Recent BESIII results on light hadrons

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OUTLINE

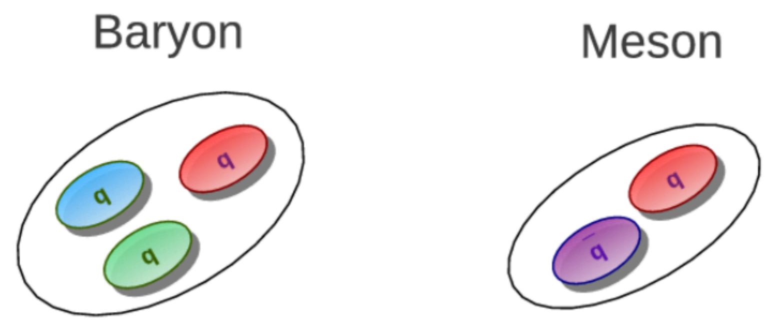
- INTRODUCTION:
  - Light hadron spectroscopy
  - The BESIII experiment

- Physics highlights
  - X(18??) states
  - Preliminary result: Observation of X(2370) in $J/\psi \rightarrow \gamma KK\eta'$
  - Search for glueballs @ BESIII
  - $a_0(980)$-$f_0(980)$ mixing

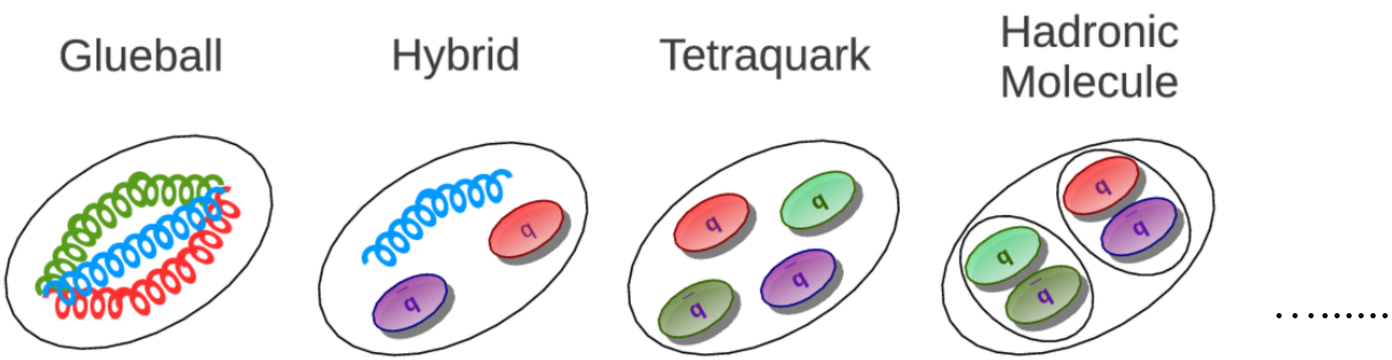
- Summary and Conclusions

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: ~ 1.5-1.7 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

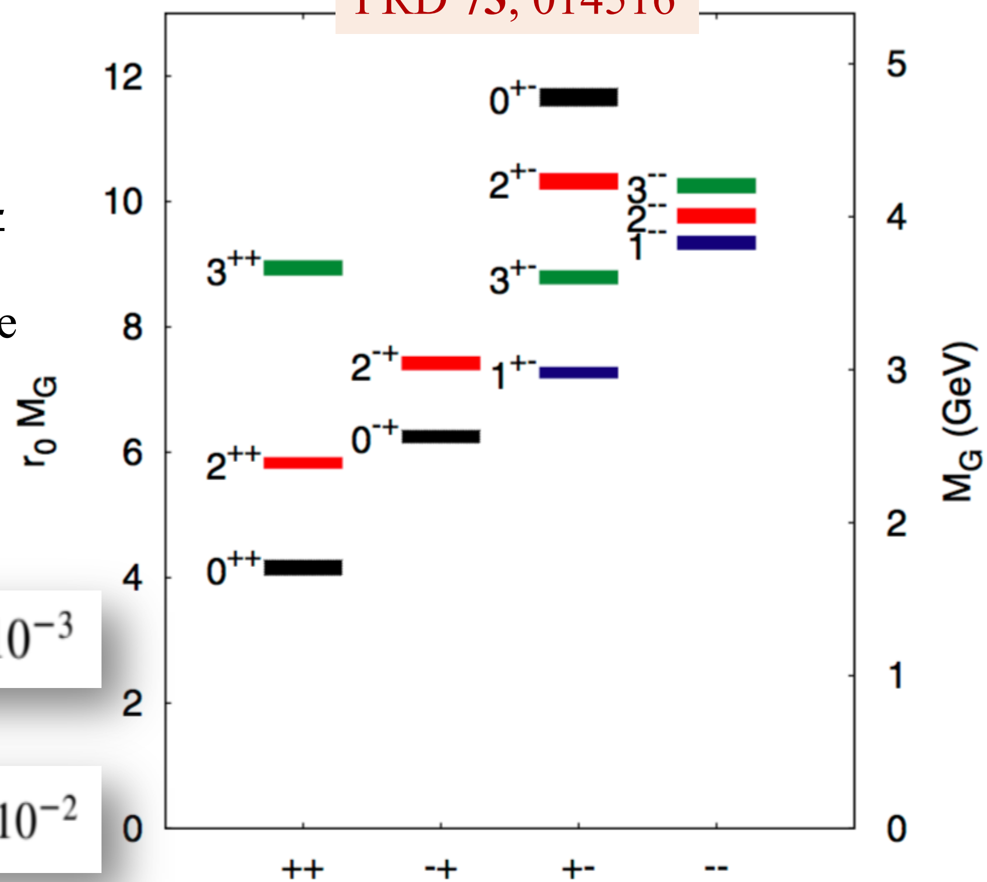
PRL**110**, 021601

$$\Gamma(J/\psi \to \gamma G_{0^{++}})/\Gamma_{\mathrm{tot}} = 3.8(9) \times 10^{-3}$$

PRL**111**, 091601

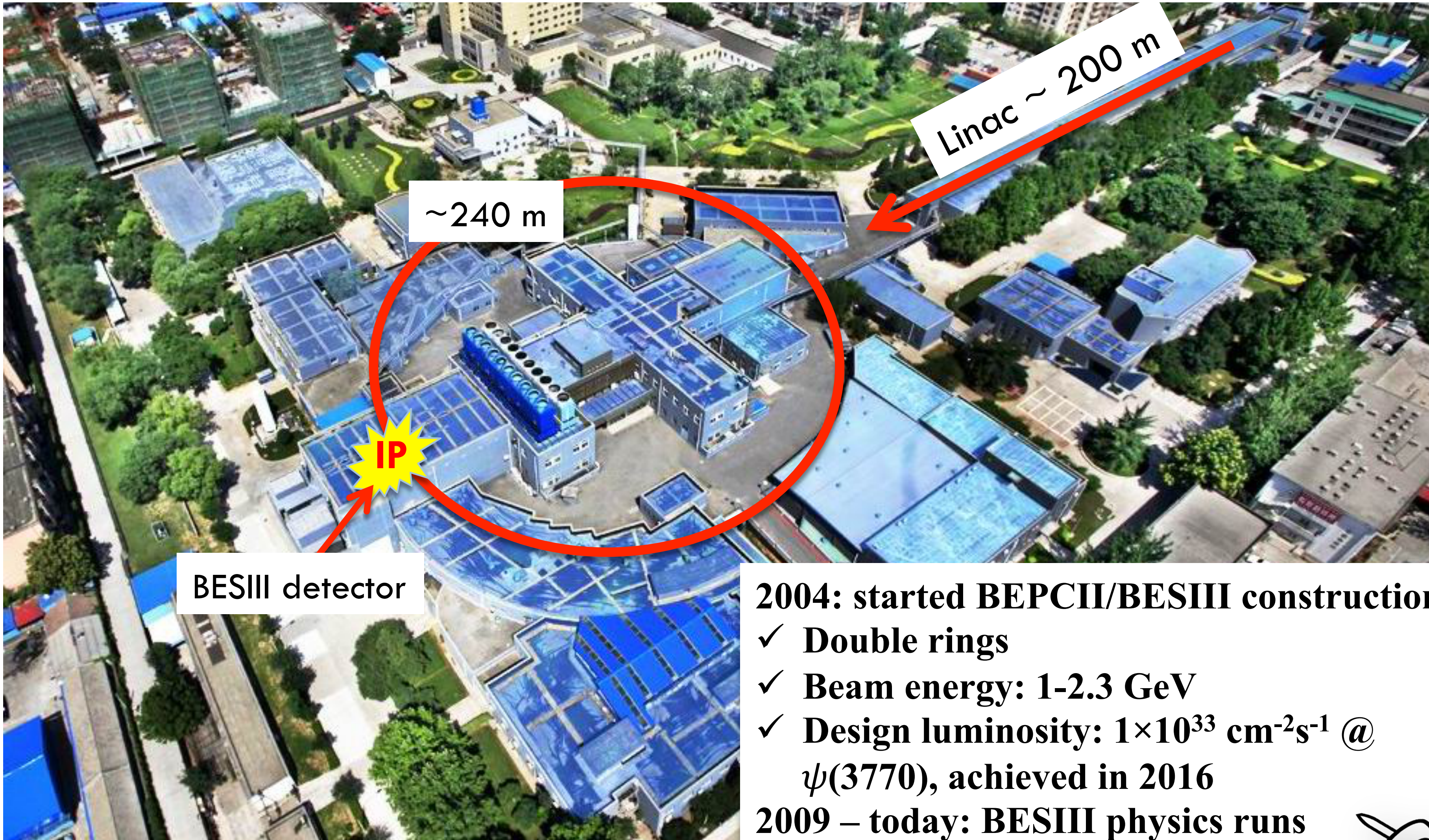
$$\Gamma(J/\psi \to \gamma G_{2^{++}})/\Gamma_{\mathrm{tot}} = 1.1(2)(1) \times 10^{-2}$$

PRD **73**, 014516



Beijing Electron Positron Collider II

http://english.ihep.cas.cn

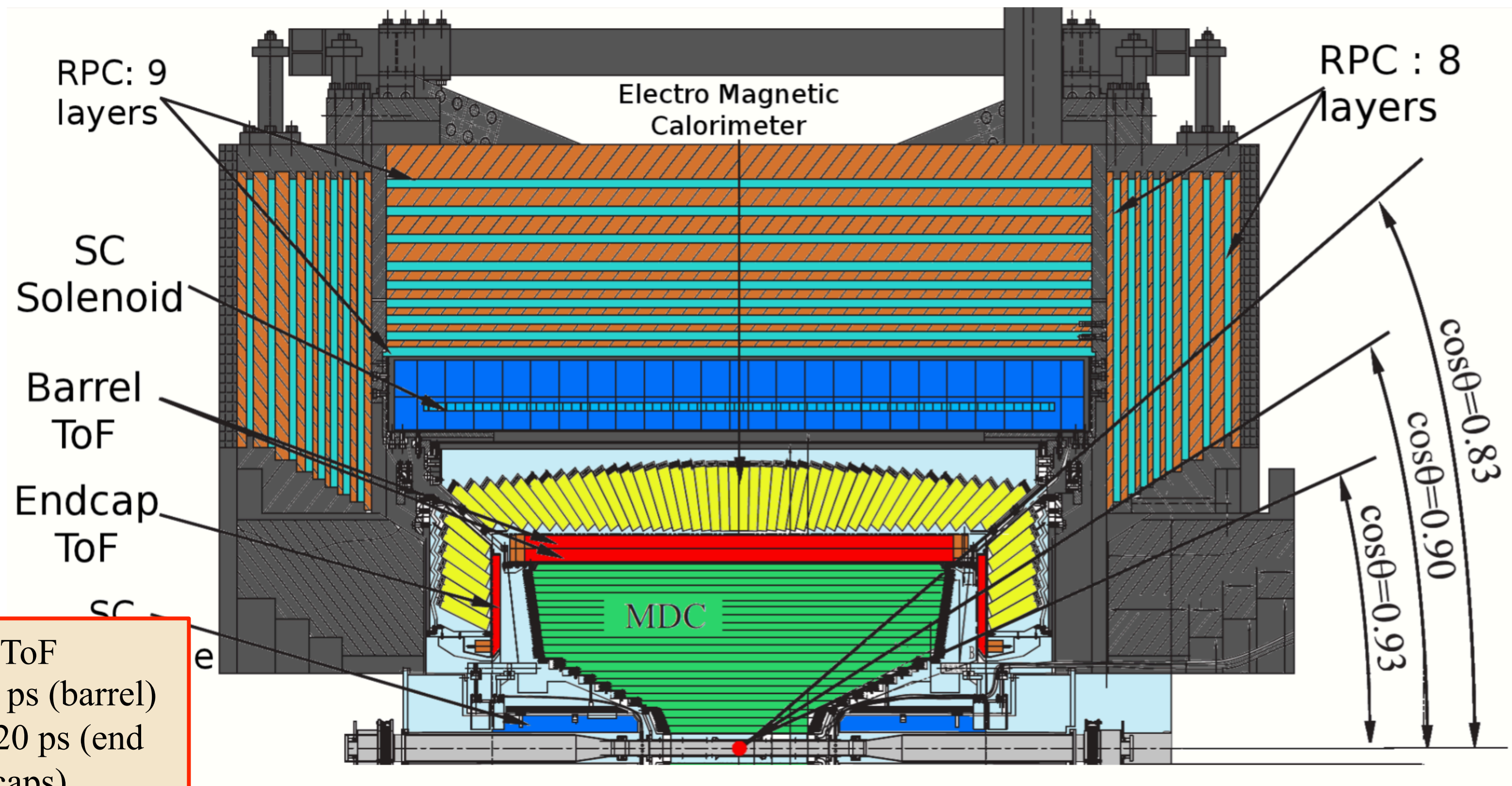


2004: started BEPCII/BESIII construction
- ✓ **Double rings**
- ✓ **Beam energy: 1-2.3 GeV**
- ✓ **Design luminosity: 1×10^{33} cm^{-2}s^{-1} @ $\psi(3770)$, achieved in 2016**

2009 – today: BESIII physics runs

The BESIII Detector

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



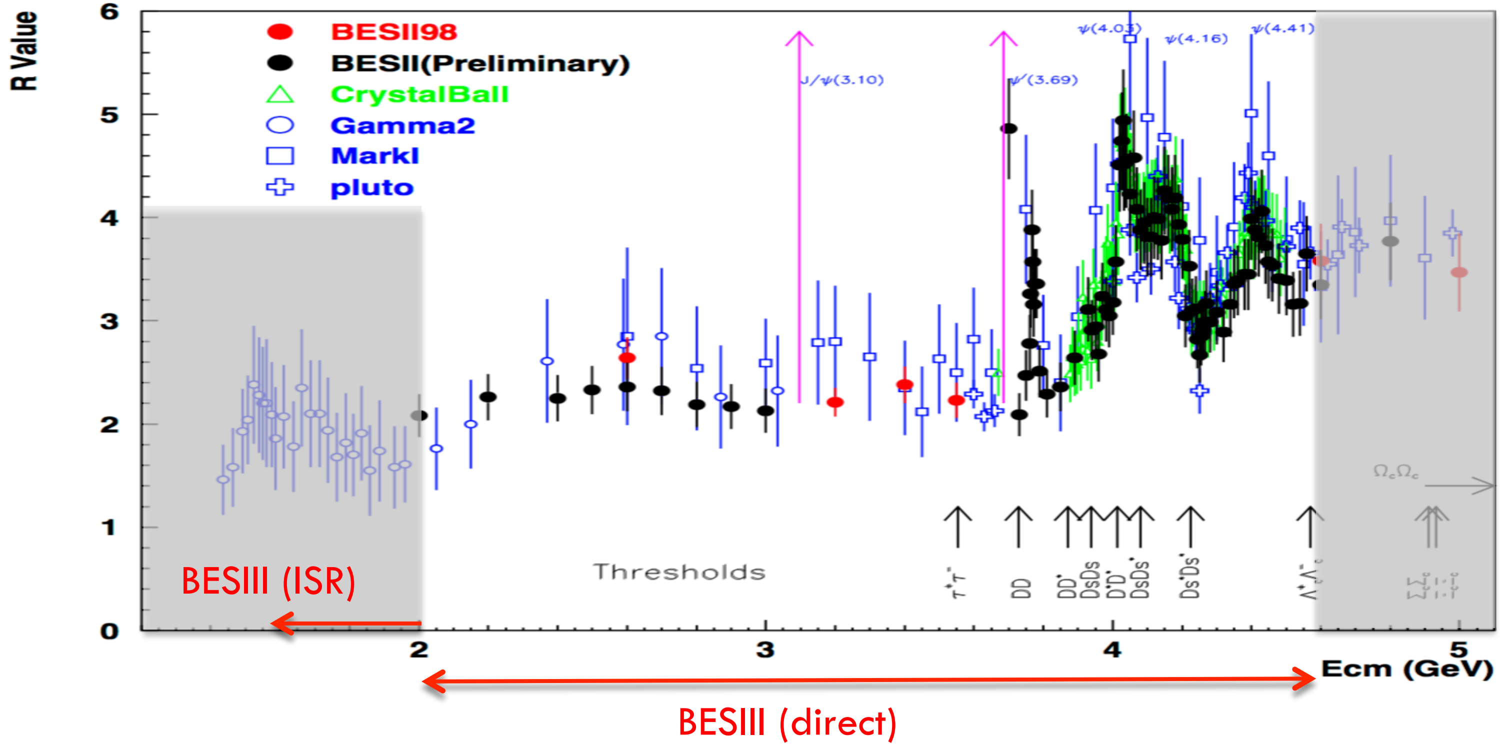
ToF
$\sigma_t \sim 90$ ps (barrel)
$\sigma_t \sim 120$ ps (end caps)

Drift Chamber
$\sigma_{r\phi} \sim 130\ \mu m$ (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



2009: 106M ψ(2S)
225M J/ψ

…

2012: 0.45B ψ(2S) (total)
1.3B J/ψ (total)

…

2018: J/ψ (and tuning new RF cavity)
2019: 10B J/ψ; more data in the XYZ region

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

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

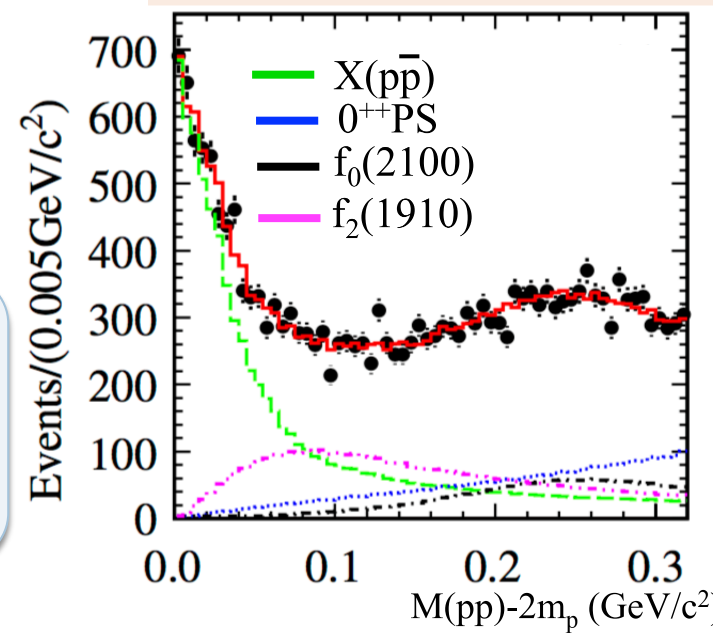
- Enhancement observed more than 15 years ago at BESII [PRL91,022001] and confirmed by CLEO-c [PRD82,092002] and BESIII [CPC 34, 421]
- Confirmed also in a PWA of the $J/\psi \to p\bar{p}\gamma$ channel
  - $J^{PC} = 0^{-+}$ ($> 30\,\sigma$)

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

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

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

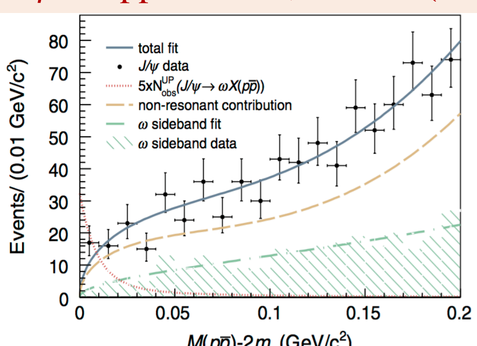
BESIII: PRL**108**,112003(2012)



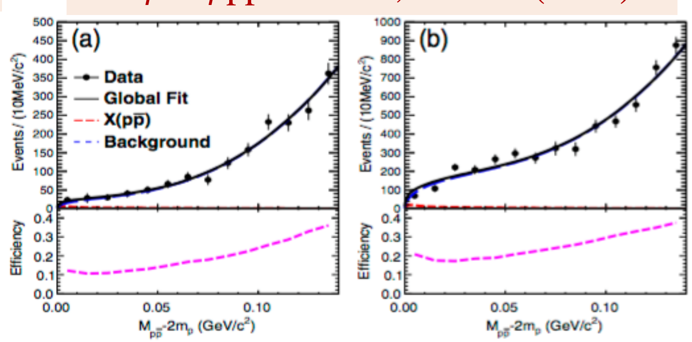
- No similar structure observed in related channels

What about its nature ? Final-State Interaction effect?

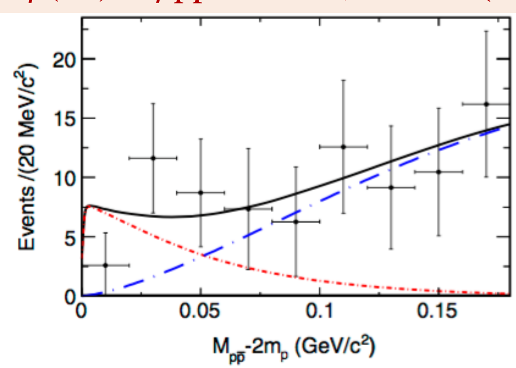
J/ψ→ωpp PRD 87, 112004 (2013)



J/ψ→φpp PRD 93, 052010 (2016)



ψ(2S)→φpp PRD 99, 112010 (2019)



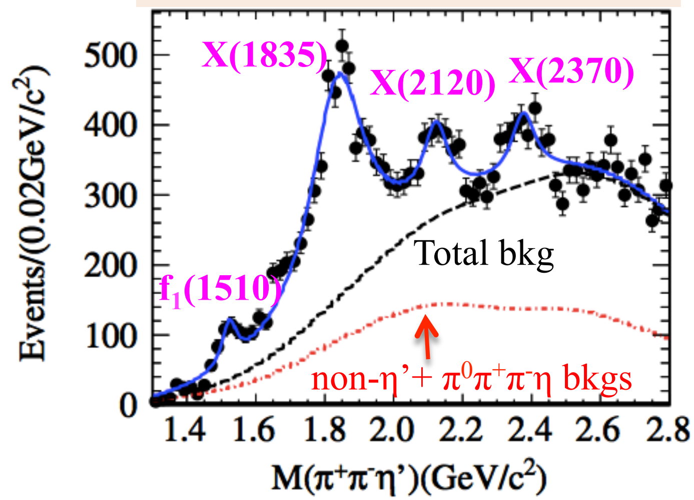
X(1835) ($X(p\bar{p})$?) in $J/\psi \to \gamma \pi^- \pi^+ \eta'$

- 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

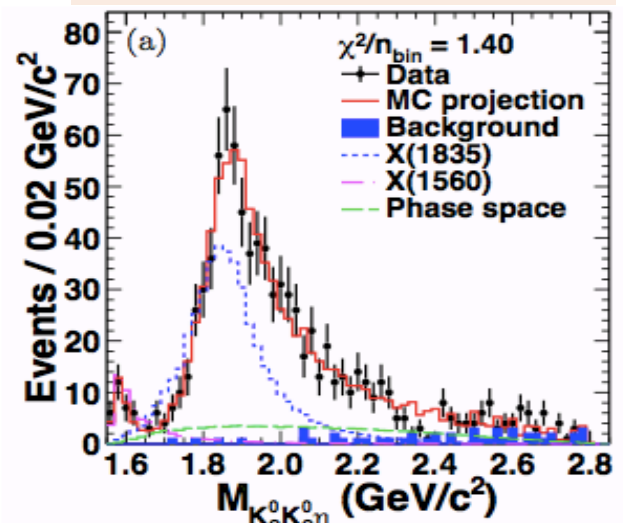
- BESIII $J/\psi \to \gamma \pi^- \pi^+ \eta'$: PRL **106,** 072002 (2011)
  - 225M J/ψ events
  - $\eta' \to \gamma \pi^- \pi^+$ and $\eta' \to \eta_{\gamma\gamma} \pi^- \pi^+$
  - 4 resonances (BW⊗Gauss)+non-resonant $\eta' \pi^- \pi^+$ (from MC) + non-η' and $\pi^- \pi^+ \pi^0 \eta'$ bkgs

- Also seen in $J/\psi \to \gamma K^0_S K^0_S \eta$ which provides a very clear environment: PRL **115**, 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
  - Partial Wave Analysis (PWA) of events with $M(K^0_S K^0_S) < 1.1$ GeV/c² and $M(K^0_S K^0_S \eta) < 2.8$ GeV/c²
  - $J^{PC} = 0^{-+}$ (>12.9σ)

PRL **106**, 072002 (2011)



PRL **115**, 091803 (2015)



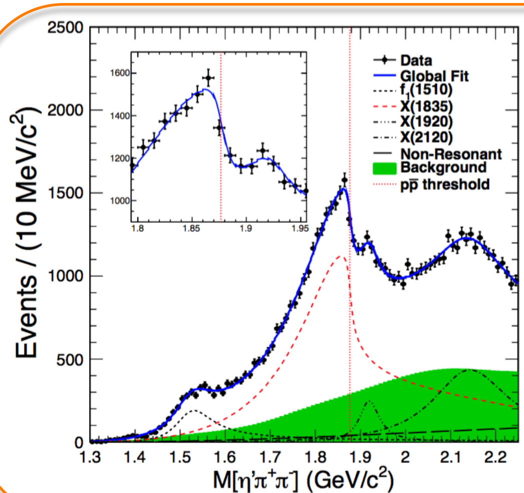
Connection between X(1835) and X($p\bar{p}$)

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

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

PRL **117**, 042002 (2016)

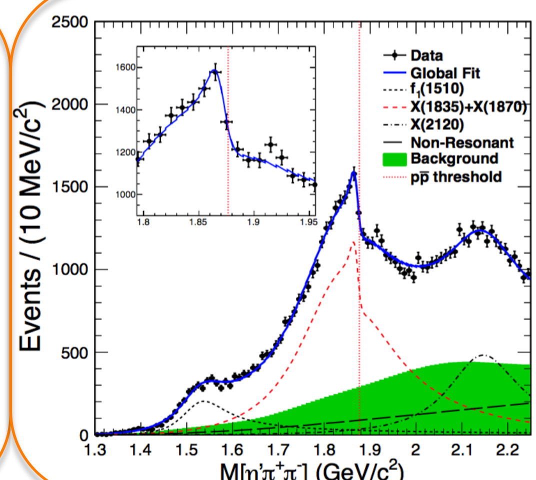
Significant distortion of the $\eta'\pi^-\pi^+$ line shape near the $p\bar{p}$ mass threshold



FIT I

Threshold structure due to the opening of additional decay mode :

- Flatté formula (PLB**63**, 224)



FIT II

Interference between two resonances:

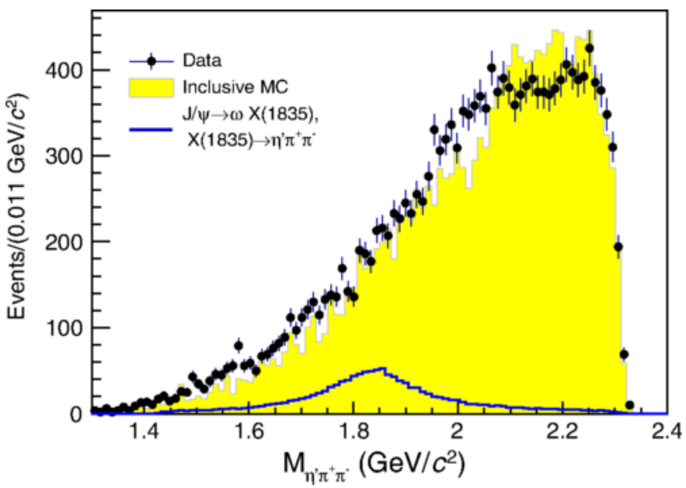
- Coherent sum of two BW amplitudes

- 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)

Search for X(1835) in other decay modes

- $J/\psi \to \omega\eta'\pi^+\pi^-$ hadronic decay and search for $X(1835) \to \eta'\pi^+\pi^-$

PRD **99**, 071101 (R) (2019)



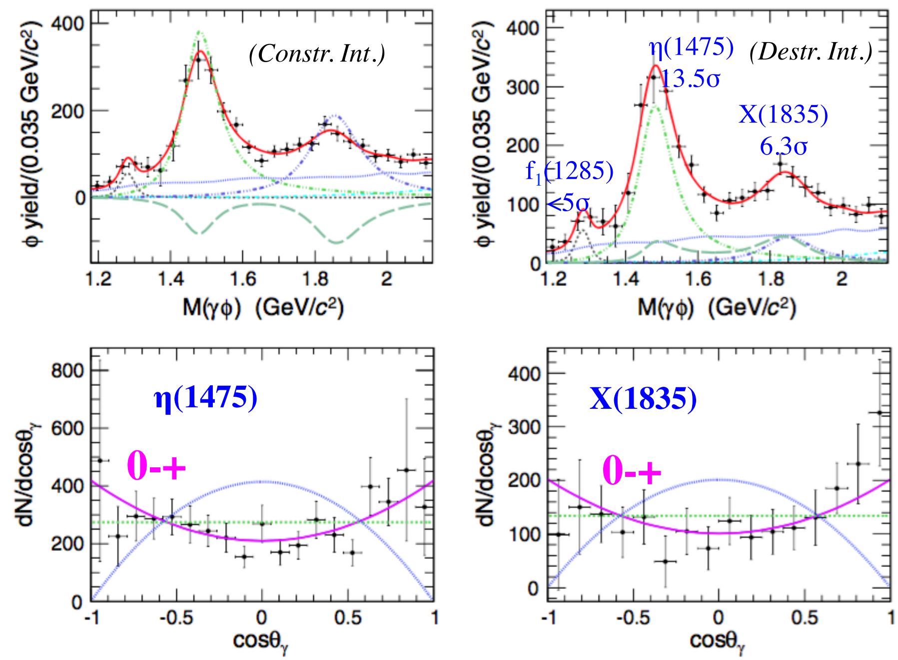
- No obvious sign of X(1835)'s existence
- Large gluon component? [PRD74,034019]

$$\mathcal{B}(J/\psi \to \omega\eta'\pi^+\pi^-) = (1.12 \pm 0.02 \pm 0.13) \times 10^{-3}$$

$$\mathcal{B}(J/\psi \to \omega X(1835),\ X(1835) \to \eta'\pi^+\pi^-) < 6.2 \times 10^{-5}$$

- $J/\psi \to \gamma\gamma\phi$: two structures corresponding to η(1475) and X(1835) are observed

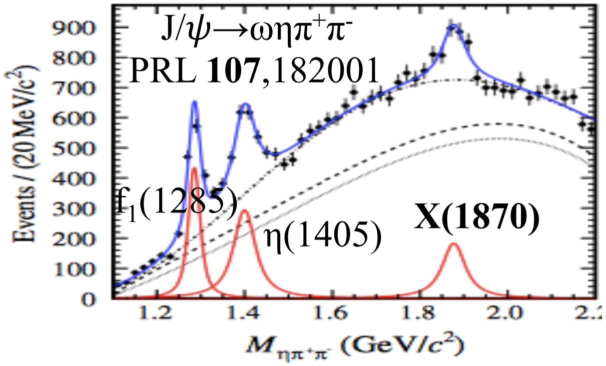
PRD **97**,051101(R) (2018)

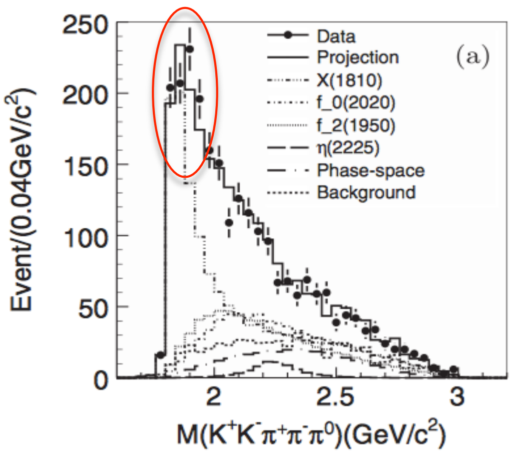


Solution	Resonance	m_R (MeV/c^2)	Γ (MeV)	B (10^{-6})
I	η(1475)	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$	$7.03 \pm 0.92 \pm 0.91$
(Destr. Int.)	X(1835)	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$	$1.77 \pm 0.35 \pm 0.25$
II	η(1475)	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$	$10.36 \pm 1.51 \pm 1.54$
(Constr.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

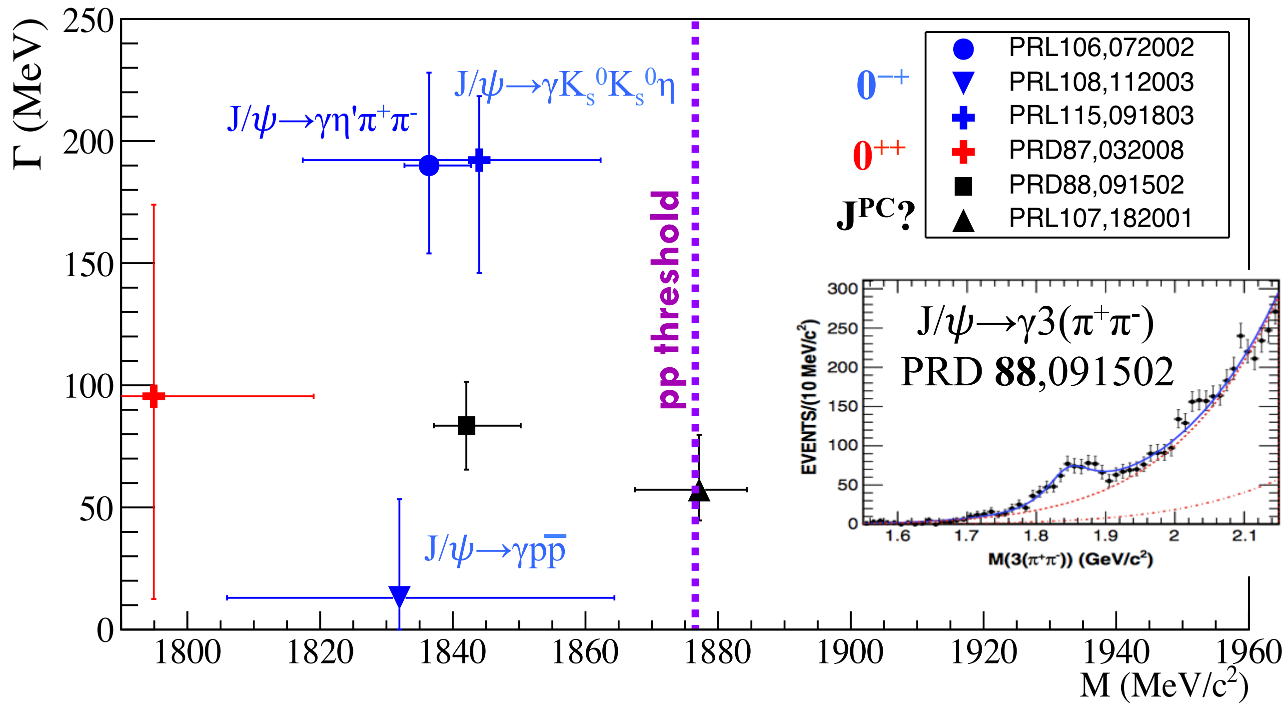
- Sizable ss component: more complicated than a pure NN state

More states between 1.8 - 1.9 GeV/c² @ BESIII





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



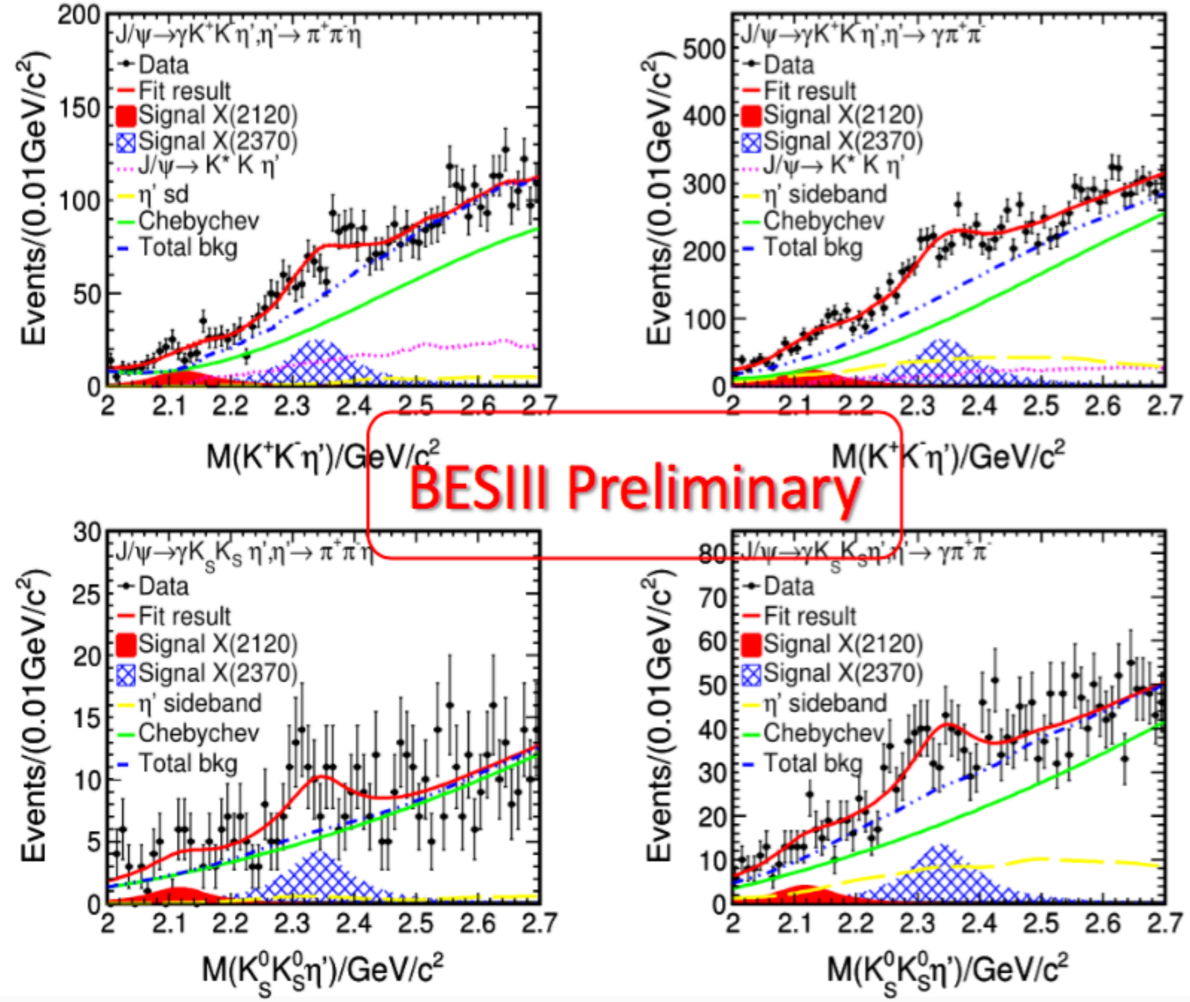
X states near proton-antiproton threshold

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

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 ($J/\psi \to \gamma\pi^-\pi^+\eta'$ PRL160,072002)
- Possible glueball candidates

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

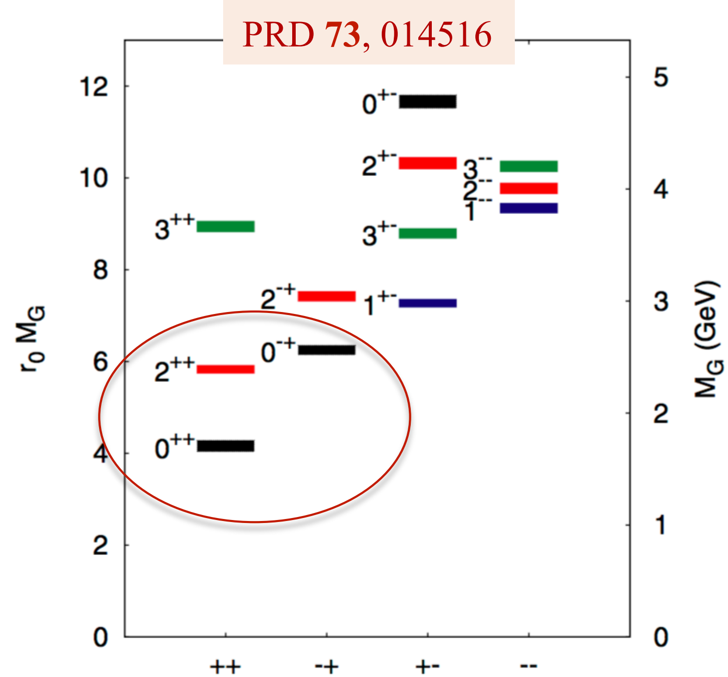


➢ **Clear X(2370) signal observed with significance of about 7.6σ**

➢ **No evidence of X(2120) is found → U.L. @ 90% C.L.**

➢ No spin-parity assignment

Amplitude Analyses in BESIII



- J/ψ radiative decays are ideal for searching glueballs
  - **$J/\psi \rightarrow \gamma PP$: 0^{++}, 2^{++}, …**
  - **$J/\psi \rightarrow \gamma PPP$, γVV: 0^{-+}**
- Neutral channel is much cleaner than the charged ones
- Very complicated mass spectrum in the low mass region: many broad, overlapping states complicate the study of the spectra

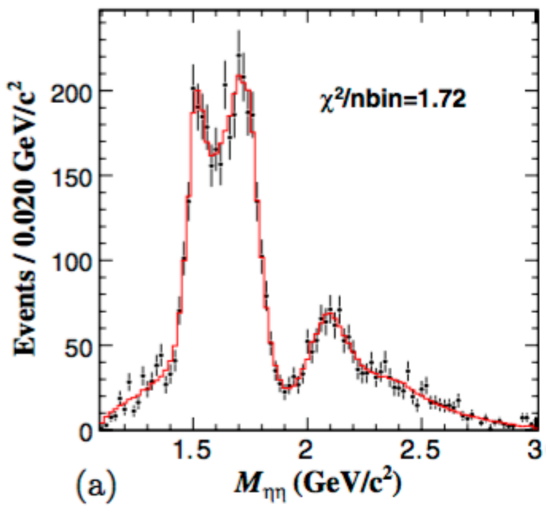
- **Amplitude analysis: toll to extract the complex amplitudes from experimental data**
  - Models with free parameters
  - Consider the kinematic of final states particles
  - Vary the parameters to maximize the likelihood

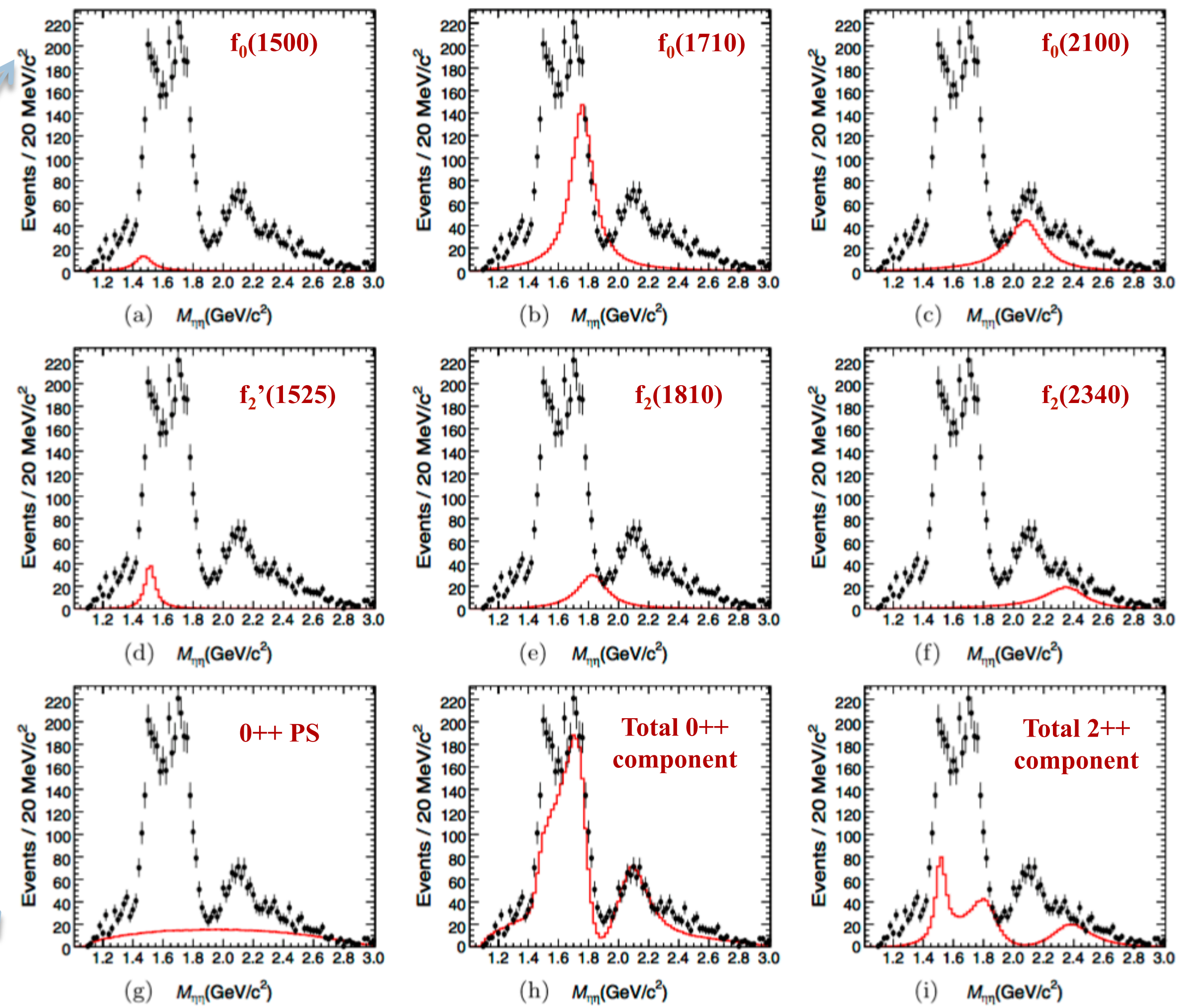
  - **Mass Dependent (MD) PWA**: model the dynamics of particle interactions as coherent sum of resonances
  - **Mass Independent (MI) PWA**: make minimal model assumptions and measure the dynamical amplitudes independently in small regions of two-meson invariant mass (PRD92, 052003 (2015))

PWA of J/ψ→γηη

PRD **87**, 092009 (2013)

- J/ψ→γηη: clean laboratory to search for 0++ and 2++ states
- PWA based on 2.25×10⁸ J/ψ events



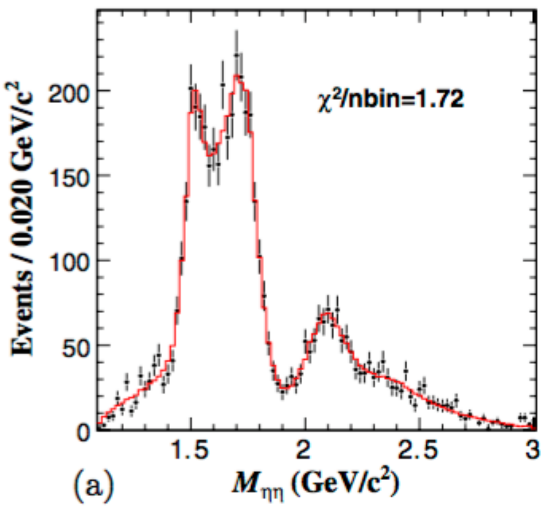


PWA of $J/\psi \to \gamma\eta\eta$

PRD **87**, 092009 (2013)

- $J/\psi \to \gamma\eta\eta$: clean laboratory to search for 0++ and 2++ states
- PWA based on 2.25×10^8 J/ψ events

Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0σ
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9σ
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6σ



- $f_0(1500)$ dominant decays are 4π and ππ
- The production rate of $f_0(1710)$ is compatible with LQCD (PRL110,021601) prediction for a pure scalar glueball
  - Suggest a large overlap with 0++ gluball

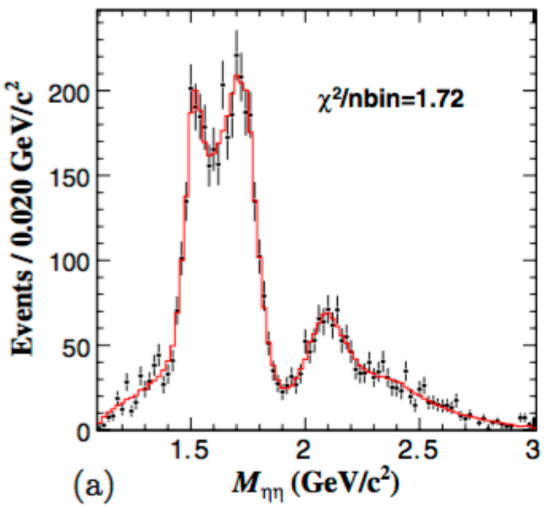
- PWA requires a strong contribution from **$f_2(2340)$** with fairly large production rate ⇒ it ***could be a good candidate for the lowest lying tensor glueball***

PWA of $J/\psi \to \gamma\eta\eta$

PRD **87**, 092009 (2013)

- $J/\psi \to \gamma\eta\eta$: clean laboratory to search for 0++ and 2++ states
- PWA based on 2.25×10^8 J/ψ events

	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	
$f_0(1500)$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	**8.2σ**
$f_0(1710)$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	**25.0σ**
$f_0(2100)$	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	**13.9σ**
$f_2'(1525)$	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	**6.4σ**
$f_2(1810)$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	**7.6σ**
$f_2(2340)$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	



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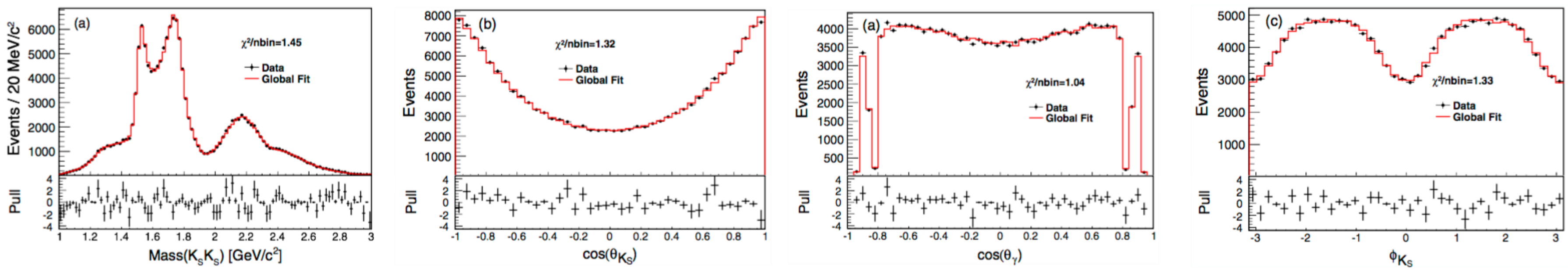
PWA of $J/\psi \to \gamma K^0_S K^0_S$

PRD **98**, 072003 (2018)

- $J/\psi \to \gamma K_S K_S$: clean laboratory to search for even++ states
- PWA based on 1311M of J/ψ events



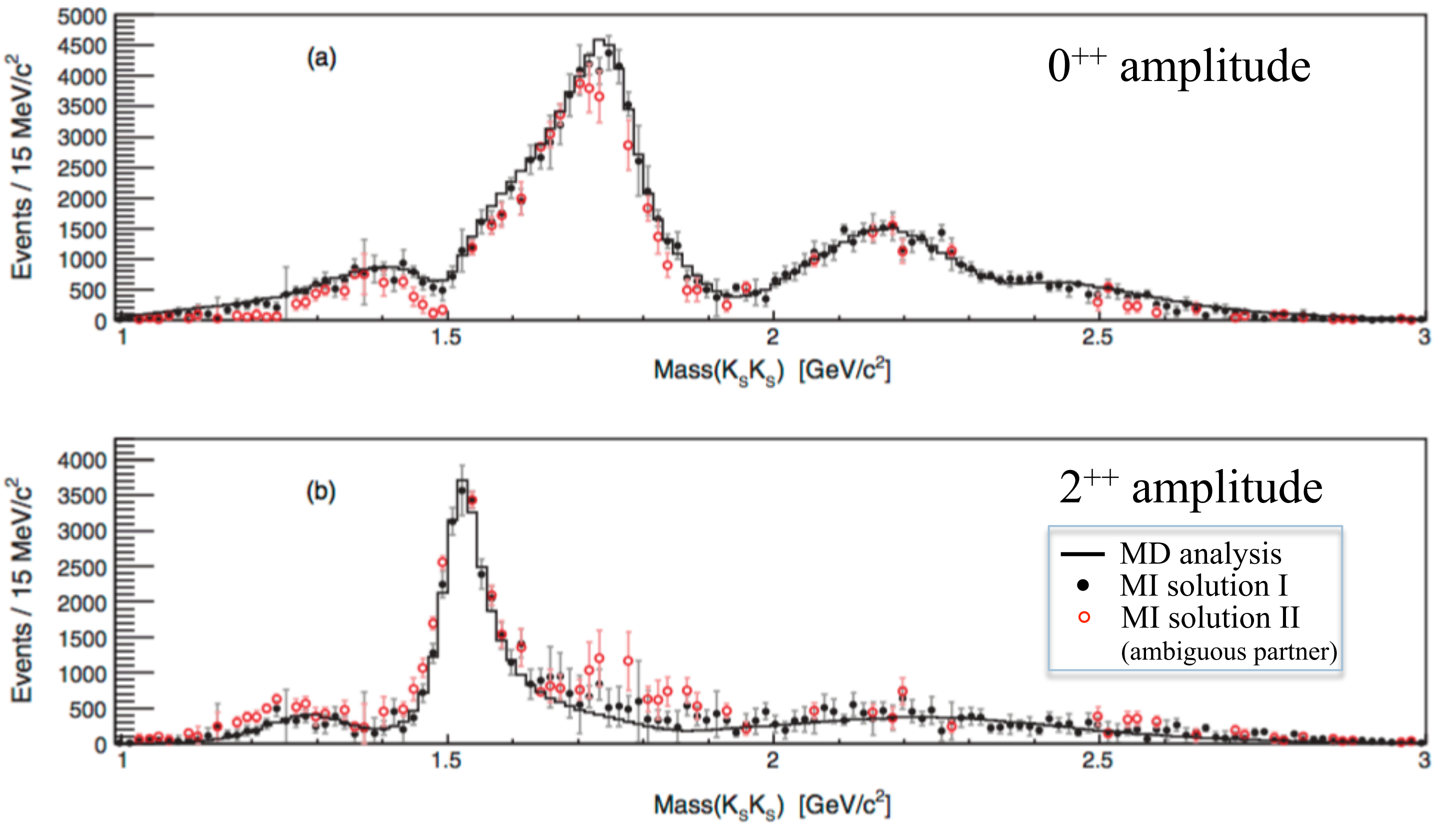
Resonance	M (MeV/c^2)	M_{PDG} (MeV/c^2)	Γ (MeV/c^2)	Γ_{PDG} (MeV/c^2)	Branching fraction	Significance
$K^*(892)$	896	895.81 ± 0.19	48	47.4 ± 0.6	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$	35σ
$K_1(1270)$	1272	1272 ± 7	90	90 ± 20	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$	16σ
$f_0(1370)$	$1350 \pm 9^{+12}_{-2}$	1200 to 1500	$231 \pm 21^{+28}_{-48}$	200 to 500	$(1.07^{+0.08+0.36}_{-0.07-0.34}) \times 10^{-5}$	25σ
$f_0(1500)$	1505	1504 ± 6	109	109 ± 7	$(1.59^{+0.16+0.18}_{-0.16-0.56}) \times 10^{-5}$	23σ
$f_0(1710)$	$1765 \pm 2^{+1}_{-1}$	1723^{+6}_{-5}	$146 \pm 3^{+7}_{-1}$	139 ± 8	$(2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(1790)$	$1870 \pm 7^{+2}_{-3}$	⋯	$146 \pm 14^{+7}_{-15}$	⋯	$(1.11^{+0.06+0.19}_{-0.06-0.32}) \times 10^{-5}$	24σ
$f_0(2200)$	$2184 \pm 5^{+4}_{-2}$	2189 ± 13	$364 \pm 9^{+4}_{-7}$	238 ± 50	$(2.72^{+0.08+0.17}_{-0.06-0.47}) \times 10^{-4}$	$\gg 35\sigma$
$f_0(2330)$	$2411 \pm 10 \pm 7$	⋯	$349 \pm 18^{+23}_{-1}$	⋯	$(4.95^{+0.21+0.66}_{-0.21-0.72}) \times 10^{-5}$	35σ
$f_2(1270)$	1275	1275.5 ± 0.8	185	$186.7^{+2.2}_{-2.5}$	$(2.58^{+0.08+0.59}_{-0.09-0.20}) \times 10^{-5}$	33σ
$f_2'(1525)$	1516 ± 1	1525 ± 5	$75 \pm 1 \pm 1$	73^{+6}_{-5}	$(7.99^{+0.03+0.69}_{-0.04-0.50}) \times 10^{-5}$	$\gg 35\sigma$
$f_2(2340)$	$2233 \pm 34^{+9}_{-25}$	2345^{+50}_{-40}	$507 \pm 37^{+18}_{-21}$	322^{+70}_{-60}	$(5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$	26σ
0^{++} PHSP	⋯	⋯	⋯	⋯	$(1.85^{+0.05+0.68}_{-0.05-0.26}) \times 10^{-5}$	26σ
2^{++} PHSP	⋯	⋯	⋯	⋯	$(5.73^{+0.99+4.18}_{-1.00-3.74}) \times 10^{-5}$	13σ

- $f_0(1710)$ and $f_0(2200)$ dominate the scalar spectrum, but we need also to include $f_0(2330)$
- BR of $f_0(1710)$ is one order of magnitude larger than BR of $f_0(1500)$: $f_0(1710)$ overlap with glueball state
- Structure near 1.5 GeV dominated by tensor contribution f_2'(1525), while above 2 GeV is dominantly $f_2(2340)$

PWA of $J/\psi \to \gamma K^0_S K^0_S$

PRD **98**, 072003 (2018)

- Mass independent PWA results
  - Amplitudes extracted independently in bins of $K_S K_S$ invariant mass



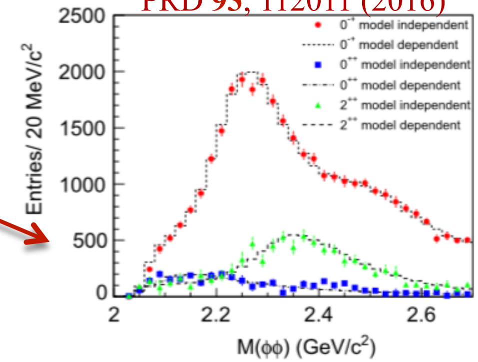
- Agreement with results from MD PWA (no acceptance correction included)
- MI results useful for a systematic study of hadronic interaction

PWA status and plans in a nutshell

<table>
<tr><th></th><th>0+</th><th>2+</th><th>0−</th></tr>
<tr><td>J/ψ→γPP</td><td colspan="2">J/ψ→γηη (PRD87,092009)
J/ψ→γ$\pi^0\pi^0$ (PRD92,052003)
J/ψ→γK_SK_S (PRD98,072003)
J/ψ→γηη’
J/ψ→γη’η’</td><td></td></tr>
<tr><td>J/ψ→γVV</td><td></td><td colspan="2">J/ψ→γωϕ (PRD87,032008)
J/ψ→γϕϕ (PRD93,112011)
J/ψ→γωω</td></tr>
<tr><td>J/ψ→γPPP</td><td></td><td></td><td>J/ψ→γη’ππ (PRL106,072002)
J/ψ→γKKη’
J/ψ→γη$\pi^0\pi^0$</td></tr>
</table>

PWA Published
Ongoing
Published, no PWA

PRD **93**, 112011 (2016)



- 0++: the production rate $f_0(1710)$ is compatible with LQCD prediction for a pure gauge scalar glueball
- 2++: $f_0(2340)$ seems to be a good candidate for tensor gluball [PRL111,091601] (large production rate)
- 0−+: η(2225) is confirmed and two additional pseudoscalar states, η(2100) and X(2500), are observed

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

PRL 121, 022001(2018)

$1^-(0^{++})$ $0^+(0^{++})$

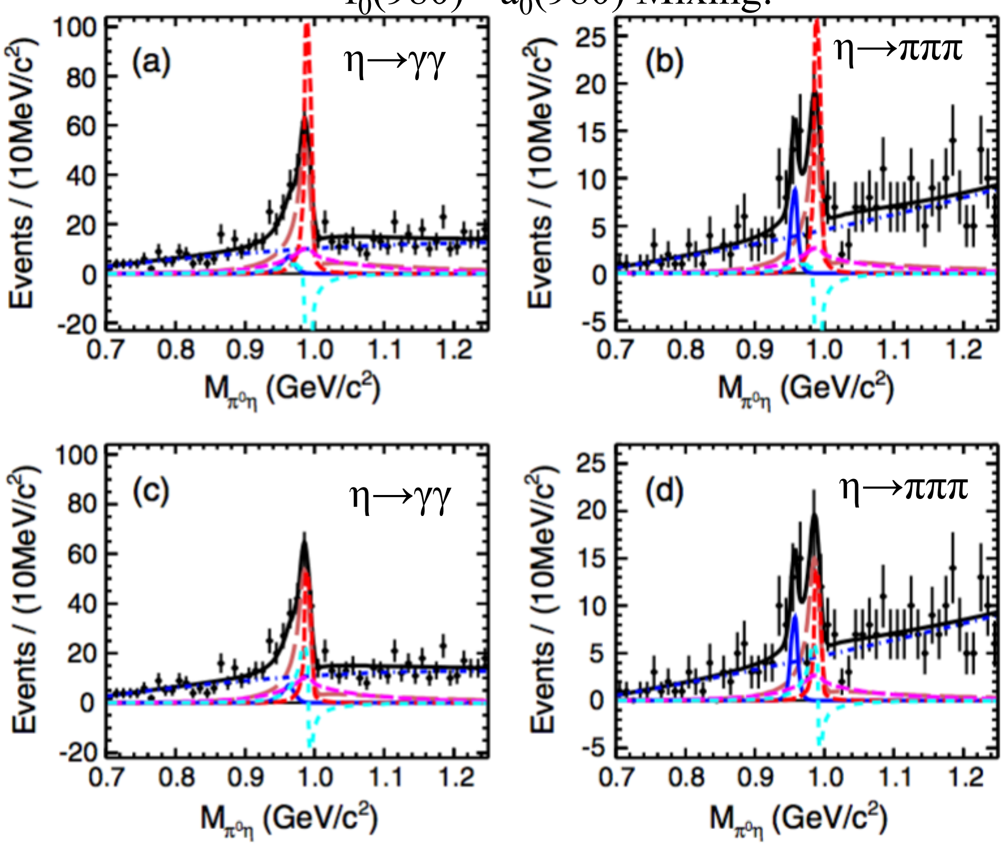
- $a_0(980)$ - $f_0(980)$ still controversial explanation about their nature
- Direct measure of the $f_0(980)$ - $a_0(980)$ mixing in the process proposed in 1979 [PLB88,367]

$\mathbf{J/\psi \to \phi f_0(980) \to \phi a^0_0(980) \to \phi \eta \pi^0}$ and $\mathbf{\chi_{c1} \to \pi^0 a^0_0(980) \to \pi^0 f_0(980) \to \pi^0 \pi^+ \pi^-}$ (isospin violating decays)

$f_0(980)$ - $a_0(980)$ Mixing:

Destructive interference

Constructive interference



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

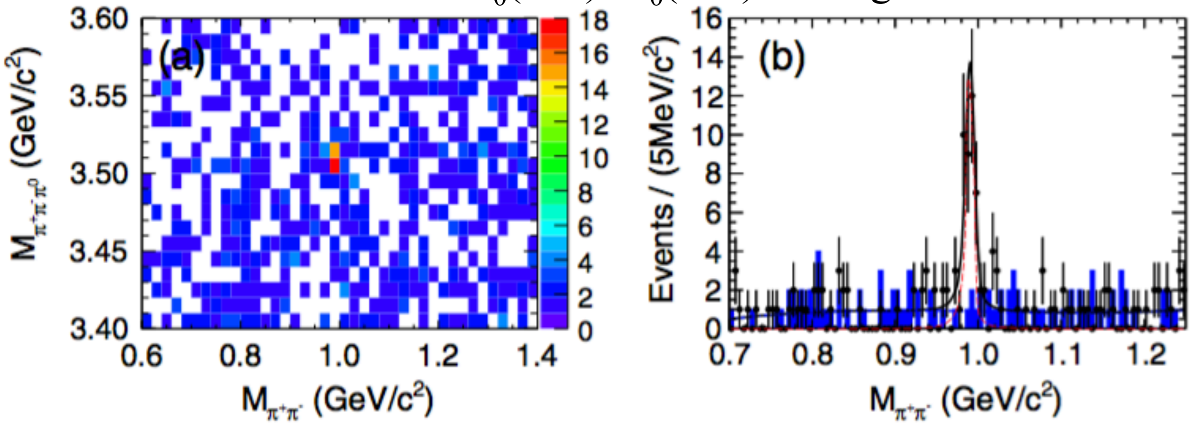
$J/\psi \to \phi a_0(980)$EM process significance: 4.6σ

- Total fit result
- Mixing signal
- $J/\psi \to \phi a^0_0(980)$ EM
- Interference term
- Sum of $a^0_0(980)$ signal
- η' peaking bkg
- Continuum bkg

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

PRL **121**, 022001(2018)

$a_0(980)$ - $f_0(980)$ Mixing:



$a_0(980)\rightarrow f^0_0(980)$ mixing significance: 5.5 σ

$f_0(980)$ signal significant narrower than PDG

Mixing intensities:

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

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

	$f_0(980) \to a_0^0(980)$		
Channel	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 (%)	$0.99 \pm 0.16 \pm 0.30 \pm 0.09$	$0.41 \pm 0.13 \pm 0.17 \pm 0.13$	$0.40 \pm 0.07 \pm 0.14 \pm 0.07$

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

  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
- Extensive and systematic searching for glueballs: $f_0(1710)$, $f_2(2340)$, X(2370), X(2500), and X(26??), ...
- **First observation of $a_0(980)$-$f_0(980)$ mixing**. Many unexpected/interesting phenomena: narrow $f_0(980)$, large isospin breaking rate, ...
- Many interesting results have been obtained, and only a small part are covered in this talk

FUTURE

- More data will be collected
- Detector and BEPCII upgrade
- ….

Back-up slides

BESIII physics programme

Light hadron physics

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

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

QCD and τ

- Precision R measurement
- τ decay

Charmonium physics

- Precision spectroscopy
- Transitions and decays

Precision mass measurements

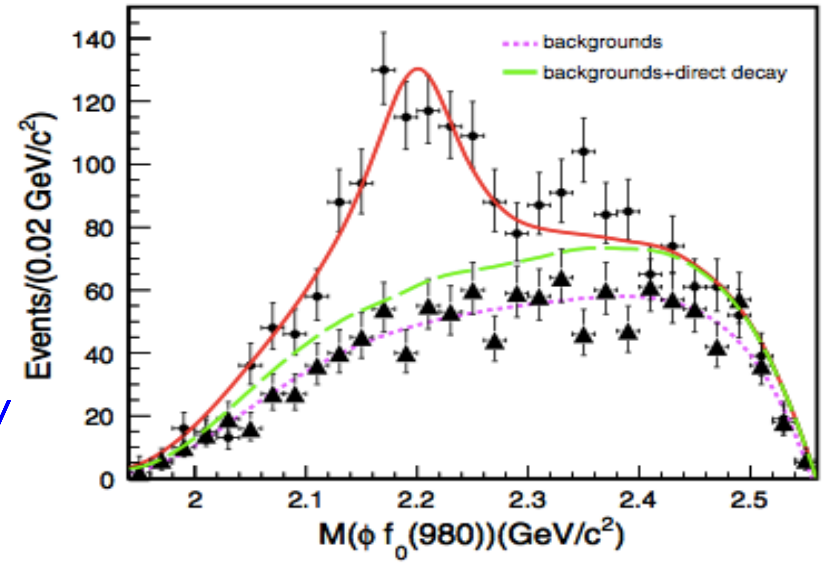
- τ mass
- D, D^* mass

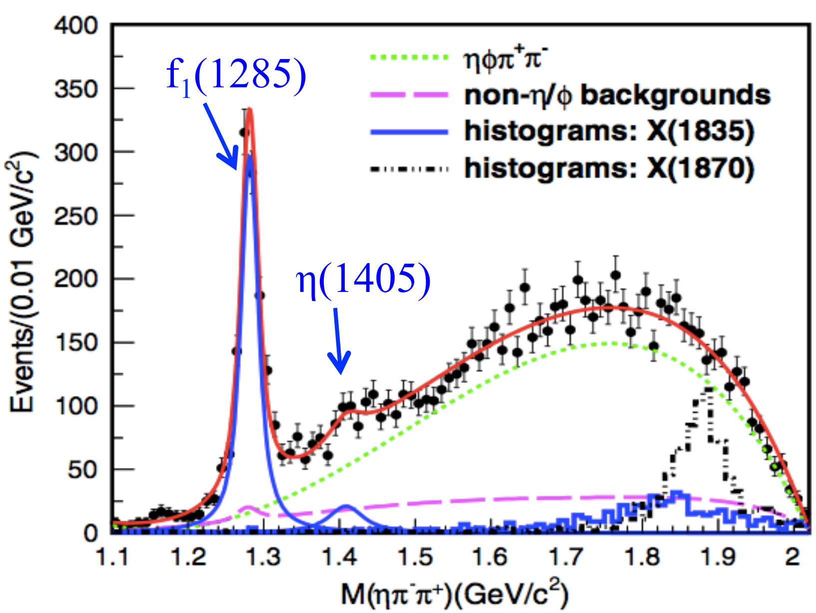
Study of $J/\psi \to \eta\, \phi \pi^+ \pi^-$

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 **10 σ**

$M = 2200 \pm 6 \pm 5\ \mathrm{MeV}/c^2$, $\Gamma = 104 \pm 15 \pm 15\ \mathrm{MeV}$





ηππ mass spectrum recoiling against the ϕ:

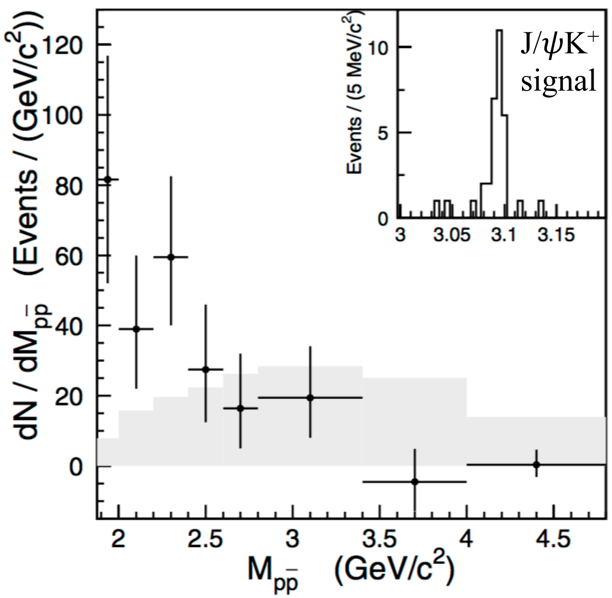
- Fit includes contributions from the $f_1(1285)$ and η(1405) signals, the $J/\psi \to \eta\, \phi \pi\pi$ decay, and backgrounds from non-η and non-ϕ processes
- No evidence of X(1835) and X(1870) states

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

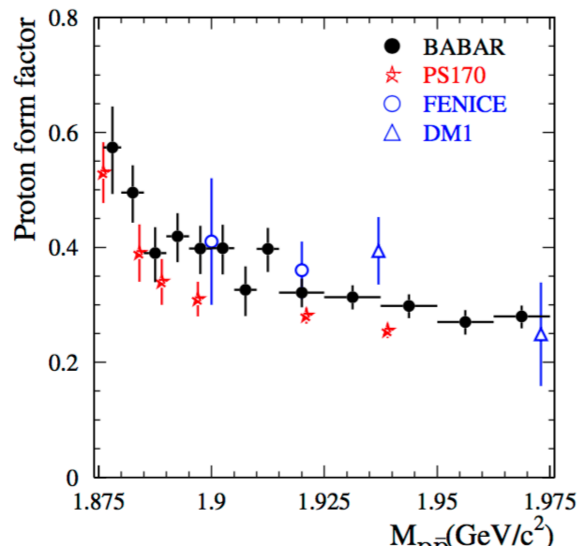
$\mathcal{B}(J/\psi \to \phi \eta(1405) \to \phi \eta \pi\pi) = (2.01 \pm 0.58 \pm 0.82) \times 10^{-5}$

ppbar enhancement in other reactions

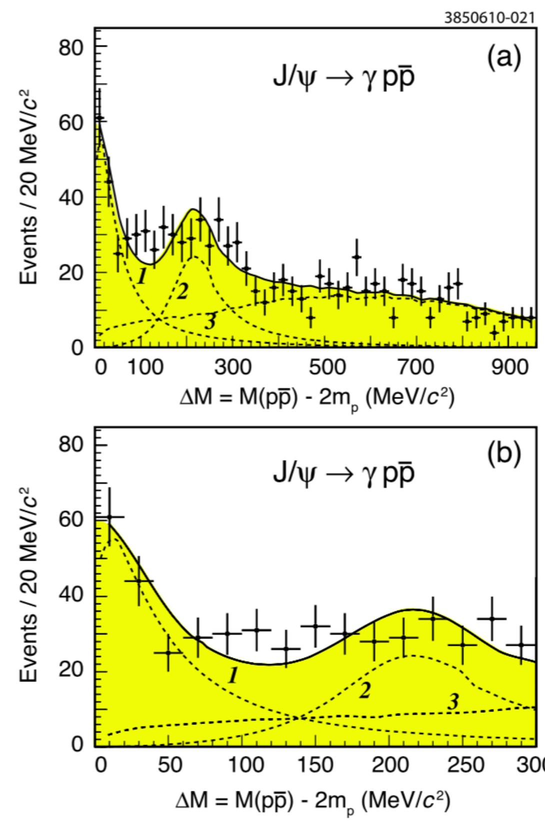
Belle: PRL**88**, 181803
$B^+ \rightarrow ppK^+$



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

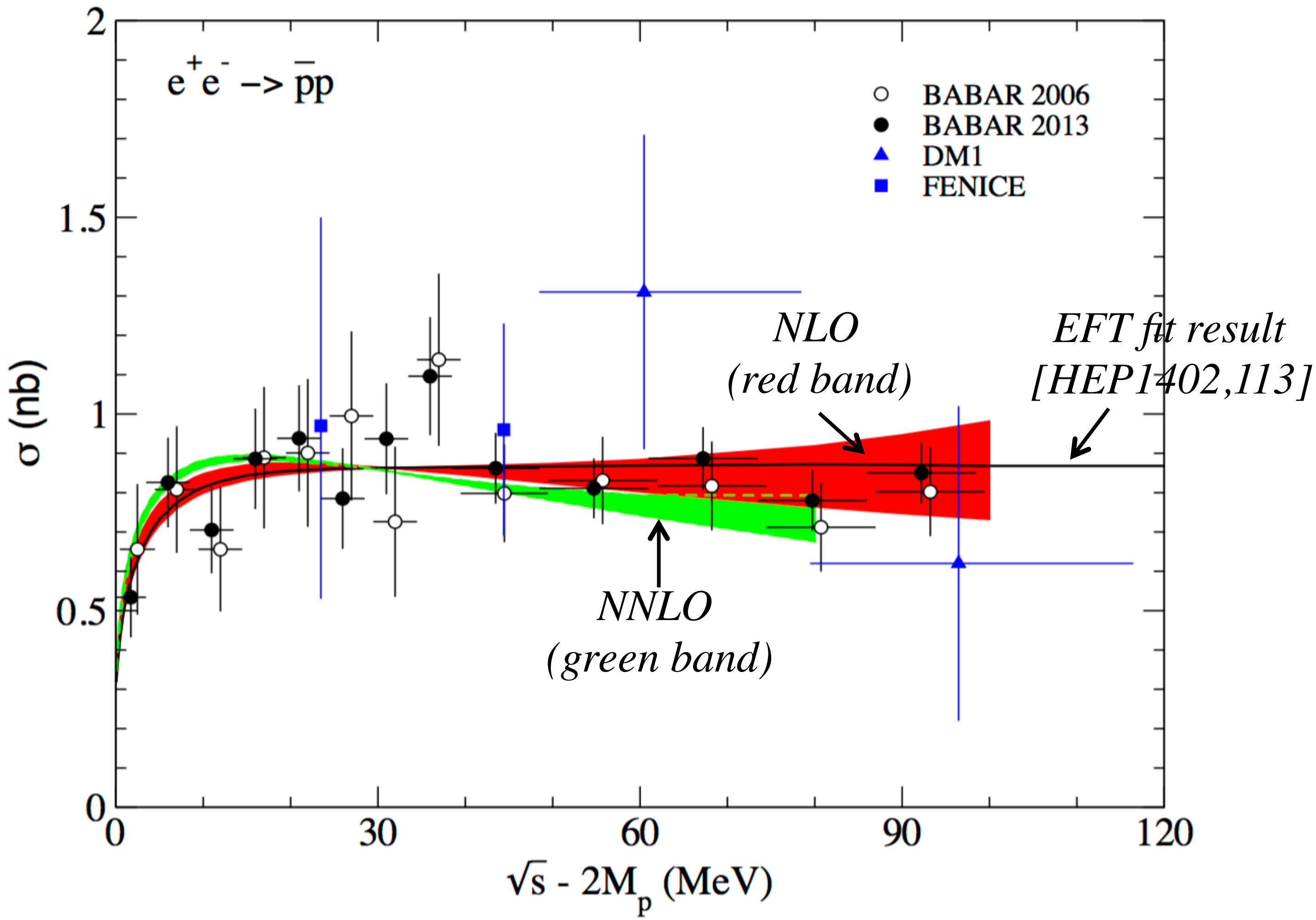


CLEO: PRD**82**, 092002
$\psi' \rightarrow \pi^+\pi^- J/\psi$



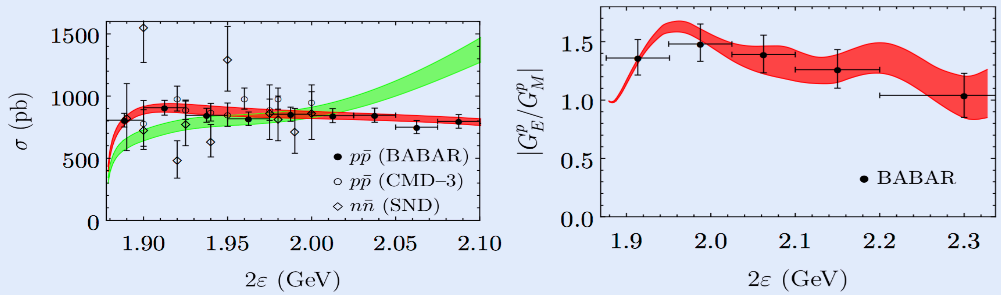
- Enhancement also seen in other B decays
- FSI? Sub-threshold resonance?
- Not enough statistic to draw any conclusion

Final State interaction [NPA 929, 102]



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

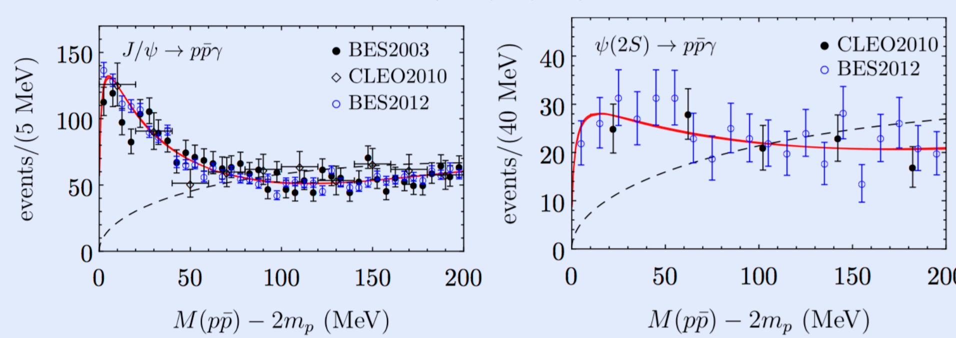
Predictions for the cross section of $e^+e^- \to N\bar{N}$ near the threshold



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).

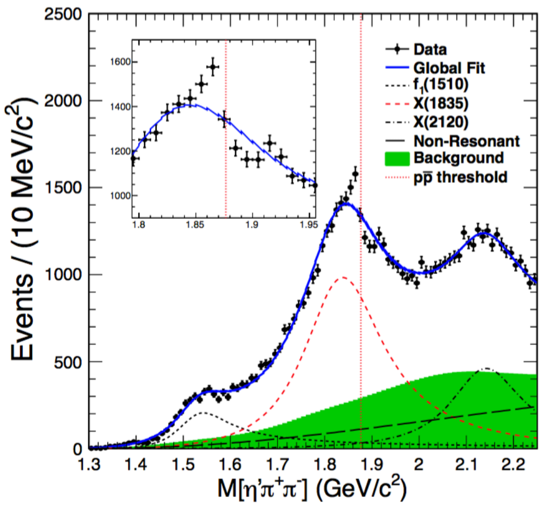
$J/\psi,\ \psi(2S) \to p\bar{p}\gamma$ decay

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

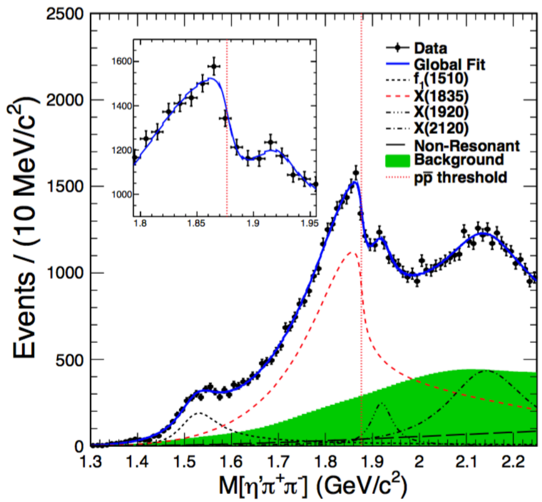


Left: $J/\psi \to p\bar{p}\gamma$ decay. Right: $\psi(2S) \to p\bar{p}\gamma$ decay.

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



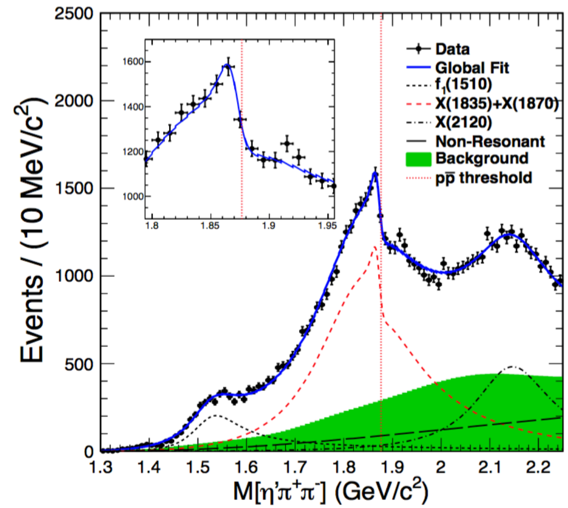
- Three efficiency-corrected Breit-Wigner functions
- Simple BW function fails in describing the $\eta'\pi^-\pi^+$ line shape near the threshold



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 σ)

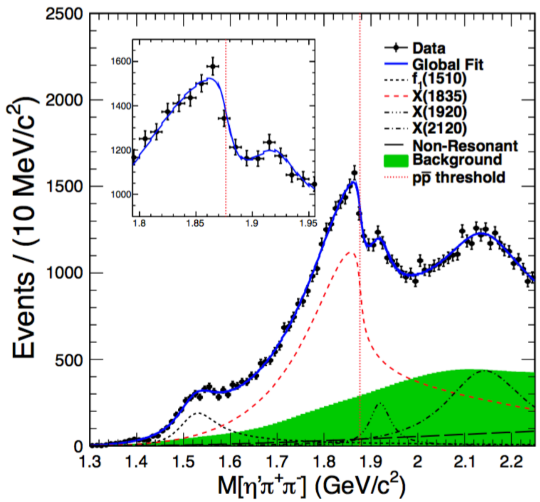


MODEL 2

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



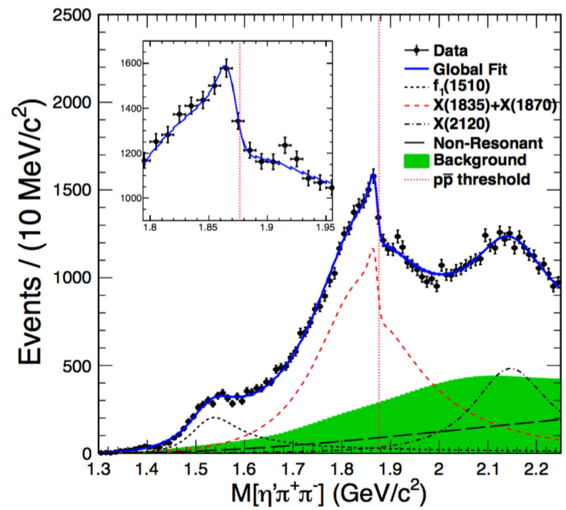


TABLE I. Fit results of using the Flatté formula. The first errors are statistical errors, and the second errors are systematic errors; the branching ratio is the product of $\mathcal{B}(J/\psi \to \gamma X)$ and $\mathcal{B}(X \to \eta' \pi^+ \pi^-)$.

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]	$93.7 \pm 35.4^{+47.6}_{-43.9}$
$g_{p\bar{p}}^2/g_0^2$	$2.31 \pm 0.37^{+0.83}_{-0.60}$
$M_{\rm pole}$ (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	$(3.93 \pm 0.38^{+0.31}_{-0.84}) \times 10^{-4}$

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 $J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta$

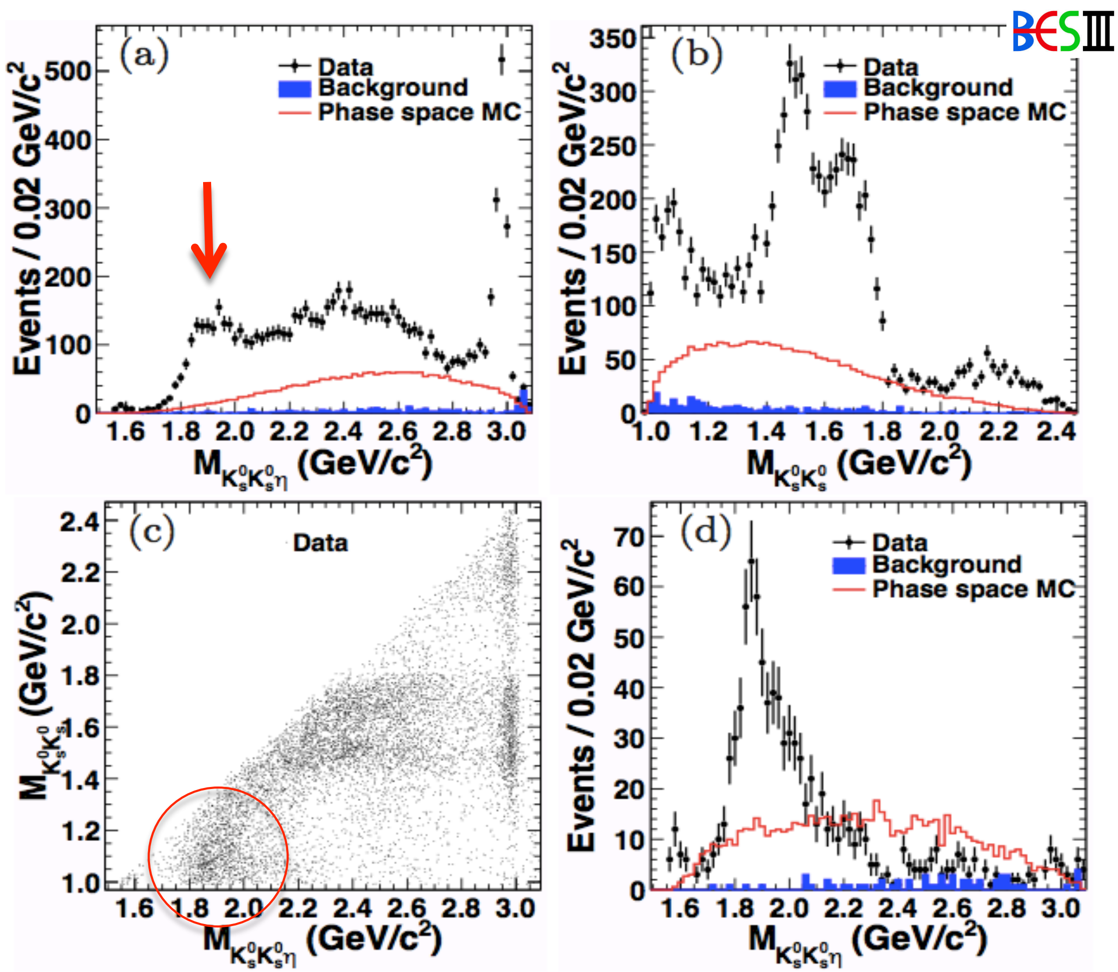
BESIII: PRL**115**,091803

$J/\psi \rightarrow \gamma K^0_S K^0_S \eta$ 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

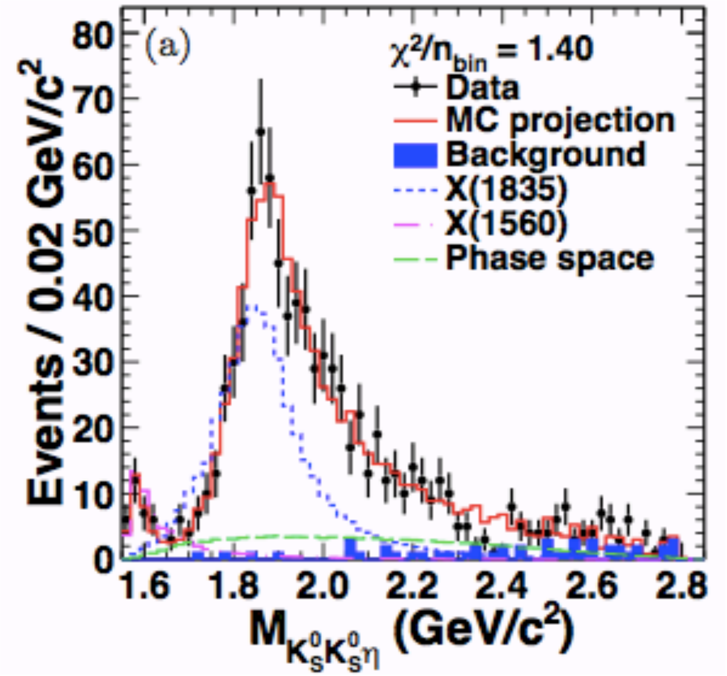


$J/\psi \to \gamma K_S^0 K_S^0 \eta$: PWA results

BESIII: PRL**115**,091803

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



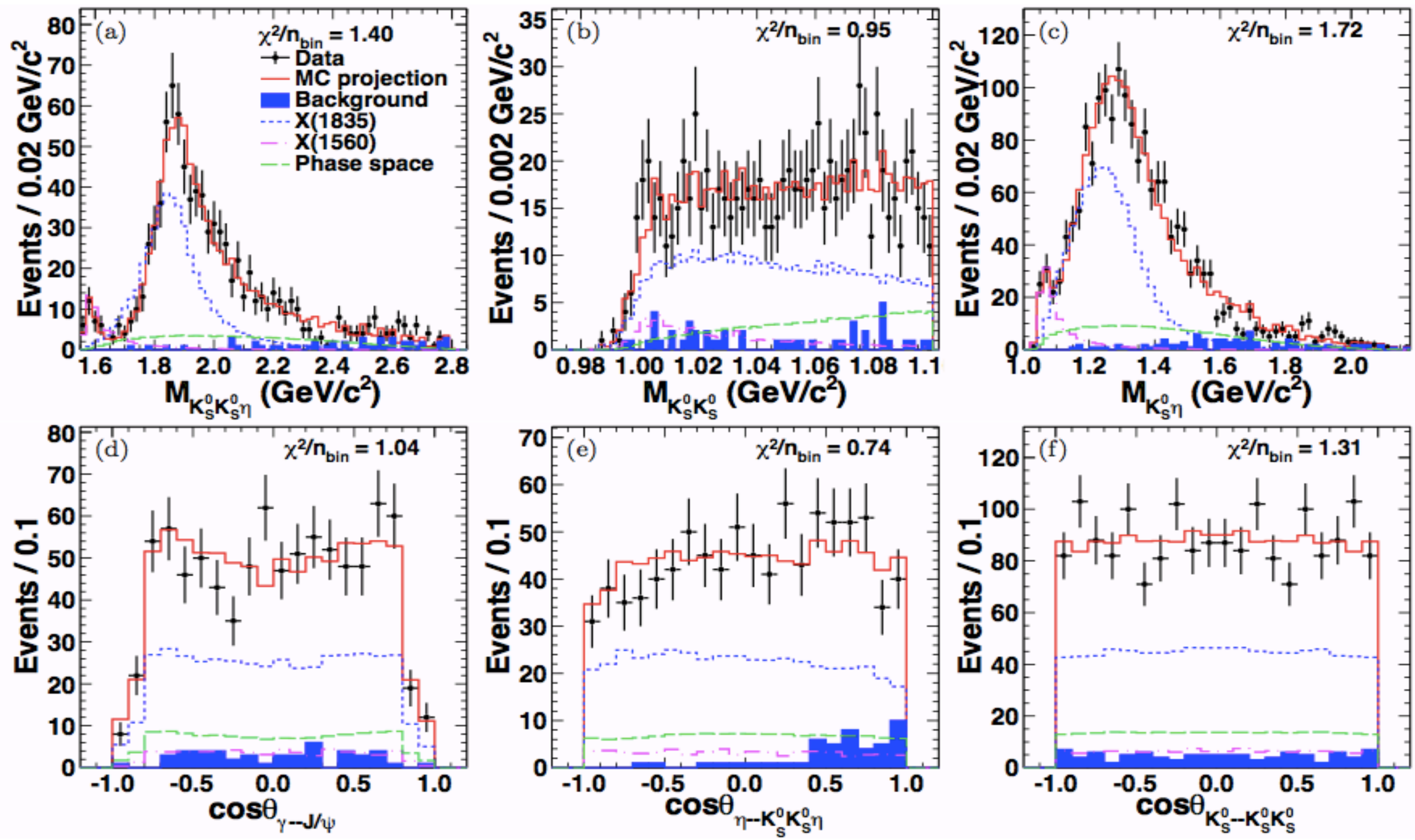
Mass and width of X(1835) consistent with PRL**106**

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

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

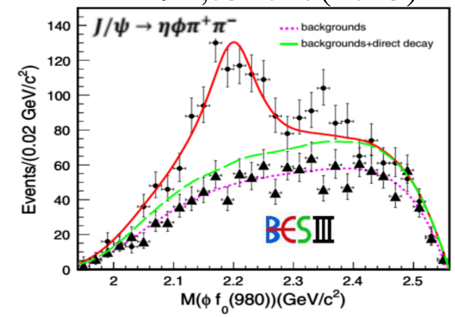
$M = 1565 \pm 8\,(stat)^{+0}_{-63}(syst)\ MeV/c^2 \quad \Gamma = 45^{+14}_{-13}(stat)^{+21}_{-28}(syst)\ MeV \quad (>8.9\sigma)$

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



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

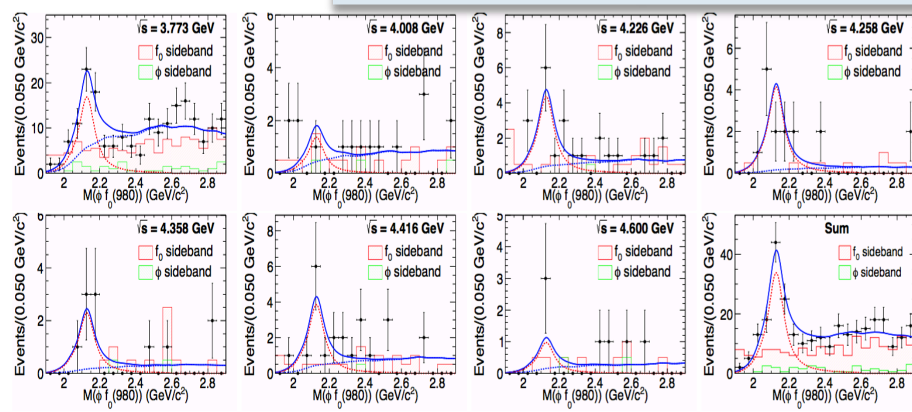
PRD91,052017(2015)



- The Y(2175) (ϕ(2170) in the PDG) 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)



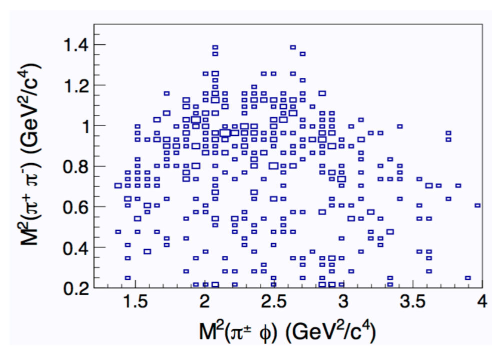
➢ The simultaneous fit result to all data sample give a **statistical significance larger than 10σ**

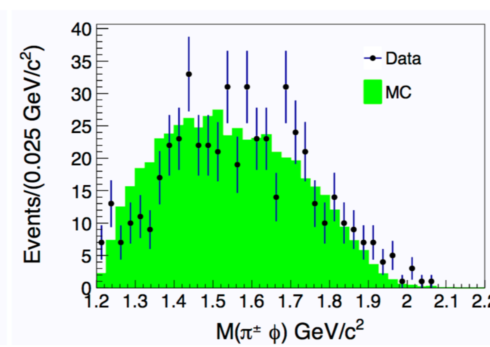
➢ In analogy with the Y(4260) and ϒ(10860), the Y(2175) represents a unique place to search for Z_S state in $\phi\pi^\pm$ spectrum

  ➢ no significant signal is observed

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

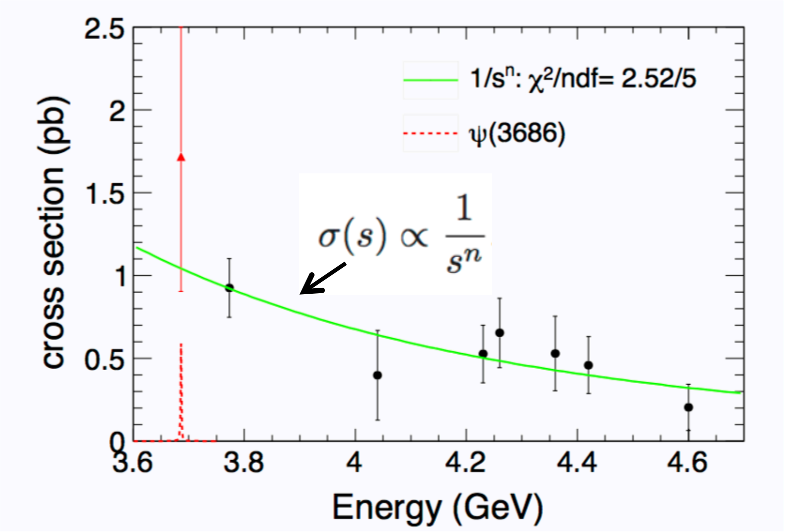
➢ No signicant $e^+e^-\to\eta' Y(2175)$ signal observed

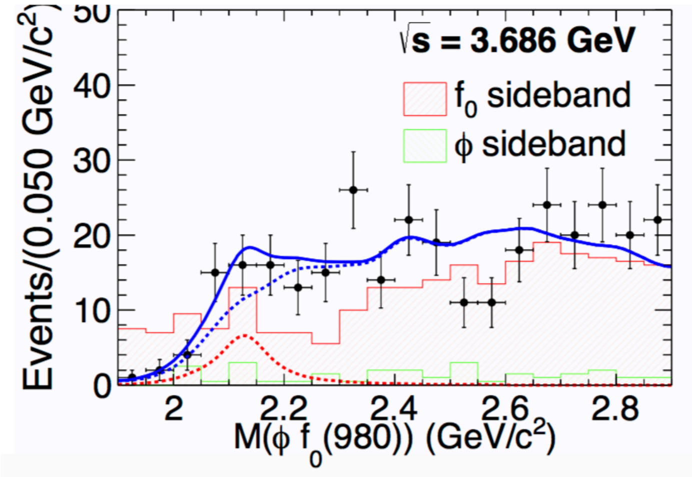


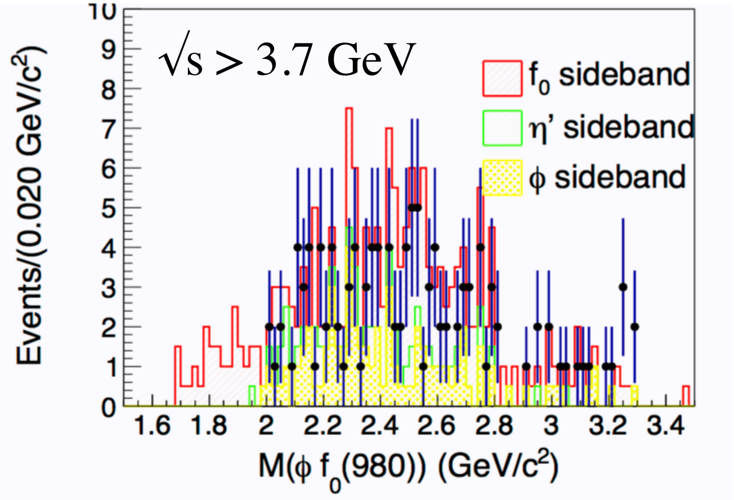


Observation of e+e−→ η Y(2175) @ √s > 3.7 GeV

arXiv:1709.04323 (submitted to PRD)

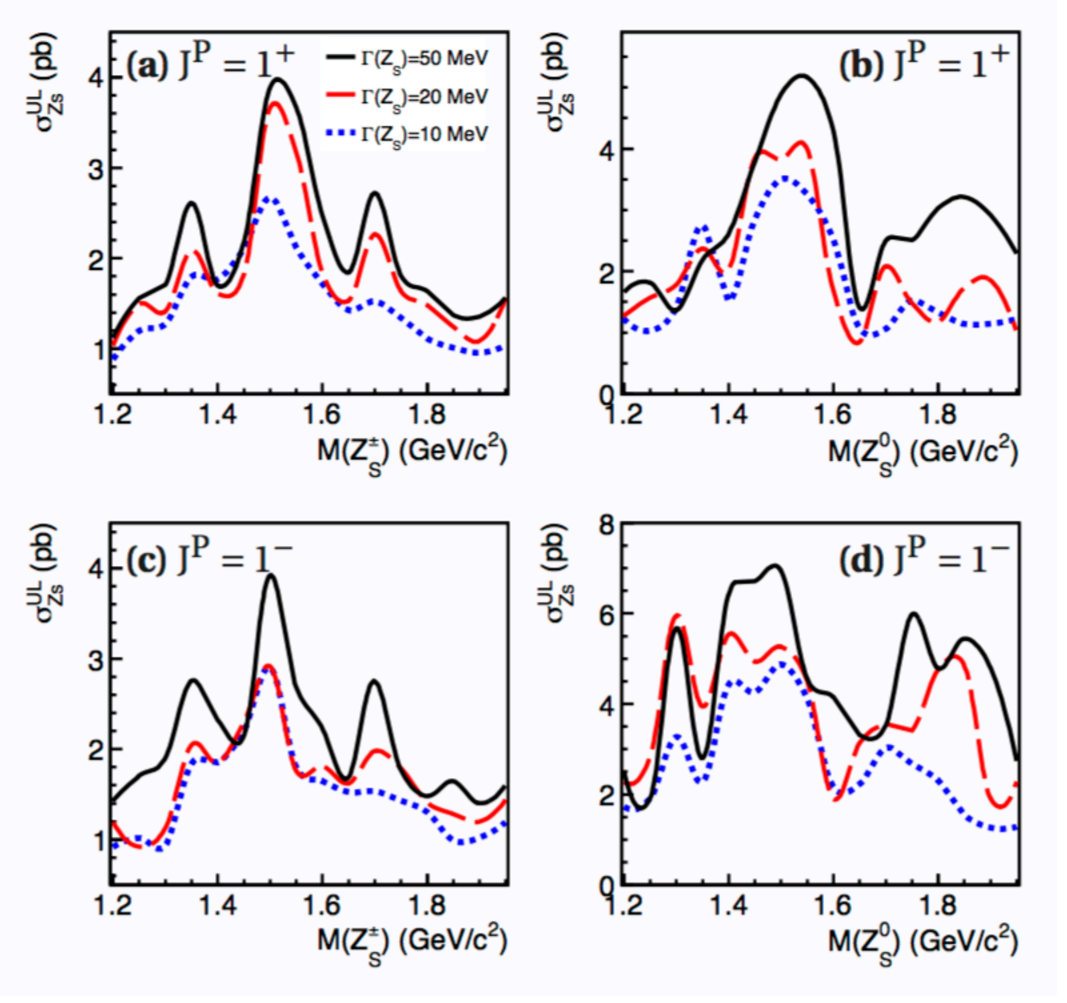






Search for ZS @ $\sqrt{s}$ = 2.125 GeV

arXiv:1801.10384(2018) – PRD 99, 011101(R), (2019)



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 $e^+e^- \rightarrow \phi\pi^+\pi^-(\phi\pi^0\pi^0)$ 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:

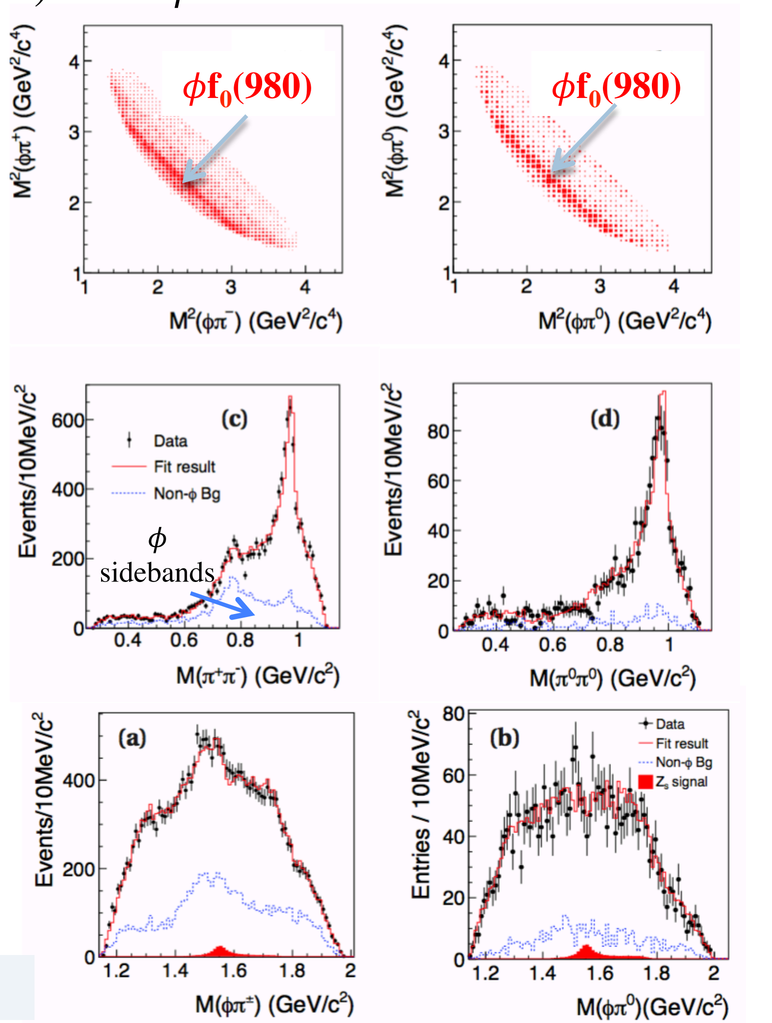
- ➢ $\phi\sigma$
- ➢ $\phi f_0(980)$
- ➢ $\phi f_0(1370)$
- ➢ $\phi f_2(1270)$
- ➢ Non-ϕ bkg from ϕ sidebands (non-interfering term)

+ 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)
- ➢ $\sigma(e^+e^- \rightarrow \phi\pi^+\pi^-) = (343.0 \pm 5.1 \pm 25.1)$ pb
- ➢ $\sigma(e^+e^- \rightarrow \phi\pi^0\pi^0) = (208.3 \pm 7.6 \pm 13.5)$ pb

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



PRL **121**, 022001(2018)

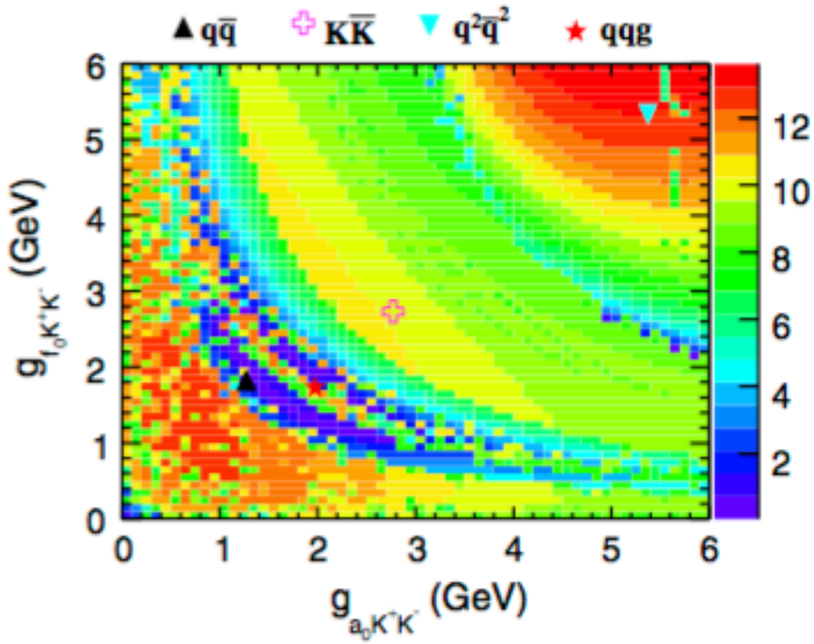


FIG. 4. The statistical significance of the signal scanned in the two-dimensional space of $g_{a_0K^+K^-}$ and $g_{f_0K^+K^-}$. The regions with higher statistical significance indicate larger probability for the emergence of the two coupling constants. The markers indicate predictions from various illustrative theoretical models.