Light hadron progress at BESIII

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Joint Workshop on theory and experiment of hadron and heavy flavor physics
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OUTLINE

➢Introduction

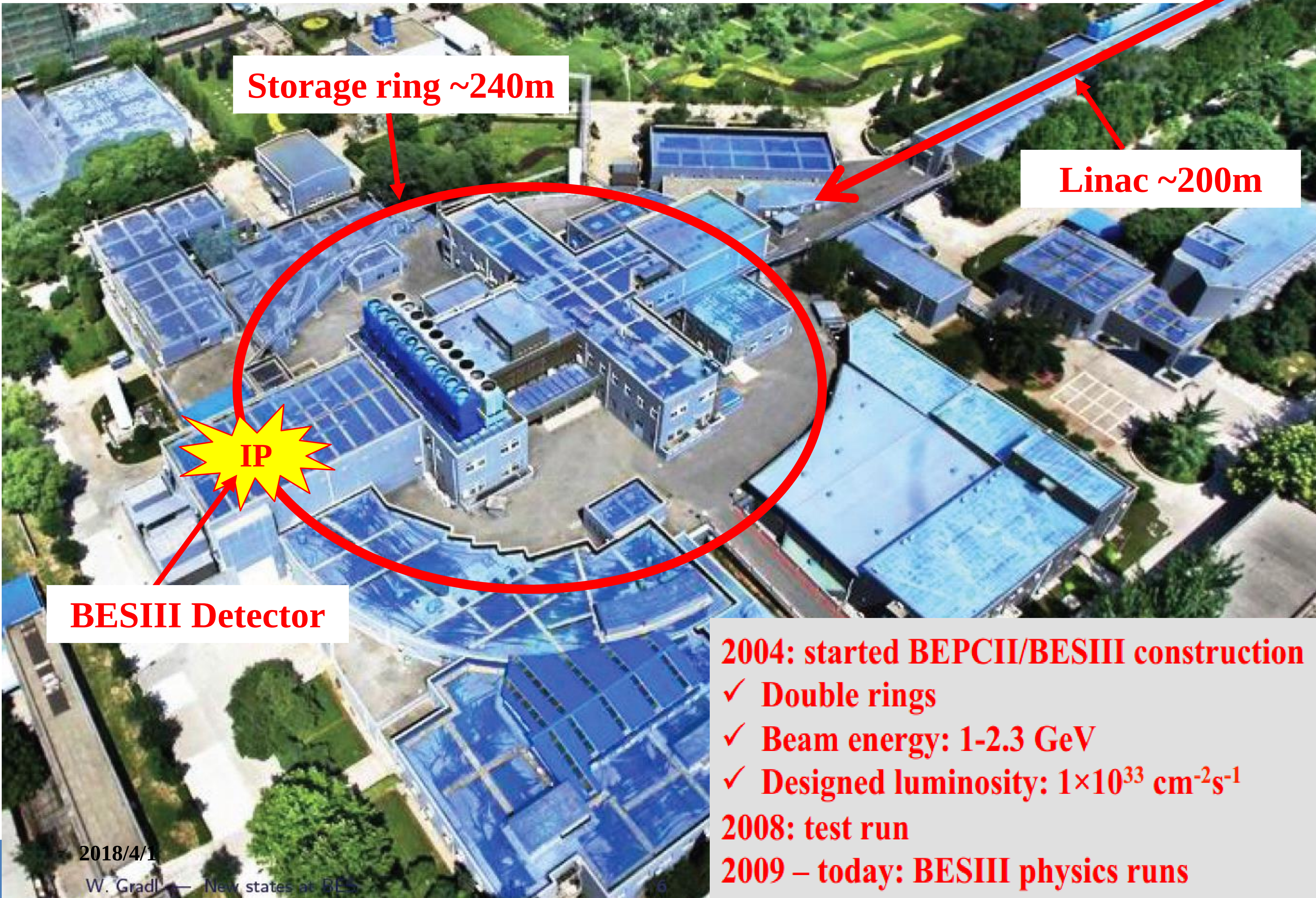
- BEPCII and BESIII Detector
- BESIII Collaboration
- BESIII data samples

➢Selected topics on light hadron

- X(18xx) states
- Isospin violation and $a_0^0(980)$-$f_0(980)$ mixing

➢Summary

Beijing Electron Positron Collider II (BEPC II)



2004: started BEPCII/BESIII construction
- ✓ Double rings
- ✓ Beam energy: 1-2.3 GeV
- ✓ Designed luminosity: 1×10^{33} cm^{-2}s^{-1}

2008: test run

2009 – today: BESIII physics runs

BESIII Detector

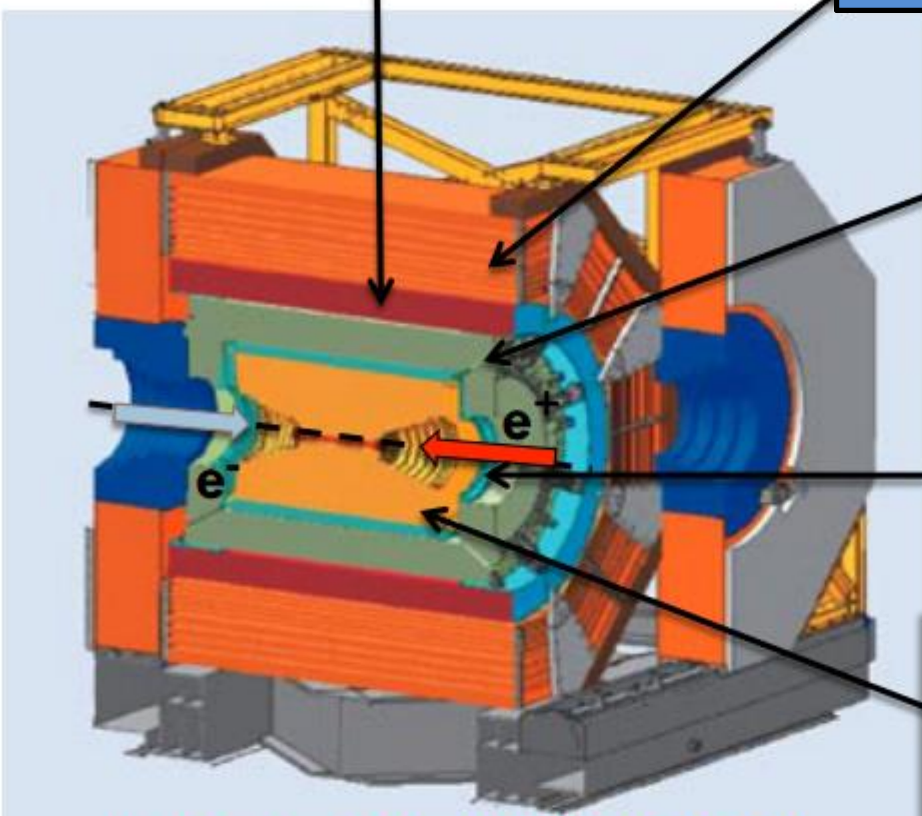
RPC Muon Detector
8 layers (end caps) + 9 layers (barrel)
$\Delta\Omega/4\pi = 93\%$

Superconducting solenoid (1T)

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

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



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

BESIII Collaboration

http://bes3.ihep.ac.cn

Europe (16)

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, Univ. of Ferrara, Frascati Lab
Netherland: KVI/Univ. of Groningen
Sweden: Uppsala Univ.
Turkey: Turkey Accelerator Center
UK: Oxford Univ., Univ. of Manchester

USA (4)

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

Mongolia (1)

Ins. of Phy. & Tech.

Korea (1)

Seoul Nat. Univ.

Japan (1)

Tokyo Univ.

China (37)

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.
Beihang Univ., Beijing Petrol Chemical Univ.
Jinan Univ., FudanUniv.
Hunan Normal Univ.

Pakistan (2)

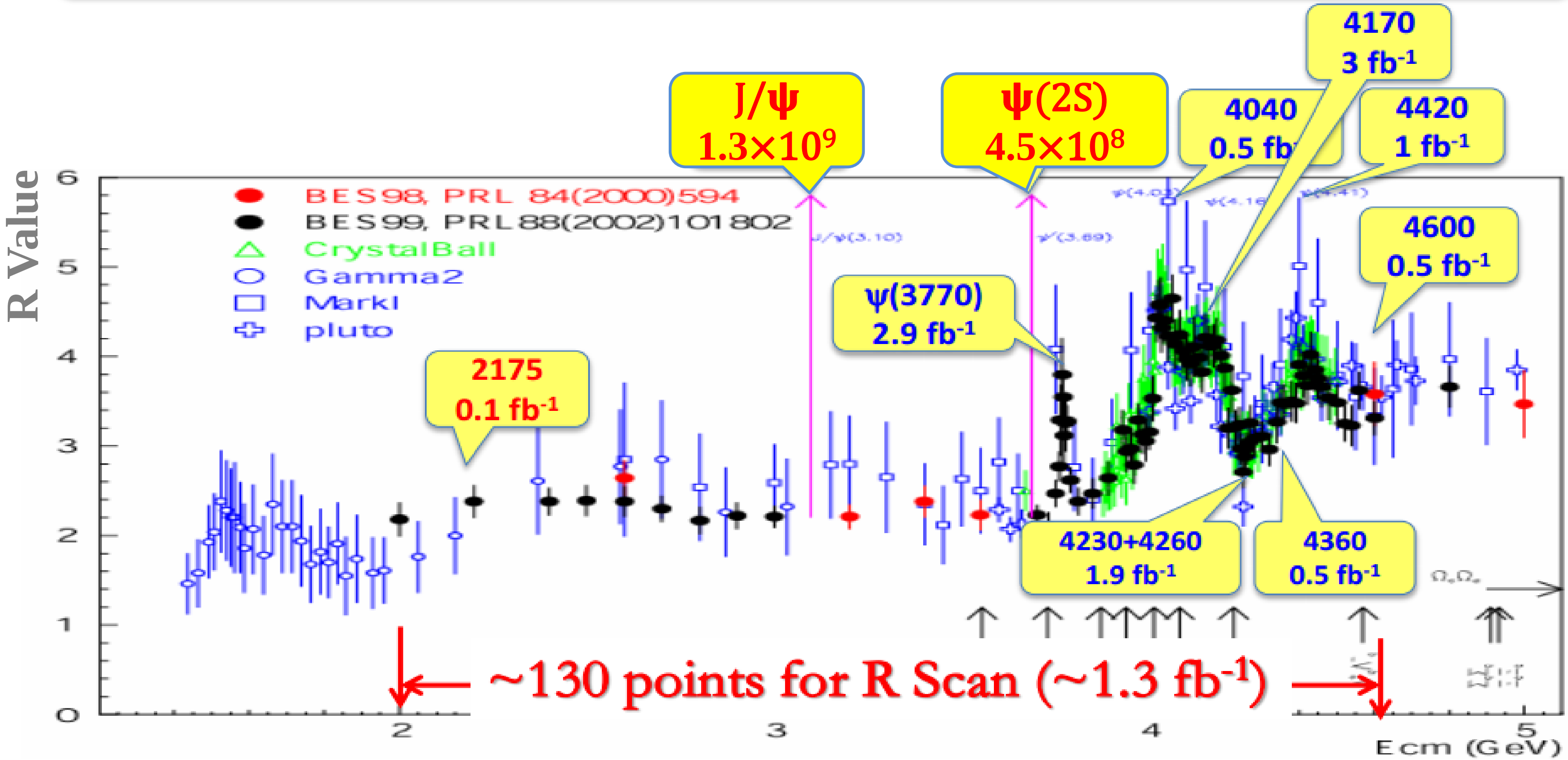
Univ. of Punjab
COMSAT CIIT

India (1)

Indian Institute of Technology

~450 members
64 institutions
14 countries

BESIII data samples

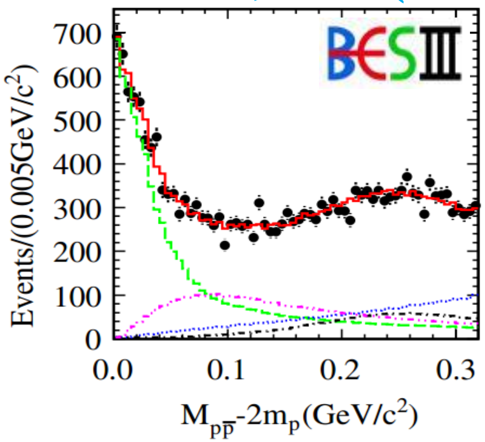


- World largest J/ψ, ψ(2S), ψ(3770), Υ(4260), … produced directly from e^+e^- collision. 3.5/fb in 4.2-4.3GeV, 500/pb at each energy.
- J/ψ data taking since Dec. 7th, 2017. Aim at 10billion J/ψ events!

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

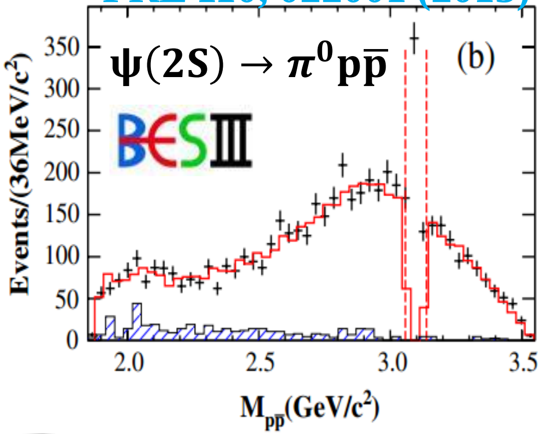
- First observed at BESII [PRL 91,022001(2003)] and confirmed by CLEO-c [PRD82,092002(2012)]
- PWA was firstly performed at BESIII [PRL 108, 112003(2012)]
- Significance of the $X(p\bar{p})$ component > 30σ
- The 0^{-+} assignment is better that other J^{PC}
- $M=1832^{+19}_{-5}(stat)^{+18}_{-17}(syst) \pm 19(model)$ MeV/c^2
- Γ<76MeV (90% C.L.)

PRL 108,112003(2012)

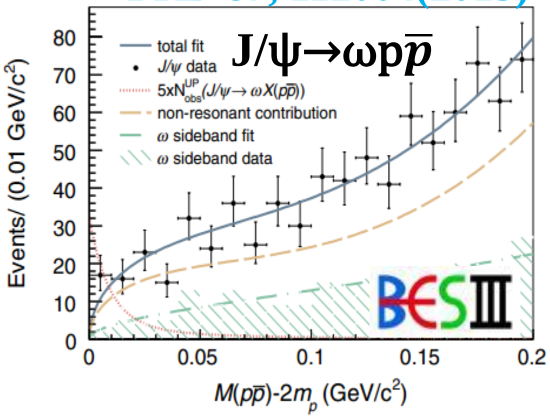


➢ No similar structure was observed in $\psi(2S) \to \pi^0 p\bar{p}$, $J/\psi \to \omega p\bar{p}$, $J/\psi \to \phi p\bar{p}$

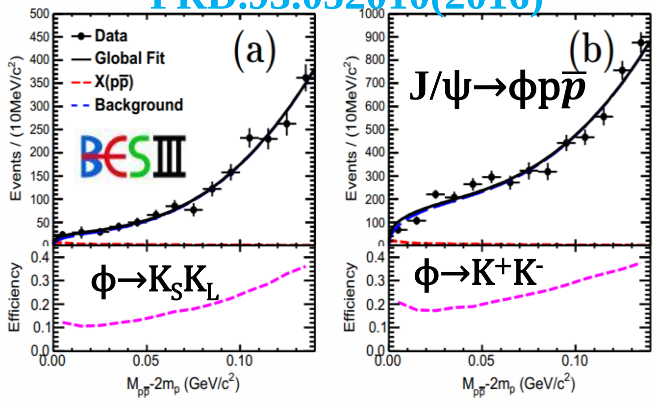
PRL 110, 022001 (2013)



PRD 87, 112004(2013)

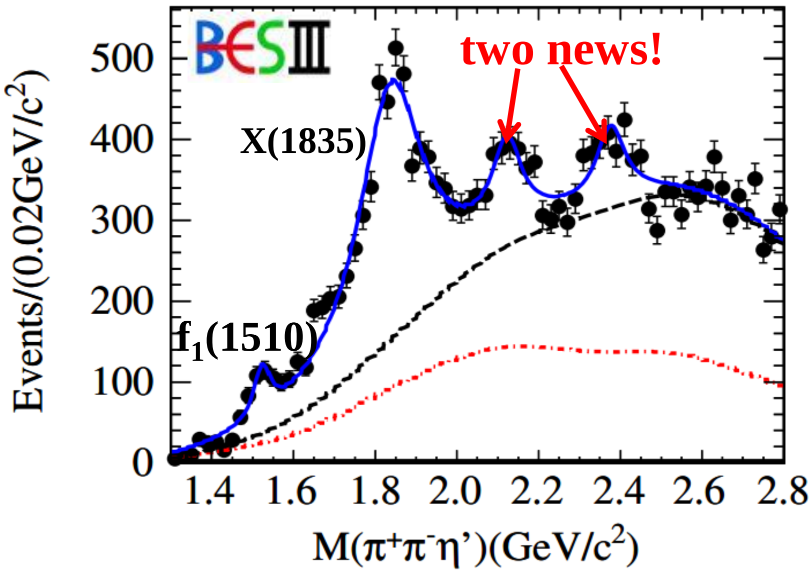


PRD.93.052010(2016)



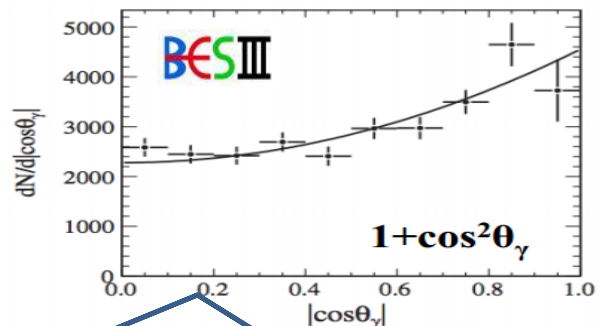
X(1835) in $J/\psi \to \gamma\pi^+\pi^-\eta'$

PRL 106, 072002 (2011)



- X(1835) was first observed at BESII [PRL95, 262001(2005)]
- Confirmed at BESIII via two η' modes based on 225M J/ψ [PRL 106, 072002 (2011)]
- Significance of the X(1835) is >20σ
- J^{PC} is assigned to be 0^-
- Two additional structures was observed
- Nature of X(2120)/X(2370): pseudoscalar glueball ? η/η' excited states?

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	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

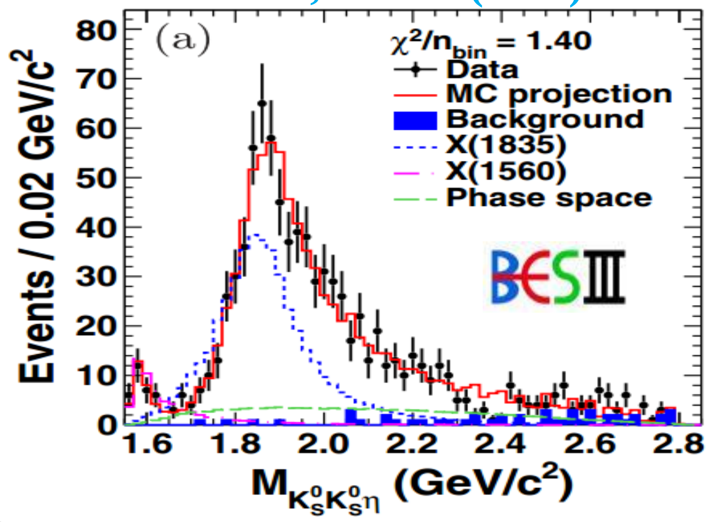


the angular distribution of γ is consistent with pseudoscalar 0^-

X(1835) in PWA of $J/\psi \to \gamma K_S^0 K_S^0 \eta$

- Based on 1310M J/ψ data in 09 and 12 [PRL 115, 091803 (2015)]
- Clear structure on mass spectrum of $K_S^0 K_S^0 \eta$ around $1.85\mathrm{GeV/c^2}$
- Strongly correlated to $f_0(980) \to K_S^0 K_S^0$
- A PWA of events satisfying $M_{K_S K_S \eta} < 2.8\mathrm{GeVc^2}$, $M_{K_S K_S} < 1.1\mathrm{GeV/c^2}$

PRL 115, 091803 (2015)



X(1835):

- J^{PC} determined to be 0^{-+}
- Significance is 12.9σ, dominated by $f_0(980) \to K_S^0 K_S^0$
- $M = 1844 \pm 9^{+16}_{-25}\mathrm{MeV/c^2}$
- $\Gamma = 192^{+20}_{-17}\ ^{+62}_{-43}\mathrm{MeV}$
- $B_{product} = 3.31^{+0.33}_{-0.30}\ ^{+1.96}_{-1.29} \times 10^{-5}$
- Consistent with X(1835) from $J/\psi \to \gamma\pi^+\pi^-\eta'$

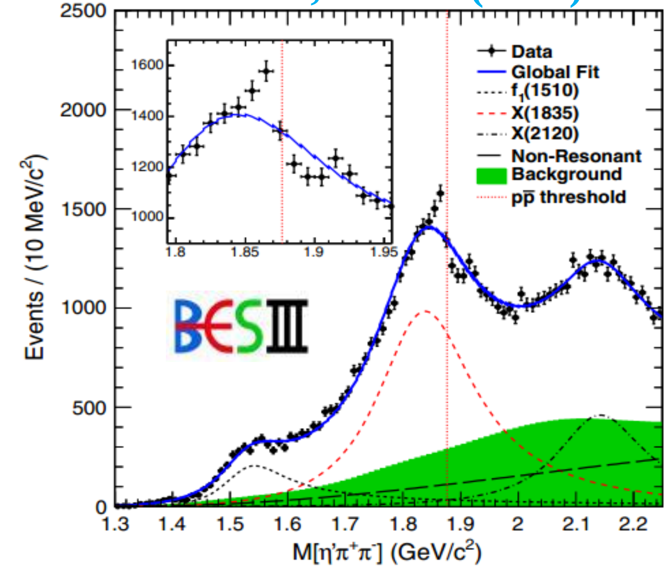
X(1560):

- J^{PC} determined to be 0^{-+}
- Significance is 8.9σ
- $M = 1565 \pm 8^{+0}_{-63}\mathrm{MeV/c^2}$
- $\Gamma = 45^{+14}_{-13}\ ^{+21}_{-28}\mathrm{MeV}$
- Consistent with $\eta(1405)/\eta(1475)$ with 2.0σ /1.4σ, but not concluded

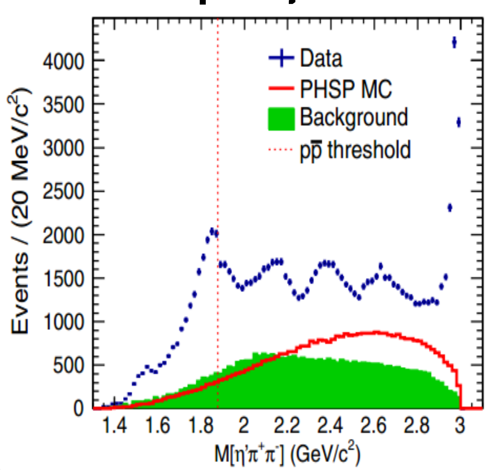
Anomalous line shape of $\pi^+\pi^-\eta'$ in $J/\psi \to \gamma\pi^+\pi^-\eta'$

- Based on new 1090M J/ψ data in 2012 [PRL 117, 042002 (2016)]
- Two η' modes of $\eta' \to \gamma\pi^+\pi^-$, $\eta' \to \eta\pi^+\pi^-$
- Clear peaks of X(1835), X(2120), X(2370), η_c and additional structure near 2.6 GeV/c^2
- A significant distortion of the $\eta'\pi^+\pi^-$ line shape near the $p\bar{p}$ mass threshold

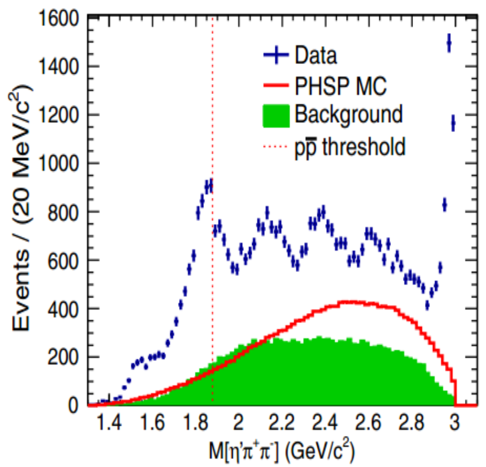
PRL 117, 042002 (2016)



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



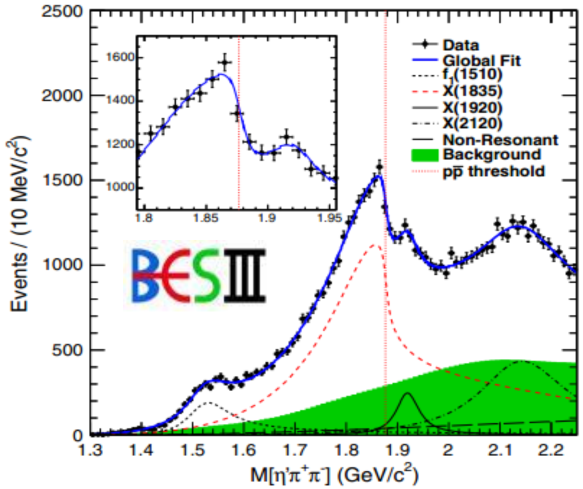
$\eta' \to \eta\pi^+\pi^-$



- Simultaneous fits to two η' modes in [1.3, 2.25](GeV/c^2)
- Three simple Breit-Wigner
- Can not describe the distortion near $p\bar{p}$ mass threshold

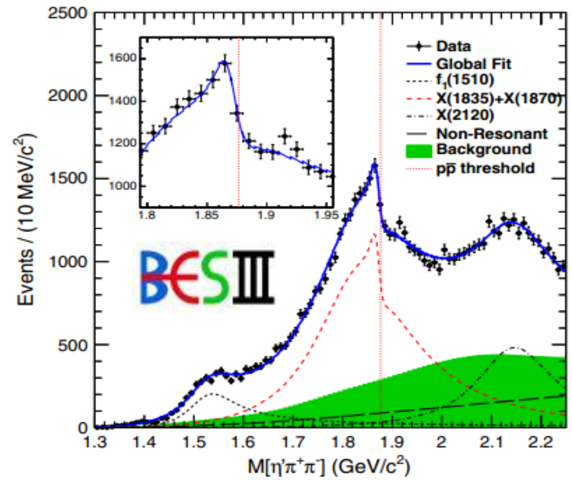
Anomalous line shape of $\pi^+\pi^-\eta'$ in $J/\psi \to \gamma\pi^+\pi^-\eta'$

- **A threshold effect caused by opening $p\bar{p}$ decay mode, use Flatt é formula, additional X(1920) is needed** (5.7σ)



The state around 1.85 GeV/c^2	
$\mathcal{M}$ (MeV/c^2)	$1638.0 \pm 121.9^{+127.8}_{-254.3}$
g_0^2 [(GeV/c^2)^2]	$93.7 \pm 35.4^{+47.6}_{-43.9}$
$g^2_{p\bar{p}}/g_0^2$	$2.31 \pm 0.37^{+0.83}_{-0.60}$ $> 7\sigma$
$M_{\rm pole}$ (MeV/c^2)	$1909.5 \pm 15.9^{+9.4}_{-27.5}$
$\Gamma_{\rm pole}$ (MeV/c^2)	$273.5 \pm 21.4^{+6.1}_{-64.0}$
Branching ratio	$(3.93 \pm 0.38^{+0.31}_{-0.84}) \times 10^{-4}$

- **Interference between two resonances**



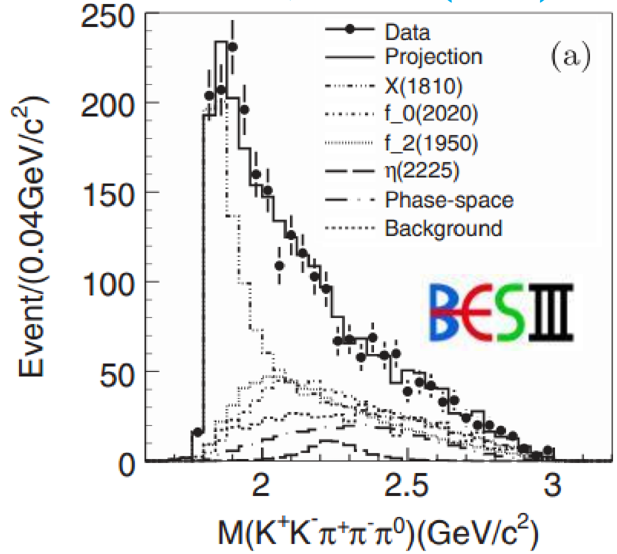
$X(1835)$	
Mass (MeV/c^2)	$1825.3 \pm 2.4^{+17.3}_{-2.4}$
Width (MeV/c^2)	$245.2 \pm 13.1^{+4.6}_{-9.6}$
B.R. (constructive interference)	$(3.01 \pm 0.17^{+0.26}_{-0.28}) \times 10^{-4}$
B.R. (destructive interference)	$(3.72 \pm 0.21^{+0.18}_{-0.35}) \times 10^{-4}$

$X(1870)$ $> 7.0\sigma$	
Mass (MeV/c^2)	$1870.2 \pm 2.2^{+2.3}_{-0.7}$
Width (MeV/c^2)	$13.0 \pm 6.1^{+2.1}_{-3.8}$
B.R. (constructive interference)	$(2.03 \pm 0.12^{+0.43}_{-0.70}) \times 10^{-7}$
B.R. (destructive interference)	$(1.57 \pm 0.09^{+0.49}_{-0.86}) \times 10^{-5}$

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)]
- X(1810) is observed and confirmed at BESIII [PRD 87, 032008(2013)]
- Significance >30σ
- the J^{PC} of the X(1810) is 0^{++}
- The X(1810) is not compatible with either X(1835) or $X(p\bar{p})$ due to the different masses and spin-parity

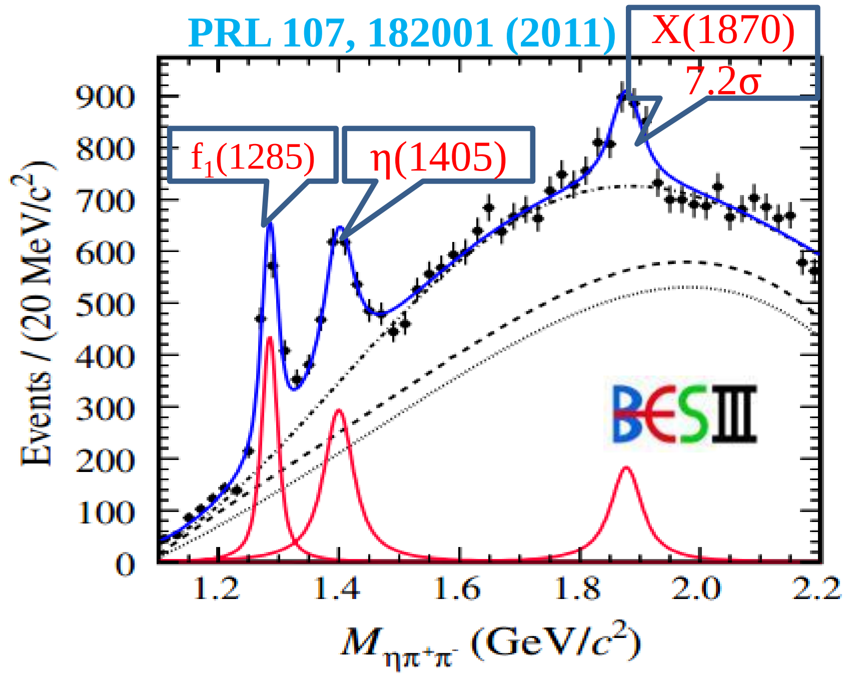
PRD 87, 032008(2013)



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

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

- **Based on 225M J/ψ data**
- **First observation of $J/\psi \to \omega X(1870)$ and $X(1870) \to a_0^{\pm}(980)\pi^{\mp}$ at BESIII**
- **A significance of 7.2σ**
- **J^{PC} is unknown**
- **$M = 1877.3 \pm 6.3(\text{stat})\,^{+3.4}_{-7.4}(\text{syst})$ MeV/c^2**
- **$\Gamma = 57 \pm 12(\text{stat})\,^{+19}_{-4.0}(\text{syst})$ MeV**
- **$f_1(1285)$ 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.**

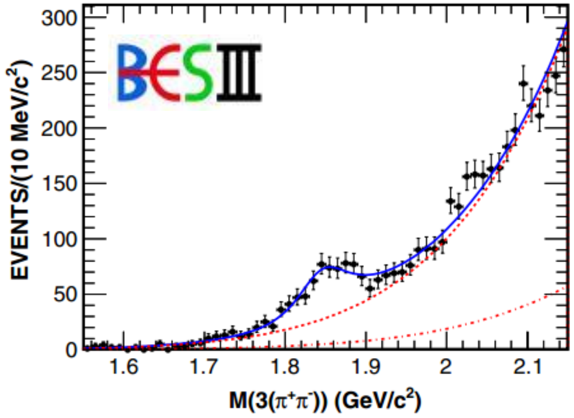


Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(10^{-4})$
$f_1(1285)$	$1285.1 \pm 1.0^{+1.6}_{-0.3}$	$22.0 \pm 3.1^{+2.0}_{-1.5}$	$1.25 \pm 0.10^{+0.19}_{-0.20}$
$\eta(1405)$	$1399.8 \pm 2.2^{+2.8}_{-0.1}$	$52.8 \pm 7.6^{+0.1}_{-7.6}$	$1.89 \pm 0.21^{+0.21}_{-0.23}$
$X(1870)$	$1877.3 \pm 6.3^{+3.4}_{-7.4}$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

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

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

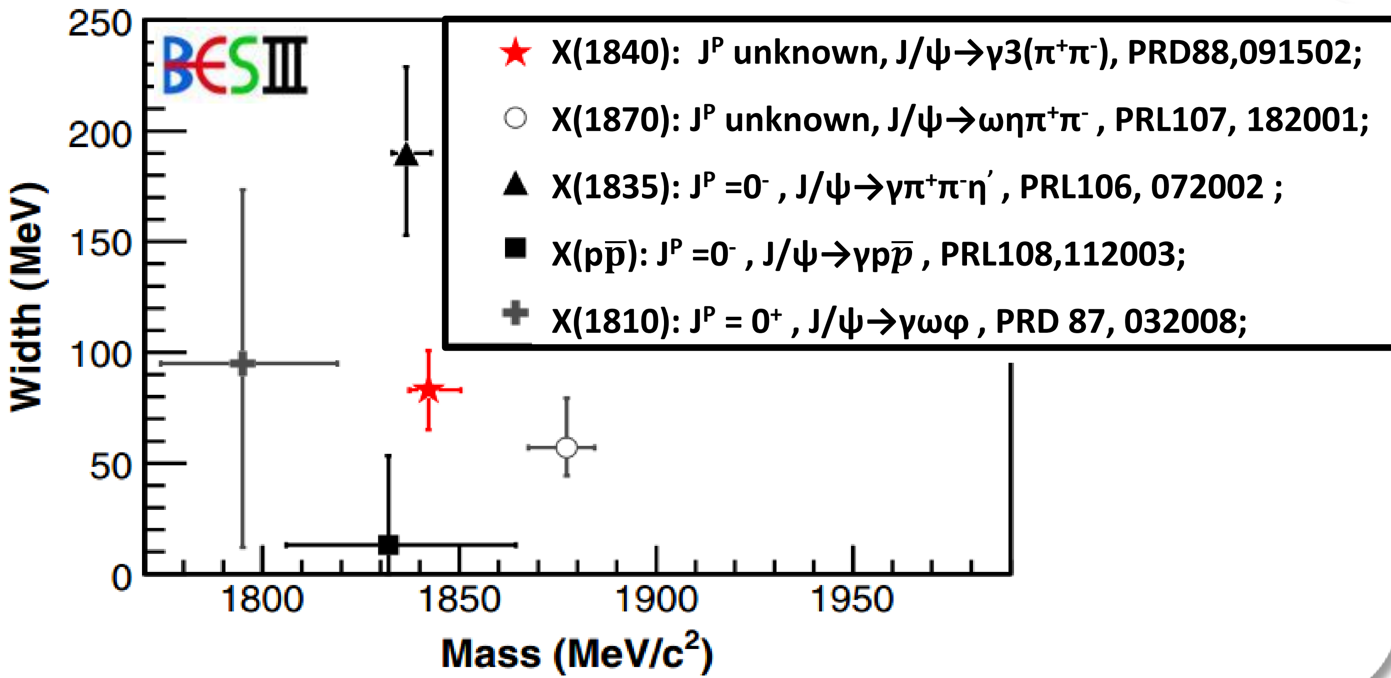
PRD 88, 091502 (2013)



- Based on 225M J/ψ data
- A structure at 1.84GeV/c² is observed in $3(\pi^+\pi^-)$ mass
- A significance of 7.6σ
- J^{PC} is unknown
- $M = 1842.2 \pm 4.2^{+7.1}_{-2.6} \mathrm{MeV}/c^2$
- $\Gamma = 83 \pm 14 \pm 11 \mathrm{MeV}$

- $B\left(J/\psi \to \gamma X(1840) \times B\left(X(1840) \to 3(\pi^+\pi^-)\right)\right) = \left(2.44 \pm 0.36^{+0.60}_{-0.74}\right) \times 10^{-5}$
- The mass is consistent with X(1835) and $X(p\bar{p})$
- But the width is very different from either of them, and much smaller than $\Gamma_{X(1835)}$ =190.1±9.0 MeV
- Cannot determine whether X(1840) is a new state or a new decay modes of existing X(1835)
- A PWA is needed to determine the spin and parity

Comparison of X(18xx) at BESIII



- X(18xx) are all near $p\bar{p}$ mass threshold
- X(1835) and X($p\bar{p}$) have similar mass, same J^{PC}, X($p\bar{p}$) may be tail of X(1835)
- X(1810) is not compatible with X(1835) or X($p\bar{p}$) due to different masses and J^{PC}

- X(1870) is due to X(1835) , η_2(1870) , or interference of both? needs PWA
- X(1840) agrees with X(1835) and X($p\bar{p}$), while their width is very different
- In theory, mesons, $p\bar{p}$ bound state, glueballs, hybrid and multiquark states

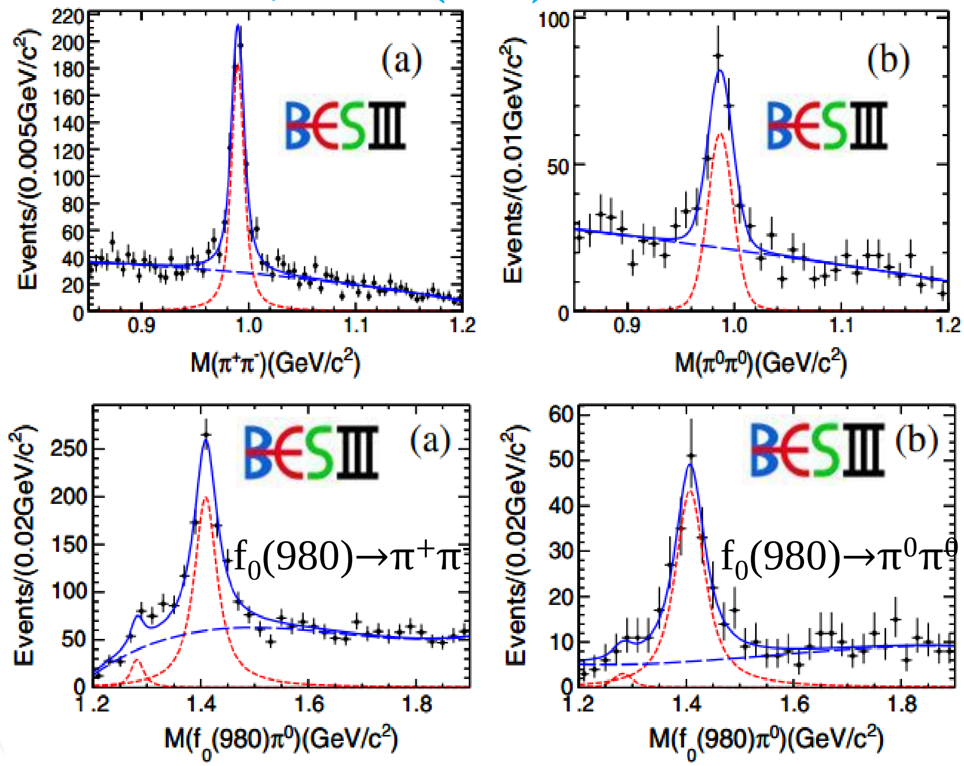
Isospin-violated decay $J/\psi \to \gamma\pi^0 f_0(980)$

- **Based on 225M J/ψ**
- **$\eta(1405)$ mainly decay to $a_0(980)\pi$**
- **First observation of isospin violated $\eta(1405) \to \pi^0 f_0(980)$ with a significance >10σ**

- **$f_0(980) \to \pi^+\pi^-$:**
  $\mathbf{M = 989.9 \pm 0.4 MeV/c^2}$
  $\mathbf{\Gamma = 9.5 \pm 1.1 MeV}$

- **$f_0(980) \to \pi^0\pi^0$:**
  $\mathbf{M = 987.0 \pm 1.4 MeV/c^2}$
  $\mathbf{\Gamma = 4.6 \pm 5.1 MeV}$ **(<11.8@90C.L.)**

PRL 108, 182001 (2012)



$$\frac{BR(\eta(1405) \to f_0(980)\pi^0)}{BR(\eta(1405) \to a_0(980)\pi)} \approx 18\%$$

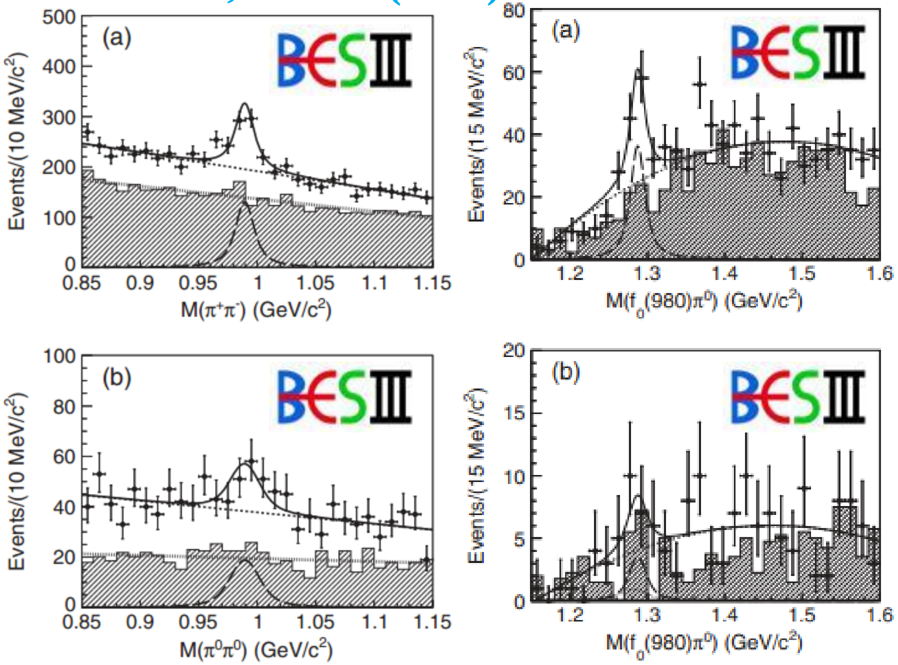
Large isospin breaking!

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	$(7.10 \pm 0.82 \pm 0.72) \times 10^{-6}$

Isospin-violating decay $J/\psi \to \phi\pi^0 f_0(980)$

- Based on 1310M J/ψ data
- $J/\psi \to \phi\pi^0 f_0(980)$is isospin-violated
- $\pi^+\pi^-$ and $\pi^0\pi^0$ simultaneous fit
  $M = 989.4 \pm 1.3 MeV/c^2$
  $\Gamma = 15.3 \pm 4.7 MeV$
- Much narrower than the world averaged value, but wider than $J/\psi \to \gamma\eta(1405) \to \gamma\pi^0 f_0(980)$
- Obvious $f_1(1285) \to \pi^0 f_0(980)$ signal

PRD 92, 012007 (2015)

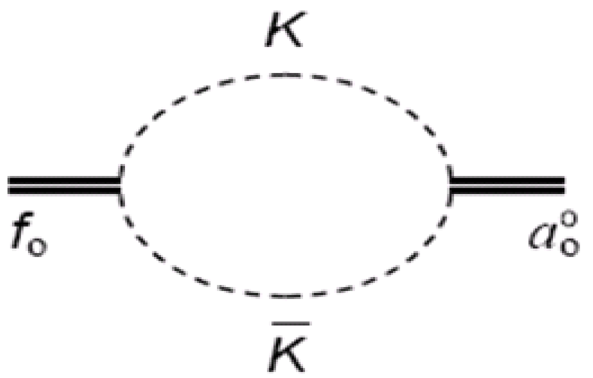


$$\frac{B(f_1(1285) \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-)}{B(f_1(1285) \to \pi^0 a_0^0(980) \to \pi^0\pi^0\eta)} = (3.6 \pm 1.4)\%$$

About 1/5 of $J/\psi \to \gamma\eta(1405) \to \gamma\pi^0 f_0(980)$

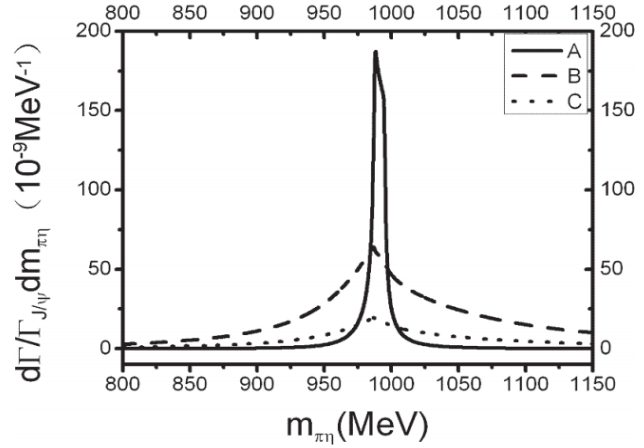
$a_0^0(980)$-$f_0(980)$ mixing

Particle	$I^G(J^{PC})$	Mass(MeV)	Width(MeV)
$a_0(980)$	$1^-(0^{++})$	980±20	50~100
$f_0(980)$	$0^+(0^{++})$	980±10	40~100



- **$a_0^0(980)$ and $f_0(980)$ are explained as mesons, tetraquarks, $K\bar{K}$ molecules, $q\bar{q}g$ hybrids**
- **In 1970s, the mixing mechanism was proposed between $a_0^0(980)$ and $f_0(980)$ [PLB 88, 367 (1979)]**
- **$m(K^0\bar{K}^0)-m(K^+K^-)\approx 8MeV/c^2$**
- **Between the K^+K^- and $K^0\bar{K}^0$ mass thresholds, amplitude is proportional to difference of phase spaces**

PRD 75 114012(2007)

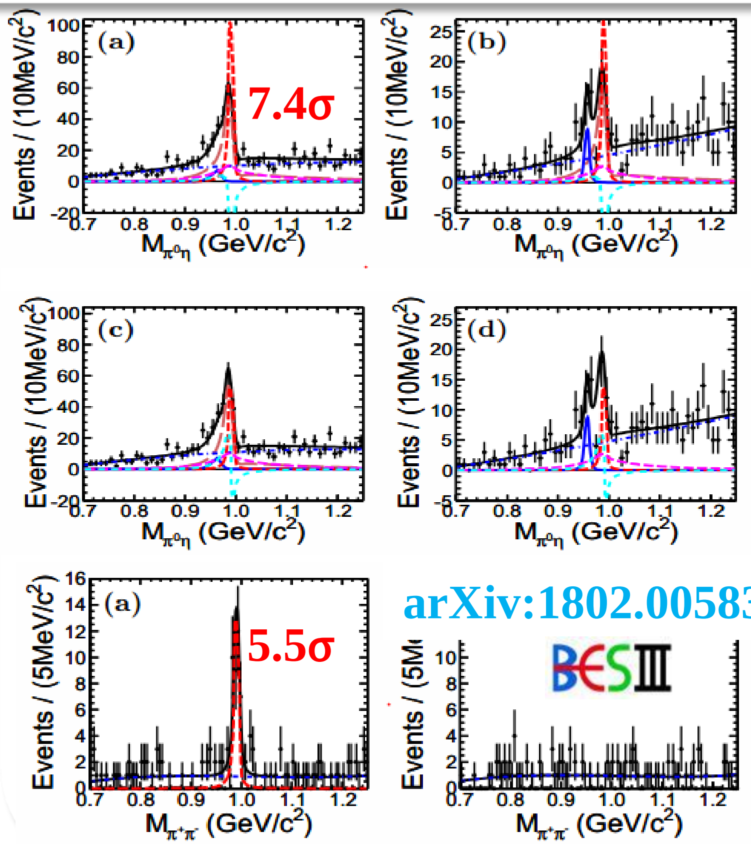


$a_0^0(980)$-$f_0(980)$ mixing

- **J.J. Wu, Q. Zhao, B.S. Zou proposed to directly measure $f_0(980) \leftrightarrow a_0^0(980)$ mixing via $J/\psi \to \phi a_0(980) \to \phi\eta\pi^0$ and $\chi_{c1} \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-$**
  [PRD 75 114012(2007), PRD 78 074017(2008)]
- **Mixing intensity is crucial to understand the nature of $a_0^0(980)$ and $f_0(980)$**

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

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



arXiv:1802.00583

Channel	$f_0(980) \to a_0^0(980)$ Solution I	Solution II	$a_0^0(980) \to f_0(980)$
$\mathcal{B}$(mixing)(10^{-6})	$3.18 \pm 0.51 \pm 0.38 \pm 0.28$	$1.31 \pm 0.41 \pm 0.39 \pm 0.43$	$0.35 \pm 0.06 \pm 0.03 \pm 0.06$
$\mathcal{B}$(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 (%)	$0.99 \pm 0.16 \pm 0.30 \pm 0.09$	$0.41 \pm 0.13 \pm 0.17 \pm 0.13$	$0.40 \pm 0.07 \pm 0.14 \pm 0.07$

Isospin violation and physical mechanism

Experimental phenomena:

1. $\mathbf{J/\psi \to \gamma\eta(1405) \to \gamma f_0(980)\pi^0 \to \gamma\pi^+\pi^-\pi^0}$

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

2. $\mathbf{J/\psi \to \phi f_1(1285) \to \phi f_0(980)\pi^0 \to \phi\pi^+\pi^-\pi^0}$

$$\frac{B(f_1(1285) \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-)}{B(f_1(1285) \to \pi^0 a_0^0(980) \to \pi^0\pi^0\eta)} = (3.6 \pm 1.4)\%$$

3. $\mathbf{J/\psi \to \phi a_0^0(980) \to \phi\eta\pi^0}$

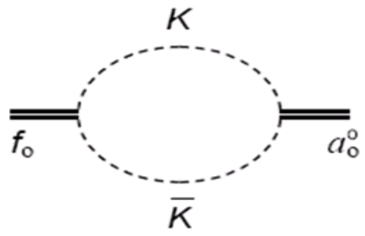
$$\frac{B(J/\psi \to \phi a_0^0(980) \to \phi\eta\pi^0)}{B(J/\psi \to \phi f_0(980) \to \phi\pi^+\pi^-)} < 1.0\%$$

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

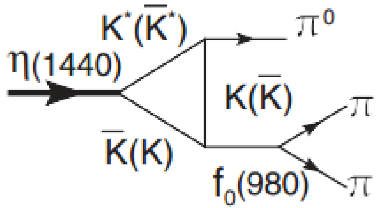
$$\frac{B(\chi_{c1} \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-)}{B(\chi_{c1} \to \pi^0 a_0^0(980 \to \pi^0\pi^0\eta))} < 1.0\%$$

Physical Mechanism:

1. $a_0^0(980)$-$f_0(980)$ **mixing**



2.Triangle Singularity (TS)



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

3. General "KK Loop" mechanism

N.N. Achasov et al PRD 93, 114027 (2016)
arXiv:1701.02122

Summary

- **Based on the largest data samples of J/ψ, ψ(2S) at BESIII, two highlight progress in light hadron are presented**

  X(18xx) states:

  $X(p\bar{p})$, X(1835), X(1810), X(1870), X(1840)

  Isospin violated processes and $a_0^0(980)$-$f_0(980)$ mixing

  $J/\psi \to \gamma\eta(1405) \to \gamma f_0(980)\pi^0 \to \gamma\pi^+\pi^-\pi^0$

  $J/\psi \to \phi f_1(1285) \to \phi f_0(980)\pi^0 \to \phi\pi^+\pi^-\pi^0$

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

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

- **J/ψ, ψ(2S) is excellent laboratory to study light hadron at BESIII**
- **More interesting results are expected to be coming soon!**

Thank you for your attention!