Recent Results on Light Hadron Physics at BESIII

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(On behalf of the BESIII Collaboration)

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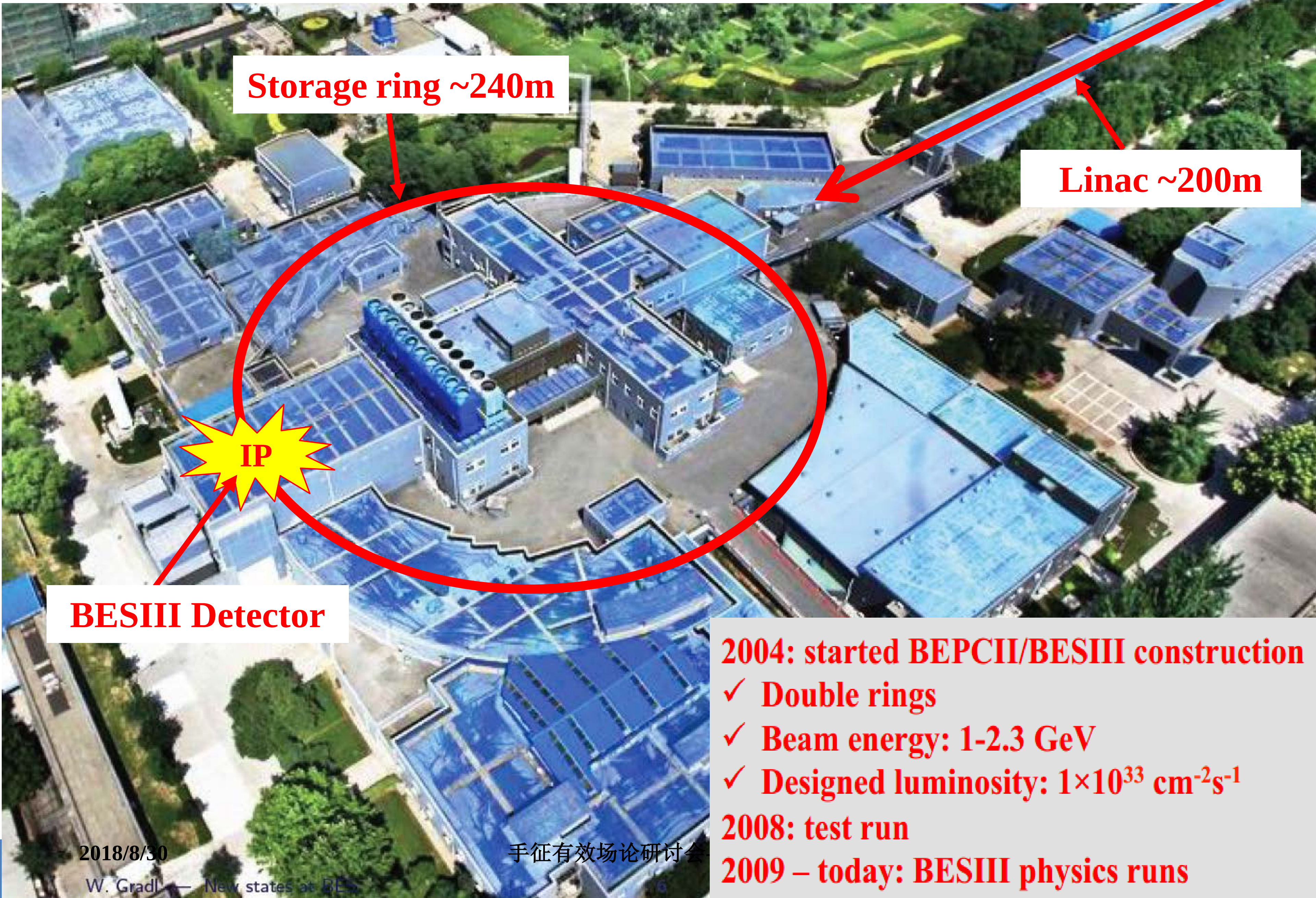
OUTLINE

- **Introduction**
- η' **meson decays**
  - **Hadonic decays:** $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$, $\eta' \to \pi^{+(0)}\pi^{-(0)}\eta$
  - **Radiative decays:** $\eta' \to \gamma\pi^+\pi^-$, $\eta' \to \gamma\gamma\pi^0$
- $a_0^0(980)$**-**$f_0(980)$ **mixing**
  - $a_0^0(980) \to f_0(980)$: $J/\psi\to\phi a_0(980)\to\phi\eta\pi^0$
  - $f_0(980) \to a_0^0(980)$: $\chi_{c1}\to\pi^0 f_0(980) \to\pi^0\pi^+\pi^-$
- **η(1440)/η(1405)/η(1475)**
- **X(18**)**
- **Summary**

Beijing Electron Positron Collider II (BEPC II)



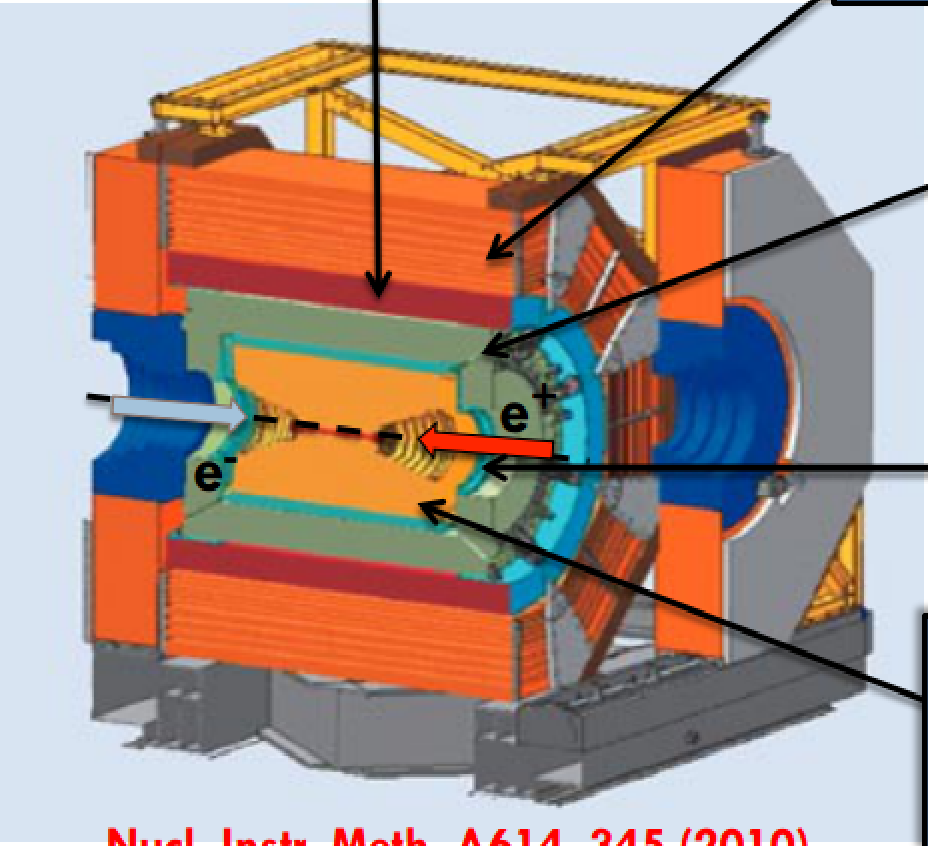
2004: started BEPCII/BESIII construction

- ✓ Double rings
- ✓ Beam energy: 1-2.3 GeV
- ✓ Designed luminosity: $1\times10^{33}\ cm^{-2}s^{-1}$

2008: test run

2009 – today: BESIII physics runs

BESIII Detector



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

Superconducting solenoid (1T)

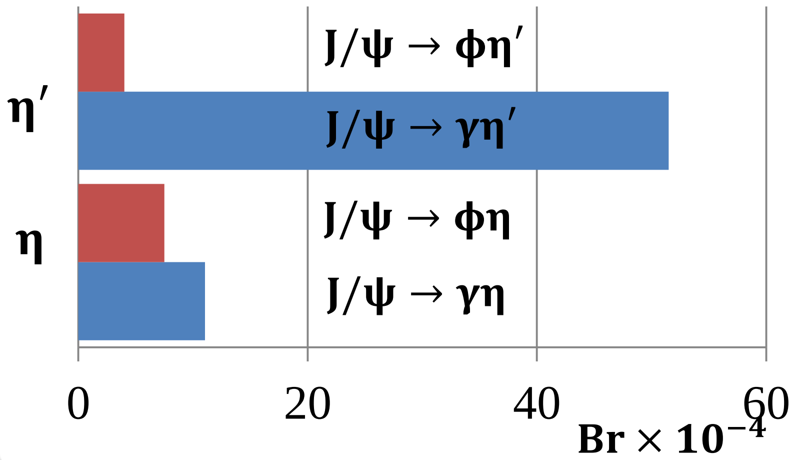
RPC Muon Detector
8 layers (end caps) + 9 layers (barrel)
$\Delta\Omega/4\pi$=93%

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

Time of Flight
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

η, η' from J/ψ decays



- **High production rate of light mesons in J/ψ decays**
- **η/η' from J/ψ radiative decays**
  - $\rightarrow 7.2 \times 10^6\ \eta'$
  - $\rightarrow 2.4 \times 10^6\ \eta$
- **η/η' from J/ψ hadronic decays (e.g. J/ψ→φη)**
  - $\rightarrow 3\times 10^5\ \eta'$
  - $\rightarrow 5\times 10^5\ \eta$

η, η':a rich physics field

- test the predictions of ChPT
- probe physics beyond the SM
- study transition form factors
- test fundamental symmetries

η decay mode	physics highlight	η' mode	physics highlight
$\eta \to \pi^0 2\gamma$	ChPT	$\eta' \to \pi\pi$	CPV
$\eta \to \gamma B$	leptophobic dark boson	$\eta' \to 2\gamma$	chiral anomaly
$\eta \to 3\pi 0$	$m_u - m_d$	$\eta' \to \gamma\pi\pi$	box anomaly, form factor
$\eta \to \pi^+\pi^-\pi^0$	$m_u - m_d$, CV	$\eta' \to \pi^+\pi^-\pi^0$	$m_u - m_d$, CV
$\eta \to 3\gamma$	CPV	$\eta' \to \mu^+\mu^-\pi^0, e^+e^-\pi^0$	CV

Recent results on η/η′ decays at BESIII

- **Hadronic decays**
  - $\eta' \to \pi^+\pi^-\pi^0$, $\pi^0\pi^0\pi^0$
  - $\eta' \to \pi^+\pi^-\eta$, $\pi^0\pi^0\eta$
- **Radiative decays**
  - $\eta' \to \gamma\pi^+\pi^-$
  - $\eta' \to \gamma\gamma\pi^0$

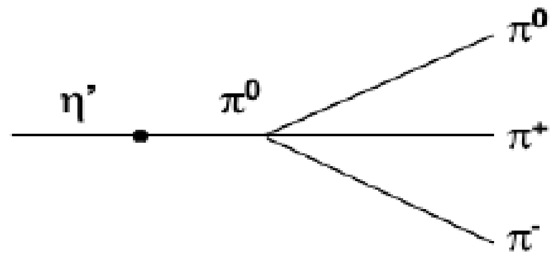
Amplitude Analysis of $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$

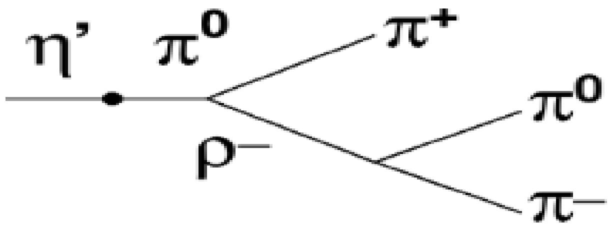
- $\eta' \to \pi\pi\pi$ are isospin-violating processes , dominated by strong interaction [Nucl. Phys. B460, 127(1996)]
- light quark mass difference $(m_d - m_u)/m_s$ can be extracted [PRD 19, 2188(1979)]

$$r_\pm = \frac{B(\eta' \to \pi^+\pi^-\pi^0)}{B(\eta' \to \pi^+\pi^-\eta)}$$

$$r_0 = \frac{B(\eta' \to \pi^0\pi^0\pi^0)}{B(\eta' \to \pi^0\pi^0\eta)}$$

- Using ChPT, large P-wave contribution of $\eta' \to \rho^\pm\pi^\mp$ is predicted [Eur. Phys. J. A 26, 383(2005)]





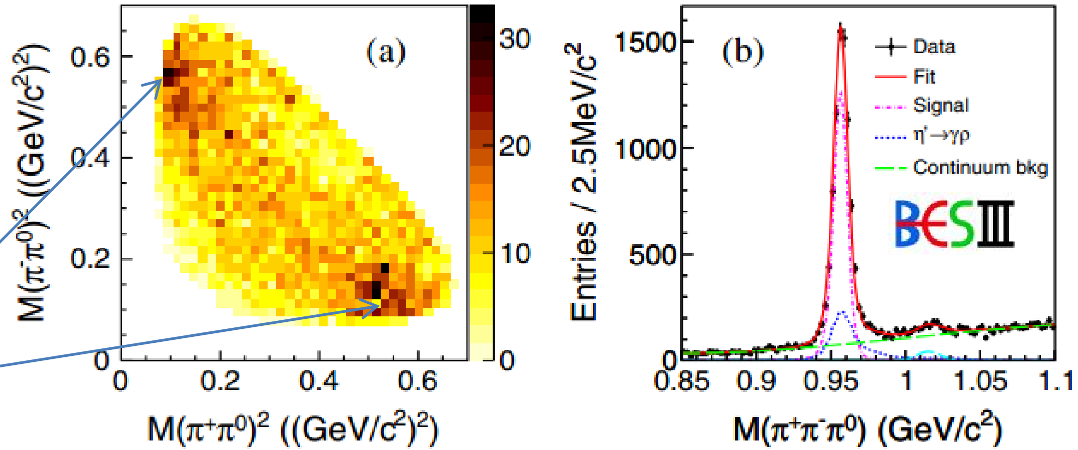
Amplitude Analysis of $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^{0}$

PRL 118, 012001 (2017)

$\eta' \to \pi^+\pi^-\pi^0$

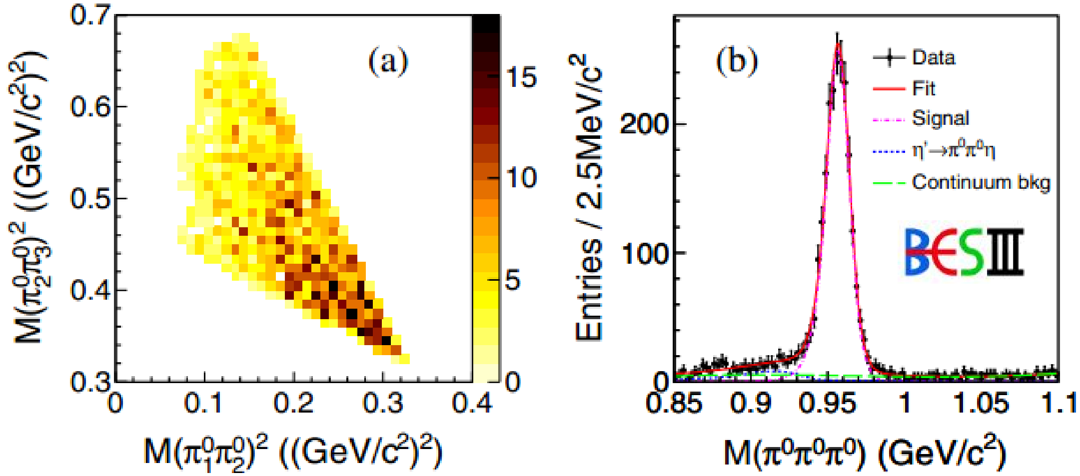
8267 events

$\eta' \to \rho^{\pm}\pi^{\mp}$



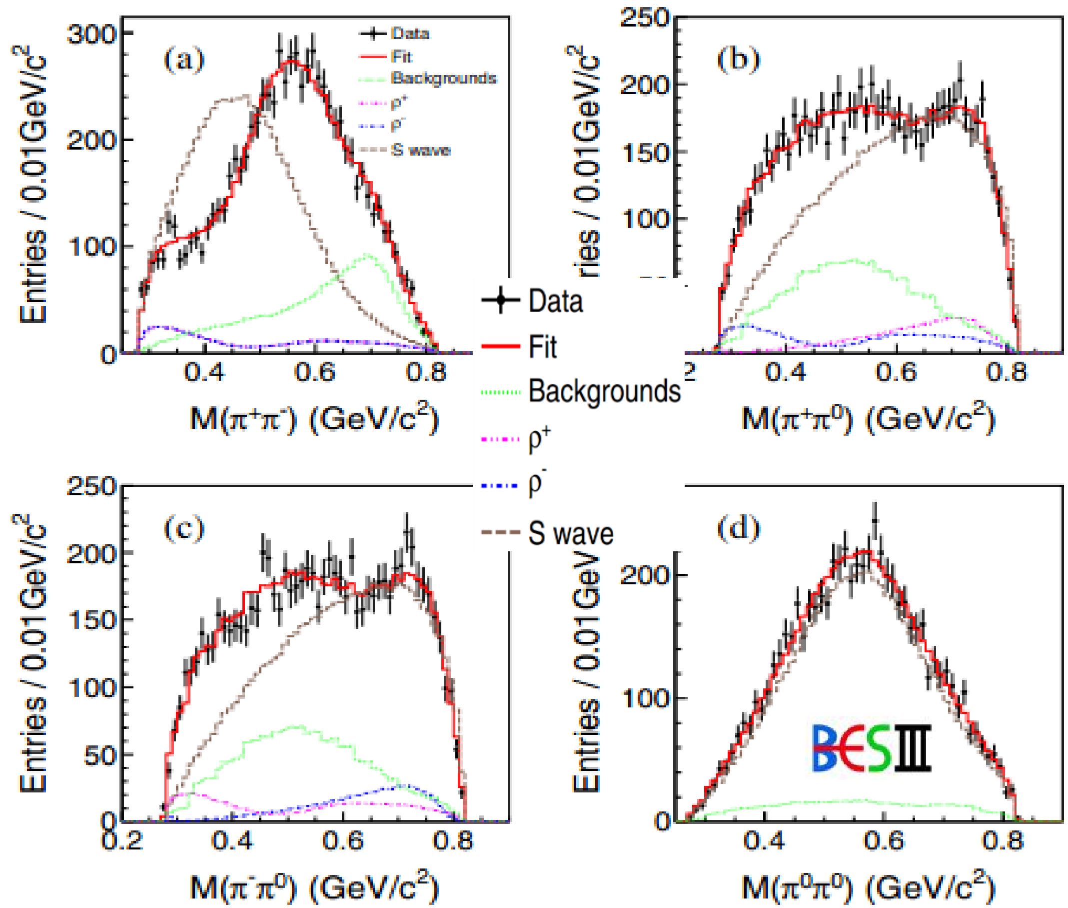
$\eta' \to \pi^0\pi^0\pi^0$

2237 events



Amplitude Analysis of $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$

PRL 118, 012001 (2017)



- Described by **three components**: P wave ($\rho^{\pm}\pi^{\mp}$), resonant S wave ($\sigma\pi^0$), phase-space S wave ($\pi\pi\pi$)
- Each component $> 24\sigma$

$B(\eta' \to \pi^+\pi^-\pi^0)$
$= (35.91 \pm 0.54 \pm 1.74) \times 10^{-4}$
$B(\eta' \to \pi^0\pi^0\pi^0)$
$= (35.22 \pm 0.82 \pm 2.54) \times 10^{-4}$
$B(\eta' \to \rho^{\pm}\pi^{\mp})$
$= (7.44 \pm 0.06 \pm 1.26 \pm 1.84)$
$\times 10^{-4}$
$B(\eta' \to \pi^+\pi^-\pi^0)_S$
$= (37.63 \pm 0.77 \pm 2.22 \pm 4.48)$
$\times 10^{-4}$

- Obtained decay width ratios:

$r_{\pm} = (8.77 \pm 1.19) \times 10^{-3}$
$r_0 = (15.86 \pm 1.33) \times 10^{-3}$

Matrix Elements for $\eta' \to \pi^{+(0)}\pi^{-(0)}\eta$

- Remains a subject of effective ChPT
- explored by CLEO, VES, GAMS Collaboration but with limited statistics
- A cusp due to $\pi^+\pi^-$ mass threshold for the Dalitz plot of $\eta' \to \pi^0\pi^0\eta$

- **For the charged decay mode**

$$X = \frac{\sqrt{3}(T_{\pi^+} - T_{\pi^-})}{Q}, \qquad Y = \frac{m_\eta + 2m_\pi}{m_\pi}\frac{T_\eta}{Q} - 1.$$

T_π and T_η are the kinetic energies of π and η in the η' rest frame, $Q = m_{\eta'} - m_\eta - 2m_\pi$

- **For the neutral decay mode**

$$X = \frac{\sqrt{3}|T_{\pi_1^0} - T_{\pi_2^0}|}{Q}.$$

- **general representation**

$$|M(X,Y)|^2 = N(1 + aY + bY^2 + cX + dX^2 + \cdots),$$

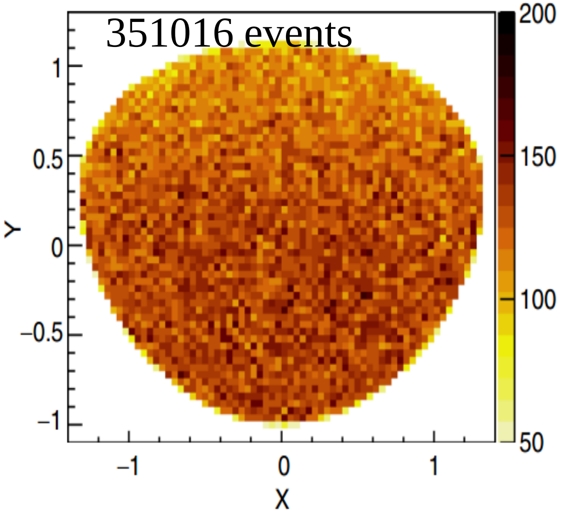
- **linear representation**

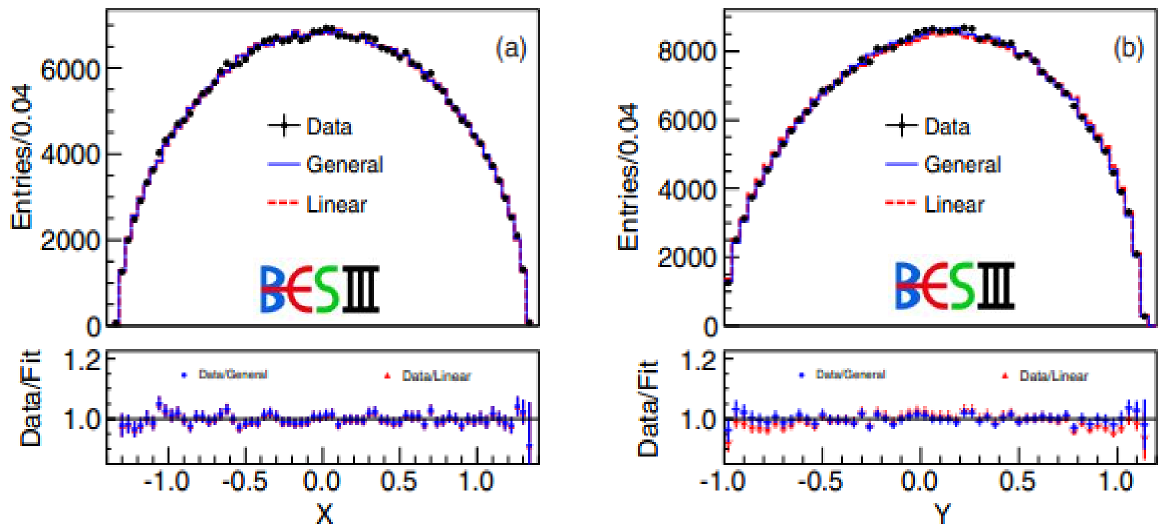
$$|M(X,Y)|^2 = N(|1 + \alpha Y|^2 + cX + dX^2 + \cdots),$$

Here, a, b, c, d are free parameters
α is a complex number, a=2Re(α),
b=Re$(\alpha)^2$ +Im$(\alpha)^2$

Matrix Elements for $\eta' \to \pi^+\pi^-\eta$

PRD 97,012003(2018)





the linear representation is less compatible with the data

Parameter	$\eta' \to \eta\pi^+\pi^-$				
	EFT [5]	Large N_C [7]	RChT [7]	VES [10]	This work
a	−0.116(11)	−0.098(48)	(fixed)	−0.127(18)	−0.056(4)(2)
b	−0.042(34)	−0.050(1)	−0.033(1)	−0.106(32)	−0.049(6)(6)
c	···	···	···	+0.015(18)	0.0027(24)(18)
d	+0.010(19)	−0.092(8)	−0.072(1)	−0.082(19)	−0.063(4)(3)
$\Re(\alpha)$	···	···	···	−0.072(14)	−0.034(2)(2)
$\Im(\alpha)$	···	···	···	0.000(100)	0.000(19)(1)
c	···	···	···	+0.020(19)	0.0027(24)(15)
d	···	···	···	−0.066(34)	−0.053(4)(4)

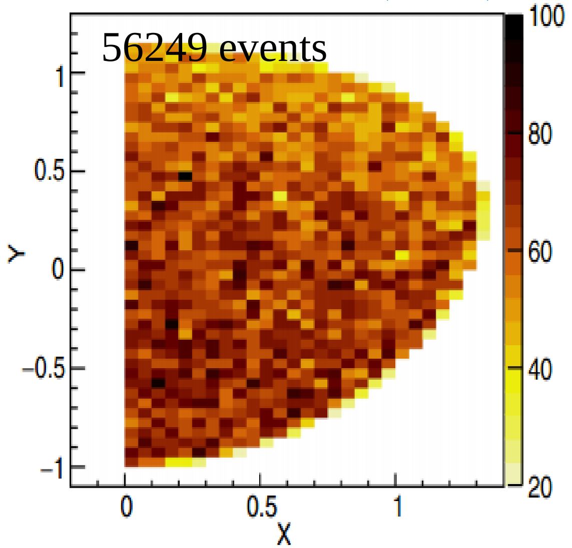
[5]Eur. Phys. J. A 26, 383(2005)

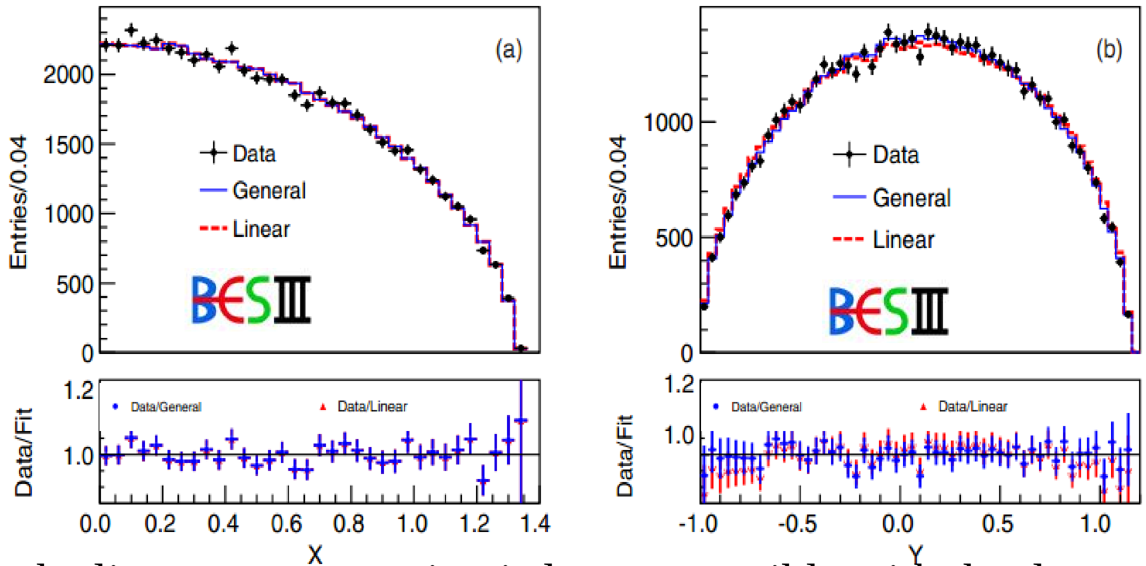
[7] JHEP 05 ,094(2011)

[10] Phys. Lett. B 651, 22 (2007)

Matrix Elements for $\eta' \to \pi^0\pi^0\eta$

PRD 97,012003(2018)





the linear representation is less compatible with the data

		$\eta' \to \eta\pi^0\pi^0$	
Parameter	EFT [5]	GAMS-4π [12]	This work
a	$-0.127(9)$	$-0.067(16)$	$-0.087(9)(6)$
b	$-0.049(36)$	$-0.064(29)$	$-0.073(14)(5)$
c	...	...	...
d	$+0.011(21)$	$-0.067(20)$	$-0.074(9)(4)$
$\Re(\alpha)$		$-0.042(8)$	$-0.054(4)(1)$
$\Im(\alpha)$		$0.000(70)$	$0.000(38)(2)$
c	...	...	...
d	...	$-0.054(19)$	$-0.061(9)(5)$

[5]Eur. Phys. J. A 26, 383(2005)

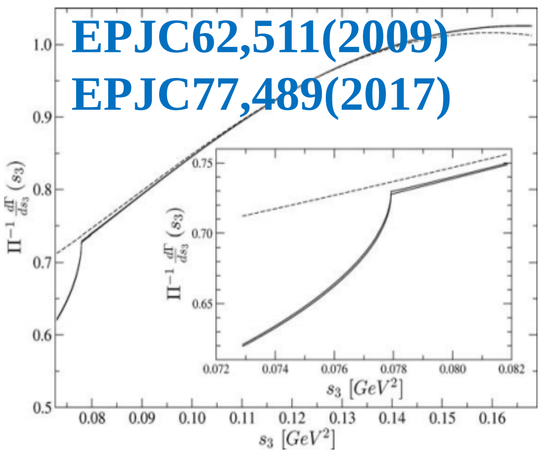
[12] Phys. At. Nucl.72, 231 (2009)

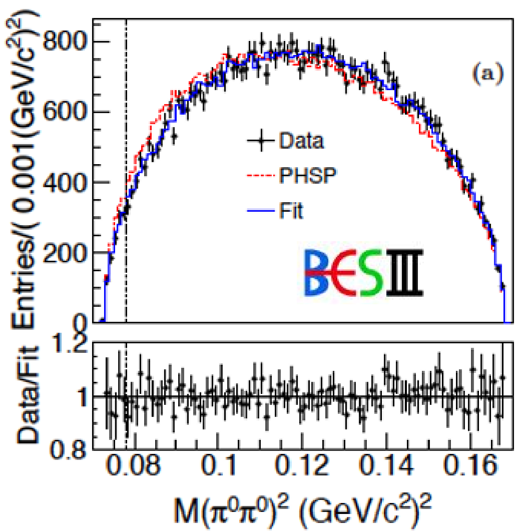
Matrix Elements for $\eta' \to \pi^0\pi^0\eta$

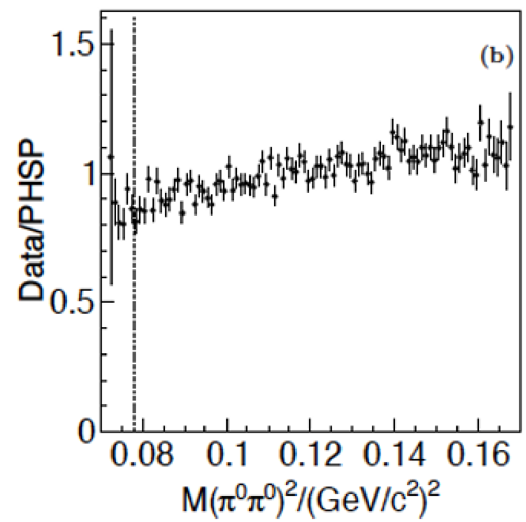
Search for cusp effect

- **FSI: A cusp effect (more than 8%) on $\pi^0\pi^0$ mass spectrum below the $\pi^+\pi^-$ mass threshold [EPJC62, 511 (2009)]**

EPJC62,511(2009)
EPJC77,489(2017)



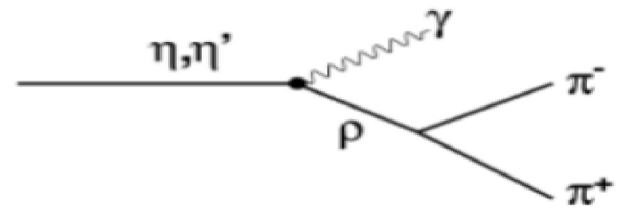


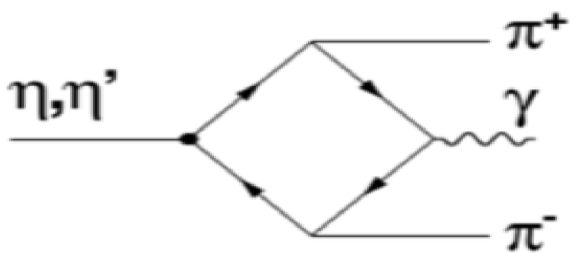


◆No evidence of a cusp effect with current statistics

Study of $\eta' \to \gamma\pi^+\pi^-$ Decay Dynamics

- In VMD model, this process is dominated by $\eta' \to \gamma\rho(770)$
- The discrepancy attributed to the Wess-Zumino-Witten anomaly in the ChPT, known as the box anomaly
  [PLB37, 95 (1971), NPB223, 422 (1983)]
- Recently a model-independent approach based on ChPT are proposed: $A \propto P(s) \cdot F_V(s)$ [PLB 707, 184 (2012)]
- Studied by several experiments , but no consistent picture due to limited statistics
  - ρ mass shift or not ?
  - box anomaly or not ?





The dipion mass dependent differential rate :

$$\frac{d\Gamma}{dM(\pi^+\pi^-)} = \frac{k_\gamma^3 q_\pi^3(s)}{48\pi^3}|A|^2$$

$$k_\gamma^3 = \left(m_{\eta'}^2 - s\right)/2m_{\eta'}$$

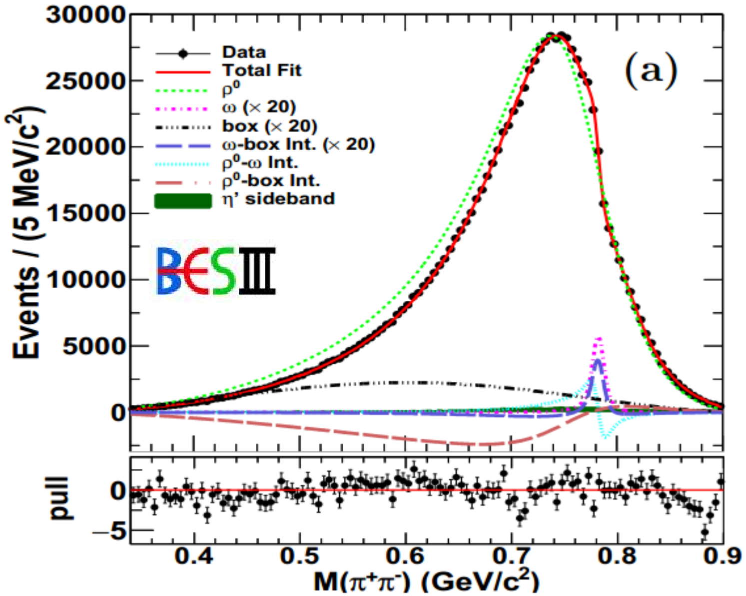
$$q_\pi(s) = \sqrt{s - 4m_\pi^2}/2$$

Study of $\eta' \to \gamma\pi^+\pi^-$ Decay Dynamics

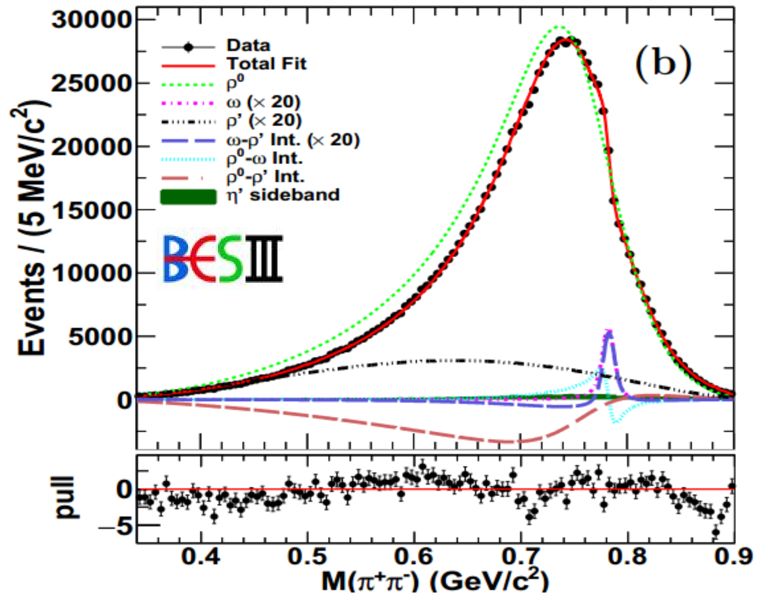
Model dependent fit

PRL 120, 242003 (2018)

Fit with $\rho(770) - \omega -$box anomaly



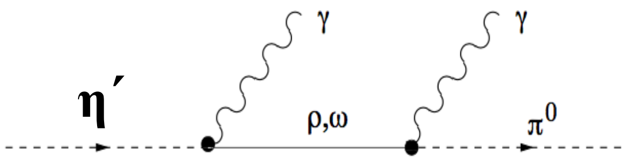
Fit with $\rho(770) - \omega - \rho(1450)$



- **Besides the ρ(770), the *ω* contribution is needed**
- **ρ(770)-ω cannot describe data well**
- **Extra contribution of box-anomaly or $\rho(1450)$, or both of them is necessary**

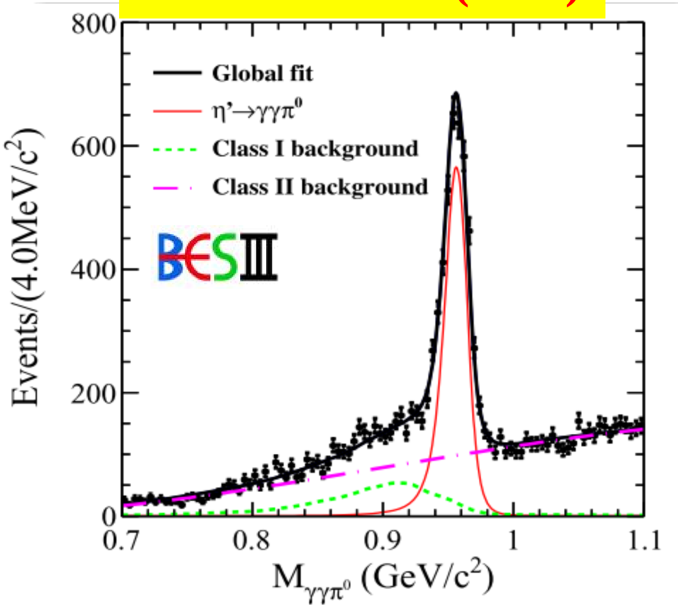
Doubly radiative decay $\eta' \to \gamma\gamma\pi^0$

- Test QCD calculations on the transition form factor
- Test the high order of ChPT
- VMD contribution is dominant



- In experiment, only an upper limit of $B(\eta' \to \gamma\gamma\pi^0) < 8\times10^{-4}$ at 90% C.L.

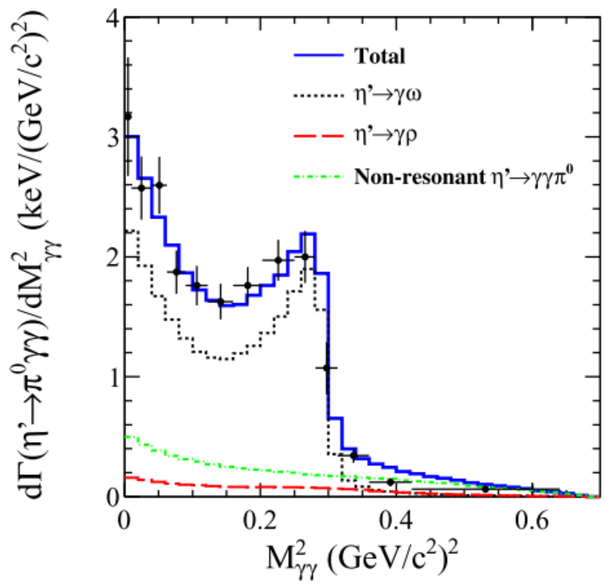
PRD.96.012005(2017)

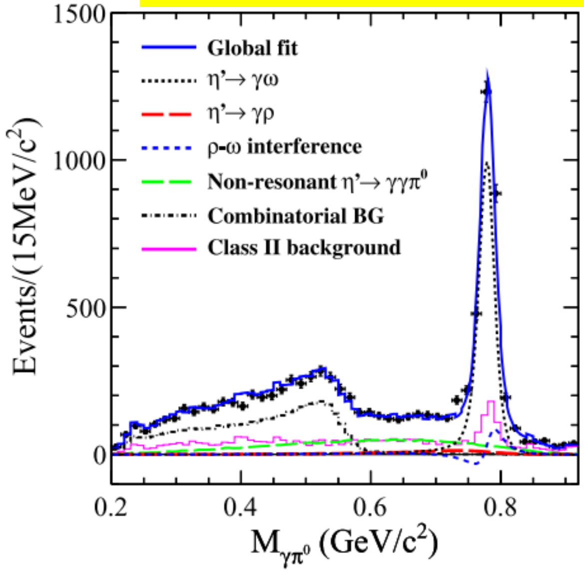


- The inclusive $\eta' \to \gamma\gamma\pi^0$ includes the vector mesons ρ /ω and the non-resonant contribution

Doubly radiative decay $\eta' \to \gamma\gamma\pi^0$

PRD.96.012005(2017)





This measurement:

$B(\eta' \to \gamma\gamma\pi^0)_{inc} = (3.20 \pm 0.07 \pm 0.23) \times 10^{-3}$

$B(\eta' \to \gamma\omega) = (23.7 \pm 1.4 \pm 1.8) \times 10^{-4}$

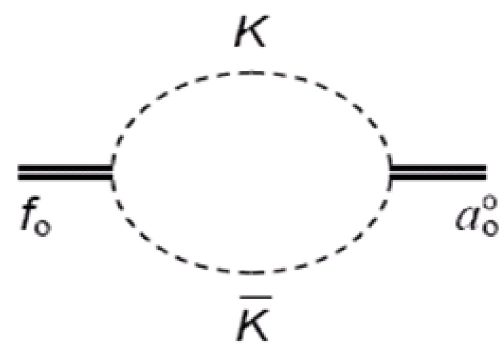
$B(\eta' \to \gamma\gamma\pi^0)_{NR} = (6.16 \pm 0.64 \pm 0.67) \times 10^{-4}$

PDG: $B(\eta' \to \gamma\gamma\pi^0) < 8.0 \times 10^{-4}$

Linear σ model and VMD: $B(\eta' \to \gamma\gamma\pi^0) \sim 6.0 \times 10^{-3}$

$a_0^0(980)$-$f_0(980)$ mixing

Meson	$I^G(J^{PC})$	Mass(MeV)	Width(MeV)	Decay
$a_0(980)$	$1^-(0^{++})$	980±20	50~100	$\eta\pi, KK$
$f_0(980)$	$0^+(0^{++})$	990±10	10~100	$\pi\pi, KK$



- In theory, $a_0^0(980)$ and $f_0(980)$ are explained as $q\bar{q}$ mesons, $K\bar{K}$ molecules, tetraquarks, $q\bar{q}g$ hybrids

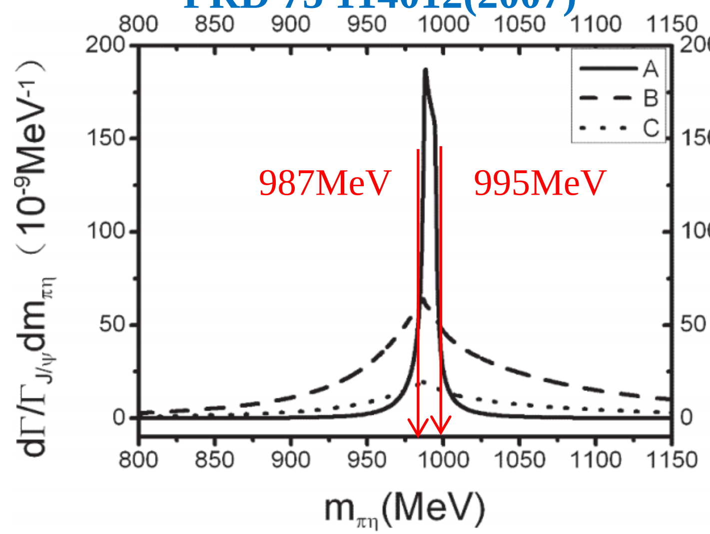
- In 1970s, the mixing mechanism was firstly proposed [PLB 88, 367 (1979)]

  $m(K^+K^-) \approx 987\text{MeV}$ $m(K^0\overline{K^0}) \approx 995\text{MeV}$

  $m(K^0\overline{K^0}) - m(K^+K^-) \approx 8\text{MeV}$

- A narrow peak of about 8MeV is predicted

PRD 75 114012(2007)



$a_0^0(980)$-$f_0(980)$ mixing

- **Theorist proposed to directly measure $f_0(980) \leftrightarrow a_0^0(980)$ mixing via $J/\psi \to \phi f_0(980) \to \phi a_0^0(980) \to \phi\eta\pi^0$ and $\chi_{c1} \to \pi^0 a_0^0(980) \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-$ [Wu, Zhao, Zou, PRD 75 114012(2007), PRD 78 074017(2008)]**

$$\xi_{fa} = \frac{\mathcal{B}(J/\psi \to \phi f_0(980) \to \phi a_0^0(980) \to \phi\eta\pi^0)}{\mathcal{B}(J/\psi \to \phi f_0(980) \to \phi\pi\pi)}$$

$$\xi_{af} = \frac{\mathcal{B}(\chi_{c1} \to \pi^0 a_0^0(980) \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-)}{\mathcal{B}(\chi_{c1} \to \pi^0 a_0^0(980) \to \pi^0\pi^0\eta)}$$

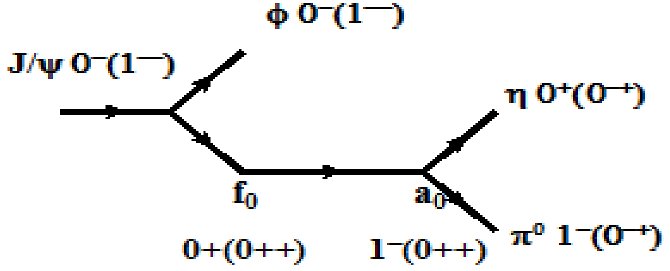
- **Mixing intensity is sensitive to couplings of $g_{a_0K^+K^-}$ and $g_{f_0K^+K^-}$**
- **Measured at BESIII based on 225M J/ψ and 108M ψ' [PRD83.032003(2011)]**

  significance <5σ

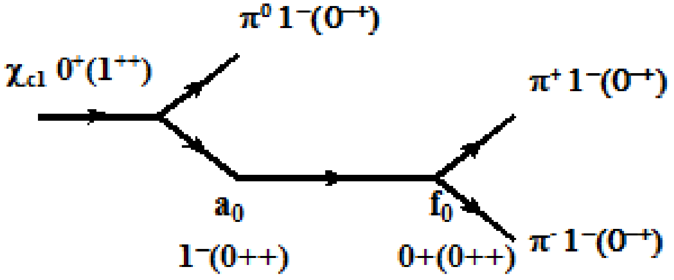
  $\xi_{af} < 1.0\%@90\%\mathrm{C.L.}$

  $\xi_{fa} < 1.1\%@90\%\mathrm{C.L.}$

$f_0(980) \to a_0^0(980)$ mixing:



$a_0^0(980) \to f_0(980)$ mixing:

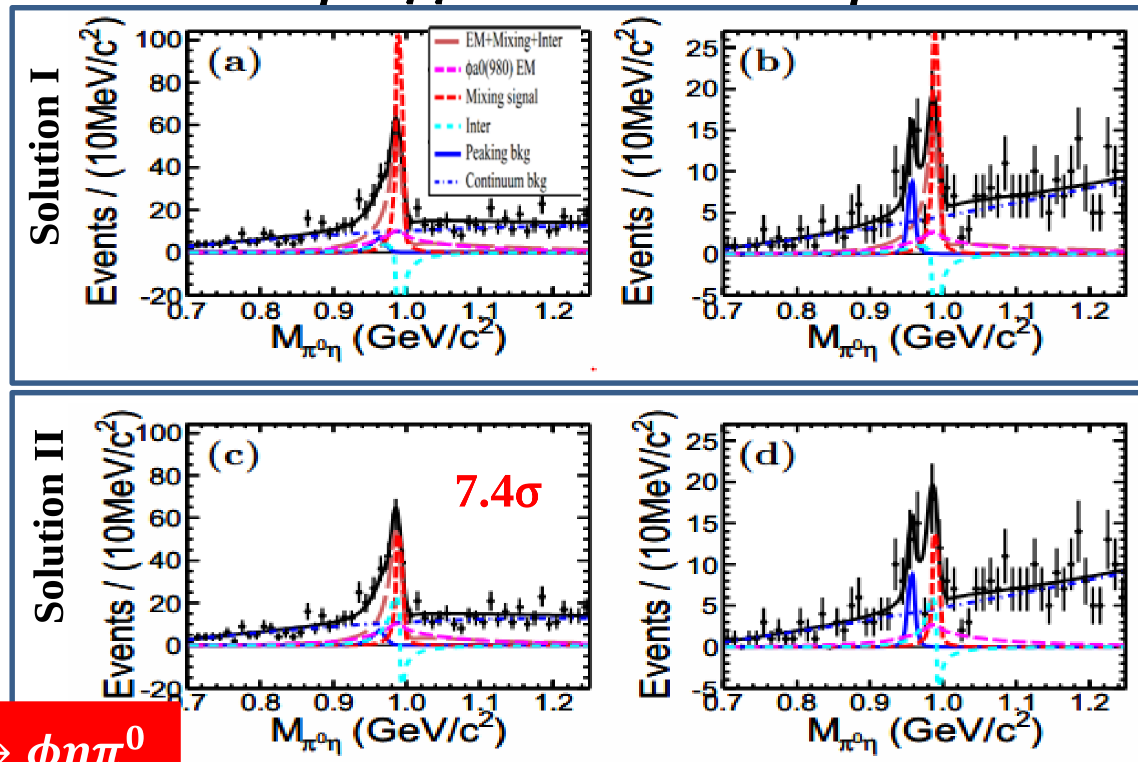


$f_0(980) \to a_0^0(980)$ mixing

arXiv:1802.00583v3 （accepted by PRL）

- Constructed by $\eta \to \gamma\gamma$ and $\eta \to 3\pi$
- Interference between EM and mixing signal
- Two solutions are found
- Significance of $f_0(980) \to a_0^0(980)$ is 7.4σ

$\eta \to \gamma\gamma$ $\eta \to 3\pi$



$J/\psi \to \phi f_0(980) \to \phi a_0^0(980) \to \phi\eta\pi^0$

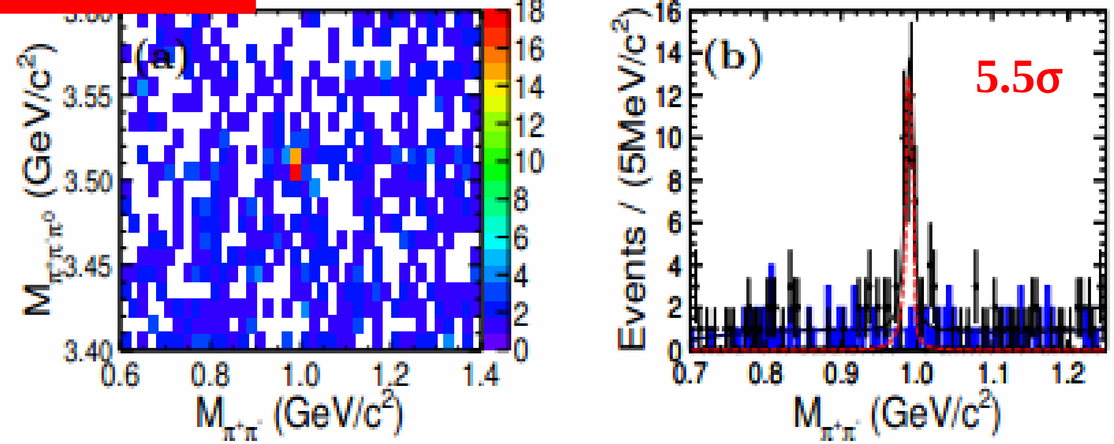
Channel	$f_0(980) \to a_0^0(980)$ Solution I	$f_0(980) \to a_0^0(980)$ Solution II
$\mathcal{B}$(mixing) (10^{-6})	$3.18 \pm 0.51 \pm 0.38 \pm 0.28$	$1.31 \pm 0.41 \pm 0.39 \pm 0.43$
$\mathcal{B}$(EM) (10^{-6})	$3.25 \pm 1.08 \pm 1.08 \pm 1.12$	$2.62 \pm 1.02 \pm 1.13 \pm 0.48$
$\mathcal{B}$(total) (10^{-6})	$4.93 \pm 1.01 \pm 0.96 \pm 1.09$	$4.37 \pm 0.97 \pm 0.94 \pm 0.06$
ξ (%)	$0.99 \pm 0.16 \pm 0.30 \pm 0.09$	$0.41 \pm 0.13 \pm 0.17 \pm 0.13$

$a_0^0(980) \to f_0(980)$ mixing

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

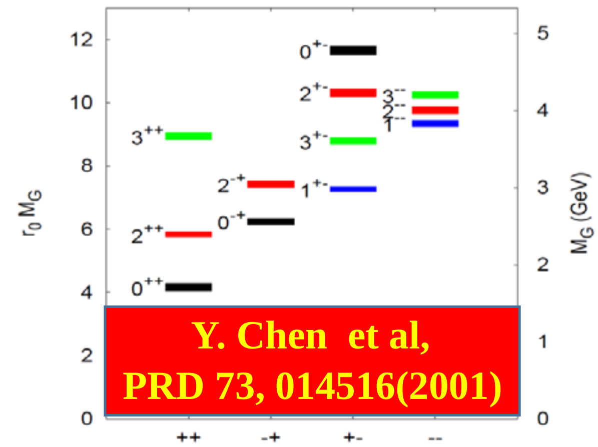
arXiv:1802.00583v3（accepted by PRL）

- Very narrow peak of $f_0(980)$
- EM contribution too weak ,can be negligible
- Interference is negligible
- Significance of $a_0^0(980) \to f_0(980)$ is 5.5σ



Channel	$a_0^0(980) \to f_0(980)$
$\mathcal{B}$(mixing) (10^{-6})	$0.35 \pm 0.06 \pm 0.03 \pm 0.06$
$\mathcal{B}$(EM) (10^{-6})	—
$\mathcal{B}$(total) (10^{-6})	—
ξ (%)	$0.40 \pm 0.07 \pm 0.14 \pm 0.07$

Pseudoscalar (0^{-+})--η(1440)



- **First observed in $p\bar{p}$**

  Nuovo Cimento 50A(1967)393

  - ✓ $p\bar{p} \to \eta(1440)\pi^{+}\pi^{-}(,\eta \to K\bar{K}\pi)$
  - ✓ 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 $a_0(980)\pi$ (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
  - $\Gamma\gamma\rho : \Gamma\gamma\phi \simeq 3.8:1$

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

PLB594(2004)47

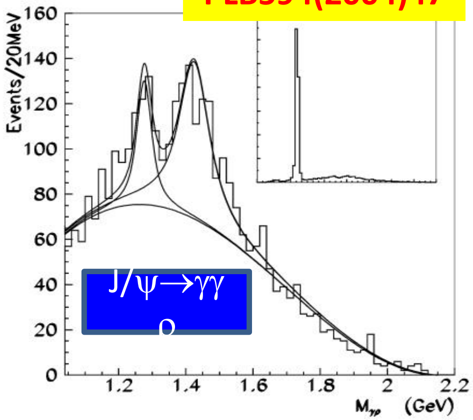


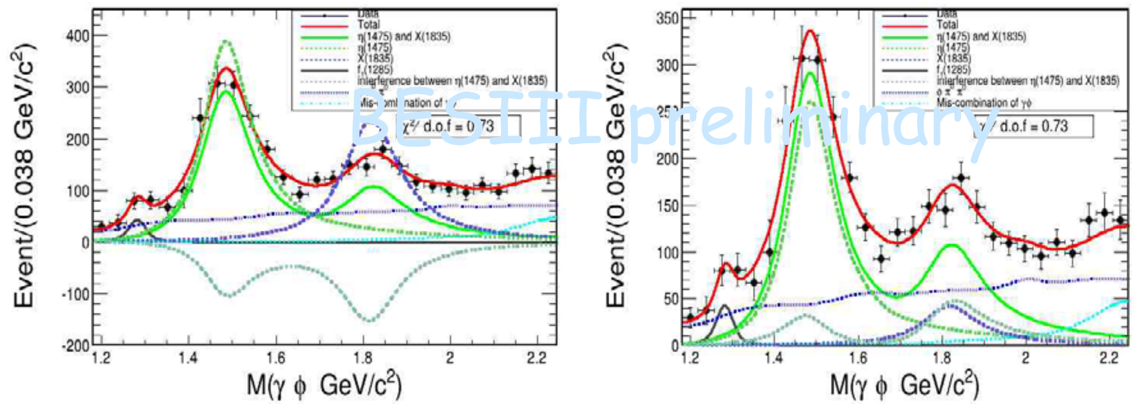
Fig. 2. The $\gamma\rho$ invariant mass distribution. The insert shows the full mass scale where the $\eta(958)$ is clearly observed.

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

✓η(1475)→γϕ

Phys. Rev. D97, 051101(R) (2018)

Γγρ : Γγϕ ≃ 11.1±3.5
7.5±2.5



	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

BES2: J/ψ→(ω,ϕ)$K\bar{K}\pi$

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

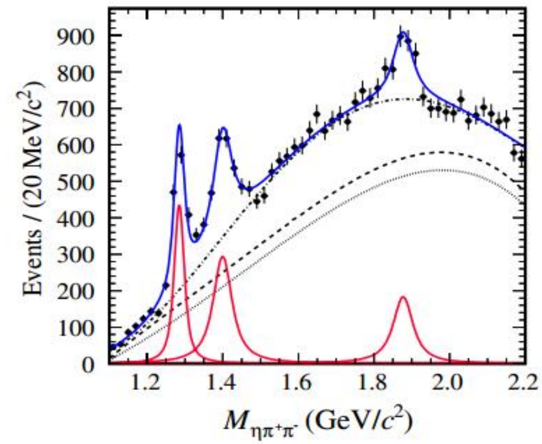
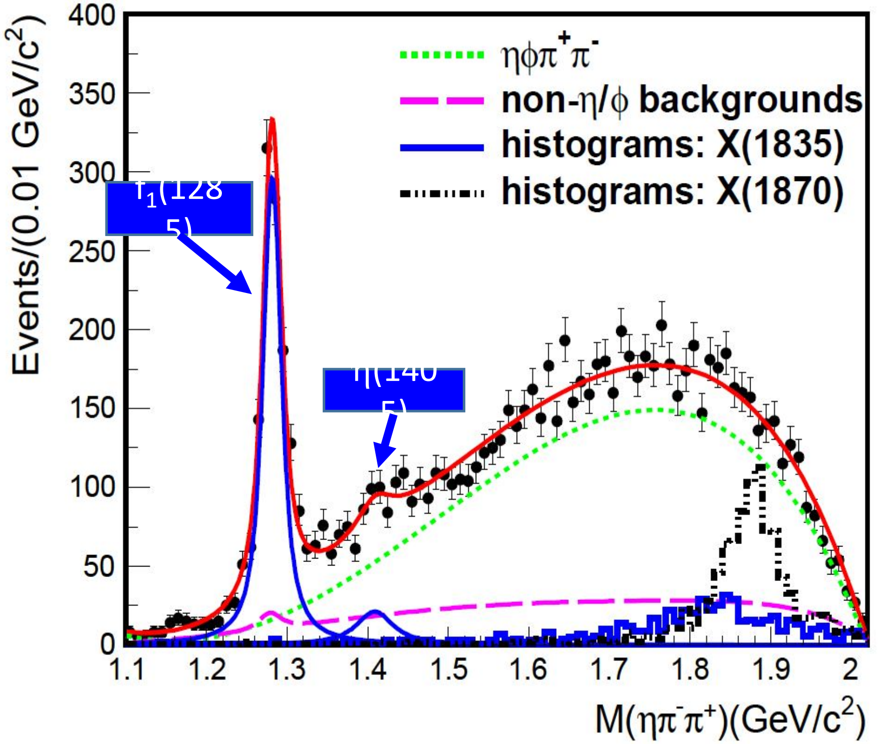


FIG. 4 (color online). Results of the fit to the $M(\eta\pi^+\pi^-)$ mass distribution for events with either the $\eta\pi^+$ or $\eta\pi^-$ in the $a_0(980)$ mass window. The dotted curve shows the contribution of non-ω and/or non-$a_0(980)$ background, the dashed line also includes the contribution 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/ψ→φηππ

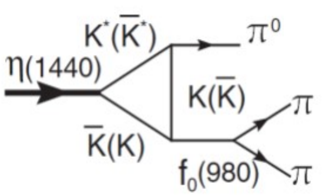


M. Ablikim et al,
Phys. Rev. D91, 052017(2011)

η(1405) in J/ψ→γ3π

PRL 108, 182001 (2012)

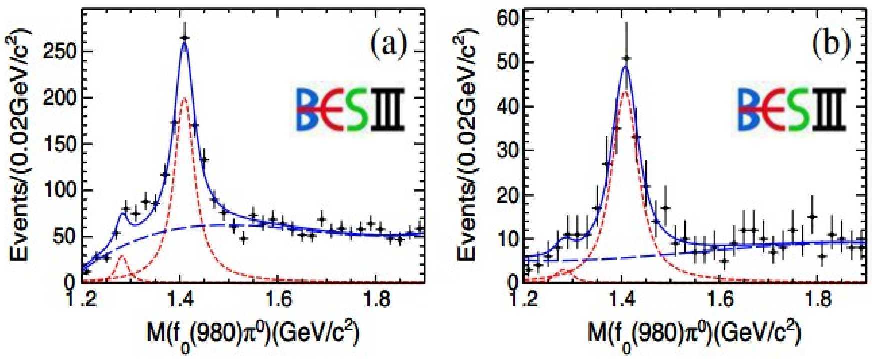
- η(1440)
  - η(1405)→$a_0\pi$
  - η(1475)→$K^*\bar{K}$
- One or two resonances?



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(MeV/c^2)	Γ(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 $(1.50\pm0.11\pm0.11)\cdot10^{-5}$ $3\pi^0$ $(7.10\pm0.82\pm0.72)\cdot10^{-6}$	η(1405)→γρ $(1.07\pm0.17\pm0.11)\cdot10^{-4}$ η(1475)→γϕ (7.9±1.3±1.9/ 11.8±2.2±1.9)$\cdot10^{-6}$
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($p\bar{p}$): $J^P = 0^-$, $J/\psi \rightarrow \gamma p\bar{p}$, 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

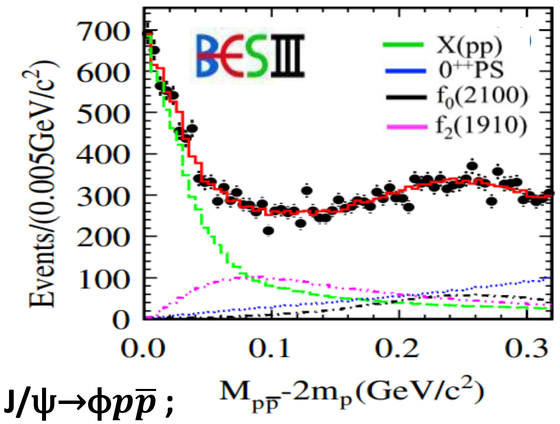
X(18??) near proton-antiproton threshold :

- **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 $J/\psi \to \gamma p\bar{p}$

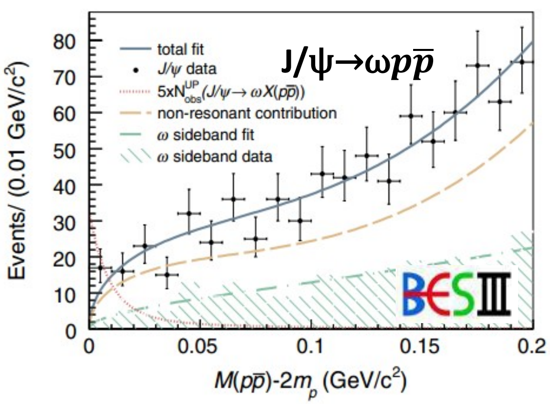
- **Strong enhancement first observed at BESII [PRL 91,022001(2003)] and confirmed by CLEO-c [PRD82,092002(2012)] ;**
- **PWA was firstly performed at BESIII;**
- **Significance of the $X(p\bar{p})$ component > 30σ, >5σ for the other components ;**
- **The 0^{-+} assignment is better that other J^{PC}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

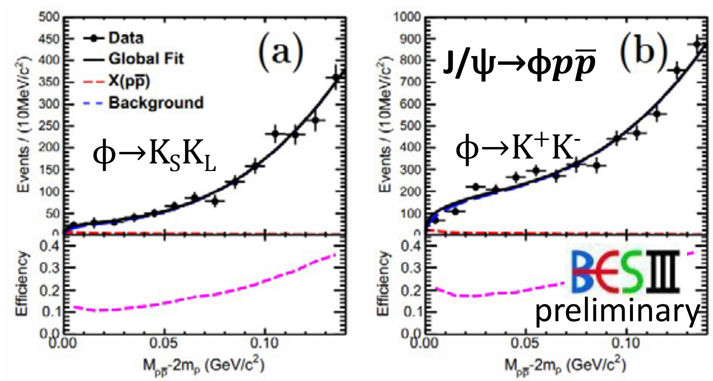
PRL 108,112003(2012)



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

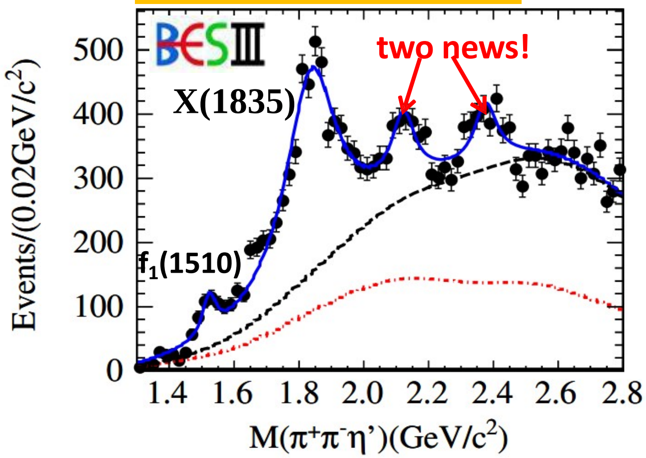
PRD 87, 112004(2013) arXiv:1512.08197





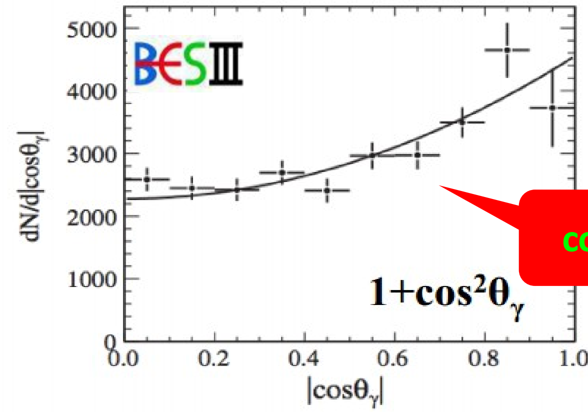
Confirm X(1835) in $J/\psi \to \gamma\pi^+\pi^-\eta'$

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	>5.7σ
$X(1835)$	1836.5 ± 3.0	190.1 ± 9.0	4265 ± 131	>20σ
$X(2120)$	2122.4 ± 6.7	83 ± 16	647 ± 103	>7.2σ
$X(2370)$	2376.3 ± 8.7	83 ± 17	565 ± 105	>6.4σ

- **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**



X(1835) consistent with 0^-

$\eta'\pi^+\pi^-$ 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**
    - **$M_{pole} = 1909.5\,^{+15.9}_{-15.9}\,^{+9.4}_{-27.5}$ MeV/c^2**
    - **$\Gamma_{pole} = 273.5\,^{+21.4}_{-21.4}\,^{+6.1}_{-64.0}$ 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**
    - **$M = 1870.2\,^{+2.2}_{-2.3}\,^{+2.3}_{-0.7}$ MeV/c^2**
    - **$\Gamma = 13.0\,^{+7.1}_{-5.5}\,^{+2.1}_{-3.8}$ MeV/c^2**

PRL 117, 042002 (2016)

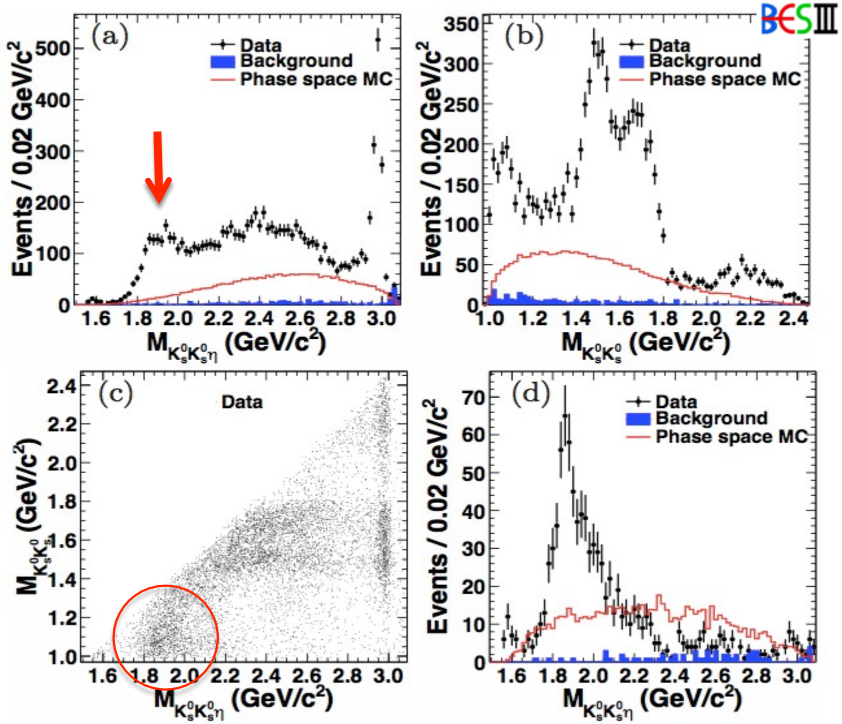
- Both models fit the data well with almost equally good quality
  - ➢ Cannot distinguish them with current data
  - ➢ **Suggest the existence of a state, either a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold**
  - ➢ **Support the existence of a $p\bar{p}$ molecule-like state or bound state**

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

BESIII: PRL115, 091803(2015)

- $K^0_S K^0_S \eta$ 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



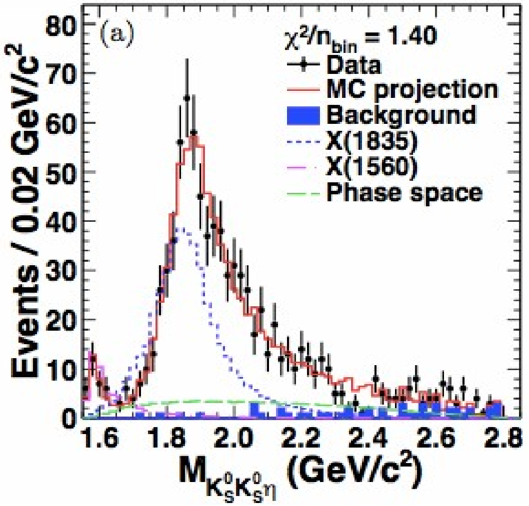
PWA of events with $M(K^0_S K^0_S)<1.1$ GeV/c^2 and $M(K^0_S K^0_S \eta)<2.8$ GeV/c^2

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



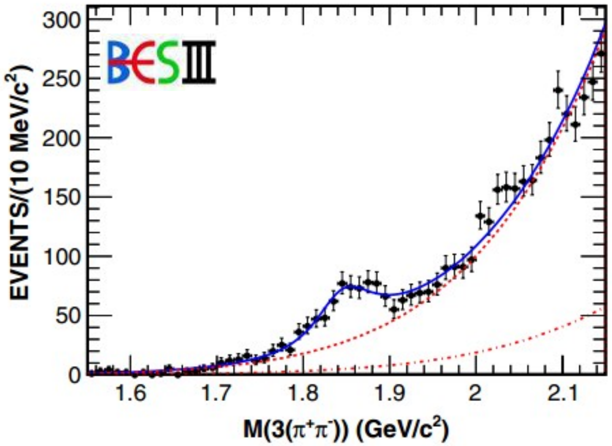
$M = 1844 \pm 9\,(stat)\pm^{16}_{25}\,(syst)$ MeV/c² **$\Gamma = 192\pm^{20}_{17}(stat)\pm^{62}_{43}(syst)$ MeV**

(>12.9σ)

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

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;
- $M=1842.2 \pm 4.2^{+7.1}_{-2.6}$ MeV/c^2 ; $\Gamma=83 \pm 14 \pm 11$ MeV/c^2 ;

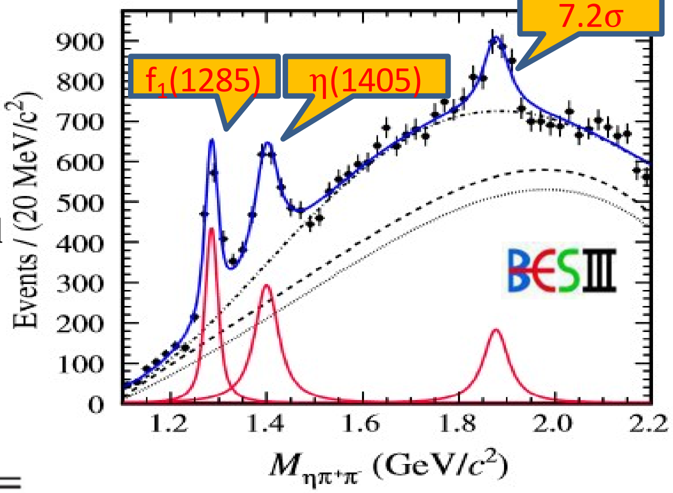
$$B(J/\psi \to \gamma X(1840)) \times B(X(1840) \to 3(\pi^+\pi^-)) = (2.44 \pm 0.36^{+0.60}_{-0.74}) \times 10^{-5}$$

- ✓ The mass is consistent with that of X(1835), but the width is significantly different from either of them, and much smaller than $\Gamma_{X(1835)} = 190.1 \pm 9.0^{+38}_{-36}$ 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;
- $M = 1877.3 \pm 6.3(stat) \pm^{3.4}_{7.4}(syst)$ MeV/c^2
- $\Gamma = 57 \pm 12(stat) \pm^{19}_{4}(syst)$ 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.

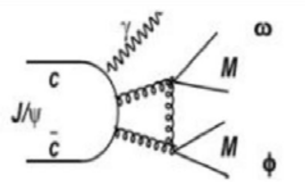
PRL 107, 182001 (2011)



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

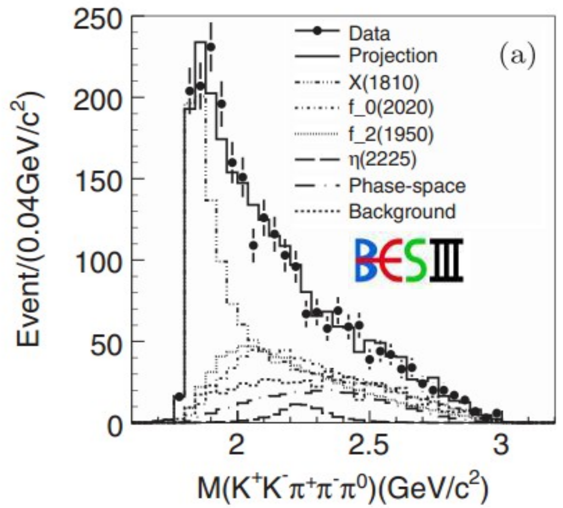
Whether the resonant structure of X(1870) is due to the X(1835) , the $\eta_2(1870)$, an interference of both, or a new resonance still needs further study!

X(1810) in PWA of J/ψ→γωϕ

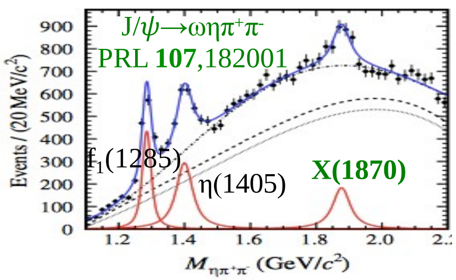


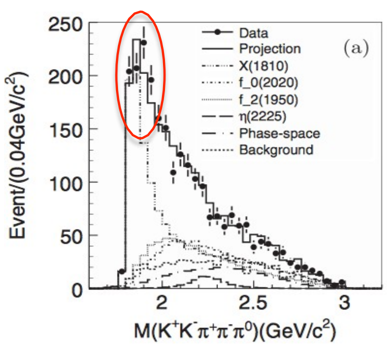
- J/ψ→γωϕ is Double OZI suppressed;
- The X(1810) is first observed by PWA at BESII [PRL 96, 162002 (2006)] ;
- Observed and confirmed at BESIII with the significance >30σ,;
- the J^{PC} of the X(1810) is 0^{++} ;
- The enhancement is not compatible with either the X(1835) or the X(p$\bar{p}$) due to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

PRD 87, 032008(2013)



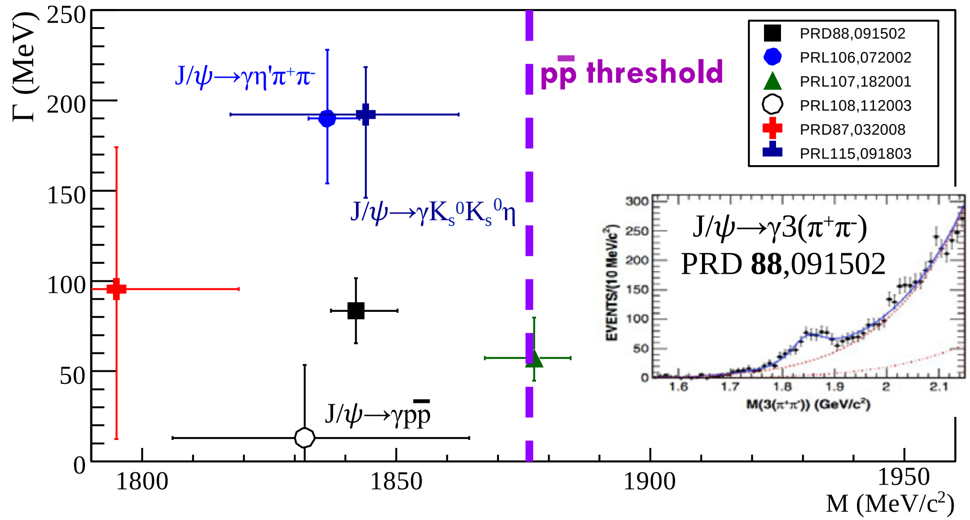
Resonance	J^{PC}	M(MeV/c^2)	Γ(MeV/c^2)	Events	ΔS	Δndf	Significance
$X(1810)$	0^{++}	1795 ± 7	95 ± 10	1319 ± 52	783	4	$>30\sigma$
$f_2(1950)$	2^{++}	1944	472	665 ± 40	211	2	20.4σ
$f_0(2020)$	0^{++}	1992	442	715 ± 45	100	2	13.9σ
$\eta(2225)$	0^{-+}	2226	185	70 ± 30	23	2	6.4σ
Coherent nonresonant component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





$J/\psi \to \gamma\omega\phi$ PRD **87**,032008

>30σ



X states near proton-antiproton threshold

More studies are needed

Summary

- J/ψ(ψ′) decay is a unique place to study light mesons
- BESIII: 1.3 billion + 4.6 billion + 4 billion J/ψ events
  - A sample of 4.6 billion J/ψ events was taken in 2018
  - So large data sample allows to study light mesons with the unprecedented statistics
  - More interesting results are expected

Thanks