Recent Results from BESIII

Isabella Garzia, University of Ferrara and INFN
On behalf of the BESIII Collaboration

September 5-9, 2022
FSU, Tallahassee, FL, USA
2004: started BEPCII/BESIII construction
✓ Double rings
✓ Beam energy: 1-2.45 GeV
✓ Design luminosity: $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ @ $\psi(3770)$, achieved in 2016
2009 – today: BESIII physics runs

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BESIII - Beijing Spectrometer III

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2009 – today: BESIII physics runs

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http://english.ihep.cas.cn

BESIII dataset

- 130 points between 2 and 4.6 GeV (~715 pb⁻¹ up to 3.08 GeV for \( \rho^*, \omega^*, \phi^* \),… studies)
- Light hadron spectroscopy
- \( \eta/\eta' \) decays
- Hyperon physics
- Charmonium transitions
- \( D^0\bar{D}^0 \) pairs
- \( D(S) \) meson decays
- ISR processes
- XYZ decays and spectroscopy
- Open charm production
- Charmed baryons
- ...

\[ R_{\text{had}} = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \]

3 loop pQCD
Naive quark model

Inclusive:
- KEDR
- BES

\[ \sqrt{s} \text{ [GeV]} \]

\[ 1 \times 10^{10} \quad (2019) \]

\[ 2.7 \times 10^9 \quad (2022) \]

\[ 20 \text{ fb}^{-1} \quad (2022) \]

\[ 4180 \text{ fb}^{-1} \]

\[ 0.5 \text{ fb}^{-1} \]

\[ 22 \text{ fb}^{-1} \text{ in XYZ region} \]

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Selected BESIII results

- Light hadron Spectroscopy
  - exotic isoscalar $\eta_1(1855)$
  - new $X(2600)$ state observed in $J/\psi$ radiative decays
- Charmonium(-like) spectroscopy
  - $Y$ states and $Z_{CS}(3985)$ triplet states
- $\phi(2170)$ strangeonium state
**Naïve Quark Model:**
conventional hadrons contain two or three quarks

… **but** QCD allows also different combinations of quarks and gluons: **EXOTIC** hadrons

---

A lot of exotic states observed experimentally, but their nature is still far from being understood!!!

Hadron spectroscopy: establish the spectrum and study the exotic hadrons properties
Hunting for glueballs and new form of hadrons

- Charmonium radiative decays is the ideal laboratory for light glueballs and hybrids hadron studies
  - Gluon-rich process
  - Clean process
  - High statistics

- **Glueballs can mix with ordinary quark-antiquark states**
- Predicted large BFs for glueballs in $J/\psi$ radiative decays

\[
\Gamma(J/\psi \rightarrow \gamma G_{0^{++}})/\Gamma_{\text{tot}} = 3.8(9) \times 10^{-3}
\]

\[
\Gamma(J/\psi \rightarrow \gamma G_{2^{++}})/\Gamma_{\text{tot}} = 1.1(2)(1) \times 10^{-2}
\]

Prediction from LQCD

https://doi.org/10.1142/S0218301309012124
Low-lying hybrids can have exotic quantum numbers forbidden in the conventional QCD scheme: 
\( J^{PC} = 0^{+-}, 1^{--}, 2^{+-} \)

The exotic \( J^{PC} = 1^{--} \) nonet of hybrids is predicted to be the lightest

Only isovector candidate observed yet: \( \pi_1(1400) \), \( \pi_1(1600) \) [the most extensively studied], \( \pi_1(2015) \)

Isoscalar \( 1^{--} \) hybrids is important to establish the hybrid nonet

Can be produced in \( J/\psi \) radiative decays

Can decay to \( \eta \eta' \) in P-wave (PRD 83, 014021, PRD 83, 014006, Eur.Phys.J.Plus 135, 945)

BESIII experiment offers the ideal environment for this search

\( J/\psi \rightarrow \gamma \eta \eta' \)
Observation of Exotic Isoscalar State $\eta_1(1855)$ in $J/\psi\rightarrow\gamma\eta\eta'$

PWA of $J/\psi\rightarrow\gamma\eta\eta'$ using 10 Billion of $J/\psi$ data @ BESIII

- $\eta\rightarrow\gamma\gamma$ and $\eta'\rightarrow\gamma\pi^+\pi^-/\eta\pi^+\pi^-$

- An isoscalar $1^{-+}$ state, $\eta_1(1855)$, has been observed with statistical significance larger than 19$\sigma$
- Mass is consistent with LQCD calculation for the $1^{-+}$ hybrid ($1.7 - 2.1$ GeV/$c^2$)

$M = (1855\pm9^{+6}_{-1})$ MeV/$c^2$; \quad $\Gamma = (188\pm18^{+3}_{-8})$ MeV

$\mathcal{B}(J/\psi \rightarrow \gamma\eta_1(1855) \rightarrow \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$

*spin information

more detail from Nils Huesken talk, 09/05
The \( \cos(\theta_\eta) \) distribution can be expressed as an expansion in terms of Legendre polynomials; the coefficients \( \langle Y^0_i \rangle = \sum_{i=1}^{N_k} W_i Y^0_i(\cos\theta_\eta) \) (called unnormalized moments of expansion), characterize the spin of the \( \eta^\prime \) resonances.

- Neglecting resonance contributions in the \( \gamma\eta^\prime \) subsystem, the moments are related to the spin-0 (S), spin-1 (P) and spin-2 (D) amplitudes.

- Good data/PWA consistency.

- Narrow structure in \( \langle Y^0_1 \rangle \): \( \eta_1(1855) \) P-wave component is needed.
Discussion about $f_0(1500)$ and $f_0(1710)$

The dominant contributions in the baseline PWA are from scalar resonance:

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Resonance</th>
<th>$M$ (MeV/$c^2$)</th>
<th>$\Gamma$ (MeV)</th>
<th>$M_{PDG}$ (MeV/$c^2$)</th>
<th>$\Gamma_{PDG}$ (MeV)</th>
<th>B.F. ($\times10^{-5}$)</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(1500)$</td>
<td>1506</td>
<td>112</td>
<td>1506</td>
<td>112</td>
<td>1.81±0.11±0.19</td>
<td>$\gg30\sigma$</td>
<td></td>
</tr>
<tr>
<td>$f_0(1810)$</td>
<td>1795</td>
<td>95</td>
<td>1795</td>
<td>95</td>
<td>0.11±0.01±0.04</td>
<td>11.1$\sigma$</td>
<td></td>
</tr>
<tr>
<td>$f_0(2020)$</td>
<td>2010±6$^{+6}_{-4}$</td>
<td>203±9$^{+13}_{-11}$</td>
<td>1992</td>
<td>442</td>
<td>2.28±0.12±0.29</td>
<td>24.6$\sigma$</td>
<td></td>
</tr>
<tr>
<td>$f_0(2330)$</td>
<td>2312±7$^{+7}_{-3}$</td>
<td>65±10$^{+3}_{-12}$</td>
<td>2314</td>
<td>144</td>
<td>0.10±0.02±0.01</td>
<td>13.2$\sigma$</td>
<td></td>
</tr>
<tr>
<td>$\eta_1(1855)$</td>
<td>1855±9$^{+6}_{-1}$</td>
<td>188±18$^{+8}_{-8}$</td>
<td>-</td>
<td>-</td>
<td>0.27±0.04±0.02</td>
<td>21.4$\sigma$</td>
<td></td>
</tr>
<tr>
<td>$f_2(1565)$</td>
<td>1542</td>
<td>122</td>
<td>1542</td>
<td>122</td>
<td>0.32±0.05±0.12</td>
<td>8.7$\sigma$</td>
<td></td>
</tr>
<tr>
<td>$f_2(2010)$</td>
<td>2062±6$^{+10}_{-7}$</td>
<td>165±17$^{+10}_{-5}$</td>
<td>2011</td>
<td>202</td>
<td>0.71±0.06±0.10</td>
<td>13.4$\sigma$</td>
<td></td>
</tr>
<tr>
<td>$f_4(2050)$</td>
<td>2018</td>
<td>237</td>
<td>2018</td>
<td>237</td>
<td>0.06±0.01±0.03</td>
<td>4.6$\sigma$</td>
<td></td>
</tr>
<tr>
<td>$h_1(1415)$</td>
<td>1416</td>
<td>90</td>
<td>1416</td>
<td>90</td>
<td>0.08±0.01±0.01</td>
<td>10.2$\sigma$</td>
<td></td>
</tr>
<tr>
<td>$h_1(1595)$</td>
<td>1584</td>
<td>384</td>
<td>1584</td>
<td>384</td>
<td>0.16±0.02±0.03</td>
<td>9.9$\sigma$</td>
<td></td>
</tr>
</tbody>
</table>

\[
\frac{\mathcal{B}(f_0(1500) \to \eta')}{\mathcal{B}(f_0(1500) \to \pi \pi)} = (8.96^{+2.95}_{-2.87}) \times 10^{-2}
\]

Consistent with PDG

\[
\frac{\mathcal{B}(f_0(1710) \to \eta')}{\mathcal{B}(f_0(1710) \to \pi \pi)} < 1.61 \times 10^{-3}
\]

@90% C.L.

This suppressed decay rate supports the hypothesis that the $f_0(1710)$ has a large overlap with the ground state scalar glueball (PRD 92,121902)
Partial Wave Analysis of $\Upsilon / \Psi \to \gamma \eta' \eta'$

PWA of $\Upsilon / \Psi \to \gamma \eta' \eta'$ using 10 Billion of $\Upsilon / \Psi$ data @ BESIII

$\eta' \to \gamma \pi^+ \pi^- / \pi^+ \pi^- (\eta \to \gamma \gamma)$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$M$(MeV/$c^2$)</th>
<th>$\Gamma$(MeV)</th>
<th>B.F.</th>
<th>Significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(2020)$</td>
<td>$1982 \pm 3^{+54}_{-0}$</td>
<td>$436 \pm 4^{+46}_{-49}$</td>
<td>$(2.63 \pm 0.06^{+0.31}_{-0.46}) \times 10^{-4}$</td>
<td>$\gg 25$</td>
</tr>
<tr>
<td>$f_0(2330)$</td>
<td>$2312 \pm 2^{+10}_{-0}$</td>
<td>$134 \pm 5^{+30}_{-9}$</td>
<td>$(6.09 \pm 0.64^{+4.00}_{-1.68}) \times 10^{-6}$</td>
<td>$16.3$</td>
</tr>
<tr>
<td>$f_0(2480)$</td>
<td>$2470 \pm 4^{+4}_{-0}$</td>
<td>$75 \pm 9^{+11}_{-8}$</td>
<td>$(8.18 \pm 1.77^{+3.73}_{-2.23}) \times 10^{-7}$</td>
<td>$5.2$</td>
</tr>
<tr>
<td>$h_1(1415)$</td>
<td>$1384 \pm 6^{+9}_{-0}$</td>
<td>$66 \pm 10^{+12}_{-10}$</td>
<td>$(4.69 \pm 0.80^{+0.74}_{-1.82}) \times 10^{-7}$</td>
<td>$5.3$</td>
</tr>
<tr>
<td>$f_2(2340)$</td>
<td>$2346 \pm 8^{+22}_{-6}$</td>
<td>$332 \pm 14^{+26}_{-12}$</td>
<td>$(8.67 \pm 0.70^{+0.61}_{-1.67}) \times 10^{-6}$</td>
<td>$16.1$</td>
</tr>
<tr>
<td>$0^{++}$ PHSP</td>
<td>...</td>
<td>...</td>
<td>$(1.17 \pm 0.23^{+4.09}_{-0.70}) \times 10^{-5}$</td>
<td>$15.7$</td>
</tr>
</tbody>
</table>

- $f_0(2020), f_0(2330)$ and $f_2(2340)$ observed in $\eta' \eta'$ decay mode for the first time

$f_0(2020)$:
- Its large production rate in radiative $\Upsilon / \Psi$ decay suggest a large overlap with scalar glueball
- Indication that it is a flavor singlet [Phys. Lett. B 826, 136906]
Structures between 1.8 - 1.9 GeV

$J/\psi \rightarrow \gamma K_s^0 K_s^0 \eta$

$J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

$J/\psi \rightarrow \gamma \phi$

$J/\psi \rightarrow \gamma K^0 S K^0 S \eta$

$J/\psi \rightarrow \gamma\eta\pi^+\pi^-$

$J/\psi \rightarrow \gamma\eta'(\pi^+\pi^-)$

$J/\psi \rightarrow \gamma\omega\phi$

$J/\psi \rightarrow \gamma (\pi^+\pi^-)$
A new state in $M(\eta'\pi^+\pi^-)$ invariant mass is observed around 2.6 GeV/$c^2$, which is correlated to a structure in $M(\pi^+\pi^-)$ @ 1.5 GeV/$c^2$.
X(2600): A New State Observed in $J/\psi \rightarrow \gamma \pi^+\pi^- \eta'$

- Simultaneous fit to $\eta'\pi^+\pi^-$ and $\pi^+\pi^-$ mass spectra is performed

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV/c²)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(1500)$</td>
<td>$1492.5 \pm 3.6^{+2.4}_{-2.05}$</td>
<td>$107 \pm 9^{+21}_{-7}$</td>
</tr>
<tr>
<td>$X(1540)$</td>
<td>$1540.2 \pm 7.0^{+36.3}_{-6.1}$</td>
<td>$157 \pm 19^{+11}_{-7}$</td>
</tr>
<tr>
<td>$X(2600)$</td>
<td>$2618.3 \pm 2.0^{+16.3}_{-1.4}$</td>
<td>$195 \pm 5^{+26}_{-17}$</td>
</tr>
</tbody>
</table>

- X(2600) resonance observed for the first time with a statistical significance greater than 20σ

- The structure in $M(\pi^+\pi^-)$ around 1.5 GeV/c² can be well described with the interference between $f_0(1500)$ and the $X(1540)$ resonances
Observation of $X(1835), X(2120), X(2370)$ in $J/\psi$ EM Dalitz Decays

10 Billion of $J/\psi$ data @ BESIII

Access to the EM transition form factor between $J/\psi$ and $X(1835)$ states
• Additional information on the internal structure of $X(1835)$

$$F(q^2) = \frac{1}{1 - q^2/\Lambda^2}$$
$$\Lambda = 1.75 \pm 0.29 \pm 0.05 \text{ GeV}/c^2$$

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Charmonium(-like) Spectroscopy

\[ \psi, Y \quad J^{PC} = 1^{--} \]
Charmonium-like states

Conventional charmonia fit well with potential model calculations

\[ V_{cc} = -\frac{4}{3} \cdot \frac{\alpha_s(r)}{r} + k \cdot r + \text{spin-dependent terms} \]

Several unexpected states observed
Vector states $\psi(4230)$ and $\psi(4360)$

Y(4260) first seen by BaBar (PRL95, 142001); split into states Y(4230) and Y(4360) by BESIII

- Inconsistent with simple $c\bar{c}$ scenario
- Candidates for exotic:
  - Hybrid?
  - Hadronic Molecule?
  - Tetraquark?
**Vector states**

**arXiv:2206.08554** \( e^+e^- \rightarrow \pi^+\pi^-J/\psi \)

- **Improved** precision w.r.t previous results [PRL118, 092001]
- Y(4220) and Y(4320) resonances are observed with > 10\(\sigma\)
- Structure around 4.0 GeV is better described using a BW
- Evidence of additional structure around 4.5 GeV, identified with the \(\psi(4415)\)
  - it influences the evaluation of the Y(4230) parameters

**arXiv:2204.07800** \( e^+e^- \rightarrow K^+K^-J/\psi \)

Observation of the Y(4230) with >5\(\sigma\) and new structure Y(4500) with >8\(\sigma\)

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Open charm production

- Measurement of $e^+e^- \rightarrow D^{*+}D^{*-}$ and $e^+e^- \rightarrow D^{*+}D^-$
- Conventional states above threshold mainly decays into open-charm mesons, while charmonium-like states mainly decay into hidden-charm final states
- Consistent with previous results with better precision
- Sophisticated models with further studies on couple-channel effects needed to understand non-trivial structure
\[ \psi_2(3823) \text{- the } \psi(1^3D_2) \text{ state?} \]

- \[ e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823); \psi_2(3823) \rightarrow \gamma\chi_{c1} \]
- update study of \( \psi_2(3823) \rightarrow \gamma\chi_{c1} \) (PRL115,011803) allowing missing photon

\[ M[\psi_2(3823)] = 3823.12 \pm 0.43 \pm 0.13 \text{ MeV}/c^2 \]
\[ \Gamma[\psi_2(3823)] < 2.9 \text{ MeV} \]
@90\% C.L.

Most precise to date

First observation of Y states decaying into D-wave charmonium state (two resonant structures with > 5\sigma)

L = 2 slightly favored over L=0
The Charged $Z_{CS}(3985)$ state

Search for the strange partner of $Z_c(3900)$

$$e^+e^- \rightarrow K^+(D_S^--D^{*0} + D_s^{*-}D^0)$$

- Using 5 new datasets collected at $\sqrt{s}>4.6$ GeV
- $5.3\sigma$ excess close to threshold for data at $\sqrt{s} = 4.681$ GeV
  - Similar to $Z_{cs}(4000)$ seen by LHCb, but with different width [PRL127,082001(2021)]
- Minimal quark-content of $c\bar{s}\bar{u}$

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Evidence of neutral open-strange hidden charm state, $Z_{CS}(3985)^0$ with a significance of 4.6σ

- Minimal quark content $c\bar{s}d$
- $\sigma^{\text{Born}}(e^+e^-\rightarrow K^0Z_{CS}(3985)^0)$ consistent with $\sigma^{\text{Born}}(e^+e^-\rightarrow K^-Z_{CS}(3985)^+)$ as expected under isospin symmetry

<table>
<thead>
<tr>
<th>Mass (MeV/c²)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{cs}(3985)^0$</td>
<td>$3992.2 \pm 1.7 \pm 1.6$ $7.7^{+4.1}_{-3.8} \pm 4.3$</td>
</tr>
<tr>
<td>$Z_{cs}(3985)^+$</td>
<td>$3985.2^{+2.1}<em>{-2.0} \pm 1.7$ $13.8^{+8.1}</em>{-5.2} \pm 4.9$</td>
</tr>
</tbody>
</table>

Evidence of the isospin partner of the $Z_{CS}(3985)^+$
Strangeonía Spectrum
Strangeonium Spectrum

**Strangeonium mesons**
- Bridge between light quarks (u, d) and heavy quarks (c, b)
- Study of exotic states

Only few states observed:
- Small BR
- Large $\Gamma$

- $\phi(2170)/Y(2175)$ observed for the first time in the $\phi f_0$ channel by BaBar (PRD 74,091103; PRD 76,031102)
  - **BESIII: PRL100,102003(2008)**
  - Belle: PRD80,031101 (2009)
What is the $\phi(2170)$? Many interpretations include:

- $\bar{s}\bar{s}g$ hybrid
- $2^3D_1$ or $3^3S_1$
- tetraquark
- molecular state $\Lambda\Lambda$
- $\phi f_0(980)$ resonance with FSI
- Three body system $\phi KK$

The nature of $\phi(2170)$ still not fully understood!
Consistent with BaBar PRD 88, 032012 (2018); PRD 92, 072008 (2015);

\[ M = 2239.2 \pm 7.1 \pm 11.3 \text{ MeV}/c^2 \]
\[ \Gamma = 139.8 \pm 12.3 \pm 20.6 \text{ MeV} \]

Consistent with BaBar PRD 104, 092014 (2021)

\[ M = 2273.7 \pm 5.7 \pm 19.3 \text{ MeV}/c^2, \]
\[ \Gamma = 86 \pm 44 \pm 51 \text{ MeV}, \]

Consistent with BaBar PRD 101, 012011 (2020)
The ratio between $\phi \eta$ and $\phi \eta'$ partial width is important observable to access $\phi(2170)$ as a $\bar{s}s$g hybrid state

- partial width larger in the $\phi \eta$ channel by a factor [3-200] w.r.t $\phi \eta'$

**PRD 104, 032007**

**PRD 102.012008(2020)**

$Br \left[ \phi(2170) \rightarrow \phi \eta \right] \Gamma_{ee} \frac{1}{Br \left[ \phi(2170) \rightarrow \phi \eta' \right] \Gamma_{ee}} = \frac{0.03^{+0.02}_{-0.01}}{1.42^{+0.56}_{-0.46}}$

Small than prediction of the $\tilde{s}s$g hybrid model by several order o magnitude
Measurement of $e^+e^- \to K^+K^−\pi^0$ cross section

PWA analysis to 19 data points between 2.000 GeV and 3.080 GeV

- Structure observed in the cross section of the intermediate processes $e^+e^- \to K^*(892)K^-$ and $e^+e^- \to K_2^{*+}(1430)K^-$ with a significance of $7.1\sigma$

$$R = \frac{Br(\phi(2170) \to K_2^{*+}(1430)K^-)}{Br(\phi(2170) \to K^{*+}(892)K^-)} \sim 12.6 \pm 4.5 \text{ Sol1} \quad 22.7 \pm 4.1 \text{ Sol2}$$
Measurement of $e^+e^-\rightarrow\phi\pi^+\pi^-$ cross section

- 22 data points between 2.000 GeV and 3.080 GeV

- Clear structure ($\phi(2170)$) and enhancement ($X(2400)$) can be seen at around 2.1 and 2.4 GeV, respectively
  - significance of 8.5$\sigma$ for the $X(2400)$

- Cross section consistent with previous BaBar (PRD86, 012008) and Belle data (PRD80, 031101(R))

- Independent data sample in the $\phi(1680)$ mass region is needed for further investigation

- More data points in the 2.4 GeV region for a deeper investigation of $X(2400)$

**Data Points**

- $\phi(2170)$
  - $M = 2158^{+30}_{-33} \pm 4$ MeV/c$^2$
  - $\Gamma = 218^{+81}_{-64} \pm 5$ MeV

- $X(2400)$
  - $M = 2298^{+60}_{-44} \pm 6$ MeV/c$^2$
  - $\Gamma = 219^{+117}_{-112} \pm 6$ MeV

$\sqrt{s}$ (GeV) vs. $\sigma^{\phi\pi^+\pi^-}$ (nb)
Summary and Outlook

- BESIII is taking data since 2008. It will continue to run ~2030
  - Selection of latest physics results (based mainly on spectroscopy) are presented
    - Observation of exotic isoscalar $\eta_1(1855)$ state and the new $X(2600)$ state observed in $J/\psi$ radiative decays
    - $Y$ states and $Z_{CS}(3985)$ triplet states
    - Latest search on the $\phi(2170)$ strangeonium state
    - …. Many other not covered in this talk
- Many analysis in progress!!!
- First data at higher c.m. energies in now available ($4.7 < \sqrt{s} < 4.94$ GeV)
- Further upgrade in energy (5.6 GeV) and luminosity (BEPCII-U, 3x) planned for the next year

Thank you for your attention
Back-up slides
The BESIII Detector


Electromagnetic CsI(Tl) Calorimeter
- $\sigma_{E}/E < 2.5\%$ @ 1 GeV (barrel)
- $\sigma_{E}/E < 5\%$ @ 1 GeV (end caps)
- $\sigma_{xy} \sim (6 \text{ mm})/E^{1/2}$ @ 1 GeV

Drift Chamber
- $\sigma_{r\phi} \sim 130$ μm (single wire)
- $\sigma_{pt}/p_{t} \sim 0.5\%$ @ 1 GeV

RPC Muon Detector
- $\Delta\Omega/4\pi = 93\%$

ToF
- $\sigma_{t} \sim 90$ ps (barrel)
- $\sigma_{t} \sim 120$ ps (end caps)

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BESIII physics programme

Light hadron physics
- Meson and baryon spectroscopy
- Multiquark states
- Threshold effects
- Glueballs and hybrids
- Two-photon physics
- Form factors

QCD and $\tau$
- Precision $R$ measurement
- $\tau$ decay

Charmonium physics
- Precision spectroscopy
- Transitions and decays

XYZ meson physics
- $Y(4260), Y(4360)$ properties
- $Z_c(3900)^+, \ldots$

Charm physics
- Semi-leptonic form factors
- Decay constants $f_D$ and $f_{D_s}$
- CKM matrix: $|V_{cd}|$ and $|V_{cs}|$
- $D^0-\overline{D}^0$ mixing, CPV
- Strong phases

Precision mass measurements
- $\tau$ mass
- $D, D^*$ mass

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Amplitude Analyses in BESIII

- J/ψ radiative decays are ideal for searching glueballs
  - J/ψ → γPP: 0^{++}, 2^{++}, ...
  - J/ψ → γPPP, γVV: 0^{++}
- Neutral channel is much cleaner than the charged ones
- Very complicated mass spectrum in the low mass region: many broad, overlapping states complicate the study of the spectra

- Amplitude analysis: toll to extract the complex amplitudes from experimental data
  - Models with free parameters
  - Consider the kinematic of final states particles
  - Vary the parameters to maximize the likelihood
  - **Mass Dependent (MD) PWA**: model the dynamics of particle interactions as coherent sum of resonances
  - **Mass Independent (MI) PWA**: make minimal model assumptions and measure the dynamical amplitudes independently in small regions of two-meson invariant mass (PRD92, 052003 (2015))

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• 0++: the production rate $f_0(1710)$ is compatible with LQCD prediction for a pure gauge scalar glueball
• 2++: $f_0(2340)$ seems to be a good candidate for tensor glueball [PRL111,091601] (large production rate)
• 0−+: $\eta(2225)$ is confirmed and two additional pseudoscalar states, $\eta(2100)$ and $X(2500)$, are observed
First Observation of X(2370) in $J/\psi \rightarrow \gamma K\bar{K}\eta'$

$1.3 \times 10^9 J/\psi$ @ BESIII

EPJC 80, 746 (2020)
PWA of $J/\psi \rightarrow K^+ K^- \pi^0$

Dominant contribution from $K^*(892)$
First observation of $K^*_2(1980)$ and $K^*_4(2045)$ in $J/\psi$ decays
Two clear $J^{PC}=1^{--}$ structures observed in $K^+ K^-$ mass spectrum: possible relation with $\omega(1650)$ and $\rho(2150)$
Observation of $\phi(1680)$ in the KK mass spectra
1$^{−−}$ state needed to describe the dip around 1.7 GeV/$c^2$ in the KK mass spectra (X(1750)? but not excluded the possibility to be the $\rho(1700)$)

A broad structure around 2.2 GeV/$c^2$ is observed, either $\phi(2170)$ or $\rho(2150)$?
<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$0^{++}$</th>
<th>$2^{++}$</th>
<th>$4^{++}$</th>
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</thead>
<tbody>
<tr>
<td>$J/\psi \rightarrow \gamma X \rightarrow \gamma \eta'$</td>
<td>$f_0(1500)$</td>
<td>$f_2(1525)$</td>
<td>$f_4(2050)$</td>
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<td>$f_0(1710)$</td>
<td>$f_2(1565)$</td>
<td>$f_4(2300)$</td>
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<td></td>
<td>$f_0(1810)$[58]</td>
<td>$f_2(1640)$</td>
<td>$f_4(2283)$[57]</td>
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<td>$f_0(2020)$</td>
<td>$f_2(1810)$</td>
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<td>$f_0(2100)$</td>
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<td>$f_0(2200)$</td>
<td>$f_2(1950)$</td>
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<td>$f_2(2010)$</td>
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<td>$f_0(2102)[57]$</td>
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<td>$f_0(2330)[57]$</td>
<td>$f_2(2220)$</td>
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<tr>
<td>$J/\psi \rightarrow \eta(1^{+}) X \rightarrow \gamma \eta'$</td>
<td>$f_2(2240)$[57]</td>
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<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$1^{--}$</th>
<th>$1^{+-}$</th>
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<tbody>
<tr>
<td>$\omega(1420)$</td>
<td>$h_1(1415)$</td>
<td>$h_1(1595)$</td>
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<tr>
<td>$\omega(1650)$</td>
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<tr>
<td>$\phi(1680)$</td>
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<tr>
<td>$\phi(2170)$</td>
<td>$\rho(1450)$</td>
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<td>$\rho(1450)$</td>
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<td>$\rho(1700)$</td>
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<td>$\rho(1900)$</td>
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</tbody>
</table>

![Graphical data](image-url)
First Observation of X(2370) in $J/\psi \rightarrow \gamma K \bar{K} \eta'$

- X(2120) and X(2370) states observed in the $\pi^- \pi^+ \eta'$ invariant mass spectra (PRL106, 072002)
- The X(2370) measured mass is consistent with the pseudoscalar glueball candidate predicted by LQCD calculation (PRD73, 014516)

Simultaneous fit performed for two decay $\eta'$ modes

- No evidence of X(2120) is found
  
  $\mathcal{B}(J/\psi \rightarrow \gamma X(2120) \rightarrow \gamma K^+ K^- \eta') < 1.49 \times 10^{-5}$
  
  $\mathcal{B}(J/\psi \rightarrow \gamma X(2120) \rightarrow \gamma K_S^0 K_S^0 \eta') < 6.38 \times 10^{-6}$

- Clear X(2370) signal observed with significance of about 8.3σ
  
  $$M_{X(2370)} = 2341.6 \pm 6.5 \pm 5.7 \text{ MeV/c}^2 \quad \Gamma_{X(2370)} = 117 \pm 10 \pm 8 \text{ MeV}$$
  
  $\mathcal{B}(J/\psi \rightarrow \gamma X(2370) \rightarrow \gamma K^+ K^- \eta') = (1.79 \pm 0.23 \pm 0.65) \times 10^{-5}$
  
  $\mathcal{B}(J/\psi \rightarrow \gamma X(2370) \rightarrow \gamma K_S^0 K_S^0 \eta') = (1.18 \pm 0.32 \pm 0.39) \times 10^{-5}$

1.3×10^9 J/ψ @ BESIII

EPJC 80, 746 (2020)
Search for $X(2370)$ in $J/\psi \to \gamma \eta \eta'$

Branching ratios prediction for the decay of pseudoscalar glueball with $M \sim 2.37$ GeV into three pseudoscalar mesons (PRD 87,054036 (2013))

$$\Gamma_{G \to \eta \eta'}/\Gamma_{G}^{tot} = 0.00082$$
$$\Gamma_{G \to KK'}/\Gamma_{G}^{tot} = 0.011$$
$$\Gamma_{G \to \pi \pi'}/\Gamma_{G}^{tot} = 0.090$$

- No obvious signal of $X(2370)$

Simultaneous unbinned maximum likelihood fit to the $\eta \eta'$ is performed and the 90% C.L. upper limit is calculated

$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma \eta \eta') < 9.2 \times 10^{-6}$$

$$\mathcal{B}(J/\psi \to \gamma \eta_c) \cdot \mathcal{B}(\eta_c \to \eta \eta') = (4.86 \pm 0.62 \pm 0.45) \times 10^{-5}$$

**FIRST OBSERVATION** in the $\eta \eta'$ invariant mass spectra
\( \phi(2170) \) @ BESIII

![Graph showing data points and theoretical prediction](image)

Data points:
- BESIII 2015
- BESIII 2012

Theoretical prediction:
Resonant structure in the 4K spectra, but difficult to disentangle from other final state

$\phi(2170)$ or new strangeonium state?

PRD 99, 112008 (2019) - $1.3 \times 10^9 \, \text{J}/\psi$ events

$\text{J}/\psi \rightarrow \phi \eta'$

- Evidence of a structure in the $\phi \eta'$ mass spectra
- Distribution of $\eta$ polar angle in the $\text{J}/\psi$ rest frame used to investigate the $J^p$ assignment
- Significance of structure: 4.4$\sigma$ for $J^p = 1^-$ and 3.8 for $J^p = 1^+$

no PDG entries

mass 5$\sigma$ away from that reported on PDG