

Hadron spectroscopy at BESIII

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IHEP, Beijing

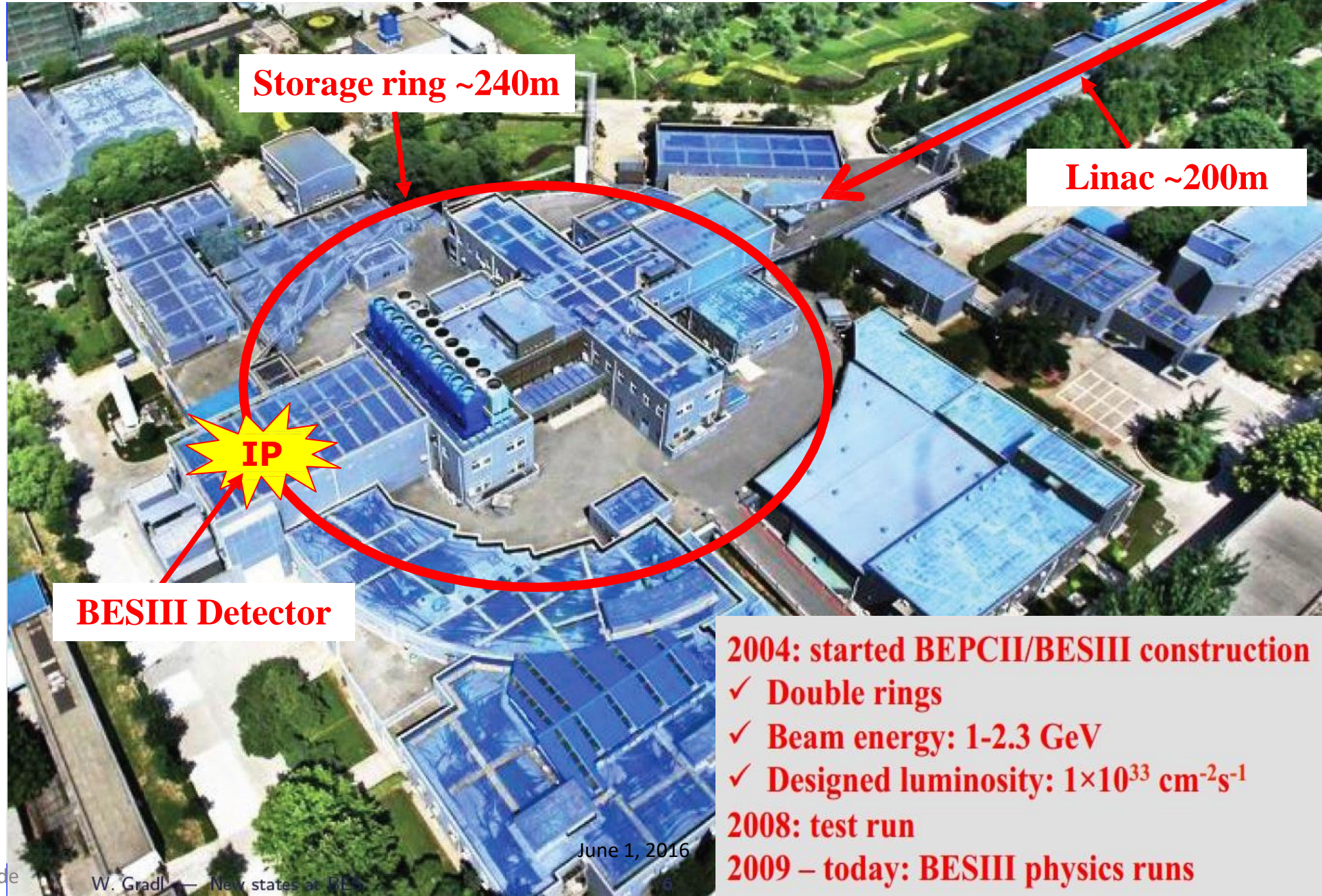
For BESIII Collaboration



Outline

- **Introduction**
- **Hadron Spectroscopy**
 - **Scalar(0^{++})** -- $f_0(1370)$, $f_0(1500)$, $f_0(1710)$
 - **Pseudoscalar(0^{-+})** -- $\eta(1440)/\eta(1405)/\eta(1475)$, $X(18XX)$
- **Summary**

Beijing Electron Positron Collider II (BEPC II)



Storage ring ~240m

Linac ~200m

IP

BESIII Detector

2004: started BEPCII/BESIII construction

✓ Double rings

✓ Beam energy: 1-2.3 GeV

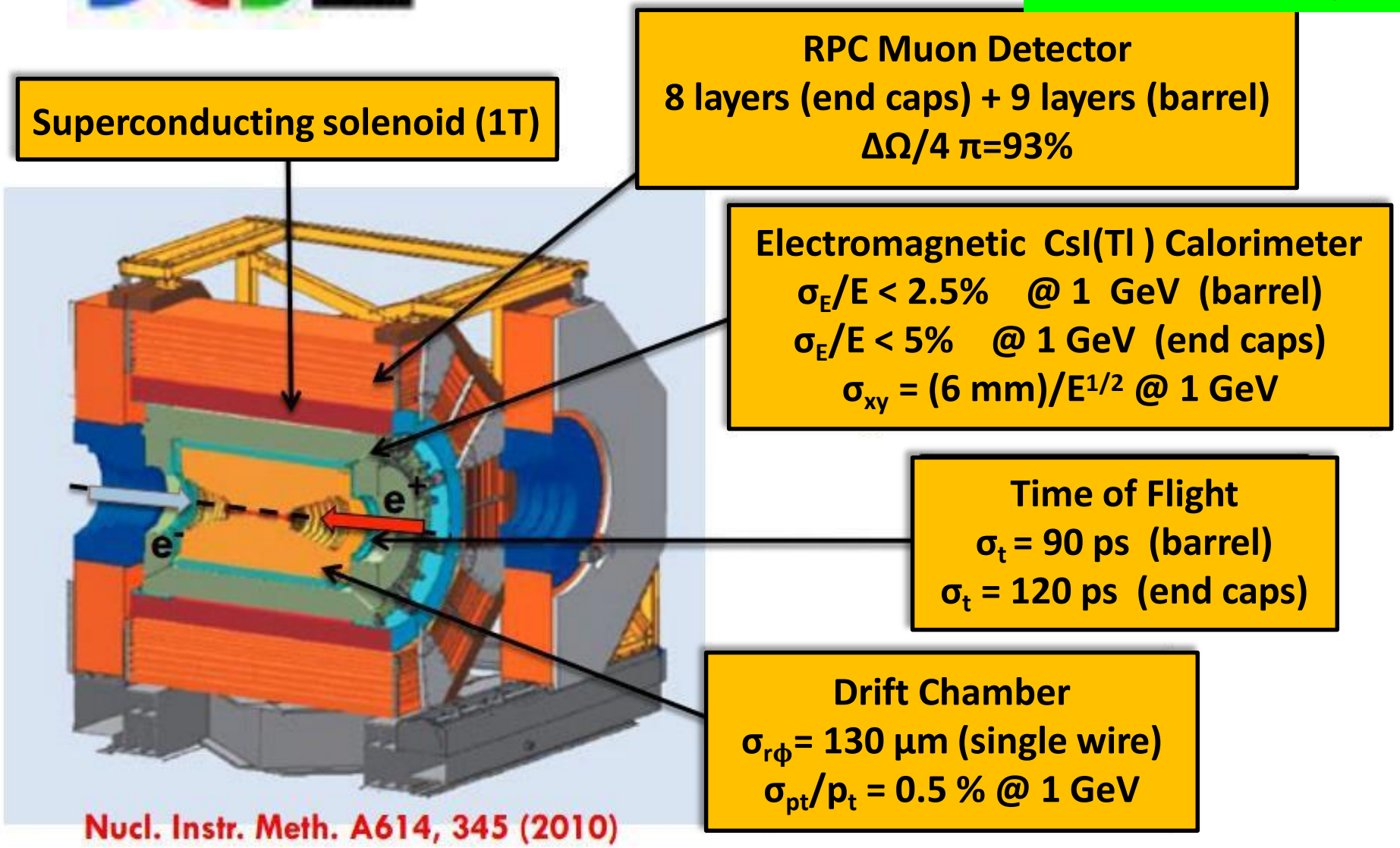
✓ Designed luminosity: $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

2008: test run

2009 – today: BESIII physics runs

BES III Detector

Total weight 730 ton
~40,000 readout chnls
Data rate: 5kHz, 50Mb/s



BESIII Collaboration

Political Map of the World, June 1999

<http://bes3.ihep.ac.cn>

US (6)

Univ. of Hawaii
Univ. of Washington
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Rochester
Univ. of Indiana

Europe (13)

Germany: Univ. of Bochum,
Univ. of Giessen, GSI
Univ. of Johannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINP Novosibirsk
Italy: **Univ. of Torino**,
Frascati Lab, Univ. of Ferrara
Netherland: KVI/Univ. of Groningen
Sweden: Uppsala Univ.
Turkey: Turkey Accelerator Center

Pakistan (2)

Univ. of Punjab
COMSAT CIIT

Korea (1)

Seoul Nat. Univ.

Japan (1)

Tokyo Univ.

China(30)

IHEP, CCAST, GUCAS, Shandong Univ.,
Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ. ,
Zhongshan Univ., Nankai Univ.
Shanxi Univ., Sichuan Univ., Univ. of South China
Hunan Univ., Liaoning Univ.
Nanjing Univ., Nanjing Normal Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.
Hong Kong Univ., Hong Kong Chinese Univ.

~400 members
11 countries

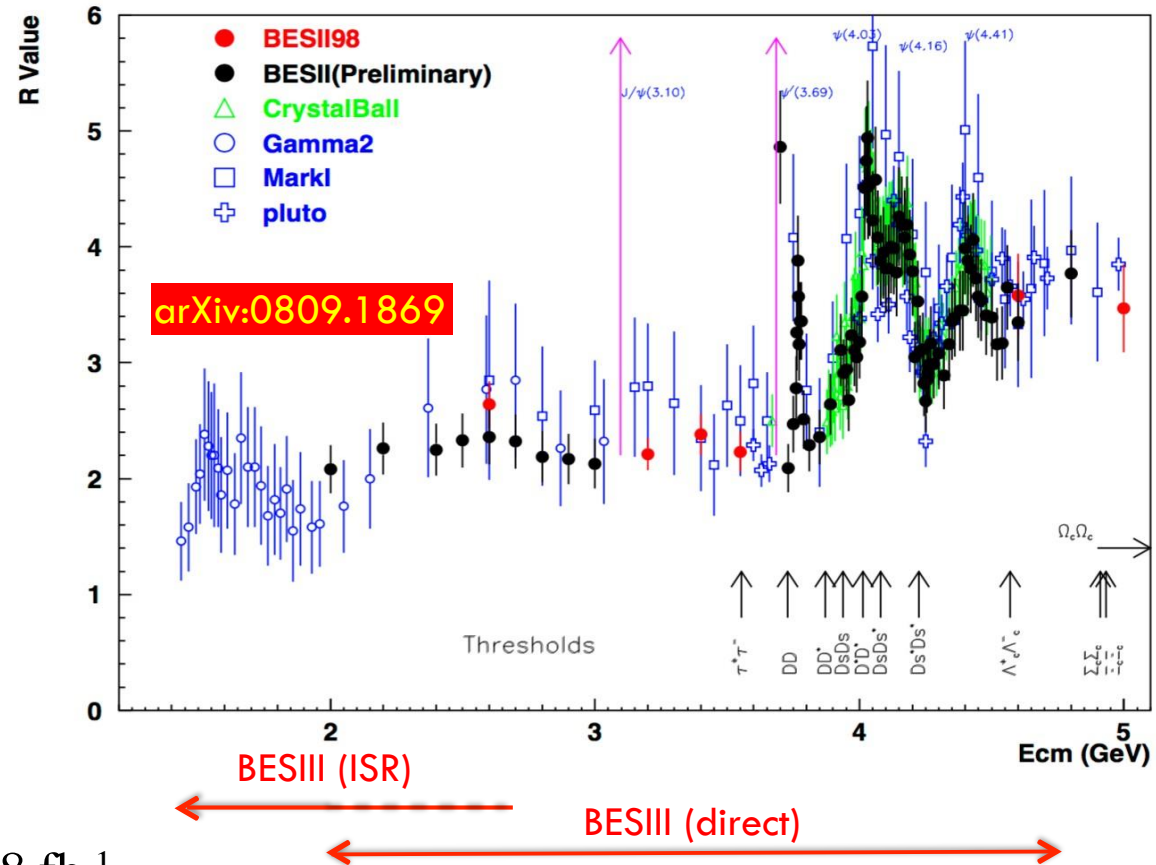
53 institutions
22 outside China

BESIII started data taking for physics since 2009

- $1.3 \times 10^9 J/\psi$
- $5 \times 10^8 \psi(2S)$
- 2.9 fb^{-1} @ ψ_{3770}
- 0.5 fb^{-1} @ ψ_{4040}
- 2.3 fb^{-1} @ 4230/4260 MeV
- 0.5 fb^{-1} @ 4360 MeV
- 0.5 fb^{-1} @ 4600 MeV
- 1 fb^{-1} @ ψ_{4415}
- 0.1 fb^{-1} @ 4470/4530 MeV
- 0.04 fb^{-1} around Λ_c threshold
- 1 fb^{-1} @ 4420 MeV
- R scan:
 - 2-3 GeV, 19 points, $\sim 0.5 \text{ fb}^{-1}$
 - 3.85-4.59 GeV, 104 points, $\sim 0.8 \text{ fb}^{-1}$

MORE:

- 3554 MeV 24 pb^{-1} τ mass; 4100-4400 MeV 0.5 fb^{-1} coarse scan
- On-going data taking

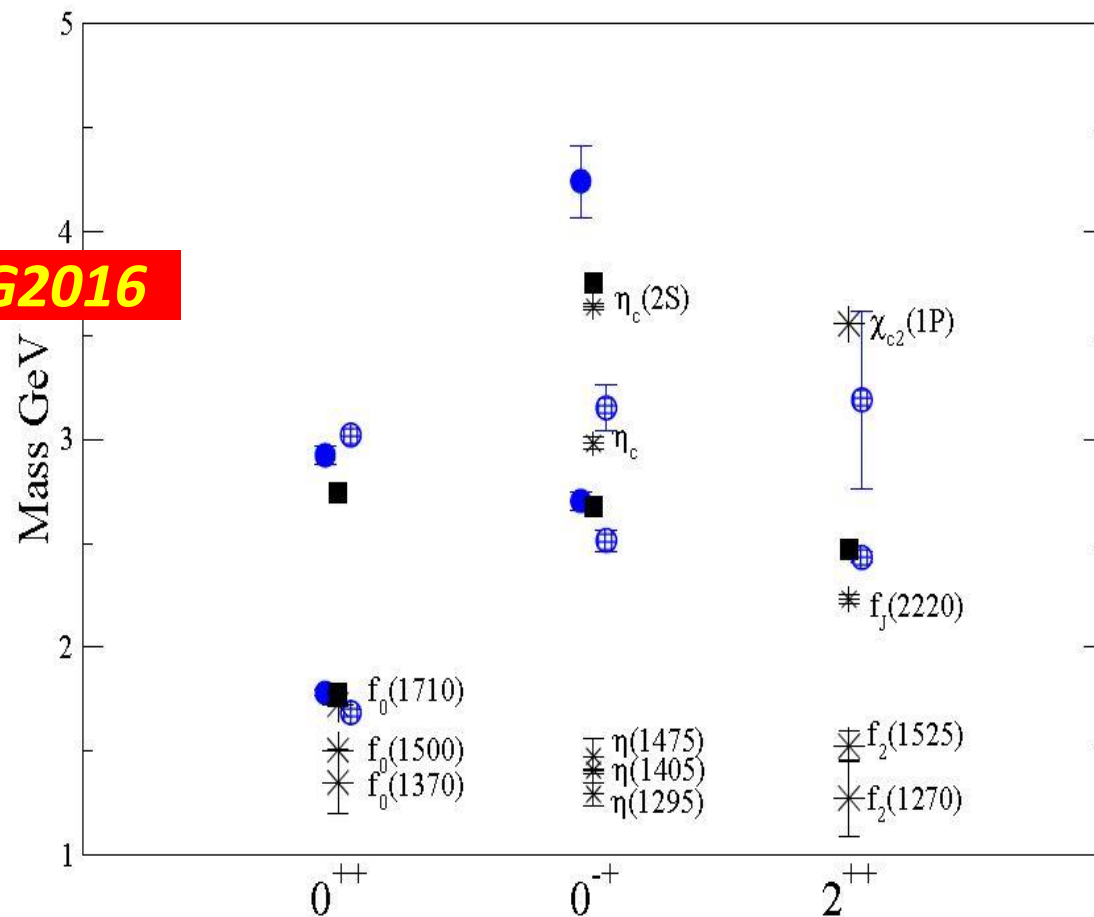


Suggested $q\bar{q}$ quark-model assignments for some of the observed light mesons.

$n^{2s+1}\ell_J$	J^{PC}	$I=1$ $u\bar{d}, \bar{u}d, \frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u})$	$I=\frac{1}{2}$ $u\bar{s}, \bar{d}\bar{s}; \bar{d}s, -\bar{u}s$	$I=0$ f'	$I=0$ f
1^1S_0	0^{-+}	π	K	η	$\eta'(958)$
1^3S_1	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$
1^1P_1	1^{+-}	$b_1(1235)$	K_{1B}^\dagger	$h_1(1380)$	$h_1(1170)$
1^3P_0	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$
1^3P_1	1^{++}	$a_1(1260)$	K_{1A}^\dagger	$f_1(1420)$	$f_1(1285)$
1^3P_2	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$
1^1D_2	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$
1^3D_1	1^{--}	$\rho(1700)$	$K^*(1680)$		$\omega(1650)$
1^3D_2	2^{--}		$K_2(1820)$		
1^3D_3	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$
1^3F_4	4^{++}	$a_4(2040)$	$K_4^*(2045)$		$f_4(2050)$
1^3G_8	5^{--}	$\rho_8(2350)$	$K_8^*(2380)$		
1^3H_6	6^{++}	$a_6(2450)$			$f_6(2510)$
2^1S_0	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$
2^3S_1	1^{--}	$\rho(1450)$	$K^*(1410)$	$\phi(1680)$	$\omega(1420)$

PDG2016

Lattice QCD predictions for glueball masses



Scalar (0^{++})

➤ Eur. Phys. J. C 21, 531–543 (2001)

- ✓ $f_0(1370)$: Large $n\bar{n}$, small $s\bar{s}$ and **significant Glue** content
- ✓ $f_0(1500)$: $s\bar{s}$ and $n\bar{n}$ out of phase
- ✓ $f_0(1710)$: Large $s\bar{s}$ content

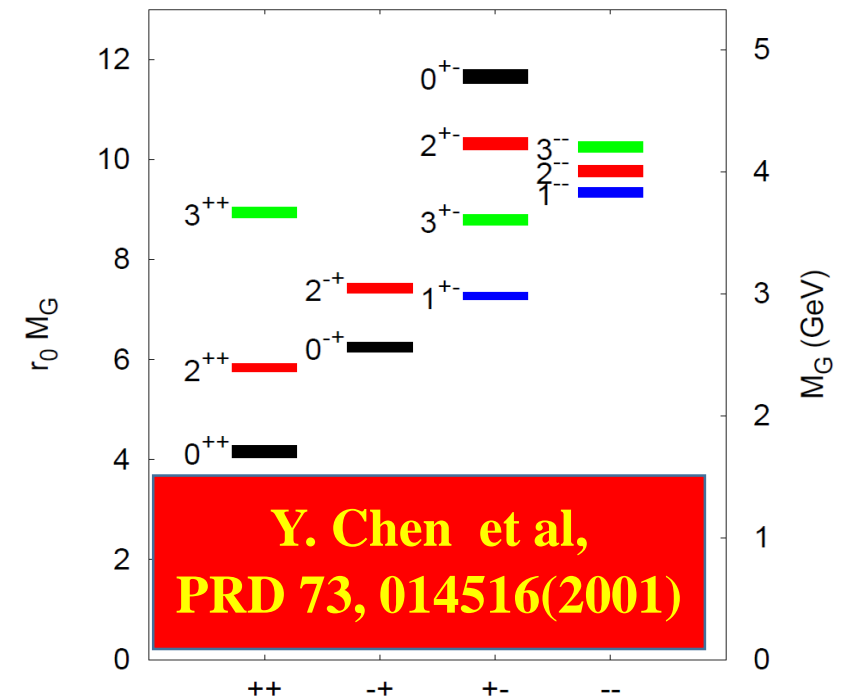
➤ Physics Reports 389 (2004) 61

- ✓ $f_0(1370)$ Largely $n\bar{n}$
- ✓ $f_0(1500)$ mainly **Glue**
- ✓ $f_0(1710)$ mainly $s\bar{s}$

➤ PRL 110, 021601 (2013)

- ✓ $f_0(1710)$ dominant **Glueball** components

➤ ...



J^{PC}	$r_0 M_G$	M_G (MeV)
0^{++}	4.16(11)(4)	1710(50)(80)
2^{++}	5.83(5)(6)	2390(30)(120)
0^{-+}	6.25(6)(6)	2560(35)(120)
1^{+-}	7.27(4)(7)	2980(30)(140)
2^{-+}	7.42(7)(7)	3040(40)(150)
3^{-+}	8.79(3)(9)	3600(40)(170)
3^{++}	8.94(6)(9)	3670(50)(180)
1^{--}	9.34(4)(9)	3830(40)(190)
2^{--}	9.77(4)(10)	4010(45)(200)
3^{--}	10.25(4)(10)	4200(45)(200)
2^{+-}	10.32(7)(10)	4230(50)(200)
0^{+-}	11.66(7)(12)	4780(60)(230)

$J/\psi \rightarrow \gamma\eta\eta$

first studied by

Crystal Ball (1982):

$f_0(1710)$

• **Crystal Barrel (1995):**

$f_0(1500)$ [$pp \rightarrow \pi^0\eta\eta$]

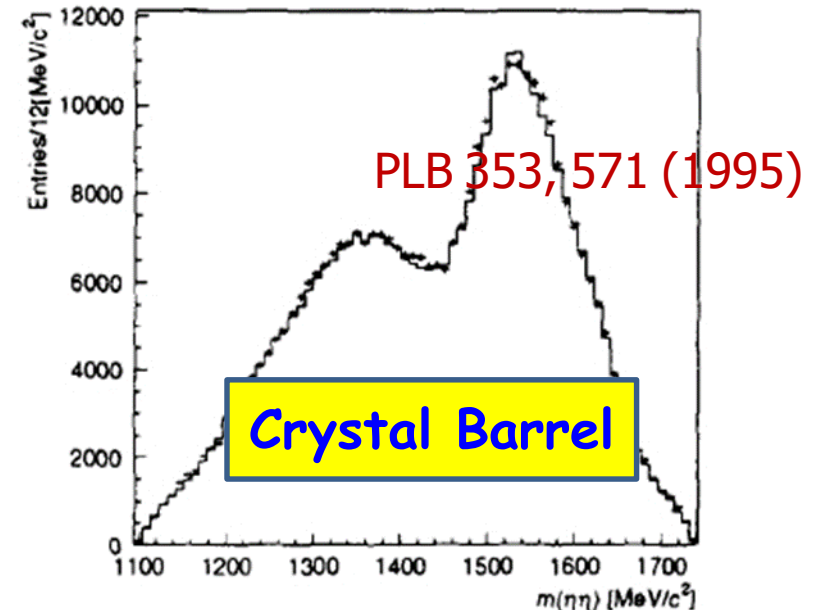
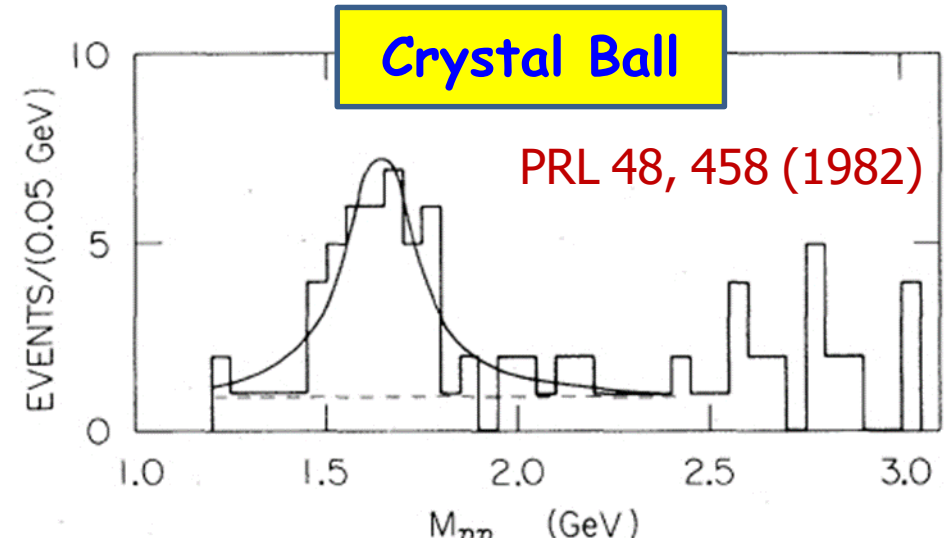
• **E835 (2006):**

$f_0(1500)$ [$pp \rightarrow \pi^0\eta\eta$]

$f_0(1710)$ [$pp \rightarrow \pi^0\eta\eta$]

• **WA102, GAMS:**

$f_0(1500)$ [$\eta\eta$ mode]

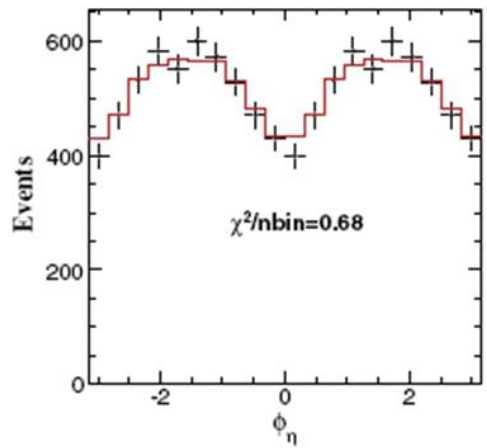
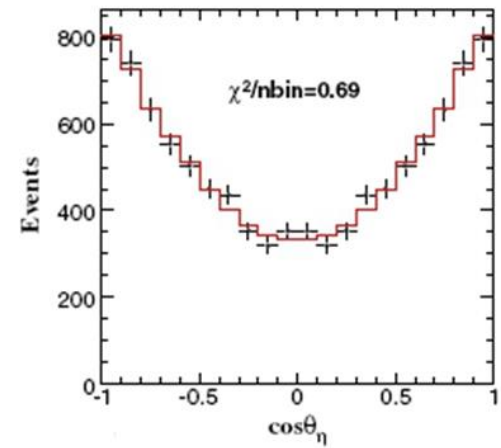
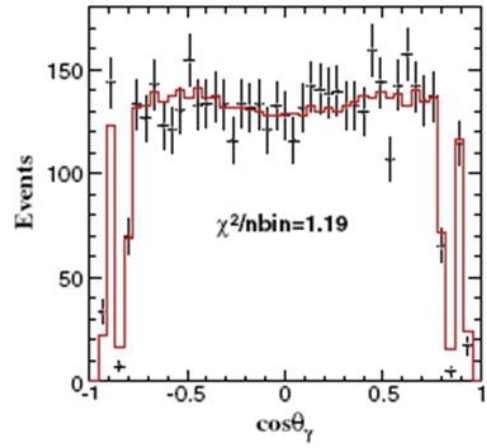
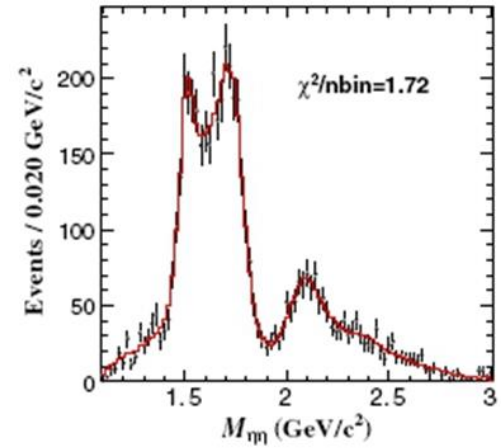


BESIII: PWA of $J/\psi \rightarrow \gamma\eta\eta, \eta \rightarrow \gamma\gamma$

PRD 87,092009

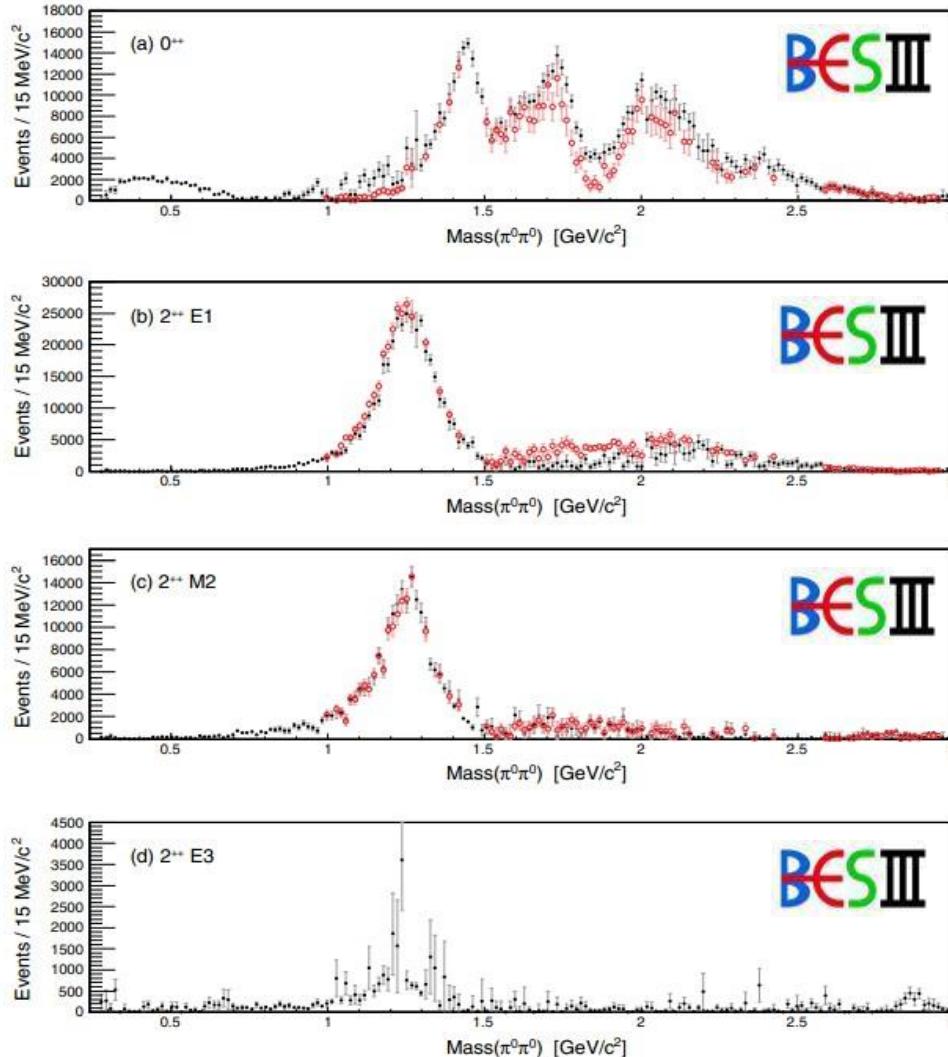
- $f_0(1710)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2σ)
- $f_2'(1525)$ is the dominant tensor
- $f_2(1810)$ and $f_2(2340)$ exist (6.4 and 7.6σ)
- No evidence for $f_J(2220)$

Resonance	Mass(MeV/c ²)	Width(MeV/c ²)	$\mathcal{B}(J/\psi \rightarrow \gamma X \rightarrow \gamma\eta\eta)$	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



PWA of $J/\psi \rightarrow \gamma \pi^0 \pi^0$

PRD 92, 052003(2015)



- Model-independent PWA;
- Provide a description of the scalar and tensor components of the $\pi^0 \pi^0$ system;
- 0^{++} : $\sigma(f_0(500))$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, and $f_0(2020)$;
- 2^{++} : dominant by $f_2(1270)$;

Decay rate of pure glueball from LQCD

➤ Pure scalar-glueball rate in J/ψ radiative decays

$$\text{BR}(J/\psi \rightarrow \gamma G(0^{++})) = 3.8(9) \times 10^{-3}$$

Long-Cheng Gui et al.
PRL 110 (2013) 021601

$$\text{BR}(J/\psi \rightarrow \gamma f_0(1710) \rightarrow \gamma K \bar{K}) = (8.5_{-0.9}^{+1.2}) \times 10^{-4}$$

$$\text{BR}(J/\psi \rightarrow \gamma f_0(1710) \rightarrow \gamma \pi \pi) = (4.0 \pm 1.0) \times 10^{-4}$$

$$\text{BR}(J/\psi \rightarrow \gamma f_0(1710) \rightarrow \gamma \omega \omega) = (3.1 \pm 1.0) \times 10^{-4}$$

$$\text{BR}(J/\psi \rightarrow \gamma f_0(1710) \rightarrow \gamma \eta \eta) = (2.35_{-0.11}^{+0.13+1.24}) \times 10^{-4}$$

$\Sigma \text{Exp.}:$
 $\sim 3.9 \times 10^{-3}$

➤ Pure Tensor-glueball rate in J/ψ radiative decays

$$\text{BR}(J/\psi \rightarrow \gamma G(2^{++})) = 1.1(2) \times 10^{-2}$$

Yi-Bo Yang et al.
PRL 111, 091601

Large decay rate is predicted

Need more experimental information!

Pseudoscalar (0^{-+})-- $\eta(1440)$

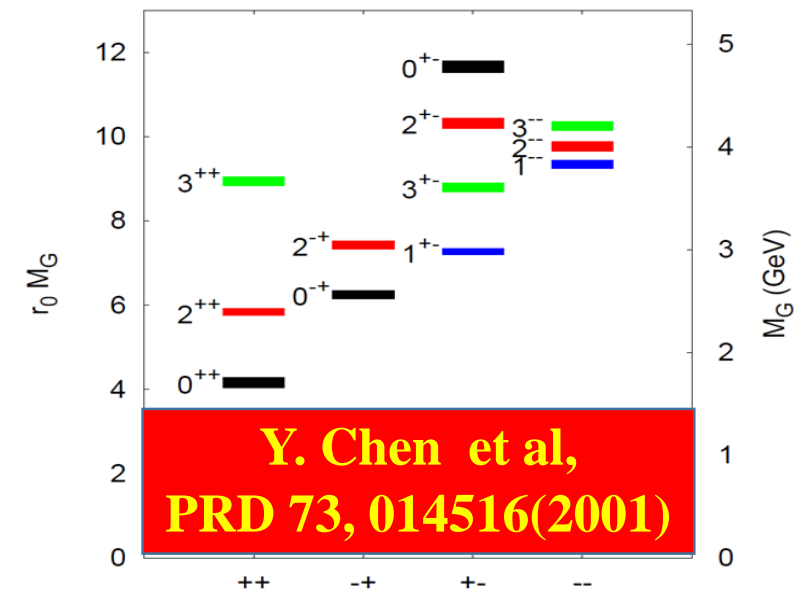
➤ First observed in $p\bar{p}$

Nuovo Cimento 50A(1967)393

- ✓ $p\bar{p} \rightarrow \eta(1440)\pi^+\pi^-$ ($\eta \rightarrow K\bar{K}\pi$)
- ✓ Mass: 1425 ± 7 MeV, Width: 80 ± 10 MeV

➤ $\eta(1405)$ and $\eta(1475)$ observed in different decay modes

- ✓ π^-p : PRD40(1989)693, PLB516(2001)264
- ✓ Radiative J/ ψ decay: PRL65(1990)2507, PRD46(1992)1951
- ✓ $p\bar{p}$ annihilation at rest: PLB361(1995)187, PLB400(1997)226, PLB462(1999)453, PLB545(2002)261



Pseudoscalar (0^{-+})-- $\eta(1405)/\eta(1475)$

The Structure of $\eta(1440)$

➤ Experiment

- ✓ $\eta(1440)$ split to $\eta(1405)$ and $\eta(1475)$ (from PDG04)
- ✓ $\eta(1405) \rightarrow \eta\pi\pi$, or through $a_0(980)\pi$ (or direct) to $KK\pi$
- ✓ $\eta(1475) \rightarrow K^*(892)K$

➤ Quark-model

- $\eta(1295)$: the first radial excitation of the η'
- $\eta(1475)$: the first radial excitation of the η
- **$\eta(1405)$?**

➤ Phys. Rev. D87, 014023(2013)

- $\eta(1405)$ and $\eta(1475)$ are the same state with a mass shift in different modes

Pseudoscalar (0^{-+})-- $\eta(1405)/\eta(1475)$

✓ $\eta(1405) \rightarrow \gamma\rho$ $\eta(1475) \rightarrow \gamma\phi$

Table 2
Comparison with other experiments

Decay mode	Mass (MeV/ c^2)	Width (MeV/ c^2)	$B(J/\psi \rightarrow \gamma X)B(X \rightarrow \gamma V)$ ($\times 10^{-4}$)	Experiment
$f_1(1285) \rightarrow \gamma\rho^0$	1281.9 ± 0.6	24.0 ± 1.2	0.34 ± 0.09	PDG [1]
	1271 ± 7	31 ± 14	$0.25 \pm 0.07 \pm 0.03$	MarkIII [7]
	$1276.1 \pm 8.1 \pm 8.0$	$40.0 \pm 8.6 \pm 9.3$	$0.38 \pm 0.09 \pm 0.06$	BESII
$\eta(1440) \rightarrow \gamma\rho^0$	1400–1470	50–80	$0.64 \pm 0.12 \pm 0.07$	PDG [1]
	1432 ± 8	90 ± 26	$0.64 \pm 0.12 \pm 0.07$	MarkIII [7]
	$1424 \pm 10 \pm 11$	$101.0 \pm 8.8 \pm 8.8$	$1.07 \pm 0.17 \pm 0.11$	BESII
$\eta(1440) \rightarrow \gamma\phi$			< 0.82 (95% C.L.)	BESII

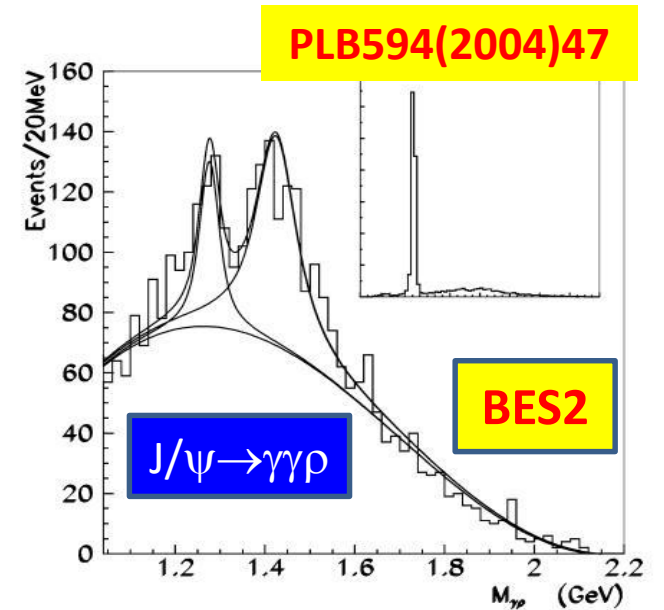
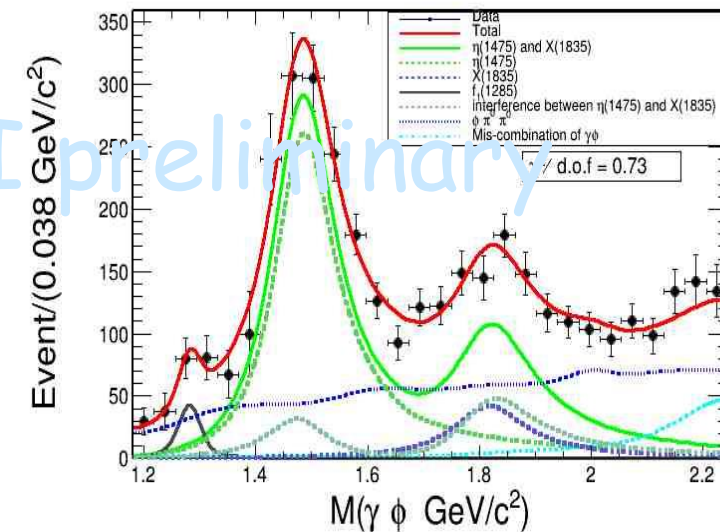
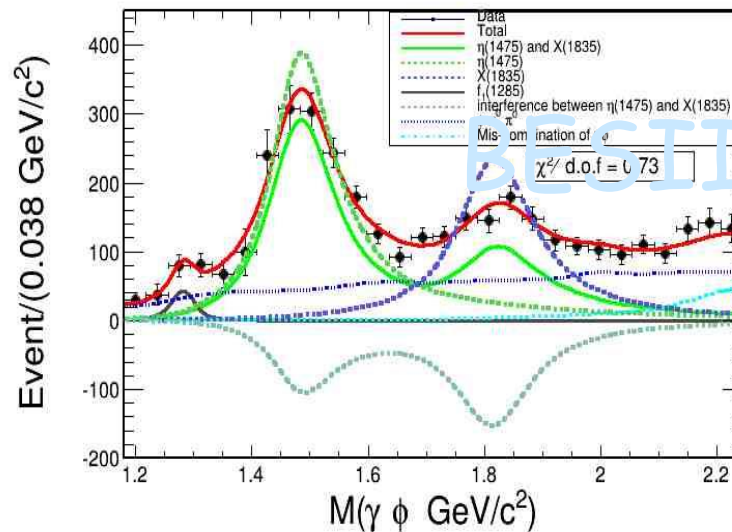


Fig. 2. The $\gamma\rho$ invariant mass distribution. The insert shows the full mass scale where the $\eta(958)$ is clearly observed.

Pseudoscalar (0^{-+})-- $\eta(1405)/\eta(1475)$

$\checkmark \eta(1475) \rightarrow \gamma \phi$



	Resonance	Mass (MeV/c ²)	Γ (MeV/c ²)	B.F. ($\times 10^{-6}$)
Destructive interference	$f_1(1285)$	PDG	PDG	$0.30 \pm 0.12 \pm 0.17$
	$\eta(1405/1475)$	$1479 \pm 11 \pm 21$	$133 \pm 35 \pm 20$	$11.8 \pm 2.2 \pm 1.9$
	$X(1835)$	$1812 \pm 59 \pm 42$	$161 \pm 47 \pm 24$	$9.0 \pm 2.6 \pm 2.2$
Constructive interference	$f_1(1285)$	PDG	PDG	$0.29 \pm 0.12 \pm 0.17$
	$\eta(1405/1475)$	$1479 \pm 11 \pm 16$	$132 \pm 36 \pm 31$	$7.9 \pm 1.3 \pm 1.9$
	$X(1835)$	$1813 \pm 61 \pm 45$	$160 \pm 81 \pm 43$	$1.6 \pm 0.5 \pm 0.3$

Result (BESIII preliminary)

Assuming $\eta(1405)$ and $\eta(1475)$ belong to one meson [1]:

$$\Gamma(\eta(1405/1475) \rightarrow \gamma\rho) : \Gamma(\eta(1405/1475) \rightarrow \gamma\phi) = 3.8 : 1$$

➤ The structure in $\gamma\phi$ favors $\eta(1475)$.

One state assumption: the ratio between $\gamma\rho$ and $\gamma\phi$ final states is a little bit larger than the prediction in Ref[1].

Two states assumption: $\eta(1475)$ probably the first radial excitation of the η

The partial width relationship of $\gamma\rho$ and $\gamma\phi$ final states

	Constructive	Destructive
$\Gamma(f_1(1285) \rightarrow \gamma\rho)[3] : \Gamma(f_1(1285) \rightarrow \gamma\phi)$	$(128.8 \pm 96.7) : 1$	$(129.3 \pm 99.8) : 1$
$\Gamma(\eta(1405/1475) \rightarrow \gamma\rho)[4] : \Gamma(\eta(1405/1475) \rightarrow \gamma\phi)$	$(6.6 \pm 2.1) : 1$	$(9.9 \pm 2.8) : 1$

[1] X. G. Wu et, al. Phys. Rev. D **87**, 014023.

[2] L. Kopke and N. Wermes Phys. Rep. **174**, 67.

[3] BES Collaboration Phys. Lett. B **594**, 47.

[4] Particle Data Group Chin. Phys. C **38**, 090001.

BES2: $J/\psi \rightarrow (\omega, \phi) K \bar{K} \pi, \eta K_S K^\pm \pi^\mp$

TABLE V. The mass, width, and branching fractions of J/ψ decays into $\{\omega, \phi\}X(1440)$.

$J/\psi \rightarrow \omega X(1440)$ ($X \rightarrow K_S^0 K^+ \pi^- + \text{c.c.}$)	$J/\psi \rightarrow \omega X(1440)$ ($X \rightarrow K^+ K^- \pi^0$)
$M = 1437.6 \pm 3.2 \text{ MeV}/c^2$	$M = 1445.9 \pm 5.7 \text{ MeV}/c^2$
$\Gamma = 48.9 \pm 9.0 \text{ MeV}/c^2$	$\Gamma = 34.2 \pm 18.5 \text{ MeV}/c^2$
$B(J/\psi \rightarrow \omega X(1440) \rightarrow \omega K_S^0 K^+ \pi^- + \text{c.c.}) = (4.86 \pm 0.69 \pm 0.81) \times 10^{-4}$	
$B(J/\psi \rightarrow \omega X(1440) \rightarrow \omega K^+ K^- \pi^0) = (1.92 \pm 0.57 \pm 0.38) \times 10^{-4}$	
$B(J/\psi \rightarrow \phi X(1440) \rightarrow \phi K_S^0 K^+ \pi^- + \text{c.c.}) < 1.93 \times 10^{-5}$ (90% C.L.)	
$B(J/\psi \rightarrow \phi X(1440) \rightarrow \phi K^+ K^- \pi^0) < 1.71 \times 10^{-5}$ (90% C.L.)	

M. Ablikim et al, Phys. Rev. D77, 032005(2008)

BESIII: $J/\psi \rightarrow \omega \eta \pi \pi$

TABLE I. Summary of measurements of the mass, width, and the product branching fraction of $\mathcal{B}(J/\psi \rightarrow \omega X) \times \mathcal{B}(X \rightarrow a_0^\pm(980)\pi^\mp) \times \mathcal{B}(a_0^\pm(980) \rightarrow \eta\pi^\pm)$ where X represents $f_1(1285)$, $\eta(1405)$ and $X(1870)$. Here the first errors are statistical and the second ones are systematic.

Resonance	Mass (MeV/ c^2)	Width (MeV/ c^2)	$\mathcal{B}(10^{-4})$
$f_1(1285)$	$1285.1 \pm 1.0_{-0.3}^{+1.6}$	$22.0 \pm 3.1_{-1.5}^{+2.0}$	$1.25 \pm 0.10_{-0.20}^{+0.19}$
$\eta(1405)$	$1399.8 \pm 2.2_{-0.1}^{+2.8}$	$52.8 \pm 7.6_{-7.6}^{+0.1}$	$1.89 \pm 0.21_{-0.23}^{+0.21}$
$X(1870)$	$1877.3 \pm 6.3_{-7.4}^{+3.4}$	$57 \pm 12_{-4}^{+19}$	$1.50 \pm 0.26_{-0.36}^{+0.72}$

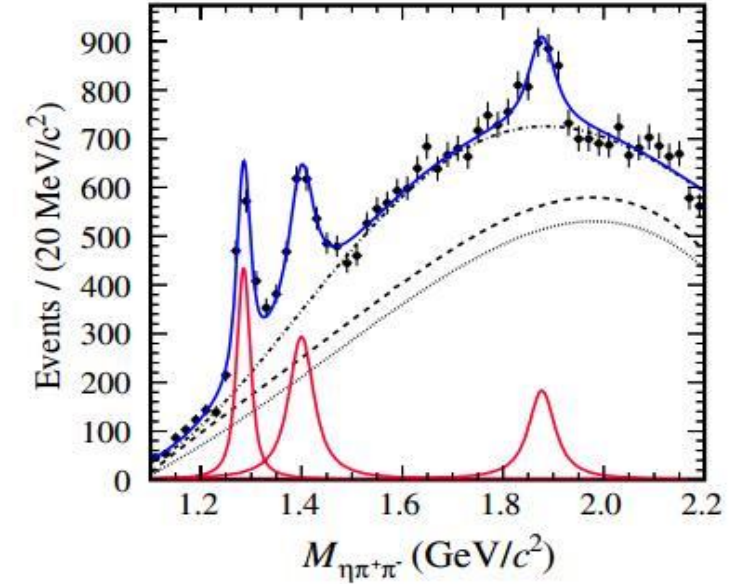


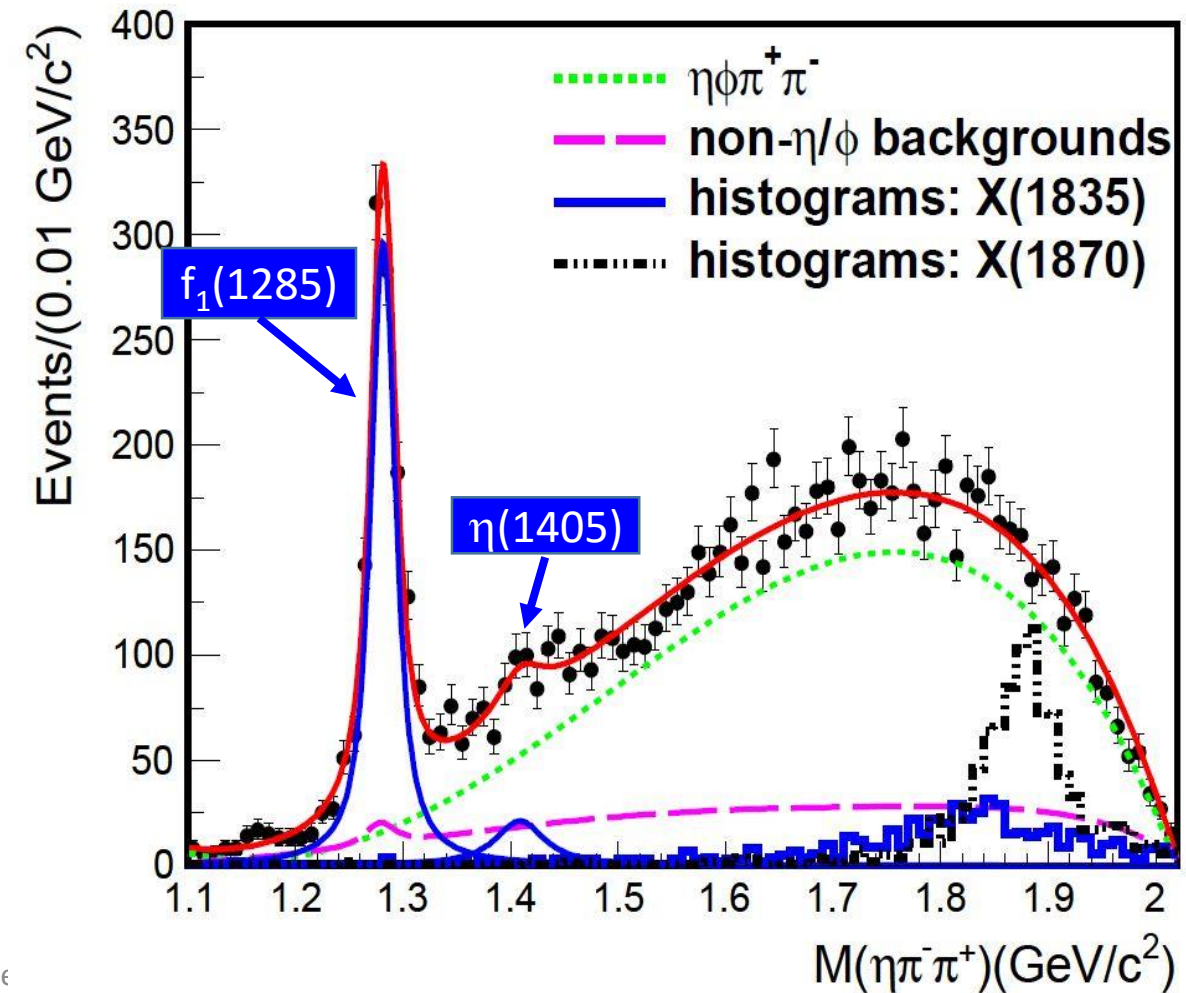
FIG. 4 (color online). Results of the fit to the $M(\eta\pi^+\pi^-)$ mass distribution for events with either the $\eta\pi^+$ or $\eta\pi^-$ in the $a_0(980)$ mass window. The dotted curve shows the contribution of non- ω and/or non- $a_0(980)$ background, the dashed line also includes the contribution from $J/\psi \rightarrow b_1(1235)a_0(980)$, and the dot-dashed curve indicates the total background with the non-resonant $J/\psi \rightarrow \omega a_0^\pm(980)\pi^\mp$ included. $\chi^2/\text{d.o.f.}$ is 1.27 for this fit.

**M. Ablikim et al, Phys. Rev. Lett. 107,
182001(2011)**

Decay mode	Branching fraction \mathcal{B}
$J/\psi \rightarrow \eta Y(2175), Y(2175) \rightarrow \phi f_0(980), f_0(980) \rightarrow \pi^+ \pi^-$	$(1.20 \pm 0.14 \pm 0.37) \times 10^{-4}$
$J/\psi \rightarrow \phi f_1(1285), f_1(1285) \rightarrow \eta \pi^+ \pi^-$	$(1.20 \pm 0.06 \pm 0.14) \times 10^{-4}$
$J/\psi \rightarrow \phi \eta(1405), \eta(1405) \rightarrow \eta \pi^+ \pi^-$	$(2.01 \pm 0.58 \pm 0.82) (< 4.45) \times 10^{-5}$
$J/\psi \rightarrow \phi X(1835), X(1835) \rightarrow \eta \pi^+ \pi^-$	$< 2.80 \times 10^{-4}$
$J/\psi \rightarrow \phi X(1870), X(1870) \rightarrow \eta \pi^+ \pi^-$	$< 6.13 \times 10^{-5}$

BESIII: $J/\psi \rightarrow \phi \eta \pi \pi$

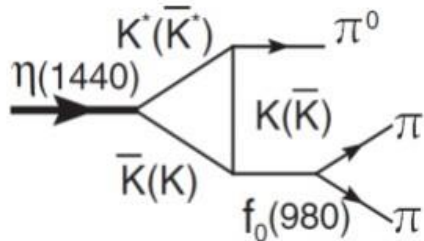
**M. Ablikim et al,
Phys. Rev. D91, 052017(2011)**



$\eta(1405)$ in $J/\psi \rightarrow \gamma 3\pi$

PRL 108, 182001 (2012)

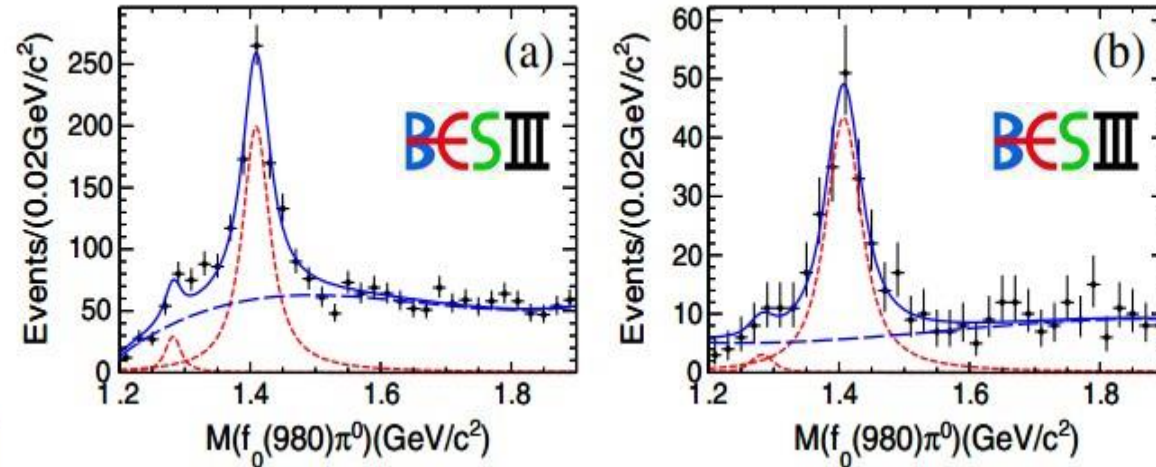
- $\eta(1440)$
 - $\eta(1405) \rightarrow a_0 \pi$
 - $\eta(1475) \rightarrow K^* \bar{K}$
- One or two resonances?



Triangle Singularity (TS)

one $\eta(1440)$ is enough to describe the experimental data !

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



The isospin violated decay $\eta(1405) \rightarrow f_0(980) \pi^0$ is observed for the first time with a significance $>10\sigma$.

Resonance	$M(\text{MeV}/c^2)$	$\Gamma(\text{MeV}/c^2)$	Branching ratios
$\eta(1405)(\pi^+ \pi^- \pi^0)$	1409.0 ± 1.7	48.3 ± 5.2	$(1.50 \pm 0.11 \pm 0.11) \times 10^{-5}$
$\eta(1405)(\pi^0 \pi^0 \pi^0)$	1407.0 ± 3.5	55.0 ± 11.0	$(7.10 \pm 0.82 \pm 0.72) \times 10^{-6}$

Measured results of $\eta(1440)$ at BES2/BESIII

BES2 BESIII

	$\eta\pi\pi$	$K\bar{K}\pi$	3π	γV
γ	$\eta(1405)$ $(2.6 \pm 0.7) \cdot 10^{-4}$	$\eta(1440/1475)$	$\eta(1405)$ $3\pi (1.50 \pm 0.11 \pm 0.11) \cdot 10^{-5}$ $3\pi^0 (7.10 \pm 0.82 \pm 0.72) \cdot 10^{-6}$	$\eta(1405) \rightarrow \gamma\rho$ $(1.07 \pm 0.17 \pm 0.11) \cdot 10^{-4}$ $\eta(1475) \rightarrow \gamma\phi$ $(7.9 \pm 1.3 \pm 1.9 /$ $11.8 \pm 2.2 \pm 1.9) \cdot 10^{-6}$
ω	$\eta(1405)$ $(1.89 \pm 0.21 \pm_{0.23}^{0.21}) \cdot 10^{-4}$	$\eta(1440/1475)$ $K_S K\pi: (4.86 \pm 0.69 \pm 0.81) \cdot 10^{-4}$ $K^+ K^- \pi^0: (1.92 \pm 0.57 \pm 0.38) \cdot 10^{-4}$		
ϕ	$\eta(1405)$ $(2.01 \pm 0.58 \pm 0.82) \cdot 10^{-5}$ $(< 4.45 \cdot 10^{-5} @ 90\%CL)$	$\eta(1440/1475)$ $K_S K\pi < 1.93 \cdot 10^{-5} @ 90\%CL$ $K^+ K^- \pi^0 < 1.71 \cdot 10^{-5} @ 90\%CL$		
ρ				

Status of X(18??) at BESIII

- $X(p\bar{p})$: $J^P = 0^-$, $J/\psi \rightarrow \gamma p\bar{p}$, PRL108,112003
- X(1835): $J^P = 0^-$, $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$, PRL106, 072002
- X(1840): J^P unknown, $J/\psi \rightarrow \gamma 3(\pi^+ \pi^-)$, PRD88,091502
- X(1870): J^P unknown, $J/\psi \rightarrow \omega \eta \pi^+ \pi^-$, PRL107, 182001
- X(1810): $J^P = 0^+$, $J/\psi \rightarrow \gamma \omega \varphi$, PRD 87, 032008

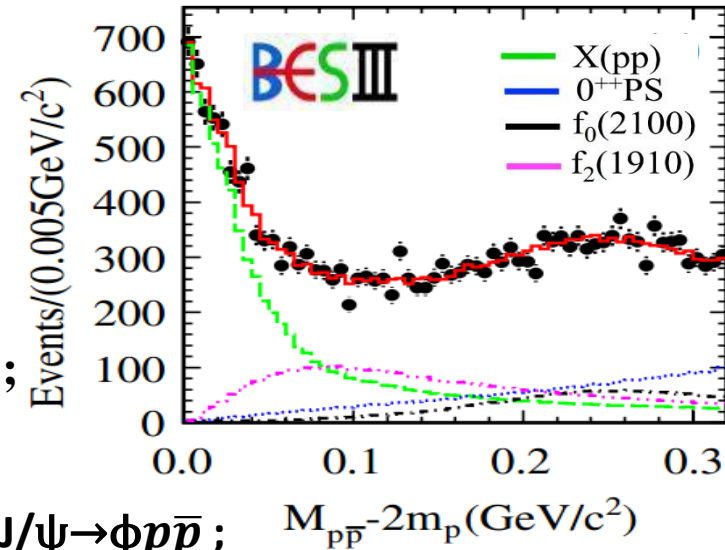
X(18??) near proton-antiproton threshold :

- **X(1840) is in agreement with X(1835) and X($p\bar{p}$), while its width is significantly different**
- **Are they the same particles?**
- **More studies are needed**

$X(p\bar{p})/X(1860)$ in $J/\psi \rightarrow \gamma p\bar{p}$

- Strong enhancement first observed at BESII [PRL 91,022001(2003)] and confirmed by CLEO-c [PRD82,092002(2012)];
- PWA was firstly performed at BESIII;
- **Significance of the $X(p\bar{p})$ component $> 30\sigma$, $> 5\sigma$ for the other components;**
- **The 0^+ assignment is better than other J^{PC} ;**
- $M = 1832 \pm 5^{19}(\text{stat}) \pm 17^{18}(\text{syst}) \pm 19(\text{mode}) \text{ MeV}/c^2$;
- $\Gamma < 76 \text{ MeV}/c^2$ (90% C.L.);

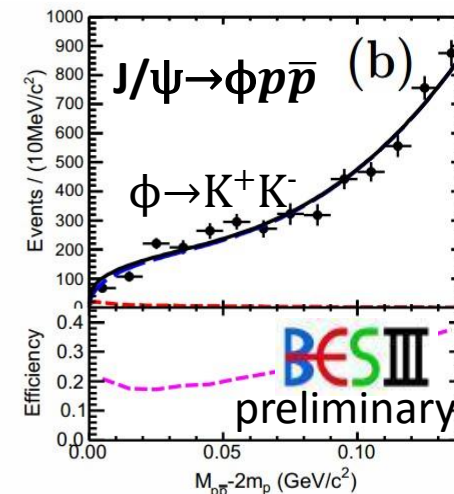
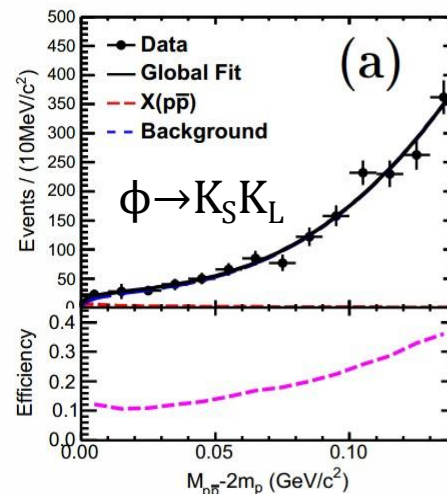
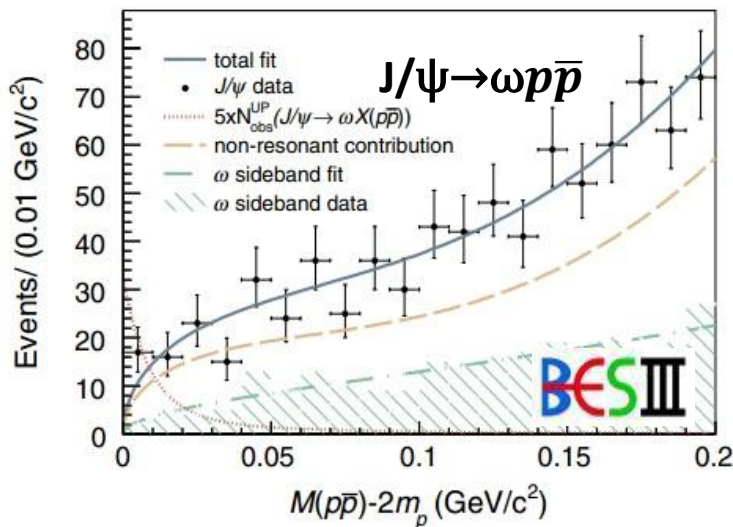
PRL 108,112003(2012)



No similar structure was observed in $J/\psi \rightarrow \omega p\bar{p}$ or $J/\psi \rightarrow \phi p\bar{p}$;

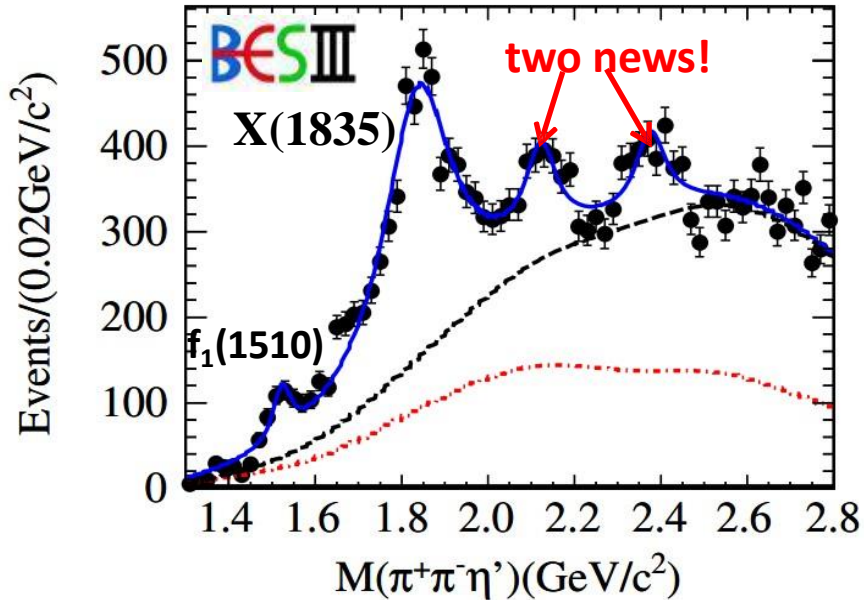
PRD 87, 112004(2013)

arXiv:1512.08197



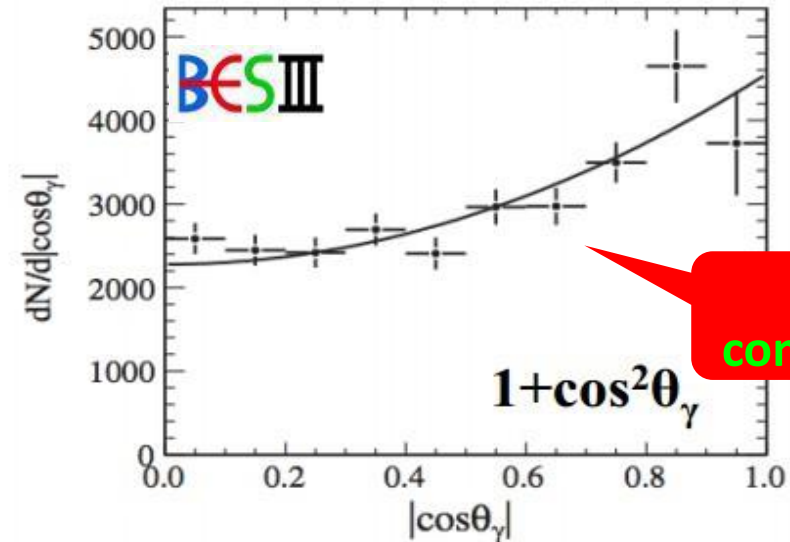
Confirm X(1835) in $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$

PRL 106, 072002 (2011)



Resonance	$M(\text{MeV}/c^2)$	$\Gamma(\text{MeV}/c^2)$	N_{event}	
$f_1(1510)$	1522.7 ± 5.0	48 ± 11	230 ± 37	$>5.7\sigma$
X(1835)	1836.5 ± 3.0	190.1 ± 9.0	4265 ± 131	$>20\sigma$
X(2120)	2122.4 ± 6.7	83 ± 16	647 ± 103	$>7.2\sigma$
X(2370)	2376.3 ± 8.7	83 ± 17	565 ± 105	$>6.4\sigma$

- X(1835) was first observed at BES, and then confirmed at BESII [PRL95,262001(2005)];
- the angular distribution of the radiative photon is consistent with expectations for pseudoscalar;
- Many interpretation: pp bound state? Glueballs? Radial excitation of the η' meson?,...
- **Needed higher statistic**



Fit to Mass spectra of $\eta'\pi^+\pi^-$: MODEL I

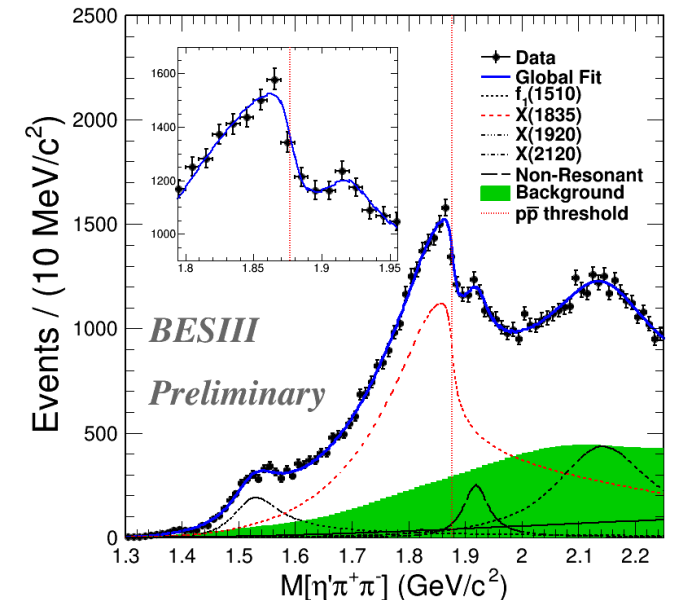
- Using the Flatté formula for the line shape

$$T = \frac{\sqrt{\rho_{out}}}{\mathcal{M}^2 - s - i \sum_k g_k^2 \rho_k}, \sum_k g_k^2 \rho_k \simeq g_0^2 (\rho_0 + \frac{g_{p\bar{p}}^2}{g_0^2} \rho_{p\bar{p}})$$

- $g_{p\bar{p}}^2/g_0^2$ is the ratio between the coupling strength to the $p\bar{p}$ channel and the summation of all other channels

The state around 1.85 GeV/c ²	
\mathcal{M} (MeV/c ²)	1638.0 ^{+121.9 +127.8} / _{-121.9 -254.3}
g_0^2 ((GeV/c ²) ²)	93.7 ^{+35.4 +47.6} / _{-35.4 -43.9}
$g_{p\bar{p}}^2/g_0^2$	2.31 ^{+0.37 +0.83} / _{-0.37 -0.60}
M_{pole} (MeV/c ²) *	1909.5 ^{+15.9 +9.4} / _{-15.9 -27.5}
Γ_{pole} (MeV/c ²) *	273.5 ^{+21.4 +6.1} / _{-21.4 -64.0}
Branching Ratio	(3.93 ^{+0.38 +0.31} / _{-0.38 -0.84}) × 10 ⁻⁴

* The pole nearest to the $p\bar{p}$ mass threshold



$\log\mathcal{L} = 630549.5$

Significance of $g_{p\bar{p}}^2/g_0^2$ being non-zero is larger than 7σ

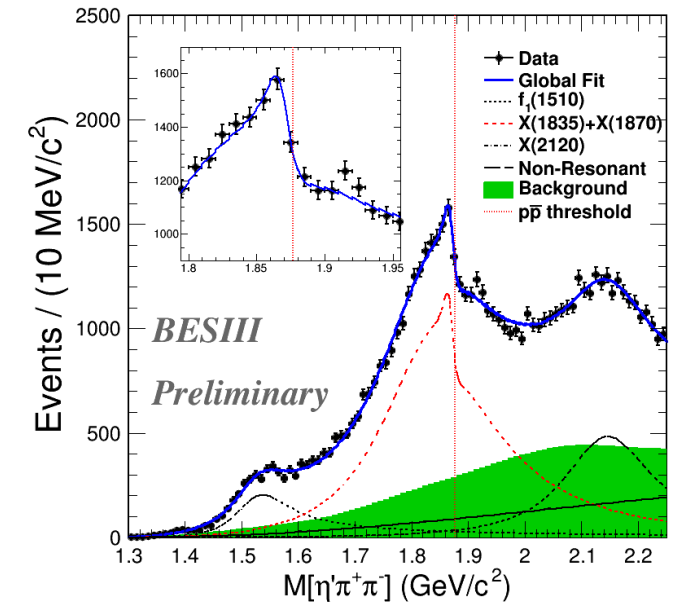
X(1920) is needed with 5.7σ

Fit to Mass spectra of $\eta'\pi^+\pi^-$: MODEL II

- Using coherent sum of two Breit-Wigner amplitudes

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

X(1835)	
M (MeV/c ²)	1825.3 ^{+2.4 +17.3} _{-2.4 -2.4}
Γ (MeV/c ²)	245.2 ^{+14.2 +4.6} _{-12.6 -9.6}
B.R. (constructive interference)	(3.01 ^{+0.17 +0.26} _{-0.17 -0.28}) × 10 ⁻⁴
B.R. (destructive interference)	(3.72 ^{+0.21 +0.18} _{-0.21 -0.35}) × 10 ⁻⁴
X(1870)	
M (MeV/c ²)	1870.2 ^{+2.2 +2.3} _{-2.3 -0.7}
Γ (MeV/c ²)	13.0 ^{+7.1 +2.1} _{-5.5 -3.8}
B.R. (constructive interference)	(2.03 ^{+0.12 +0.43} _{-0.12 -0.70}) × 10 ⁻⁷
B.R. (destructive interference)	(1.57 ^{+0.09 +0.49} _{-0.09 -0.86}) × 10 ⁻⁵



$\log\mathcal{L} = 630540.3$

Significance of X(1870)
is larger than 7σ

X(1920) is not significant

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

- A significant distortion of the $\eta'\pi^+\pi^-$ line shape near the $p\bar{p}$ mass threshold is observed in $J/\psi \rightarrow \gamma\eta'\pi^+\pi^-$
 - Simple Breit-Wigner function fails in describing the line shape near the $p\bar{p}$ mass threshold
- Two models have been used
 - MODEL I: threshold structure due to the opening of the $p\bar{p}$ decay mode
 - Using the Flatté formula
 - **Strong $X(1835) \rightarrow p\bar{p}$ coupling, with significance larger than 7σ**
 - $M_{\text{pole}} = 1909.5^{+15.9+9.4}_{-15.9-27.5} \text{ MeV}/c^2$
 - $\Gamma_{\text{pole}} = 273.5^{+21.4+6.1}_{-21.4-64.0} \text{ MeV}/c^2$
 - MODEL II: interference between two resonances
 - Using coherent sum of two Breit-Wigner amplitudes
 - **A narrow resonance below the $p\bar{p}$ mass threshold, with significance larger than 7σ**
 - $M = 1870.2^{+2.2+2.3}_{-2.3-0.7} \text{ MeV}/c^2$
 - $\Gamma = 13.0^{+7.1+2.1}_{-5.5-3.8} \text{ MeV}/c^2$
- Both models fit the data well with almost equally good quality
 - Cannot distinguish them with current data
 - **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**

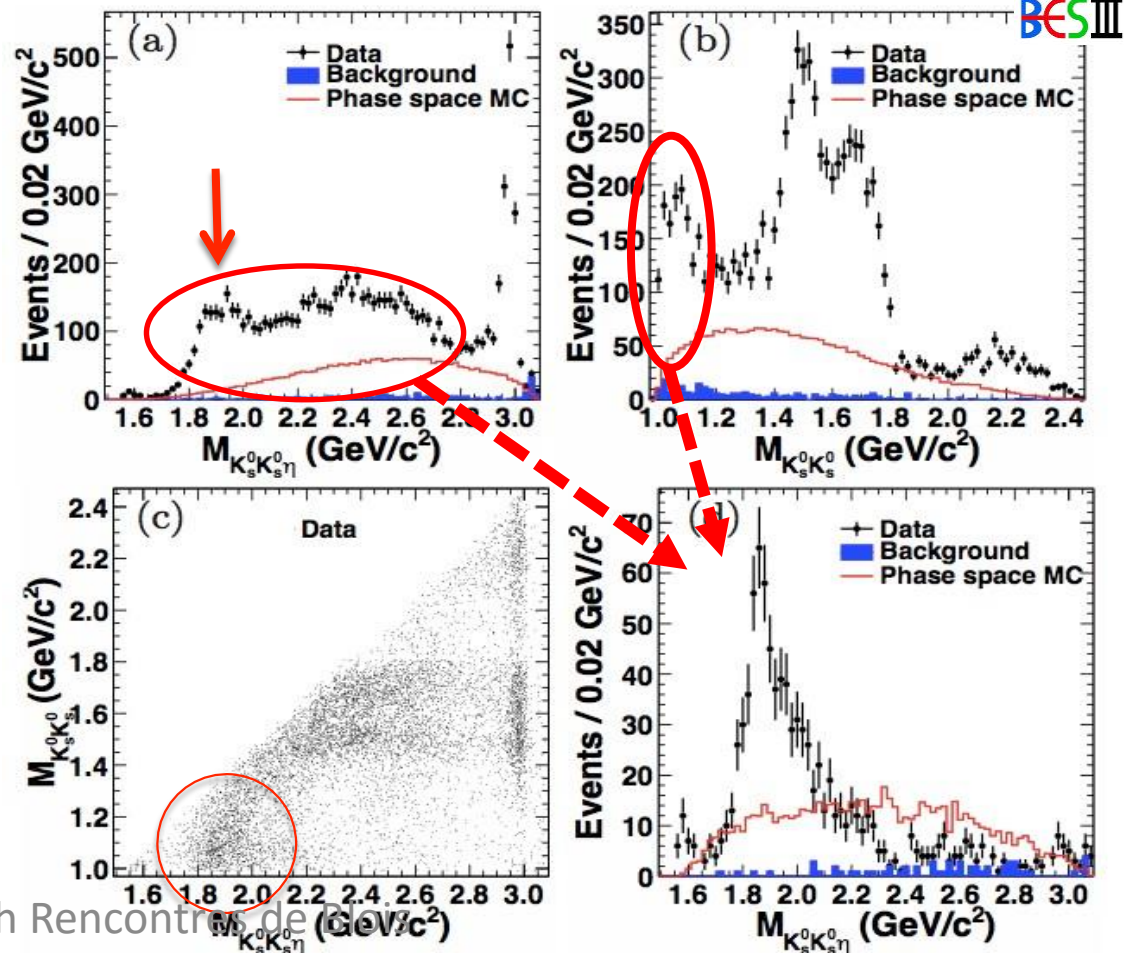
$X(1835)$ in $J/\psi \rightarrow K_S^0 K_S^0 \eta$ provides a clear environment

BESIII: PRL115,091803

- $K_S^0 K_S^0 \eta$ and $\pi^0 K_S^0 K_S^0 \eta$ bkg are forbidden by exchange symmetry and CP conservation

- 1.3×10^9 J/ψ events
- (a) Structure around $1.85 \text{ GeV}/c^2$
- (b) Strong enhancement near the $K_S^0 K_S^0$ threshold interpreted as the $f_0(980)$
- (c) Strong correlation between the $f_0(980)$ and the structure near $1.85 \text{ GeV}/c^2$
- (d) $M(K_S^0 K_S^0) < 1.1 \text{ GeV}/c^2$ is the structure near $1.85 \text{ GeV}/c^2$ became more pronounced

PWA of events with
 $M(K_S^0 K_S^0) < 1.1 \text{ GeV}/c^2$ and
 $M(K_S^0 K_S^0 \eta) < 2.8 \text{ GeV}/c^2$



$X(1835)$ in $J/\psi \rightarrow \gamma K_S K_S \eta$

BESIII: PRL115,091803

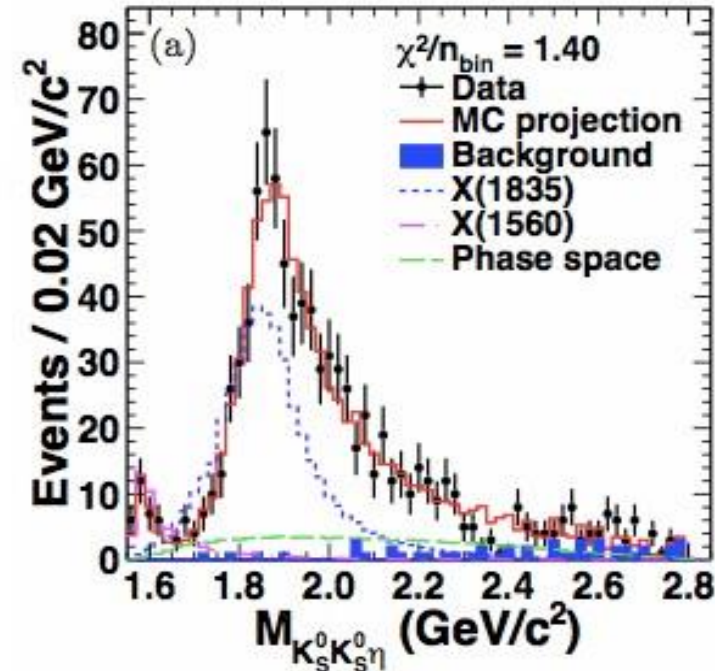
Final fit results: the data can be best described with three components:
 $X(1835) \rightarrow f_0(980) \eta$, $X(1560) \rightarrow f_0(980) \eta$, and a non-resonant $f_0(1500) \eta$ component

✓ Mass/Width consistent with the $X(1835)$ in

$$J/\psi \rightarrow \gamma \eta' \pi \pi$$

✓ Mass/spin consistent with those of the $X(p\bar{p})$

✓ Width is larger than the width of the $X(p\bar{p})$

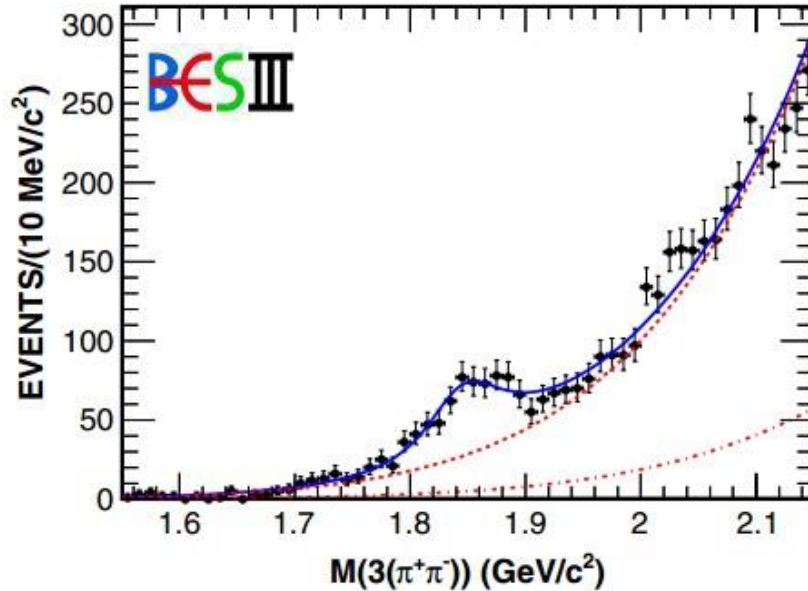


$$M = 1844 \pm 9 \text{ (stat)} \pm_{25}^{16} \text{ (syst)} \text{ MeV}/c^2 \quad \Gamma = 192 \pm_{17}^{20} \text{ (stat)} \pm_{43}^{62} \text{ (syst)} \text{ MeV} \quad (>12.9 \sigma)$$

$$\text{BR} = (3.3 \pm_{0.30}^{0.32} \text{ (stat)} \pm_{1.29}^{1.96} \text{ (syst)}) \times 10^{-5}$$

X(1840) in $J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$

PRD 88, 091502 (2013)



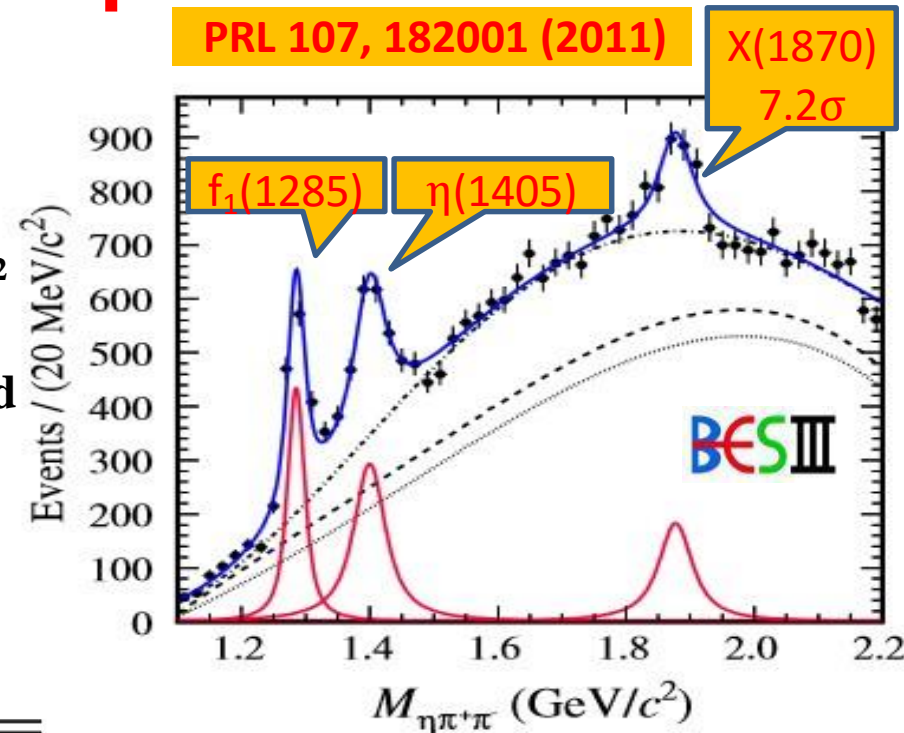
- A structure at $1.84\text{GeV}/c^2$ is observed in the mass spectrum $3(\pi^+\pi^-)$ with a significance of 7.6σ ;
- $M=1842.2\pm 4.2^{+7.1}_{-2.6}\text{ MeV}/c^2$;
 $\Gamma=83\pm 14\pm 11\text{ MeV}/c^2$;

$$B(J/\psi \rightarrow \gamma X(1840)) \times B(X(1840) \rightarrow 3(\pi^+\pi^-)) = (2.44 \pm 0.36^{+0.60}_{-0.74}) \times 10^{-5}$$

- ✓ The mass is consistent with that of X(1835), but the width is significantly different from either of them, and much smaller than $\Gamma_{X(1835)} = 190.1\pm 9.0^{+38}_{-36}\text{ MeV}/c^2$;
- ✓ We cannot determine whether X(1840) is a new state a new decay modes of existing X(1835)?

X(1870) in $J/\psi \rightarrow \omega \eta \pi^+ \pi^-$

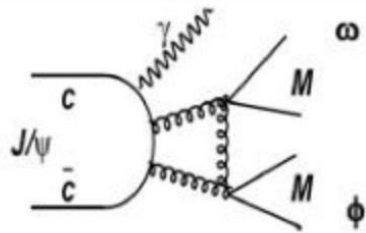
- First observation of $J/\psi \rightarrow \omega X(1870)$ and $X(1870) \rightarrow a_0(980)^\pm \pi^\mp$ with the significance 7.2σ ;
- $M = 1877.3 \pm 6.3(\text{stat}) \pm 7.4^{3.4}(\text{syst}) \text{ MeV}/c^2$
- $\Gamma = 57 \pm 12(\text{stat}) \pm 4^{19}(\text{syst}) \text{ MeV}/c^2$;
- $f_1(1285)$ and $\eta(1405)$ are also observed with significances $>10\sigma$;
- the product branching fractions for $X(1870)$, $f_1(1285)$ and $\eta(1405)$ are measured for the first time.



Resonance	Mass (MeV/ c^2)	Width (MeV/ c^2)	$\mathcal{B}(10^{-4})$
$f_1(1285)$	$1285.1 \pm 1.0^{+1.6}_{-0.3}$	$22.0 \pm 3.1^{+2.0}_{-1.5}$	$1.25 \pm 0.10^{+0.19}_{-0.20}$
$\eta(1405)$	$1399.8 \pm 2.2^{+2.8}_{-0.1}$	$52.8 \pm 7.6^{+0.1}_{-7.6}$	$1.89 \pm 0.21^{+0.21}_{-0.23}$
$X(1870)$	$1877.3 \pm 6.3^{+3.4}_{-7.4}$	$57 \pm 12^{+19}_{-4}$	$1.50 \pm 0.26^{+0.72}_{-0.36}$

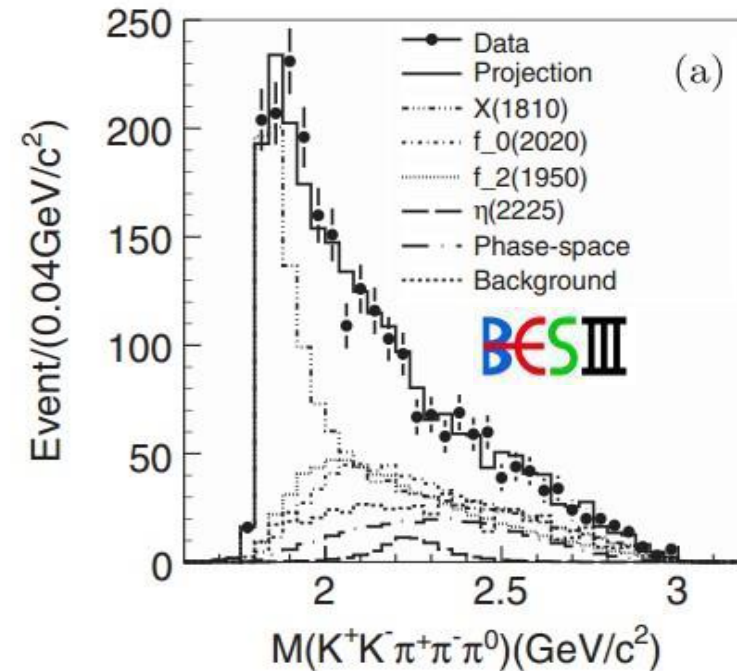
Whether the resonant structure of X(1870) is due to the X(1835), the $\eta_2(1870)$, an interference of both, or a new resonance still needs further study!

X(1810) in PWA of $J/\psi \rightarrow \gamma \omega \phi$

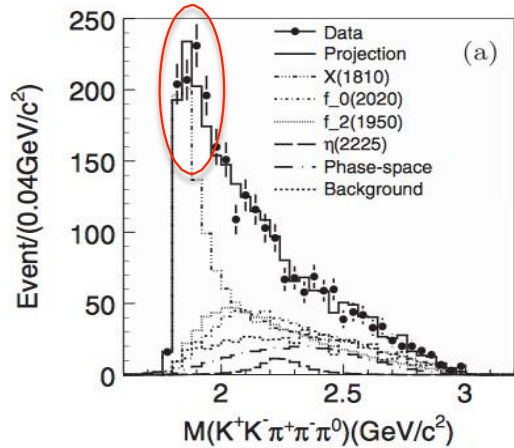
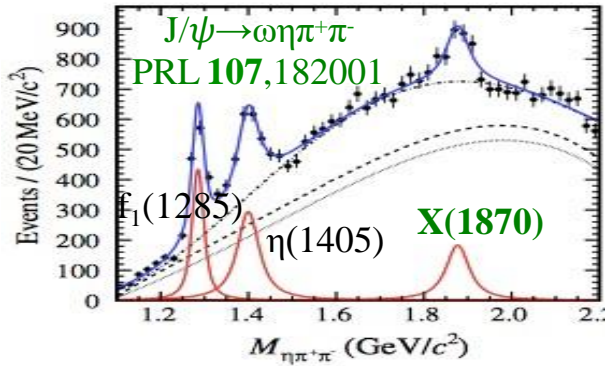


- $J/\psi \rightarrow \gamma \omega \phi$ is Double OZI suppressed;
- The X(1810) is first observed by PWA at BESII [PRL 96, 162002 (2006)] ;
- Observed and confirmed at BESIII with the significance $>30\sigma$;
- **the J^{PC} of the X(1810) is 0^{++} ;**
- The enhancement is not compatible with either the X(1835) or the X(pp) due to the different masses and spin-parity.

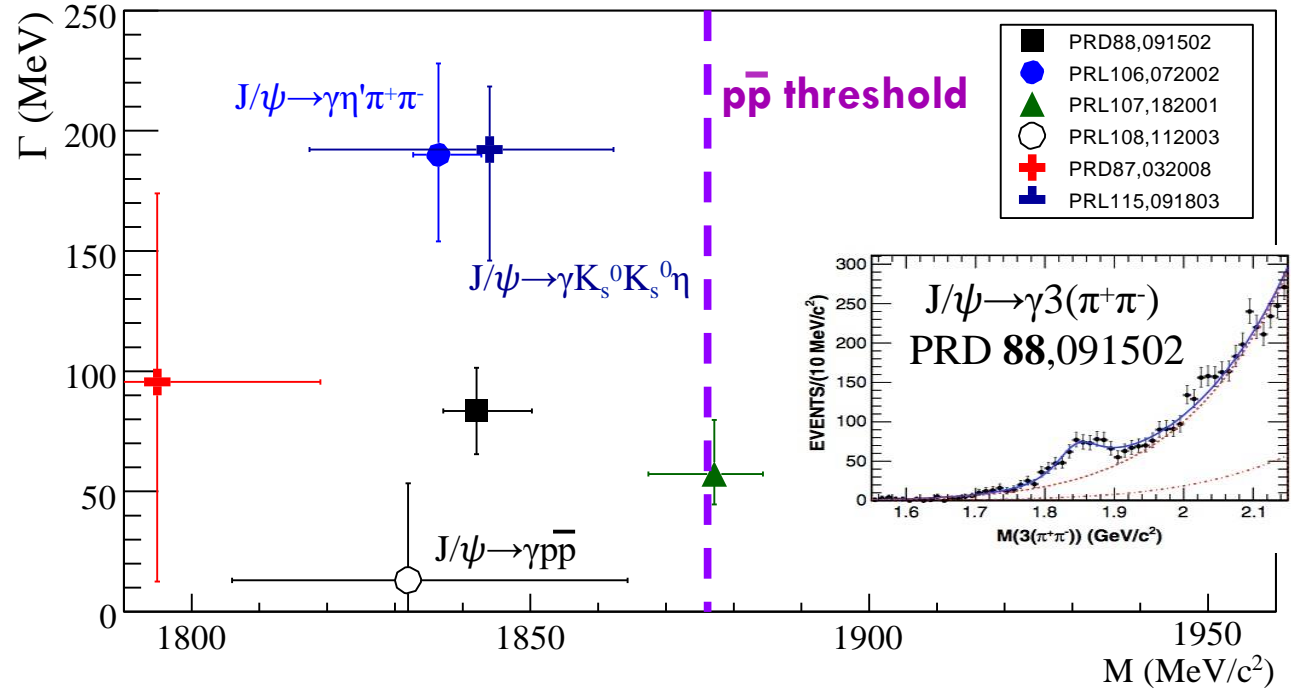
PRD 87, 032008(2013)



Resonance	J^{PC}	$M(\text{MeV}/c^2)$	$\Gamma(\text{MeV}/c^2)$	Events	ΔS	Δndf	Significance
X(1810)	0^{++}	1795 ± 7	95 ± 10	1319 ± 52	783	4	$>30\sigma$
$f_2(1950)$	2^{++}	1944	472	665 ± 40	211	2	20.4σ
$f_0(2020)$	0^{++}	1992	442	715 ± 45	100	2	13.9σ
$\eta(2225)$	0^{-+}	2226	185	70 ± 30	23	2	6.4σ
Coherent nonresonant component	0^{-+}	319 ± 24	45	2	9.1σ



$J/\psi \rightarrow \gamma\omega\phi$ PRD
87,032008
>30 σ



X states near proton-antiproton threshold

More studies are needed

Summary

BESIII started data taking for physics since 2009

- World largest data samples at J/ψ , ψ' , $\psi(3770)$, $\psi(4040)$, $Y(4260)$ already collected, more data in future coming soon
- BESIII is in her golden age, more results will appear: charm meson, form factors, tau physics, two-photon, rare processes ...
- **BESIII is playing leading role on hadron spectroscopy**
- Expect more results from BESIII in the future !

Thanks!