New Results on Light Hadron Spectroscopy from BESIII

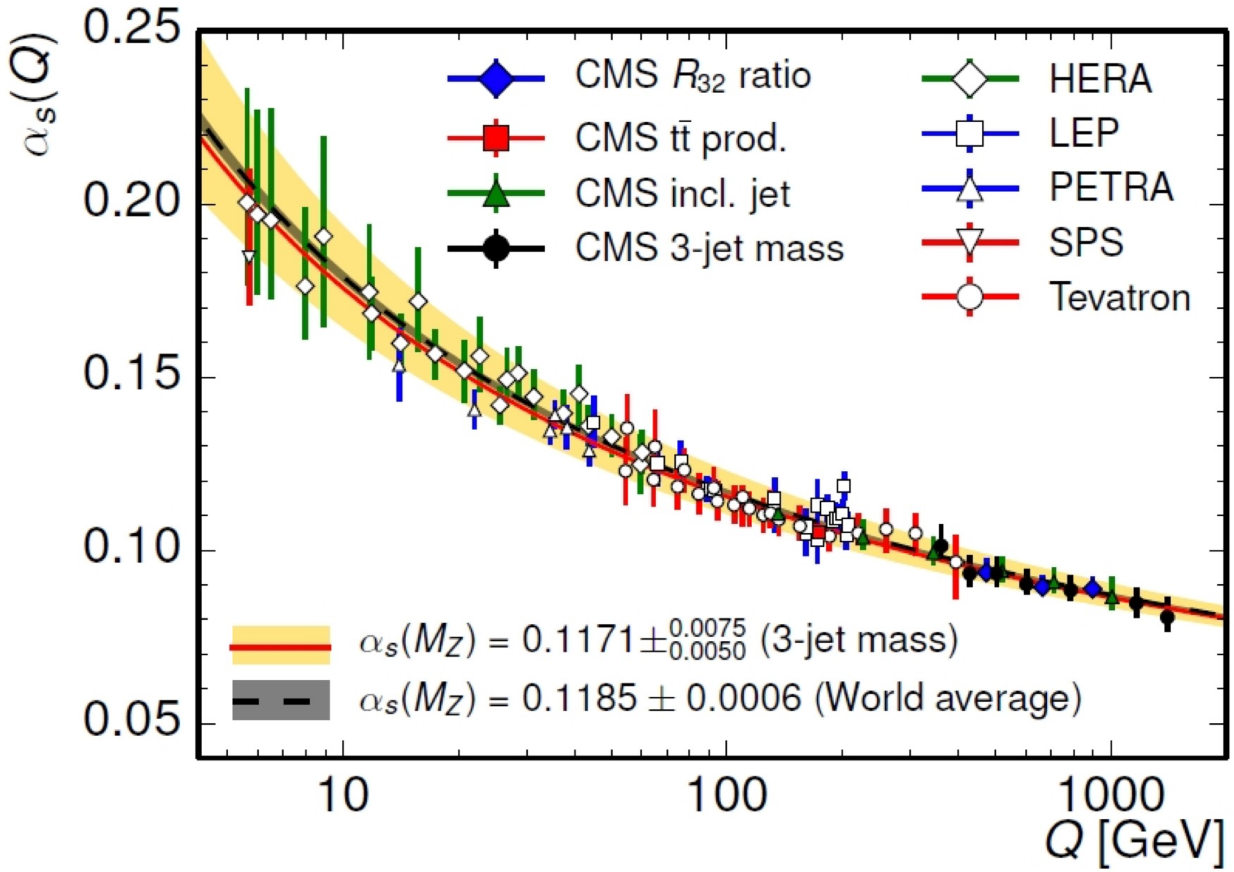
Isabella Garzia,
On behalf of the πFE working group

September 8, 2021
University of Ferrara

INFN
Istituto Nazionale di Fisica Nucleare

Università degli Studi di Ferrara

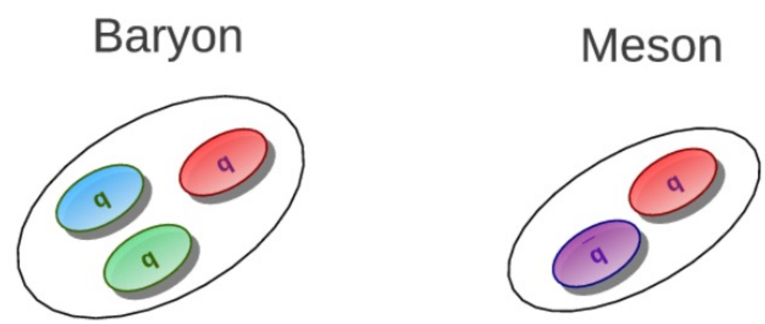
Light Hadron Physics



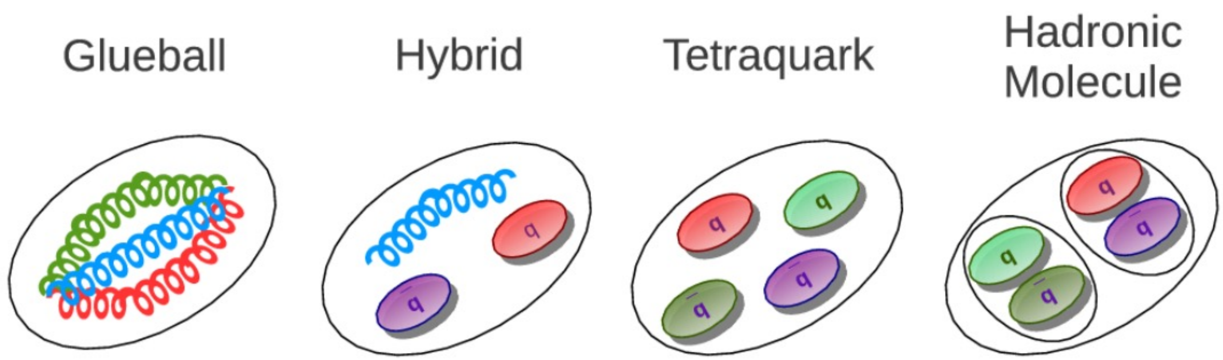
The study of light hadron physcis is central to the understanding of confinement physcis

Hadron Spectrum

Naïve Quark Model:
conventional hadrons
contain two or three quarks



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



……….

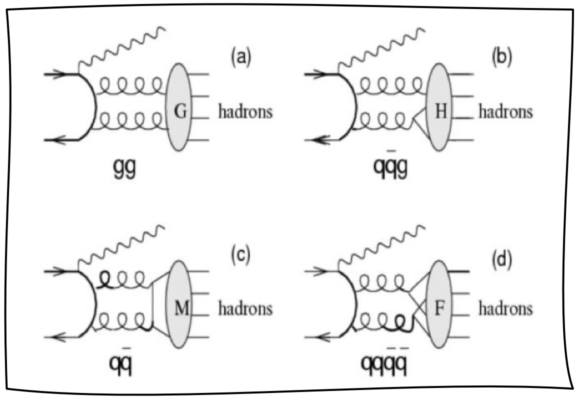
A lot of exotic states observed experimentally, but their nature is still far from being understood!!!

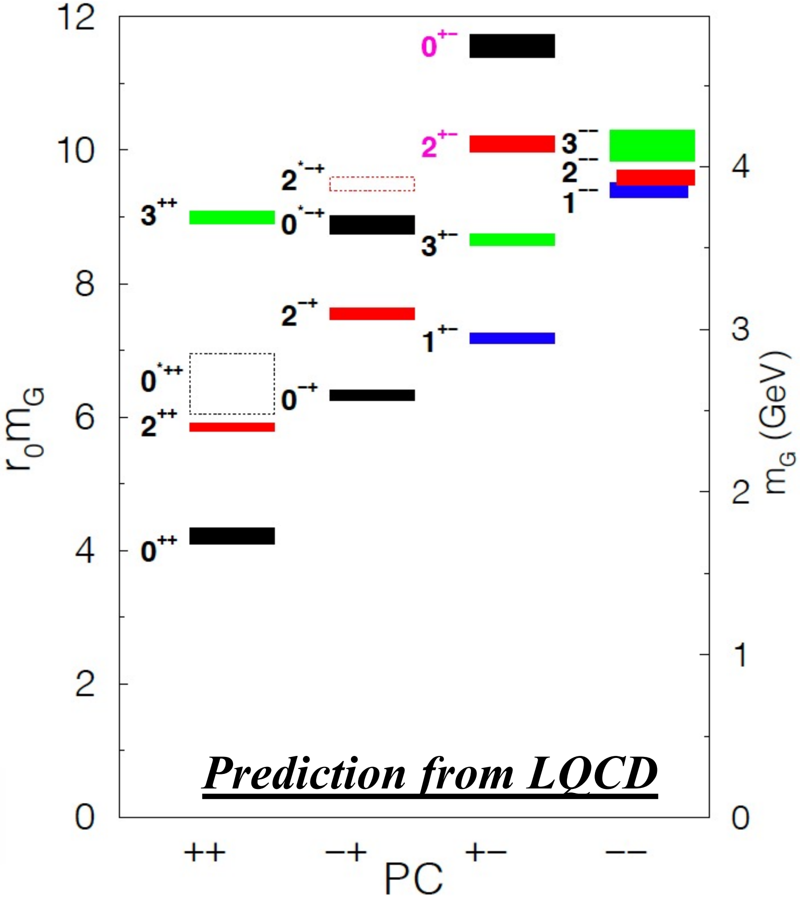
Hadron spectroscopy: establish the spectrum and study the exotic hadrons properties

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

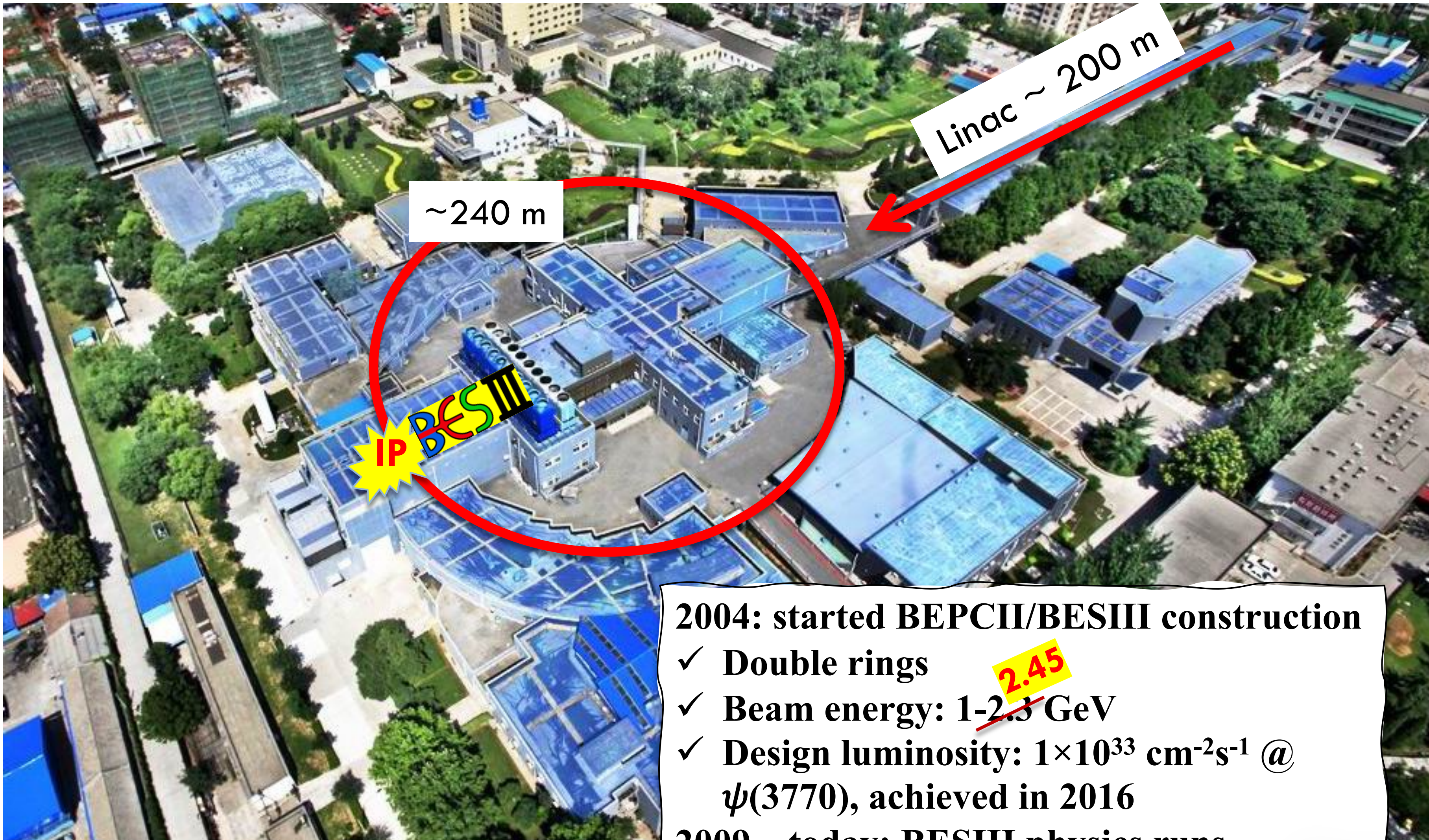
$$\Gamma(J/\psi \rightarrow \gamma G_{0^{++}})/\Gamma_{tot} = 3.8(9) \times 10^{-3}$$

PRL**111**, 091601

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

Beijing Electron Positron Collider II

http://english.ihep.cas.cn



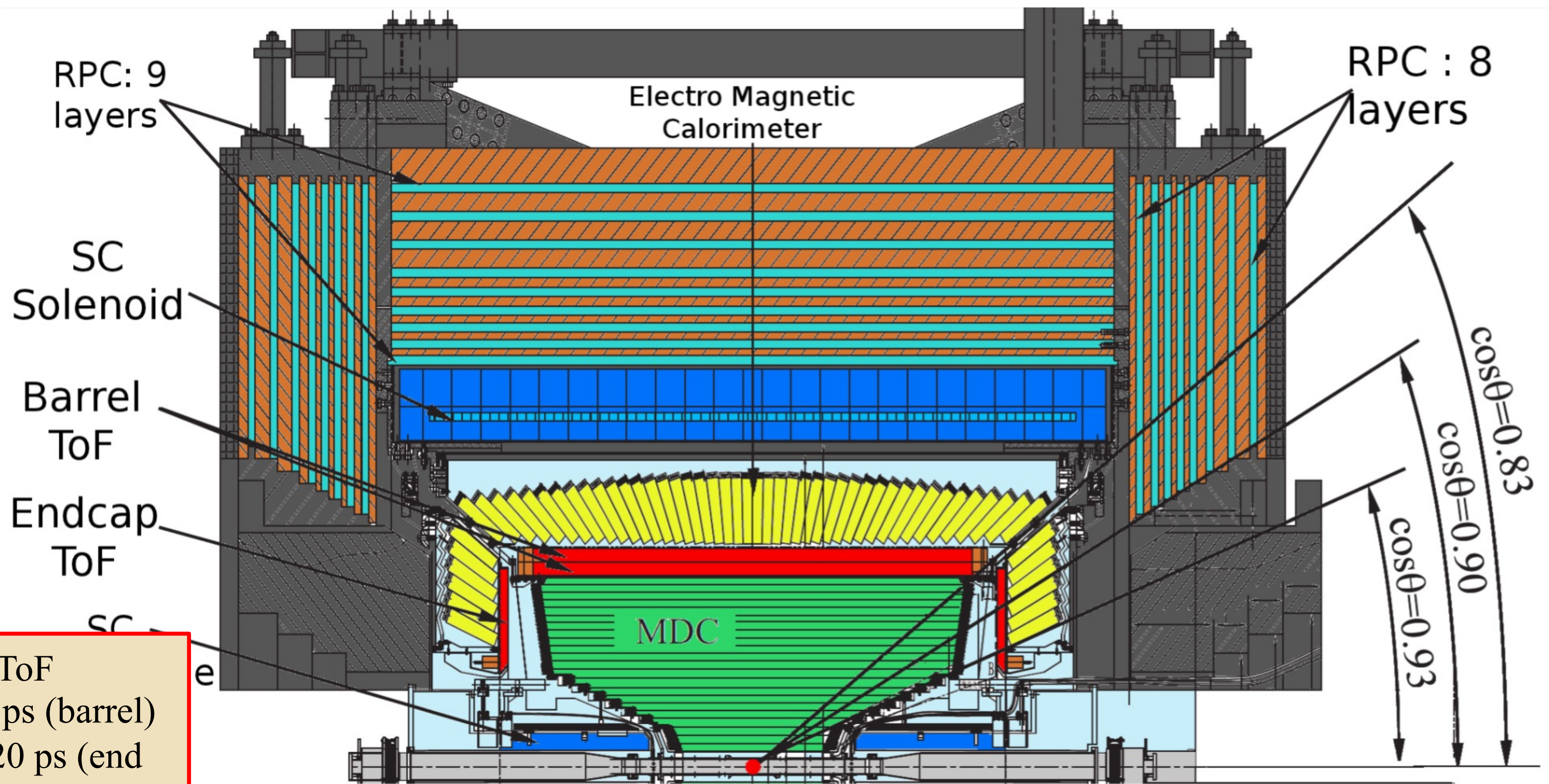
2004: started BEPCII/BESIII construction

- ✓ 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

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
$\Delta\Omega/4\pi=93\%$

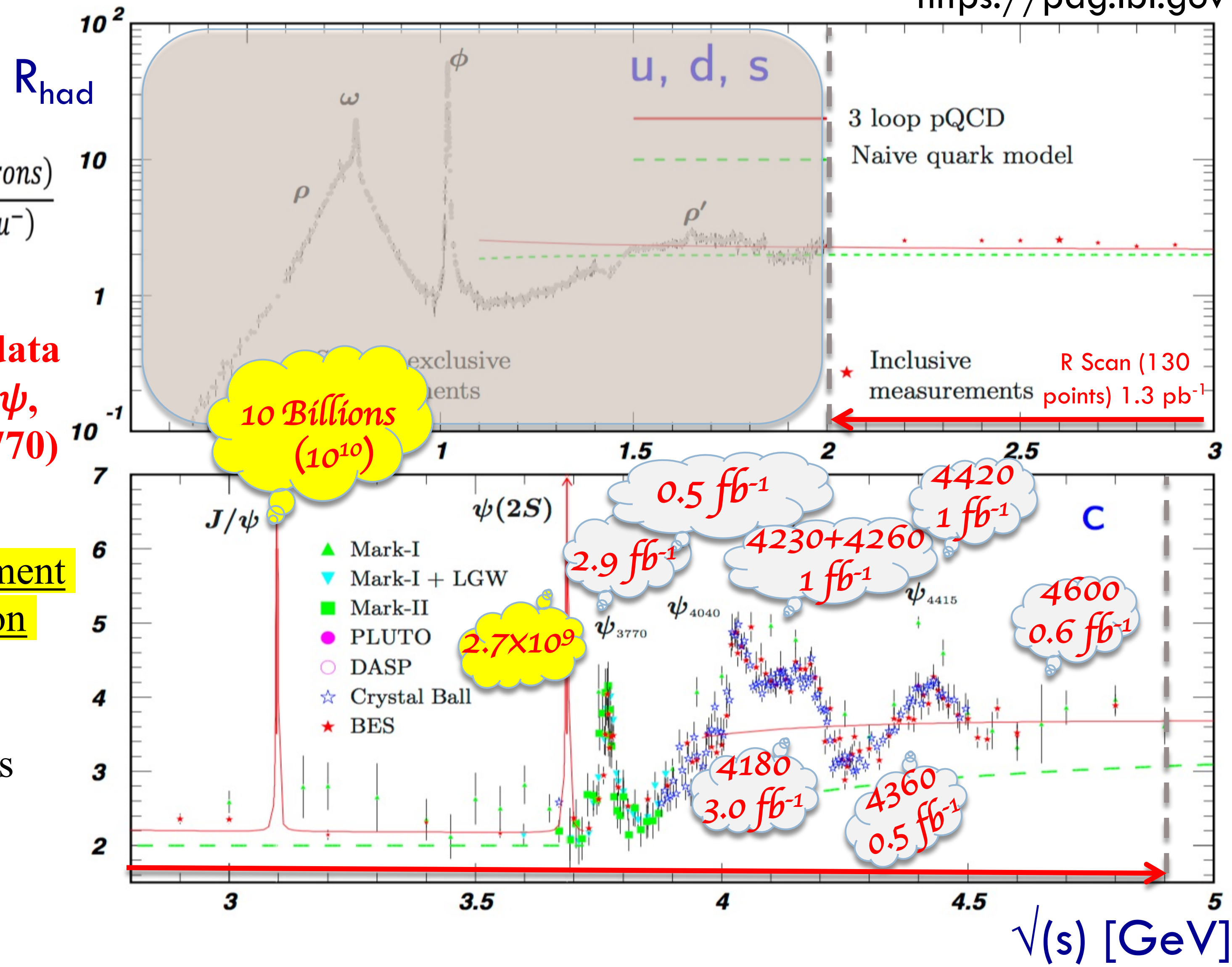
Dataset

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

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
- ….

https://pdg.lbl.gov



Dataset

http://english.ihep.cas.cn/bes/doc/2250.html

User Information

- Useful Information
- Data Sets
- Meetings
- Hypernews
- Documentation
- Other Links
- Visitor Information
- Contact US

Data Sets

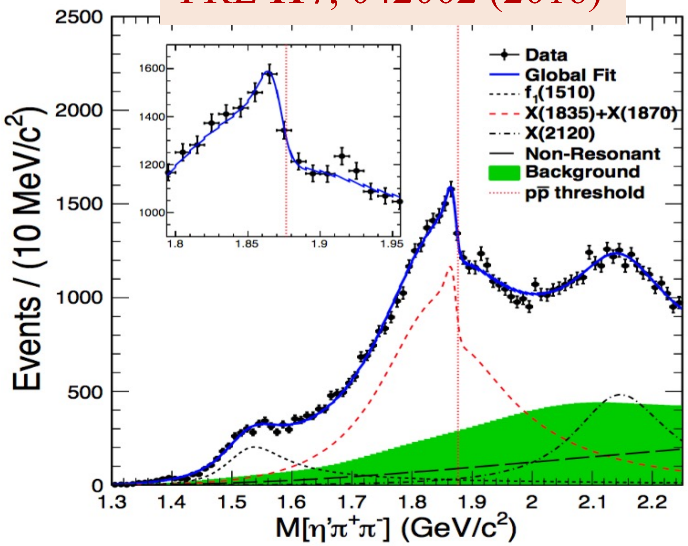
BESIII started data taking for physics since 2009, and the following data samples were collected:

- 2009 : 0.225×10^9 J/psi at Ecm=3.097 GeV, 0.106×10^9 psi(3686) at Ecm=3.686 GeV
- 2010 + 2011 : 2.9 fb^{-1} psi(3770) at 3.773 GeV
- 2011 : 0.5 fb^{-1} psi(4040) at 4.009 GeV, 0.024 fb^{-1} tau mass scan at around 3.554 GeV, 2011
- 2012 : 1.3×10^9 J/psi at Ecm=3.097 GeV, 2009 (0.225×10^9) , 0.5×10^9 psi(3686) at Ecm=3.686 GeV, 2009 (0.106×10^9)
- 2013 : 1.9 fb^{-1} Y(4260) at 4.23 and 4.26 GeV, 0.5 fb^{-1} Y(4360) at 4.36 GeV, 0.5 fb^{-1} Y(4260) and Y(4360) scan
- 2014 : 0.8 fb^{-1} R scan, 104 energy points between 3.85 and 4.59 GeV, 0.5 fb^{-1} at 4.60 GeV, 0.1 fb^{-1} at 4.47 and 4.53 GeV for line shape, 0.05 fb^{-1} around the threshold of Lambda_c pair, 1.0 fb^{-1} at 4.42 GeV
- 2015 : 0.5 fb^{-1} data for R scan from 2.0 to 3.08 GeV, 0.1 fb^{-1} data @ 2.125 GeV
- 2016 : 3.1 fb^{-1} data at 4.18 GeV
- 2017 : 3.8 fb^{-1} 8 energy points from 4190~4280 MeV, 0.46 fb^{-1} around chi_c1 mass , 0.22 fb^{-1} around 3872 MeV
- 2018 : 4.6 x 10^9 J/psi data set (1.4 /fb), 0.13 /fb tau scan data, 0.5 /fb, 9 points for psi(3686) scan data
- 2019 : 4.2 x 10^9 J/psi data set (1.218 /fb), 3.8/fb scan data for XYZ, 8points (4.13, 4.16, 4.29-4.44 GeV)
- 2020 : 3.8/fb scan data for XYZ and Lambda_c, 6 points (4.61-4.70 GeV)

…. and more data will be collected in the next years

Latest Results on X(1835)

PRL **117**, 042002 (2016)



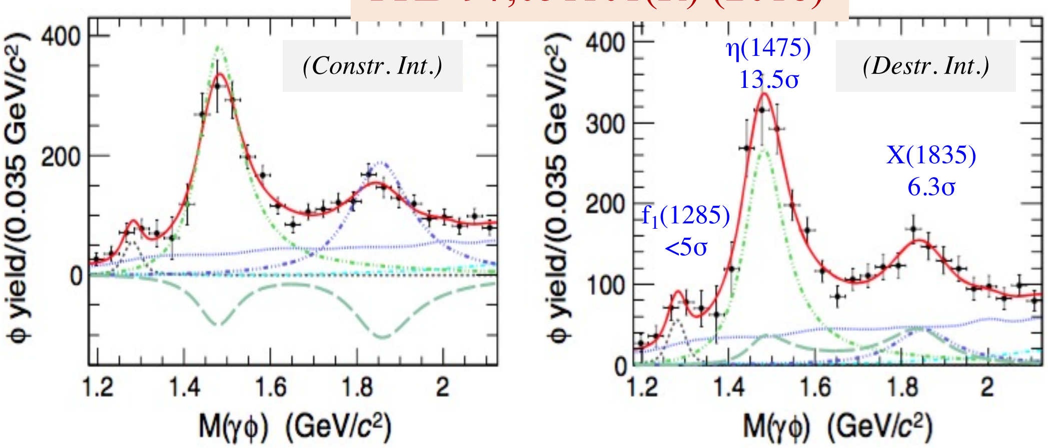
1.09×10^9 J/ψ @ BESIII

J/ψ→γ η'π⁻π⁺

Significant distortion of the η'π⁻π⁺ line shape near the ppbar mass threshold

Two fit models are taken into account and both support the existence of a pp̄ moleculelike or bound state

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



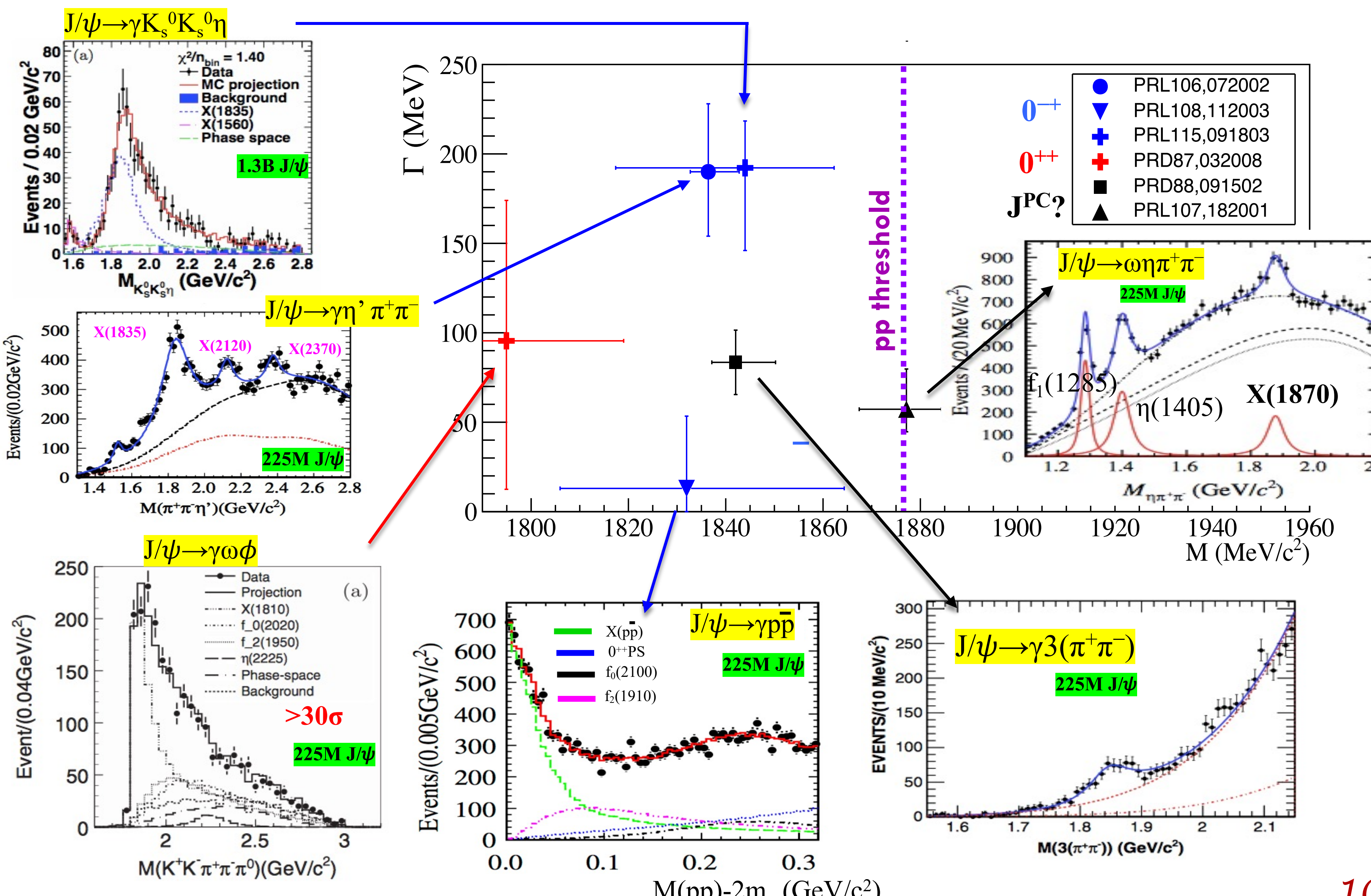
1.3×10^9 J/ψ @ BESIII

J/ψ→γγφ: two structures corresponding to η(1475) and X(1835) are observed

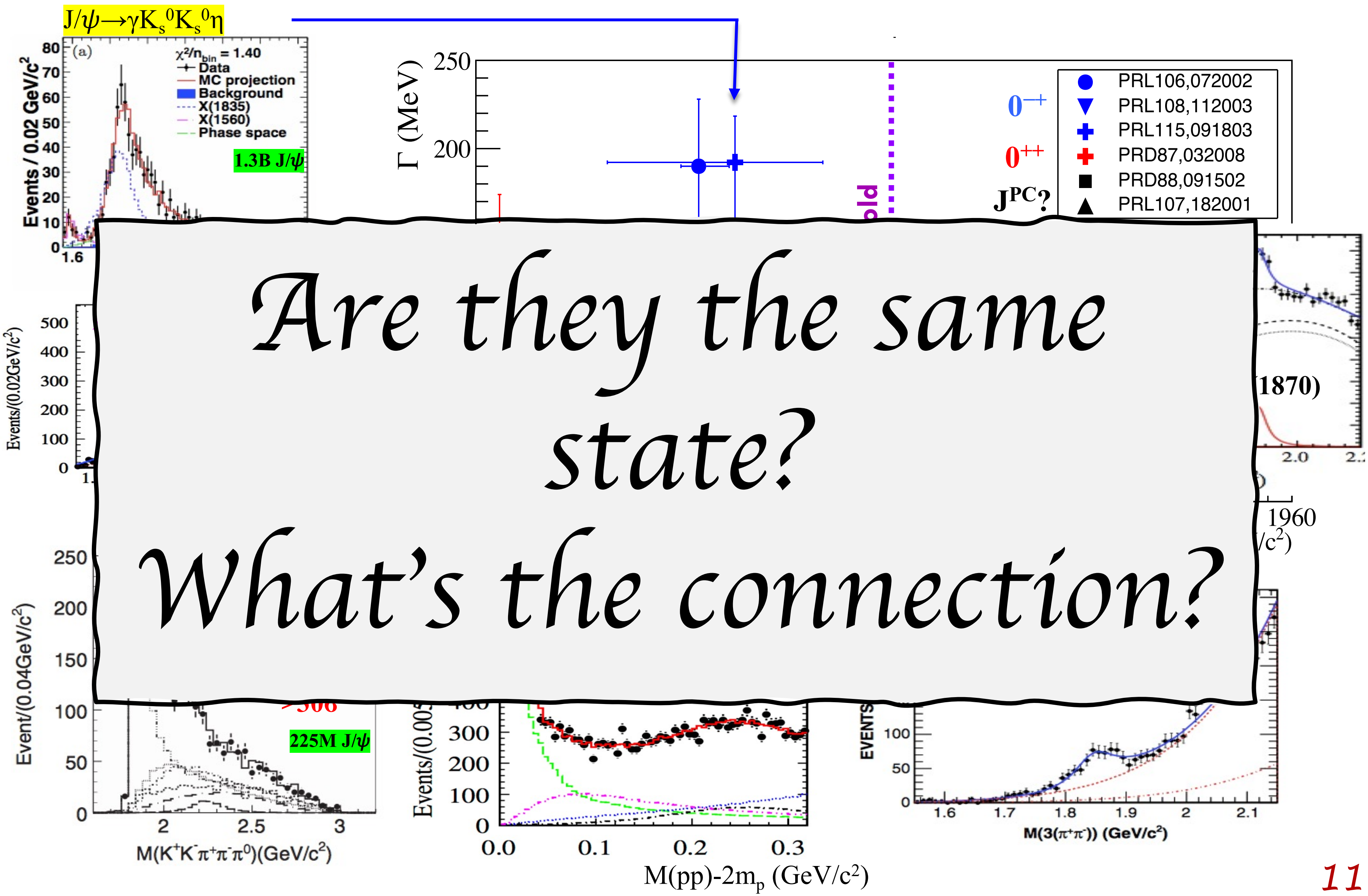
- X(1835) and η(1475): $J^{PC} = 0^{-+}$ assignment favored
- Sizable $s\bar{s}$ component in X(1835)
  - more complicated than a pure $N\bar{N}$ state

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

X(18xx) between 1.8-1.9 GeV



X(18xx) between 1.8-1.9 GeV



Are they the same state?

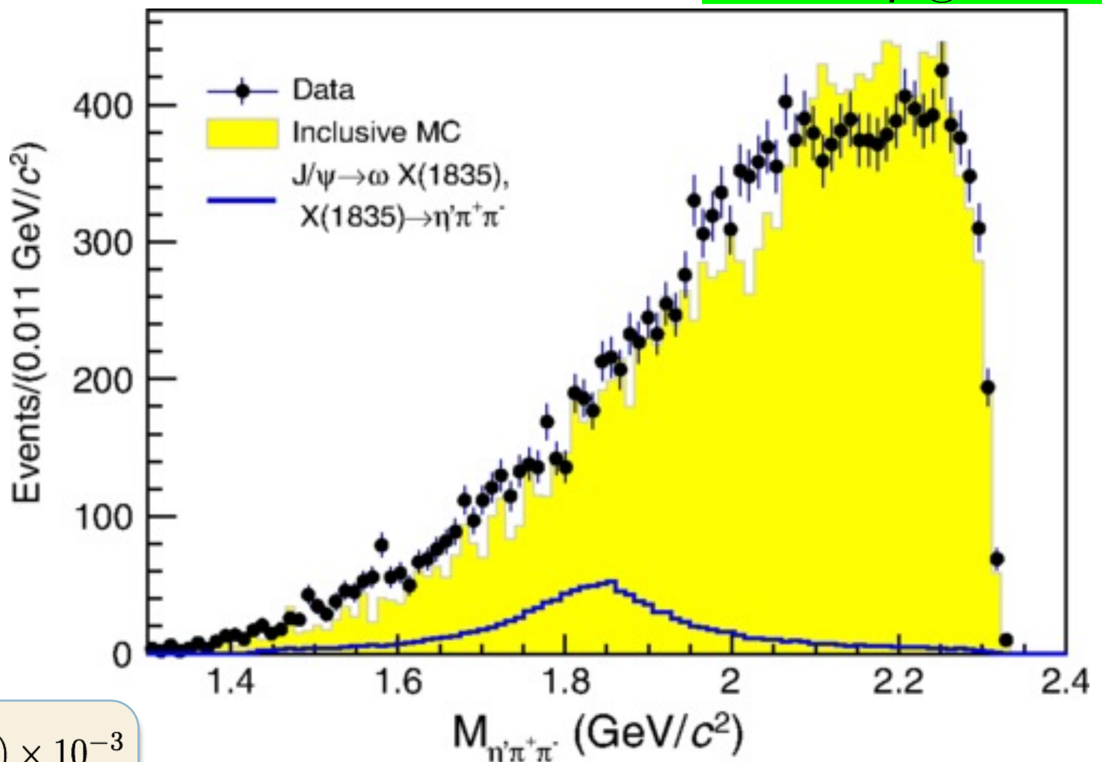
What's the connection?

Search for X(1835) in other decay modes

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

1.3×10^9 J/ψ @ BESIII

PRD **99**, 071101 (R) (2019)
done in FERRARA



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

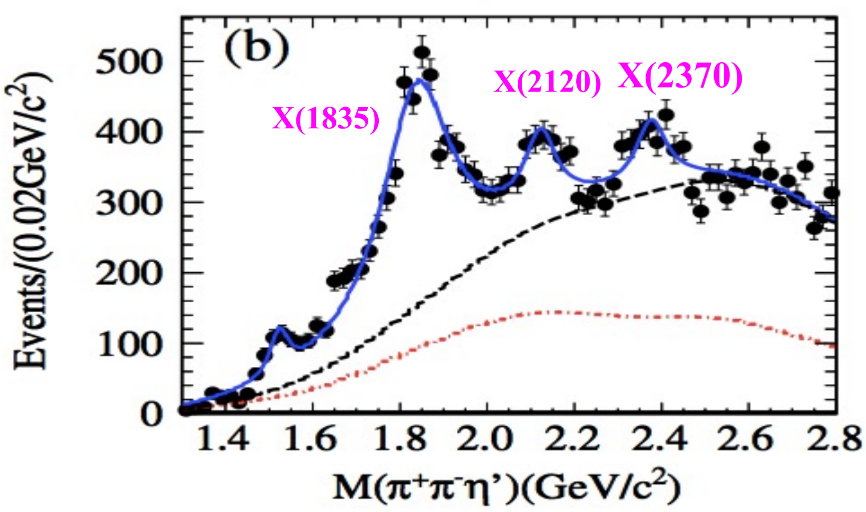
$$\mathcal{B}(J/\psi \to \omega\eta'\pi^+\pi^-) = (1.12 \pm 0.02 \pm 0.13) \times 10^{-3}$$
$$\mathcal{B}(J/\psi \to \omega X(1835),\ X(1835) \to \eta'\pi^+\pi^-) < 6.2 \times 10^{-5}$$

@ 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)

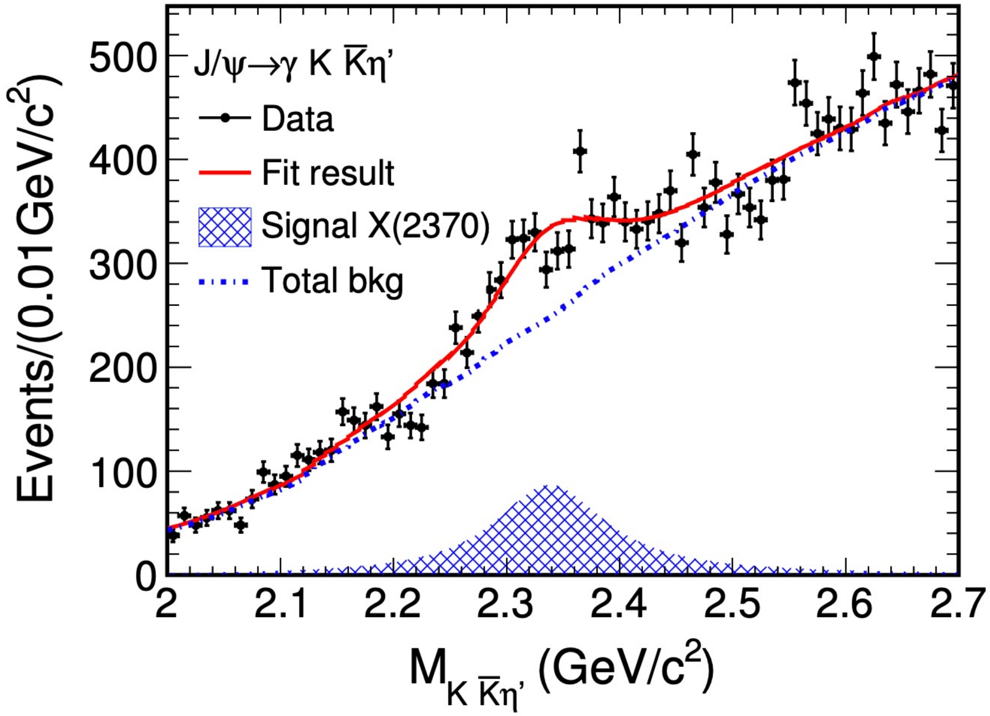


First Observation of X(2370) in $J/\psi \to \gamma K\bar{K}\eta'$

1.3×10^9 J/ψ @ BESIII

EPJC **80**, 746 (2020)

- 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)



➢ **No evidence of X(2120) is found**

$\mathcal{B}(J/\psi \to \gamma X(2120) \to \gamma K^+K^-\eta') < 1.49\times10^{-5}$

$\mathcal{B}(J/\psi \to \gamma X(2120) \to \gamma K^0_S K^0_S\eta') < 6.38\times10^{-6}$

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

$$M_{X(2370)} = 2341.6 \pm 6.5 \pm 5.7\ \mathrm{MeV}/c^2 \quad \Gamma_{X(2370)} = 117 \pm 10 \pm 8\ \mathrm{MeV}$$

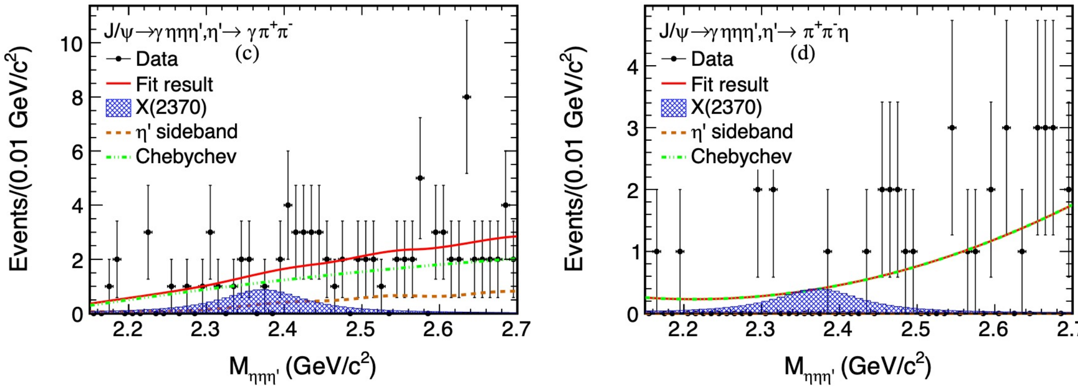
$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma K^+K^-\eta') = (1.79 \pm 0.23 \pm 0.65)\times10^{-5}$$

$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma K^0_S K^0_S\eta') = (1.18 \pm 0.32 \pm 0.39)\times10^{-5}$$

Search for X(2370) in J/ψ→γηηη'

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

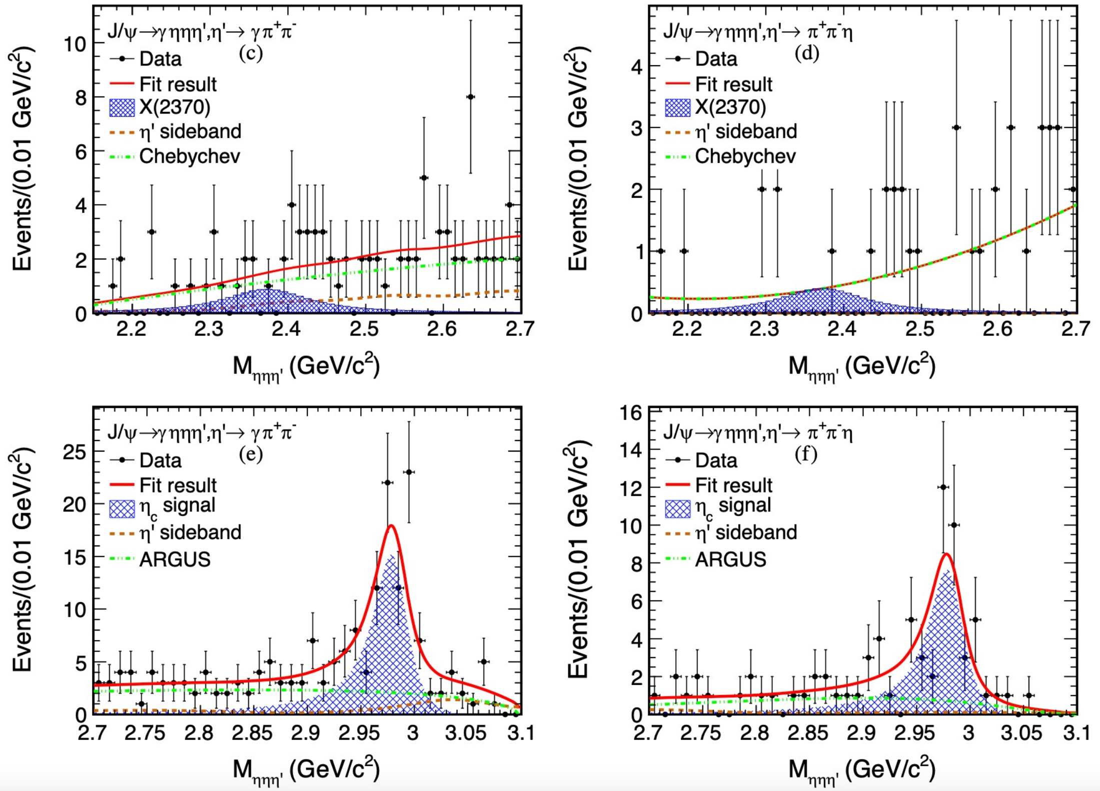
$$\mathcal{B}(J/\psi\to\gamma X(2370)\to\gamma\eta\eta\eta') < 9.2\times10^{-6}$$

(agree with PRD **87**,054036)

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

$$\mathcal{B}(J/\psi\to\gamma X(2370)\to\gamma\eta\eta\eta') < 9.2\times10^{-6}$$

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

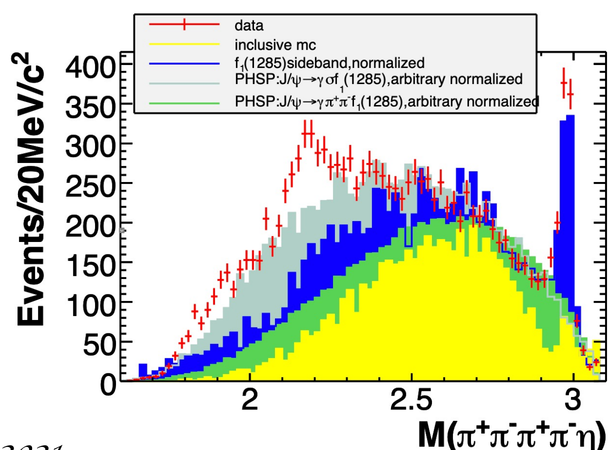
$$\mathcal{B}(J/\psi\to\gamma\eta_c)\cdot\mathcal{B}(\eta_c\to\eta\eta\eta') = (4.86\pm0.62\pm0.45)\times10^{-5}$$

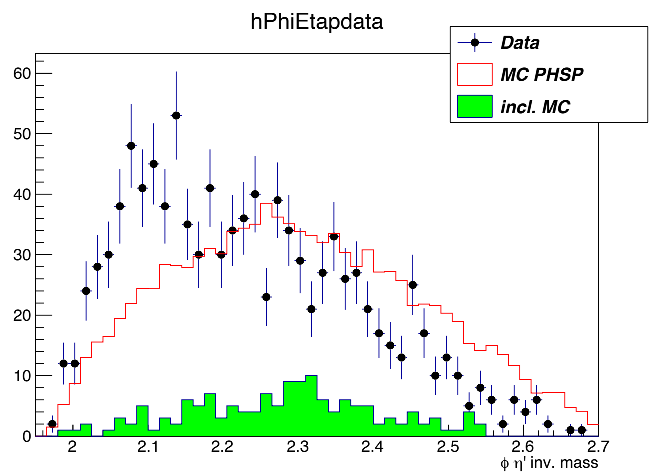
FIRST OBSERVATION in the ηηη' invariant mass spectra

Search for X(1835) in other decay modes

What we can do?

- $J/\psi \to \omega\eta'\pi^+\pi^-$ hadronic decay and search for $X(1835) \to \eta'\pi^+\pi^-$ using the full BESIII dataset (still free analysis)
- $J/\psi \to \phi\eta'\pi^+\pi^-$ (there is another group working on it – advanced state)
- $J/\psi \to \rho X(1835)$, $X(1835) \to \eta'\pi^+\pi^-$ (BR predicted to be very small in ref. https://arxiv.org/pdf/hep-ph/0511186.pdf)
- $J/\psi \to \gamma\pi^+\pi^- f_1(1285)$: observation of a new state X(2200) in the 4pi eta invariant mass spectra - analysis with principal author left - https://hnbes3.ihep.ac.cn//HyperNews/get/AUX/2013/12/17/22.43-54155-gammapipif1_v7.pdf
- …..





Search for X(1835) in other decay modes

What we can do?

- $J/\psi \rightarrow \omega\eta'\pi^+\pi^-$ hadronic decay and search for $X(1835) \rightarrow \eta'\pi^+\pi^-$ using the full BESIII dataset (still free analysis)
- $J/\psi \rightarrow \phi\eta'\pi^+\pi^-$ (there is another group working on it – advanced state)
- $J/\psi \rightarrow \rho X(1835)$, $X(1835) \rightarrow \eta'\pi^+\pi^-$ (BR predicted to be very small in ref. https://arxiv.org/pdf/hep-ph/0511186.pdf)
- $J/\psi \rightarrow \gamma\pi^+\pi^- f_1(1285)$: observation of a new state X(2200) in the 4pi eta invariant mass spectra - analysis with principal author left - https://hnbes3.ihep.ac.cn//HyperNews/get/AUX/2013/12/17/22.43-54155-gammapipif1_v7.pdf
- …..

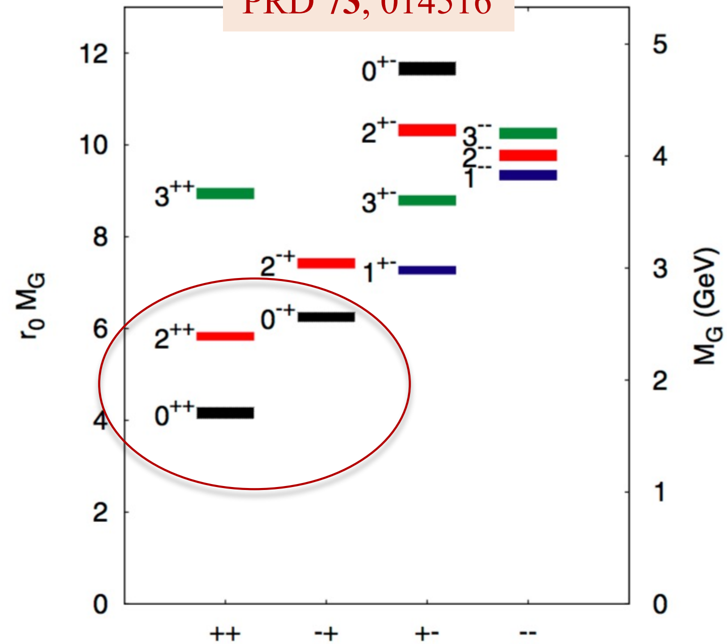
All the analysis presented up to now were performed with lower 2009 and/or 2012 Jpsi data only ➔ all the analysis can be improved

Amplitude Analyses in BESIII

Amplitude Analyses in BESIII

- J/ψ radiative decays are ideal for searching glueballs
  - **$J/\psi \to \gamma PP$: 0^{++}, 2^{++}, …**
  - **$J/\psi \to \gamma PPP$, 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

PRD **73**, 014516



- **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

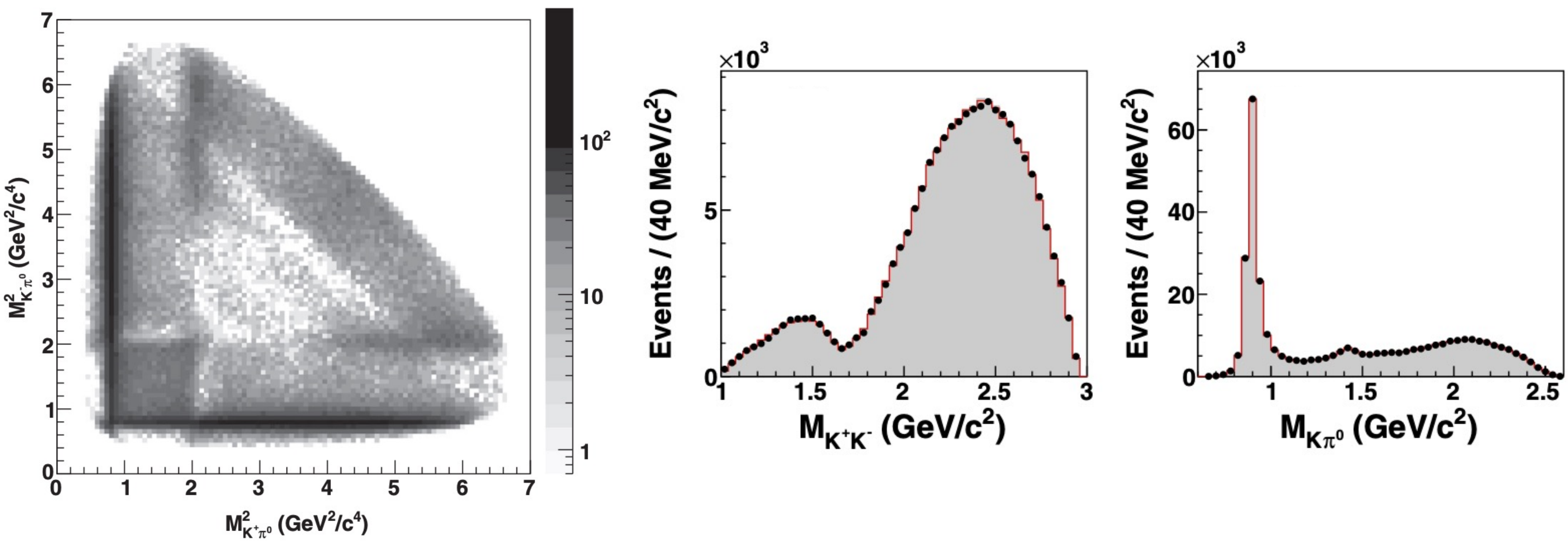
  - **Mass Dependent (MD) PWA**: model the dynamics of particle interactions as coherent sum of resonances
  - **Mass Independent (MI) PWA**: make minimal model assumptions and measure the dynamical amplitudes independently in small regions of two-meson invariant mass (PRD92, 052003 (2015))

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

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)

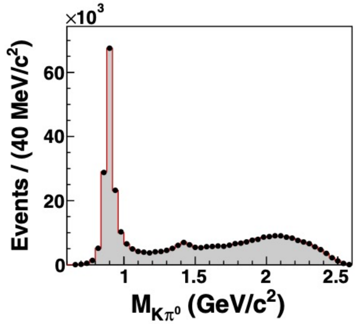


Isobar model: the amplitude is parameterized as a sum of sequential quasi-two-body decay process [EPJA16,537(2003)]

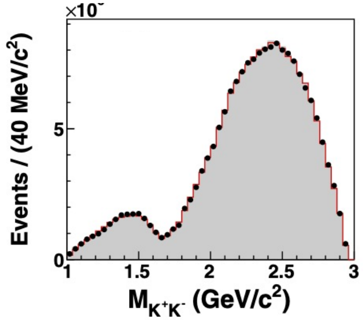
PWA of $J/\psi \to K^+K^-\pi^0$

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%



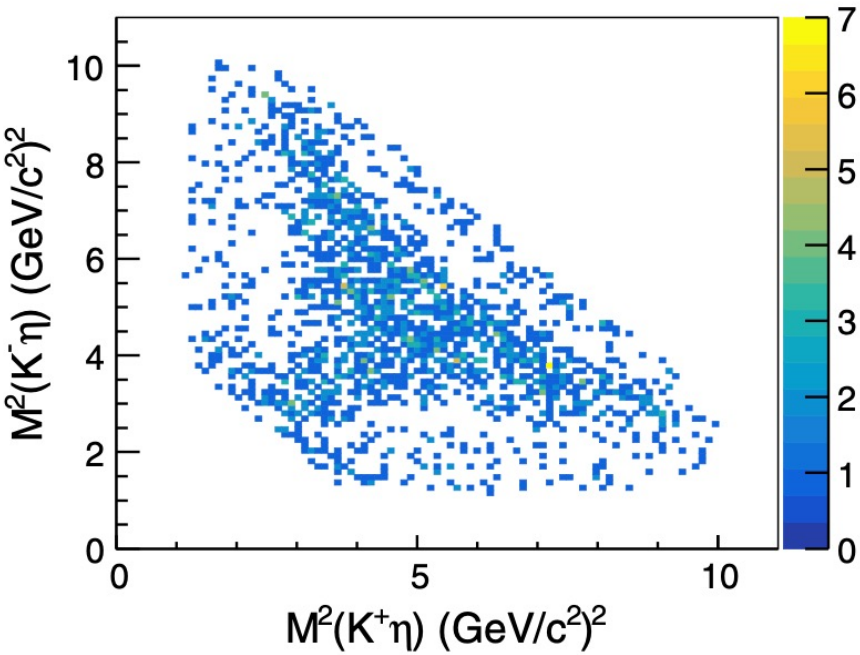
J^{PC}	M (MeV/c^2)	Γ (MeV/c^2)	b (%)
1^{--}	$1651 \pm 3^{+16}_{-6}$	$194 \pm 8^{+15}_{-7}$	$1.83 \pm 0.11^{+0.19}_{-0.17}$
1^{--}	$2039 \pm 8^{+36}_{-18}$	$196 \pm 23^{+25}_{-27}$	$0.23 \pm 0.04^{+0.07}_{-0.06}$

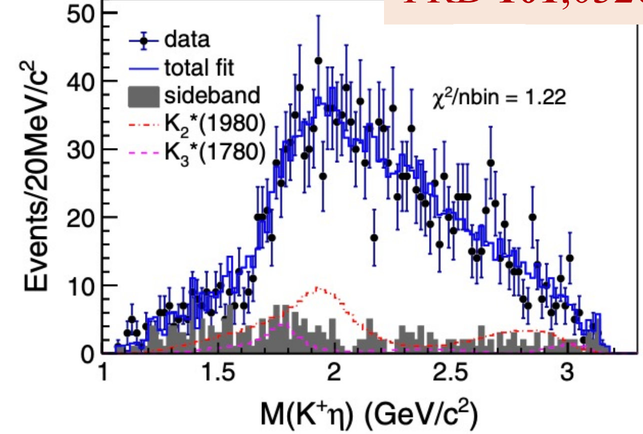


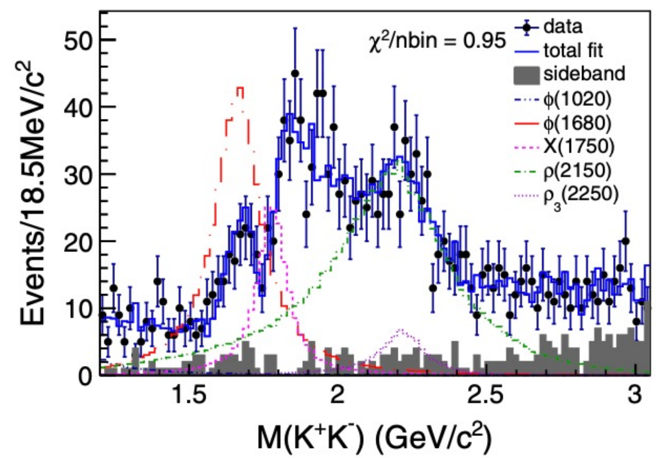
- Dominant contribution from K*(892)
- First observation of $K^*_2(1980)$ and $K^*_4(2045)$ in J/ψ decays
- Two clear $J^{PC}=1^{--}$ structures observed in K^+K^- mass spectrum: possible relation with ω(1650) and ρ(2150)

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 (not excluded the possibility to be the ρ(1700))

- 1^{--} state needed to describe the dip around 1.7 GeV/c^2 in the KK mass spectra (not excluded the possibility to be the ρ(1700))

- A broad structure around 2.2 GeV/c2 is observed, either $\phi(2170)$ or ρ(2150)?

Conclusions and PWA possibilities

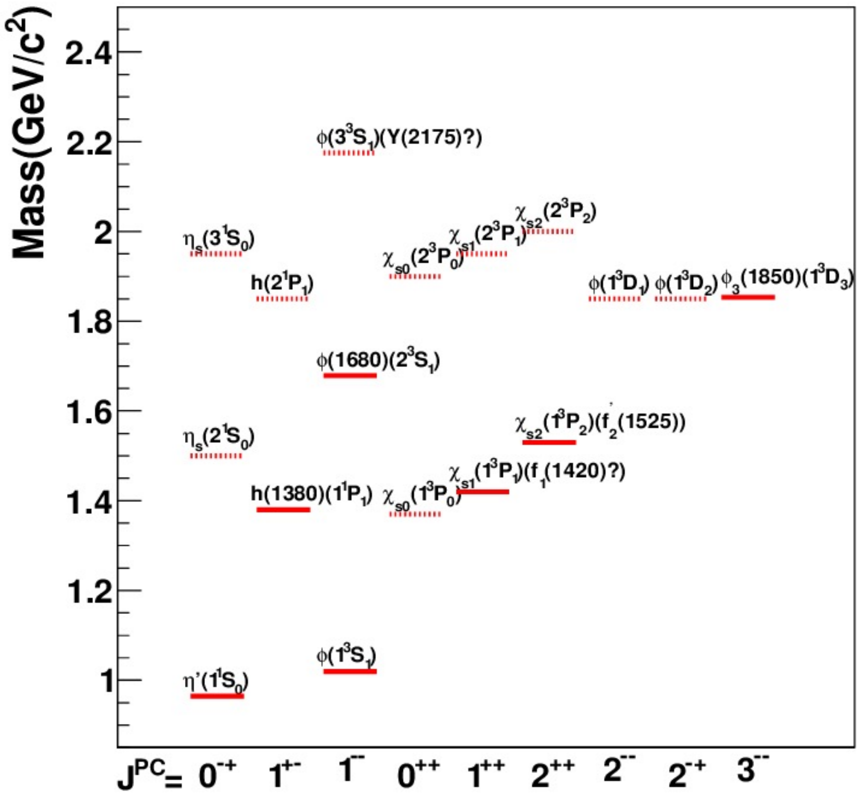
- $J/\psi \rightarrow KK\eta$ still PWA free analysis
- Start a collaboration with Mainz group (a lot of PWA analyses were done)
- There is also the possibility to collaborate with Ismail (expert of PWA analysis)
- Other ideas are very welcome ….

- In the next future (I hope beginning of 2022) I plan to start a PWA analysis

Thanks for your attention

Strangeonia Spectrum

Strangeonia Spectrum



Strangeonium meson

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

Only few states observed:

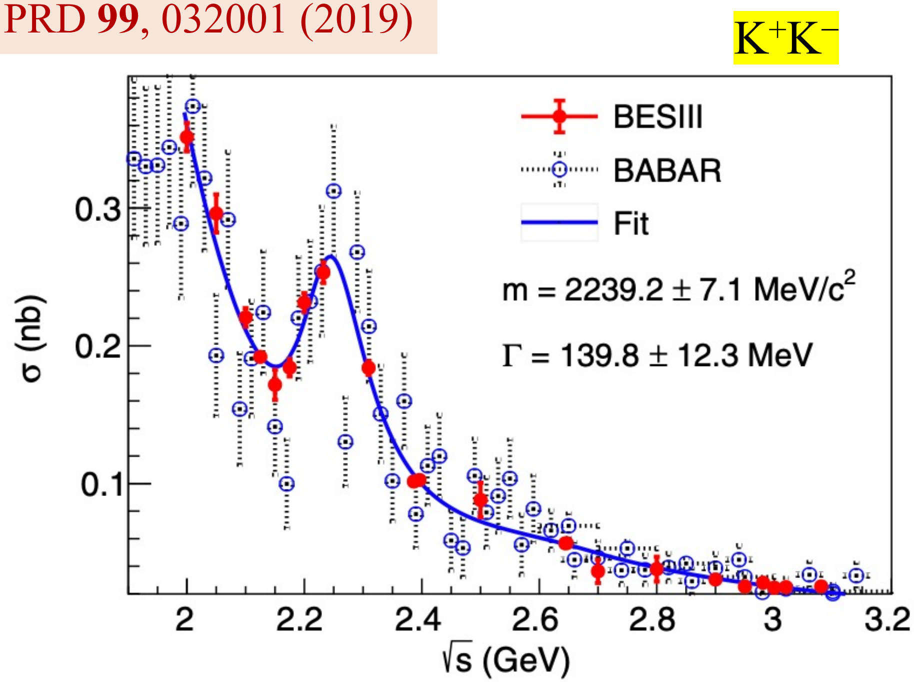
- Small BR
- Large Γ

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

- $\phi(2170)$/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)

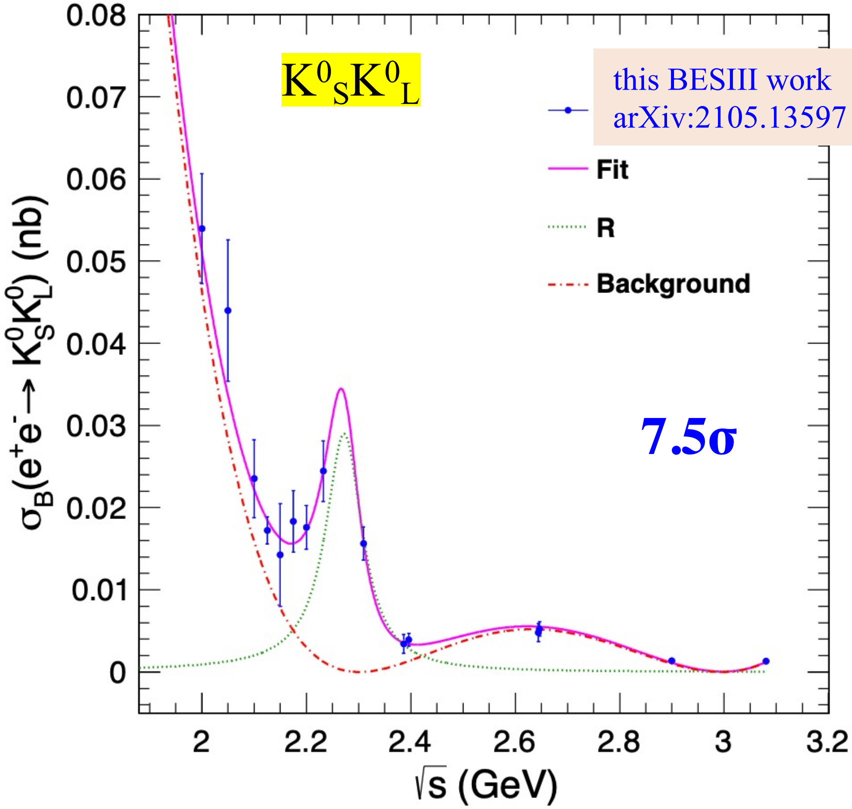
$\phi(2170)$ @ BESIII

PRD **99**, 032001 (2019)



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

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



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

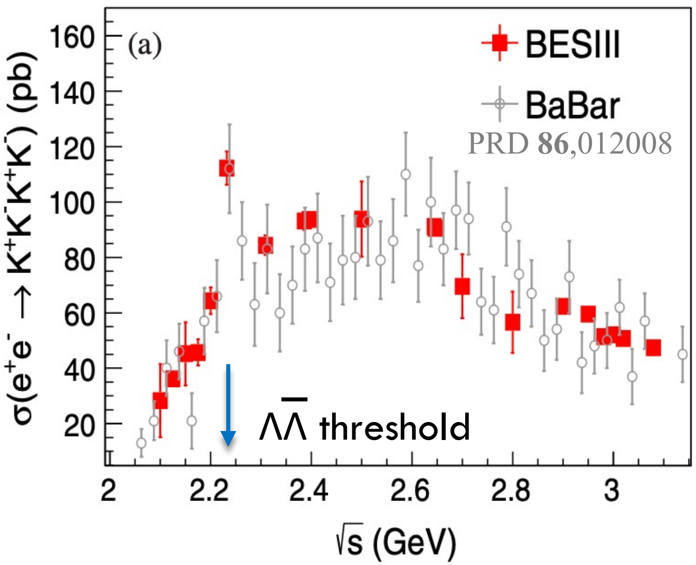
Consistent with BaBar PRD **101**,012011(2020)

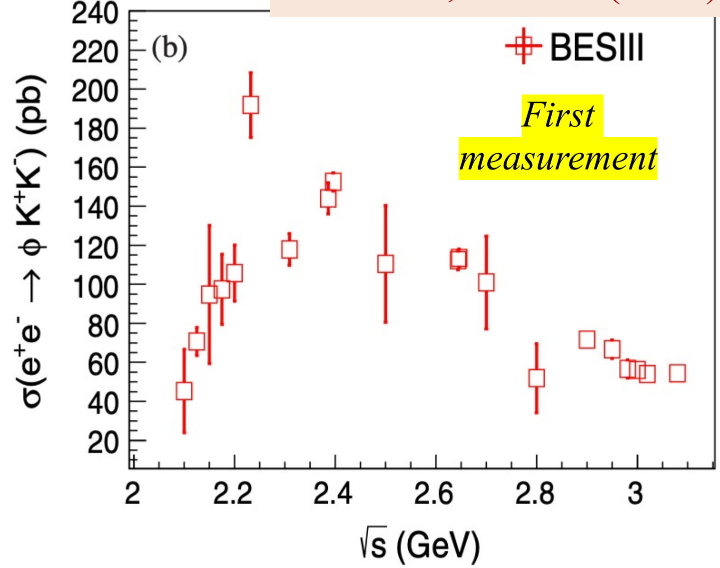
$\phi(2170)$ @ BESIII

PRD **100**, 032009 (2019)

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

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

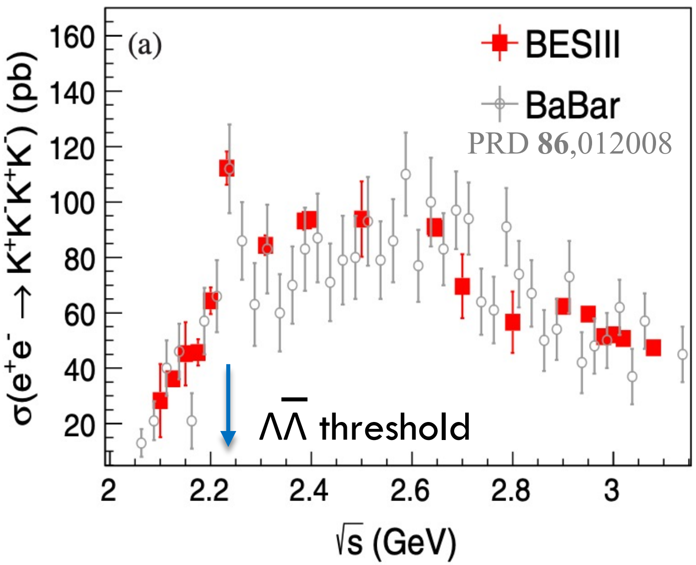




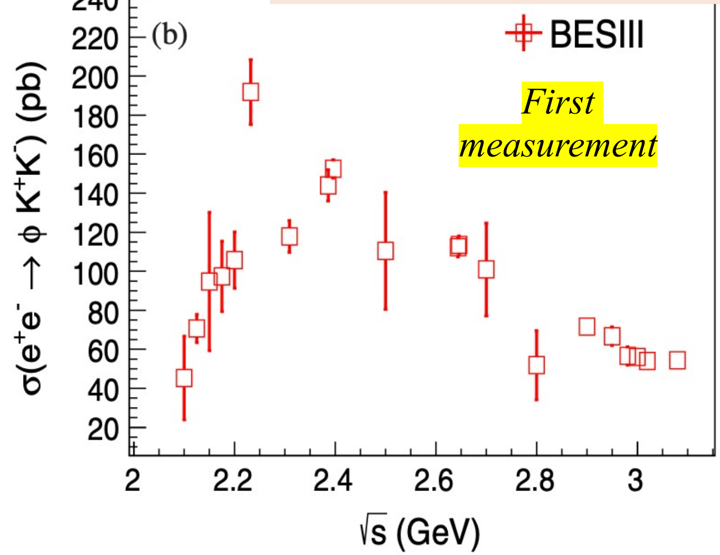
$\phi(2170)$ @ BESIII

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

ϕ(2170) or new strangeonium state?



PRD **100**, 032009 (2019)



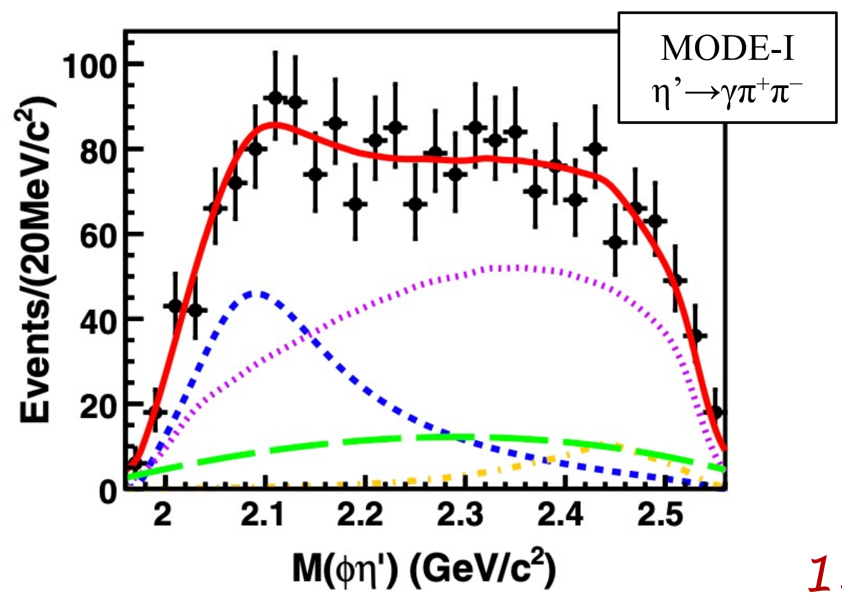
PRD **99**, 112008 (2019) - **1.3×10^9 J/ψ events**

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 consistent with
- Significance of structure: 4.4σ for $J^P = 1^-$ and 3.8 for $J^P = 1^+$

no PDG entries

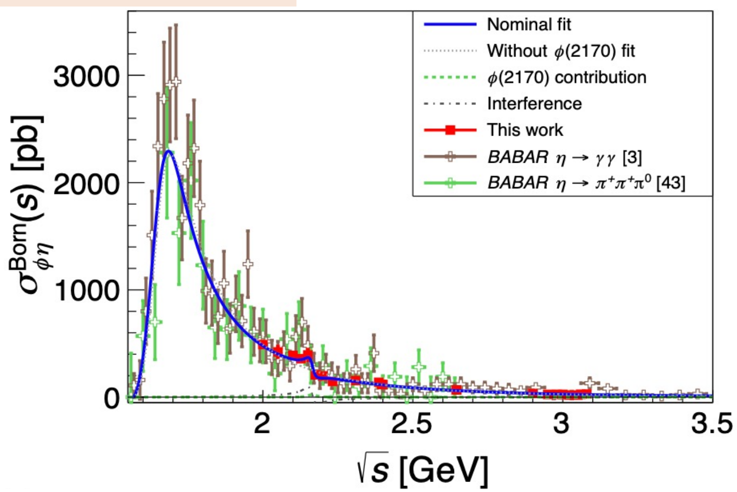
mass 5σ away from that reported on PDG

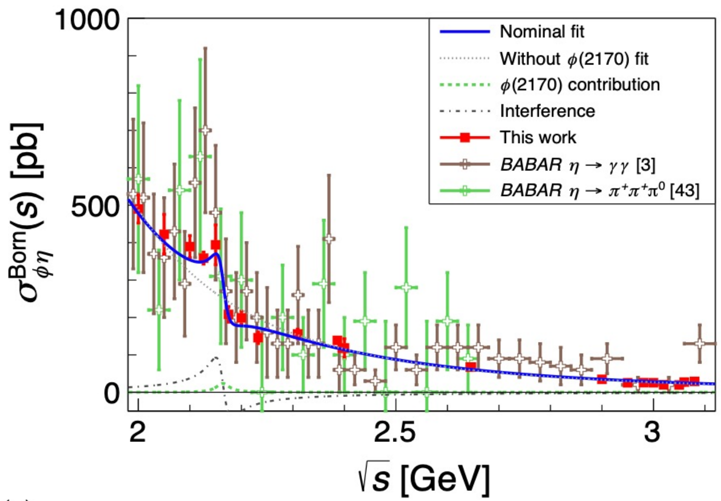


$e^+e^- \to \phi\eta$ and $\phi\eta'$

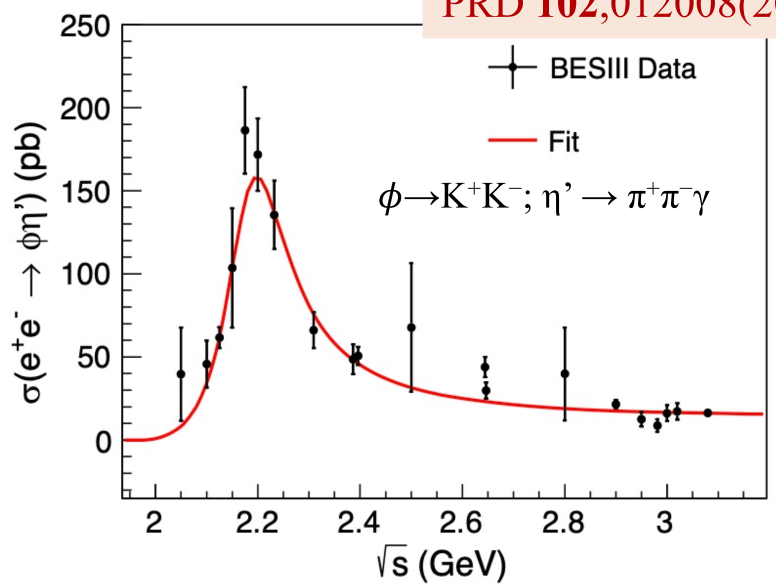
- The ratio between $\phi\eta$ and $\phi\eta'$ partial width is important observable to access $\phi(2170)$ as a $s\bar{s}g$ hybrid state
  - partial width larger in the $\phi\eta$ channel by a factor [3-200] w.r.t $\phi\eta'$

arXiv:2104.05549





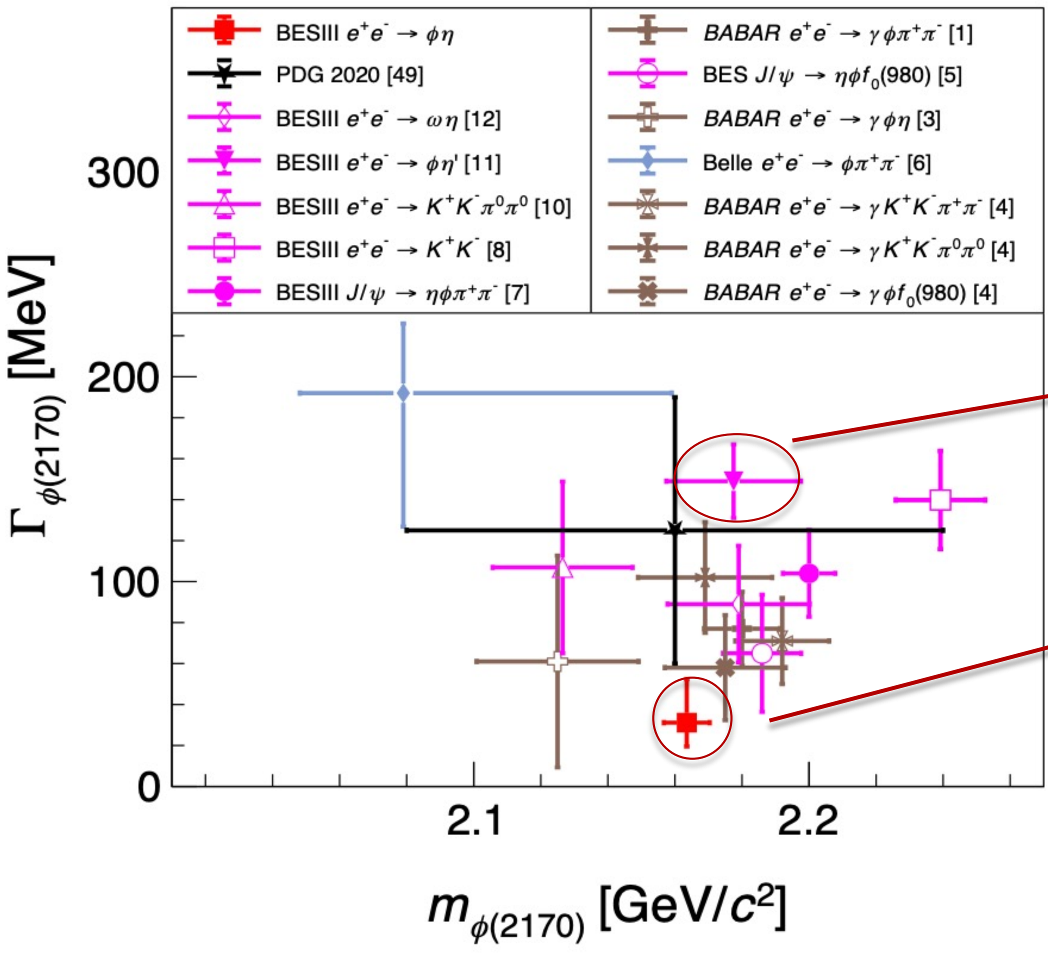
PRD **102**,012008(2020)



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

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

$$M = 2177.5 \pm 4.8 \pm 19.5 \text{ MeV}/c^2$$
$$\Gamma = 149.0 \pm 15.6 \pm 8.9 \text{ MeV}$$

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

$$M = 2163.5 \pm 6.2 \pm 3.0 \text{ MeV}/c^2$$
$$\Gamma = 31.1^{+21.1}_{-11.6} \pm 1.1 \text{ MeV}$$

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

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

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

Conclusions

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

- ***<u>10 billion of J/ψ data collected at BESIII</u>***
  - 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

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

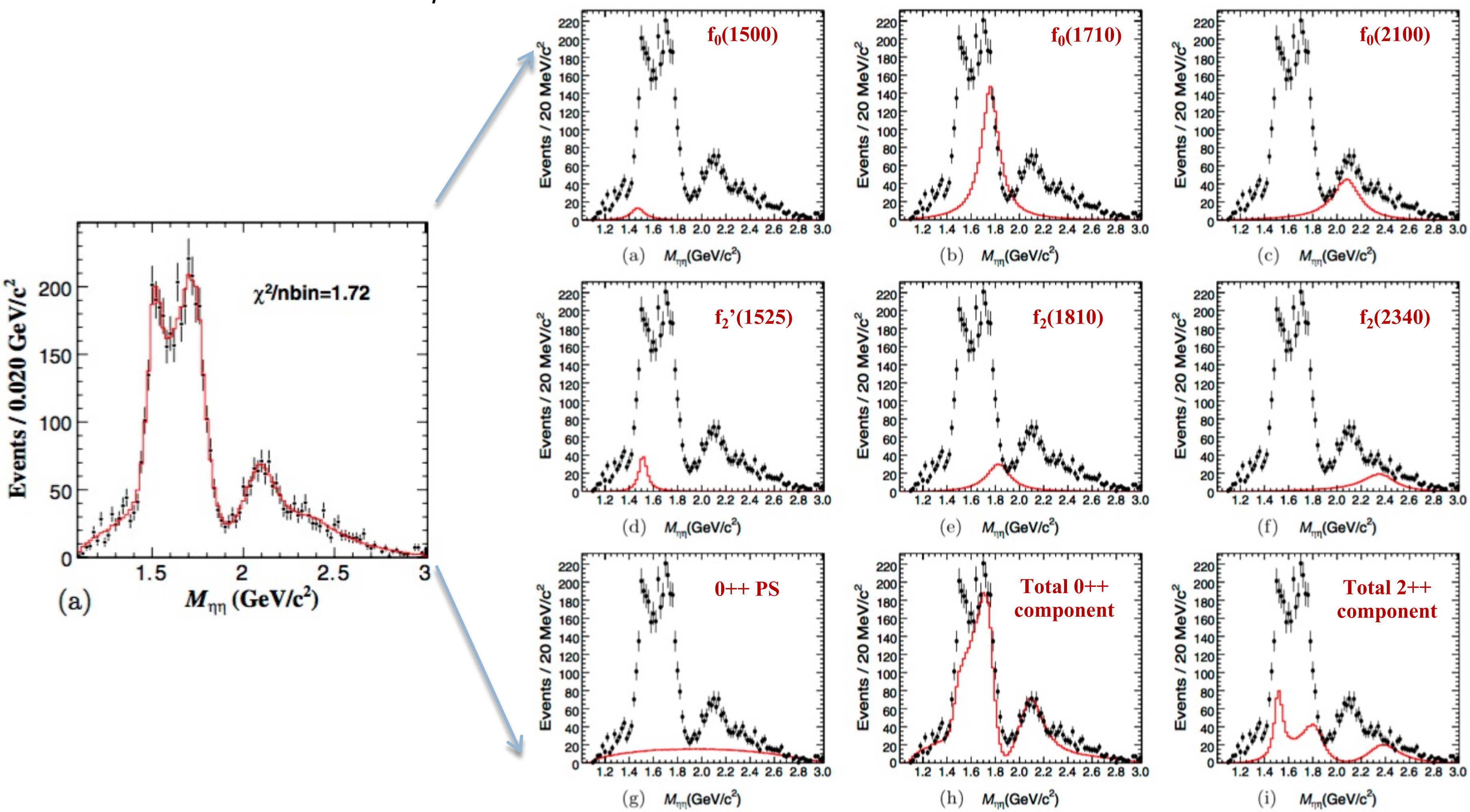
Charmonium physics
- Precision spectroscopy
- Transitions and decays

Precision mass measurements
- τ mass
- D, D^* mass

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

PRD **87**, 092009 (2013)

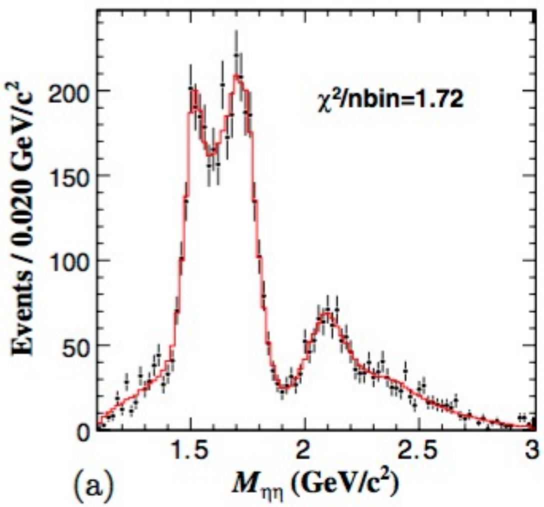
- $J/\psi \rightarrow \gamma\eta\eta$: clean laboratory to search for 0++ and 2++ states
- PWA based on 2.25×10^{8} J/ψ events



PWA of J/ψ→γηη

PRD **87**, 092009 (2013)

- J/ψ→γηη: clean laboratory to search for 0++ and 2++ states
- PWA based on $2.25{\times}10^8$ 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

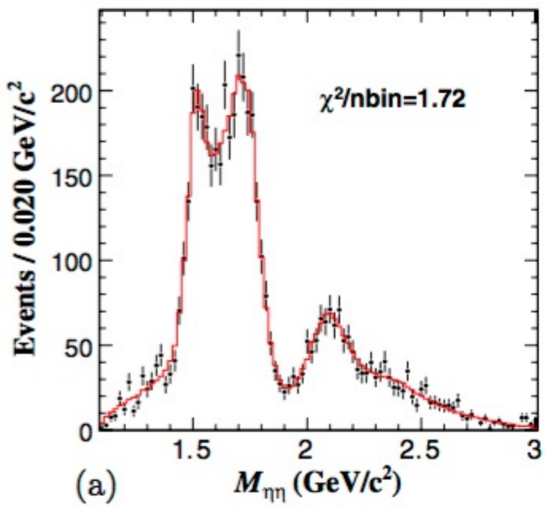
- PWA requires a strong contribution from **$f_2(2340)$** with fairly large production rate ⇒ it ***could be a good candidate for the lowest lying tensor glueball***

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

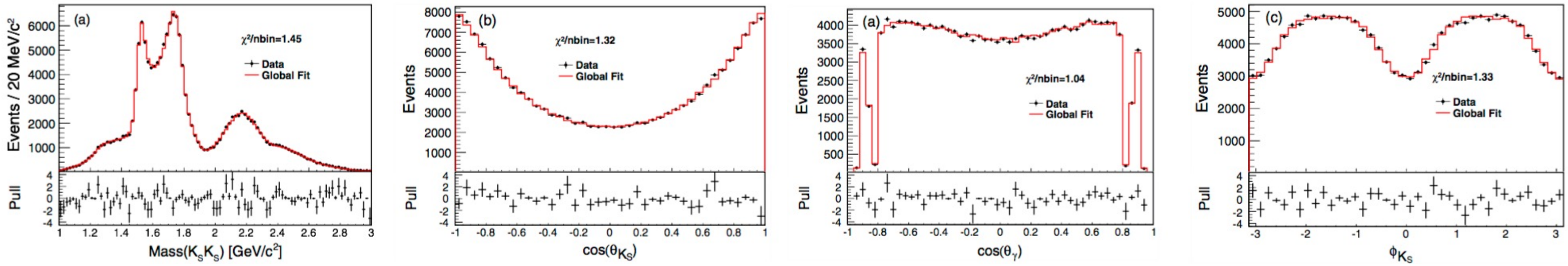


- $f_0(1500)$ dominant decays are 4π and $\pi\pi$
- The production rate of $f_0(1710)$ is compatible with LQCD (PRL110,021601) prediction for a pure scalar glueball
  - Suggest a large overlap with 0++ glueball
- PWA requires a strong contribution from **$f_2(2340)$** with fairly large production rate ⇒ it ***could be a good candidate for the lowest lying tensor glueball***

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

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



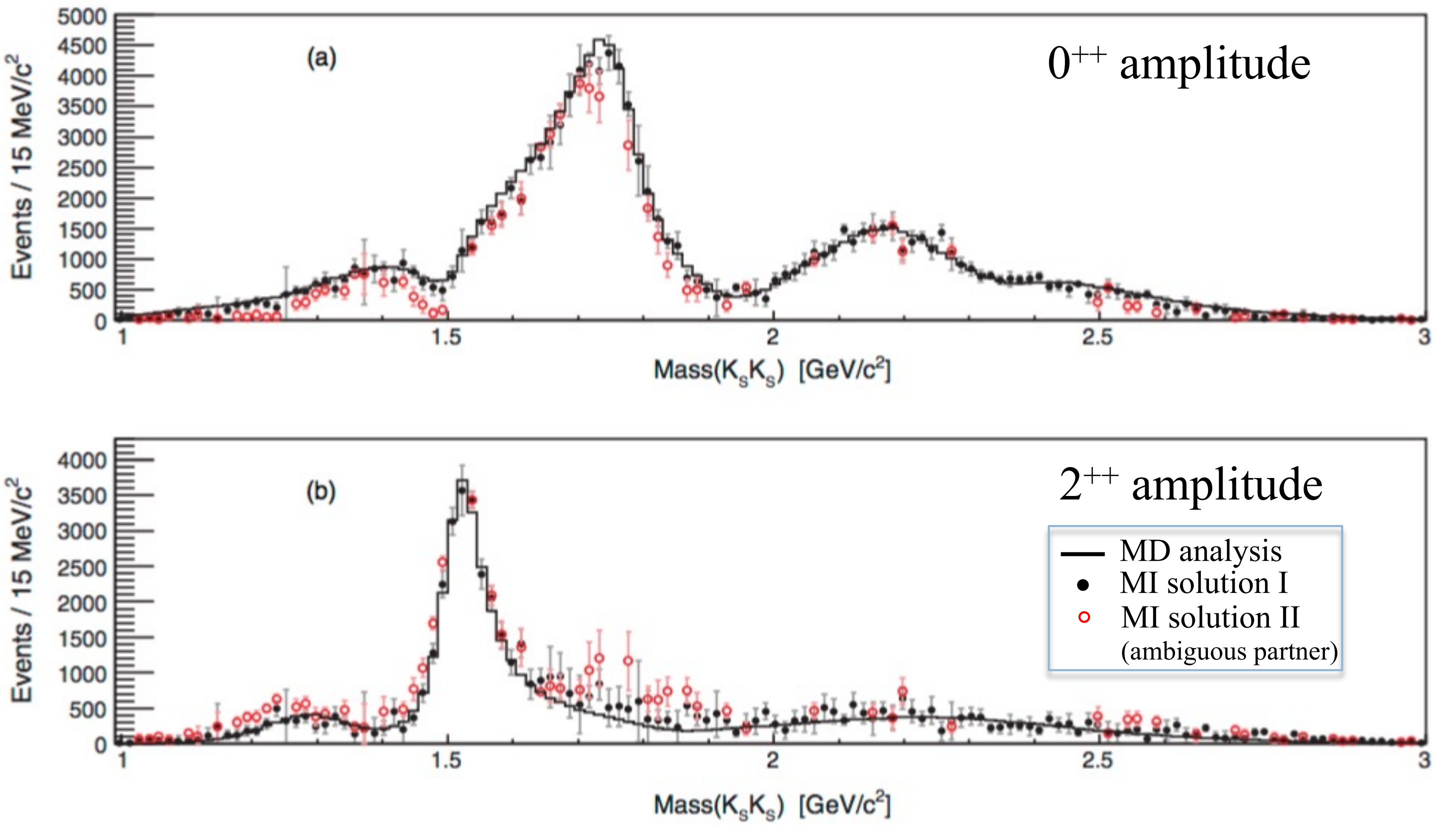
Resonance	M (MeV/c^2)	M_{PDG} (MeV/c^2)	Γ (MeV/c^2)	Γ_{PDG} (MeV/c^2)	Branching fraction	Significance
$K^*(892)$	896	895.81 ± 0.19	48	47.4 ± 0.6	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$	35σ
$K_1(1270)$	1272	1272 ± 7	90	90 ± 20	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$	16σ
$f_0(1370)$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



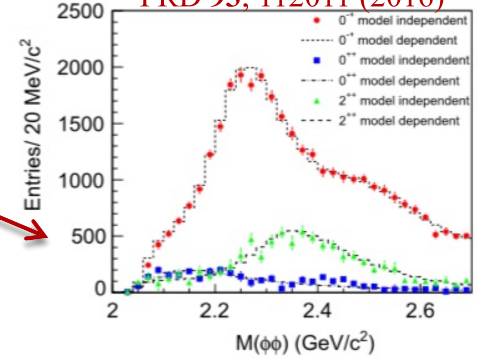
  - Agreement with results from MD PWA (no acceptance correction included)
  - MI results useful for a systematic study of hadronic interaction

PWA status and plans in a nutshell

	0+	2+	0−
$J/\psi \to \gamma PP$	$J/\psi \to \gamma\eta\eta$ (PRD87,092009) $J/\psi \to \gamma\pi^0\pi^0$ (PRD92,052003) $J/\psi \to \gamma K_S K_S$ (PRD98,072003) $J/\psi \to \gamma\eta\eta'$ $J/\psi \to \gamma\eta'\eta'$		
$J/\psi \to \gamma VV$		$J/\psi \to \gamma\omega\phi$ (PRD87,032008) $J/\psi \to \gamma\phi\phi$ (PRD93,112011) $J/\psi \to \gamma\omega\omega$	
$J/\psi \to \gamma PPP$			$J/\psi \to \gamma\eta'\pi\pi$ (PRL106,072002) $J/\psi \to \gamma KK\eta'$ $J/\psi \to \gamma\eta\pi^0\pi^0$

PWA Published
Ongoing
Published, no PWA

PRD **93**, 112011 (2016)

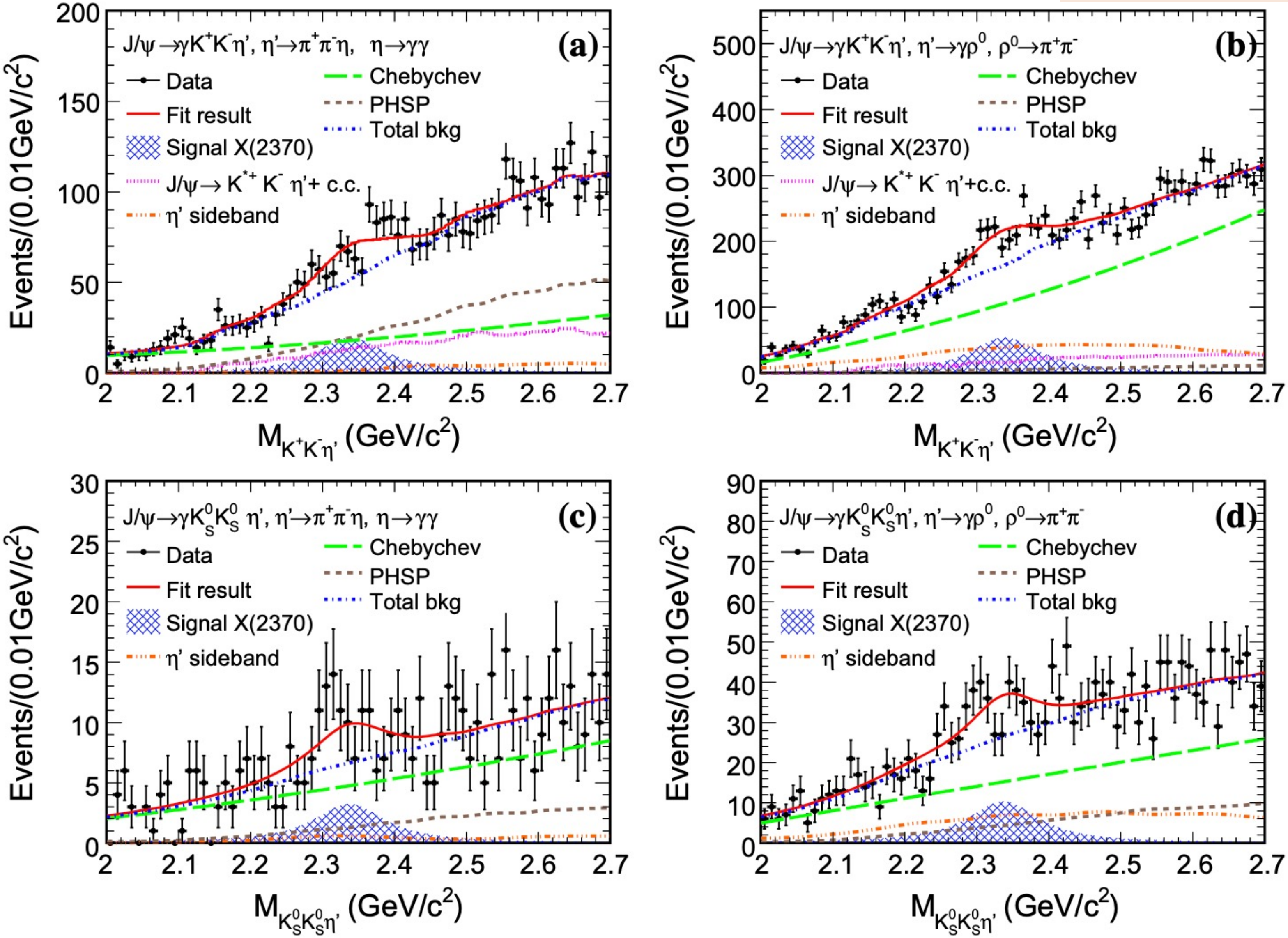


- 0++: the production rate $f_0(1710)$ is compatible with LQCD prediction for a pure gauge scalar glueball
- 2++: $f_0(2340)$ seems to be a good candidate for tensor gluball [PRL111,091601] (large production rate)
- 0−+: η(2225) is confirmed and two additional pseudoscalar states, η(2100) and X(2500),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

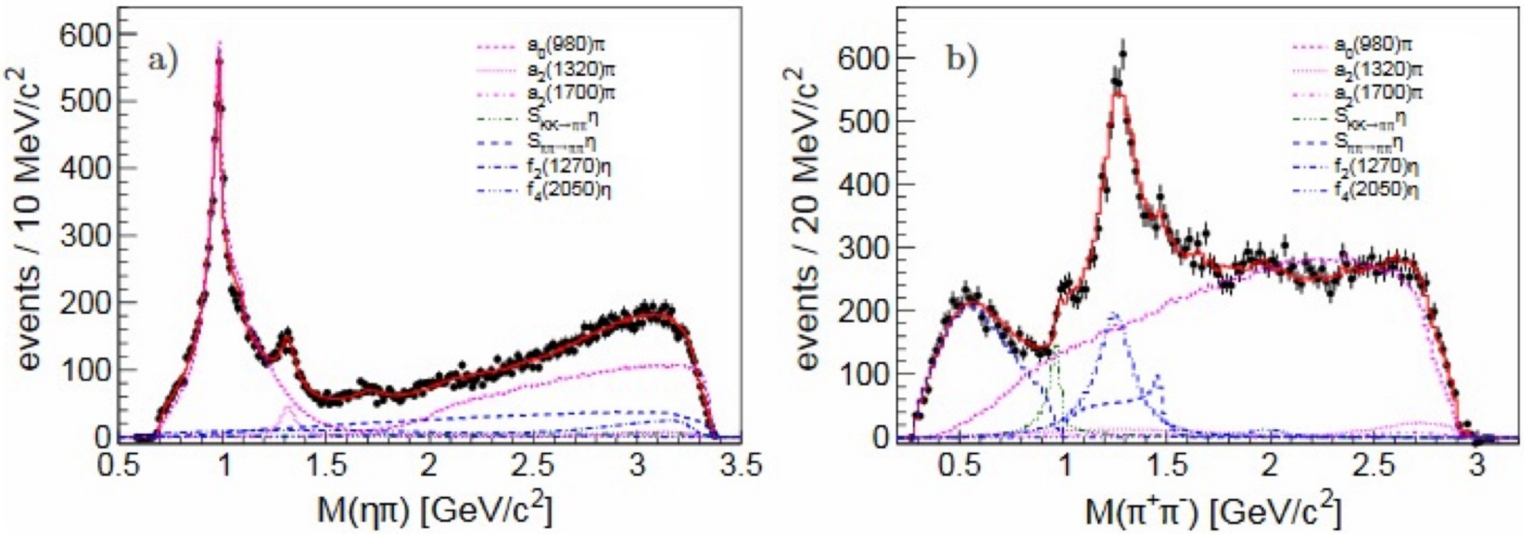
First Observation of X(2370) in $J/\psi \to \gamma K\bar{K}\eta'$

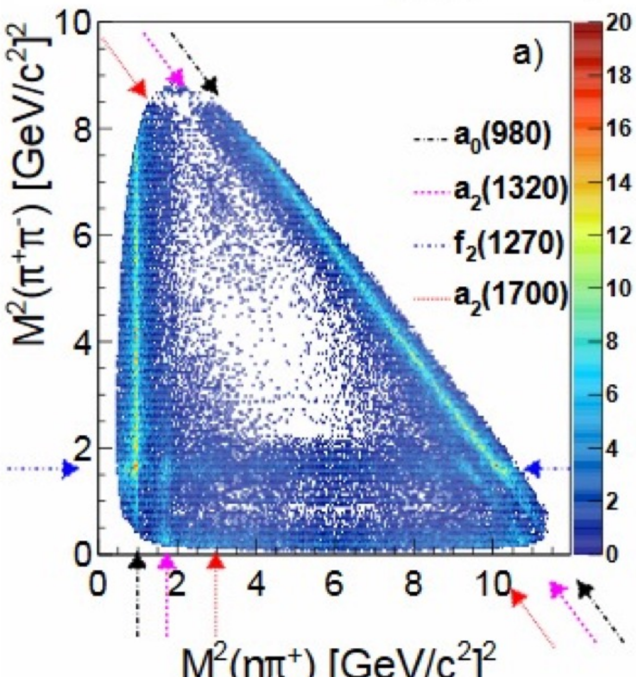
1.3×10^9 J/ψ @ BESIII

EPJC **80**, 746 (2020)

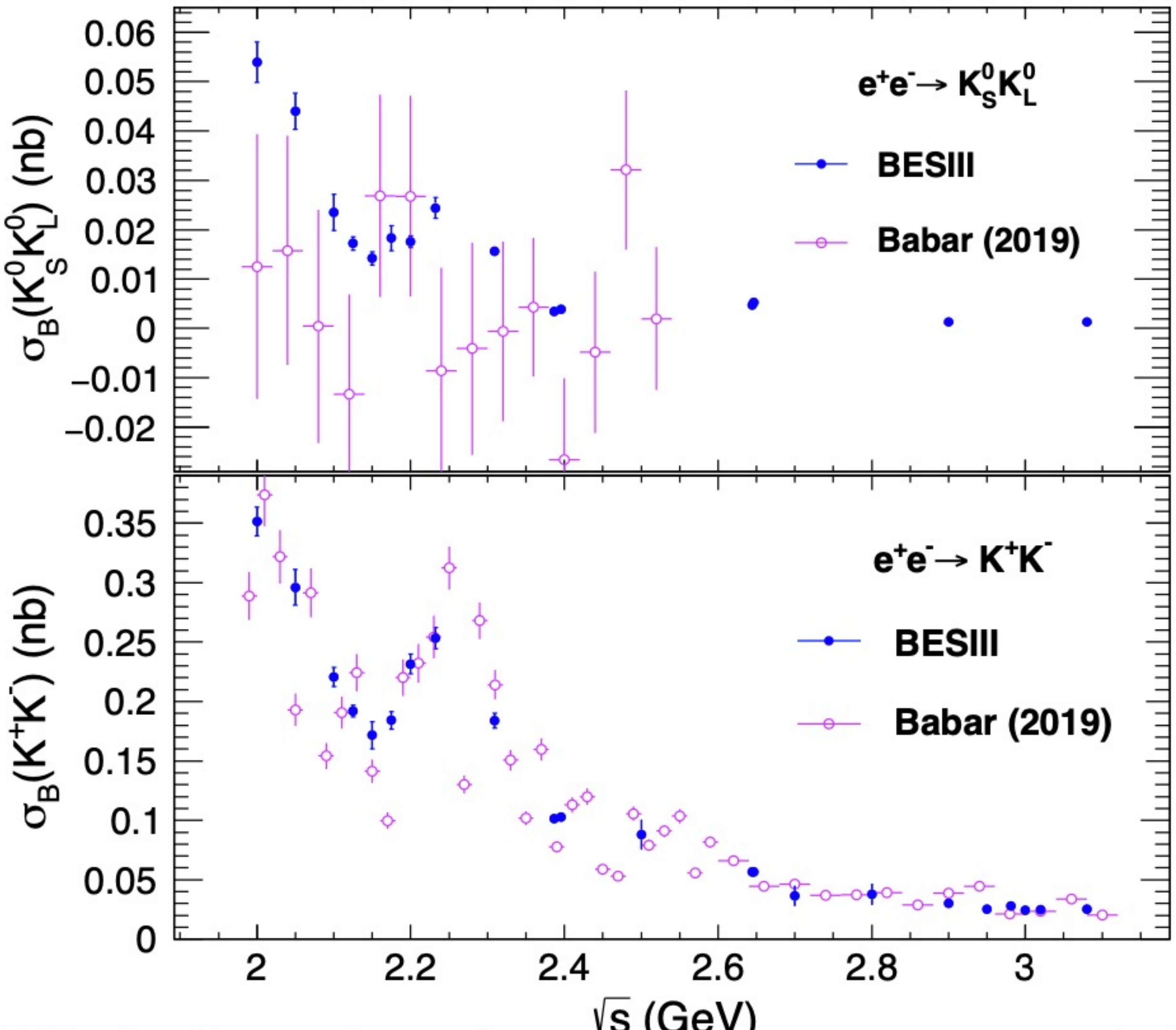


Search exotics in $\chi_{c1} \rightarrow \eta\pi^+\pi^-$





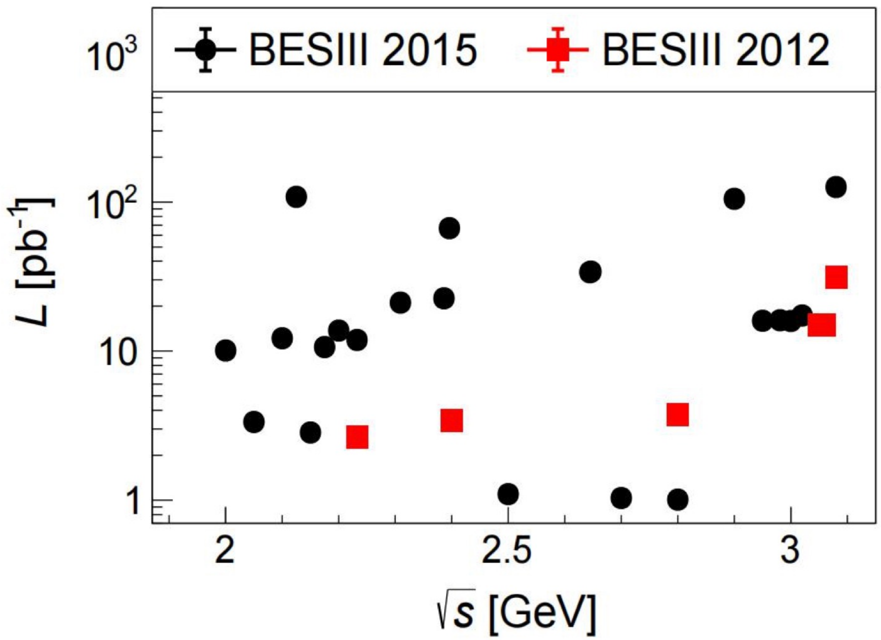
- Clear evidence for $a_2(1700)$ in χ_{c1}decays
- Upper limits for $\pi_1(1^{-+})$ in 1.4 - 2.0 GeV/c^2
- More works in progress in J/ψ and χ_{c1} decays



BESIII work
arXiv:2105.13597

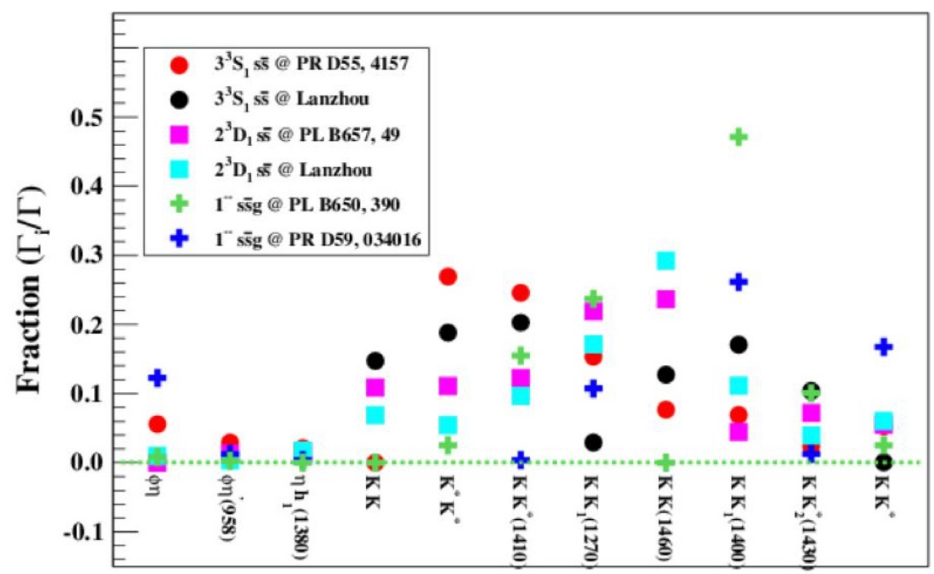
FIG. 5: Comparison of cross-section measurements of the processes $e^+e^- \to K^0_S K^0_L$ (top panel) and $e^+e^- \to K^+K^-$ (bottom panel) by BESIII (filled dots) [13] and BaBar (open circles) [35].

$\phi(2170)$ @ 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

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

PRL **121**, 022001(2018)

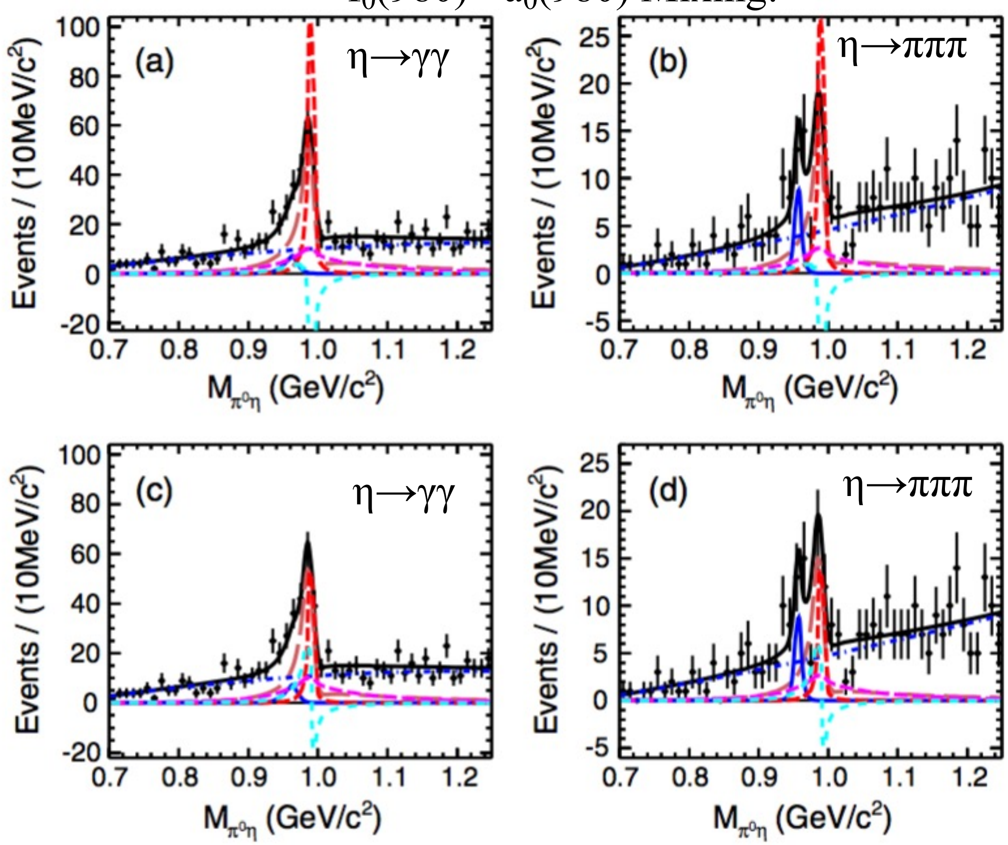
- $a_0(980)$ - $f_0(980)$ still controversial explanation about their nature [$1^-(0^{++})$, $0^+(0^{++})$]
- Direct measure of the $f_0(980)$ - $a_0(980)$ mixing in the process proposed in 1979 [PLB88,367]

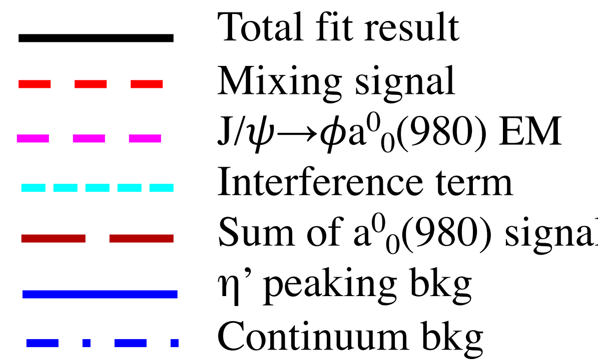
$J/\psi \to \phi f_0(980) \to \phi a^0_0(980) \to \phi\eta\pi^0$ and **$\chi_{c1} \to \pi^0 a^0_0(980) \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-$** (isospin violating decays)

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

Destructive interference

Constructive interference





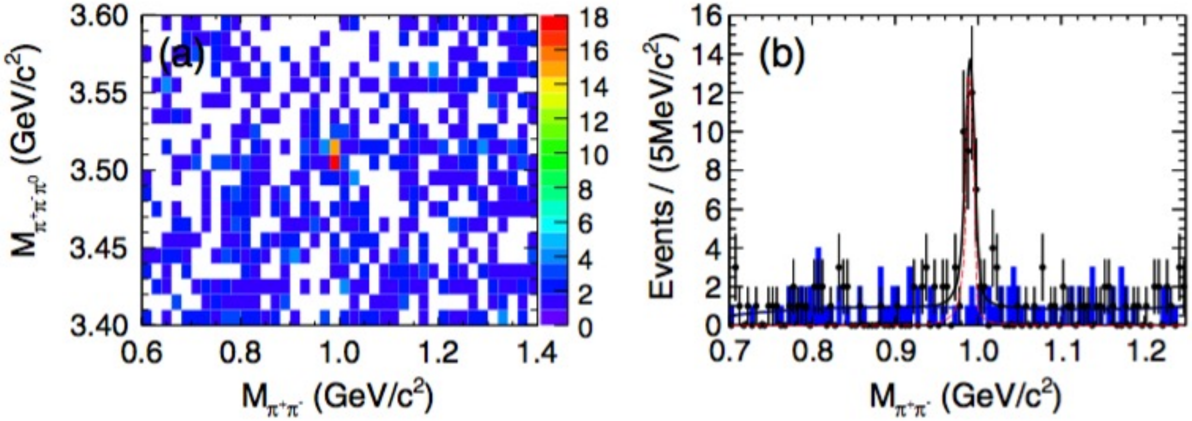
$f_0(980) \to a^0_0(980)$ mixing significance: 7.4σ

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

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

PRL **121**, 022001(2018)

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



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

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