Glueball and exotics searches at BESIII

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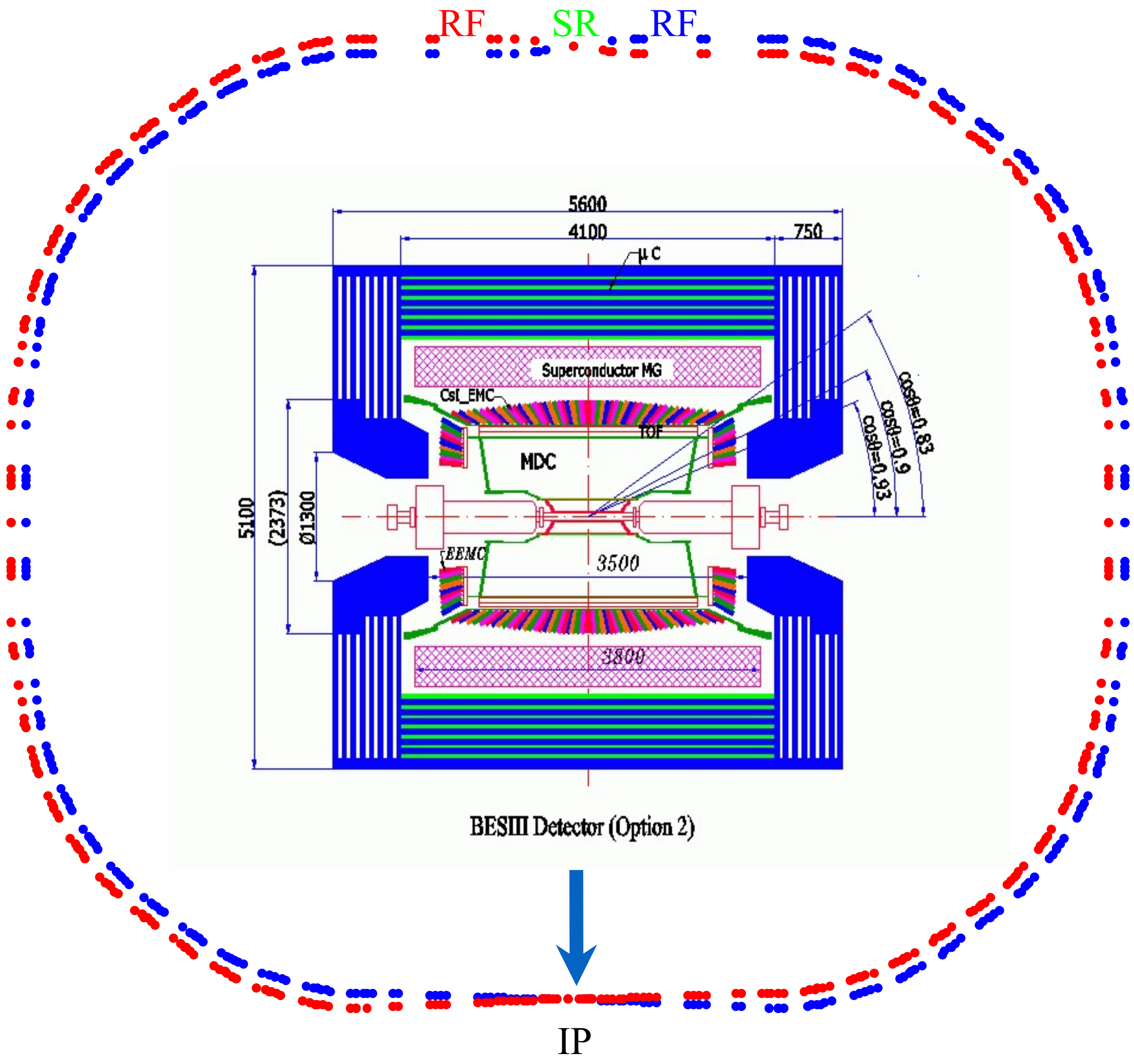
Outline

- BEPCII/BESIII
- Glueball searches
- Exotics searches
- Summary

BEPC II Storage ring: Large angle, double-ring



Beam energy: 1-2 GeV

Luminosity: 1×10^{33} cm^{-2}s^{-1}

Optimum energy: 1.89 GeV

Energy spread: 5.16×10^{-4}

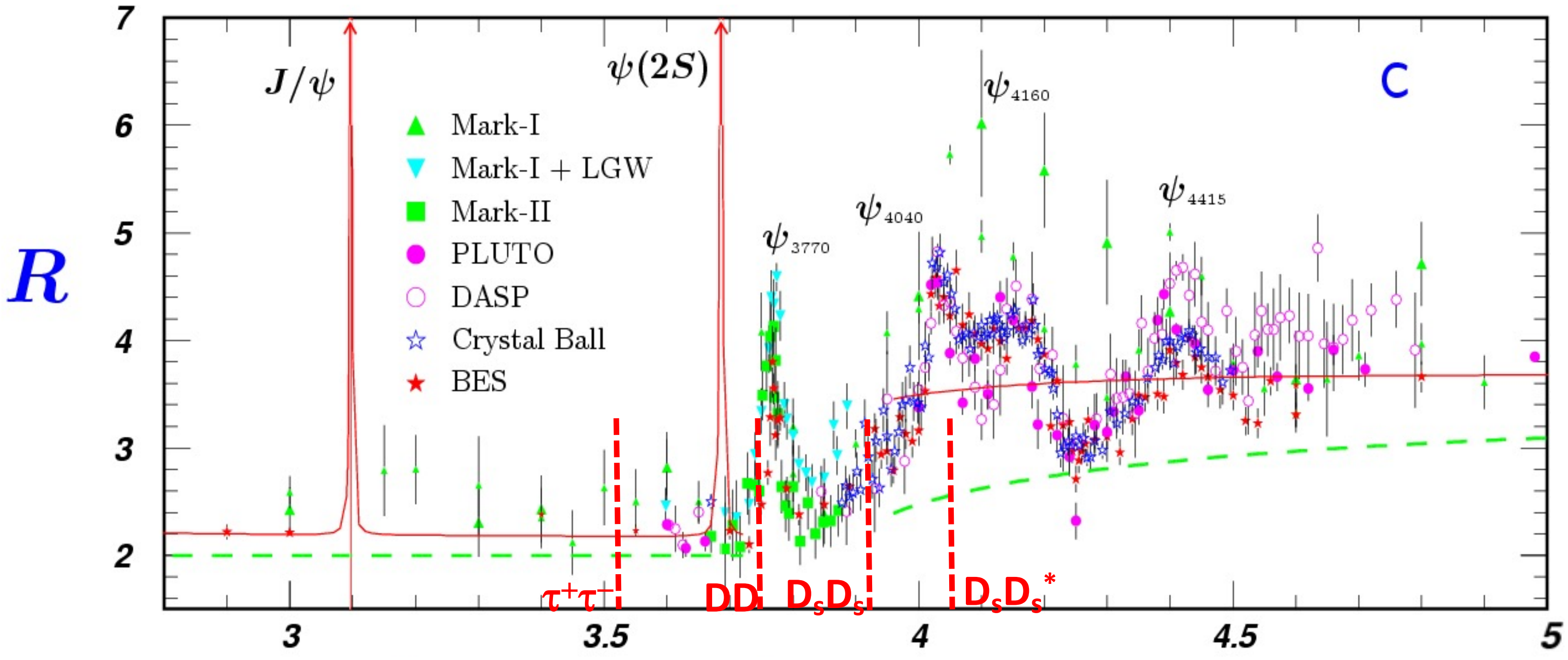
No. of bunches: 93

Bunch length: 1.5 cm

Total current: 0.91 A

SR mode: 0.25A @ 2.5 GeV

World largest data sample directly collected in the τ-charm region

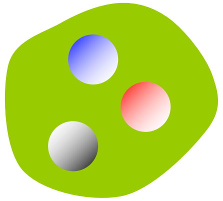


- Charmonium physics
- Light hadron physics
- Charm physics
- R-QCD physics
- New physics searches

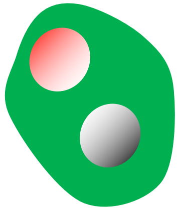
BESIII: ~40 fb^{-1} data in E_{cm} = 2-4.95 GeV

Conventional & Exotic hadrons

- Quark Model

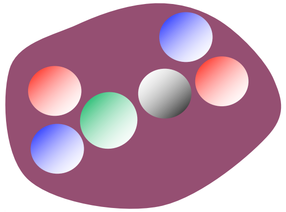


baryon

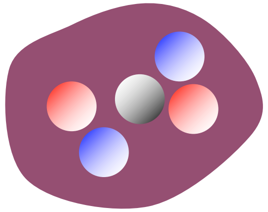


meson

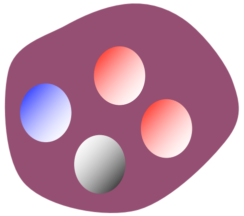
- QCD allows for hadrons beyond Quark Model



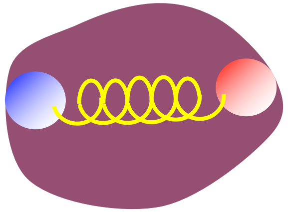
dibaryon



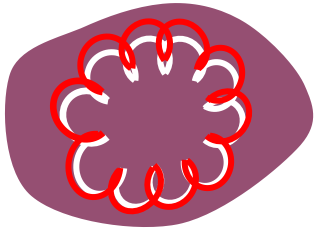
Penta-quark



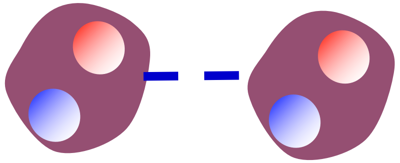
tetra-quark



hybrid

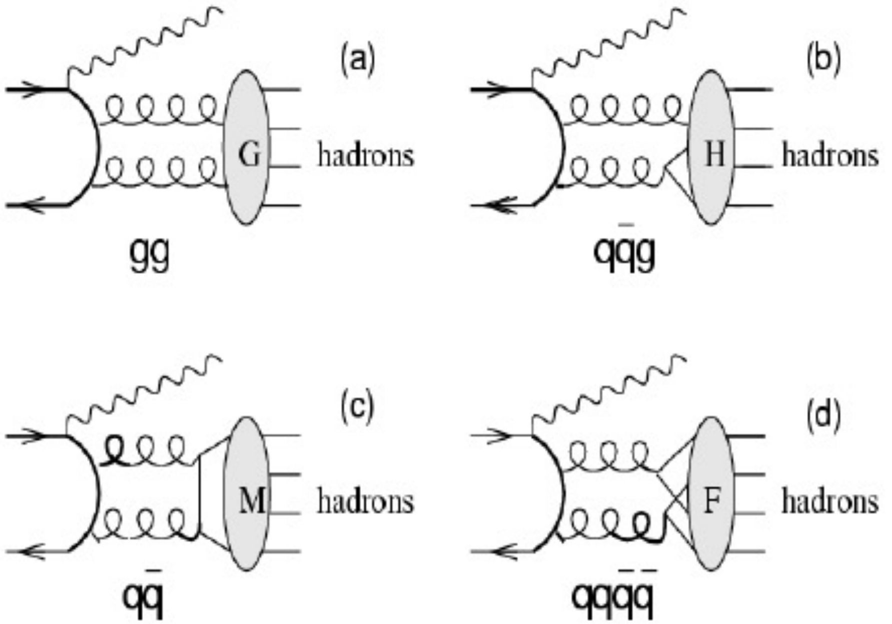


glueball



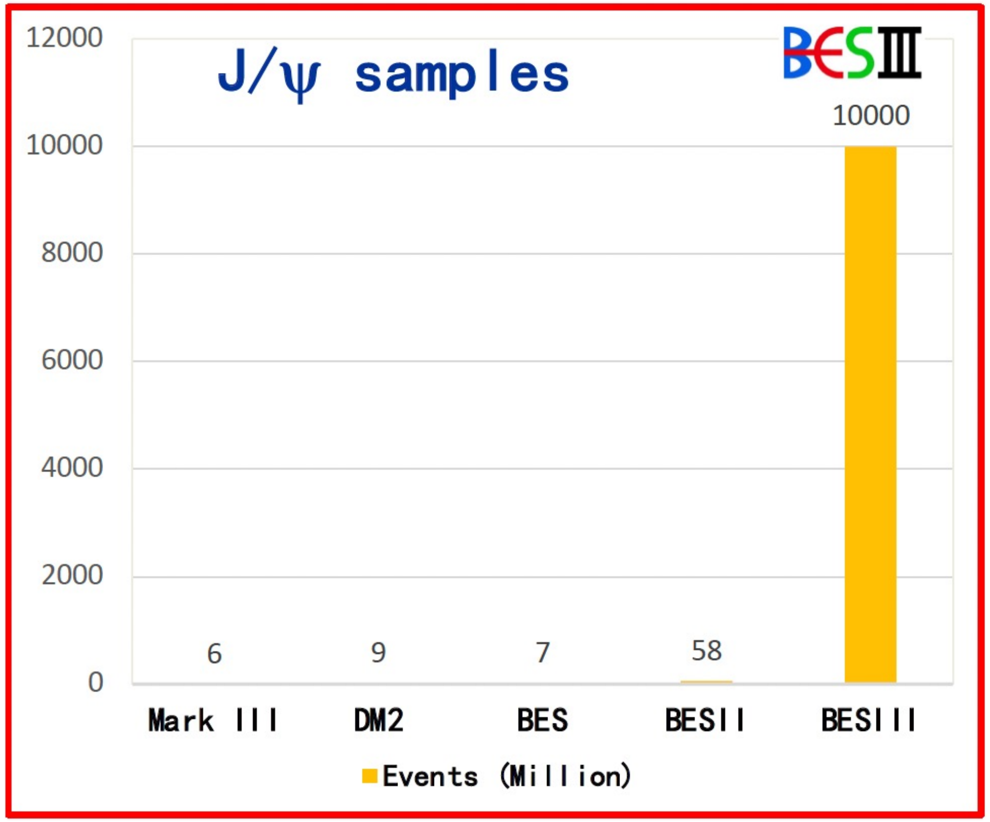
molecule

J/ψ decays provide an ideal lab for light hadron physics



$$\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2), \Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3),$$

$$\Gamma(J/\psi \to \gamma M) \sim O(\alpha\alpha_s^4), \Gamma(J/\psi \to \gamma F) \sim O(\alpha\alpha_s^4)$$



- Clean high statistics data samples
- “Gluon-rich” process

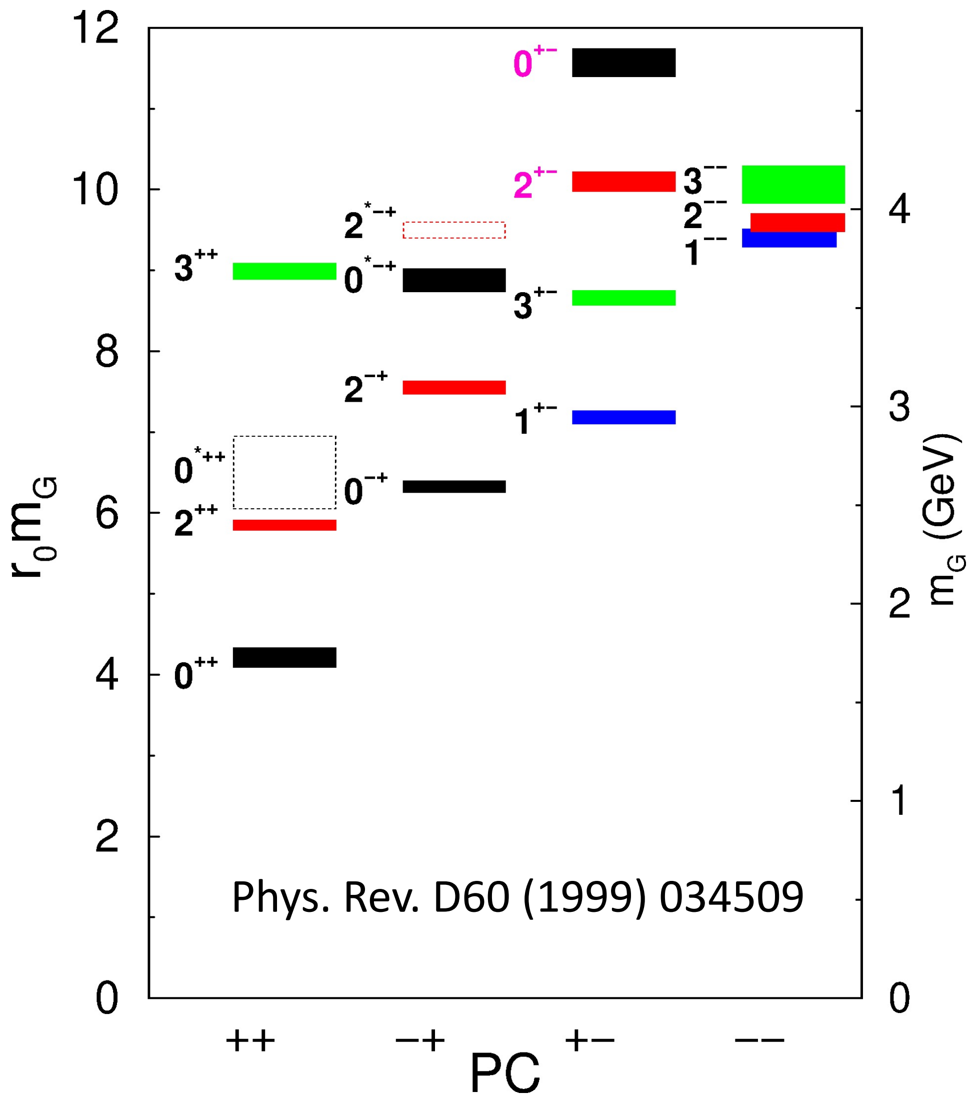
Glueball searches

- Evidence of gluon self interaction
- Provide critical information on the gluon field
- quantitative understanding of confinement

Low lying glueballs with ordinary quantum number
→mixing with qqbar mesons

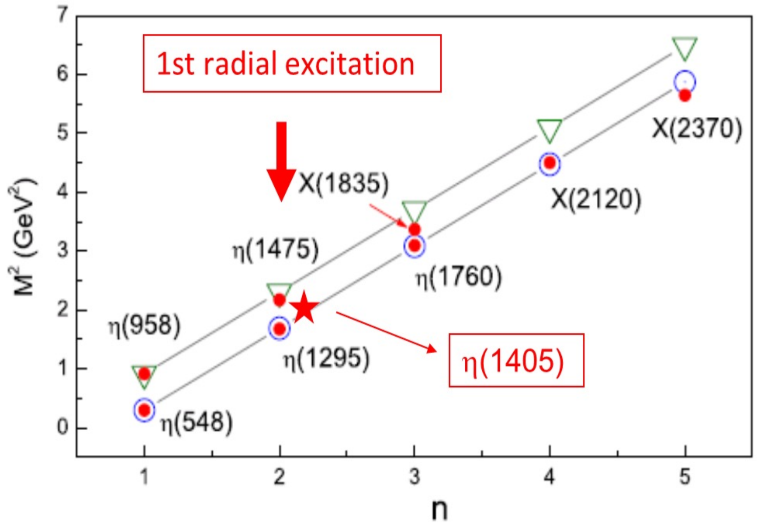
Systematic studies needed

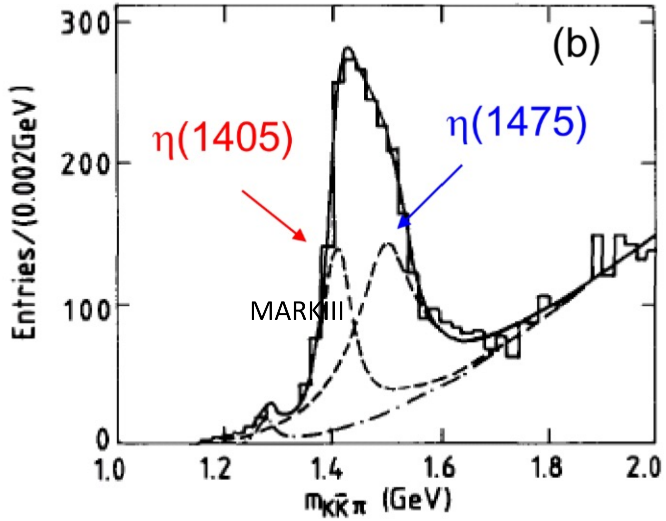
- Outnumbering of conventional QM states
- Abnormal properties ?



Pseudoscalar glueball searches

The small number of expected pseudoscalars in the quark model provide a clean and promising environment for the search of glueballs





Where is the 0^{-+} glueball?

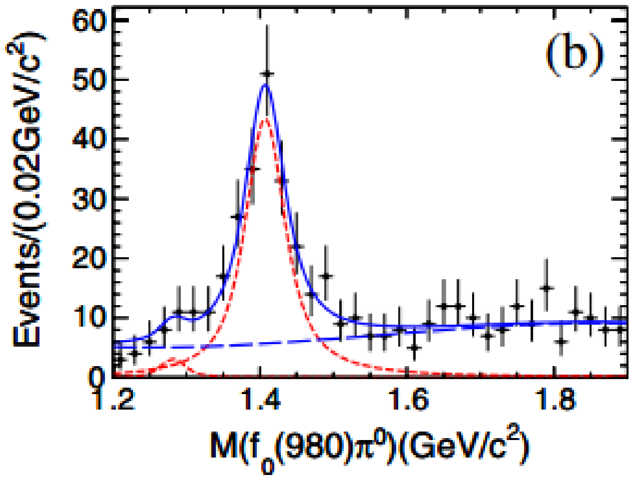
- LQCD：0^{-+}(2.3~2.6 GeV)
- Does $\eta(1295)$ exist?
- the nature of the outnumbered $\eta(1405)$?

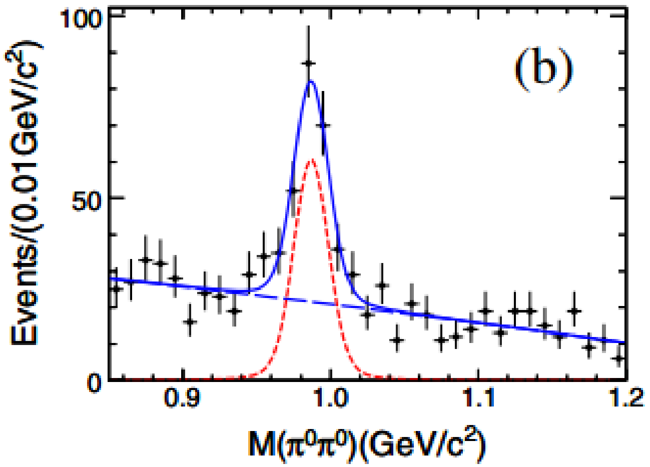
Long standing E-ι puzzle

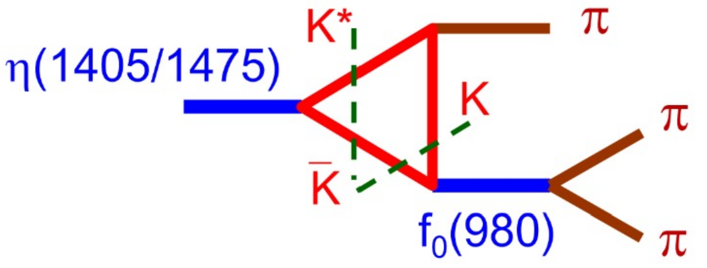
η(1440) { η(1405)→$a_0\pi$; η(1475)→$K^*\bar{K}$ }

Isospin-violating decay of $\eta(1405) \to f_0(980)\pi^0$

BESIII PRL 108 182001







J.J.Wu et al, PRL 108, 081803(2012)

$f_0(980)$ is extremely narrow: $\Gamma \cong 10$ MeV.

PDG: $\Gamma(f0(980)) \cong$ 40~100 MeV.

PDG2012

However, the issue remains controversial as to whether two pseudoscalar mesons really exist. According to Ref. [18] the splitting of a single state could be due to nodes in the decay amplitudes which differ in $\eta\pi\pi$ and $K^*(892)\overline{K}$. Based on the isospin violating decay $J/\psi(1S) \to \gamma 3\pi$ observed by BES [19] the splitting could also be due to a triangular singularity mixing $\eta\pi\pi$ and $K^*(892)\overline{K}$ [20].

Anomalously large isospin violation:

$$\frac{Br(\eta(1405) \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\eta(1405) \to a_0^0(980)\pi^0 \to \eta\pi^0\pi^0)} \cong (17.9 \pm 4.2)\%$$

$$\xi_{af} = \frac{Br(\chi_{c1} \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\chi_{c1} \to a_0(980)\pi^0 \to \eta\pi^0\pi^0)} < 1\% (90\%\ C.L.)$$

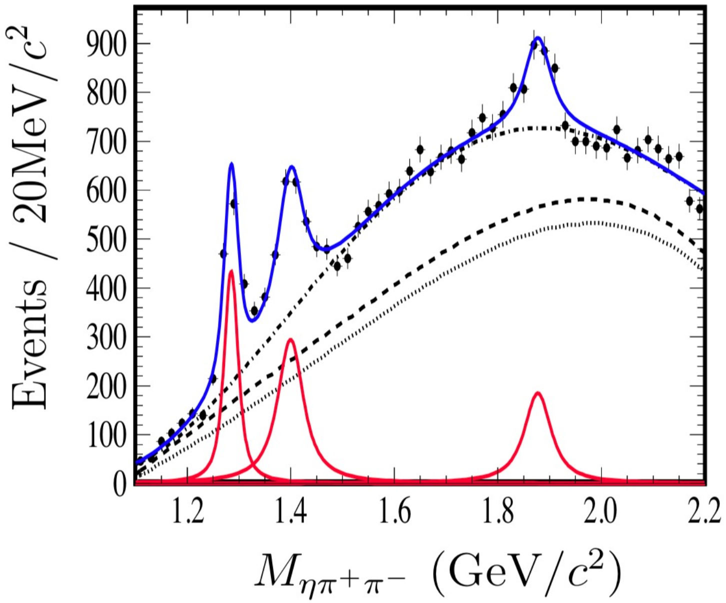
PRD, 83(2100)032003

→No need for two pseudoscalars around 1.4 GeV

→Look for pseudoscalar glueball in higher mass region

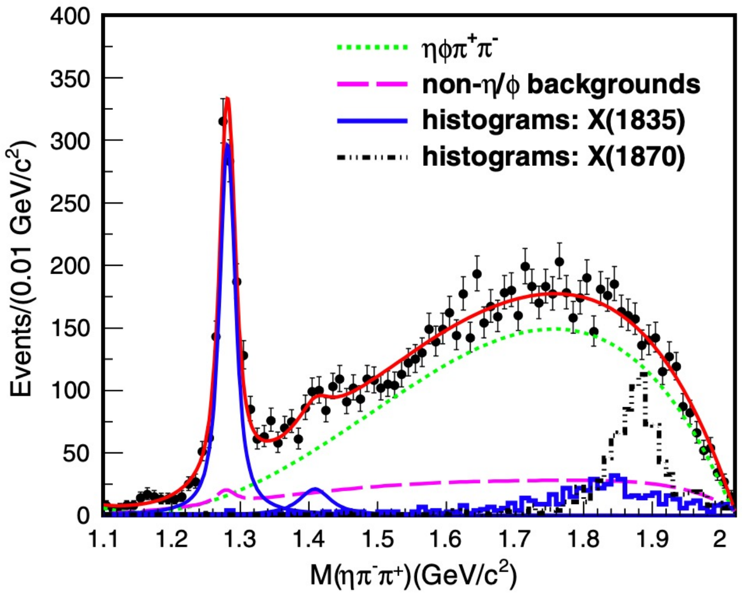
$\eta(1405)$ in J/ψ hadronic decays

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



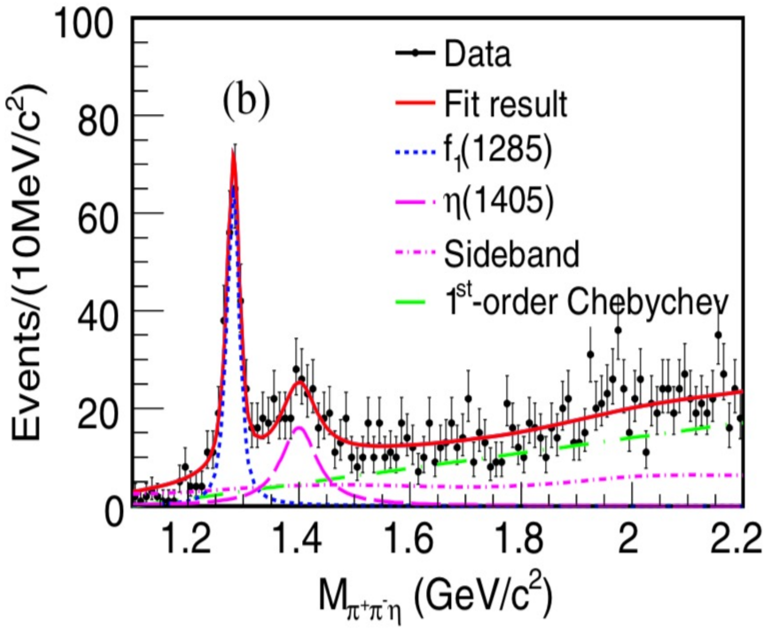
PRL 107, 182001(2011)

J/ψ→φηππ



PRD97,052017(2015)

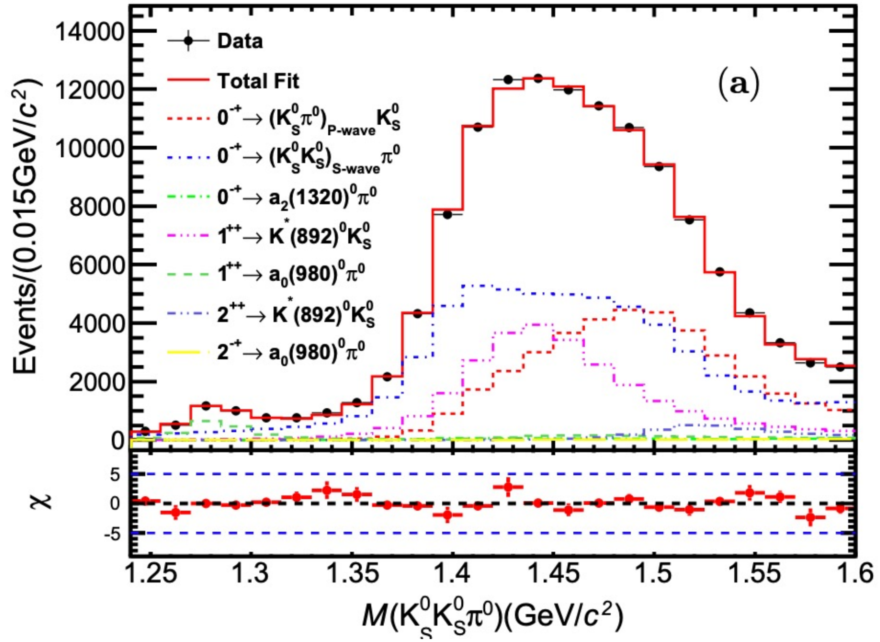
$\psi(3686) \to \phi\pi^+\pi^-\eta$



PRD100,092003(2019)

$\eta(1405)/\eta(1475)$

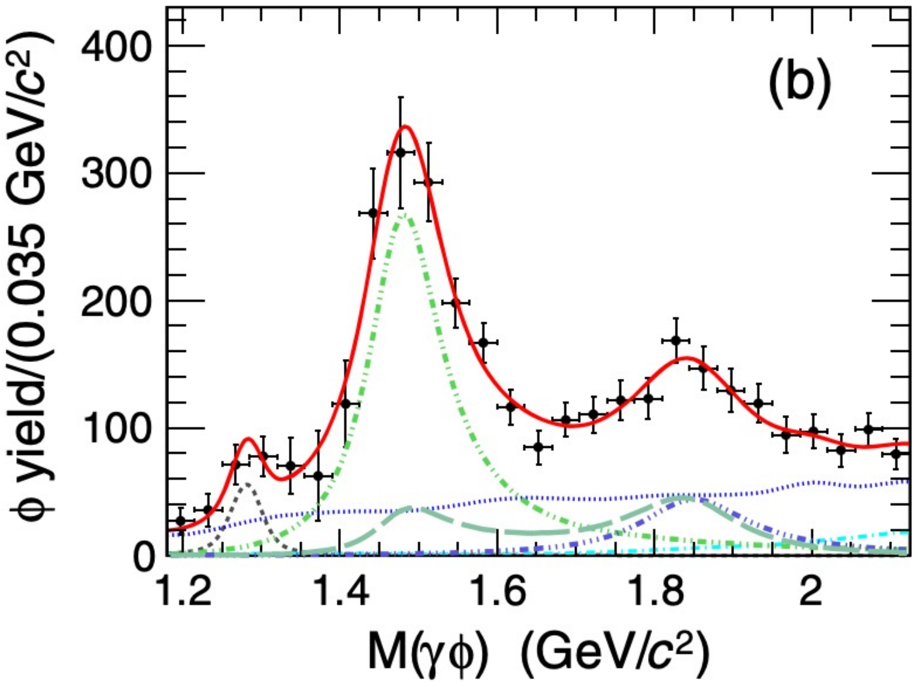
$J/\psi \to \gamma K_S^0 K_S^0 \pi^0$



arXiv:2209.11175, accepted by JHEP

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV})$
$\eta(1405)$	$1391.7 \pm 0.7^{+11.3}_{-0.3}$	$60.8 \pm 1.2^{+5.5}_{-12.0}$
$\eta(1475)$	$1507.6 \pm 1.6^{+15.5}_{-32.2}$	$115.8 \pm 2.4^{+14.8}_{-10.9}$

$J/\psi \to \gamma\gamma\phi$

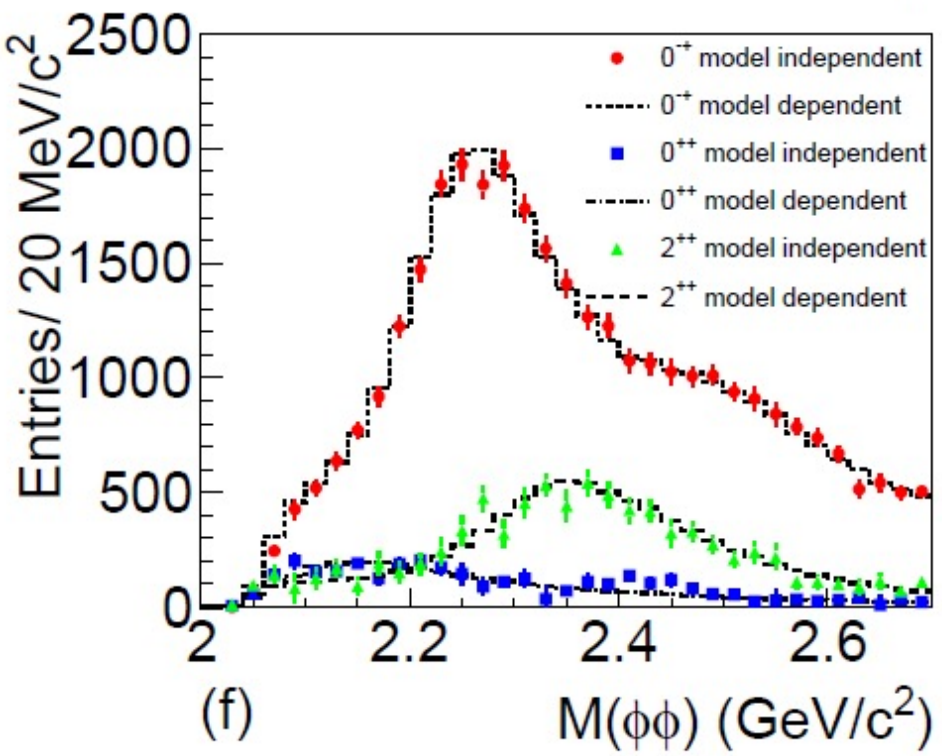


Phys. Rev. D97, 051101(2018)

-- sizable $s\bar{s}$ component
-- likely to be radial excited states ?

Pseudoscalars above 2 GeV

Very little was known for pseudoscalars above 2 GeV. Experimental results are essential for mapping out the pseudoscalar excitations and searching for 0^{-+} glueball



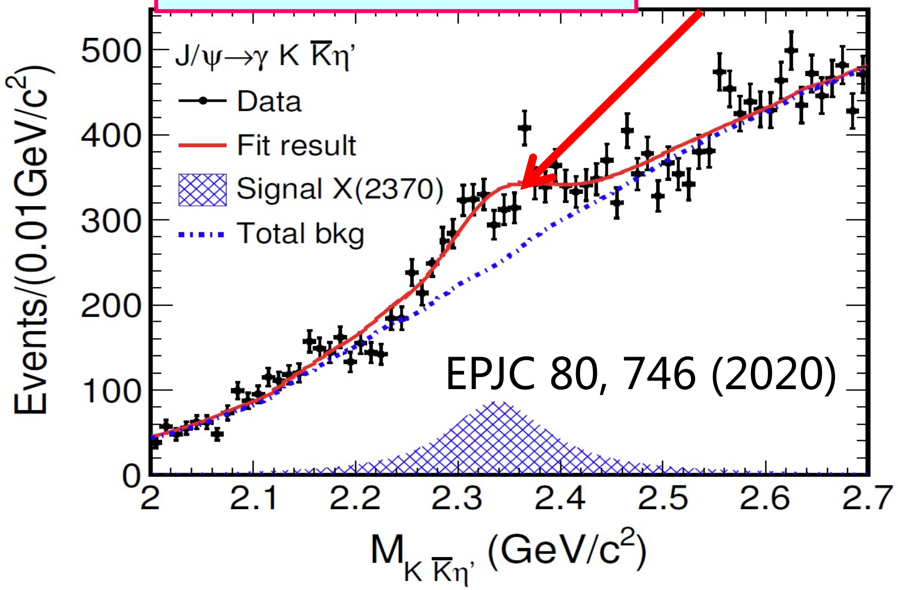
Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	B.F.$(\times 10^{-4})$	Sig.
$\eta(2225)$	2216^{+4+18}_{-5-11}	185^{+12+44}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28.1σ
$\eta(2100)$	2050^{+30+77}_{-24-26}	$250^{+36+187}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	21.5σ
X(2500)	2470^{+15+63}_{-19-23}	230^{+64+53}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2102	211	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24.2σ
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$	9.5σ
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$	6.4σ
$f_2(2340)$	2339	319	$(1.91 \pm 0.07^{+0.72}_{-0.69})$	10.7σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ

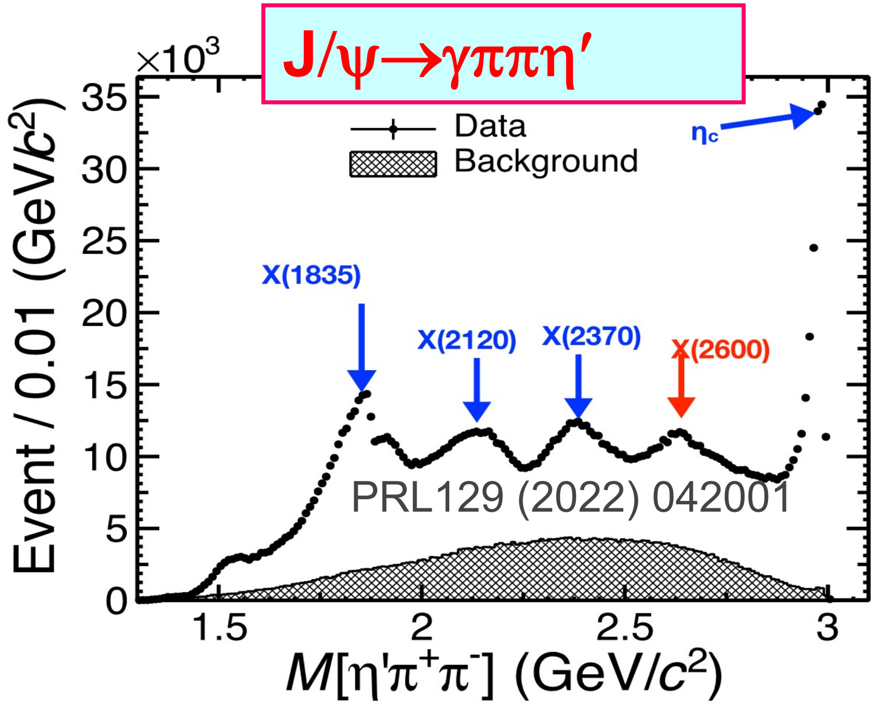
Phys. Rev. D97, 051101 (2018)

- Dominant contribution from pseudoscalars: η(2225), η(2100) and X(2500)
- Three tensors $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$

X(2370): new glueball candidate ?

J/ψ→γKKη′





An updated review of the new hadron states

We collect as many theoretical predictions on the pseudoscalar glueball mass as we can, and summarize them in Fig. 71. The average value of the mass predictions obtained after the year 1990 is

$$M_{|gg;0^{-+}\rangle} \sim 2360 \text{ MeV} . \quad (125)$$

Accordingly, the resonance $X(2370)$ first observed in 2010 [880] becomes a possible candidate for the low-lying pseudoscalar glueball, whose mass and width were measured to be [884]:

$$X(2370) : M = 2341.6 \pm 6.5 \pm 5.7 \text{ MeV} , \quad \Gamma = 117 \pm 10 \pm 8 \text{ MeV} . \quad (126)$$

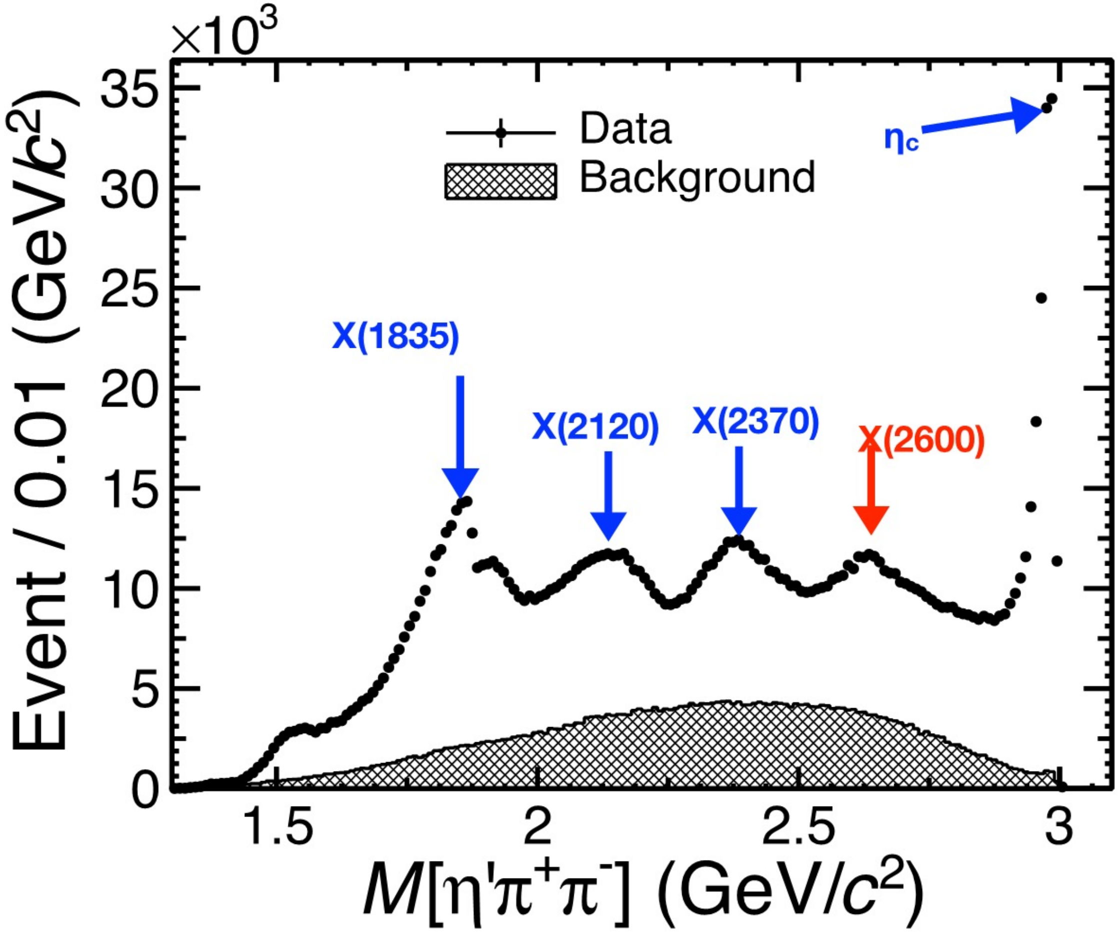
arXiv:2204.02649

X(2600): new glueball candidate ?

QCD sum rules

arXiv:2206.13133

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



PRL129 (2022) 042001

Motivated by the newly observed resonance $X(2600)$ by BESIII Collaboration, we examine the trigluon glueball interpretation for it in the framework of QCD sum rules. We evaluate the mass spectra of the trigluon glueballs with quantum numbers 0^{-+} and 2^{-+} up to dimension 8 condensate in the operator product expansion. Our numerical results indicate that the mass of the 2^{-+} trigluon glueball is about 2.66 ± 0.06 GeV, which is consistent with the mass of the X(2600) within the uncertainties, while 0^{-+} has a mass of 2.01 ± 0.14 GeV. The possible decay channels of the 2^{-+} state are analyzed, which are crucial in decoding $X(2600)$'s internal structure and are hopefully measurable in BESIII, BEllEII, PANDA, and LHCb experiments.

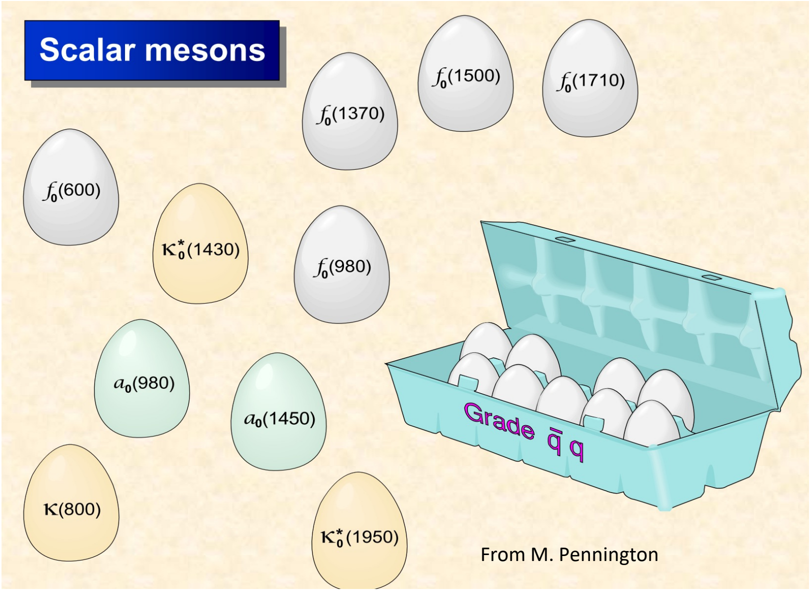
Cases	Possible decay channels	
0^{-+} two-gluon glueball $\to$	$a_0(980) + \pi$	$\{f_0(500),\ f_0(980)\} + \eta$
0^{-+} trigluon glueball $\to$	$\{f_0(500),\ f_0(980),\ f_0(1370),\ f_0(1500)\} + \eta$	$\eta\eta\eta,\ \eta\eta\eta',\ \{\eta,\ \eta'\} + \pi + \pi$
	$f_0(500) + f_0(980) + \eta$	$\{\omega\omega,\ \rho\rho\} + f_0(500)$
	$f_0(500) + f_0(500) + \{\eta,\ \eta'\}$	$N\bar{N}$
	$\{f_0(500),\ f_0(980)\} + a_0(980) + \pi$	
2^{-+} two-gluon glueball $\to$	$a_2(1320) + \pi$	$f_0(500) + f_1(1285)$
	$f_2(1270) + \eta$	
2^{-+} trigluon glueball $\to$	$\eta_2(1645) + f_0(500)$	$2f_1(1285),\ 2a_1(1260),\ 2h_1(1170)$
	$\{f_2(1270),\ f_2'(1525)\} + \{\eta,\ \eta'\}$	$\rho + \rho + f_0(980)$
	$a_2(1320) + f_0(500) + \pi$	$\{\omega\omega,\ \rho\rho,\ \omega + \phi\} + f_0(500)$
	$\{f_2(1270),\ f_2'(1525)\} + f_0(500) + \eta$	$h_1(1170) + \omega + \eta$
	$\{f_2(1270),\ f_2'(1525)\} + a_0(980) + \pi$	$\{h_1(1170),\ h_1(1415)\} + \rho + \pi$
	$\omega + \phi + \eta,\ \{\pi\pi,\ \omega\omega,\ \rho\rho\} + \{\eta,\ \eta'\}$	$N\bar{N},\ \Lambda\bar{\Lambda},\ \Sigma\bar{\Sigma},\ \Xi\bar{\Xi}$

Scalar glueball searches

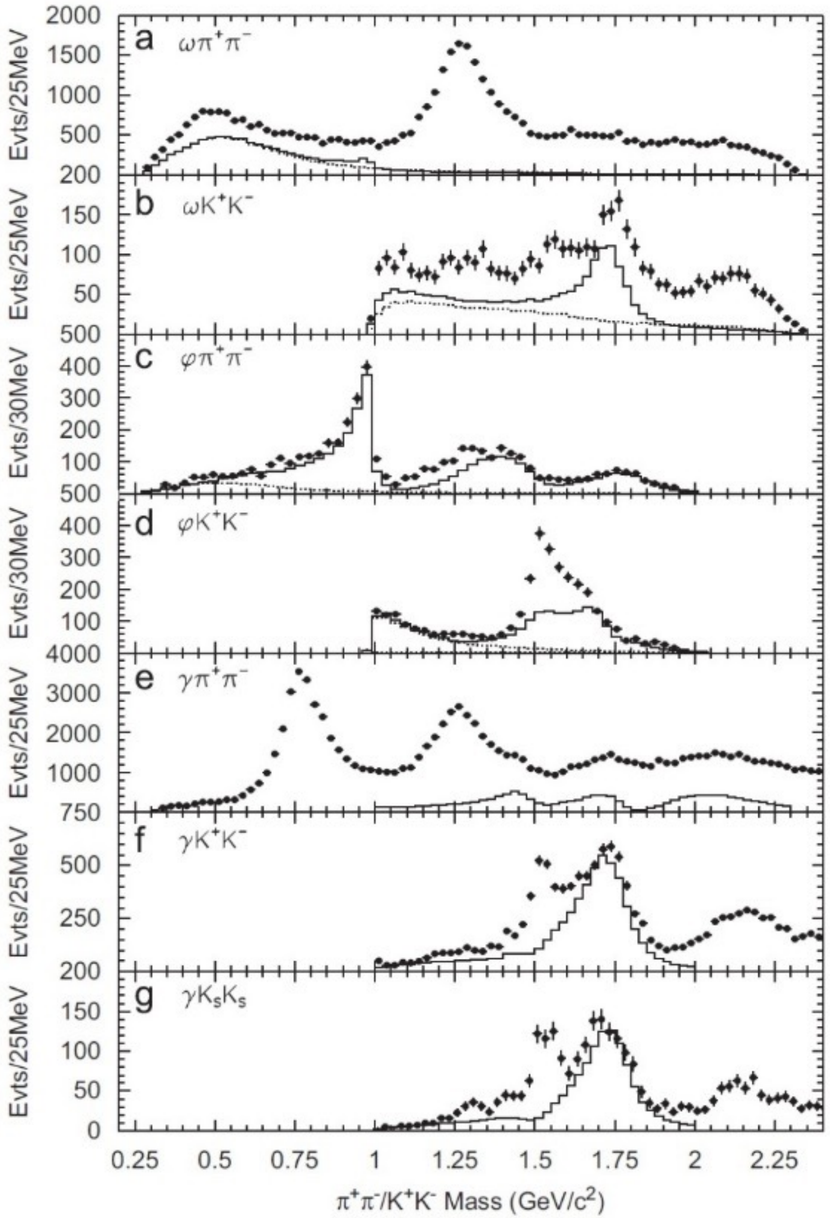
- Why light scalar mesons are interesting?
  - There have been hot debates on **the existence of** **σ and κ**
  - **σ, κ and $f_0(980)$ are also possible mutiquark states. They are all near threshold.**
  - Lattice QCD predicts the 0^{++} **scalar glueball mass ~ 1.6 GeV.** $f_0(1500)$ and $f_0(1710)$ are good candidates.

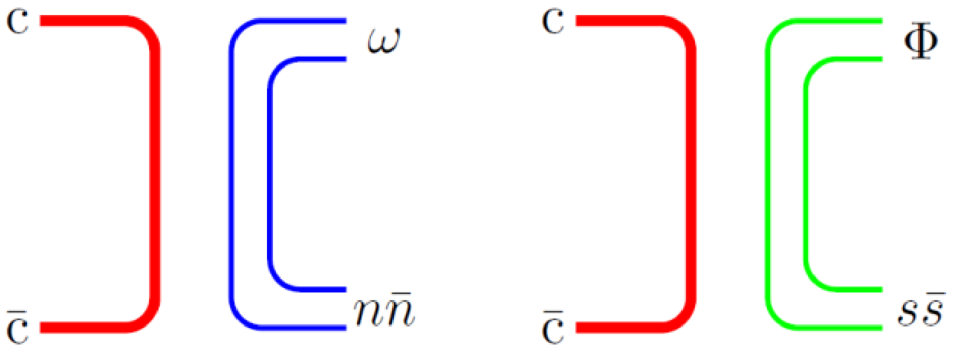
Name	Mass [MeV/c^2]	Width [MeV/c^2]	Decays
$f_0(600)$ *	400 − 1200	600 − 1000	$\pi\pi$, $\gamma\gamma$
$f_0(980)$ *	980 ± 10	40 − 100	$\pi\pi$, $K\bar{K}$, $\gamma\gamma$
$f_0(1370)$ *	1200 − 1500	200 − 500	$\pi\pi$, $\rho\rho$, $\sigma\sigma$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $K\bar{K}$
$f_0(1500)$ *	1507 ± 5	109 ± 7	$\pi\pi$, $\sigma\sigma$, $\rho\rho$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $\eta\eta'$ $K\bar{K}$, $\gamma\gamma$
$f_0(1710)$ *	1718 ± 6	137 ± 8	$\pi\pi$, $K\bar{K}$, $\eta\eta$, $\omega\omega$, $\gamma\gamma$
$f_0(1790)$			
$f_0(2020)$	1992 ± 16	442 ± 60	$\rho\pi\pi$, $\pi\pi$, $\rho\rho$, $\omega\omega$, $\eta\eta$
$f_0(2100)$	2103 ± 7	206 ± 15	$\eta\pi\pi$, $\pi\pi$, $\pi\pi\pi\pi$, $\eta\eta$, $\eta\eta'$
$f_0(2200)$	2189 ± 13	238 ± 50	$\pi\pi$, $K\bar{K}$, $\eta\eta$

Overpopulated!



$f_0(1710)$ / $f_0(1790)$ at BESII experiment





Flavor Tagging

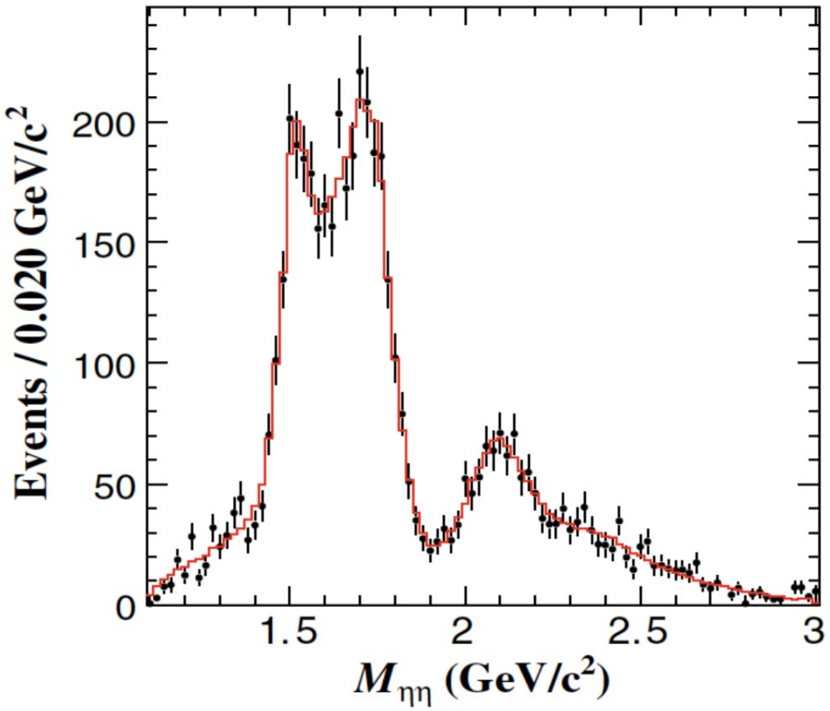
ωK^+K^- ➜ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

$\phi\pi^+\pi^-$ ➜ Enhancement at 1790 MeV/c^2

ϕK^+K^- ➜ No peak around 1700 MeV/c^2

Amplitude analysis of $J/\psi \to \gamma\eta\eta$

BESIII PRD 87, 092009 (2013)



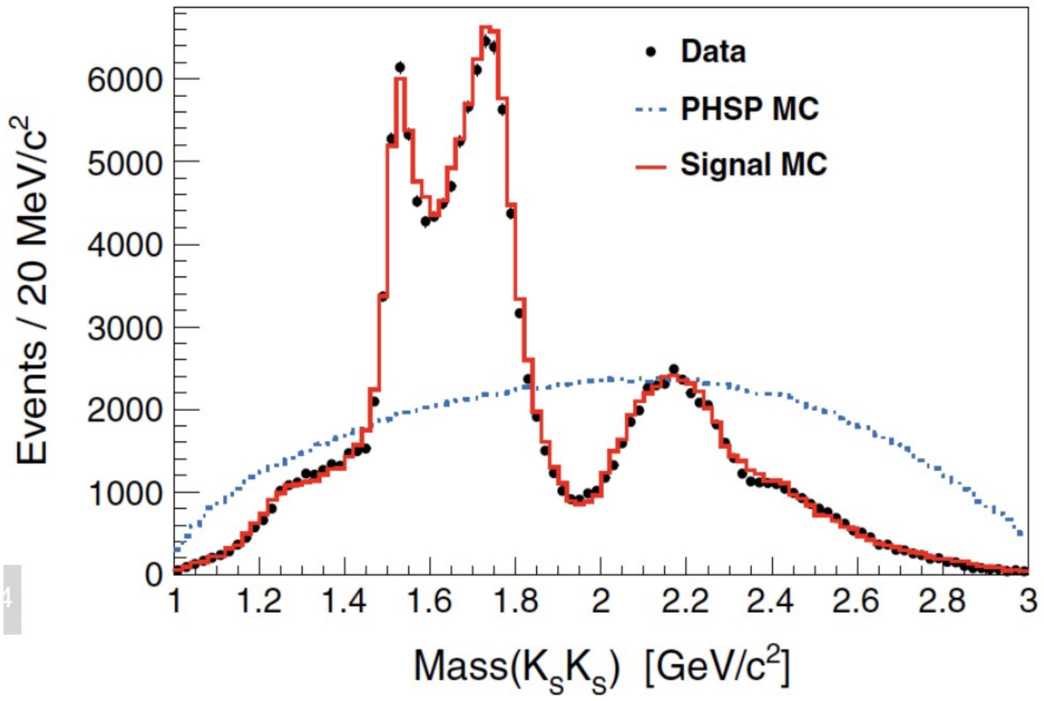
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$

- $f_0(1710)$ and $f_0(2100)$ are dominant scalars
- $f_2'(1525)$ is the dominant tensor
- $f_2(1810)$ and $f_2(2340)$ exist

Branching fraction of $f_0(1710)$ around 10 times larger than $f_0(1500)$!

Amplitude analysis of $J/\psi \to \gamma K_S^0 K_S^0$

BESIII PRD 98, 072003 (2018)

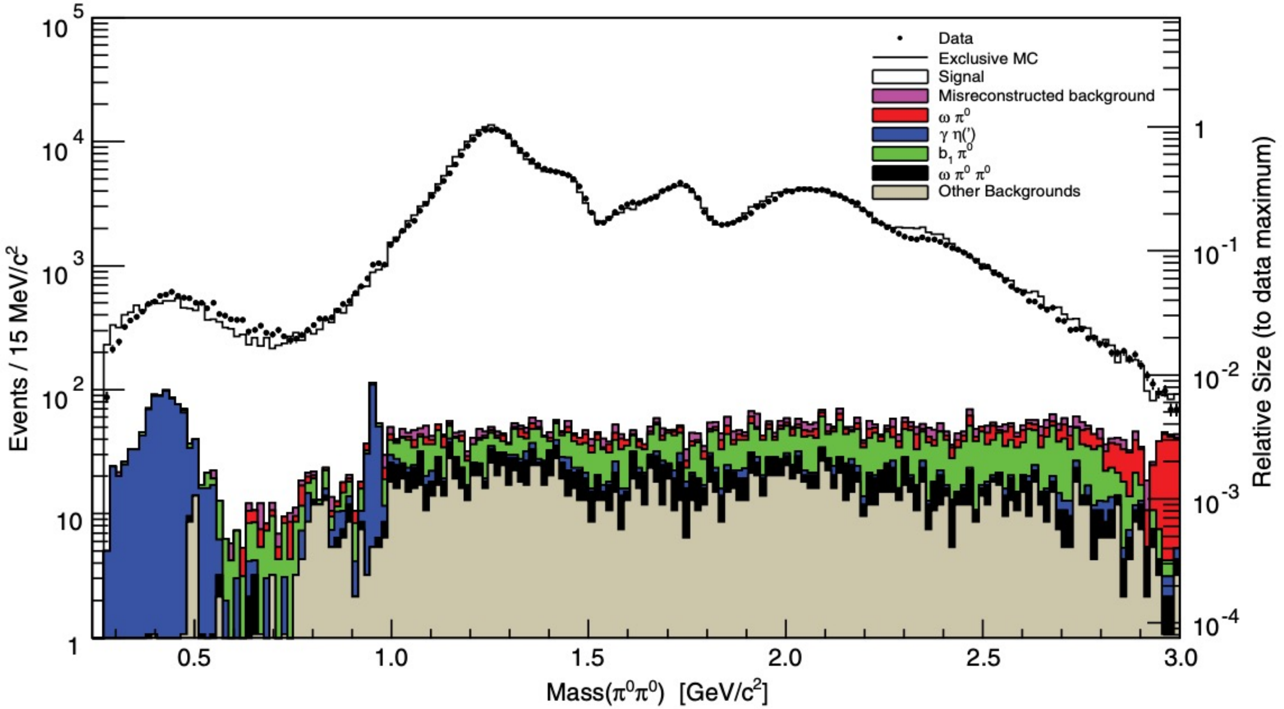


Resonance	M (MeV/c^2)	Γ (MeV/c^2)	Branching fraction
$K^*(892)$	896	48	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$
$K_1(1270)$	1272	90	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$
$f_0(1370)$	$1350 \pm 9^{+12}_{-2}$	$231 \pm 21^{+28}_{-48}$	$(1.07^{+0.08+0.36}_{-0.07-0.34}) \times 10^{-5}$
$f_0(1500)$	1505	109	$(1.59^{+0.16+0.18}_{-0.16-0.56}) \times 10^{-5}$
$f_0(1710)$	$1765 \pm 2^{+1}_{-1}$	$146 \pm 3^{+7}_{-1}$	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	$146 \pm 14^{+7}_{-15}$	$(1.11^{+0.06+0.19}_{-0.06-0.32}) \times 10^{-5}$
$f_0(2200)$	$2184 \pm 5^{+4}_{-2}$	$364 \pm 9^{+4}_{-7}$	$(2.72^{+0.08+0.17}_{-0.06-0.47}) \times 10^{-4}$
$f_0(2330)$	$2411 \pm 10 \pm 7$	$349 \pm 18^{+23}_{-1}$	$(4.95^{+0.21+0.66}_{-0.21-0.72}) \times 10^{-5}$
$f_2(1270)$	1275	185	$(2.58^{+0.08+0.59}_{-0.09-0.20}) \times 10^{-5}$
$f_2'(1525)$	1516 ± 1	$75 \pm 1 \pm 1$	$(7.99^{+0.03+0.69}_{-0.04-0.50}) \times 10^{-5}$
$f_2(2340)$	$2233 \pm 34^{+9}_{-25}$	$507 \pm 37^{+18}_{-21}$	$(5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$

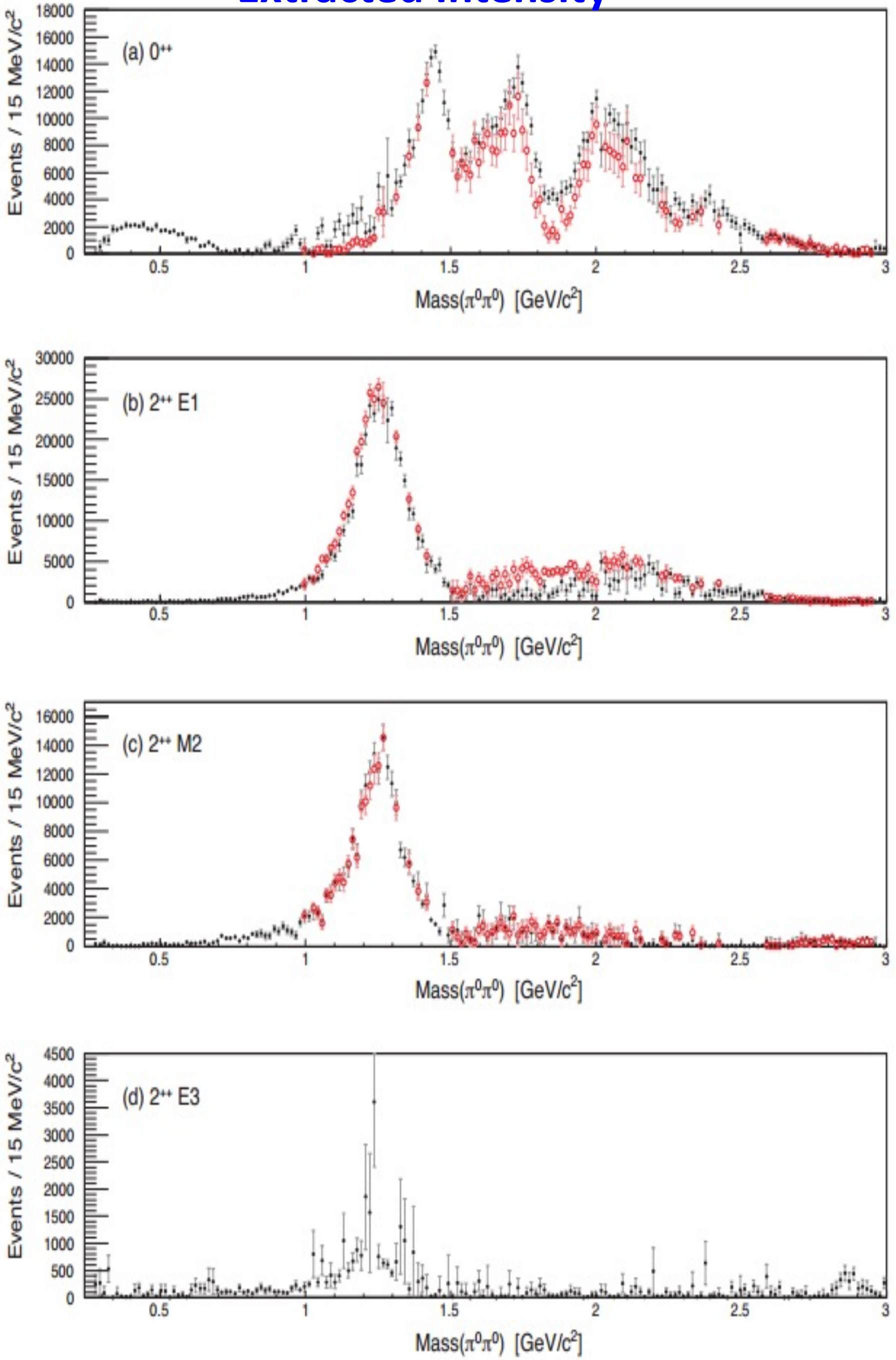
- **$f_0(1710)$ and $f_0(2200)$ are dominant scalars, $f_2'(1525)$, $f_2(2340)$ are the dominant tensor**

Branching fraction of $f_0(1710)$ also around 10 times larger than $f_0(1500)$!

Mass-independent PWA of $J/\psi \to \gamma\pi^0\pi^0$



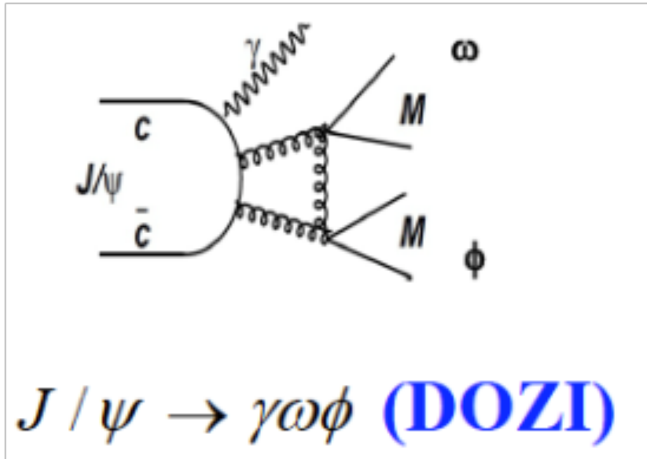
Extracted Intensity

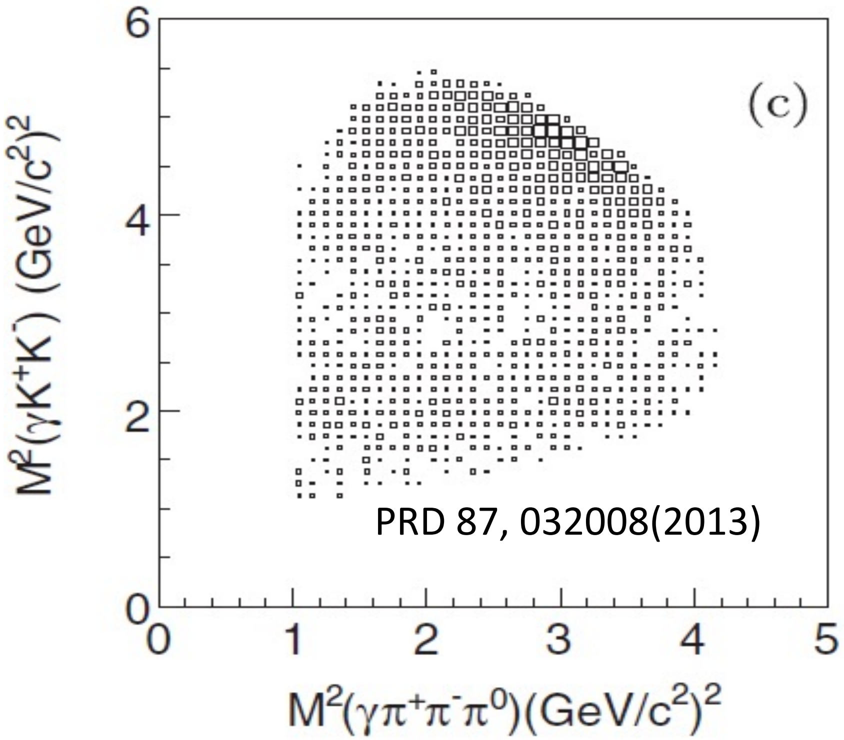


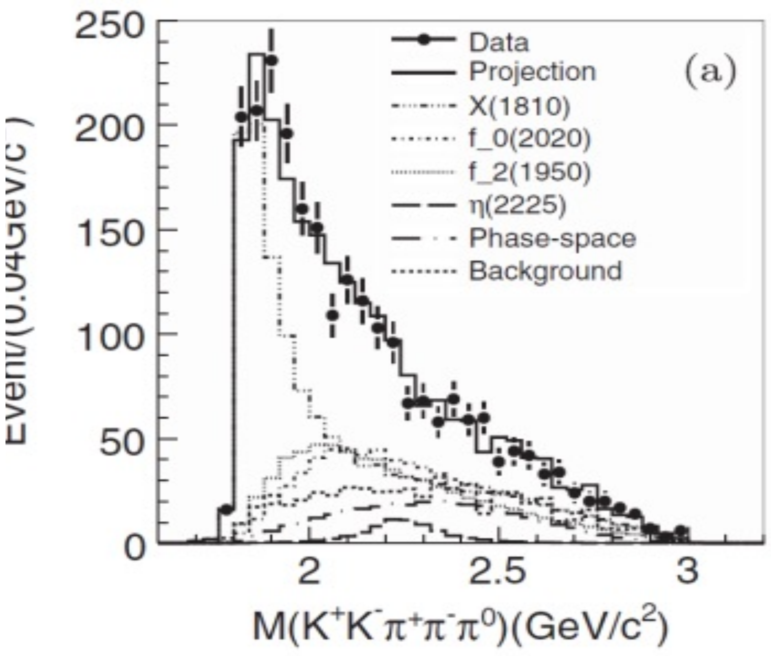
- ✓ Extract amplitudes in each $M(\pi^0\pi^0)$ mass bin
- ✓ **Significant features of the scalar spectrum includes structures near 1.5, 1.7 and 2.0 GeV/c^2**

Phys. Rev. D 92, 052003 (2015)

PWA of $J/\psi \to \gamma\omega\phi$







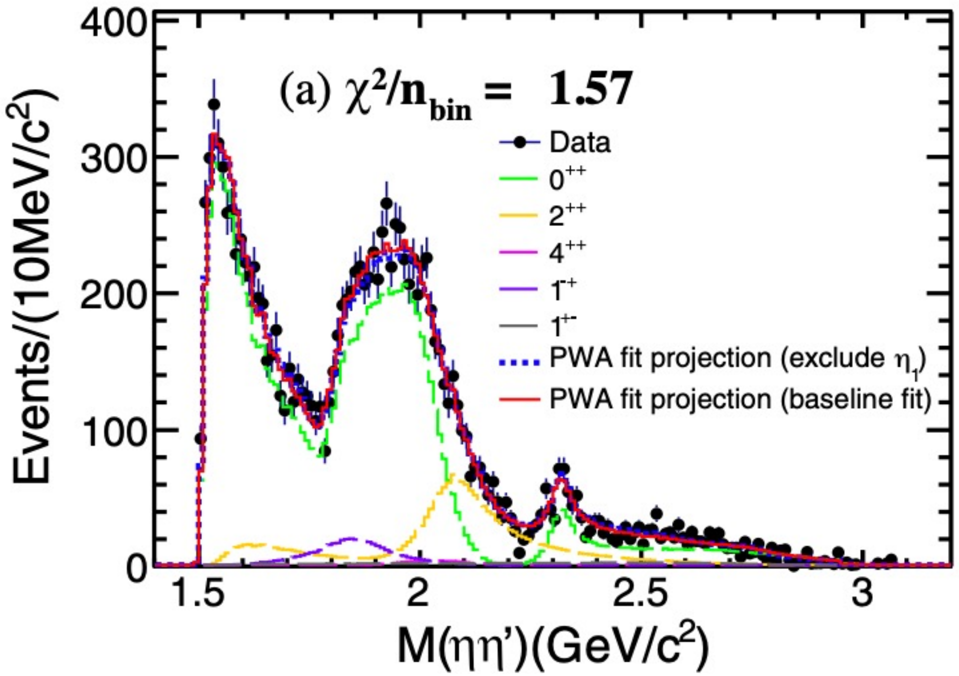
- Clear enhancement with JP= **0^+**

$M = 1795 \pm 7^{+13}_{-5} \pm 19$(model) MeV/c^2,

$\Gamma = 95 \pm 10^{+21}_{-34} \pm 75$(model) MeV

- the same as $f_0(1710)/f_0(1790)$, or a new state ? Pure glueball cannot decay to $\omega\phi$

Amplitude analysis of J/ψ → γηη′



PRD 106, 072012 (2022)

Since glueball decays to the ηη′ final state are suppressed due to gauge duality, the ηη′ final state is a crucial probe for distinguishing glueballs from conventional mesons

$$\mathcal{B}(f_0(1500)\to\eta\eta')/\mathcal{B}(f_0(1500)\to\pi\pi) = (1.66^{+0.42}_{-0.40})\times 10^{-1}$$

$$\mathcal{B}(f_0(1810)\to\eta\eta')/\mathcal{B}(f_0(1710)\to\pi\pi) = (2.9^{+1.1}_{-0.8})\times 10^{-3}$$

$$\mathcal{B}(f_0(1710)\to\eta\eta')/\mathcal{B}(f_0(1710)\to\pi\pi) < (2.87)\times 10^{-3}$$

Resonance	M (MeV/c^2)	Γ (MeV)	M_{PDG} (MeV/c^2)	Γ_{PDG} (MeV)	B.F. ($\times 10^{-5}$)
$f_0(1500)$	1506	112	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$
$f_0(1810)$	1795	95	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$
$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	1992	442	$2.28\pm0.12^{+0.29}_{-0.20}$
$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	2314	144	$0.10\pm0.02^{+0.01}_{-0.02}$

Scalar glueball candidate: $f_0(1710)$

$$\Gamma(J/\psi \to \gamma G_{0^+}) = \frac{4}{27}\alpha\frac{|p|}{M^2_{J/\psi}}|E_1(0)|^2 = 0.35(8)keV$$
$$\Gamma/\Gamma_{tot} = 0.33(7)/93.2 = 3.8(9)\times 10^{-3}$$

CLQCD, Phys. Rev. Lett. 110, 021601 (2013)

Experimental results

- $B(J/\psi \to \gamma f_0(1710) \to \gamma K\bar{K}) = (8.5^{+1.2}_{-0.9})\times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi) = (4.0\pm1.0)\times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\omega\omega) = (3.1\pm1.0)\times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta) = (2.35^{+0.13}_{-0.11}{}^{+1.24}_{-0.74})\times 10^{-4}$

$\Rightarrow$ $B(J/\psi \to \gamma f_0(1710)) > 1.7\times 10^{-3}$

Flavor-blindness of glueball decays

$$\frac{1}{P.S.}\Gamma(G\to \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta') = 3:4:1:0:1$$

*with chiral suppression

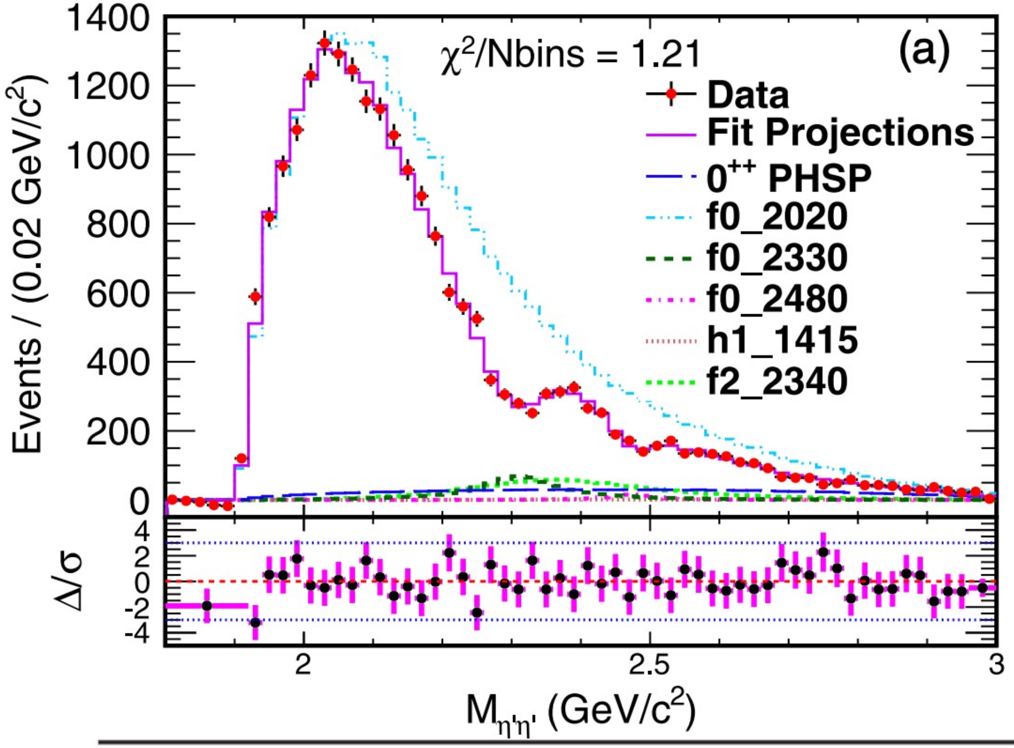
PRL 98 149103

$$\Gamma(G\to\pi\pi)/\Gamma(G\to K\bar{K}) \approx \frac{f_\pi^4}{f_K^4} \approx 0.48$$

$$\frac{1}{P.S.}\Gamma(G\to\pi\pi : K\bar{K} : \eta\eta) \approx 1.3 : 3.16 : 1$$

$f_0(1710)$ largely overlapped with scalar glueball

Amplitude analysis of $J/\psi \to \gamma\eta'\eta'$



The dominant contributions are from the scalars, f0(2020), the same as $f_0(2010)$ in $J/\psi \to \gamma\eta'\eta'$, $f_0(2100)$ in $J/\psi \to \gamma KsKs$?

The structure around 2.1 GeV has a large production in J/ψ radiative decays

Coupled channel analysis is essential!

PRD 105, 072002 (2022)

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

Tensor glueball searches

$$\Gamma(J/\psi \to \gamma G_{2+}) = 1.01(22) keV$$

$$\Gamma(J/\psi \to \gamma G_{2+})/\Gamma_{tot} = 1.1 \times 10^{-2}$$

CLQCD, Phys. Rev. Lett. 111, 091601 (2013)

Experimental results

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = (3.8^{+0.62}_{-0.65}{}^{+2.37}_{-2.07}) \times 10^{-5}$$

Phys.Rev. D87, 092009 (2013)

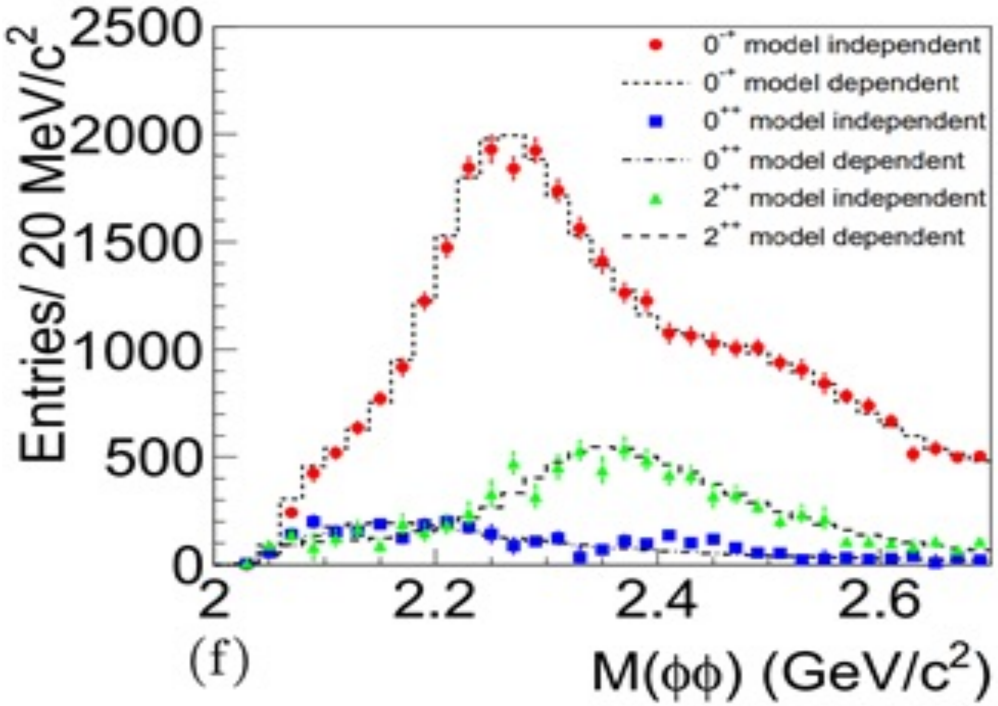
$$Br(J/\psi \to f_2(2340) \to \gamma\phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73}) \times 10^{-4}$$

Phys.Rev. D93, 112011 (2016)

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma K_S K_S) = (5.54^{+0.34}_{-0.40}{}^{+3.82}_{-1.49}) \times 10^{-5}$$

Phys.Rev. D98, 072003 (2018)

$J/\psi \to \gamma\phi\phi$



$f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ are observed with a strong production of $f_2(2340)$; consist with central production and pp-bar annihilations

It is desirable to search for more decay modes

Landscape of light glueball has updated

Scalar : Overpopulation

- LQCD : ground state 0^+ glueball ~1.7 GeV, first excitation ~2.1 GeV

✓ **Strong production of $f_0(1710)/f_0(2100)$ in $J/\psi \to \gamma\, \eta\eta/KK/\pi\pi$**, the pattern consists with LQCD' s prediction

Tensor : large uncertainty

- LQCD : 2^{++}(2.3~2.4 GeV)

✓ **Strong production of $f_2(2340)$ in $J/\psi \to \gamma\eta\eta/KK/\pi\pi/\phi\phi$** ; consists with LQCD' s prediction

Pseudoscalar : very little known above 2 GeV, puzzles in low mass region

- LQCD : 0^{-+}(2.3~2.6 GeV)

✓ **Trajectory :**
- **$f_1(1285)$, no $\eta(1295)$**
- **$\eta(1405)$ /$\eta(1475)$ can be one resonance**

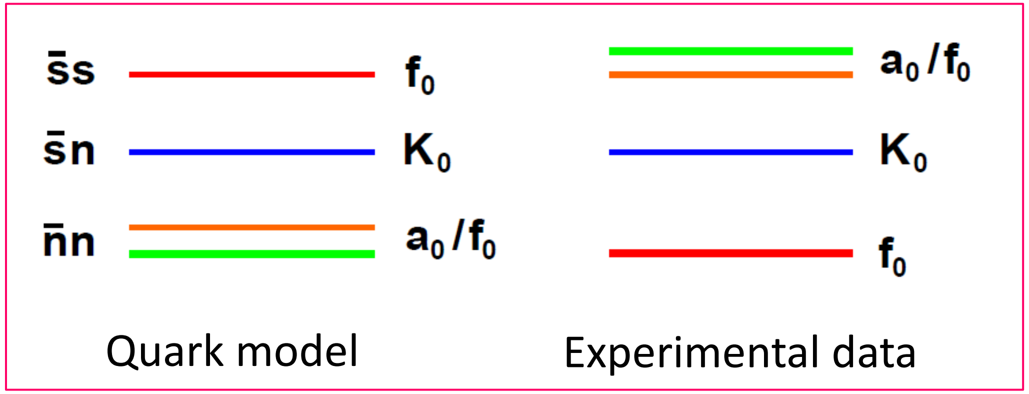
□ **Above 2 GeV: X(2370)?**

Exotics searches

- Mutiquarks
- States with exotic J^{PC}
- Four quark matter: Z_c particles

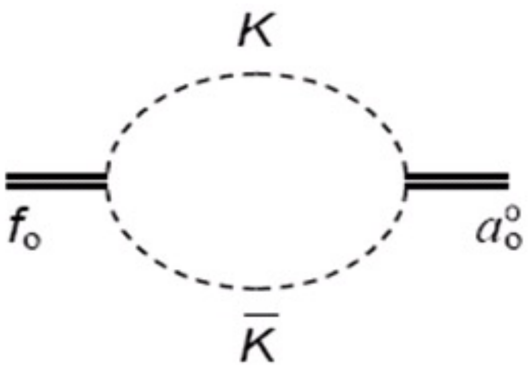
Nature of $a_0(980) - f_0(980)$

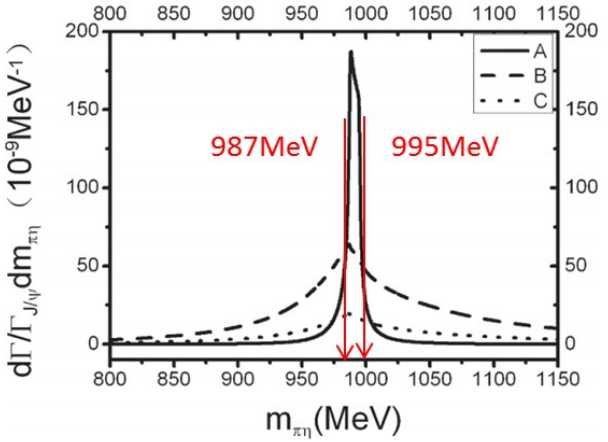
- The nature of ground state scalar $a_0(980)$ and $f_0(980)$ are controversial



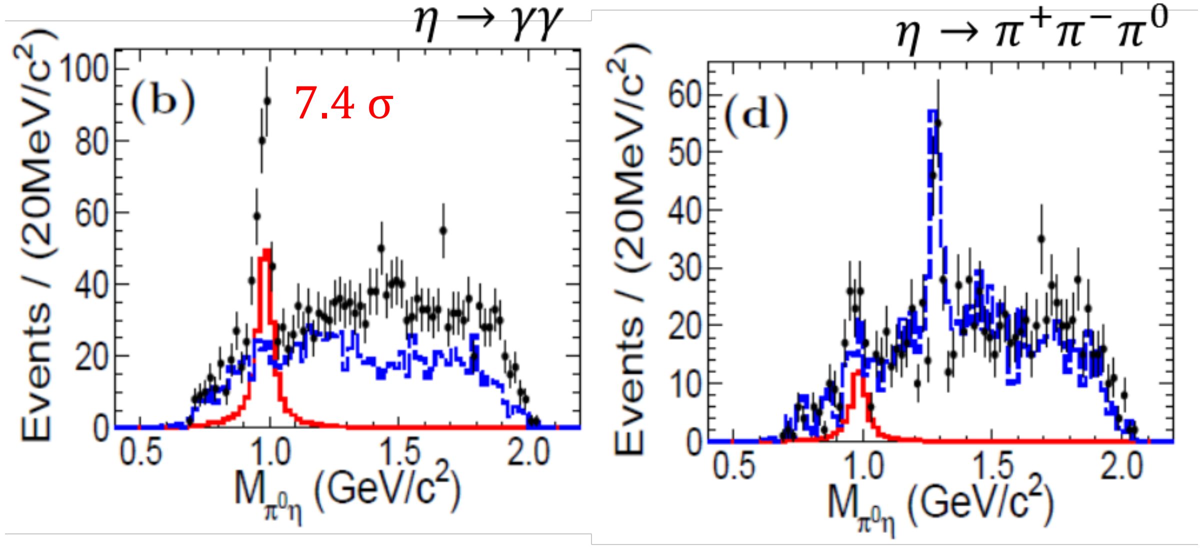
$q\bar{q}$ mesons, $K\bar{K}$ molecules, tetraquarks, hybrids,... ?

- $a_0(980) - f_0(980)$ mixing (proposed in 1979) is very sensitive to $K\bar{K}$ coupling, which is an important probe to the internal structure of $a_0(980)$ and $f_0(980)$

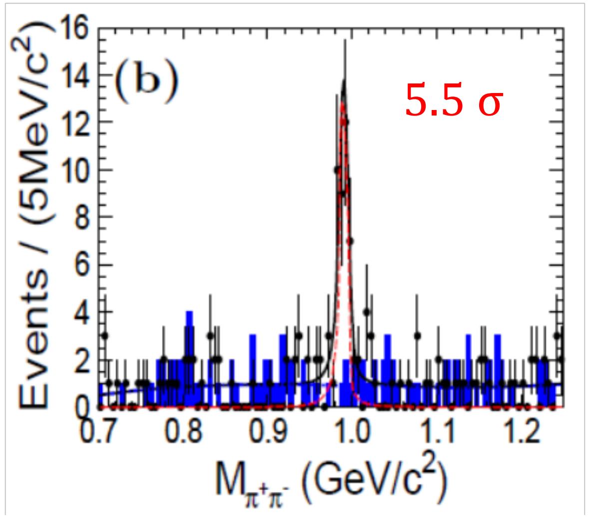


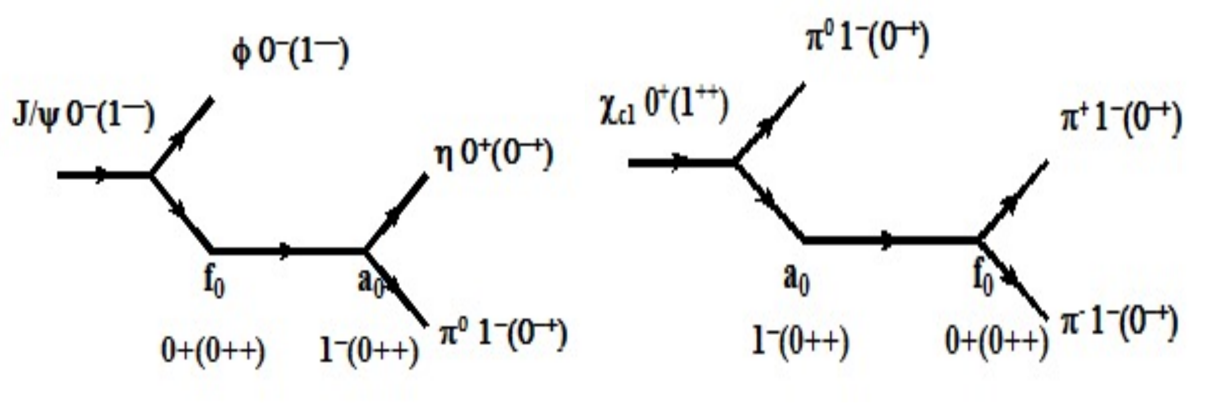


$a_0(980) - f_0(980)$ mixing



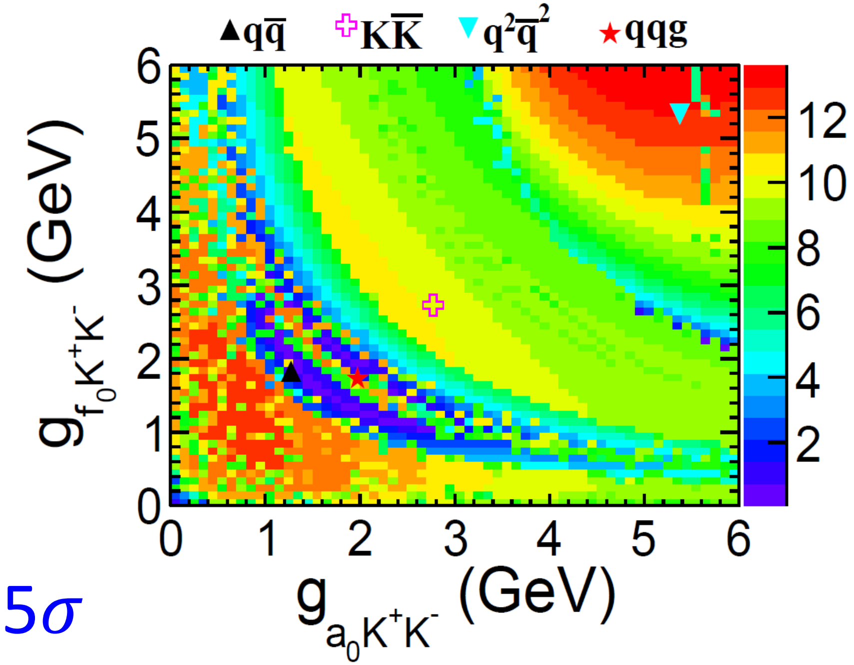
PRL 121,022001(2018)





PRD75 114012,PRD76, 074028

PR D78 074017

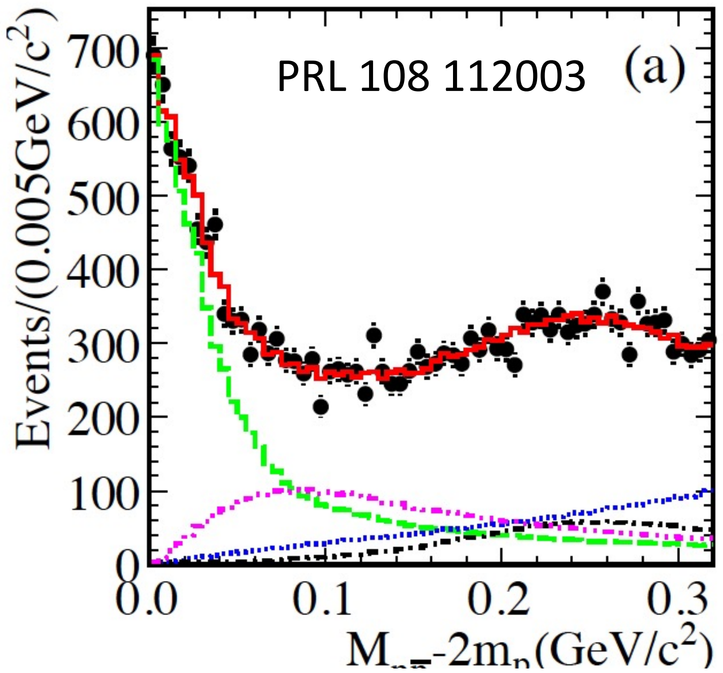


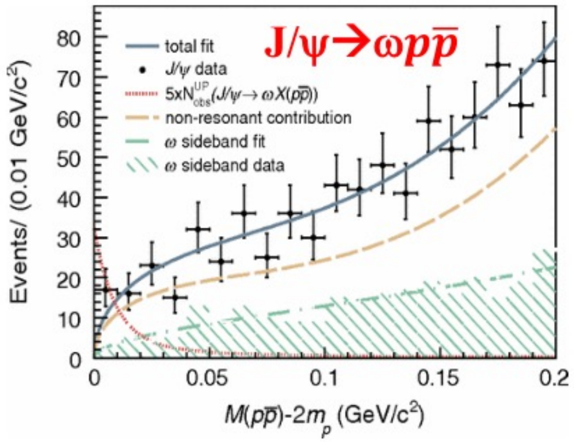
First observation with > 5σ

Favors the multiquark model!

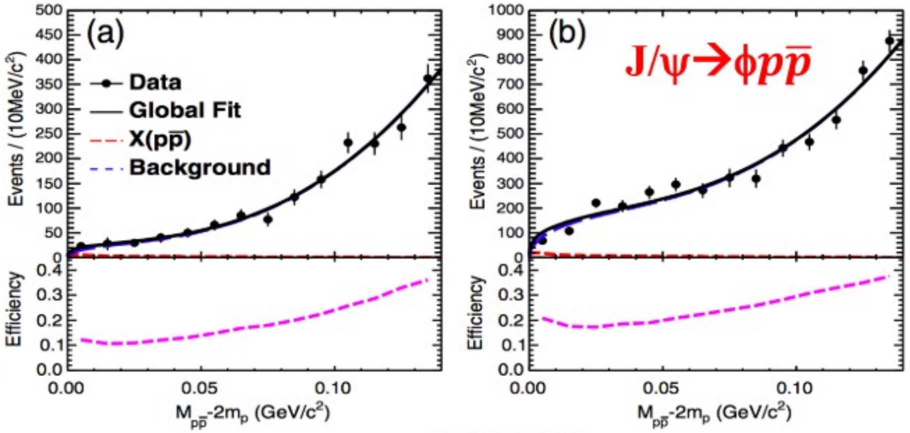
$p\bar{p}$ threshold enhancement X($p\bar{p}$) : Baryonium state?

- First observed in $J/\psi \to \gamma p\bar{p}$ at BESII, confirmed by BESIII and CLEO-c
- PWA of $J/\psi \to \gamma p\bar{p}$: $J^{PC} = 0^{-+}$
  - The fit with a BW and S-wave FSI (I=0) factor can well describe $p\bar{p}$ mass threshold structure
- Non-observation in hadronic decays: not from pure FSI

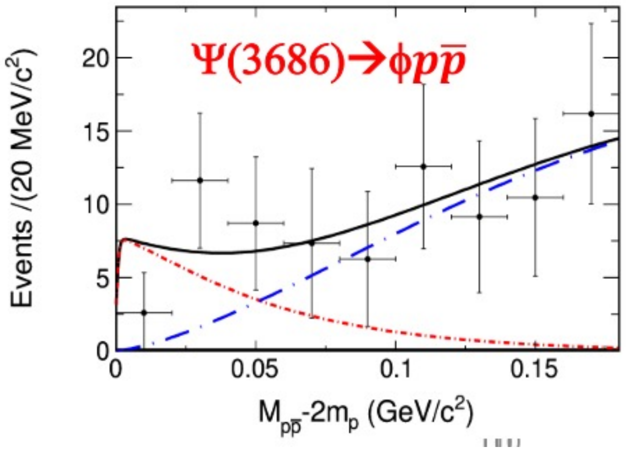




PRD87,112014(2013)

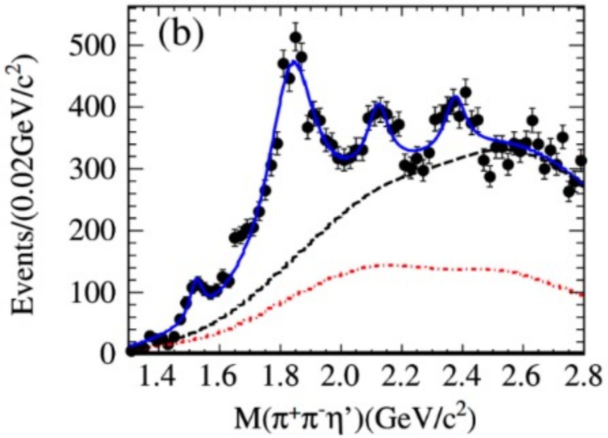


PRD93,052010(2016)



PR D99 112010(2019)

Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold



X(1835) observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$

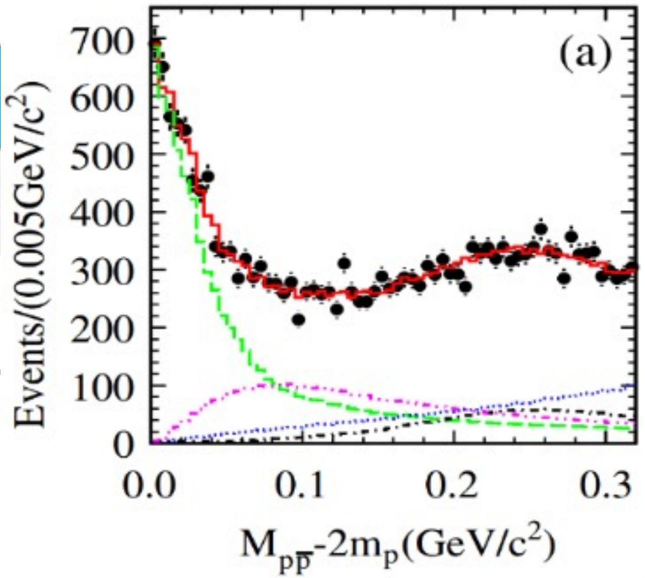
X(1835) $J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2

PRL 106, 072002 (2011)

X($p\bar{p}$) observed in $J/\psi \to \gamma p\bar{p}$

X($p\bar{p}$) $J^{PC}=0^{-+}$
$M = 1832^{+19}_{-5}{}^{+18}_{-17} \pm 19$ MeV/c^2
$\Gamma = 13 \pm 19$ MeV/c^2 (< 76 MeV/c^2 @ 90% C.L.)

PRL 108, 112003 (2012)

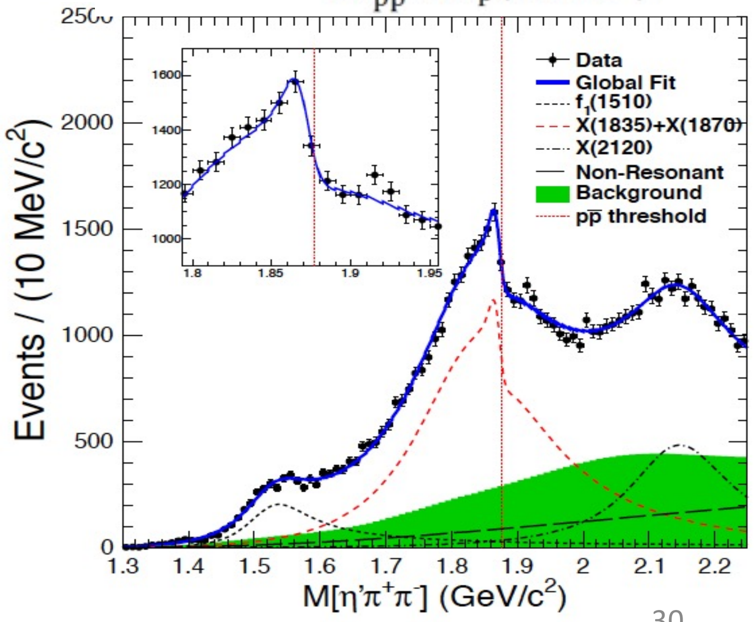


connection between X(1835) and X($p\bar{p}$)

The anomalous line shape :

-- 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

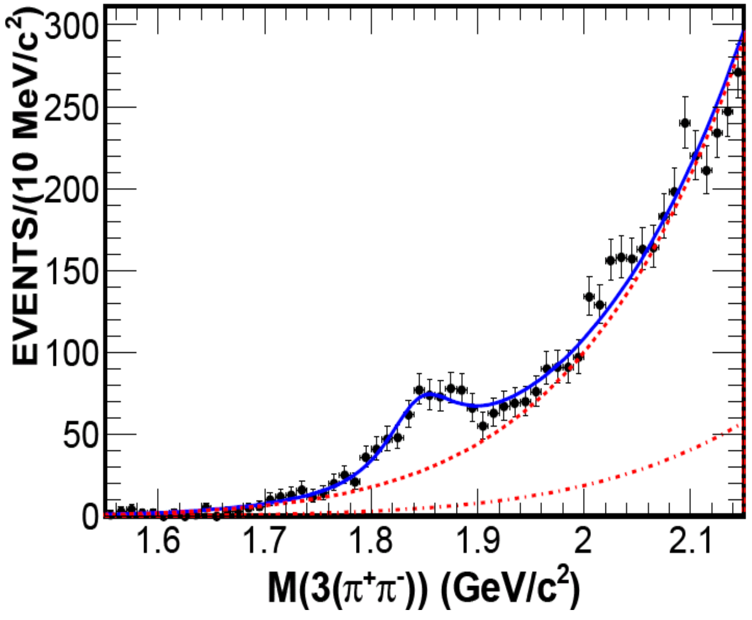
-- Support the existence of a $p\bar{p}$ molecule-like state or bound state



PRL 117, 042002 (2016)

New decay modes of X(1835)

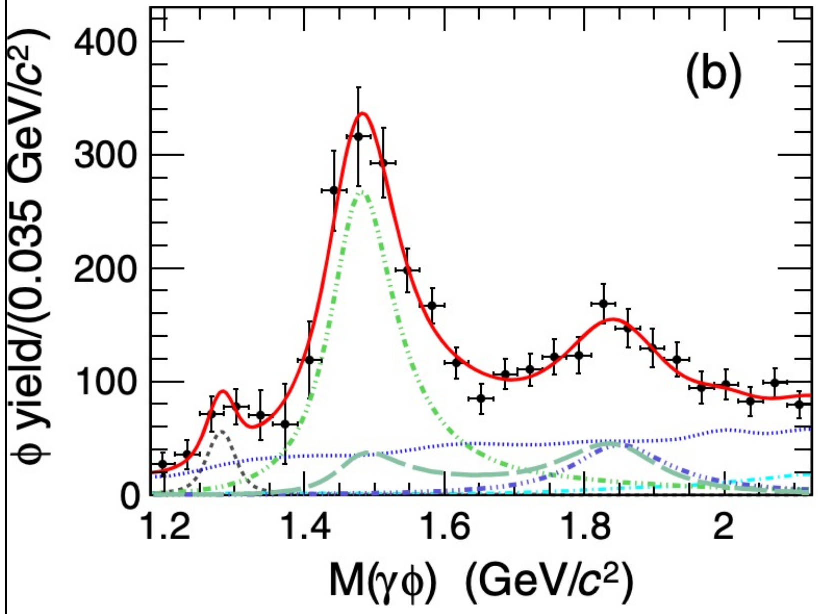
J/ψ→γ 3($\pi^+\pi^-$)



PRD 88, 091502 (2013)

X(1840) → 3($\pi^+\pi^-$) , new decay mode?

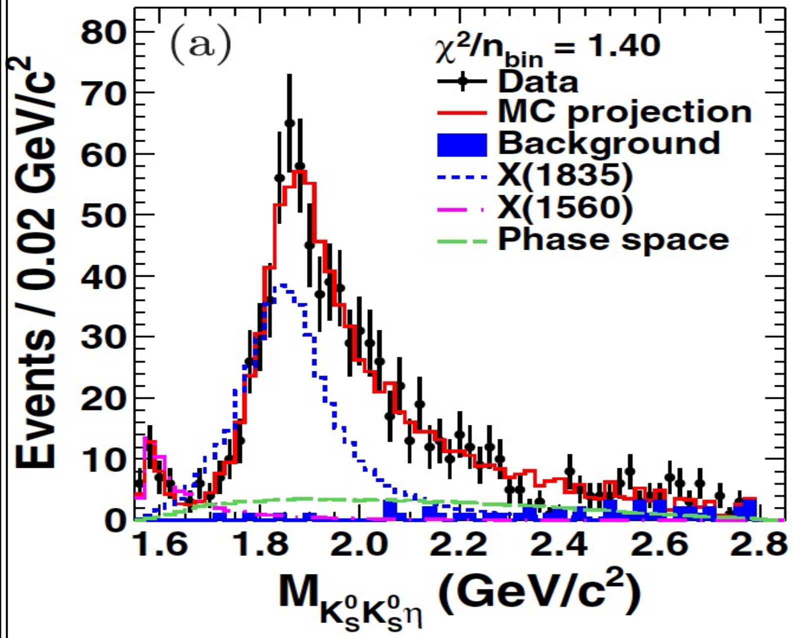
J/ψ→γ γ ϕ



PRD97, 051101(2018)

X(1840) → γ ϕ, sizable $s\bar{s}$ component

J/ψ→γ $K_sK_s\eta$



PRL 115, 091803(2018)

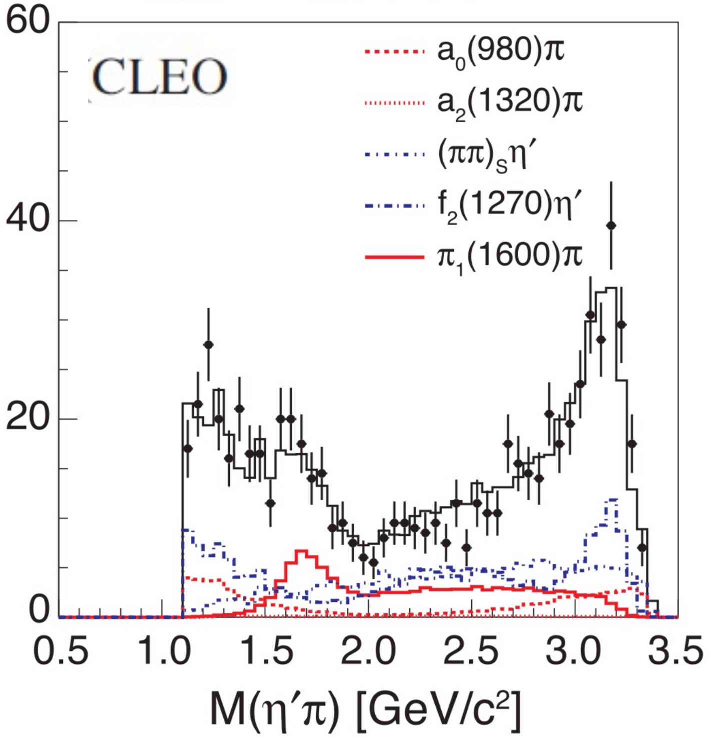
X(1835)→$K_SK_S\eta$ with $J^{PC}=0^{-+}$

More experimental results needed to understand the structures around 1.85 GeV

Exotics (J^{PC}=0^{--},0^{+-},1^{-+},2^{+-},3^{-+},…)

- J^{PC} exotic particles: beyond the naive quark model
- easily to distinguish from others due to the exotic J^{PC}
- production rate and dynamics are not well understood
- candidates? $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2150)$

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



PRD84 (2011) 112009

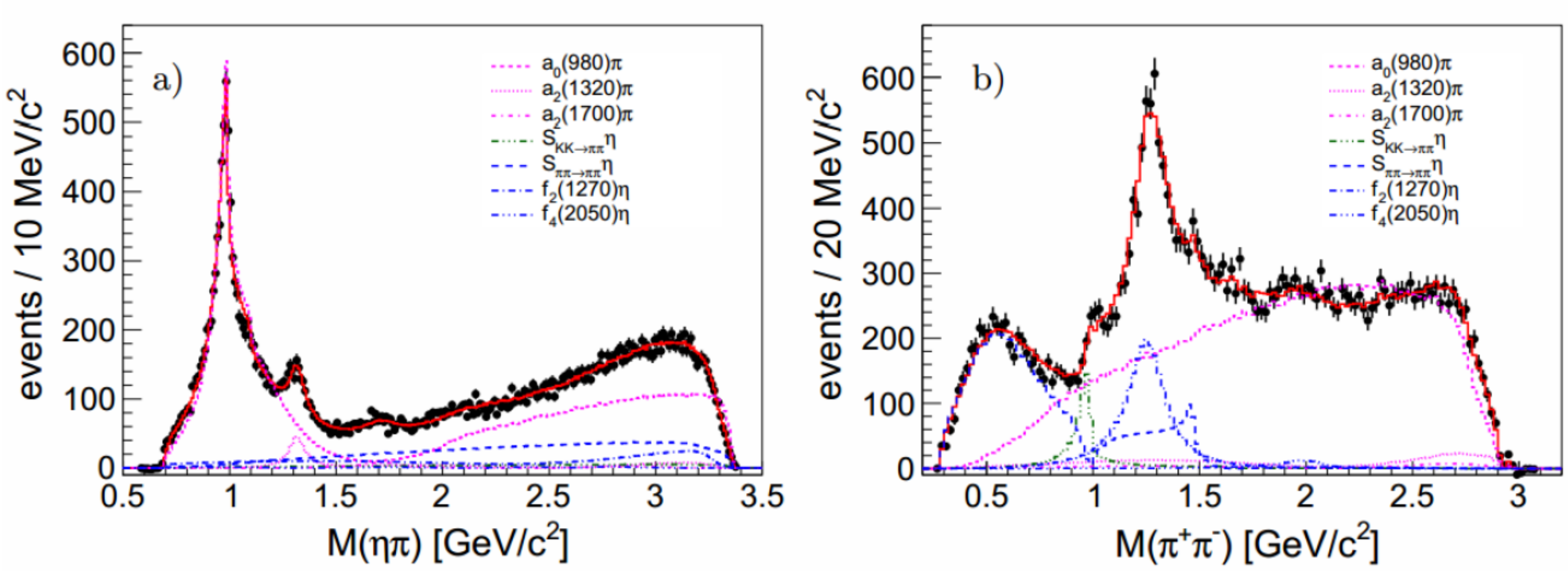
Evidence of $\pi_1(1600)$ was seen !

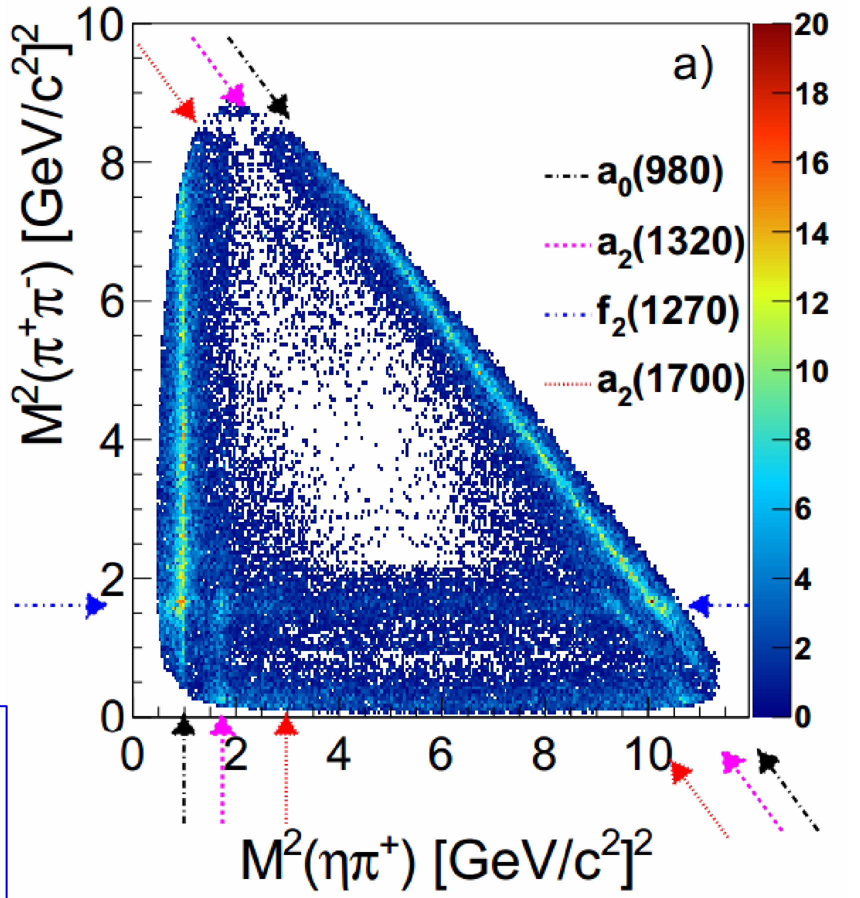
χ_{cJ} decays: an important source for exotics

- Only π_1 are observed. Isoscalar 1^{-+} is critical to establish the nonet
- Isoscalar 1^{-+} is expected to be produced J/ψ radiative decays
- $J/\psi \to \gamma + a_1\pi/\eta f_1/K_1K/\eta\eta'/\eta f_2$ /…,
- Synergies between other experiments with different production mechanism

Search for exotics with $J^{PC} = 1^{-+}$ in $\chi_{cJ} \to \eta\pi^+\pi^-$

PRD95, 032002(2017)

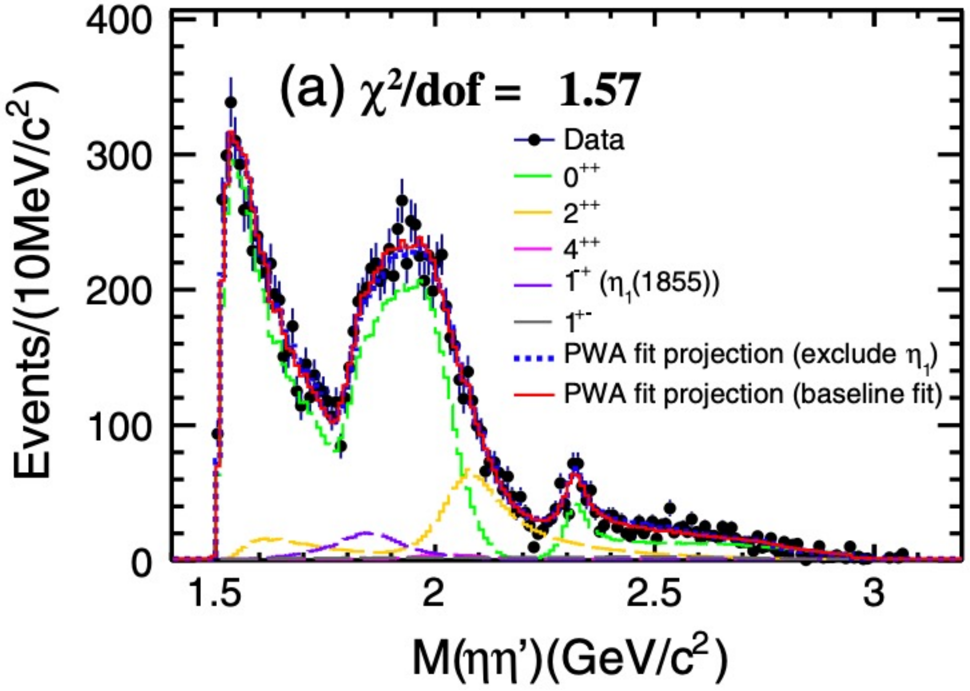


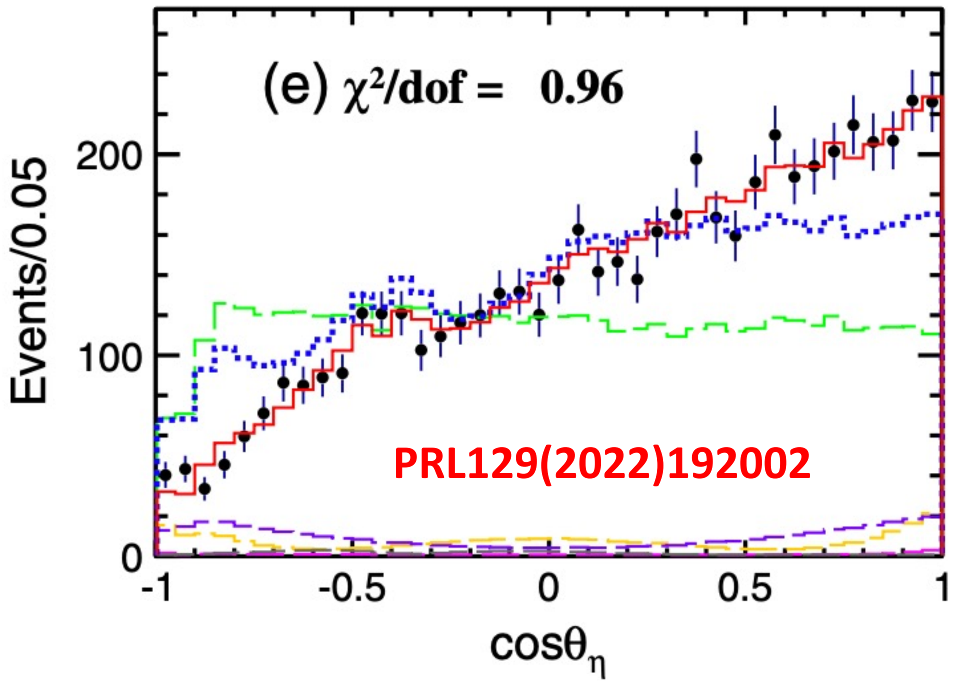


- Clear evidence for $a_2(1700)$ in χ_{c1}decays.
- First measurement of $g'_{\eta'\pi} \neq 0$ using $a_0(980) \to \eta\pi$ line shape
- Measured upper limits for $\pi_1(1^{-+})$ in 1.4 - 2.0 GeV/c² region

η

Observation of $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$





PRL129, 192002(2022)

Isoscalar state with exotic quantum numbers $J^{PC}=1^{-+}$

$M = 1855 \pm 9^{+6}_{-1}$ MeV/c^2

$\Gamma = 188 \pm 18^{+3}_{-8}$ MeV

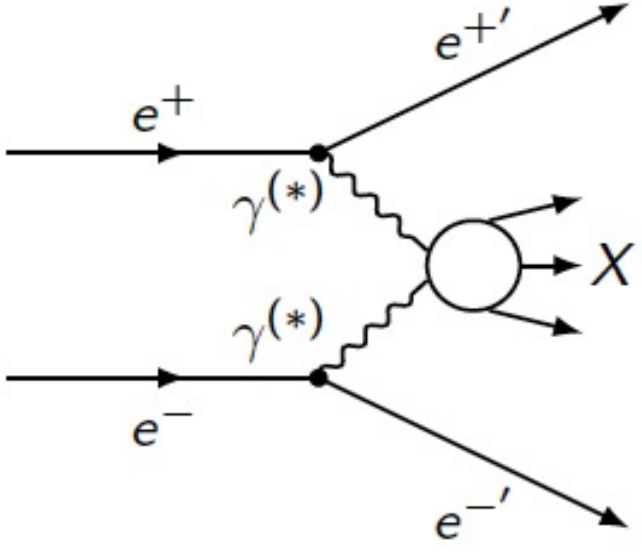
Critical to establish the 1^{-+} hybrid nonet !

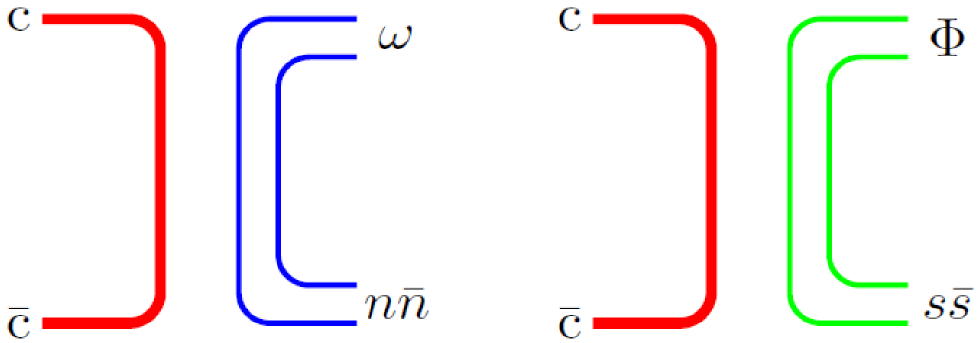
Prospects: 10B J/ψ and 2.7B ψ(2S) provide great opportunities

	0^+	2^+	0^-
J/ψ→γPP			
J/ψ→γVV			
J/ψ→γPPP			
J/ψ→γPPPP			

- 0^+, 2^+ : coupled channel analysis
  - J/ψ→γPP
  - J/ψ→ω/φ + X
- 0^- : trajectory >2 GeV, X(2370)
  - J/ψ→γPPP
  - J/ψ→γγ V
- 1^{-+}
  - J/ψ→$\gamma\eta_1^{(\prime)}$
  - $\chi_{c1} \to \eta\eta_1^{(\prime)}, \pi\pi_1$

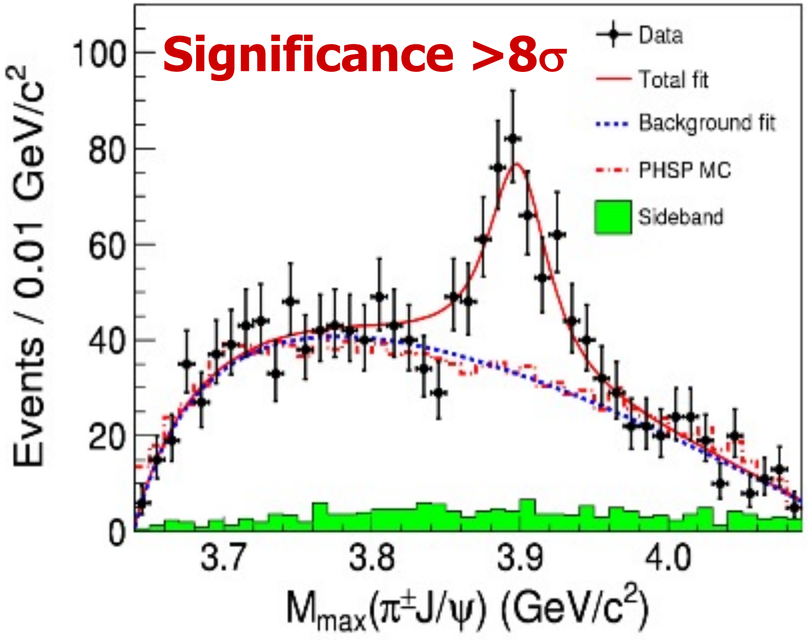
Anti filter:

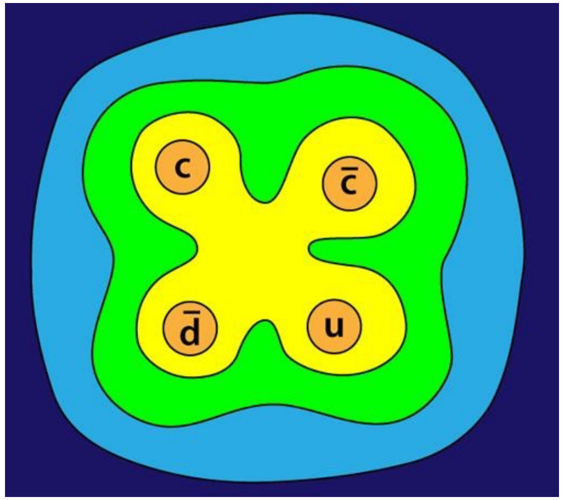




Flavor Filters：J/ψ→ω/ϕ + X

Observation of four-quark state $Z_c(3900)$ in $e^+e^- \to \pi^+\pi^- J/\psi$



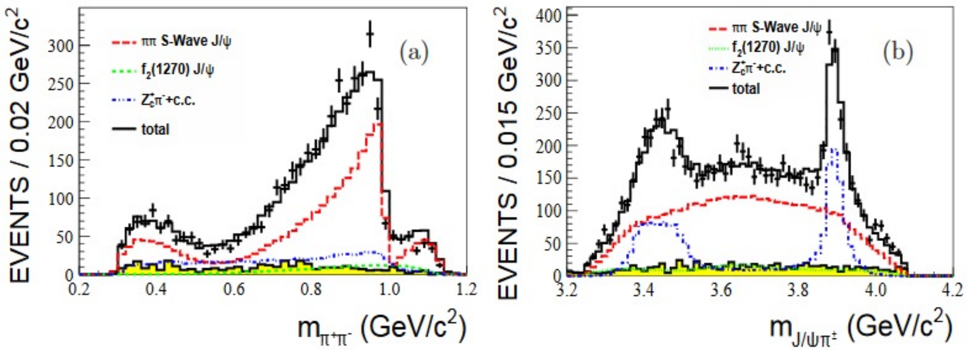


PRL110, 252001 (2013)

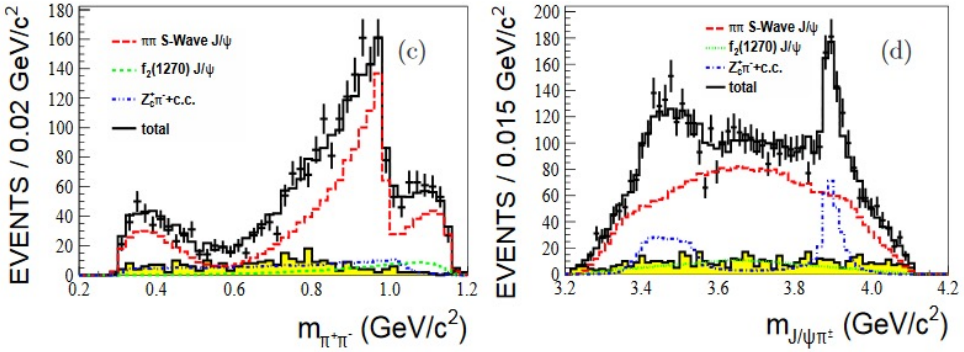
- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV
- $\Gamma = 46 \pm 10 \pm 20$ MeV

Confirmed by Belle and CLEOc: established !

PWA indicates $J^P = 1^+$

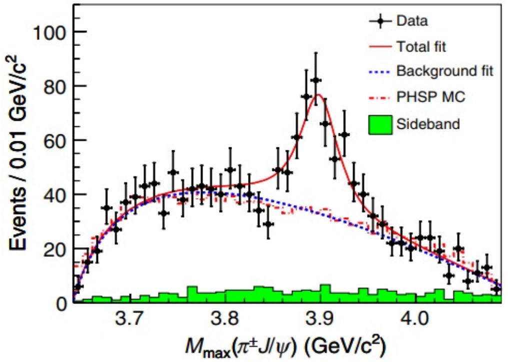


PRL119, 072001(2017)

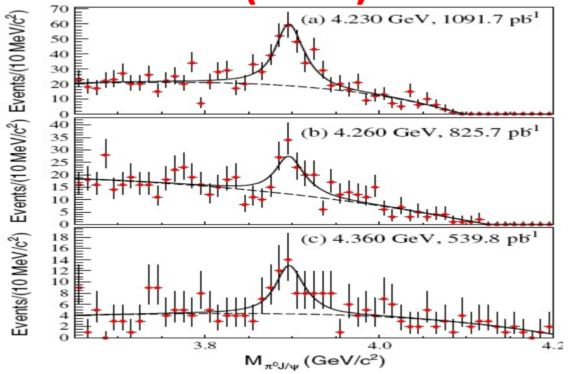


The Z_c states

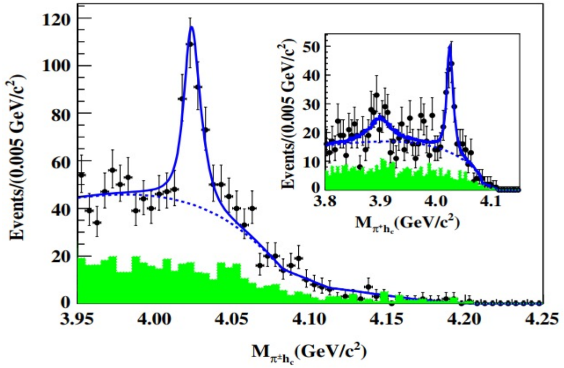
$e^+e^- \to \pi^+\pi^- J/\psi$
$Z_c(3900)^+$
PRL110(2013)252001



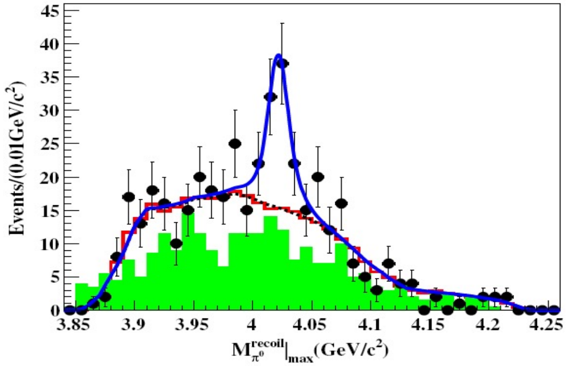
$e^+e^- \to \pi^0\pi^0 J/\psi$
$Z_c(3900)^0$
PRL115(2015)112003



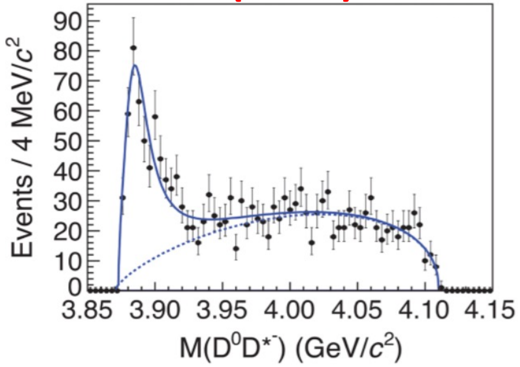
$e^+e^- \to \pi^+\pi^- h_c$
$Z_c(4020)^+$
PRL111(2013)242001



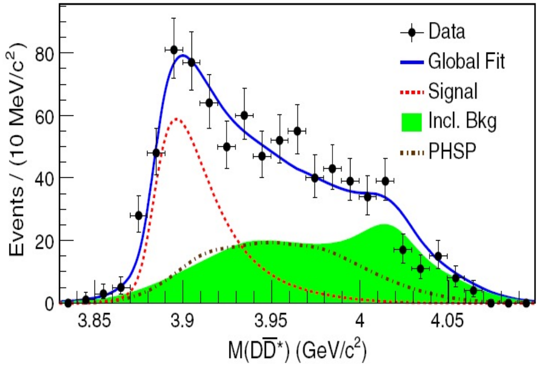
$e^+e^- \to \pi^0\pi^0 h_c$
$Z_c(4020)^0$
PRL113(2014)212002



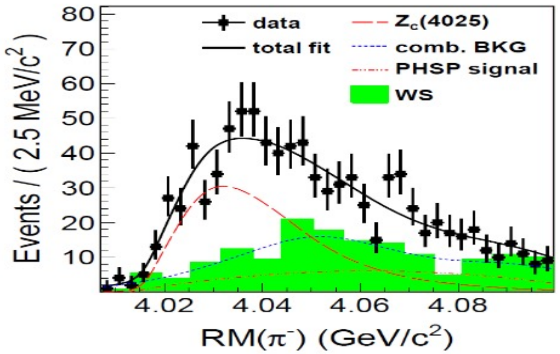
$e^+e^- \to \pi^-(D\bar{D}^*)^+$
$Z_c(3885)^+$
PRL112(2014)022001



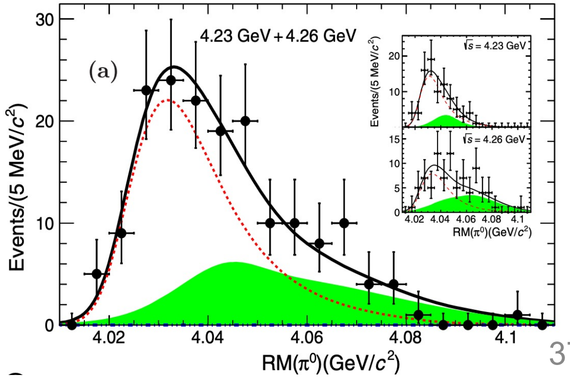
$e^+e^- \to \pi^0(D\bar{D}^*)^0$
$Z_c(3885)^0$
PRL115(2015)222002



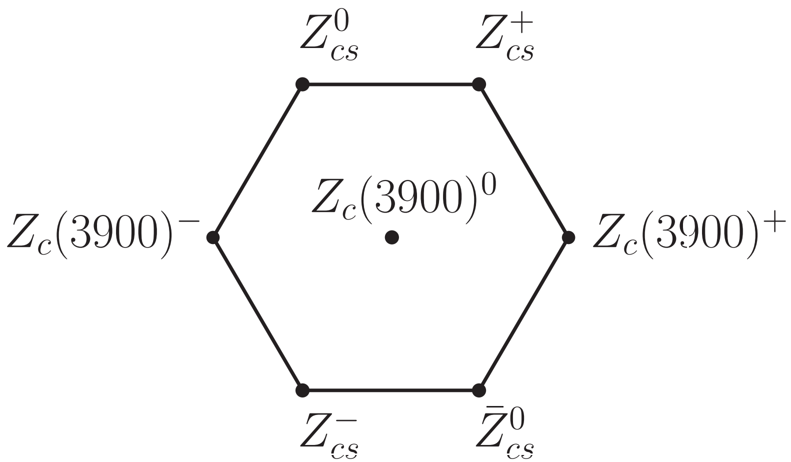
$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$
$Z_c(4025)^+$
PRL112(2014)132001

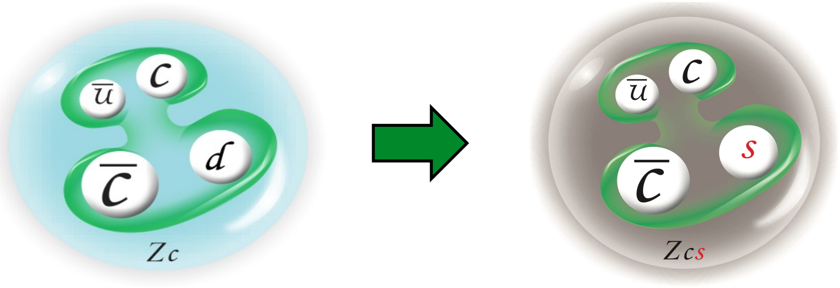


$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$
$Z_c(4025)^0$
PRL115(2015)182002

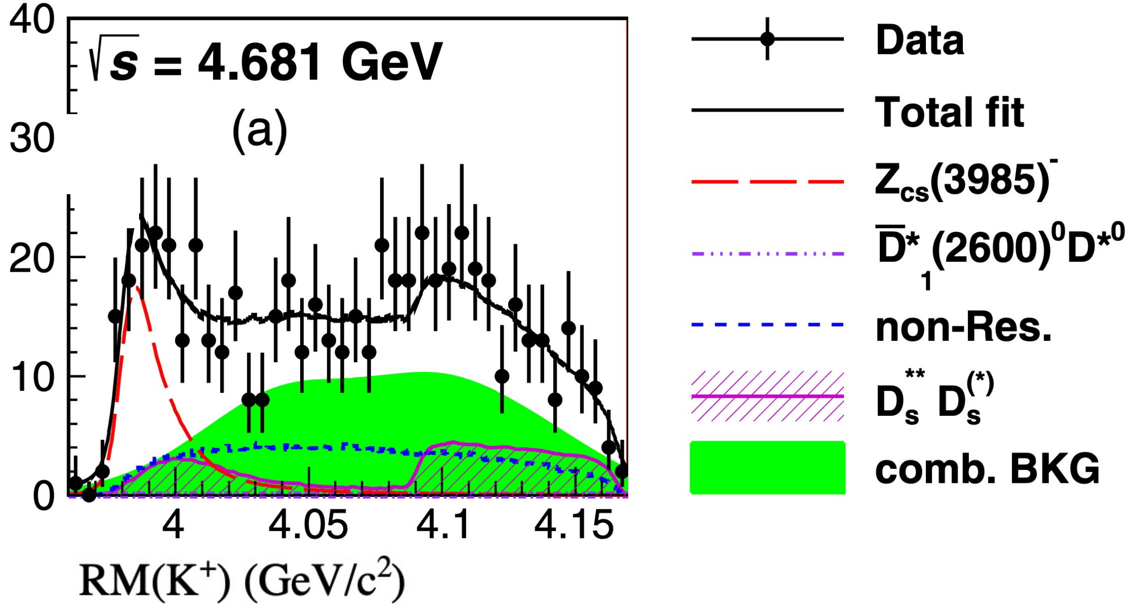


Observation of $Z_{cs}(3985)$: SU(3) partner of Z_c

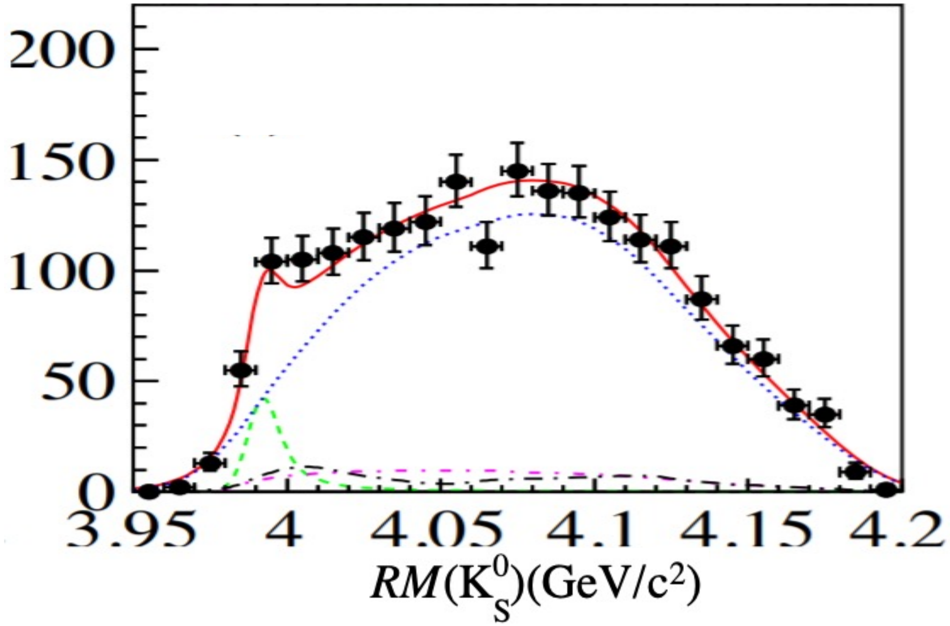




$e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$



$e^+e^- \to K_S^0(D_s^+ D^{*-} + D_s^{*+} D^-)$



PRL126(2021)102001

PRL129(2022)112003

Summary

- Data with unprecedented statistical accuracy from BESIII provides great opportunities to search for glueballs and exotics
- To obtain a complete picture, different experiments with complementary information are needed
- To explore the high statistics data sets, more advanced tools and closer experimental-theoretical cooperation are needed

- It is crucial for theoretical studies to provide information of the production property
- BEPCII/BESIII upgrades in 2024, then continues to take data till ~2030

Many thanks for your attention!