Observation of an isoscalar resonance with exotic $J^{PC} = 1^{-+}$ quantum numbers in $J/\psi \to \gamma\eta\eta'$

Phys. Rev. Lett. 129, 192002 (2022), Phys. Rev. D 106, 072012 (2022)

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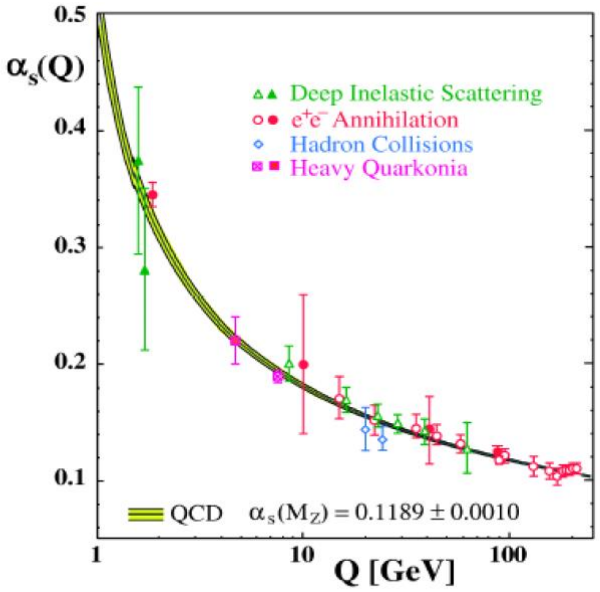
Hadron Physics Online Forum (HAPOF), Nov. 11, 2022

Introduction

- Hadrons, the complex building blocks of our world, emerge from interaction of quarks and gluons as described by QCD

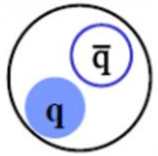
- NPQCD: How does QCD give rise to hadrons?
  - What is the origin of confinement? (Quarks and gluons not isolated in nature)
  - Role of gluons: Mass? Spin? …
  - Quark model seems to work really well. Why?
  - Existence of states beyond Quark Model?

Asymptotic Freedom
PQCD

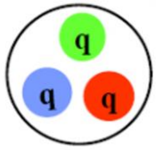


Confinement & NPQCD
“World of Hadrons”

Quark model



meson



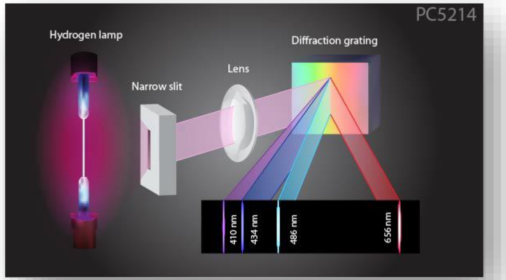
baryons

Hadron spectroscopy

- Testing QCD in the confinement regime
- Revealing the fundamental degrees of freedom

Atomic Spectrum:

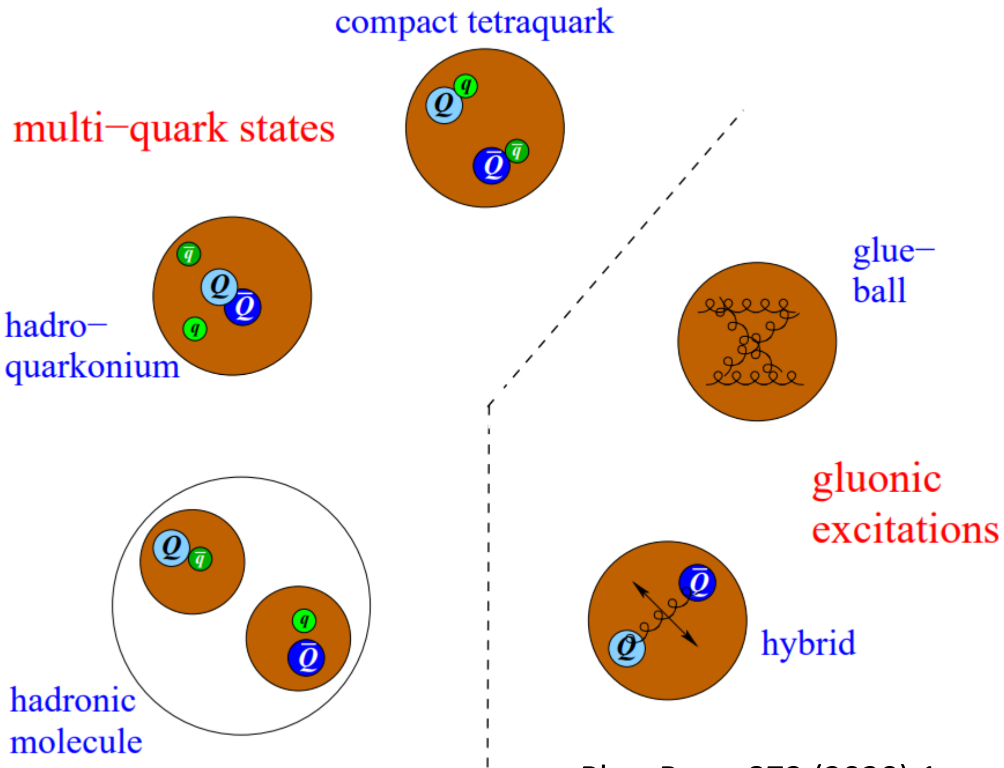
Bohr model → QED



Hadron spectrum:

Quark model → QCD

Key things to search for:
further possible configurations beyond quark model

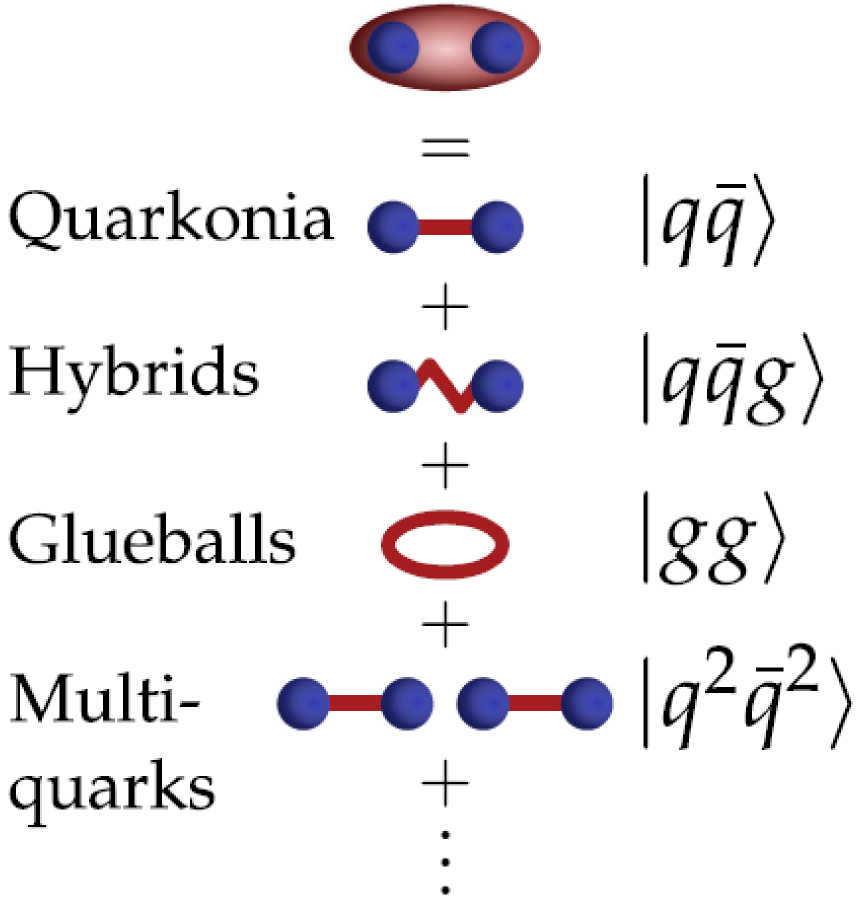


Phys.Rept. 873 (2020) 1

QCD exotics

- QCD permits additional color-singlet configurations

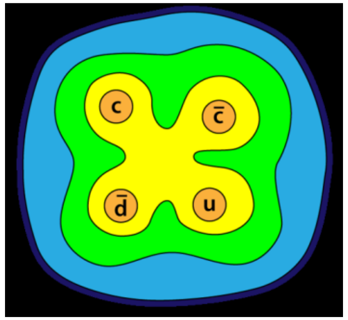
- Physical mesons
  - Linear superpositions of all allowed basis states
  - “Configuration mixing”
  - Disentanglement of contributions difficult
    - Detailed information about couplings to production and decay channels required

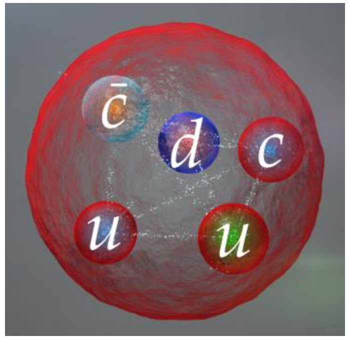


→ Discovery with precision measurement

So far…

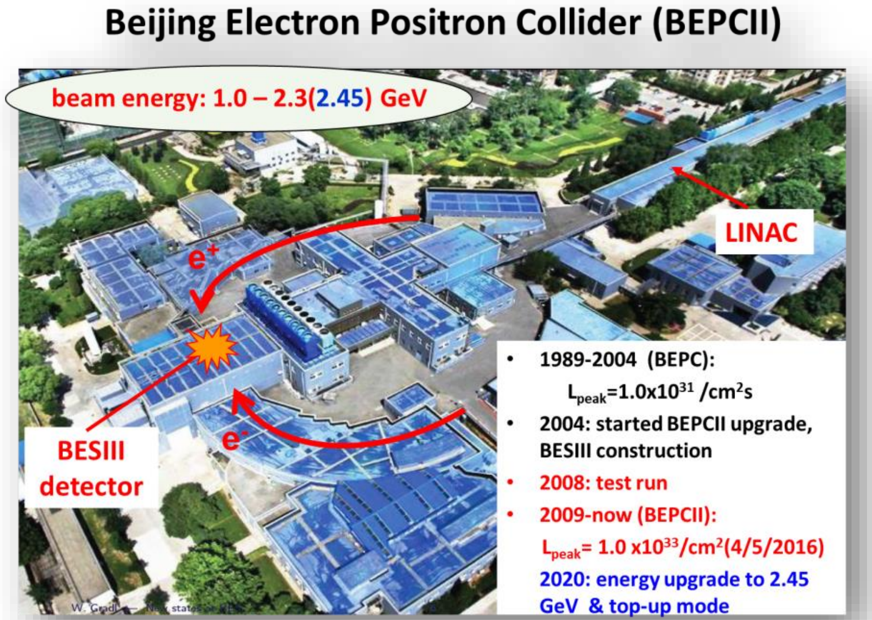
- Strong evidence for QCD exotics in heavy quark sector, e.g.Tetraquark candidates $Z_c^+ \to J/\psi\pi$,Pentaquark candidates $P_c^+ \to J/\psi p$, …

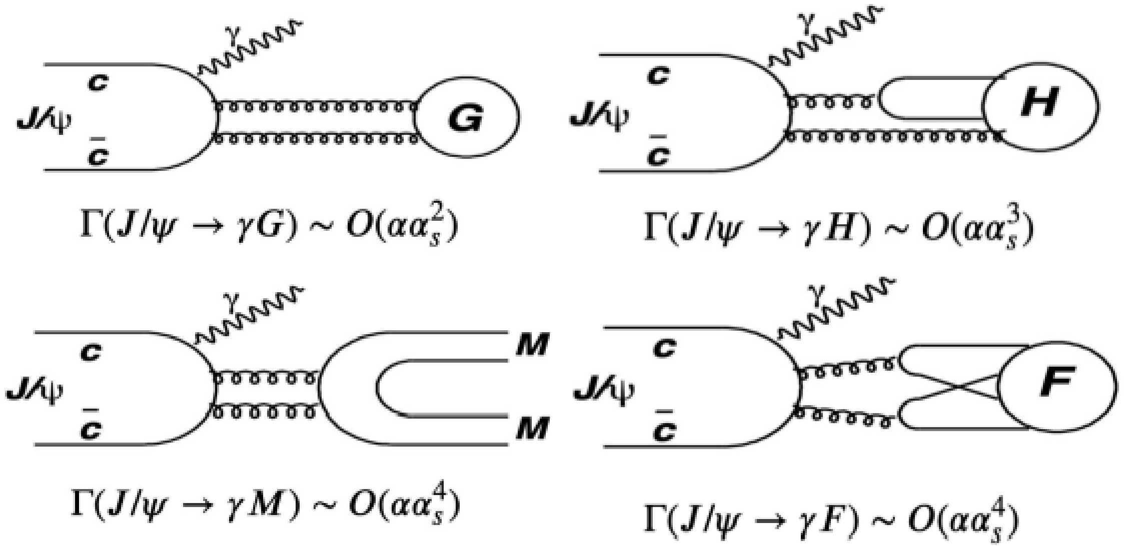




- Light quark sector is more complicated
  - evidence for gluonic degrees of freedom remains sparse

But, an absolute necessity to claim that we understand hadrons





Charmonium decays provide an ideal lab for light QCD exotics

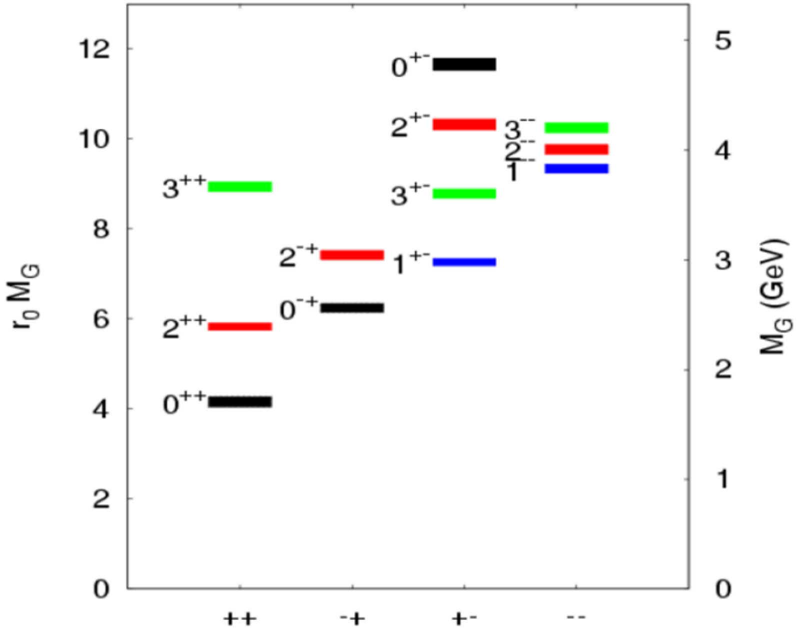
- **Clean high statistics data samples**
  High cross sections of $e^+e^- \to J/\psi,\ \psi'$
  Low background
- **Well defined initial and final states**
  Kinematic constraints
  $I(J^{PC})$ filter
- **"Gluon-rich" process**

Glueballs

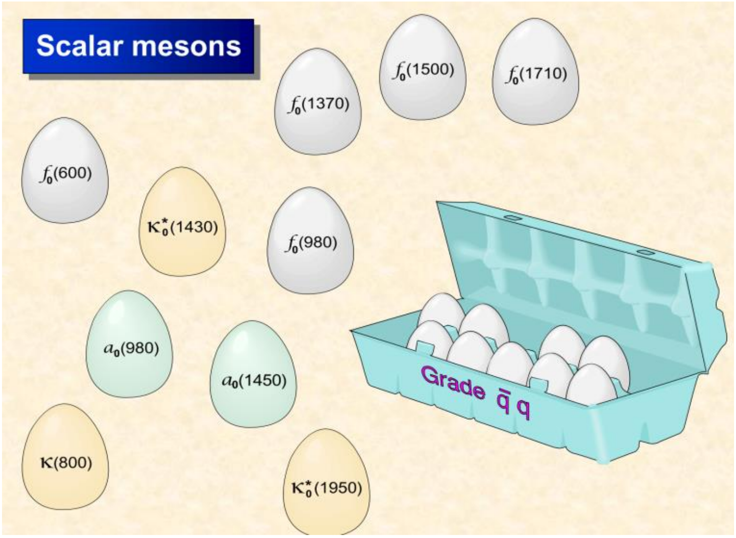
- Evidence of gluon self interaction

- Gluonic Excitations provide a measurement of the excited QCD potential

- Low-lying glueballs with ordinary J^{PC} → mixing with $q\bar{q}$ mesons
  - ~~Observe a new peak~~
  - "overpopulation" , e.g. $f_0(1370)$& $f_0(1500)$& $f_0(1710)$
    - Solve the mixing scheme



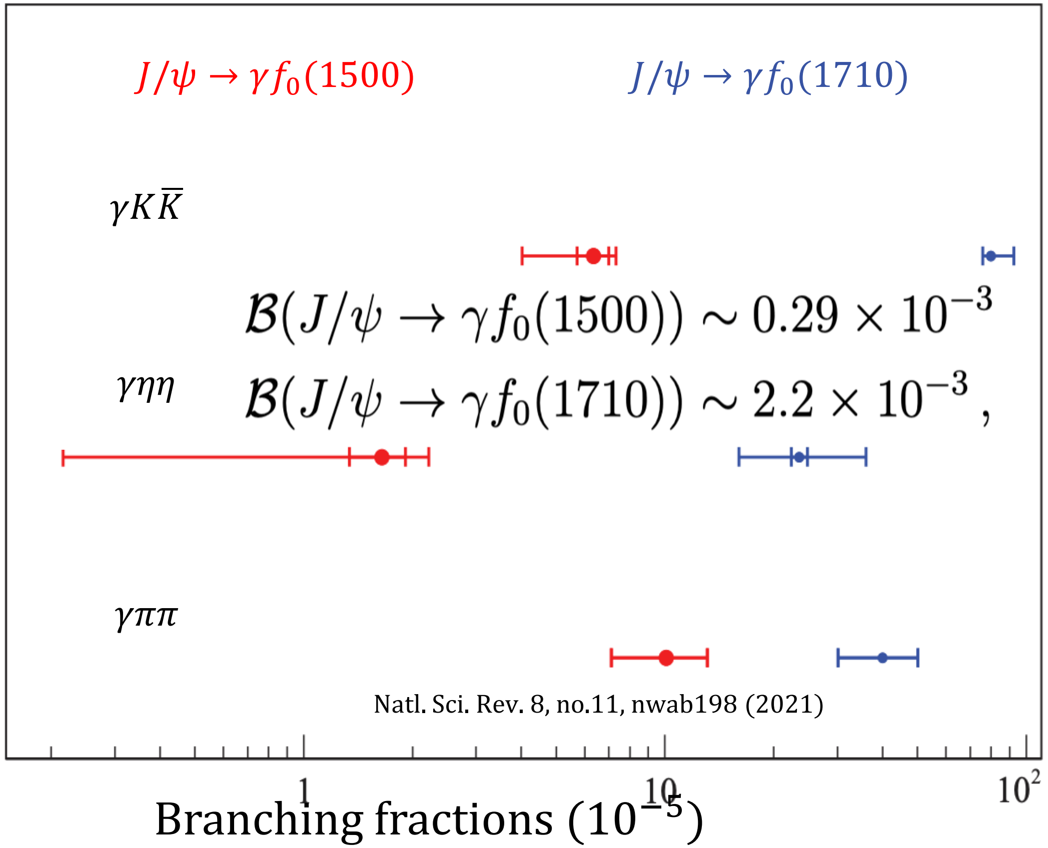
Glueballs from Lattice simulations in the pure gauge theory without quarks



Scalar glueball candidate: production properties

- **Scalar glueball is expected to have a large production in J/ψ radiative decays**:
  $B(J/\psi \to \gamma G_{0^+}) = 3.8(9) \times 10^{-3}$ by Lattice QCD
  - Observed $B(J/\psi \to \gamma f_0(1710))$ is x10 larger than $f_0(1500)$

➢ BESIII: $f_0(1710)$ largely overlapped with scalar glueball



Scalar glueball candidate: decay properties

- "Flavor-blindness of gluon" →SU(3)$_F$ for a pure glueball,

$$\Gamma(G \to \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta') = 3:4:1:0:1$$

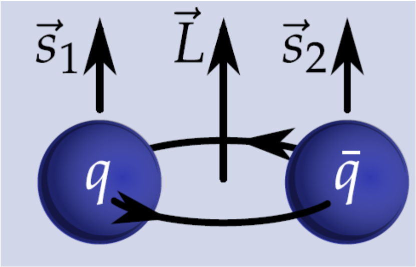
B(G → ηη')/B(G → ππ)<0.04, predicted in Phys. Rev. D 92, 121902

Using 10B of J/ψ events,

$J/\psi \to \gamma\eta\eta'$, Phys. Rev. Lett. 129, 192002 (2022), Phys. Rev. D 106, 072012 (2022)

$J/\psi \to \gamma\eta'\eta'$, Phys.Rev.D 105 (2022) 7, 072002

Spin-exotic mesons



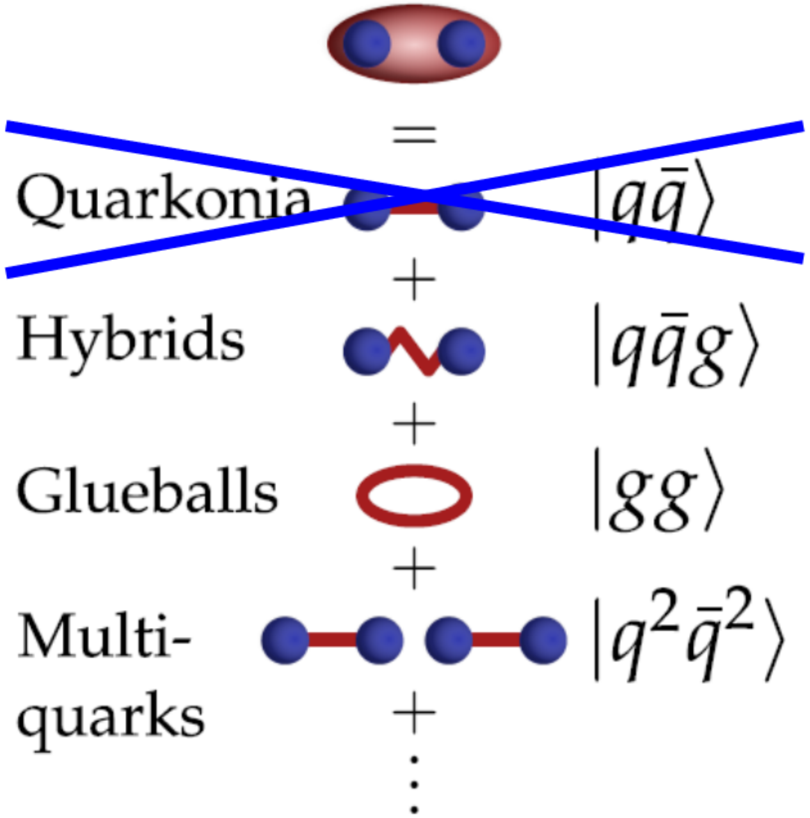
$\vec{\mathbf{J}} = \vec{\mathbf{L}} + \vec{\mathbf{S}}$ $\quad \mathbf{P} = (-\mathbf{1})^{\mathbf{L+1}}$ $\quad \mathbf{C} = (-\mathbf{1})^{\mathbf{L+S}}$

Allowed $\mathbf{J^{PC}}$: $\mathbf{0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots}$

Forbidden $\mathbf{J^{PC}}$: $\mathbf{0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots}$

- **States with $\mathbf{J^{PC} = 0^{--}, even^{+-}, odd^{-+}}$ forbidden for $\mathbf{q\bar{q}}$ configuration**

- **Finding them would be an unambiguous signature for configurations beyond simple quark model**



Detailed reviews:
Phys. Rev. C 82, 025208 (2010)
Prog. Part. Nucl. Phys. 82, 21 (2015)

Spin-exotic mesons

- **Only 3 candidates so far: All 1^{-+} isovectors**
  - $\pi_1(1400)$: seen in $\eta\pi$
  - $\pi_1(1600)$: seen in $\rho\pi$, $\eta'\pi$, $b_1\pi$, and $f_1\pi$
  - $\pi_1(2015)$ (needs confirmation): seen in $b_1\pi$, and $f_1\pi$
- Some claims are controversial

Experiments:

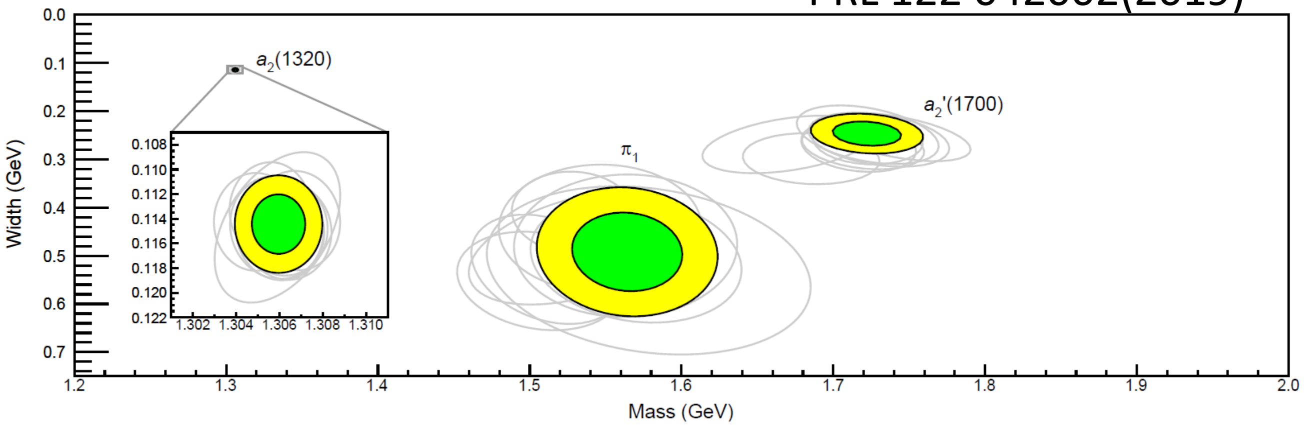
- **Hadroproduction:** E852, VES, COMPASS
- **$p\bar{p}$ annihilation:** Crystal Barrel, OBELIX, PANDA(2026)
- **Photoproduction:** GlueX(major goal, 2017-)

	Decay mode	Reaction	Experiment
$\pi_1(1400)$	$\eta\pi$	$\pi^-p \to \pi^-\eta p$ $\pi^-p \to \pi^0\eta n$ $\pi^-p \to \pi^-\eta p$ $\pi^-p \to \pi^0\eta n$ $\bar{p}n \to \pi^-\pi^0\eta$ $\bar{p}p \to \pi^0\pi^0\eta$	GAMS KEK E852 E852 CBAR CBAR
	$\rho\pi$	$\bar{p}p \to 2\pi^+2\pi^-$	Obelix
$\pi_1(1600)$	$\eta'\pi$	$\pi^-Be \to \eta'\pi^-\pi^0Be$ $\pi^-p \to \pi^-\eta'p$	VES E852
	$b_1\pi$	$\pi^-Be \to \omega\pi^-\pi^0Be$ $\bar{p}p \to \omega\pi^+\pi^-\pi^0$ $\pi^-p \to \omega\pi^-\pi^0p$	VES CBAR E582
	$\rho\pi$	$\pi^-Pb \to \pi^+\pi^-\pi^-X$ $\pi^-p \to \pi^+\pi^-\pi^-p$	COMPASS E582
	$f_1\pi$	$\pi^-p \to p\eta\pi^+\pi^-\pi^-$ $\pi^-A \to \eta\pi^+\pi^-\pi^-A$	E582 VES
$\pi_1(2015)$	$f_1\pi$	$\pi^-p \to \omega\pi^-\pi^0p$	E582
	$b_1\pi$	$\pi^-p \to p\eta\pi^+\pi^-\pi^-$	

Spin-exotic mesons

- $\pi_1(1400)$ and $\pi_1(1600)$ can be explained as one pole with recent coupled channel analyses
  - broad width consist with LQCD calculation for 1^{-+} hybrid, while a two-pole scenario cannot be completely excluded
  - $\pi_1(1400)$ is also interpreted as a four-quark state or a $f_1\pi$ molecule

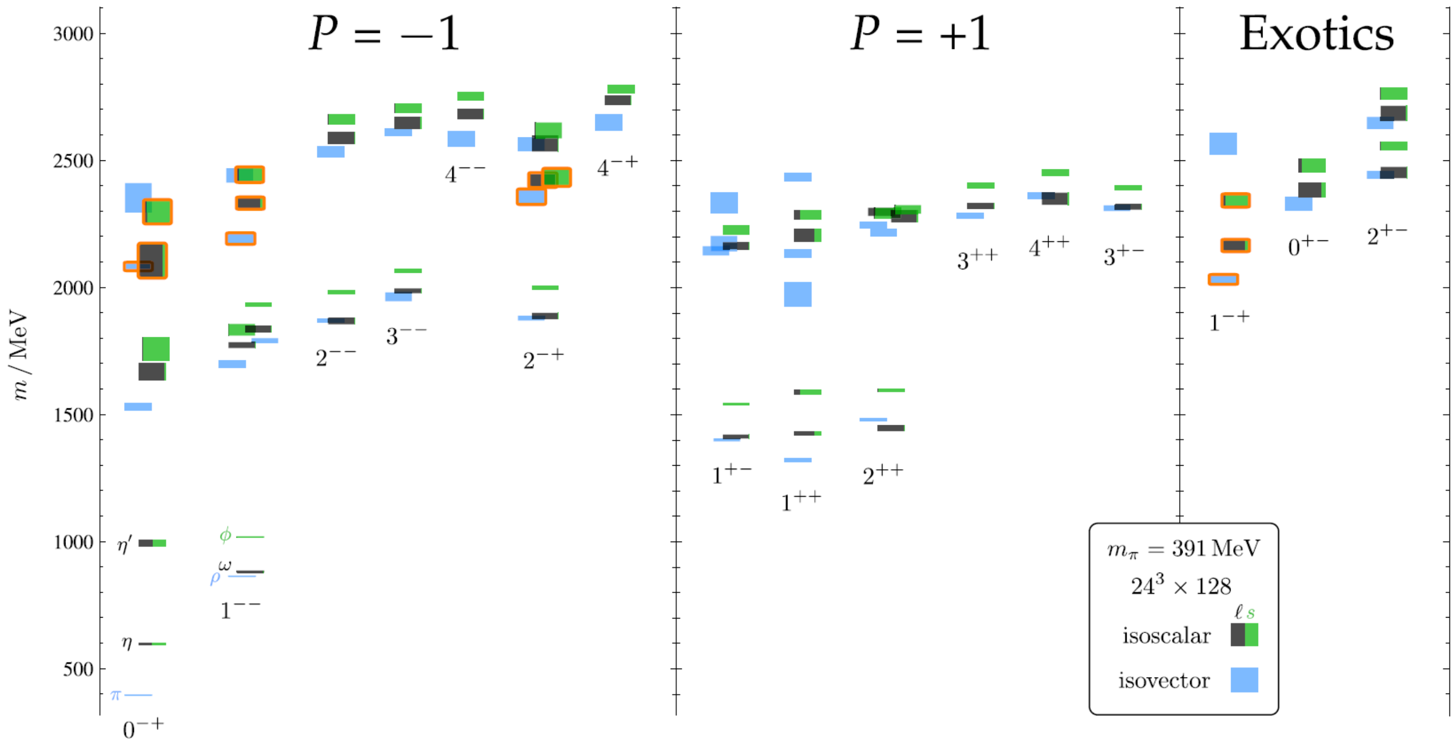
PRL 122 042002(2019)



- 1^{-+} contribution observed in $\chi_{c1} \to \eta'\pi^+\pi^-$ at CLEO-c (, but without significant BW phase shift) [Phys.Rev.D 95 (2017) 3, 032002]

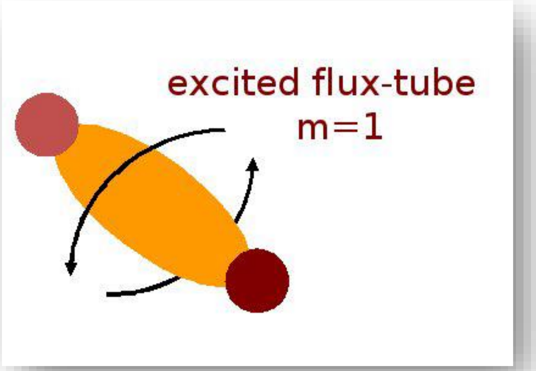
- No 1^{-+} observed in $\chi_{c1} \to \eta\pi^+\pi^-$ at BESIII [PRD 95, 032002 (2017)]

1^{-+} Hybrids on Lattice



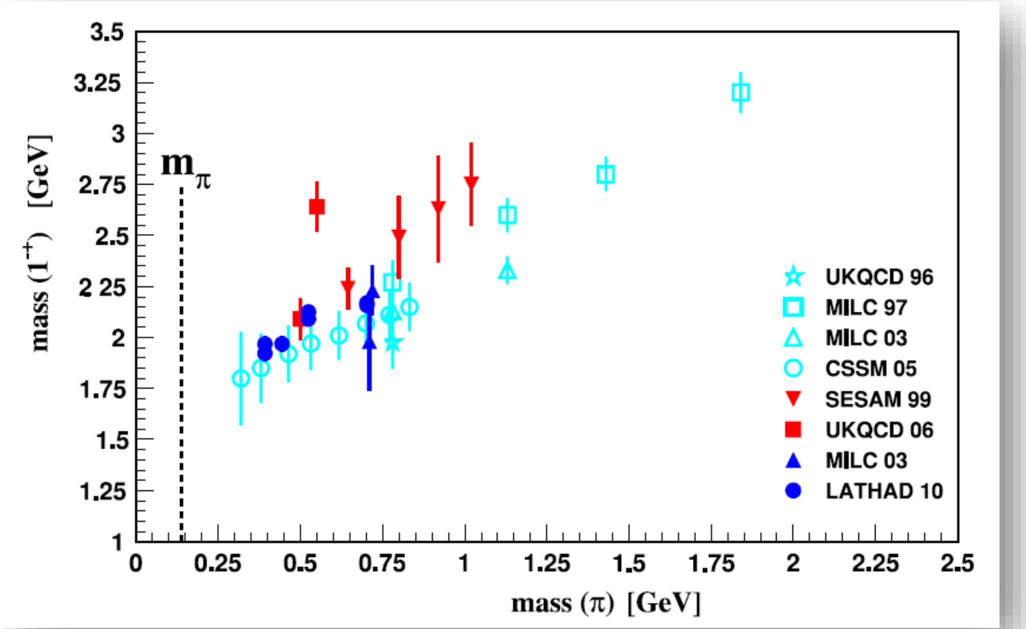
PRD 88 094505(2013)

Lightest nonet of hybrids: 1^{--} ; 0^{-+} , 1^{-+} ,2^{-+}



"Constituent gluon"

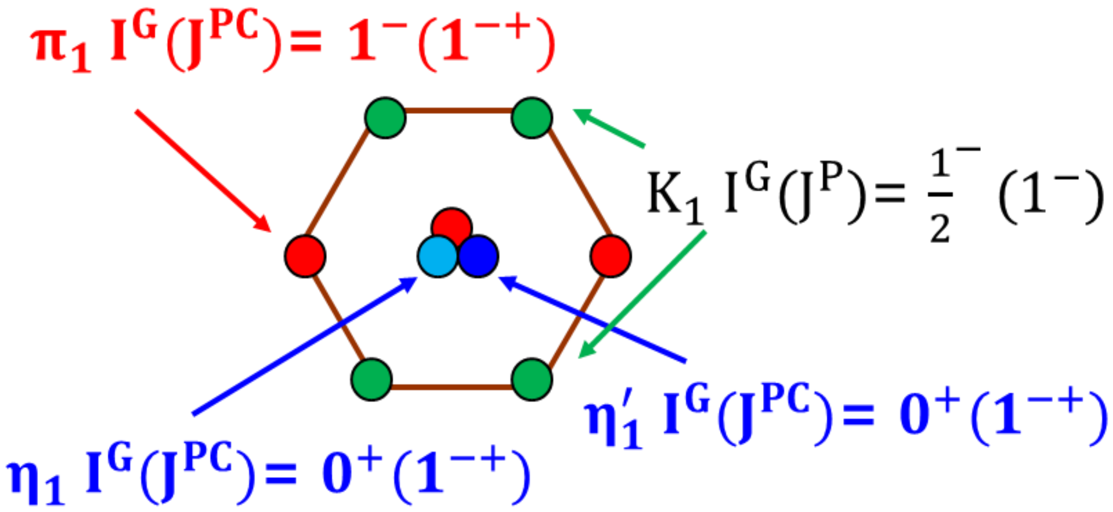
- $\left(J^{PC}\right)_g = 1^{+-}$
- M_g~1.3 GeV



Prog. Part. Nucl. Phys. 82, 21 (2015)

1^{-+} Hybrids

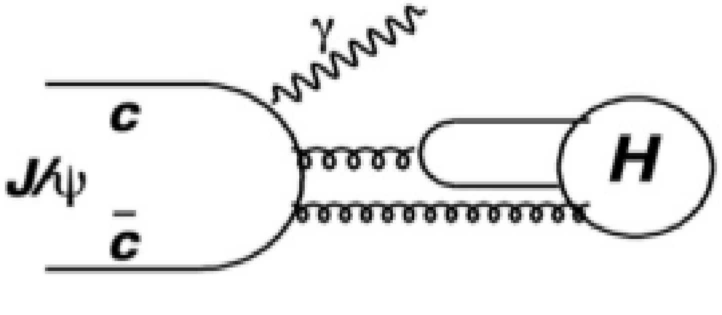
- **Isoscalar 1^{-+} is critical to establish the hybrid nonet**
  - **Can be produced in the gluon-rich charmonium decays**
  - **Can decay to $\eta\eta'$ in P-wave**



(hybrid kaons do not have exotic QNs)

PRD 83,014021 (2011), PRD 83,014006 (2011), EPJ.P 135, 945(2020)

→ Search for η_1 (1^{-+}) in $J/\psi \to \gamma\eta\eta'$

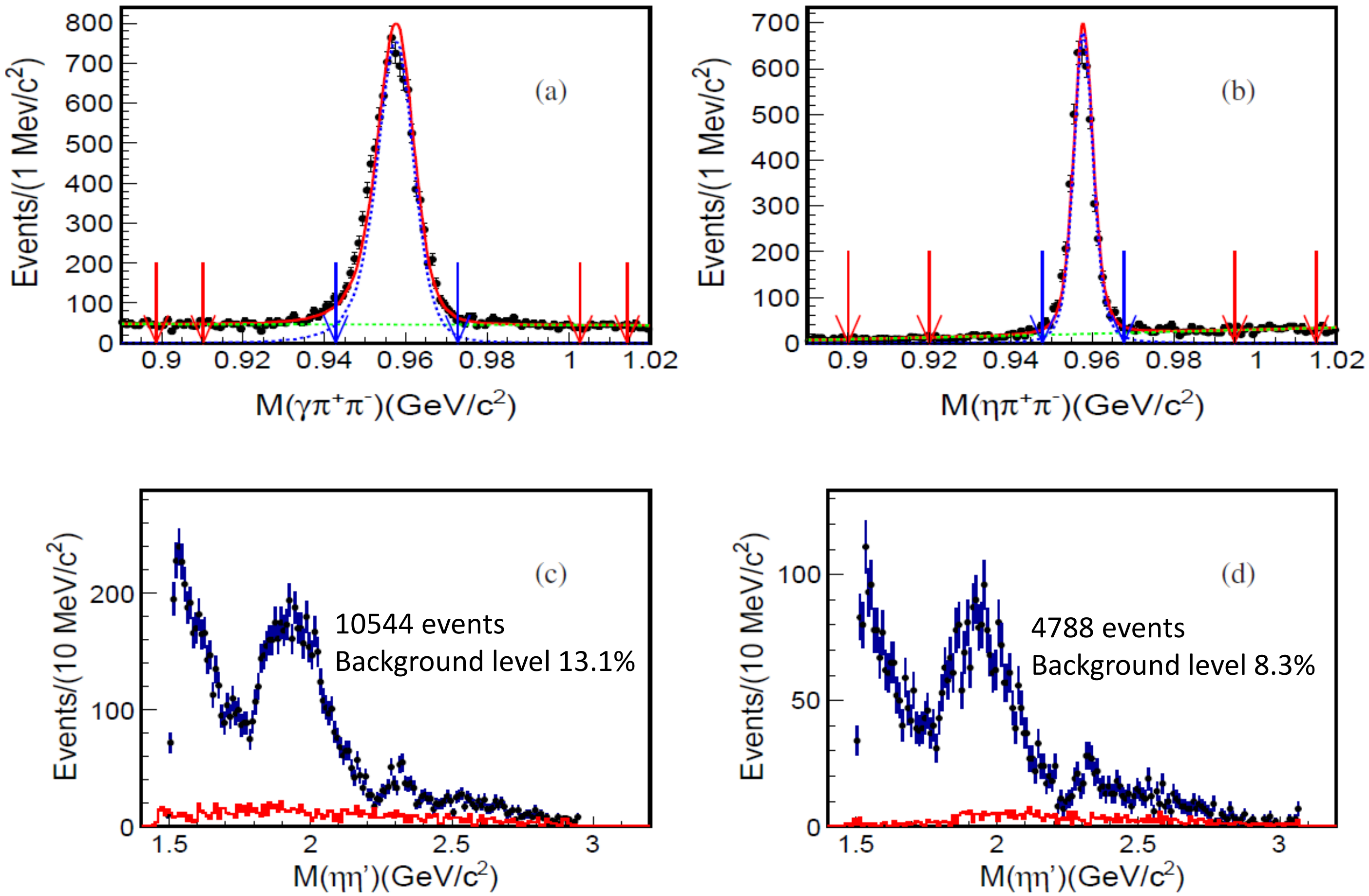


$$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$$

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

Phys. Rev. Lett. 129, 192002 (2022),
Phys. Rev. D 106, 072012 (2022)

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



- Potential backgrounds are studied using an inclusive MC sample of 10B J/ψ decays
- No significant peaking background is observed in the invariant mass distribution of the η'
- Backgrounds are estimated by the η' sidebands in the data

Partial wave analysis

- Similar as the analyses of $J/\psi \to \gamma\eta\eta$ [Phys.Rev. D 87, 092009]and $J/\psi \to \gamma K_S K_S$ [Phys.Rev. D 98, 072003], based on the covariant tensor amplitudes [Eur. Phys. J. A 16, 537] and the GPUPWA framework*
  - Isobars in $J/\psi \to \gamma X, X \to \eta\eta'$ and $J/\psi \to \eta X, X \to \gamma\eta'$ and $J/\psi \to \eta' X, X \to \gamma\eta$. X: constant-width, relativistic BW
- A combined unbinned maximum likelihood fit is performed for the two decay channels of η'
  - sharing the same set of masses, widths, relative magnitudes, and phases
- Backgrounds estimated by η' sidebands are subtracted

$$S = -(\ln\mathcal{L}_{data} - \sum_i \omega_i \cdot \ln\mathcal{L}_{background})$$

**The first PWA framework with GPU acceleration , J. Phys. Conf. Ser. 219, 042031(2010)*

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

Decay mode	0^{++}	2^{++}	4^{++}
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	$f_2(1525)$	$f_4(2050)$
	$f_0(1710)$	$f_2(1565)$	$f_4(2300)$
	$f_0(1810)$[58]	$f_2(1640)$	$f_4(2283)$[57]
	$f_0(2020)$	$f_2(1810)$	
	$f_0(2100)$	$f_2(1910)$	
	$f_0(2200)$	$f_2(1950)$	
	$f_0(2330)$	$f_2(2010)$	
	$f_0(2102)$[57]	$f_2(2150)$	
	$f_0(2330)$[57]	$f_2(2220)$	
		$f_2(2300)$	
		$f_2(2340)$	
		$f_2(2240)$[57]	

	1^{--}	1^{+-}
$J/\psi \to \eta^{(\prime)} X \to \gamma\eta\eta'$	$\omega(1420)$	$h_1(1415)$
	$\omega(1650)$	$h_1(1595)$
	$\phi(1680)$	
	$\phi(2170)$	
	$\rho(1450)$	
	$\rho(1700)$	
	$\rho(1900)$	

PDG and

[57] $\bar{p}p$ reactions at Crystal Barrel and PS172, Phys. Rept. 397, 257

[58] $J/\psi \to \gamma\phi\omega$ at BESIII, Phys. Rev. D 87,032008

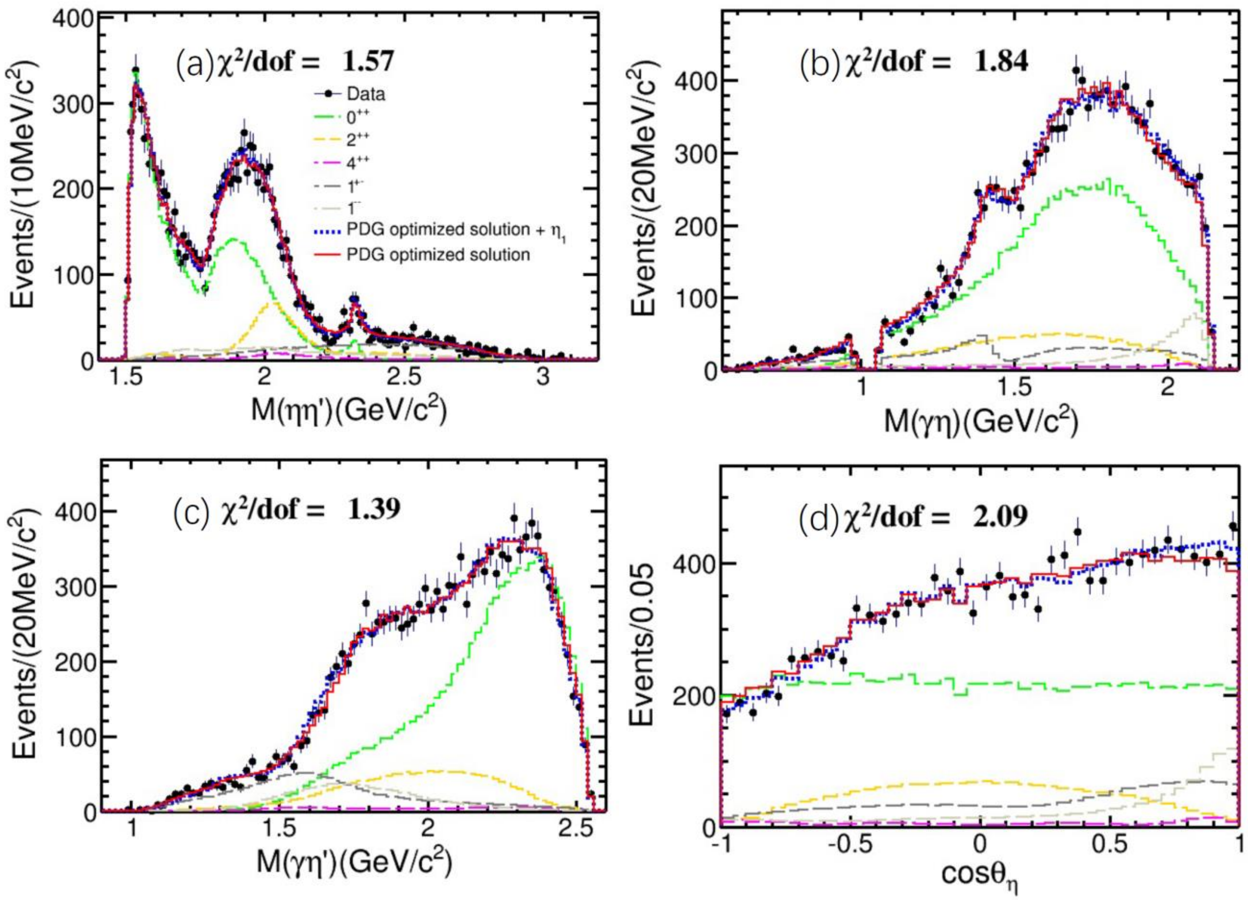
PDG-optimized set of amplitudes

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	3.05±0.07	$\gg 30\sigma$
	$f_0(1810)$	1795	95	1795	95	0.07±0.01	7.6σ
	$f_0(2020)$	1935±5	266±9	1992	442	1.67±0.07	11.0σ
	$f_0(2100)$	2109±11	253±21	2086	284	0.33±0.03	5.2σ
	$f_0(2330)$	2327±4	44±5	2314	144	0.07±0.01	8.5σ
	$f_2(1565)$	1542	122	1542	122	0.20±0.03	6.2σ
	$f_2(1810)$	1815	197	1815	197	0.37±0.03	7.0σ
	$f_2(2010)$	2022±6	212±8	2011	202	1.36±0.10	8.8σ
	$f_2(2340)$	2345	322	2345	322	0.25±0.04	6.5σ
	$f_4(2050)$	2018	234	2018	234	0.11±0.02	5.6σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	1416	90	0.14±0.01	10.3σ
	$h_1(1595)$	1584	384	1584	384	0.41±0.04	9.7σ
	$\phi(2170)$	2160	125	2160	125	0.24±0.03	5.6σ
$J/\psi \to \eta X \to \gamma\eta\eta'$	$h_1(1595)$	1584	384	1584	384	0.50±0.03	11.0σ
	$\rho(1700)$	1720	250	1720	250	0.22±0.03	8.8σ

The masses and widths of the resonances near ηη′ threshold ($f_0(1500)$, $f_2(1525)$, $f_2(1565)$ and $f_2(1640)$) as well as those with small fit fractions (<3%) are always fixed to the PDG values

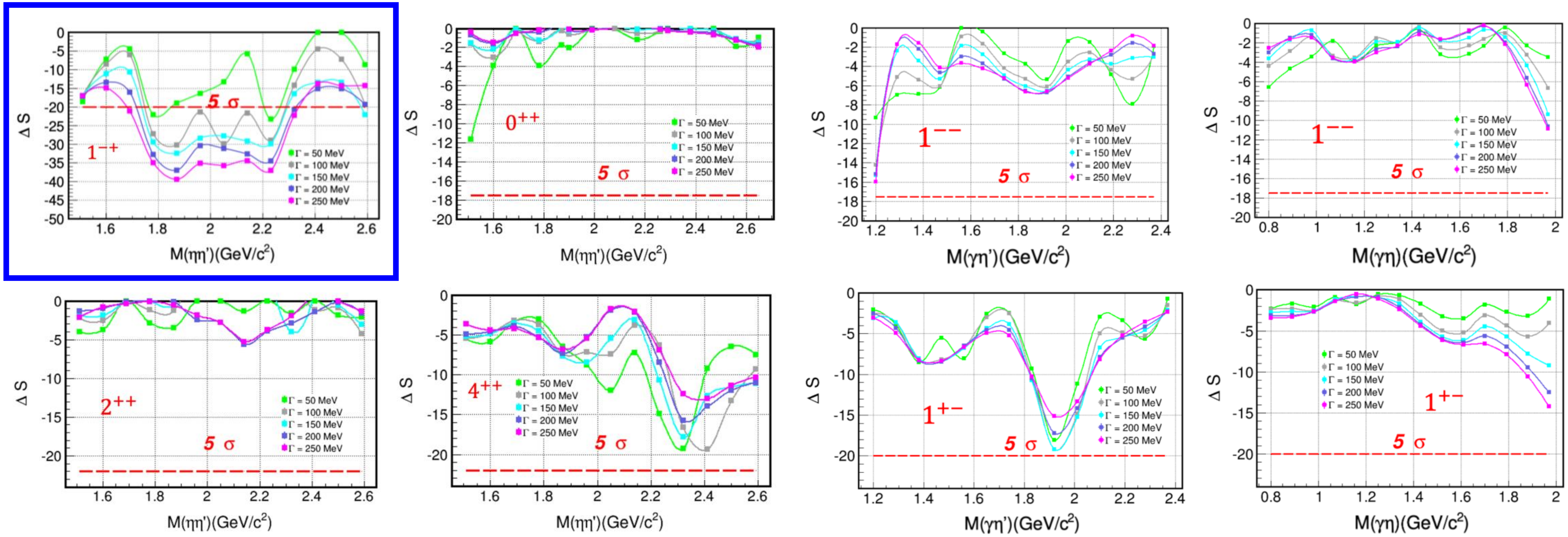
Components with statistical significance larger than 5σ

PWA projections for PDG-optimized set



Search for new resonances

scans of additional resonance with different J^{PC}, masses and widths



Baseline set of amplitudes by adding the η_1 state

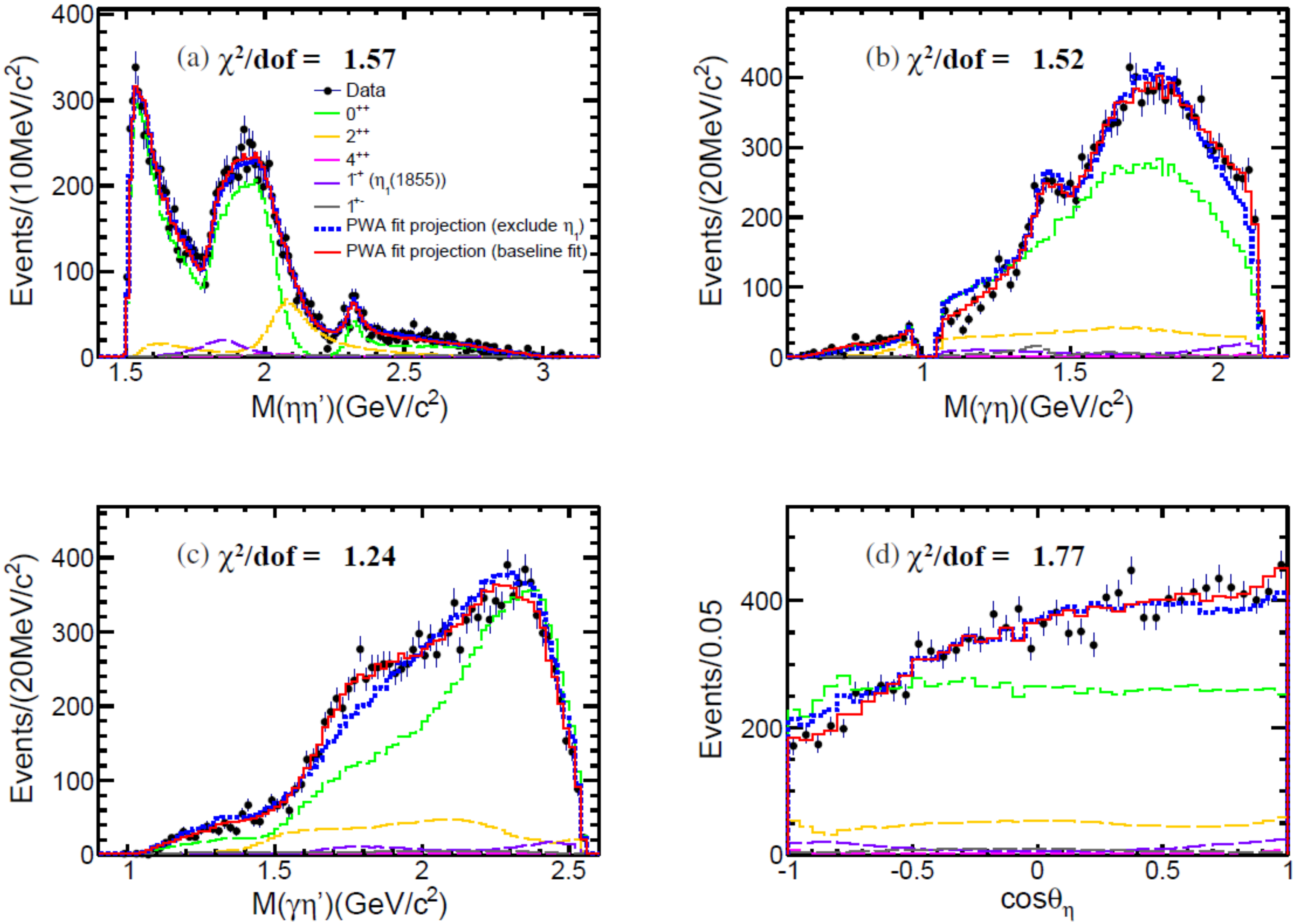
Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	$M_{\rm PDG}$ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg 30\sigma$
	$f_0(1810)$	1795	95	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	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

- Contributions from the $f_0(2100)$, $h_1(1595)(\gamma\eta')$, $\rho(1700)(\gamma\eta')$, $\phi(2170)(\gamma\eta)$, $f_2(1810)$, and $f_2(2340)$, in the PDG-optimized set become insignificant (< 3σ), omitted
- **Comparing to the PDG-optimized set, ln L of the baseline set is improved by 32 and the number of free parameters reduced by 16**

- **An isoscalar 1^{-+}, $\eta_1(1855)$, has been observed**
- **Mass is consistent with LQCD calculation for the 1^{-+} hybrid ($1.7\sim2.1$ GeV/c^2)**

Baseline set of amplitudes

PWA fit projections

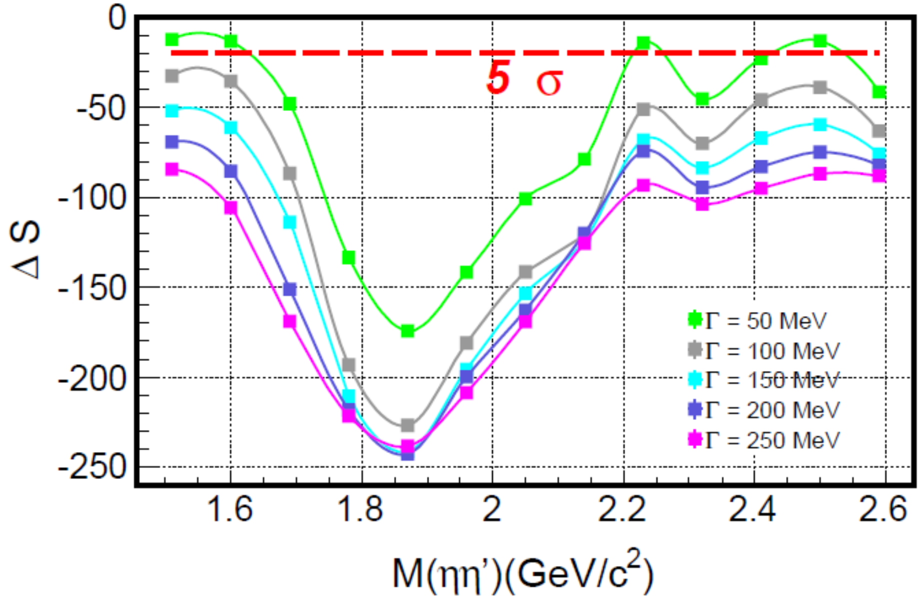


Significance for additional resonances

Decay mode	Resonance	J^{PC}	ΔS	ΔNdof	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_2(1525)$	2^{++}	6.3	6	1.9σ
	$f_2(1810)$	2^{++}	2.7	6	0.7σ
	$f_0(1710)$	0^{++}	3.4	2	2.1σ
	$f_2(1910)$	2^{++}	3.9	6	1.1σ
	$f_2(1950)$	2^{++}	2.6	6	0.6σ
	$f_0(2100)$	0^{++}	1.1	2	1.1σ
	$f_2(2150)$	2^{++}	2.3	6	0.5σ
	$f_0(2200)$	0^{++}	0.4	2	0.4σ
	$f_2(2220)$	2^{++}	8.6	6	2.6σ
	$f_2(2300)$	2^{++}	7.2	6	2.2σ
	$f_4(2300)$	4^{++}	2.3	6	0.5σ
	$f_0(2330)$	0^{++}	1.5	2	1.2σ
	$f_2(2340)$	2^{++}	6.3	6	1.9σ
	$f_0(2102)$[57]	0^{++}	0.1	2	0.2σ
	$f_2(2240)$[57]	2^{++}	2.9	6	0.7σ
	$f_2(2293)$[57]	2^{++}	4.1	6	1.2σ
	$f_4(2283)$[57]	4^{++}	0.9	6	0.1σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$\rho(1450)$	1^{--}	3.4	2	2.1σ
	$\rho(1700)$	1^{--}	0.8	2	0.7σ
	$\rho(1900)$	1^{--}	0.0	2	0σ
	$\omega(1420)$	1^{--}	5.3	2	2.8σ
	$\omega(1650)$	1^{--}	2.6	2	1.7σ
	$\phi(1680)$	1^{--}	4.3	2	2.5σ
	$\phi(2170)$	1^{--}	0.4	2	0.4σ
$J/\psi \to \eta X \to \gamma\eta\eta'$	$h_1(1415)$	1^{+-}	1.3	4	0.5σ
	$h_1(1595)$	1^{+-}	8.1	4	2.9σ
	$\rho(1450)$	1^{--}	1.3	2	1.1σ
	$\rho(1700)$	1^{--}	3.1	2	2.0σ
	$\rho(1900)$	1^{--}	6.1	2	3.0σ
	$\omega(1420)$	1^{--}	2.5	2	1.7σ
	$\omega(1650)$	1^{--}	0.8	2	0.7σ
	$\phi(1680)$	1^{--}	2.1	2	1.5σ
	$\phi(2170)$	1^{--}	0.1	2	0.1σ

all insignificant ($< 3\sigma$)

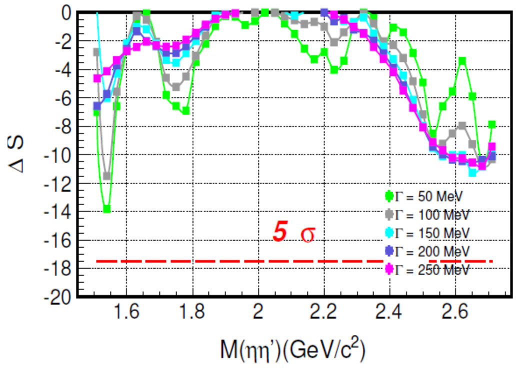
- Assuming $\eta_1(1855)$ is an additional resonance, scans of with different masses and widths



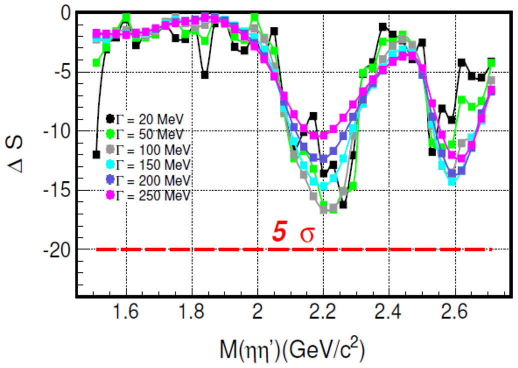
- The most significant additional contribution comes from another exotic 1^{-+} component around 2.2 GeV (4.4σ) with a very small fit fraction

Baseline set of amplitudes

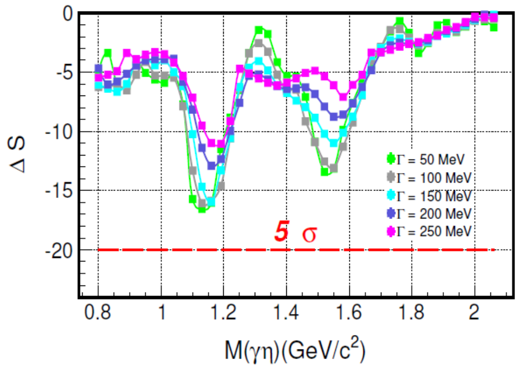
No significant contributions from additional resonances



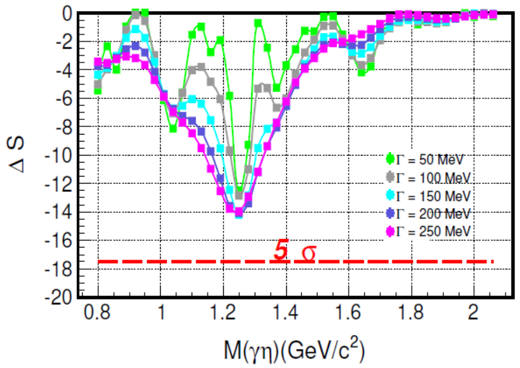
(a) Additional 0^{++} state scan in $\eta\eta'$



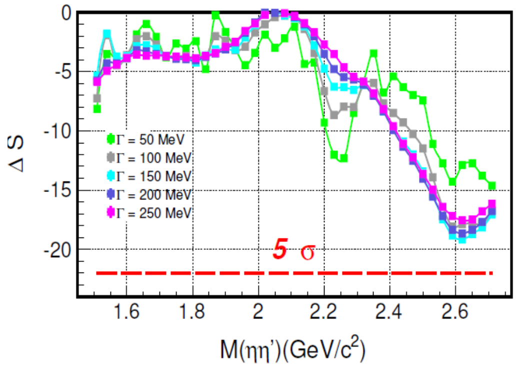
(b) Additional 1^{-+} state scan in $\eta\eta'$



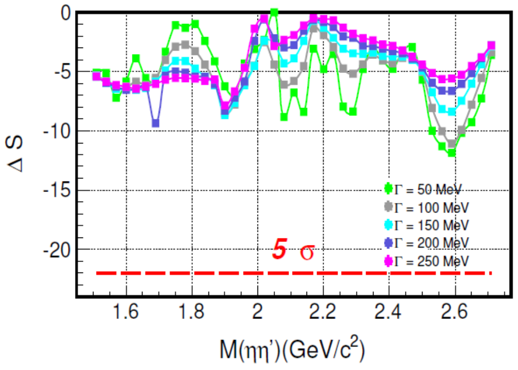
(e) Additional 1^{+-} state scan in $\gamma\eta$



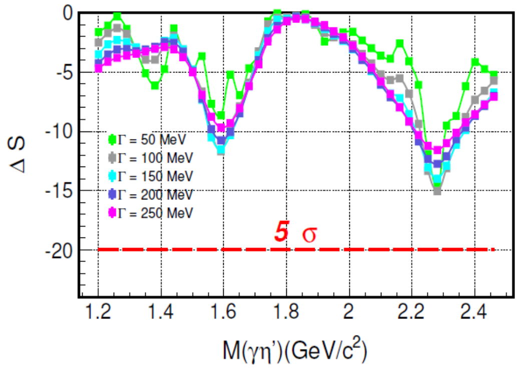
(f) Additional 1^{--} state scan in $\gamma\eta$



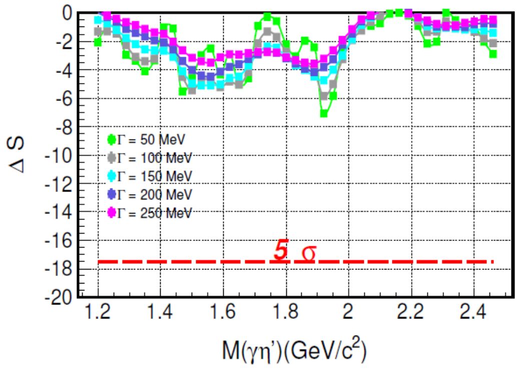
(c) Additional 2^{++} state scan in $\eta\eta'$



(d) Additional 4^{++} state scan in $\eta\eta'$



(g) Additional 1^{+-} state scan in $\gamma\eta'$



(h) Additional 1^{--} state scan in $\gamma\eta'$

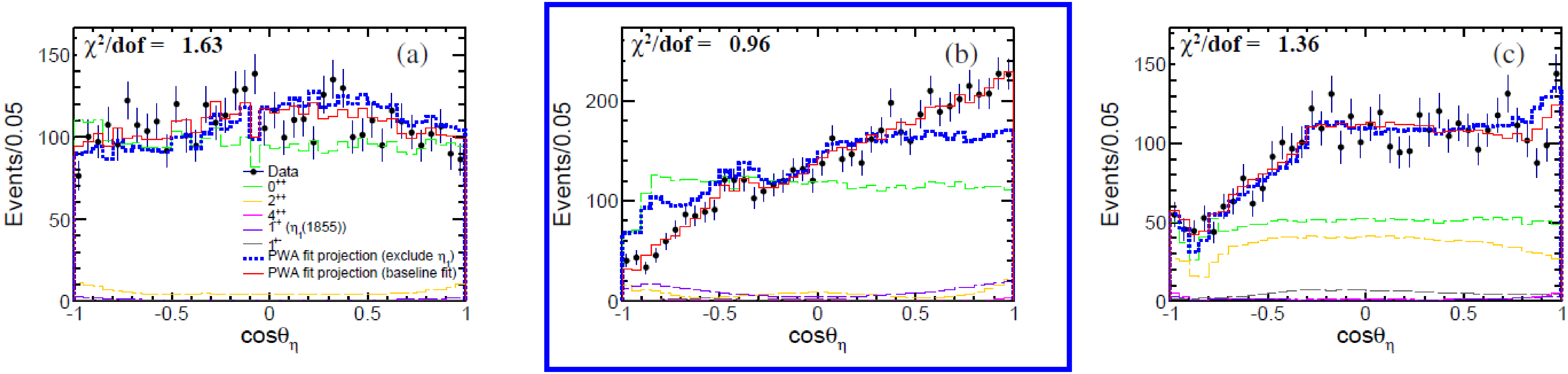
Further checks on the 1^{-+} state $\eta_1(1855)$

- Changing the J^{PC} to the $\eta_1(1855)$, and the log-likelihoods are worse by at least 235 units
- BW Phase motion of $\eta_1(1855)$

$$\text{from } \frac{1}{M^2 - s - iM\Gamma} \text{ to } \sqrt{\frac{1}{(M^2-s)^2 + M^2\Gamma^2}}$$

→ln L worsen by 43 units

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



[1.5,1.7] GeV/c^2 [1.7,2.0] GeV/c^2 [2.0,3.2] GeV/c^2

a clear asymmetry largely due to $\eta_1(1855)$ signal

Further Checks on the 1^{-+} State $\eta_1(1855)$

- Angular distribution as a function of $M(\eta\eta')$ expressed **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:

$$\sqrt{4\pi}\langle Y_0^0\rangle = S^2 + P^2 + D^2$$

$$\sqrt{4\pi}\langle Y_1^0\rangle = 2SP\cos\phi_P + 4PD\cos(\phi_P - \phi_D)$$

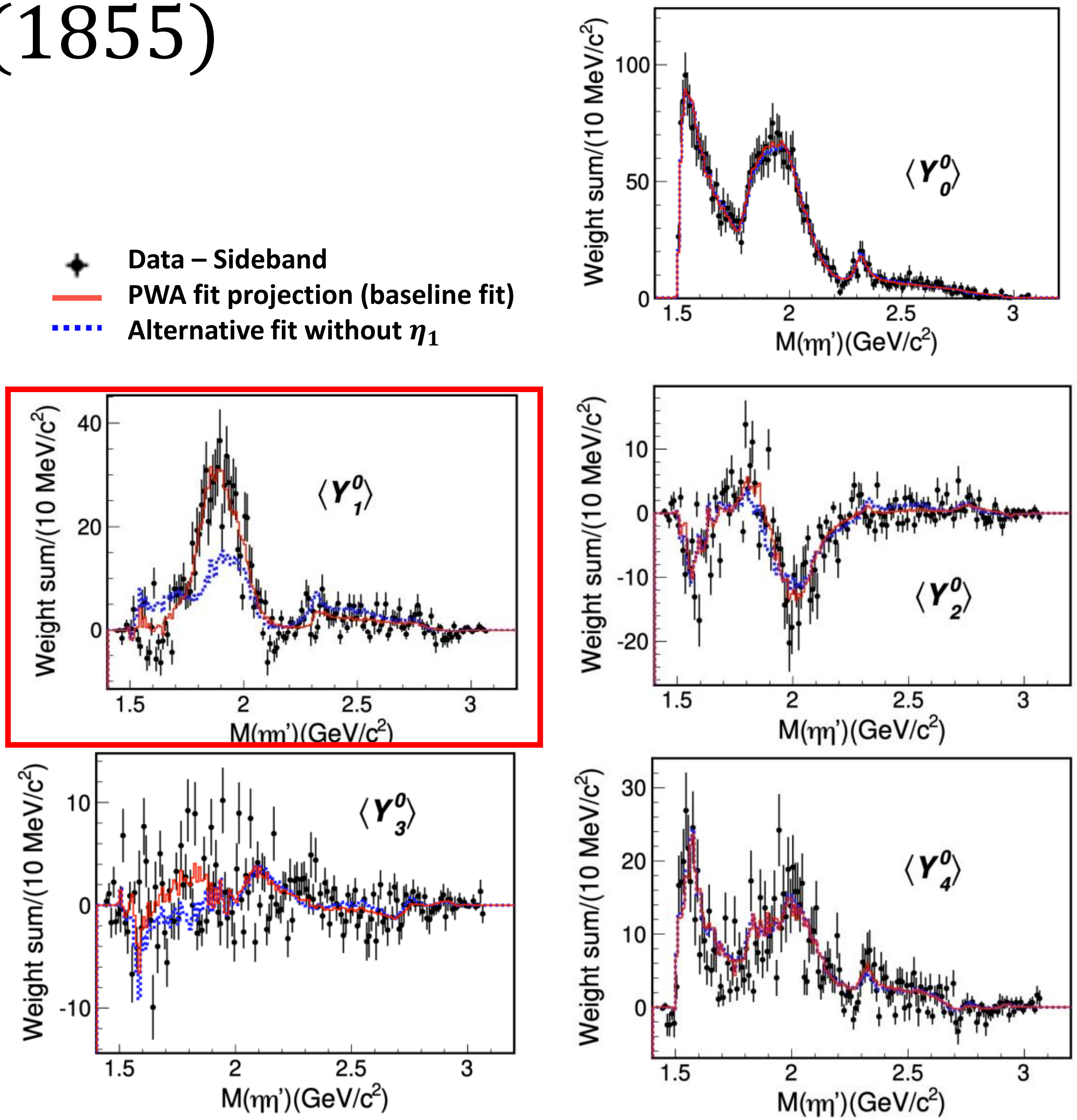
$\langle Y_1^0 \rangle = 0$ **without P-wave contribution**

$$\sqrt{4\pi}\langle Y_2^0\rangle = \frac{2}{\sqrt{5}}P^2 + \frac{2\sqrt{5}}{7}D^2 + 2SD\cos\phi_D$$

$$\sqrt{4\pi}\langle Y_3^0\rangle = \frac{6}{5}\sqrt{\frac{15}{7}}PD\cos(\phi_P - \phi_D)$$

$$\sqrt{4\pi}\langle Y_4^0\rangle = \frac{6}{7}D^2$$

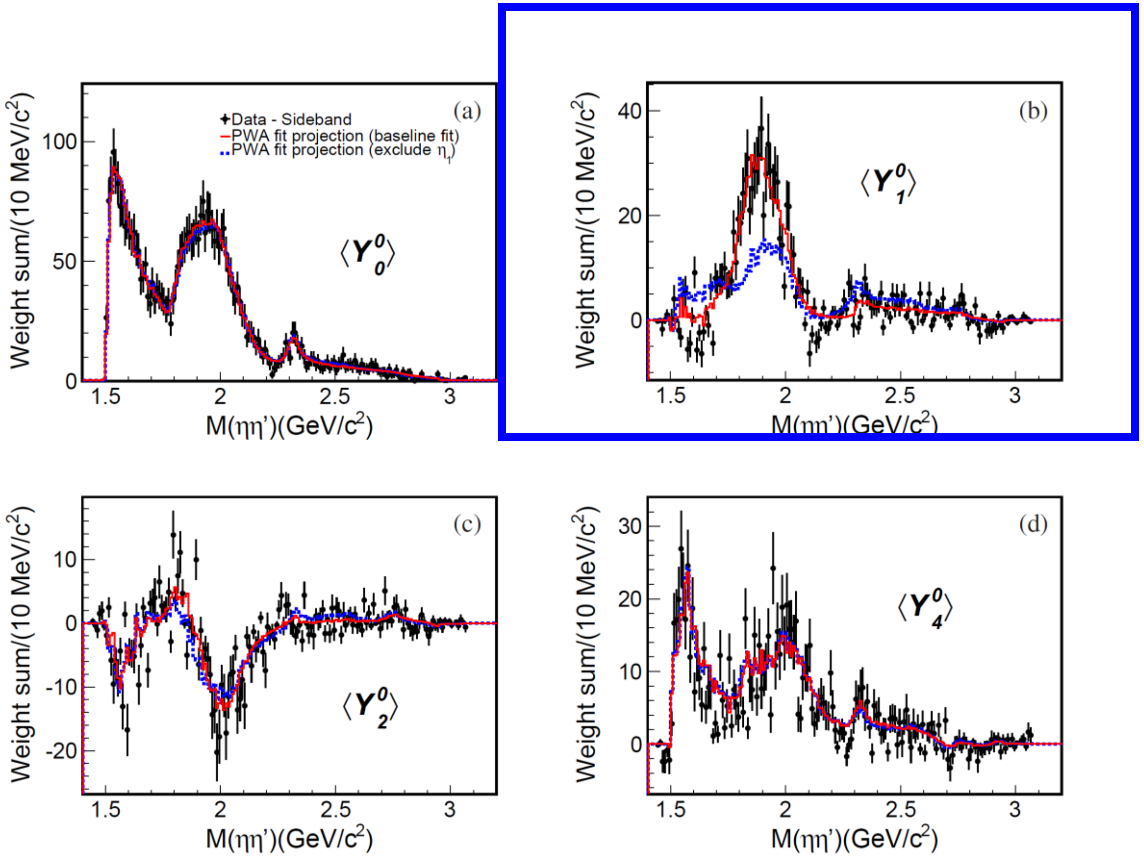
- **Narrow structure** in $\langle Y_1^0 \rangle$
  - **Cannot be described by resonances in $\gamma\eta(\eta')$**
  - **$\eta_1(1855) \to \eta\eta'$ needed**



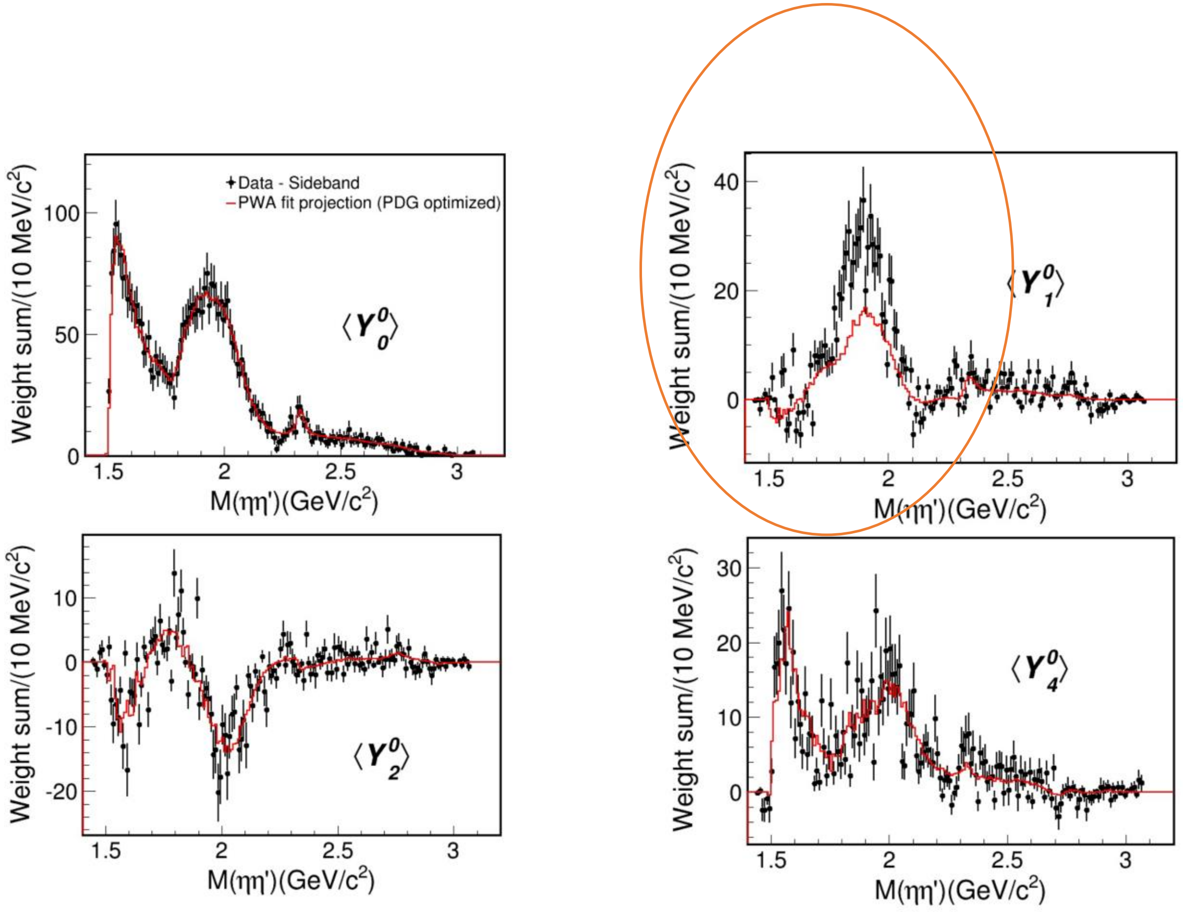
For comparison

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

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



Baseline set of amplitudes



PDG-optimized set of amplitudes

Systematic uncertainties (event selection)

Common systematic uncertainties		
Sources	$\eta' \to \eta\pi^+\pi^-$	$\eta' \to \gamma\pi^+\pi^-$
Pion tracking	2	
Four photon detection	4	
Number of J/ψ events	0.43	
$\mathcal{B}(\eta \to \gamma\gamma)$	0.2	
Total	4.5	
Independent systematic uncertainties		
Sources	$\eta' \to \eta\pi^+\pi^-$	$\eta' \to \gamma\pi^+\pi^-$
Another photon detection	1	-
Kinematic fit	1.5	2.6
η' mass resolution	0.3	0.2
$\mathcal{B}(\eta' \to \eta\pi^+\pi^-)$	0.5	-
$\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)$	-	0.4
$\mathcal{B}(\eta \to \gamma\gamma)$ for another one	0.2	-
Total	1.9	2.6
Combined result	4.8	

Combined with the weighted least squares method

Systematic uncertainties (PWA)

- BW parametrization for $f_0(1500)$
  - replace the BW with a Flatte-like form

$$\Gamma(s) = g\Gamma(\frac{M^2}{s})(\frac{\rho(s)}{\rho(M^2)})^{2l+1} + (1-g)\Gamma_0$$, g ~0.02

- Fixed resonance parameters
  - varying within 1 σ of the PDG values
- Background uncertainty
  - different sideband regions and normalization factors
- Additional resonances
  - adding the most significant additional resonances for each possible J^{PC} into the baseline fit individually

Sources	$f_0(2020)$ ΔM	$f_0(2020)$ $\Delta\Gamma$	$f_0(2330)$ ΔM	$f_0(2330)$ $\Delta\Gamma$	$\eta_1(1855)$ ΔM	$\eta_1(1855)$ $\Delta\Gamma$	$f_2(2010)$ ΔM	$f_2(2010)$ $\Delta\Gamma$
Breit-Wiger formula	-1	$+10$	-1	$+1$	-1	$+2$	-4	$+3$
Resonance parameters	$+1$	-10	-3	$+2$	$+2$	-1	0	-2
Extra resonances	$^{+4}_{-2}$	$^{+9}_{-2}$	$+7$	$^{+1}_{-9}$	$+4$	$^{+1}_{-6}$	$^{+10}_{-5}$	$+10$
Backgroud uncertainty	-1	-4	$+3$	$^{+1}_{-7}$	$+3$	$^{+1}_{-5}$	-1	-5
Total	$^{+4}_{-3}$	$^{+13}_{-11}$	$^{+7}_{-3}$	$^{+3}_{-12}$	$^{+6}_{-1}$	$^{+3}_{-8}$	$^{+10}_{-7}$	$^{+10}_{-5}$

Sources	$f_0(1500)$	$f_0(1810)$	$f_0(2020)$	$f_0(2330)$	$\eta_1(1855)$	$f_2(1565)$	$f_2(2010)$	$f_4(2050)$	0^{++}PHSP	$h_1(1415)(\gamma\eta)$	$h_1(1595)(\gamma\eta)$
Event selection					±4.8						
Breit-Wigner formula	-1.7	$+11.6$	$+6.9$	$+3.2$	-1.1	$+17.8$	$+0.2$	$+4.2$	-0.6	-8.2	-4.1
Extra resonances	$^{+9.4}_{-1.0}$	$^{+30.4}_{-8.4}$	$+10.0$	$^{+7.8}_{-13.4}$	$^{+3.5}_{-10.4}$	$^{+31.5}_{-2.7}$	$^{+12.9}_{-6.5}$	$^{+44.4}_{-4.7}$	$^{+5.1}_{-12.2}$	$^{+11.0}_{-9.1}$	$^{+16.2}_{-2.2}$
Resonance parameters	-4.8	-25.6	-6.5	$+3.6$	-6.1	$+5.5$	$+0.2$	-1.4	-4.6	-11.4	-4.3
Backgroud uncertainty	$^{+0.5}_{-0.6}$	$^{+0.4}_{-7.5}$	$^{+0.8}_{-3.4}$	$^{+0.3}_{-10.4}$	$^{+0.2}_{-1.1}$	$+11.0$	-2.7	$^{+31.9}_{-6.5}$	-1.8	-8.8	$^{+8.4}_{-0.6}$
Total	$^{+10.6}_{-7.1}$	$^{+32.9}_{-28.4}$	$^{+13.1}_{-8.8}$	$^{+10.3}_{-17.6}$	$^{+5.9}_{-13.1}$	$^{+38.5}_{-5.5}$	$^{+13.7}_{-8.5}$	$^{+55.0}_{-9.5}$	$^{+7.0}_{-14.0}$	$^{+12.0}_{-19.5}$	$^{+18.8}_{-8.0}$

The statistical significance of the $\eta_1(1855)$ is recalculated in every variation. >19 σ

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

- Significant $f_0(1500)$

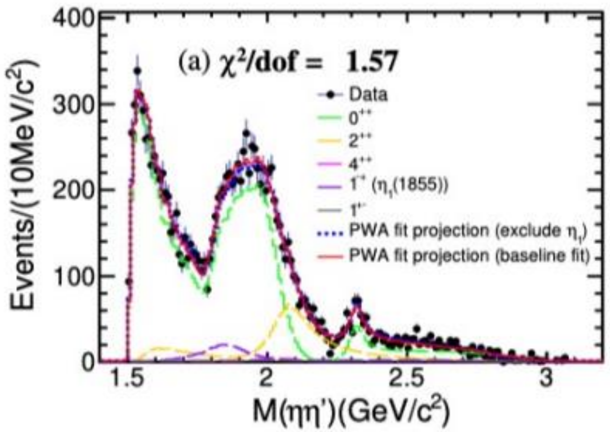
$$\frac{B(f_0(1500) \to \eta\eta')}{B(f_0(1500) \to \pi\pi)} = \left(8.96^{+2.95}_{-2.87}\right) \times 10^{-2}$$

consistent with PDG

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

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

➢ Supports to the hypothesis that $f_0(1710)$ overlaps with the ground state scalar glueball
  - Scalar glueball expected to be suppressed $B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$



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.
	$f_0(1500)$	1506	112	1506	112	$1.81 \pm 0.11^{+0.19}_{-0.13}$	$\gg 30\sigma$
	$f_0(1810)$	1795	95	1795	95	$0.11 \pm 0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010 \pm 6^{+6}_{-4}$	$203 \pm 9^{+13}_{-11}$	1992	442	$2.28 \pm 0.12^{+0.29}_{-0.20}$	24.6σ
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(2330)$	$2312 \pm 7^{+7}_{-3}$	$65 \pm 10^{+3}_{-12}$	2314	144	$0.10 \pm 0.02^{+0.01}_{-0.02}$	13.2σ
	$\eta_1(1855)$	$1855 \pm 9^{+6}_{-1}$	$188 \pm 18^{+3}_{-8}$	-	-	$0.27 \pm 0.04^{+0.02}_{-0.04}$	21.4σ
	$f_2(1565)$	1542	122	1542	122	$0.32 \pm 0.05^{+0.12}_{-0.02}$	8.7σ
	$f_2(2010)$	$2062 \pm 6^{+10}_{-7}$	$165 \pm 17^{+10}_{-5}$	2011	202	$0.71 \pm 0.06^{+0.10}_{-0.06}$	13.4σ
	$f_4(2050)$	2018	237	2018	237	$0.06 \pm 0.01^{+0.03}_{-0.01}$	4.6σ
	0^{++} PHSP	-	-	-	-	$1.44 \pm 0.15^{+0.10}_{-0.20}$	15.7σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	1416	90	$0.08 \pm 0.01^{+0.01}_{-0.02}$	10.2σ
	$h_1(1595)$	1584	384	1584	384	$0.16 \pm 0.02^{+0.03}_{-0.01}$	9.9σ

Summary

- **An isoscalar 1^{-+} , $\eta_1(1855)$, has been observed in $J/\psi \rightarrow \gamma\eta\eta'$ (>19σ)**

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

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

  - **An important step forward of light QCD exotics**

- Further more, significant $J/\psi \rightarrow \gamma f_0(1500) \rightarrow \gamma\eta\eta'$ has been observed, while $f_0(1710)$ is insignificant
  - $B(f_0(1710) \rightarrow \eta\eta')/\ B(f_0(1710) \rightarrow \pi\pi)< 1.61 \times 10^{-3}$ @90% C.L. , which further supports the f0(1710) has a large overlap with glueball

Prospects

- Together with $\pi_1(1600)$
  - Opens a new direction to completing the picture of the hybrid multiplets
- LQCD: $\mathrm{B}(\mathrm{J}/\psi \rightarrow \gamma\eta_1(\mathrm{hybrid}))\sim\mathrm{O}(10^{-5})$[2207.04694]
  - $\boldsymbol{\eta\eta}'$ is not a dominate mode→ Search for more
- Interpretations: Hybrid/$\mathrm{K\bar{K}_1}$Molecule/Tetraquark?

Sci.China Phys.Mech.Astron. 65 (2022) 6, 261011;
CPC 46 , 051001(2022);
CPL 39, 051201 (2022);
PLB 834, 137478(2022);
PRD 106 , 074003(2022);
PRD 106, 036005(2022) ;
…
& Snowmass2021 summer study whitepapers

Prospects

Isoscalar: $\boldsymbol{\eta_1(1855)}$

- **Decay properties**
  - $J/\psi \to \gamma\pi a_1, \eta f_1, K_1\bar{K}, \omega\phi$、 ……
- **Production properties**
  - $J/\psi \to \omega\eta\eta', \phi\eta\eta'$, ……
- **Where is $\boldsymbol{\eta_1^{(\prime)}}$**
  - **Other partners**

Isovector: $\boldsymbol{\pi_1(1600)}$

- $J/\psi \to \rho\eta'\pi$, ……
- $\chi_{c1} \to \pi\pi b_1, \pi\pi f_1, \pi\pi\eta'$, ……
  - LQCD predicted major decay modes: πb_1, πf_1

➢ ***Data with unprecedented statistical accuracy from BESIII provides great opportunities to study QCD exotics. Will continue to run until ~2030***

➢ ***To explore the high statistics data sets, synergies between experiment and theory are essential***

Stay tuned

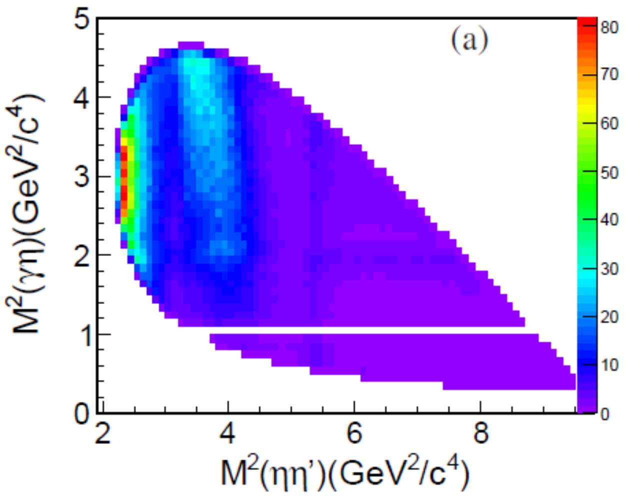
Thank you

Light hadron spectroscopy experiments

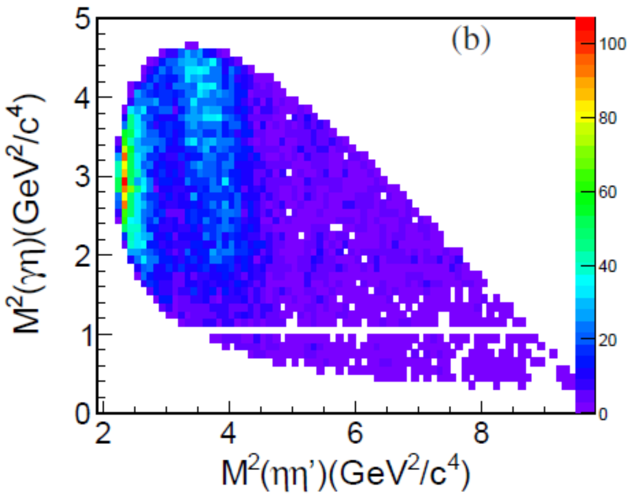
- Hadroproduction
  - COMPASS: finished data taking
  - VES: running
- Lepto/photoproduction
  - GlueX: finished phase-I campaign, phase II running
  - CLAS12: MesonEx program
- Charmonium decays
  - BESIII: running, 10B of J/ψ and 3B ψ' on disk
- Further future
  - Under construction: $\mathrm{p}\bar{\mathrm{p}}$ at PANDA
  - Proposal: COMPASS++/AMBER
  - Proposal: STCF

Baseline set of amplitudes

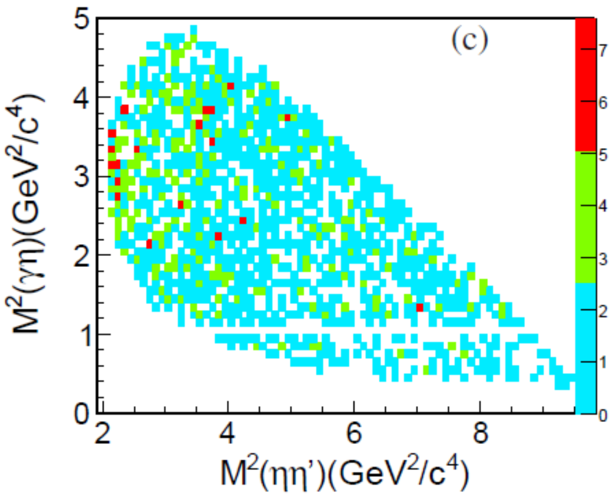
PWA fit projections



PWA result



Data



Sideband

Baseline set of amplitudes

Fit fractions in the PWA fit with the baseline set of amplitudes

Resonance	$f_0(1500)$	$f_0(1810)$	$f_0(2020)$	$f_0(2330)$	$h_1(1415)(\gamma\eta)$	$h_1(1595)$	$\eta_1(1855)$	$f_2(1565)$	$f_2(2010)$	$f_4(2050)$	0^{++} PHSP
$f_0(1500)$	21.9±1.4	−4.3±0.4	16.2±0.5	−1.0±0.1	1.6±0.2	−1.6±0.9	0.2±0.0	0.2±0.1	0.6±0.1	0.0±0.0	13.4±1.1
$f_0(1810)$		1.4±0.1	−5.6±0.6	0.4±0.0	−0.1±0.0	0.6±0.1	0.0±0.0	−0.2±0.0	0.1±0.0	0.0±0.0	2.0±0.3
$f_0(2020)$			29.5±1.6	−3.7±0.5	0.0±0.2	−3.6±0.4	0.2±0.0	1.1±0.1	0.1± 0.1	0.1±0.0	−15.9±1.8
$f_0(2330)$				1.4±0.2	0.1±0.0	0.3±0.1	0.0±0.0	−0.1±0.0	−0.2± 0.0	0.0±0.0	2.6±0.3
$h_1(1415)$					1.1±0.2	−1.1±0.3	−0.2±0.1	0.1±0.1	0.2±0.1	0.0±0.0	2.3±0.3
$h_1(1595)$						2.1±0.3	0.5±0.1	−0.3±0.3	0.0±0.2	0.1±0.0	2.3±1.0
$\eta_1(1855)$							3.5±0.5	0.0±0.0	−0.1±0.0	0.0±0.0	0.1±0.0
$f_2(1565)$								4.6±0.7	−0.6±0.8	0.0±0.0	−0.9±0.1
$f_2(2010)$									10.2±0.8	−0.1±0.1	0.2±0.1
$f_4(2050)$										0.8±0.2	0.0±0.0
0^{++} PHSP											18.5±1.9