



# Light meson spectroscopy at BESIII

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### Outline



- Glueball
- Structure near pp
   threshold
- Strange quarkonium(*s*s̄)
- 2 Summary

- Light meson spectroscopy
  - Key tool to study/develop QCD in non-perturbative region
- Conventional quark model: Meson(qq̄), Baryon(qqq)
- Exotic hadronic state predicted by QCD
  - Glueball( $gg, ggg \cdots$ )
  - Hybrid state(qqg, qqqg)
  - Multi-quark state( $N_{q(\bar{q})} \ge 4$ )
- Searching for those states helps study gluon field and understand color confinement
- Lattice QCD(LQCD) predicted the glueball spectrum and their quantum numbers
- Glueball with ordinary quantum number can be mixed with nearby qq
   states
  - Systematical study needed in the identification

#### Phys.Rev.D 73 (2006) 014516



# **BESIII's advantages**

- Gluon-rich process
- Clean, high-statistics data samples directly from  $e^+e^-$  collisions
- $I, J^{PC}$  filter



# Amplitude analysis of $J/\psi \rightarrow \gamma K_S K_S$

#### LQCD prediction of scalar glueball

- Mass: 1.5~1.7 GeV [Phys.Rev.D 87 (2013) 9, 092009]
- Production in radiative  $J/\psi$  decay:  $\mathcal{B}(J/\psi \to \gamma G_{0^+}) = 3.8(9) \times 10^{-3}$ [Phys.Rev.Lett. 110 (2013) 2, 021601]



- Dominant amplitudes include the  $f_0(1710), f_0(2200), f'_2(1525)$
- $f_0(1710) \sim 10$  times larger production than  $f_0(1500)$  in  $J/\psi \rightarrow \gamma \eta \eta$  [Phys.Rev.D 87 (2013) 9, 092009] and  $J/\psi \rightarrow \gamma K_S K_S$ 
  - Measured mass  $\sim$ 1.7 GeV
  - Production of  $f_0(1710)$  in radiative  $J/\psi$  decay (>  $1.7 \times 10^{-3}$ ) close to theoretical prediction of scalar glueball

### Pseudo-scalar glueball candidate

#### LQCD prediction of Pseudo-scalar glueball

- Mass: 2.3~2.6 GeV [Phys.Rev.D 73 (2006) 014516]
- Production in radiative J/ $\psi$  decay:  $\mathcal{B}(J/\psi \to \gamma G_{0^{-+}}) = 2.31(80) \times 10^{-4}$  [Phys.Rev.D 100 (2019) 5, 054511]
- X(2370) firstly observed in  $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$ 
  - Measured mass:  $2376.3 \pm 8.7(\text{stat.})^{+3.2}_{-4.3}(\text{sys.}) \text{ MeV}$
  - Consistent with LQCD prediction to pseudo-scalar glueball



Chiral effective Lagrangian calculation[Phys.Rev.D 87 (2013) 5, 054036]

• For pseudo-scalar glueball mass of 2.37 GeV,  $\mathcal{B}(G \to \eta \eta \eta'), \ \mathcal{B}(G \to KK\eta'), \ \mathcal{B}(G \to \pi \pi \eta')=0.00082, 0.011, 0.090$ 



• X(2370) is observed in  $J/\psi \rightarrow \gamma K \bar{K} \eta'$ 

- Measured mass:  $2341.6 \pm 6.5 (stat.) \pm 5.7 (sys.)$  MeV
- $\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma K \bar{K} \eta')$ : 1.79 ± 0.23(stat.) ± 0.65(sys.) × 10<sup>-5</sup>

### Search of X(2370)



### • No X(2370) signal in $J/\psi \rightarrow \gamma \eta \eta \eta'$ , $\mathcal{B}(J/\psi \rightarrow \gamma X(2370) \rightarrow \gamma \eta \eta \eta')$ < 9.2 × 10<sup>-6</sup> at 90% C.L.

• No contradiction to the calculation for X(2370) as 0<sup>-+</sup> glueball

• Search X(2370) in more decays with high statistics  $J/\psi$  data to determine its  $J^{PC}$ 

#### Structure near $p\bar{p}$ threshold

# $X(1835)/X(p\bar{p})$

### X(pp̄)

 Anomalous strong enhancement structure at pp
 threshold in J/ψ → γpp
 , firstly observed by
 BES, J<sup>PC</sup> favor 0<sup>-+</sup>



#### ● X(1835)

- Observed in  $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$  (BESII, BESIII),  $J^{PC}$  favor  $0^{-+}$
- Anomaly line shape near pp
   threshold
- ? pp molecule state or bound state



#### Structure near $p\bar{p}$ threshold

## Search of X(1835)

- $J/\psi \to \gamma \gamma \phi$ 
  - Flavor filter
  - First observation of  $\eta(1475)/X(1835) \rightarrow \gamma \phi$ ,  $J^{PC}$  favor  $0^{-+}$ 
    - Sizable ss components
  - *X*(1835) seems unlikely to be a pure *NN* bound state

•  $J/\psi \to \omega \pi^+ \pi^- \eta'$ 

- Provide information on  $q\bar{q}$  or gluon component of X(1835)
- No evident signal of X(1835)
- $\mathcal{B}(J/\psi \to \omega X(1835) \to \omega \pi^+ \pi^- \eta') < 6.2 \times 10^{-5}$  at 90% C.L.

#### Phys.Rev.D 97 (2018) 5, 051101





#### Strange quarkonium(ss)

- Strangeonium spectroscopy is not well understood experimentally
  - Only 7 states in the expected spectrum assigned to the observed mesons(marked with red solid lines)
- Study of the strangeonium mesons is of particular interest
  - Bridge between light u, d quark and heavy c, b quark
  - Helps to identify the exotics



# Recent highlights

#### Strange quarkonium(ss)

# Partial wave analysis of $J/\psi \rightarrow K^+ K^- \pi^0$

- Reveal signals not observed before due to low statistics [Phys.Rev.Lett. 97 (2006) 142002]
- Precisely determine properties of intermediate states



Phys.Rev.D 100 (2019) 3, 032004

- $K\pi^0$ 
  - Dominated by  $K^*(892)^{\pm}$
  - Observe  $K_2^*(1980)^{\pm}$  and  $K_4^*(2045)^{\pm}$  for the first time in  $J/\psi$  decays
- *K*<sup>+</sup>*K*<sup>−</sup>
  - Two broad 1<sup>--</sup> structures in K<sup>+</sup>K<sup>-</sup>
    - Possibly assigned to  $\omega(1650)$  and  $\rho(2150)$
    - Further studies on  $J/\psi \to K_S K \pi$  and  $J/\psi \to K^+ K^- \eta$  needed

# Recent highlights

#### Strange quarkonium(ss)

# Partial wave analysis of $\psi(3686) \rightarrow K^+ K^- \eta$

 Large statistics allows re-examine previous analysis [Phys.Rev.D 86 (2012) 072011] and study of K\* states



● K<sup>+</sup>K<sup>-</sup>

- Observe  $\phi(1680)$  and another  $1^{--}$  state, which consistent with X(1750) reported by FOCUS
- Broad structure around 2.2 GeV contributed from:
  - $1^{--}$ :  $\phi(2170)/\rho(2150)$  or both
  - $3^{--}$ :  $\rho_3(2250)$
- Difficult to distinguish these excited  $\rho$  and  $\phi$  states due to limited statistics
  - Need help from other decays, e.g.  $\psi(3686) \rightarrow \pi^+\pi^-\eta$

• Dominated by  $\textit{K}^*_2(1980)^\pm$  and  $\textit{K}^*_3(1780)^\pm$ 

#### Strange quarkonium(ss)

# Strangeonium-like Zs

- Replace cc̄ with ss̄ in Z<sub>c</sub>
  - Analogous structure: Z<sub>s</sub>
- Search  $Z_s$  in  $\pi^{\pm}\phi$  around  $K^*\bar{K}$  threshold
- Amplitude analysis on  $e^+e^- \rightarrow \phi \pi \pi$ 
  - Can be described by  $\phi \sigma$ ,  $\phi f_0(980)$ ,  $\phi f_0(1370)$ ,  $\phi f_2(1270)$
  - Upper limit on the cross section of Z<sub>s</sub> at 90% C.L. for different mass/width hypotheses determined





#### Phys.Rev.D 99 (2019) 1, 011101



#### 108.49 pb<sup>-1</sup>@ 2.125 GeV

### Summary

- Glueball
  - Production of  $f_0(1710)$  ~10 times larger than  $f_0(1500)$  in radiative  $J/\psi$  decays
    - $f_0(1710)$  largely overlap with scalar glueball
  - X(2370) observed in  $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$ ,  $\gamma K \bar{K} \eta'$ , and no signal in  $J/\psi \rightarrow \gamma \eta \eta \eta'$
- Structure near pp
   threshold
  - $\eta(1475)/X(1835)$  observed in  $J/\psi \to \gamma\gamma\phi$
  - No X(1835) signal in  $J/\psi \rightarrow \omega \pi^+ \pi^- \eta'$
- Strangeonium
  - X(1750) and possible  $\phi(2170)$  observed in  $\psi(3686) \rightarrow K^+ K^- \eta$
  - Two  $1^{--}$  structures, possibly  $\omega(1650)$  and  $\rho(2150),$  observed in  $J/\psi\to K^+K^-\pi^0$
  - Upper limit of  $Z_s$  determined in  $e^+e^- \rightarrow \phi \pi \pi$
- BESIII already collected  ${\sim}10{\rm B}\,{\rm J}/\psi,\,{\sim}3{\rm B}\,\psi(3686)$  and going to run for another 10 years
- ★ Using the unprecedented high statistics data, more fascinating results in light meson spectroscopy are expected

# **BACK UP**

# Beijing Electron Positron Collider(BEPC)





- Start construction since 1984
- *E<sub>cm</sub>*: 2 ~ 4.6 GeV (5.0 GeV since summer 2019)

### BEPC(1989-2005)

• 
$$L_{\text{peak}} = 1.0 \times 10^{31} (\text{cm}^2 \cdot \text{s})^{-1}$$

### BEPCII(2008-now)

• 
$$L_{\text{peak}} = 1.0 \times 10^{33} (\text{cm}^2 \cdot \text{s})^{-1}$$
  
(April 5, 2016)

### **BESIII** detector



### Glueball spectrum



- Those states with ordinary quantum number can be mixed with nearby qq
   states
  - Systematical study needed in the identification

### Scalar glueball candidate

s.Rev.D 8	7 (2013) 9, 0	92009	Phys.Rev.D 98	(2018)	7, 072	003	Phys	.Rev.D	92 (2015	) 5, 052003	
Events, 0.020 GeV/c <sup>2</sup> Events, 0.020 GeV/c <sup>2</sup> 200	M	all Events / 20 MeV/c <sup>2</sup>		2 <sup>4</sup> mbin=1.42 + Data - Global I	na na tist Maria	10 <sup>5</sup> 10 <sup>5</sup> 10 <sup>1</sup> 10 <sup>1</sup> 10 <sup>1</sup> 10 <sup>1</sup> 10 10					Relative Stave (2004 and maximum)
	1.5 2 2 M <sub>rp1</sub> (GeV/c <sup>2</sup> )	۵ 5 3	4 1 12 14 16 18 2 Mass(K <sub>6</sub> K <sub>6</sub>	1 11 1 2.2 2.4 ) [GeV/c <sup>2</sup> ]	<u>11 11</u> 26 28 3	, L	0.5 1.	0 1.5 Mas	2.0 s(1 <sup>0</sup> 11 <sup>0</sup> ) [GeV/c <sup>2</sup> ]	2.5	10 <sup>-4</sup> 3.0
ind <sub>o</sub>	1.5 2 2 M <sub>iji</sub> (GeV/c <sup>2</sup> )	1.5 3 .5 3	4 12 14 16 18 2 Mass(K <sub>8</sub> K <sub>8</sub>	1411 11 " 2.2 2.4 .) [GeV/c <sup>2</sup> ]	Resonance	1 M (MeV/c <sup>2</sup> )	0.5 1.	0 1.5 Mas Γ (MeV/c <sup>2</sup> )	2.0 (π <sup>0</sup> π <sup>0</sup> ) [GeV/c <sup>2</sup> ] Γ <sub>PDG</sub> (MeV/c <sup>2</sup> )	2.5 Branching fraction	3.0 10 <sup>-4</sup> Significance
	1.5 2 2 M <sub>ηη</sub> (GeV/c <sup>2</sup> )	15 3	2 12 14 18 18 2 4 1 12 14 18 18 2 Mass(K <sub>8</sub> K <sub>8</sub>	11      2.2 2.4 .) [GeV/c <sup>2</sup> ]	Resonance K*(892)	1 <u>M (MeV/c<sup>2</sup>)</u> 896	0.5 1. M <sub>PDG</sub> (MeV/c <sup>2</sup> ) 895.81 ± 0.19	0 1.5 Mas Γ (MeV/c <sup>2</sup> ) 48	$\frac{2.0}{6}$ s(tPtt) [GeV(c <sup>2</sup> ) $\Gamma_{PDG}$ (MeV/c <sup>2</sup> ) $47.4 \pm 0.6$	2.5 Branching fraction (6.28 <sup>+0.10+0.39</sup> )×10 <sup>-6</sup>	10 <sup>-4</sup> Significance 35σ
	1.5 2 2 M <sub>rpl</sub> (GeV/c <sup>2</sup> )	5 3	a <b>1</b> 1.2 1.4 1.6 1.8 2 Mass(K <sub>6</sub> K <sub>6</sub>	  ) [GeV/c <sup>2</sup> ]	Resonance K*(892) K_1(1270)	M (MeV/c <sup>2</sup> ) 896 1272	0.5 1. <i>M<sub>PDG</sub></i> (MeV/c <sup>2</sup> ) 895.81 ± 0.19 1272 ± 7	0 1.5 Mas Γ (MeV/c <sup>2</sup> ) 48 90	$\Gamma_{PDG} (MeV/c^2)$ $47.4 \pm 0.6$ $90 \pm 20$	2.5 Branching fraction $(6.28^{+0.16+0.99}_{-17-0.52}) \times 10^{-6}$ $(8.54^{+1.07+2.53}_{-1.27-21.1}) \times 10^{-7}$	Significance 350 160
	1.5 2 2 M <sub>rpl</sub> (GeV/c <sup>2</sup> )	<u>.</u>	4 1.2 1.4 1.6 1.8 2 1.2 1.4 1.6 1.8 2 Mass(K <sub>S</sub> K <sub>S</sub>	  ) [GeV/c <sup>2</sup> ]	Resonance K*(892) K_1(1270) f_0(1370)	1 M (MeV/c <sup>2</sup> ) 896 1272 1350 ± 9 <sup>+12</sup> <sub>-2</sub>	0.5 1. <i>M<sub>PDG</sub></i> (MeV/c <sup>2</sup> ) 895.81 ± 0.19 1272 ± 7 1200 to 1500	0 1.5 Mas $\Gamma (MeV/c^2)$ 48 90 231 ± 21 <sup>±28</sup> _{48}	Σ.0         Σ.0           (m <sup>2</sup> m <sup>2</sup> )         [GeVVe <sup>2</sup> ]           Γ <sub>PDG</sub> (MeV/c <sup>2</sup> )           47.4 ± 0.6         90 ± 20           200 to 500         500	2.5 Branching fraction $(6.28^{+0.16+0.99}_{-0.753}) \times 10^{-6}$ $(8.54^{+0.023}_{-1.03}) \times 10^{-7}$ $(1.07^{+0.08+0.25}_{-0.03}) \times 10^{-5}$	3.0 <sup>-4</sup> Significance 35σ 16σ 25σ
	1.5 2 2 M <sub>rpl</sub> (GeV/c <sup>2</sup> )	<u>5</u> 3	2 <b>11 12 14 16 18 2</b> 1 12 14 16 18 2 Mass(K <sub>6</sub> K <sub>5</sub>	∦   †¶  `∦ '" 22 24 .)[GeV/c <sup>2</sup> ]	Resonance K*(892) K_1(1270) f_0(1370) f_0(1500)	M (MeV/c <sup>2</sup> ) 896 1272 1350 ± 9 <sup>+12</sup> 1505	0.5 1. M <sub>PDO</sub> (MeV/c <sup>2</sup> ) 895.81±0.19 1272±7 1200 to 1500 1504±6	0 1.5 Mas $\Gamma (MeV/c^2)$ 48 90 231 ± 21 <sup>28</sup> 109	Ξ.0           s(m <sup>2</sup> m <sup>2</sup> )         [GeV/c <sup>2</sup> ]           Γ <sub>PDO</sub> (MeV/c <sup>2</sup> )         47.4 ± 0.6           90 ± 20         200 to 500           109 ± 7         109 ± 7	$\begin{array}{c} \hline & \\ \hline \\ \hline$	10 <sup>-4</sup> 3.0 Significance 35σ 16σ 25σ 23σ
	1.5 2 2 1.5 M <sub>171</sub> (GeV/c <sup>2</sup> )	<u></u> 3	2 <b>17 1 17 17 1</b> 17 1 17 17 1 1 1.2 1.4 1.6 1.8 2 Mass(K <sub>2</sub> K <sub>3</sub>	₩ ₩ ₩ " 22 24 )[GeV/c <sup>2</sup> ]	Resonance K <sup>*</sup> (892) K <sub>1</sub> (1270) f <sub>0</sub> (1370) f <sub>0</sub> (1700) f <sub>0</sub> (1710)	$M$ (MeV/ $c^2$ ) 896 1272 1350 $\pm 9^{\pm 12}_{-2}$ 1505 1765 $\pm 2^{\pm 1}_{-1}$	0.5 1. M <sub>PD0</sub> (MeV/c <sup>2</sup> ) 895.81 ± 0.19 1272 ± 7 1200 to 1500 1504 ± 6 1723 <sup>+5</sup>	0 1.5 Mas $\Gamma$ (MeV/c <sup>2</sup> ) 48 90 231 ± 21 $\pm 38$ 109 146 ± 3 $\pm 7$ 10	Ξ.0           a(m <sup>2</sup> m <sup>2</sup> )         [GeV/c <sup>2</sup> ]           Γ <sub>PDD</sub> (MeV/c <sup>2</sup> )         47.4 ± 0.6           90 ± 20         200 to 500           109 ± 7         139 ± 8	$\begin{array}{c} \hline & \\ \hline \\ \hline$	3.0 Significance 35σ 16σ 25σ 23σ ≫ 35σ
	1.5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2		2 <b>1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1</b>	11       " 2.2 2.4 .)[GeV/c <sup>2</sup> ]	Resonance K <sup>*</sup> (892) K <sub>1</sub> (1270) f <sub>0</sub> (1370) f <sub>0</sub> (1500) f <sub>0</sub> (1700) f <sub>0</sub> (170)	$\frac{M (MeV/c^3)}{896}$ $\frac{896}{1272}$ $1505$ $\frac{1765 \pm 2^{+12}_{-1}}{1505}$ $\frac{1765 \pm 2^{+1}_{-1}}{1870 \pm 7^{+2}_{-2}}$	0.5 1. M <sub>PDO</sub> (MeV/c <sup>2</sup> ) 895.81±0.19 1272±7 1200 to 1500 1504±6 1723 <sup>1</sup> / <sub>2</sub>	0 1.5 Mas Γ (MeV/c <sup>2</sup> ) 48 90 231 ± 21 <sup>238</sup> / <sub>47</sub> 109 146 ± 3 <sup>+3</sup> / <sub>47</sub> 146 ± 14 <sup>25</sup> / <sub>47</sub>	L0           2.0           s(n <sup>2</sup> n <sup>2</sup> )           Γ <sub>PDG</sub> (MeV/c <sup>2</sup> )           47.4 ± 0.6           90 ± 20           200 to 500           109 ± 7           139 ± 8	2.5 Branching fraction $(6.28^{+0.18+0.97}) \times 10^{-6}$ $(8.54^{+0.23}) \times 10^{-7}$ $(1.0^{-0.08+0.03}) \times 10^{-7}$ $(1.39^{+0.18+0.05}) \times 10^{-5}$ $(2.00^{+0.02+0.05}) \times 10^{-5}$ $(2.00^{+0.02+0.05}) \times 10^{-5}$ $(1.14^{-0.06+0.05}) \times 10^{-5}$	10 <sup>-4</sup> Significance 35σ 16σ 25σ 23σ ≫ 35σ 24σ
Resource	1.5 2 2 M <sub>ηγ1</sub> (GeV/c <sup>2</sup> )	.5 3 With (MeV/c <sup>2</sup> )	$\frac{2}{\pi} \int_{-\infty}^{\infty} \frac{\left[ \frac{1}{2} \int_{-\infty}^{\infty} \frac{1}{2$	2.2 2.4 ) [GeV/c <sup>2</sup> ]	Resonance           K*(892)           K_1(1270)           fo(1370)           fo(1500)           fo(1710)           fo(2200)	$\frac{M \ ({\rm MeV}/c^2)}{896} \\ \frac{896}{1272} \\ \frac{1350 \ \pm 9^{-12}_{-1}}{1505} \\ \frac{1765 \ \pm 2^{-1}_{-1}}{1870 \ \pm 7^{-2}_{-3}} \\ 2184 \ \pm 5^{-4}_{-2} \\ \frac{1}{2}$	$\begin{array}{ccc} 0.5 & 1.\\ \hline M_{FDG} & (MeV/c^2) \\ 895.81 \pm 0.19 \\ 1272 \pm 7 \\ 1200 & 10 & 1500 \\ 1504 \pm 6 \\ 1723\frac{16}{12} \\ \dots \\ 2189 \pm 13 \end{array}$	0 1.5 Mas $\Gamma (MeV/c^2)$ 48 90 231 ± 21 <sup>258</sup> / <sub>44</sub> 146 ± 3 <sup>47</sup> / <sub>13</sub> 146 ± 14 <sup>27</sup> / <sub>13</sub> 364 ± 9 <sup>24</sup> / <sub>14</sub> 146 ± 9 <sup>24</sup> / <sub>13</sub> 364 ± 9 <sup>24</sup> / <sub>14</sub>	Image: Second	2.5 Branching fraction $(6.28^{+0.114+0.39}) \times 10^{-6}$ $(8.34^{-1.39+2.39}) \times 10^{-5}$ $(1.59^{-0.114+0.39}) \times 10^{-5}$ $(1.59^{-0.114+0.39}) \times 10^{-5}$ $(1.59^{-0.114+0.39}) \times 10^{-5}$ $(1.11^{-0.014+0.39}) \times 10^{-5}$ $(1.11^{-0.014+0.39}) \times 10^{-5}$ $(2.27^{-0.014+0.39}) \times 10^{-5}$ $(2.77^{-0.014+0.39}) \times 10^{-5}$ $(2.77^{-0.014+0.39}) \times 10^{-5}$	10 <sup>-4</sup> Significance 35σ 16σ 25σ 23σ ≫ 35σ 24σ ≫ 35σ
Resonance fa(1500)	1.5 2 2 M <sub>rp1</sub> (GeV/e <sup>2</sup> ) Mass (MeV/c <sup>2</sup> ) 1468: 11:22	Wiała (MeV/c <sup>2</sup> ) 136 <sup>+13-28</sup>	$\frac{2}{1} \frac{\left[ \frac{1}{2} + \frac{1}{12} + \frac{1}{12}$	Significance 8.27	Resonance           K <sup>*</sup> (892)           K <sub>1</sub> (1270)           f <sub>0</sub> (1370)           f <sub>0</sub> (1710)           f <sub>0</sub> (2200)           f <sub>0</sub> (2200)           f <sub>0</sub> (2200)	$\frac{M \ ({\rm MeV}/c^2)}{886} \\ \frac{886}{1272} \\ \frac{1350 \pm 9^{+1}_{\pm 2}}{1350 \pm 2^{+1}_{\pm 1}} \\ \frac{1870 \pm 7^{+1}_{\pm 2}}{1870 \pm 7^{+1}_{\pm 2}} \\ \frac{11870 \pm 7^{+1}_{\pm 2}}{2441 \pm 10 \pm 7} \\ \frac{2441 \pm 10 \pm 7}{4411 \pm 10 \pm 7} \\ \frac{110}{100} \\ $	0.5 1. $M_{TPG} (MeV/c^2)$ $895.81 \pm 0.19$ $1272 \pm 7$ 1200 to 1500 $1504 \pm 6$ $1723_{-5}^{16}$  $2189 \pm 13$ 	$\begin{array}{c} 0 & 1.5\\ Mas\\ \hline \Gamma (MeV/c^2)\\ 48\\ 90\\ 231 \pm 21 \frac{c_{28}}{c_{24}}\\ 146 \pm 3 \frac{c_{13}}{c_{13}}\\ 146 \pm 4 \frac{c_{13}}{c_{13}}\\ 364 \pm 9 \frac{c_{14}}{c_{13}}\\ 349 \pm 18 \frac{c_{13}}{c_{13}}\\ \end{array}$	2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0	2.5 Branching fraction $(6.28^{+0.17+0.29}_{-0.17+0.29}) \times 10^{-6}$ $(8.44^{+0.12+0.29}_{-0.29}) \times 10^{-5}$ $(1.59^{+0.19+0.29}_{-0.29}) \times 10^{-5}$ $(2.00^{+0.00+0.03}_{-0.09}) \times 10^{-5}$ $(2.12^{+0.00+0.03}_{-0.09}) \times 10^{-5}$ $(2.12^{+0.00+0.03}_{-0.09}) \times 10^{-5}$ $(2.12^{+0.00+0.03}_{-0.09}) \times 10^{-5}$ $(2.12^{+0.00+0.03}_{-0.09}) \times 10^{-5}$ $(2.12^{+0.00+0.03}_{-0.09}) \times 10^{-5}$	3.0 Significance 35σ 16σ 25σ ≥ 35σ 24σ ≥ 35σ 35σ 35σ
Resonance <i>f</i> _1(1590) <i>f</i> _2(1710)	$\frac{1.5  2  2}{M_{rp} (GeV/c^2)}$ $\frac{Mass (MeV/c^2)}{1408_{-15-21}^{-11}}$ $\frac{1408_{-15-21}^{-11}}{179 \approx 10}$	Widh (MeV/c <sup>2</sup> ) 136 <sup>-12-13</sup> 172 ± 10 <sup>-12</sup> 172 ± 10 <sup>-12</sup>	$\frac{2}{1} \frac{\left[\frac{1}{2} + \frac{1}{2} + $	Significance 8.20 25.00	Resonance           K* (892)           K_1 (1270)           f_0 (1370)           f_0 (1370)           f_0 (1270)           f_0 (2200)           f_0 (2330)           f_2 (1270)	$\frac{M (MeV/c^2)}{886}$ $\frac{886}{1272}$ $\frac{1550 \pm 9 \frac{12}{2}}{1500 \pm 7 \frac{13}{2}}$ $\frac{1765 \pm 2 \frac{11}{11}}{1870 \pm 7 \frac{13}{2}}$ $\frac{2184 \pm 5 \frac{14}{24}}{2184 \pm 5 \frac{14}{24}}$ $\frac{2411 \pm 10 \pm 7}{1275}$	0.5 1. $M_{TCO} (MeV/c^2)$ $895.81 \pm 0.19$ $1272 \pm 7$ 1200  to  1500 $1504 \pm 6$ $1723\frac{16}{2}$  $2189 \pm 13$  $1275.5 \pm 0.8$	$\begin{array}{c} 0 & 1.5\\ \text{Mas}\\ \hline \Gamma (\text{MeV}/c^2)\\ 48\\ 90\\ 231\pm 21\frac{24}{48}\\ 109\\ 146\pm 3\frac{1.7}{13}\\ 146\pm 14\frac{21}{13}\\ 364\pm 9\frac{1.7}{13}\\ 364\pm 9\frac{1.7}{13}\\ 185\\ 185\\ \end{array}$	2.0           2.0	$\begin{array}{c} 1\\ \hline 2.5\\ \hline \\ \hline$	3.0 Significance 35σ 16σ 25σ 23σ ≫ 35σ 35σ 35σ 35σ 35σ 35σ
Resonance f.(1300) f.(1710) f.(1210)	$\frac{1.5}{1.5} \frac{2}{2} \frac{2}{2}$ $M_{ref} (GeV/c^2)$ $\frac{Mass (MeV/c^2)}{1400 \frac{111.22}{110.22}}$ $\frac{1400 \frac{111.22}{110.22}}{2001 \pm 11.22}$	Wiah (MeV/c <sup>2</sup> ) 136 <sup>-13-25</sup> 172 : 10 <sup>-15</sup> 237 <sup>-121</sup> 237 <sup>-121</sup>		Significance 8.207 25.007 13.907 13.907 13.907	Resonance           K*(892)           K_1(1270)           fo(1370)           fo(1370)           fo(1200)           fo(1200)           fo(1200)           fo(12200)           fo(122	$M (MeV/c^2)$ 896 1272 1350 $\pm 9t_{-2}^{+12}$ 1505 1765 $\pm 2t_{-1}^{+1}$ 1870 $\pm 7t_{-2}^{-3}$ 2184 $\pm 5t_{-2}^{+1}$ 2181 $\pm 10 \pm 7$ 1275 1516 $\pm 1$ 2271 $\pm 10t_{-}^{0}$	$\begin{array}{cccc} 0.5 & 1.\\ \hline M_{FDG} & (MeV/c^2) \\ 895.81 \pm 0.19 \\ 1272 \pm 7 \\ 1200 \ \text{to} 1500 \\ 1504 \pm 6 \\ 1723 \frac{1}{5} \\ \dots \\ 2189 \pm 13 \\ \dots \\ 2189 \pm 13 \\ \dots \\ 1275.5 \pm 0.8 \\ 1325 \pm 5 \\ 3247 \frac{15}{5} \\ 0.277 \frac{1}{5} \end{array}$	$\begin{array}{c} 0 & 1.5\\ \\ Max\\ \hline \Gamma (MeV/c^2)\\ 8\\ 8\\ 90\\ 231\pm 21^{-28}_{-48}\\ 109\\ 146\pm 3^{-1}_{-1}\\ 146\pm 14^{-1}_{-1}\\ 364\pm 9^{-2}_{-1}\\ 349\pm 18^{+23}_{-1}\\ 185\\ 75\pm 1\pm 1\\ 8\\ 8\\ 75\pm 1\pm 1\end{array}$	$1 + \frac{1}{20}$ $1 + \frac{1}{20}$	$\frac{1}{2.5}$ Branching fraction $(6.25^{+0.17+0.27}_{-0.17+0.27}) \times 10^{-6}$ $(8.54^{+1.15+0.27}_{-0.17+0.27}) \times 10^{-7}$ $(1.07^{-0.08+0.03}_{-0.07+0.07}) \times 10^{-4}$ $(1.11^{-0.08+0.03}_{-0.07+0.07}) \times 10^{-4}$ $(4.55^{-0.07+0.07}_{-0.07+0.07}) \times 10^{-4}$ $(4.55^{-0.07+0.07}_{-0.07+0.07}) \times 10^{-5}$ $(7.99^{+0.07+0.07}_{-0.07+0.07}) \times 10^{-5}$ $(7.99^{+0.07+0.07}_{-0.07+0.07}) \times 10^{-5}$	30 Significance 35σ 16σ 25σ 23σ ≫ 35σ 24σ ≫ 35σ 35σ 35σ 35σ 35σ 35σ
Resource [4:0300 [4:0200 [4:0200 [4:0200 [4:0200]	Mass (MeV/c <sup>2</sup> ) Mass (	Width (MeV/c <sup>2</sup> )           136 <sup>-14-28</sup> / <sub>16-28</sub>	ボリノターフターフッキュ     ボット 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	Significance 8.2 <i>a</i> 11.0 <i>a</i> 11.0 <i>a</i> 11.0 <i>a</i>	T         T         T           2.6         2.8         3           Resonance $K^*_1(1270)$ $f_0(1370)$ $f_0(1370)$ $f_0(1370)$ $f_0(1270)$ $f_0(2200)$ $f_0(2330)$ $f_2(1270)$ $f_2(1525)$ $f_2(1240)$ $h^+$ $huggp$	$\begin{array}{c} M \ (\mathrm{MeV}/c^2) \\ 886 \\ 1272 \\ 1350 \pm 9^{+12}_{-2} \\ 1905 \pm 2^{+1}_{-1} \\ 1870 \pm 7^{-2}_{-3} \\ 2184 \pm 5^{+1}_{-2} \\ 2411 \pm 10 \pm 7 \\ 1275 \\ 1516 \pm 1 \\ 2233 \pm 34^{+29}_{-29} \end{array}$	$\begin{array}{c} 0.5 & 1.\\ \hline M_{FOG} \; (MeV/c^2) \\ 895.81 \pm 0.19 \\ 1272 \pm 7 \\ 1200 to \; 1500 \\ 1504 \pm 6 \\ 1723^{+6}_{-5} \\ \\ 2189 \pm 13 \\ \\ 1275.5 \pm 0.8 \\ 1525 \pm 5 \\ 2345^{+6}_{-50} \end{array}$	$\begin{array}{c} 0 & 1.5\\ \\ Max\\ \hline \\ \hline \\ \hline \\ 80\\ 231\pm21^{+28}_{-24}\\ 146\pm4^{+7}_{-15}\\ 146\pm4^{-7}_{-15}\\ 364\pm9^{+7}_{-3}\\ 349\pm18^{-23}_{-18}\\ 185\\ 75\pm1\pm1\\ 507\pm37^{-24}_{-21}\\ \end{array}$	$\begin{array}{c c} & & & 1\\ & & & 2.0 \\ \hline & & & 2.0 \\ \hline & & & & 2.0 \\ \hline & & & & & & \\ & & & & & & \\ & & & &$	25 Branching fraction (6.32%)(1+32%)×10* (1.67%)(1+32%)×10* (1.67%)(1+32%)×10* (1.67%)(1+32%)×10* (1.67%)(1+32%)×10* (1.67%)(1+32%)×10* (1.67%)(1+32%)×10* (1.67%)(1+32%)×10* (1.68%)(1+32%)(1+32%)×10* (1.68%)(1+32%)(1+32%)×10* (1.68%)(1+32\%)(1+32\%)(1+32\%)(1+32\%)(1+32\%)(1+32\%)(1+32\%)(1+32\%)(1+32\%)(1+32\%	3.0 <sup>-4</sup> 3.0 <sup>-4</sup> 3.0 <sup>-4</sup> 3.0 <sup>-4</sup> 3.0 <sup>-4</sup> 1.6 <sup>-</sup> 2.5 <sup>-</sup> 2.3 <sup>-</sup> 3.5 <sup>-</sup> 3.5 <sup>-</sup> 3.5 <sup>-</sup> 3.5 <sup>-</sup> 3.5 <sup>-</sup> 3.5 <sup>-</sup> 3.5 <sup>-</sup> 2.6 <sup>-</sup> 3.5 <sup>-</sup> 2.6 <sup>-</sup> 3.5 <sup>-</sup> 3.5 <sup>-</sup> 2.6 <sup>-</sup> 3.5 <sup>-</sup>

- $f_0(1710) \sim 10$  times larger production than  $f_0(1500)$  in  $J/\psi \rightarrow \gamma \eta \eta$ ,  $\gamma K_S K_S$ 
  - Production of  $f_0(1710)$  in radiative  $J/\psi$  decay (>  $1.7 \times 10^{-3}$ ) close to theoretical prediction of scalar glueball ( $3.8 \times 10^{-3}$ )
- Broad scalar contribution ~2.1 GeV observed in  $J/\psi \rightarrow \gamma \eta \eta$ ,  $\gamma K_S K_S$ , also seen in  $J/\psi \rightarrow \gamma \pi^0 \pi^0$

### Scalar glueball candidate



LQCD prediction	Experimental results					
	$\mathcal{B}(J/\psi \to \gamma f_0(1710) \to \gamma K\bar{K}) = (8.5^{+1.2}_{-0.9}) \times 10^{-4}$					
Mass: 1.5~1.7 GeV	$\mathcal{B}(J/\psi \to \gamma f_0(1710) \to \gamma \pi \pi) = (4.0 \pm 1.0) \times 10^{-4}$					
$\mathcal{B}(J/\psi \rightarrow \gamma G_{0+})=$	$\mathcal{B}(J/\psi \to \gamma f_0(1710) \to \gamma \omega \omega) = (3.1 \pm 1.0) \times 10^{-4}$					
$3.9(9) \times 10^{-3}$	$\mathcal{B}(J/\psi \to \gamma f_0(1710) \to \gamma \eta \eta) = (2.35^{+0.13}_{-0.11} + 1.24) \times 10^{-4}$					
	$\implies \mathcal{B}(J/\psi \to \gamma f_0(1710)) > 1.7 \times 10^{-3}$					
$f_0\left(1710 ight)$ largely overlapped with scalar glueball						

### Tensor glueball candidate



- f<sub>2</sub>(2340): a good tensor glueball candidate
  - largely produced in  $J/\psi \rightarrow \gamma \eta \eta$ ,  $\gamma \phi \phi$ , significant tensor contribution ~2.4 GeV also seen in  $J/\psi \rightarrow \gamma \pi^0 \pi^0$ ,  $\gamma K_S K_S$
  - Measured mass close to LQCD prediction of tensor glueball(2.3~2.4 GeV)
- Production of  $f_2(2340)$  in radiative  $J/\psi$  decay is much lower than LQCD prediction $(1.1 \times 10^{-2})$ 
  - More measurements needed

# $X(1835)/X(p\bar{p})$

#### ● X(pp̄)

 Anomalous strong enhancement structure at pp
 threshold in J/ψ → γpp
 , firstly observed by
 BES, J<sup>PC</sup> favor 0<sup>-+</sup>)

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#### ● X(1835)

- Observed in  $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$  (BESII, BESIII),  $J^{PC}$  favor  $0^{-+}$
- ? pp molecule state or bound state
- Also seen in  $J/\psi \rightarrow \gamma K_S K_S \eta$  ( $J^{PC}$  determined to be  $0^{-+}$ )



# BACK UP

### Search of $Z_s$ in $e^+e^- \rightarrow \phi \pi \pi$

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- Amplitude analysis performed
  - Well described by φσ, φf<sub>0</sub>(980), φf<sub>0</sub>(1370), φf<sub>2</sub>(1270)
  - No Z<sub>s</sub> signal
  - Upper limit on the cross section of Z<sub>s</sub> at 90% C.L. for different mass/width hypotheses determined <sup>®</sup>/<sub>44</sub>