LIGHT HADRON SPECTROSCOPY @ BESIII

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On behalf of BESIII Collaboration
Università degli studi di Torino
INFN sez. Di Torino
• Introduction to BESIII and BEPCII

• Highlights of light hadron spectroscopy:
  - X states @ pp mass threshold
  - PWA in charmonia decays

• Summary and conclusions
Upgrade of BEPC (started 2004, first collisions July 2008)
Beam energy 1 . . . 2.3 GeV
Optimum energy 1.89 GeV
Single beam current 0.91 A
Crossing angle: ±11 mrad

Design luminosity: $10^{33} \text{cm}^{-2} \text{s}^{-1}$
Achieved in April 5th, 2016
Beam energy measurement by Laser compton backscattering
$\Delta E/E \approx 5 \times 10^{-5}$ (50 keV at $\tau$ threshold)
Main Drift Chamber (MDC)
\[ \sigma_r/P = 0.5\% \text{ (1 GeV)} \]
\[ \sigma_{dE/dx} = 6\% \]

Time of Flight (TOF)
\[ \sigma_T: 90\text{ ps (barrel)} \]
\[ 110\text{ ps (endcap)} \]

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

Super-Condensing Magnet
1.0 T (2009)
0.9 T (2012)

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

93\% of 4\pi acceptance
BESIII: the collaboration

US (6)
- Univ. of Hawaii
- Carnegie Mellon Univ.
- Univ. of Minnesota
- Univ. of Rochester
- Univ. of Indiana
- Univ. of Washington

Europe (13)
- Germany: Univ. of Bochum,
  Univ. of Giessen, GSI
  Univ. of Johannes Gutenberg
  Helmholtz Ins. in Mainz
- Russia: JINR Dubna; BINP Novosibirsk
- Italy: Univ. di Torino, Univ. di Ferrara, LNF Frascati
- Netherlands: KVI/Univ. of Groningen
- Sweden: Uppsala Univ.
- Turkey: Turkey Accelerator Center

Pakistan (2)
- Univ. of Punjab
- COMSAT CIIT

China (31)
- IHEP, CCAST, GUCAS, Shandong Univ.,
  Univ. of Sci. and Tech. of China
  Zhejiang Univ., Huangshan Coll.
  Huazhong Normal Univ., Wuhan Univ.
  Zhengzhou Univ., Henan Normal Univ.
  Peking Univ., Tsinghua Univ.,
  Zhongshan Univ., Nankai Univ.
  Shanxi Univ., Sichuan Univ., Univ. of South China
  Hunan Univ., Liaoning Univ.
  Nanjing Univ., Nanjing Normal Univ.
  Guangxi Normal Univ., Guangxi Univ.
  Suzhou Univ., Hangzhou Normal Univ.
  Lanzhou Univ., Henan Sci. and Tech. Univ.
  Beihang Univ., Beijing Petrol Chemical Univ.

Korea (1)
- Seoul Nat. Univ.

Japan (1)
- Tokyo Univ.

400 members
53 institutions
11 nations
• **Light Hadrons**
  - Meson and baryon spectroscopy
  - Search for exotic hadrons
  - Light meson decays

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

• **Open Charm Physics**
  - D meson decays
  - mixing
  - CP violation in the charm sector

And many other topics e.g. tau and two-photon physics
World largest samples of J/ψ, ψ(2S), ψ(3770) directly produced in e+e− collisions

IDEAL ENVIRONMENT TO STUDY LIGHT HADRON SPECTROSCOPY!!

MORE:
Coarse scan 4100-4400 MeV/c²; 0.04 fb−1 around Λc threshold; Data taking on-going
Conventional hadrons consist of 2 or 3 quarks

- Meson: two quarks
- Baryon: three quarks

But QCD allows other forms of hadrons:

- Multi-quark state: > 3 quarks
- Glueball: gg, ggg, ...
- Hybrid: qqq, qqqq, ...
- Molecule: bound state of more than 2 hadrons

Lots of candidates but not established yet

Searching for new forms of hadrons provide test of QCD
Light Hadron Spectroscopy

- Motivation:
  - Establish spectrum
  - Search for exotic hadrons

BESIII advantages?
Charmonium decays can be used (high statistics)
  - Gluon rich processes
  - Kinematics favorable
  - Clean environment, no combinatorial bkg
  - $J^{PC}$ and Isospin filters in strong decays compared to hadron colliders

Why $J/\psi$ decays are mostly used?
- $J/\psi$ production cross section is high and the BR of hadrons in $J/\psi$ decays higher than $\psi'$ decays ("12% rule").
- Large phase space to 1-3 GeV hadrons in $J/\psi$ decays
- Production BR of exotic hadrons expected to be larger or similar to the one for conventional hadrons in $J/\psi$ decays.
Hunting Glueballs

Direct test of QCD

- Lattice QCD prediction
  - $0^{++}$ ground state: $1\sim1.7$ GeV/$c^2$
  - $2^{++}$ ground state: $2.3\sim2.4$ GeV/$c^2$
  - $0^{-+}$ ground state: $2.3\sim2.6$ GeV/$c^2$

They can mix with ordinary $q\bar{q}$ states

$J/\psi$ radiative decays are gluon-rich environment (large BR forseen): an ideal place to search for glueballs.

Systematic experimental studies needed:
- Map of the resonances
- Study of the production patterns ($J/\psi \rightarrow \gamma/\omega/\phi+X$)
- Study of the decay patterns

PRD 73 (2006) 014516
X states @ pp mass threshold
The $p\bar{p}$ threshold enhancement

- Observed by BESII in $J/\psi \rightarrow \gamma pp$ more than 10 years ago

- Confirmed by BESIII and CLEO-c in $\psi(3686) \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow \gamma pp$

$\psi(3686) \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow \gamma pp$

Confirmed by BESIII in $J/\psi \rightarrow \gamma pp$ (PWA below 2.2GeV/c$^2$)

- $X(p\bar{p}) \rightarrow J^{PC} = 0^{-+} (>30 \sigma)$ with BW parametrization
  - $M = 1832^{+19}_{-5}^{+18}_{-12} \text{(syst)} \pm 19 \text{ (Model) MeV/c}^2$
  - $\Gamma = 13 \pm 39 \text{(stat)}^{+4}_{-10} \text{(syst)} \pm 4 \text{ (Model) MeV/c}^2 (< 76 \text{ MeV/c}^2 \text{ @ 90\% C.L.})$

- PWA: 4 contributions included: $X(p\bar{p}), f_2(1910), f_0(2100)$, non-resonant $0^{+-}$ contribution, FSI)

No similar structure observed in related channels (e.g. $Y(1S) \rightarrow \gamma pp, \psi' \rightarrow \gamma pp$)

nature of these states? $p\bar{p}$ bound state?
look into the subthreshold energy region.
• Discovery by BESII in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$ in 2005

- (58M $J/\psi$)
  - Phys. Rev. Lett. 95, 262001 (2005)

  ![Graph showing discovery by BESII](#)

  - 7.7 $\sigma$

• Confirmed by BESIII in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

  - $M = 1836.5 \pm 3.0^{+3.6}_{-2.1} \text{ MeV/c}^2$
  - $\Gamma = 190 \pm 9^{+38}_{-36} \text{ MeV/c}^2$
  - $>20\sigma$

![Graph showing confirmed discovery by BESIII](#)

- $\eta' \rightarrow \gamma \rho (\rho \rightarrow \pi^+ \pi^-)$
- $\eta' \rightarrow \eta \pi^+ \pi^-$, $\eta \rightarrow \gamma \gamma$

4 resonances (BW $\otimes$ GAUSS) + non resonant contribution (from MC) + $\eta' + \eta' \pi^+ \pi^- \pi^0$ bkg

- $X(2370)$
- $f_1(1510)$

$X(1835)$

- Angular distribution is consistent with $0^-$

LQCD predicts the glueball mass of $0^+$ is $\sim 2.3 \text{ GeV}$. For $0^+$ glueball, it may have similar property as $\eta_c$ (the main decay mode is $\pi \pi \eta'$).

![Graphic representation of $X(1835)$](#)

EPS-HEP2017

13
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 and anomalous distortion of the $\eta'\pi^+\pi^-$ line shape close to the $p\bar{p}$ mass threshold as expected for a $p\bar{p}$ bound state.

Simultaneous fits for the two $\eta'$ decay modes: simple BW function fails description near the $p\bar{p}$ mass threshold.

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Threshold structure caused by the opening of additional \( p\bar{p} \) decay mode (Flatté formula):

\[
T = \frac{\sqrt{P_{out}}}{M - s - i \sum_k g_k^2 \rho_k}; \quad \sum_k g_k^2 \rho_k \approx g_0^2 (\rho_0 + \frac{g_{pp}^2}{g_0^2} \rho_{pp})
\]

S.M. Flatté PLB 63, 224 (1976)

<table>
<thead>
<tr>
<th>Fitting results</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M (\text{MeV}/c^2) )</td>
</tr>
<tr>
<td>( g_0^2 (\text{MeV}/c^2)^2 )</td>
</tr>
<tr>
<td>( g_{pp}^2/g_0^2 )</td>
</tr>
<tr>
<td>( M_{\text{pole}} (\text{MeV}/c^2) )</td>
</tr>
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<td>( \Gamma_{\text{pole}} (\text{MeV}/c^2) )</td>
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An additional resonance, “X(1920)”, is needed with 5.7\( \sigma \)

Significance of \( g_{pp}^2/g_0^2 \) being non-zero is larger than 7\( \sigma \)

**Interference between X(1835) and another very narrow resonance close to threshold:**

\[
T = \frac{\sqrt{P_{out}}}{M^2 - s - i M_1 \Gamma_1} + \frac{\beta e^{i\theta} \sqrt{P_{out}}}{M^2 - s - i M_2 \Gamma_2}
\]

Coherent sum of two BW

**FIRST RESONANCE: X(1835)**

- \( M(\text{MeV}/c^2) \): 1825.3 \( \pm 2.4 \) \( \pm 1.7 \) \( \pm 2.4 \) \( \pm 1.7 \)
- \( \Gamma(\text{MeV}/c^2) \): 245.2 \( \pm 11.2 \) \( \pm 4.6 \) \( \pm 12.6 \) \( \pm 9.6 \)
- B.R. (c.i.) \( (3.01 \pm 0.17 \pm 0.26) \times 10^{-4} \)
- B.R. (d.i.) \( (3.72 \pm 0.21 \pm 0.19) \times 10^{-4} \)

**SECOND RESONANCE: X(1870)**

- \( M(\text{MeV}/c^2) \): 1870.2 \( \pm 2.2 \) \( \pm 2.2 \) \( \pm 2.3 \) \( \pm 2.3 \)
- \( \Gamma(\text{MeV}/c^2) \): 13.0 \( \pm 2.1 \) \( \pm 2.1 \) \( \pm 2.5 \) \( \pm 2.5 \)
- B.R. (c.i.) \( (2.03 \pm 0.12 \pm 0.42) \times 10^{-7} \)
- B.R. (d.i.) \( (1.57 \pm 0.09 \pm 0.49) \times 10^{-5} \)

**X(1920) is not significant**

**EPS-HEP2017 Is it a \( p\bar{p} \) bound state?**
Both models fit the data well, both suggest two structures:

- a broad state and a narrow state very close to \( p\bar{p} \) mass threshold,
- a \( p\bar{p} \) molecule-like state or bound state?

Whatever the \( X(1835) \) is, it has large coupling to \( p\bar{p} \)!

- To understand the nature of this exotic state
  - Larger data sample needed
  - Study other decay modes
    - \( J/\psi \to \gamma p\bar{p} \) (seen before)
    - \( J/\psi \to \gamma K_S K_S \eta \)
    - ...

\[ J/\psi \to \gamma \eta' \pi^+ \pi^- \]
X(1835) in J/ψ → γηK_s\bar{K}_s

Search for new decay modes to understand X(1835) nature

1.3×10^9 J/ψ events (2009 and 2012)

Clean environment: ηK_s\bar{K}_s and ηπ^0K_s\bar{K}_s bkg forbidden

• Clear structure on mass spectrum of K_sK_s\eta @1.85 GeV/c^2, strongly correlated to f_0(980)

• PWA for M(K^0_sK^0_s) < 1.1 GeV/c^2 and
  M(K^0_sK^0_s\eta) < 2.8 GeV/c^2
  to determine spin parity
\( X(1835) \) in \( J/\psi \to \gamma K_S^0 K_S^0 \eta \) (II)

**\( X(1835) \)**

\( J^{PC}=0^-+; \ X(1835) \to K_S^0 K_S^0 \eta (\geq 12.9 \sigma) \), dominated by \( f_0(980) \) production

\[
\begin{align*}
M &= 1844 \pm 9_{-25}^{+16} \text{ MeV} \\
\Gamma &= 192_{-17}^{+20+62} - 43 \text{ MeV}/c^2
\end{align*}
\]

Consistent with \( X(1835) \) parameters obtained from \( J/\psi \to \gamma \eta' \pi^+ \pi^- \), mass consistent and width larger than \( X(pp) \)

\[
\mathcal{B}(J/\psi \to \gamma X(1835)) \cdot \mathcal{B}(X(1835) \to K_S K_S \eta) = (3.31 \pm 0.33^{+1.96}_{-0.30} - 1.29) \times 10^{-5}
\]

**\( X(1560) \).**

\( J^{PC}=0^-+; \ X(1560) \to K_S^0 K_S^0 \eta (\geq 8.9 \sigma) \)

\[
\begin{align*}
M &= 1565 \pm 8_{-63}^{+0} \text{ MeV} \\
\Gamma &= 45_{-13}^{+21+28} \text{ MeV}/c^2
\end{align*}
\]

Consistent with \( \eta(1405)/\eta(1475) \) within 2.0 \( \sigma \)

Interference allowed in PWA

More statistics and other channels analysis needed to understand, like \( \gamma K_S K_S \pi^0 \)
Comparison between BESIII results

• More studies are needed to answer this question, but connections are emerging!

Larger statistics will help!

X states near proton-antiproton threshold, what’s the role of that threshold?

• X(pp) in agreement with X(1835), while its width is significantly different

Are X(1835) and X(pp) them SAME state?

More studies are needed to answer this question, but connections are emerging!

Larger statistics will help!

EPS-HEP2017
PWA in charmonia decays

- Model Independent PWA of \( J/\psi \rightarrow \eta \pi^0 \pi^0 \)
- PWA of \( J/\psi \rightarrow \gamma \phi \phi \)
- Amplitude analysis of the \( \chi_{c1} \rightarrow \eta \pi^+ \pi^- \) decays
π⁰π⁰ is a very clean system with large statistics
- Many broad and overlapping resonances (parameterization challenging)
- Model independent PWA (MIPWA): a piecewise complex function is built to describe the s dependence of ππ dynamics
  ✓ More than 440,000 reconstructed events
  ✓ Background level ~ 1.8%

- 1.3×10⁹ J/ψ events (2009 and 2012)
- Extract amplitudes in each M(π⁰π⁰) mass bin
- Scalar spectrum -> significant structures near 1.5, 1.7 and 2.0 GeV/c²
- 2+ spectrum -> dominated by f₂(1270) (tensor glueball candidate f₆(2230) don’t show up)
  ✓ Multiple solutions in MIPWA are usually unavoidable.

- Provides the scattering amplitude minimizing systematic bias due to assumptions about ππ dynamics and in an experiment-independent way

- Model Independent PWA of J/ψ→γπ⁰π⁰

**Extracted Intensity**

**Relative Phase**

- Solution 1-nominal
- Solution 2-ambiguous

**EPS-HEP2017**
PWA of $J/\psi \to \gamma \phi \phi$

1.3×10^9 $J/\psi$ events (2009 and 2012)

**BASELINE SOLUTION**

Resonance | $M$(MeV/c^2) | $\Gamma$(MeV/c^2) | B.F.(×10^-4) | Sig. |
---|---|---|---|---|
$\eta(2225)$ | 2216^{+118+14+14} | 185^{+12+14+12} | (2.40 ± 0.10+0.10) | 28.1σ |
$\eta(2100)$ | 2050^{+77+26+26} | 250^{+70+16+16} | (3.30 ± 0.09+0.08) | 21.5σ |
$X(2500)$ | 2470^{+63+19+23} | 230^{+53+35+33} | (0.17 ± 0.02+0.02) | 8.8σ |

$f_0(2100)$: 2102 | 211 | (0.43 ± 0.04×0.04) | 24.2σ |

$f_2(2010)$: 2011 | 202 | (0.35 ± 0.05±0.10) | 9.5σ |

$f_2(2300)$: 2297 | 149 | (0.44 ± 0.07±0.10) | 6.4σ |

$f_2(2340)$: 2339 | 319 | (1.91 ± 0.07±0.07) | 10.7σ |

0^- PHSP: To model direct decay (2.74 ± 0.15±0.14) | 6.8σ |

**PDG fixed**

Compatible with LQCD pred. for Tensor glueball

**Scalar state:** $f_0(2100)$

**Tensor states:** $f_2(2010), f_2(2300), f_2(2340)$, obs. in $\pi N$ and pp, strong $f_2(2340)$ production, Tensor glueball?

**Pseudoscalar states (DOMINANT):**

$\eta(2225)$ confirmed (DM2, MARKII, BESII)

$\eta(2100)$ and $X(2500)$ observed.

✓ Well consistent with the results from Model-independent PWA
Amplitude analysis of the $\chi_{c1} \to \eta\pi^+\pi^-$ decay

448.0 $10^6 \psi(3686)$ events ($>15 \times$ CLEO-c sample), ≈ 34k$\chi_{c1}$ (World largest sample!)

$\psi(3686) \to \gamma\chi_{c1}$ and

$\chi_{c1} \to \eta\pi^+\pi^-$

95% of $\eta$ decays $\eta \to 3\pi$, $\eta \to \gamma\gamma$

Search for exotic mesons with $1^{-+}$ in (1.3-2.0) GeV/c$^2$ mass region decaying $\eta\pi$ ($\pi_1$ states, only $\pi_1(1400)$ decaying $\eta\pi$ by CLEO-C, e.g.)

Test sensitivity to $a_0(980) \to \eta'\pi$ production of $a_0(980)$ lineshape

Search for $\chi_{c1} \to a_2(1700)\pi$ with $a_2(1700) \to \eta\pi$
Amplitude analysis of the $\chi_{c1} \to \eta\pi^+\pi^-$ decays (II)

Isobar model ($\eta\pi, \pi\pi$)
Helicity formalism for Amplitudes

BW+ Blatt-Weisskopf factors for most of the resonances, $a_0(980)$ and $a_2(1700)$ free parameters, PDG for the others

Dispersion integrals for $a_0(980)$ considering $\eta\pi, \eta'\pi, K\bar{K}$ decay channels

OPTIMAL SOLUTION using amplitude with >0.5% contribution and significance >5$\sigma$

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\mathcal{F}$ [%]</th>
<th>Significance [σ]</th>
<th>$B(\chi_{c1} \to \eta\pi^+\pi^-)$ [10^{-3}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta\pi^+\pi^-$</td>
<td>...</td>
<td>...</td>
<td>4.67 ± 0.03 ± 0.23 ± 0.16</td>
</tr>
<tr>
<td>$a_0(980)^+\pi^-$</td>
<td>72.8 ± 0.6 ± 2.3</td>
<td>&gt;100</td>
<td>3.40 ± 0.03 ± 0.19 ± 0.11</td>
</tr>
<tr>
<td>$a_2(1320)^+\pi^-$</td>
<td>3.8 ± 0.2 ± 0.3</td>
<td>32</td>
<td>0.18 ± 0.01 ± 0.02 ± 0.01</td>
</tr>
<tr>
<td>$a_2(1700)^+\pi^-$</td>
<td>1.0 ± 0.1 ± 0.1</td>
<td>20</td>
<td>0.047 ± 0.004 ± 0.006 ± 0.002</td>
</tr>
<tr>
<td>$S_{\eta\pi}\eta$</td>
<td>2.5 ± 0.2 ± 0.3</td>
<td>22</td>
<td>0.119 ± 0.007 ± 0.015 ± 0.004</td>
</tr>
<tr>
<td>$S_{\pi\pi}\eta$</td>
<td>16.4 ± 0.5 ± 0.7</td>
<td>&gt;100</td>
<td>0.76 ± 0.02 ± 0.05 ± 0.03</td>
</tr>
<tr>
<td>$(\pi^+\pi^-)_{g}\eta$</td>
<td>17.8 ± 0.5 ± 0.6</td>
<td>...</td>
<td>0.83 ± 0.02 ± 0.05 ± 0.03</td>
</tr>
<tr>
<td>$f_2(1270)\eta$</td>
<td>7.8 ± 0.3 ± 1.1</td>
<td>&gt;100</td>
<td>0.36 ± 0.01 ± 0.06 ± 0.01</td>
</tr>
<tr>
<td>$f_2(2050)\eta$</td>
<td>0.6 ± 0.1 ± 0.2</td>
<td>9.8</td>
<td>0.026 ± 0.004 ± 0.008 ± 0.001</td>
</tr>
</tbody>
</table>

Exotic candidates

- $\pi_1(1400)^+\pi^-$: 0.58 ± 0.20
- $\pi_1(1600)^+\pi^-$: 0.11 ± 0.10
- $\pi_1(2015)^+\pi^-$: 0.06 ± 0.03
BES III is successfully operating since 2008, and continues to take data until 2022 at least.

Excellent laboratory to study light hadron spectroscopy (and many other items):
  • High statistics
  • Low backgrounds

Many interesting results have been obtained, and only a few have been reported in this talk.

In the next three years new DATA for $J/\psi$ are awaited towards 8 Billions $J/\psi$. 

EPS - EPS-HEP2017
Thank you for your attention!
No $p\bar{p}$ threshold enhancement
Fitting results

\[ T = \frac{\sqrt{\text{P}_{\text{out}}}}{M^2 - s - i \sum_k g_k^2 \rho_k} \]

\[ \sum_k g_k^2 \rho_k \approx g_0^2 (\rho_0 + \frac{g_{pp}^2}{g_0^2} \rho_{pp}) \]

An additional resonance, \(X(1920)\), is needed with 5.7\(\sigma\)

**Fitting results**

<table>
<thead>
<tr>
<th>(M) (MeV/c²)</th>
<th>1638.0 (+121.9 +127.8) (-1219 -2543)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(g_0^2 ((\text{GeV/c}^2)^2))</td>
<td>93.7 (+354 +47.6) (-354 -439)</td>
</tr>
<tr>
<td>(g_{pp}^2 / g_0^2)</td>
<td>2.31 (+0.37 +0.83) (-0.37 -0.60)</td>
</tr>
<tr>
<td>(M_{\text{pole}}) (MeV/c²) *</td>
<td>1909.5 (+159 +94) (-159 -275)</td>
</tr>
<tr>
<td>(\Gamma_{\text{pole}}) (MeV/c²) *</td>
<td>273.5 (+214 +6.1) (-214 -64.0)</td>
</tr>
<tr>
<td>Branching Ratio</td>
<td>((3.93 +0.38 +0.31) (-0.38 -0.04) \times 10^{-4})</td>
</tr>
</tbody>
</table>

**Significance of \(g_{pp}^2 / g_0^2\) being non-zero is larger than 7\(\sigma\)**

An additional resonance, \(X(1920)\), is needed with 5.7\(\sigma\)

*The pole nearest to the \(pp\) mass threshold

**PRL 117, 042002 (2016)**
**FIRST RESONANCE:** X(1835)

\[ M = (1825.3 \pm 2.4 \pm 17.3) \pm 2.4 - 2.4 \]  
\[ \Gamma = (136.2 \pm 4.6 \pm 12.6) \pm 9.6 \]  
\[ \text{B.R. (constructive interference)} = (3.01 \pm 0.17 \pm 0.26) \times 10^{-4} \]  
\[ \text{B.R. (destructive interference)} = (3.72 \pm 0.21 \pm 0.19) \times 10^{-4} \]  

**SECOND RESONANCE:** X(1870)

\[ M = (1871.2 \pm 2.3 \pm 4.3) \pm 1.3 \]  
\[ \Gamma = (13.6 \pm 2.1 \pm 5.5) \pm 3.8 \]  
\[ \text{B.R. (constructive interference)} = (2.03 \pm 0.12 \pm 0.45) \times 10^{-7} \]  
\[ \text{B.R. (destructive interference)} = (1.57 \pm 0.09 \pm 0.49) \times 10^{-5} \]  

Significance of narrow X(1870) is larger than 7\( \sigma \)

X(1920) is not significant

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Interference between two resonances with one very narrow close to threshold:

Coherent sum of two Breit-Wigner amplitudes for the line shape:

\[ T = \frac{\sqrt{p_{\text{out}}} \cdot e^{i\theta}}{M_1^2 - s - iM_1 \Gamma_1} + \frac{\beta \cdot e^{i\theta} \cdot \sqrt{p_{\text{out}}}}{M_2^2 - s - iM_2 \Gamma_2} \]

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**EPS-HEP2017**
X(1840) in J/ψ→γ3(π⁺π⁻)

230M J/ψ data sample

X(1840) (> 7.6σ)

\[ M = 1842.2 \pm 4.2^{+7.1}_{-2.6} \text{ MeV} / c^2 \]
\[ \Gamma = 83 \pm 14 \pm 11 \text{ MeV} / c^2 \]

NO PWA

Mass consistent with the other X(1835), but width is much smaller

Results with higher statistics in progress.
**X(1870) in J/ψ → ωηπ⁺π⁻**

230M J/ψ data sample

\[ J/ψ \rightarrow ωηπ⁺π⁻ \]

\[ a₀(980) \text{ in } ηπ⁺π⁻ \]

X(1870) : 7.2σ

0⁺ (?)

Is it X(1835) ?

NO PWA

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PRL 107,182001 (2011)

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### Resonance Parameters

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV/c²)</th>
<th>Width (MeV/c²)</th>
<th>B(10⁻⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_1(1285) )</td>
<td>1285.1 ± 1.0^{+1.6}_{-0.3}</td>
<td>22.0 ± 3.1^{+2.0}_{-1.5}</td>
<td>1.25 ± 0.10^{+0.19}_{-0.20}</td>
</tr>
<tr>
<td>( η(1405) )</td>
<td>1399.8 ± 2.2^{+2.8}_{-0.1}</td>
<td>52.8 ± 7.6^{+0.1}_{-7.6}</td>
<td>1.89 ± 0.21^{+0.21}_{-0.23}</td>
</tr>
<tr>
<td>X(1870)</td>
<td>1877.3 ± 6.3^{+3.4}_{-7.4}</td>
<td>57 ± 12^{+19}_{-4}</td>
<td>1.50 ± 0.26^{+0.72}_{-0.36}</td>
</tr>
</tbody>
</table>
PWA of $J/\psi \rightarrow \gamma \phi \phi$

1.3×10^9 $J/\psi$ events collected by BESIII in 2009 and 2012

- 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

Both MIPWA and model dependent PWA performed on data

**BASELINE SOLUTION**

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$M$(MeV/$c^2$)</th>
<th>$\Gamma$(MeV/$c^2$)</th>
<th>B.F.($\times10^{-4}$)</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta(2225)$</td>
<td>$2216^{+18+18}_{-15-11}$</td>
<td>$185^{+12+14}_{-14-17}$</td>
<td>$(2.40 \pm 0.10)_{-0.16}^{+0.23}$</td>
<td>28.1$\sigma$</td>
</tr>
<tr>
<td>$\eta(2100)$</td>
<td>$2050^{+90+77}_{-24-26}$</td>
<td>$250^{+26+18}_{-30-164}$</td>
<td>$(3.30 \pm 0.09)_{-0.18}^{+0.15}$</td>
<td>21.5$\sigma$</td>
</tr>
<tr>
<td>$X(2500)$</td>
<td>$2470^{+15+63}_{-19-23}$</td>
<td>$230^{+64+53}_{-35-33}$</td>
<td>$(0.17 \pm 0.02)_{-0.06}^{+0.02}$</td>
<td>8.8$\sigma$</td>
</tr>
<tr>
<td>$f_0(2100)$</td>
<td>2102</td>
<td>211</td>
<td>$(0.43 \pm 0.04)_{-0.09}^{+0.24}$</td>
<td>24.2$\sigma$</td>
</tr>
<tr>
<td>$f_2(2010)$</td>
<td>2011</td>
<td>202</td>
<td>$(0.35 \pm 0.05)_{-0.13}^{+0.28}$</td>
<td>9.5$\sigma$</td>
</tr>
<tr>
<td>$f_2(2300)$</td>
<td>2297</td>
<td>149</td>
<td>$(0.44 \pm 0.07)_{-0.15}^{+0.90}$</td>
<td>6.4$\sigma$</td>
</tr>
<tr>
<td>$f_2(2340)$</td>
<td>2339</td>
<td>319</td>
<td>$(1.91 \pm 0.07)_{-0.15}^{+0.73}$</td>
<td>0.7$\sigma$</td>
</tr>
</tbody>
</table>

$0^+\text{PHSP}$ To model direct decay $(2.74 \pm 0.15)_{-1.46}^{+0.16}$ 6.8$\sigma$

**Scalar state:**
- $f_0(2100)$

**Tensor states:**
- $f_2(2010)$,
- $f_2(2300)$,
- $f_2(2340)$, obs. in $\pi p$ reac.
- strong $f_2(2340)$ production
- Is it tensor glueball candidate (consistent with LQCD predictions)?

**Pseudoscalar states (DOMINANT):**
- $\eta(2225)$ confirmed
- $\eta(2100)$ and $X(2500)$ observed.

✓ Well consistent with the results from Model-independent PWA

EPS-HEP2017

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

<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>$1468^{+14+23}_{-15-74}$</td>
<td>$136^{+41+28}_{-26-100}$</td>
<td>$(1.65^{+0.26+0.51}_{-0.31-1.46}) \times 10^{-5}$</td>
<td>$8.2 \sigma$</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>$1759^{+6+14}_{-25}$</td>
<td>$172^{+10+32}_{-16}$</td>
<td>$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$</td>
<td>$25.0 \sigma$</td>
</tr>
<tr>
<td>$f_0(2100)$</td>
<td>$2081^{+13+24}_{-36}$</td>
<td>$273^{+27+70}_{-24-23}$</td>
<td>$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$</td>
<td>$13.9 \sigma$</td>
</tr>
<tr>
<td>$f_2(1525)$</td>
<td>$1513^{+5+4}_{-10}$</td>
<td>$75^{+12+16}_{-10-8}$</td>
<td>$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$</td>
<td>$11.0 \sigma$</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>$6.4 \sigma$</td>
</tr>
<tr>
<td>$f_2(2340)$</td>
<td>$2362^{+31+140}_{-30-63}$</td>
<td>$334^{+62+165}_{-54-100}$</td>
<td>$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$</td>
<td>$7.6 \sigma$</td>
</tr>
</tbody>
</table>

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