analysis for m(K_{S^0}K_{S^0})<1.1 GeV/c^2 and m(K_{S^0}K_{S^0}η)<2.8 GeV/c^2

- Two resonant pseudoscalar components (Breit-Wigner parameterization) required in best fit hypothesis

\[ X(1835) \rightarrow f_0(980)η \ (>12.9\sigma) \]
\[ m = 1844 \pm 19_{-25}^{+16} \text{ MeV/c}^2 \]
\[ \Gamma = 192_{-17}^{+20}+62_{-43} \text{ MeV} \]

\[ X(1560) \rightarrow f_0(980)η \ (>8.9\sigma) \]
\[ m = 1565 \pm 8_{-63}^{+0} \text{ MeV/c}^2 \]
\[ \Gamma = 45_{-13}^{+14}+21_{-28} \text{ MeV} \]

consistent with those of η(1405)/η(1475) within 2σ and more further study is needed
A comparison of the decay rate for $X\rightarrow\gamma V\ (V=\rho,\phi,\omega)$ can provide information on the flavor content of $X(1835)$. $f_1(1285), \eta(1405)/\eta(1475)$ and $X(1835)$ are evident by fitting $M(\gamma\phi)$.

<table>
<thead>
<tr>
<th></th>
<th>Mass (MeV/c²)</th>
<th>$\Gamma$(MeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta(1405/1475)$</td>
<td>$1475 \pm 7 \pm 16$</td>
<td>$132 \pm 15 \pm 23$</td>
</tr>
<tr>
<td>$X(1835)$</td>
<td>$1826 \pm 13 \pm 29$</td>
<td>$148 \pm 39 \pm 31$</td>
</tr>
</tbody>
</table>

Assuming no interference:

Interference between $\eta(1405/1475)$ and $X(1835)$:

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<tr>
<td>$\eta(1405/1475)$</td>
<td>$1479 \pm 11 \pm 21$</td>
<td>$133 \pm 35 \pm 20$</td>
</tr>
<tr>
<td>$X(1835)$</td>
<td>$1812 \pm 59 \pm 42$</td>
<td>$161 \pm 47 \pm 24$</td>
</tr>
</tbody>
</table>

$M(\eta(1405))=(1408 \pm 1.8)\text{MeV/c}^2; \quad \Gamma(\eta(1405))=(51.0 \pm 2.9)\text{MeV/c}^2$

$M(\eta(1475))=(1476 \pm 4)\text{MeV/c}^2; \quad \Gamma(\eta(1475))=(85 \pm 9)\text{MeV/c}^2$

$M(X(1835))=(1835.7_{-3.2}^{+5.0})\text{MeV/c}^2; \quad \Gamma(X(1835))=(99 \pm 50)\text{MeV/c}^2$

PDG Value
X(1835) and other states in J/ψ → γγφ

- X(1835) is first observed in γφ final state, more studies are needed to make sure the nature of X(1835).
- The structure in γφ favors η(1475).

One state assumption: the ratio between γφ and γφ final states is a little larger than the prediction in Ref[1].

Two states assumption: η(1475) probably contains the s̅s component.

- Assuming η(1405) and η(1475) belong to one meson [1]:
  \[ \Gamma(\eta(1405/1475) \rightarrow γφ) : \Gamma(\eta(1405/1475) \rightarrow γφ) = 3.8 : 1 \]

- Assuming η(1405/1475) is glueball[2]:
  \[ \Gamma(\eta(1405/1475) \rightarrow γφ) : \Gamma(\eta(1405/1475) \rightarrow γφ) = 1 : 1 \]

<table>
<thead>
<tr>
<th>The partial width relationship of γφ and γφ final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma(f_1(1285) \rightarrow γφ)[3]:\Gamma(f_1(1285) \rightarrow γφ) )</td>
</tr>
<tr>
<td>( \Gamma(\eta(1405/1475) \rightarrow γφ)[4]:\Gamma(\eta(1405/1475) \rightarrow γφ) )</td>
</tr>
</tbody>
</table>

Connection of $X(p \bar{p})$ and $X(1835)$

- If $X(1835)$ couples to $p\bar{p}$ the lineshape would be affected at the $p\bar{p}$ threshold.
- Update of $J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$ analysis with $1.09 \times 10^9$ $J/\psi$ events.
  - Using $\eta' \rightarrow \eta \pi^+\pi^-$ and $\eta \rightarrow \gamma \pi^+\pi^-$.
  - $X(1835)$, $X(2120)$, $X(2370)$ and $\eta_c$ signals; structure at $\sim 2600$ MeV/c².

Drop of the $X(1835)$ lineshape at the $p\bar{p}$ threshold!
Parameterization with single Breit-Wigner fails to describe the data.

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

Model 2:
Coherent sum of $X(1835)$ Breit-Wigner and one additional, narrow Breit-Wigner at $\sim 1870$ MeV/c$^2$.

Model 1 and 2 yield almost equal fit quality. Both fits suggest two resonances:
- one broad resonance below threshold
- one narrow state very close to $p\bar{p}$ threshold
Further study of $X(p \bar{p})$ threshold and $X(1835)$

- Same origin?
- Further investigations required to clarify
  - $J^{PC}$ not determined for all structures
  - Coupled channel analysis including various final states and production mechanisms
Model Independent PWA of $J/\psi \rightarrow \gamma \pi^0\pi^0$

- Radiative $J/\psi$ decays into two pseudoscalar mesons
  - Search for scalar and tensor glueballs (predicted at $\sim 1.5$ to $\sim 2$ GeV/$c^2$)
- $\pi^0\pi^0$ system: only significant $0^{++}$ and $2^{++}$ contributions
  - Many broad and overlapping resonances, many open channels → complex structure, parameterization challenging
  - Model Independent Partial Wave Analysis

>440k reconstructed events at a background level of 1.8%
A piecewise function that describes the dynamics of the $\pi^0\pi^0$ system is determined as a function of $M(\pi^0\pi^0)$.

Significant features of the scalar spectrum includes structures below 1.5, near 1.7 and 2.0 GeV/c².

$2^{++}$ amplitude indicates a dominant contribution from $f_2(1270)$.

Ambiguities present above $K\bar{K}$ threshold.
PWA of $J/\psi \rightarrow \gamma \phi \phi$

- Lattice QCD predictions:
  - Ground state of $2^{++}$ glueball in $2.3 \sim 2.4 \text{ GeV}/c^2$
  - Ground state of $0^{-+}$ glueball in $2.3 \sim 2.6 \text{ GeV}/c^2$

- Structures in $\phi \phi$ spectrum:
  - Pseudoscalar state $\eta(2225)$ was observed in $J/\psi \rightarrow \gamma \phi \phi$
  - For higher $0^{-+}$ mass states above $2 \text{ GeV}/c^2$, very little is known.
  - Broad $2^{++}$ structures decaying to $\phi \phi$ were reported around $2.3 \text{ GeV}$ in $\pi^- N$ reactions and in $p\bar{p}$ central collisions
PWA of $J/\psi \rightarrow \gamma \phi \phi$

- 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 parameterized by relative Breit-Wigner with constant width
  ✓ Resonance with significance $>5\sigma$ are selected as components in solution
PWA of $J/\psi \rightarrow \gamma \Phi \Phi$

- **Pesudoscalar:**
  - $\eta(2225)$, dominant $\eta(2100)$ and $X(2500)$

- **Tensor:**
  - $f_2(2010)$, $f_2(2300)$, $f_2(2340)$: stated in $\pi$-$p$ reaction; strong $f_2(2340)$ production

The new experimental results are helpful for mapping out the pseudoscalar excitations and searching for a $0^{++}$ glueball.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$M$(MeV/$c^2$)</th>
<th>$\Gamma$(MeV/$c^2$)</th>
<th>B.F.$\times 10^{-4}$</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta(2225)$</td>
<td>2216$^{+4+1}_{-5-11}$</td>
<td>185$^{+12+43}_{-14-17}$</td>
<td>(2.40 ± 0.10$^{+2.47}_{-2.19}$)</td>
<td>28 $\sigma$</td>
</tr>
<tr>
<td>$\eta(2100)$</td>
<td>2050$^{+30+75}_{-24-26}$</td>
<td>250$^{+36+181}_{-30-164}$</td>
<td>(3.30 ± 0.09$^{+0.18}_{-3.04}$)</td>
<td>22 $\sigma$</td>
</tr>
<tr>
<td>$X(2500)$</td>
<td>2470$^{+15+101}_{-16-23}$</td>
<td>230$^{+64+56}_{-35-33}$</td>
<td>(0.17 ± 0.02$^{+0.02}_{-0.08}$)</td>
<td>8.8 $\sigma$</td>
</tr>
<tr>
<td>$f_0(2100)$</td>
<td>2101</td>
<td>224</td>
<td>(0.43 ± 0.04$^{+0.34}_{-0.03}$)</td>
<td>24 $\sigma$</td>
</tr>
<tr>
<td>$f_2(2010)$</td>
<td>2011</td>
<td>202</td>
<td>(0.35 ± 0.05$^{+0.28}_{-0.15}$)</td>
<td>9.5 $\sigma$</td>
</tr>
<tr>
<td>$f_2(2300)$</td>
<td>2297</td>
<td>149</td>
<td>(0.44 ± 0.07$^{+0.09}_{-0.15}$)</td>
<td>6.4 $\sigma$</td>
</tr>
<tr>
<td>$f_2(2340)$</td>
<td>2339</td>
<td>319</td>
<td>(1.91 ± 0.14$^{+0.72}_{-0.73}$)</td>
<td>11 $\sigma$</td>
</tr>
<tr>
<td>$0^{-+}$ PHSP</td>
<td></td>
<td></td>
<td>(2.74 ± 0.15$^{+0.16}_{-1.48}$)</td>
<td>6.8 $\sigma$</td>
</tr>
</tbody>
</table>

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

- $\chi_{c1} \rightarrow \eta \pi^+ \pi^-$ is suitable to look for $1^{++}$ exotics
  - $\pi_1(1600)$ was studied in $\chi_{c1}$ decays by CLEO-c
  - only $\pi_1(1400)$ was reported in $\eta \pi$ final state
- Further study of $a_0(980)$ and $a_2(1700)$ in $\eta \pi$ final state

- Two body structures $a_0(980)$, $a_2(1320)$ and $f_2(1270)$ are evident similar to previous analysis
- The events in the upper left corner are compatible with $a_2(1700)$ hypothesis
Amplitude Analysis of $\chi_{c1} \rightarrow \eta\pi^+\pi^-$

<table>
<thead>
<tr>
<th>Decay</th>
<th>$B(\chi_{c1} \rightarrow \eta\pi^+\pi^-) \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta\pi^+\pi^-$</td>
<td>$4.676 \pm 0.030 \pm 0.232 \pm 0.158$</td>
</tr>
<tr>
<td>$a_0(980)^+\pi^-$</td>
<td>$3.422 \pm 0.033 \pm 0.193 \pm 0.115$</td>
</tr>
<tr>
<td>$a_2(1320)^+\pi^-$</td>
<td>$0.181 \pm 0.009 \pm 0.017 \pm 0.006$</td>
</tr>
<tr>
<td>$a_2(1700)^+\pi^-$</td>
<td>$0.049 \pm 0.005 \pm 0.007 \pm 0.002$</td>
</tr>
<tr>
<td>$S_{KK}\eta$</td>
<td>$0.114 \pm 0.006 \pm 0.014 \pm 0.004$</td>
</tr>
<tr>
<td>$S_{\pi\pi}\eta$</td>
<td>$0.761 \pm 0.019 \pm 0.005 \pm 0.026$</td>
</tr>
<tr>
<td>$(\pi^+\pi^-)_{S\pi\eta}$</td>
<td>$0.829 \pm 0.020 \pm 0.049 \pm 0.028$</td>
</tr>
<tr>
<td>$f_2(1270)\eta$</td>
<td>$0.368 \pm 0.012 \pm 0.056 \pm 0.012$</td>
</tr>
<tr>
<td>$f_4(2050)\eta$</td>
<td>$0.026 \pm 0.004 \pm 0.008 \pm 0.001$</td>
</tr>
</tbody>
</table>

Exotic candidates

<table>
<thead>
<tr>
<th>Decay</th>
<th>U.L. [90% C.L.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi_1(1400)$</td>
<td>0.58±0.20 &lt; 0.046</td>
</tr>
<tr>
<td>$\pi_1(1600)$</td>
<td>0.11±0.10 &lt; 0.015</td>
</tr>
<tr>
<td>$\pi_1(2015)$</td>
<td>0.06±0.03 &lt; 0.008</td>
</tr>
</tbody>
</table>

- Clear evidence for $a_2(1700)$ in $\chi_{c1}$ decays
- First measurement of $g_{\eta/\pi}$ using $a_0(980)\rightarrow\eta\pi$ line shape
- Upper limits for $\pi_1(1^{++})$ in 1.4 - 2.0 GeV$/c^2$ region are measured
Many interesting results in light quark spectroscopy from BESIII

- Systematic studies to understand X(1835) and other structures observed near ppbar threshold
  - X(1835) nature unclear: p\bar{p} bound state, glueball, excited \eta meson?
- Sophisticated model independent partial wave analysis of J/\psi\rightarrow\gamma\pi^0\pi^0
- PWA of J/\psi\rightarrow\gamma\phi\phi
- Amplitude Analysis of \chi_{c1}\rightarrow\eta\pi^+\pi^-

Expect more important results from BESIII