Light QCD exotics at BESIII

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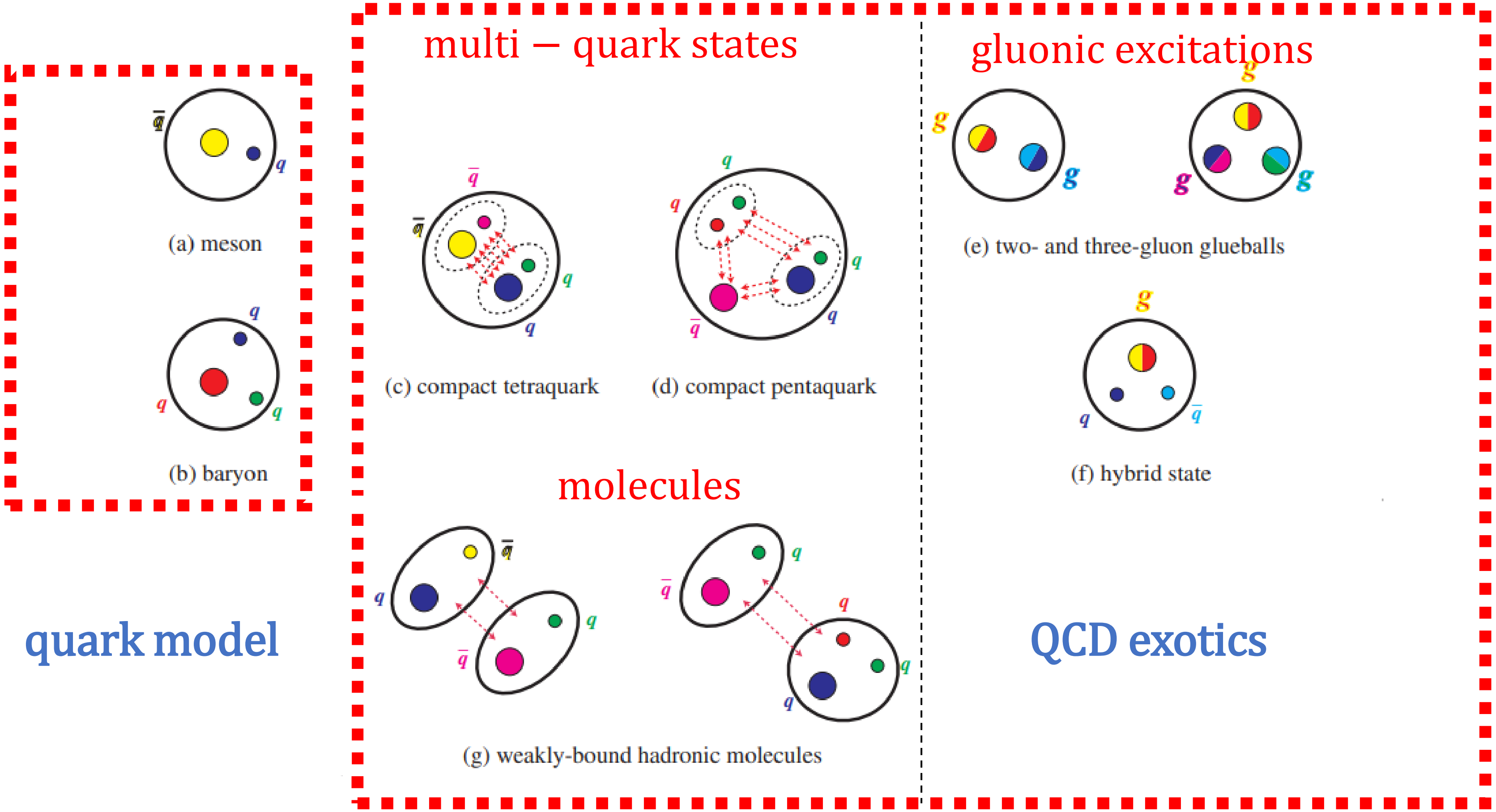
QCD allows the existence of exotic hadrons

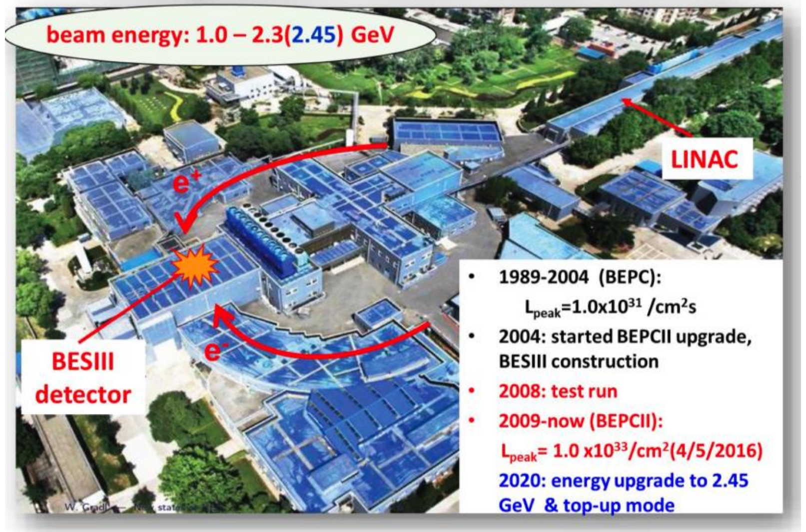
Rept.Prog.Phys. 86 (2023) 2, 026201

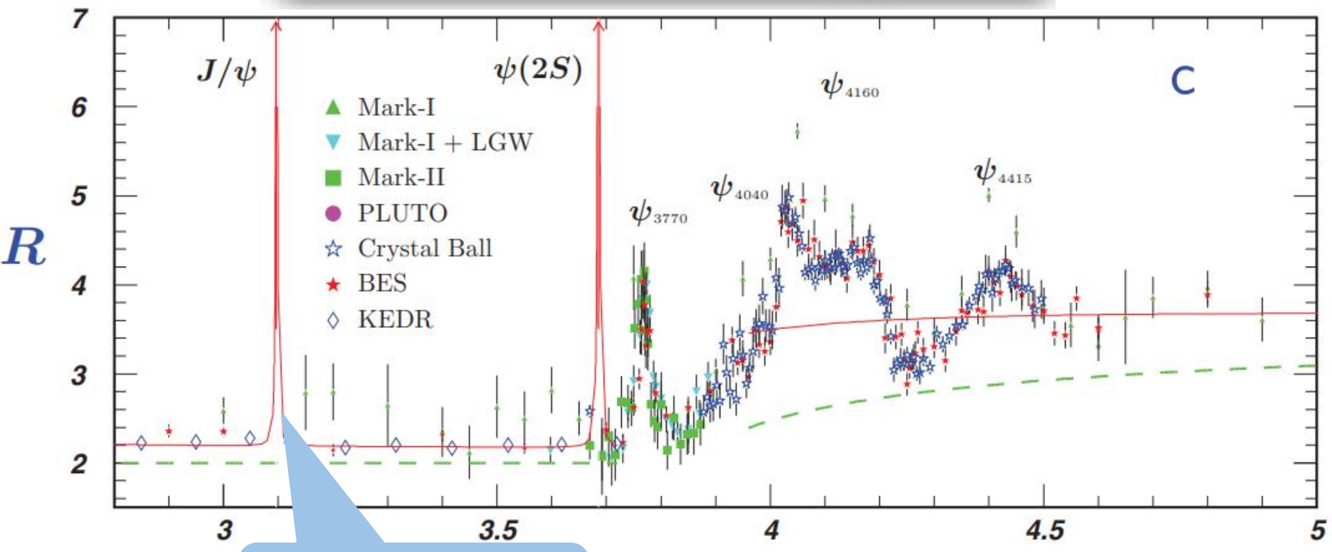


A lot of exotic states observed experimentally, the nature of them is far from being understood

World's Largest τ-$charm$ Data Sets in e^+e^- Annihilation

Beijing Electron Positron Collider (BEPCII)

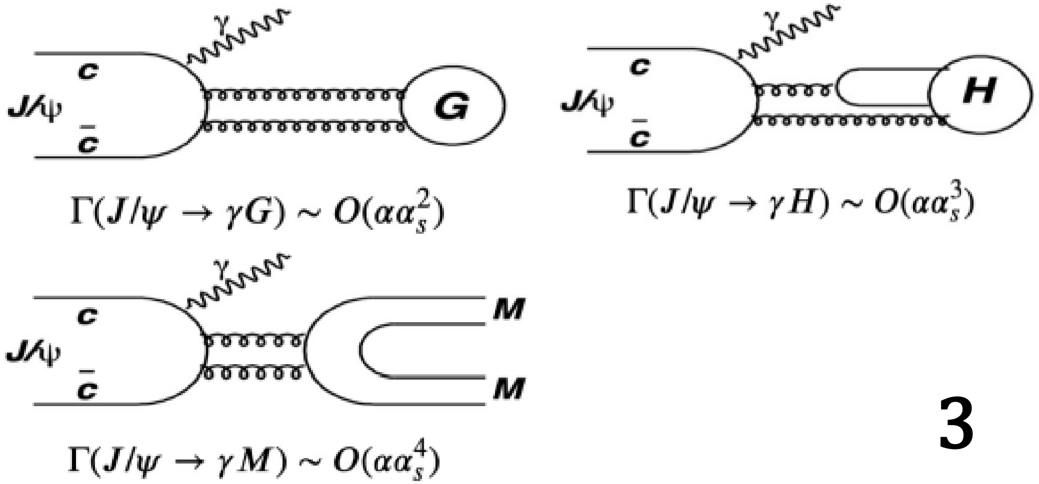




$10 \times 10^9\ J/\psi$

Ideal lab for light hadron physics

- Clean high statistics data samples
- Well defined initial and final states
  - Kinematic constraints
  - $I(J^{PC})$ filter
- "Gluon-rich" processes
  $\Gamma(J/\psi \to \gamma G) > \Gamma(J/\psi \to \gamma H) > \Gamma(J/\psi \to \gamma M)$



Glueballs

- Low-lying glueballs with ordinary J^{PC} $(0^{++}, 2^{++}, 0^{-+})$

→ mixing with $q\bar{q}$ mesons

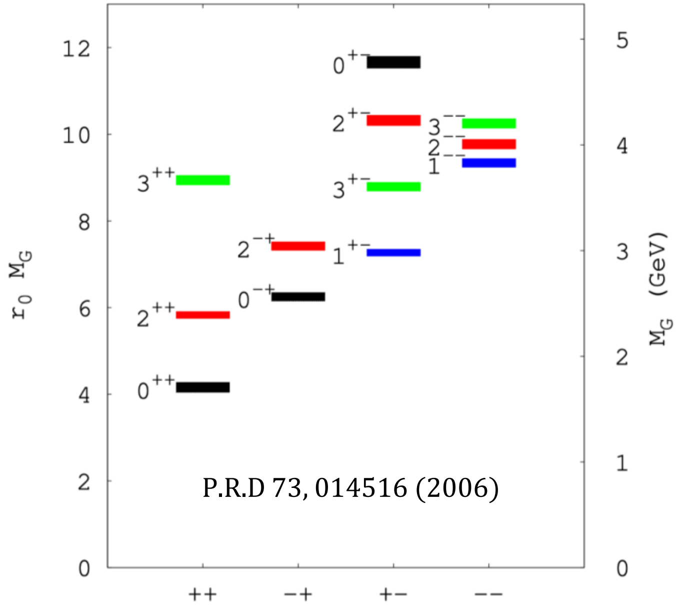
  - ➢ Non-$q\bar{q}$ nature difficult to established: Cryptoexotic
    - ➢ Supernumerary states
    - ➢ Unusual pattern of production and decay

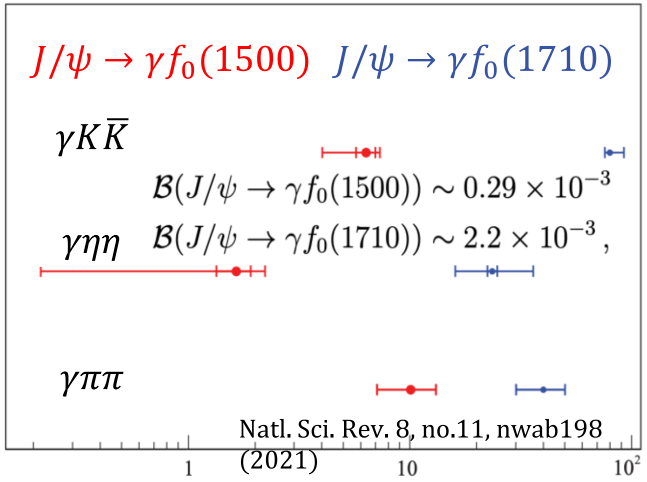
- Scalar glueball is expected to have a large production in J/ψ radiative decays: $B(J/\psi \to \gamma G_{0^+})$=3.8(9) × 10^{-3} by Lattice QCD
  - Observed $B(J/\psi \to \gamma f_0(1710))$ is × 10 larger than $f_0(1500)$
  - ➢ BESIII: $f_0(1710)$ largely overlapped with scalar glueball

PRD 87 092009 (2013)
PRD 92 052003 (2015)
PRD 98 072003 (2018)

phenomenology studies of coupled channel analysis with BESIII results:
PLB 816, 136227 (2021), EPJC 82, 80 (2022)

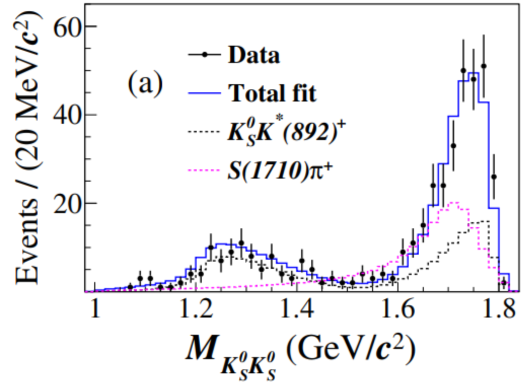
Lattice QCD predictions





Branching fractions (10^{-5})

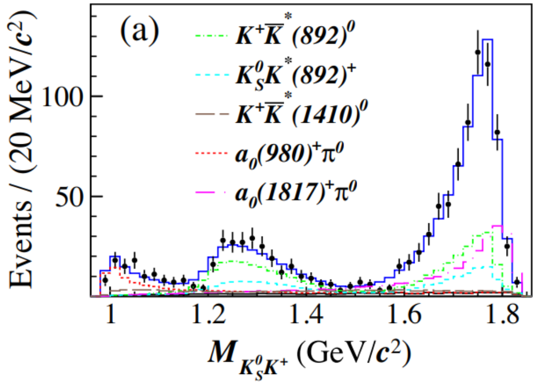
More scalar mesons at BESIII



PRD105, L051103 (2022)

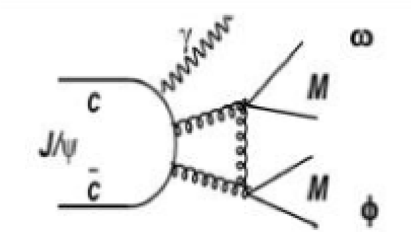
$D_s^+ \to K_S^0 K_S^0 \pi^+$

$a_0(1817)$

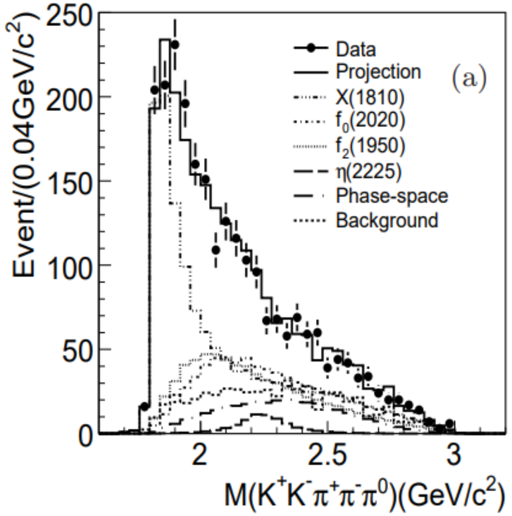


PRL129, 182001 (2022)

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



$J/\psi \to \gamma\omega\phi$ **(DOZI)**



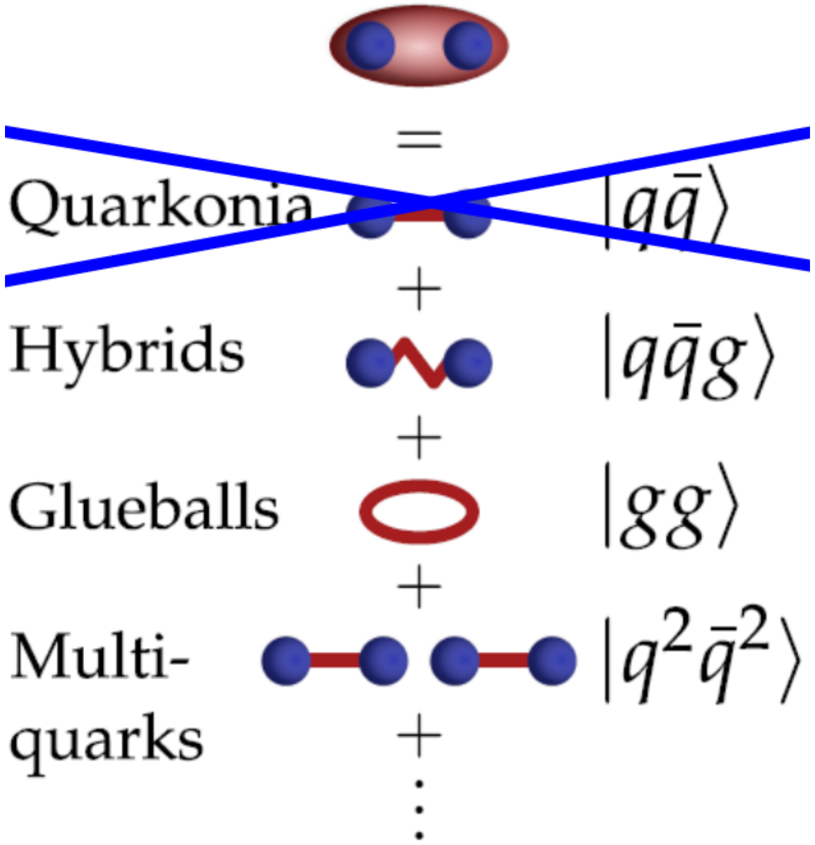
PRD 87, 032008(2013)

$f_0(1800)$

- $a_0(1817)$ could be the isospin one partner of the $SU(3)_f$ octet $f_0(1800)$
- The possibility of the $f_0(1710)$ as the scalar glueball cannot be excluded

Light hadrons with exotic quantum numbers

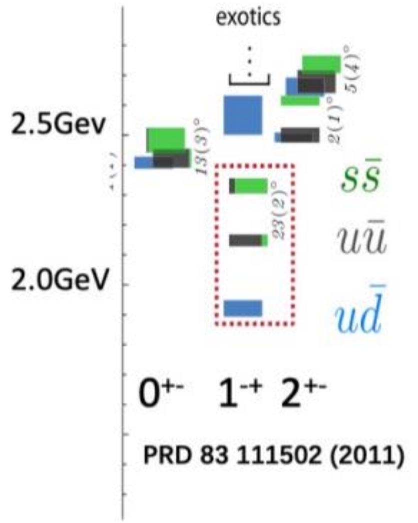
- **Unambiguous signature for exotics**
  - Light Flavor-exotic hard to establish
  - Exotic quantum numbers forbidden for simple $q\bar{q}$ system
  - Efforts concentrate on Spin-exotic
    - $J^{PC} = 0^{--}, \text{even}^{+-}, \text{odd}^{-+}(1^{-+})$

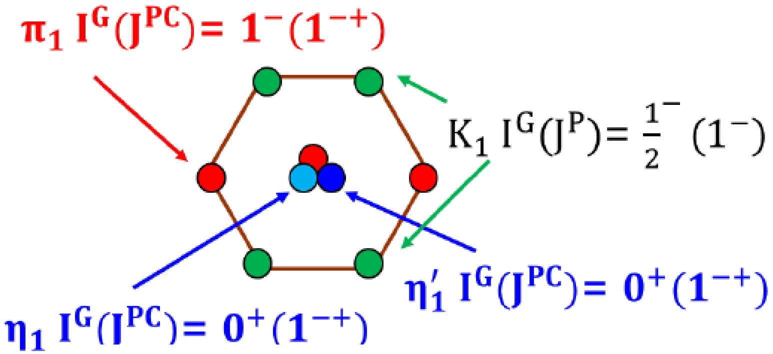


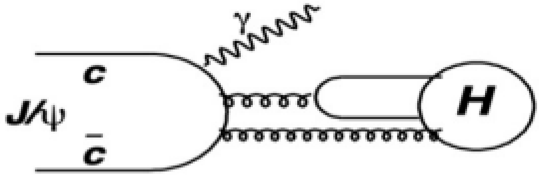
Hybrids

- Low-lying hybrids can have **exotic quantum numbers**
- The exotic $J^{PC} = 1^{-+}$ nonet of hybrids is predicted to be the lightest
  - Only isovector candidates $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2015)$ observed yet
    - * $\pi_1(1400)$, $\pi_1(1600)$ can be explained as one resonance with recent coupled channel analysis
- **Isoscalar 1^{-+}** is critical to establish the hybrid nonet
  - Can be produced in the gluon-rich J/ψ radiative decays
  - Can decay to $\eta\eta'$ in P-wave

Lattice QCD Predictions:







$$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$$

PRD 83,014021 (2011)
PRD 83,014006 (2011)
Eur.Phys.J.Plus 135, 945(2020)

Observation of An Exotic Isoscalar State $\eta_1(1855)$ (1^{-+}) in $J/\psi \to \gamma\eta\eta'$

PRL 129, 192002 (2022)
PRL 130, 159901 (2023)
PRD 106,072012 (2022)
PRD 107,079901 (2023)

- Partial wave analysis of $J/\psi \to \gamma\eta\eta'$

  Quasi two-body decay amplitudes in the sequential decay processes $J/\psi \to \gamma X, X \to \eta\eta'$ and $J/\psi \to \eta X, X \to \gamma\eta'$ and $J/\psi \to \eta' X, X \to \gamma\eta$ are constructed using the covariant tensor formalism

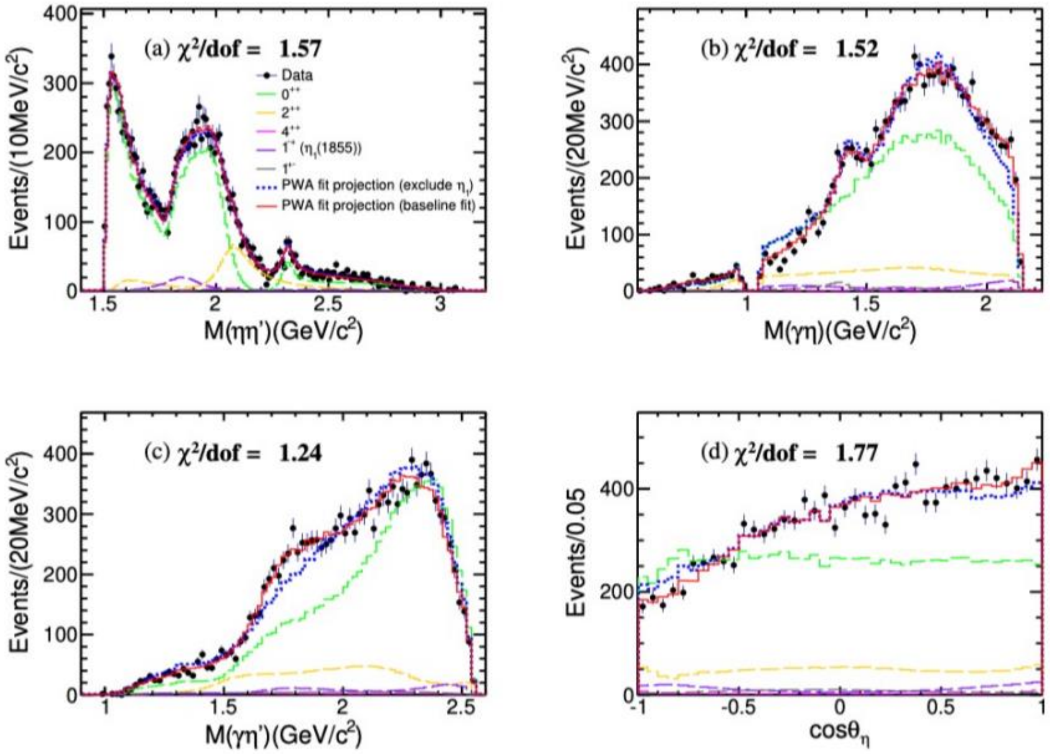
- All kinematically allowed known resonances with 0^{++}, 2^{++}, 4^{++} $(\eta\eta')$ and 1^{+-}, $1^{--}(\gamma\eta^{(\prime)})$ are considered

  1^{-+} in $\eta\eta'$ is also considered (η/η' not identical particle)

- An **isoscalar** resonance with **exotic** $J^{PC} = 1^{-+}$, $\eta_1(1855)$, has been firstly observed with significance larger than 19σ

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

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



➢ **Consistent** with **LQCD calculation** for the 1^{-+} hybrid $(1.7\sim2.1\ \mathrm{GeV/c^2})$

➢ Hybrid? Molecule? Tetraquark? … needs **further study**

Observation of An Exotic Isoscalar State $\eta_1(1855)$ (1^{-+}) in $J/\psi \to \gamma\eta\eta'$

- Angular distribution expressed as an expansion in terms of Legendre polynomials **model-independently**

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

- Related to the spin-0(S), spin-1(P), spin-2(D) amplitudes in $\eta\eta'$ by :

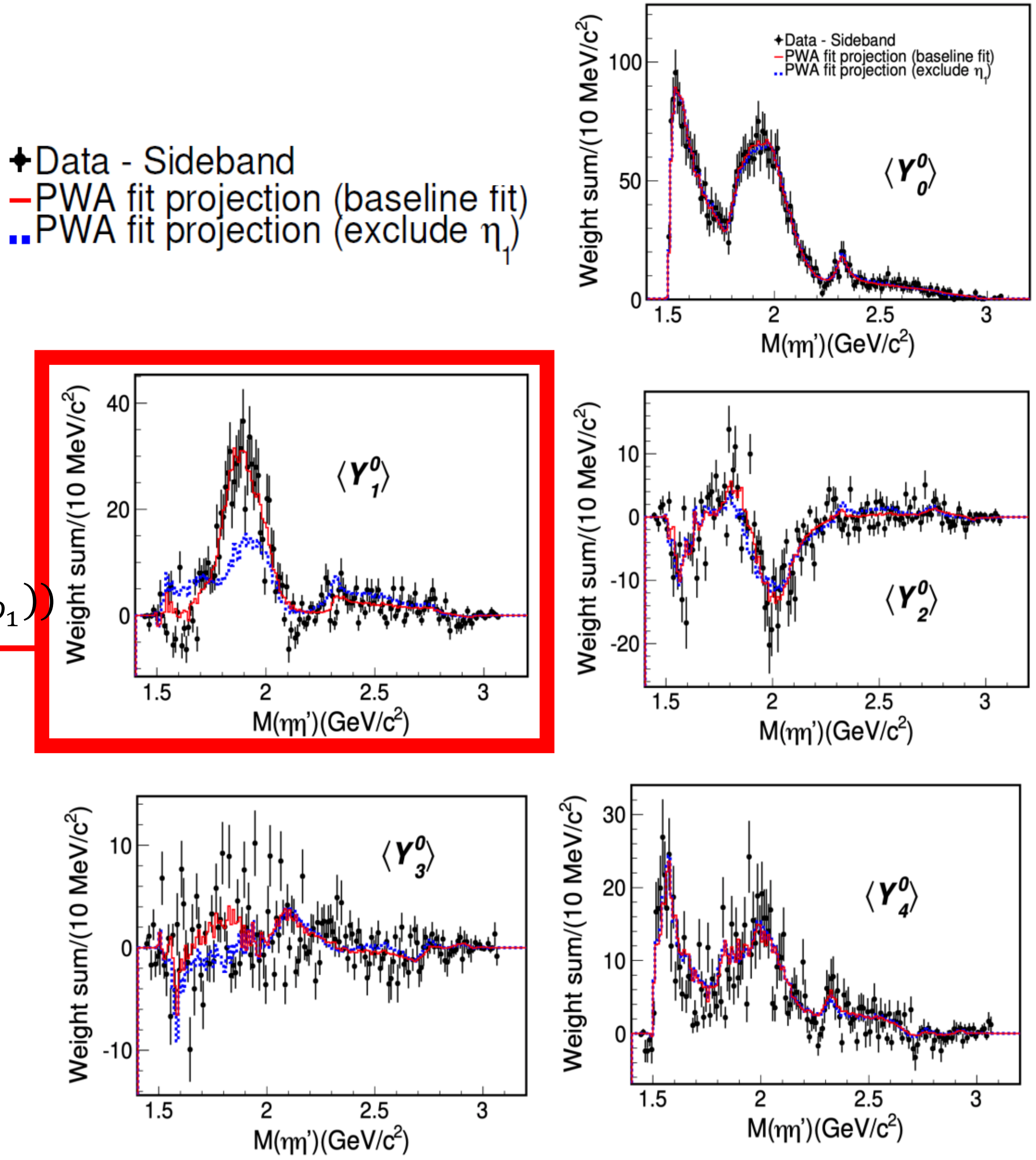
$$\sqrt{4\pi} < Y_0^0 > = S_0^2 + P_0^2 + P_1^2 + D_0^2 + D_1^2 + D_2^2$$

$$\sqrt{4\pi} < Y_1^0 > = 2S_0P_0\cos\phi_{P_0} + \frac{2}{\sqrt{5}}(2P_0D_0\cos(\phi_{P_0} - \phi_{D_0}) + \sqrt{3}P_1D_1\cos(\phi_{P_1} - \phi_{D_1}))$$

$$\sqrt{4\pi} < Y_2^0 > = \frac{1}{7\sqrt{5}}(14P_0^2 - 7P_1^2 + 10D_0^2 + 5D_1^2 - 10D_2^2) + 2S_0D_0\cos\phi_{D_0}$$

$$\sqrt{4\pi} < Y_3^0 > = \frac{6}{\sqrt{35}}(\sqrt{3}P_0D_0\cos(\phi_{P_0} - \phi_{D_0}) - P_1D_1\cos(\phi_{P_1} - \phi_{D_1}))$$

$$\sqrt{4\pi} < Y_3^0 > = \frac{1}{7}(6D_0^2 - 4D_1^2 + D_2^2)$$



- $<Y_1^0>$ Indicates significant P-wave needed
- In $\eta\eta'$system, only η_1 (1^{-+}) contribute P-wave

➢ Need for $\eta_1(1855)$

Discussions about $f_0(1500)$ & $f_0(1710)$

- **Decay properties :**
  - The pure glueball is a flavor singlet, the process $G \to \eta\eta'$ is significantly suppressed .

    $B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$

  - Significant $f_0(1500)$

    $$\frac{B(f_0(1500)\to\eta\eta')}{B(f_0(1500)\to\pi\pi)} = (1.66^{+0.42}_{-0.40}) \times 10^{-1}$$

  - Absence of $f_0(1710)$

    $$\frac{B(f_0(1710)\to\eta\eta')}{B(f_0(1710)\to\pi\pi)} < 2.87 \times 10^{-3} \text{ @90\% C. L.}$$

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	M_{PDG} (MeV/c^2)	Γ_{PDG} (MeV)	B.F. ($\times 10^{-5}$)	Sig.
	$f_0(1500)$	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
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	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

➢Supports to the hypothesis that $f_0(1710)$ overlaps with the ground state scalar (0^{++}) glueball

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

PRD 105,072002 (2022)

Observation of the three f_0 and one f_2

- New state $f_0(2480)$
- Components of $f_0(2020)$
  - flavor singlet

$$\frac{\Gamma(f_0(2020)\rightarrow\eta\eta')}{\Gamma(f_0(2020)\rightarrow\eta'\eta')} = 0.0148$$

Resonance	M(MeV/c^2)	Γ(MeV)	B.F.	Significance (σ)
$f_0(2020)$	$1982 \pm 3^{+54}_{-0}$	$436 \pm 4^{+46}_{-49}$	$(2.63 \pm 0.06^{+0.31}_{-0.46}) \times 10^{-4}$	≫25
$f_0(2330)$	$2312 \pm 2^{+10}_{-0}$	$134 \pm 5^{+30}_{-9}$	$(6.09 \pm 0.64^{+4.00}_{-1.68}) \times 10^{-6}$	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
$h_1(1415)$	$1384 \pm 6^{+9}_{-0}$	$66 \pm 10^{+12}_{-10}$	$(4.69 \pm 0.80^{+0.74}_{-1.82}) \times 10^{-7}$	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

- New decay mode of tensor glueball candidate $f_2(2340)$

$$B(J/\psi \rightarrow \gamma f_2(2340) \rightarrow \gamma\eta\eta) = 3.8^{+0.62\,+2.37}_{-0.65\,-2.07} \times 10^{-5}$$

PRD 87, 092009

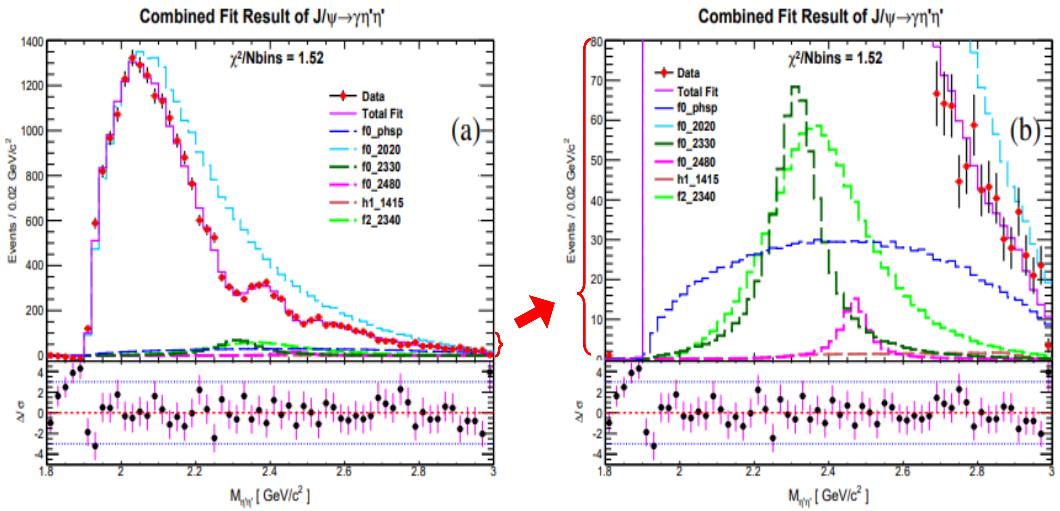
$$B(J/\psi \rightarrow \gamma f_2(2340) \rightarrow \gamma\phi\phi) = 1.91 \pm 0.14^{+0.72}_{-0.73} \times 10^{-4}$$

PRD93,112011

$$B(J/\psi \rightarrow \gamma f_2(2340) \rightarrow \gamma K_S K_S) = 5.54^{+0.34\,+3.82}_{-0.40\,-1.49} \times 10^{-5}$$

PRD 98, 072003

$$B(J/\psi \rightarrow \gamma f_2(2340) \rightarrow \gamma\eta'\eta') = 3.8^{+0.62\,+2.37}_{-0.65\,-2.07} \times 10^{-6}$$



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

JHEP03(2023)121

- Mass Independent PWA(MI)

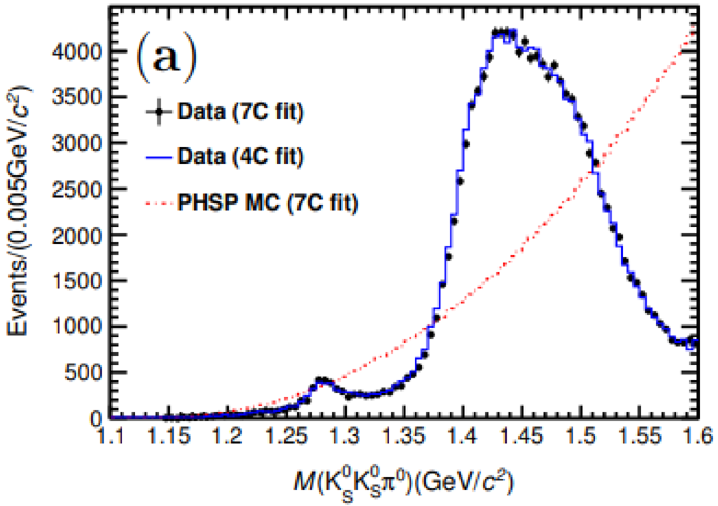
  explore the lineshape of $K_S^0 K_S^0 \pi^0$ invariant mass for the different decay modes, and minimize bias from model dynamics of the intermediate states

  - Non-trivial 0^{-+} line shape

- Mass Dependent PWA(MD)

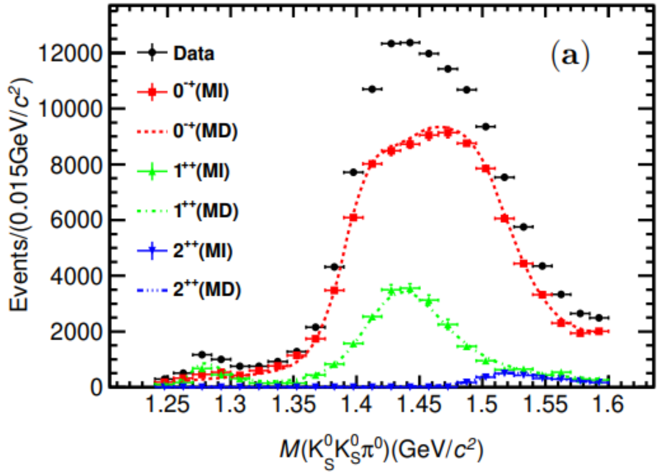
  extract the resonance parameters of the intermediate states

  - Two resonances parameterization

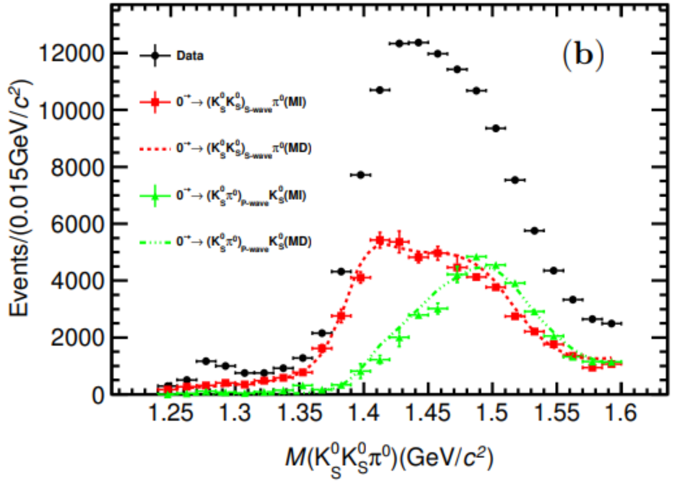


Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV})$
$\eta(1405)$	$1391.7 \pm 0.7^{+11.3}_{-0.3}$	$60.8 \pm 1.2^{+5.5}_{-12.0}$
$\eta(1475)$	$1507.6 \pm 1.6^{+15.5}_{-32.2}$	$115.8 \pm 2.4^{+14.8}_{-10.9}$
$f_1(1285)$	$1280.2 \pm 0.6^{+1.2}_{-1.5}$	$28.2 \pm 1.1^{+5.5}_{-2.9}$
$f_1(1420)$	$1433.5 \pm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

MD PWA dominant components



dominant spin-parity components

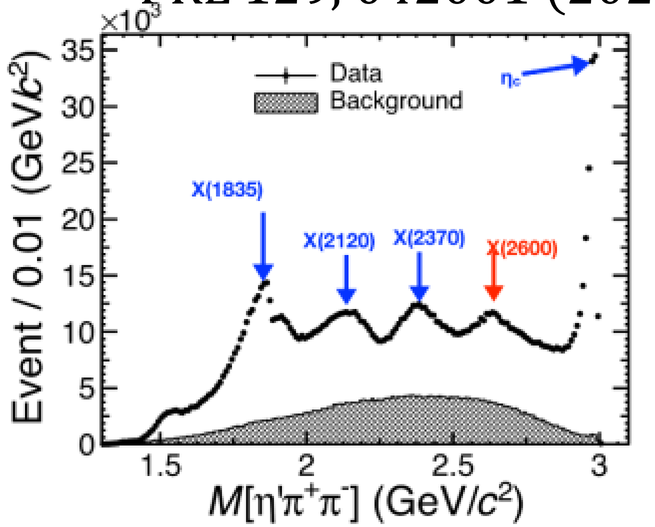


dominant decay modes for the pseudoscalar component

New states in $J/\psi \to \gamma\pi^+\pi^-\eta'$

10B J/ψ

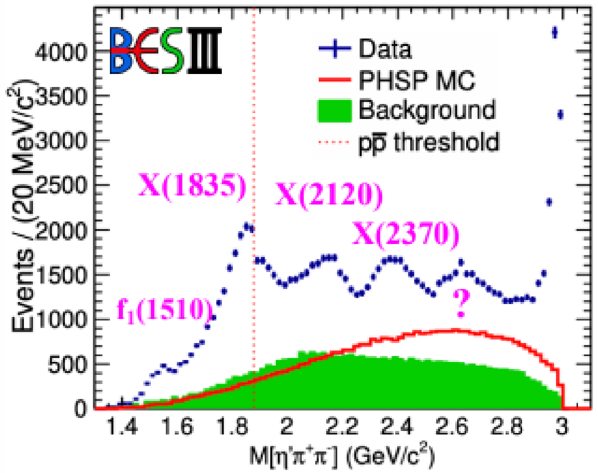
PRL 129, 042001 (2022)



Observation of X(2600)

1.3B J/ψ

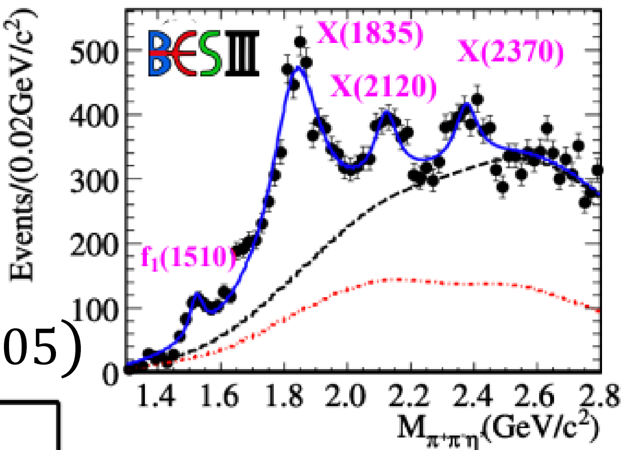
PRL 117 042002(2016)



Observation of anomalous line shape at $p\bar{p}$ threshold

225M J/ψ

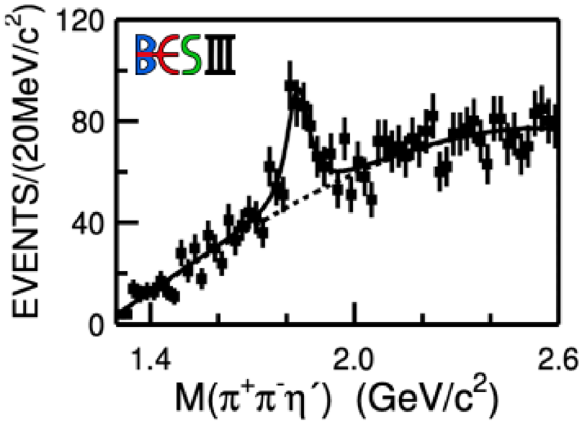
PRL 106 072002(2011)



Observation of X(2120), X(2370)

58M J/ψ

PRL 95 262001(2005)



Observation of X(1835)

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

PRL 129, 042001 (2022)

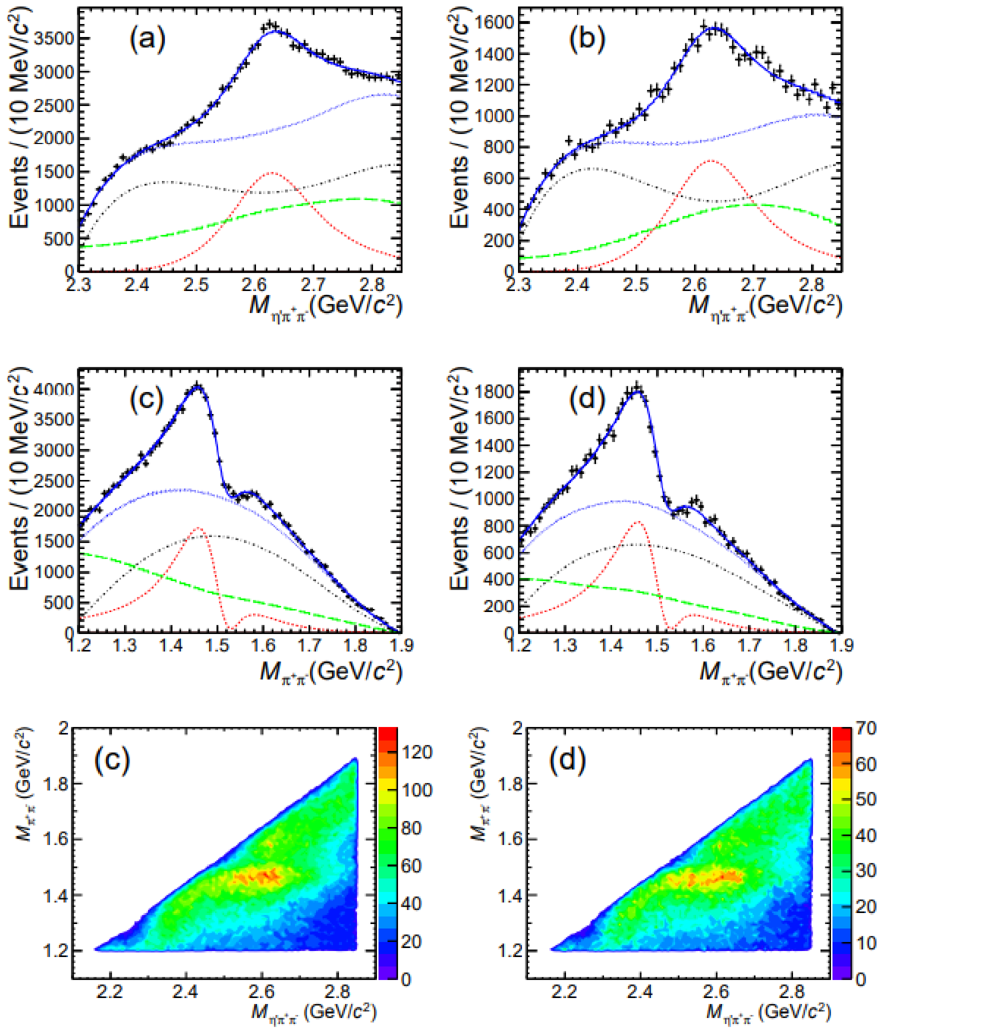
- To study **X(2600) parameters**, a simultaneous fit to $\eta'\pi^+\pi^-$ and $\pi^+\pi^-$ is performed
- The **structure in $M(\pi^+\pi^-)$** well described with the interference between $f_0(1500)$ and X(1540)

@ > 20σ	Mass (MeV/c^2)	Width (MeV)
$f_0(1500)$	$1492.5 \pm 3.6^{+2.4}_{-20.5}$	$107 \pm 9^{+21}_{-7}$
$X(1540)$	$1540.2 \pm 7.0^{+36.3}_{-6.1}$	$157 \pm 19^{+11}_{-77}$
$X(2600)$	$2618.3 \pm 2.0^{+16.3}_{-1.4}$	$195 \pm 5^{+26}_{-17}$

Case	$f_0(1500)$	$X(1540)$
Events	24585 ± 1689	21203 ± 1456
BF ($\times 10^{-5}$)	$3.09 \pm 0.21^{+1.14}_{-0.77}$	$2.69 \pm 0.19^{+0.38}_{-1.21}$

X(2600)

$$J^{PC} = 0^{-+} or\ 2^{-+}$$



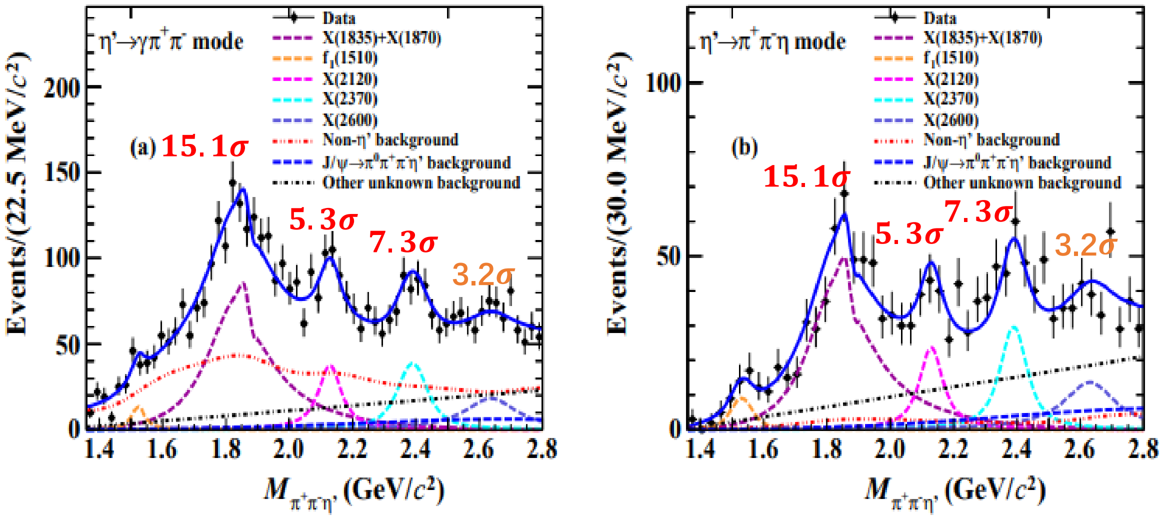
reconstruct η' from $\gamma\pi^+\pi^-$(left) & $\eta(\to\gamma\gamma)\pi^+\pi^-$ (right)

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

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

PRL 129, 022002

- **Confirmation** of $\mathbf{X(1835), X(2120), X(2370)}$ previously observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$



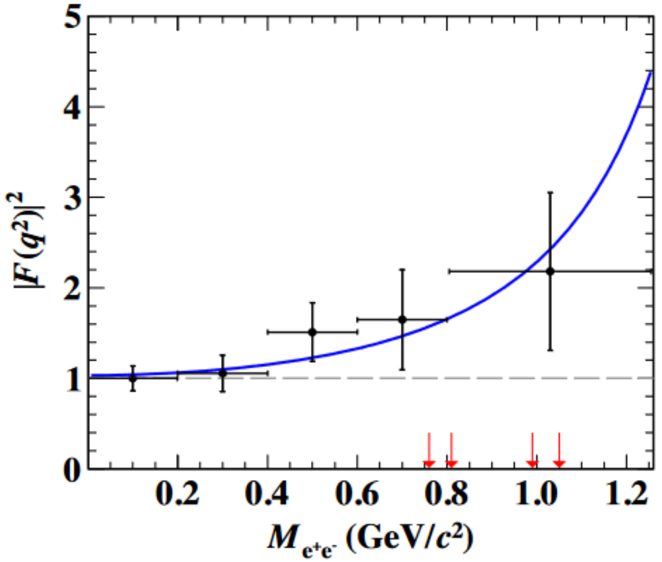
reconstruct η' from $\gamma\pi^+\pi^-$(left) & $\eta(\to\gamma\gamma)\pi^+\pi^-$ (right)

- Measurement of the **Transition Form Factor** of $J/\psi \to e^+e^-X(1835)$
  - ➢Gives additional information of the **internal structure of $\mathbf{X(1835)}$**

$$\frac{d\Gamma(J/\psi\to X(1835)e^+e^-)}{dq^2\Gamma(J/\psi\to X(1835)\gamma)} = |F(q^2)|^2 \times |QED(q^2)|\,,$$

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

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



Summary

- Exciting results from new J/ψ data are presented
  - Isoscalar 1^{-+} exotic : $\eta_1(1855)$
  - New state X(2600) in J/ψ radiative decays

  …
- Data with unprecedented statistical accuracy from BESIII provides great opportunities to study QCD exotics. Will continue to run until ~2030
- BESIII is in good status, inner detector upgrade in progress;

➢ BEPCII-U: 3x upgrade on luminosity

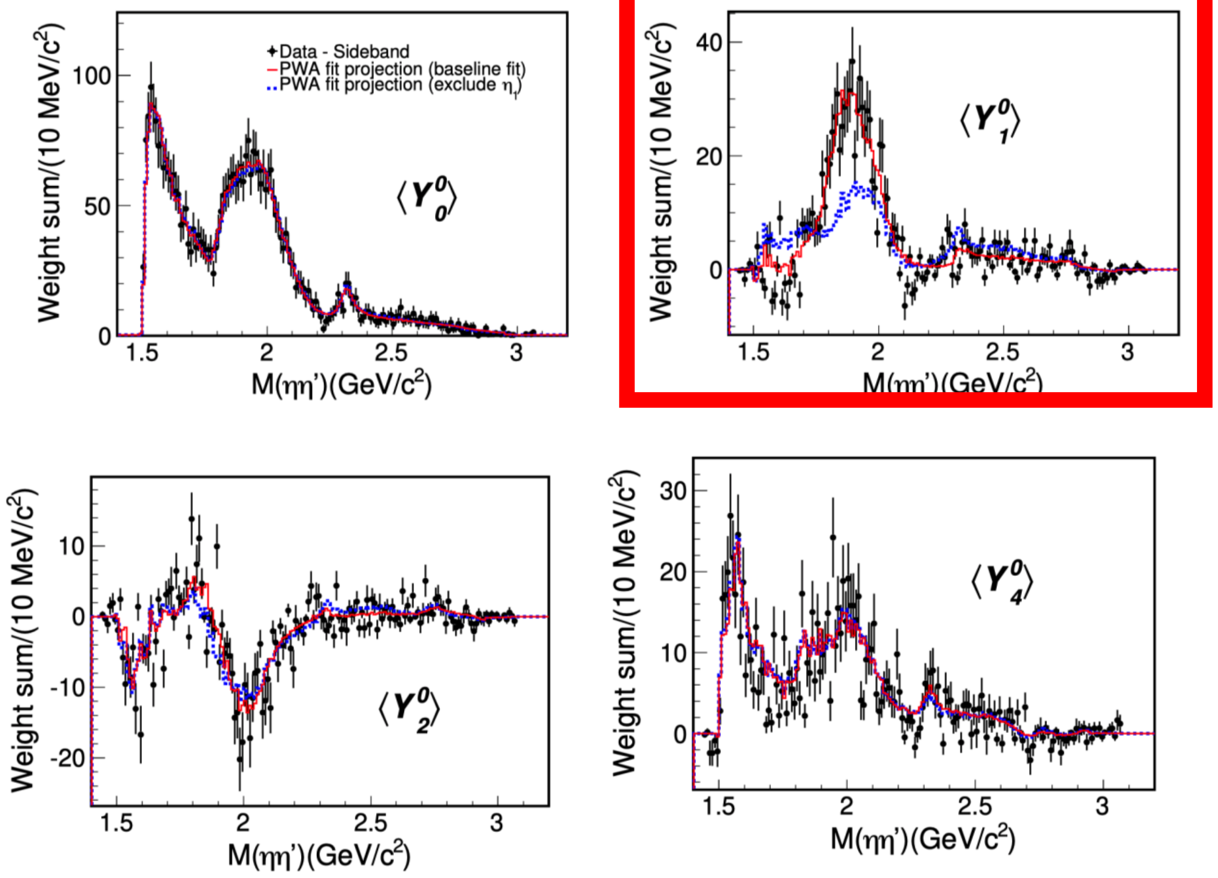
Thank you for your attention!

Backup slide

For comparison

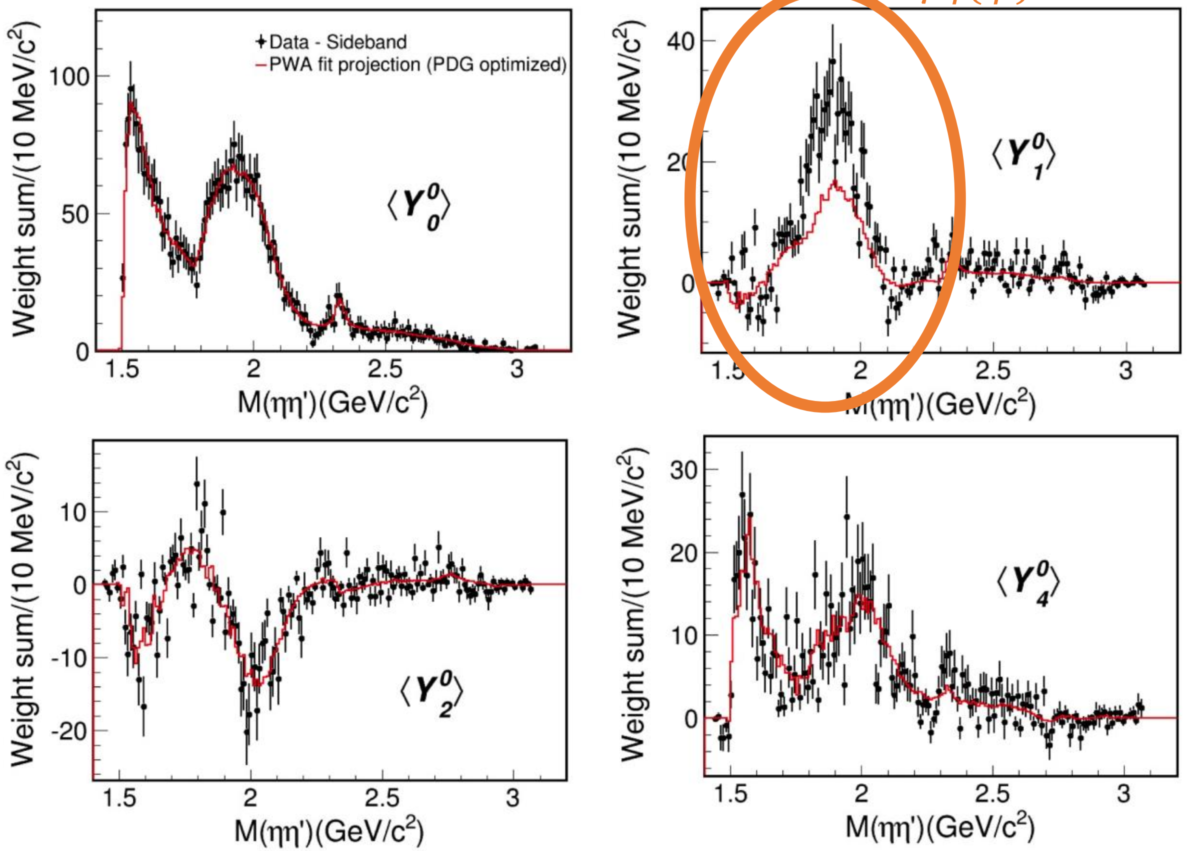
Baseline set of amplitudes

Need for the $\eta_1(1855)$ P-wave



PDG-optimized set of amplitudes

Can not be described only with 1^{+-} and 1^{--} states in $\gamma\eta(\eta')$

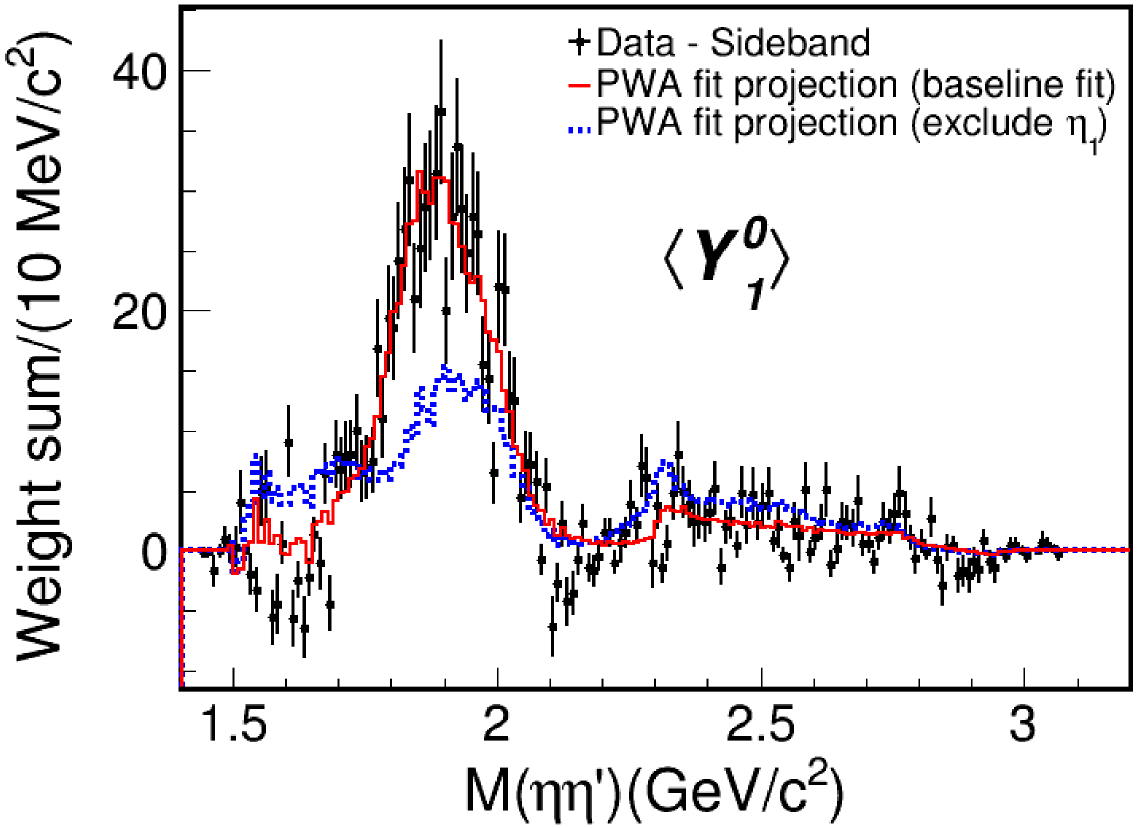


- Narrow structure in $< Y_1^0 >$ cannot be described by resonances in $\gamma\eta(\eta')$
  - $\eta_1(1855) \rightarrow \eta\eta'$ needed

Angular moments without contribution from D wave and F wave

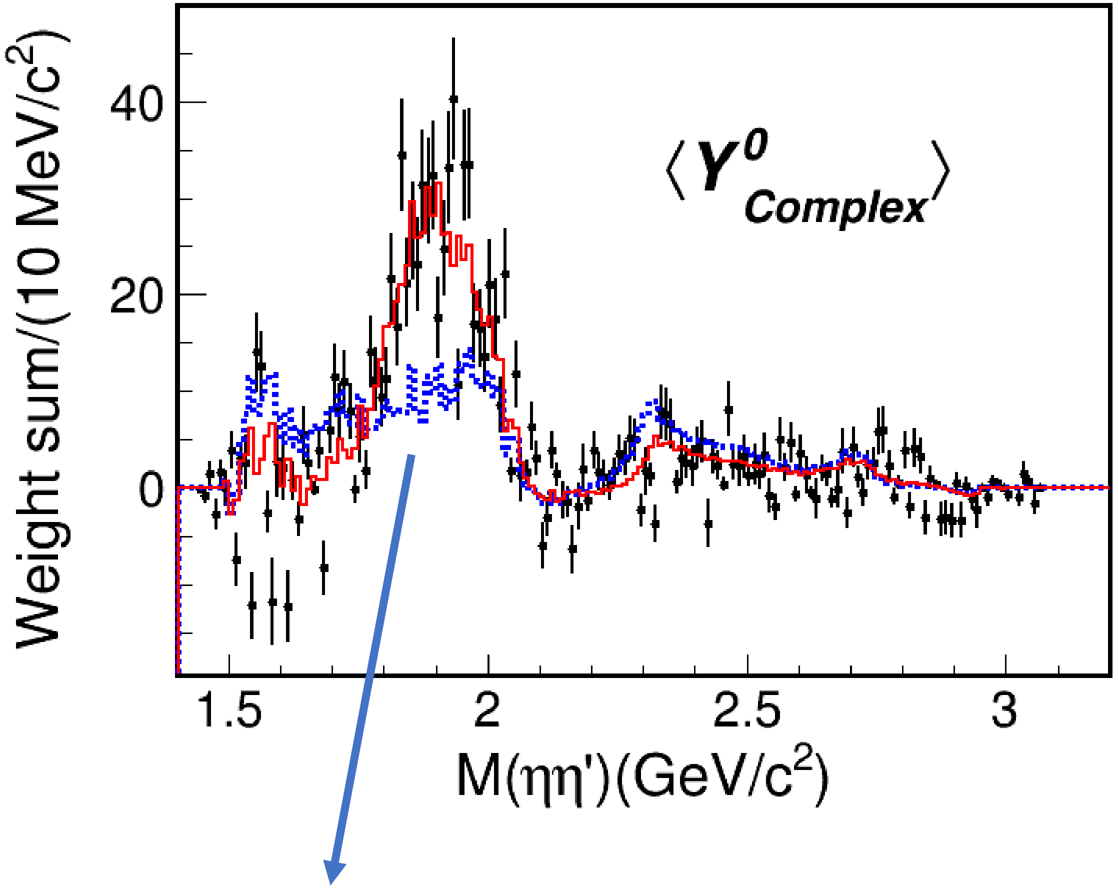
P wave

$$< Y_1^0 > \propto \frac{2}{\sqrt{3}} SP\cos(\phi_P) + \frac{4}{\sqrt{15}} PD\cos(\phi_P - \phi_D) + \frac{6}{\sqrt{35}} DF\cos(\phi_D - \phi_F)$$



P wave

$$< Y_1^0 > - \frac{14}{9} < Y_3^0 > - \frac{308}{225} < Y_5^0 > = \frac{2}{\sqrt{3}} SP\cos(\phi_P)$$

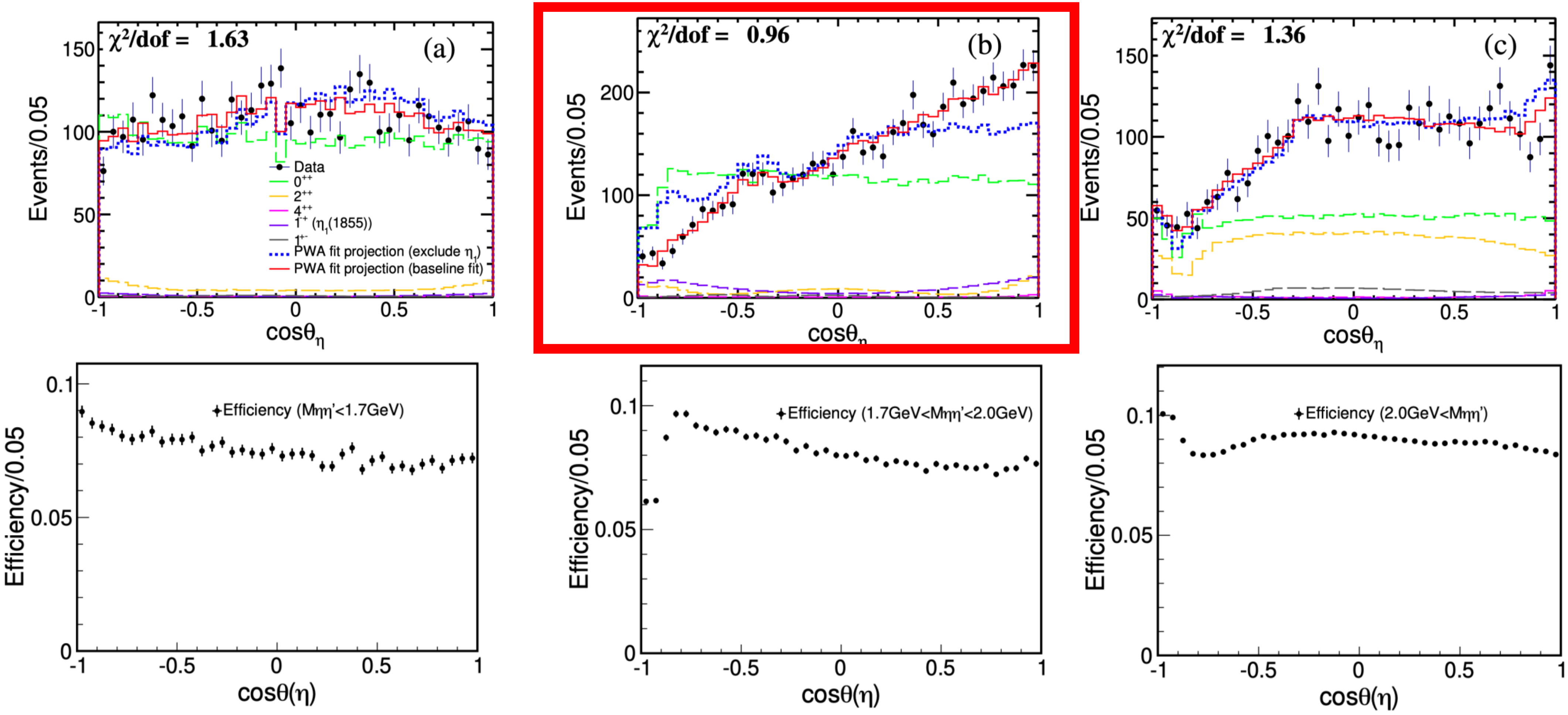


The blue line becomes flat from a peak structure

Further checks on the 1^{-+} state $\eta_1(1855)$

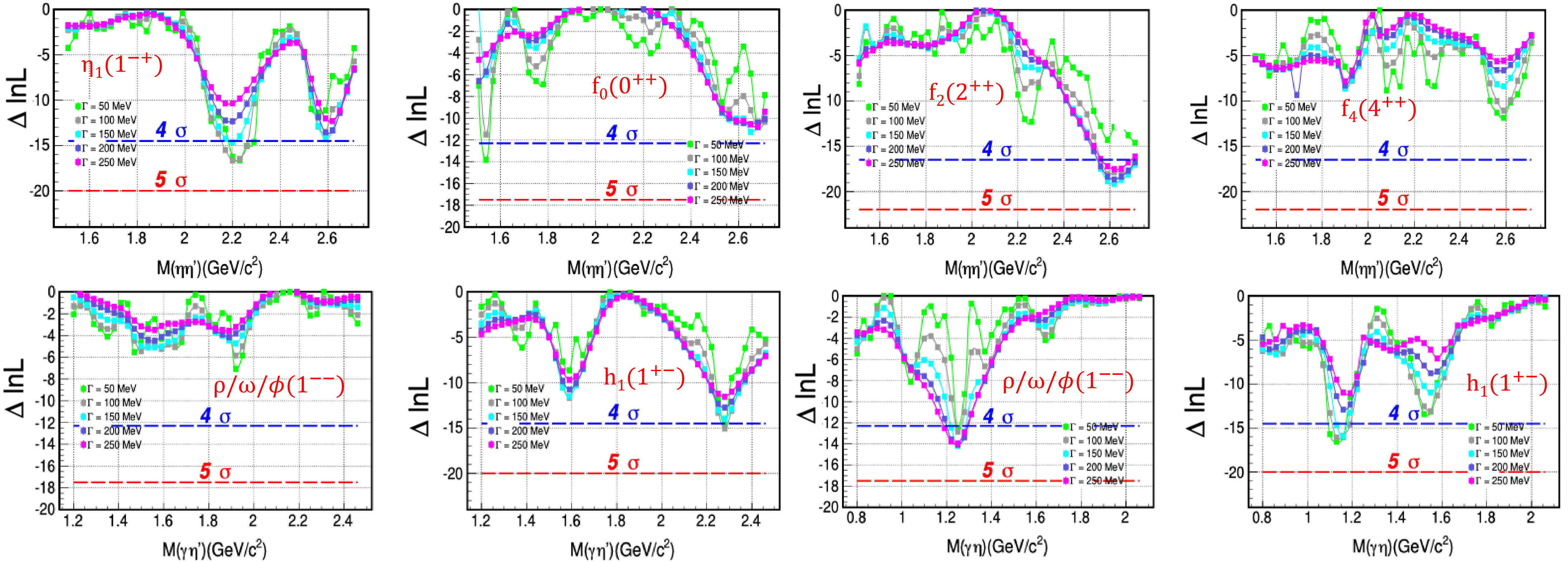
- $\cos\theta_\eta$ distributions in different $M(\eta\eta')$ regions

$M(\eta\eta')<1.7$ GeV/c^2 | 1.7 GeV/c^2 $<M(\eta\eta')<2.0$ GeV/c^2 | $M(\eta\eta')>2.0$ GeV/c^2



✓ Clear asymmetry in the region $[1.7,2.0]\mathrm{GeV}/c^2$, largely due to $\eta_1(1855)$ signal

Scan of additional resonance (based on Baseline set of amplitudes)



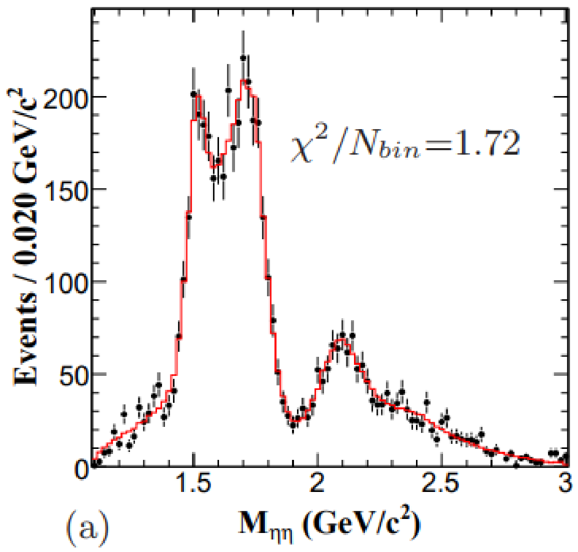
- If two 1^{-+} are introduced in PWA
  - $\eta_1(1855)$: M=1873 ± 7 MeV/c^2, $\Gamma = 225 \pm 7$ MeV, Br is $(2.6 \pm 0.2) \times 10^{-6}$, significance is 15.7σ
  - η_1(additional) : M=2152 ± 3 MeV/c^2, $\Gamma = 134 \pm 2$ MeV, Br is $(3 \pm 1) \times 10^{-7}$, significance is 4.6σ

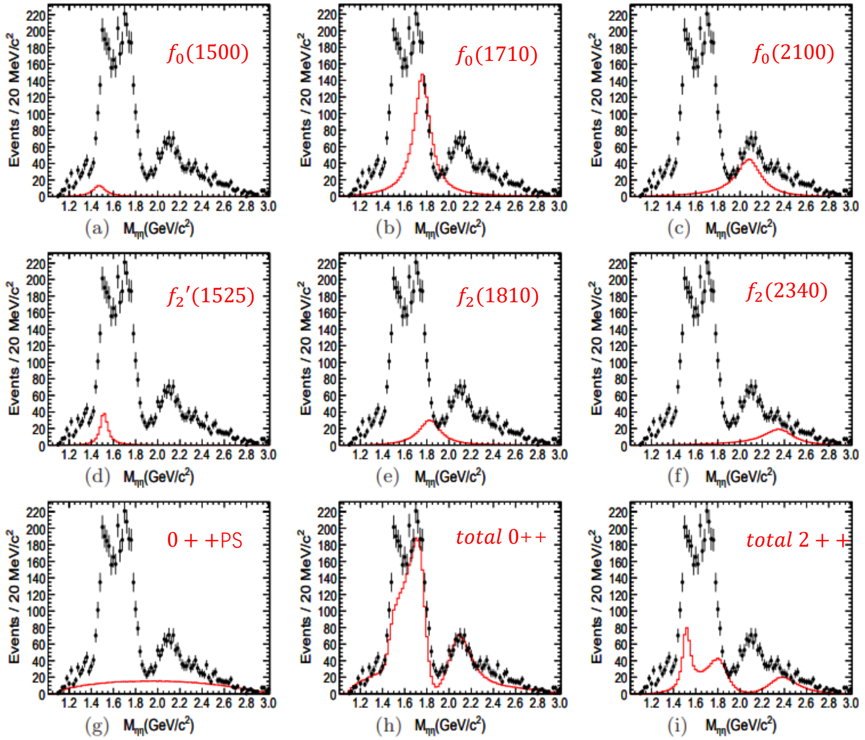
➢ The η_1(additional) is not included in PWA, because of small fraction (0.4%), and significance $< 5\sigma$

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

$2.25 \times 10^8 J/\psi$ at BESIII

PRD 87, 092009 (2013)



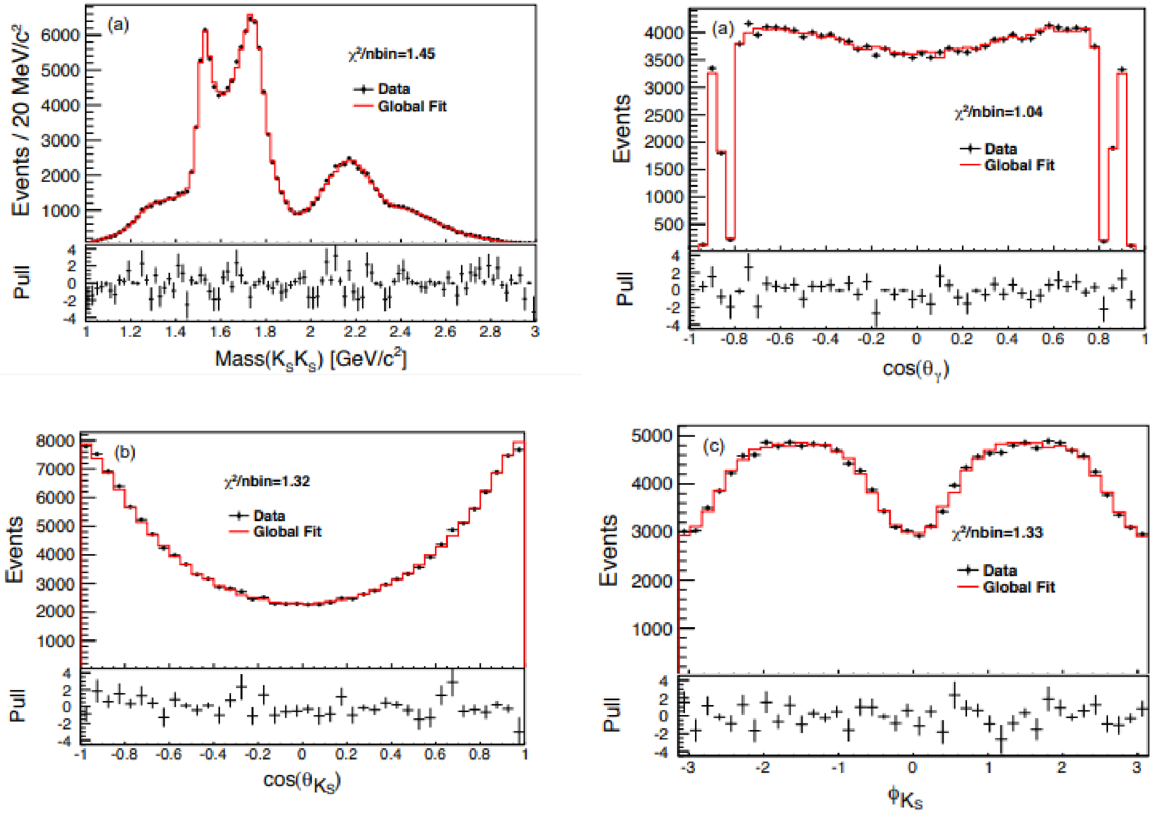


Resonance	Mass(MeV/c^2)	Width(MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2 σ
$f_0(1710)$	$1759\pm6^{+14}_{-25}$	$172\pm10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0 σ
$f_0(2100)$	$2081\pm13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9 σ
$f_2'(1525)$	$1513\pm5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0 σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4 σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6 σ

PWA of $J/\psi \to \gamma K_S^0 K_S^0$

1311M J/ψ at BESIII

PRD 98, 072003 (2018)



Resonance	M (MeV/c^2)	$M_{\rm PDG}$ (MeV/c^2)	Γ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV/c^2)	Branching fraction	Significance
$K^*(892)$	896	895.81±0.19	48	47.4±0.6	$(6.28^{+0.16+0.59}_{-0.17-0.52})\times10^{-6}$	35σ
$K_1(1270)$	1272	1272±7	90	90±20	$(8.54^{+1.07+2.35}_{-1.20-2.13})\times10^{-7}$	16σ
$f_0(1370)$	$1350\pm9^{+12}_{-2}$	1200 to 1500	$231\pm21^{+28}_{-48}$	200 to 500	$(1.07^{+0.08+0.36}_{-0.07-0.34})\times10^{-5}$	25σ
$f_0(1500)$	1505	1504±6	109	109±7	$(1.59^{+0.16+0.18}_{-0.16-0.56})\times10^{-5}$	23σ
$f_0(1710)$	$1765\pm2^{+1}_{-1}$	1723^{+6}_{-5}	$146\pm3^{+7}_{-1}$	139±8	$(2.00^{+0.03+0.31}_{-0.02-0.10})\times10^{-4}$	$\gg35\sigma$
$f_0(1790)$	$1870\pm7^{+2}_{-3}$	-	$146\pm14^{+7}_{-15}$	-	$(1.11^{+0.06+0.19}_{-0.06-0.32})\times10^{-5}$	24σ
$f_0(2200)$	$2184\pm5^{+4}_{-2}$	2189±13	$364\pm9^{+4}_{-7}$	238±50	$(2.72^{+0.08+0.17}_{-0.06-0.47})\times10^{-4}$	$\gg35\sigma$
$f_0(2330)$	2411±10±7	-	$349\pm18^{+23}_{-1}$	-	$(4.95^{+0.21+0.66}_{-0.21-0.72})\times10^{-5}$	35σ
$f_2(1270)$	1275	1275.5±0.8	185	$186.7^{+2.2}_{-2.5}$	$(2.58^{+0.08+0.59}_{-0.09-0.20})\times10^{-5}$	33σ
$f_2'(1525)$	1516±1	1525±5	75±1±1	73^{+6}_{-5}	$(7.99^{+0.03+0.69}_{-0.04-0.50})\times10^{-5}$	$\gg35\sigma$
$f_2(2340)$	$2233\pm34^{+9}_{-25}$	2345^{+50}_{-40}	$507\pm37^{+18}_{-21}$	322^{+70}_{-60}	$(5.54^{+0.34+3.82}_{-0.40-1.49})\times10^{-5}$	26σ
0^{++} PHSP	-	-	-	-	$(1.85^{+0.05+0.68}_{-0.05-0.26})\times10^{-5}$	26σ
2^{++} PHSP	-	-	-	-	$(5.73^{+0.99+4.18}_{-1.00-3.74})\times10^{-5}$	13σ

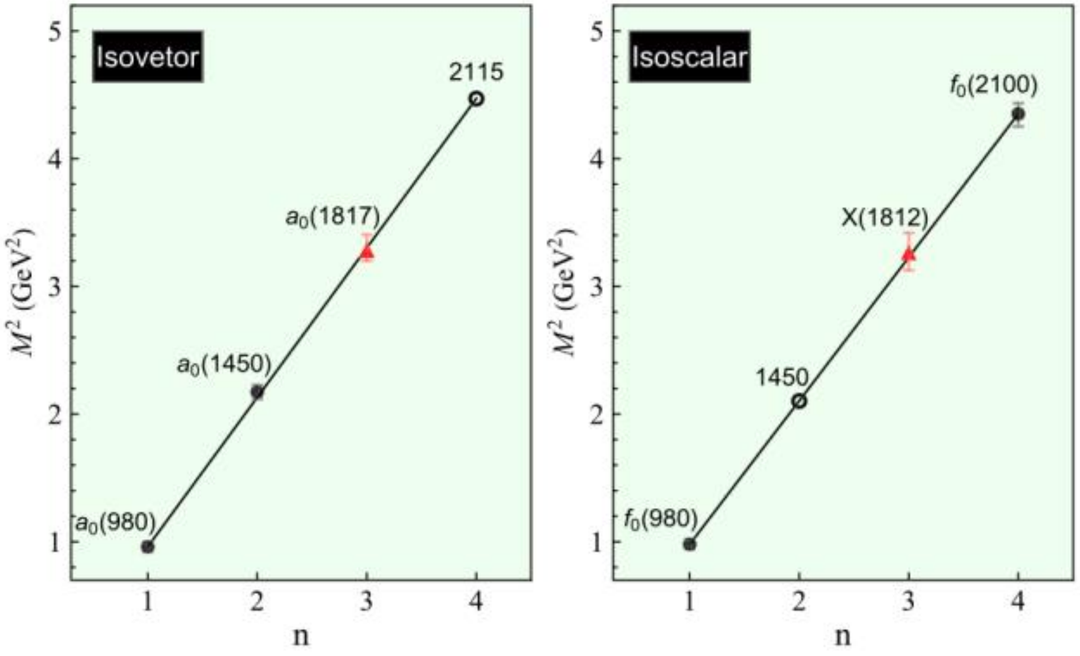
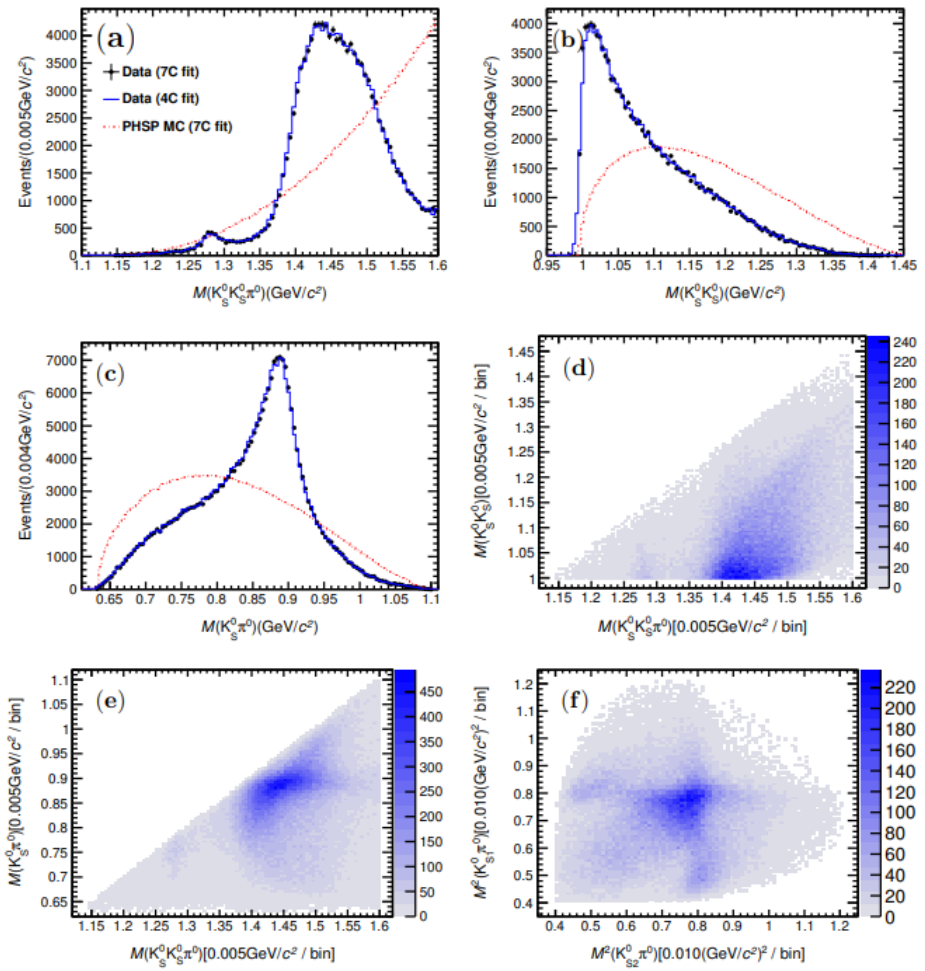
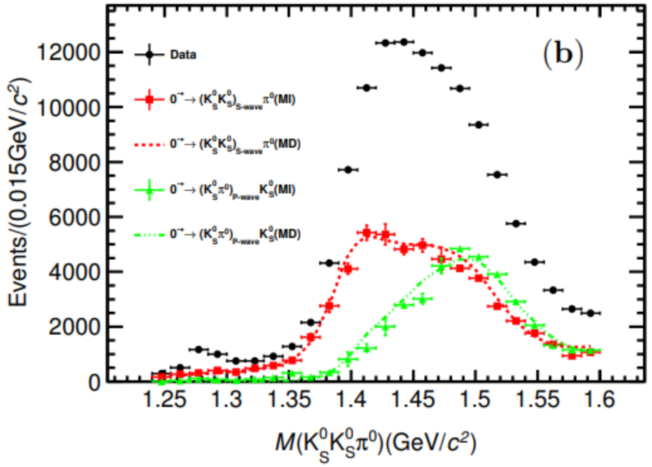


FIG. 1. Two Regge trajectories for the isovector and isoscalar scalar states. Here, the red triangles denote the $a_0(1817)$ and $X(1812)$, while the solid points and empty circles are the experimental and predicted states, respectively. Except the $a_0(1817)$, $X(1812)$ and predicted $a_0(2115)$, $f_0(1450)$, 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.

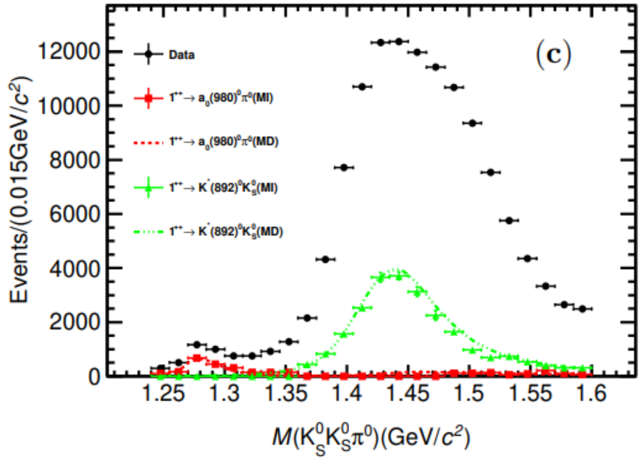
Detail plots of $J/\psi \to \gamma K_s^0 K_s^0 \pi^0$



Mass distributions and Dalitz plots

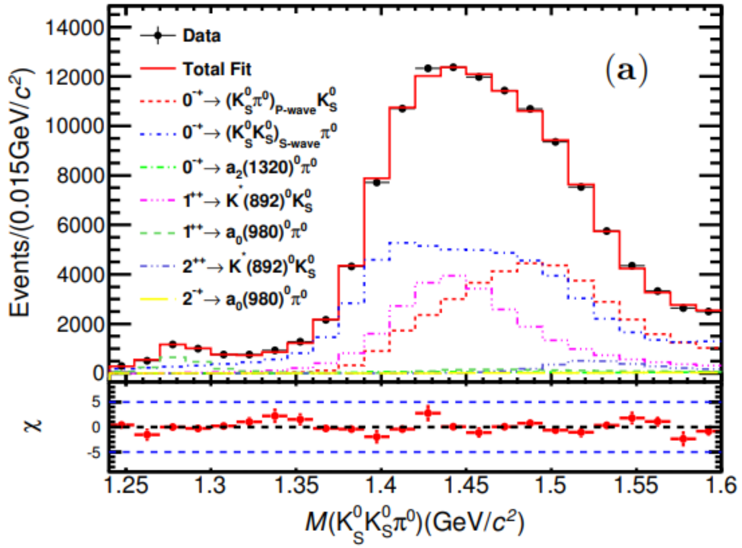


dominant decay modes for the pseudoscalar component



dominant decay modes for the axial vector component

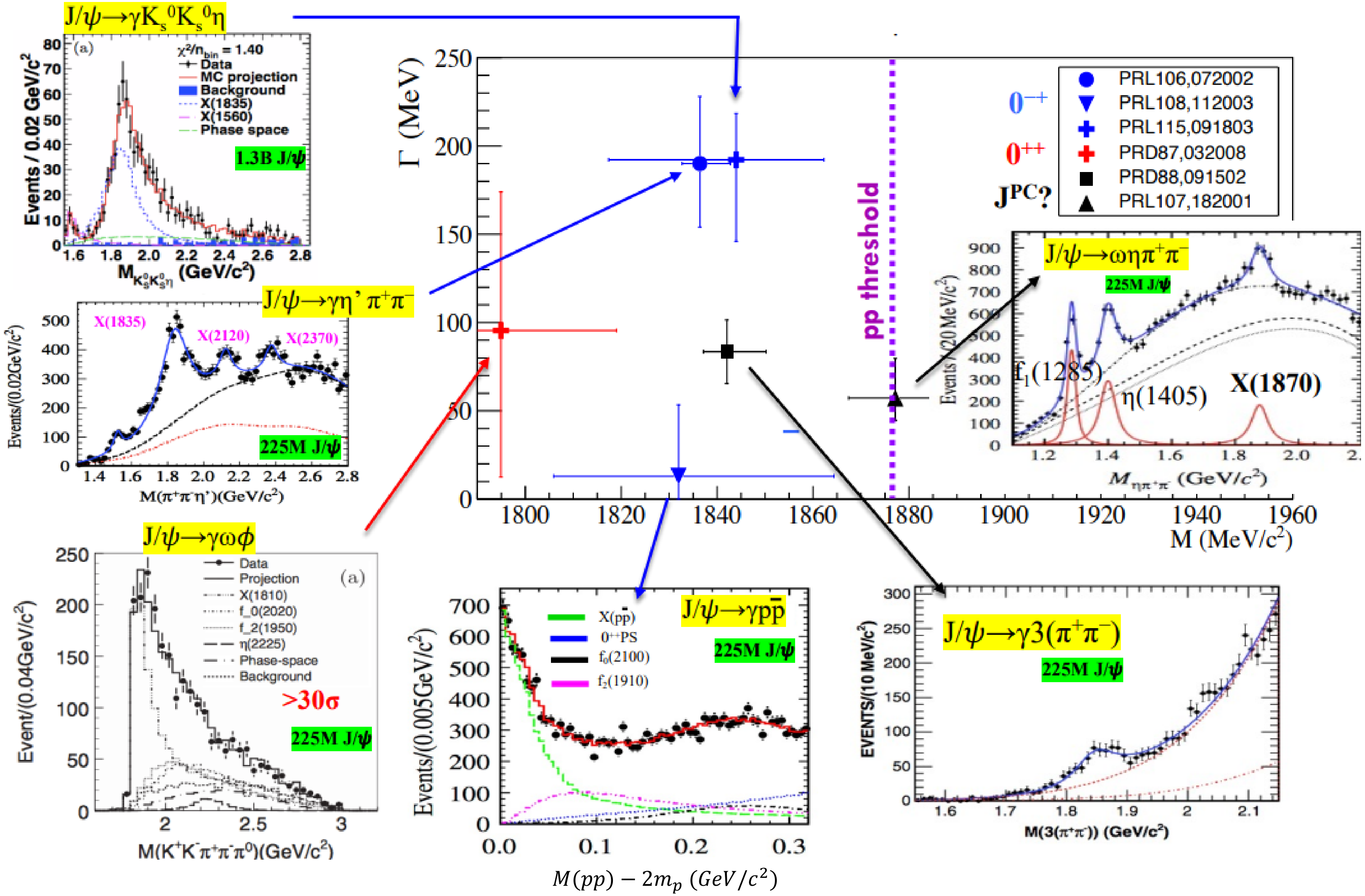
Detail plots of $J/\psi \to \gamma K_s^0 K_s^0 \pi^0$



Resonance	Decay Mode	Event selection	Breit-Wigner formula	Resonance parameters	Extra components	Total
$\eta(1405)$	$J/\psi \to \gamma\eta(1405) \to \gamma K_S^0(K_S^0\pi^0)_{\text{P-wave}} \to \gamma K_S^0K_S^0\pi^0$	±4.0	$^{+28.1}_{-56.8}$	$+20.0$	$^{+2.8}_{-7.8}$	$^{+34.8}_{-57.5}$
	$J/\psi \to \gamma\eta(1405) \to \gamma(K_S^0K_S^0)_{\text{S-wave}}\pi^0 \to \gamma K_S^0K_S^0\pi^0$	±4.0	$^{+19.0}_{-7.5}$	$+53.1$	$^{+6.1}_{-10.0}$	$^{+56.9}_{-13.1}$
$\eta(1475)$	$J/\psi \to \gamma\eta(1475) \to \gamma K_S^0(K_S^0\pi^0)_{\text{P-wave}} \to \gamma K_S^0K_S^0\pi^0$	±4.0	$^{+59.4}_{-42.5}$	$+8.9$	$^{+5.8}_{-3.1}$	$^{+60.5}_{-42.8}$
	$J/\psi \to \gamma\eta(1475) \to \gamma(K_S^0K_S^0)_{\text{S-wave}}\pi^0 \to \gamma K_S^0K_S^0\pi^0$	±4.0	$^{+5.5}_{-7.4}$	-13.7	$^{+7.8}_{-4.3}$	$^{+10.3}_{-16.6}$
$f_1(1285)$	$J/\psi \to \gamma f_1(1285) \to \gamma a_0(980)^0\pi^0 \to \gamma K_S^0K_S^0\pi^0$	±4.0	$^{+1.0}_{-11.2}$	$+4.3$	$^{+39.6}_{-2.5}$	$^{+40.0}_{-12.2}$
$f_1(1420)$	$J/\psi \to \gamma f_1(1420) \to \gamma K^*(892)^0K_S^0 \to \gamma K_S^0K_S^0\pi^0$	±4.0	$^{+2.5}_{-16.8}$	$+6.4$	$^{+6.1}_{-1.2}$	$^{+10.0}_{-17.3}$
	$J/\psi \to \gamma f_1(1420) \to \gamma a_0(980)^0\pi^0 \to \gamma K_S^0K_S^0\pi^0$	±4.0	$^{+15.8}_{-41.8}$	$+7.8$	$+47.8$	$^{+51.1}_{-42.0}$
$f_2(1525)$	$J/\psi \to \gamma f_2(1525) \to \gamma K^*(892)^0K_S^0 \to \gamma K_S^0K_S^0\pi^0$	±4.0	$^{+15.3}_{-4.7}$	-3.3	$^{+1.9}_{-0.5}$	$^{+15.9}_{-7.0}$

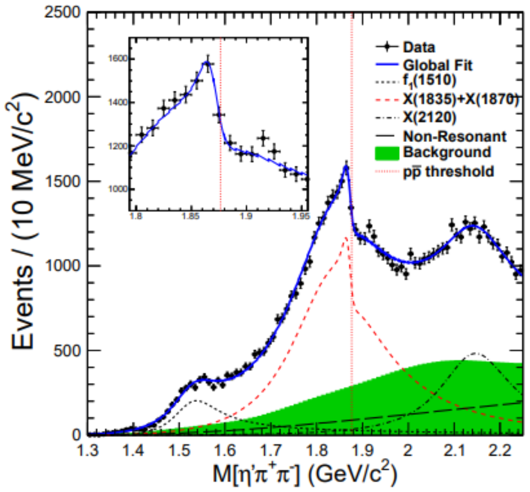
MD PWA results

X(18xx) between 1.8-1.9GeV



Other results on X(1835)

PRL 117, 042002 (2016)



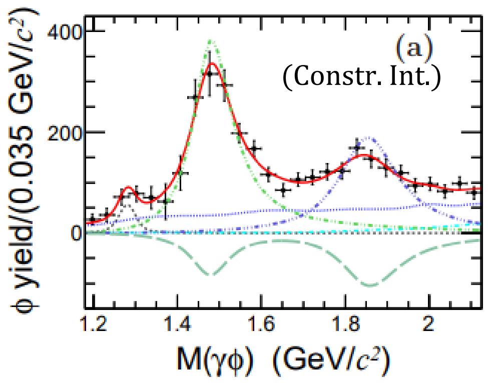
$1.09\times10^{9} J/\psi$ at BESIII

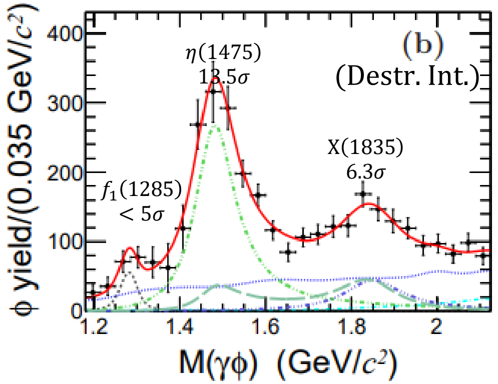
$\boldsymbol{J/\psi \to \gamma\pi^{+}\pi^{-}\eta'}$

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

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

PRD 97,051101(R) (2018)





$1.3\times10^{9} J/\psi$ at BESIII

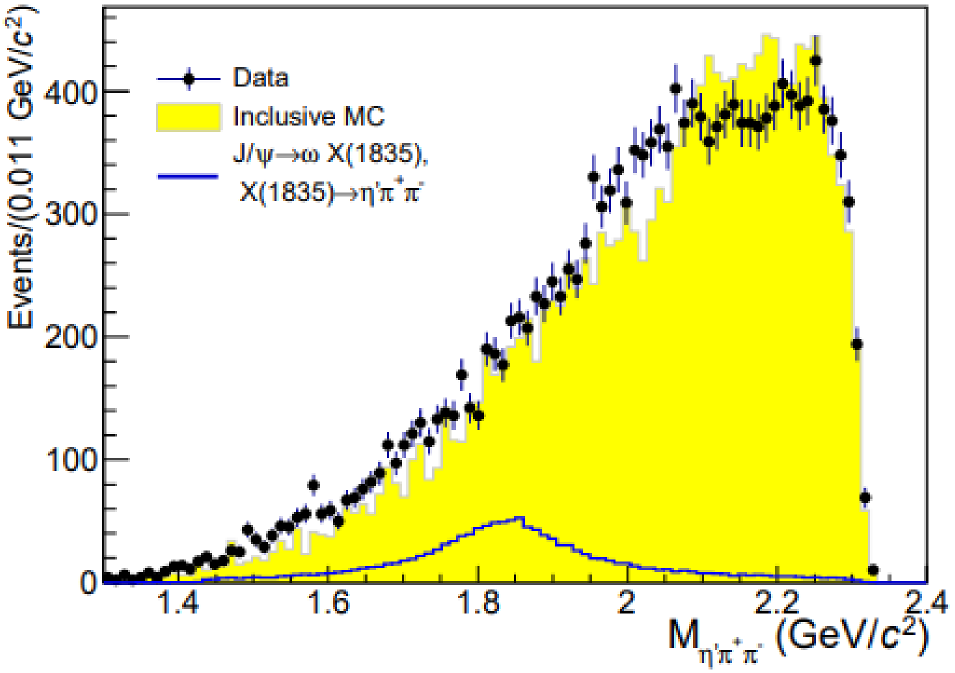
$\boldsymbol{J/\psi \to \gamma\gamma\phi}$: two structures corresponding to $\eta(1475)$ and X(1835) are observed

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

Solution	Resonance	m_R (MeV/c^2)	Γ (MeV)	B (10^{-6})
(Destr. Int.)	$\eta(1475)$	$1477\pm7\pm13$	$118\pm22\pm17$	$7.03\pm0.92\pm0.91$
	$X(1835)$	$1839\pm26\pm26$	$175\pm57\pm25$	$1.77\pm0.35\pm0.25$
(Constr. Int.)	$\eta(1475)$	$1477\pm7\pm13$	$118\pm22\pm17$	$10.36\pm1.51\pm1.54$
	$X(1835)$	$1839\pm26\pm26$	$175\pm57\pm25$	$8.09\pm1.99\pm1.36$

Search for X(1835) in other decay modes

PRD 99, 071101 (R) (2019)



$1.3 \times 10^9 J/\psi$ at BESIII

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

No obvious sign of X(1835)'s existence

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

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

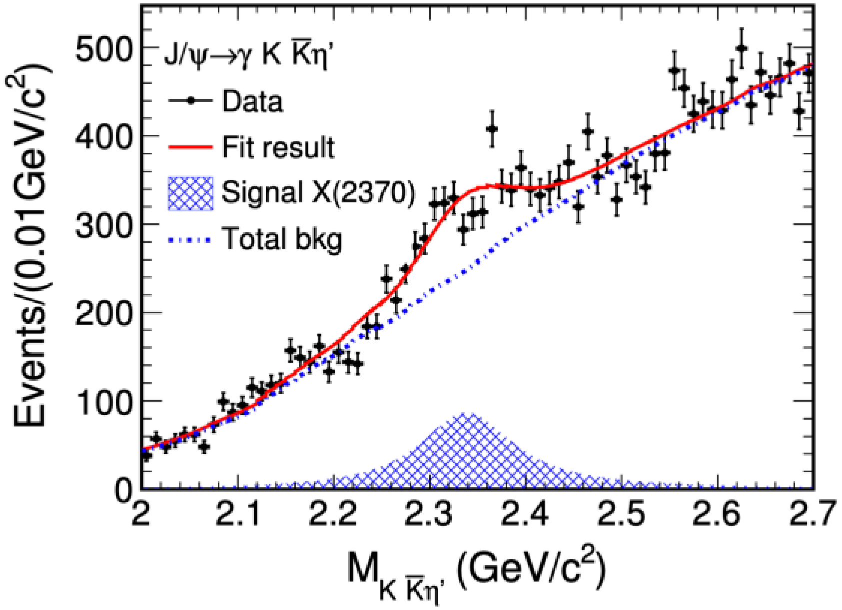
@90%C.L.

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

$1.3 \times 10^9 J/\psi$ at BESIII

EPJC 80, 746 (2020)

- X(2120) and X(2370) states observed in the $\eta'\pi^+\pi^-$ invariant mass spectra(PRL106,072002)
- The X(2370) measured mass is consistent with the pseudoscalar glueball candidate predicted by LQCD calculation(PRD73,014516)



No evidence of X(2120)

$B(J/\psi \rightarrow \gamma X(2120) \rightarrow \gamma K^+K^-\eta') < 1.49 \times 10^{-5}$

$B(J/\psi \rightarrow \gamma X(2120) \rightarrow \gamma K_S^0 K_S^0 \eta') < 6.38 \times 10^{-5}$

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

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

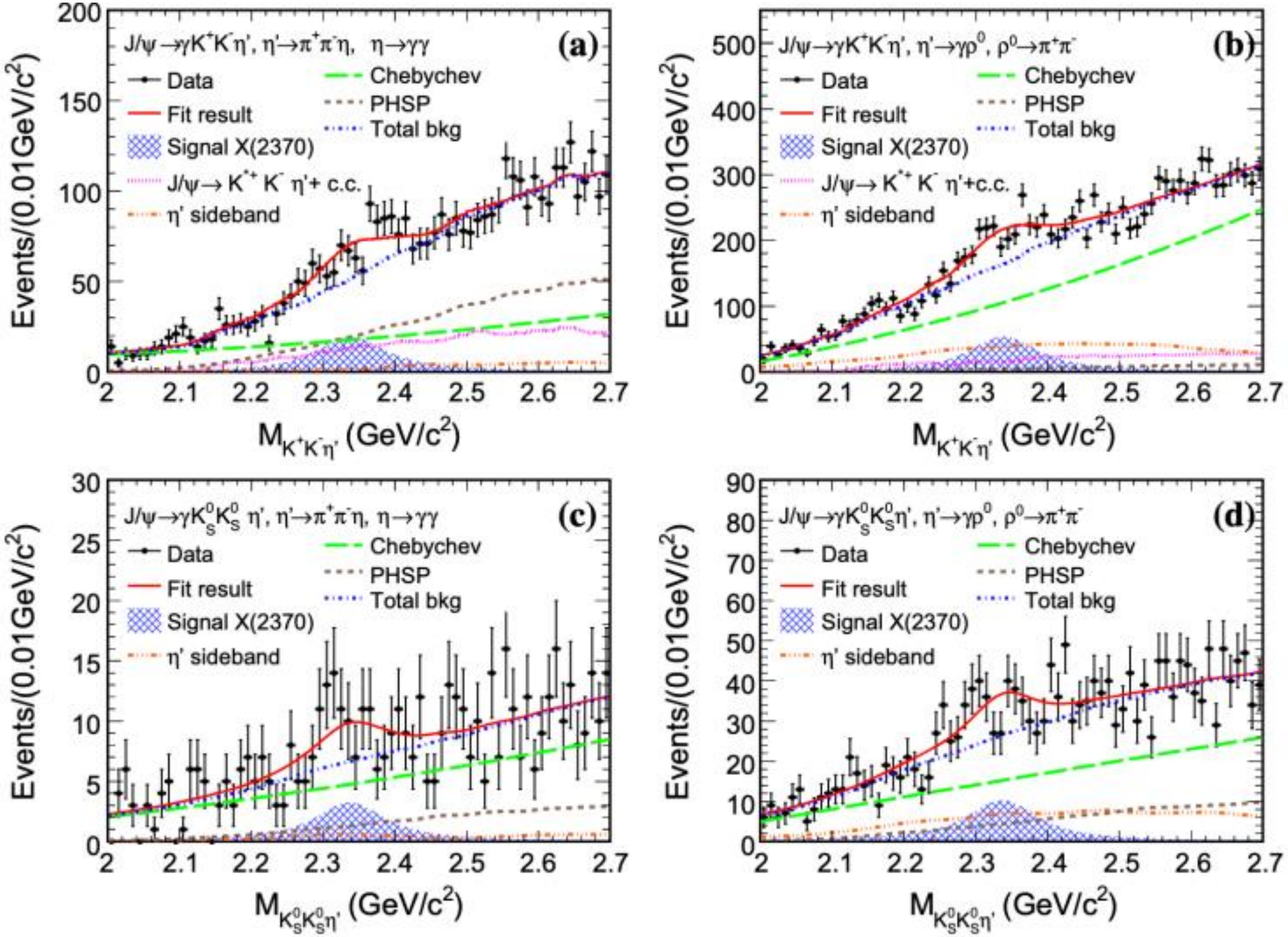
$B(J/\psi \rightarrow \gamma X(2370) \rightarrow \gamma K^+K^-\eta') < 1.49 \times 10^{-5}$

$B(J/\psi \rightarrow \gamma X(2370) \rightarrow \gamma K_S^0 K_S^0 \eta') < 6.38 \times 10^{-5}$

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

$1.3 \times 10^9 J/\psi$ at BESIII

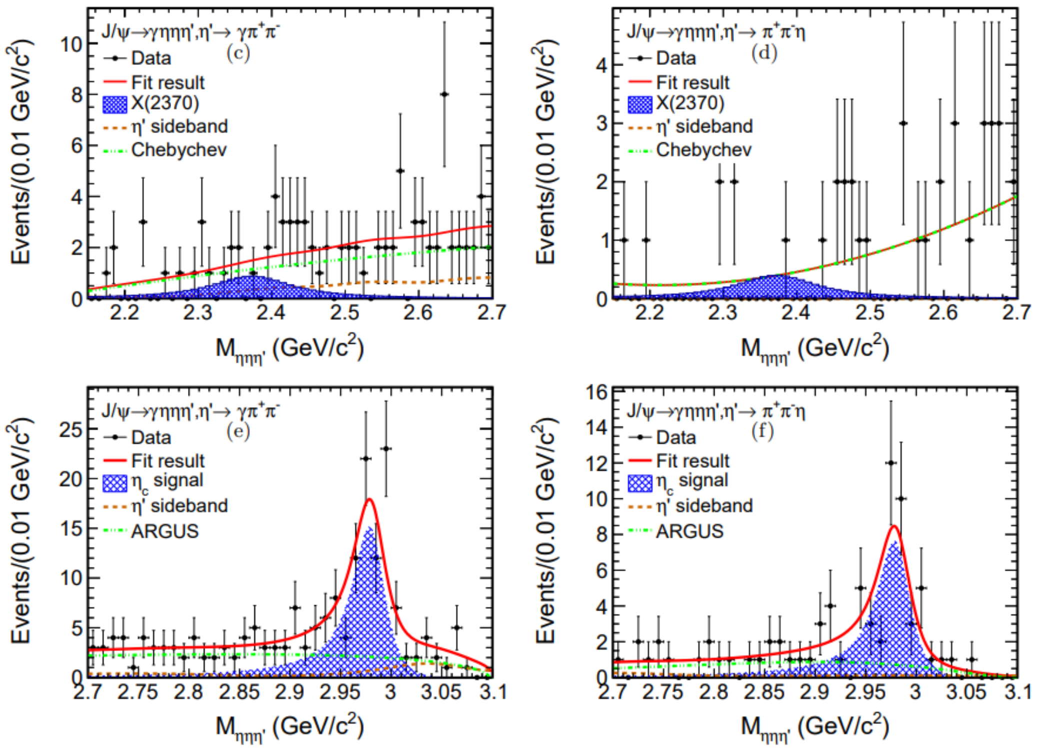
EPJC 80, 746 (2020)



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

$1.3 \times 10^9 J/\psi$ at BESIII

PRD 103, 012009 (2021)



No evidence of X(2120)

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

First Observation in the $\eta\eta\eta'$ invariant mass spectra

$B(J/\psi \to \gamma\eta_c) \cdot B(\eta_c \to \eta\eta\eta') = (4.86 \pm 0.62 \pm 0.45) \times 10^{-5}$