Light Hadron Spectroscopy at BESIII

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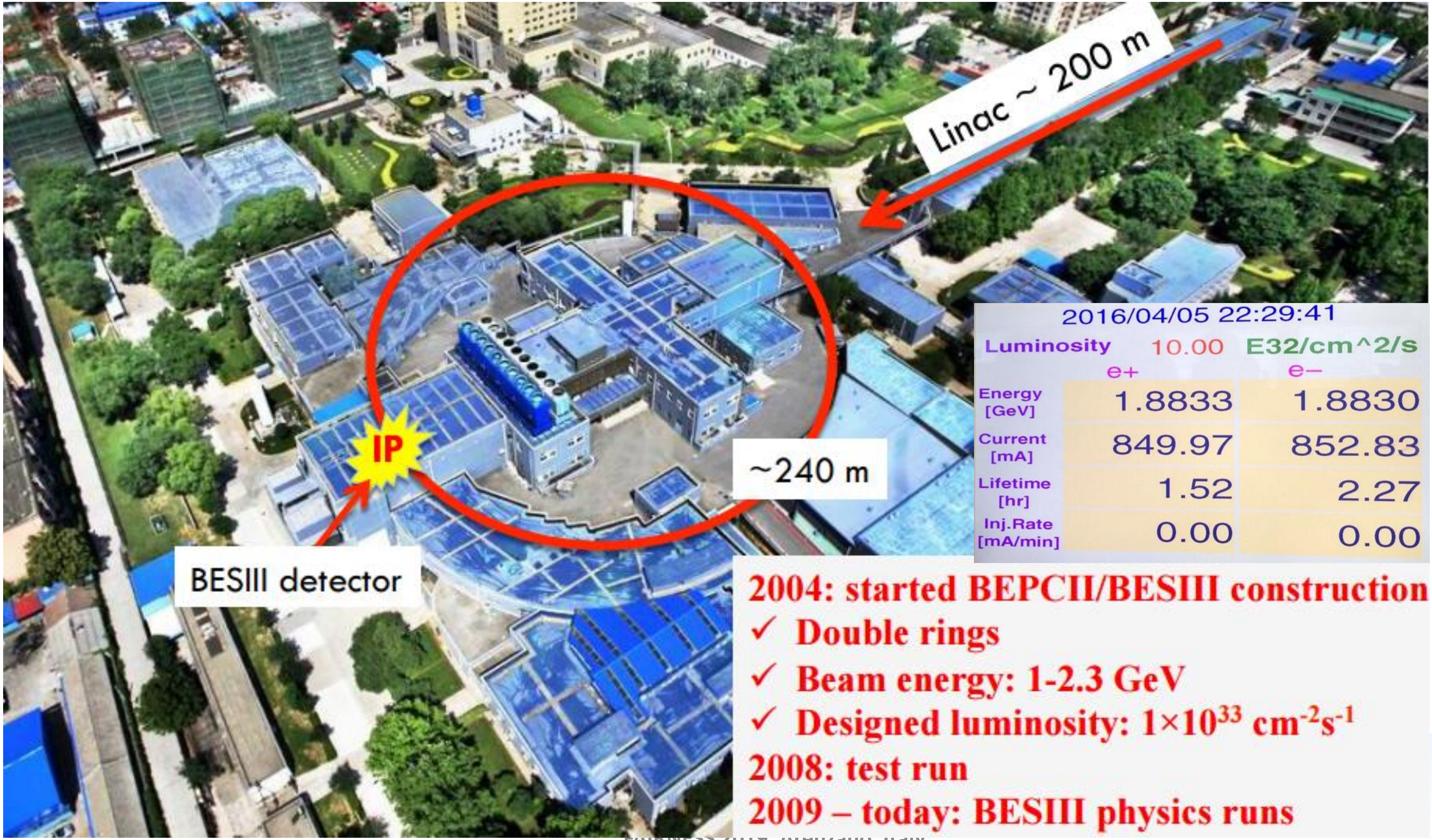
Outline

- **Introduction**
- **Recent highlights of BESIII results**
  - ✓ **$p\bar{p}$ threshold enhancement X($p\bar{p}$)/X(1835)**
  - ✓ **Study of the glueball candidates**
  - ✓ **$f_0(980)$-$a_0(980)$ mixing**
- **Summary**



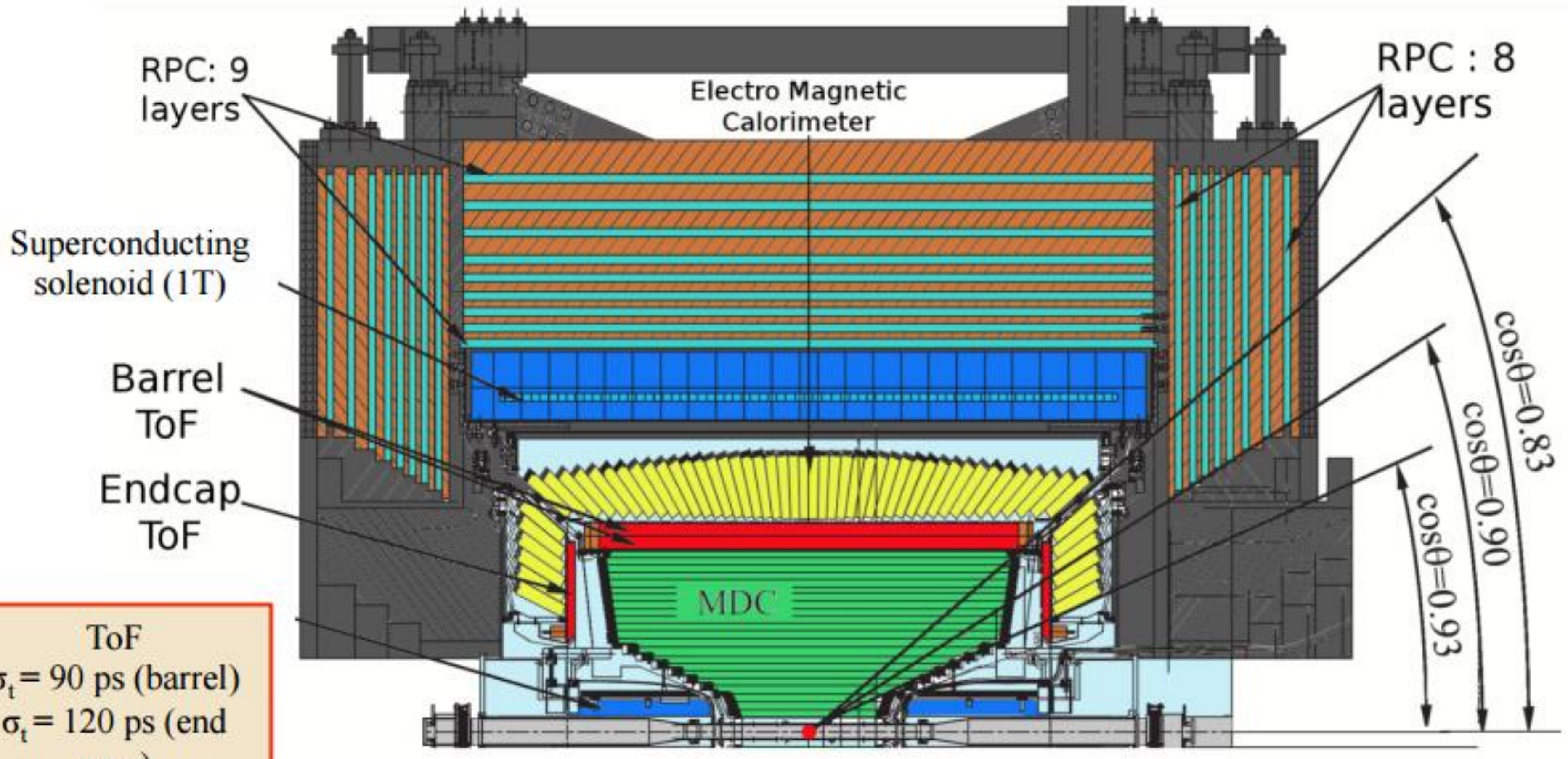
2004: started BEPCII/BESIII construction

- ✓ **Double rings**
- ✓ **Beam energy: 1-2.3 GeV**
- ✓ **Designed luminosity: 1×10^{33} $cm^{-2}s^{-1}$**

2008: test run

2009 – today: BESIII physics runs

BESIII detector



ToF
σ_t = 90 ps (barrel)
σ_t = 120 ps (end caps)

Drift Chamber
$\sigma_{r\phi}$ = 130 μm (single wire)
σ_{pt}/p_t = 0.5 % @ 1 GeV

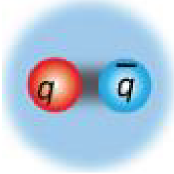
Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
σ_{xy} = (6 mm)/$E^{1/2}$ @ 1 GeV

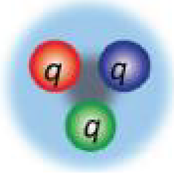
RPC Muon Detector
$\Delta\Omega/4\pi$=93%

Introduction

- Conventional hadrons consist of 2 or 3 quarks:

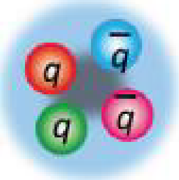
Naive Quark Model: meson

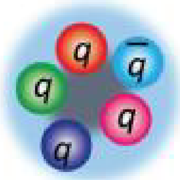




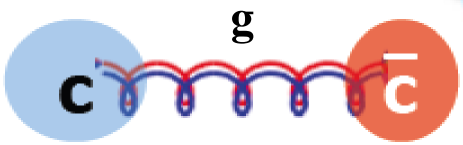
baryon

- QCD predicts the new forms of hadrons:
  - ✓ Multi-quark states: Number of quarks ≥ 4





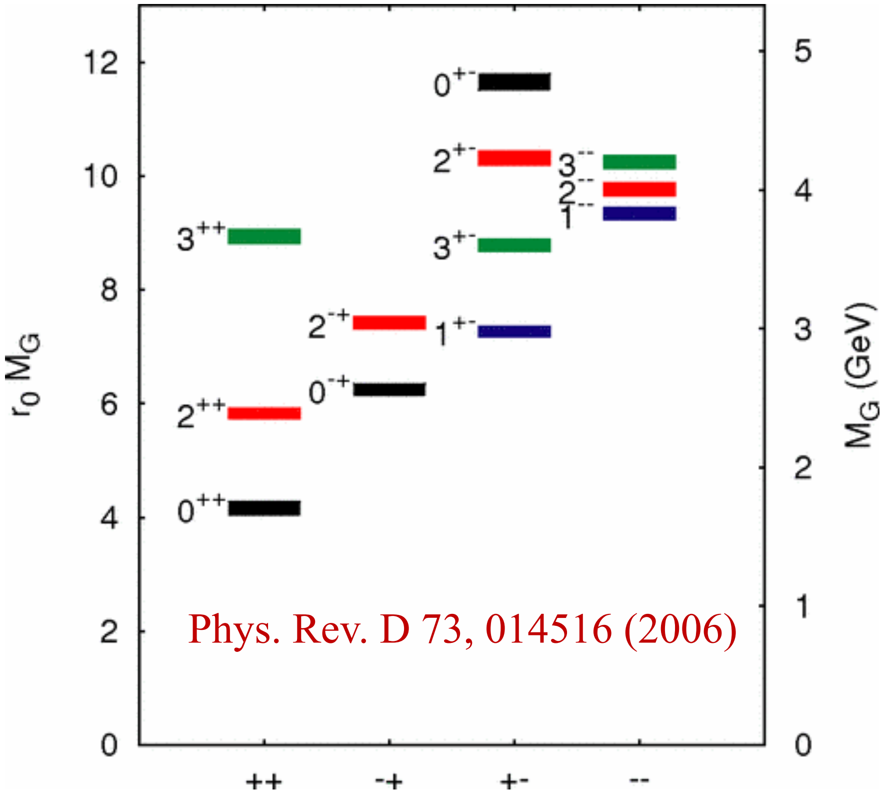
  - ✓ Hybrids: $q\bar{q}g$, $qqqg$ …



  - ✓ Glueballs: gg, ggg …
    - 0^{++} ground state: 1.5~1.7 GeV/c²
    - 2^{++} ground state: 2.3~2.4 GeV/c²
    - 0^{-+} ground state: 2.3~2.6 GeV/c²

g

g g



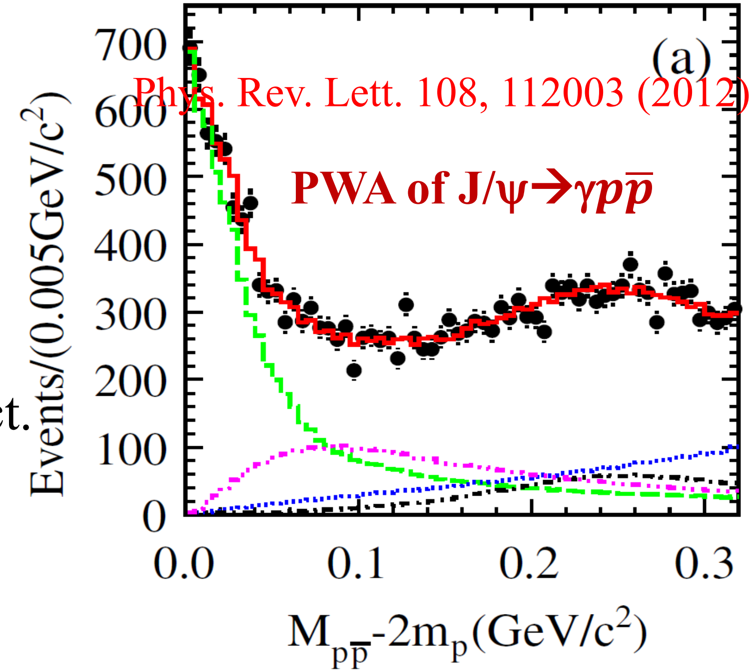
None of the new forms of hadrons is settled!

World largest J/ψ (1.0×10^{10}), ψ(3686) (4.5×10^{8}) … produced directly from e^+e^- collision!

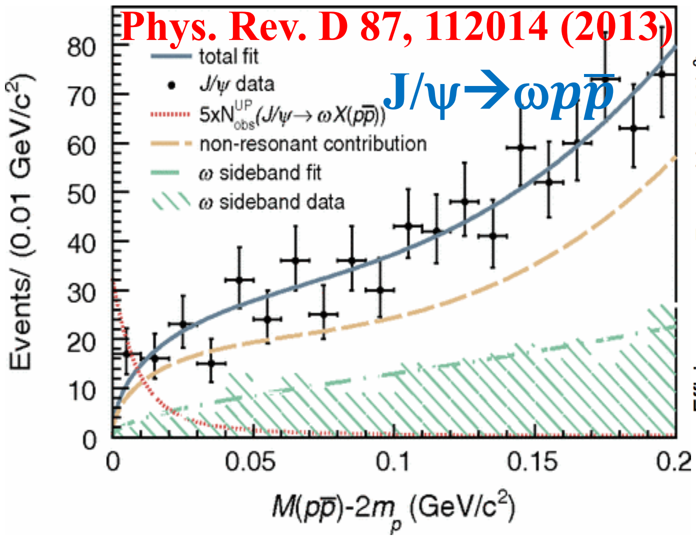
$p\bar{p}$ threshold enhancement X($p\bar{p}$)/X(1835)

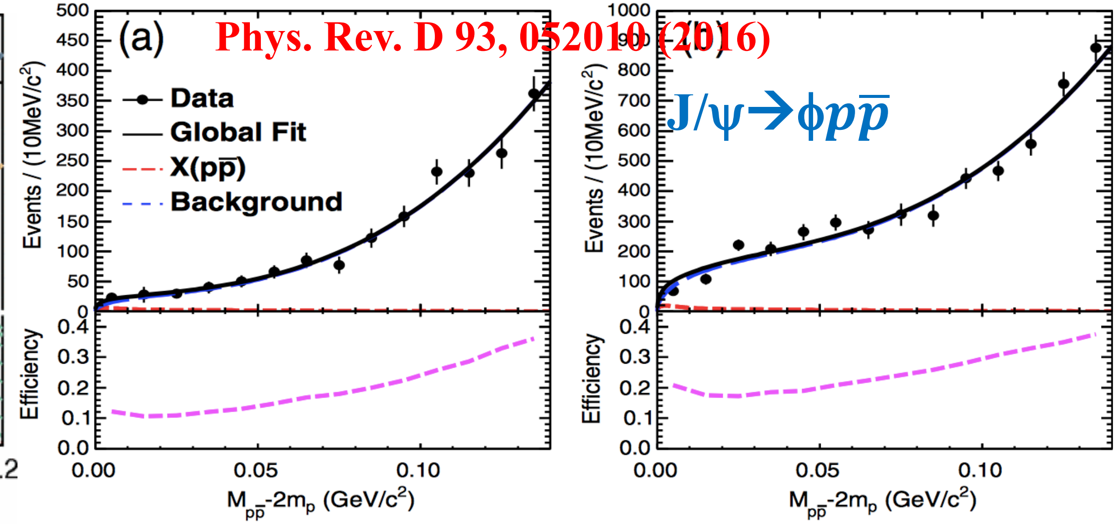
$p\bar{p}$ threshold enhancement X($p\bar{p}$)

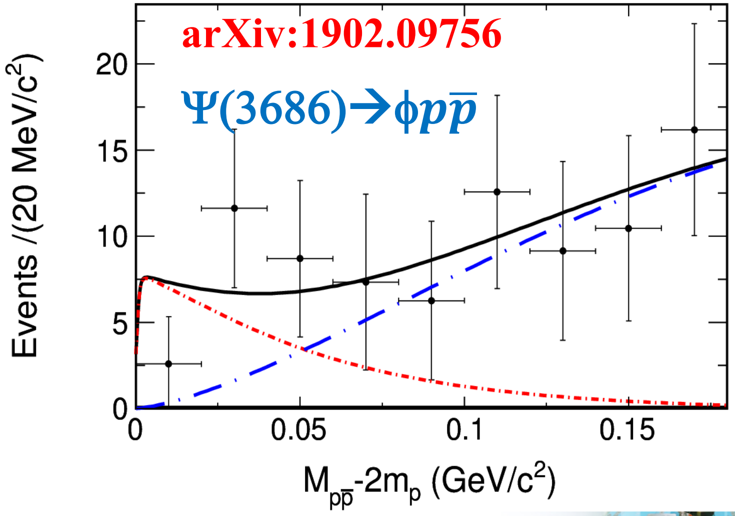
- First observed in J/ψ→$\gamma p\bar{p}$ at BESII. Then confirmed by BESIII and CLEO.
- PWA of J/ψ→$\gamma p\bar{p}$: $J^{PC} = 0^{-+}$
  - ✓ A signal model of BW and S-wave FSI factor can well describe $p\bar{p}$ mass threshold structure, the fit quality is much better than that without FSI effect.



No significant narrow threshold enhancement observed here:



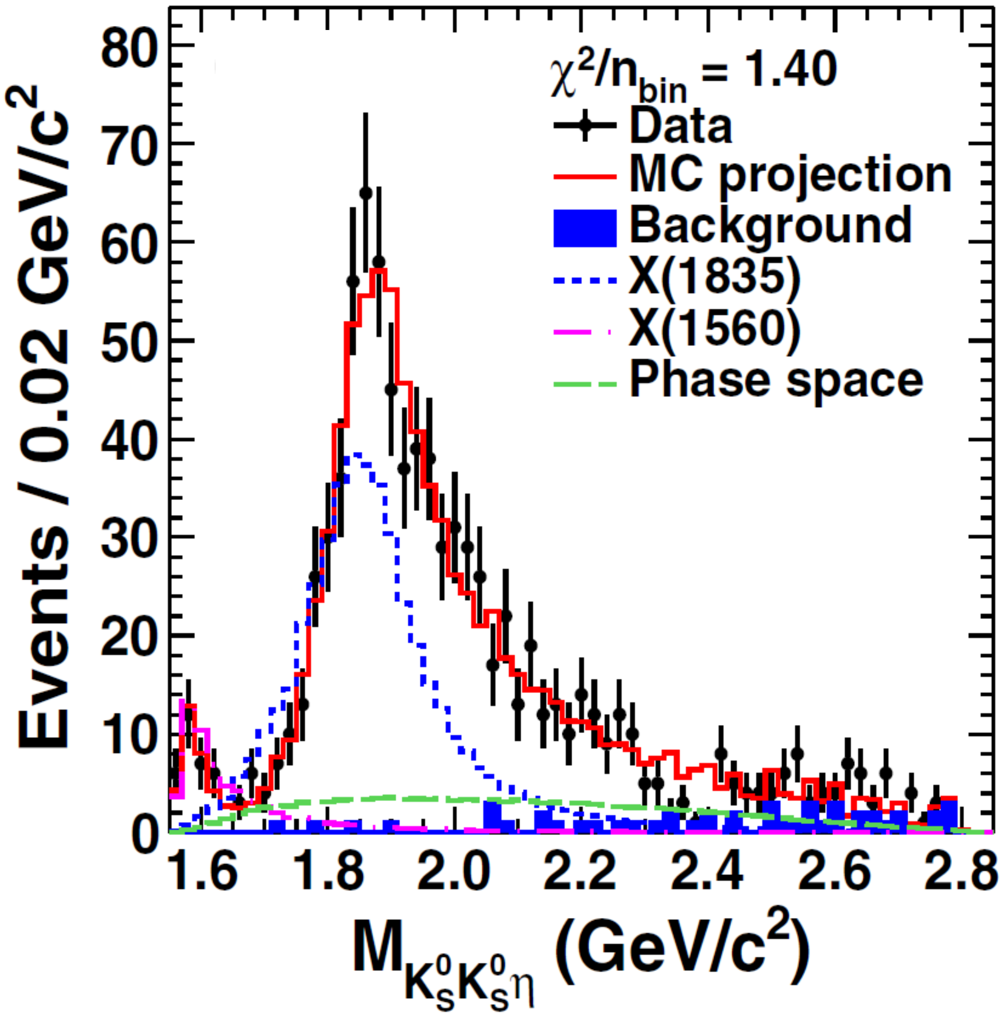




Seems not from pure FSI effect

X(1835)

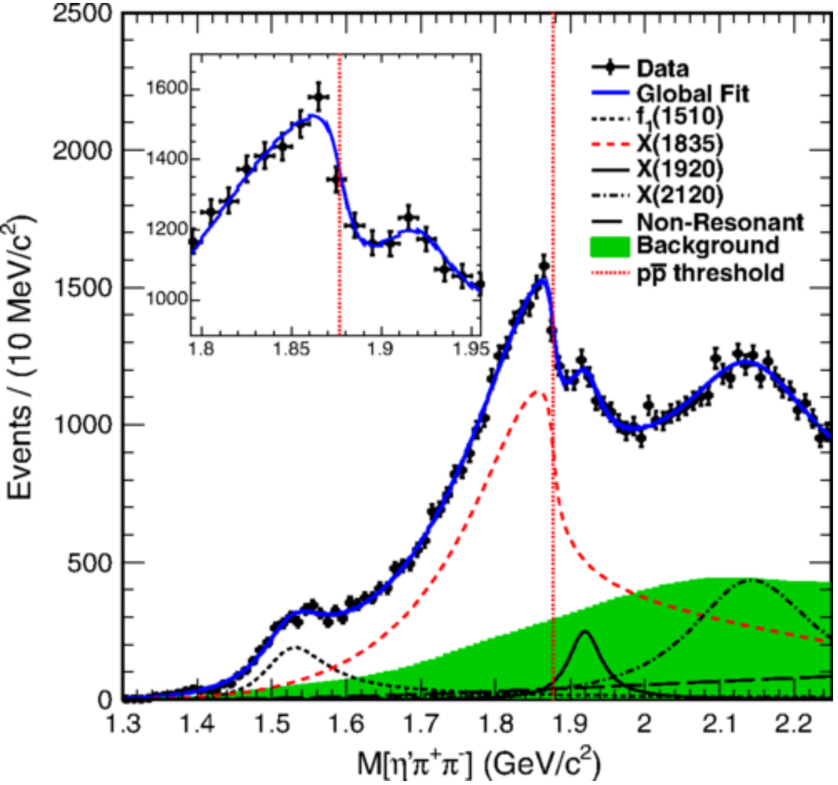
- First observed in $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ by BESII and then confirmed by BESIII using the same decay channel with more J/ψ data.
- PWA of $J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta$:
  - ✓ $J^{PC} = 0^{-+}$.
  - ✓ $M = 1844 \pm 9(stat.)^{+16}_{-25}(syst.)$ MeV/c^2
  - ✓ $\Gamma = 192^{+20}_{-17}(stat.)^{+62}_{-43}(syst.)$ MeV
  - ✓ Consistent with X(1835) in $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$.



BESIII: Phys. Rev. Lett. 115, 091803 (2015)

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

Phys. Rev. Lett. 117, 042002 (2016)



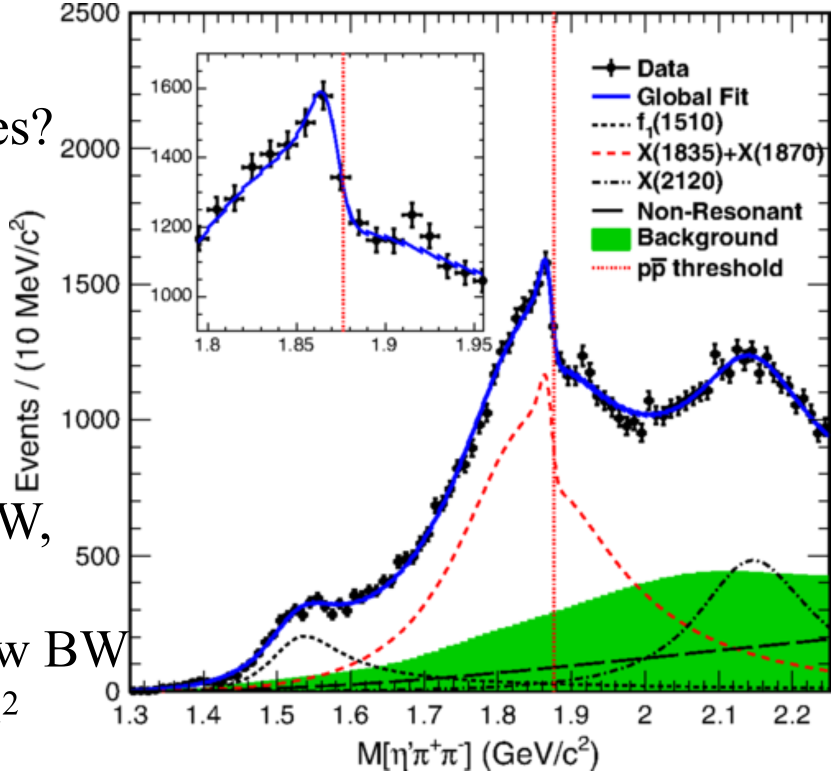
What causes this distorted line shape?

✓ The opening of X(1835)→$p\bar{p}$?

✓ Interference between two resonances?

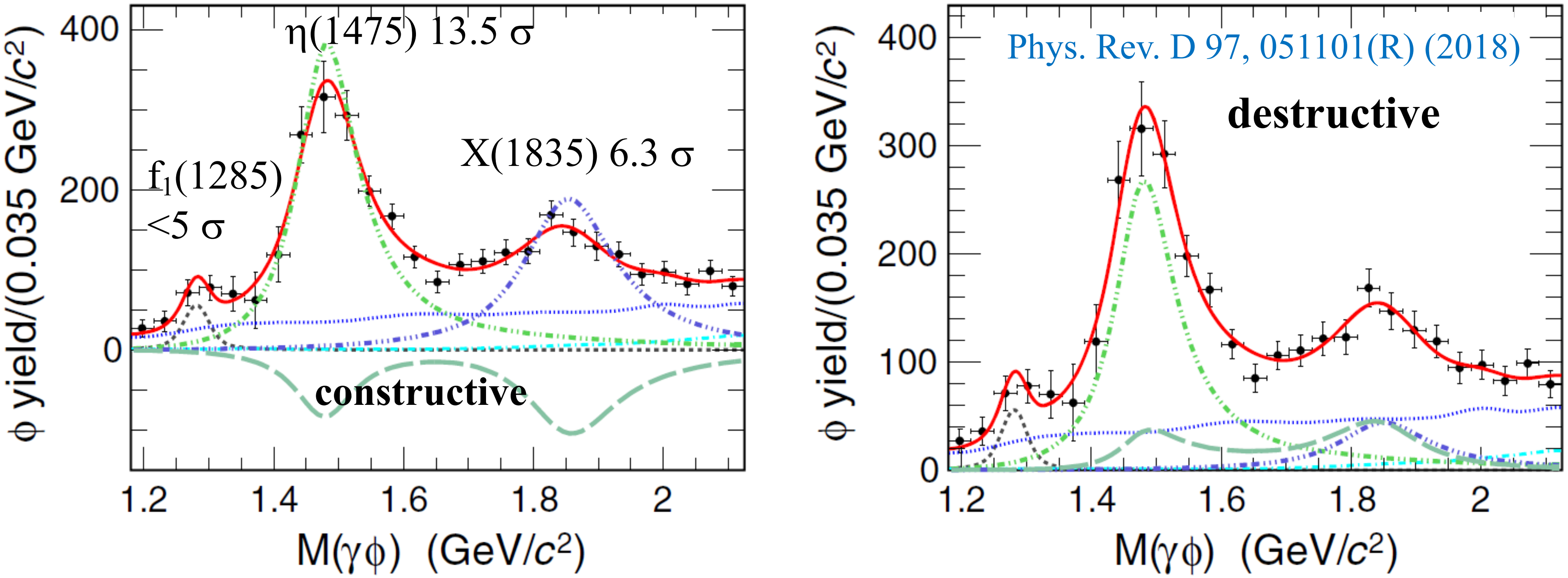
Model I:
Flatte line shape with strong coupling to $p\bar{p}$ and one additional narrow BW at ~ 1920 MeV/c²

Model II:
Two coherent BW, X(1835) and one additional, narrow BW at ~ 1870 MeV/c²



- Both models well describes data with almost equally good fit quality.
- Suggest the existence of a state, either a broad one 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.

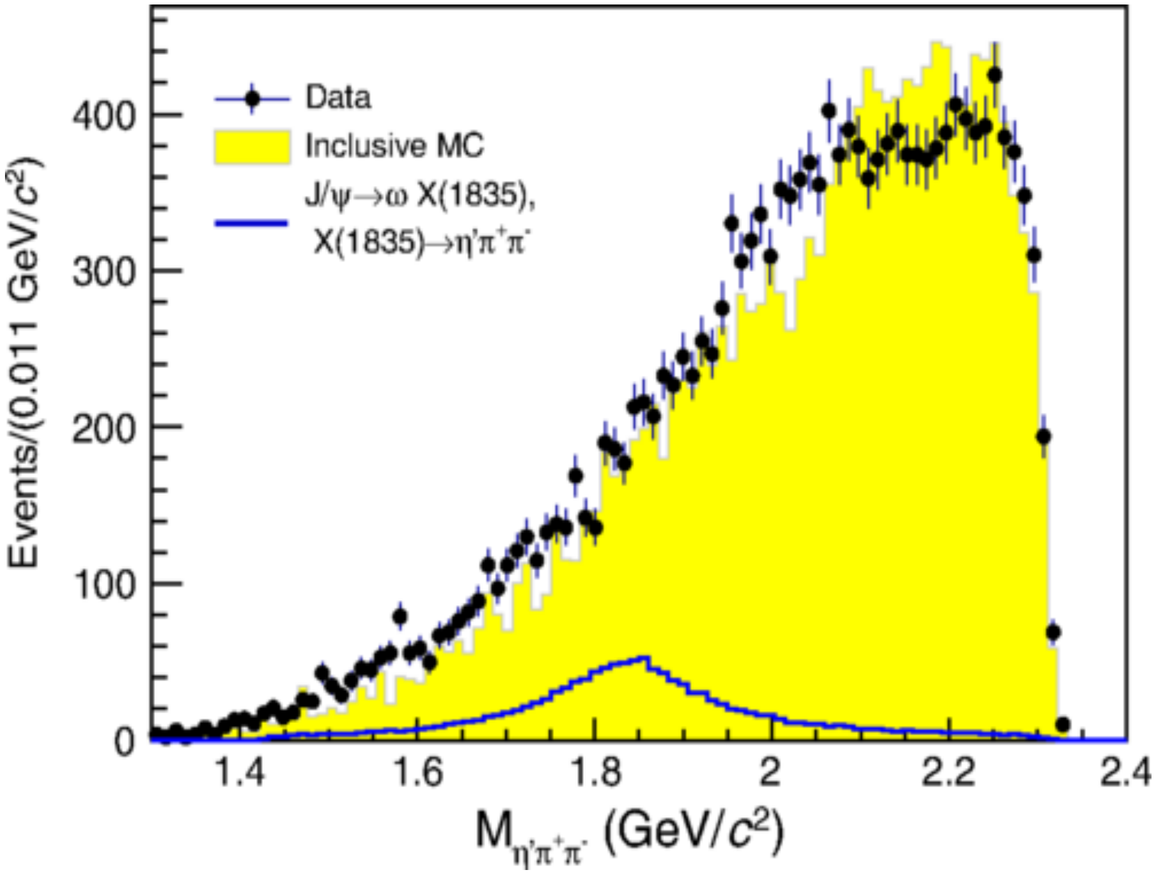
Observation of η(1475) and X(1835) in J/ψ→γγϕ



- ✓ First observation of η(1475)/X(1835)→γϕ.
- ✓ Angular distribution favor $J^{PC} = 0^{-+}$.
- ✓ Sizeable $s\bar{s}$ components in X(1835):

Search for X(1835) in $J/\psi \rightarrow \omega\pi^+\pi^-\eta'$

Phys. Rev. D 99, 071101(R) (2019)

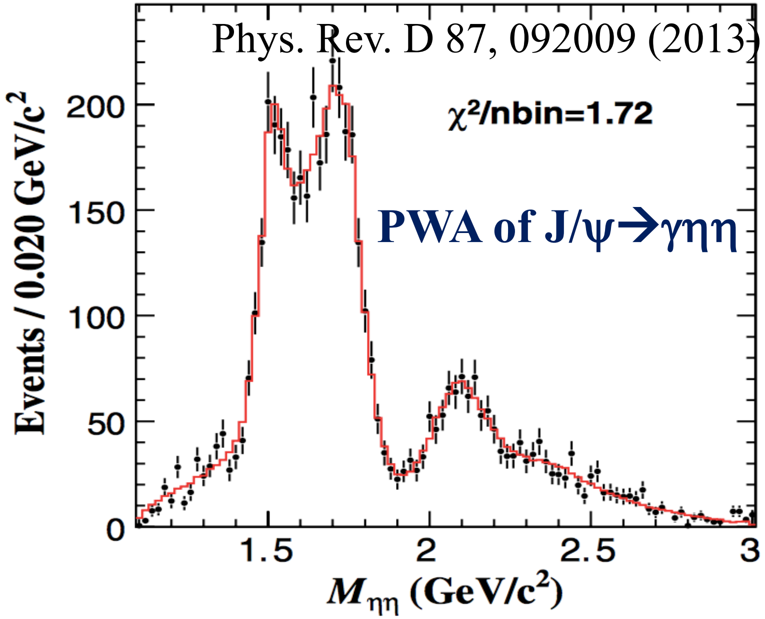


- ✓ No obvious signal of X(1835) is found.
- ✓ Upper limit on the branching fraction at 90% C. L.,

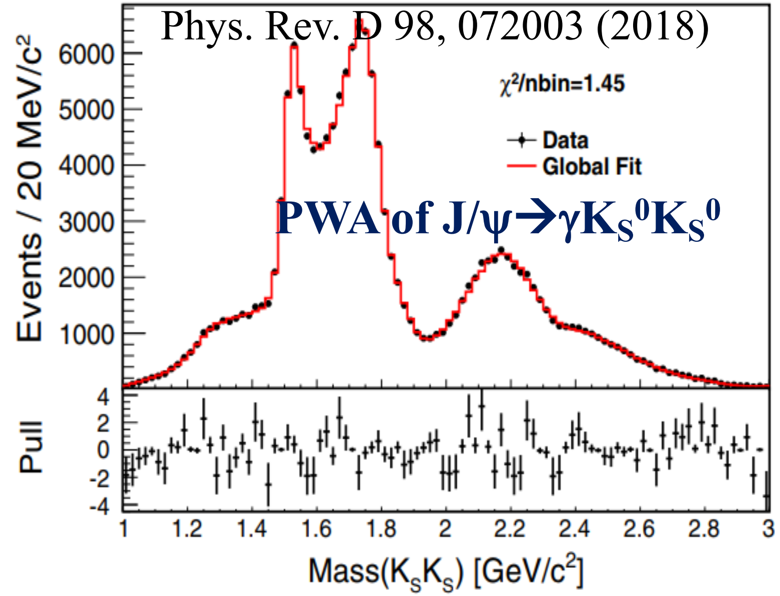
$B(J/\psi \rightarrow \omega X(1835) \rightarrow \omega\pi^+\pi^-\eta') < 6.2\times10^{-5}$.

Study of glueball and hybrid candidates

PWA of $J/\psi \rightarrow \gamma\eta\eta / \gamma K_S^0 K_S^0$



Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0σ
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9σ
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6σ

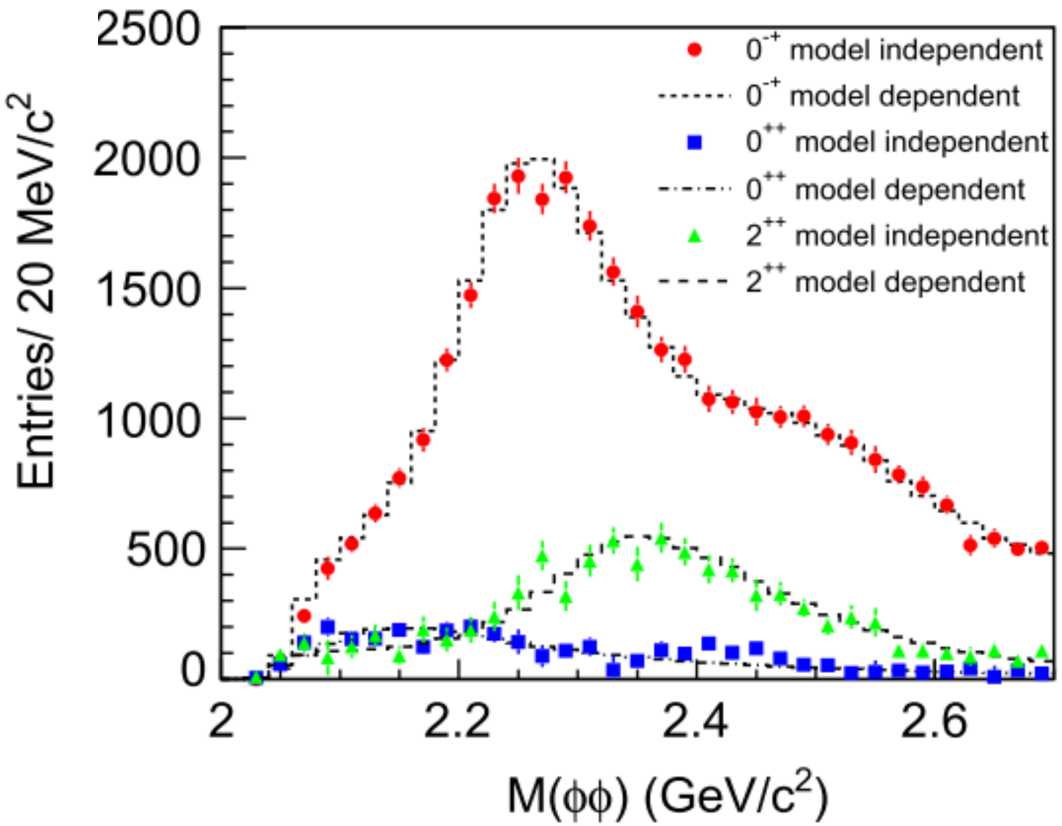


Resonance	M (MeV/c^2)	$M_{\rm PDG}$ (MeV/c^2)	Γ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV/c^2)	Branching fraction	Significance
$K^*(892)$	896	895.81 ± 0.19	48	47.4 ± 0.6	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$	35σ
$K_1(1270)$	1272	1272 ± 7	90	90 ± 20	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$	16σ
$f_0(1370)$	$1350 \pm 9^{+12}_{-2}$	1200 to 1500	$231 \pm 21^{+28}_{-48}$	200 to 500	$(1.07^{+0.08+0.36}_{-0.07-0.34}) \times 10^{-5}$	25σ
$f_0(1500)$	1505	1504 ± 6	109	109 ± 7	$(1.59^{+0.16+0.18}_{-0.16-0.56}) \times 10^{-5}$	23σ
$f_0(1710)$	$1765 \pm 2^{+1}_{-1}$	1723^{+6}_{-5}	$146 \pm 3^{+7}_{-1}$	139 ± 8	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	...	$146 \pm 14^{+7}_{-15}$	...	$(1.11^{+0.06+0.19}_{-0.06-0.32}) \times 10^{-5}$	24σ
$f_0(2200)$	$2184 \pm 5^{+4}_{-2}$	2189 ± 13	$364 \pm 9^{+4}_{-7}$	238 ± 50	$(2.72^{+0.08+0.17}_{-0.06-0.47}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(2330)$	$2411 \pm 10 \pm 7$	...	$349 \pm 18^{+23}_{-1}$	...	$(4.95^{+0.21+0.66}_{-0.21-0.72}) \times 10^{-5}$	35σ
$f_2(1270)$	1275	1275.5 ± 0.8	185	$186.7^{+2.2}_{-2.5}$	$(2.58^{+0.08+0.59}_{-0.09-0.20}) \times 10^{-5}$	33σ
$f_2'(1525)$	1516 ± 1	1525 ± 5	$75 \pm 1 \pm 1$	73^{+6}_{-5}	$(7.99^{+0.03+0.69}_{-0.04-0.50}) \times 10^{-5}$	$\gg 35\sigma$
$f_2(2340)$	$2233 \pm 34^{+9}_{-25}$	2345^{+50}_{-40}	$507 \pm 37^{+18}_{-21}$	322^{+70}_{-60}	$(5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$	26σ
0^{++} PHSP	...	...	...	...	$(1.85^{+0.05+0.68}_{-0.05-0.26}) \times 10^{-5}$	26σ
2^{++} PHSP	...	...	...	...	$(5.73^{+0.99+4.18}_{-1.00-3.74}) \times 10^{-5}$	13σ

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

- Besides $\eta(2225)$, the structures in the pseudoscalar sector above 2 GeV/c^2 are poorly understand.
- Provide an opportunity to study 0^{-+} and 2^{++} states above 2 GeV/c^2.
- Dominant contribution from 0^{-+} states
  - ✓ $\eta(2225)$ is confirmed
  - ✓ $\eta(2100)$ and X(1500) are observed
- 2^{++} contibutions
  - ✓ $f_2(2010)$, $f_2(2300)$, $f_2(2340)$ are observed.
  - ✓ Large production rate of $f_2(2340)$
- Model dependent PWA results are well consistent with the results from MIPWA.

Phys. Rev. D 93, 112011 (2016)



Scalar glueball candidate (0^{++})

Decay rate of pure glueball from LQCD:

$$\Gamma(J/\psi \to \gamma G_{0^+}) = \frac{4}{27}\alpha\frac{|p|}{M_{J/\psi}^2}|E_1(0)|^2 = 0.35(8)keV$$

$$\Gamma/\Gamma\_tot = 0.33(7)/93.2 = 3.8(9)\times 10^{-3}$$

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

Experimental results from J/ψ radiative decays to scalars:

- $B(J/\psi \to \gamma f_0(1710) \to \gamma K\bar{K}) = (8.5^{+1.2}_{-0.9})\times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi) = (4.0\pm 1.0)\times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\omega\omega) = (3.1\pm 1.0)\times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta) = (2.35^{+0.13+1.24}_{-0.11-0.74})\times 10^{-4}$

$\Rightarrow$ $B(J/\psi \to \gamma f_0(1710)) > 1.9\times 10^{-3}$

$f_0(1710)$: The candidate of the scalar glueball ?

Tensor glueball candidate (2^{++})

LQCD:

$$\Gamma(J/\psi \to \gamma G_{2^+}) = 1.01(22)keV$$
$$\Gamma(J/\psi \to \gamma G_{2^+})/\Gamma_{tot} = 1.1(2) \times 10^{-2}$$

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

Experimental results from J/ψ radiative decays to scalars:

- $B(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = (5.60^{+0.62}_{-0.65}{}^{+2.37}_{-2.07}) \times 10^{-5}$
- $B(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73}) \times 10^{-4}$
- $B(J/\psi \to \gamma f_2(2340) \to \gamma K_S^0 K_S^0) = (5.54^{+0.34}_{-0.40}{}^{+3.28}_{-1.49}) \times 10^{-5}$

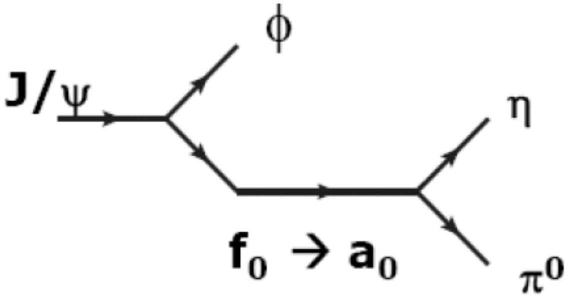
$f_2(2340)$: The candidate of the tensor glueball ?

a0(980)-f0(980) mixing

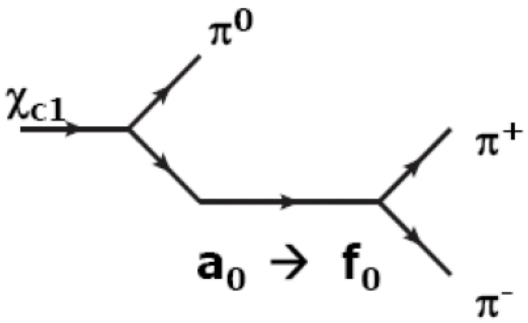
$a_0(980)$-$f_0(980)$ mixing

- Mixing intensity provides important information in understanding the nature of $a_0(980)$ and $f_0(980)$.
- Narrow peak (8 MeV) at around 980 MeV can be expected in $\eta\pi^0$ ($J/\psi \rightarrow \phi f_0(980) \rightarrow \phi a_0(980) \rightarrow \phi\eta\pi^0$) or $\pi^+\pi^-$($\chi_{c1} \rightarrow a_0(980)\pi^0 \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$) invariant mass spectra.

J.Wu, Q.Zhao, B.Zou PRD75 114012,
C. Hanhart etc. PRD76 074028,
etc.



J.Wu, B.Zou PRD78 074017

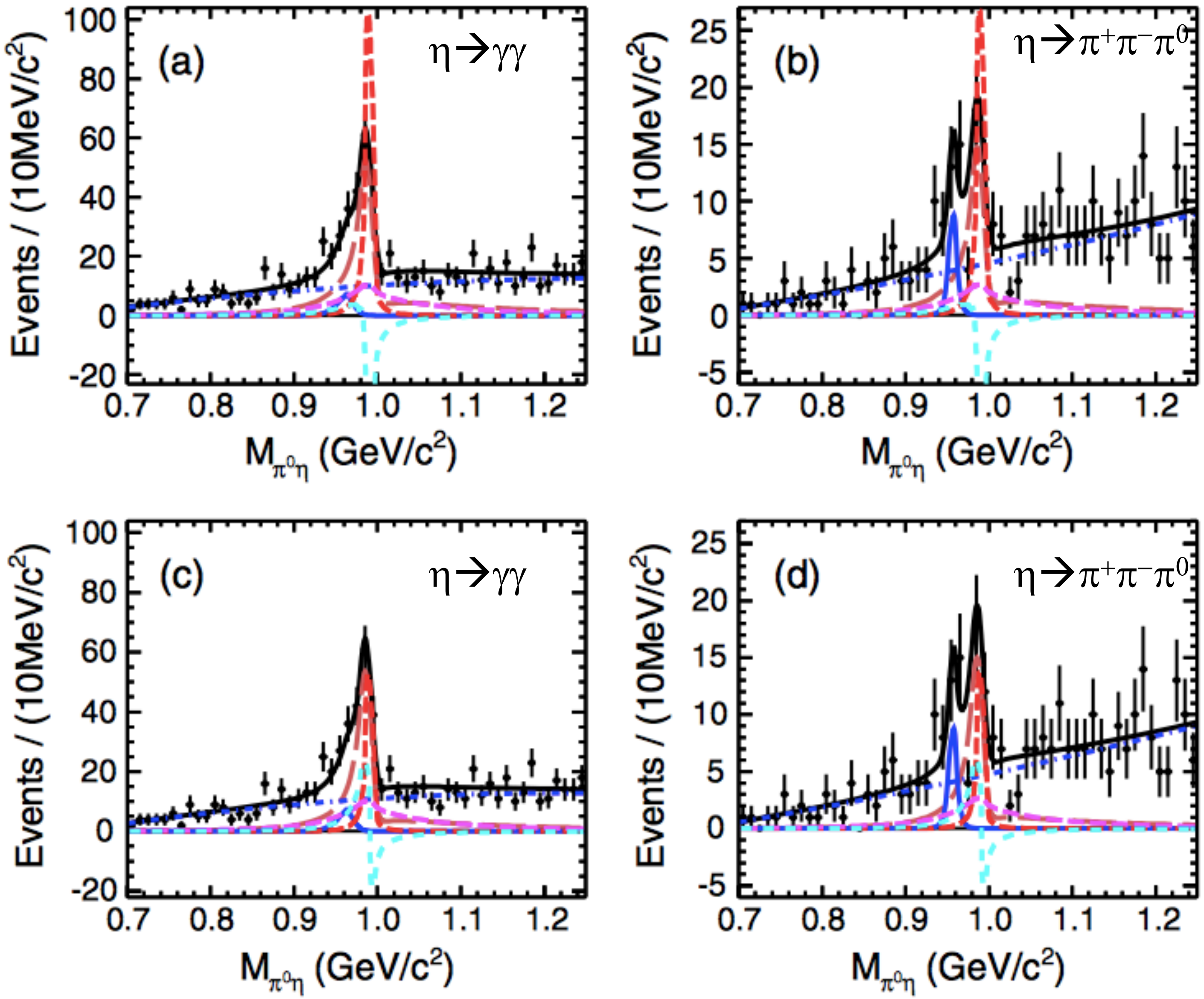


Observation of $a_0(980)$-$f_0(980)$ mixing

Phys. Rev. Lett. 121, 022001 (2018)

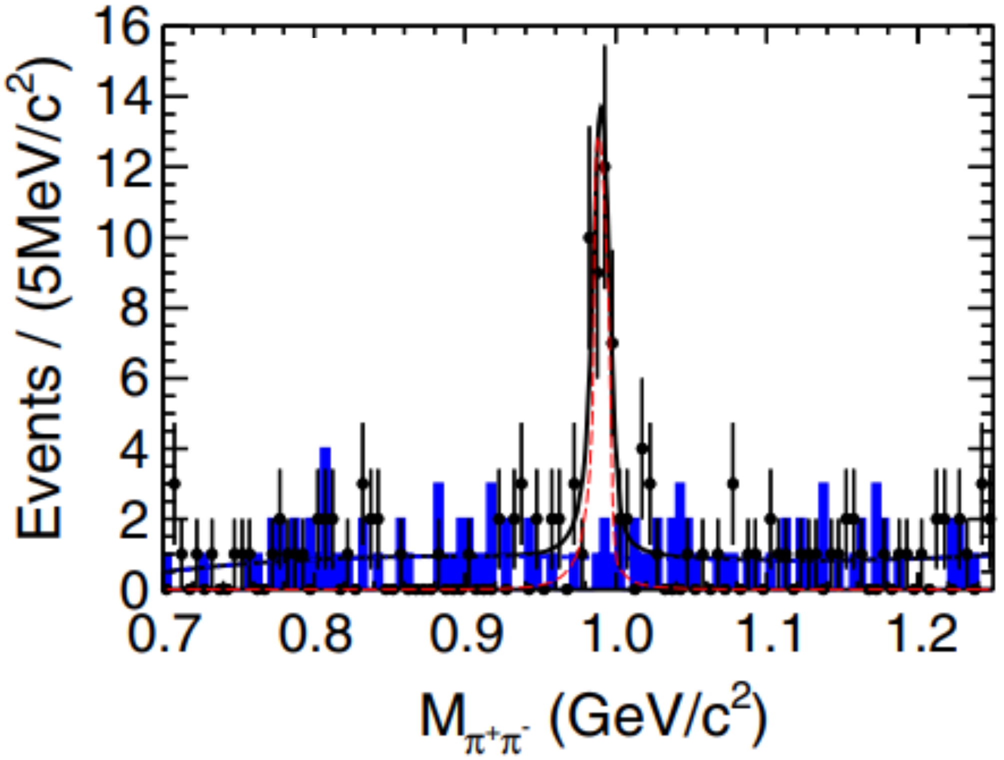
- Using 1.3 billion J/ψ events, $f_0(980) \rightarrow a_0(980)$ is observed in the isospin violating $J/\psi \rightarrow \phi f_0(980) \rightarrow \phi a_0(980) \rightarrow \phi\eta\pi^0$ (7.4 σ)

destructive (upper) and constructive (lower)



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

Phys. Rev. Lett. 121, 022001 (2018)

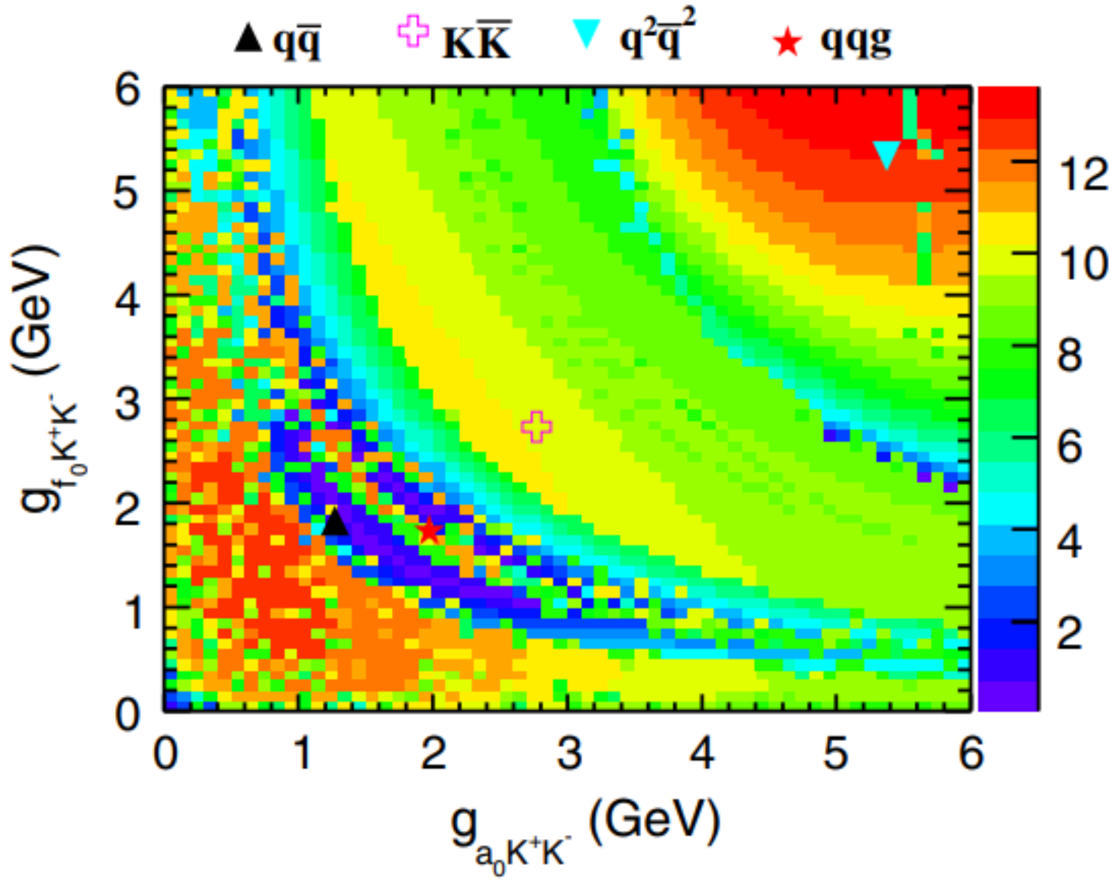


- Using 450 million $\psi(3686)$ events,

  $a_0(980) \rightarrow f_0(980)$ is observed in the isospin violating

  $\chi_{c1} \rightarrow a_0(980)\pi^0 \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0$ (5.5 σ)

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



- ✓ The statistical significance of the mixing signal scanned in the 2D space of $g_{f_0\to K^+K^-}$ and $g_{a_0\to K^+K^-}$
- ✓ The region with higher significance indicate the larger probability
- ✓ The markers indicate predictions from various theoretical models (without uncertainties of model)

Summary

- A set of interesting and important results from the light hadron spectroscopy achieved:
  - ✓ Both X(1835) and $p\bar{p}$ are confirmed by BESIII.
    - J^{PC} (X(1835)/X($p\bar{p}$))= 0^{-+};
    - Anomalous line shape of $\pi^+\pi^-\eta'$ near $p\bar{p}$ mass threshold is observed.
  - ✓ 0^{++} and 2^{++} structures are studied from J/ψ radiative decays:
    - Strong production of $f_0(1710)$ in $J/\psi \to \gamma\eta\eta/\gamma K_S^0 K_S^0$,

      production rate of $f_0(1710)$ is about 1 order of magnitude larger than that of $f_0(1500)$.
    - Strong production of $f_2(2340)$ in $J/\psi \to \gamma\eta\eta/\gamma K_S^0 K_S^0/\gamma\phi\phi$;

      could be a candidate for the lowest lying tensor glueball?
  - ✓ First observation of $a_0(980)$-$f_0(980)$ mixing.
- With 10 billion J/ψ events, more and more interesting results are expected in the near future.

Thanks!

谢谢！