Recent Results from Light Hadron Spectroscopy @ BESIII

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On behalf of the BESIII Collaboration

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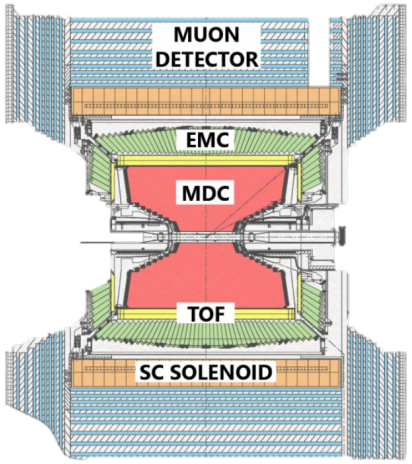
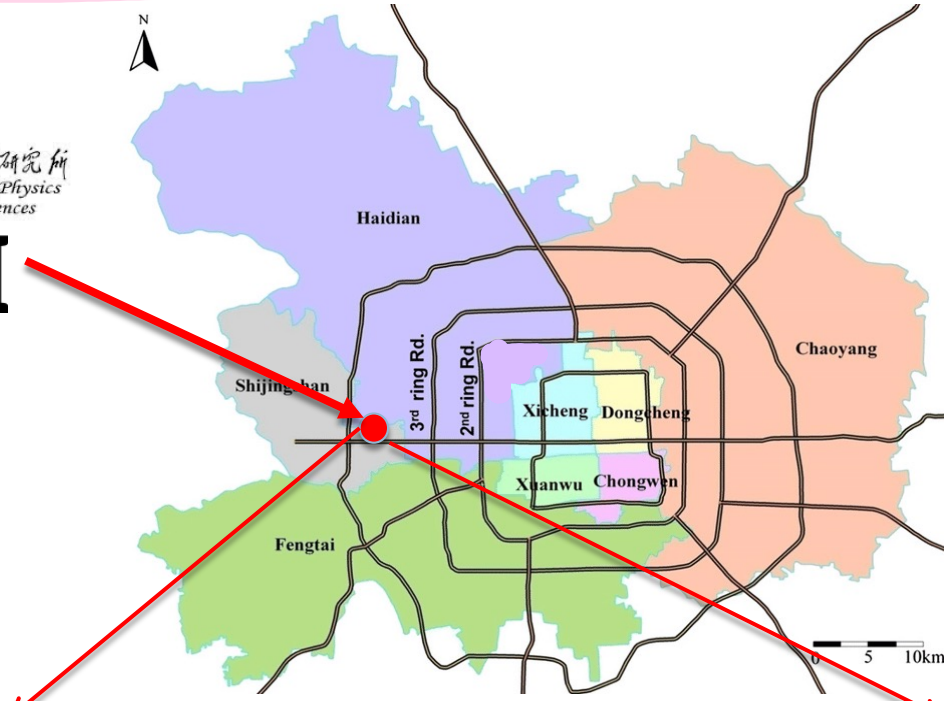
The BESIII experiment @ BEPCII



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

BESIII



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

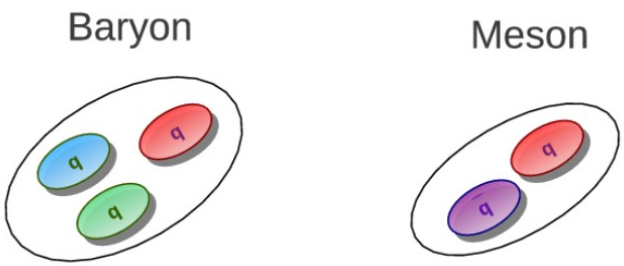
2004: started Beijing Electron Positron Collider II/BESIII construction

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

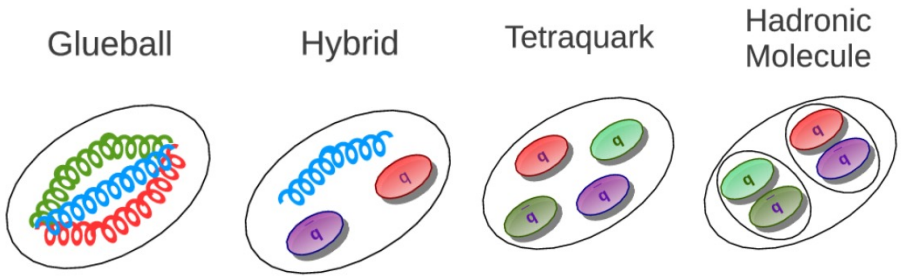
2009 – today: BESIII physics runs

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

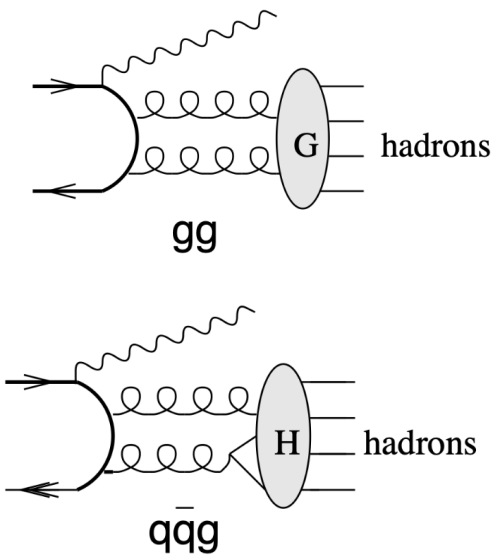
A lot of exotic states observed experimentally, but their nature is still far from being understood!!!

@ BESIII J/ψ **10.1×10^9**

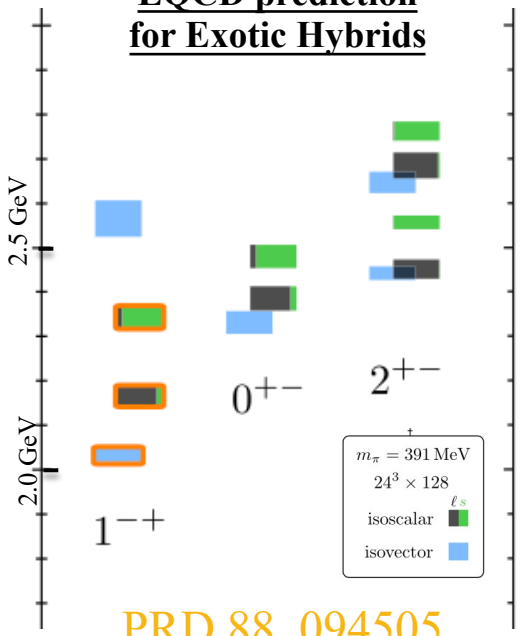
Light hadron physics
- Meson and baryon spectroscopy
- Glueballs and hybrids
- ….

Hunting for glueballs and new form of hadrons

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

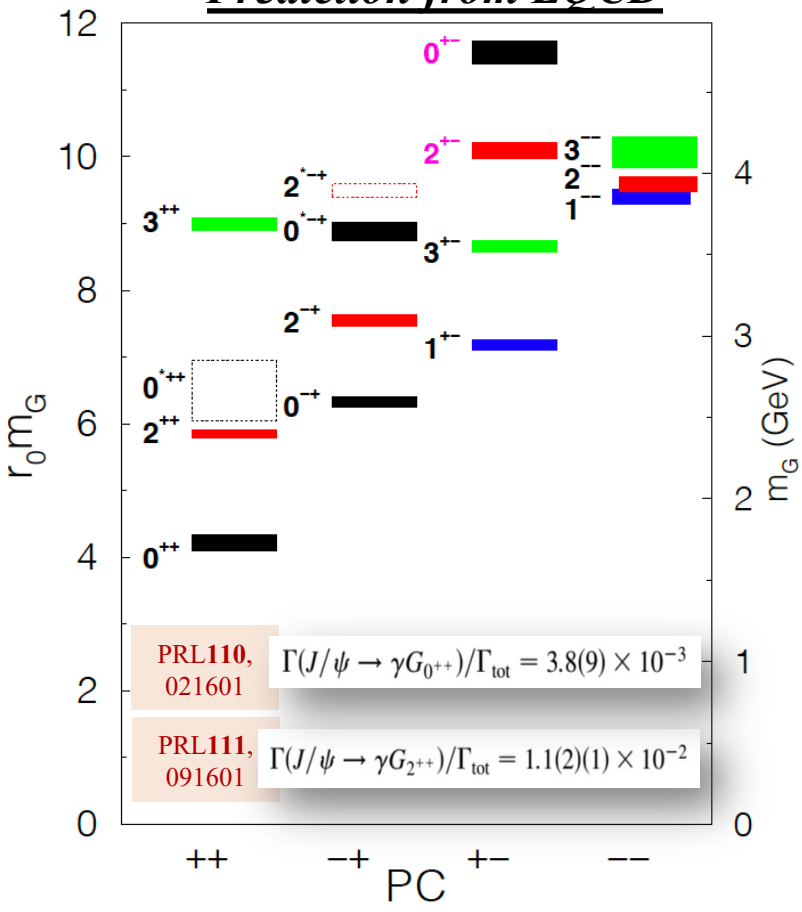


LQCD prediction for Exotic Hybrids



PRD 88, 094505

Prediction from LQCD



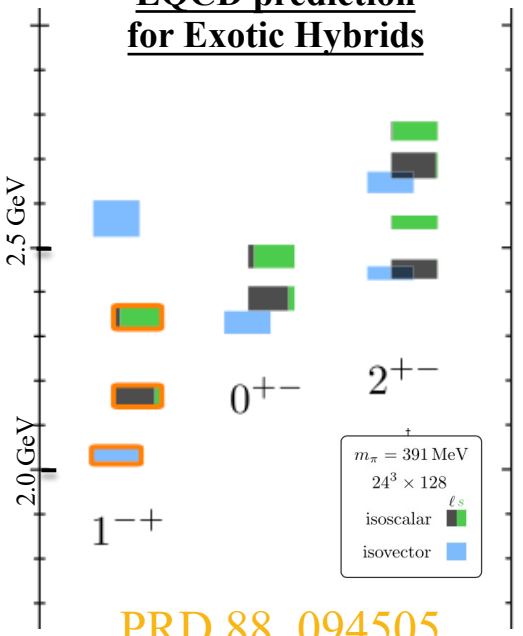
https://doi.org/10.1142/S0218301309012124

Hunting for glueballs and new form of hadrons

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

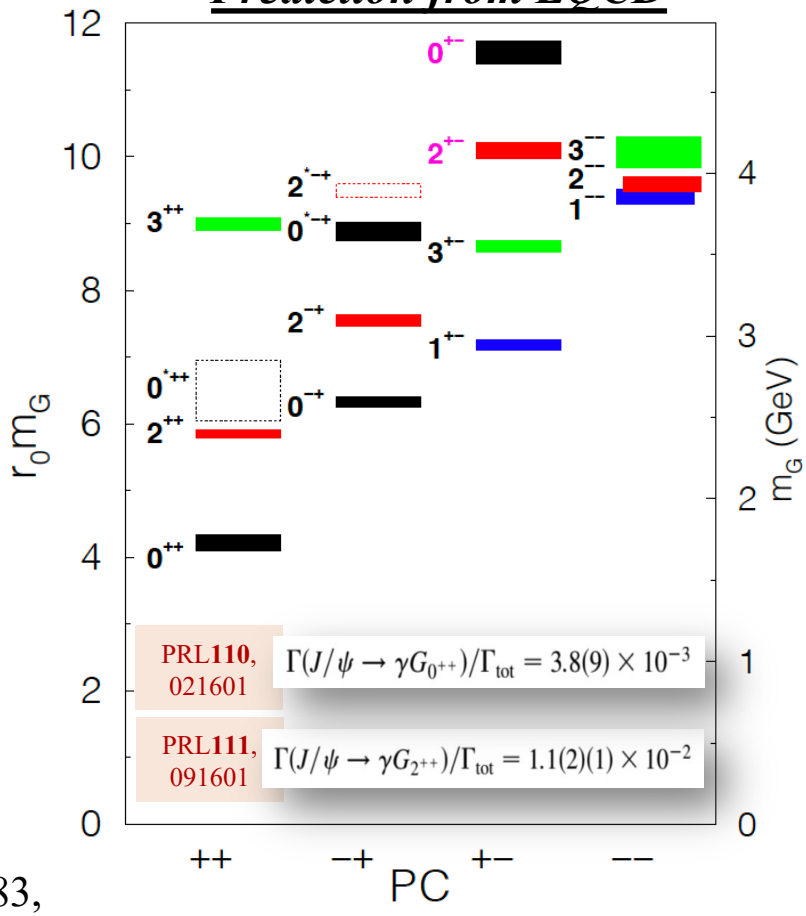
- **Exotic Hybrids**:
  $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$ (forbidden in the conventional QCD scheme)
- The exotic $J^{PC} = 1^{-+}$ nonet of hybrids is predicted to be the lightest
- Only isovector candidate observed yet: $\pi_1(1400)$, $\pi_1(1600)$ [the most extensively studied], $\pi_1(2015)$

LQCD prediction for Exotic Hybrids



PRD 88, 094505

Prediction from LQCD



https://doi.org/10.1142/S0218301309012124

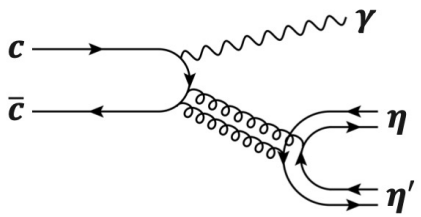
- **Establish the hybrid nonet**:
  - Isoscalar 1^{-+} hybrids
  - Can decay to ηη' in P-wave (PRD 83,014021, PRD 83, 014006, Eur.Phys.J.Plus 135, 945)

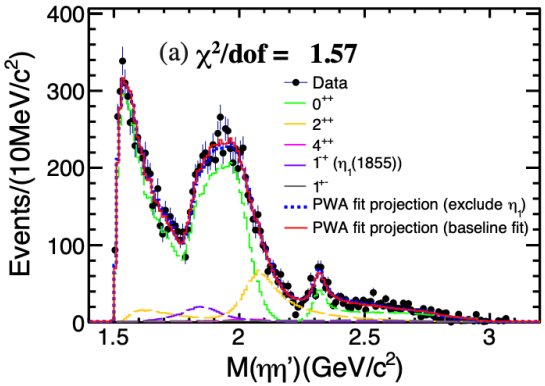
Observation of Exotic Isoscalar State $\eta_1(1855)$ in $J/\psi\to\gamma\eta\eta'$

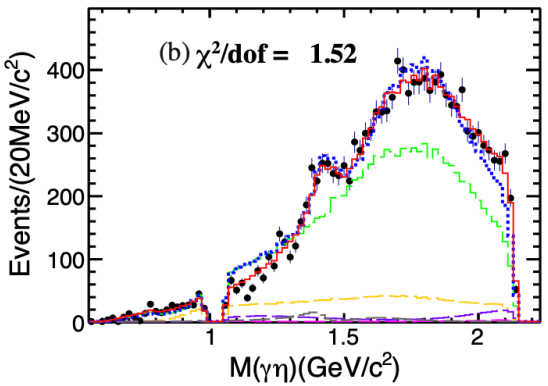
PRL 129, 192002 (2022)
PRD 106,072012 (2022)

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

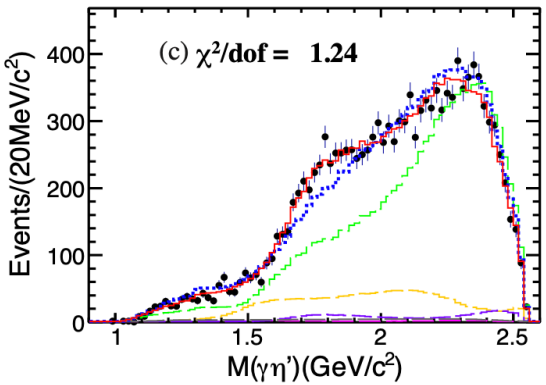
- $\eta\to\gamma\gamma$ and $\eta'\to\gamma\pi^+\pi^-$/ $\eta\pi^+\pi^-$

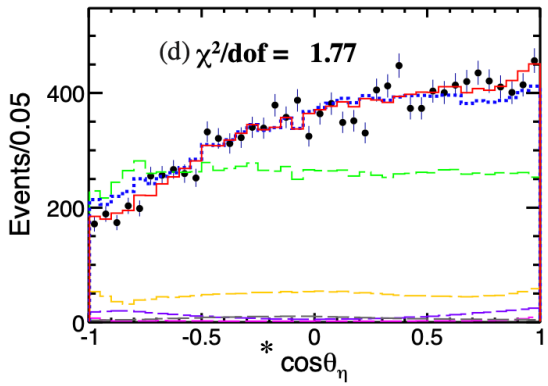






- An isoscalar 1^{-+} state, $\eta_1(1855)$, has been observed with statistical significance larger than 19σ
- Mass is consistent with LQCD calculation for the 1^{-+} hybrid (1.7 – 2.1 GeV/c^2)





*spin information

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

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

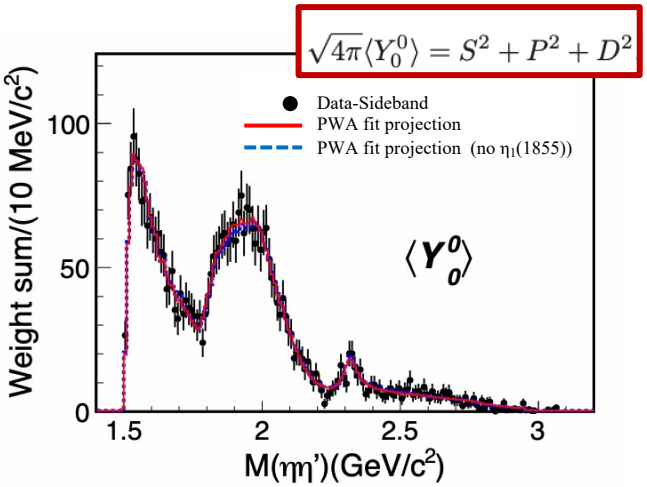
Further Checks on the $\eta_1(1855)$

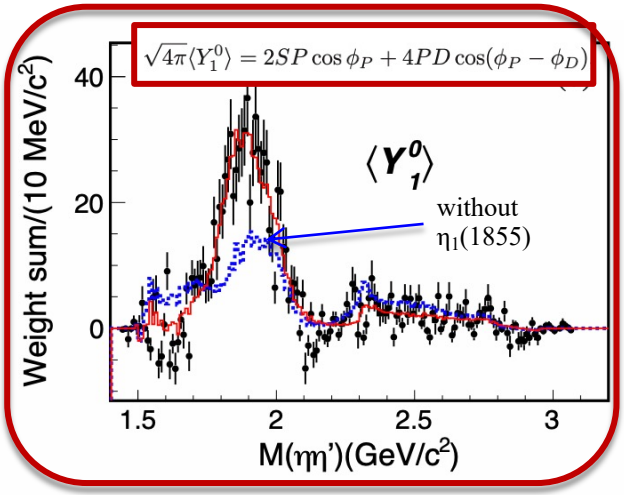
PRL 129, 192002 (2022)
PRD 106,072012 (2022)

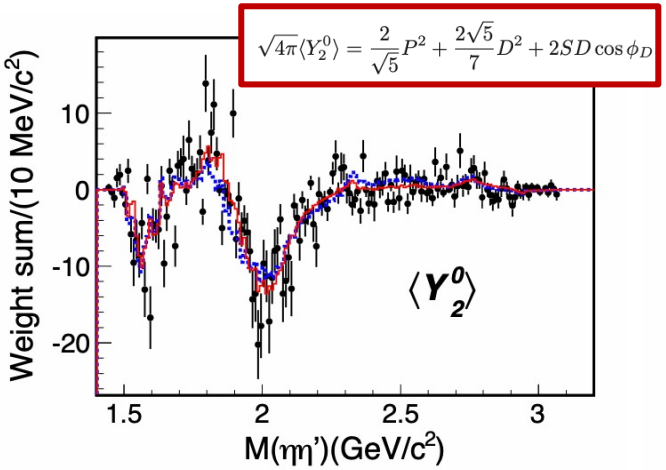
The $\cos(\theta_\eta)$ distribution can be expressed as an expansion in terms of Legendre polynomials; the coefficients (unnormalized moments of expansion) characterize the spin of the ηη' resonances

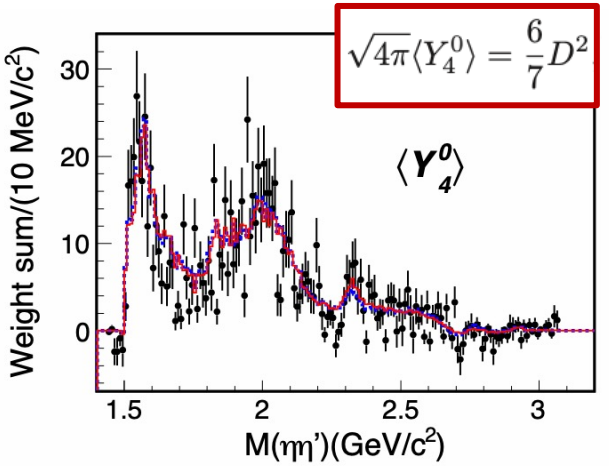
$$\langle Y_l^0 \rangle \equiv \sum_{i=1}^{N_k} W_i Y_l^0(\cos\theta_\eta^i).$$

- Neglecting resonance contributions in the $\gamma\eta^{(')}$ 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









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

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

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

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	$M_{\rm PDG}$ (MeV/c^2)	$\Gamma_{\rm PDG}$ (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

$$\frac{\mathcal{B}(f_0(1500)\to\eta\eta')}{\mathcal{B}(f_0(1500)\to\pi\pi)} = (8.96^{+2.95}_{-2.87})\times 10^{-2}$$

Consistent with PDG

$$\frac{\mathcal{B}(f_0(1710)\to\eta\eta')}{\mathcal{B}(f_0(1710)\to\pi\pi)} < 1.61\times 10^{-3} \quad @90\%\ \text{C.L.}$$

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)

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

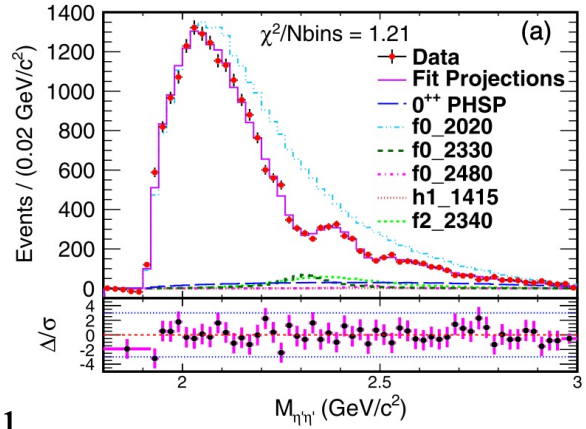
PRD 105, 072002(2022)

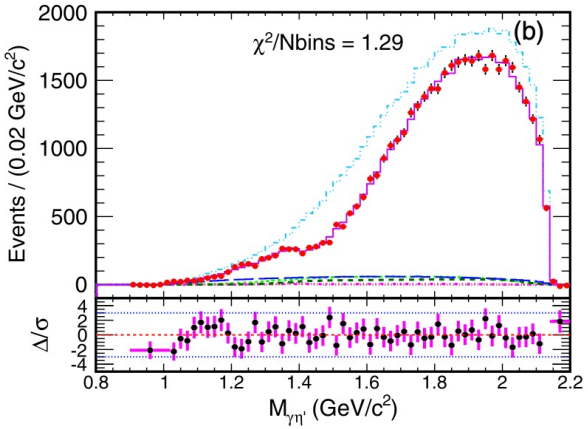
PWA of $J/\psi\to\gamma\eta'\eta'$ using 10 Billion of J/ψ data @ BESIII

- $\eta'\to\gamma\pi^+\pi^-$/ $\eta\pi^+\pi^-$ ($\eta\to\gamma\gamma$)

Resonance	M(MeV/c^2)	Γ(MeV)	B.F.	Significance (σ)	
$f_0(2020)$	$1982\pm3^{+54}_{-0}$	$436\pm4^{+46}_{-49}$	$(2.63\pm0.06^{+0.31}_{-0.46})\times10^{-4}$	$\gg25$	Dominant contributions
$f_0(2330)$	$2312\pm2^{+10}_{-0}$	$134\pm5^{+30}_{-9}$	$(6.09\pm0.64^{+4.00}_{-1.68})\times10^{-6}$	16.3	
$f_0(2480)$	$2470\pm4^{+4}_{-6}$	$75\pm9^{+11}_{-8}$	$(8.18\pm1.77^{+3.73}_{-2.23})\times10^{-7}$	5.2	new 0^{++} state
$h_1(1415)$	$1384\pm6^{+9}_{-0}$	$66\pm10^{+12}_{-10}$	$(4.69\pm0.80^{+0.74}_{-1.82})\times10^{-7}$	5.3	
$f_2(2340)$	$2346\pm8^{+22}_{-6}$	$332\pm14^{+26}_{-12}$	$(8.67\pm0.70^{+0.61}_{-1.67})\times10^{-6}$	16.1	
0^{++} PHSP	...	...	$(1.17\pm0.23^{+4.09}_{-0.70})\times10^{-5}$	15.7	

- $f_0(2020)$, $f_0(2330)$ and $f_2(2340)$ observed in $\eta'\eta'$ decay mode for the first time





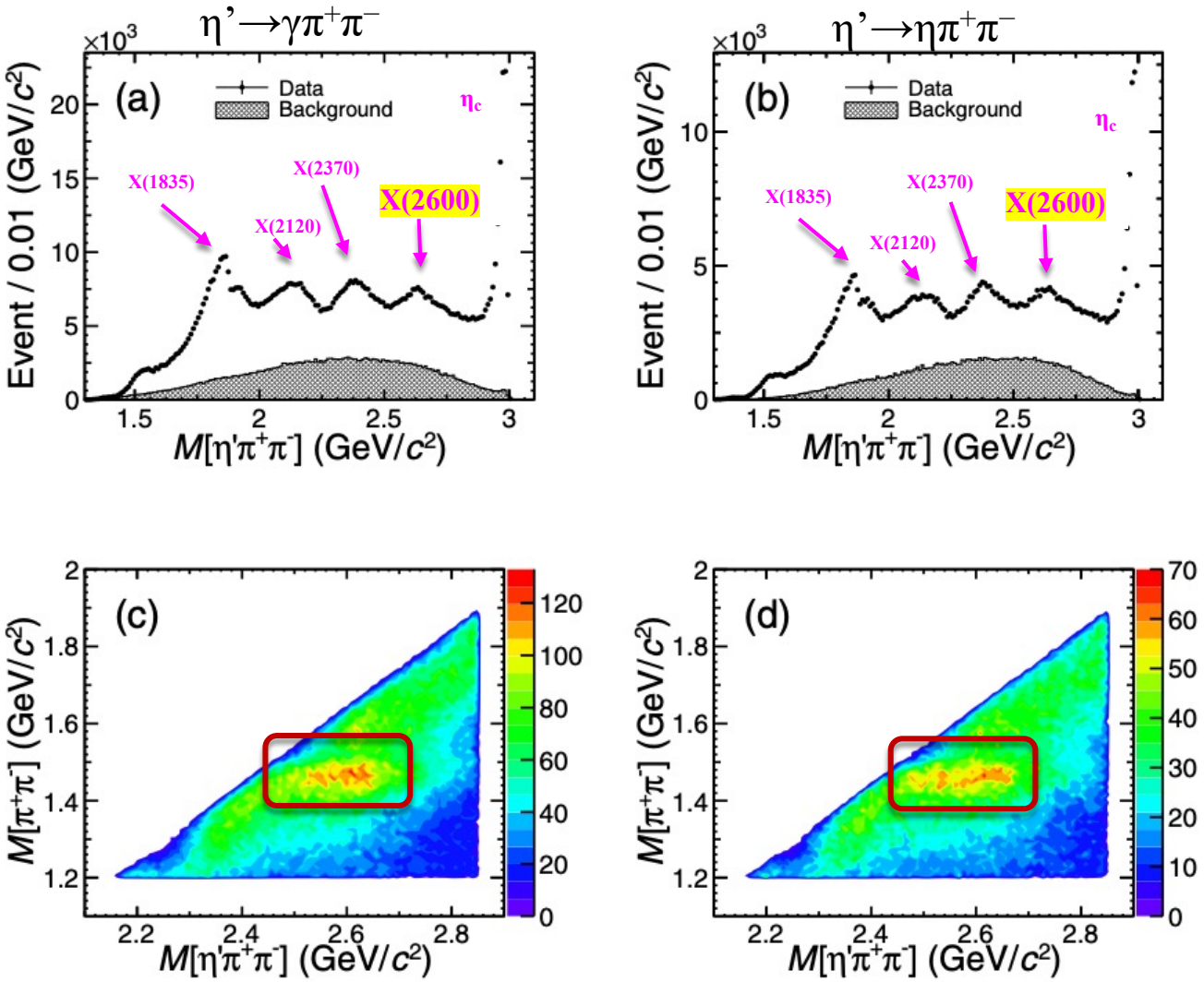
$f_0(2020)$:

- 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)

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

10 Billion of J/ψ data @ BESIII

PRL 129, 042001



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

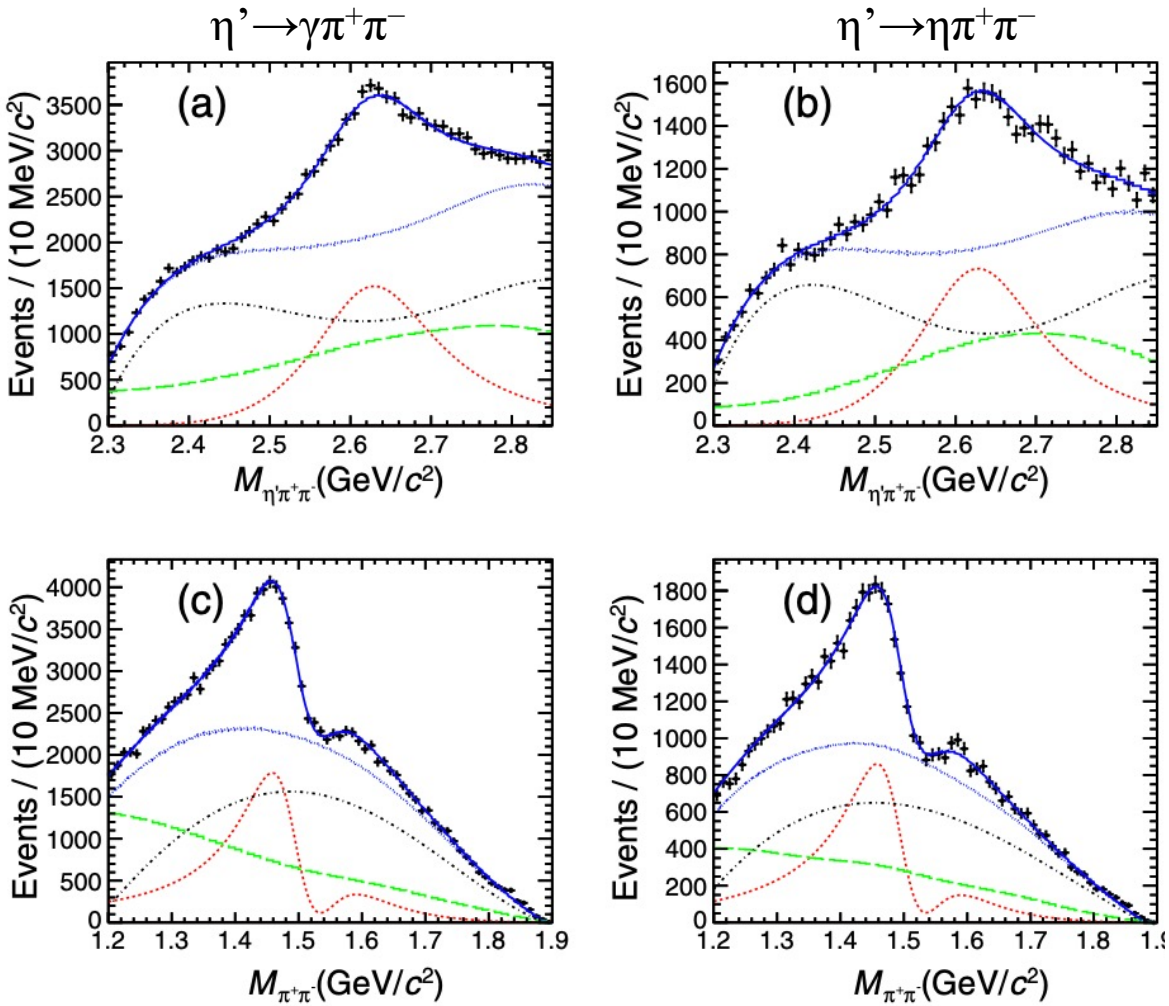
X(2600): A New State Observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$

PRL 129, 042001

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

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

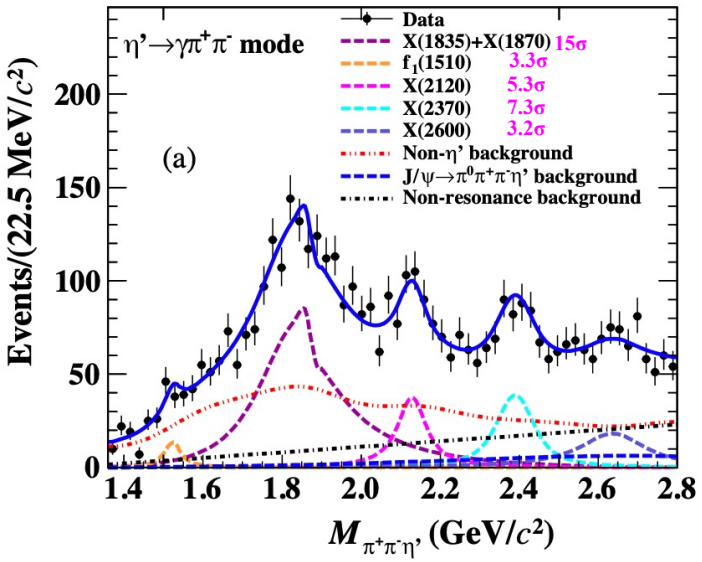
- X(2600) resonance observed for the first time with a statistical significance greater than 20σ
- The structure in $M(\pi^+\pi^-)$ around 1.5 GeV/c^2 can be well described with the interference between $f_0(1500)$ and the X(1540) resonances

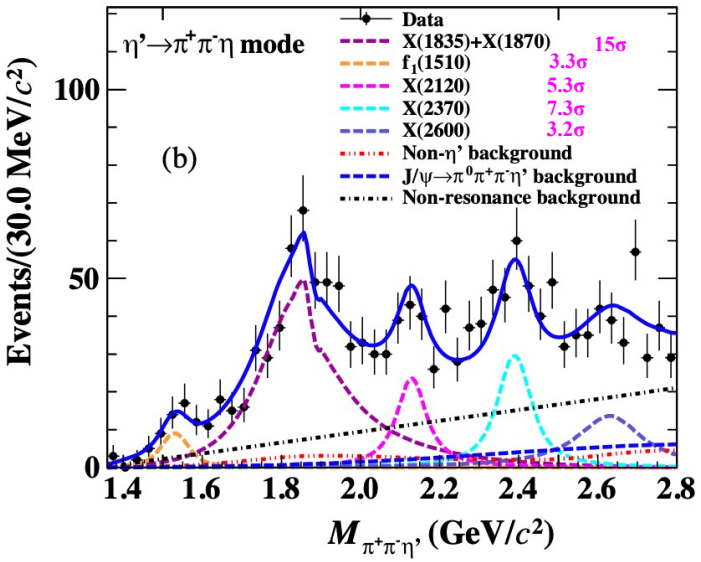


Observation of X(1835), X(2120), X(2370) in J/ψ EM Dalitz Decays

10 Billion of J/ψ data @ BESIII

PRL 129, 022002





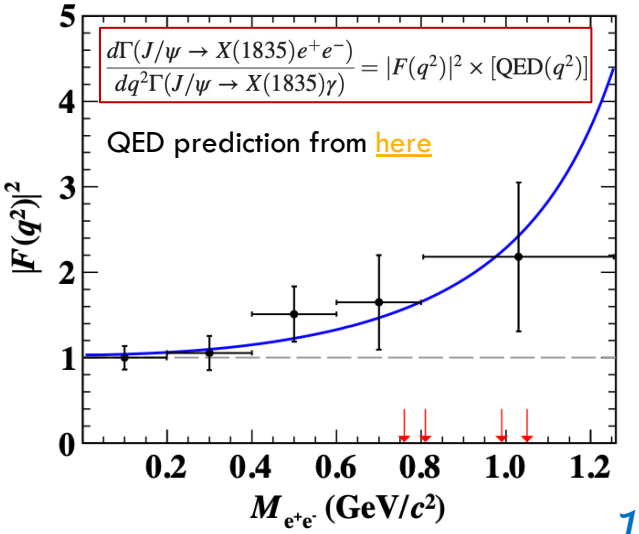
$J/\psi \to e^+e^-\eta'\pi^+\pi^-$
Confirmation of X(1835), X(2120) and X(2370) observed in J/ ψ radiative decays

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

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

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

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



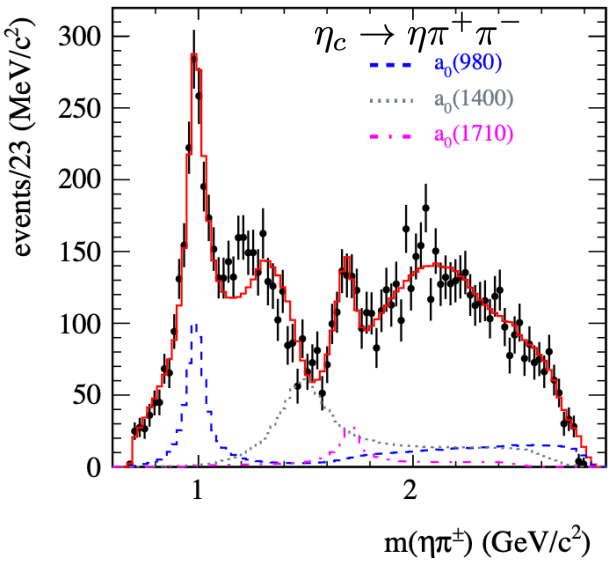
Light hadrons in open-charm decays

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
- $f_0(1710)$, $f_0(1770)$
- $a_0(1710)$???

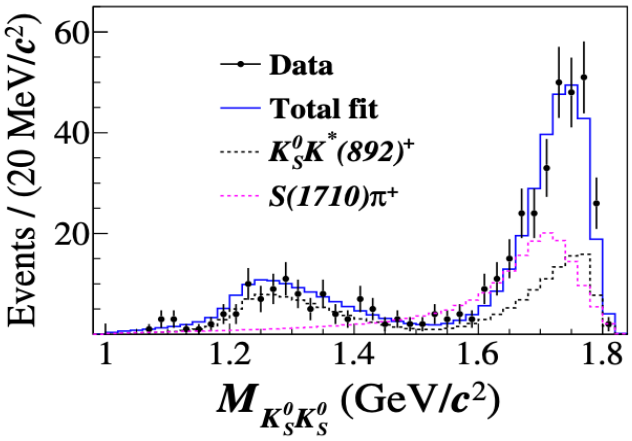
BABAR PRD104, 072002 (2021)



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

$\Gamma(a_0(1700)) = 110 \pm 15_{\rm stat} \pm 11_{\rm sys}$ 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

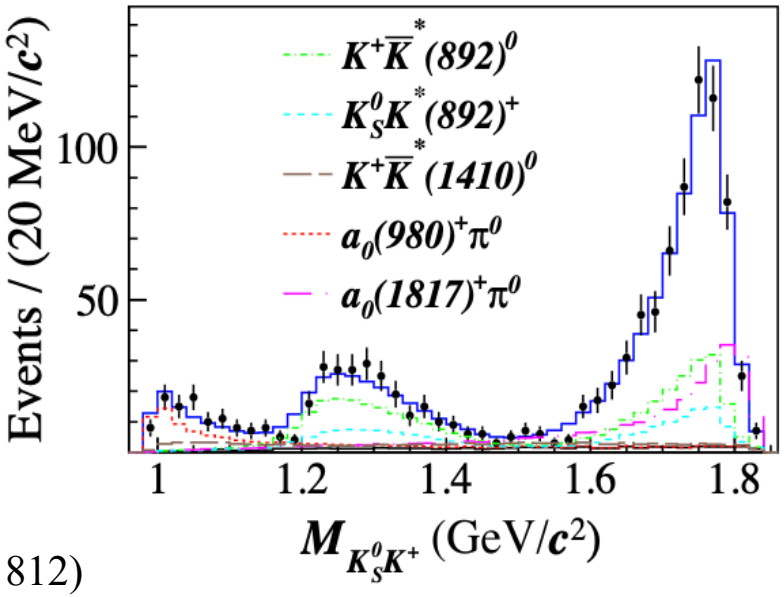
6.32 fb^{-1} between 4.178 and 4.226 GeV

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 $D_s^+ \to a_0(1817)^+ \pi^0$ with $a_0(1817)^+ \to K^0_S K^+ \pi^0$ is roughly consistent with the prediction EPJC **82**, 225(2022)
- $m(a_0)$ about 100 MeV/c^2 greater than the expectation

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



- $a_0(1817)$ could be the isospin one partner of the X(1812) PRD105, 114014(2022)

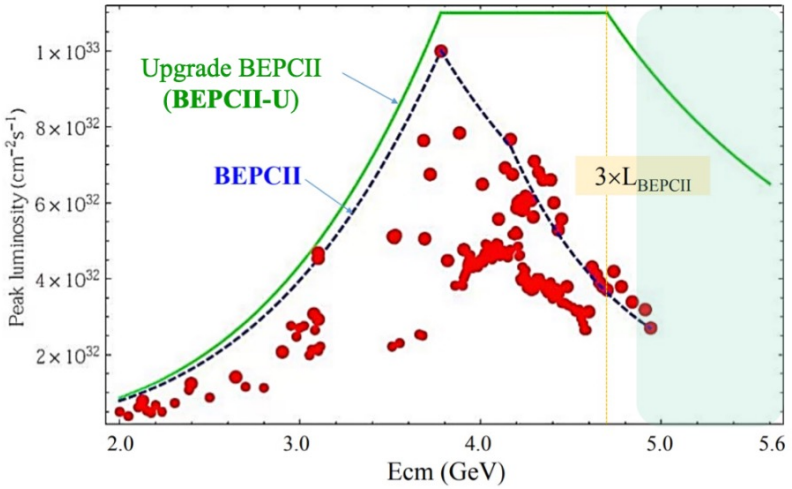
Amplitude	Phase (rad)	FF (%)	BF (10^{-3})	σ
$D_s^+ \to \bar{K}^*(892)^0 K^+$	0.0 (fixed)	$32.7 \pm 2.2 \pm 1.9$	$4.77 \pm 0.38 \pm 0.32$	> 10
$D_s^+ \to K^*(892)^+ K^0_S$	$-0.16 \pm 0.12 \pm 0.11$	$13.9 \pm 1.7 \pm 1.3$	$2.03 \pm 0.26 \pm 0.20$	> 10
$D_s^+ \to a_0(980)^+ \pi^0$	$-0.97 \pm 0.27 \pm 0.25$	$7.7 \pm 1.7 \pm 1.8$	$1.12 \pm 0.25 \pm 0.27$	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

- ***J/ψ decay provides an excellent laboratory to study light hadron decays: 10 billion of J/ψ data collected at BESIII***
  - This huge data sample allows to study light meson decays with unprecedent statistics: unique opportunity to map the light hadron spectroscopy and search for glueball and exotic states
    - First observation of exotic isoscalar state $\eta_1(1855)$ PRL 129, 192002 (2022) PRD 106,072012 (2022)
    - X(2600) state in $J/\psi \to \gamma\pi^+\pi^-\eta'$ PRL 129, 042001
    - X(1835), X(2120), X(2370) in J/ψ EM Dalitz Decays PRL 129, 022002

- ***Light hadrons in open-charm decays*** (6.32 fb^{-1} between 4.178 and 4.226 GeV)

PRD129, 182001 (2022)



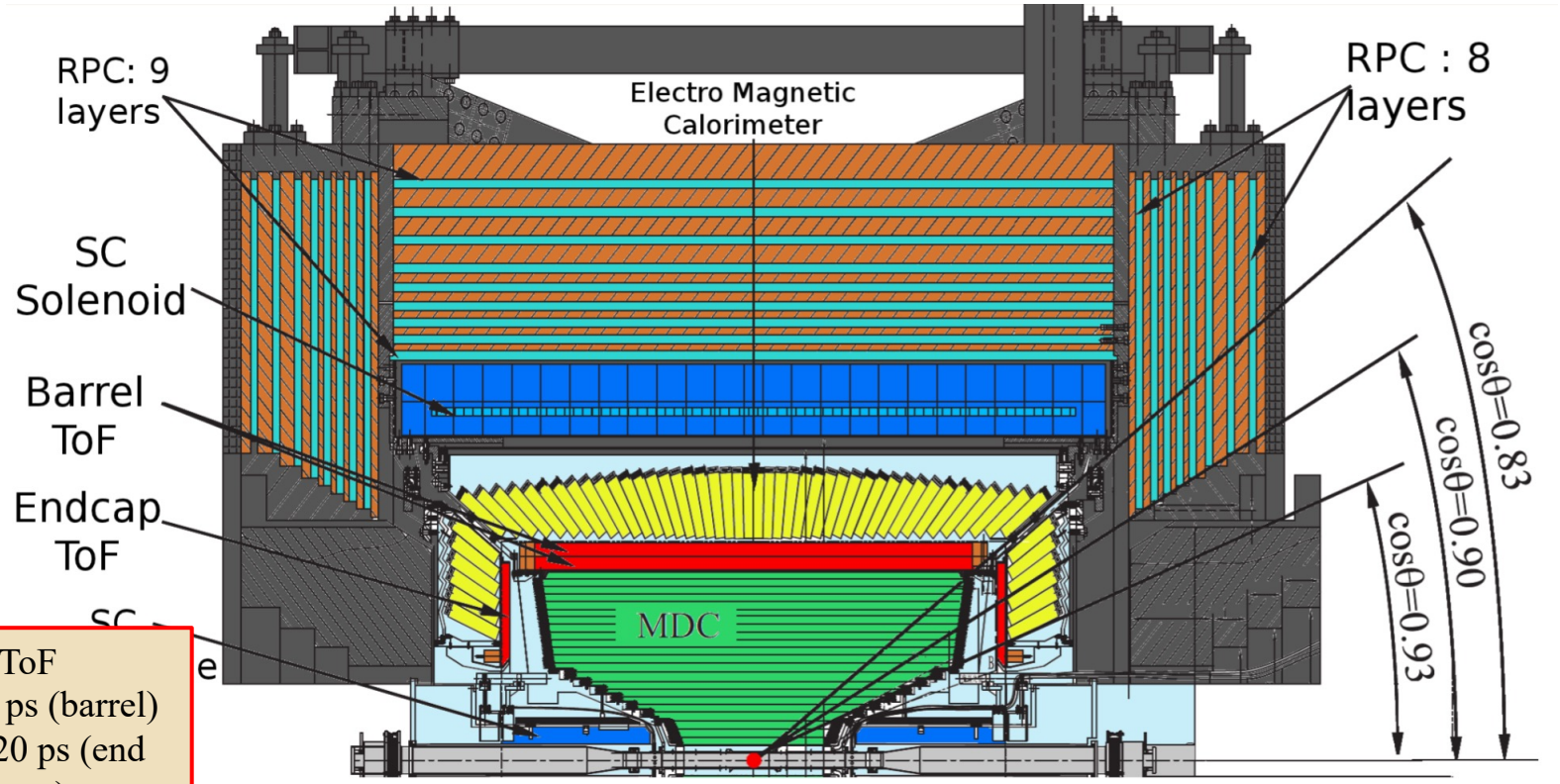
- Further upgrade in energy (5.6 GeV) and luminosity (BEPCII-U, 3x) planned for the next year
- Inner MDC ➔ CGEM-IT

More interesting results are expected

Back-up slides

The BESIII Detector

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



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

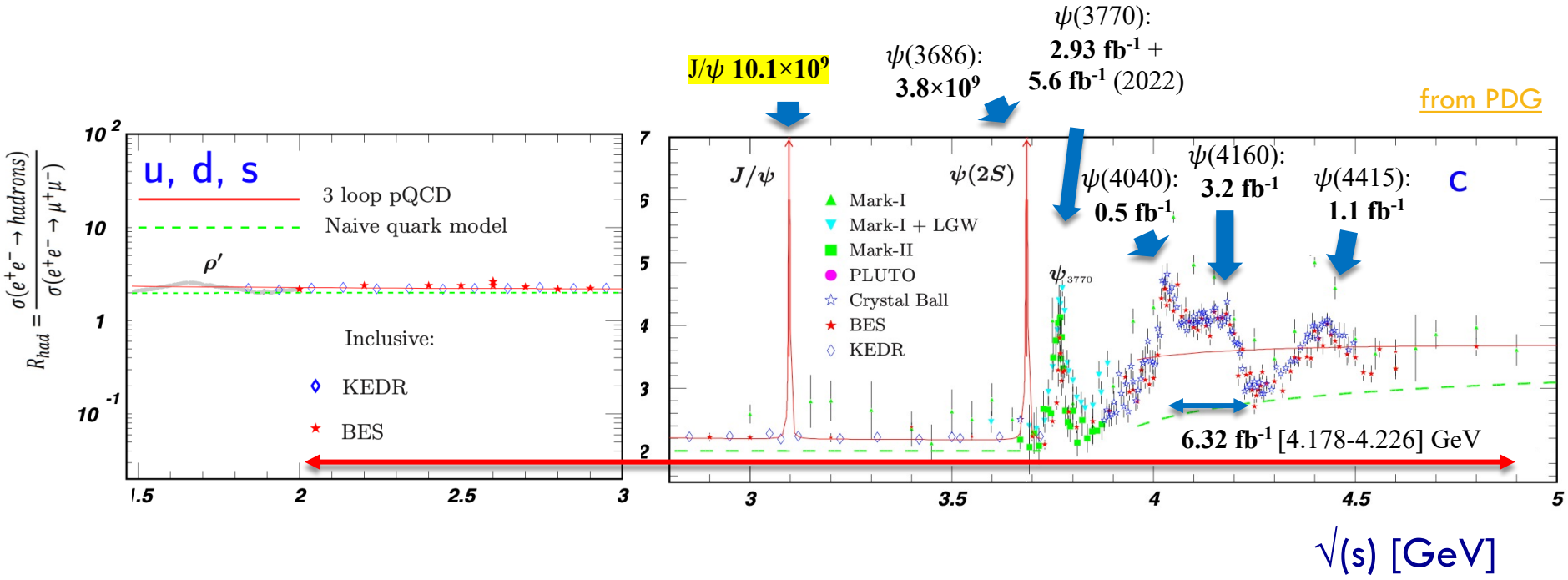
Drift Chamber
$\sigma_{r\phi} \sim 130$ μm (single wire)
$\sigma_{pt}/p_t \sim 0.5$ % @ 1 GeV

Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
$\sigma_{xy} \sim (6\text{ mm})/E^{1/2}$ @ 1 GeV

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

BESIII 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

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

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

BESIII physics programme

Light hadron physics

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

XYZ meson physics

- Y(4260), Y(4360) properties
- $Z_c(3900)^+$, …

QCD and τ

- Precision R measurement
- τ decay

Charm physics

- Semi-leptonic form factors
- Decay constants f_D and f_{Ds}
- CKM matrix: $|V_{cd}|$ and $|V_{cs}|$
- D^0-$\overline{D}^0$ mixing, CPV
- Strong phases

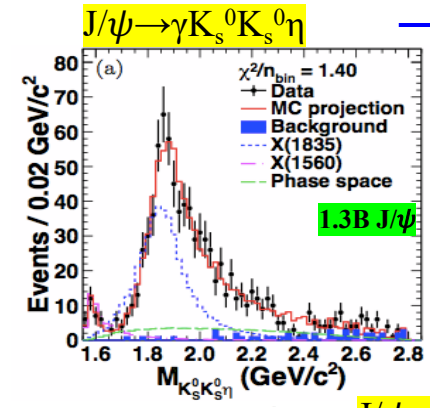
Charmonium physics

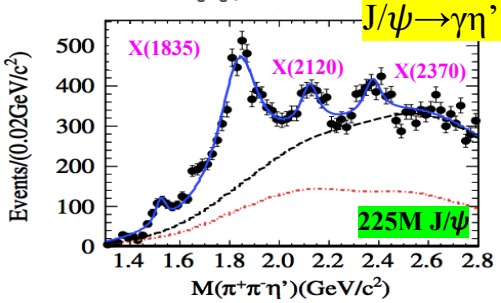
- Precision spectroscopy
- Transitions and decays

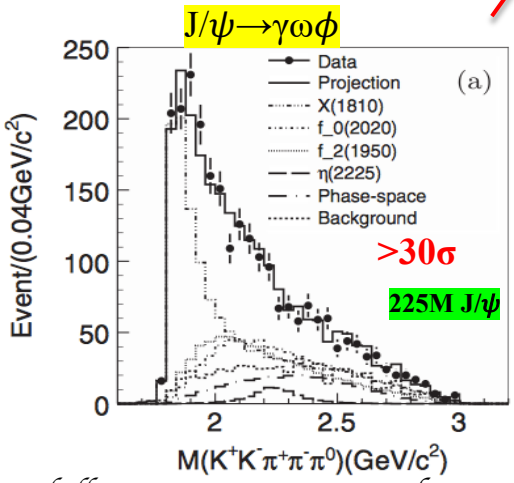
Precision mass measurements

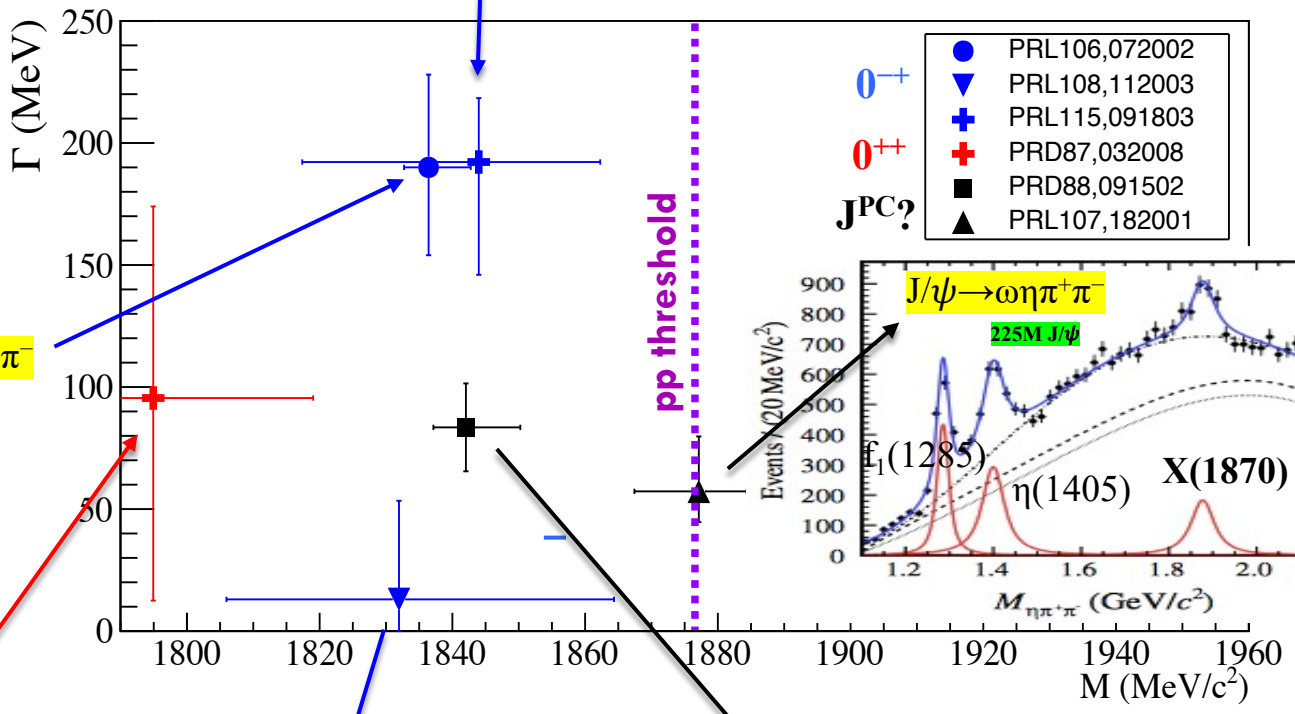
- τ mass
- D, D^* mass

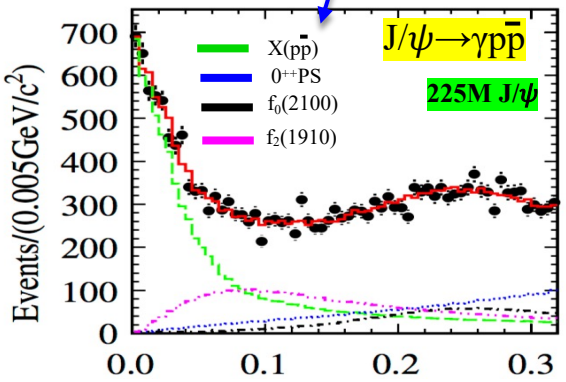
X(18xx) between 1.8 -1.9 GeV

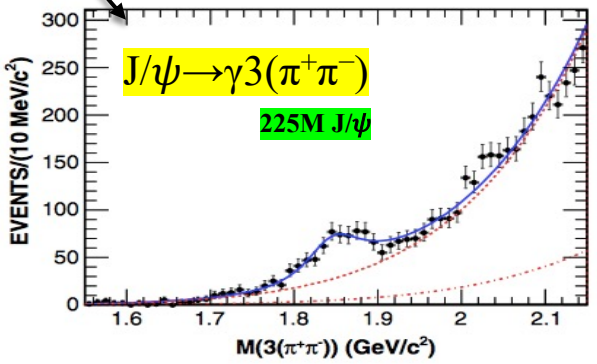






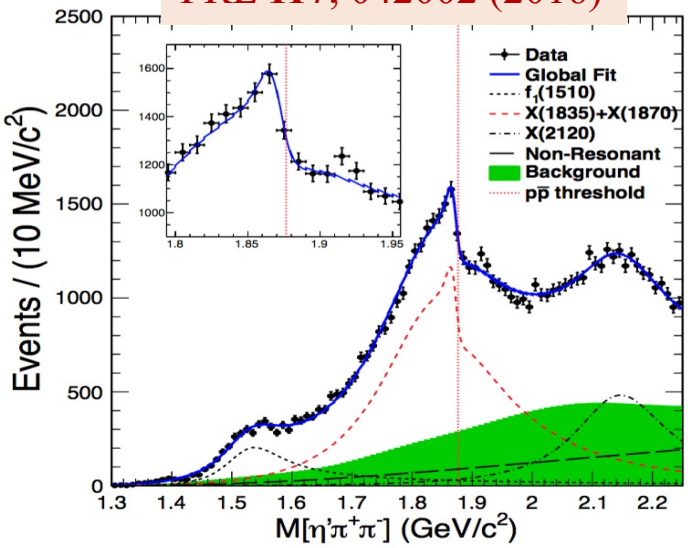






Other Results on X(1835)

PRL **117**, 042002 (2016)



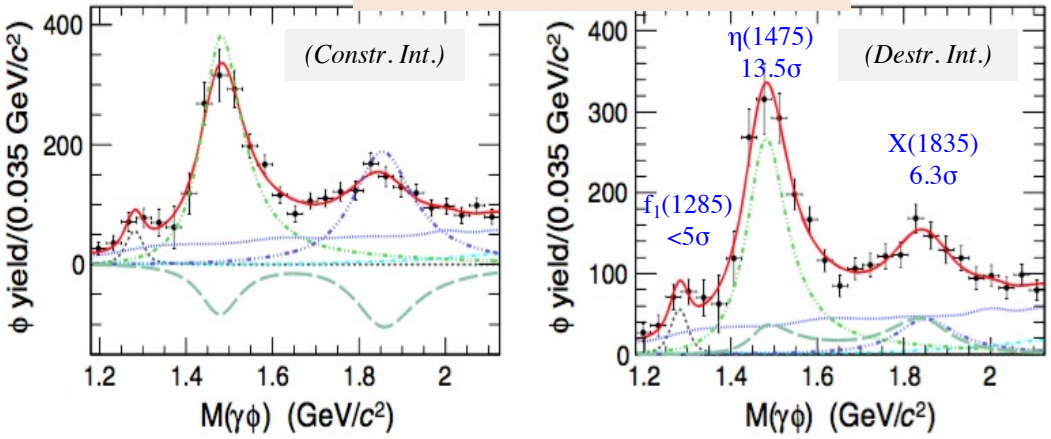
1.09×10⁹ J/ψ @ BESIII

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

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

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

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



1.3×10⁹ J/ψ @ BESIII

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

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

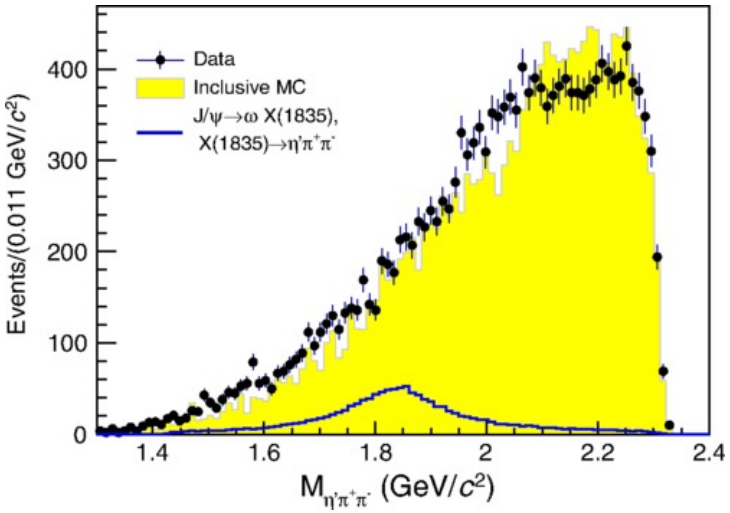
Solution	Resonance	m_R (MeV/c^2)	Γ (MeV)
I *(Destr. Int.)*	η(1475)	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$
	X(1835)	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$
II *(Constr. Int.)*	η(1475)	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$
	X(1835)	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$

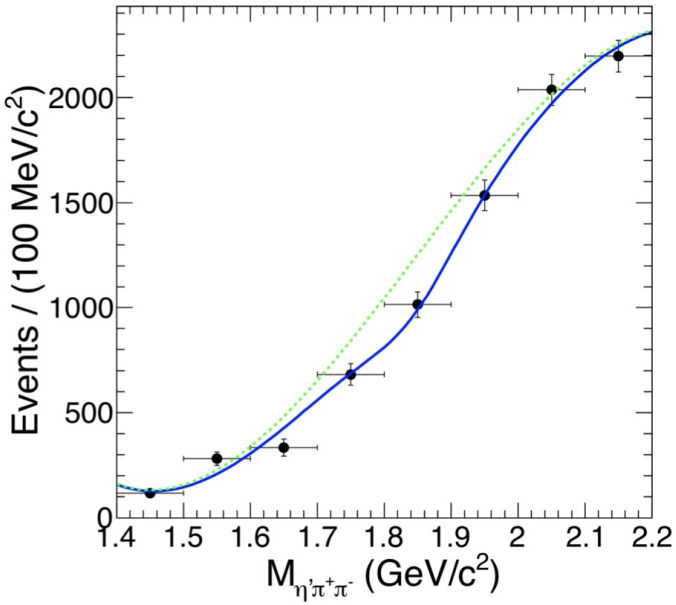
Search for X(1835) in other decay modes

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

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

1.3×10^9 J/ψ @ BESIII





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

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

@ 90% C.L.

The puzzle is still not complete ….

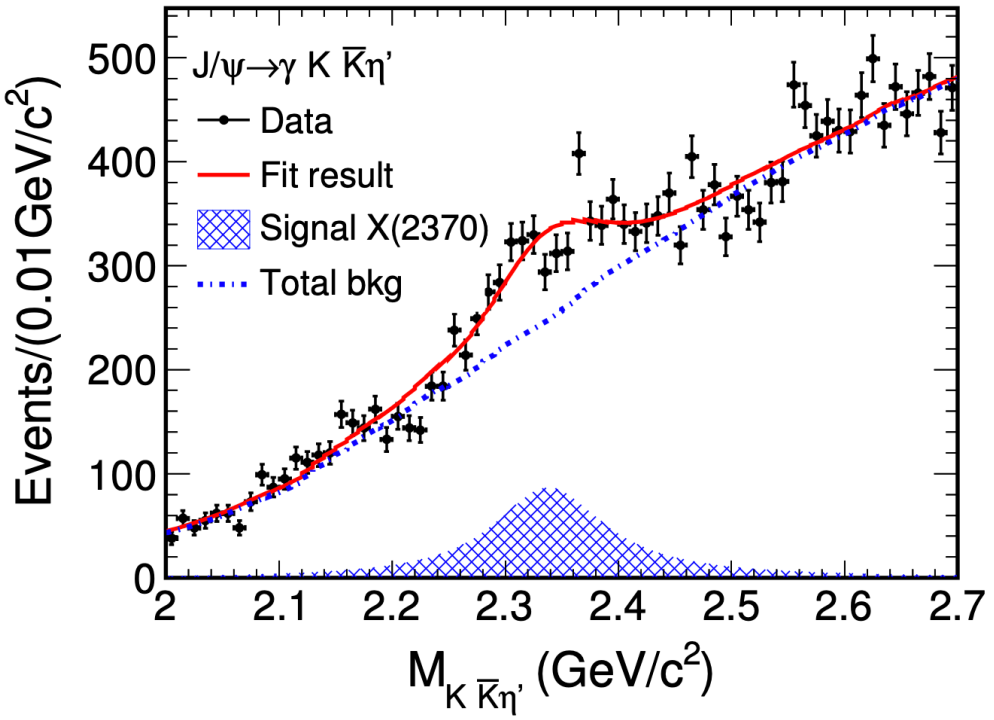
First Observation of X(2370) in $J/\psi \to \gamma K\bar{K}\eta'$

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

➢ Simulataneus fit performed for two decay η' modes

1.3×10^9 J/ψ @ BESIII

EPJC **80**, 746 (2020)



➢ **No evidence of X(2120) is found**

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

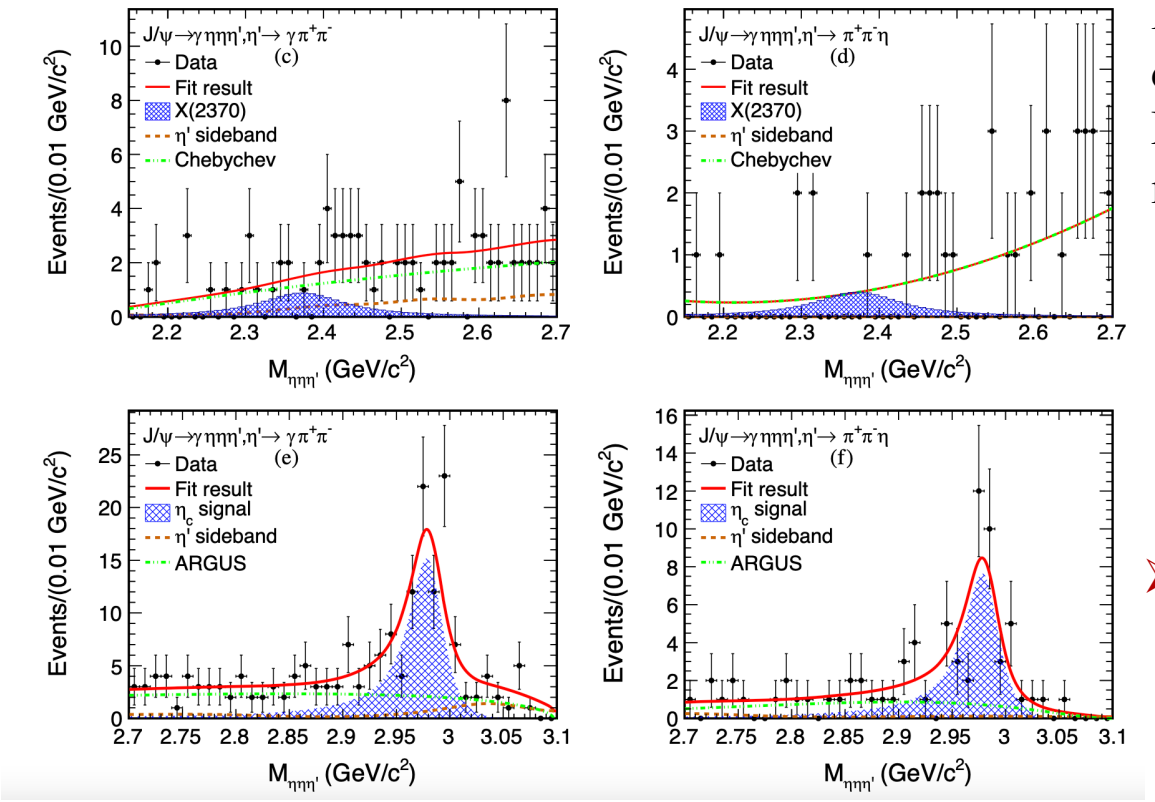
➢ **Clear X(2370) signal observed with significance of about 8.3σ**

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

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

PRD **103**, 012009 (2021)

1.3×10^9 J/ψ @ BESIII



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

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

➢ **No obvious signal of X(2370)**

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

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

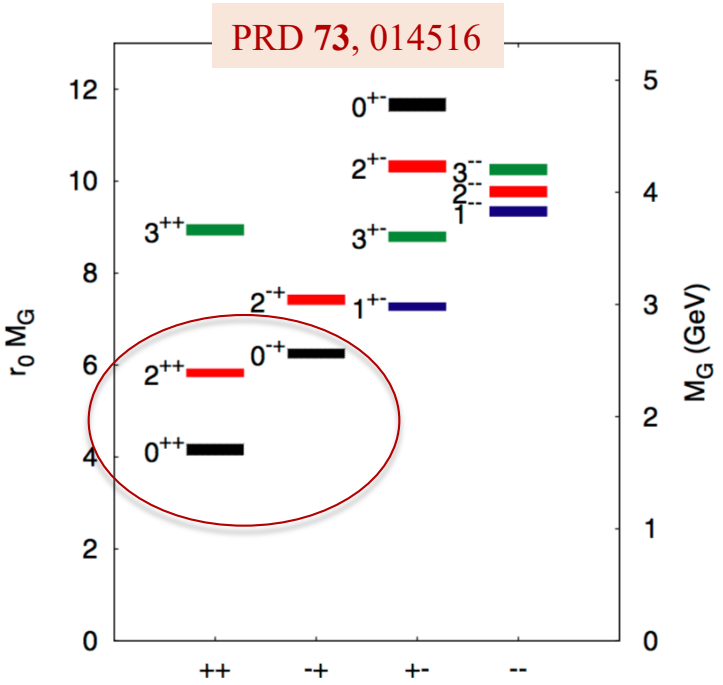
(it does not contradict PRD **87**,054036)

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

FIRST OBSERVATION in the ηηη' invariant mass spectra

Amplitude Analyses in BESIII

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

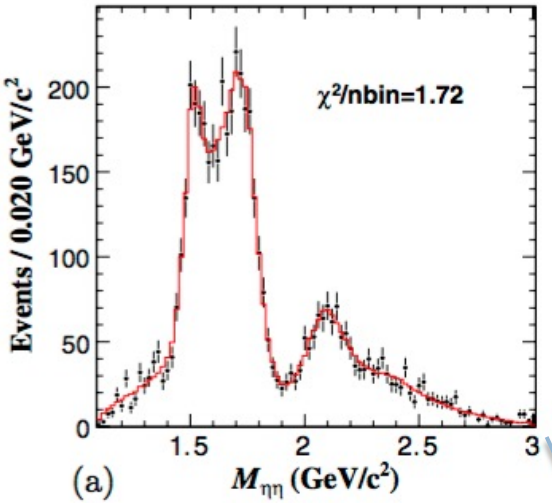


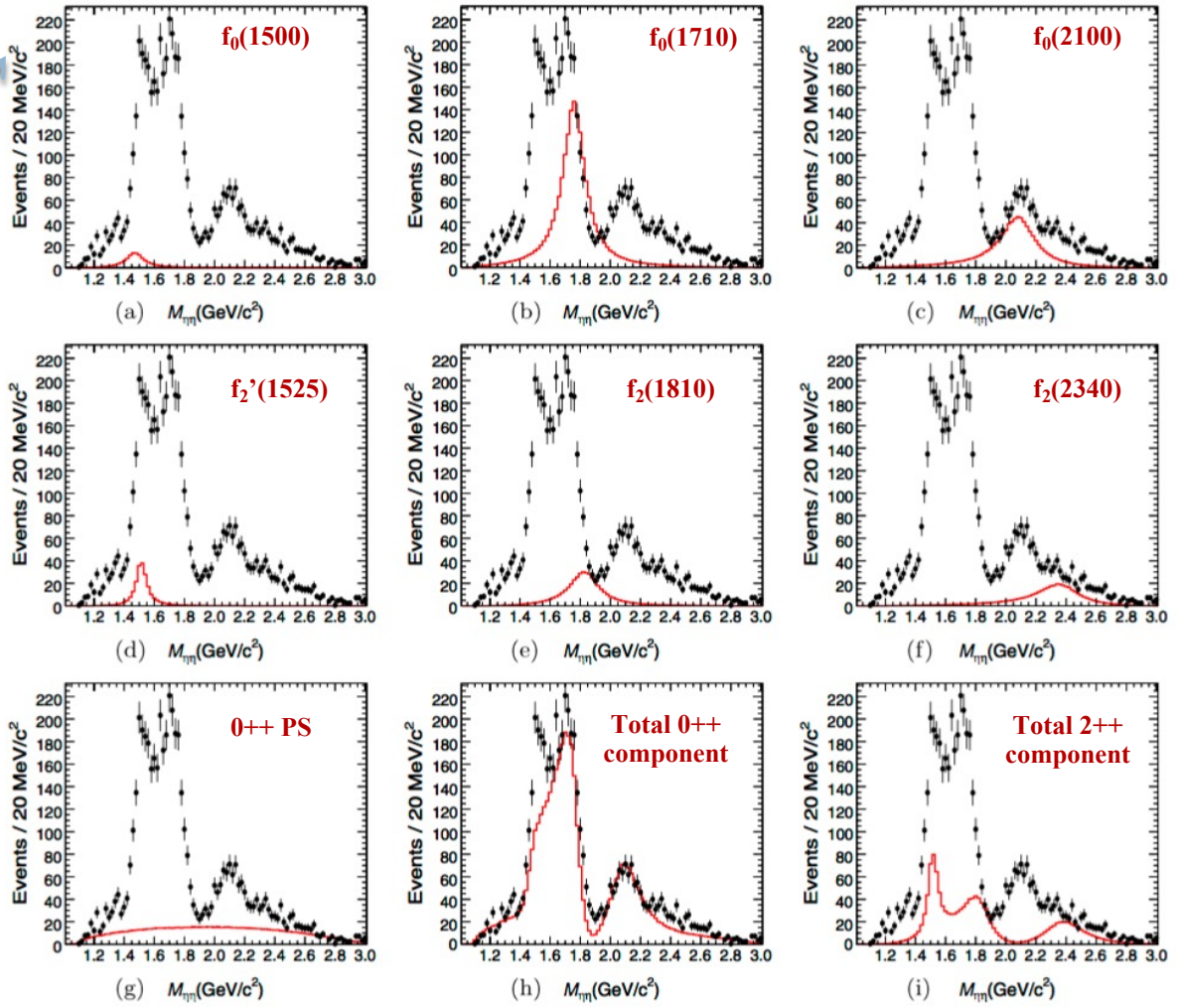
- **Amplitude analysis: toll to extract the complex amplitudes from experimental data**
  - Models with free parameters
  - Consider the kinematic of final states particles
  - Vary the parameters to maximize the likelihood
  - **Mass Dependent (MD) PWA**: model the dynamics of particle interactions as coherent sum of resonances
  - **Mass Independent (MI) PWA**: make minimal model assumptions and measure the dynamical amplitudes independently in small regions of two-meson invariant mass (PRD92, 052003 (2015))

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

PRD **87**, 092009 (2013)

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





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PRD **87**, 092009 (2013)

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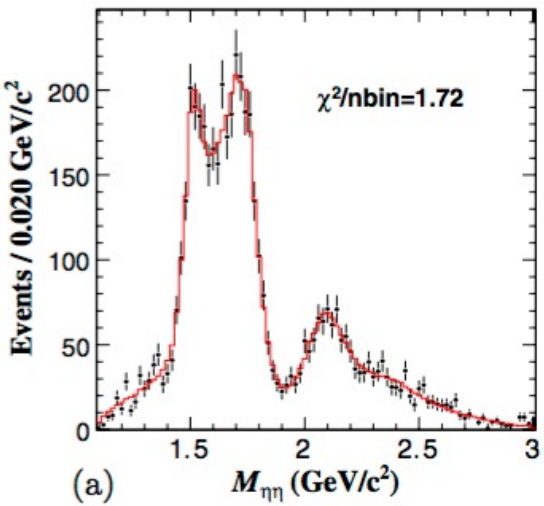


Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74})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

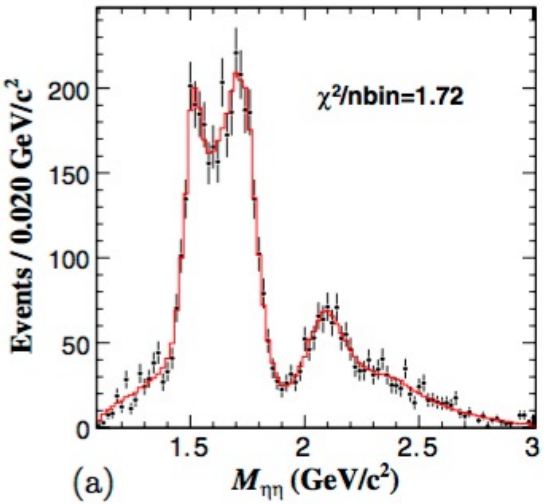
- $f_0(1500)$ dominant decays are 4π and $\pi\pi$
- The production rate of $f_0(1710)$ is compatible with LQCD (PRL110,021601) prediction for a pure scalar glueball
  - Suggest a large overlap with 0++ gluball

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

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

PRD **87**, 092009 (2013)

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



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

- $f_0(1500)$ dominant decays are 4π and $\pi\pi$
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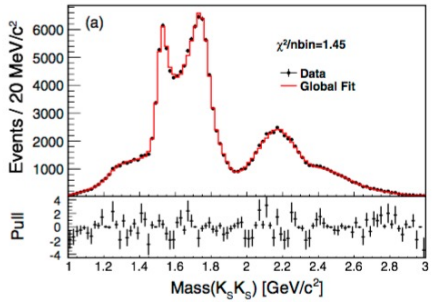
  - Suggest a large overlap with 0++ glueball

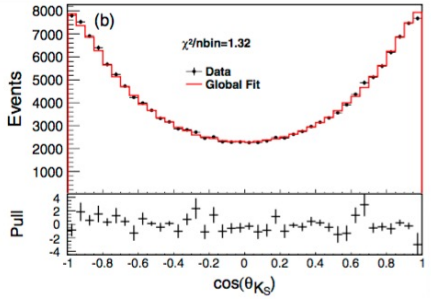
- PWA requires a strong contribution from **$f_2(2340)$** with fairly large production rate ⇒ it ***could be a good candidate for the lowest lying tensor glueball***

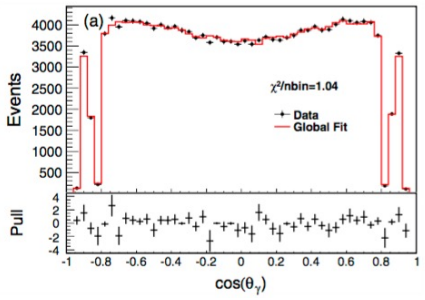
PWA of $J/\psi \to \gamma K^0_S K^0_S$

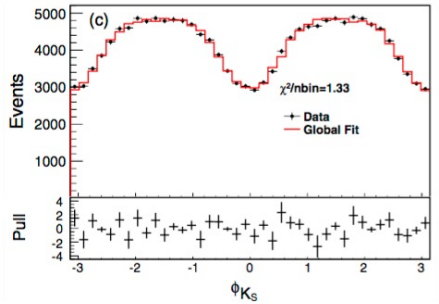
PRD **98**, 072003 (2018)

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









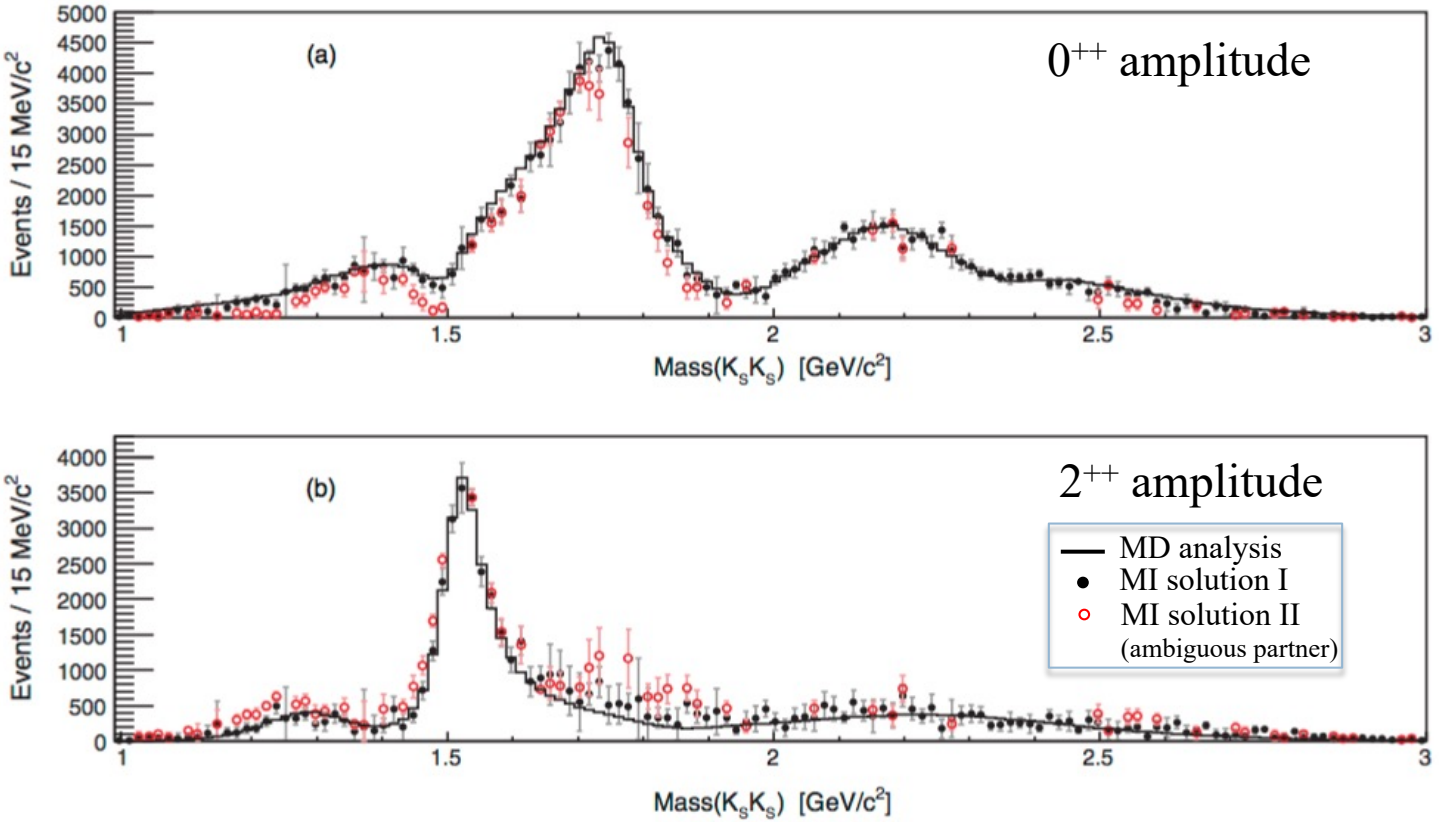
Resonance	M (MeV/c^2)	M_{PDG} (MeV/c^2)	Γ (MeV/c^2)	Γ_{PDG} (MeV/c^2)	Branching fraction	Significance
$K^*(892)$	896	895.81 ± 0.19	48	47.4 ± 0.6	$(6.28^{+0.16+0.59}_{-0.17-0.52}) \times 10^{-6}$	35σ
$K_1(1270)$	1272	1272 ± 7	90	90 ± 20	$(8.54^{+1.07+2.35}_{-1.20-2.13}) \times 10^{-7}$	16σ
$f_0(1370)$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



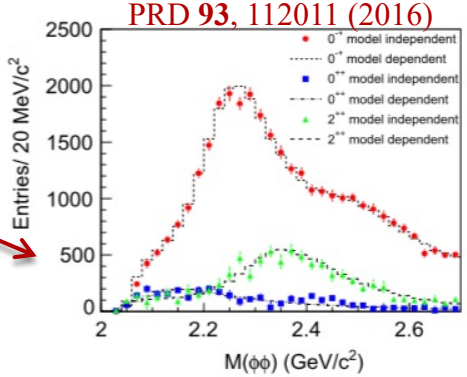
- Agreement with results from MD PWA (no acceptance correction included)
- MI results useful for a systematic study of hadronic interaction

PWA status and plans in a nutshell

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

PWA Published
Ongoing
Published, no PWA

PRD **93**, 112011 (2016)



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

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

1.3×10^9 J/ψ @ BESIII

EPJC **80**, 746 (2020)