MENU 2023

The 16th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

Light Hadron Spectroscopy at BESIII

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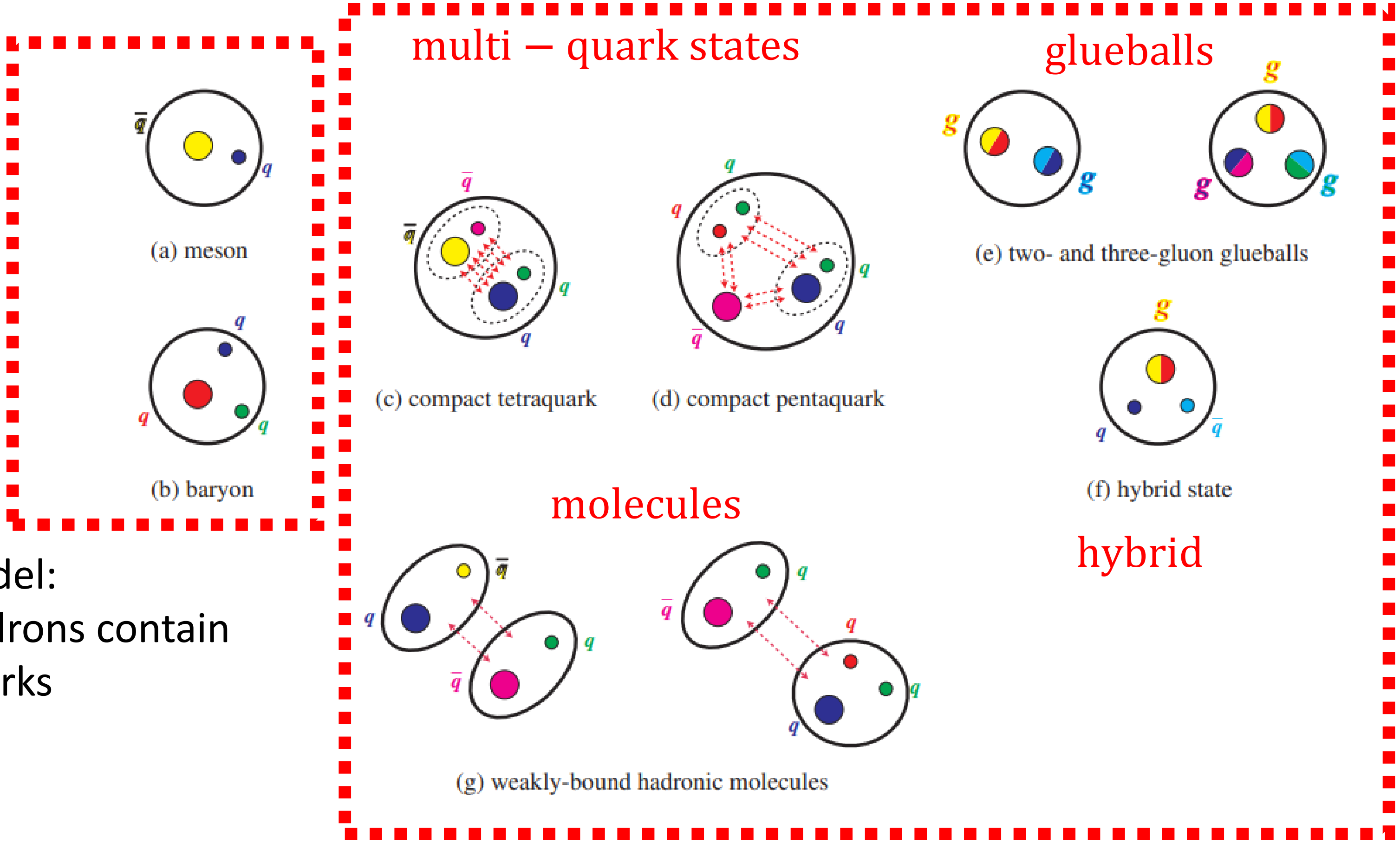
QCD allows the existence of exotic hadrons



Naive Quark Model:
conventional hadrons contain two or three quarks

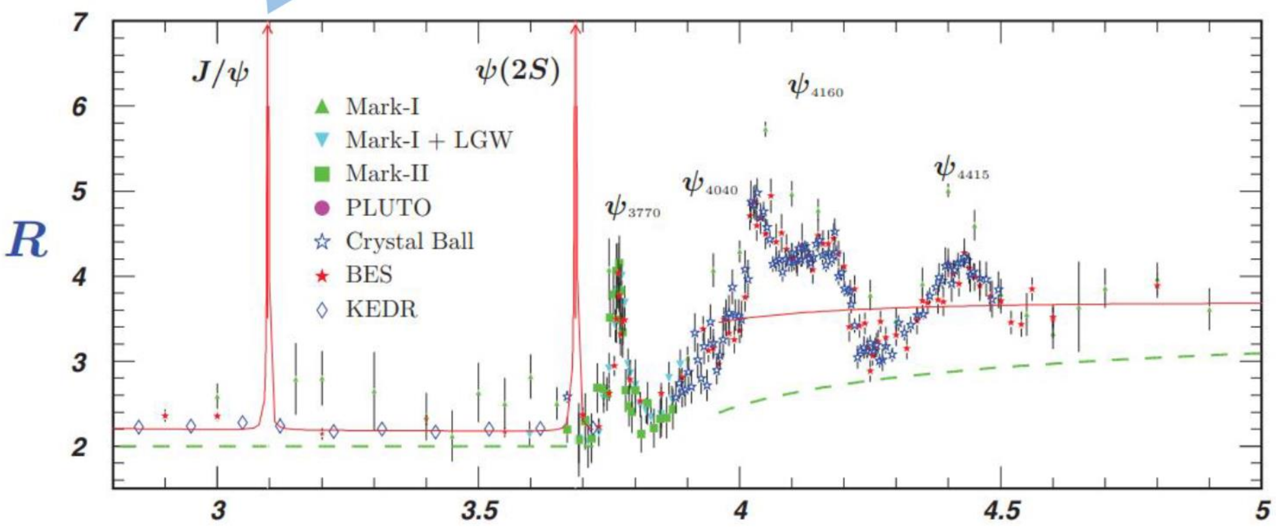
QCD allows also different combinations of quarks and gluons:
EXOTIC hadrons

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

BESIII:

- $\sqrt{s} = 2.0 - 4.9$ GeV
- Peak luminosity : $1.05 \times 10^{33} cm^{-2}s^{-1}$ at $\psi(3770)$
- 2009 – today: BESIII physics runs

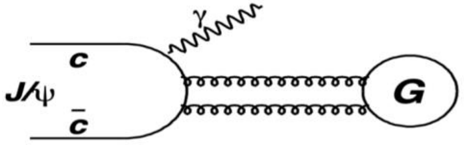
$10 \times 10^9\ J/\psi$



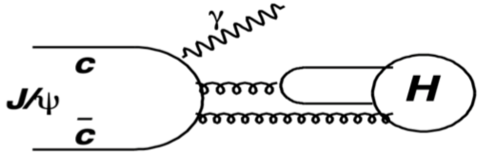
Ideal place for light hadron physics

- Clean high statistics data sample
- Well defined initial and final states
  - Kinematic constraints
  - I (J^{PC}) filter
- "Gluon-rich" processes

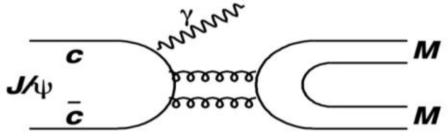
$$\Gamma(J/\psi \to \gamma G) > \Gamma(J/\psi \to \gamma H) > \Gamma(J/\psi \to \gamma M) > \Gamma(J/\psi \to \gamma F)$$



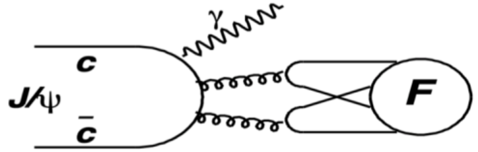
$\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2)$



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



$\Gamma(J/\psi \to \gamma M) \sim O(\alpha\alpha_s^4)$

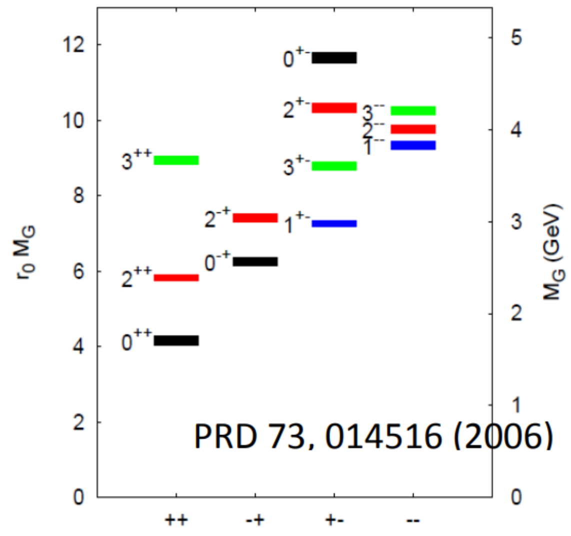


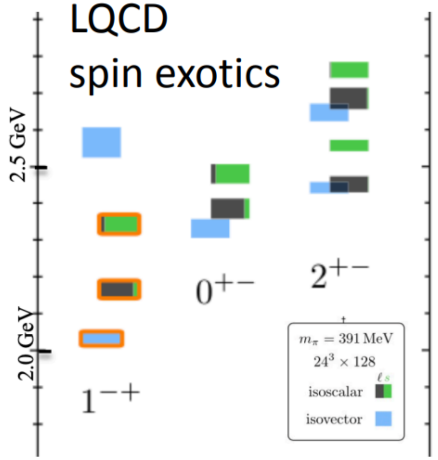
$\Gamma(J/\psi \to \gamma F) \sim O(\alpha\alpha_s^4)$

Exotic Gluonic Hadrons

- difficult to experimentally identify glueballs and hybrid mesons unambiguously
  - difficulty in differentiating them from conventional $q\bar{q}$ mesons
  - mixing with $q\bar{q}$ complicates clear identification
- LQCD spectrum of glueballs and hybrids
- glueballs
  - low-lying glueballs with ordinary J^{PC} $(0^{++}, 2^{++}, 0^{-+})$
  - mass of ground state $G_{0^+} \sim 1.5 - 1.7\ \mathrm{GeV}/c^2$
  - $f_0(1500), f_0(1710)$: mixed glueball-$q\bar{q}$ candidates
- hybrids
  - low-lying hybrids can have **exotic quantum numbers**
  - lightest spin-exotic: 1^{-+} around 2 GeV/c^2
  - only isovector candidates observed yet: $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2015)$
    - $\pi_1(1400)$, $\pi_1(1600)$ can be explained as one pole
  - search for isoscalar 1^{-+} to establish the hybrid nonet
    - can decay to $\eta\eta'$ in P-wave

LQCD Glueball Spectrum





PRD 88, 094505 (2013)

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

- 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**

- $J^{PC} = 0^{++}, 2^{++}, 4^{++}$ $(\eta\eta')$, $J^{PC} = 1^{+-}, 1^{--}(\gamma\eta^{(\prime)})$ are considered

  $J^{PC} = 1^{-+}$ in $\eta\eta'$ is also considered

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

$$M = 1855 \pm 9^{+6}_{-1}\ \mathrm{MeV}/c^2; \Gamma = (188 \pm 18^{+3}_{-8}\ \mathrm{MeV})$$
$$\mathcal{B}(J\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$$

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

Eur. Phys. J. A 16, 537 (2003)

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

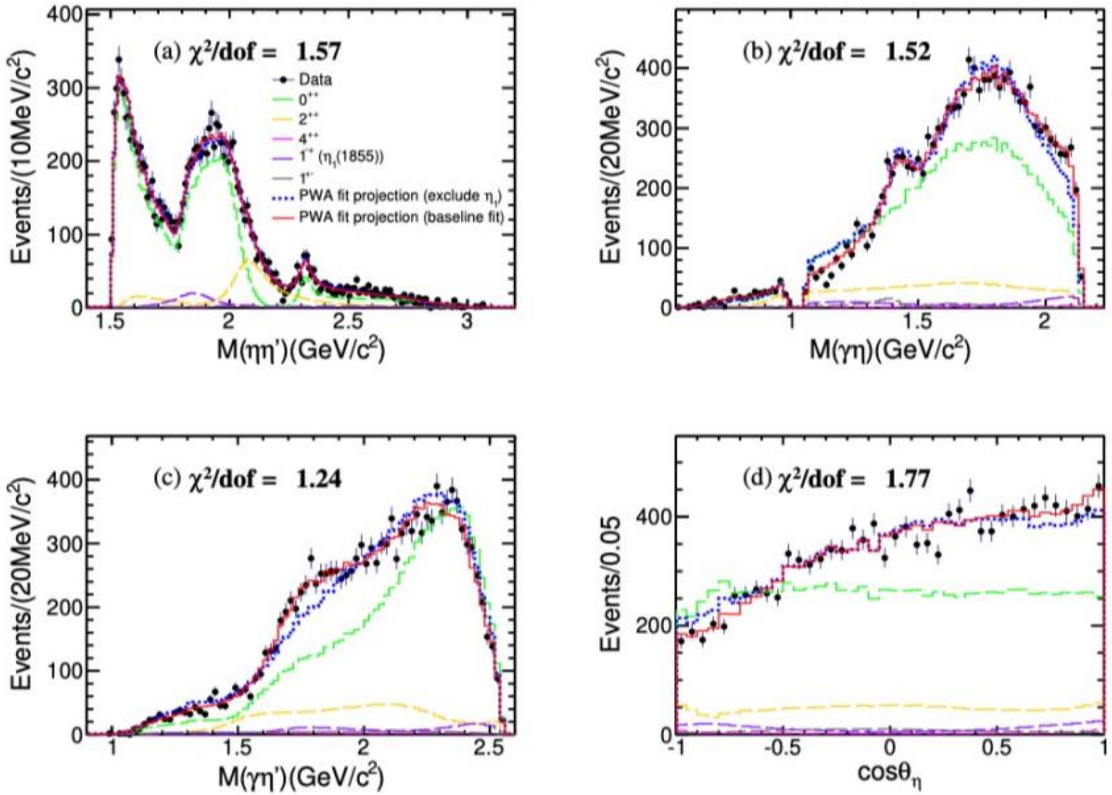
10 billion of J/ψ data

PRL 129, 192002 (2022)

PRL 130, 159901 (2023)

PRD 106,072012 (2022)

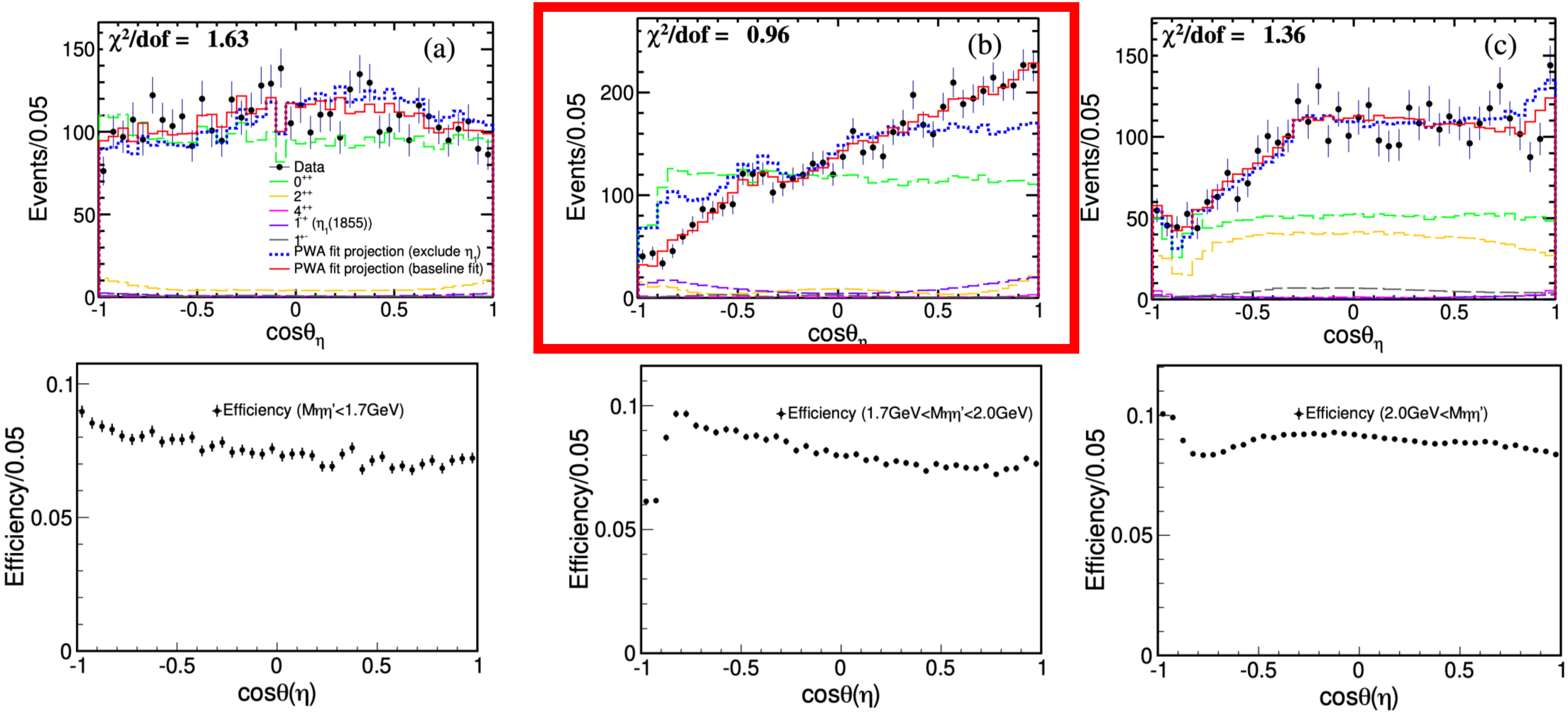
PRD 107,079901 (2023)



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

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

- 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 :

$$\sqrt{4\pi}\langle Y_0^0\rangle = S_0^2 + P_0^2 + P_1^2 + D_0^2 + D_1^2 + D_2^2,$$

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

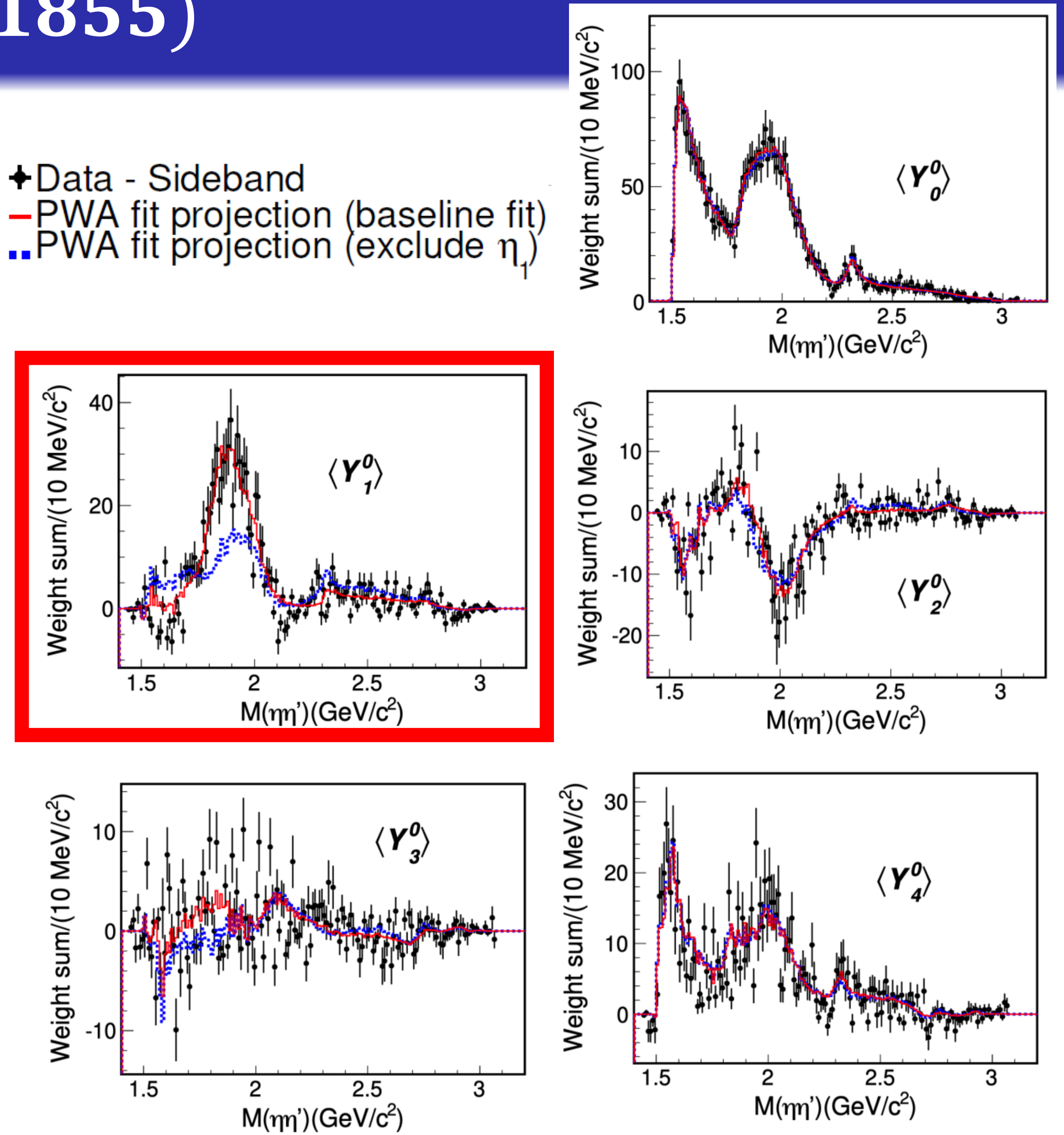
$$\sqrt{4\pi}\langle Y_2^0\rangle = \frac{1}{7\sqrt{5}}(14P_0^2 - 7P_1^2 + 10D_0^2 + 5D_1^2 - 10D_2^2) + 2S_0D_0 \cos\phi_{D_0},$$

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

$$\sqrt{4\pi}\langle Y_4^0\rangle = \frac{1}{7}(6D_0^2 - 4D_1^2 + D_2^2).$$

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

- Other checks…



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

- Components in the PWA fit

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg 30\sigma$
	$f_0(1810)$	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	$2.28\pm0.12^{+0.29}_{-0.20}$	24.6σ
	$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	$0.10\pm0.02^{+0.01}_{-0.02}$	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	$0.32\pm0.05^{+0.12}_{-0.02}$	8.7σ
	$f_2(2010)$	$2062\pm6^{+10}_{-7}$	$165\pm17^{+10}_{-5}$	$0.71\pm0.06^{+0.10}_{-0.06}$	13.4σ
	$f_4(2050)$	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	$0.08\pm0.01^{+0.01}_{-0.02}$	10.2σ
	$h_1(1595)$	1584	384	$0.16\pm0.02^{+0.03}_{-0.01}$	9.9σ

- The decay of scalar glueball to the $\eta\eta'$ final state are suppressed due to gauge duality

$$\frac{\mathrm{Br}(G\to\eta\eta')}{\mathrm{Br}(G\to\pi\pi)} < 0.04$$

- **Significant $f_0(1500)$**

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

- **Absence of $f_0(1710)$**

$$\frac{\mathrm{Br}(f_0(1710)\to\eta\eta')}{\mathrm{Br}(f_0(1710)\to\pi\pi)} < 2.87\times10^{-3} \text{ @ 90\% C.L}$$

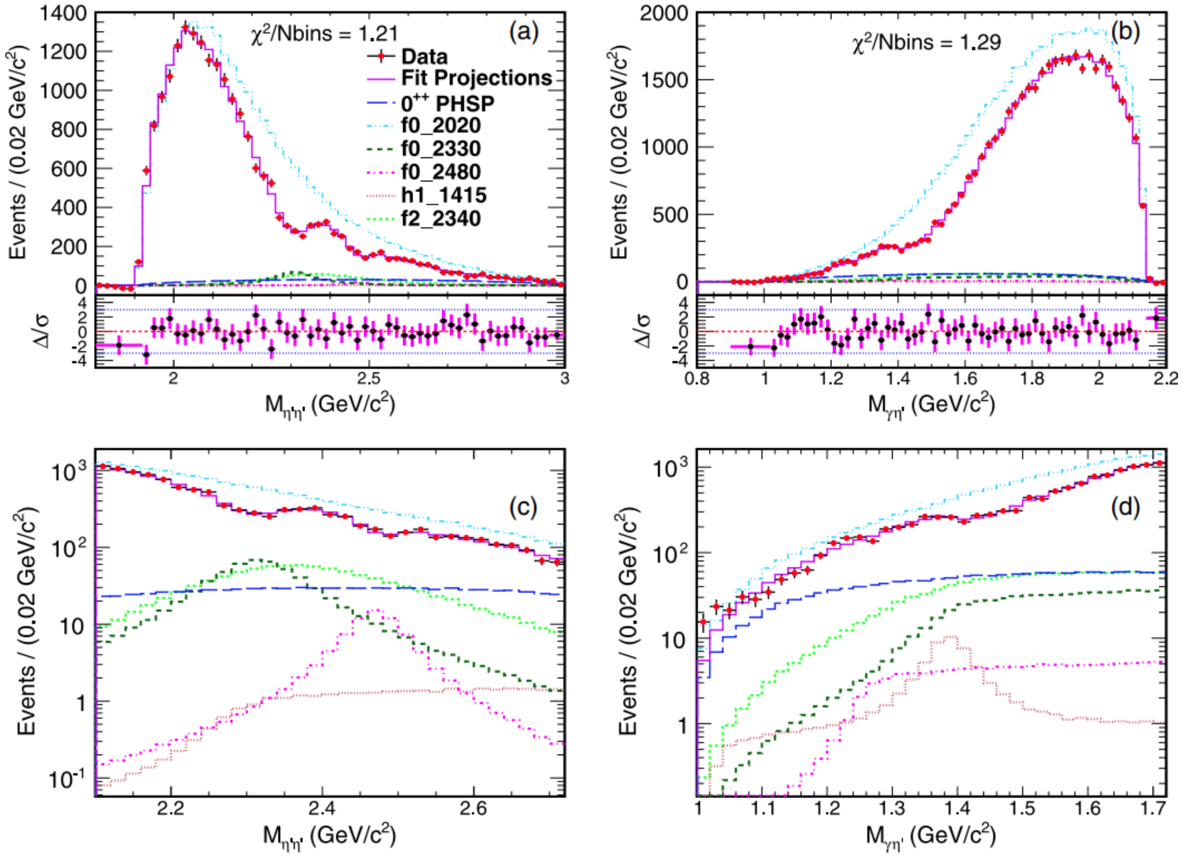
- Supports to the hypothesis that $f_0(1710)$ overlaps with the ground state scalar (0^{++}) glueball

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

- $J^{PC} = 0^{++}, 2^{++}, 4^{++}$ in $\eta'\eta'$, $J^{PC} = 1^{+-}, 1^{--}$ in $\gamma\eta'$

PRD 105, 072002(2022)

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



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

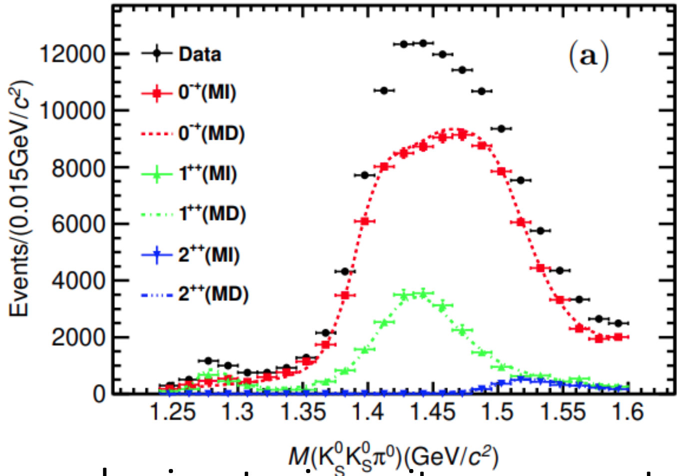
➢ $f_0(2020)$:
  - large production rate in radiative J/ψ decay suggests a large overlap with scalar glueball
  - but its mass is lower than the mass of the first excitation of scalar glueball from the LQCD prediction

➢ $f_0(2048)$: new 0^{++} state observed

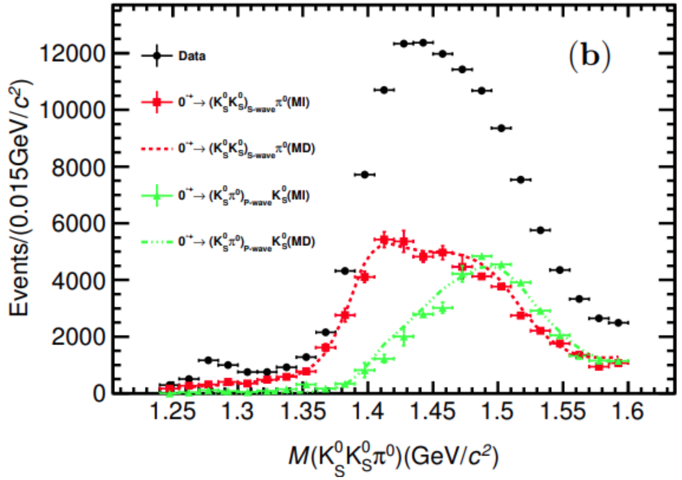
Partial Wave Analysis of $J/\psi \rightarrow \gamma K_s K_s \pi^0$

JHEP03(2023)121

- Prominent structure around 1.45 GeV/c^2 -> study the $\eta(1405)/(1475)$
- Mass independent PWA
  - The pseudoscalar component is the dominant contribution
  - $(K_S^0 K_S^0)_{S-wave}\pi^0$and $(K_S^0\pi^0)_{P-wave}K_S^0$ partial waves are of comparable magnitude, but with different lineshape and peaks
  - Non-trivial 0^{-+} line shape
- Mass Dependent PWA
  - two resonances parameterization needed



dominant spin-parity components

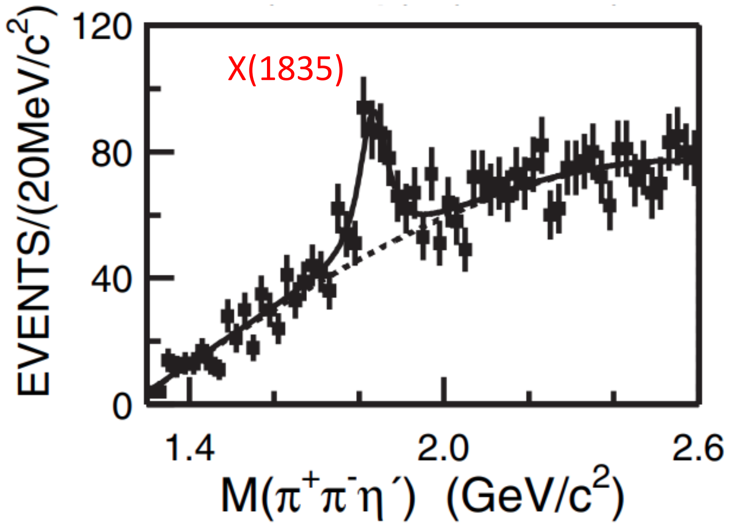


dominant decay modes for the pseudoscalar component

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV})$	Decay Mode	B.F.	Sig.(σ)
$\boxed{\eta(1405)}$	$1391.7\pm0.7^{+11.3}_{-0.3}$	$60.8\pm1.2^{+5.5}_{-12.0}$	$J/\psi\to\gamma\eta(1405)\to\gamma K_S^0(K_S^0\pi^0)_{\text{P-wave}}\to\gamma K_S^0K_S^0\pi^0$	$(5.84\pm0.12^{+2.03}_{-3.36})\times10^{-5}$	$\gg 35$
			$J/\psi\to\gamma\eta(1405)\to\gamma(K_S^0K_S^0)_{\text{S-wave}}\pi^0\to\gamma K_S^0K_S^0\pi^0$	$(2.88\pm0.04^{+1.64}_{-0.38})\times10^{-5}$	18.4
$\boxed{\eta(1475)}$	$1507.6\pm1.6^{+15.5}_{-32.2}$	$115.8\pm2.4^{+14.8}_{-10.9}$	$J/\psi\to\gamma\eta(1475)\to\gamma K_S^0(K_S^0\pi^0)_{\text{P-wave}}\to\gamma K_S^0K_S^0\pi^0$	$(6.58\pm0.12^{+3.98}_{-2.82})\times10^{-5}$	$\gg 35$
			$J/\psi\to\gamma\eta(1475)\to\gamma(K_S^0K_S^0)_{\text{S-wave}}\pi^0\to\gamma K_S^0K_S^0\pi^0$	$(3.99\pm0.09^{+0.41}_{-0.66})\times10^{-5}$	$\gg 35$
$f_1(1285)$	$1280.2\pm0.6^{+1.2}_{-1.5}$	$28.2\pm1.1^{+5.5}_{-2.9}$	$J/\psi\to\gamma f_1(1285)\to\gamma a_0(980)^0\pi^0\to\gamma K_S^0K_S^0\pi^0$	$(8.55\pm0.41^{+3.42}_{-1.04})\times10^{-6}$	$\gg 35$
$f_1(1420)$	$1433.5\pm1.1^{+27.9}_{-0.7}$	$95.9\pm2.3^{+13.6}_{-10.9}$	$J/\psi\to\gamma f_1(1420)\to\gamma K^*(892)^0K_S^0\to\gamma K_S^0K_S^0\pi^0$	$(7.25\pm0.12^{+0.73}_{-1.25})\times10^{-5}$	$\gg 35$
			$J/\psi\to\gamma f_1(1420)\to\gamma a_0(980)^0\pi^0\to\gamma K_S^0K_S^0\pi^0$	$(4.62\pm0.36^{+2.36}_{-1.94})\times10^{-6}$	17.8
$f_2(1525)$	$1515.4\pm2.5^{+3.2}_{-7.6}$	$64.0\pm4.3^{+2.0}_{-6.1}$	$J/\psi\to\gamma f_2(1525)\to\gamma K^*(892)^0K_S^0\to\gamma K_S^0K_S^0\pi^0$	$(9.47\pm0.43^{+1.51}_{-0.66})\times10^{-6}$	23.8

X States Observed in the Process $J/\psi \to \gamma\pi^+\pi^-\eta'$ at BESIII

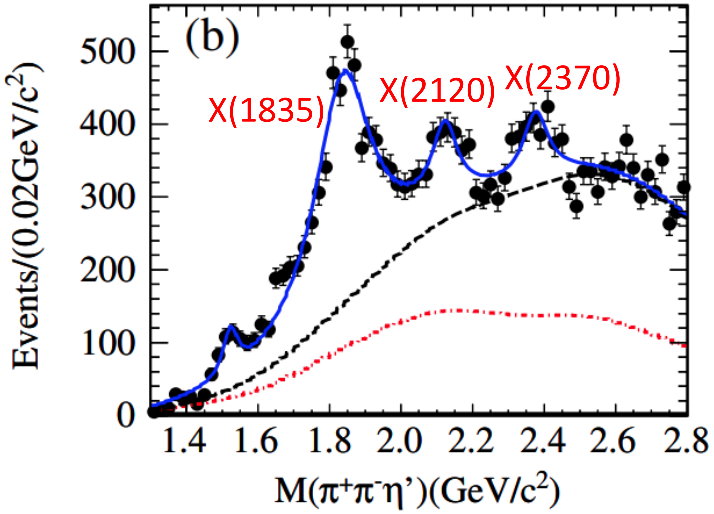
PRL 95, 262001 (2005)



58×10^6 J/ψ events

Observation of X(1835)

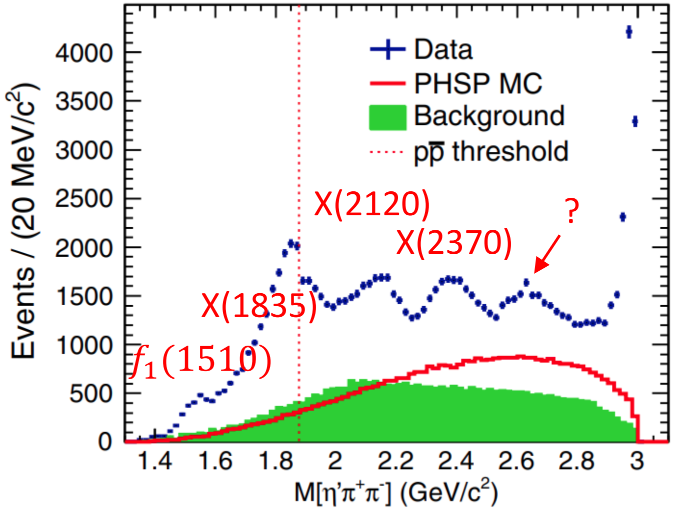
PRL 106, 072002 (2011)



225.2×10^6 J/ψ events

Observation of X(2120), X(2370)

PRL 117, 042002 (2016)



1090×10^6 J/ψ events

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

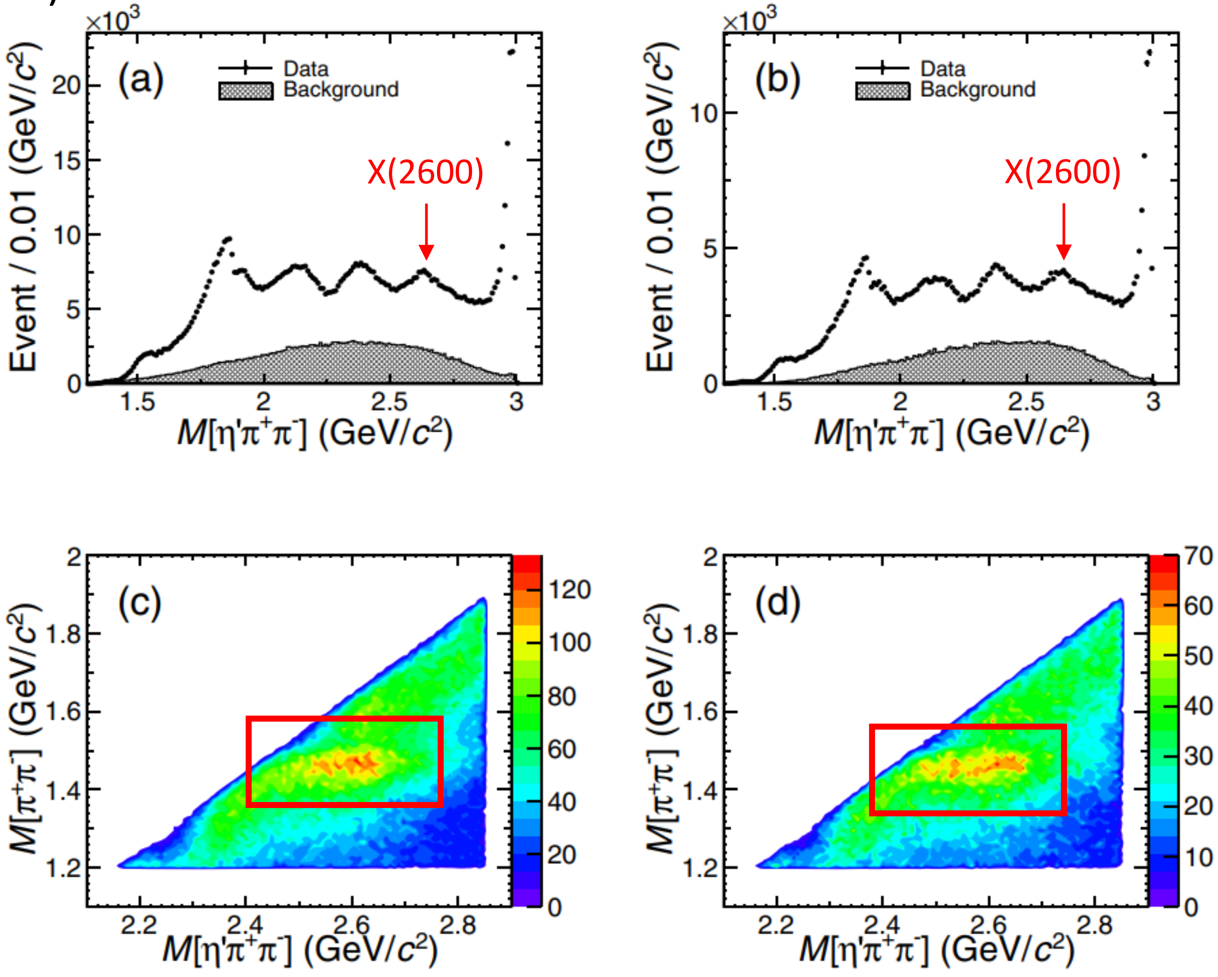
Additional structures: X(2120), X(2370), ?

Observation of a State X(2600) in the Process $J/\psi \to \gamma\pi^+\pi^-\eta'$

PRL 129, 042001 (2022)

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

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



$\eta' \to \gamma\pi^+\pi^-$ channel

$\eta' \to \pi^+\pi^-\eta$ channel

Observation of a State X(2600) in the Process $J/\psi \to \gamma\pi^+\pi^-\eta'$

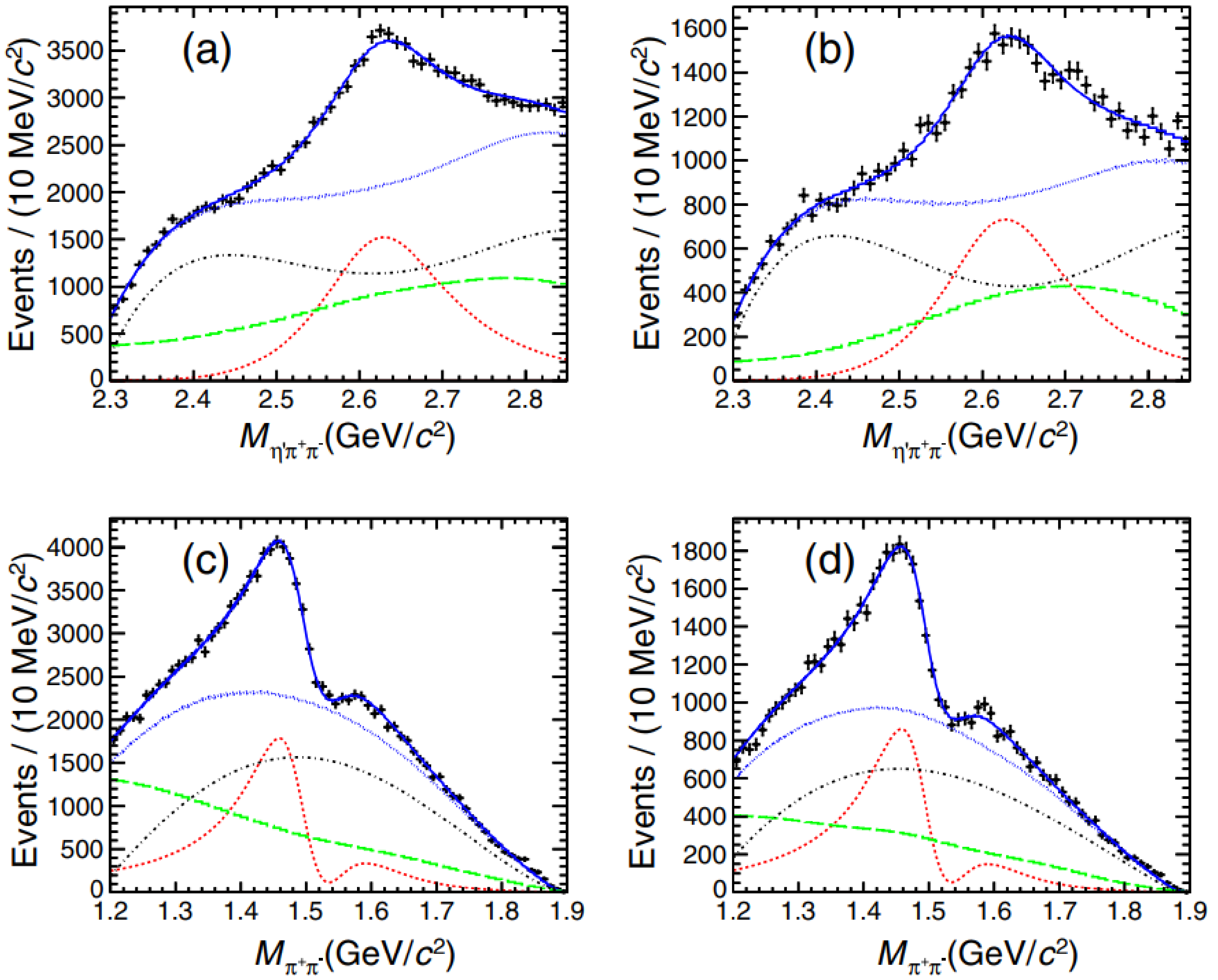
- Simultaneous fit to $\pi^+\pi^-\eta'$ and $\pi^+\pi^-$ mass spectra is performed

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

- Pseudoscalar glueballs or excited $q\bar{q}$ state ?
  - $f_0(1500)$ is a scalar glueball or not



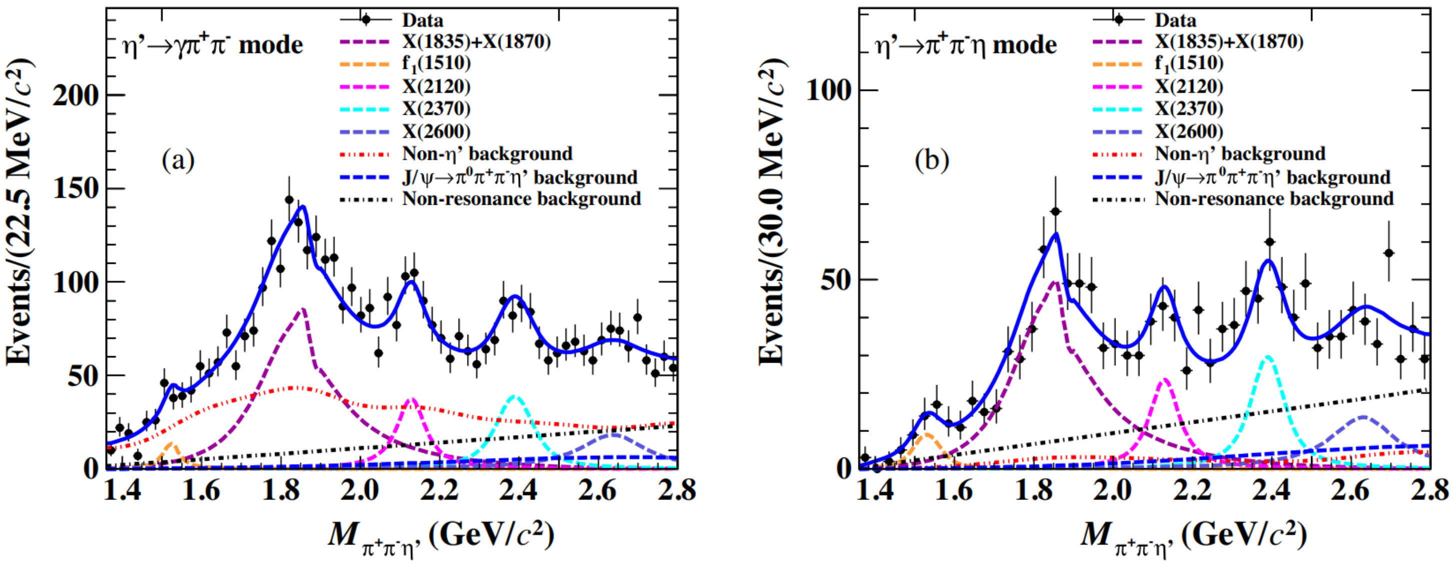
$\eta' \to \gamma\pi^+\pi^-$ channel $\eta' \to \pi^+\pi^-\eta$ channel

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

10 Billion of J/ψ data

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

- The observation of the EM Dalitz decay $J/\psi \to e^+e^-\pi^+\pi^-\eta'$. This is also the first observation of the states X(1835), X(2120), and X(2370) in the EM Dalitz decays.

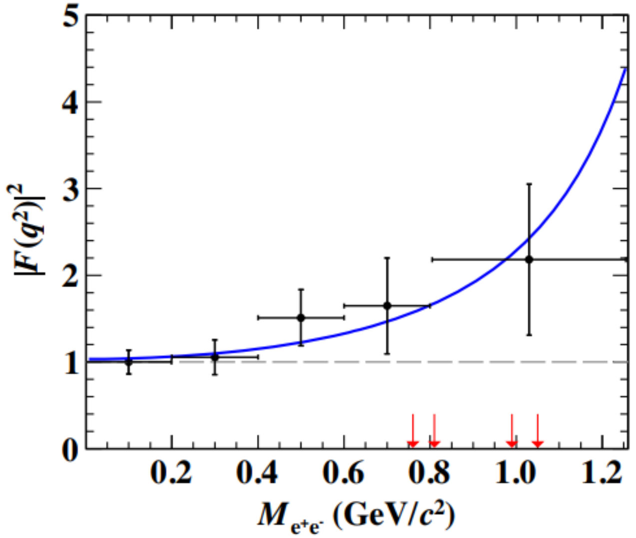


- Access to the EM transition form factor between J/ψ and X(1835) states:

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

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

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



PRL 129, 022002

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
  - …

- BESIII will continue to run ~2030
- Excellent opportunities for light hadron spectroscopy

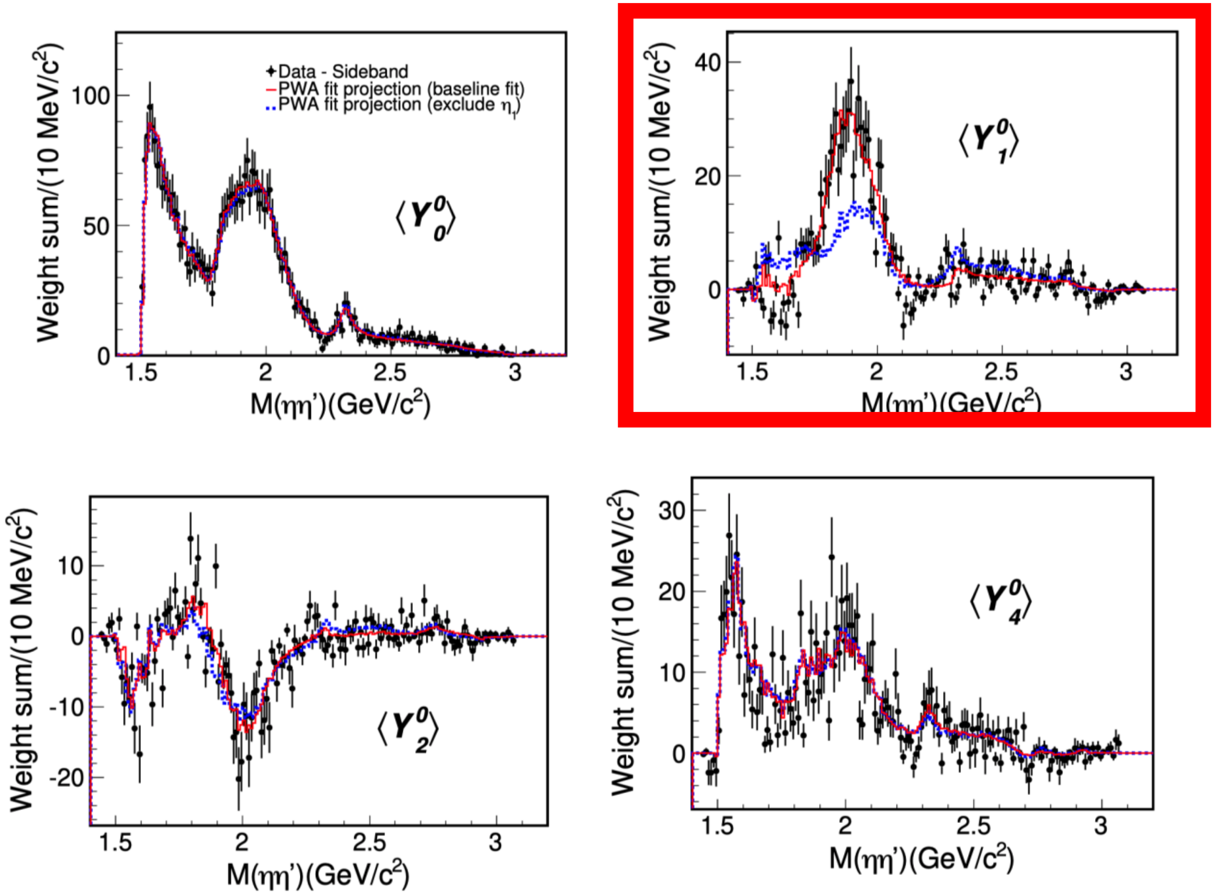
More interesting results are expected!

backup

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

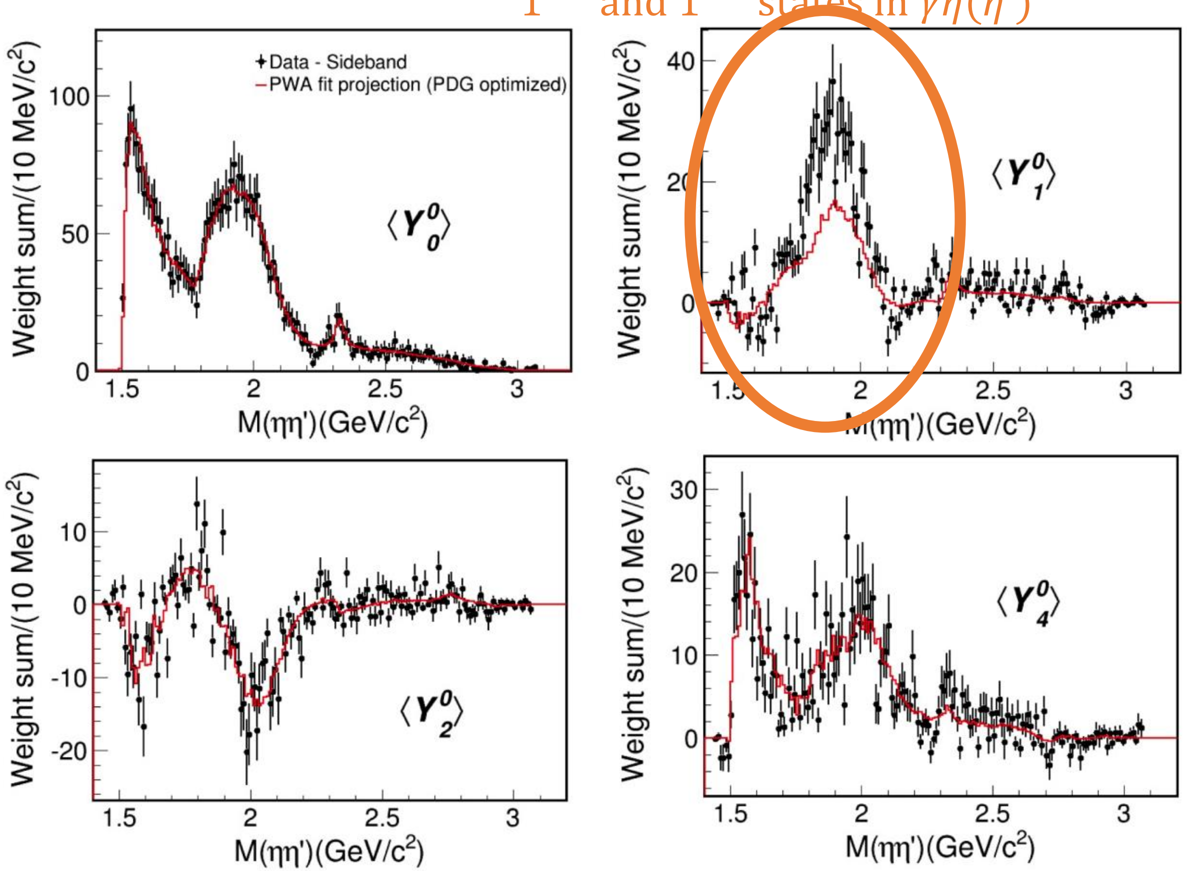
Baseline set of amplitudes

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



PDG-optimized set of amplitudes

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

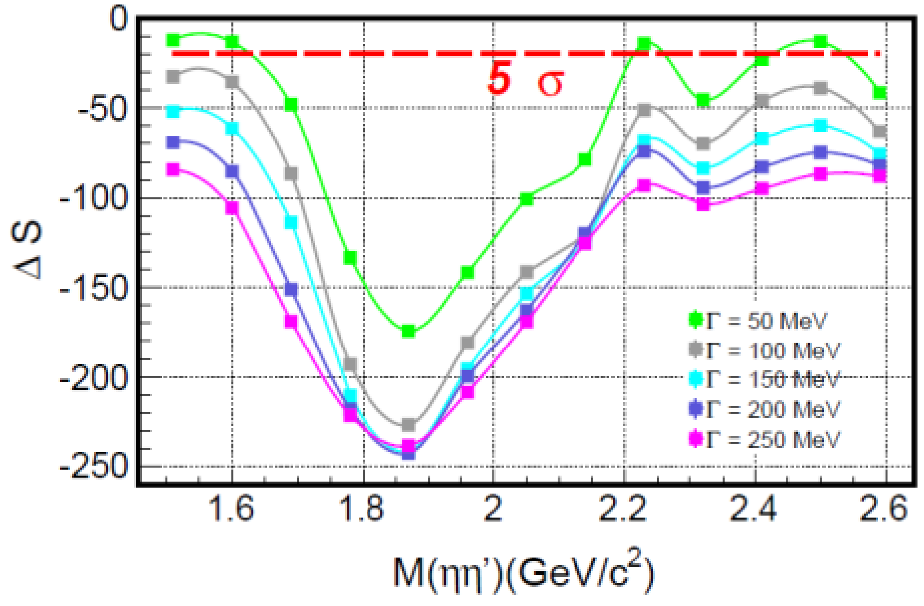


- Narrow structure in $< Y_1^0 >$ cannot be described by resonances in $\gamma\eta(\eta')$
  - ➢ $\eta_1(1855) \to \eta\eta'$ needed

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

- Change J^{PC} of $\eta_1(1855)$: log-likelihood ↓235
  - ➢ J^{PC} **prefer** 1^{-+}
- Remove **BW phase motion** of $\eta_1(1855)$: log-likelihood ↓43
  - ➢ **Resonance structure** needed
- **Assuming $\eta_1(1855)$ as additional resonance**, evaluate its significance with various **masses and widths**
  - ➢ Significant 1^{-+} contribution around $1.8\ \mathrm{GeV}/c^2$ needed
- Systematic uncertainties are studied, and **significance of $\eta_1(1855)$ remains larger than 19σ** in all cases

significance of $\eta_1(1855)$ with various masses and widths



X(18xx) between 1.8-1.9GeV