HADRON 2023

20th International Conference on Hadron Spectroscopy and Structure

Light QCD exotics @ BESIII

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On behalf of the BESIII Collaboration

Università degli Studi di Ferrara

INFN Istituto Nazionale di Fisica Nucleare

Genova

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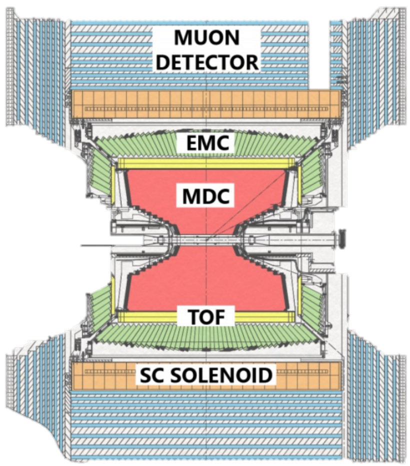
The BESIII experiment @ BEPCII



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

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

BESIII

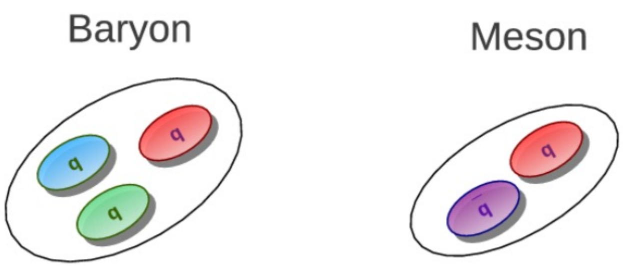
2004: started Beijing Electron Positron Collider II/BESIII construction

- ✓ Double rings
- ✓ Beam energy: 1 - 2.45 GeV
- ✓ Peak luminosity: 1.05×10^{33} cm^{-2}s^{-1} @ $\psi(3770)$ (January 7th, 2023)

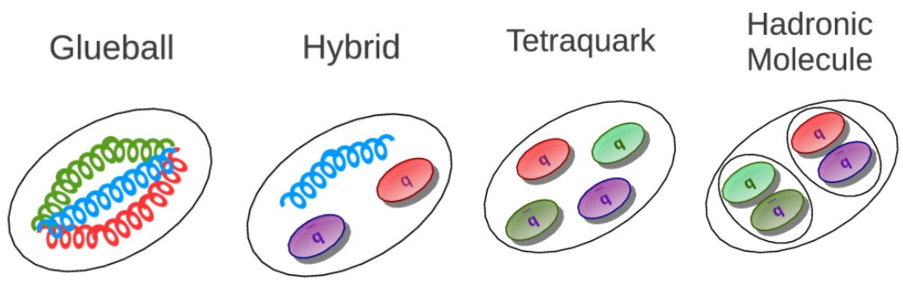
2009 – today: BESIII physics runs

Hadron Spectrum

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



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!!!

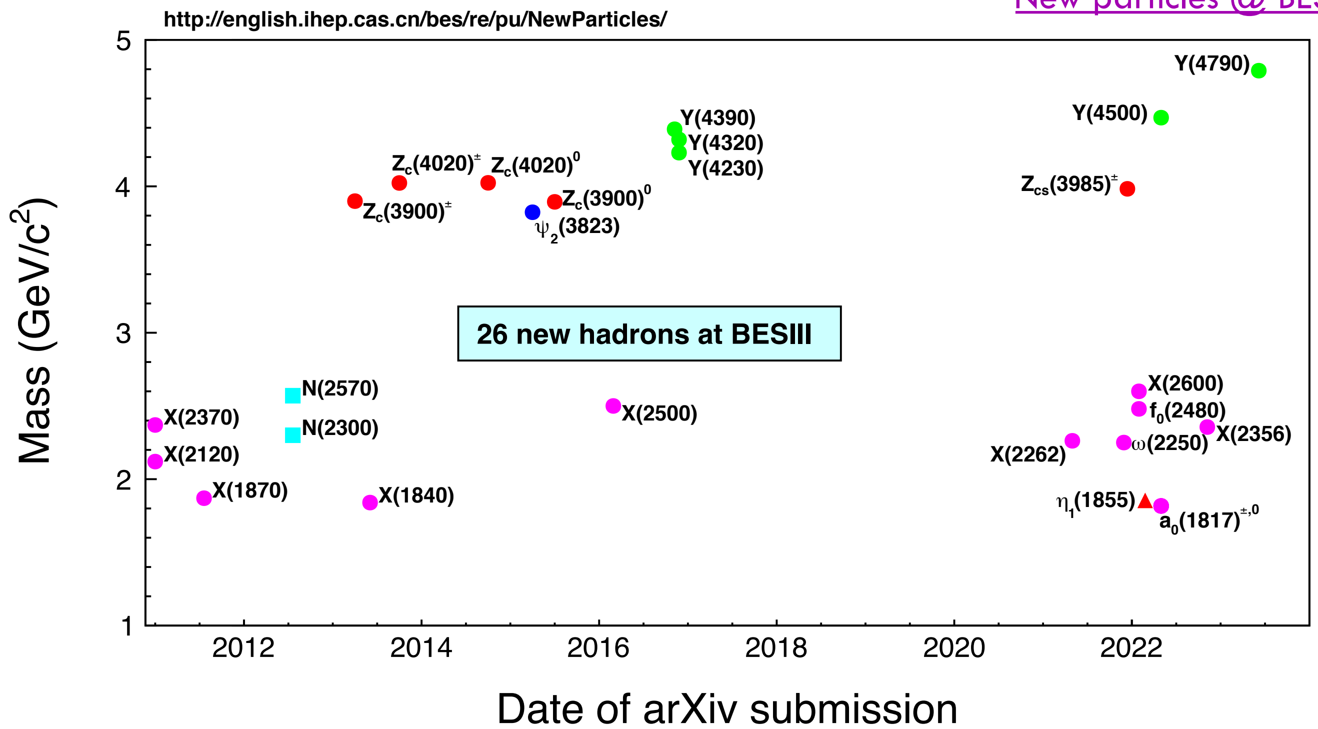
@ BESIII **J/ψ 10.1×10^9**

Light hadron physics

- Meson and baryon spectroscopy
- Glueballs and hybrids
- ….

New discoveries at BESIII

New particles @ BESIII



Manifestly exotic

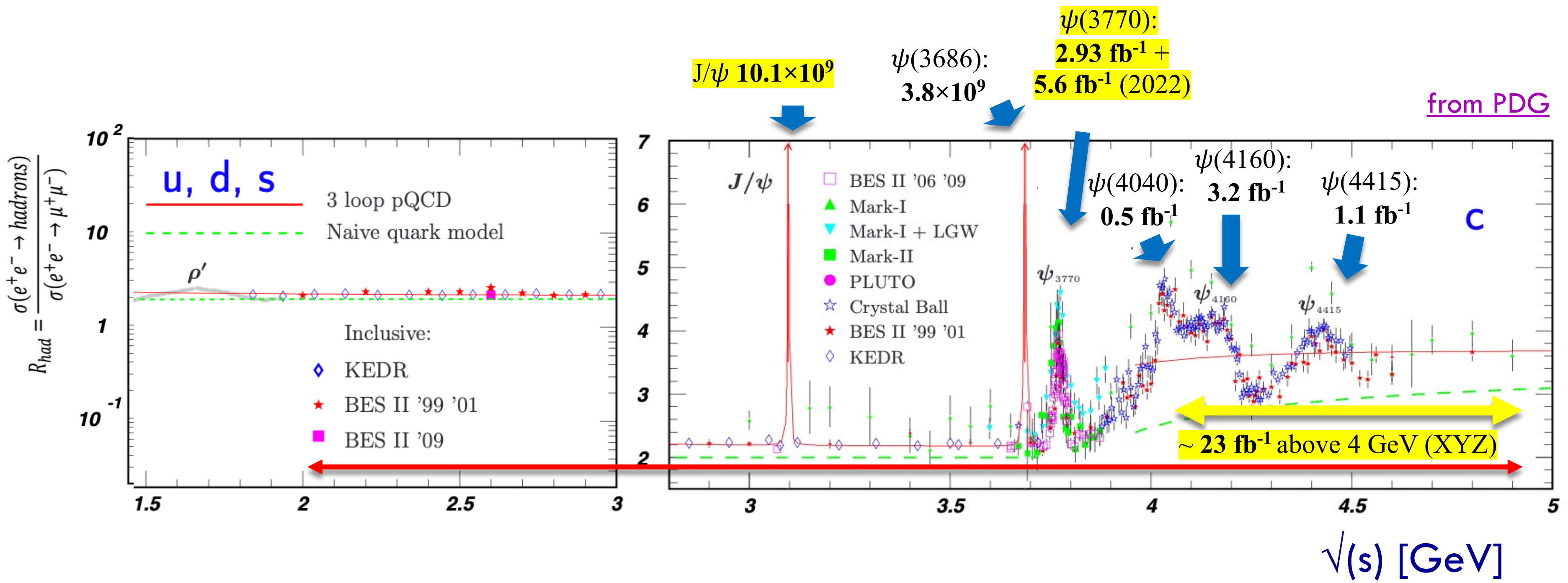
- *Quark contents more than $q\bar{q}$ or qqq*
- *Quantum number J^{PC} not reachable for ordinary mesons or baryons*

'Cryptoexotic' exotic

- *overpopulation of states*
- *mass/width not fitting in spectra*
- *production and/or decay patterns incompatible with standard mesons/baryons*

BESIII dataset and physics program

Optimised for flavour physics in the τ-charm region



- 130 points between 2 and 4.6 GeV (~715 pb^{-1} up to 3.08 GeV for ρ*, ω*, ϕ*,… studies)

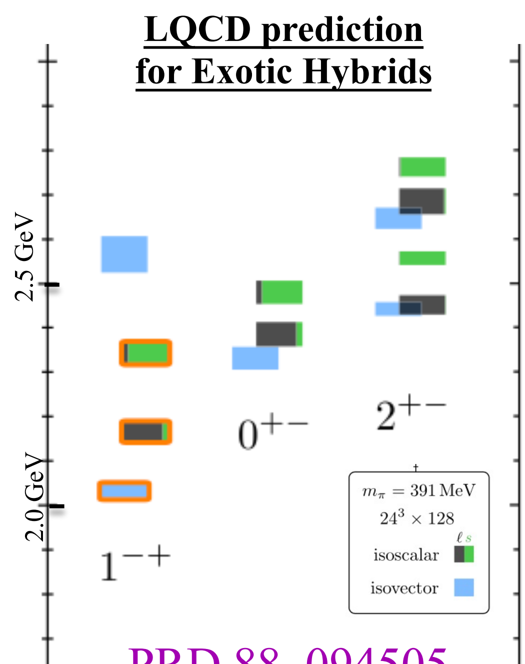
- Light hadron spectroscopy
- η/η' decays
- Hyperon physics
- Charmonium transitions

- D^0D^0pairs
- $D_{(S)}$ meson decays
- $D^*_{(s)}$
- …

- XYZ decays and spectroscopy
- Open charm production
- Charmed baryons
- ...

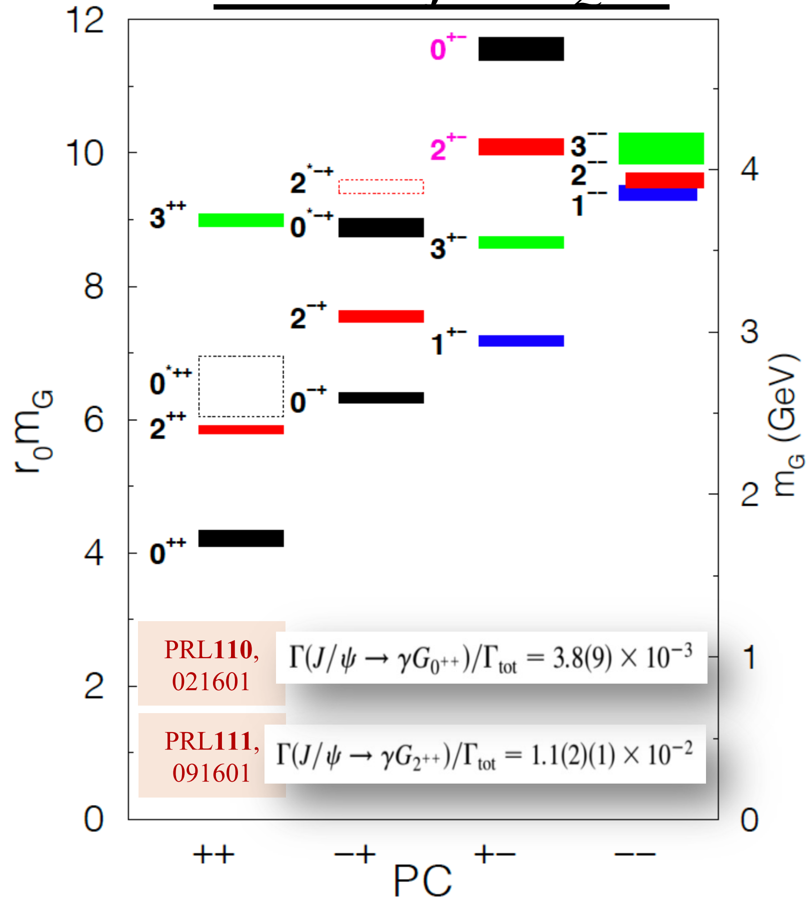
Hunting for glueballs and new forms of hadrons

- Charmonium radiative decays is the ideal laboratory for light glueballs and hybrids hadron studies (clean, high statistics and gluon-rich process)



PRD 88, 094505

Prediction from LQCD



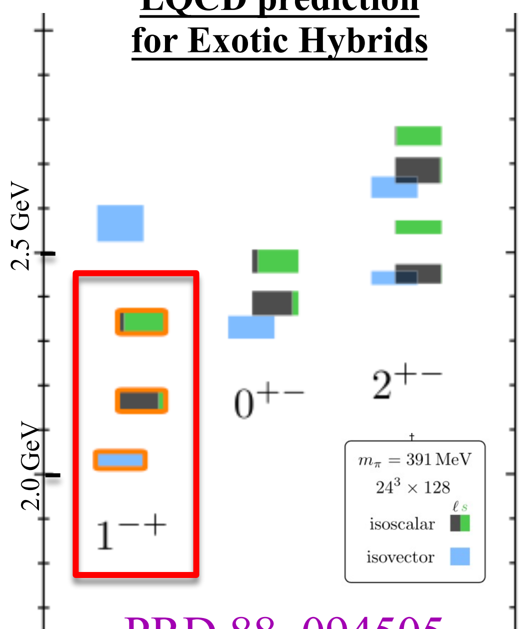
https://doi.org/10.1142/S0218301309012124

Hunting for glueballs and new forms of hadrons

- Charmonium radiative decays is the ideal laboratory for light glueballs and hybrids hadron studies (clean, high statistics and gluon-rich process)

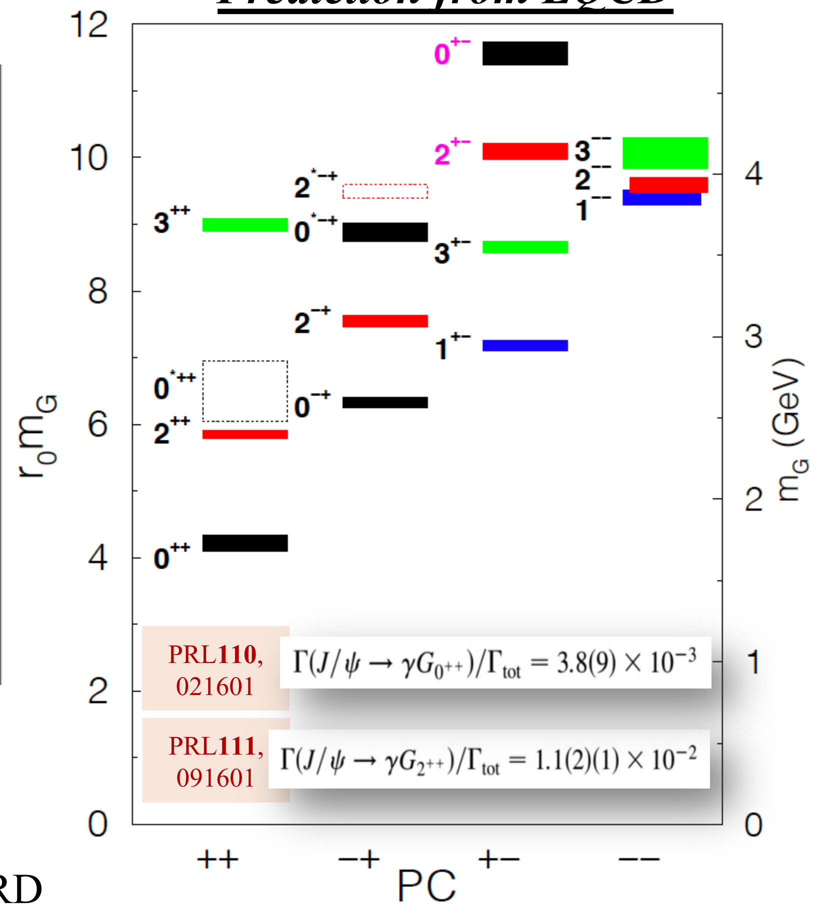
- **Exotic Hybrids**:
  $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$
  (forbidden in the conventional QCD scheme)
- The exotic $J^{PC} = 1^{-+}$ nonet of hybrids is predicted to be the lightest
- Only isovector candidate observed yet: $\pi_1(1400)$, $\pi_1(1600)$ [the most extensively studied], $\pi_1(2015)$

LQCD prediction for Exotic Hybrids



PRD 88, 094505

Prediction from LQCD



https://doi.org/10.1142/S0218301309012124

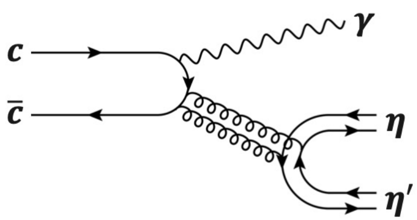
- **Establish the hybrid nonet**:
  - Isoscalar 1^{-+} hybrids can decay to ηη’ in P-wave (PRD 83,014021, PRD 83, 014006, Eur.Phys.J.Plus 135, 945)

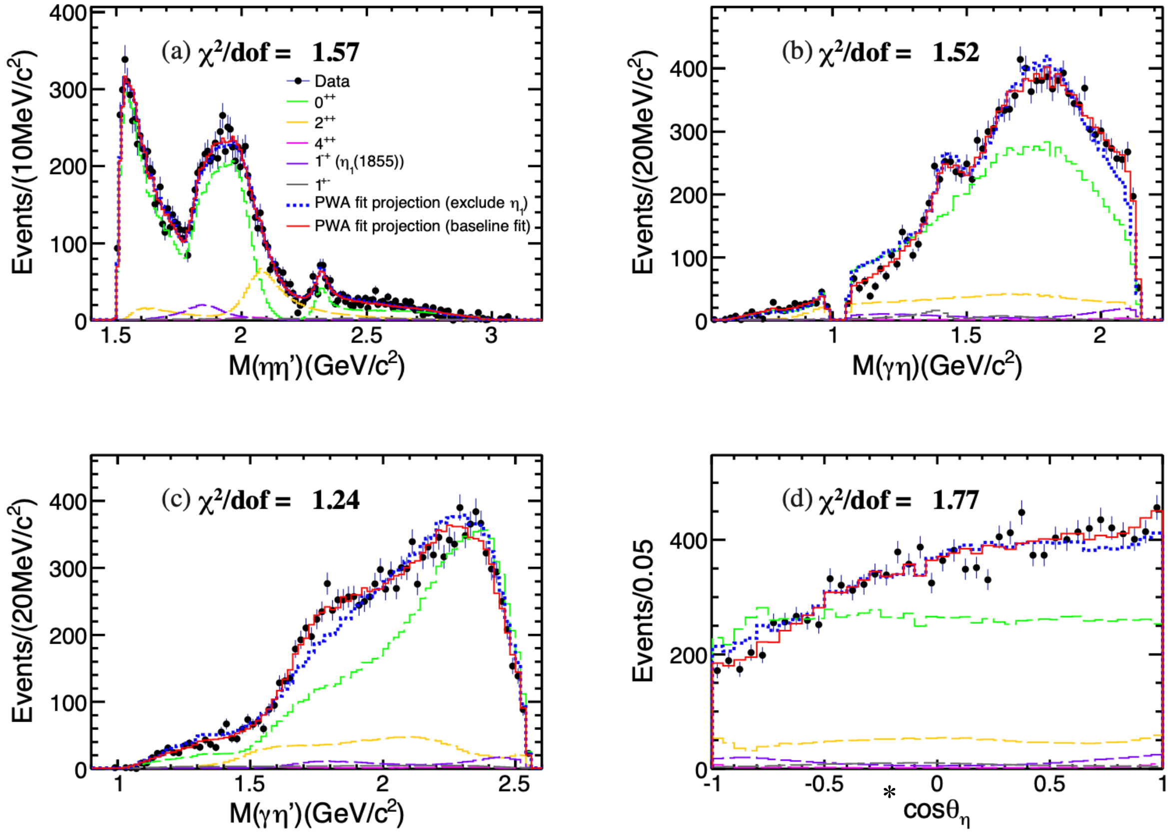
Observation of Exotic Isoscalar State $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$

PRL **129**, 192002 (2022)
PRD **106**,072012 (2022)
PRD **107**,079901 (2023)

PWA of **$J/\psi \to \gamma\eta\eta'$** using 10 Billion of J/ψ data @ BESIII

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





*spin information

- An isoscalar 1^{-+} state, $\eta_1(1855)$, has been observed with statistical significance larger than 19σ
- Mass is consistent with LQCD calculation for the 1^{-+} hybrid (1.7 – 2.1 GeV/c^2)

$$M = (1855 \pm 9^{+6}_{-1})\,\mathrm{MeV}/c^2; \quad \Gamma = (188 \pm 18^{+3}_{-8})\,\mathrm{MeV}$$

$$\mathcal{B}(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$$

see talk by Runqui Ma
5 June 2023 - 16:30

J/ψ radiative decay: PWA status in a nutshell

*lightest glueball candidates

	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) $J/\psi\to\gamma\eta\eta'$ (PRL129,192002) $J/\psi\to\gamma\eta'\eta'$ (PRD105,072002)		
$J/\psi\to\gamma VV$		$J/\psi\to\gamma\omega\phi$ (PRD87,032008) $J/\psi\to\gamma\phi\phi$ (PRD93,112011) $J/\psi\to\gamma\omega\omega$ (PRD100,052012)	
$J/\psi\to\gamma PPP$			$J/\psi\to\gamma\eta'\pi\pi$ (PRL106,072002, noPWA) $J/\psi\to\gamma K_S K_S\eta$ (PRL115,091803) $J/\psi\to\gamma K_S K_S\pi^0$ (JHEP 03,121)

- **$J/\psi\to\gamma PP$: 0^{++}, 2^{++}, …**
- **$J/\psi\to\gamma PPP$, γVV: 0^{-+}**
- Neutral channel is much cleaner than the charged ones

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 (JHEP 03,121 (2023))

Partial Wave Analysis of J/ψ→γη'η'

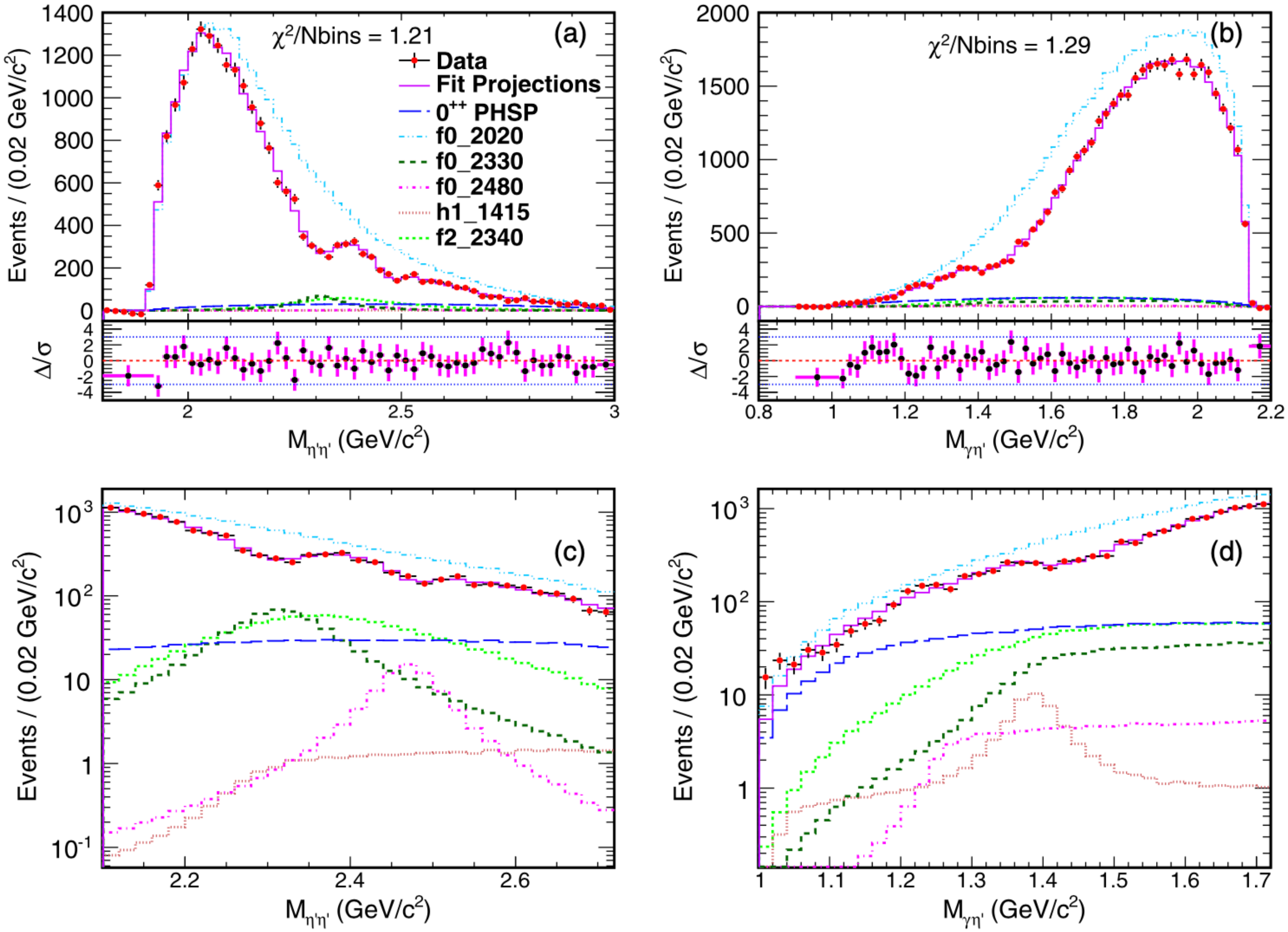
PRD 105, 072002(2022)

PWA of J/ψ→γη'η' using 10 Billion of J/ψ data @ BESIII

- η'→γ$\pi^+\pi^-$/ η$\pi^+\pi^-$ (η→γγ)

- decay width of scalar glueball to η'η' should be comparable to that of scalar glueball to ηη
- more studies of the f_2(2340)

- $J^{PC} = 0^{++}, 2^{++}, 4^{++}$ in η'η'
- $J^{PC} = 1^{+-}, 1^{--}$ in γη'



Partial Wave Analysis of $J/\psi \to \gamma\eta'\eta'$

PRD 105, 072002(2022)

Only component with significance larger than 5σ

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV})$	B.F.	Significance (σ)	
$f_0(2020)$	$1982 \pm 3^{+54}_{-0}$	$436 \pm 4^{+46}_{-49}$	$(2.63 \pm 0.06^{+0.31}_{-0.46}) \times 10^{-4}$	$\gg 25$	Dominant contributions
$f_0(2330)$	$2312 \pm 2^{+10}_{-0}$	$134 \pm 5^{+30}_{-9}$	$(6.09 \pm 0.64^{+4.00}_{-1.68}) \times 10^{-6}$	16.3	
$f_0(2480)$	$2470 \pm 4^{+4}_{-6}$	$75 \pm 9^{+11}_{-8}$	$(8.18 \pm 1.77^{+3.73}_{-2.23}) \times 10^{-7}$	5.2	new 0^{++} state
$h_1(1415)$	$1384 \pm 6^{+9}_{-0}$	$66 \pm 10^{+12}_{-10}$	$(4.69 \pm 0.80^{+0.74}_{-1.82}) \times 10^{-7}$	5.3	
$f_2(2340)$	$2346 \pm 8^{+22}_{-6}$	$332 \pm 14^{+26}_{-12}$	$(8.67 \pm 0.70^{+0.61}_{-1.67}) \times 10^{-6}$	16.1	
0^{++} PHSP	...	...	$(1.17 \pm 0.23^{+4.09}_{-0.70}) \times 10^{-5}$	15.7	

- $f_0(2020)$, $f_0(2330)$ and $f_2(2340)$ observed in η'η' decay mode for the first time
- $f_0(2480)$: new 0^{++} state observed

$f_0(2020)$:

- production compatible with that of $f_0(2100)$ in $J/\psi \to \gamma\eta\eta$ [PRD87, 092009(2013)] and $f_0(2200)$ in $J/\psi \to \gamma K_S^0 K_S^0$ [PRD98, 072003(2018)]
  - its large production rate in radiative J/ψ decay suggest a large overlap with scalar glueball
  - consistent with previous analysis results, but its mass is lower than the mass of the first excitation of scalar glueball from the LQCD prediction (Phys. Lett. B 309, 378, Phys. Rev. D 60, 034509)

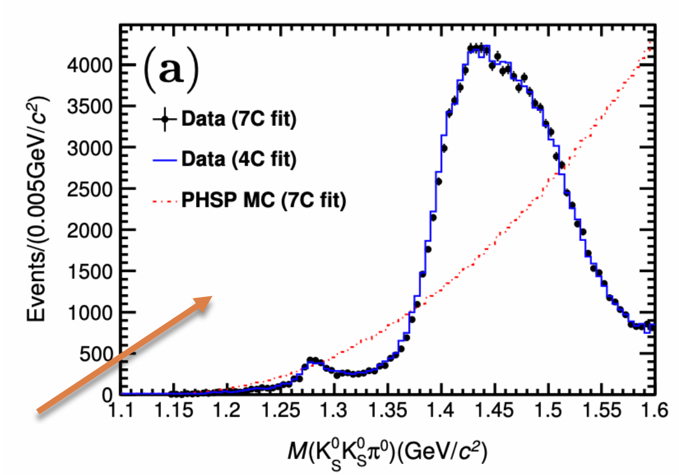
Partial Wave Analysis of $J/\psi \to \gamma K^0_S K^0_S \pi^0$

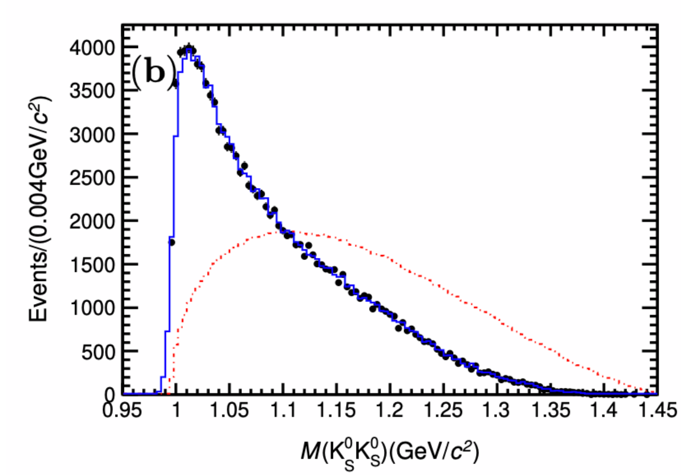
JHEP03(2023)121

10 Billion of J/ψ data @ BESIII

- $K^0_S \to \pi^+\pi^-$; $\pi^0 \to \gamma\gamma$
- $M(K^0_S K^0_S \pi^0) < 1.6$ GeV/c^2

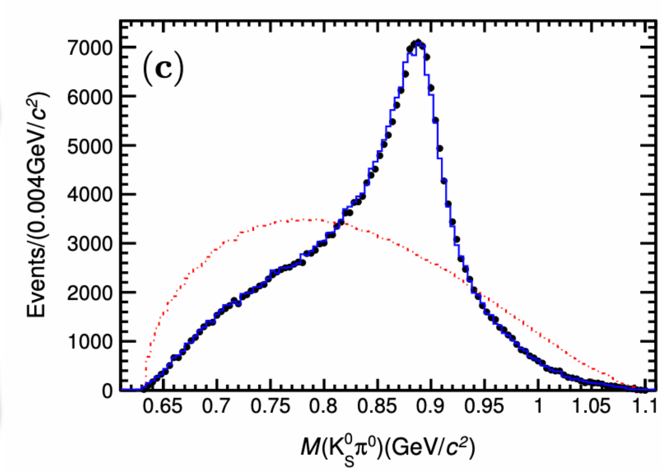
- Study of $\eta(1405)/\eta(1475)$
- Prominent structure around 1.45 GeV/c^2 and clear bump around 1.28 GeV/c^2





Mass Dependent PWA:
extract the resonance parameters of the intermediate states

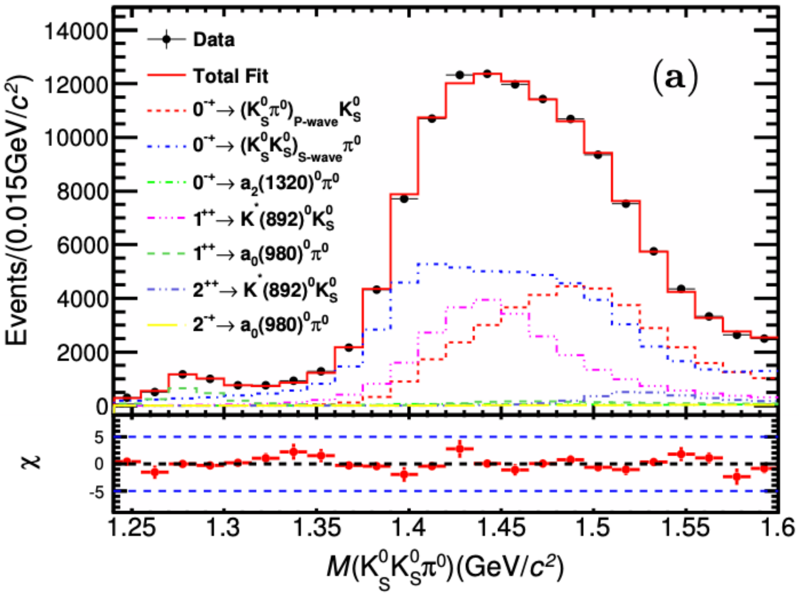
Mass Independent PWA:
explore the lineshape of $K^0_S K^0_S \pi^0$ invariant mass for the different decay modes, and minimize bias from model dynamics of the intermediate states



$J/\psi \to \gamma K^0_S K^0_S \pi^0$ - Mass Dependent PWA

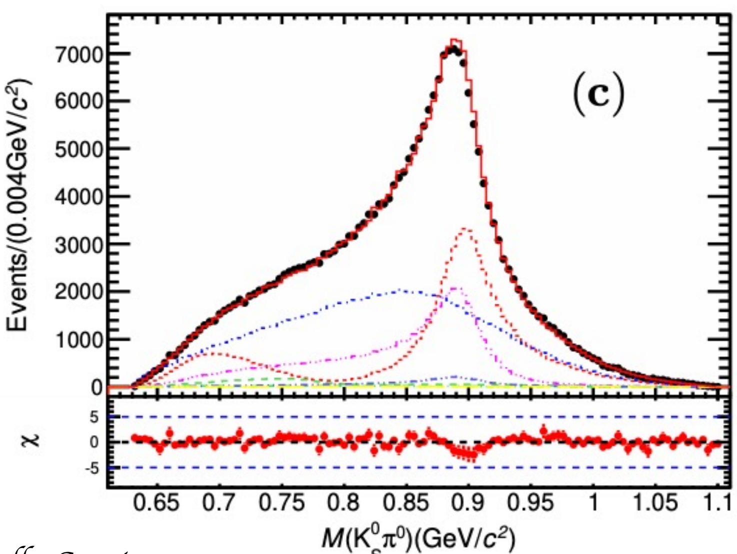
* full table link

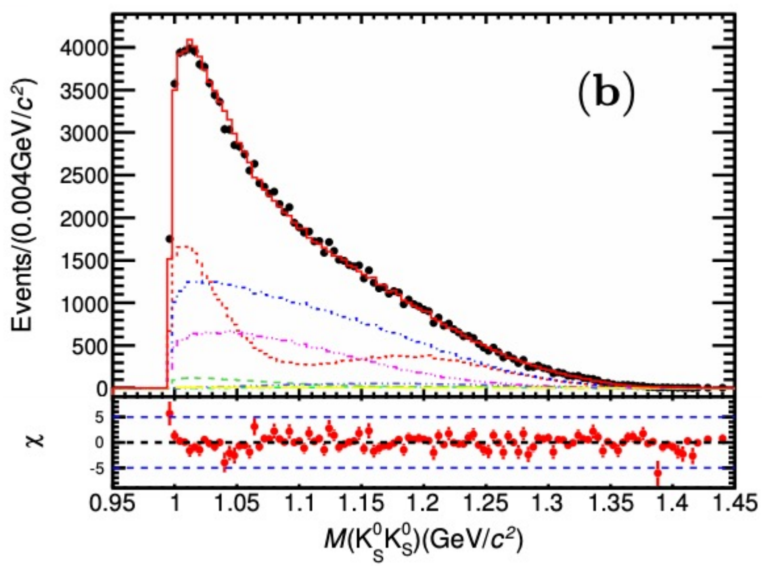
JHEP03(2023)121



- Masses and widths of intermediate states from J/ψ radiative decay are floating in the fit (all the other resonances fixed)
- 0^{-+} component: two isoscalar states using relativistic BW model

Resonance	M(MeV/c^2)	Γ(MeV)
$\eta(1405)$	$1391.7 \pm 0.7^{+11.3}_{-0.3}$	$60.8 \pm 1.2^{+5.5}_{-12.0}$
$\eta(1475)$	$1507.6 \pm 1.6^{+15.5}_{-32.2}$	$115.8 \pm 2.4^{+14.8}_{-10.9}$
$f_1(1285)$	$1280.2 \pm 0.6^{+1.2}_{-1.5}$	$28.2 \pm 1.1^{+5.5}_{-2.9}$
$f_1(1420)$	$1433.5 \pm 1.1^{+27.9}_{-0.7}$	$95.9 \pm 2.3^{+13.6}_{-10.9}$
$f_2(1525)$	$1515.4 \pm 2.5^{+3.2}_{-7.6}$	$64.0 \pm 4.3^{+2.0}_{-6.1}$



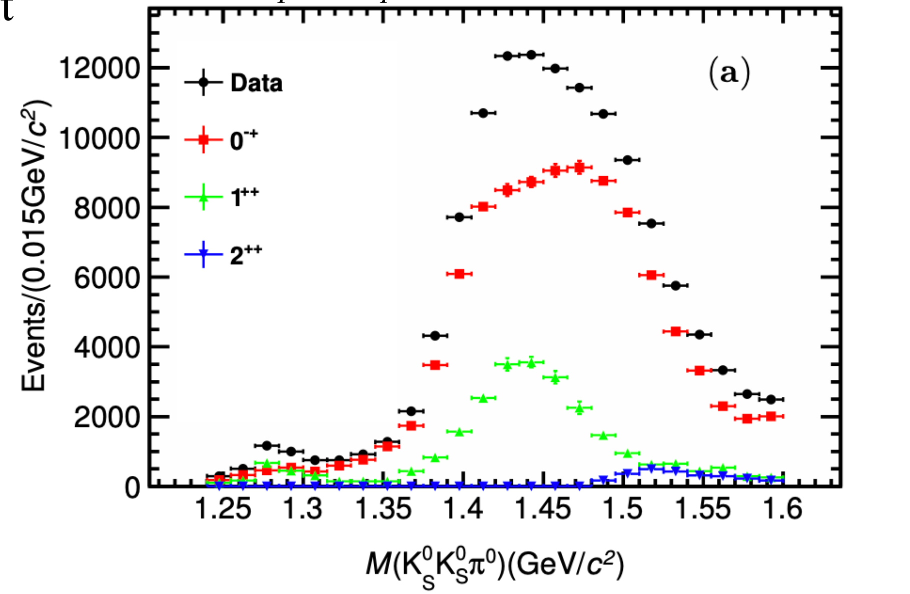


$J/\psi \to \gamma K^0_S K^0_S \pi^0$ - Mass Independent PWA

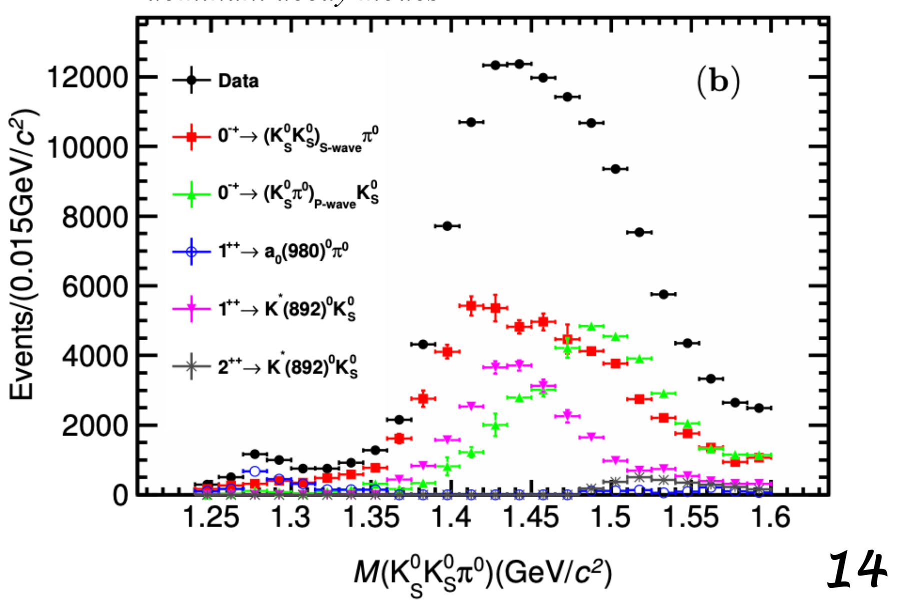
JHEP03(2023)121

- Mass independent fit by scanning the invariant $K^0_S K^0_S \pi^0$ mass
  - identification of the strongest waves
- The pseudoscalar component is the dominant contribution
  - relatively constant around 1.4 GeV/c^2
  - $(K^0_S K^0_S)_{S\text{-wave}}\pi^0$ and $(K^0_S \pi^0)_{P\text{-wave}} K^0_S$ partial waves are of comparable magnitude, but with different lineshape and peaks
  - two resonances parameterization needed
  - Triangle Singularity Mechanism cannot describe data well

dominant spin components



dominant decay modes



$J/\psi \to \gamma K^0_S K^0_S \pi^0$ - Mass Independent PWA

JHEP03(2023)121

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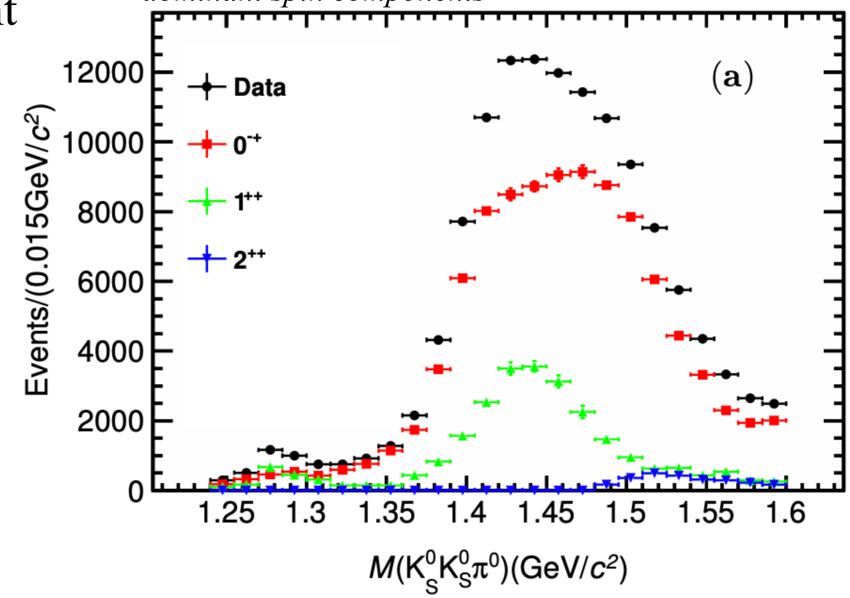
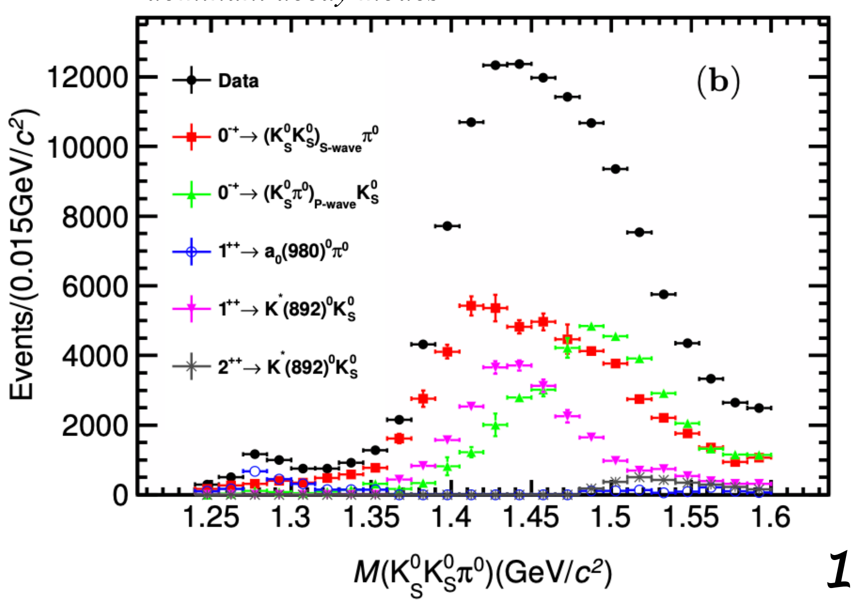
  - two resonances parameterization needed
  - Triangle Singularity Mechanism cannot describe data well
- Axial vector component peaking at 1.28 GeV/c^2 and 1.42 GeV/c^2
- Tensor component around 1.52 GeV/c^2 decaying into $K^*(892)^0 K^0_S$ observed for the first time
- Consistency between MI and MD results

dominant spin components

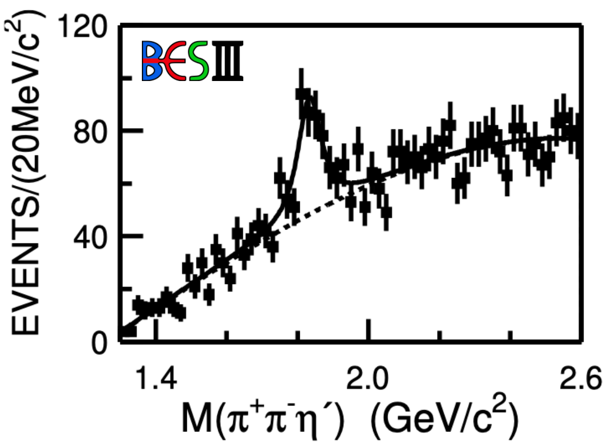


dominant decay modes



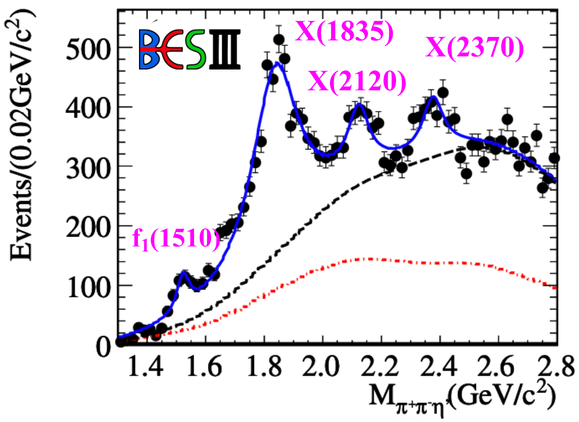
X states observed in the $J/\psi \to \gamma\pi^+\pi^-\eta'$ decay

PRL 95, 262001 (2005)



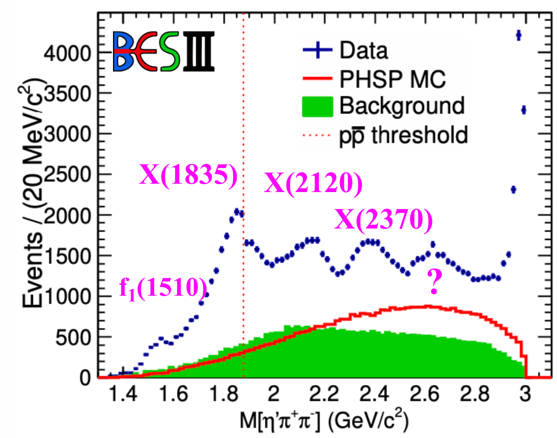
58×10^6 J/ψ events

PRL 106, 072002 (2011)



225.2×10^6 J/ψ events

PRL 117, 042002 (2016)

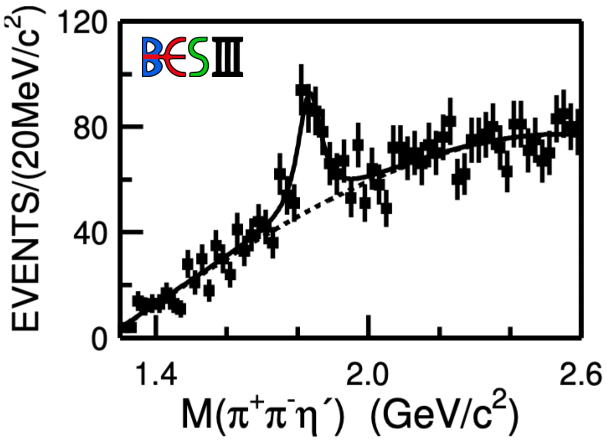


1090×10^6 J/ψ events

- Structure just at or below $p\bar{p}$ threshold: X(1835)
  - Non-trivial lineshape: try to fit with Flatté or sum of interfering BWs

X states observed in the $J/\psi \to \gamma\pi^+\pi^-\eta'$ decay

PRL 95, 262001 (2005)



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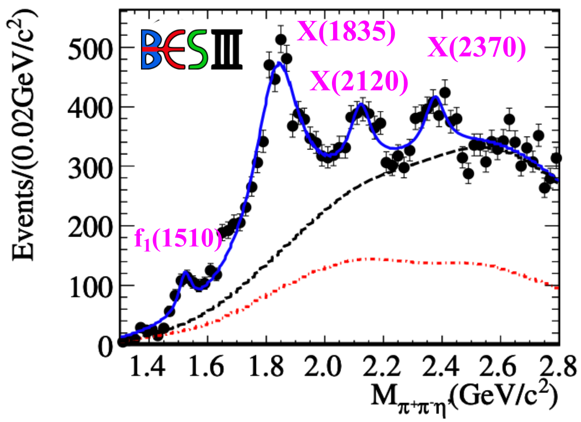
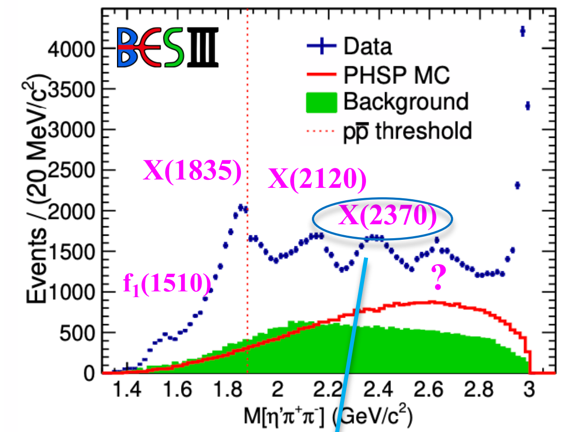
PRL 106, 072002 (2011)



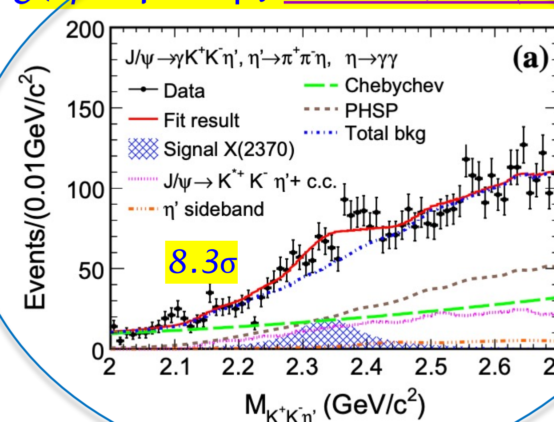
225.2×10^6 J/ψ events

PRL 117, 042002 (2016)



1090×10^6 J/ψ events

$J/\psi \to \gamma KK\eta'$, EPJC80, 746(2020)

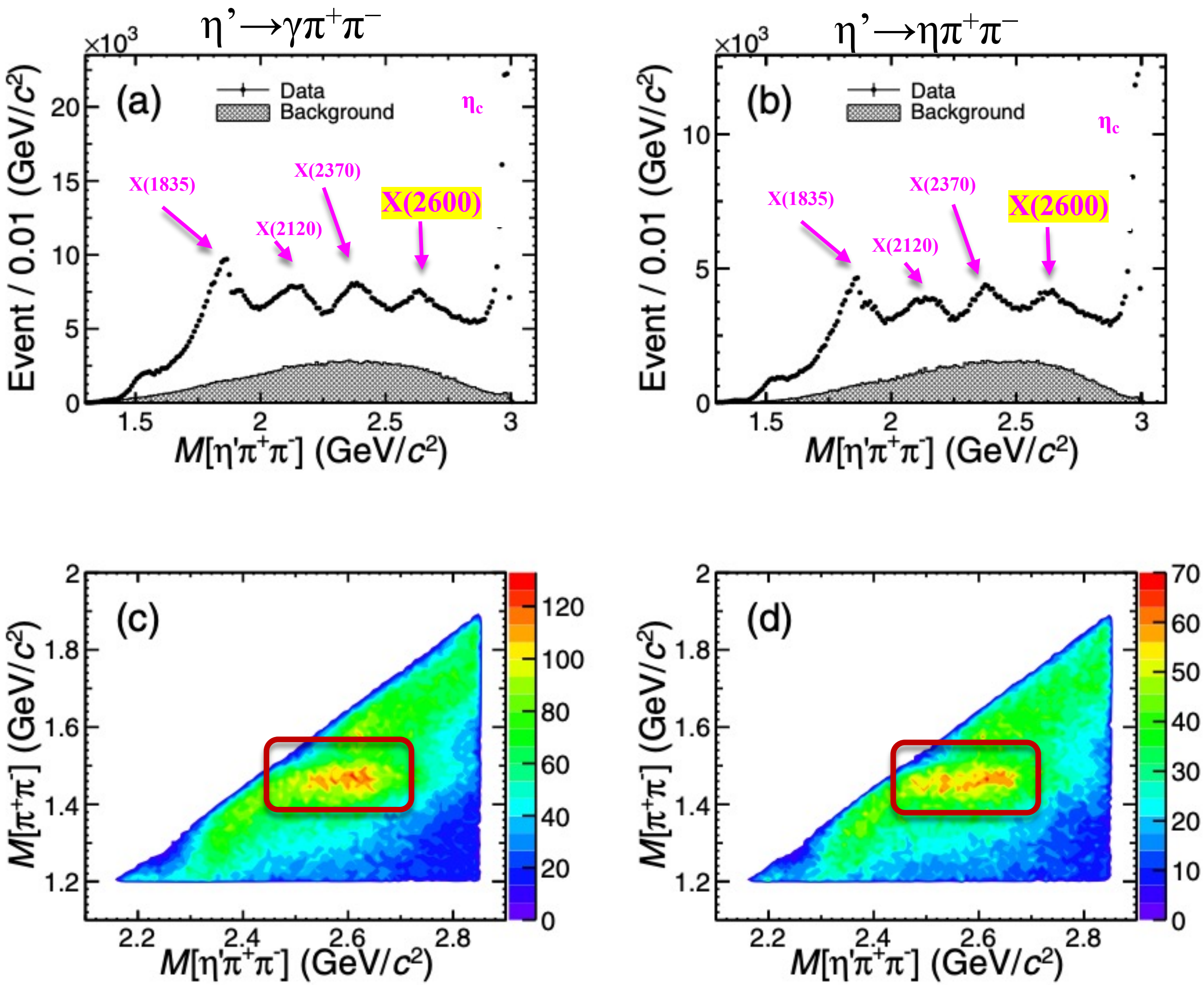


- Structure just at or below $p\bar{p}$ threshold: X(1835)
  - Non-trivial lineshape: try to fit with Flatté or sum of interfering BWs
- Additional structures: X(2120), X(2370), ?

X(2600): A New State Observed in $J/\psi \to \gamma \pi^+ \pi^- \eta'$

10 Billion of J/ψ data @ BESIII ($\eta' \to \gamma \pi^+ \pi^- / \eta \pi^+ \pi^-$)

PRL 129, 042001 (2022)



A new state in $M(\eta' \pi^+ \pi^-)$ invariant mass is observed around 2.6 GeV/c^2, which is correlated to a structure in $M(\pi^+ \pi^-)$ @ 1.5 GeV/c^2

$X(2600)$: A New State Observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$

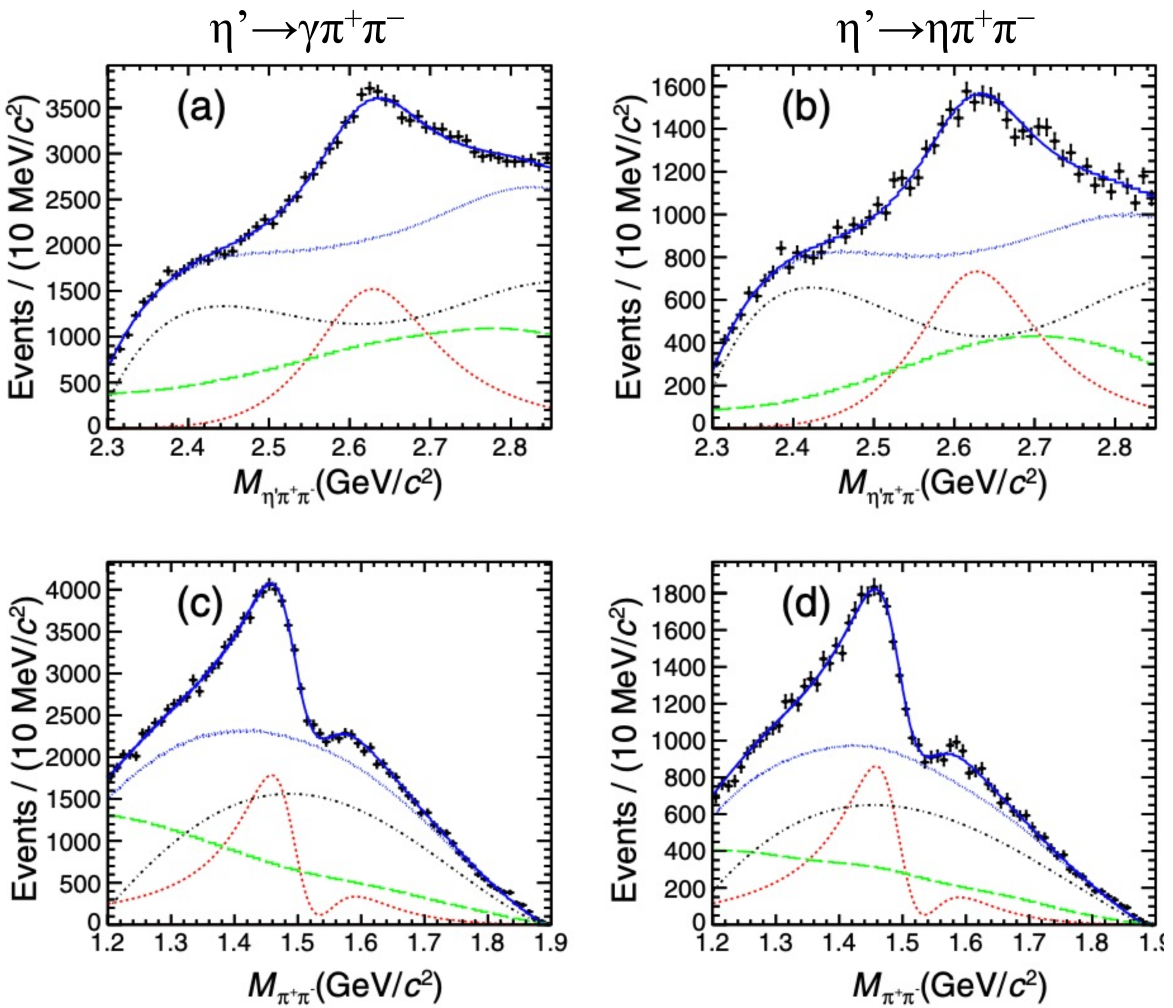
PRL 129, 042001 (2022)

- Simultaneous fit to $\eta'\pi^+\pi^-$ and $\pi^+\pi^-$ mass spectra is performed

Resonance	Mass (MeV/c^2)	Width (MeV)
$f_0(1500)$	$1492.5 \pm 3.6^{+2.4}_{-20.5}$	$107 \pm 9^{+21}_{-7}$
$X(1540)$	$1540.2 \pm 7.0^{+36.3}_{-6.1}$	$157 \pm 19^{+11}_{-77}$
$X(2600)$	$2618.3 \pm 2.0^{+16.3}_{-1.4}$	$195 \pm 5^{+26}_{-17}$

- X(2600) resonance observed for the first time with a statistical significance greater than 20σ

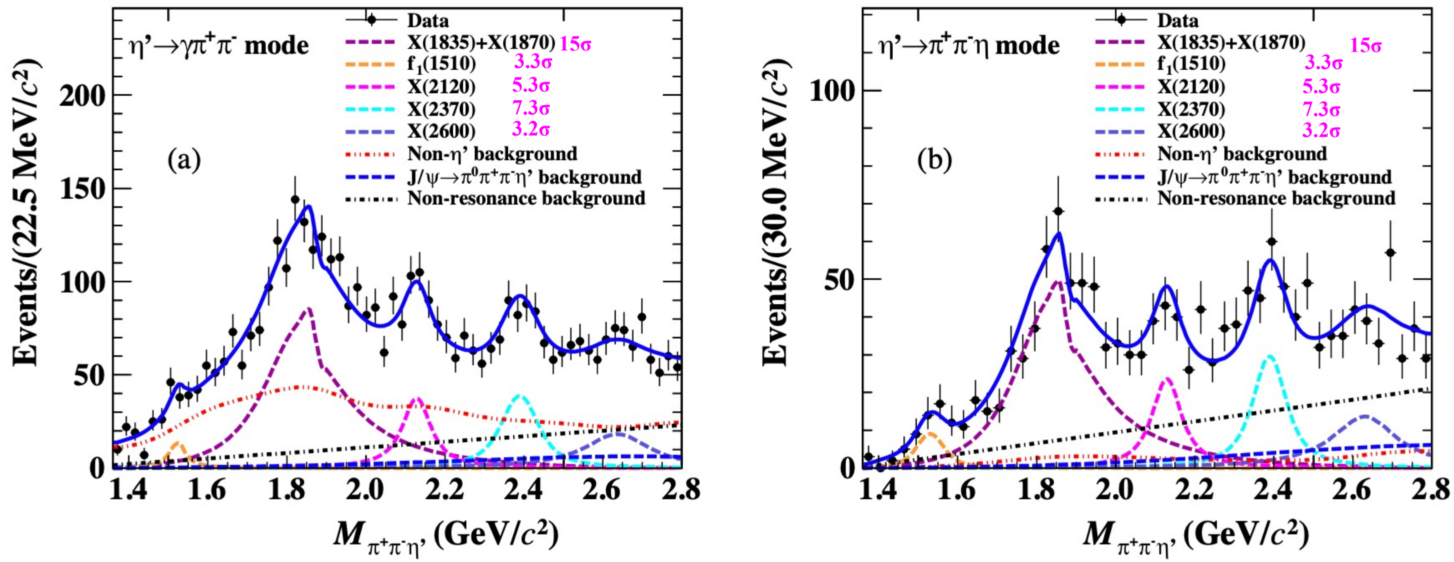
- The structure in $M(\pi^+\pi^-)$ around 1.5 GeV/c^2 can be well described with the interference between $f_0(1500)$ and the X(1540) resonances



Observation of X(1835), X(2120), X(2370) in J/ψ EM Dalitz Decays

10 Billion of J/ψ data @ BESIII

PRL 129, 022002



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

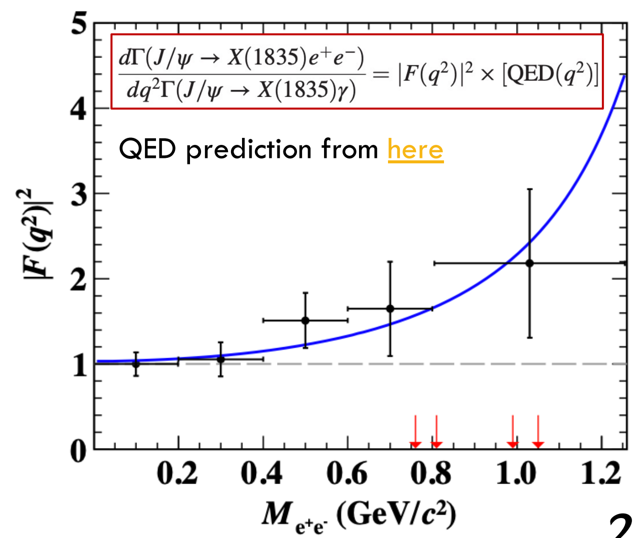
Confirmation of X(1835), X(2120) and X(2370) observed in J/ ψ radiative decays

Access to the EM transition form factor between J/ ψ and X(1835) states

- Additional information on the internal structure of X(1835)

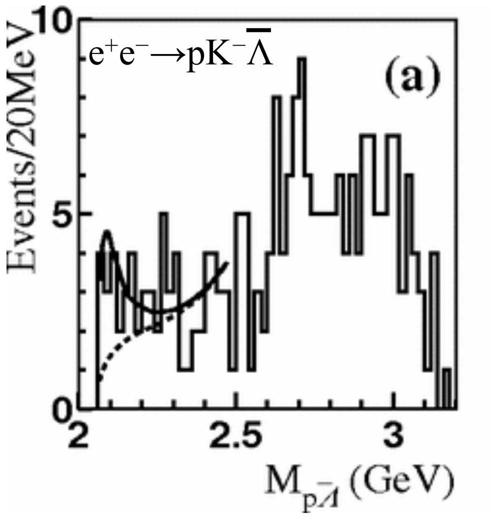
$$F(q^2) = \frac{1}{1 - q^2/\Lambda^2}$$

$$\Lambda = 1.75 \pm 0.29 \pm 0.05\ GeV/c^2$$

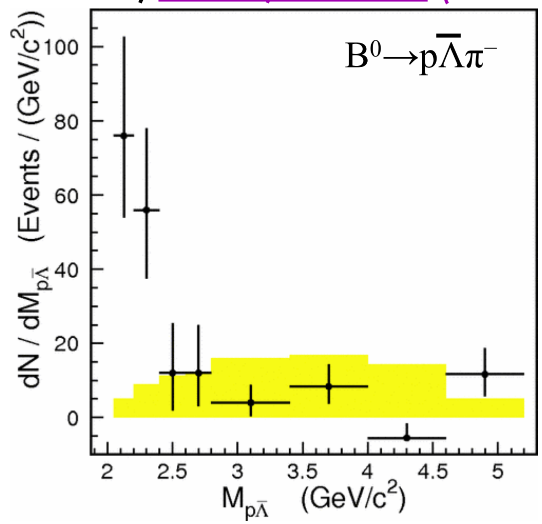


$e^+e^-\to pK^-\bar{\Lambda}$: narrow structure in $p\bar{\Lambda}$ system

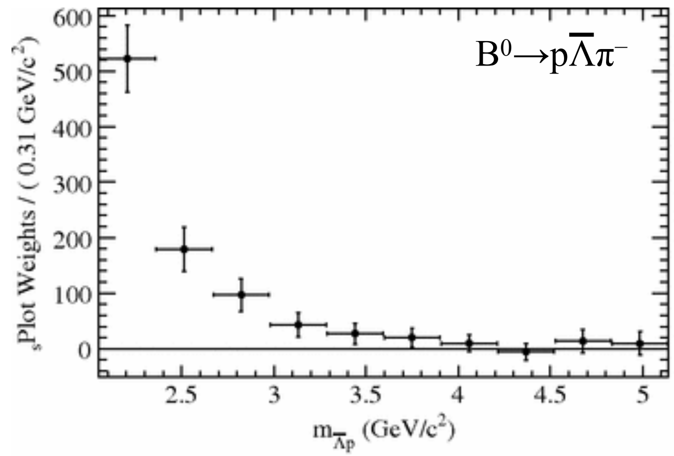
BES, PRL93, 112002 (2004)



BELLE, PRL90, 201802 (2003)



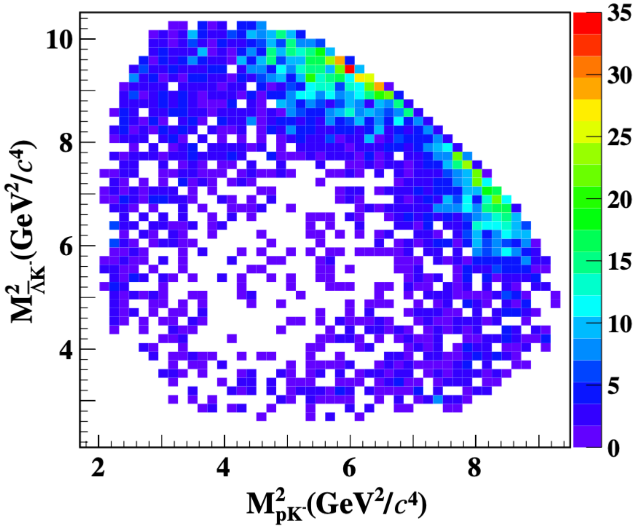
BaBar, PRD79, 112009 (2009)



- Evidence of a structure in the $p\bar{\Lambda}$ system reported in several decays of B mesons and charmonium states
- Different scenarios investigated: baryonium state [PRD74,014029], barion-antibaryon SU(3) nonets [PLB626,95], final state interaction [IJMPA22,5401], …
- @ BESIII: observation of a narrow structure near the $p\bar{\Lambda}$ mass threshold, named **X(2085)**, in the $e^+e^-\to pK^-\bar{\Lambda}$ at 6 different center of mass energies between 4.008 GeV to 4.682 GeV ArXiv:2303.01989

$e^+e^-\to pK^-\bar{\Lambda}$: PWA results

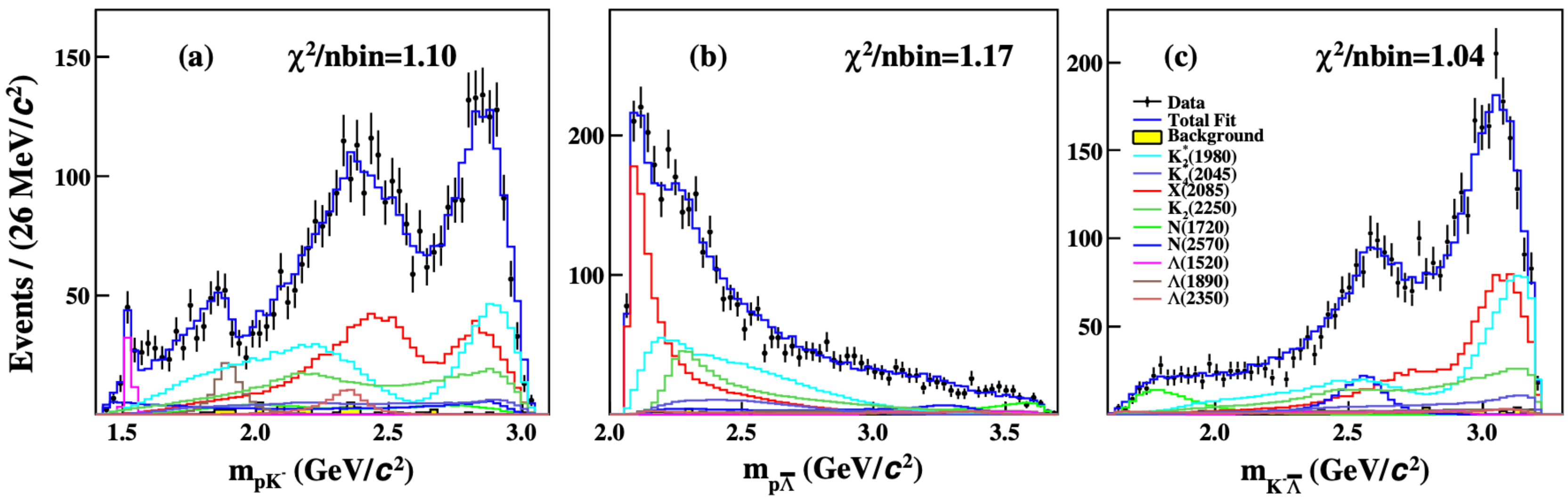
ArXiv:2303.01989



- Significant near threshold enhancement in the $p\bar{\Lambda}$
- X(2085):
  - observed with statistical significance > 20σ
  - $J^P = 1^+$ with statistical significance > 5σ over other quantum number

$$M_{pole} = (2086 \pm 4 \pm 6)\ \mathrm{MeV} \quad \Gamma_{\mathrm{pole}} = (56 \pm 5 \pm 16)\ \mathrm{MeV}$$

- No matching with any state predicted by the potential model + narrow width ➔ exotic properties of X(2085)
- Same structure as in PRL93, 112002 ?



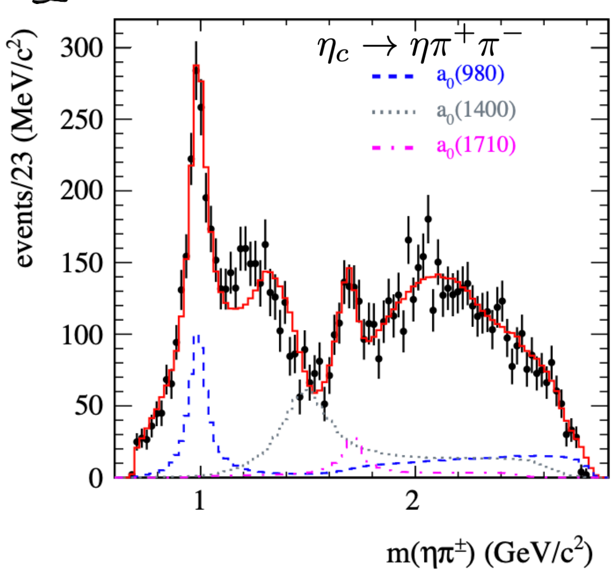
Light hadrons in open-charm decays

Ground state
- $f_0(500)$, $f_0(980)$: 0++, I = 0
- $a_0(980)$: 0++, I = 1

Radially excited states
- $f_0(1370)$, $f_0(1500)$
- $a_0(1450)$

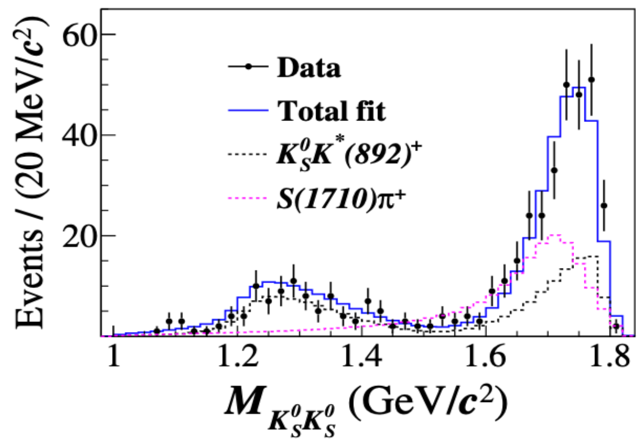
Higher set of excitations
- $f_0(1710)$, $f_0(1770)$
- $a_0(1710)/a_0(1817)$???

BABAR PRD104, 072002 (2021)



$$m(a_0(1700)) = 1704 \pm 5_{\rm stat} \pm 2_{\rm sys}\ {\rm MeV}/c^2,$$
$$\Gamma(a_0(1700)) = 110 \pm 15_{\rm stat} \pm 11_{\rm sys}\ {\rm MeV}/c^2.$$

$D_s^+ \to K_S^0 K_S^0 \pi^+$



BESIII PRD105, L051103 (2022)

$$\mathcal{B}(D_s^+ \to S(980)\pi^+) < 1.8 \times 10^{-4}$$
@ 90% CL

suppression attributed to the destructive int. between $a_0(980)$ and $f_0(980)$

$$\mathcal{B}(D_s^+ \to S(1710)\pi^+) = (0.31 \pm 0.03 \pm 0.01)\%$$

One order of magnitude larger than the expectation ➔ existence of isospin partner of $f_0(1710)$ ➔ constructive int.

Light hadrons in open-charm decays

6.32 fb^{-1} between 4.178 and 4.226 GeV

PRL129, 182001 (2022)

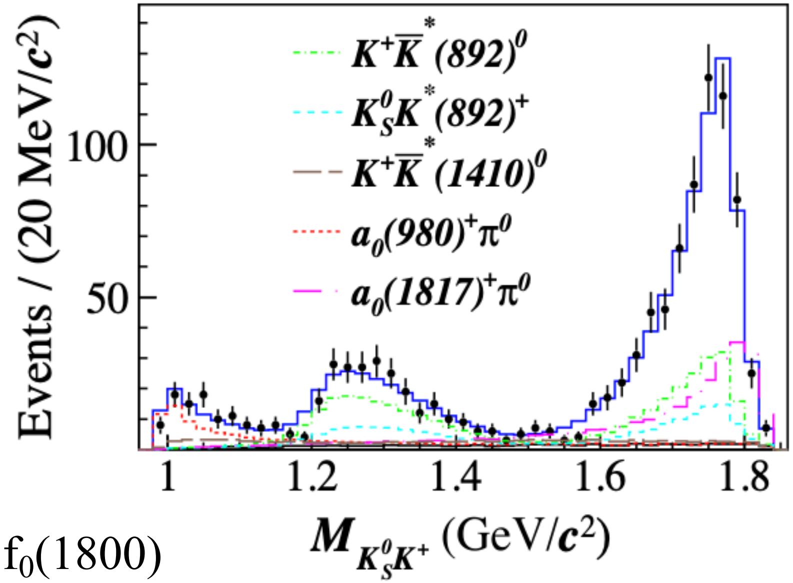
➢ Amplitude analysis of Cabibbo-favored $D_s^+ \to K^0_S K^+ \pi^0$

➢ Together with $D_s^+ \to K^0_S K^0_S \pi^+$ BESIII analysis, this result support the existence of a new a_0 triplet

➢ BF of $D_s^+ \to a_0^+ \pi^0$ with $a_0^+ \to K^0_S K^+$ is roughly consistent with the prediction EPJC **82**, 225(2022)

➢ $m(a_0)$ about 100 MeV/c^2 greater than the expectation for $a_0(1710)$

$$m(a_0) = (1.817 \pm 0.008 \pm 0.020)\ \mathrm{GeV/c^2}$$
$$\Gamma(a_0) = (0.097 \pm 0.022 \pm 0.015)\ \mathrm{GeV/c^2}$$



➢ $a_0(1817)$ could be the isospin one partner of the $f_0(1800)$ [X(1812) in PRD105, 114014(2022)]

➢ the possibility of the $f_0(1710)$ as the scalar glueball cannot be excluded

Amplitude	Phase (rad)	FF (%)	BF (10^{-3})	σ
$D_s^+ \to \bar{K}^*(892)^0 K^+$	0.0 (fixed)	$32.7 \pm 2.2 \pm 1.9$	$4.77 \pm 0.38 \pm 0.32$	> 10
$D_s^+ \to K^*(892)^+ K^0_S$	$-0.16 \pm 0.12 \pm 0.11$	$13.9 \pm 1.7 \pm 1.3$	$2.03 \pm 0.26 \pm 0.20$	> 10
$D_s^+ \to a_0(980)^+ \pi^0$	$-0.97 \pm 0.27 \pm 0.25$	$7.7 \pm 1.7 \pm 1.8$	$1.12 \pm 0.25 \pm 0.27$	6.7
$D_s^+ \to \bar{K}^*(1410)^0 K^+$	$0.17 \pm 0.15 \pm 0.08$	$6.0 \pm 1.4 \pm 1.3$	$0.88 \pm 0.21 \pm 0.19$	7.6
$D_s^+ \to a_0(1817)^+ \pi^0$	$-2.55 \pm 0.21 \pm 0.07$	$23.6 \pm 3.4 \pm 2.0$	$3.44 \pm 0.52 \pm 0.32$	> 10

Conclusions

BESIII experiment is an excellent laboratory to study light hadron physics and search for light QCD exotic states

- BESIII is taking data since 2008. It will continue to run ~2030
- Selection of latest physics results on light exotic states are presented
  - J/ψ radiative PWA
    - $\eta_1(1855)$: first observation of exotic isoscalar 1^{-+} resonance in $J/\psi \to \gamma\eta\eta'$ [PRL **129**, 192002 (2022)]
      - new results on $f_0(1500)$; f0(1710) has a large overlap with the ground state scalar glueball
    - $J/\psi \to \gamma\eta'\eta'$: $f_0(2020)$, $f_0(2330)$ and $f_2(2340)$ observed in $\eta'\eta'$ decay mode for the first time [PRD 105, 072002(2022)]
      - $f_2(2340)$ as tensor glueball candidate
    - $\eta(1405)/\eta(1475)$ puzzle: $J/\psi \to \gamma K^0_S K^0_S \pi^0$ [JHEP03(2023)121]
      - sizable ss component
      - two separate states

Conclusions

BESIII experiment is an excellent laboratory to study light hadron physics and search for light QCD exotic states

- BESIII is taking data since 2008. It will continue to run ~2030
- Selection of latest physics results on light exotic states are presented
  - X(1835), X(2120), X(2370), X(2600) observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$
    - X(2600) observed for the first time [PRL 129, 042001 (2022)]
    - X(1835), X(2120), X(2370) observed in J/ψ EM Dalitz Decay [PRL 129, 022002]
  - $e^+e^- \to pK^-\bar{\Lambda}$ PWA: new narrow structure in $p\bar{\Lambda}$ system: X(2085) [ArXiv:2303.01989]
  - Light hadron $a_0(1817)$ observed in open-charm decays [PRL129, 182001 (2022)]

More interesting results are expected

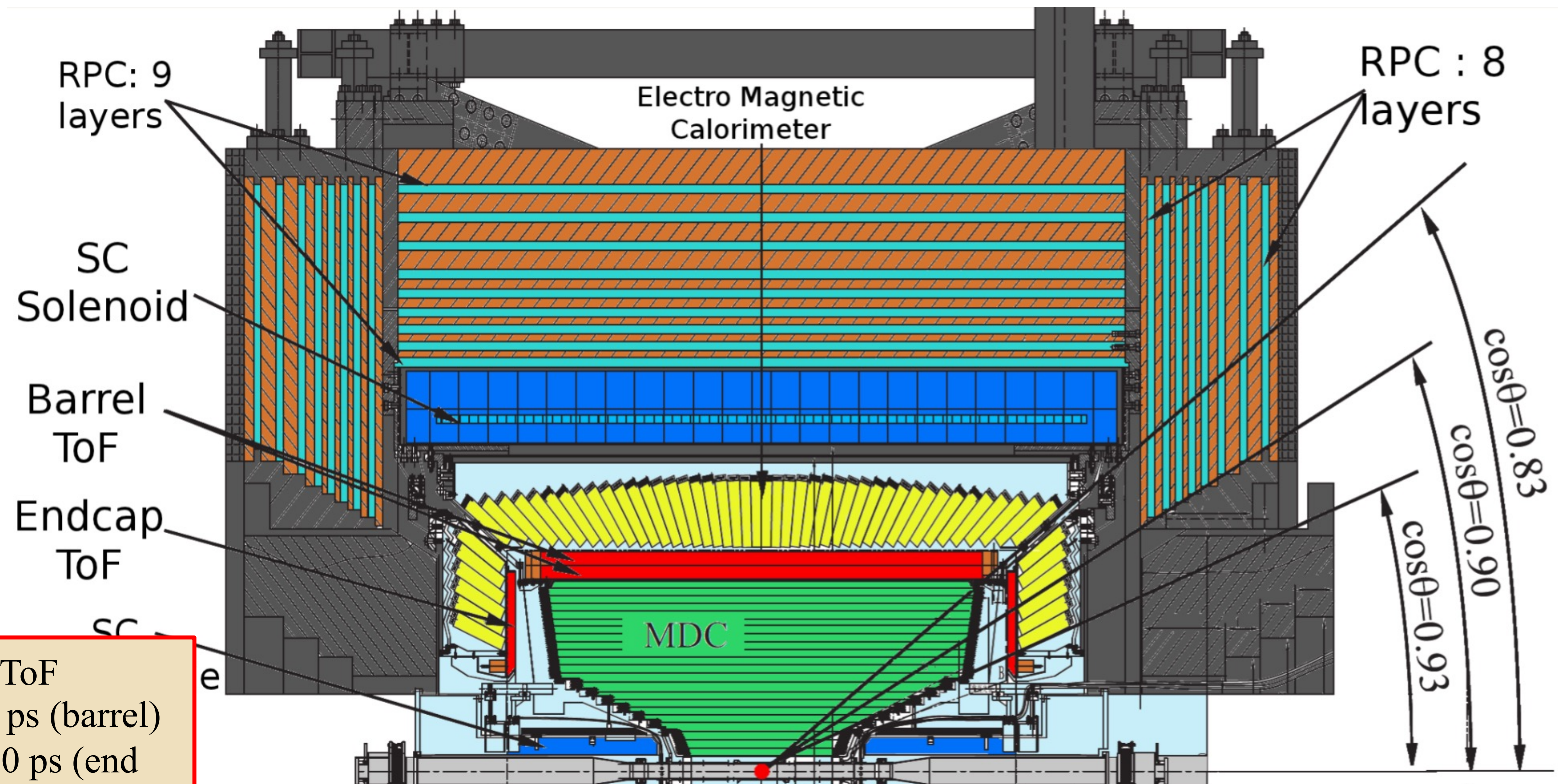
HADRON 2023

Thank you for your attention

Back-up slides

The BESIII Detector

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



ToF
$\sigma_t \sim 68$ ps (barrel)
$\sigma_t \sim 60$ ps (end caps, upgrade)

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)
$\sigma_{xy} \sim (6\text{ mm})/E^{1/2}$ @ 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
- $Z_c(3900)^+$, …

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

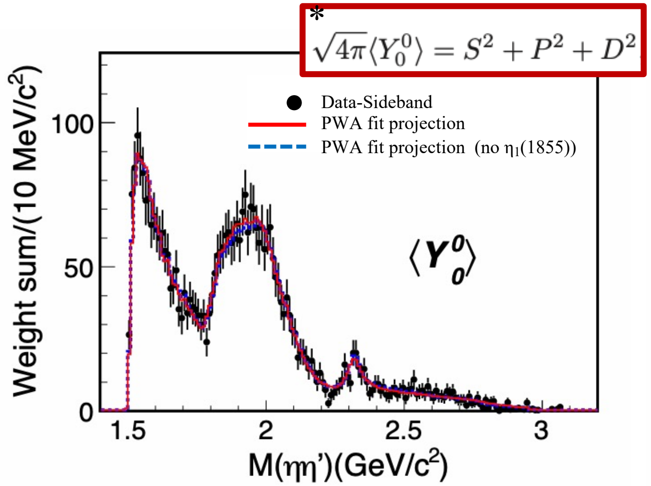
Further Checks on the $\eta_1(1855)$

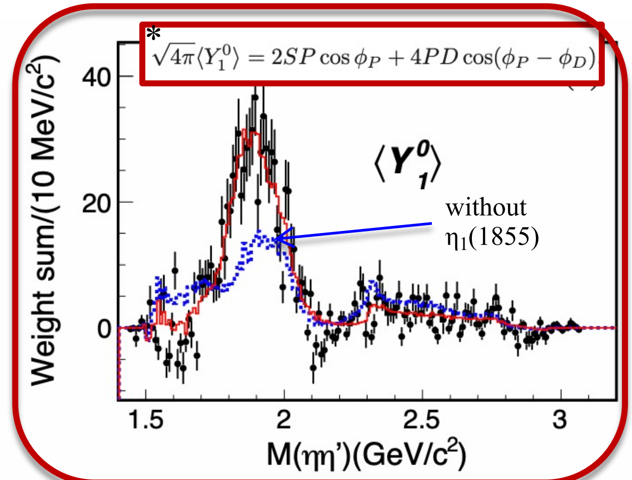
PRL 129, 192002 (2022)
PRD 106,072012 (2022)

The $\cos(\theta_\eta)$ distribution can be expressed as an expansion in terms of Legendre polynomials; the coefficients (unnormalized moments of expansion) characterize the spin of the ηη' resonances

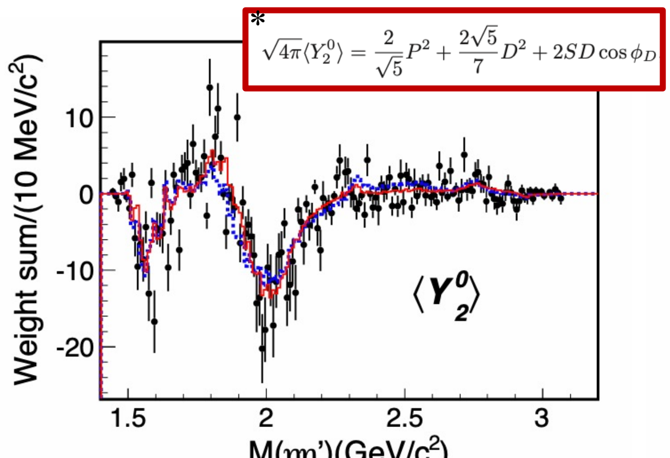
$$\langle Y_l^0 \rangle \equiv \sum_{i=1}^{N_k} W_i Y_l^0(\cos\theta_\eta^i).$$

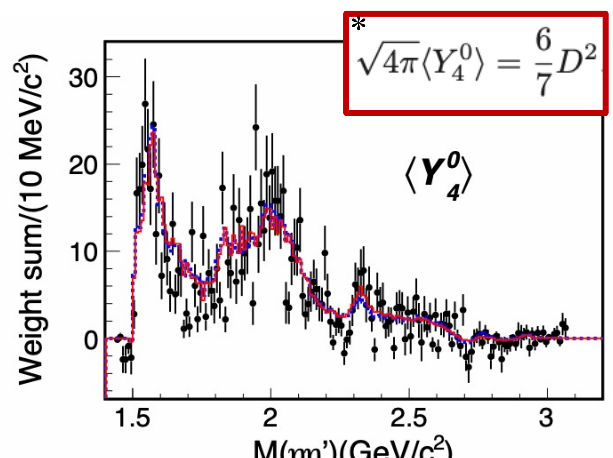
- Neglecting resonance contributions in the $\gamma\eta^{(\prime)}$ subsystem and amplitude with spin greater than 2, the moments are related to the spin-0 (S), spin-1 (P) and spin-2 (D) amplitudes





- Good data/PWA consistency
- Narrow structure in $\langle Y^0{}_1\rangle$: $\eta_1(1855)$ P-wave component is needed





*Assuming ηη' system has zero helicity

Discussion about $f_0(1500)$ and $f_0(1710)$

PRL 129, 192002 (2022)
PRD 106,072012 (2022)

The dominant contributions in the baseline PWA are from scalar resonance:

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	M_{PDG} (MeV/c^2)	Γ_{PDG} (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg 30\sigma$
	$f_0(1810)$	1795	95	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	1992	442	$2.28\pm0.12^{+0.29}_{-0.20}$	24.6σ
	$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	2314	144	$0.10\pm0.02^{+0.01}_{-0.02}$	13.2σ
	$\eta_1(1855)$	$1855\pm9^{+6}_{-1}$	$188\pm18^{+3}_{-8}$	-	-	$0.27\pm0.04^{+0.02}_{-0.04}$	21.4σ
	$f_2(1565)$	1542	122	1542	122	$0.32\pm0.05^{+0.12}_{-0.02}$	8.7σ
	$f_2(2010)$	$2062\pm6^{+10}_{-7}$	$165\pm17^{+10}_{-5}$	2011	202	$0.71\pm0.06^{+0.10}_{-0.06}$	13.4σ
	$f_4(2050)$	2018	237	2018	237	$0.06\pm0.01^{+0.03}_{-0.01}$	4.6σ
	0^{++} PHSP	-	-	-	-	$1.44\pm0.15^{+0.10}_{-0.20}$	15.7σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	1416	90	$0.08\pm0.01^{+0.01}_{-0.02}$	10.2σ
	$h_1(1595)$	1584	384	1584	384	$0.16\pm0.02^{+0.03}_{-0.01}$	9.9σ

$$\frac{\mathcal{B}(f_0(1500)\to\eta\eta')}{\mathcal{B}(f_0(1500)\to\pi\pi)} = \frac{\cancel{(8.96^{+2.95}_{-2.87}\times10^{-2})}}{(1.66^{+0.42}_{-0.40}\times10^{-1})\ *}$$

Consistent with PDG

$$\frac{\mathcal{B}(f_0(1710)\to\eta\eta')}{\mathcal{B}(f_0(1710)\to\pi\pi)} < \frac{\cancel{1.61\times10^{-3}}}{2.87\times10^{-3}\ *}$$

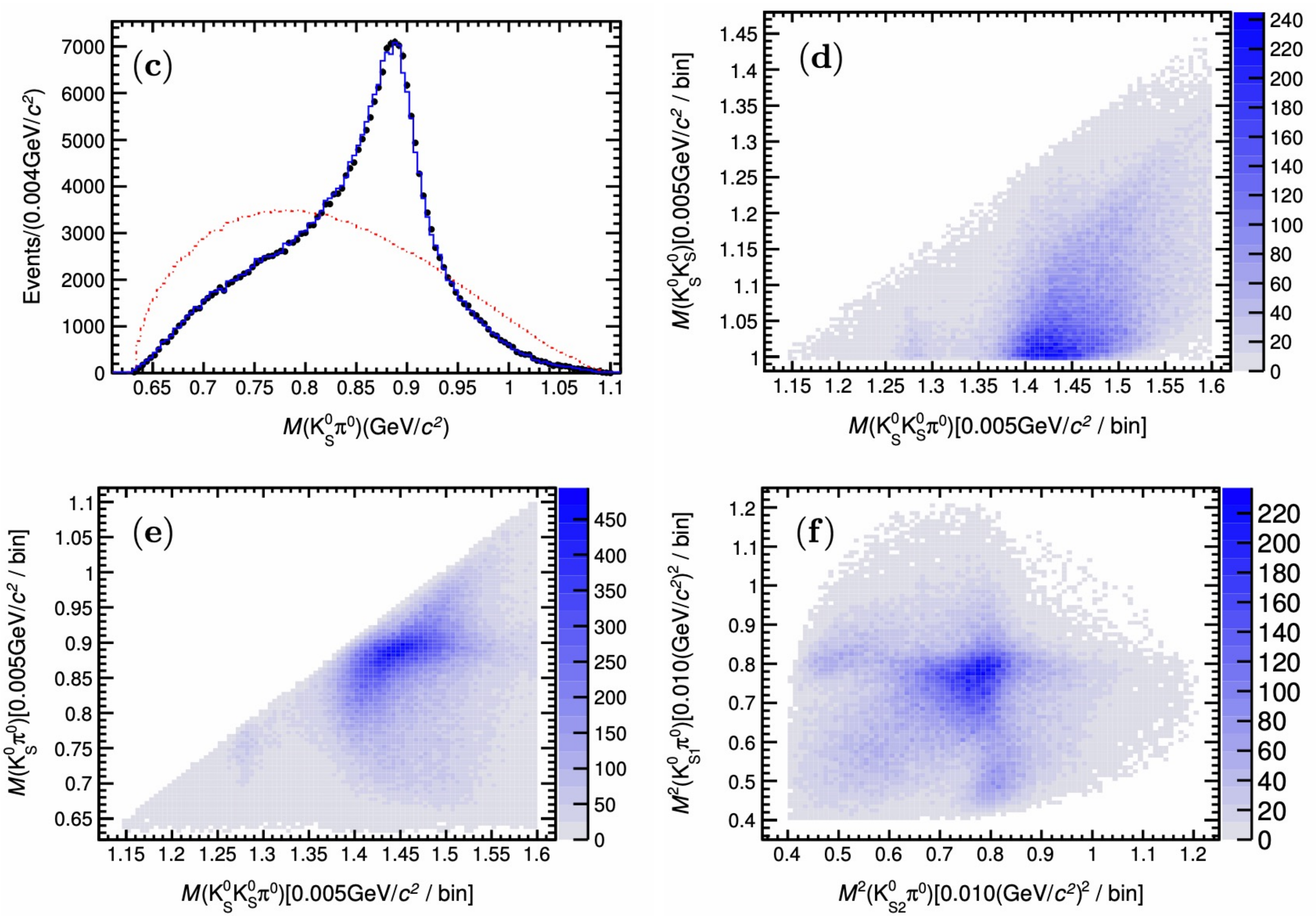
@90% C.L.

This suppressed decay rate supports the hypothesis that the $f_0(1710)$ has a large overlap with the ground state scalar glueball (PRD 92,121902)

*Erratum ready soon

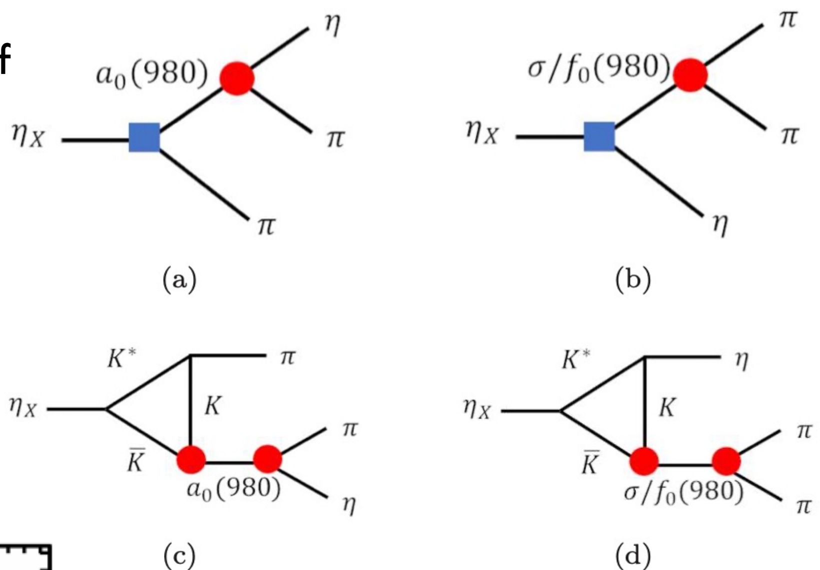
Dalitz Plot - $J/\psi \to \gamma K^0_S K^0_S \pi^0$

JHEP03(2023)121

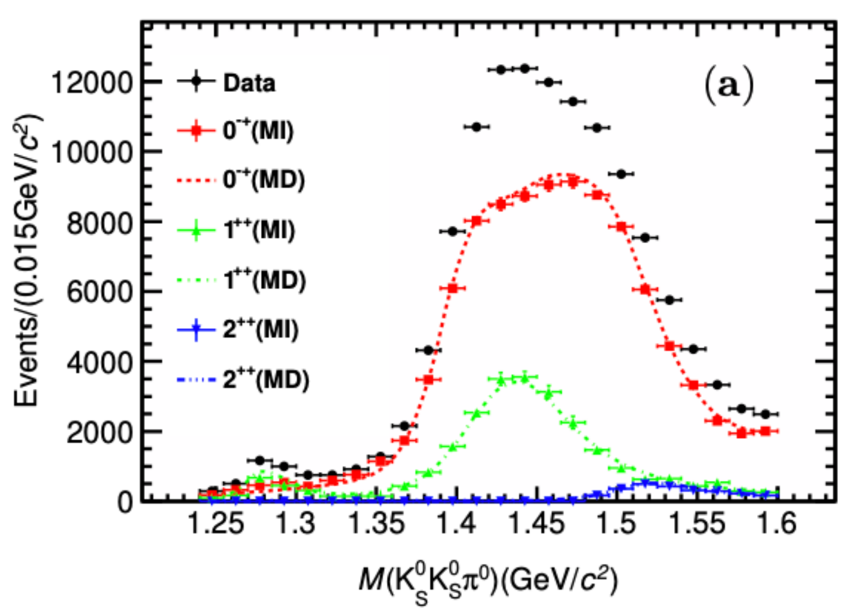


Dalitz Plot - $J/\psi \rightarrow \gamma K^0_S K^0_S \pi^0$

https://arxiv.org/pdf/2302.01210.pdf



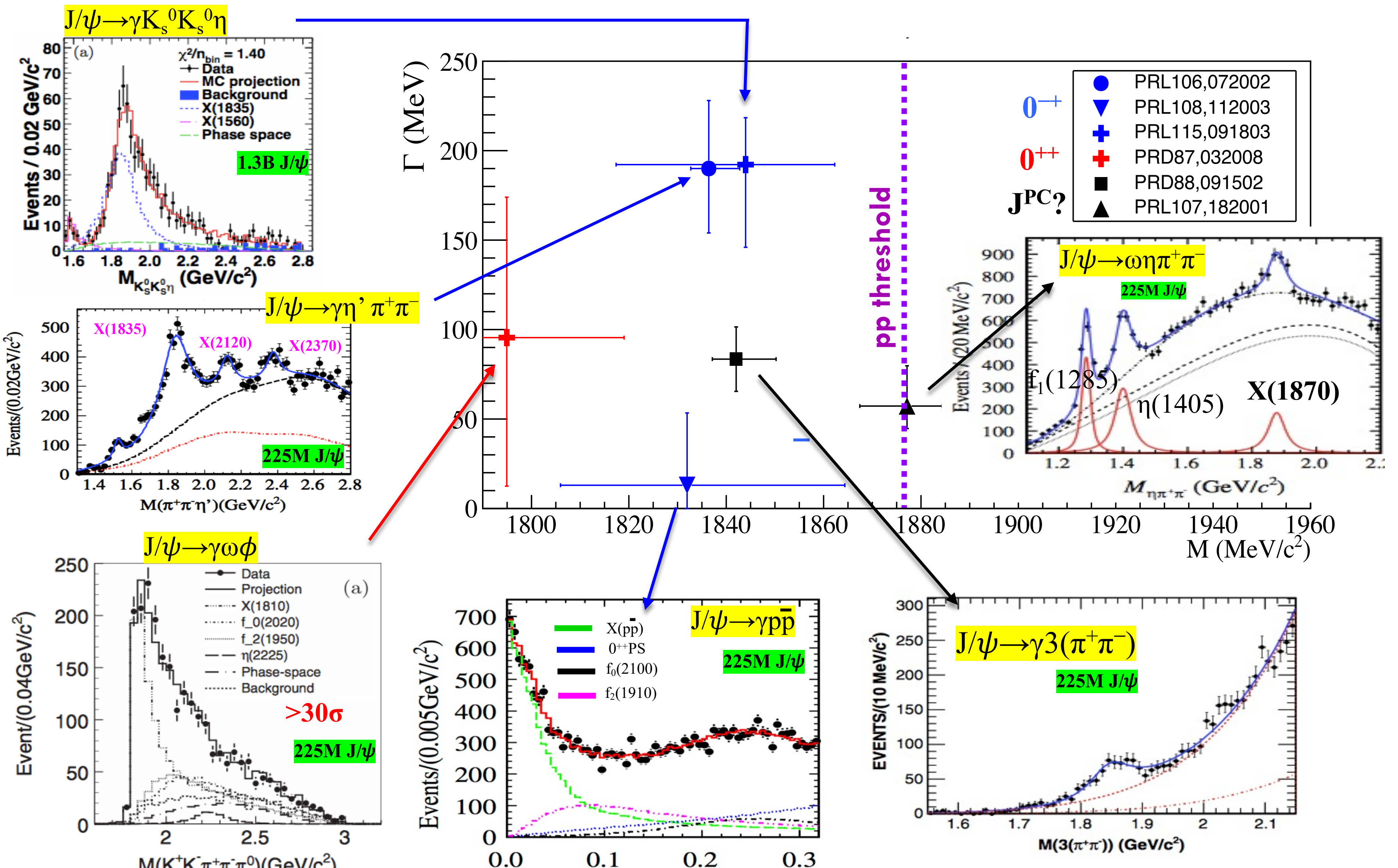
(a) (b) (c) (d)



JHEP03(2023)121

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV})$	Decay Mode	B.F.	Sig.(σ)
$\eta(1405)$	$1391.7 \pm 0.7^{+11.3}_{-0.3}$	$60.8 \pm 1.2^{+5.5}_{-12.0}$	$J/\psi \to \gamma\eta(1405) \to \gamma K^0_S(K^0_S\pi^0)_{\text{P-wave}} \to \gamma K^0_S K^0_S \pi^0$	$(5.84 \pm 0.12^{+2.03}_{-3.36}) \times 10^{-5}$	$\gg 35$
			$J/\psi \to \gamma\eta(1405) \to \gamma(K^0_S K^0_S)_{\text{S-wave}}\pi^0 \to \gamma K^0_S K^0_S \pi^0$	$(2.88 \pm 0.04^{+1.64}_{-0.38}) \times 10^{-5}$	18.4
$\eta(1475)$	$1507.6 \pm 1.6^{+15.5}_{-32.2}$	$115.8 \pm 2.4^{+14.8}_{-10.9}$	$J/\psi \to \gamma\eta(1475) \to \gamma K^0_S(K^0_S\pi^0)_{\text{P-wave}} \to \gamma K^0_S K^0_S \pi^0$	$(6.58 \pm 0.12^{+3.98}_{-2.82}) \times 10^{-5}$	$\gg 35$
			$J/\psi \to \gamma\eta(1475) \to \gamma(K^0_S K^0_S)_{\text{S-wave}}\pi^0 \to \gamma K^0_S K^0_S \pi^0$	$(3.99 \pm 0.09^{+0.41}_{-0.66}) \times 10^{-5}$	$\gg 35$
$f_1(1285)$	$1280.2 \pm 0.6^{+1.2}_{-1.5}$	$28.2 \pm 1.1^{+5.5}_{-2.9}$	$J/\psi \to \gamma f_1(1285) \to \gamma a_0(980)^0\pi^0 \to \gamma K^0_S K^0_S \pi^0$	$(8.55 \pm 0.41^{+3.42}_{-1.04}) \times 10^{-6}$	$\gg 35$
$f_1(1420)$	$1433.5 \pm 1.1^{+27.9}_{-0.7}$	$95.9 \pm 2.3^{+13.6}_{-10.9}$	$J/\psi \to \gamma f_1(1420) \to \gamma K^*(892)^0 K^0_S \to \gamma K^0_S K^0_S \pi^0$	$(7.25 \pm 0.12^{+0.73}_{-1.25}) \times 10^{-5}$	$\gg 35$
			$J/\psi \to \gamma f_1(1420) \to \gamma a_0(980)^0\pi^0 \to \gamma K^0_S K^0_S \pi^0$	$(4.62 \pm 0.36^{+2.36}_{-1.94}) \times 10^{-6}$	17.8
$f_2(1525)$	$1515.4 \pm 2.5^{+3.2}_{-7.6}$	$64.0 \pm 4.3^{+2.0}_{-6.1}$	$J/\psi \to \gamma f_2(1525) \to \gamma K^*(892)^0 K^0_S \to \gamma K^0_S K^0_S \pi^0$	$(9.47 \pm 0.43^{+1.51}_{-0.66}) \times 10^{-6}$	23.8

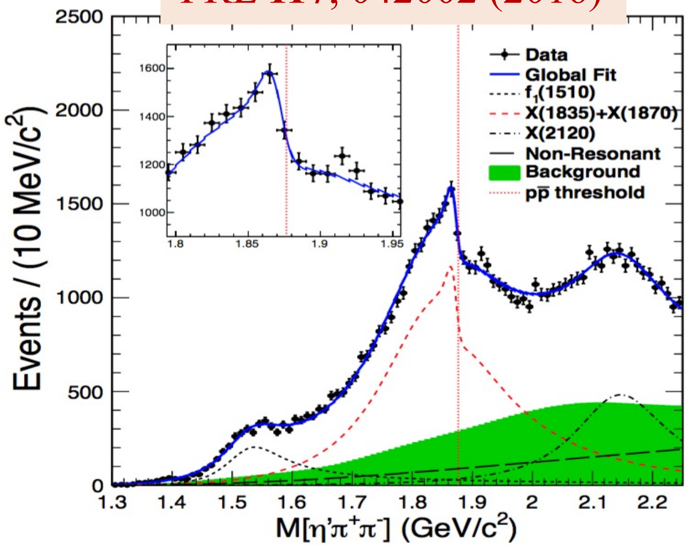
X(18xx) between 1.8-1.9 GeV



Isabella Garzia – University of Ferrara and INFN

Other Results on X(1835)

PRL **117**, 042002 (2016)



1.09×10^9 J/ψ @ BESIII

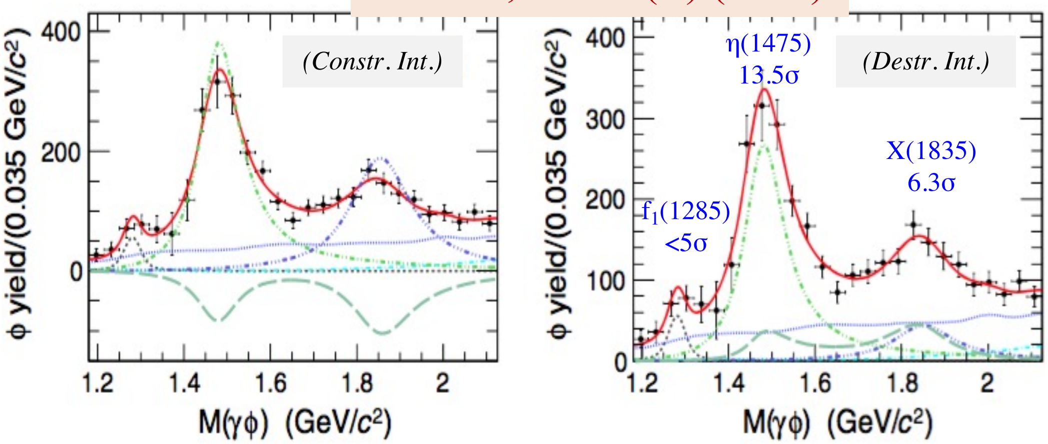
$J/\psi\to\gamma\,\eta'\pi^-\pi^+$

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

1.3×10^9 J/ψ @ BESIII

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



$J/\psi\to\gamma\gamma\phi$: 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

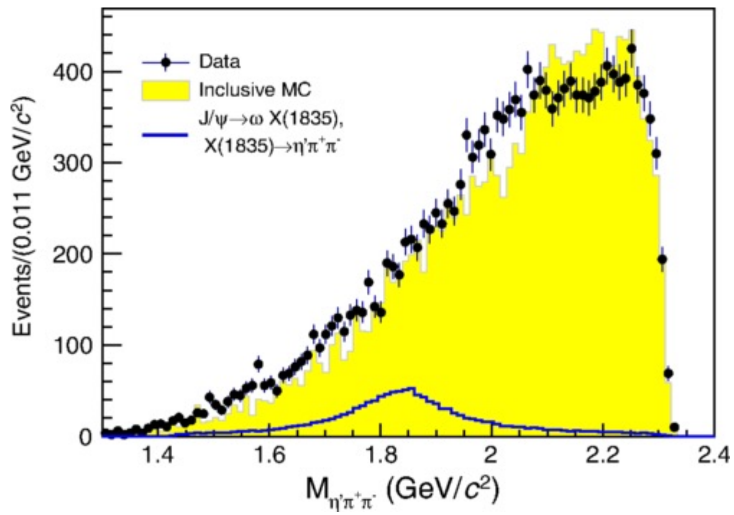
Solution	Resonance	m_R (MeV/c^2)	Γ (MeV)
I (*Destr. Int.*)	$\eta(1475)$	$1477\pm7\pm13$	$118\pm22\pm17$
	$X(1835)$	$1839\pm26\pm26$	$175\pm57\pm25$
II (*Constr. Int.*)	$\eta(1475)$	$1477\pm7\pm13$	$118\pm22\pm17$
	$X(1835)$	$1839\pm26\pm26$	$175\pm57\pm25$

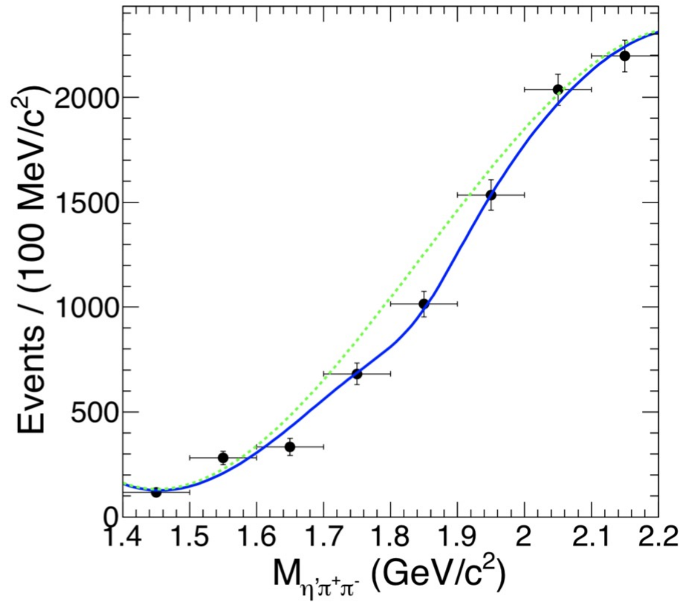
Search for X(1835) in other decay modes

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

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

1.3×10^9 J/ψ @ BESIII





- 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 ….

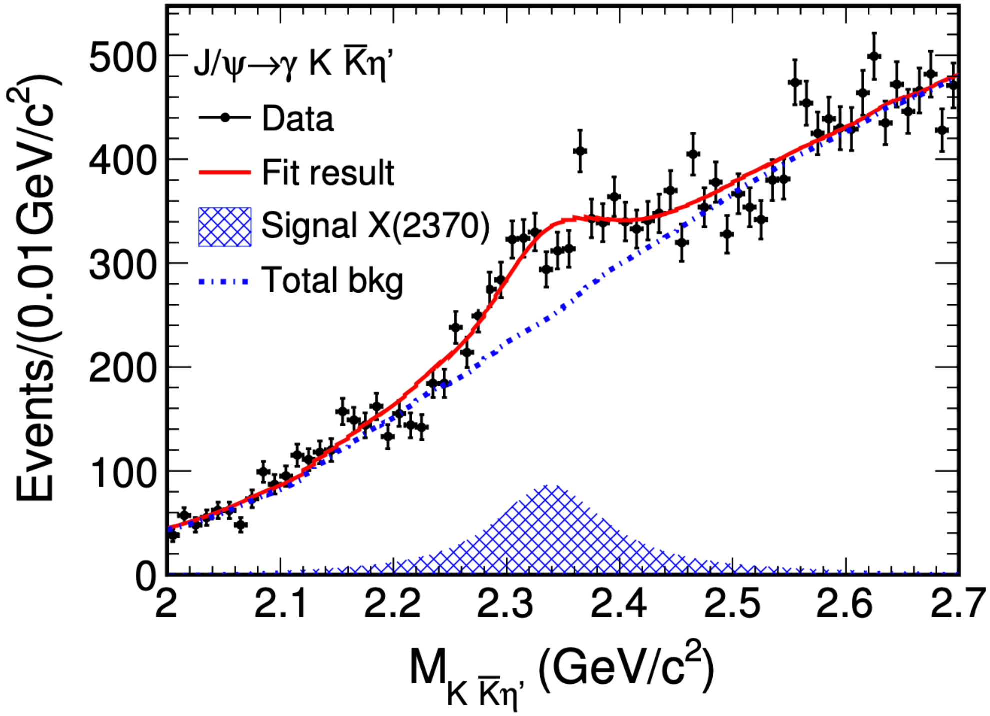
First Observation of X(2370) in $J/\psi \to \gamma K\bar{K}\eta'$

1.3×10⁹ 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)

➢ Simulataneus fit performed for two decay η' modes



➢ **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**

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

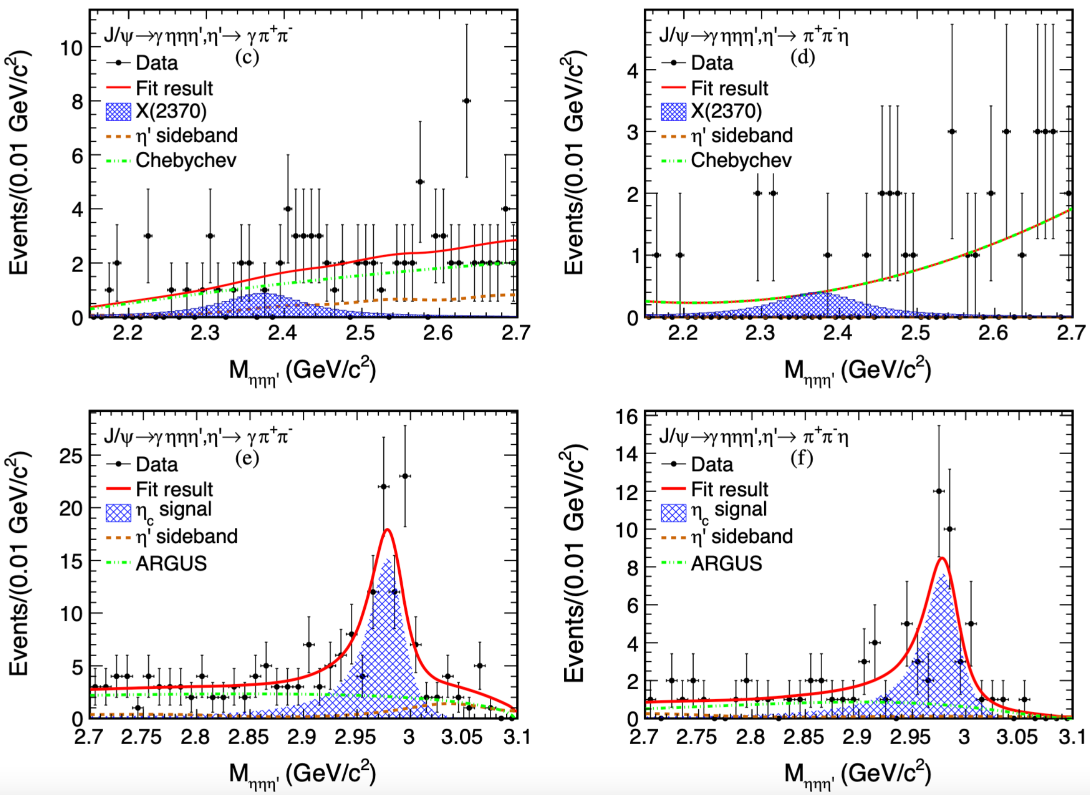
$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma K^+K^-\eta') = (1.79 \pm 0.23 \pm 0.65) \times 10^{-5}$$

$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma K^0_S K^0_S\eta') = (1.18 \pm 0.32 \pm 0.39) \times 10^{-5}$$

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

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

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

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

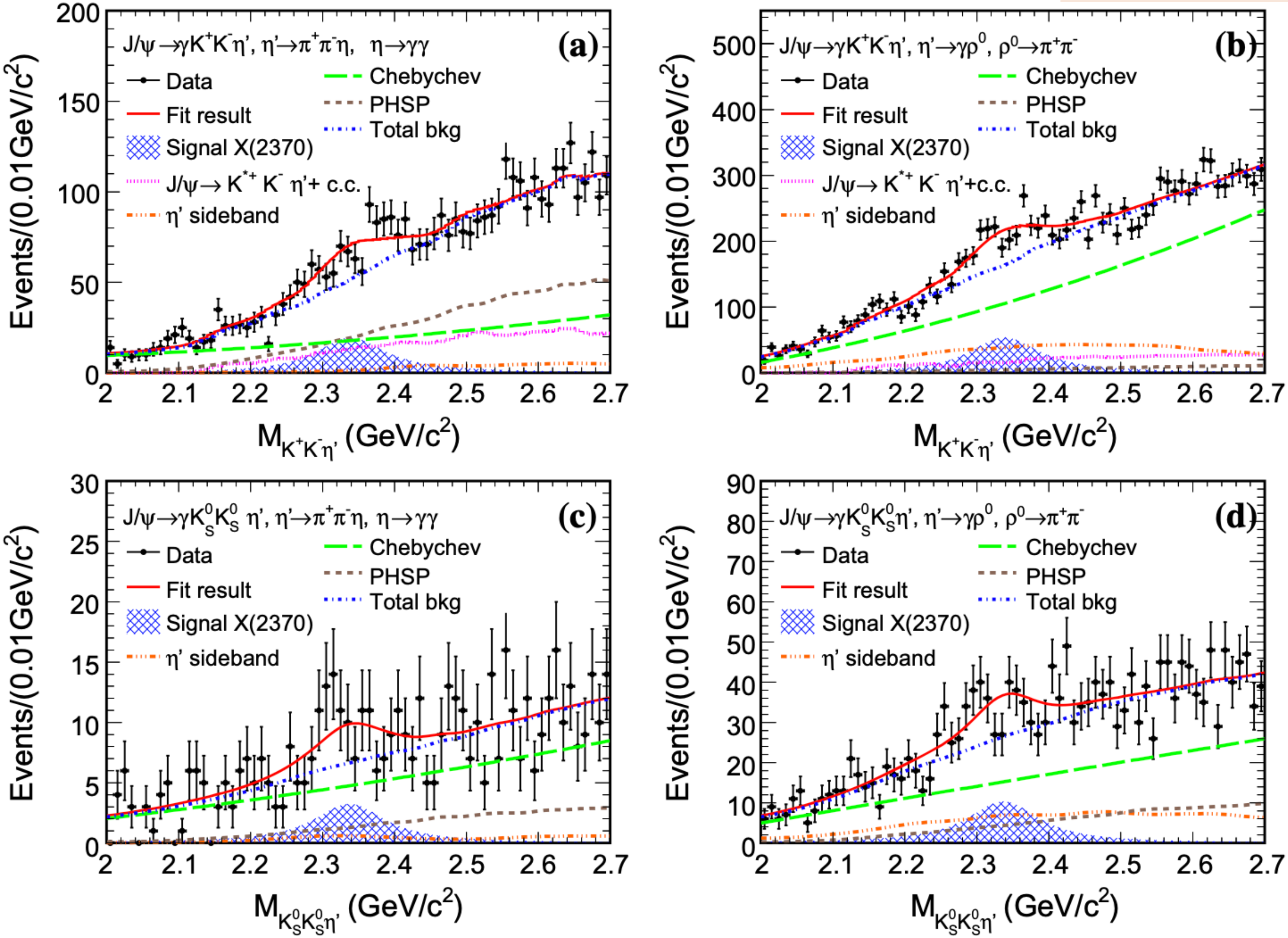
$$\boxed{\mathcal{B}(J/\psi \to \gamma\eta_c)\cdot\mathcal{B}(\eta_c \to \eta\eta\eta') = (4.86\pm0.62\pm0.45)\times10^{-5}}$$

FIRST OBSERVATION in the ηηη' invariant mass spectra

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

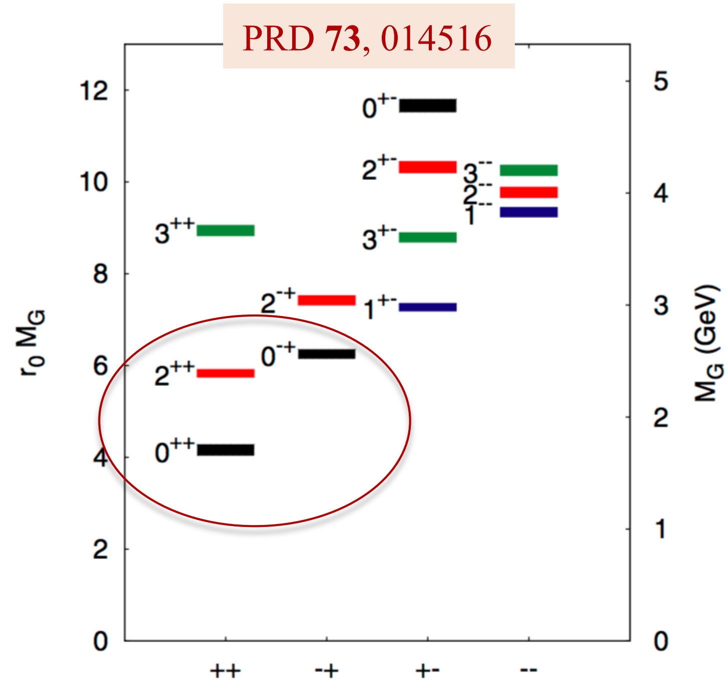
1.3×10^9 J/ψ @ BESIII

EPJC **80**, 746 (2020)



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

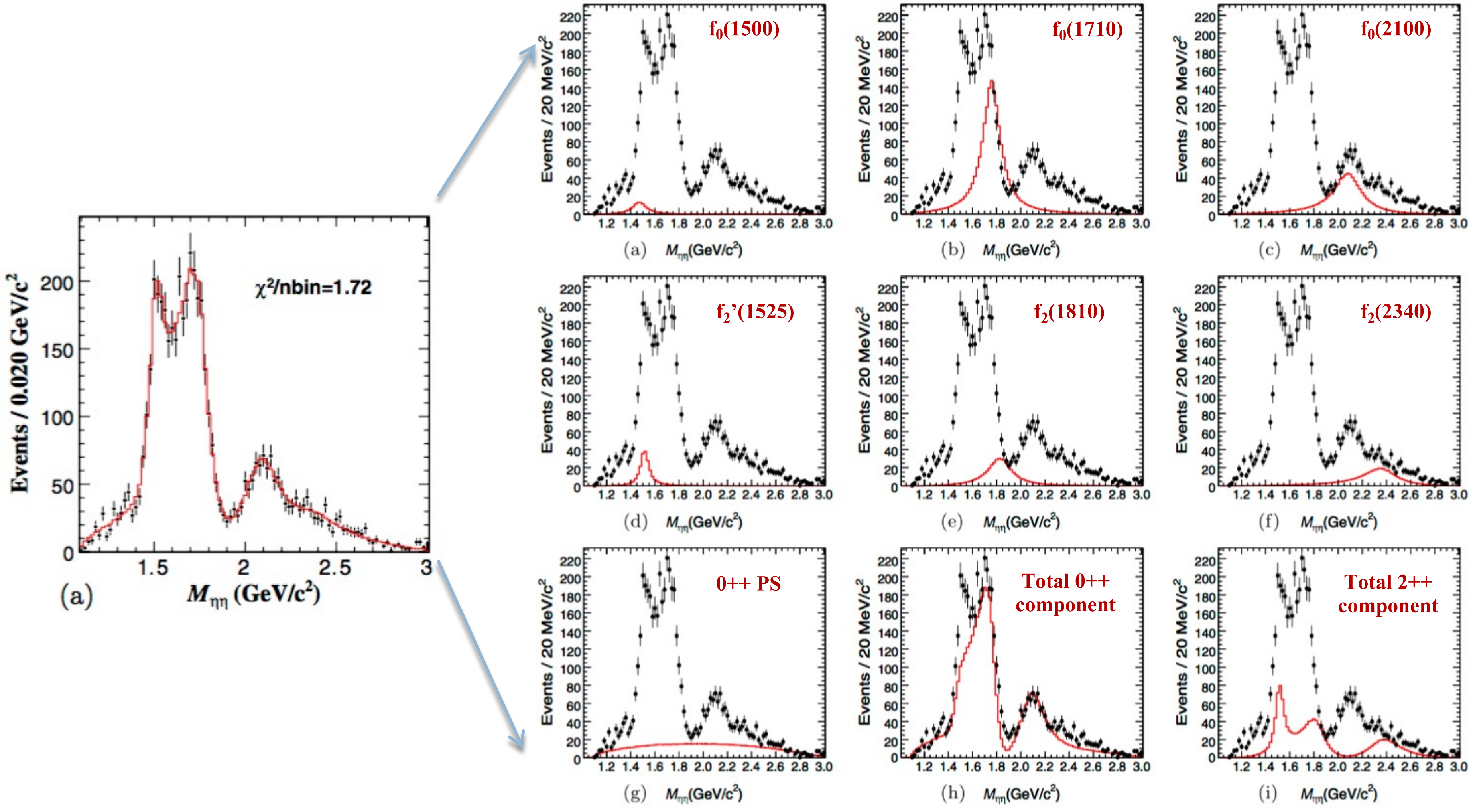


- **Amplitude analysis: toll to extract the complex amplitudes from experimental data**
  - Models with free parameters
  - Consider the kinematic of final states particles
  - Vary the parameters to maximize the likelihood
  - **Mass Dependent (MD) PWA**: model the dynamics of particle interactions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

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

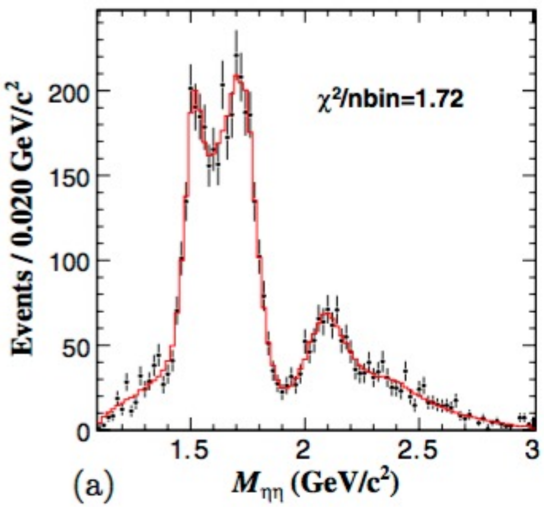


PWA of J/ψ→γηη

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}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40})\times10^{-5}$	8.2σ
$f_0(1710)$	$1759\pm6^{+14}_{-25}$	$172\pm10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74})\times10^{-4}$	25.0σ
$f_0(2100)$	$2081\pm13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28})\times10^{-4}$	13.9σ
$f_2'(1525)$	$1513\pm5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30})\times10^{-5}$	11.0σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35})\times10^{-5}$	6.4σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07})\times10^{-5}$	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

	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	
$f_0(1500)$	$(1.65^{+0.26+0.51}_{-0.31-1.40})\times10^{-5}$	8.2σ
$f_0(1710)$	$(2.35^{+0.13+1.24}_{-0.11-0.74})\times10^{-4}$	25.0σ
$f_0(2100)$	$(1.13^{+0.09+0.64}_{-0.10-0.28})\times10^{-4}$	13.9σ
$f_2'(1525)$	$(3.42^{+0.43+1.37}_{-0.51-1.30})\times10^{-5}$	6.4σ
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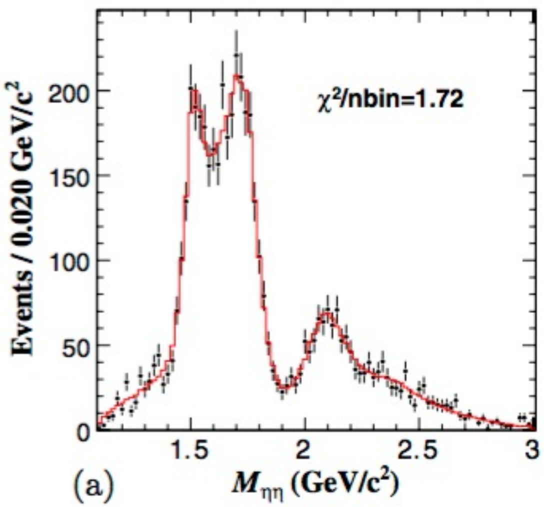
$f_2(2340)$	$(5.60^{+0.62+2.37}_{-0.65-2.07})\times10^{-5}$	



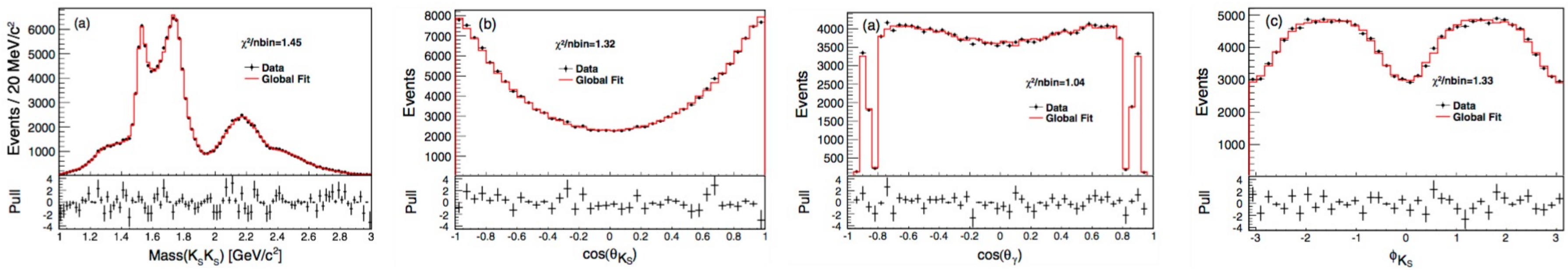
- $f_0(1500)$ dominant decays are 4π and $\pi\pi$
- The production rate of $f_0(1710)$ is compatible with LQCD (PRL110,021601) prediction for a pure scalar glueball
  - Suggest a large overlap with 0++ glueball

- 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 $f_2(2340)$

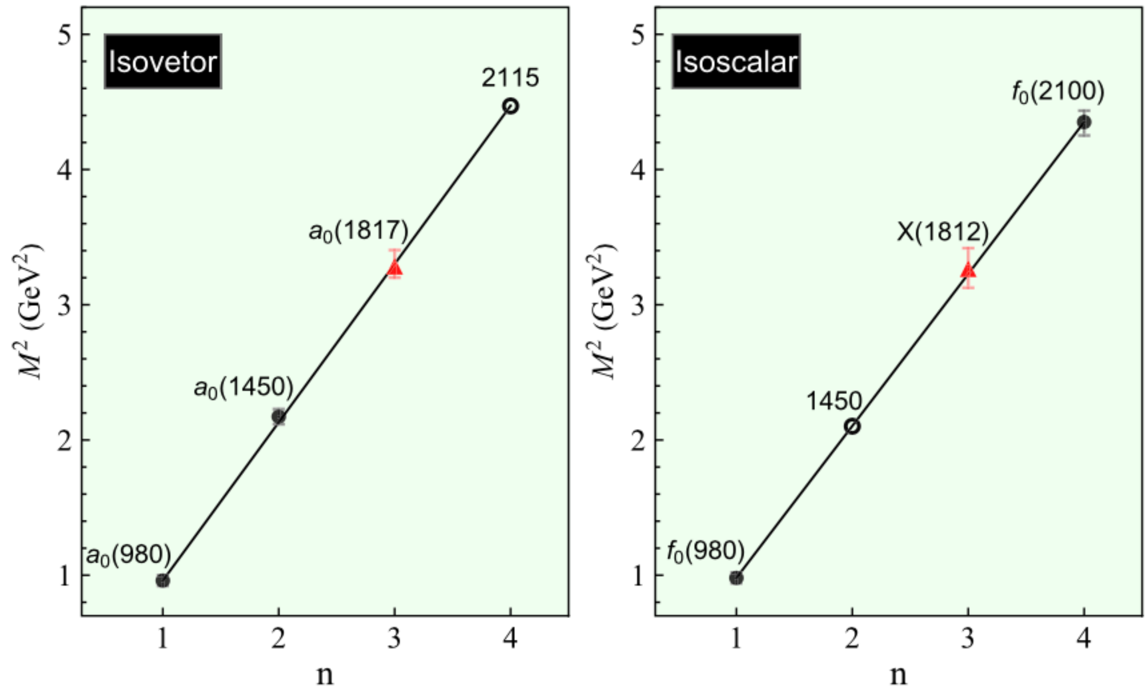


FIG. 1. Two Regge trajectories for the isovector and isoscalar scalar states. Here, the red triangles denote the $a_0(1817)$ and $X(1812)$, while the solid points and empty circles are the experimental and predicted states, respectively. Except the $a_0(1817)$, $X(1812)$ and predicted $a_0(2115)$, $f_0(1450)$, the masses of the other scalar states are taken from PDG. Here, the established states are marked by the black solid points, while the predicted states are denoted by the black circles. The error bars present total experimental uncertainties.