25th Anniversary of the Rencontres du Vietnam

Light Hadron decays at BESIII

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On behalf of the BESIII Collaboration

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BESIII

OUTLINE

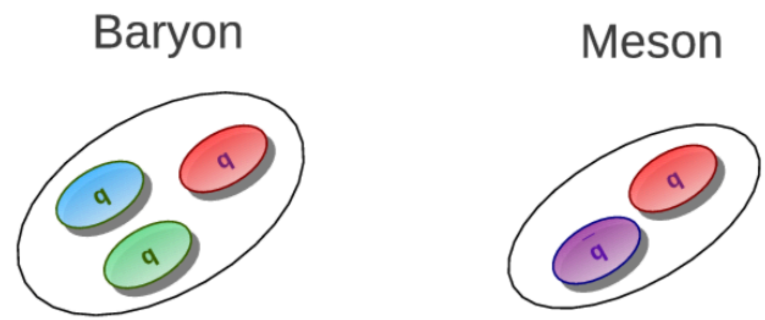
- ✓ INTRODUCTION:
  - Light hadron spectroscopy
  - The BESIII experiment

- ✓ Physics highlights
  - X(18??) states
  - $\eta(1405)/\eta(1475)$ puzzle
  - $e^+e^- \rightarrow \eta Y(2175)$ at $\sqrt{s} > 3.7$ GeV
  - Search for Z_S at $\sqrt{s} = 2.125$ GeV

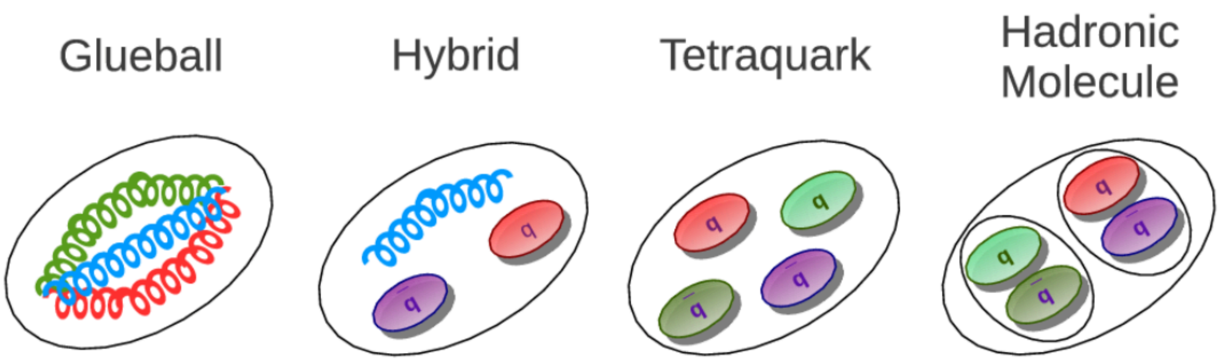
- ✓ Summary and Conclusions

Light Hadron Spectroscopy

<u>Naïve Quark Model:</u>
conventional hadrons
contain two or three quarks



… ***<u>but</u>*** QCD allows also different combinations of quarks and gluons: ***<u>EXOTIC</u>*** hadrons



……….

A lot of exotic states observed experimentally, but their nature is still far from being understood!!!

Hadron spectroscopy: establish the spectrum and study the exotic hadrons properties

Hunting for Glueballs

Charmonium radiative decays provide the ideal laboratory for light glueballs and hybrids, due to the gluon-rich environment, and the the clean high statistics from e^+e^- annihilation

Prediction from LQCD

- 0^{++} ground state: ~ 1.6-1.7 GeV/c^2
- 2^{++} first excited state: ~ 2.3 GeV/c^2
- 0^{-+} state: ~ 2.3-2.6 GeV/c^2

Glueballs can mix with ordinary quark-antiquark states

- The key problem is to identify those state with the dominant gluon component
- Predicted large BF for glueballs in J/ψ radiative decays

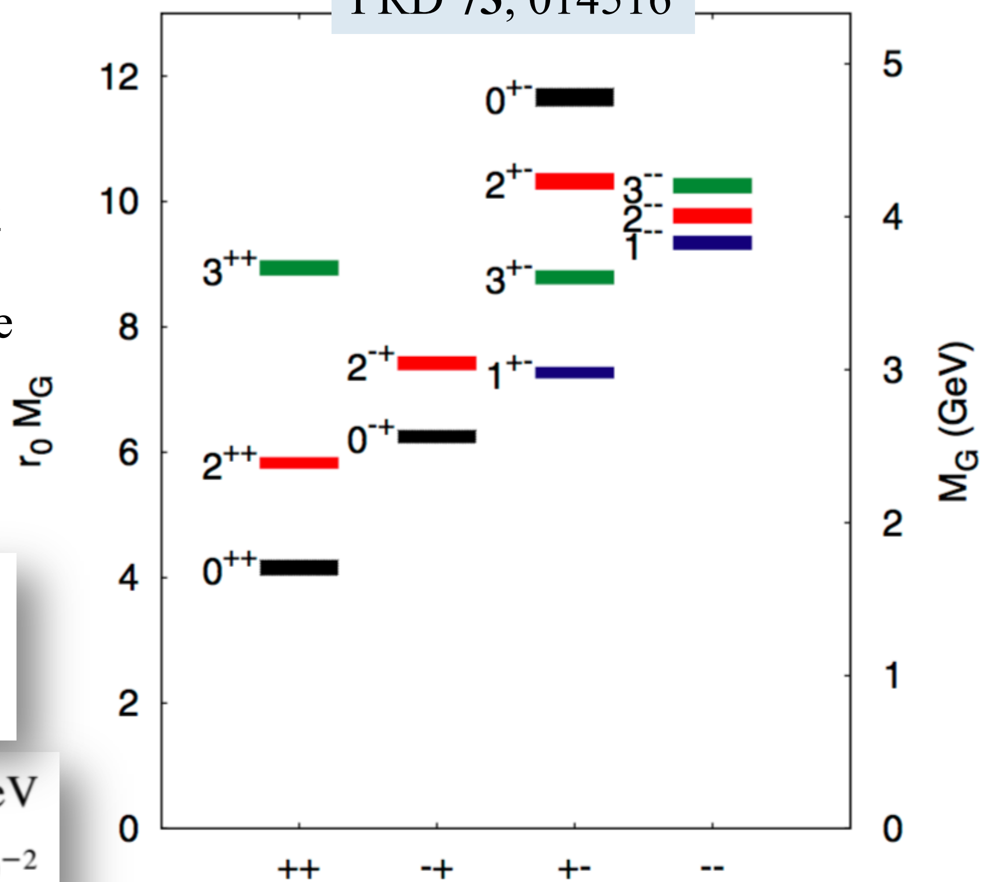
PRL**110**, 021601

$$\Gamma(J/\psi \to \gamma G_{0^{++}}) = 0.35(8)\ \text{keV}$$
$$\Gamma_{\text{tot}} = 92.9(2.8)\ \text{keV}$$
$$\Gamma(J/\psi \to \gamma G_{0^{++}})/\Gamma_{\text{tot}} = 3.8(9) \times 10^{-3}$$

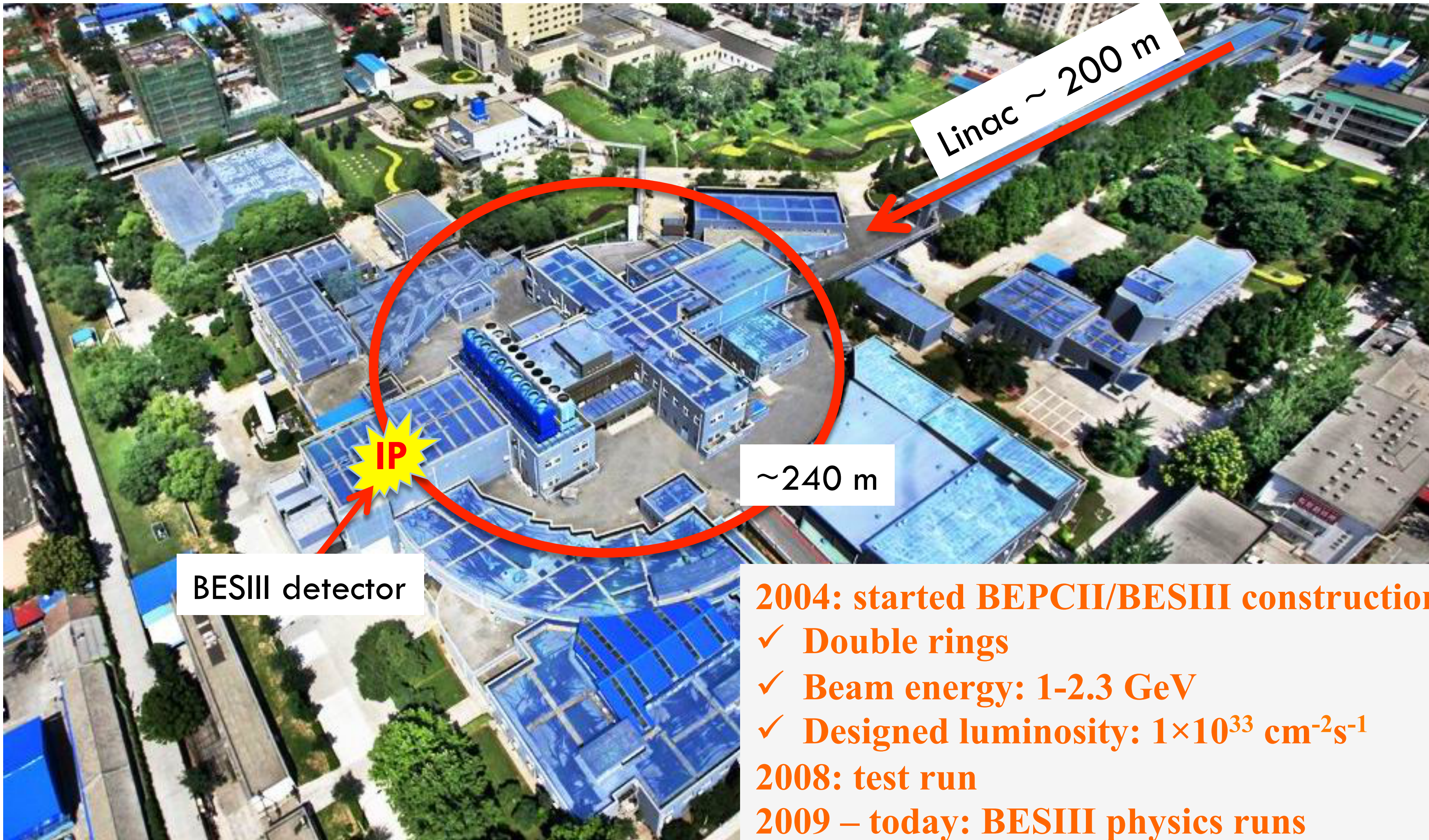
PRL**111**, 091601

$$\Gamma(J/\psi \to \gamma G_{2^{++}}) = 1.01(22)(10)\ \text{keV}$$
$$\Gamma(J/\psi \to \gamma G_{2^{++}})/\Gamma_{\text{tot}} = 1.1(2)(1) \times 10^{-2}$$

PRD **73**, 014516



Beijing Electron Positron Collider II

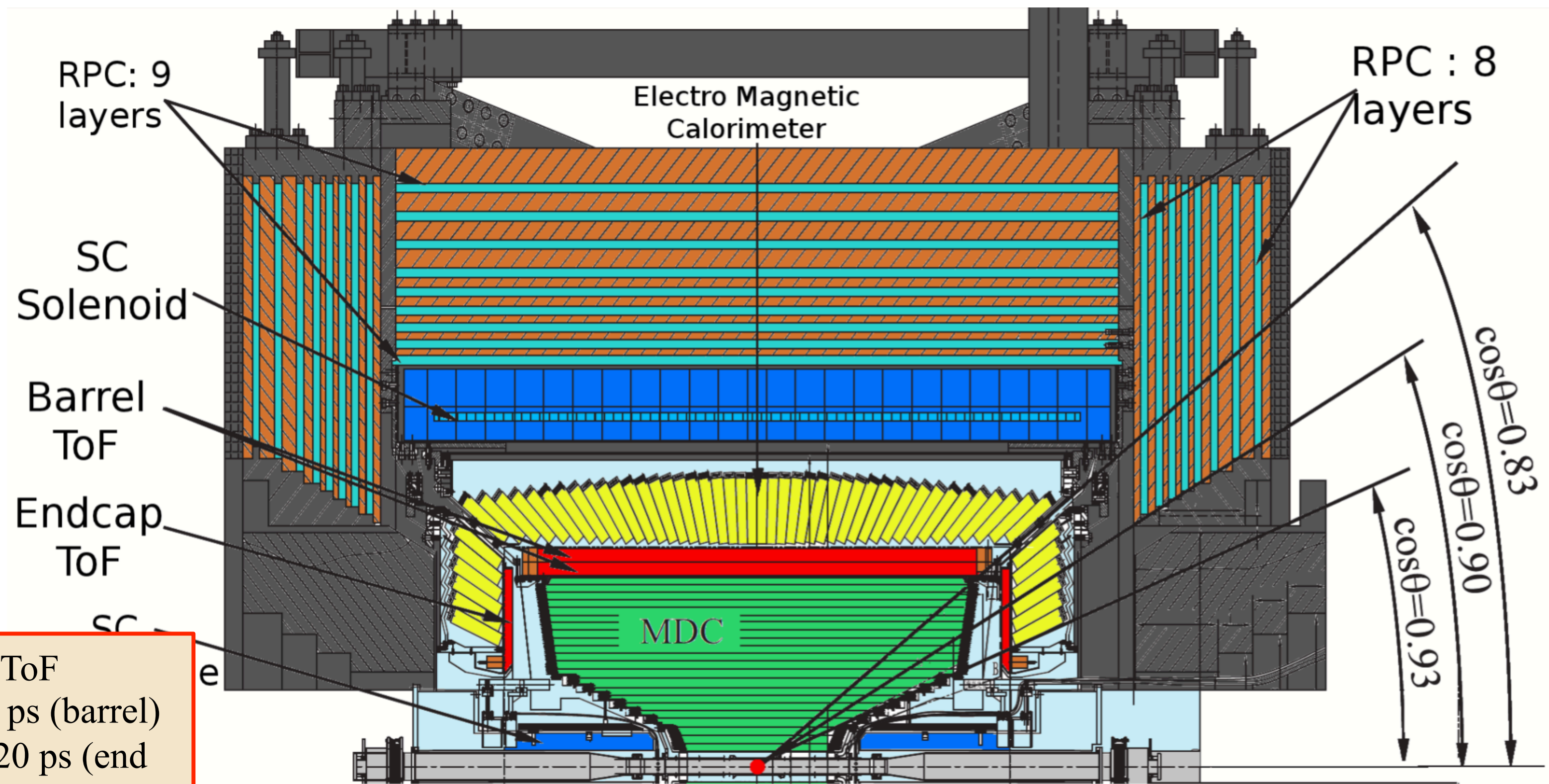


2004: started BEPCII/BESIII construction
- ✓ Double rings
- ✓ Beam energy: 1-2.3 GeV
- ✓ Designed luminosity: 1×10^{33} cm^{-2}s^{-1}

2008: test run
2009 – today: BESIII physics runs

The BESIII Detector

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



ToF
$\sigma_t \sim$ 90 ps (barrel)
$\sigma_t \sim$ 120 ps (end caps)

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

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

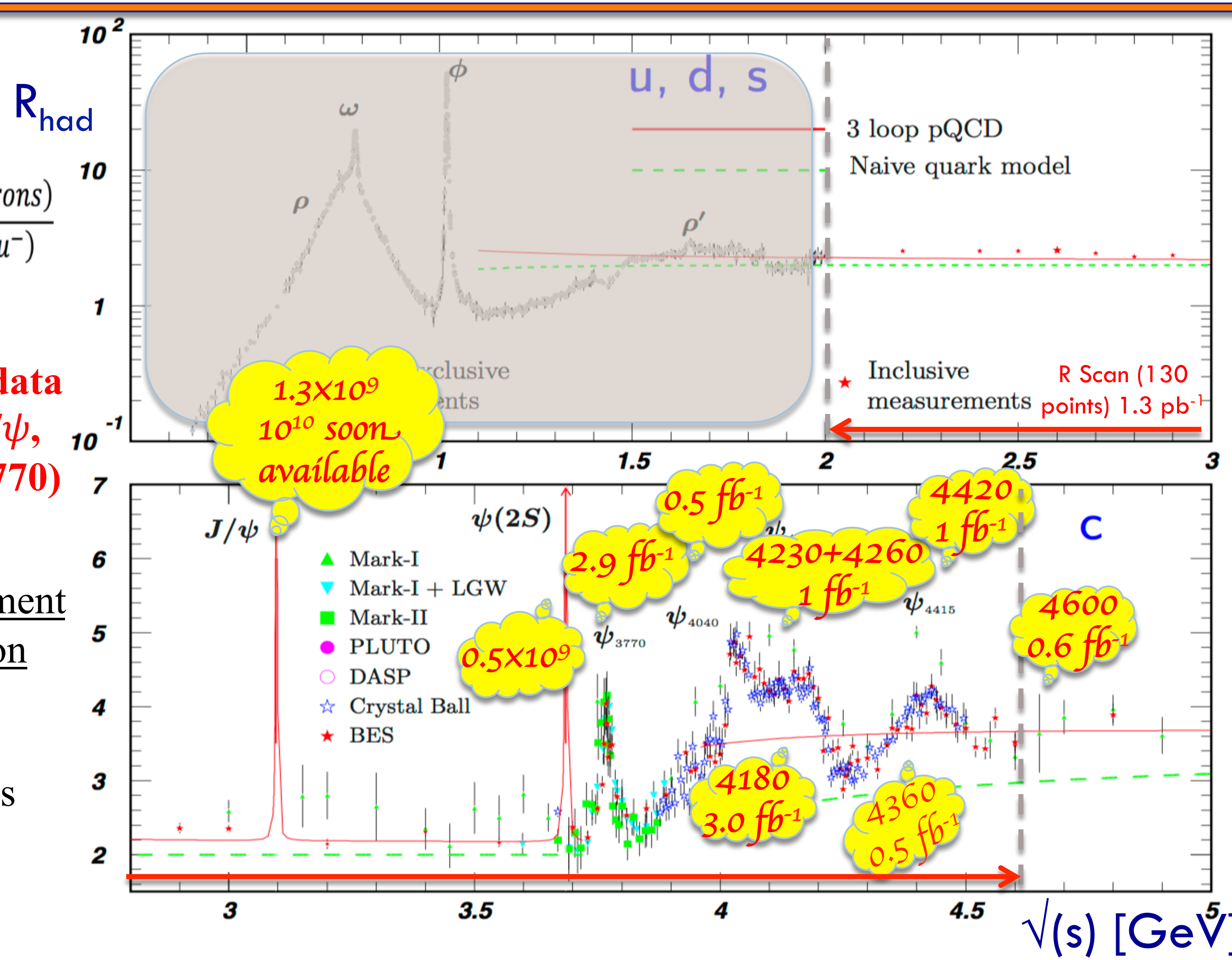
RPC Muon Detector
$\Delta\Omega/4\pi$=93%

The BESIII data set

$$R_{had} = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

World largest data samples for J/ψ, ψ(2S) and ψ(3770)

- Light hadron: ideal environment for light hadron spectroscopy studies
- Charm physics
- Charmonium spectroscopy

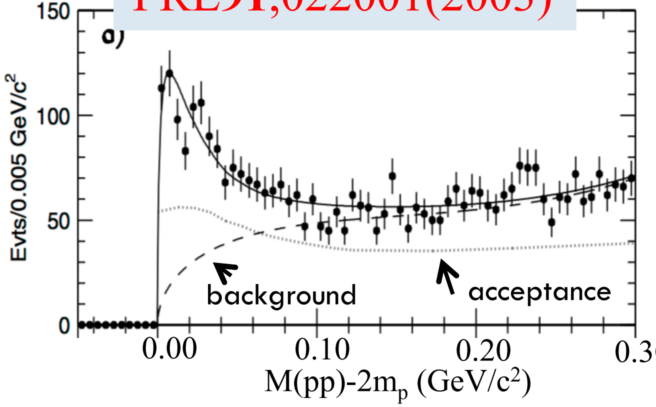


http://pdg.lbl.gov/2017/reviews/rpp2017-rev-cross-section-plots.pdf

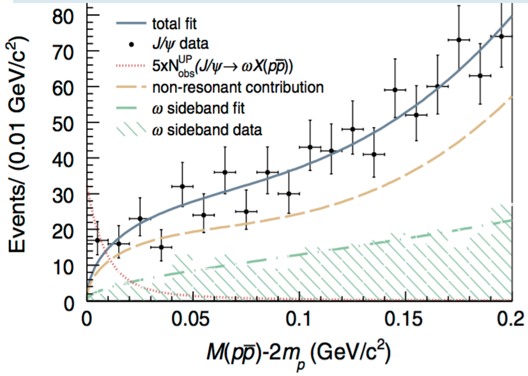
$J/\psi \to \gamma p\bar{p}$: threshold enhancement in $p\bar{p}$ mass

- Enhancement observed more than 10 years ago at BESII and confirmed by CLEO-c [PRD82,092002] and BESIII [CPC 34, 421]
- What about its nature ?
  - Final-State Interaction effect? [NPA929, 102; A. Milstein @ PhiPsi2017]
- No similar structures observed in related channels

PRL**91**,022001(2003)



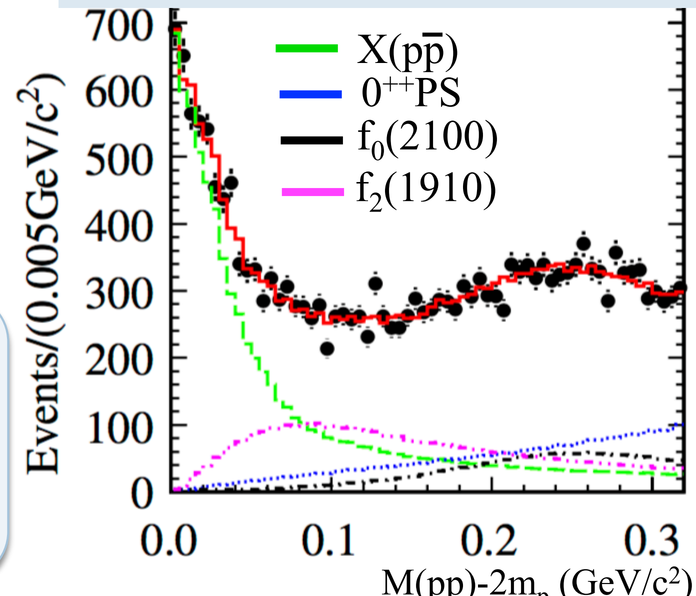
$J/\psi \to \omega p\bar{p}$ PRD 87, 112004



Confirmed also in a PWA of the $J/\psi \to p\bar{p}\gamma$ channel in the region below 2.2 GeV using 225M J/ψ decays

- Four components included in the PWA fit
- $J^{PC} = 0^{-+}$ ($> 30\,\sigma$)

BESIII: PRL**108**,112003(2012)



$$M = 1832^{+19}_{-5}(\text{stat})\ ^{+18}_{-17}(\text{syst}) \pm 19(\text{model})\ \text{MeV}/c^2$$

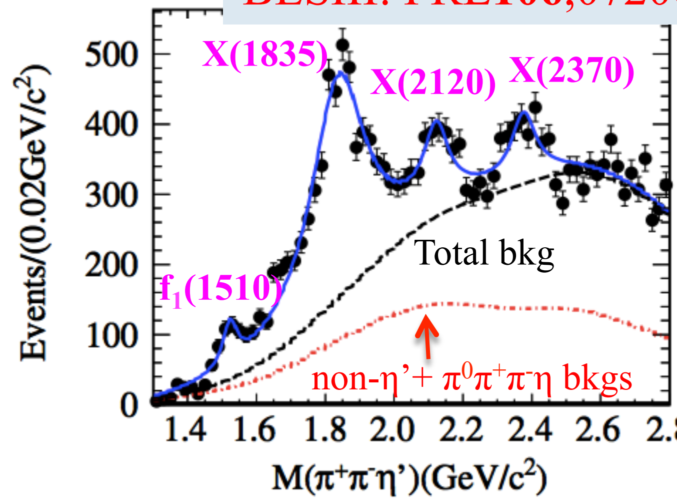
$$\Gamma < 76\ \text{MeV} \ @\ 90\%\ \text{C.L.}$$

$$BR_{[J/\psi \to \gamma X]} \times BR_{[X \to pp]} = (9.0^{+0.4}_{-1.1}(\text{stat})^{+1.5}_{-5.0}(\text{syst}) \pm 2.3(\text{model})) \times 10^{-5}$$

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

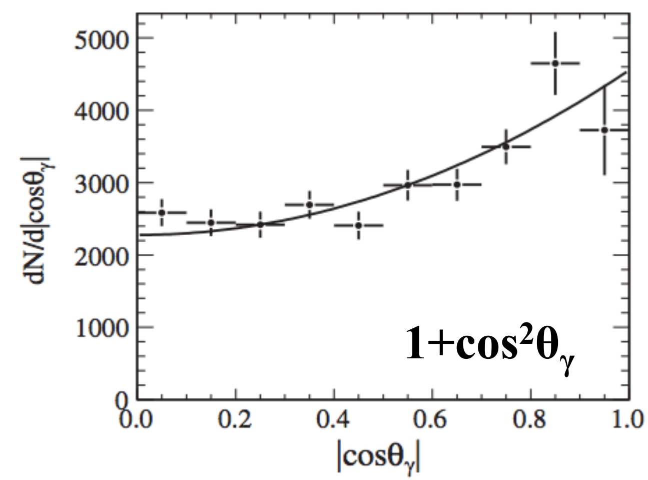
- X(1835) was first observed at BES, and then confirmed at BESII [PRL95,262001]
- Two additional structures observed at BESIII
- Many interpretation: $p\bar{p}$ bound state? Glueballs? Radial excitation of the η' meson

BESIII: PRL**106**,072002



- BESIII $J/\psi \rightarrow \gamma\pi^-\pi^+\eta'$: PRL **106,** 072002
  - 225M J/ψ events
  - $\eta' \rightarrow \gamma\pi^-\pi^+$ and $\eta' \rightarrow \eta_{\gamma\gamma}\pi^-\pi^+$
  - 4 resonances (BW⊗Gauss)+non-resonant η' $\pi^-\pi^+$ (from MC) + non-η' and $\pi^-\pi^+\pi^0\eta'$ bkgs

Resonance	M(MeV/c^2)	Γ(MeV/c^2)
$f_1(1510)$	1522.7 ± 5.0	48 ± 11
$X(1835)$	1836.5 ± 3.0	190.1 ± 9.0
$X(2120)$	2122.4 ± 6.7	83 ± 16
$X(2370)$	2376.3 ± 8.7	83 ± 17



- The polar angle distribution of the photon in the J/ψ center-of-mass system supports $J^{PC}=0^{-+}$ → need PWA analysis to determine spin-parity assignment

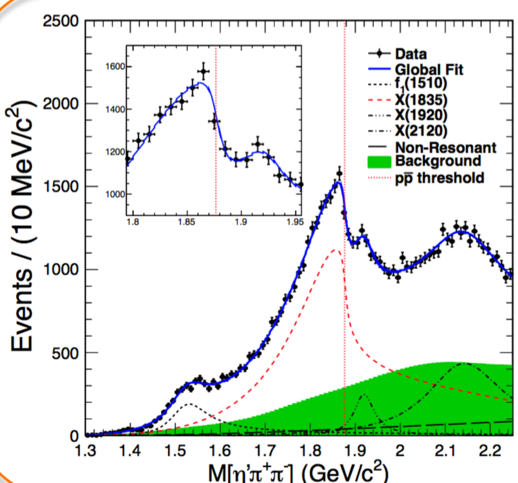
New: connection between X(1835) and X($p\bar{p}$)

The study of the $\eta'\pi^-\pi^+$ line shape at the $p\bar{p}$ threshold with high statistical precision provides valuable information on the X(1835) and X($p\bar{p}$) nature

BESIII: PRL**117**,042002

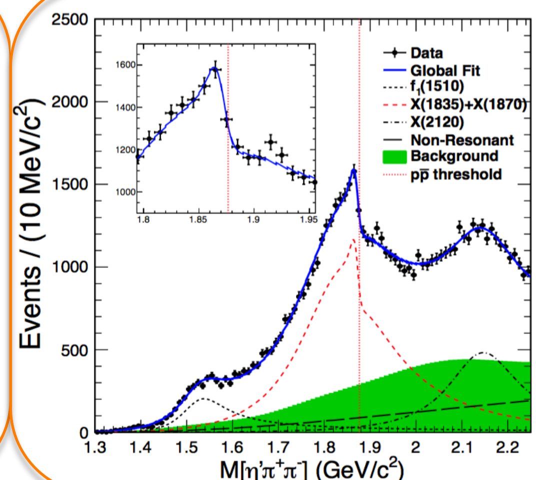
- 1.09×10^9 J/ψ events collected in 2012
- $\eta' \rightarrow \gamma\pi^-\pi^+$ and $\eta' \rightarrow \eta_{\gamma\gamma}\pi^-\pi^+$

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



Threshold structure due to the opening of additional decay mode

- Flatté formula (PLB**63**, 224)
- X(1920) needed (5.7σ)



Interference between two resonances

- Coherent sum of two BW amplitudes : X(1835) and a narrow resonance called X(1870)

- The two models used to describe the data give almost equal fit quality
- Both fits support the existence of one of
  - a $p\bar{p}$ molecule-like state (broad state)
  - an unconventional meson, most likely a $p\bar{p}$ bound state (narrow state)

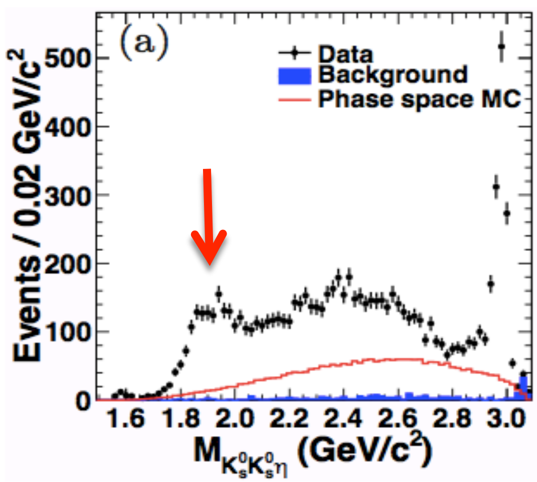
$X(1835)$ in $J/\psi \to \gamma K_S^0 K_S^0 \eta$

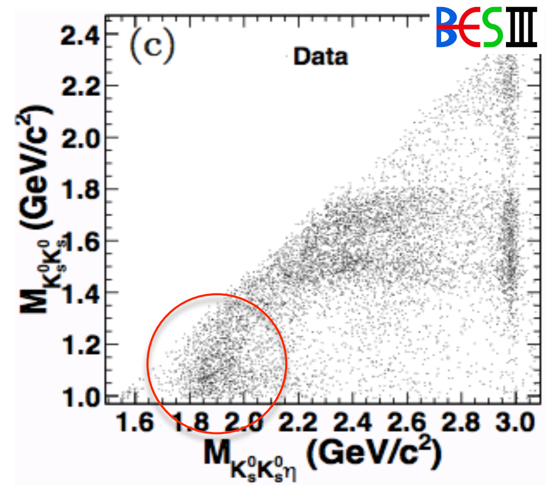
BESIII: PRL**115**,091803

$J/\psi \to \gamma K^0_S K^0_S \eta$ provides a clear environment: first measurement in this channel

- $K^0_S K^0_S \eta$ 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
- Structure around 1.85 GeV/c^2
- Strong correlation between the $f_0(980)$ (near the $K^0_S K^0_S$ threshold) and the structure near 1.85 GeV/c^2
- $M(K^0_S K^0_S)<1.1$ GeV/c^2 ➔ the structure near 1.85 GeV/c^2 became more pronounced

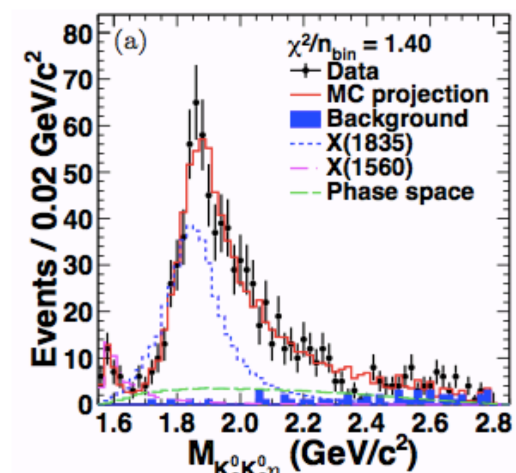




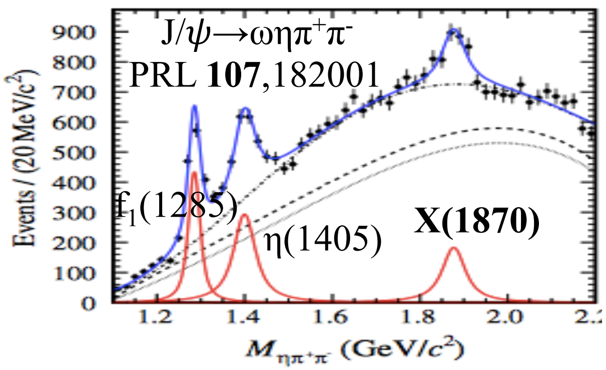
PWA of events with $M(K^0_S K^0_S)<1.1$ GeV/c^2 and $M(K^0_S K^0_S \eta)<2.8$ GeV/c^2

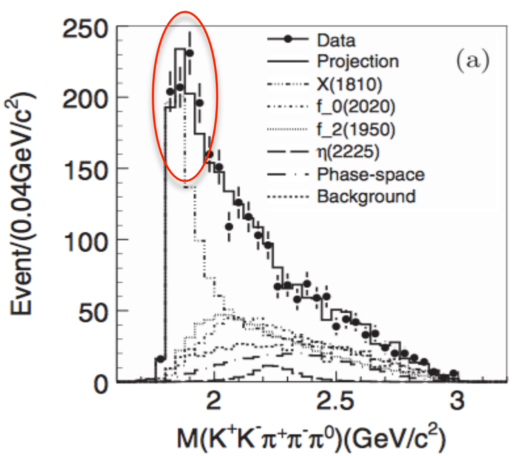
FIT RESULTS: $X(1835)\to f_0(980)\eta$, $X(1560)\to f_0(980)\eta$, and a non-resonant $f_0(1500)\eta$ components

- **$J^{PC} = 0^{-+}$** for $X(1835)$ ($>12.9\sigma$): M and Γ consistent with PRL106, 072002
- **$J^{PC} = 0^{-+}$** for $X(1560)$ ($>8.9\sigma$): M and Γ consistent with $\eta(1405)/\eta(1475)$ (PRD) within 2σ. More statistics needed

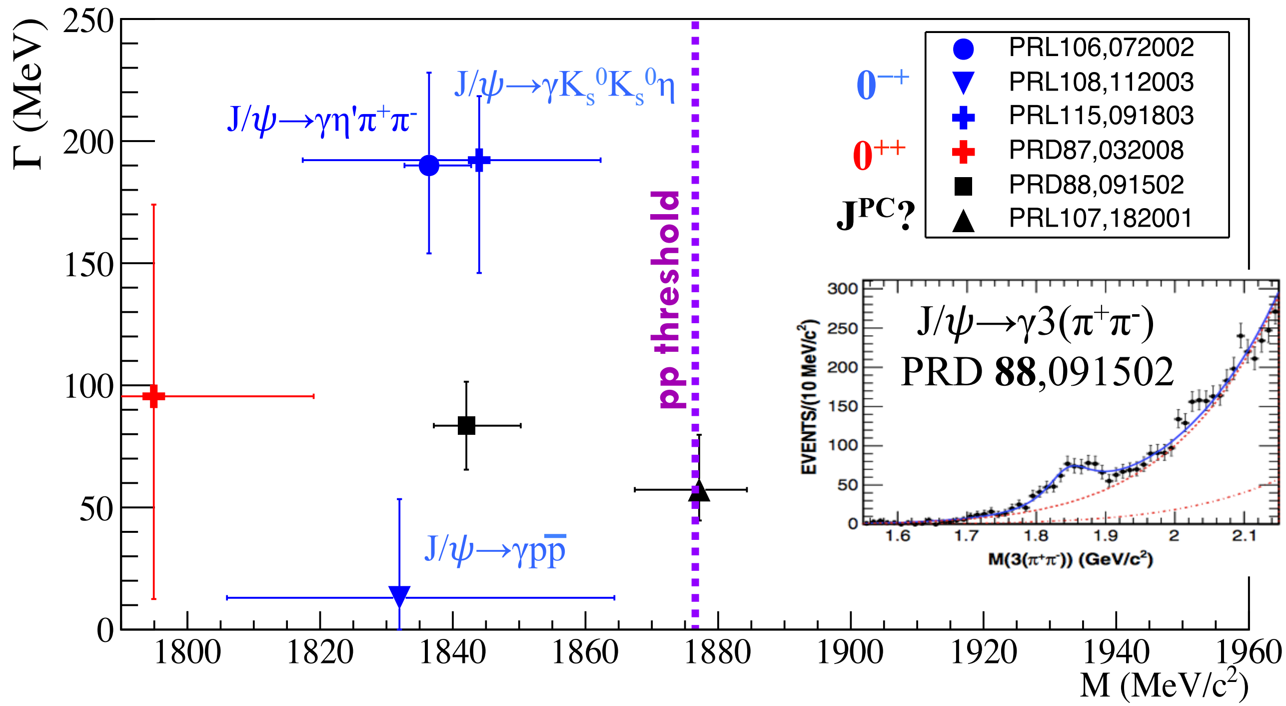


Other BESIII observations





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



X states near proton-antiproton threshold

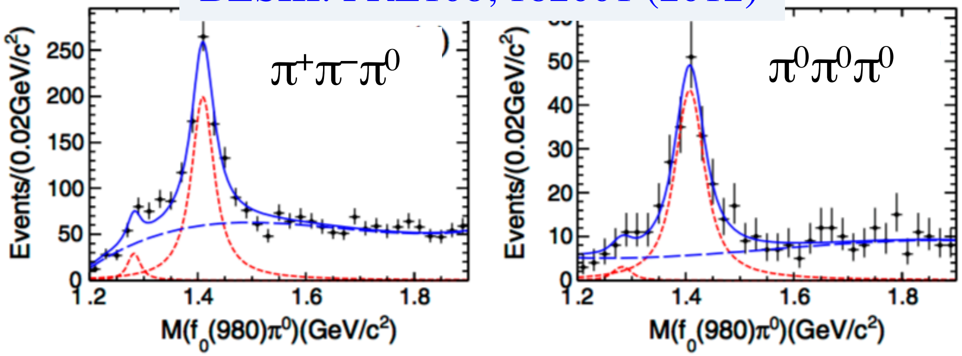
- X($p\bar{p}$) in agreement with X(1835), while its width is significantly different
- **Are they the same particles?**
- **More studies are needed to answer this question**

η (1405)/η (1475) puzzle

$\eta(1405)/\eta(1475)$: are they two different states or a $J^{PC} = 0^{-+}$ state in different decay modes?

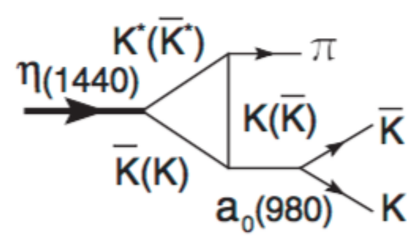
- PWA $J/\psi \to \gamma K^0_S K^{\pm}\pi^{\mp}$ by MARKIII (PRL 65, 2507 (1990)): mixture of two states in the $K^0_S K^{\pm}\pi^{\mp}$ invariant mass region around 1400 MeV/c^2
    - Described by $a^0(980)\pi$ and $K^*\overline{K}$ amplitudes
    - Confirmed by Crystall Barrel and Obelix (PLB545, 261)
    - No observation by L3 on $\eta(1405)$; both states not found by CLEO
- First observation of $\eta(1405)$ decays into the isospin violating decay $f_0(980)\pi^0$ with an anomalously narrower $f_0(980)$ width than the world average

BESIII: PRL108, 182001 (2012)



The triangle singularity (TS) could be a natural solution for the long-standing puzzle about the *$\eta(1405)/\eta(1475)$* nature

TS mechanism: can lead to different mass spectra for $\eta(1405)/\eta(1475) \to \overline{K}K^*$+cc and $a_0(980)\pi^0$ and explain the isospin-violating decay into $f_0(980)\pi^0 \to 3\pi$



η (1475) and X(1835) in $J/\psi\rightarrow\gamma\gamma\phi$

PRD**97**,051101(R)(2018)

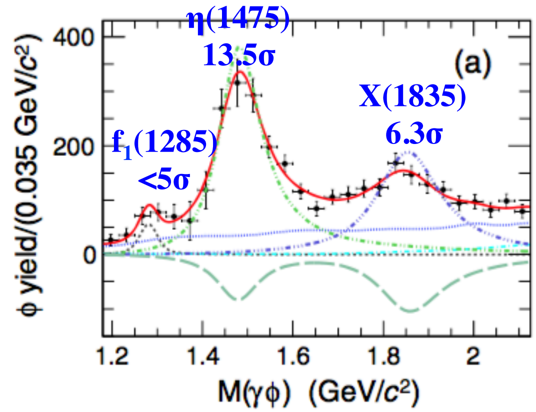
- Two structures corresponding to η(1475) and X(1835) are observed
- Binned least-χ2 fit to $M(\gamma\phi)$

$$BW_{\text{total}} = (BW_0^2(s) + |A_1 \times BW_1(s) + A_2 \times BW_2(s) \times e^{i\varphi}|^2) \otimes G(m_0, \sigma(s)) \times \varepsilon(s),$$

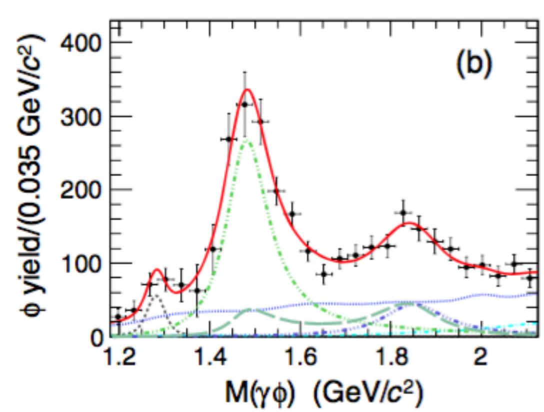
- Polar angle distributions of the radiative photon favor 0^{-+} assignment
- Γ(η→γρ):Γ(η→γϕ) is slightly larger than the prediction of 3.8:1 in PRD87, 014023 for the case of single pseudoscalar case

INTERPRETATION:

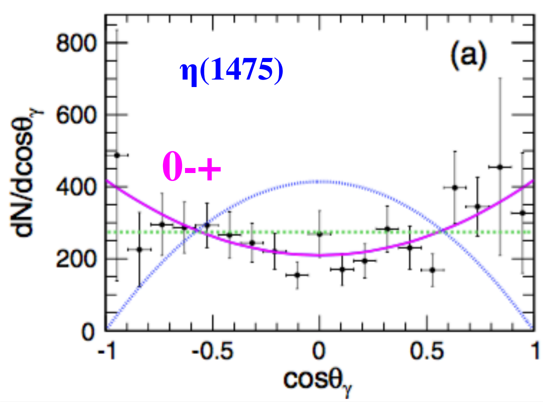
- **Sizable $s\bar{s}$ component**
- η(1475) should be the radial excitation of the η' (PRD70,114033), if η(1405) and η(1475) are different states

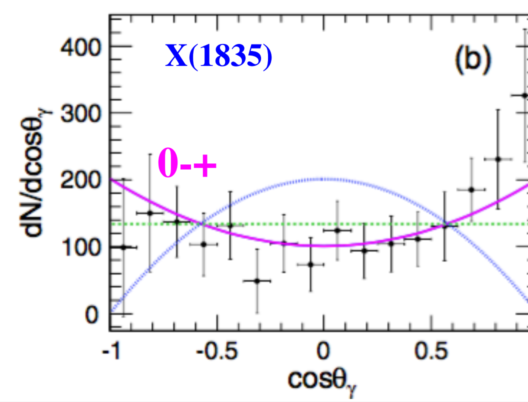


Sol. II: Constructive Int.



Sol. I: Destructive Int.

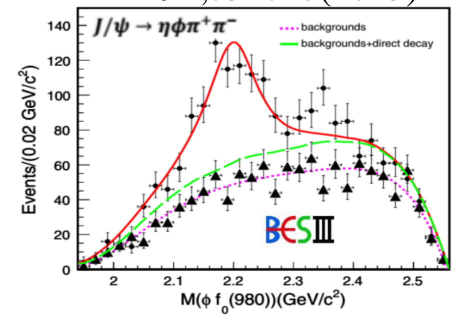




Solution	Resonance	m_R (MeV/c^2)	Γ (MeV)	$\mathcal{B}$ (10^{-6})
I	$\eta(1475)$	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$	$7.03 \pm 0.92 \pm 0.91$
	$X(1835)$	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$	$1.77 \pm 0.35 \pm 0.25$
II	$\eta(1475)$	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$	$10.36 \pm 1.51 \pm 1.54$
	$X(1835)$	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$	$8.09 \pm 1.99 \pm 1.36$

Observation of $e^+e^- \to \eta Y(2175)$ @ $\sqrt{s} > 3.7$ GeV

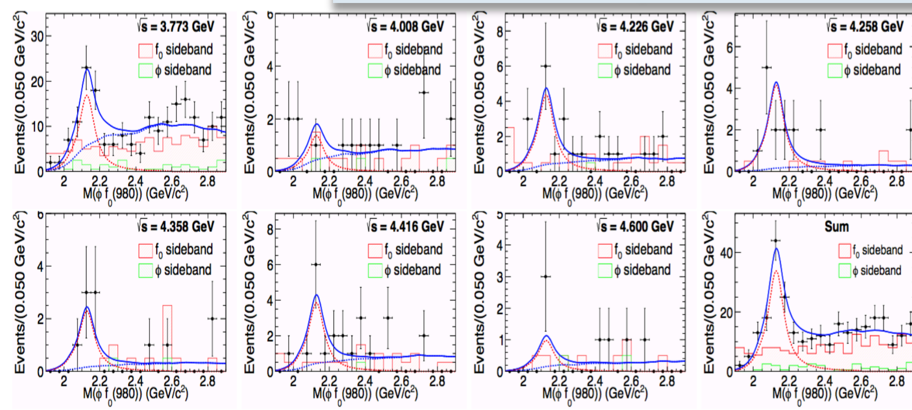
PRD91,052017(2015)



- The Y(2175) (<u>ϕ(2170) in the PDG</u>) was observed by BaBar (PRD74, 091103(2006)), and confirmed by Belle (PRD80,031101(2009)) and BESIII
- Y(2175) is regared as **strangeonium-like state**
  - Candidate for a tetraquark state, a strangeonium hybrid state, or a conventional ss state

➢ Search for Y(2175) resonance in the process $e^+e^- \to \eta\phi f_0(980)$ using data collected at the center-of-mass energies between 3.7 and 4.6 GeV

arXiv:1709.04323 (submitted to PRD)



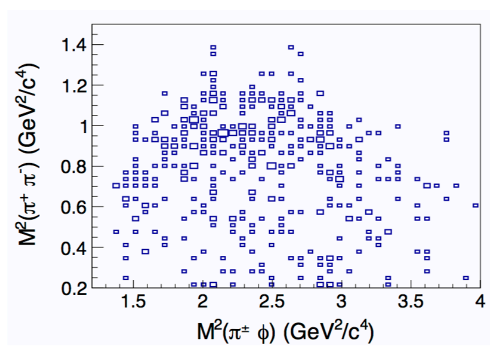
➢ The simultaneous fit result to all data sample give a **statistical significance larger than 10σ**

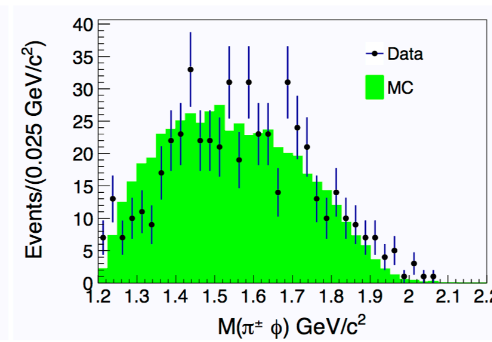
➢ In analogy with the Y(4260) and ϒ(10860), the Y(2175) represents a unique place to search for Z_s state in $\phi\pi^\pm$ spectrum

  ➢ no significant signal is observed

➢ No significant $\psi(3686) \to \eta Y(2175)$ signal observed

➢ No signicant $e^+e^- \to \eta' Y(2175)$ signal observed





Search for Z_S @ $\sqrt{s} = 2.125$ GeV

arXiv:1801.10384(2018) – submitted to PRL

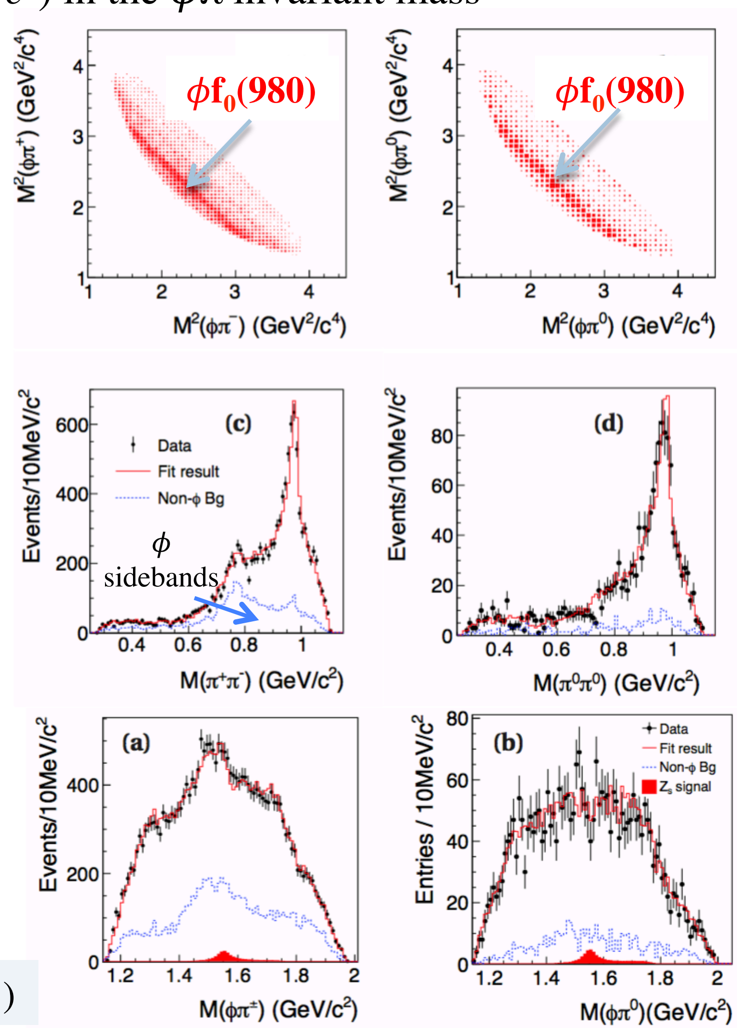
- We search for Z_S a strangeonium-like structure via $e^+e^- \to \phi\pi^+\pi^-(\phi\pi^0\pi^0)$ using 108 pb^{-1} of data collected at $\sqrt{s} = 2.125$ GeV
  - Structure expected around the K^*K threshold (1.4 GeV/c^2) in the $\phi\pi$ invariant mass
- PWA analysis performed

Four subprocesses considered:
- ➢ $\phi\sigma$
- ➢ $\phi f_0(980)$
- ➢ $\phi f_0(1370)$
- ➢ $\phi f_2(1270)$
- ➢ Non-ϕ bkg from ϕ sidebands (non-interfering term)

+ Z_S component
- ➢ $J^P = 1^+$ and 1^-
- ➢ Only S-wave contribution
- ➢ $M = (1.2\text{-}1.95)$ GeV/c^2
- ➢ Γ: steps of 0.05 GeV

- ➢ No clear Z_S signal is observed:
  - Maximum local significance = 3.3σ at $M(Z_S)$ = 1.55 GeV/c^2 and $\Gamma(Z_S)$ = 50 MeV
  - 90% C.L. upper limit on the cross section for Z_S production are determined
  - More data to check for the single pion emission mechanism (ISPE)
- ➢ $\sigma(e^+e^- \to \phi\pi^+\pi^-) = (343.0 \pm 5.1 \pm 25.1)$ pb
- ➢ $\sigma(e^+e^- \to \phi\pi^0\pi^0) = (208.3 \pm 7.6 \pm 13.5)$ pb

Within 3σ from BaBar (PRD86,012008) and Belle (PRD80, 031101)



Conclusions

- BESIII is successfully operating since 2008, and continues to take data
  - This year, *BESIII has collected about 4.6 billion of new J/ψ data*, which will be analysed soon
  - *Additional 4 billions of J/ψ events will be collected in 2019,* ***for a total statistics of 10 billion of J/ψ data***
- *Excellent laboratory to study hadron spectroscopy*, complementary to scattering and photon production experiments
  - High statistics
  - Low backgrounds
- Many interesting results have been obtained, and only a small part are covered in this talk

FUTURE

- More data will be collected
- Inner Drift Chamber replacement with CGEM detector
- Higher luminosity and energy upgrade expected from BEPCII
- More detailed studies will be done

Back-up slides

The BESIII Collaboration

EUROPE

Bochum University, Budker Instituteof Nuclear Physics, **Ferrara University**, GSI Darmstadt, Helmholtz Institute Mainz, **INFN, Laboratori Nazionali di Frascati**, Johannes Gutenberg University of Mainz, Joint Institute for Nuclear Research (JINR), KVI/ University of Groningen,Turkish Accelerator Center Particle Factory Group (TAC-PF),Universitaet Giessen, University of Münster, **University of Turin**, Uppsala University

USA

Carnegie Mellon University; Indiana University; University of Hawaii; University of Minnesota; University of Rochester

CHINA

IHEP, CCAST, UCAS, Beijing Institute of Petro-chemical Technology, Beihang Univ., Guangxi Normal Univ., Guangxi Univ., Hangzhou Normal Univ., Henan Normal Univ., Henan Univ. of Science and Technology, Huazhong Normal Univ., Huangshan College, Hunan Univ., Lanzhou Univ., Liaoning Univ., Nanjing Normal Univ., Nanjing Univ., Nankai Univ., Peking Univ., Shanxi Univ., Sichuan Univ., Shandong Univ., Shanghai Jiaotong Univ., Soochow Univ., Southeast Uny., Sun Yat-sen Univ., Tsinghua Univ., Univ. of Jinan, Univ. of Science and Technology of China, Univ. of Science and Technology Liaoning, Univ. of South China, Wuhan Univ., Zhejiang Univ., Zhengzhou Univ.

~350 members
66 institutions from
14 countries

OTHER IN ASIA

COMSATS Institute of Information Technology (CIIT), Institute of Physics and Technology, Mongolia; Tokyo University; Seoul National University; University of the Punjab

http://bes3.ihep.ac.cn

BESIII physics programme

Light hadron physics

- Meson and baryon spectroscopy
- Multiquark states
- Threshold effects
- Glueballs and hybrids
- two-photon physics
- Form factors

QCD and τ

- Precision R measurement
- τ decay

Charmonium physics

- Precision spectroscopy
- Transitions and decays

XYZ meson physics

- Y(4260), Y(4360) properties
- $Z_c(3900)^+$, …

Charm physics

- Semi-leptonic form factors
- Decay constants f_D and f_{Ds}
- CKM matrix: $|V_{cd}|$ and $|V_{cs}|$
- D^0-$\overline{D}^0$ mixing, CPV
- Strong phases

Precision mass measurements

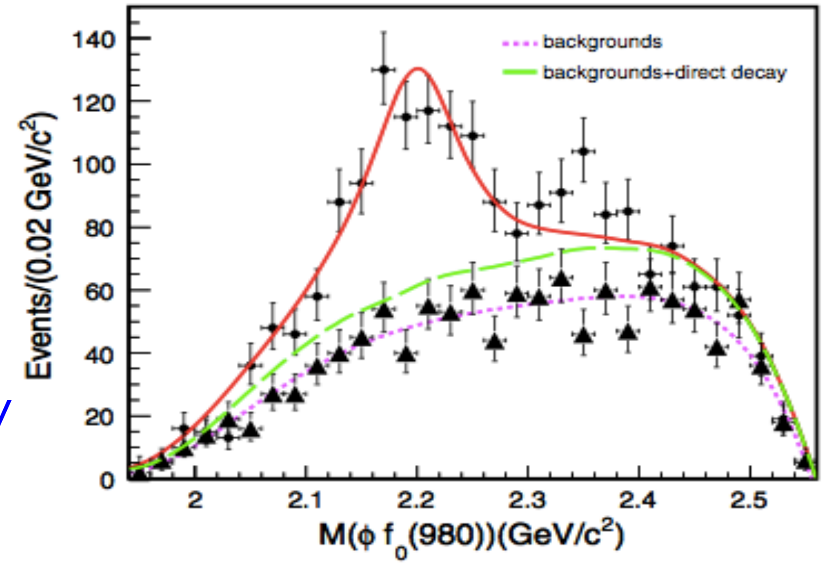
- τ mass
- D, D^* mass

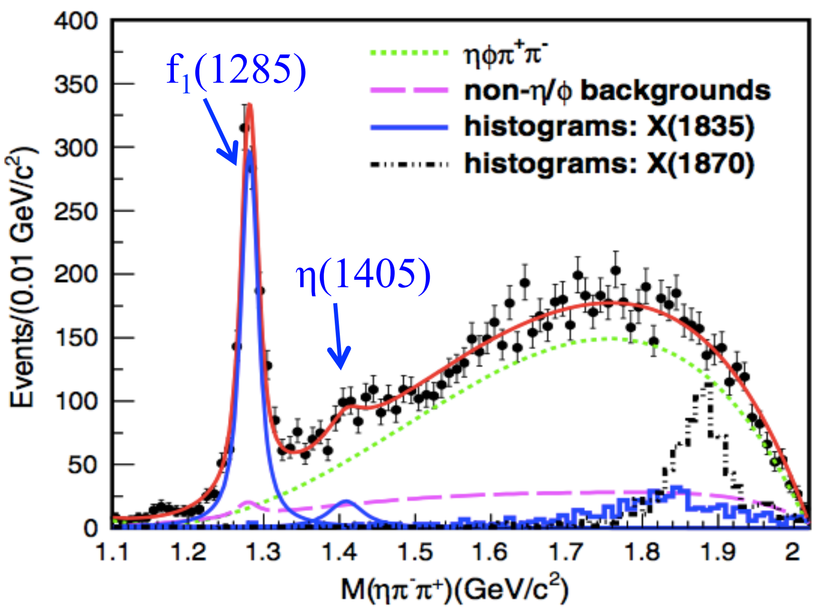
Study of $J/\psi \to \eta\phi\pi^+\pi^-$

BESIII: PRD**91**,052017

- Study based on 2.25×108 J/ψ events
- Unbinned maximum likelihood fit is performed to the $\phi f_0(980)$ invariant mass distribution
- No interference between Y(2175) and direct three-body decay of $J/\psi \to \eta\,\phi f_0(980)$
- Y(2175) resonance observed with a significance greater than **10σ**

M=2200 ± 6 ± 5 MeV/c^2, Γ=104 ± 15 ± 15 MeV





ηππ mass spectrum recoiling against the ϕ:

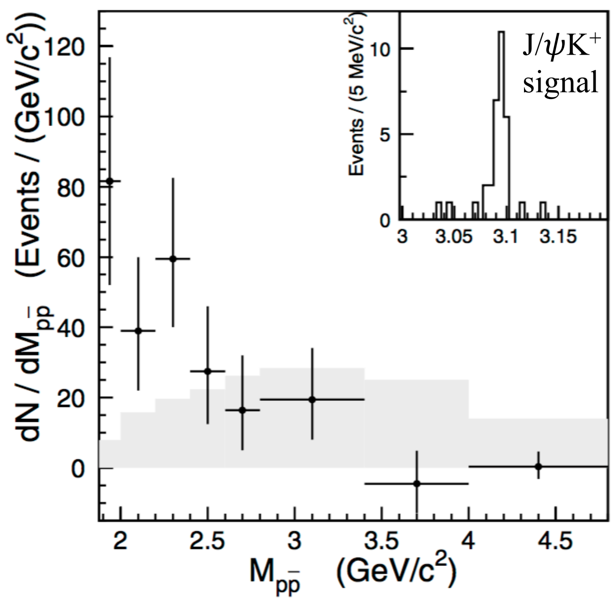
- Fit includes contributions from the $f_1(1285)$ and η(1405) signals, the $J/\psi \to \eta\,\phi\pi\pi$ decay, and backgrounds from non-η and non-ϕ processes
- No evidence of X(1835) and X(1870) states

$\mathcal{B}(J/\psi \to \phi f_1 \to \phi\eta\pi\pi) = (1.20 \pm 0.06 \pm 0.14) \times 10^{-4}$

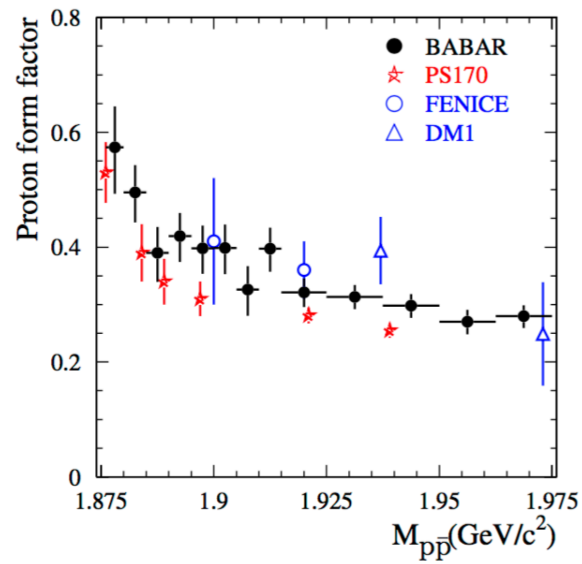
$\mathcal{B}(J/\psi \to \phi\eta(1405) \to \phi\eta\pi\pi) = (2.01 \pm 0.58 \pm 0.82) \times 10^{-5}$

ppbar enhancement in other reactions

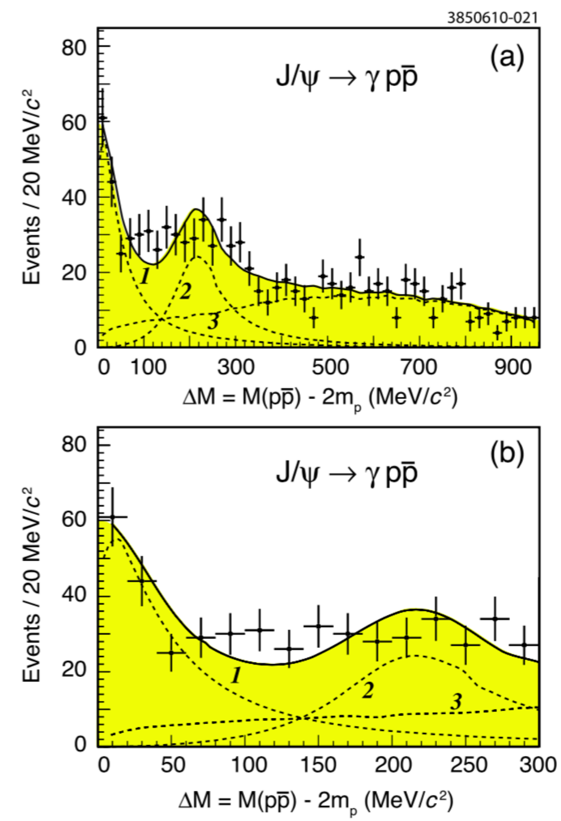
Belle: PRL**88**, 181803
$B^+ \to ppK^+$



BaBar: PRD**73**, 012005
$e^+e^- \to \gamma ppar$

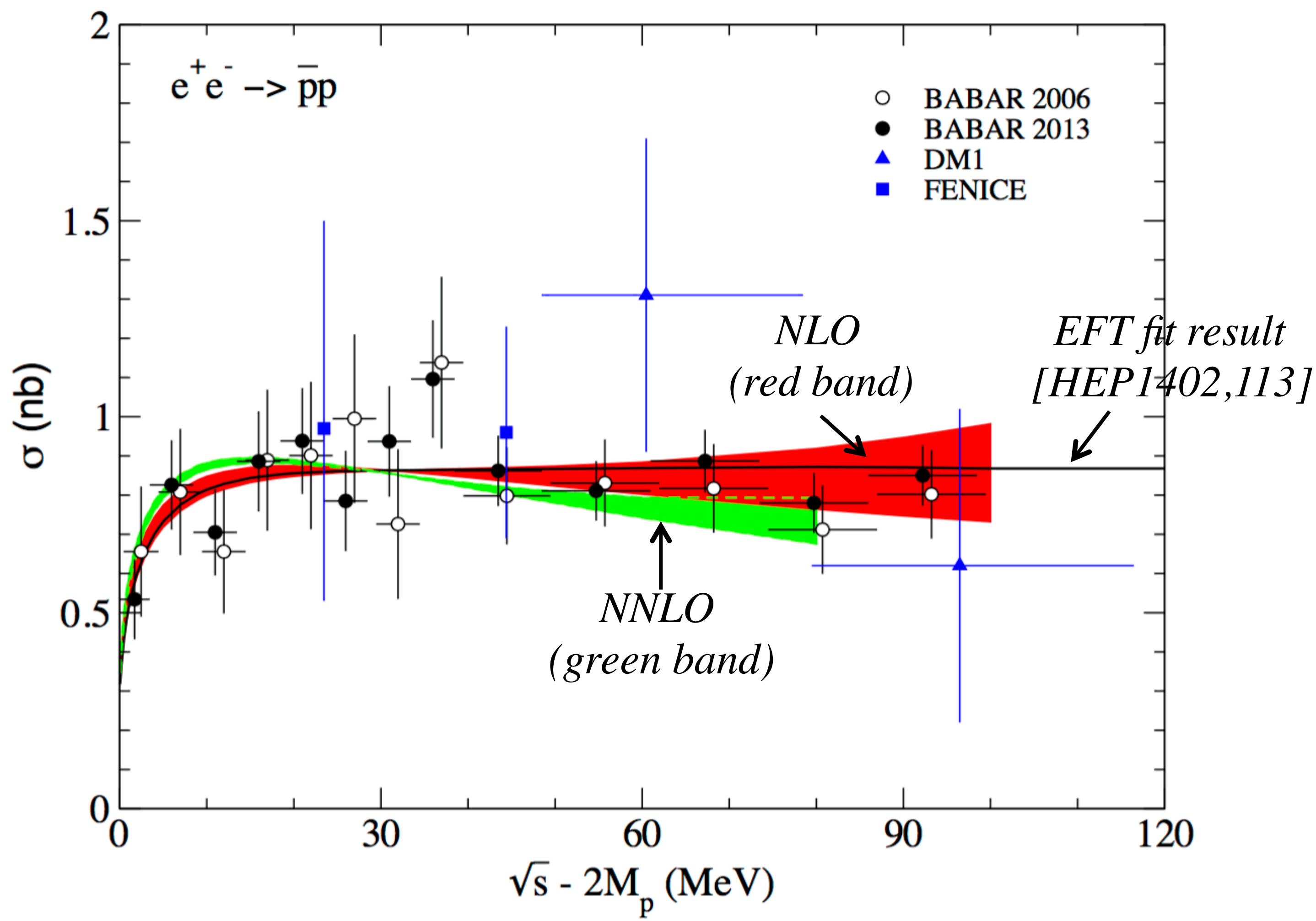


CLEO: PRD**82**, 092002
$\psi' \to \pi^+\pi^- J/\psi$



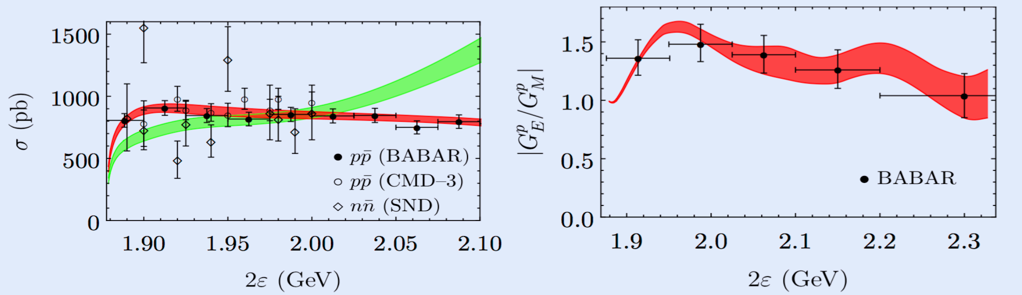
- Enhancement also seen in other B decays
- FSI? Sub-threshold resonance?
- Not enough statistic to draw any conclusion

Final State interaction [NPA 929, 102]



Final State interaction [A. Milstein, PhiPsi2017, Maitz]

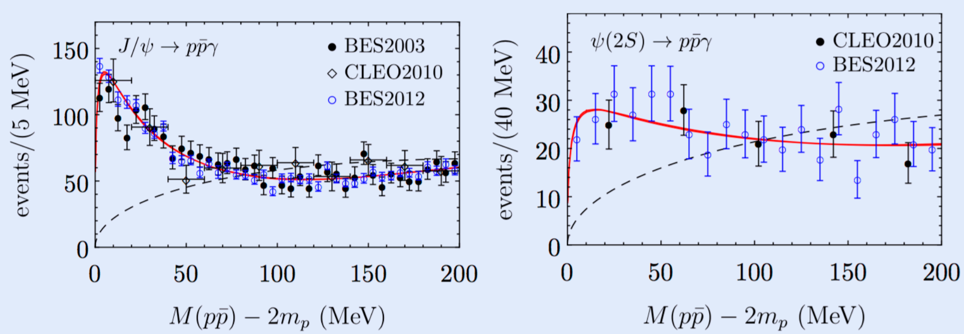
Predictions for the cross section of $e^+e^- \to N\bar{N}$ near the threshold



Left: the cross sections of $p\bar{p}$ (red line) and $n\bar{n}$ (green line) production, Right: G_E^p/G_M^p for proton. The experimental data are from J.P.Lees et al., BaBar, Phys.Rev. D 87, 092005 (2013), R.R. Akhmetshin et al., CMD3, Physics Letters B759, 634 (2016) M.N. Achasov et al.,SND, Phys. Rev. D 90, 112007 (2014).

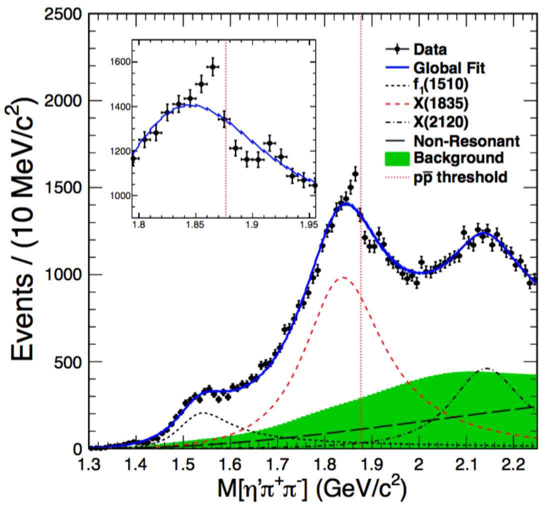
$J/\psi,\ \psi(2S) \to p\bar{p}\gamma$ decay

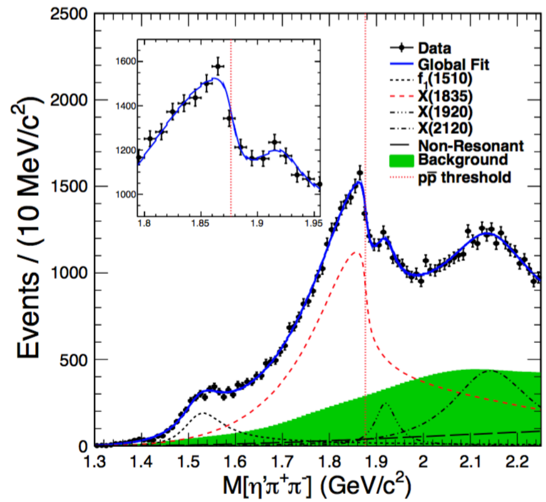
The invariant mass spectra in $J/\psi(\psi(2S) \to p\bar{p}\gamma$ decays:

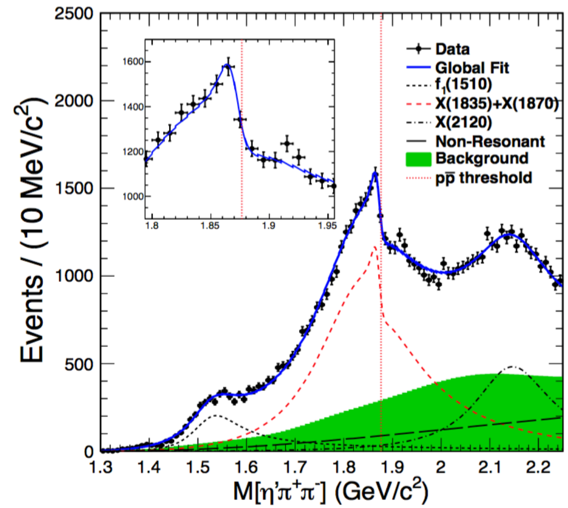


Left: $J/\psi \to p\bar{p}\gamma$ decay. Right: $\psi(2S) \to p\bar{p}\gamma$ decay.

Connection between X(1835) and X(pp): Fit results I







- Three efficiency-corrected Breit-Wigner functions
- Simple BW function fails in describing the $\eta'\pi^-\pi^+$ line shape near the threshold

MODEL 1

Threshold structure caused by the opening of additional decay mode

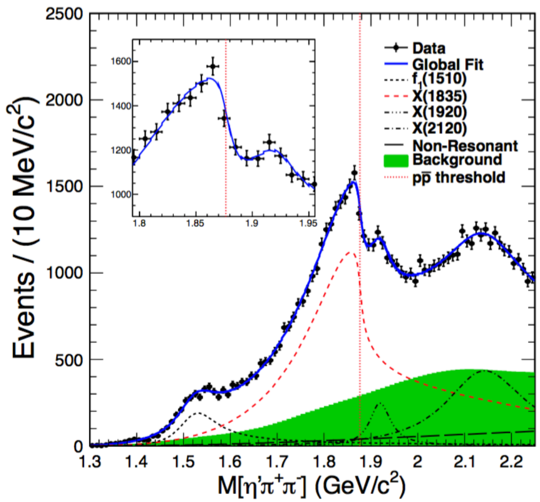
- Flatté formula for the shape (Phys.Lett.B**63**, 224)
- An additional BW resonance (X(1920)) is needed ($5.7\,\sigma$)

MODEL 2

Interference between two resonances

- Use coherent sum of two BW amplitudes for the line shape: X(1835) and a narrow resonance called X(1870)
- X(1920) not significant

Connection between X(1835) and X(pp): Fit results II



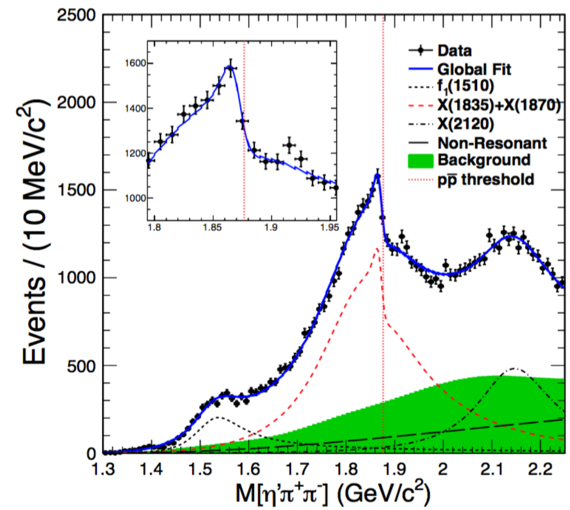


TABLE I. Fit results of using the Flatté formula. The first errors are statistical errors, and the second errors are systematic errors; the branching ratio is the product of $\mathcal{B}(J/\psi \to \gamma X)$ and $\mathcal{B}(X \to \eta' \pi^+ \pi^-)$.

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

TABLE II. Fit results using a coherent sum of two Breit-Wigner amplitudes. The first errors are statistical errors, and the second errors are systematic errors; the branching ratio (B.R.) is the product of $\mathcal{B}(J/\psi \to \gamma X)$ and $\mathcal{B}(X \to \eta' \pi^+ \pi^-)$.

$X(1835)$	
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)	$(3.72 \pm 0.21^{+0.18}_{-0.35}) \times 10^{-4}$
$X(1870)$	
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)	$(1.57 \pm 0.09^{+0.49}_{-0.86}) \times 10^{-5}$

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

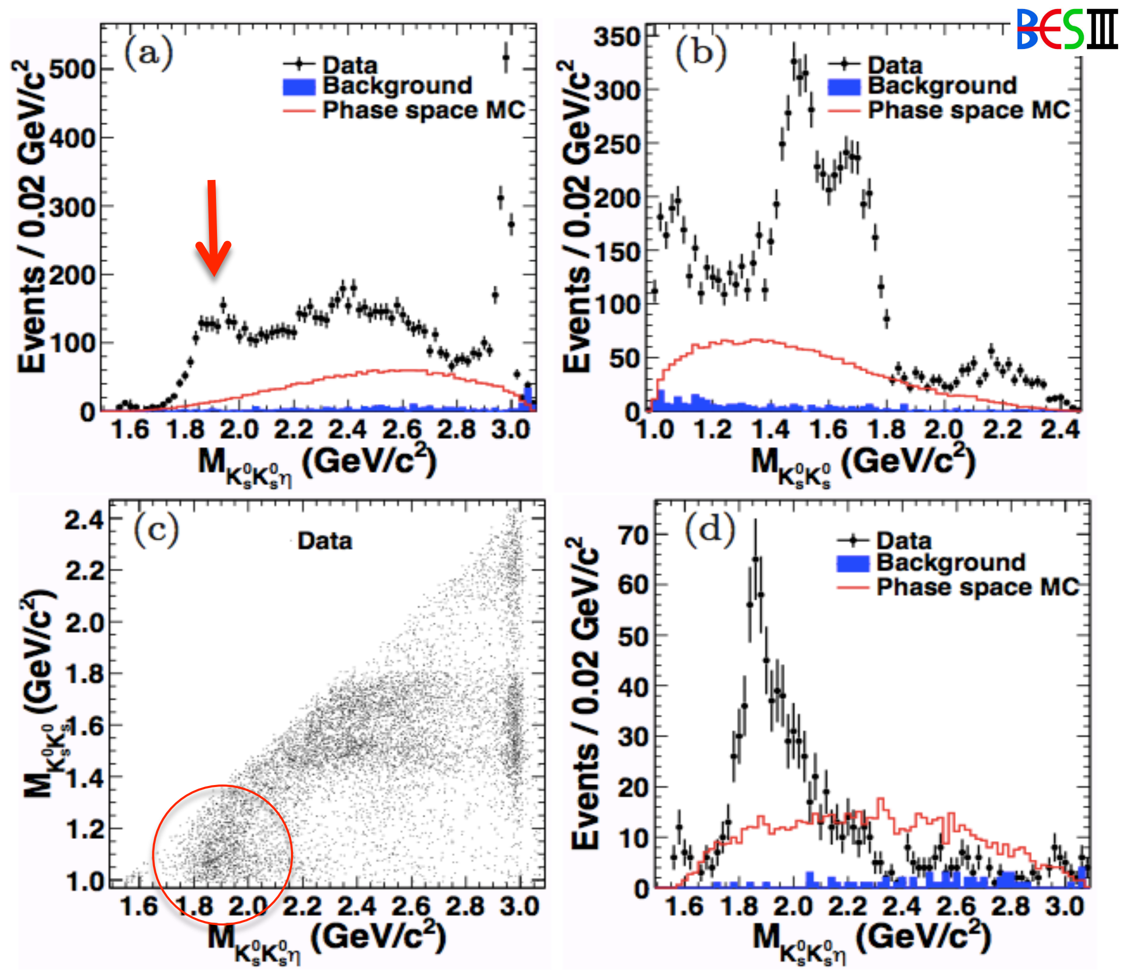
BESIII: PRL**115**,091803

$J/\psi \to \gamma K^0_S K^0_S \eta$ provides a clear environment

- $K^0_S K^0_S \eta$ 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 ➔ 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



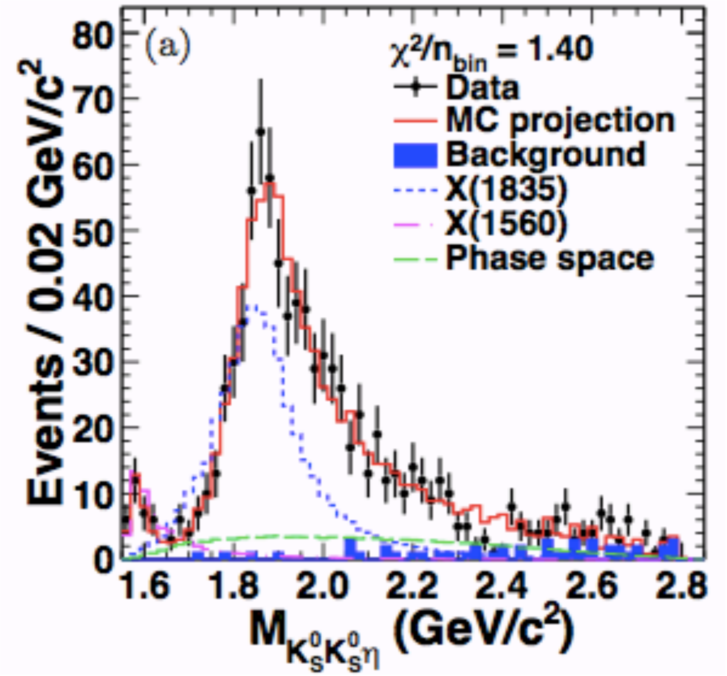
$J/\psi \to \gamma K_S^0 K_S^0 \eta$: PWA results

BESIII: PRL**115**,091803

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

- The X(1560) component improves the fit quality when interference with the X(1835) is allowed
- Several fits with different J^{PC} hypothesis
- **$J^{PC} = 0^{-+}$** for X(1835), X(1560), and non-resonant component
- $J^{PC} = 1^{++}$ for non-resonant component cannot be excluded

Mass and width of X(1835) consistent with PRL**106**

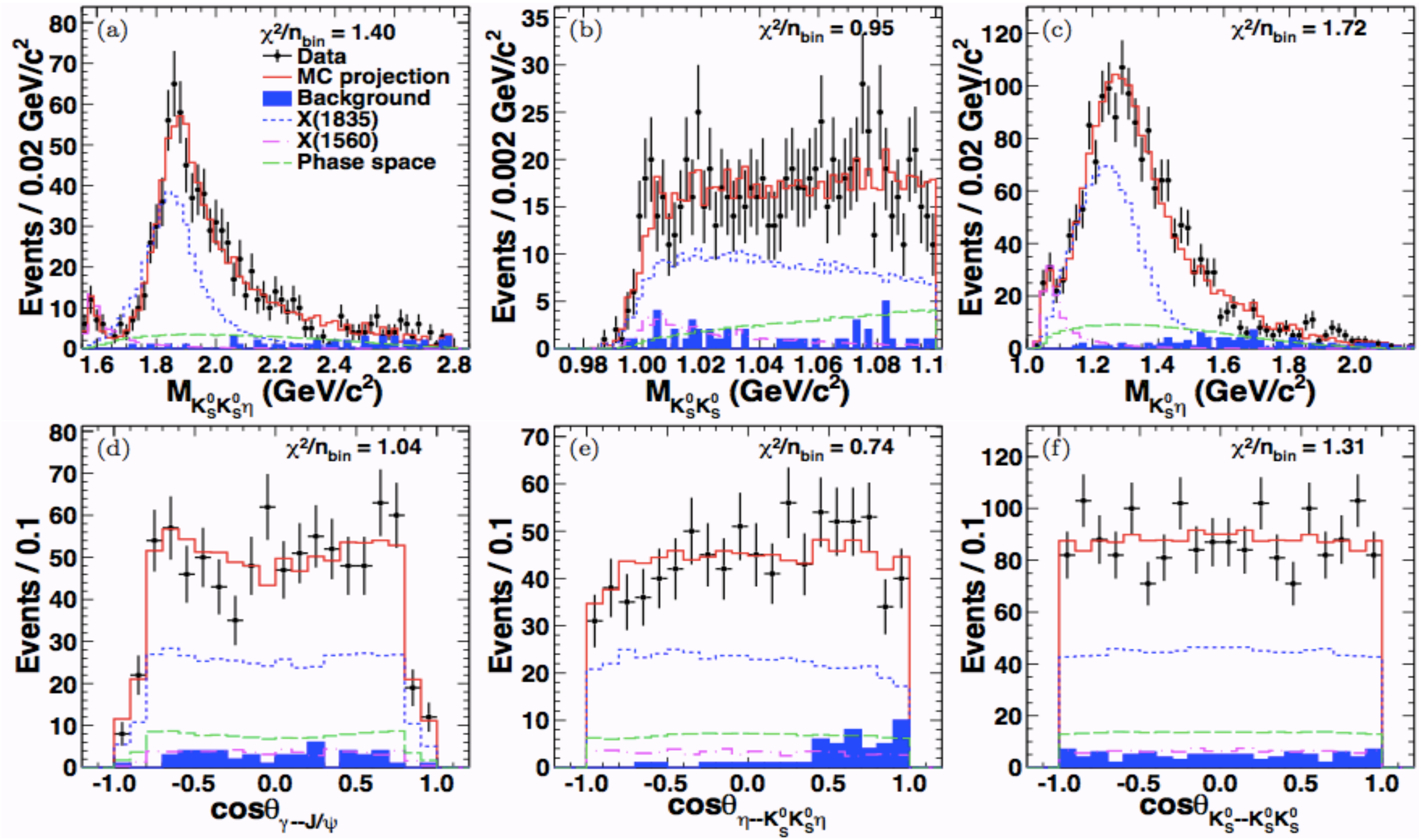


$M = 1844 \pm 9\ (\text{stat})\ ^{+16}_{-25}(\text{syst})\ \text{MeV}/c^2 \quad \Gamma = 192^{+20}_{-17}(\text{stat})\ ^{+62}_{-43}(\text{syst})\ \text{MeV} \quad (>12.9\sigma)$

$BR = (3.3^{+0.33}_{-0.30}(\text{stat})\ ^{+1.96}_{-1.29}(\text{syst}))\times 10^{-5}$

$M = 1565 \pm 8\ (\text{stat})^{+0}_{-63}(\text{syst})\ \text{MeV}/c^2 \quad \Gamma = 45^{+14}_{-13}(\text{stat})^{+21}_{-28}(\text{syst})\ \text{MeV} \quad (>8.9\sigma)$

$J/\psi \to \gamma K_S^0 K_S^0 \eta$: PWA results



Observation of X(2370) in $J/\psi \to \gamma KK\eta'$

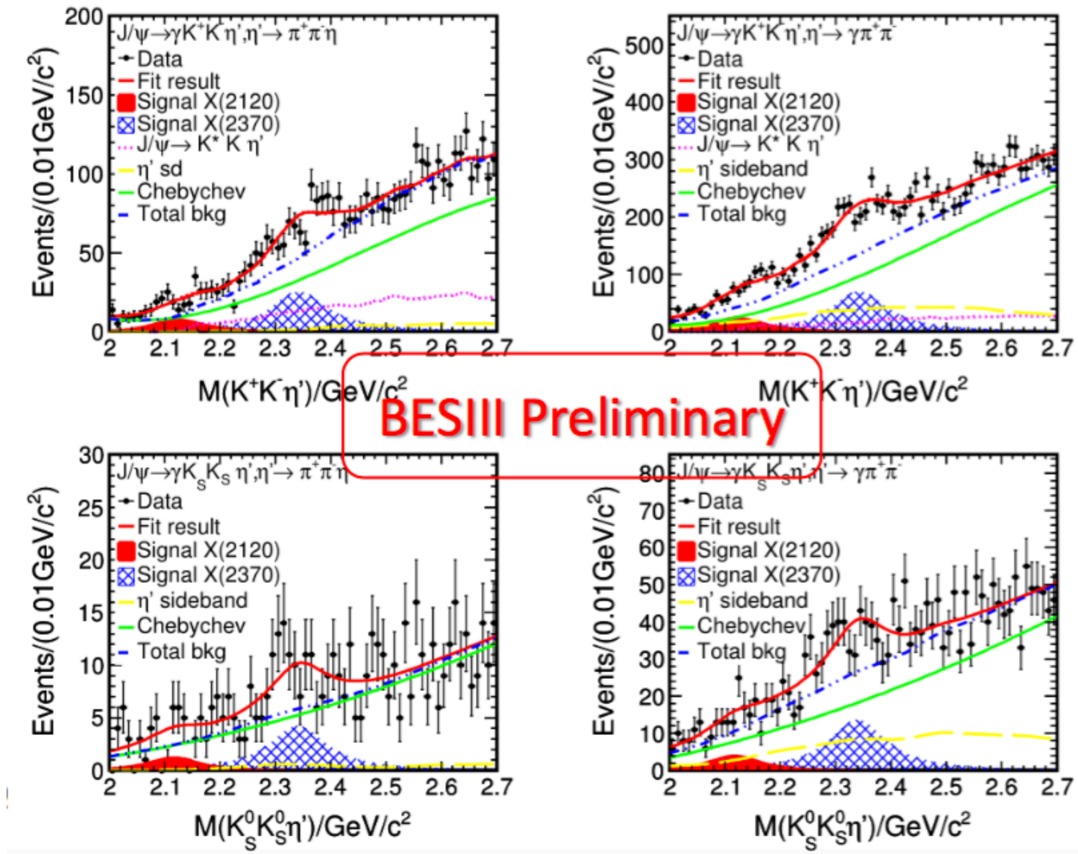
- The X(2120) and X(2370) states observed in the $\pi^-\pi^+\eta'$ invariant mass spectra ($J/\psi \to \gamma\pi^-\pi^+\eta'$)
- Possible glueball candidates
- PREDICTIONS:

$$\frac{\Gamma_{G\to\eta' KK}}{\Gamma_G^{Tot}} = 0.011, \frac{\Gamma_{G\to\eta'\pi\pi}}{\Gamma_G^{Tot}} = 0.090$$

with M(G) = 2.370 GeV/c^2 (PRD87,054036)

- Great chance to find them in the KKη' decay channel

➢ A simulataneus fit is performed on all the four decay modes: $J/\psi \to \gamma K^-K^+\eta'$ and $J/\psi \to \gamma K_S^0K_S^0\eta'$, where $\eta' \to \pi^-\pi^+\eta$ and $\pi^-\pi^+\gamma$



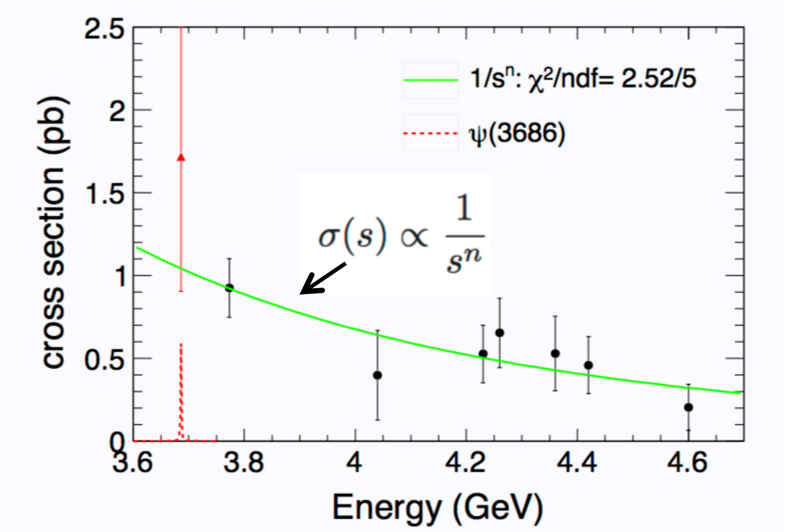
- **No evidence of X(2120) is found → U.L. @ 90% C.L.**
- **M and Γ consistent with the X(2370) with a significance of about 7.6σ**
- No spin-parity assignment

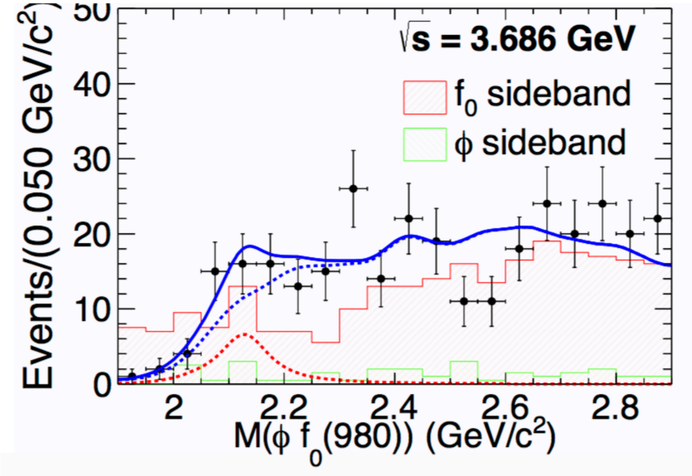
BESIII Preliminary

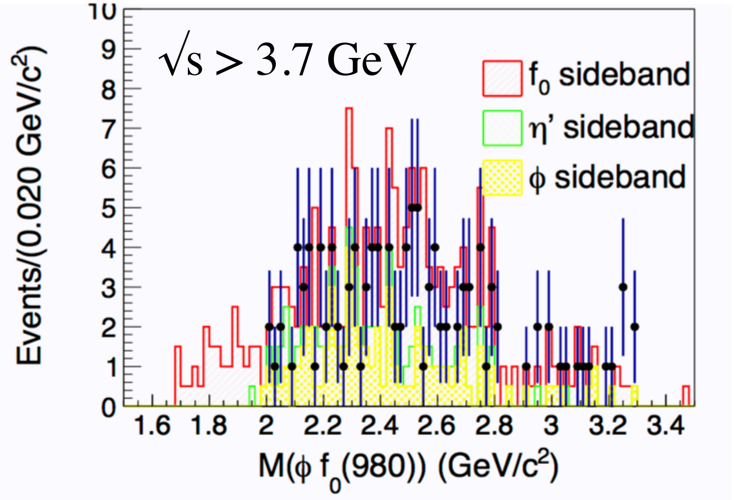
	combined results
M (MeV/c^2)	$2343.91 \pm 6.88(stat.) \pm 1.23(sys.)$
Γ (MeV)	$117.73 \pm 12.75(stat.) \pm 4.14(sys.)$
$B(J/\psi \to \gamma X(2370) \to \gamma K^+K^-\eta')$	$(1.86 \pm 0.39\ (stat.) \pm 0.29\ (sys.)) \times 10^{-5}$
$B(J/\psi \to \gamma X(2370) \to \gamma K_S^0K_S^0\eta')$	$(1.19 \pm 0.37\ (stat.) \pm 0.18\ (sys.)) \times 10^{-5}$
$B(J/\psi \to \gamma X(2120) \to \gamma K^+K^-\eta')$	$< 1.48 \times 10^{-5}$
$B(J/\psi \to \gamma X(2120) \to \gamma K_S^0K_S^0\eta')$	$< 4.57 \times 10^{-6}$

Observation of $e^+e^- \to \eta Y(2175)$ @ $\sqrt{s} > 3.7$ GeV

arXiv:1709.04323 (submitted to PRD)

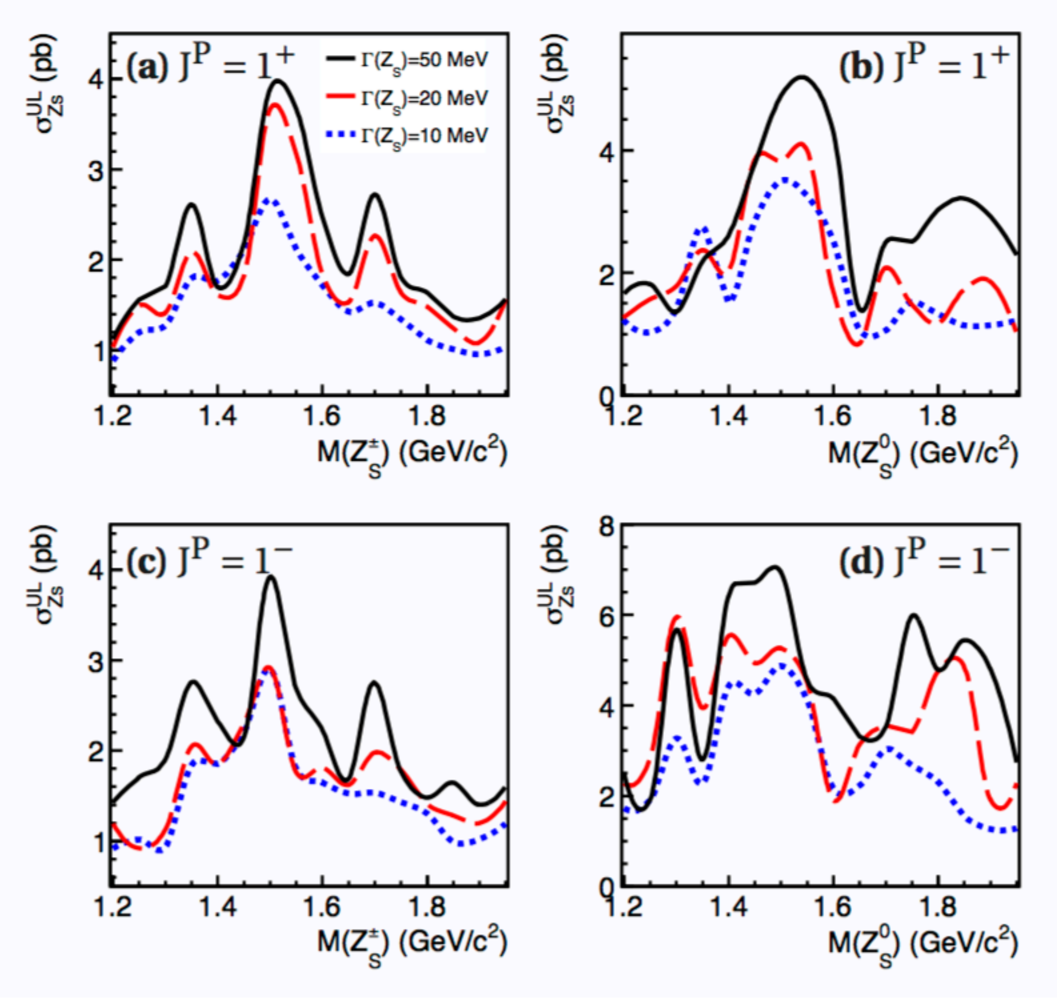






Search for ZS @ $\sqrt{s}$ = 2.125 GeV

arXiv:1801.10384(2018) – submitted to PRL



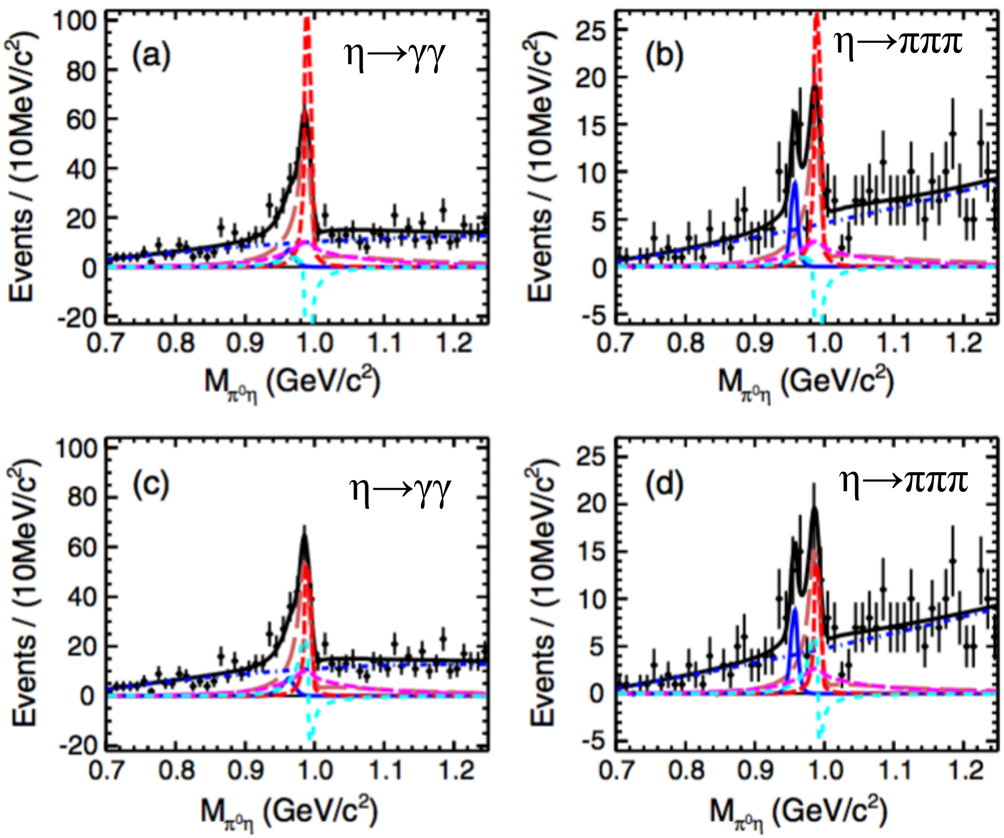
$a_0(980)$-$f_0(980)$ mixing

PRL**121**, 022001(2018)

- $f_0(980)$ width in isospin-violating processes is always narrow ($\Gamma \sim 10$ MeV), but it is 50-100 MeV if isospin is conserved
- Direct measure of the $f_0(980)$ - $a_0(980)$ mixing in the process $J/\psi \to \phi f_0(980) \to \phi a^0_0(980) \to \phi \eta \pi^0$ and $\chi_{c1} \to \phi a^0_0(980) \to \phi f_0(980) \to \pi^+\pi^-\pi^0$

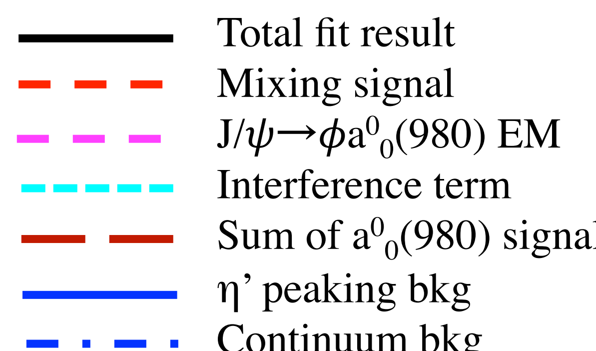
Destructive interference

Constructive interference



PRL**121**, 022001(2018)

- **$f_0(980) \to a^0_0(980)$ mixing significance: 7.4 σ**



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

PRL**121**, 022001(2018)

Mixing intensities:

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

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

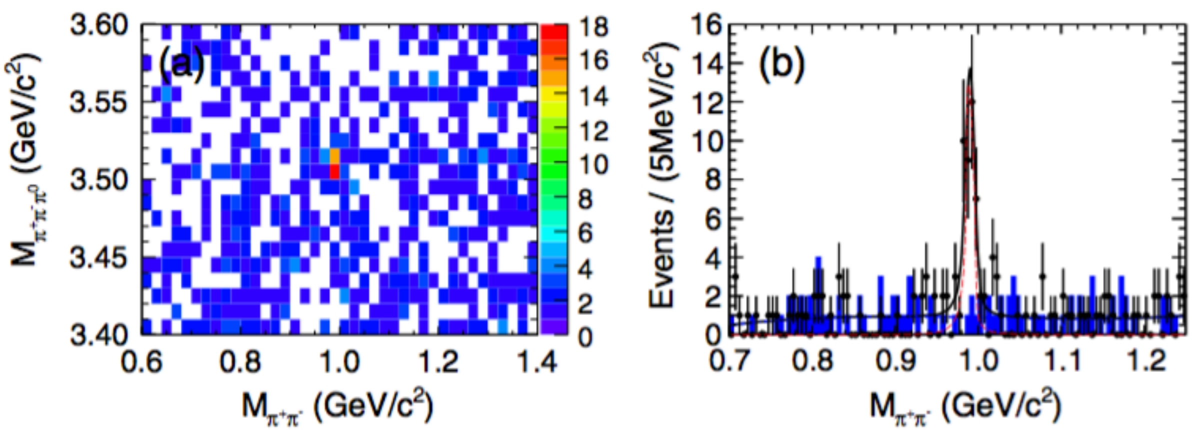
TABLE II. The branching fractions ($\mathcal{B}$) and the intensities (ξ) of the $a_0^0(980)$-$f_0(980)$ mixing. The first uncertainties are statistical, the second ones are systematic, and the third ones are obtained using different parameters for $a_0^0(980)$ and $f_0(980)$ as described in the text.

	$f_0(980) \to a_0^0(980)$	
Channel	Solution I	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 (%)	$0.99 \pm 0.16 \pm 0.30 \pm 0.09$	$0.41 \pm 0.13 \pm 0.17 \pm 0.13$

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

PRL**121**, 022001(2018)

- $\chi_{c1} \to \phi a^0_0(980) \to \phi f_0(980) \to \pi^+\pi^-\pi^0$
- **$a^0_0(980) \to f_0(980)$ mixing significance: 5.5 σ**



- Very Narrow peak around 1 GeV
- Negligible EM contribution (~0.2 σ)
- Also the interference term is negligible

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 (%)	$0.40 \pm 0.07 \pm 0.14 \pm 0.07$

About Exotic States

Exotics of type I

J^{PC} are not allowed by the quark-antiquark configurations, such as 0^{--}, 0^{-+}, …

- Direct observation

Exotics of type II

J^{PC} are the same as quark-antiquark configurations

- Outnumbering of conventional states?
- Peculiar properties

Exotics of type III

Leading kinematic singularity can cause measurable effects, e.g. the triangle singularity

- What's the impact?
- How to distinguish a genuine state from kinetic effects?