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

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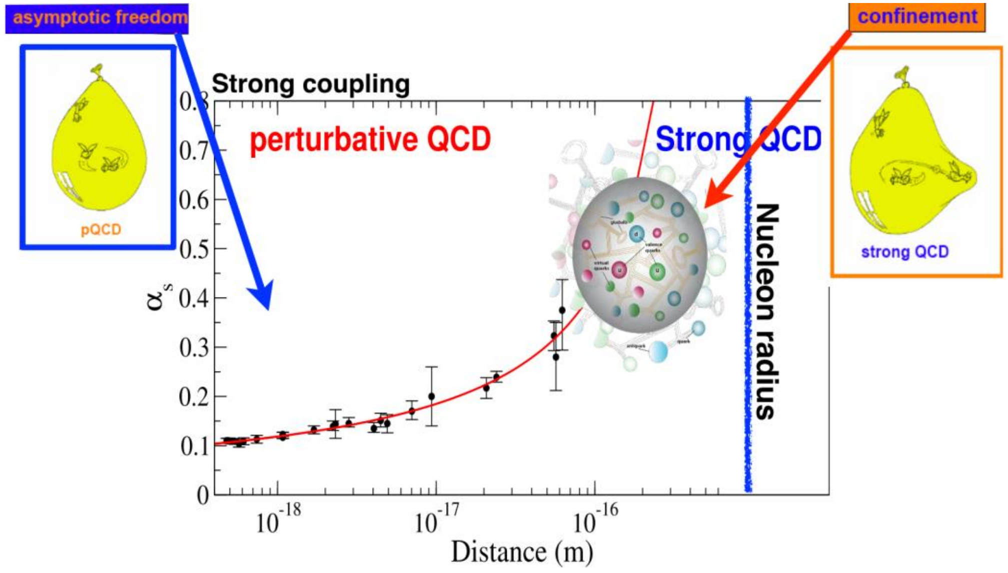
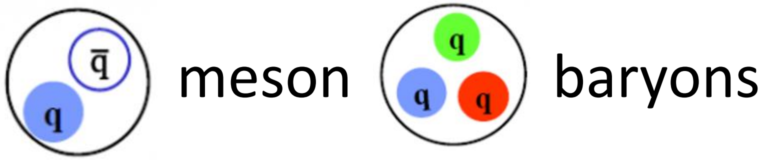
Introduction

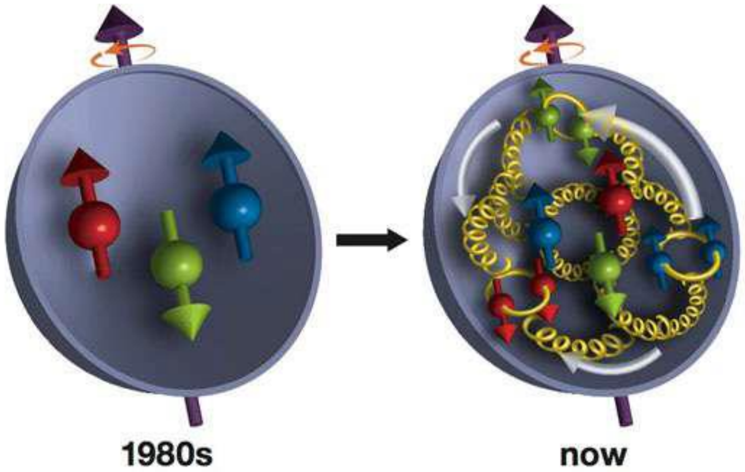
- Hadrons, the complex building blocks of our world, emerge from interaction of quarks and gluons as described by QCD

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



Quark model

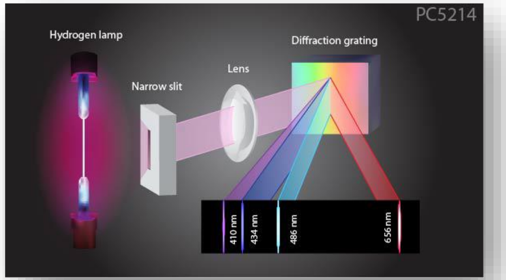




Hadron spectroscopy

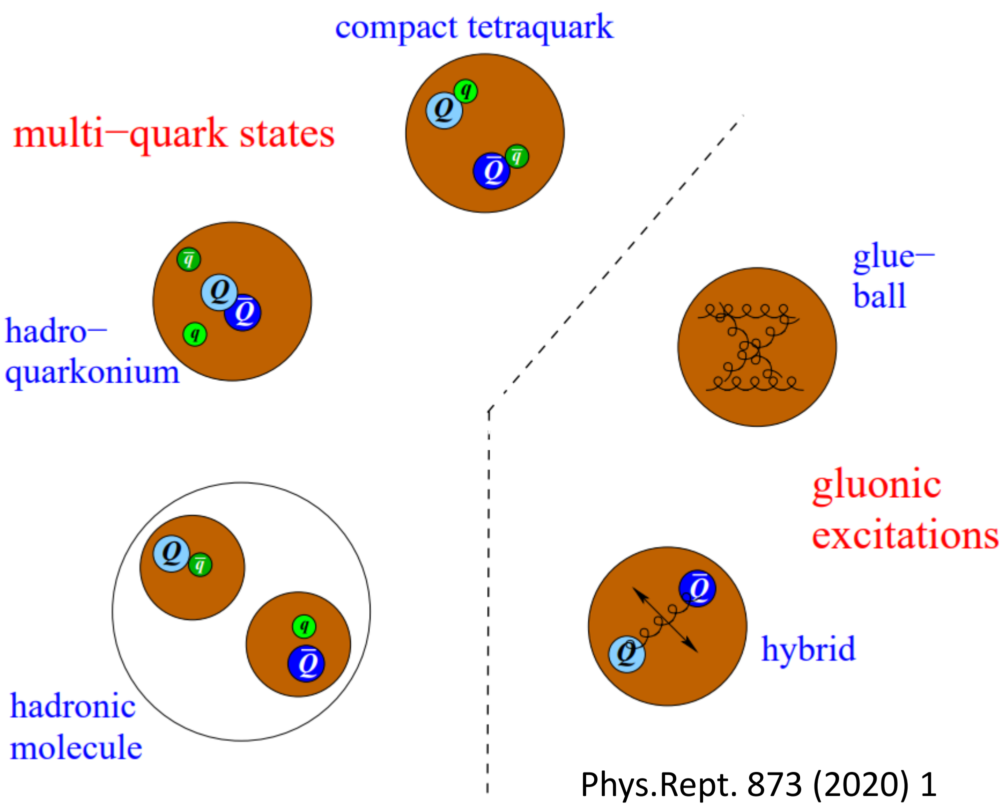
- Testing QCD in the confinement regime
- Revealing the fundamental degrees of freedom

Atomic Spectrum:
Bohr model → QED



Hadron spectrum:
Quark model → QCD

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

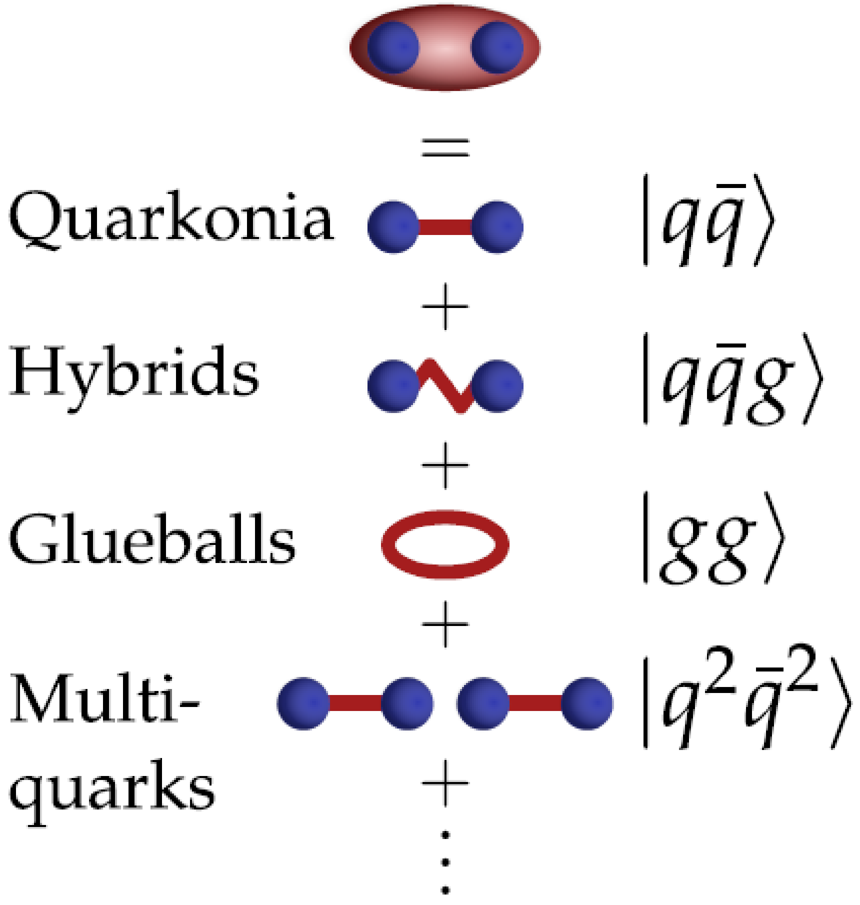


Phys.Rept. 873 (2020) 1

QCD exotics

- QCD permits additional color-singlet mesonic configurations

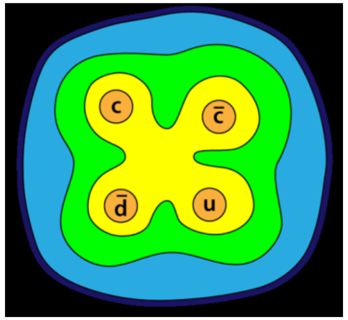
- Physical mesons
  - Linear superpositions of all allowed basis states
  - “Configuration mixing”
  - Disentanglement of contributions difficult
    - Detailed information about couplings to production and decay channels required

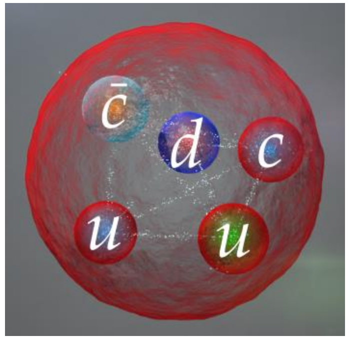


→ Discovery with precision measurement

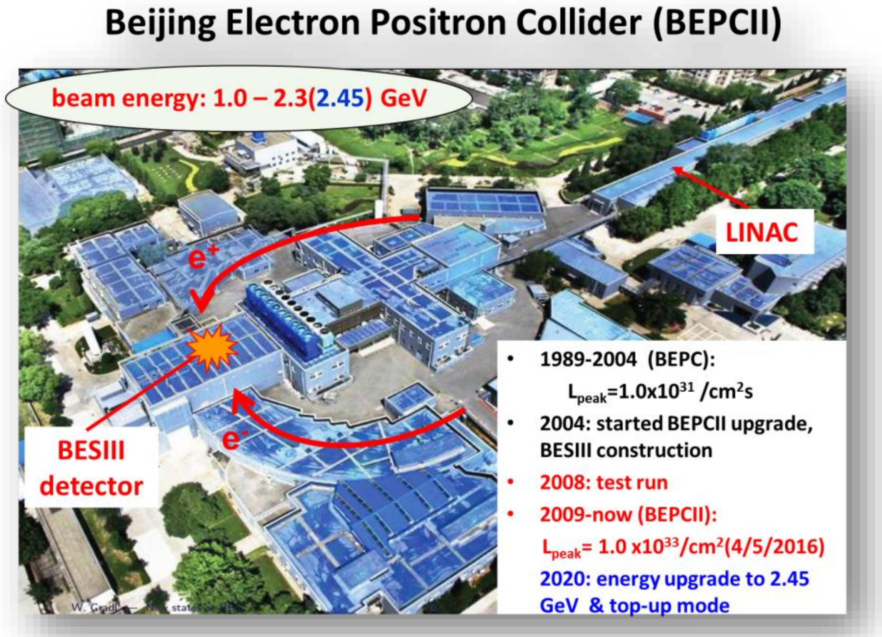
So far…

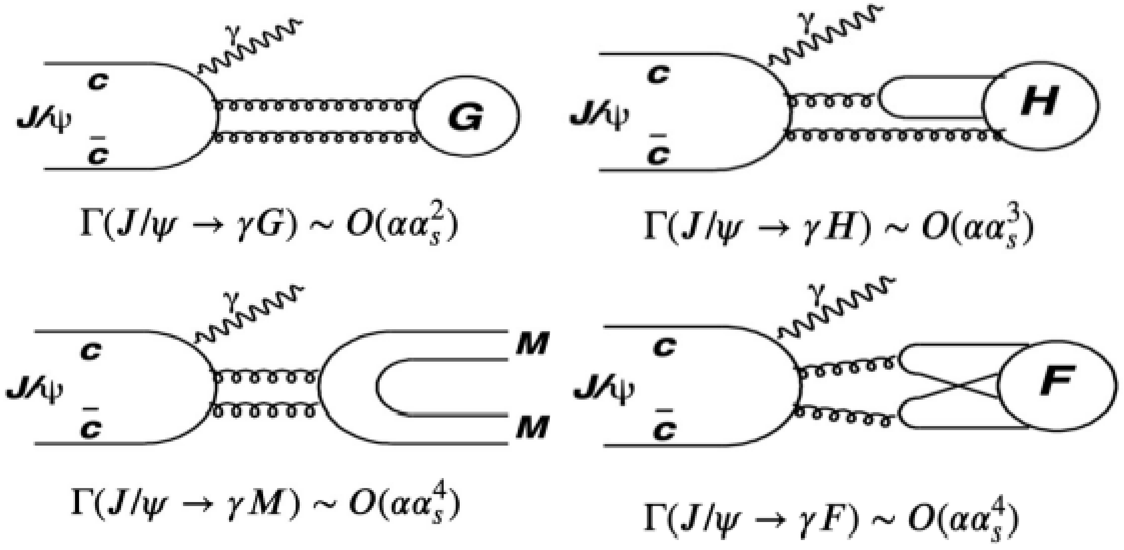
- Strong evidence for QCD exotics in heavy quark sector, e.g.Tetraquark candidates $Z_c^+ \to J/\psi\pi$,Pentaquark candidates $P_c^+ \to J/\psi p$, …





- Light quark sector is more complicated
  - but, an absolute necessity to claim that we understand hadrons



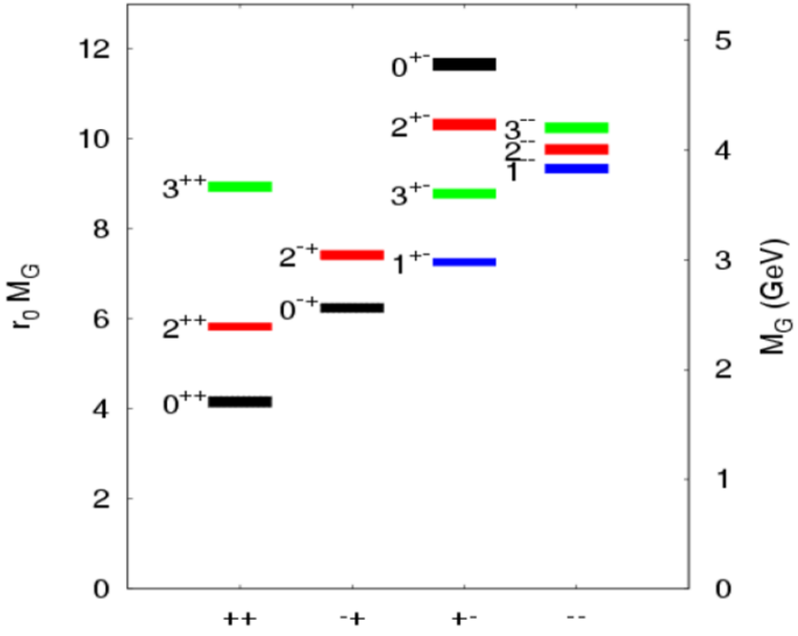


Charmonium decays provide an ideal lab for light QCD exotics

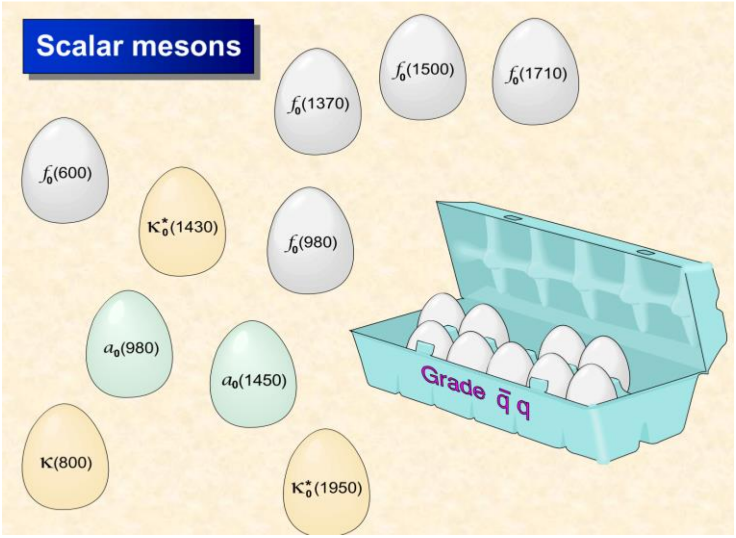
- **Clean high statistics data samples**
  High cross sections of $e^+e^- \to J/\psi,\ \psi'$
  Low background
- **Well defined initial and final states**
  Kinematic constraints
  $I(J^{PC})$ filter
- **"Gluon-rich" process**

Glueballs

- Evidence of gluon self interaction
- Provide critical information on the gluon field and the quantitative understanding of confinement
- 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

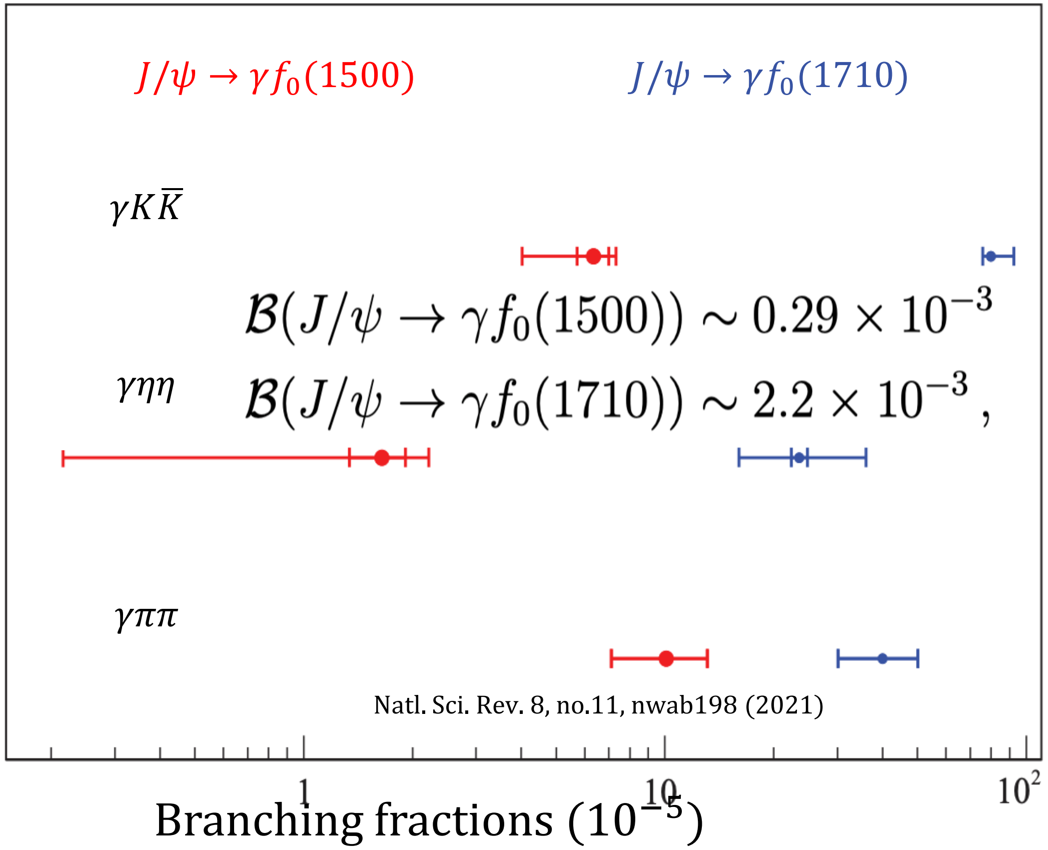


Glueballs from Lattice simulations in the pure gauge theory without quarks



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,

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

$B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$, predicted in Phys. Rev. D 92, 121902

Using 10B of J/ψ events,
$J/\psi \to \gamma\eta\eta'$, arXiv:2202.00621, 2202.00623
$J/\psi \to \gamma\eta'\eta'$, Phys.Rev.D 105 (2022) 7, 072002

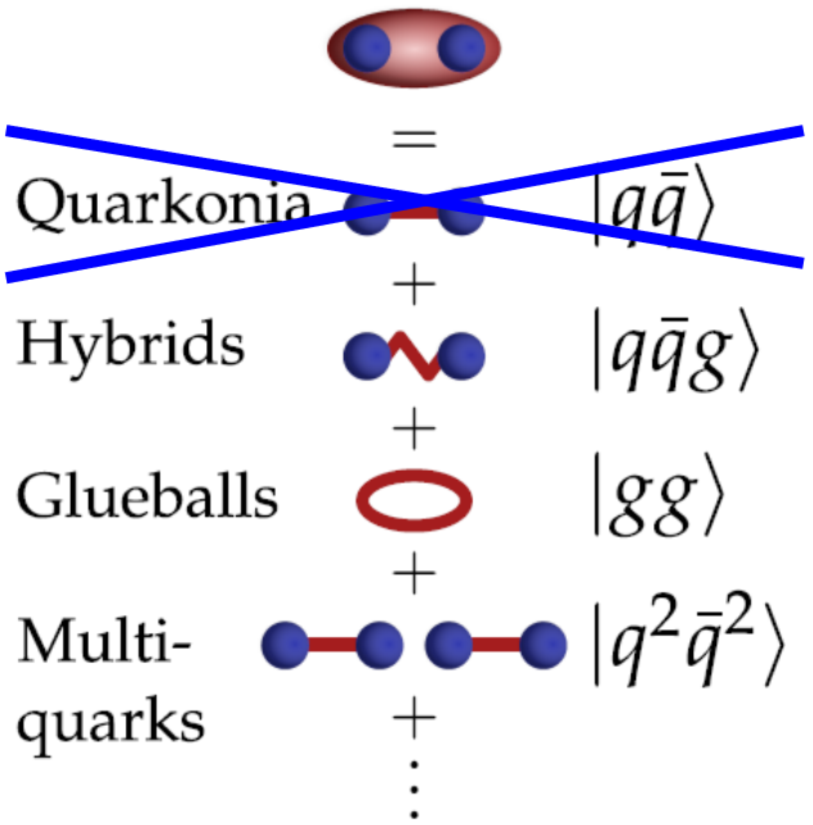
Spin-exotic mesons

Meson spin: $\vec{J} = \vec{L} + \vec{S}$
Parity: $P = (-1)^{L+1}$
Charge conjugation: $C = (-1)^{L+S}$

- Mesons with quantum numbers forbidden by $q\bar{q}$ configuration:
  - $0^{+-}, 1^{-+}, 2^{+-}$

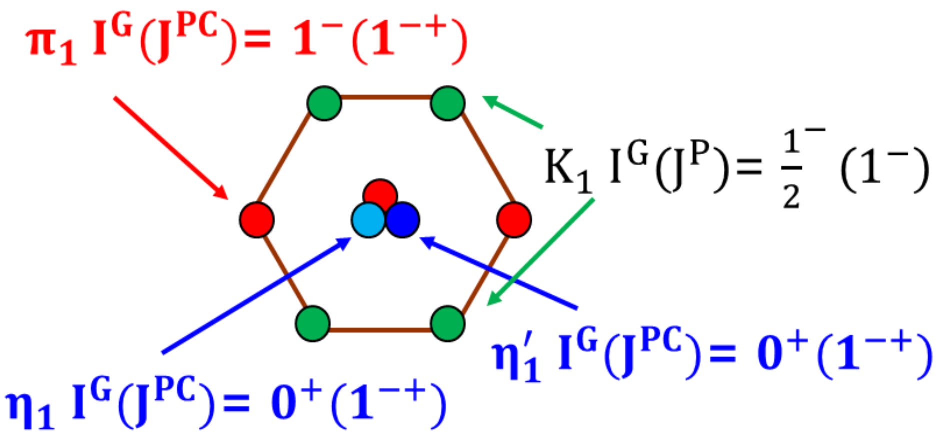
- Only 3 candidates so far: $\pi_1(1400)$, $\pi_1(1600)$ and $\pi_1(2015)$
  - All 1^{-+}
  - All isovectors

    $\pi_1(1400)$ and $\pi_1(1600)$ can be explained as one resonance with recent coupled channel analyses

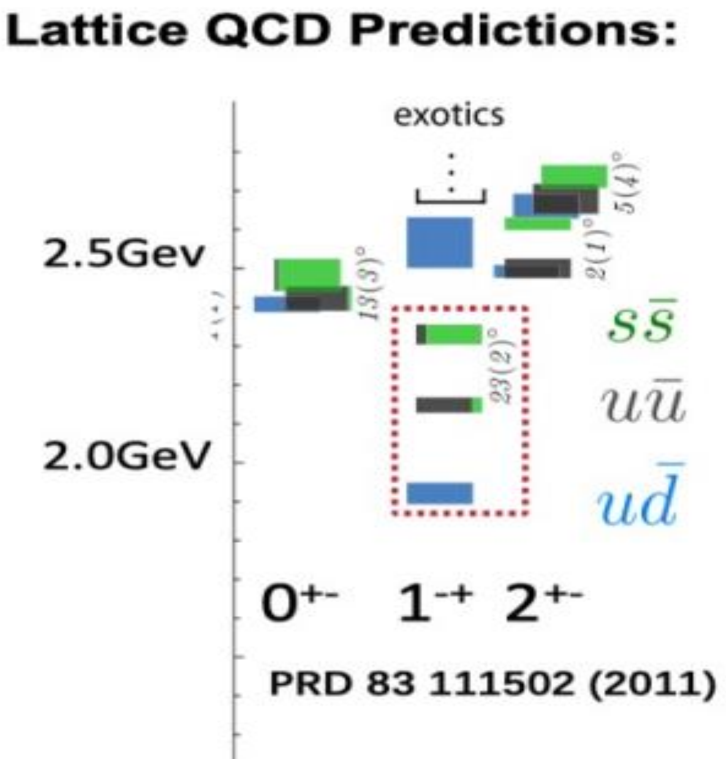


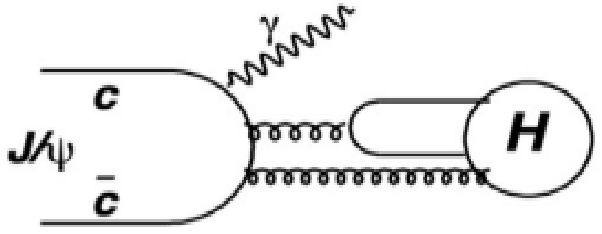
1^{-+} Hybrids

- The exotic $J^{PC} = 1^{-+}$ nonet of hybrids is predicted to be the lightest (1.7~2.1 GeV/c^2)



- **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**





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

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

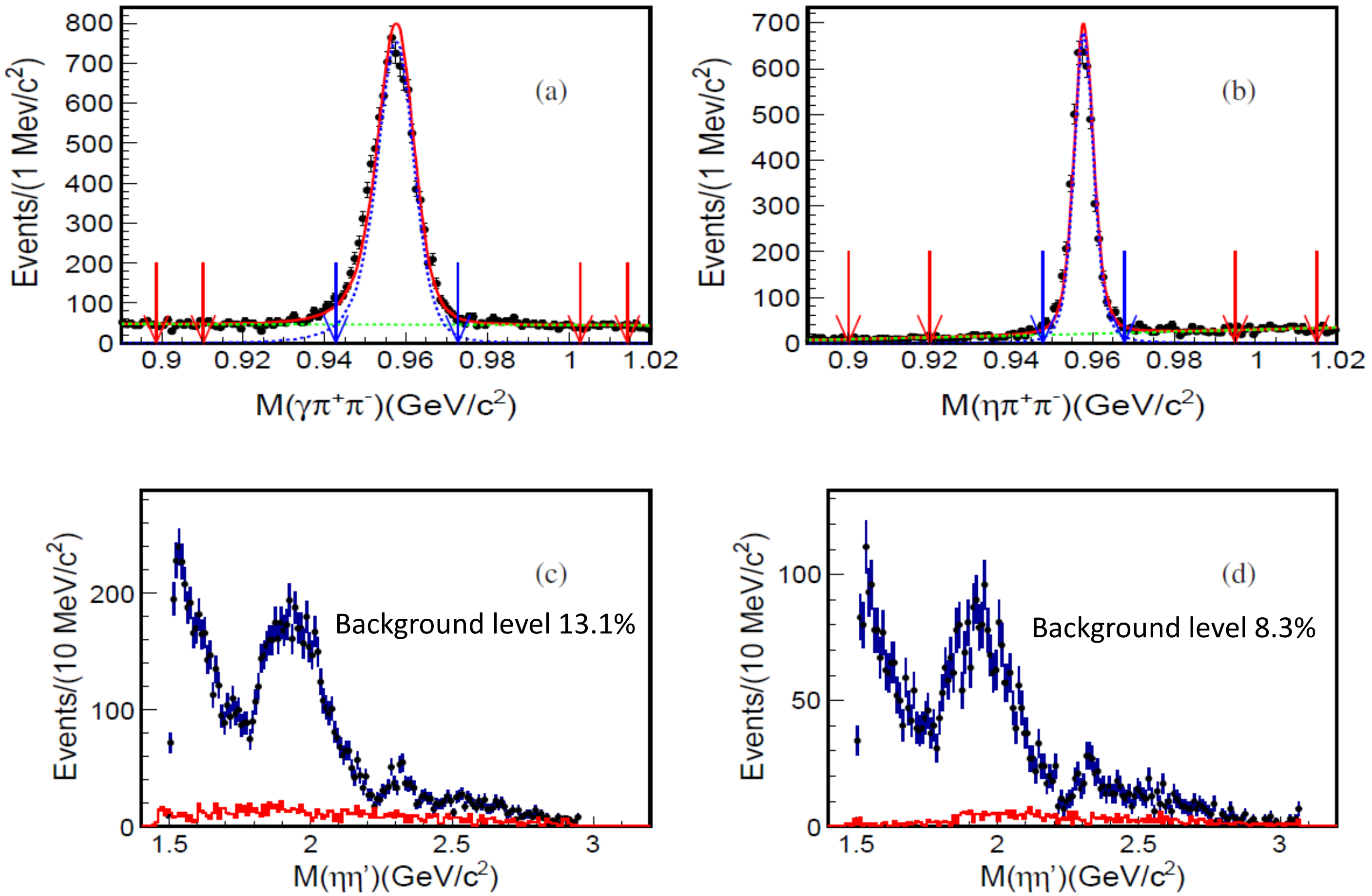
Observation of An Exotic Isoscalar State $\eta_1(1855)$ (1^{-+}) in $J/\psi \rightarrow \gamma\eta\eta'$

10 billion J/ψ

arXiv:2202.00621, to be appeared in PRL

arXiv:2202.00623 , to be appeared in PRD

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



- 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 $J/\psi \rightarrow \gamma\eta\eta$ [Phys.Rev. D 87, 092009]and $J/\psi \rightarrow \gamma K_S K_S$ [Phys.Rev. D 98, 072003], based on the covariant tensor amplitudes [Eur. Phys. J. A 16, 537] and the GPUPWA framework [J. Phys. Conf. Ser. 219, 042031]
  - Isobars in $J/\psi \rightarrow \gamma X, X \rightarrow \eta\eta'$ and $J/\psi \rightarrow \eta X, X \rightarrow \gamma\eta'$ and $J/\psi \rightarrow \eta' X, X \rightarrow \gamma\eta$. 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

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

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

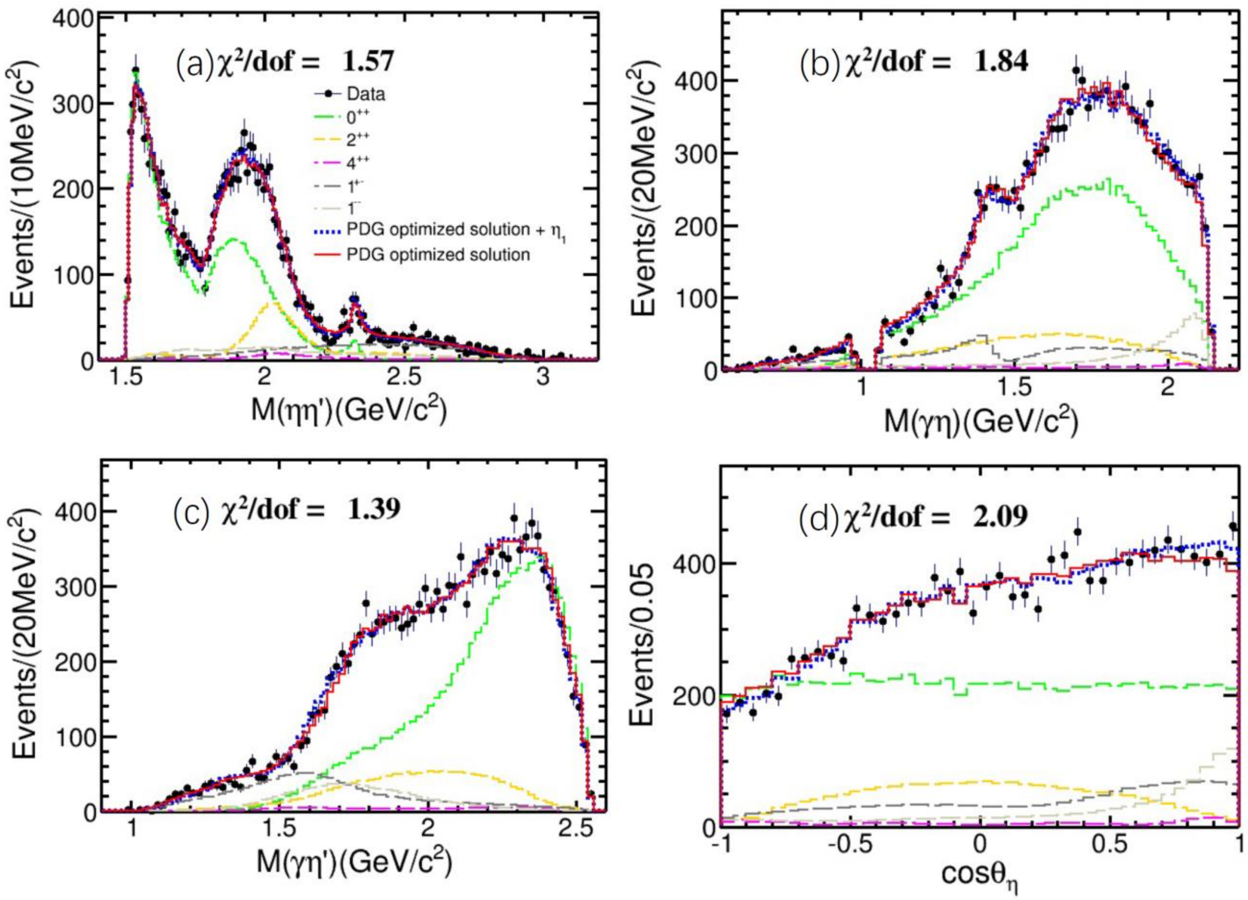
PDG-optimized set of amplitudes

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

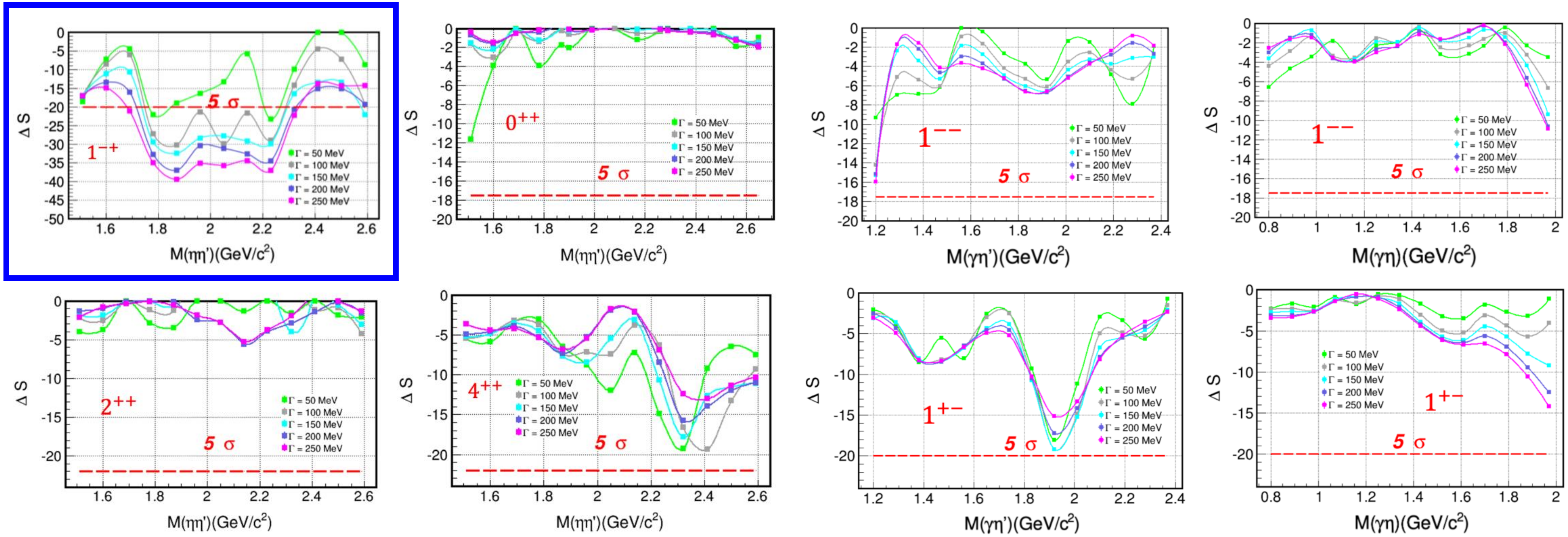
Components with statistical significance larger than 5σ

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

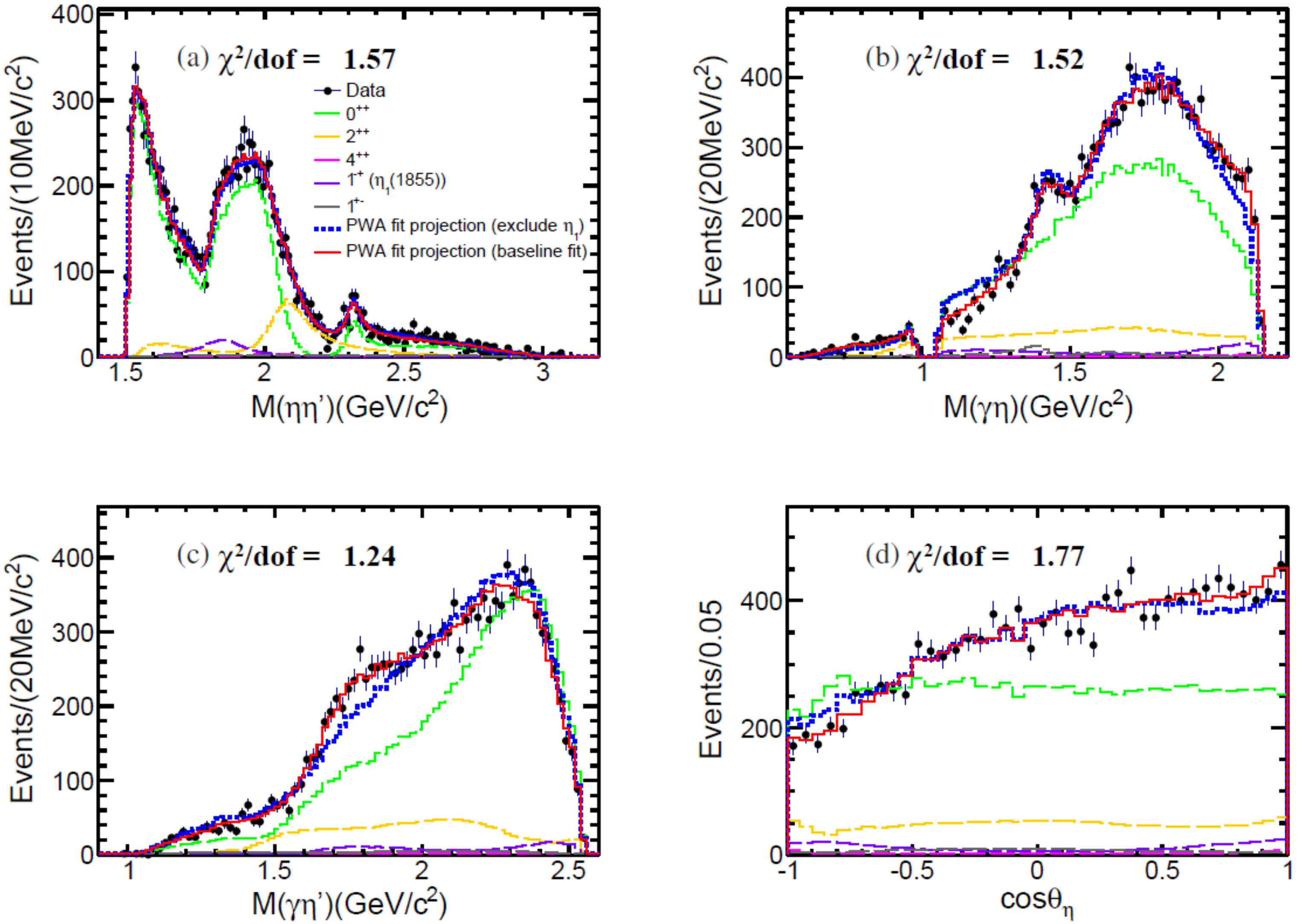
Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	$M_{\rm PDG}$ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg 30\sigma$
	$f_0(1810)$	1795	95	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	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 ($1.7 \sim 2.1$ GeV/c^2)**

Baseline set of amplitudes

PWA fit projections

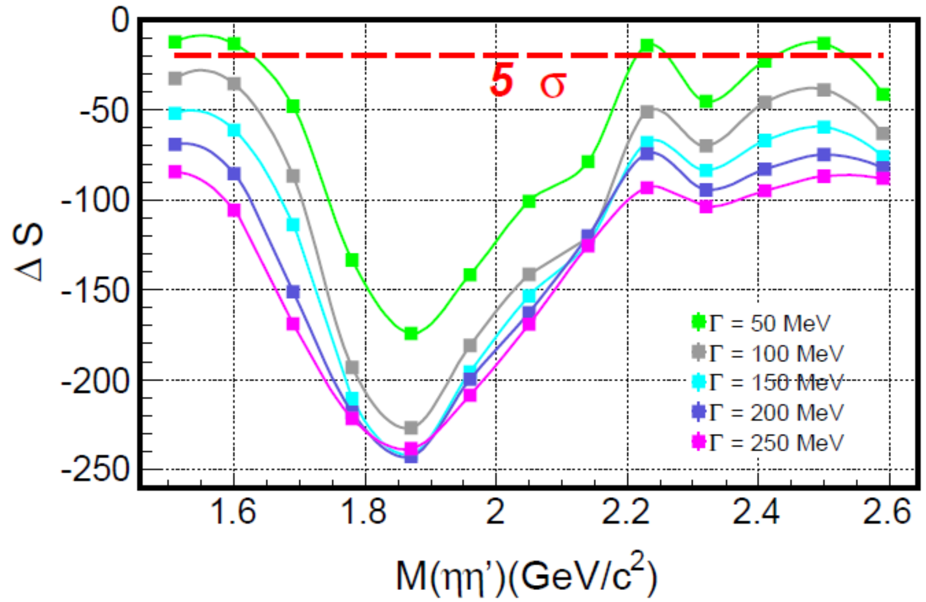


Significance for additional resonances

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 (< 3σ)

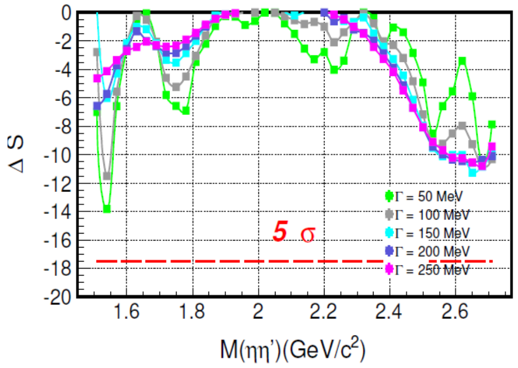
- Assuming $\eta_1(1855)$ is an additional resonance, scans of with different masses and widths



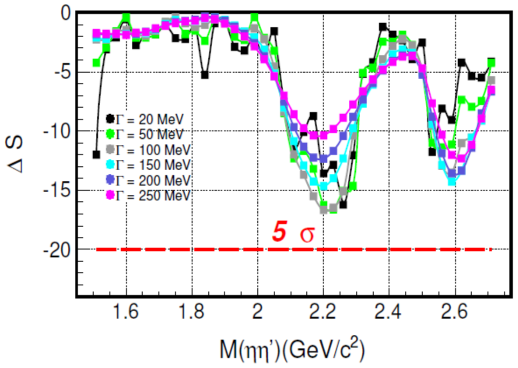
  - The most significant additional contribution (4.4σ) comes from another exotic 1^{-+} component around 2.2 GeV with a very small fit fraction

Baseline set of amplitudes

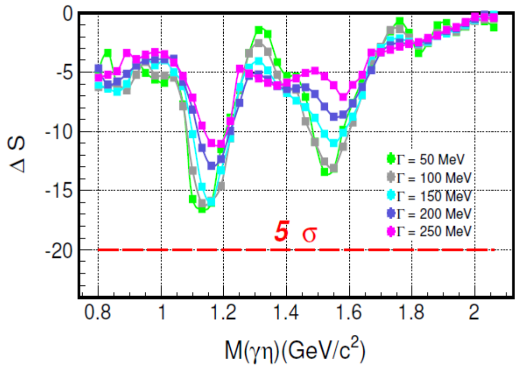
No significant contributions from additional resonances



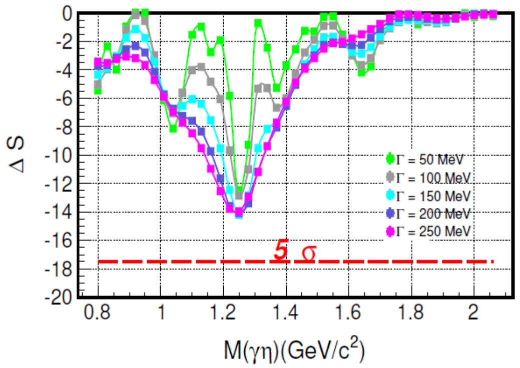
(a) Additional 0^{++} state scan in $\eta\eta'$



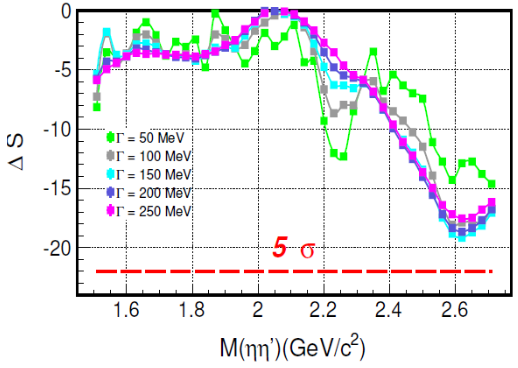
(b) Additional 1^{-+} state scan in $\eta\eta'$



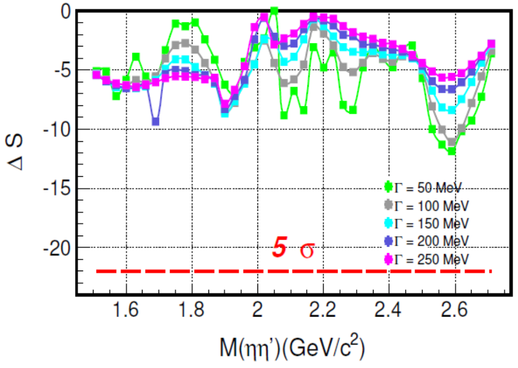
(e) Additional 1^{+-} state scan in $\gamma\eta$



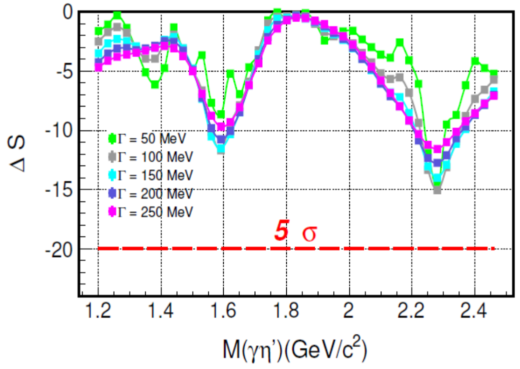
(f) Additional 1^{--} state scan in $\gamma\eta$



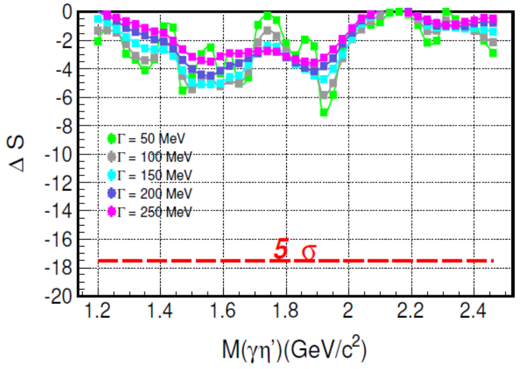
(c) Additional 2^{++} state scan in $\eta\eta'$



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



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



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

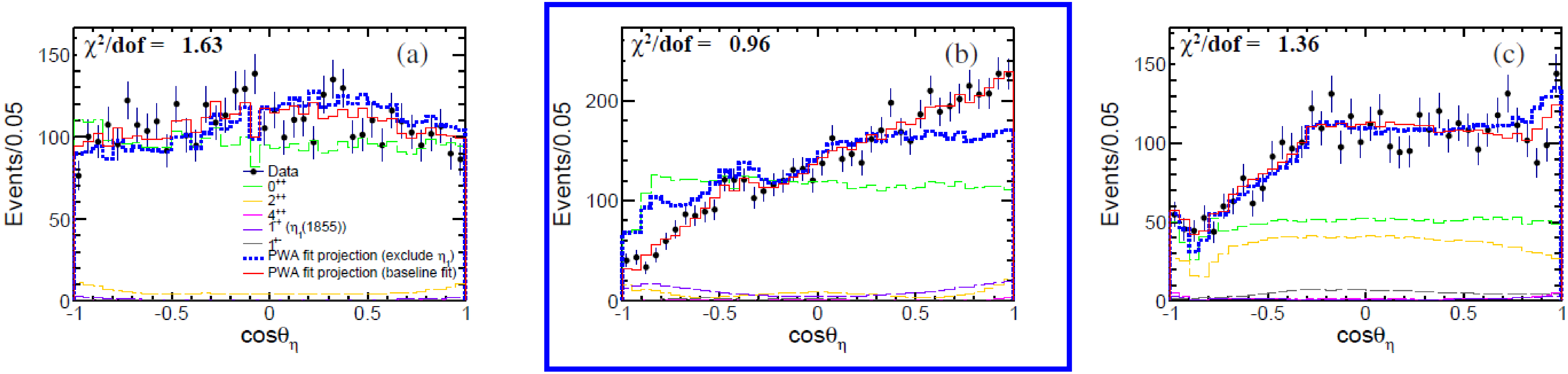
Further checks on the 1^{-+} state $\eta_1(1855)$

- 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:

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

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

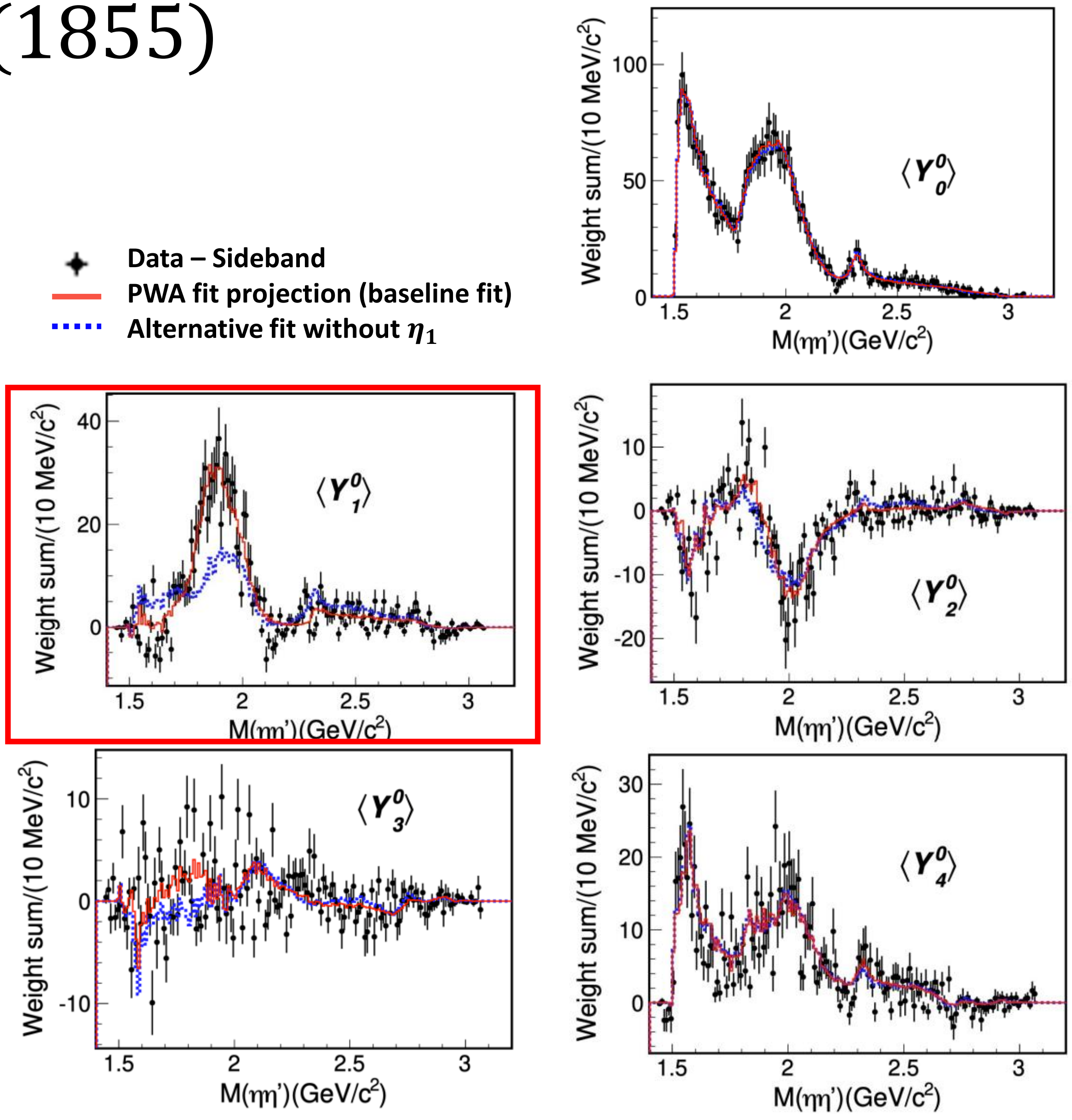
$\langle Y_1^0 \rangle = 0$ without P-wave contribution

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

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

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

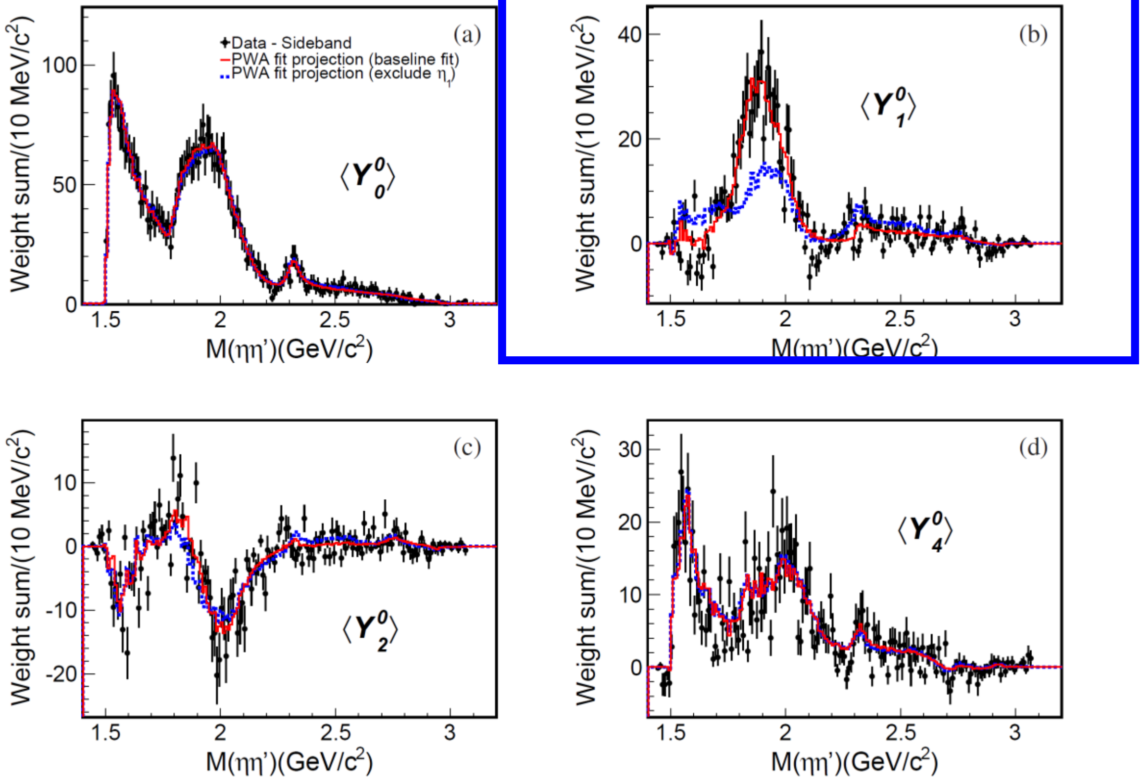
- **Narrow structure** in $\langle Y_1^0 \rangle$
  - ➢ **Cannot be described by resonances in $\gamma\eta(\eta')$**
  - **$\eta_1(1855) \to \eta\eta'$ needed**



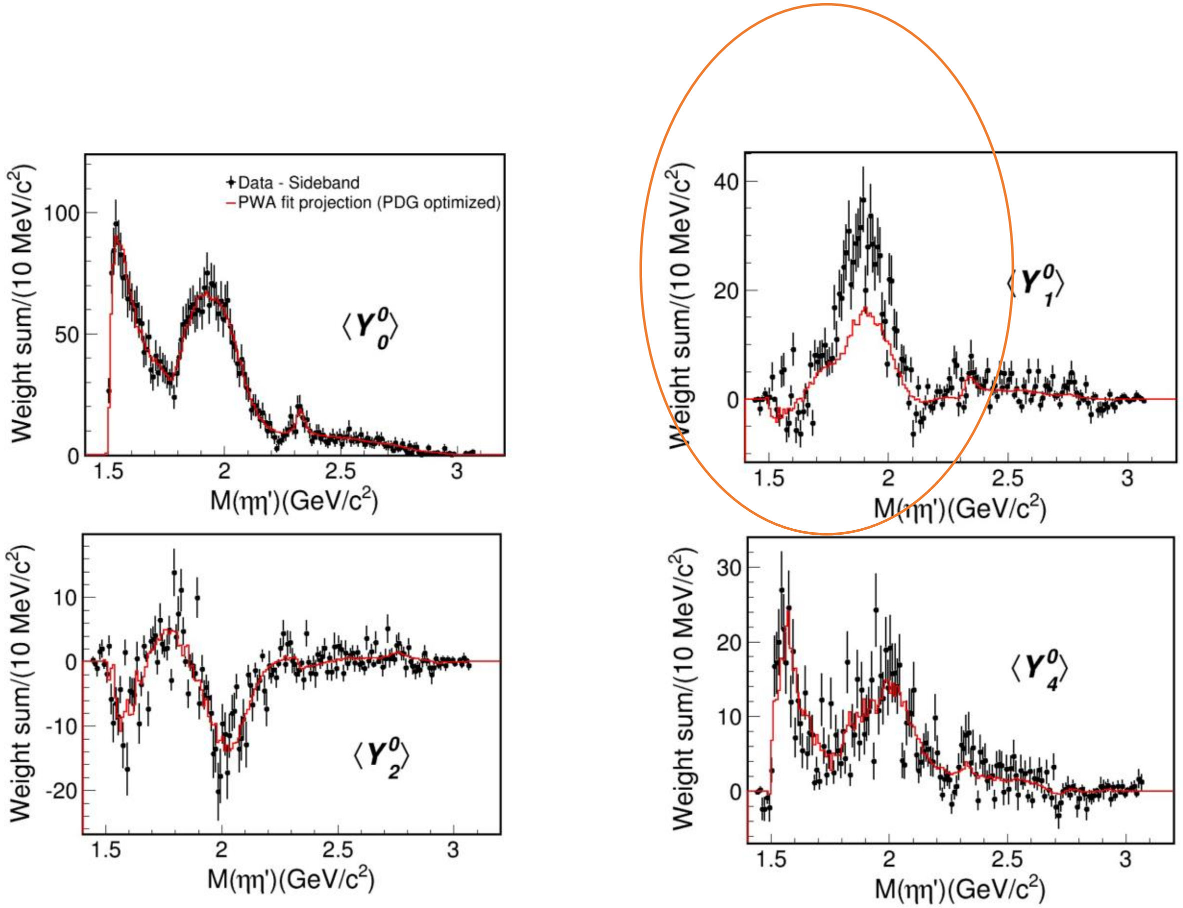
For comparison

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	$f_0(2020)$		$f_0(2330)$		$\eta_1(1855)$		$f_2(2010)$	
	ΔM	$\Delta\Gamma$	ΔM	$\Delta\Gamma$	ΔM	$\Delta\Gamma$	ΔM	$\Delta\Gamma$
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 $f_0(1500)$

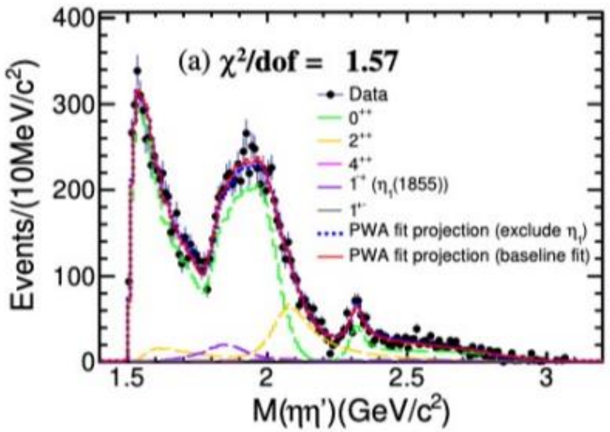
$$\frac{B(f_0(1500) \to \eta\eta')}{B(f_0(1500) \to \pi\pi)} = (8.96^{+2.95}_{-2.87}) \times 10^{-2}$$

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_{PDG} (MeV/c^2)	Γ_{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 and prospects

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

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

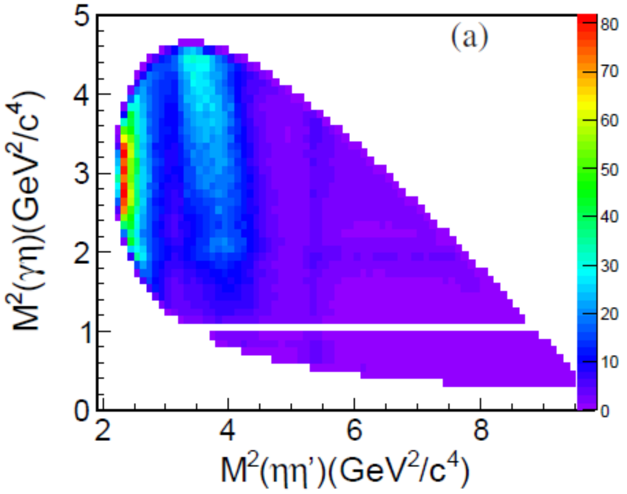
  $B(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = \left(2.70 \pm 0.41^{+0.16}_{-0.35}\right) \times 10^{-6}$

  - **An important step forward of light QCD exotics**
  - **Hybrid? Molecule? Tetraquark?**
  - **Investigate production/decay mechanism and search for other partners in more reactions**
- Further more, significant $J/\psi \to \gamma f_0(1500) \to \gamma\eta\eta'$ has been observed, while $f_0(1710)$ is insignificant
  - $B(f_0(1710) \to \eta\eta')/ B(f_0(1710) \to \pi\pi)< 1.61 \times 10^{-3}$ @90% C.L. , which further supports the f(1710) has a large overlap with glueball
- Data with unprecedented statistical accuracy from BESIII provides great opportunities to study QCD exotics. Will continue to run until ~2030

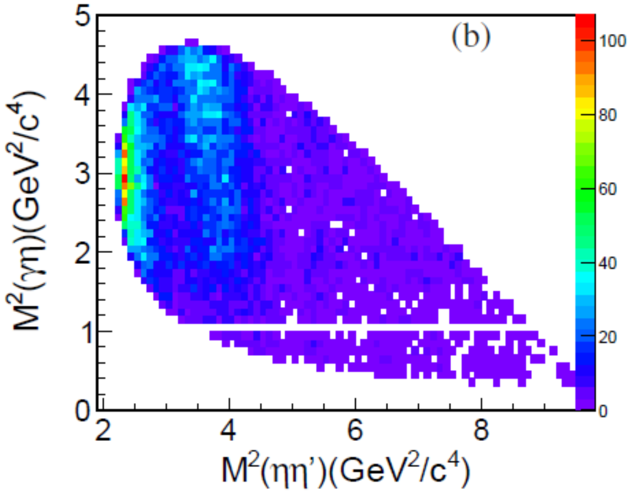
Thank you

Baseline set of amplitudes

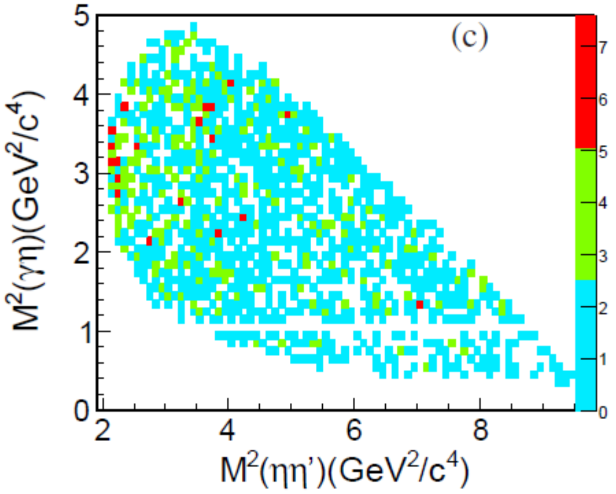
PWA fit projections



PWA result



Data



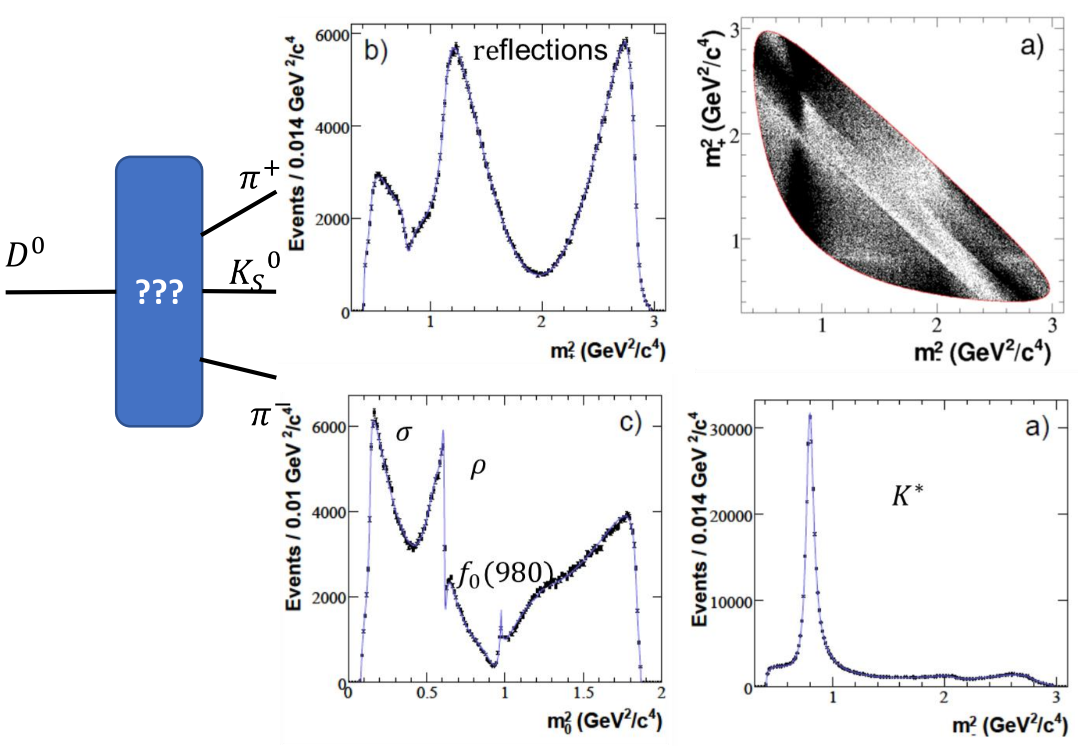
Sideband

Baseline set of amplitudes

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

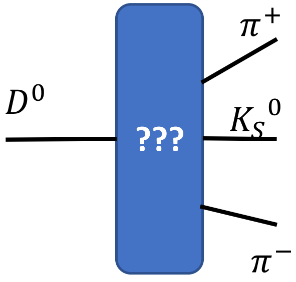
Resonance	$f_0(1500)$	$f_0(1810)$	$f_0(2020)$	$f_0(2330)$	$h_1(1415)(\gamma\eta)$	$h_1(1595)$	$\eta_1(1855)$	$f_2(1565)$	$f_2(2010)$	$f_4(2050)$	0^{++} PHSP
$f_0(1500)$	21.9±1.4	−4.3±0.4	16.2±0.5	−1.0±0.1	1.6±0.2	−1.6±0.9	0.2±0.0	0.2±0.1	0.6±0.1	0.0±0.0	13.4±1.1
$f_0(1810)$		1.4±0.1	−5.6±0.6	0.4±0.0	−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

Amplitude analysis



- **Production Amplitude** produces a state **X** with **J^{PC}** quantum numbers
- **Decay Amplitude** describes the decay of **X** to final state particles
- **Observables** are the four-momenta of the final-state particles

Amplitude analysis



Perform an un-binned log-likelihood fit (fit the data event-wise to high-dimensional distributions using complex weights) to make our model for ω agree with the experimental distribution by varying the α.

Several different states, all decaying to the same final particles are produced, and they interfere (complex amplitudes)

The probability to observe the event characterized by the measurement ξ (i.e. the four-momenta of the final-state particles)

$$P(\xi:\alpha) = \frac{\omega(\xi,\alpha)\epsilon(\xi)}{\int d\xi\,\omega(\xi,\alpha)\epsilon(\xi)}$$

Differential cross section

$$\omega(\xi,\alpha) = \frac{d\sigma}{d\Phi} = |\textstyle\sum_i A_i\ |^2$$

Efficiency

$$\epsilon(\xi)$$

Likelihood

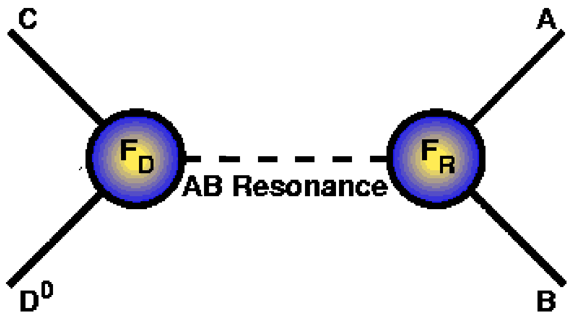
$$L = \prod_{i=1}^{N} P(\xi:\alpha)$$

Perform an un-binned log-likelihood fit (fit the data event-wise to high-dimensional distributions using complex weights) to make our model for ω agree with the experimental distribution by varying the α.

Isobar model formalism

quasi two-body decay amplitudes via intermediate resonances

D^0 three-body decay D^0 →ABC decaying through an r=[AB] resonance



D^0 three-body amplitude

$$\mathcal{A}_D(s_{12}, s_{13}) = a_0 e^{i\delta_0} + \sum_r a_r e^{i\delta_r} \mathcal{A}_r(s_{12}, s_{13})$$

NR term(direct 3 body decay)

a_0, δ_0, a_r, δ_r : Free parameters of fit

$$\mathcal{A}_r(s_{12}, s_{13}) = F_D^J F_r^J \times M_r^J \times BW_r^J$$

$J \to L + l$	Angular distribution
$0 \to 0+0$	uniform
$0 \to 1+1$	$(1+\zeta^2)\cos^2\theta$
$0 \to 2+2$	$\left(\zeta^2 + \frac{3}{2}\right)^2 (\cos^2\theta - 1/3)^2$

Dynamical function, e.g. Breit-Wigner (BW) propagator

Angular distribution: spin formalism

Blatt-Weisskopf centrifugal barrier factor for the D (resonance) decay vertex with radius R,