Hadron spectroscopy at BESIII

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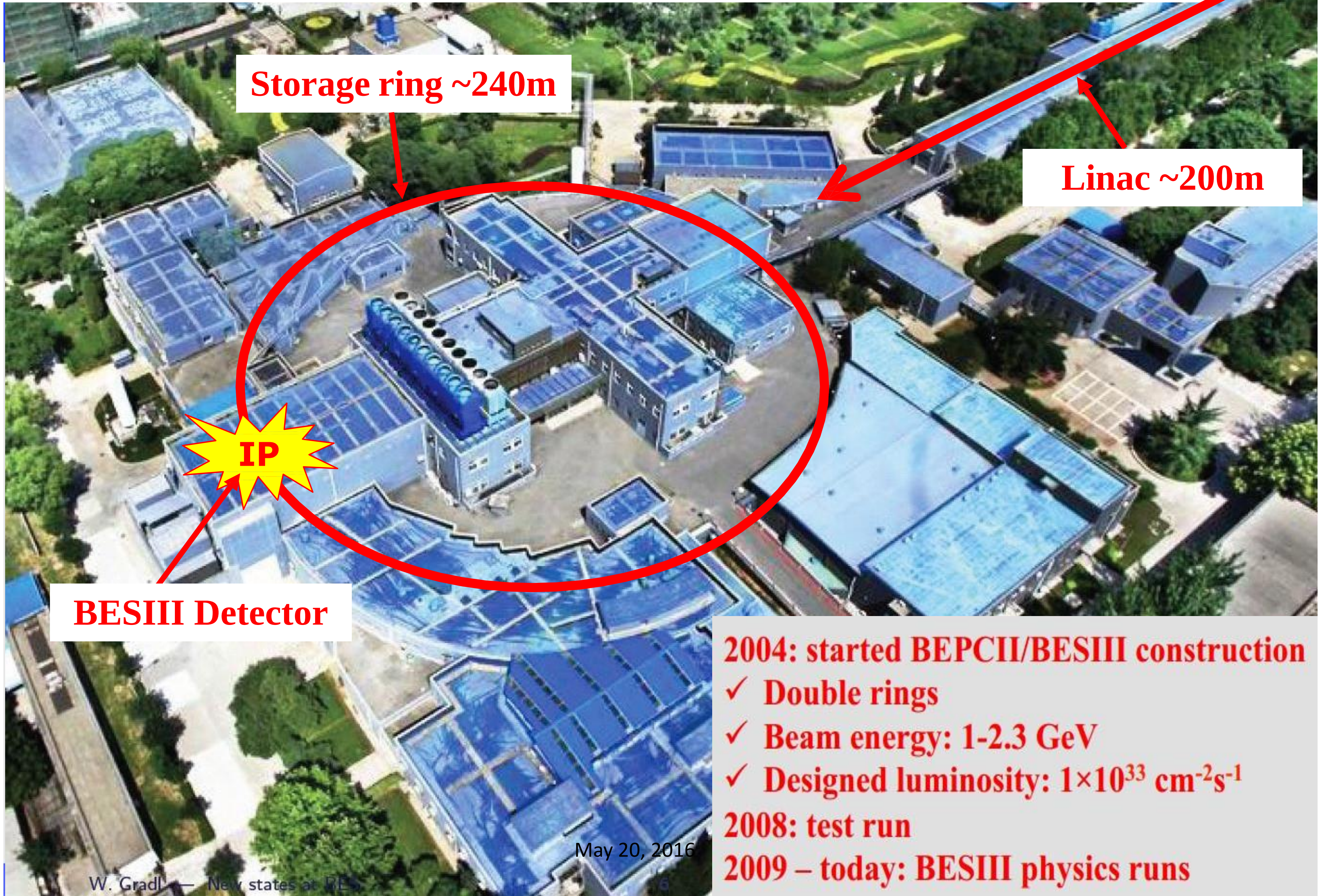
IHEP, Beijing

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)



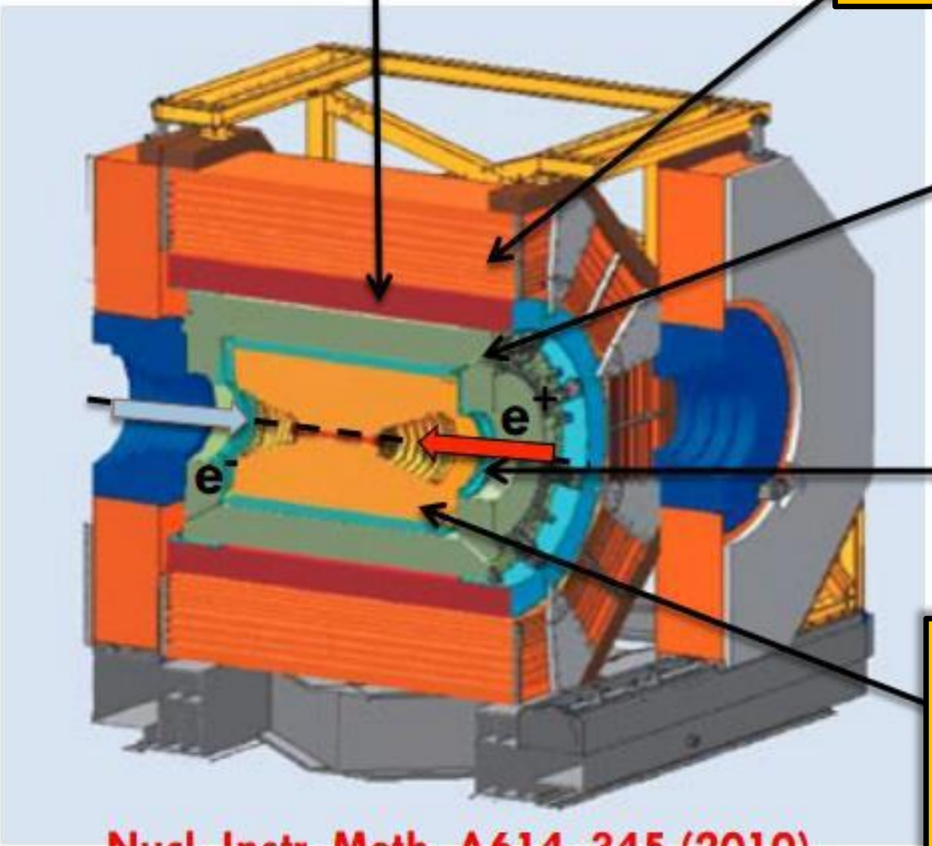
BESIII Detector

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

RPC Muon Detector
8 layers (end caps) + 9 layers (barrel)
$\Delta\Omega/4\pi = 93\%$

Superconducting solenoid (1T)

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

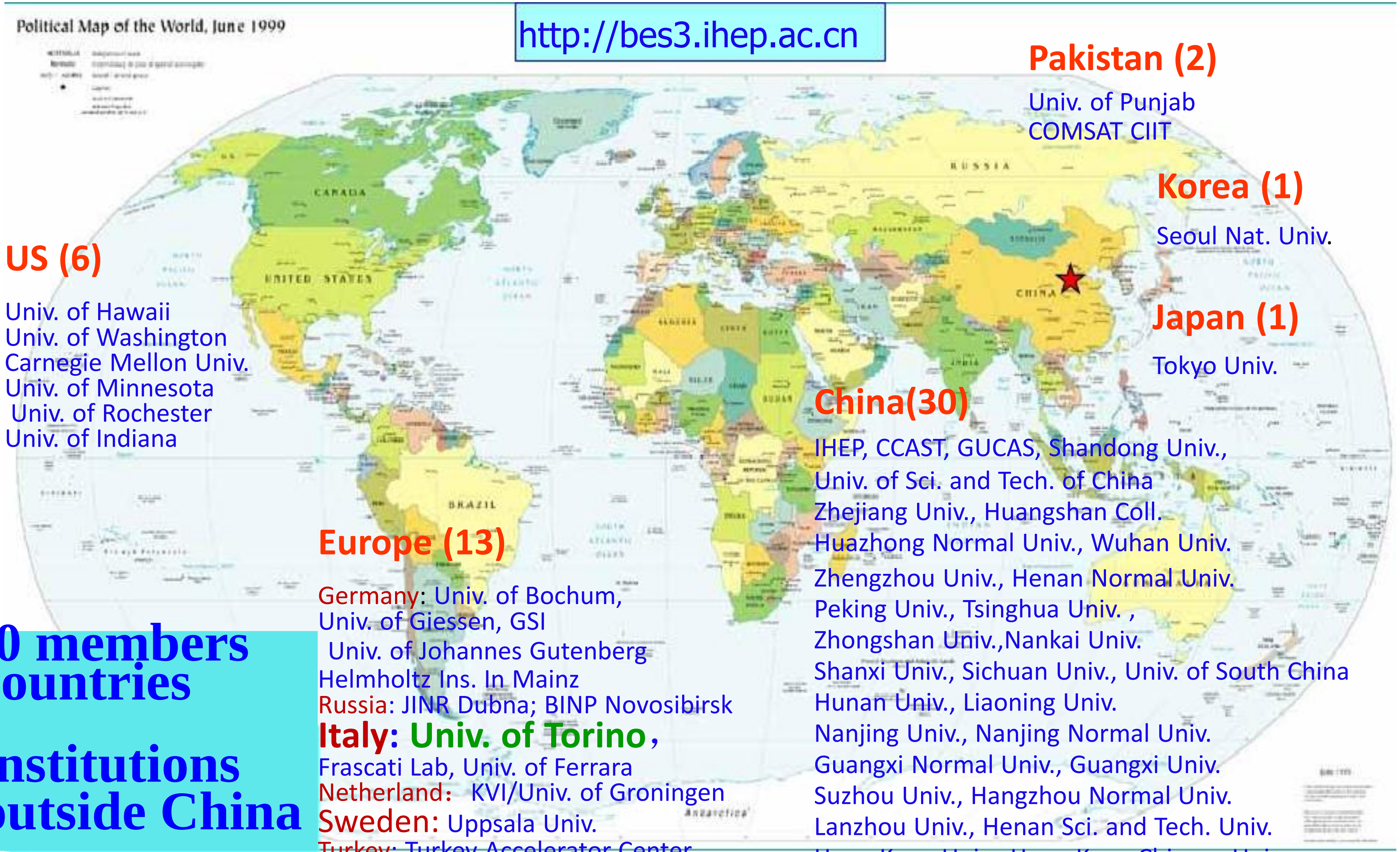


Nucl. Instr. Meth. A614, 345 (2010)

Time of Flight
$\sigma_t = 90$ ps (barrel)
$\sigma_t = 120$ ps (end caps)

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

BESIII Collaboration



http://bes3.ihep.ac.cn

Pakistan (2)

Univ. of Punjab
COMSAT CIIT

Korea (1)

Seoul Nat. Univ.

Japan (1)

Tokyo Univ.

US (6)

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

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.

Europe (13)

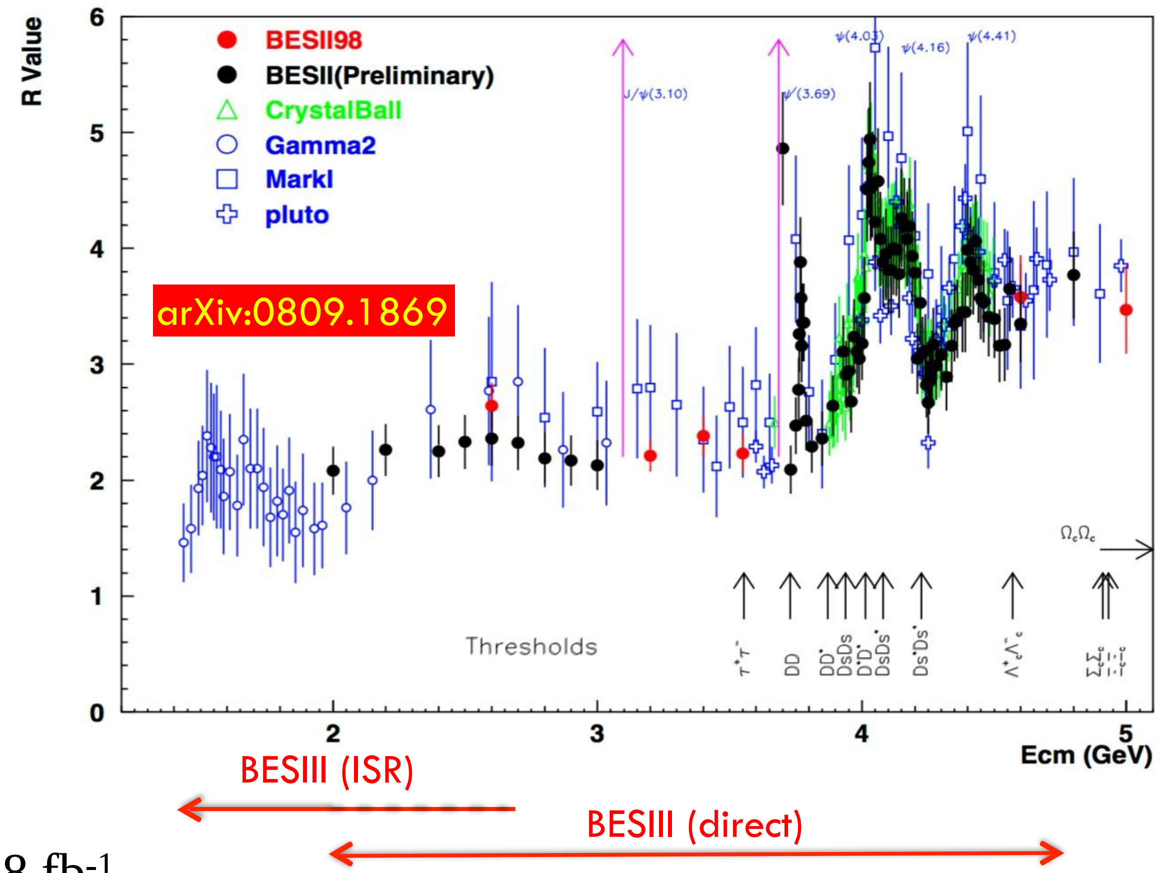
Germany: Univ. of Bochum,
Univ. of Giessen, GSI
Univ. of Johannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. of Torino,
Frascati Lab, Univ. of Ferrara
Netherland: KVI/Univ. of Groningen
Sweden: Uppsala Univ.
Turkey: Turkey Accelerator Center

~400 members
11 countries

53 institutions
22 outside China

BESIII started data taking for physics since 2009

- **1.3×10^9 J/ψ**
- **5×10^8 $\psi(2S)$**
- 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, ~0.5 fb^{-1}
  - 3.85-4.59 GeV, 104 points, ~0.8 fb^{-1}



MORE:

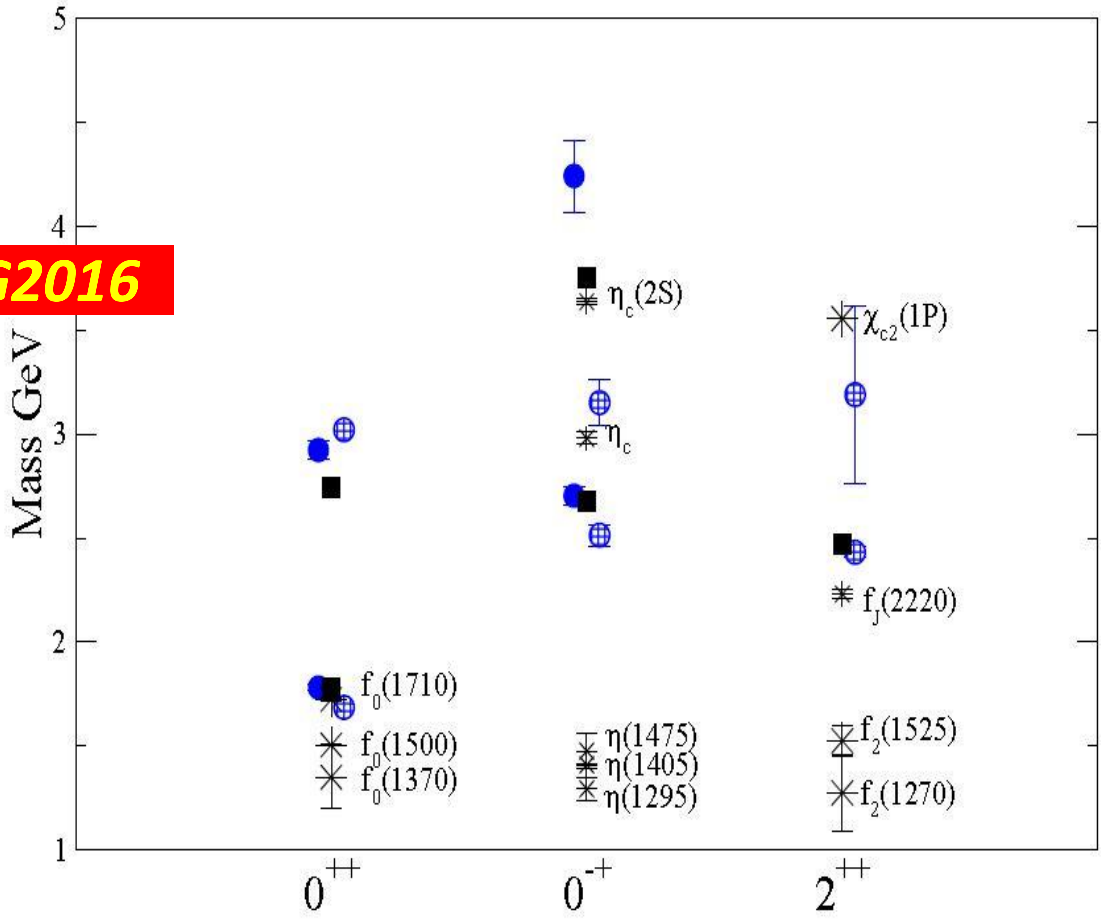
- 3554 MeV 24 pb^{-1} τ mass; 4100-4400 MeV 0.5 fb^{-1} coarse scan
- On-going data taking

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 = $\frac{1}{2}$ $u\bar{s}$, $d\bar{s}$; $\bar{d}s$, $-\bar{u}s$	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^{++}	$a_4(2040)$	$K_4^*(2045)$		$f_4(2050)$
$1\,^3G_5$	5^{--}	$\rho_5(2350)$	$K_5^*(2380)$		
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$
$2\,^3S_1$	1^{--}	$\rho(1450)$	$K^*(1410)$	$\phi(1680)$	$\omega(1420)$

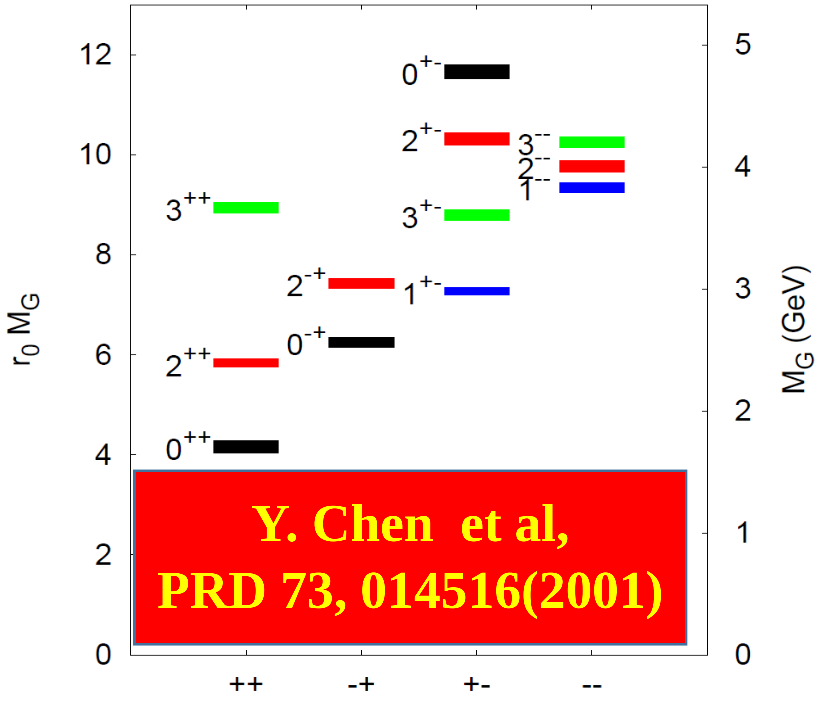
PDG2016

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):

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

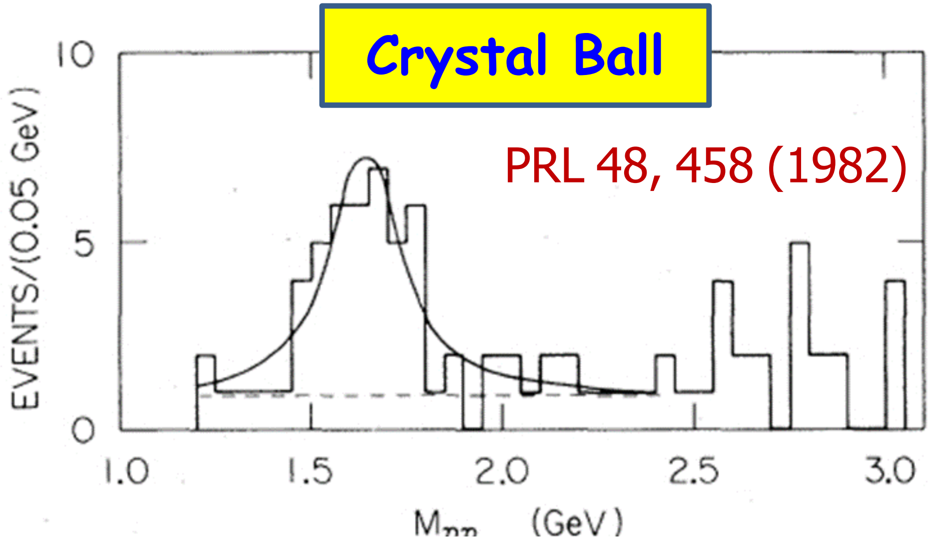
- E835 (2006):

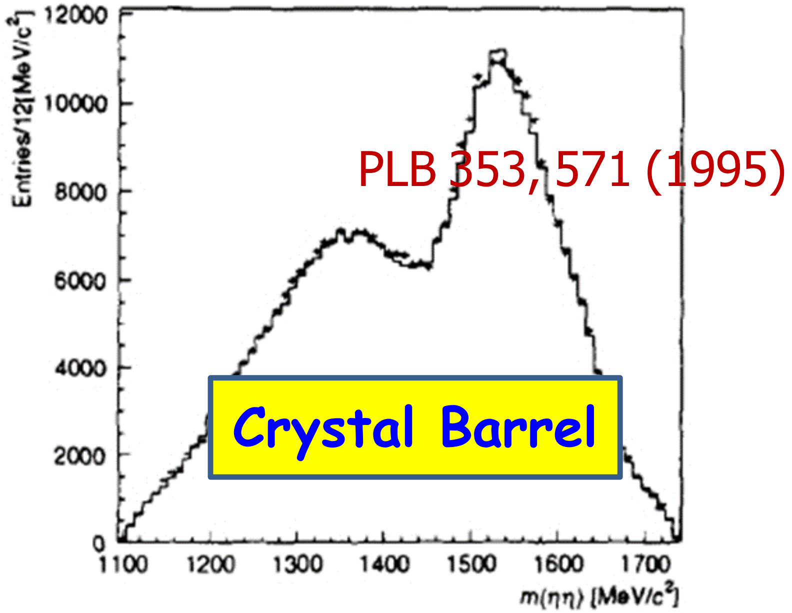
  $f_0(1500)$ [$pp\rightarrow\pi^0\eta\eta$]

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

- WA102, GAMS:

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



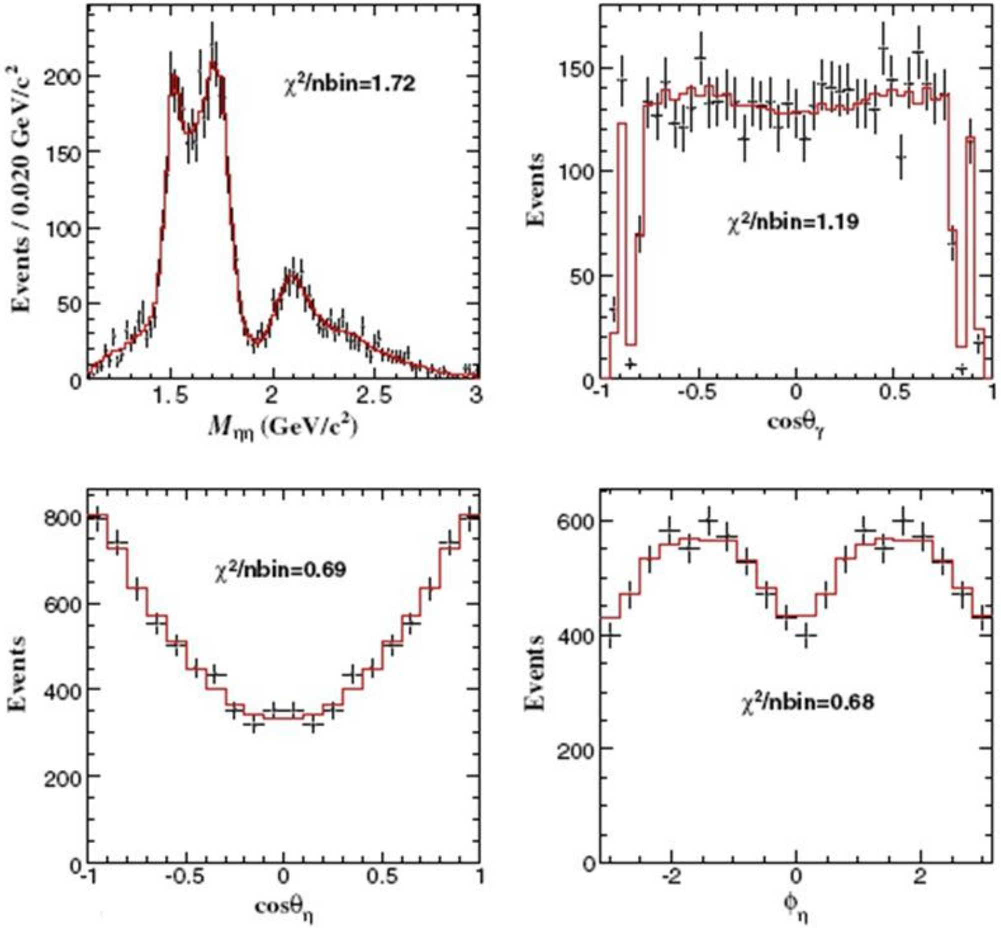


BESIII: PWA of $J/\psi \rightarrow \gamma\eta\eta$, $\eta \rightarrow \gamma\gamma$

PRD 87,092009

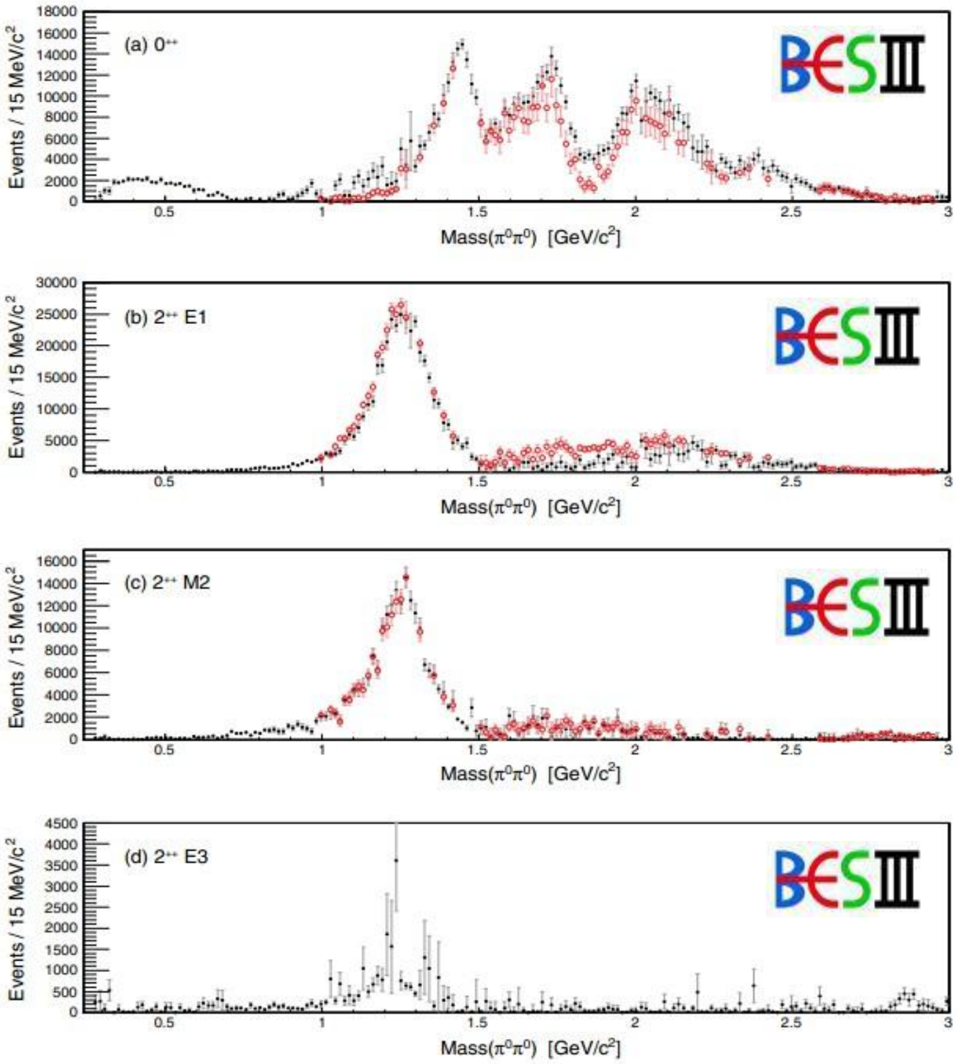
- $f_0(1710)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2σ)
- $f_2'(1525)$ is the dominant tensor
- $f_2(1810)$ and $f_2(2340)$ exist (6.4 and 7.6σ)
- No evidence for $f_J(2220)$

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



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

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

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

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

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

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

$BR(J/\psi \to \gamma f_0(1710) \to \gamma \eta\eta) = (2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$

Exp.

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

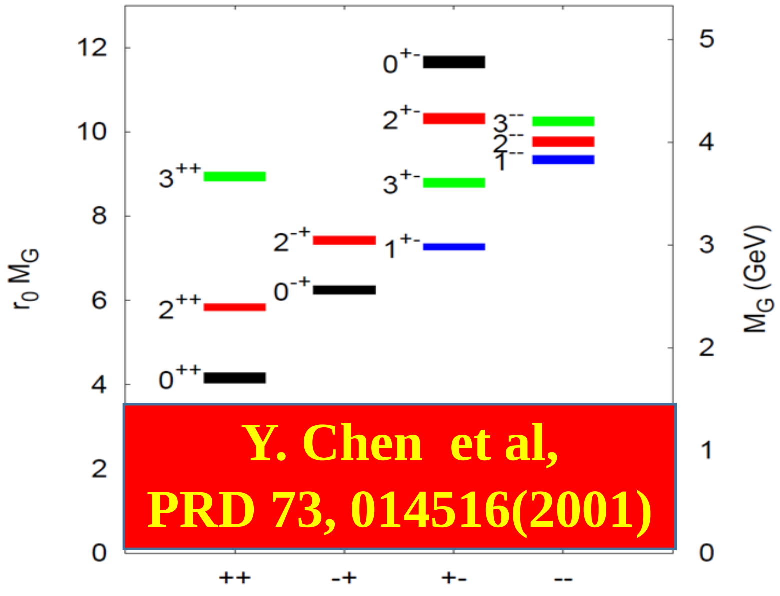
$BR(J/\psi \to \gamma G(2^{++})) = 1.1(2) \times 10^{-2}$

Yi-Bo Yang et al.
PRL 111, 091601

Large decay rate is predicted

Need more experimental information!

Pseudoscalar (0^{-+})--η(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

➢η(1405) and η(1475) observed in different decay modes

- ✓$\pi^- p$: 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^{-+})--η(1405)/η(1475)

The Structure of η(1440)

- **Experiment**
  - ✓η(1440) split to η(1405) and η(1475) (from PDG04)
  - ✓η(1405)→ηππ , or through a_0(980)π (or direct) to KKπ
  - ✓η(1475)→K*(892)K
- **Quark-model**
  - η(1295): the first radial excitation of the η'
  - η(1475): the first radial excitation of the η
  - **η(1405) ?**
- **Phys. Rev. D87, 014023(2013)**
  - η(1405) and η(1475) are the same state with a mass shift in different modes

Pseudoscalar (0^{-+})--η(1405)/η(1475)

✓ η(1405)→γρ   η(1475)→γϕ

Table 2
Comparison with other experiments

Decay mode	Mass (MeV/c^2)	Width (MeV/c^2)	$B(J/\psi \to \gamma X)B(X \to \gamma V)$ ($\times 10^{-4}$)	Experiment
$f_1(1285) \to \gamma\rho^0$	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
$\eta(1440) \to \gamma\rho^0$	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
$\eta(1440) \to \gamma\phi$			< 0.82 (95% C.L.)	BESII

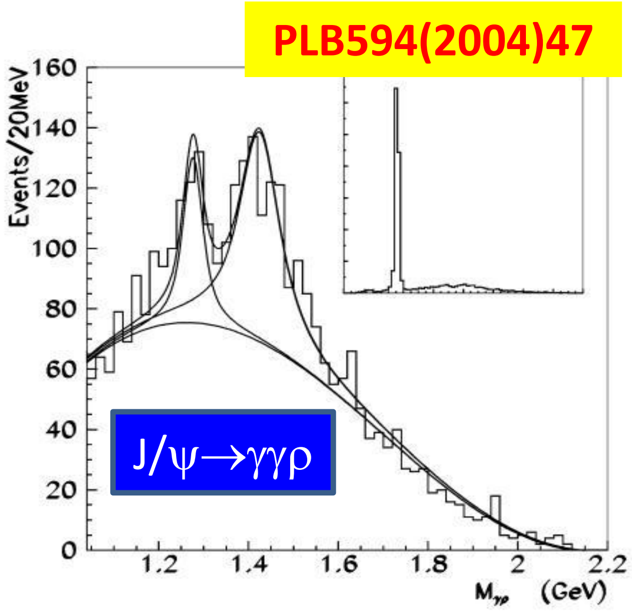
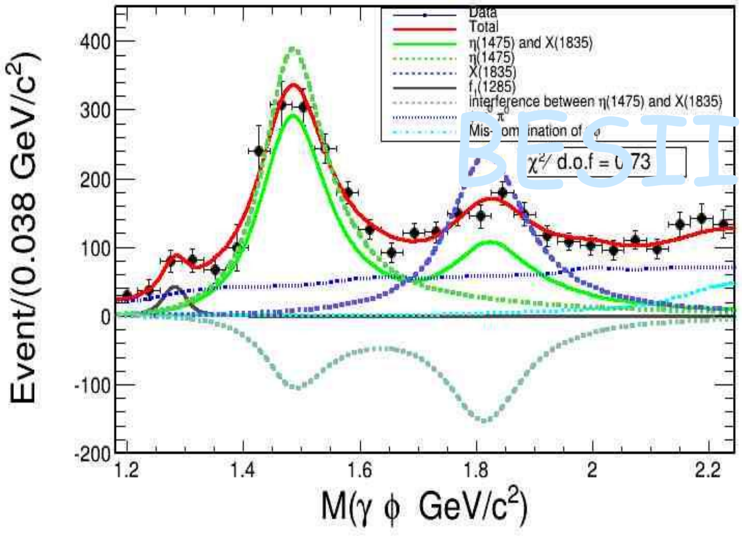
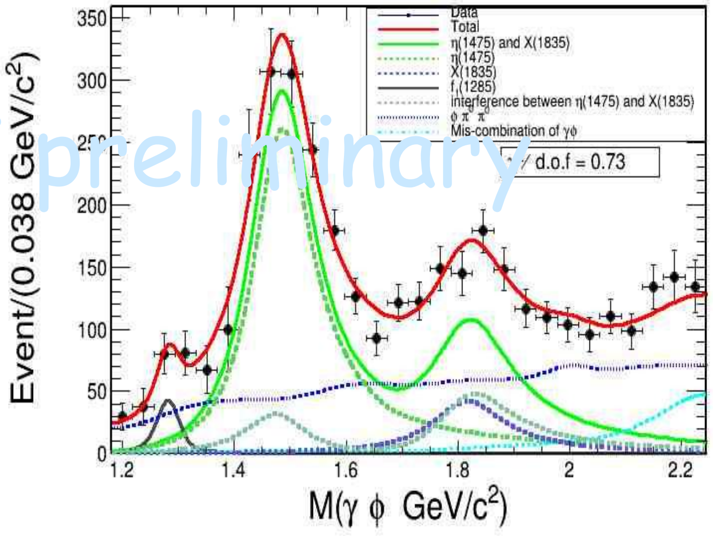


Fig. 2. The $\gamma\rho$ invariant mass distribution. The insert shows the full mass scale where the $\eta(958)$ is clearly observed.

Pseudoscalar (0^{-+})--η(1405)/η(1475)

✓η(1475)→γϕ





	Resonance	Mass (MeV/c²)	Γ (MeV/c²)	B.F.(×10⁻⁶)
Destructive interference	$f_1(1285)$	PDG	PDG	0.30±0.12±0.17
	η(1405/1475)	1479±11±21	133±35±20	11.8±2.2±1.9
	X(1835)	1812±59±42	161±47±24	9.0±2.6±2.2
Constructive interference	$f_1(1285)$	PDG	PDG	0.29±0.12±0.17
	η(1405/1475)	1479±11±16	132±36±31	7.9±1.3±1.9
	X(1835)	1813±61±45	160±81±43	1.6±0.5±0.3

Result (BESIII preliminary)

Assuming η(1405) and η(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 γϕ favors η(1475).
  One state assumption: the ratio between γρ and γϕ final states is a little bit larger than the prediction in Ref[1].
  Two states assumption: η(1475) probably the first radial excitation of the η

The partial width relationship of γρ and γϕ final states		
	Constructive	Destructive
$\Gamma(f_1(1285) \rightarrow \gamma\rho)[3] : \Gamma(f_1(1285) \rightarrow \gamma\phi)$	(128.8 ±96.7):1	(129.3 ±99.8):1
$\Gamma(\eta(1405/1475) \rightarrow \gamma\rho)[4] : \Gamma(\eta(1405/1475) \rightarrow \gamma\phi)$	(6.6 ± 2.1) : 1	(9.9 ± 2.8) : 1

BESIII preliminary

[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/ψ→(ω,ϕ)$K\bar{K}$π, η$K_s$$K^{\pm}$$\pi^{\mp}$

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

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

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

BESIII: J/ψ→ωηππ

TABLE I. Summary of measurements of the mass, width, and the product branching fraction of $\mathcal{B}(J/\psi \to \omega X) \times \mathcal{B}(X \to a_0^{\pm}(980)\pi^{\mp}) \times \mathcal{B}(a_0^{\pm}(980) \to \eta\pi^{\pm})$ 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)	$\mathcal{B}(10^{-4})$
$f_1(1285)$	$1285.1 \pm 1.0^{+1.6}_{-0.3}$	$22.0 \pm 3.1^{+2.0}_{-1.5}$	$1.25 \pm 0.10^{+0.19}_{-0.20}$
$\eta(1405)$	$1399.8 \pm 2.2^{+2.8}_{-0.1}$	$52.8 \pm 7.6^{+0.1}_{-7.6}$	$1.89 \pm 0.21^{+0.21}_{-0.23}$
$X(1870)$	$1877.3 \pm 6.3^{+3.4}_{-7.4}$	$57 \pm 12^{+19}_{-4}$	$1.50 \pm 0.26^{+0.72}_{-0.36}$

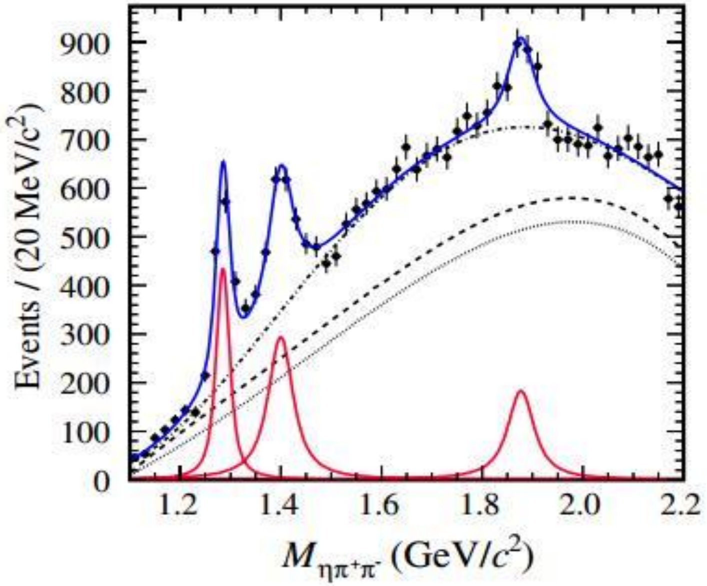


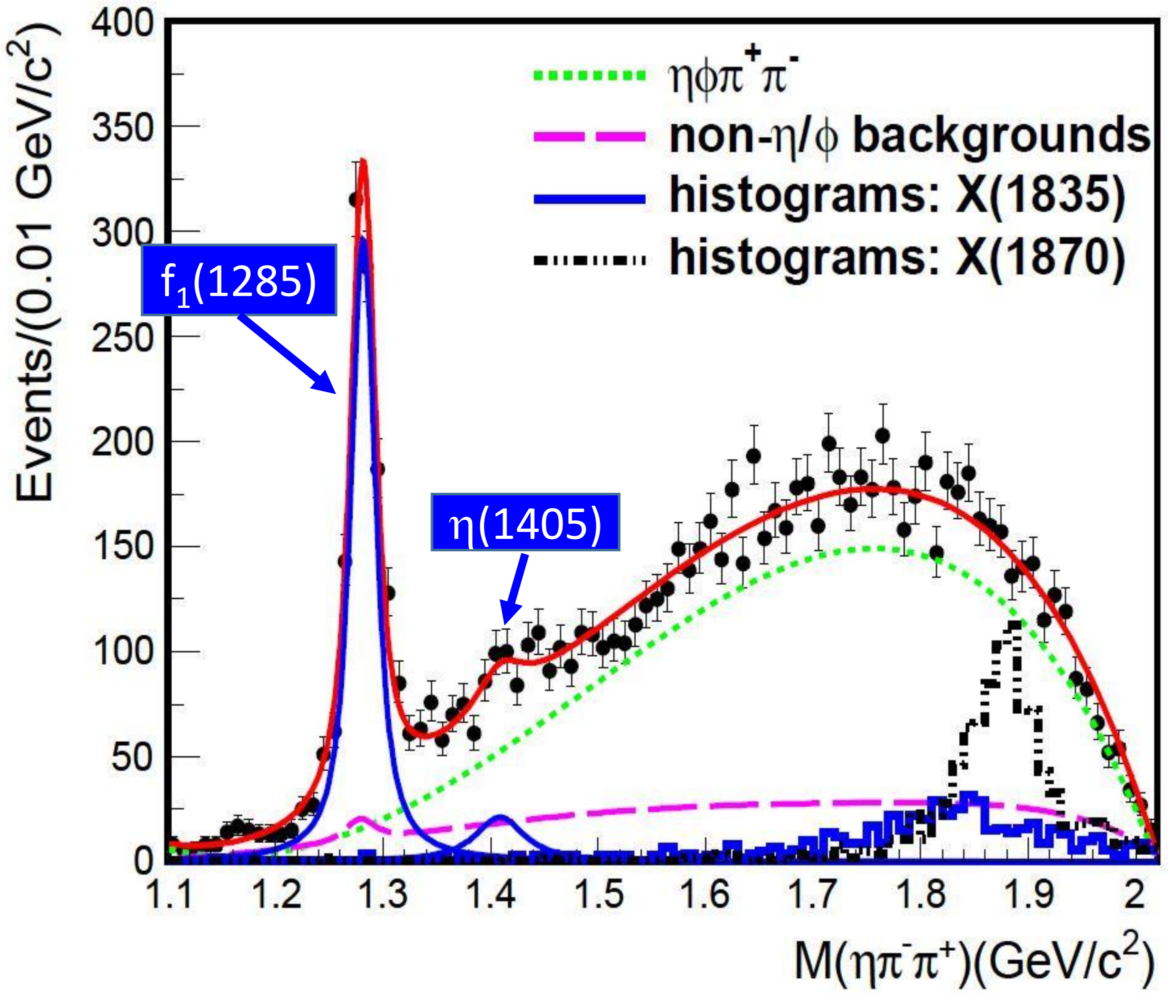
FIG. 4 (color online). Results of the fit to the $M(\eta\pi^+\pi^-)$ mass distribution for events with either the $\eta\pi^+$ or $\eta\pi^-$ in the $a_0(980)$ mass window. The dotted curve shows the contribution of non-ω and/or non-$a_0(980)$ background, the dashed line also includes the contribution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

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

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

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

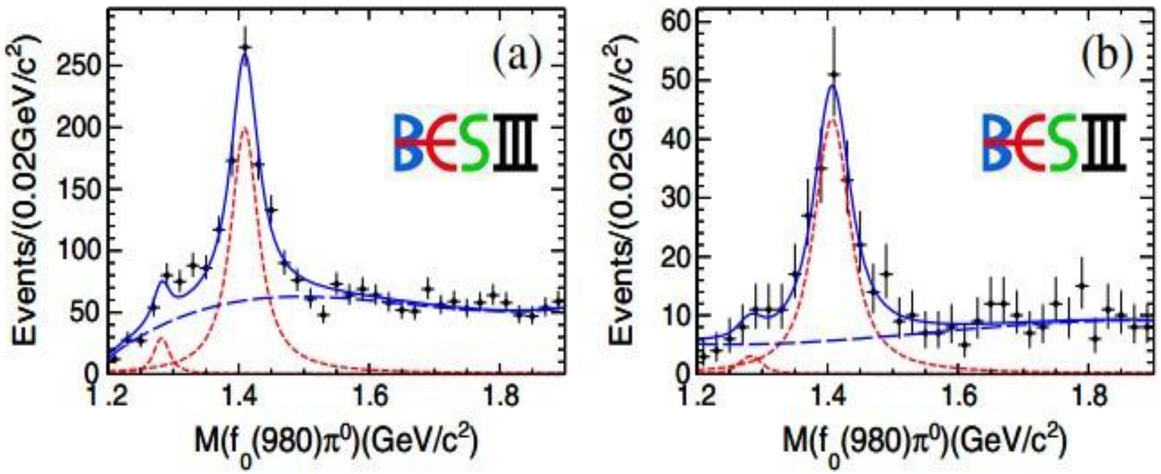
M. Ablikim et al,
Phys. Rev. D91, 052017(2011)

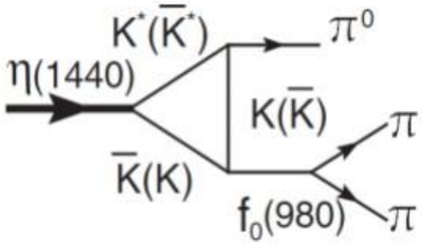


η(1405) in J/ψ→γ3π

PRL 108, 182001 (2012)

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





Triangle Singularity (TS)

one η(1440) is enough to describe the experimental data !

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

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

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	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 η(1440) at BES2/BESIII

BES2 BESIII

	$\eta\pi\pi$	$K\bar{K}\pi$	3π	γV
γ	η(1405) $(2.6\pm0.7)\cdot10^{-4}$	η(1440)	η(1405) 3π $(1.50\pm0.11\pm0.11)\cdot10^{-5}$ $3\pi^0$ $(7.10\pm0.82\pm0.72)\cdot10^{-6}$	$\eta(1405)\to\gamma\rho$ $(1.07\pm0.17\pm0.11)\cdot10^{-4}$ $\eta(1475)\to\gamma\phi$ $(7.9\pm1.3\pm1.9/$ $11.8\pm2.2\pm1.9)\cdot10^{-6}$
ω	η(1405) $(1.89\pm0.21\pm^{0.21}_{0.23})\cdot10^{-4}$	η(1440) $K_SK\pi$: $(4.86\pm0.69\pm0.81)\cdot10^{-4}$ $K^+K^-\pi^0$: $(1.92\pm0.57\pm0.38)\cdot10^{-4}$		
ϕ	η(1405) $(2.01\pm0.58\pm0.82)\cdot10^{-5}$ $(<4.45\cdot10^{-5}$ @90%CL)	η(1440) $K_SK\pi$ $<1.93\cdot10^{-5}$ @90%CL $K^+K^-\pi^0$ $<1.71\cdot10^{-5}$ @90%CL		
ρ				

Status of X(18??) at BESIII

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

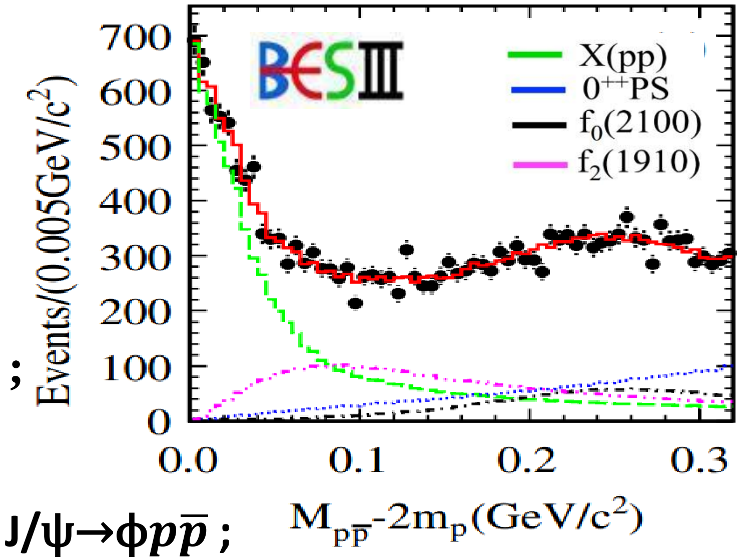
X(18??) near proton-antiproton threshold :

- **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/ψ→γ$p\bar{p}$

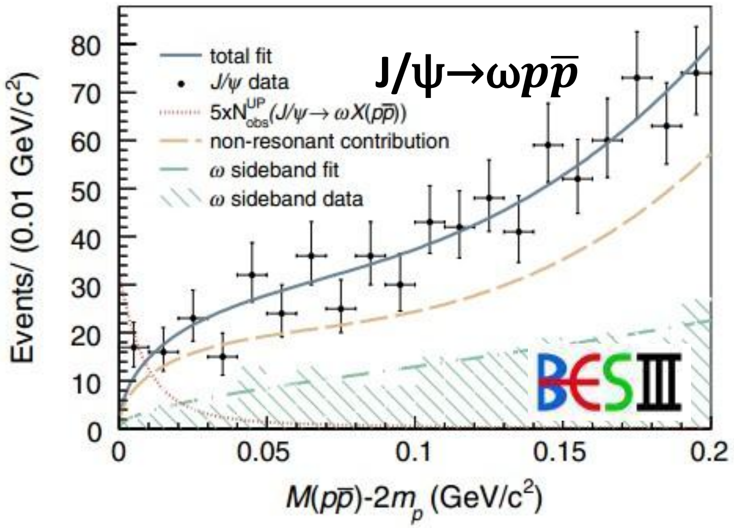
- **Strong enhancement first observed at BESII [PRL 91,022001(2003)] and confirmed by CLEO-c [PRD82,092002(2012)] ;**
- **PWA was firstly performed at BESIII;**
- **Significance of the X($p\bar{p}$) component > 30σ, >5σ for the other components ;**
- **The 0^{-+} assignment is better that other J^{PC} ;**
- **M=1832$\pm^{19}_{5}$(stat)$\pm^{18}_{17}$(syst)±19(mode)MeV/c² ;**
- **Γ<76MeV/c² (90% C.L.);**

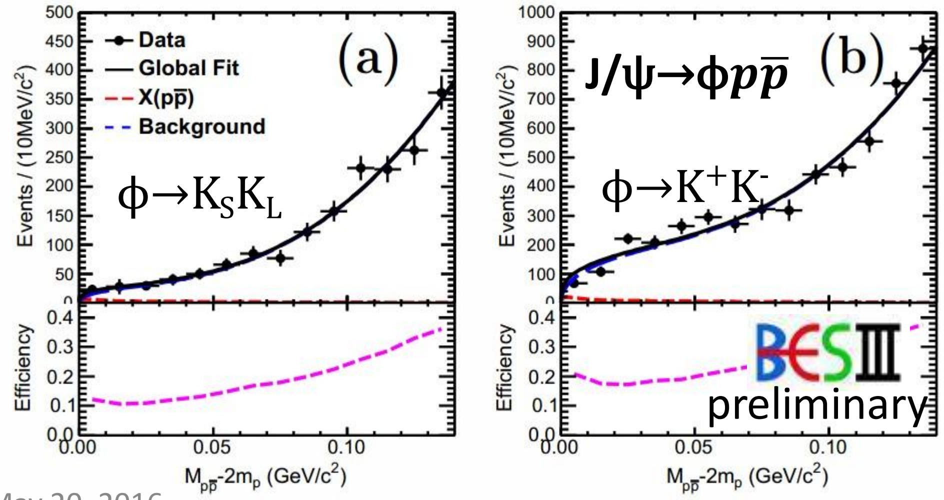
PRL 108,112003(2012)



No similar structure was observed in J/ψ→ω$p\bar{p}$ or J/ψ→ϕ$p\bar{p}$;

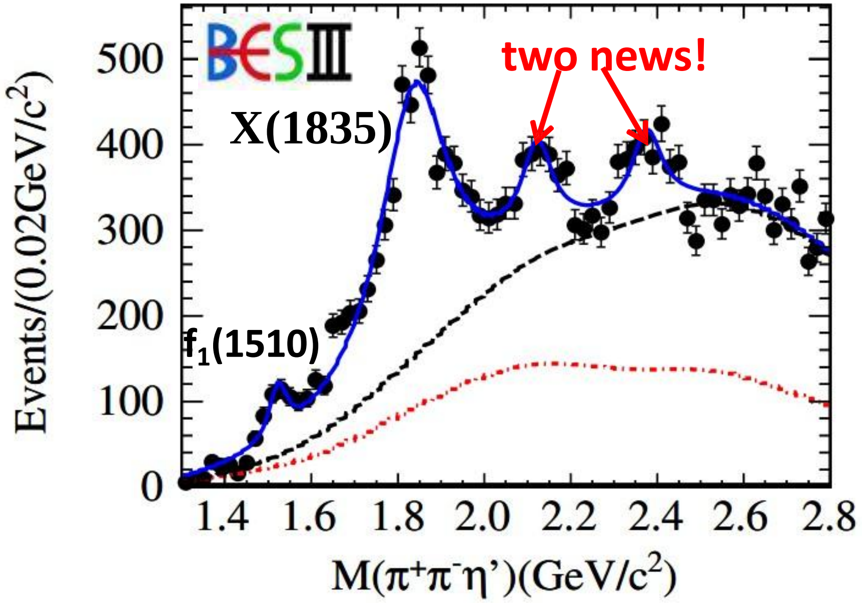
PRD 87, 112004(2013) arXiv:1512.08197





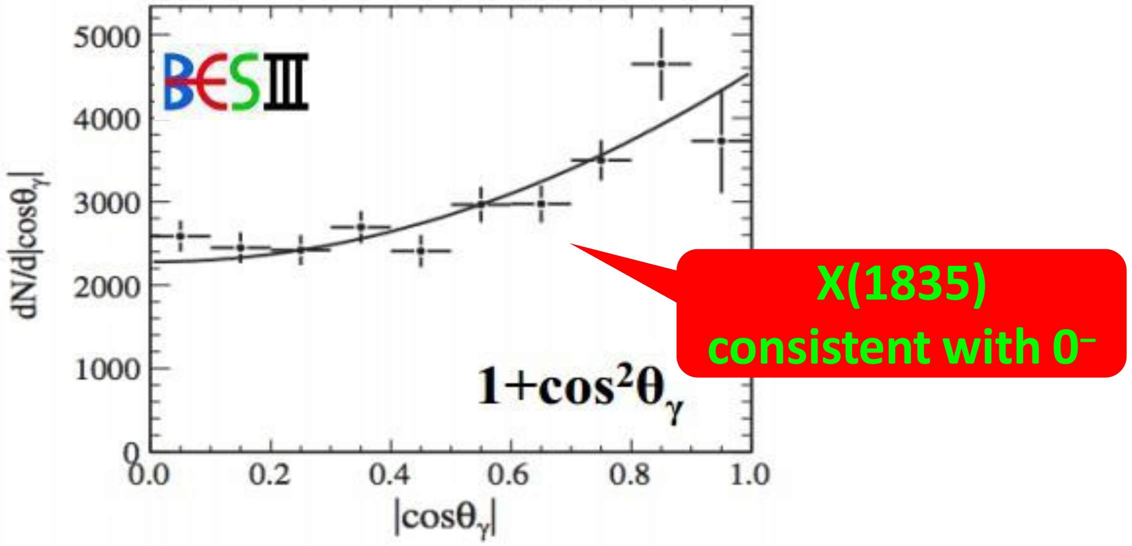
Confirm X(1835) in $J/\psi \to \gamma \pi^+ \pi^- \eta'$

PRL 106, 072002 (2011)



Resonance	M(MeV/c^2)	Γ(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**

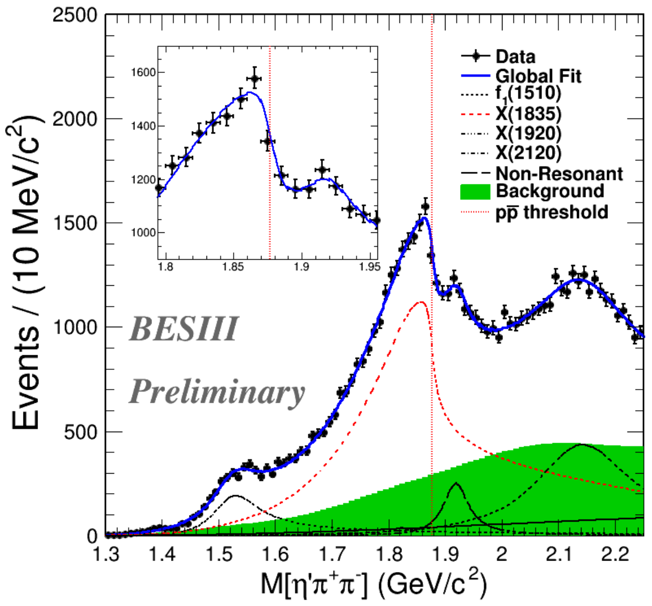


Fit to Mass spectra of $\eta'\pi^+\pi^-$: MODEL I

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

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



$\log\mathcal{L}$ = 630549.5

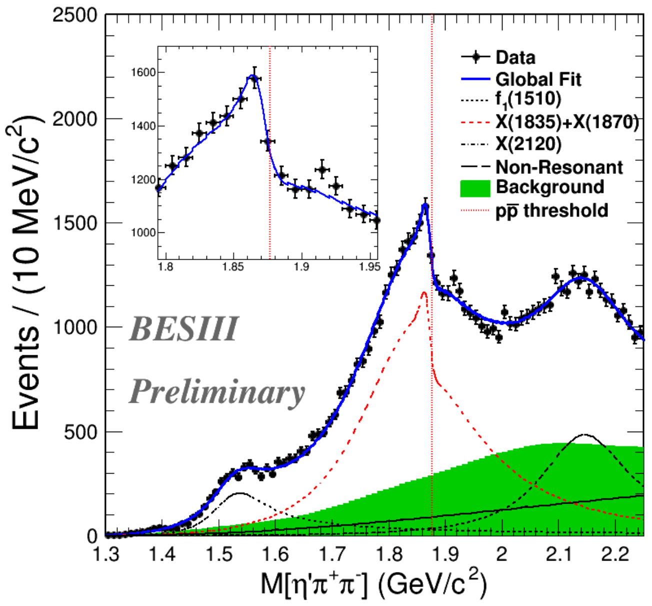
Significance of $g_{p\bar{p}}^2/g_0^2$ being non-zero is larger than 7σ

X(1920) is needed with 5.7σ

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



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

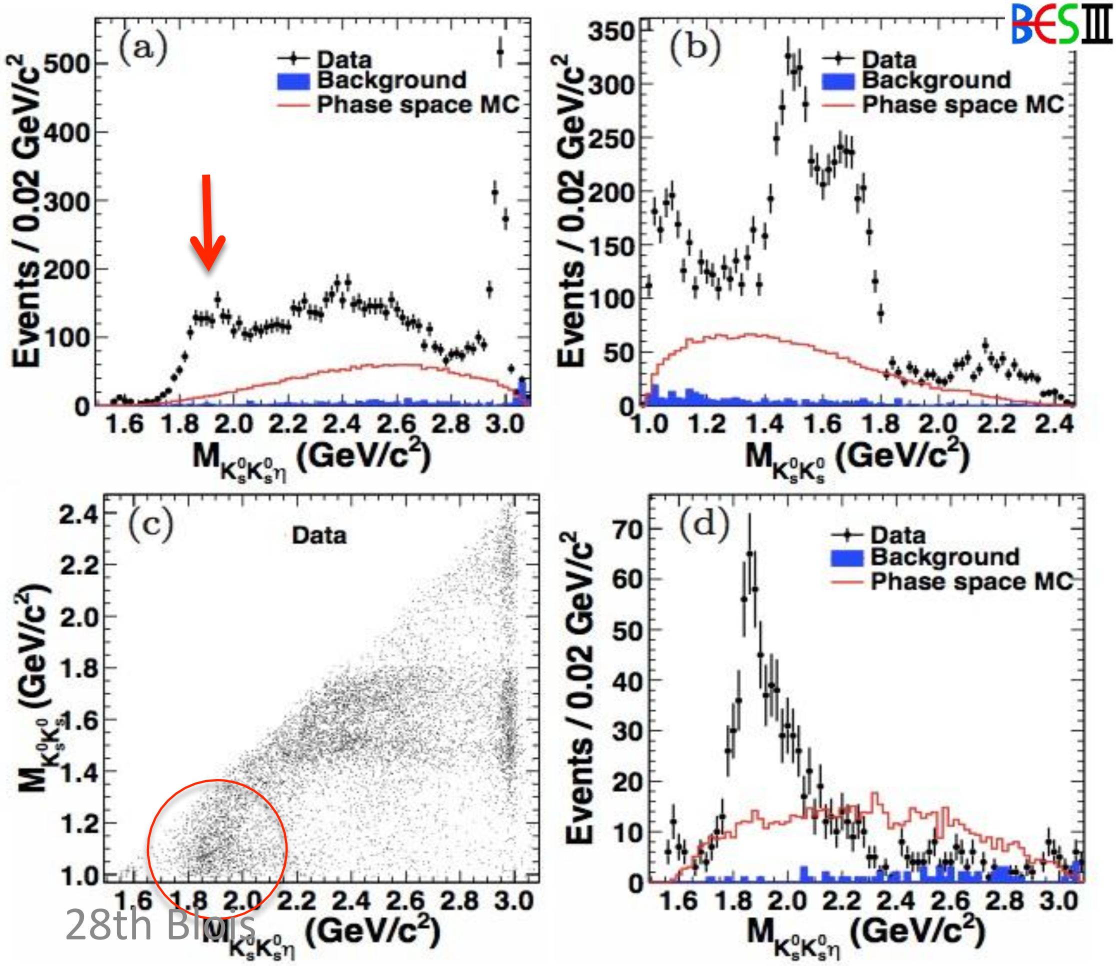
- A significant distortion of the $\eta'\pi^+\pi^-$ line shape near the $p\bar{p}$ mass threshold is observed in $J/\psi\to\gamma\eta'\pi^+\pi^-$
  - ➢ Simple Breit-Wigner function fails in describing the line shape near the $p\bar{p}$ mass threshold
- Two models have been used
  - ➢ MODEL I: threshold structure due to the opening of the $p\bar{p}$ decay mode
    - Using the Flatté formula
    - **Strong $X(1835)\to p\bar{p}$ coupling, with significance larger than 7σ**
    - $\mathbf{M_{pole} = 1909.5\,^{+15.9}_{-15.9}\,^{+9.4}_{-27.5}\ MeV/c^2}$
    - $\mathbf{\Gamma_{pole} = 273.5\,^{+21.4}_{-21.4}\,^{+6.1}_{-64.0}\ MeV/c^2}$
  - ➢ 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**
    - $\mathbf{M = 1870.2\,^{+2.2}_{-2.3}\,^{+2.3}_{-0.7}\ MeV/c^2}$
    - $\mathbf{\Gamma = 13.0\,^{+7.1}_{-5.5}\,^{+2.1}_{-3.8}\ MeV/c^2}$
- 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 $J/\psi \to K_S^0 K_S^0 \eta$ provides a clear environment

BESIII: PRL**115**,091803

- $K^0_S K^0_S \eta$ and $\pi^0 K^0_S K^0_S \eta$ bkgs are forbidden by exchange symmetry and CP conservation

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



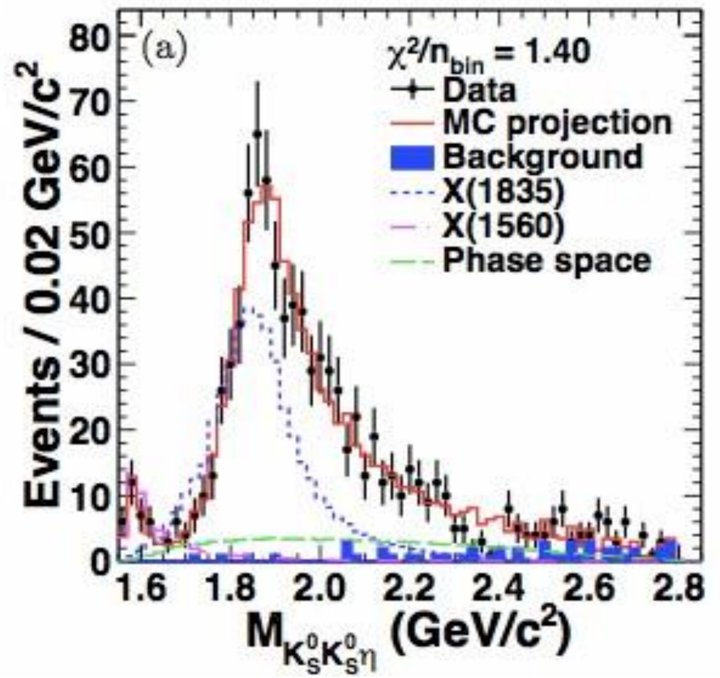
PWA of events with $M(K^0_S K^0_S)<1.1$ GeV/c^2 and $M(K^0_S K^0_S \eta)<2.8$ GeV/c^2

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

BESIII: PRL**115**,091803

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

- ✓ Mass/Width consistent with the X(1835) in $J/\psi \to \gamma\eta'\pi\pi$
- ✓ Mass/spin consistent with those of the X($p\bar{p}$)
- ✓ Width is larger than the width of the X($p\bar{p}$)

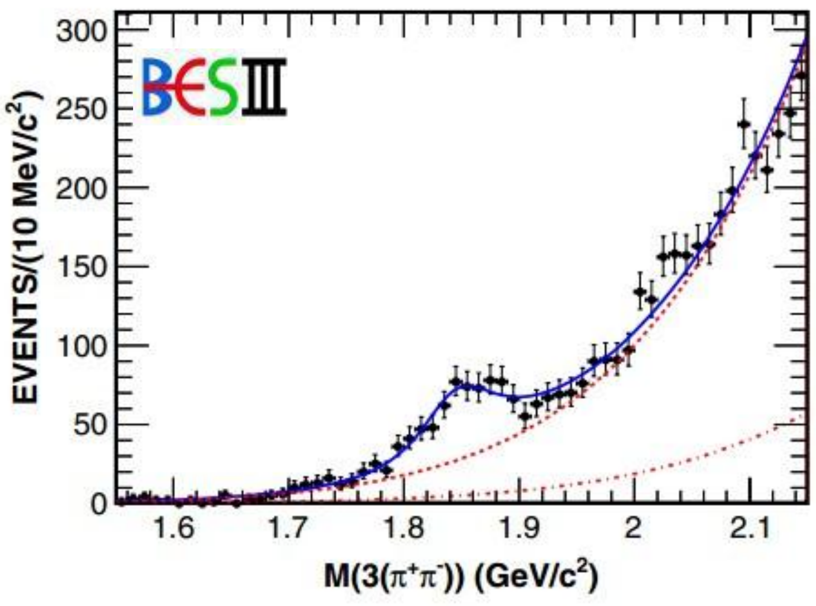


M = 1844 ± 9 (stat)$\pm^{16}_{25}$ (syst) MeV/c² **Γ = 192$\pm^{20}_{17}$(stat)$\pm^{62}_{43}$(syst) MeV (>12.9σ)**

BR = $(3.3\pm^{0.32}_{0.30}(stat)\pm^{1.96}_{1.29}$ (syst)) × 10^{-5}

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

PRD 88, 091502 (2013)



- **A structure at 1.84GeV/c^2 is observed in the mass spectrum $3(\pi^+\pi^-)$ with a significance of 7.6σ;**
- **$M=1842.2\pm4.2^{+7.1}_{-2.6}$ MeV/c^2 ;** **$\Gamma=83\pm14\pm11$ MeV/c^2 ;**

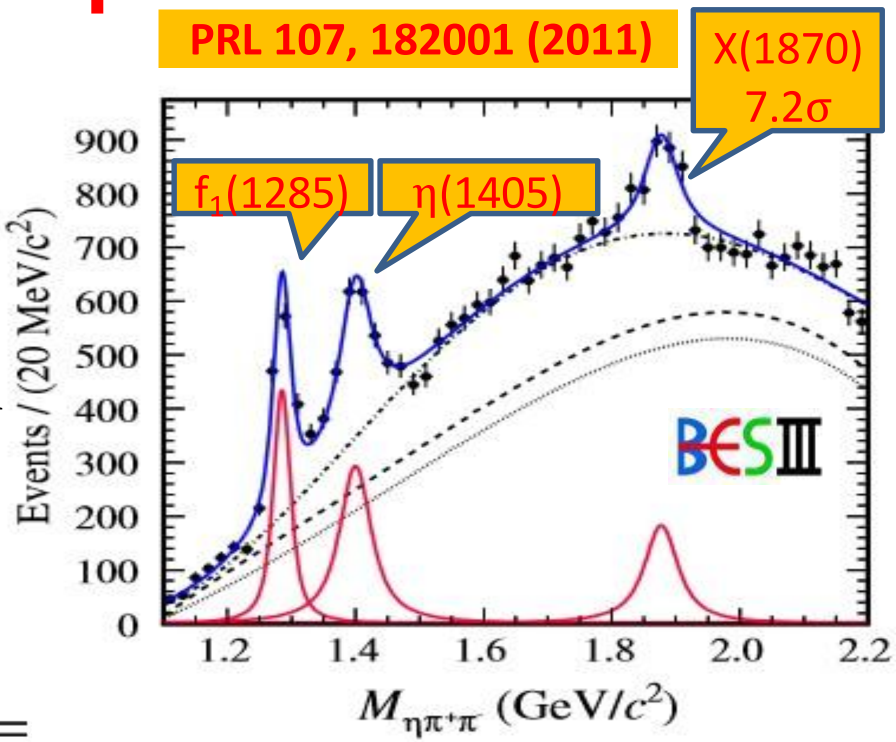
$$B(J/\psi \to \gamma X(1840)) \times B(X(1840) \to 3(\pi^+\pi^-)) = (2.44 \pm 0.36^{+0.60}_{-0.74}) \times 10^{-5}$$

- ✓ **The mass is consistent with that of X(1835), but the width is significantly different from either of them, and much smaller than $\Gamma_{X(1835)}=190.1\pm9.0^{+38}_{-36}$ MeV/c^2 ;**
- ✓ **We cannot determine whether X(1840) is a new state a new decay modes of existing X(1835)?**

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

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

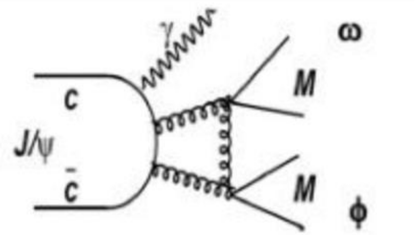
PRL 107, 182001 (2011)



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

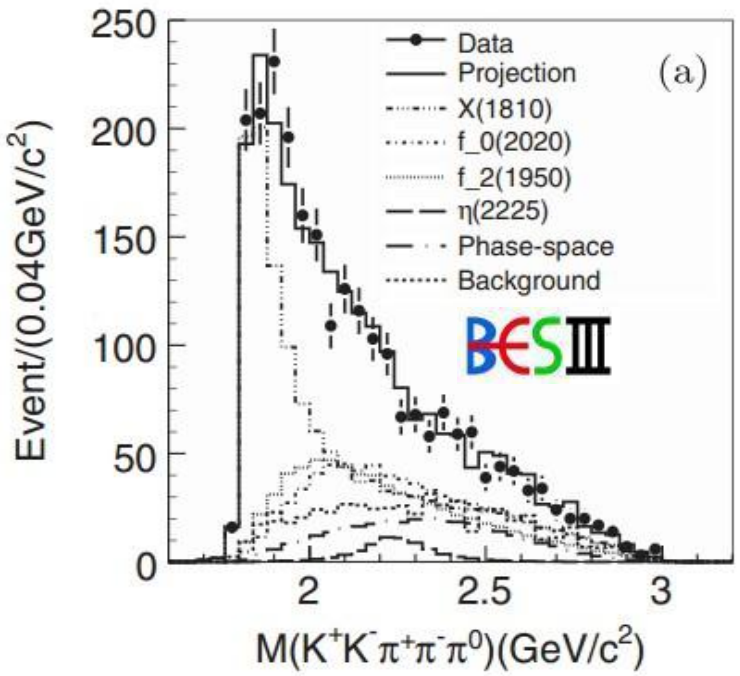
Whether the resonant structure of X(1870) is due to the X(1835) , the $\eta_2(1870)$, an interference of both, or a new resonance still needs further study!

X(1810) in PWA of J/ψ→γωϕ

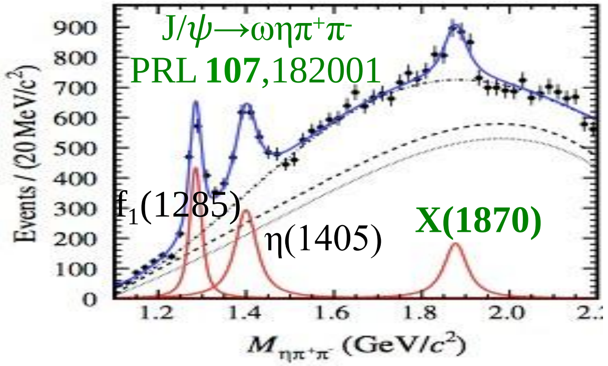


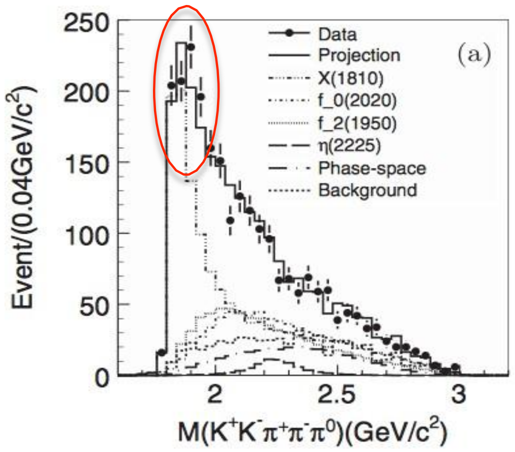
- J/ψ→γωϕ is Double OZI suppressed;
- The X(1810) is first observed by PWA at BESII [PRL 96, 162002 (2006)] ;
- Observed and confirmed at BESIII with the significance >30σ,;
- the J^{PC} of the X(1810) is 0^{++} ;
- The enhancement is not compatible with either the X(1835) or the X(p*p*) due to the different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

PRD 87, 032008(2013)



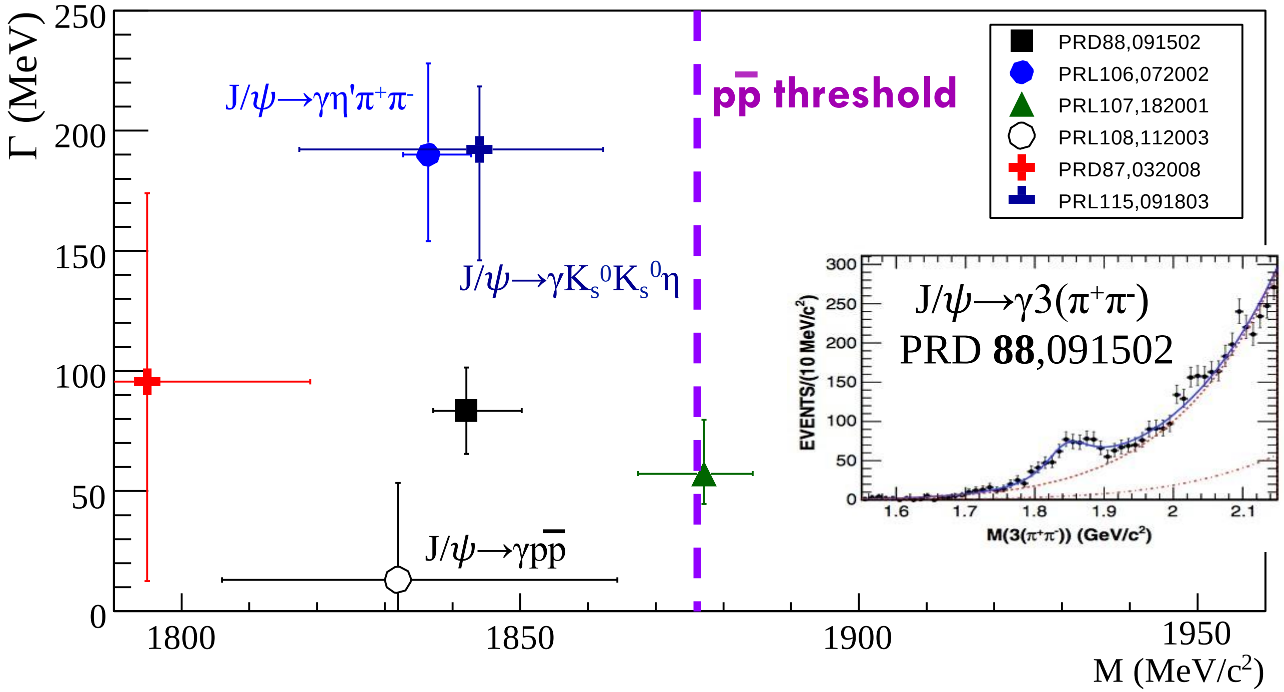
Resonance	J^{PC}	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	Events	ΔS	Δndf	Significance
$X(1810)$	0^{++}	1795 ± 7	95 ± 10	1319 ± 52	783	4	$>30\sigma$
$f_2(1950)$	2^{++}	1944	472	665 ± 40	211	2	20.4σ
$f_0(2020)$	0^{++}	1992	442	715 ± 45	100	2	13.9σ
$\eta(2225)$	0^{-+}	2226	185	70 ± 30	23	2	6.4σ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





J/ψ→γωϕ PRD **87**,032008

>30σ



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!