WARWICK

HQL2021 – The XV International Conference on Heavy Quarks and Leptons

New Results on Light Hadron Spectroscopy from BESIII

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On behalf of the BESIII Collaboration

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University of Warwich - UK

INFN
Istituto Nazionale di Fisica Nucleare

Università degli Studi di Ferrara

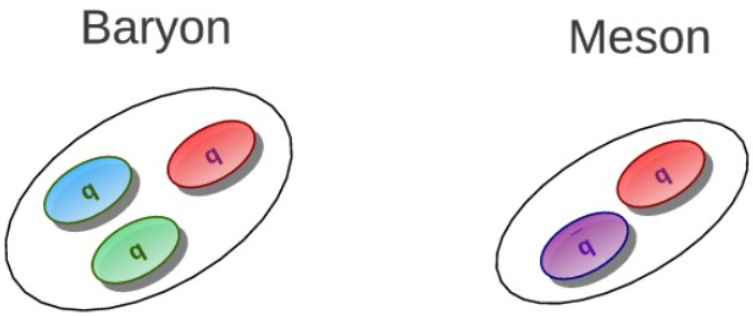
BESIII

Outline

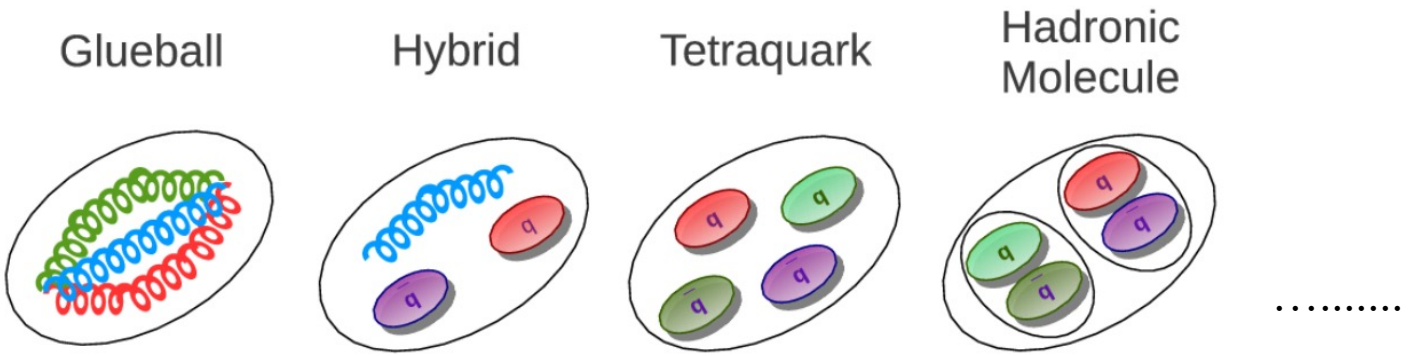
- ✓ INTRODUCTION:
  - Light hadron spectroscopy
  - The BESIII experiment
- ✓ Physics highlights
  - X(18xx) states
  - Observation of X(2370) in $J/\psi \to \gamma KK\eta'$ and search for X(2370) $J/\psi \to \gamma\eta\eta\eta'$ decays
  - Strangeonia spectrum and $\phi(2170)$ @ BESIII
  - Partial Wave Analysis: $J/\psi \to K^+K^-\pi^0$ and $\psi(3686) \to KK\eta$
- ✓ Summary and Conclusions

Hadron Spectrum

Naïve Quark Model:
conventional hadrons
contain two or three quarks



… ***but*** QCD allows also different combinations of quarks and gluons: ***EXOTIC*** hadrons



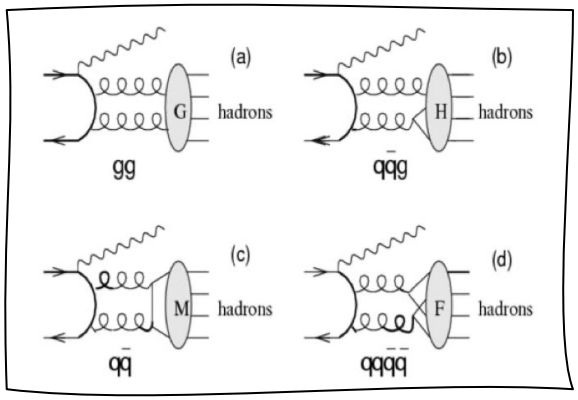
A lot of exotic states observed experimentally, but their nature is still far from being understood!!!

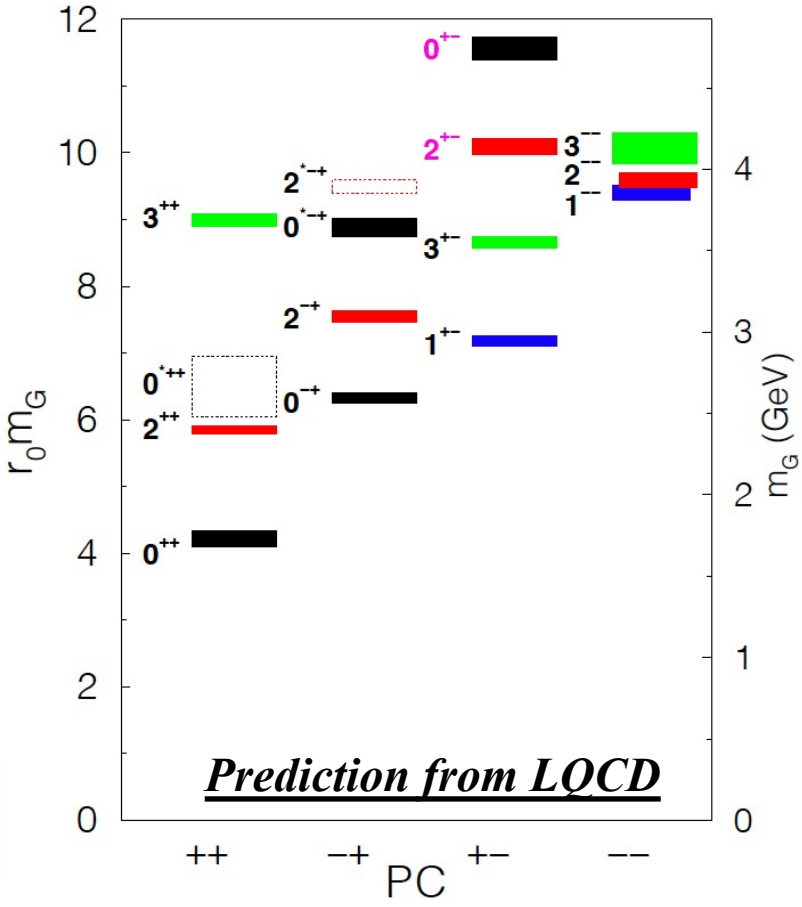
Hadron spectroscopy: establish the spectrum and study the exotic hadrons properties

Hunting for glueballs and new form of hadrons

- Charmonium radiative decays is the ideal laboratory for light glueballs and hybrids hadron studies

✓ Gluon-rich process
✓ Clean process
✓ High statistics





https://doi.org/10.1142/S0218301309012124

- ***Glueballs can mix with ordinary quark-antiquark states***
- Predicted large BFs for glueballs in J/ψ radiative decays

PRL**110**, 021601

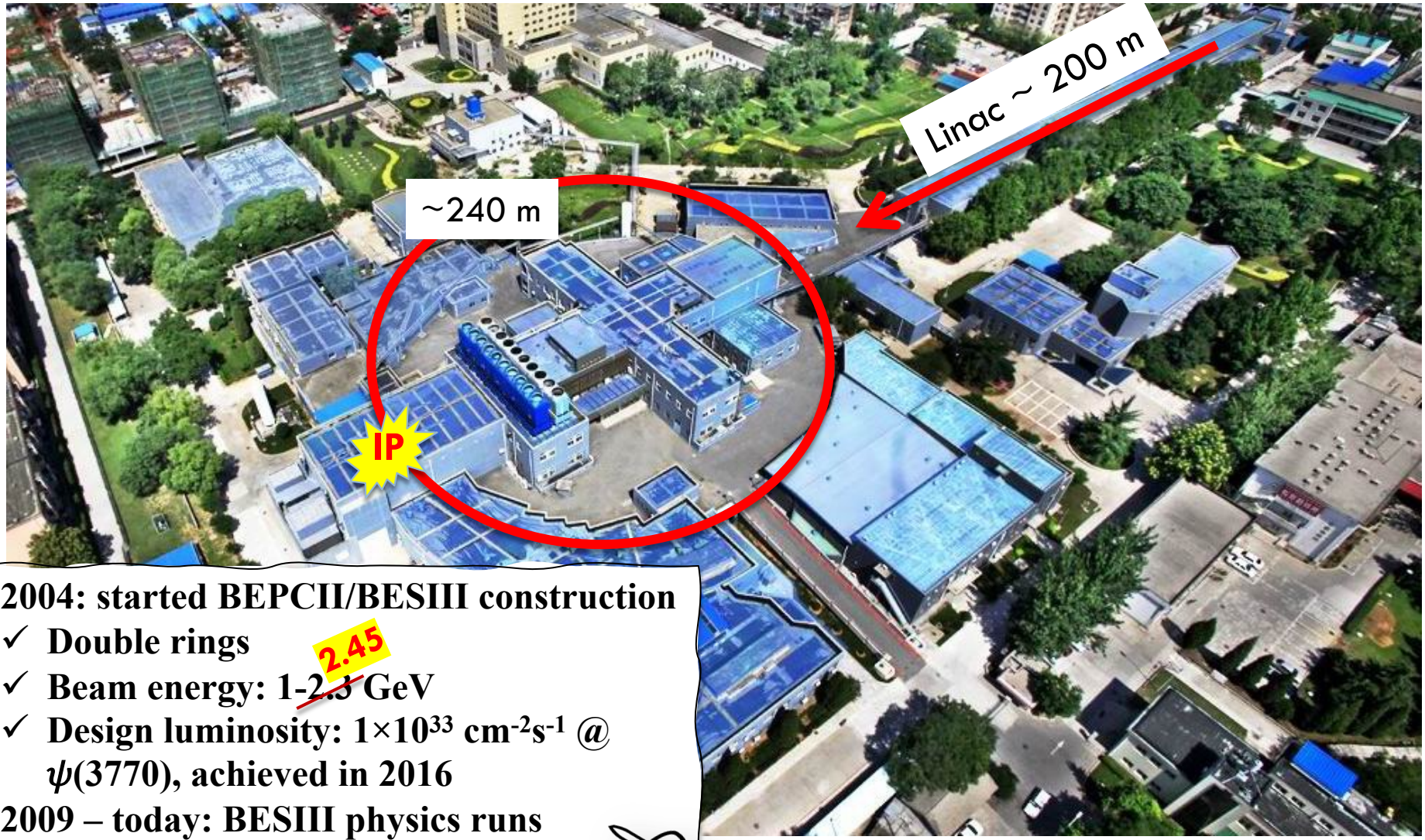
$$\Gamma(J/\psi \to \gamma G_{0^{++}})/\Gamma_{\text{tot}} = 3.8(9) \times 10^{-3}$$

PRL**111**, 091601

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

Beijing Electron Positron Collider II

http://english.ihep.cas.cn



2004: started BEPCII/BESIII construction

- ✓ **Double rings**
- ✓ **Beam energy: 1-~~2.3~~ 2.45 GeV**
- ✓ **Design luminosity: 1×10^{33} $cm^{-2}s^{-1}$ @ $\psi(3770)$, achieved in 2016**

2009 – today: BESIII physics runs

Beijing Electron Positron Collider II

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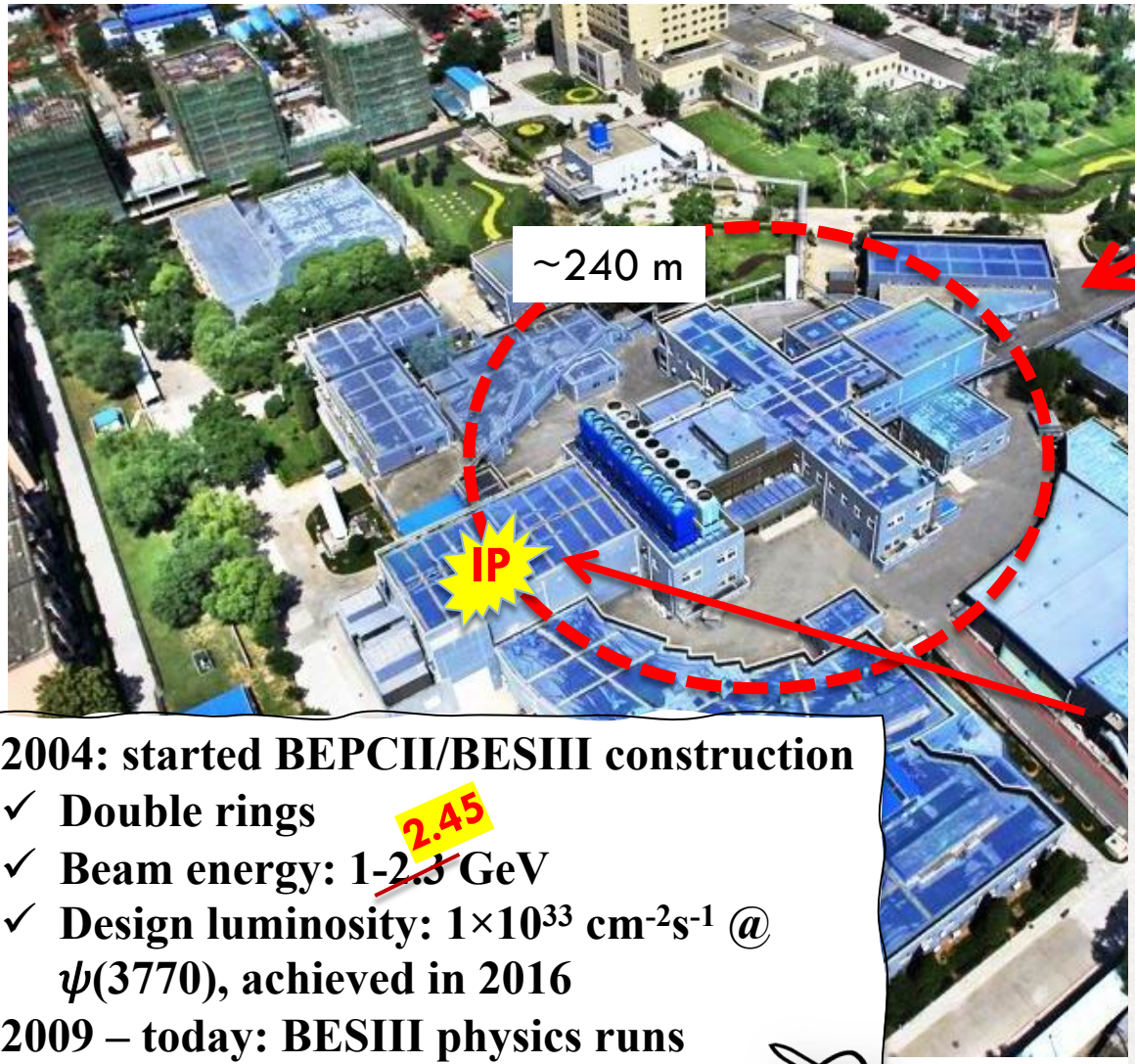

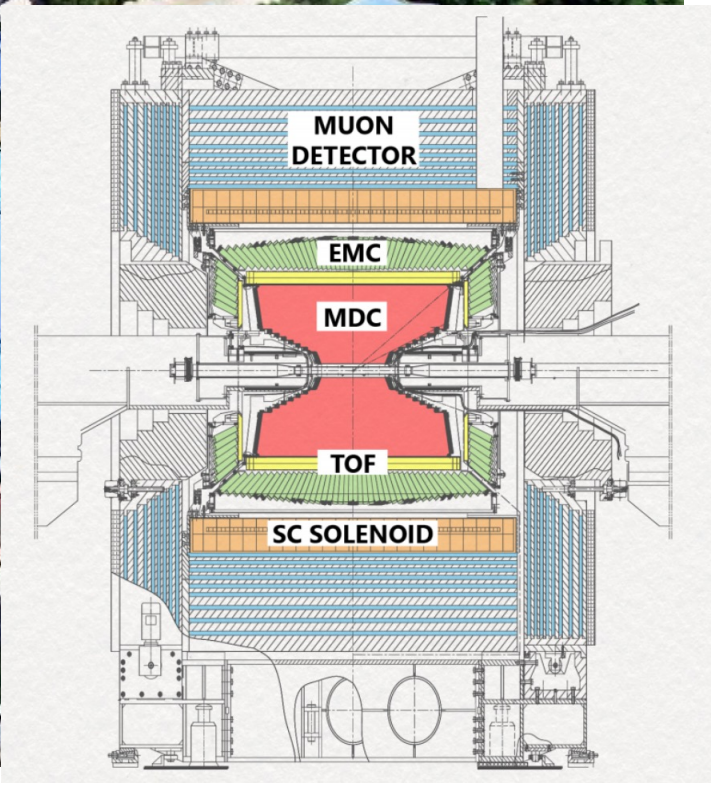

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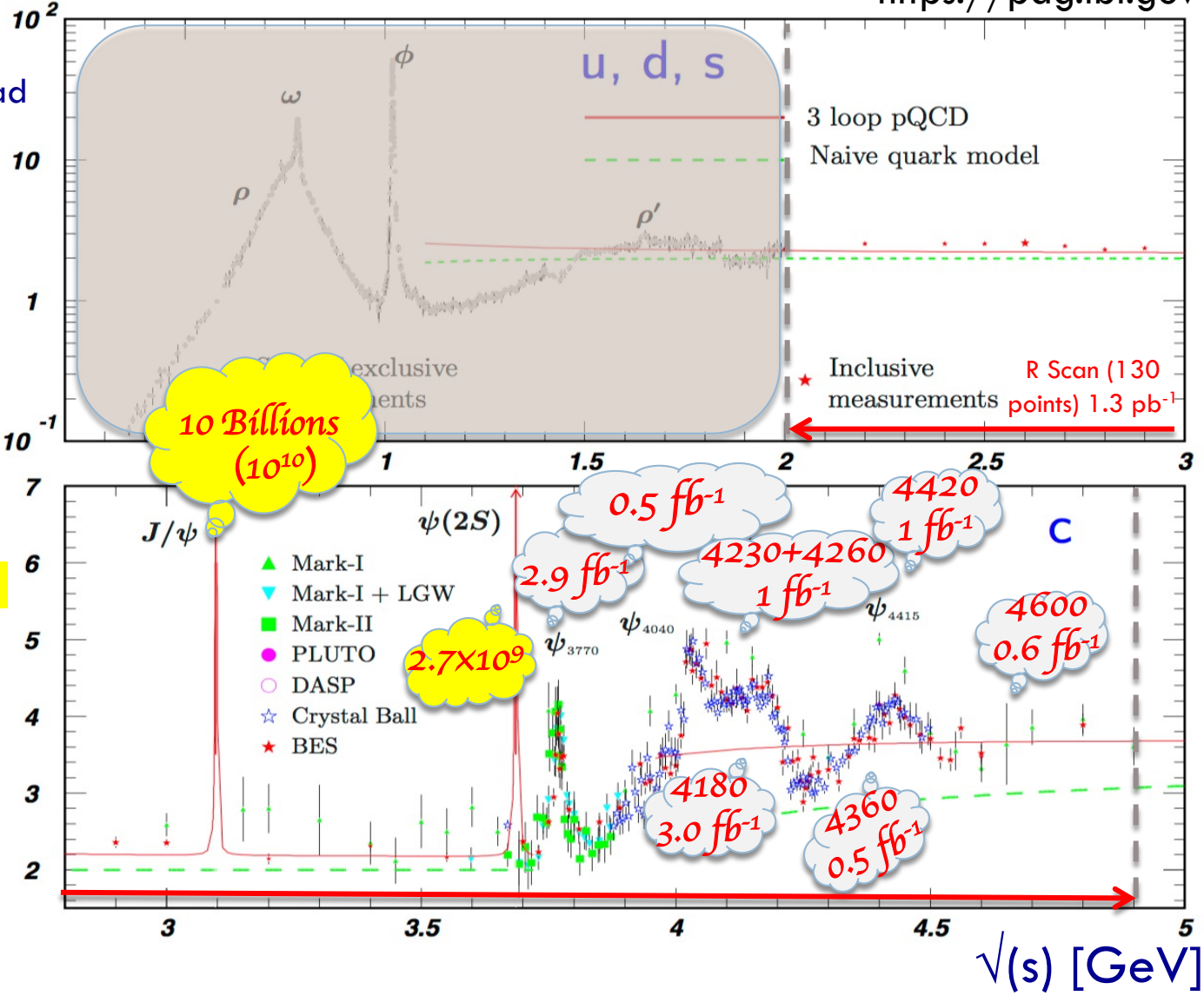
Nucl. Instr. Meth. A614, 345 (2010)

BESIII dataset

https://pdg.lbl.gov

R_{had}

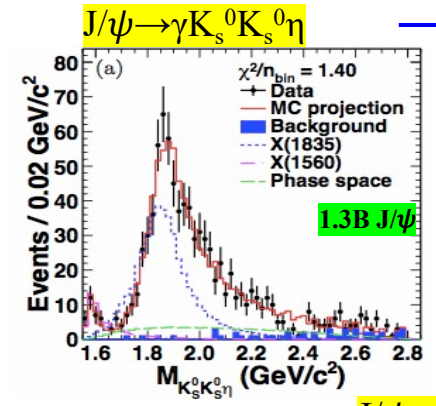
$$R_{had} = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

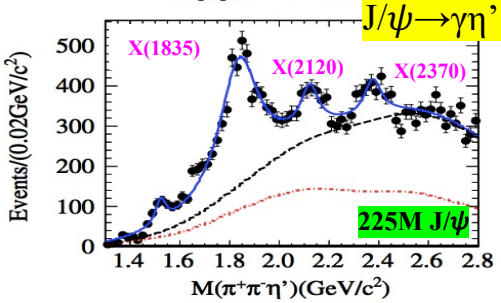


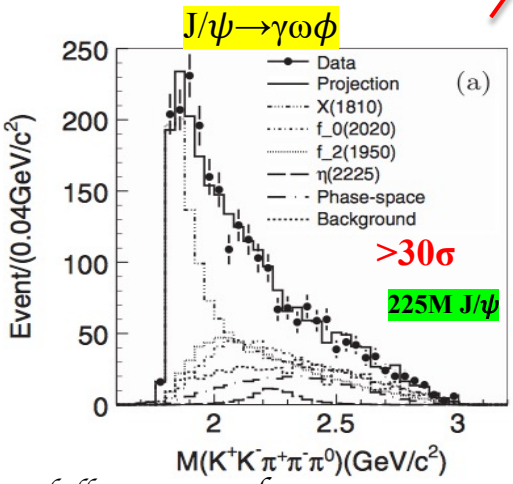
World largest data samples for J/ψ, ψ(2S) and ψ(3770)

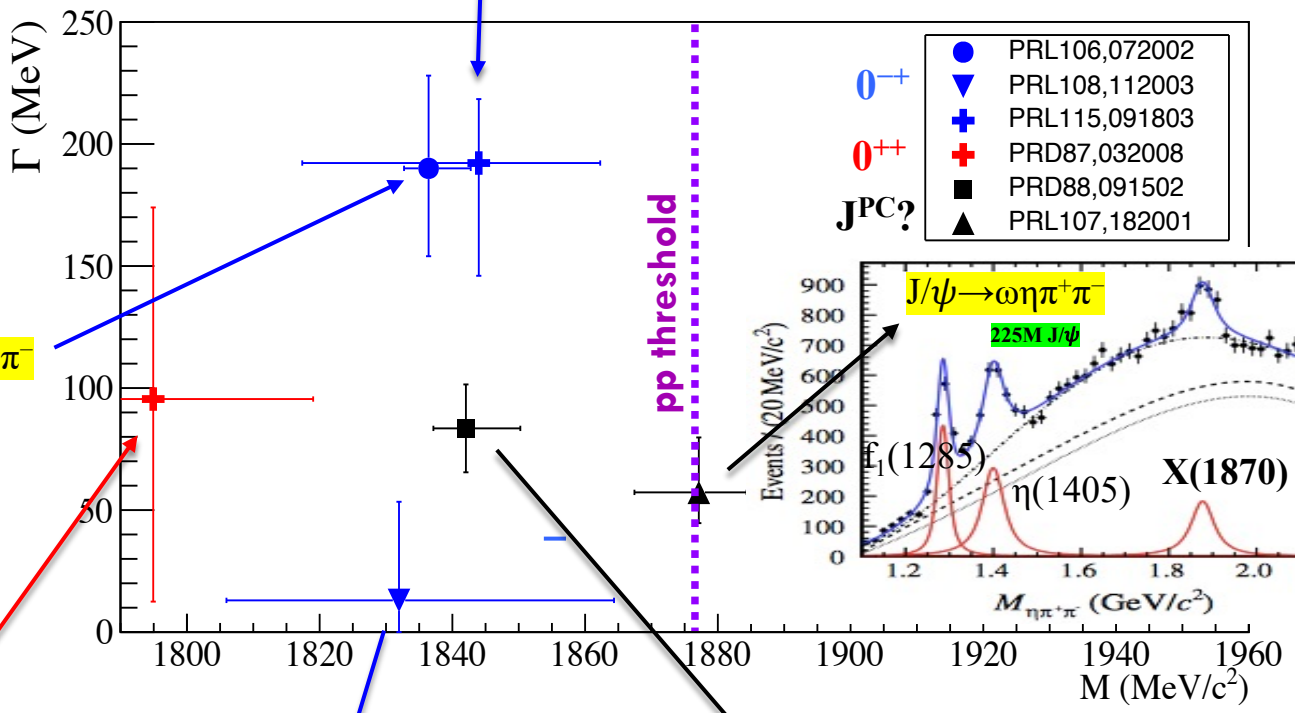
- Light hadron: ideal environment for light hadron spectroscopy studies
- Charm physics
- Charmonium spectroscopy
- ….

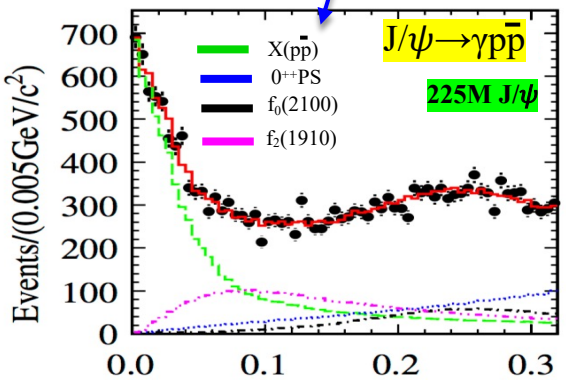
X(18xx) between 1.8-1.9 GeV

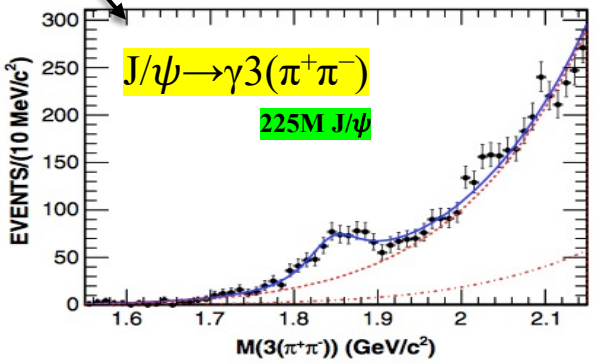












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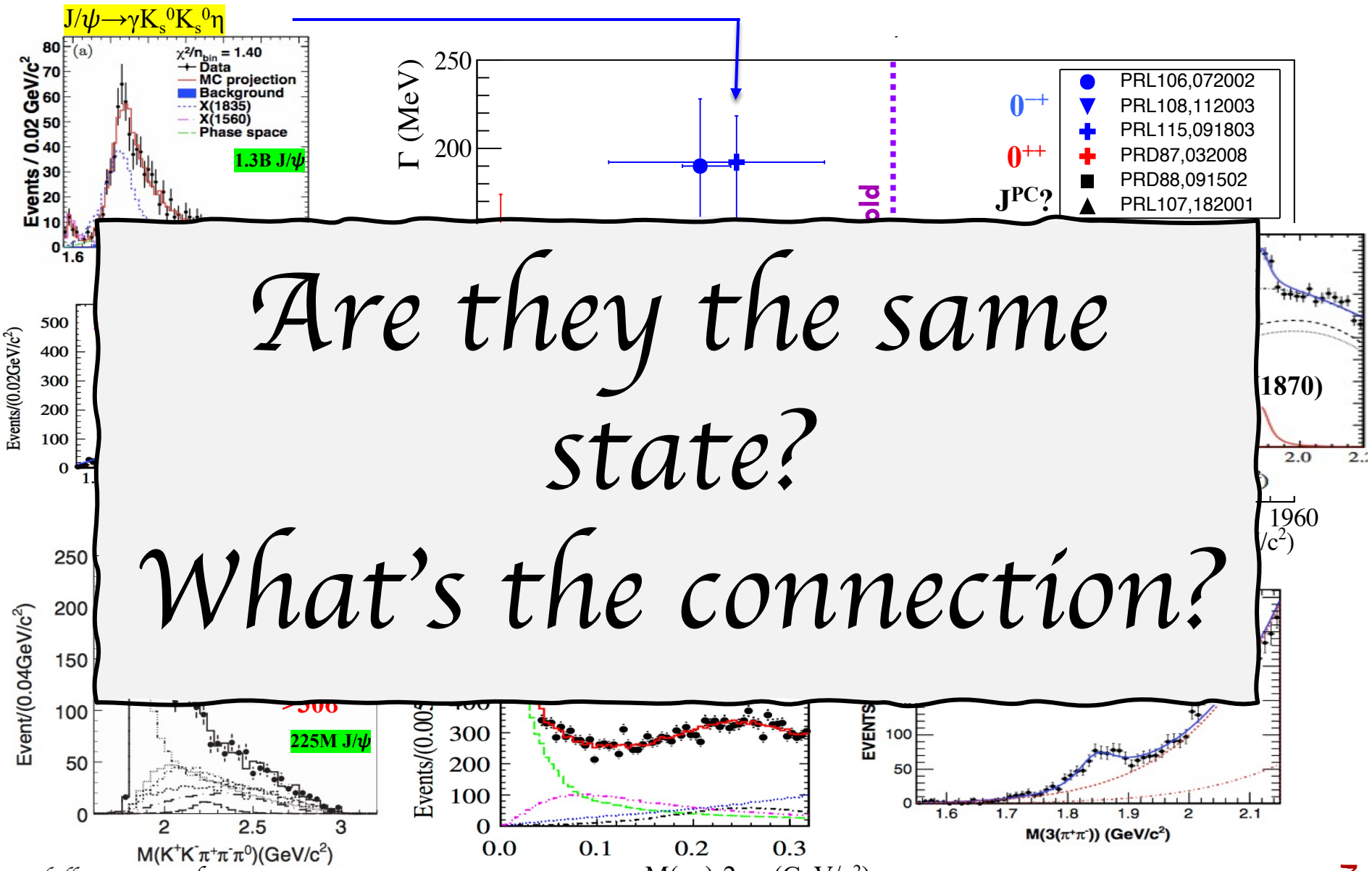
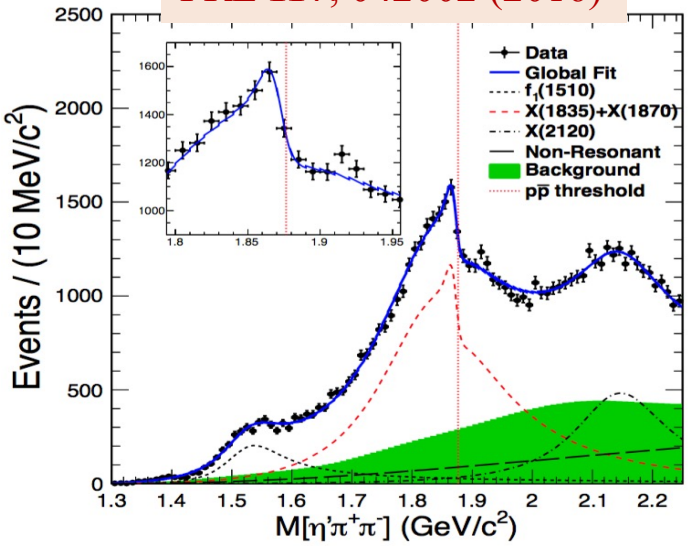


Latest Results on X(1835)

PRL **117**, 042002 (2016)



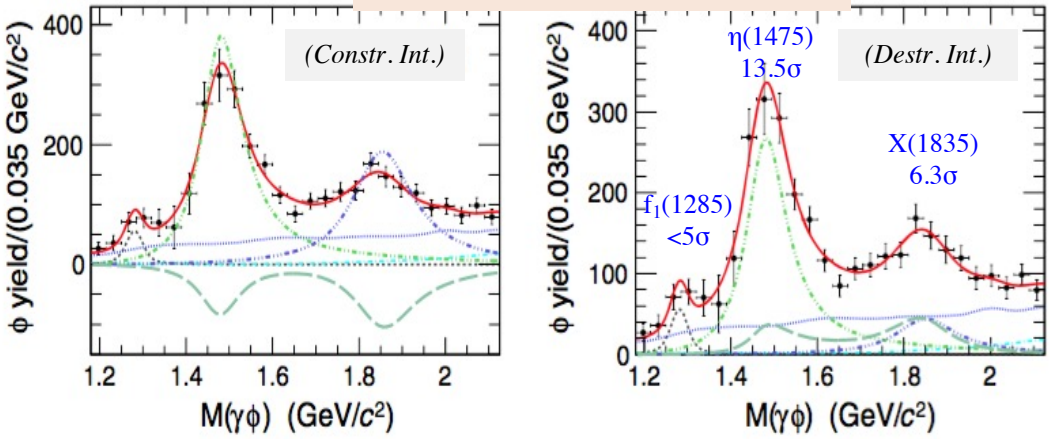
1.09×10⁹ J/ψ @ BESIII

$J/\psi \to \gamma\, \eta'\pi^-\pi^+$

Significant distortion of the $\eta'\pi^-\pi^+$ line shape near the ppbar mass threshold

Two fit models are taken into account and both support the existence of a $p\bar{p}$ moleculelike or bound state

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



1.3×10⁹ J/ψ @ BESIII

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

- X(1835) and η(1475): $J^{PC} = 0^{-+}$ assignment favored
- Sizable $s\bar{s}$ component in X(1835)
  - more complicated than a pure $N\bar{N}$ state

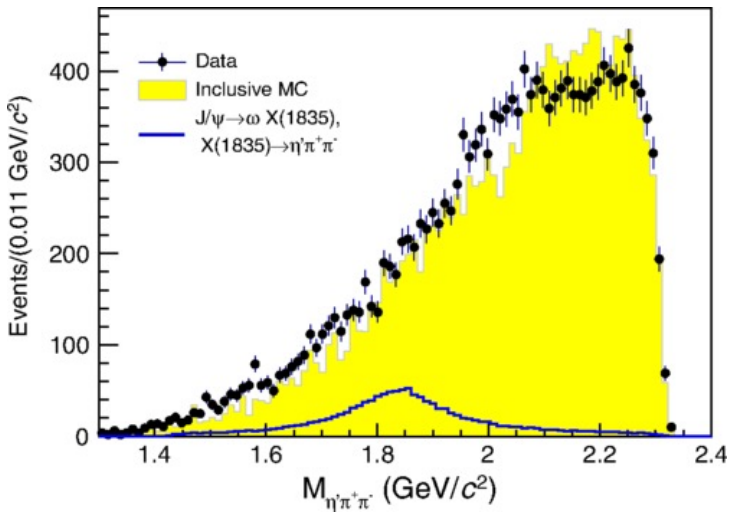
Solution	Resonance	m_R (MeV/c^2)	Γ (MeV)
I *(Destr. Int.)*	η(1475)	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$
	X(1835)	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$
II *(Constr. Int.)*	η(1475)	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$
	X(1835)	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$

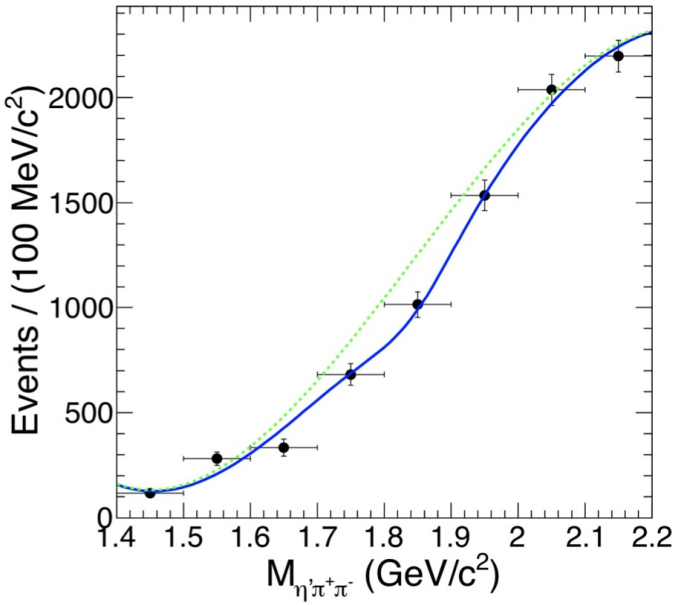
Search for X(1835) in other decay modes

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

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

1.3×10^9 J/ψ @ BESIII





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

$$\mathcal{B}(J/\psi \to \omega\eta'\pi^+\pi^-) = (1.12 \pm 0.02 \pm 0.13) \times 10^{-3}$$
$$\mathcal{B}(J/\psi \to \omega X(1835),\ X(1835) \to \eta'\pi^+\pi^-) < 6.2 \times 10^{-5}$$

@ 90% C.L.

The puzzle is still not complete ….

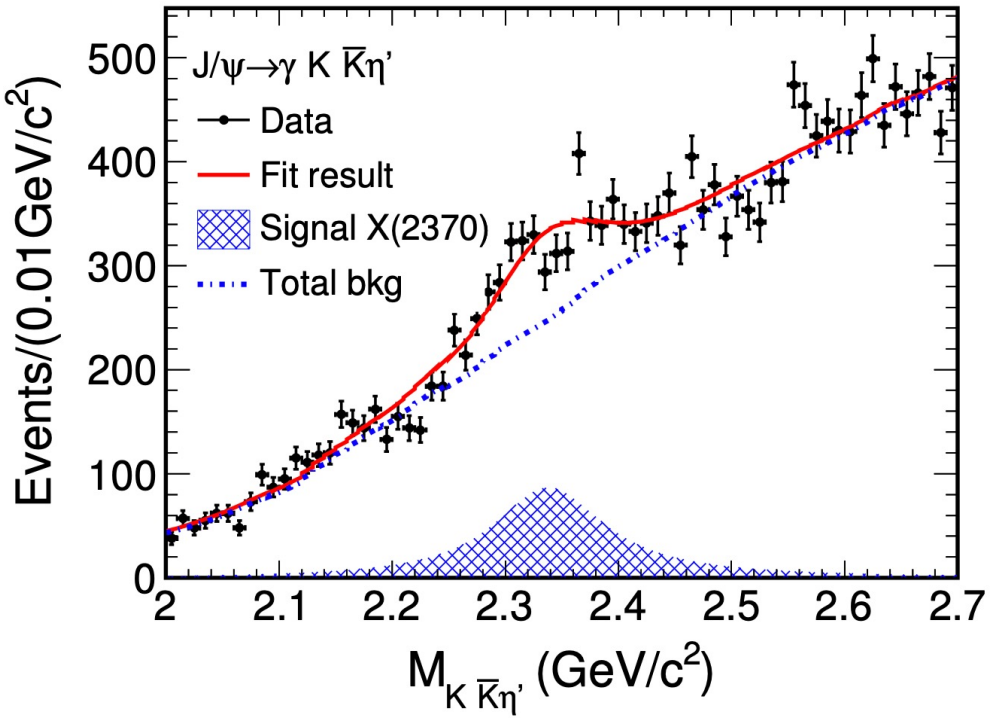
First Observation of X(2370) in $J/\psi \to \gamma K\bar{K}\eta'$

- X(2120) and X(2370) states observed in the $\pi^-\pi^+\eta'$ invariant mass spectra (PRL**106**,072002)
- The **X(2370)** measured mass is consistent with the pseudoscalar glueball candidate predicted by LQCD calculation (PRD**73**,014516)

➢ Simulataneus fit performed for two decay η' modes

1.3×10^9 J/ψ @ BESIII

EPJC **80**, 746 (2020)



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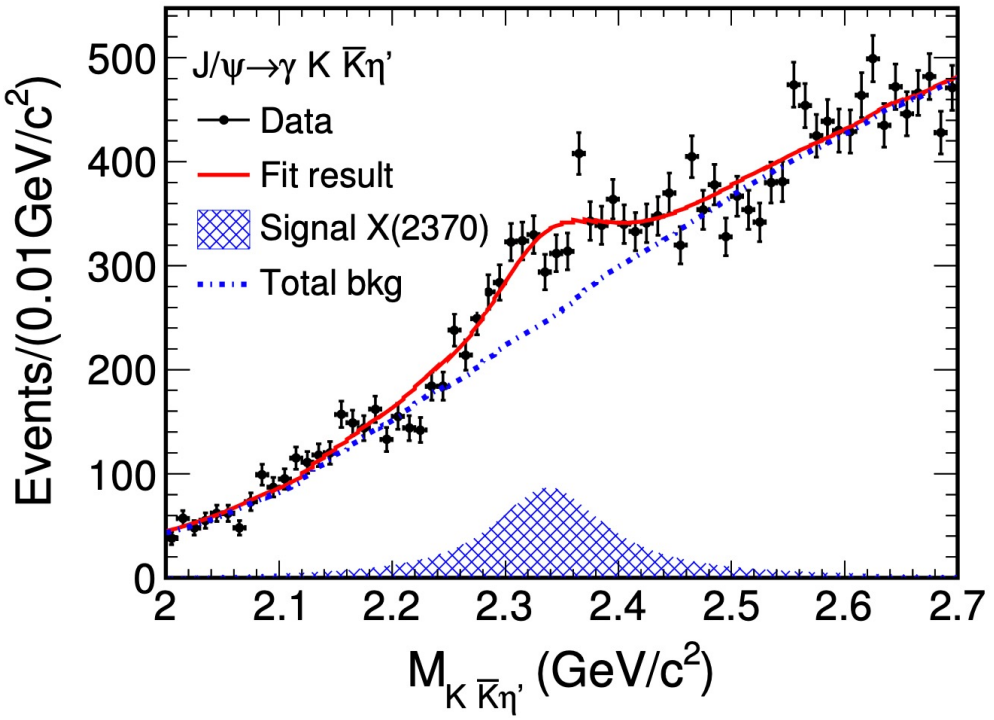


➢ **No evidence of X(2120) is found**

$$\mathcal{B}(J/\psi \to \gamma X(2120) \to \gamma K^+K^-\eta') < 1.49 \times 10^{-5}$$
$$\mathcal{B}(J/\psi \to \gamma X(2120) \to \gamma K^0_S K^0_S \eta') < 6.38 \times 10^{-6}$$

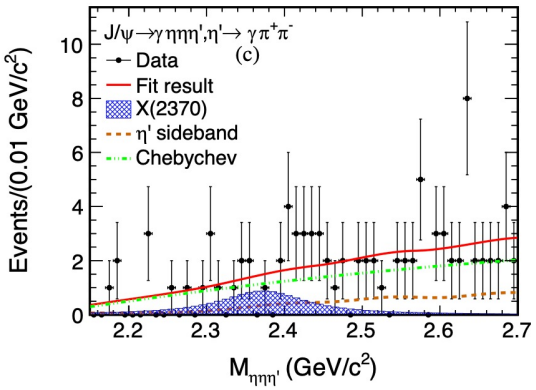
➢ **Clear X(2370) signal observed with significance of about 8.3σ**

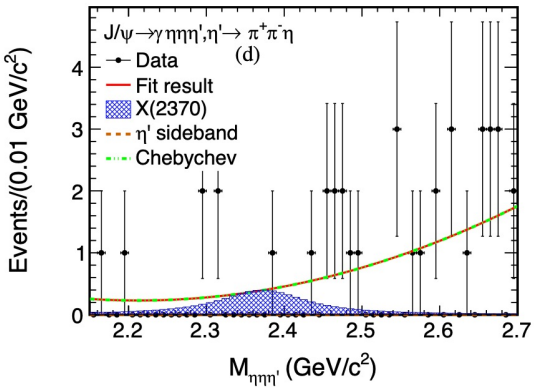
$$M_{X(2370)} = 2341.6 \pm 6.5 \pm 5.7\ \mathrm{MeV}/c^2 \quad \Gamma_{X(2370)} = 117 \pm 10 \pm 8\ \mathrm{MeV}$$
$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma K^+K^-\eta') = (1.79 \pm 0.23 \pm 0.65) \times 10^{-5}$$
$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma K^0_S K^0_S \eta') = (1.18 \pm 0.32 \pm 0.39) \times 10^{-5}$$

Search for X(2370) in $J/\psi \to \gamma\eta\eta\eta'$

PRD **103**, 012009 (2021)

1.3×10^9 J/ψ @ BESIII





Branching ratios prediction for the decay of pseudoscalar glueball with M~2.37 GeV into three pseudoscalar mesons (PRD **87**,054036 (2013))

$$\Gamma_{G\to\eta\eta\eta'}/\Gamma_G^{tot} = 0.00082$$
$$\Gamma_{G\to KK\eta'}/\Gamma_G^{tot} = 0.011$$
$$\Gamma_{G\to\pi\pi\eta'}/\Gamma_G^{tot} = 0.090$$

- **No obvious signal of X(2370)**

Simultaneous unbinned maximum likelihood fit to the ηηη' is performed and the 90% C.L. upper limit is calculated

$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma\eta\eta\eta') < 9.2 \times 10^{-6}$$

(it does not contradict PRD **87**,054036)

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PRD **103**, 012009 (2021)

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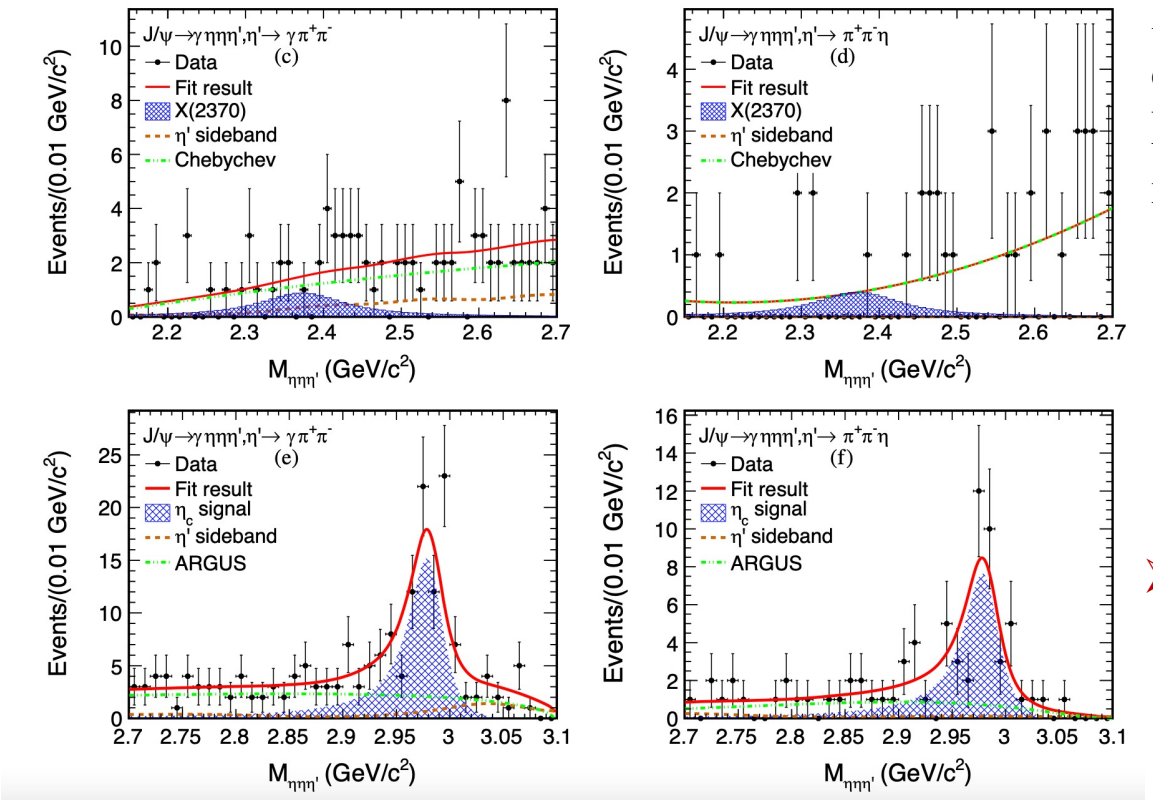

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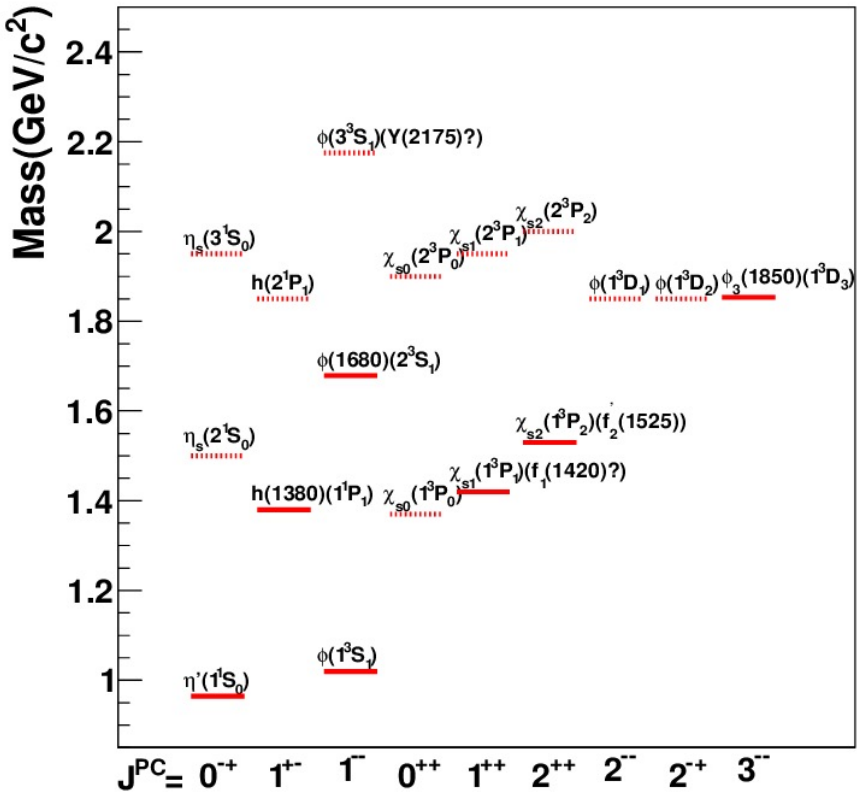
$$\mathcal{B}(J/\psi \to \gamma\eta_c)\cdot\mathcal{B}(\eta_c \to \eta\eta\eta') = (4.86\pm0.62\pm0.45)\times10^{-5}$$

FIRST OBSERVATION in the ηηη' invariant mass spectra

Strangeonia Spectrum



Strangeonium mesons

- Bridge between light quarks (u, d) and heavy quarks (c, b)
- Study of exotic states

Only few states observed:

- Small BR
- Large Γ

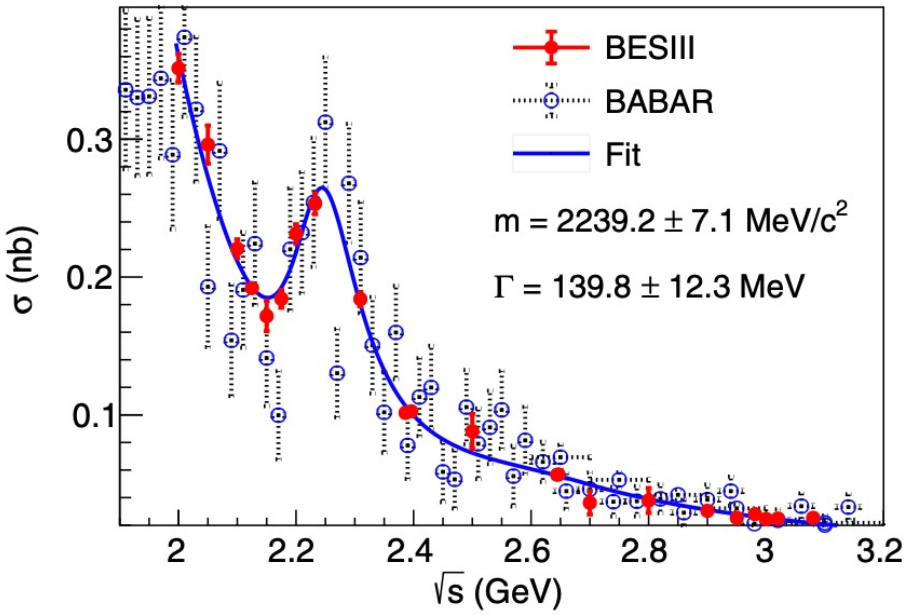
$$e^+e^- \Rightarrow \begin{cases} Y(2175) \to \phi(1020)\pi^+\pi^- & \text{strange,} \\ Y(4260) \to J/\psi\pi^+\pi^- & \text{charm,} \\ \Upsilon(10860) \to \Upsilon(1S,2S)\pi^+\pi^- & \text{bottom,} \end{cases}$$

- ϕ(2170)/Y(2175) observed for the first time in the ϕf_0 channel by BaBar (PRD **74**,091103; PRD **76**,031102)
  - BESIII: PRL**100**,102003(2008)
  - Belle: PRD**80**,031101 (2009)

$\phi(2170)$ @ BESIII

PRD **99**, 032001 (2019)

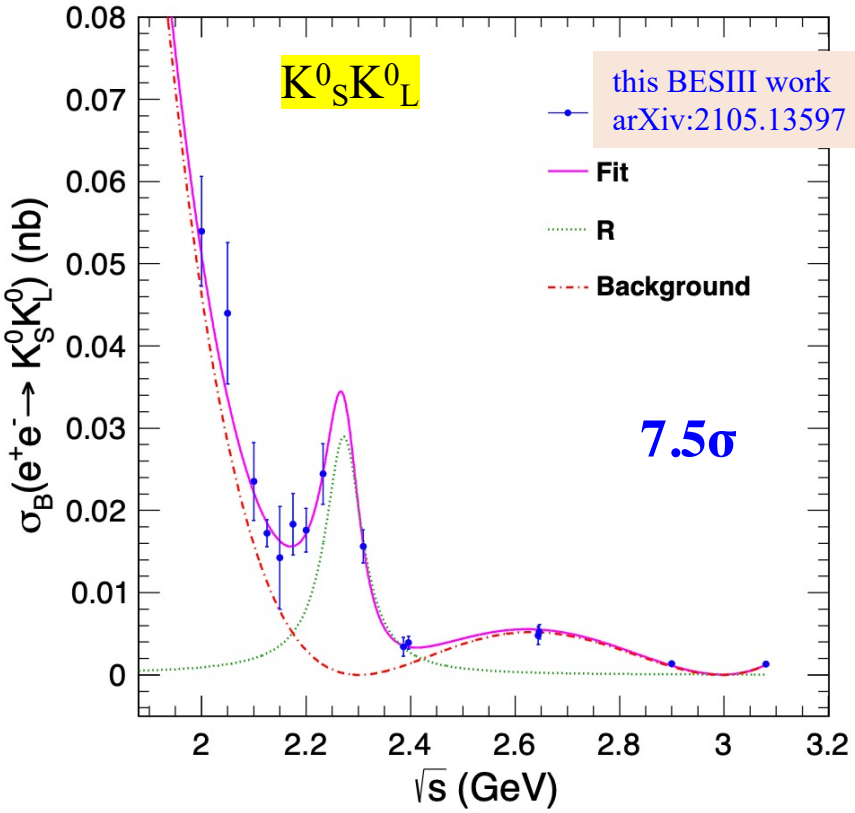
K^+K^-



$$M = 2239.2 \pm 7.1 \pm 11.3\ \mathrm{MeV}/c^2$$
$$\Gamma = 139.8 \pm 12.3 \pm 20.6\ \mathrm{MeV}$$

Consistent with BaBar PRD **88**,032012 (2018); PRD **92**,072008 (2015);

$K^0_S K^0_L$



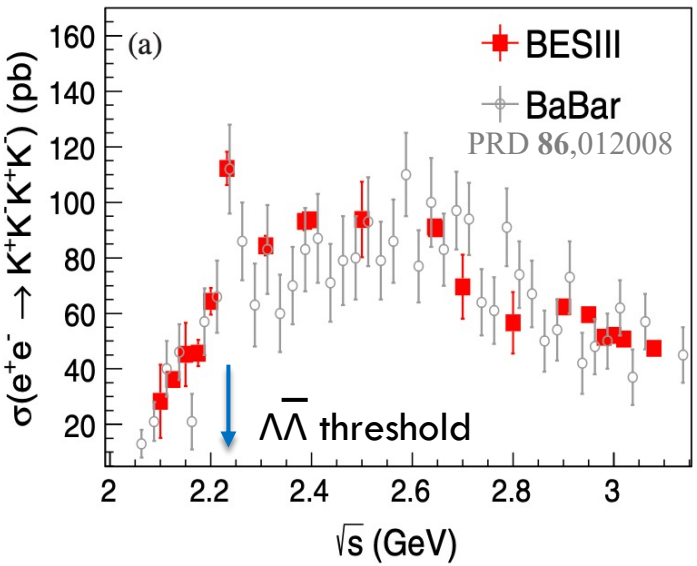
$$M = 2273.7 \pm 5.7 \pm 19.3\ \mathrm{MeV}/c^2\,,$$
$$\Gamma = 86 \pm 44 \pm 51\ \mathrm{MeV}\,,$$

Consistent with BaBar PRD **101**,012011(2020)

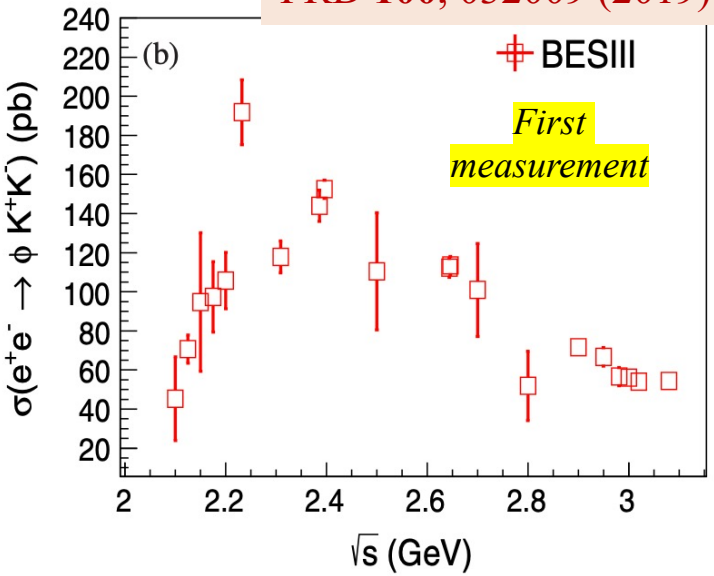
$\phi(2170)$ @ BESIII

Resonant structure in the 4K spectra, but difficult to disentangle from other final state

$\phi(2170)$ or new strangeonium state?



PRD **100**, 032009 (2019)



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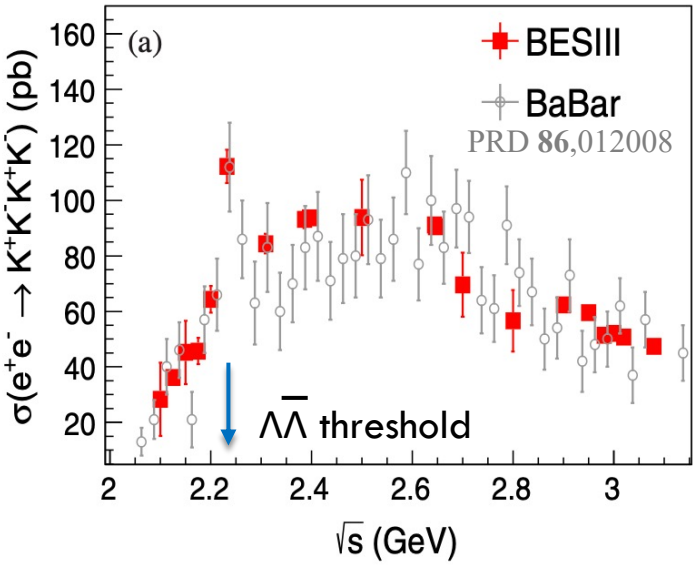
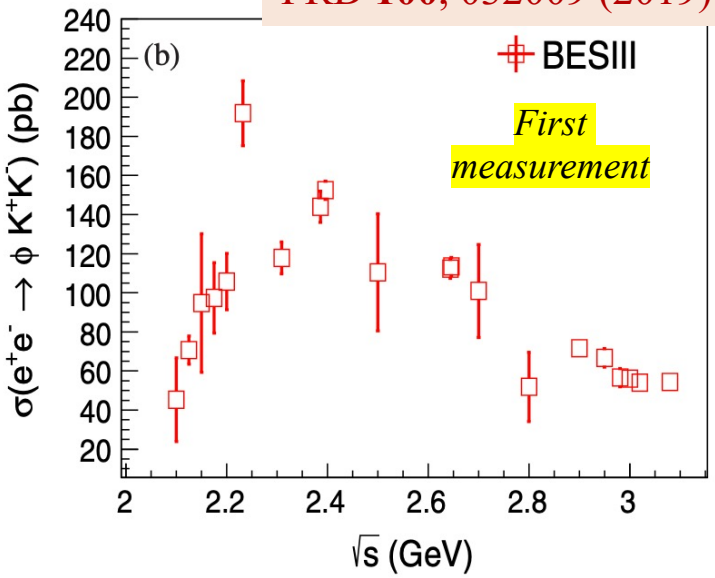


PRD **100**, 032009 (2019)



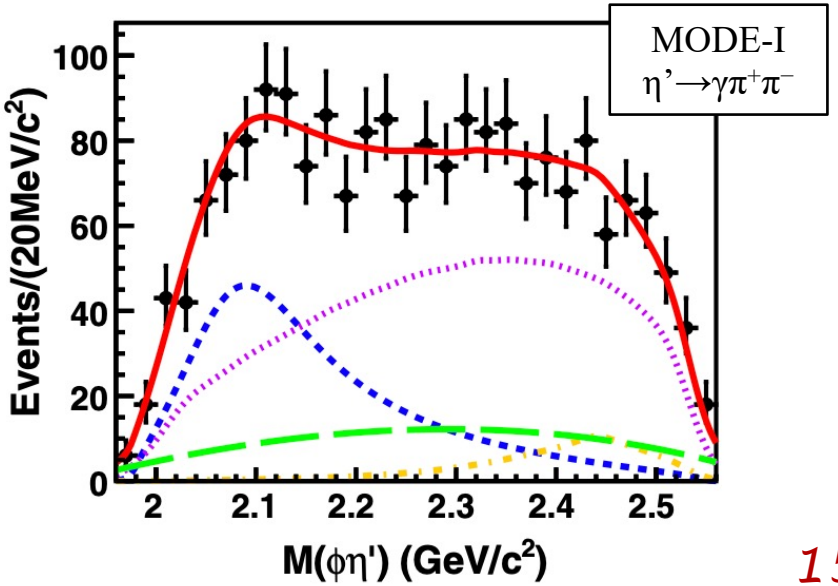
PRD **99**, 112008 (2019) - **1.3×10^9 J/ψ events**

$J/\psi \to \phi\eta\eta'$

- Evidence of a structure in the $\phi\eta'$ mass spectra
- Distribution of η polar angle in the J/ψ rest frame used to investigate the J^P assignment
- Significance of structure: 4.4σ for $J^P = 1^-$ and 3.8 for $J^P = 1^+$

$J^P = 1^+$: no PDG entries

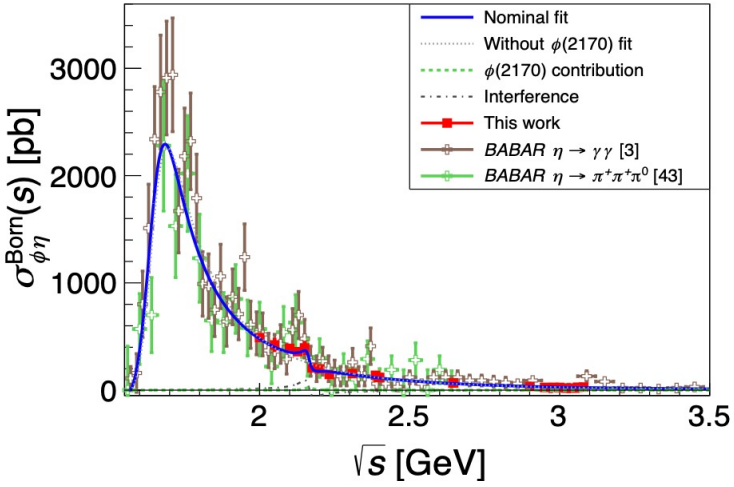
$J^P = 1^-$: mass 5σ away from that reported on PDG

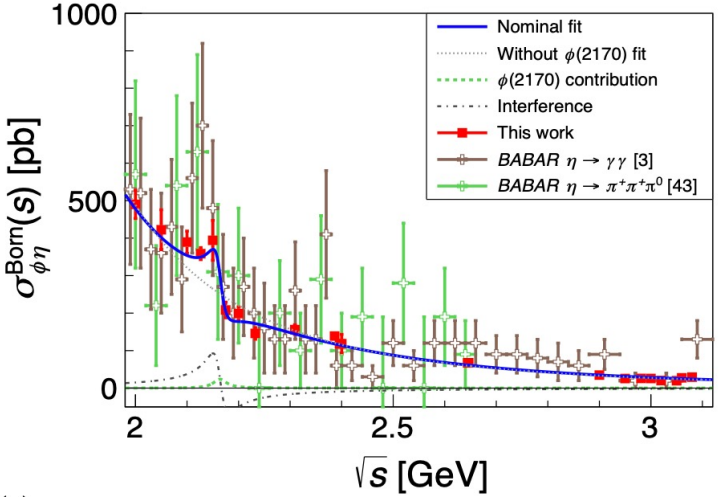


$e^+e^- \to \phi\eta$ and $\phi\eta'$

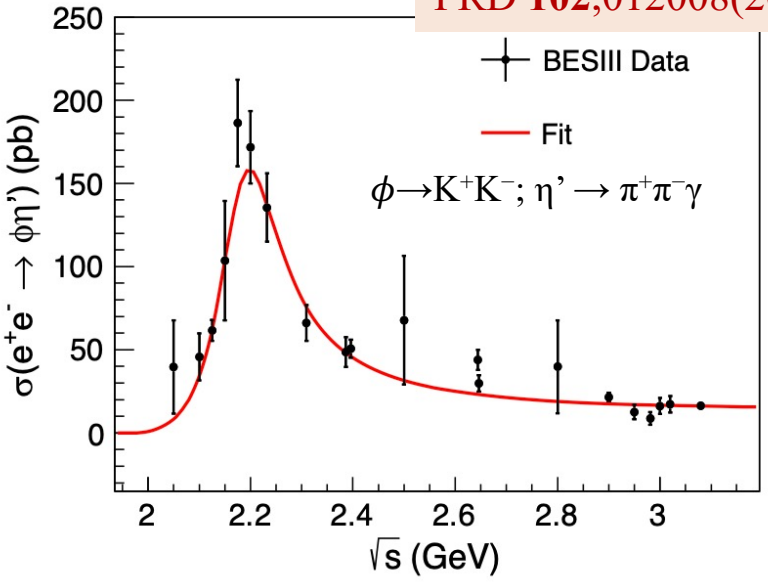
- The ratio between $\phi\eta$ and $\phi\eta'$ partial width is important observable to access $\phi(2170)$ as a $s\bar{s}g$ hybrid state
  - partial width larger in the $\phi\eta$ channel by a factor [3-200] w.r.t $\phi\eta'$

arXiv:2104.05549





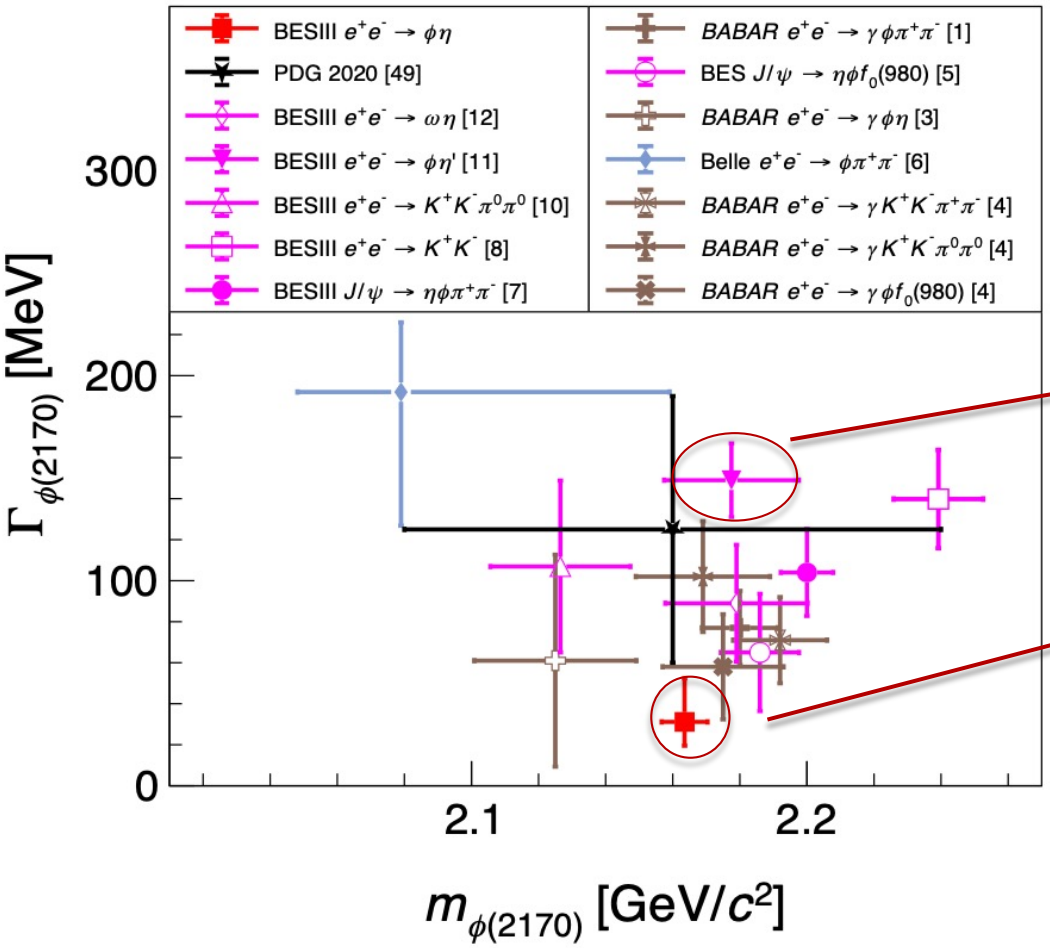
PRD **102**,012008(2020)



$$\frac{Br\,[\phi(2170)\to\phi\eta]\Gamma_{ee}}{Br\,[\phi(2170)\to\phi\eta\prime]\Gamma_{ee}} = \begin{cases} 0.03^{+0.02}_{-0.01} \\ 1.42^{+0.56}_{-0.46} \end{cases}$$

Small than prediction of the $s\bar{s}g$ hybrid model by several order o magnitude

Summary of $\phi(2170)$



[1] PRD74,091103
[3] PRD77,092002
[4] PRD86,012008
[5] PRL100,102003
[6] PRD80,031101
[7] PRD91,052017
[8] PRD99,031001
[10] PRL124,112001
[11] PRD102,012008
[12] PLB813,136059

PRD102,012008 ($e^+e^- \to \phi\eta'$)

$M = 2177.5 \pm 4.8 \pm 19.5$ MeV/c^2

$\Gamma = 149.0 \pm 15.6 \pm 8.9$ MeV

arXiv:2104.05549 ($e^+e^- \to \phi\eta$)

$M = 2163.5 \pm 6.2 \pm 3.0$ MeV/c^2

$\Gamma = 31.1^{+21.1}_{-11.6} \pm 1.1$ MeV

The nature of $\phi(2170)$ still not fully understood!

What is the $\phi(2170)$? Many interpretation

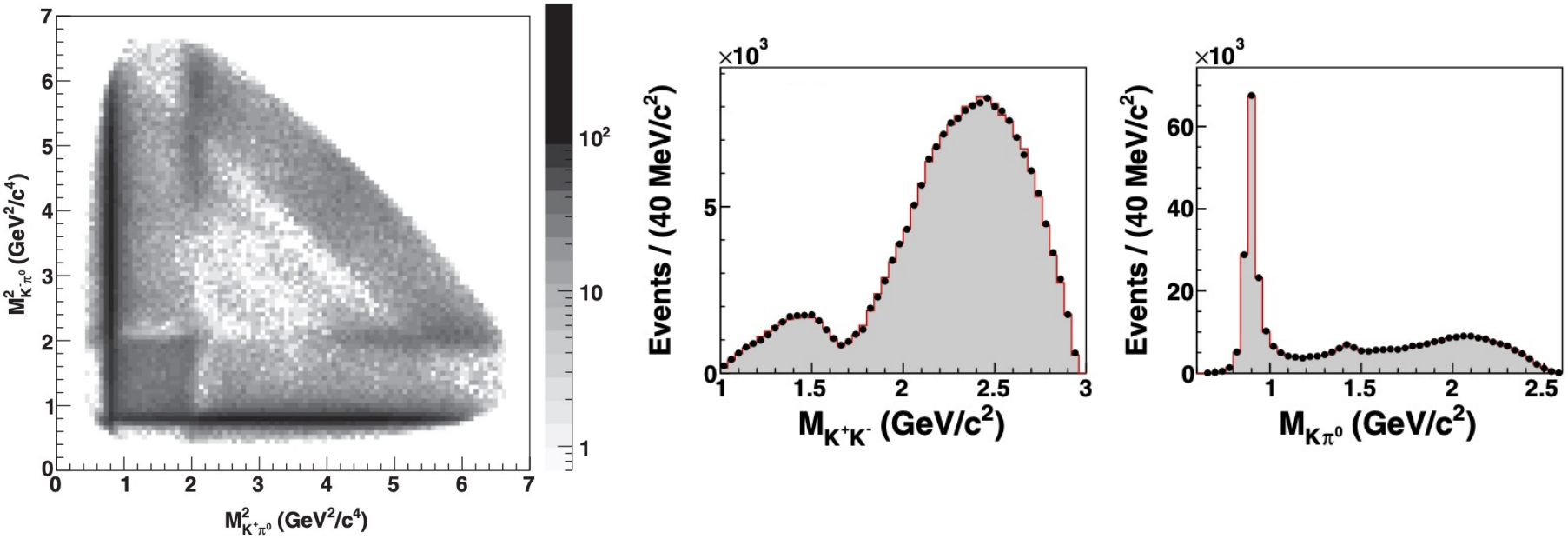
- $s\bar{s}g$ hybrid
- 2^3D_1 or 3^3S_1
- tetraquark
- molecular state $\Lambda\Lambda$
- $\phi f_0(980)$ resonance with FSI
- Three body system ϕKK

PWA of $J/\psi \to K^+K^-\pi^0$

Partial Wave Analysis (PWA) is a powerful tool to study hadron spectra and to search for glueball and exotic states in J/ψ radiative decays

~225×10^6 J/ψ @ BESIII

PRD **100**,032004(2019)



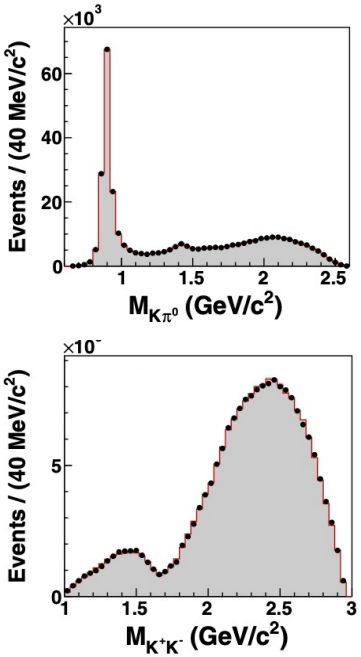
Isobar model: the amplitude is parameterized as a sum of sequential quasi-two-body decay process [EPJA16,537(2003)]

PWA of $J/\psi \to K^+K^-\pi^0$

PRD **100**,032004(2019)

J^{PC}	PDG	M (MeV/c^2)	Γ (MeV/c^2)	b (%)
1^-	$K^*(892)^\pm$	$893.6 \pm 0.1^{+0.2}_{-0.3}$	$46.7 \pm 0.2^{+0.1}_{-0.2}$	$93.4 \pm 0.4^{+1.8}_{-5.8}$
1^-	$K^*(1410)^\pm$	1380⋆	176⋆	0.26 ± 0.04
1^-	$K^*(1680)^\pm$	1677⋆	205⋆	0.20 ± 0.03
2^+	$K_2^*(1430)^\pm$	$1432.7 \pm 0.7^{+2.2}_{-2.3}$	$102.5 \pm 1.6^{+3.1}_{-2.8}$	$9.4 \pm 0.1^{+0.8}_{-0.5}$
2^+	$K_2^*(1980)^\pm$	$1868 \pm 8^{+40}_{-57}$	$272 \pm 24^{+50}_{-15}$	$0.38 \pm 0.04^{+0.22}_{-0.05}$
3^-	$K_3^*(1780)^\pm$	1781⋆	203⋆	0.16 ± 0.02
4^+	$K_4^*(2045)^\pm$	$2090 \pm 9^{+11}_{-29}$	$201 \pm 19^{+57}_{-17}$	$0.21 \pm 0.02^{+0.10}_{-0.05}$
3^-	Nonresonant	...	...	~1.5%

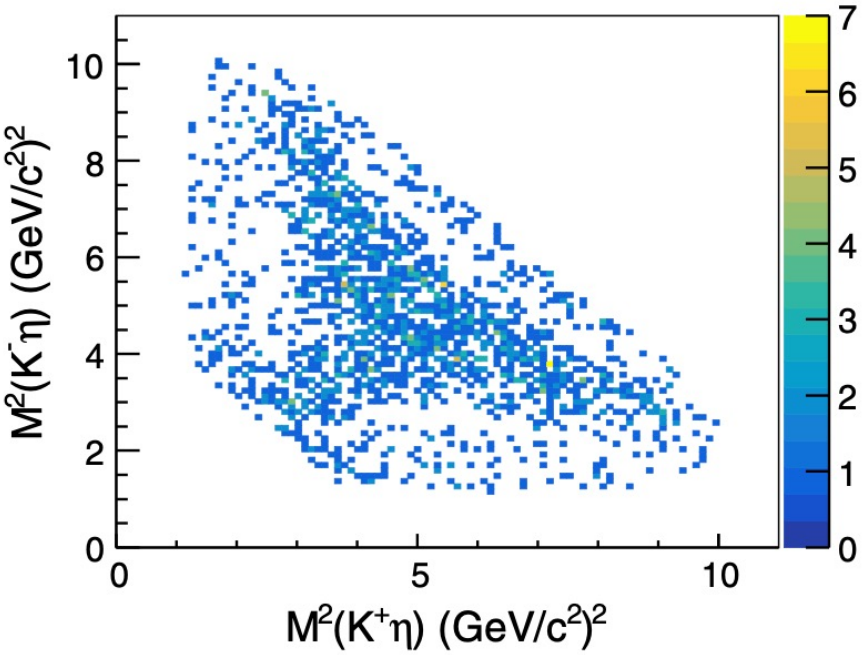
J^{PC}	M (MeV/c^2)	Γ (MeV/c^2)	b (%)
1^{--}	$1651 \pm 3^{+16}_{-6}$	$194 \pm 8^{+15}_{-7}$	$1.83 \pm 0.11^{+0.19}_{-0.17}$
1^{--}	$2039 \pm 8^{+36}_{-18}$	$196 \pm 23^{+25}_{-27}$	$0.23 \pm 0.04^{+0.07}_{-0.06}$

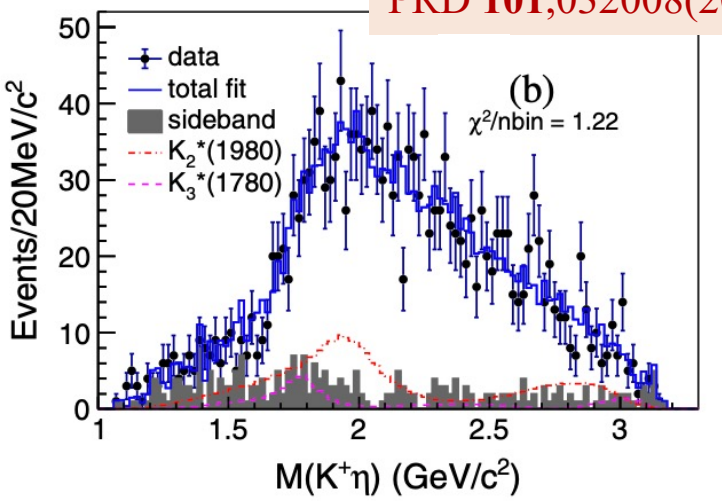


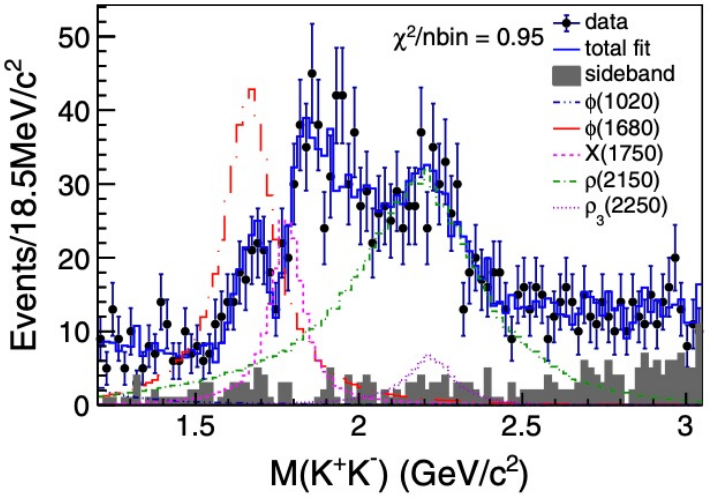
- Dominant contribution from $K^*(892)$
- First observation of $K^*_2(1980)$ and $K^*_4(2045)$ in J/ψ decays
- Two clear $J^{PC}=1^{--}$ structures observed in K^+K^- mass spectrum: possible relation with $\omega(1650)$ and $\rho(2150)$

PWA of $\psi(3686)\to KK\eta$

PRD **101**,032008(2020)







- Observation of $\phi(1680)$ in the KK mass spectra
- 1^{--} state needed to describe the dip around 1.7 GeV/c^2 in the KK mass spectra (X(1750)? but not excluded the possibility to be the ρ(1700))

- A broad structure around 2.2 GeV/c^2 is observed, either $\phi(2170)$ or ρ(2150)?

Conclusions

- ***J/ψ decay provides an excellent laboratory to study light hadron decays***
  - Search for glueball and exotic states

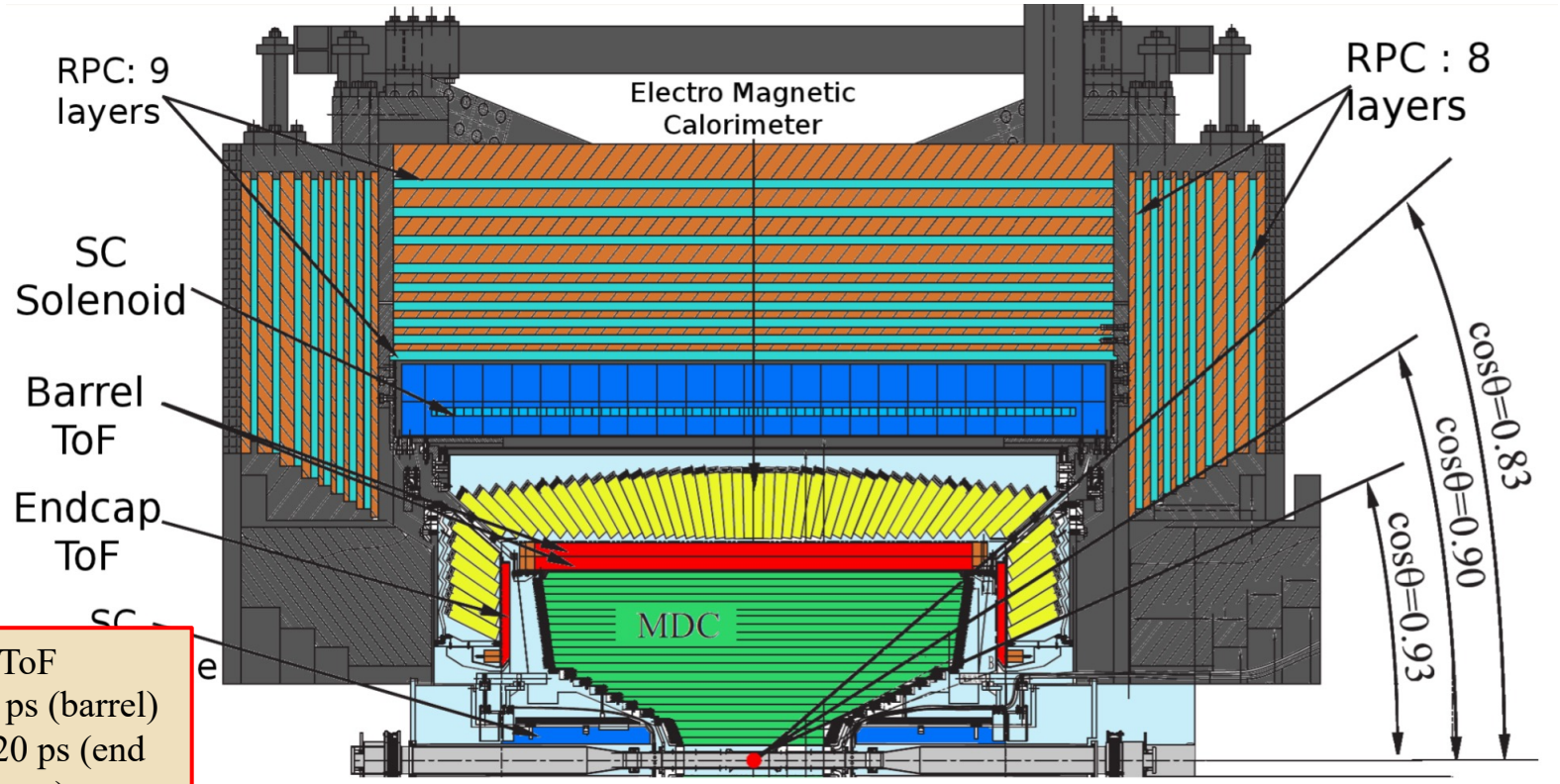
- ***10 billion of J/ψ data collected at BESIII***
  - This huge data sample allows to study light meson decays with unprecedent statistics: unique opportunity to map the light hadron spectroscopy
  - More interesting results are expected

- ***More data will be collected in the next years***
  - More studies in the strangeonium sector
  - New PWA
  - …

Back-up slides

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)
$\sigma_{xy} \sim (6\text{ mm})/E^{1/2}$ @ 1 GeV

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

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
- $Z_c(3900)^+$, …

QCD and τ

- Precision R measurement
- τ decay

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

Charmonium physics

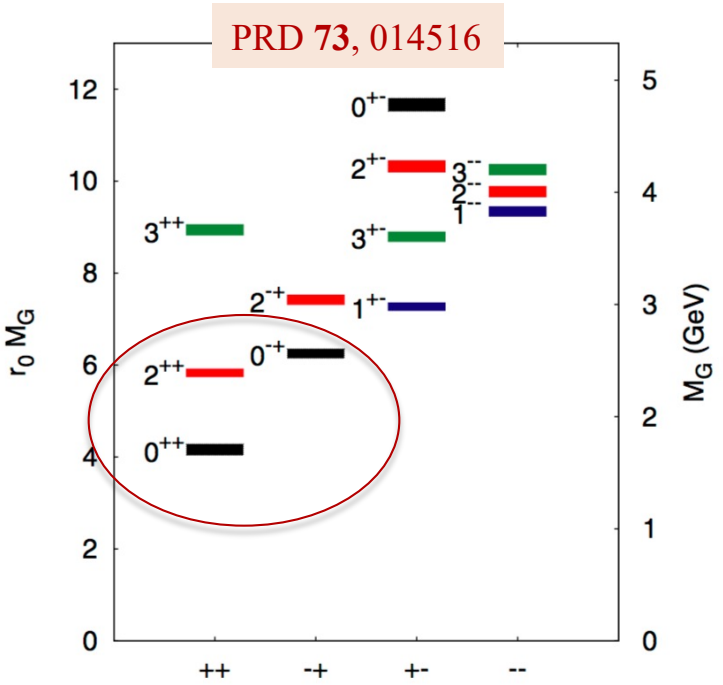
- Precision spectroscopy
- Transitions and decays

Precision mass measurements

- τ mass
- D, D^* mass

Amplitude Analyses in BESIII

- J/ψ radiative decays are ideal for searching glueballs
  - **J/ψ → γPP: 0^{++}, 2^{++}, …**
  - **J/ψ → γPPP, 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

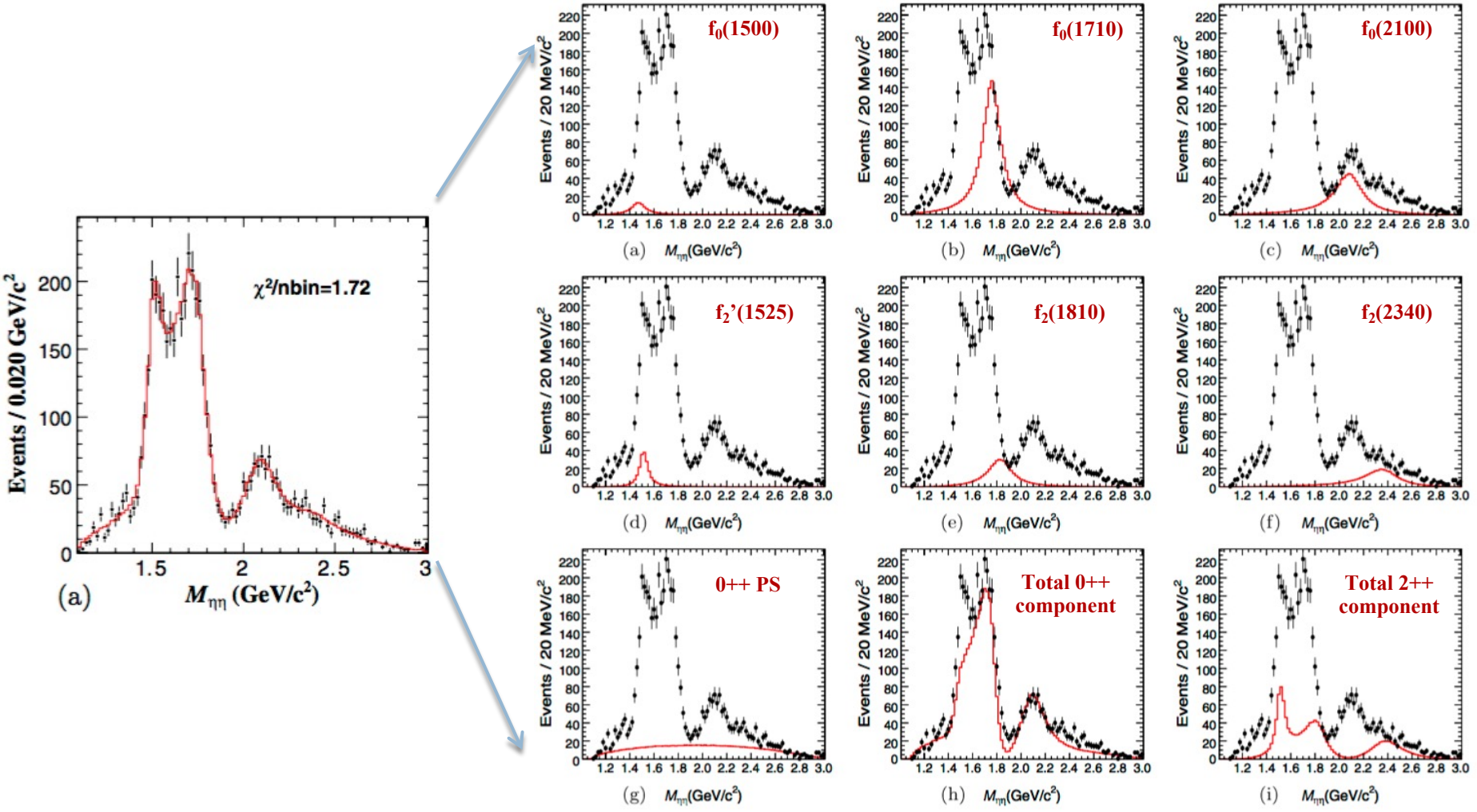


- **Amplitude analysis: toll to extract the complex amplitudes from experimental data**
  - Models with free parameters
  - Consider the kinematic of final states particles
  - Vary the parameters to maximize the likelihood
  - **Mass Dependent (MD) PWA**: model the dynamics of particle interactions 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 $J/\psi \to \gamma\eta\eta$

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



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

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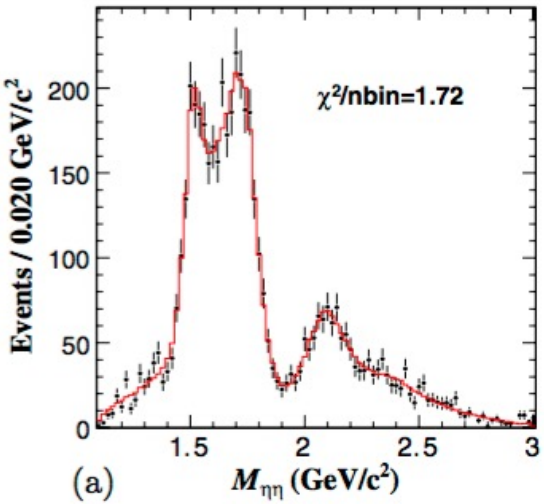


Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	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

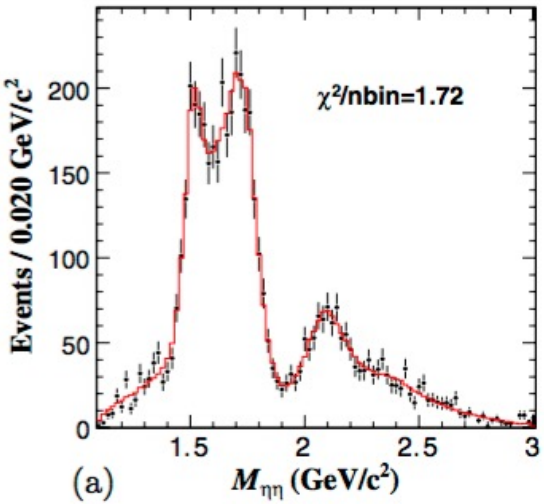
- $f_0(1500)$ dominant decays are 4π and $\pi\pi$
- The production rate of $f_0(1710)$ is compatible with LQCD (PRL110,021601) prediction for a pure scalar glueball
  - Suggest a large overlap with 0++ gluball

- 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**
$f_2(2340)$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	

- $f_0(1500)$ dominant decays are 4π and $\pi\pi$
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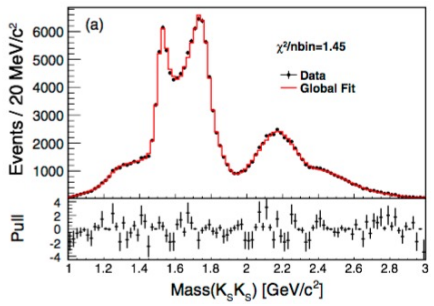
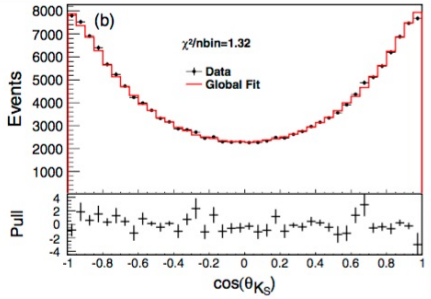
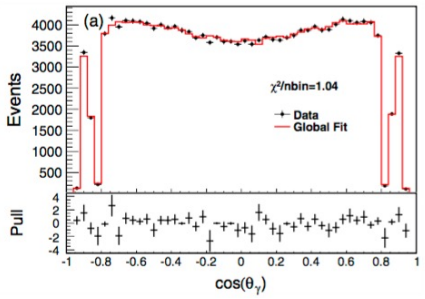
PWA of $J/\psi \to \gamma K^0_S K^0_S$

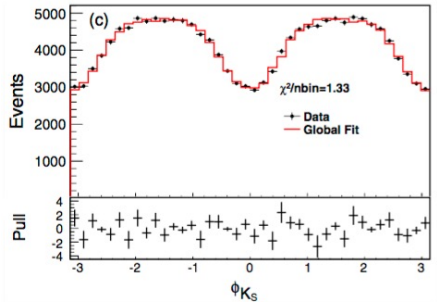
PRD **98**, 072003 (2018)

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









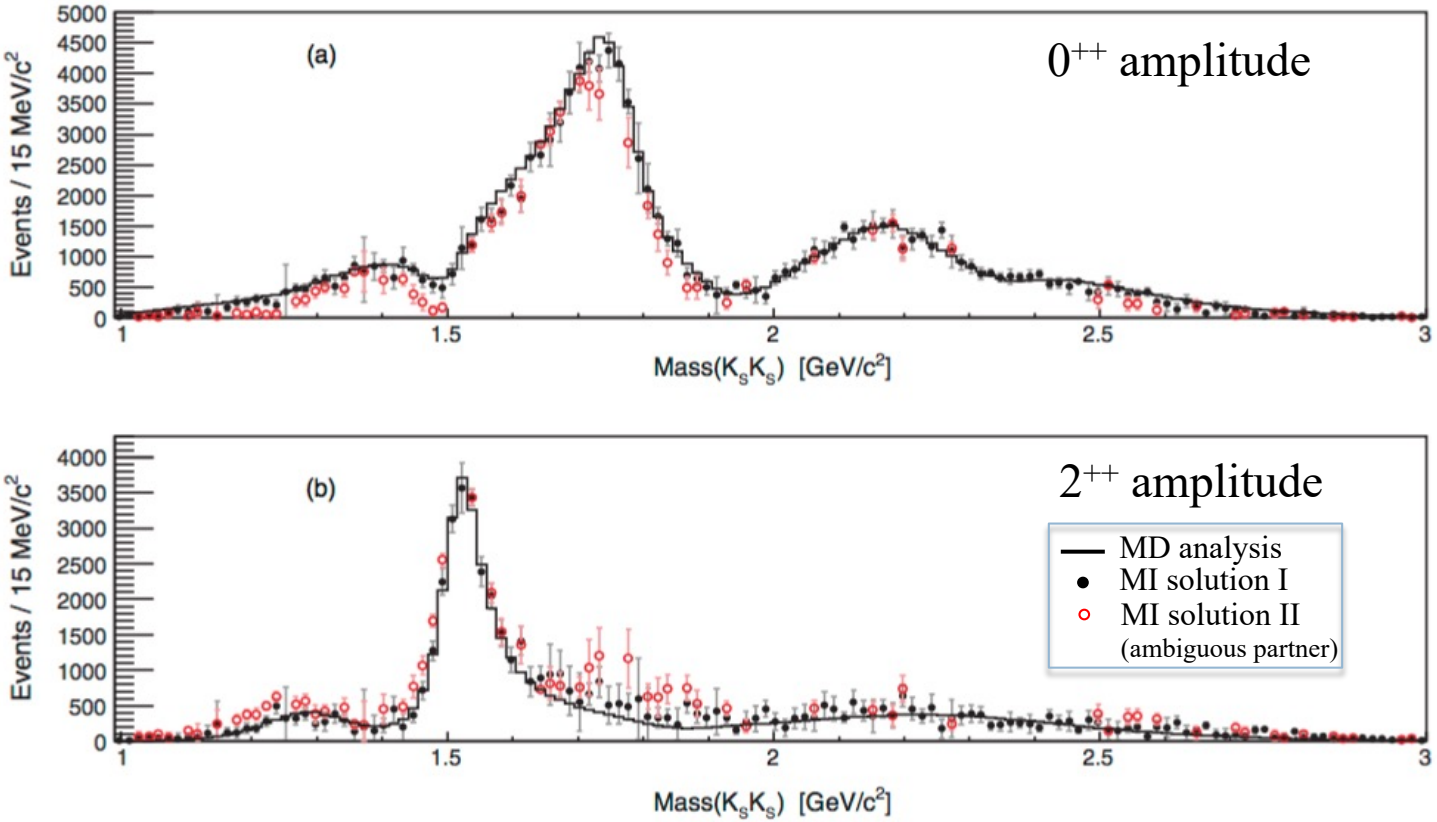
Resonance	M (MeV/c^2)	M_{PDG} (MeV/c^2)	Γ (MeV/c^2)	Γ_{PDG} (MeV/c^2)	Branching fraction	Significance
$K^*(892)$	896	895.81 ± 0.19	48	47.4 ± 0.6	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$	35σ
$K_1(1270)$	1272	1272 ± 7	90	90 ± 20	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$	16σ
$f_0(1370)$	$1350 \pm 9^{+12}_{-2}$	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



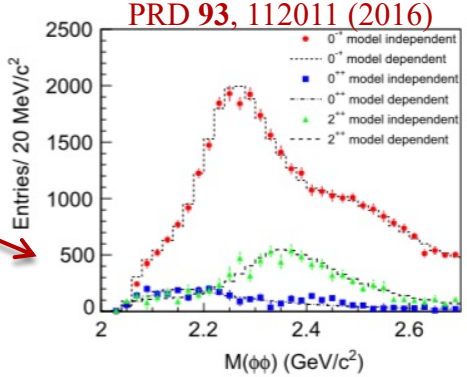
- Agreement with results from MD PWA (no acceptance correction included)
- MI results useful for a systematic study of hadronic interaction

PWA status and plans in a nutshell

	0+	2+	0−
J/ψ→γPP	J/ψ→γηη (PRD87,092009) J/ψ→γπ^{0}π^0 (PRD92,052003) J/ψ→γK$_S$K$_S$ (PRD98,072003) J/ψ→γηη' J/ψ→γη'η'		
J/ψ→γVV		J/ψ→γωφ (PRD87,032008) J/ψ→γφφ (PRD93,112011) J/ψ→γωω	
J/ψ→γPPP			J/ψ→γη'ππ (PRL106,072002) J/ψ→γKKη' J/ψ→γηπ^{0}π^0

PWA Published
Ongoing
Published, no PWA

PRD **93**, 112011 (2016)

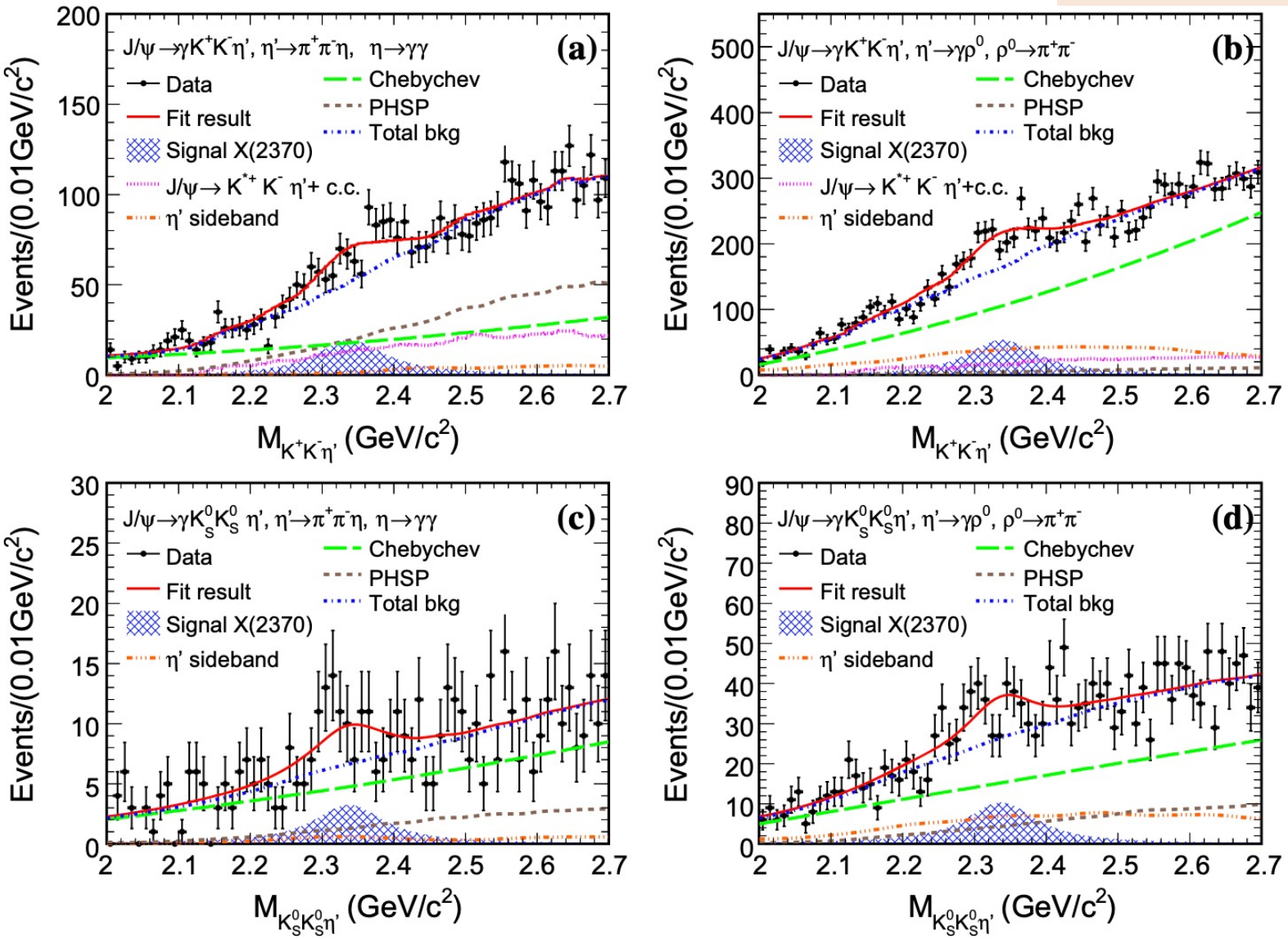


- 0++: the production rate $f_0(1710)$ is compatible with LQCD prediction for a pure gauge scalar glueball
- 2++: $f_0(2340)$ seems to be a good candidate for tensor gluball [PRL111,091601] (large production rate)
- 0−+: η(2225) is confirmed and two additional pseudoscalar states, η(2100) and X(2500),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

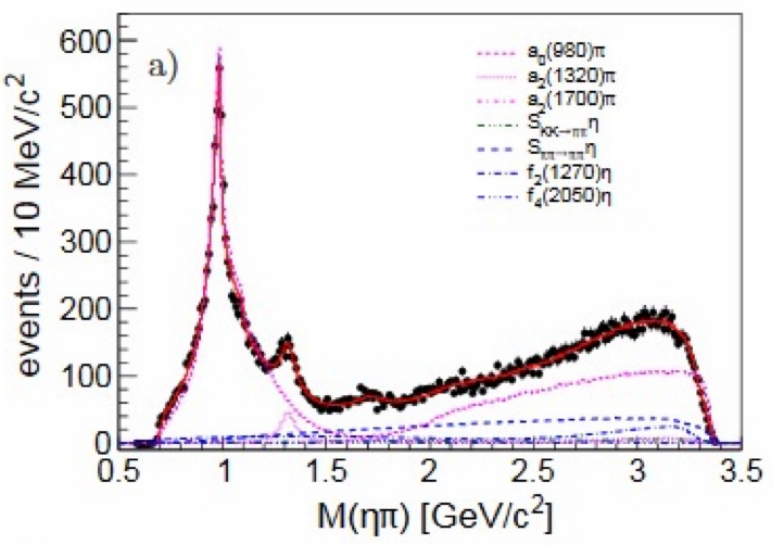
First Observation of X(2370) in $J/\psi\to\gamma K\bar{K}\eta'$

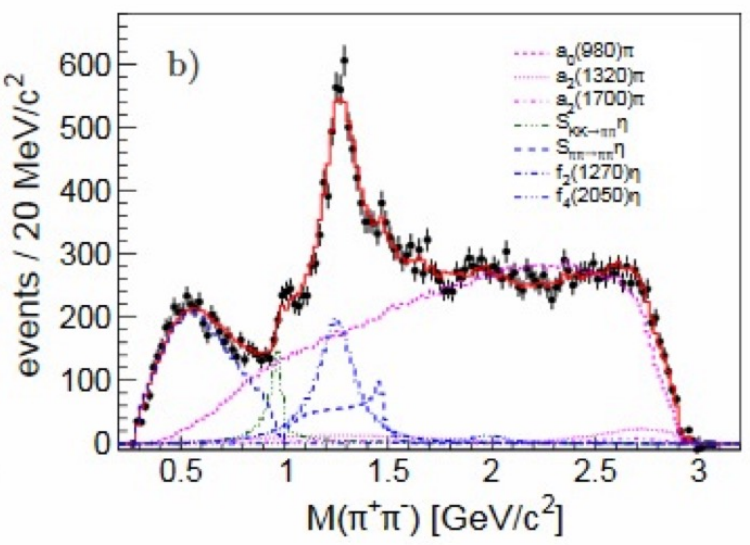
1.3×10^9 J/ψ @ BESIII

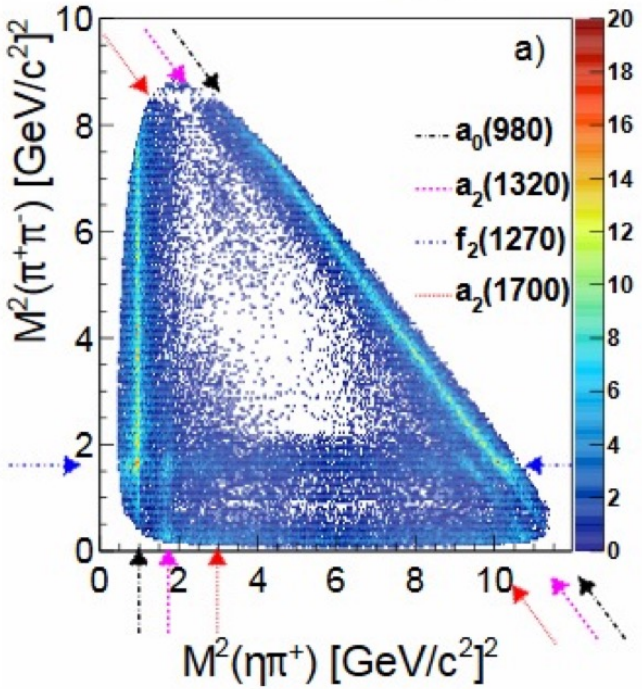
EPJC **80**, 746 (2020)



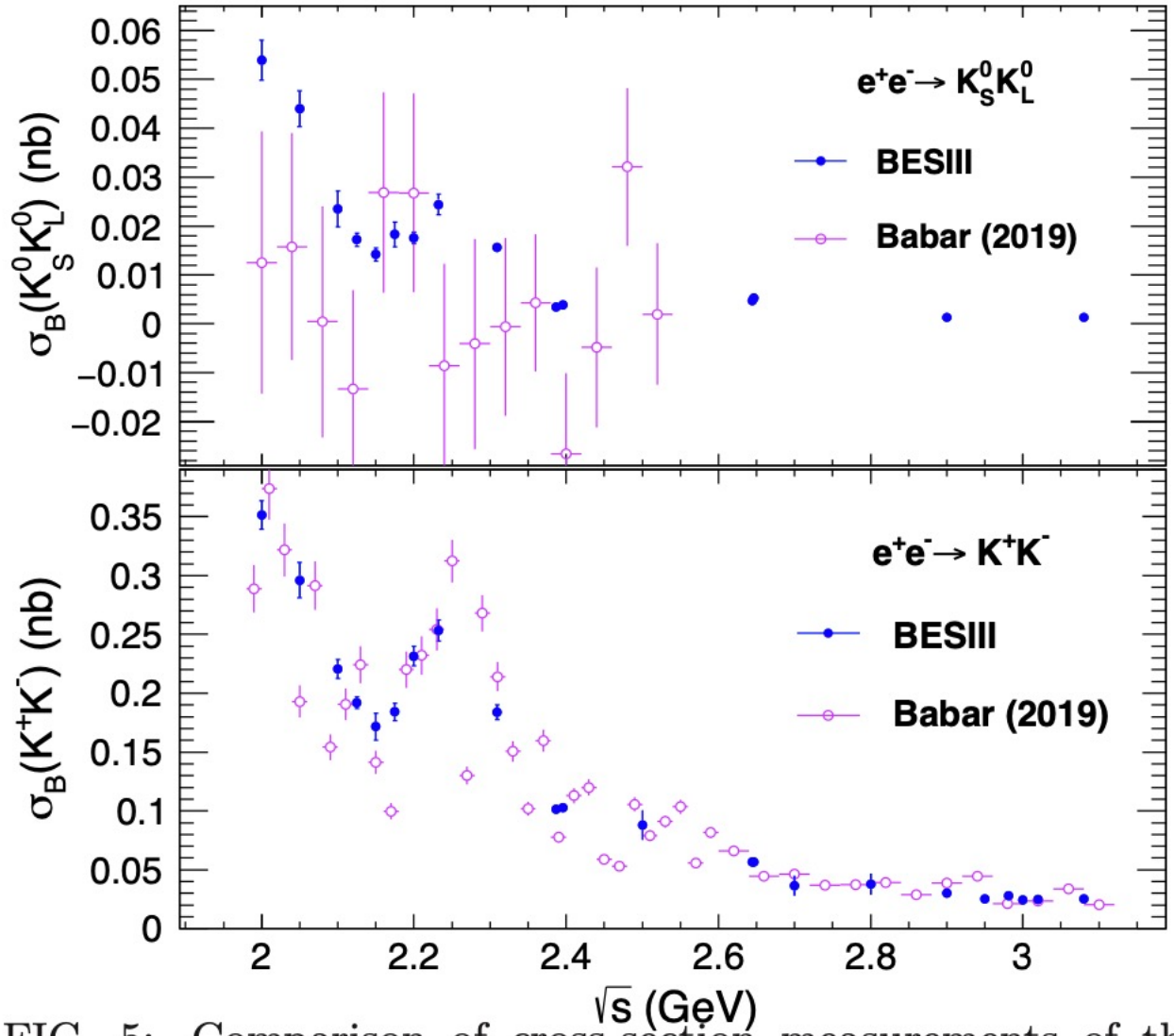
Search exotics in $\chi_{c1} \to \eta\pi^+\pi^-$







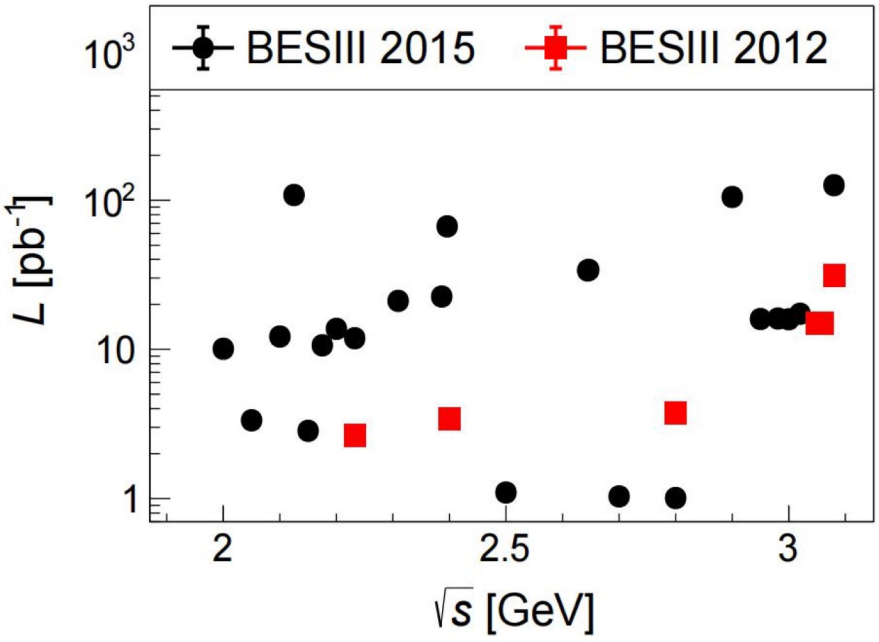
- Clear evidence for $a_2(1700)$ in χ_{c1} decays
- Upper limits for $\pi_1(1^{-+})$ in 1.4 - 2.0 GeV/c^2
- More works in progress in J/ψ and χ_{c1} decays



BESIII work
arXiv:2105.13597

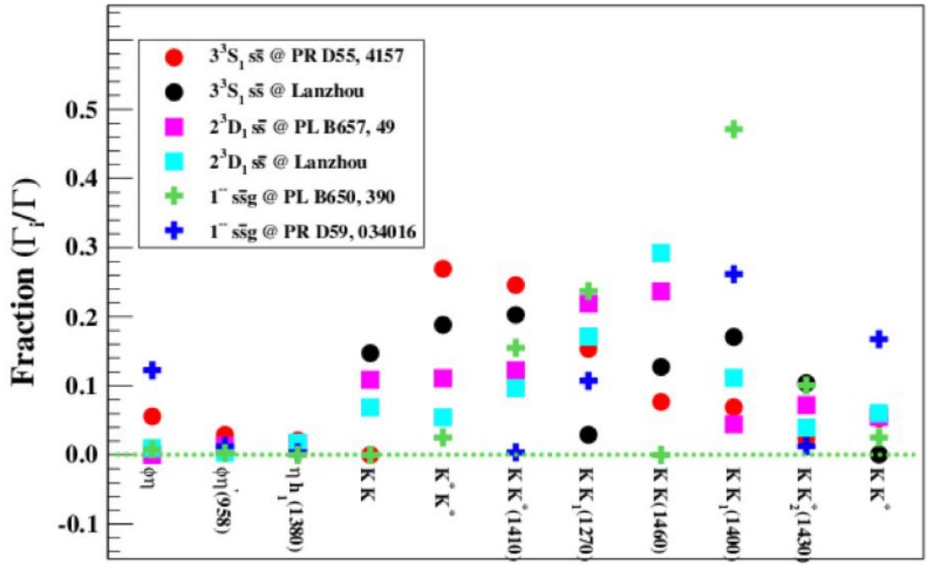
FIG. 5: Comparison of cross-section measurements of the processes $e^+e^- \to K^0_S K^0_L$ (top panel) and $e^+e^- \to K^+K^-$ (bottom panel) by BESIII (filled dots) [13] and BaBar (open circles) [35].

$\phi(2170)$ @ BESIII



dataset

theoretical prediction



PWA of $\psi(3686) \to KK\eta$

PRD **101**,032008(2020)

TABLE I. Mass, width and significance of each component in the baseline solution. The first uncertainties are statistical and the second are systematic.

Resonance	M (MeV/c^2)	Γ (MeV)	Significance
$\phi(1680)$	1680^{+12+21}_{-13-21}	185^{+30+25}_{-26-47}	14.3σ
$X(1750)$	1784^{+12+0}_{-12-27}	106^{+22+8}_{-19-36}	10.0σ
$\rho(2150)$	2255^{+17+50}_{-18-41}	$460^{+54+160}_{-48-90}$	23.5σ
$\rho_3(2250)$	2248^{+17+59}_{-17-5}	$185^{+31+17}_{-26-103}$	8.5σ
$K_2^*(1980)$	2046^{+17+67}_{-16-15}	408^{+38+72}_{-34-44}	19.9σ
$K_3^*(1780)$	1813^{+15+65}_{-15-16}	191^{+43+3}_{-37-81}	11.2σ

PWA of $\psi(3686) \to KK\eta$

PRD **101**,032008(2020)

	This work		PDG [23]	
Resonance	M (MeV/c^2)	Γ (MeV)	M (MeV/c^2)	Γ (MeV)
$\phi(1680)$	1680^{+12+21}_{-13-21}	185^{+30+25}_{-26-47}	1680 ± 20	150 ± 50
$X(1750)$	1784^{+12+0}_{-12-27}	106^{+22+8}_{-19-36}	$(1720 \pm 20)_{\rho(1700)}$ $(1753.5 \pm 1.5 \pm 2.3)_{X(1750)}$ [15]	$(250 \pm 100)_{\rho(1700)}$ $(122.2 \pm 6.2 \pm 8.0)_{X(1750)}$ [15]
$\rho(2150)$	2255^{+17+50}_{-18-41}	$460^{+54+160}_{-48-90}$	$(2153 \pm 27)_{\rho(2150)}$ [31] $(2175 \pm 15)_{\phi(2170)}$	$(389 \pm 79)_{\rho(2150)}$ [31] $(61 \pm 18)_{\phi(2170)}$
$\rho_3(2250)$	2248^{+17+59}_{-17-5}	$185^{+31+17}_{-26-103}$	2232 [32]	220 [32]
$K_2^*(1980)$	2046^{+17+67}_{-16-15}	408^{+38+72}_{-34-44}	$1973 \pm 8 \pm 25$	$373 \pm 33 \pm 60$
$K_3^*(1780)$	1813^{+15+65}_{-15-16}	191^{+43+3}_{-37-81}	1776 ± 6	159 ± 21

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

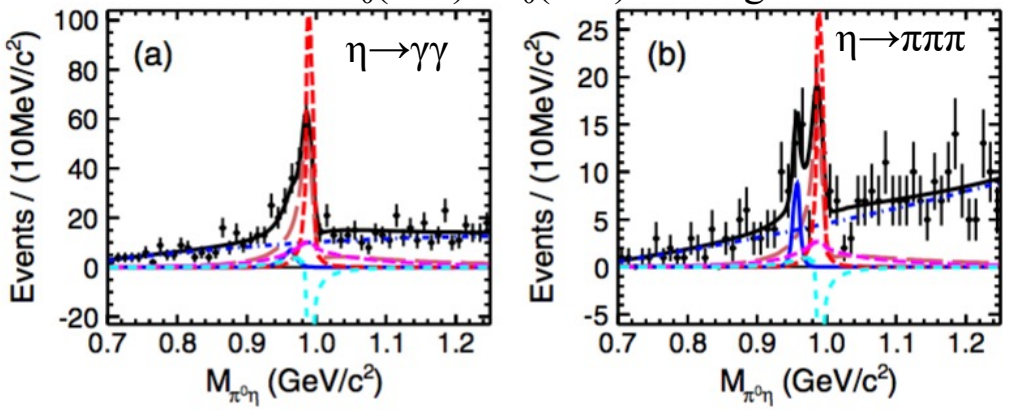
PRL **121**, 022001(2018)

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

- $a_0(980)$ - $f_0(980)$ 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]
  $J/\psi \to \phi f_0(980) \to \phi a^0_0(980) \to \phi\eta\pi^0$ and **$\chi_{c1} \to \pi^0 a^0_0(980) \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-$** (isospin violating decays)

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

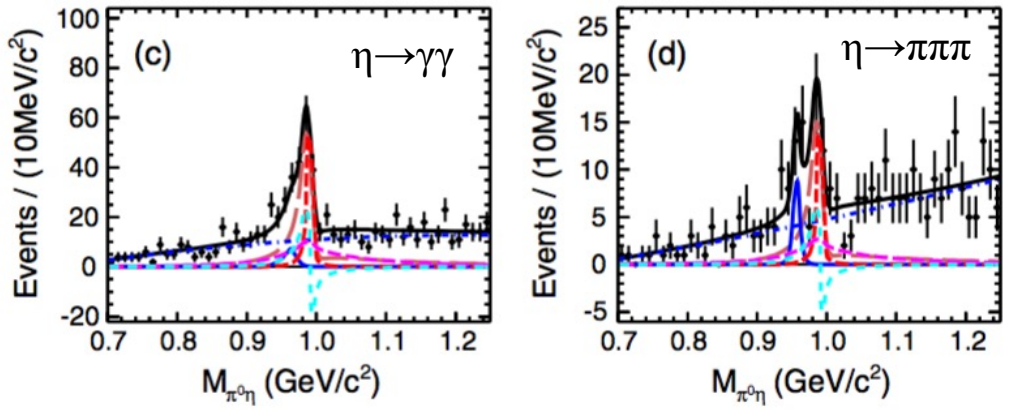
Destructive interference

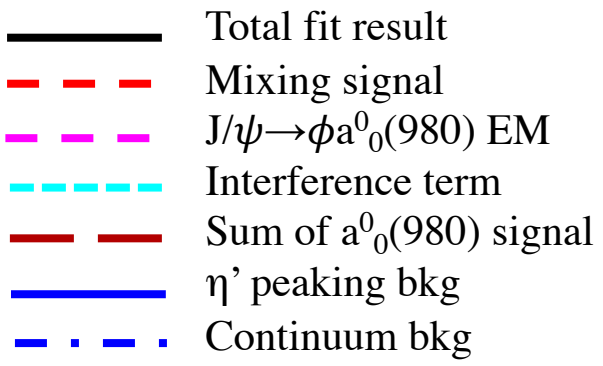


$f_0(980) \to a^0_0(980)$ mixing significance: 7.4σ

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

Constructive interference

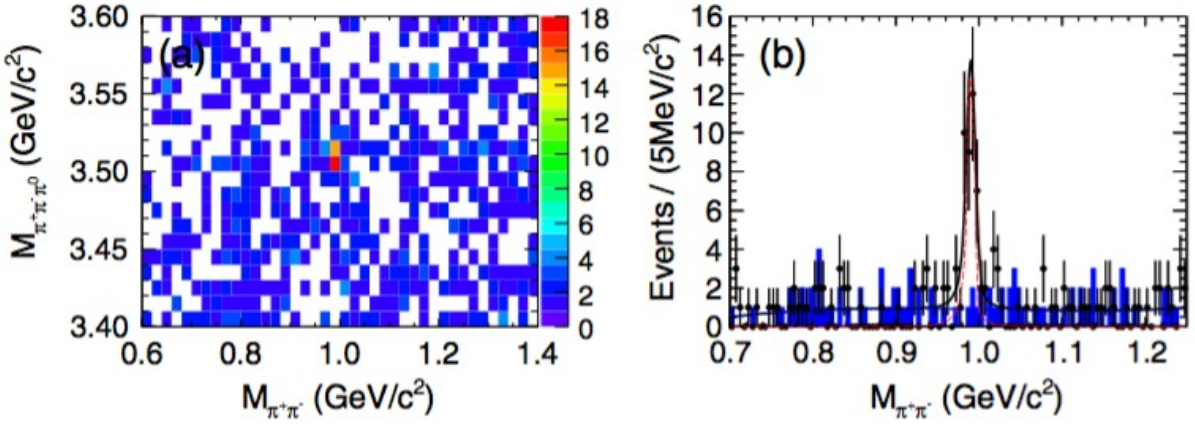




$a_0(980)$-$f_0(980)$ mixing

PRL **121**, 022001(2018)

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



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

$f_0(980)$ 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 (%)	$0.99 \pm 0.16 \pm 0.30 \pm 0.09$	$0.41 \pm 0.13 \pm 0.17 \pm 0.13$	$0.40 \pm 0.07 \pm 0.14 \pm 0.07$