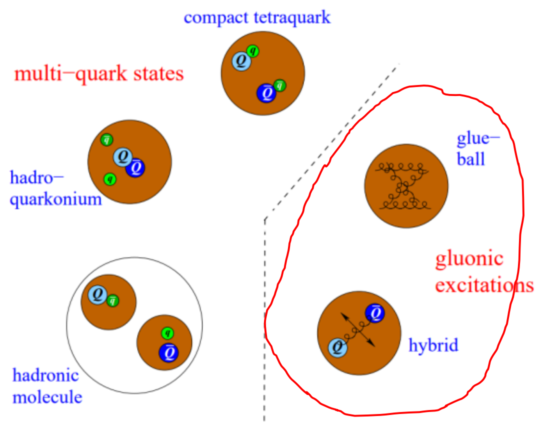
Recent results of spin exotics at BESIII

Beijiang LIU
IHEP

Mini workshop on Light QCD exotics states
2024-10-18, IHEP

configurations beyond QM



Phys.Rept. 873 (2020) 1

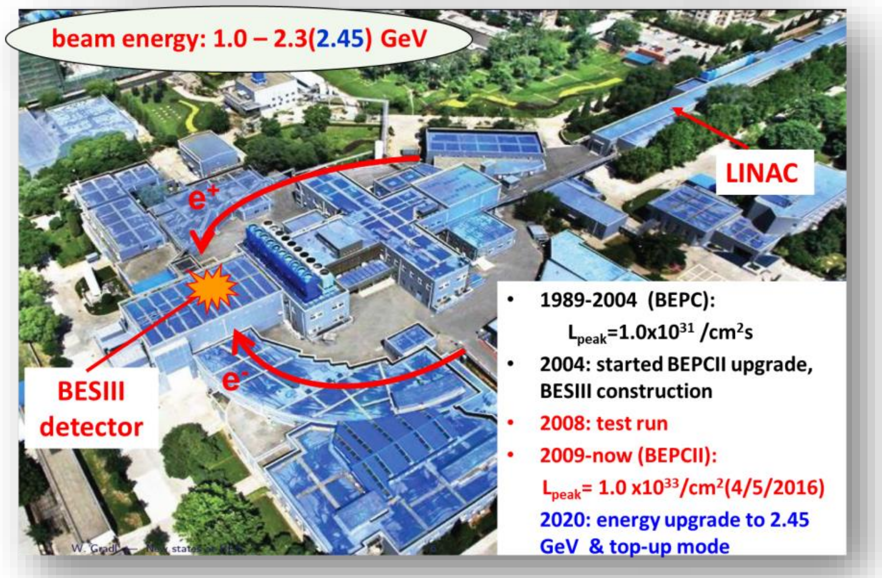
Light QCD exotics

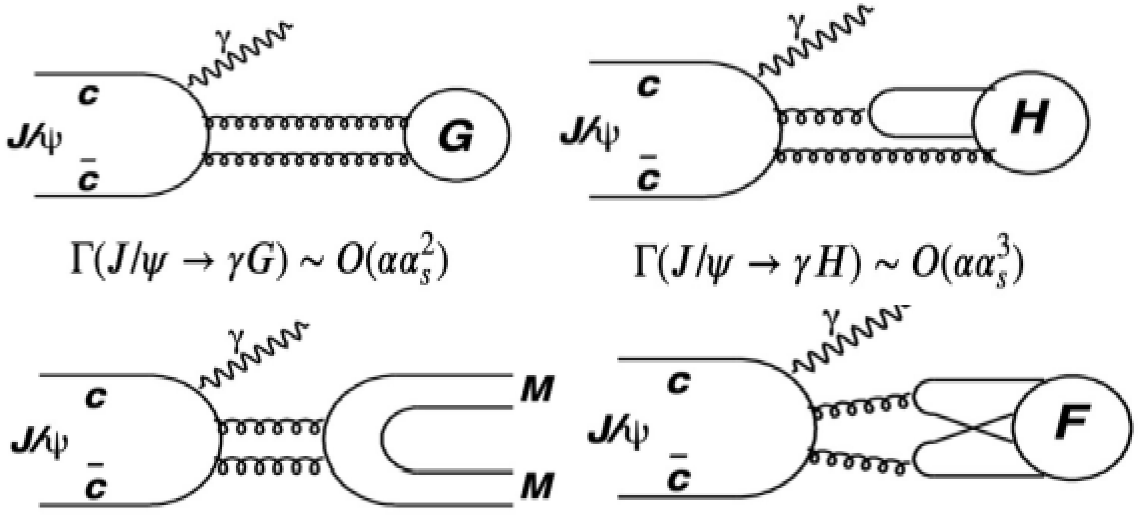
- **Strong evidences for multi-quark in heavy quark sector**
- **However, evidence for gluonic excitations remains sparse**
  - Light Flavor-exotic hard to establish
  - Assignment of some $SU(3)_{flavor}$ $|q\bar{q}>$ nonets difficult
- **Role of gluons:**
  - Gluons mediate the strong force
  - Gluons' unique self-interacting property

    → New form of matter: glueballs, hybrids
  - **Gluonic Excitations provide measurements of the QCD potential**

Critical to confinement and mass dynamical generation

Beijing Electron Positron Collider (BEPCII)





$\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2)$ $\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$

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

Charmonium decays provide an ideal lab for Gluonic Excitations

- **Gluon-rich process**
- **Well defined initial and final states**
  - Kinematic constraints
  - Isospin and J^{PC} filters
- **Clean high statistics data samples:** 10×10^9 J/ψ and 2.7×10^9 ψ' @ BESIII
  - High cross sections of $e^+e^- \to J/\psi,\ \psi'$
  - Low background

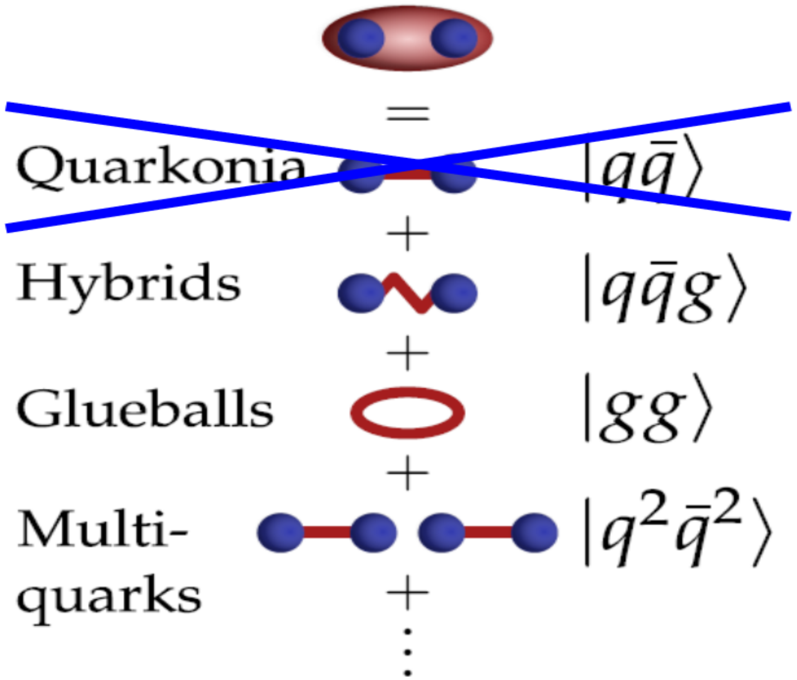
Light hadrons with exotic quantum numbers

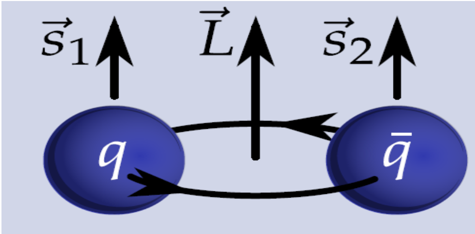
- **Unambiguous signature for exotics**
  - **Efforts concentrate on Spin-exotic**
    - **Forbidden for $q\bar{q}$:**

      $\mathbf{J^{PC} = 0^{--}, even^{+-}, odd^{-+}}$

Experiments:

- **Hadroproduction:** GAMS, VES, E852, COMPASS
- **$p\bar{p}$ annihilation:** Crystal Barrel, OBELIX, PANDA(under construction)
- **Photoproduction:** GlueX(2017-), CLAS

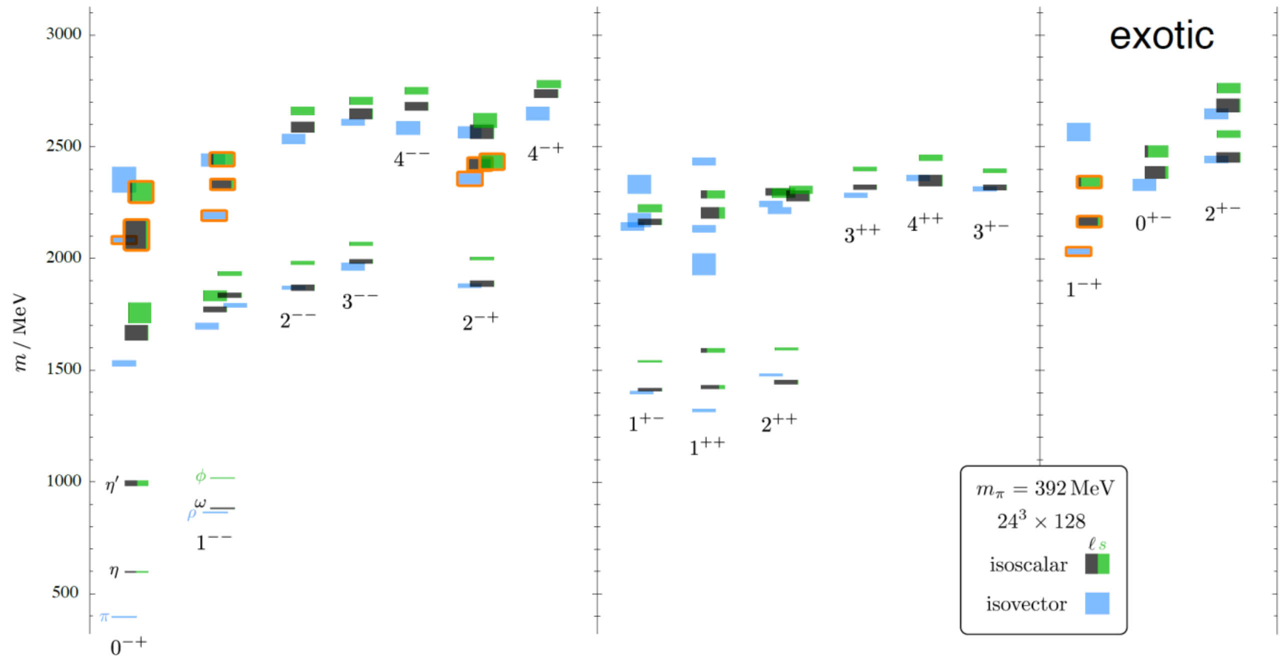




$\vec{J} = \vec{L} + \vec{S}$ $\quad P = (-1)^{L+1}$ $\quad C = (-1)^{L+S}$

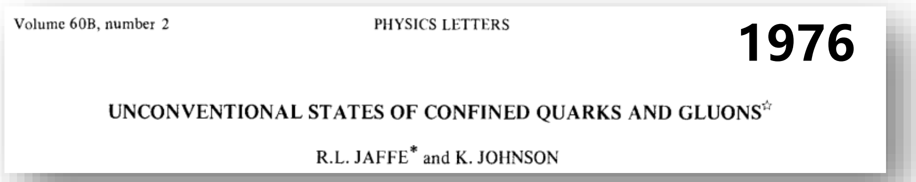
Allowed J^{PC}: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$

Predictions



PRD 88 094505(2013)

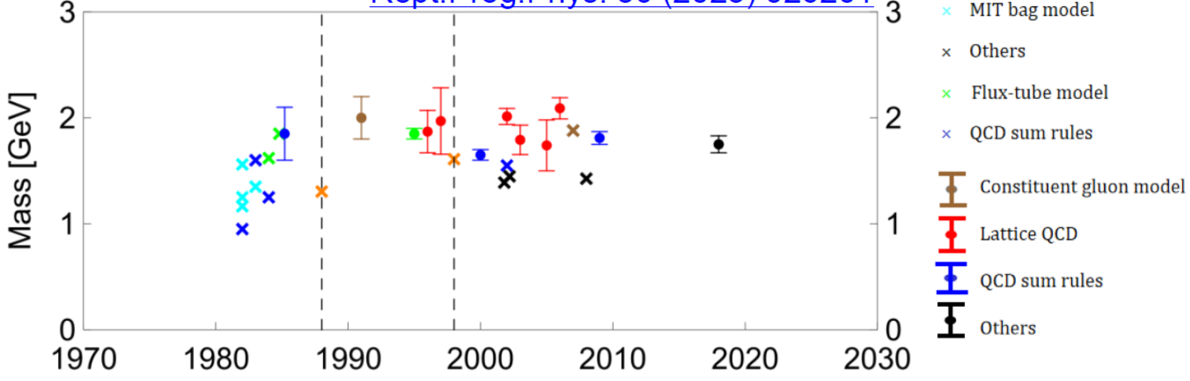
Lightest spin-exotic state in LQCD: $\mathbf{1^{-+}}$ hybrid


Volume 60B, number 2 PHYSICS LETTERS

UNCONVENTIONAL STATES OF CONFINED QUARKS AND GLUONS☆

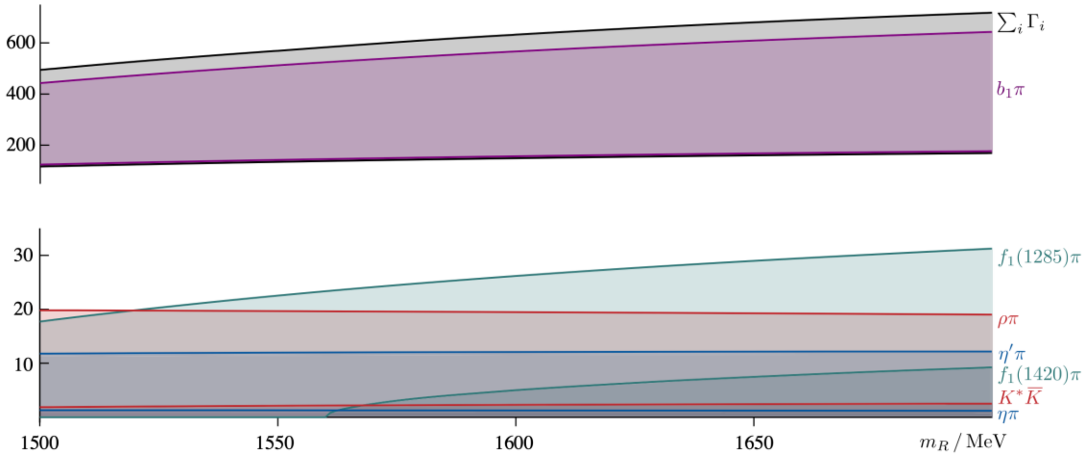
R.L. JAFFE* and K. JOHNSON

Rept.Prog.Phys. 86 (2023) 026201



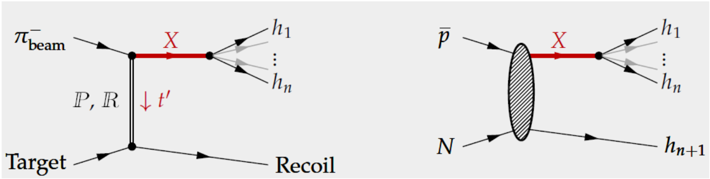
Mass of $\mathbf{1^{-+}}$ hybrid

PRD 103, 054502(2021)



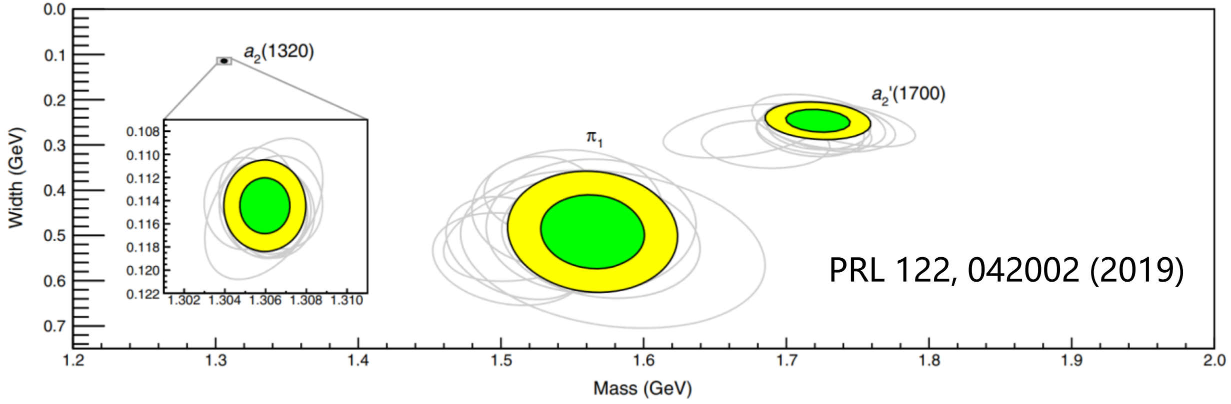
Decay width of $\mathbf{1^{-+}}$ hybrid π_1

Detailed reviews: PRC 82, 025208 (2010)， PPNP 82, 21 (2015)



Spin-exotic mesons

- **Over 3 decades, only 3 candidates so far:** **All 1^{-+} isovectors**
  - $\pi_1(1400)$: seen in $\eta\pi$
  - $\pi_1(1600)$: seen in $\rho\pi$, $\eta'\pi$, $b_1\pi$, $f_1\pi$
  - $\pi_1(2015)$ (needs confirmation): seen in $b_1\pi$, and $f_1\pi$
- A big step forward: $\pi_1(1400)$ & $\pi_1(1600)$ can be one pole [PRL 122, 042002 (2019), EPJ C 81, 1056 (2021])

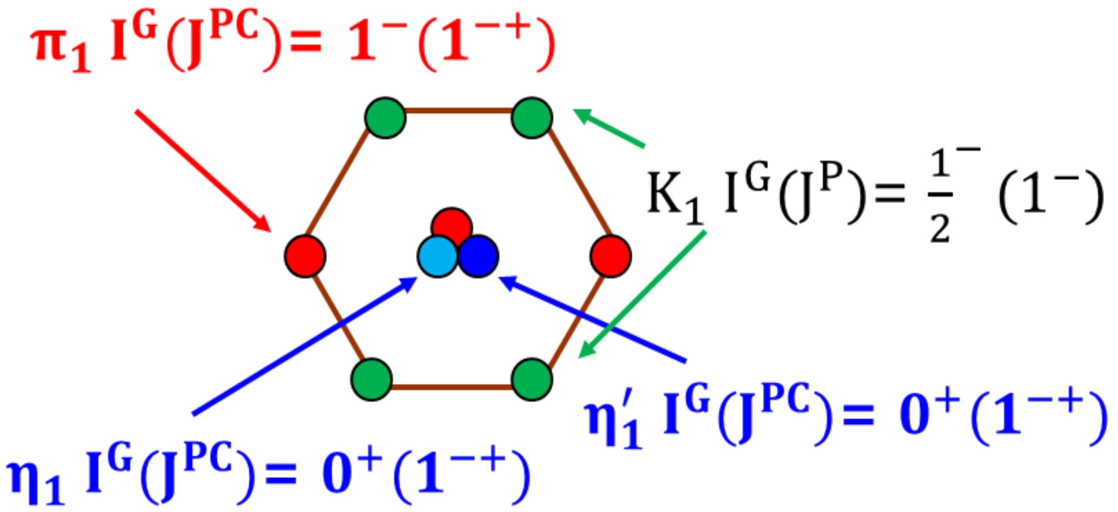


Coupled-channel analysis of the $\eta\pi$ and $\eta'\pi$ P- and D-wave

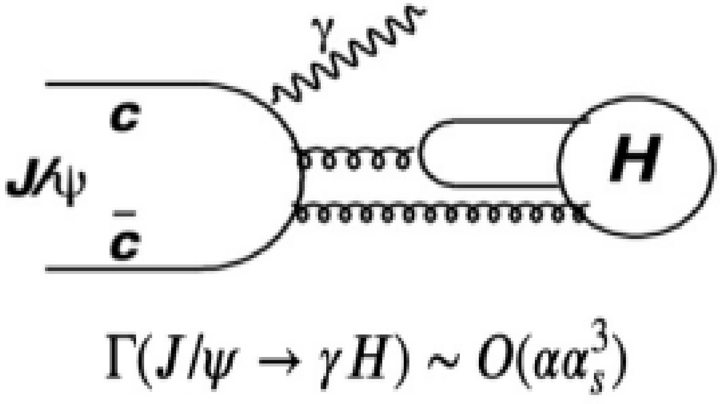
	Decay mode	Reaction	Experiment
$\pi_1(1400)$	$\eta\pi$	$\pi^- p \to \pi^- \eta p$	GAMS
		$\pi^- p \to \pi^0 \eta n$	KEK
		$\pi^- p \to \pi^- \eta p$	E852
		$\pi^- p \to \pi^0 \eta n$	E852
		$\bar{p} n \to \pi^- \pi^0 \eta$	CBAR
		$\bar{p} p \to \pi^0 \pi^0 \eta$	CBAR
	$\rho\pi$	$\bar{p} p \to 2\pi^+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

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**



PRD 83,014021 (2011), PRD 83,014006 (2011), EPJ P135, 945(2020)

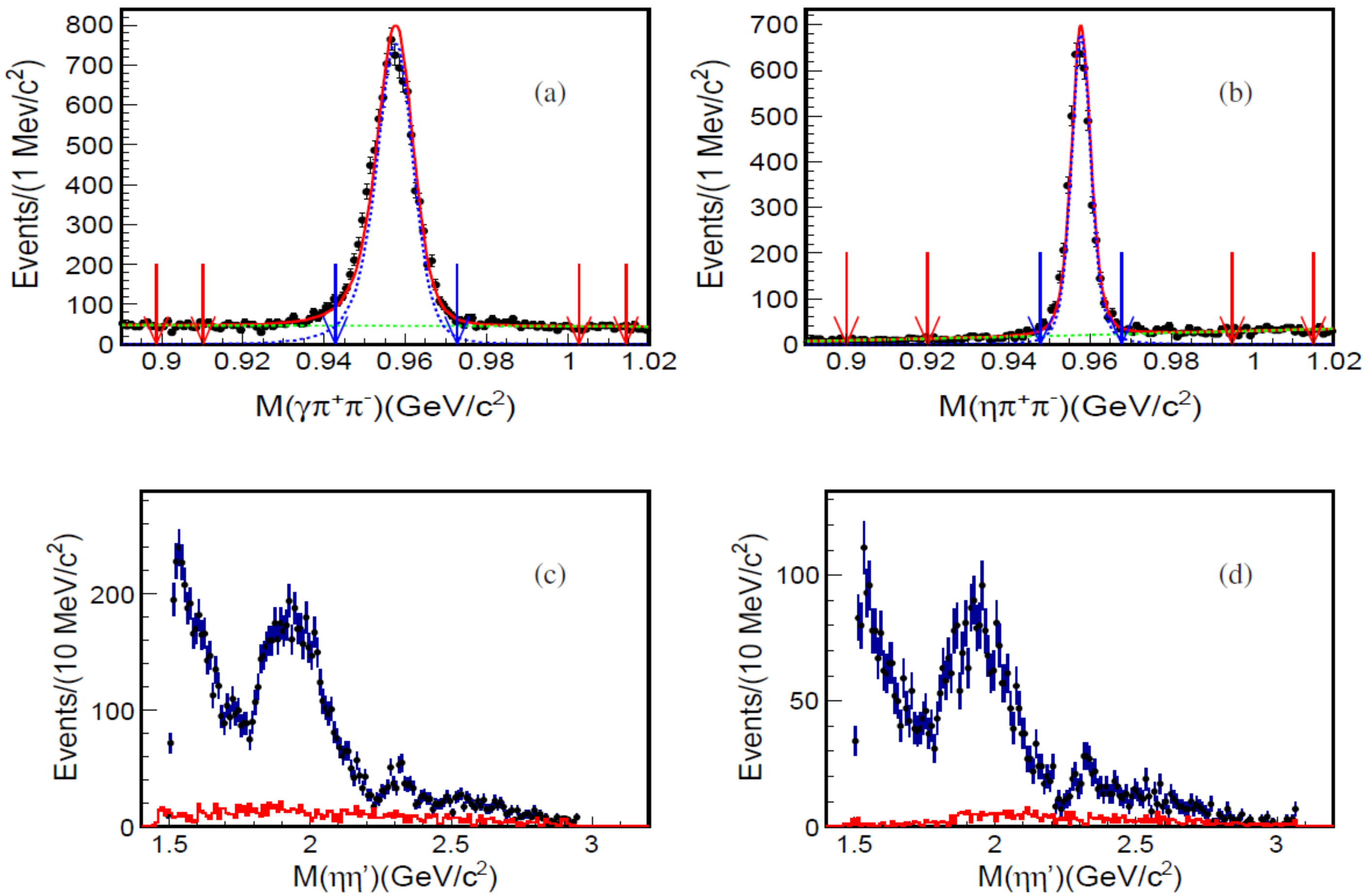


→ Search for $\eta_1\ (1^{-+})$ in $J/\psi \to \gamma\eta\eta'$

Observation of An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$

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

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



- 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

Observation of **An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$**

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Amplitude 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

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

Observation of **An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$**

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

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

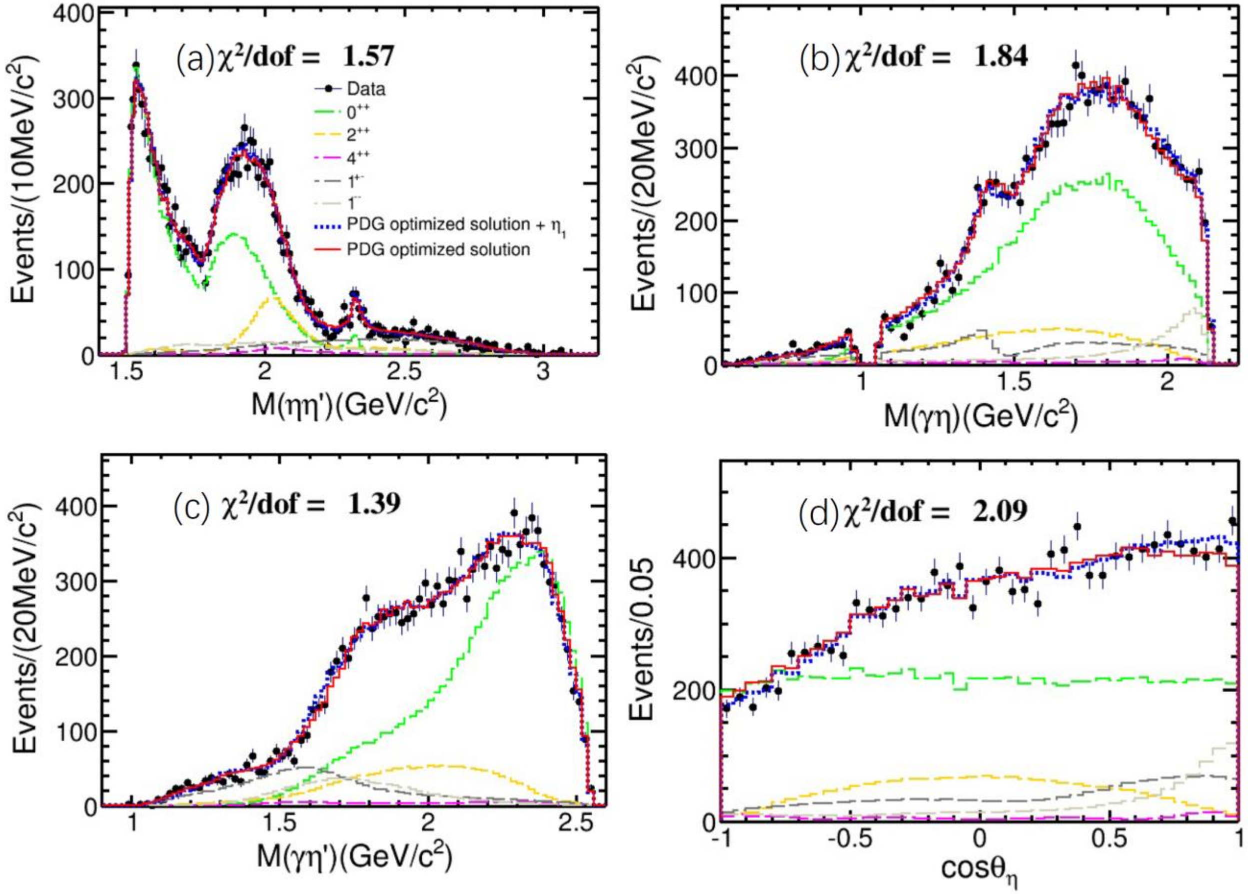
[57] $\bar{p}p$ reactions at Crystal Barrel and PS172, Phys. Rept. 397, 257

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

Observation of **An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$**

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

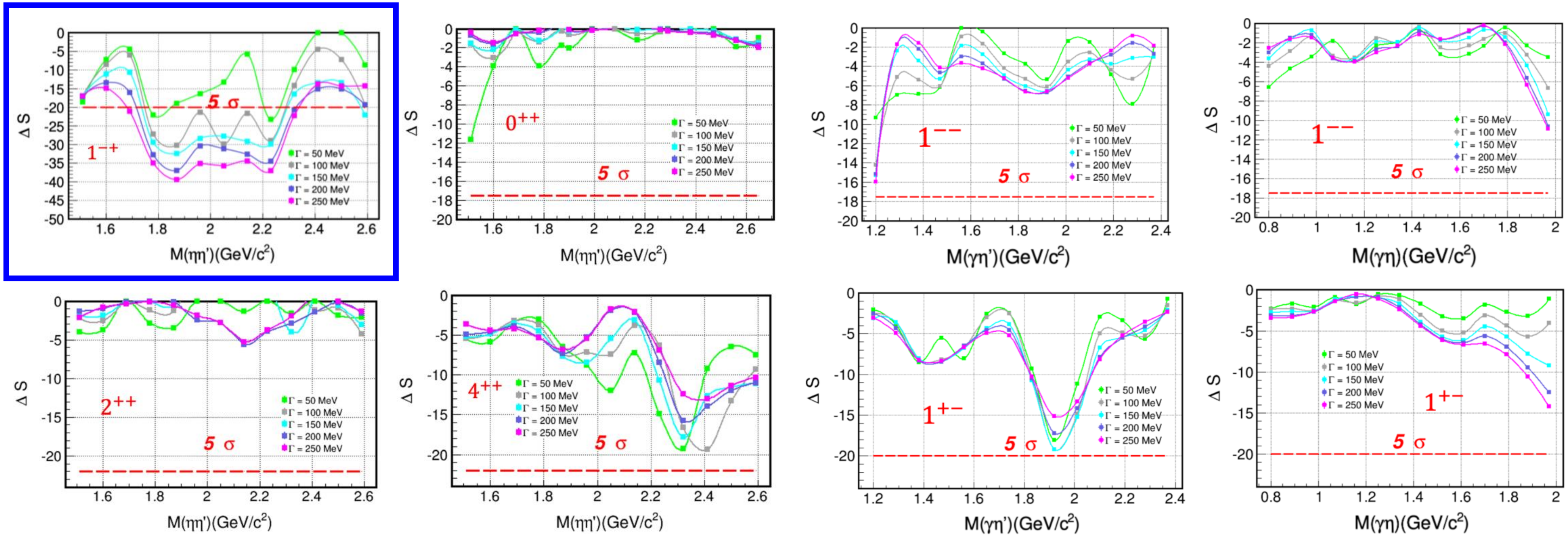
PWA projections for the set of amplitudes with known resonances(PDG-optimized set)



Observation of **An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$**

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

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



Observation of An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$

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

Baseline set of amplitudes by adding the η_1 state

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	M_{PDG} (MeV/c^2)	Γ_{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

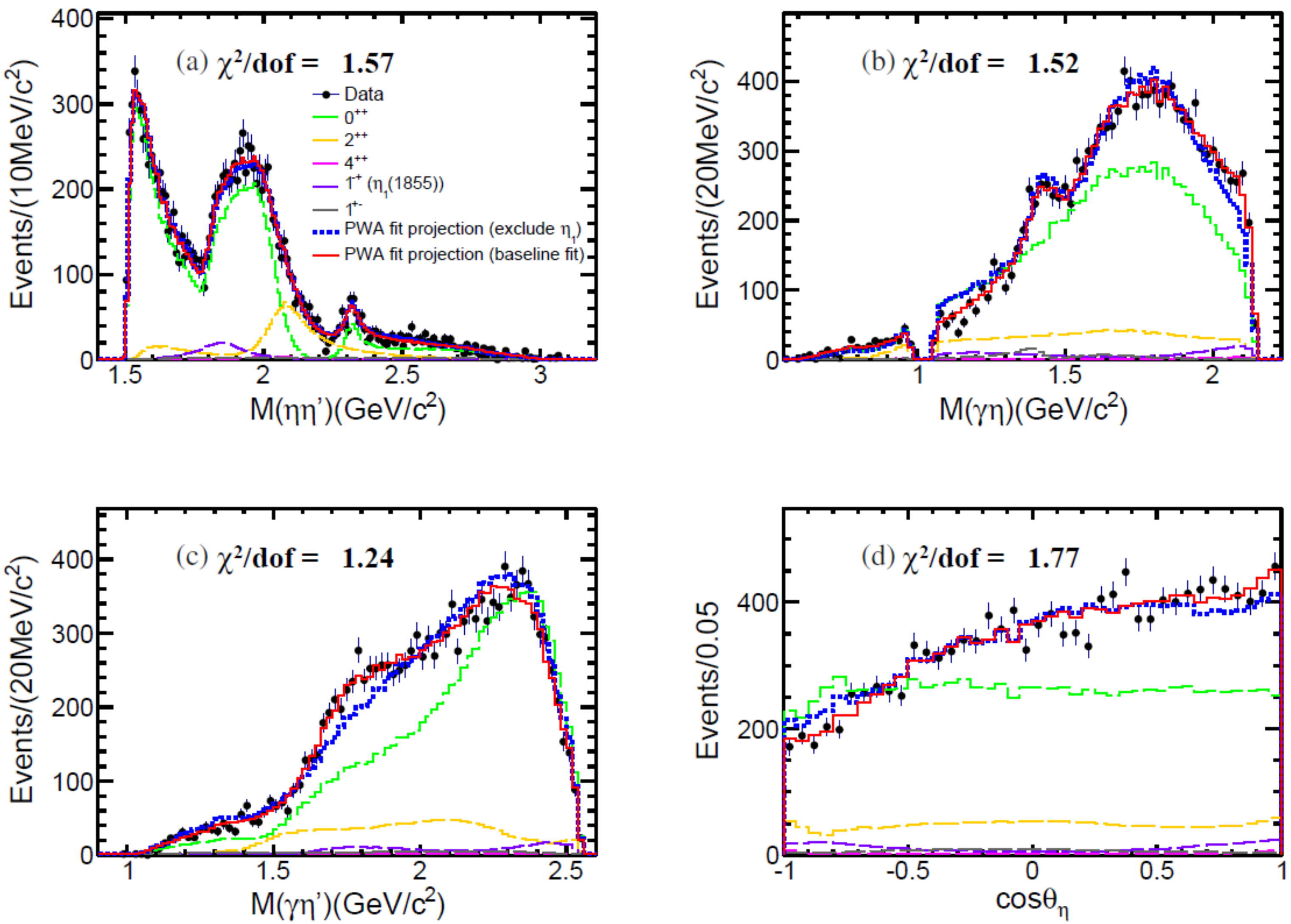
- Contributions from the $f_0(2100)$, $h_1(1595)(\gamma\eta')$, $\rho(1700)(\gamma\eta')$, $\phi(2170)(\gamma\eta)$, $f_2(1810)$, and $f_2(2340)$, in the PDG-optimized set become insignificant (< 3σ), omitted
- Comparing to the PDG-optimized set, ln L of the baseline set is improved by 32 and the number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

Observation of **An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$**

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

PWA projections for the baseline set of amplitudes



Observation of **An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$**

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

- 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:

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

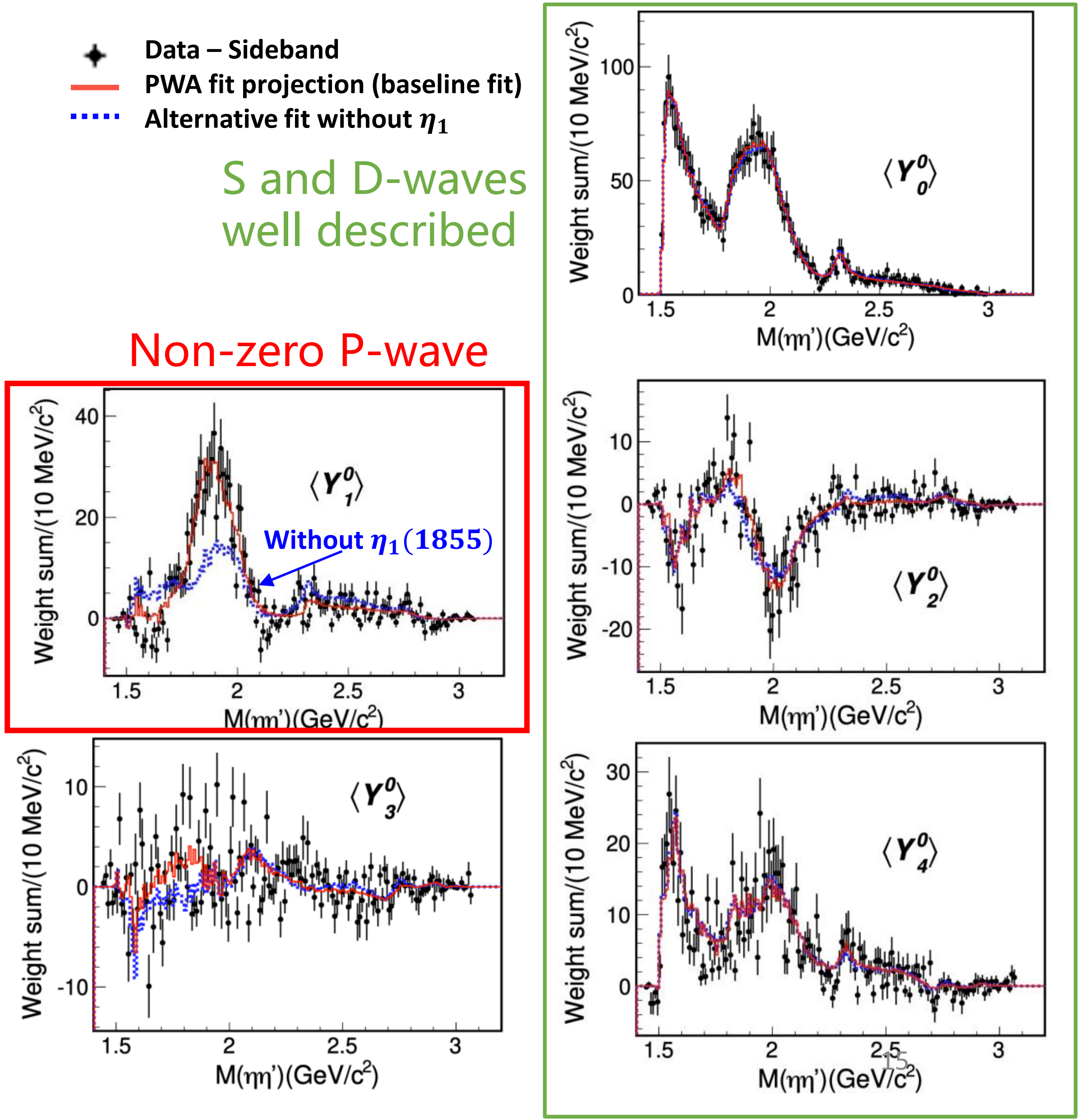
$$\sqrt{4\pi}\langle Y_1^0\rangle = 2S_0P_0\cos\phi_{P_0} + \frac{2}{\sqrt{5}}(2P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) + \sqrt{3}P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

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

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

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

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



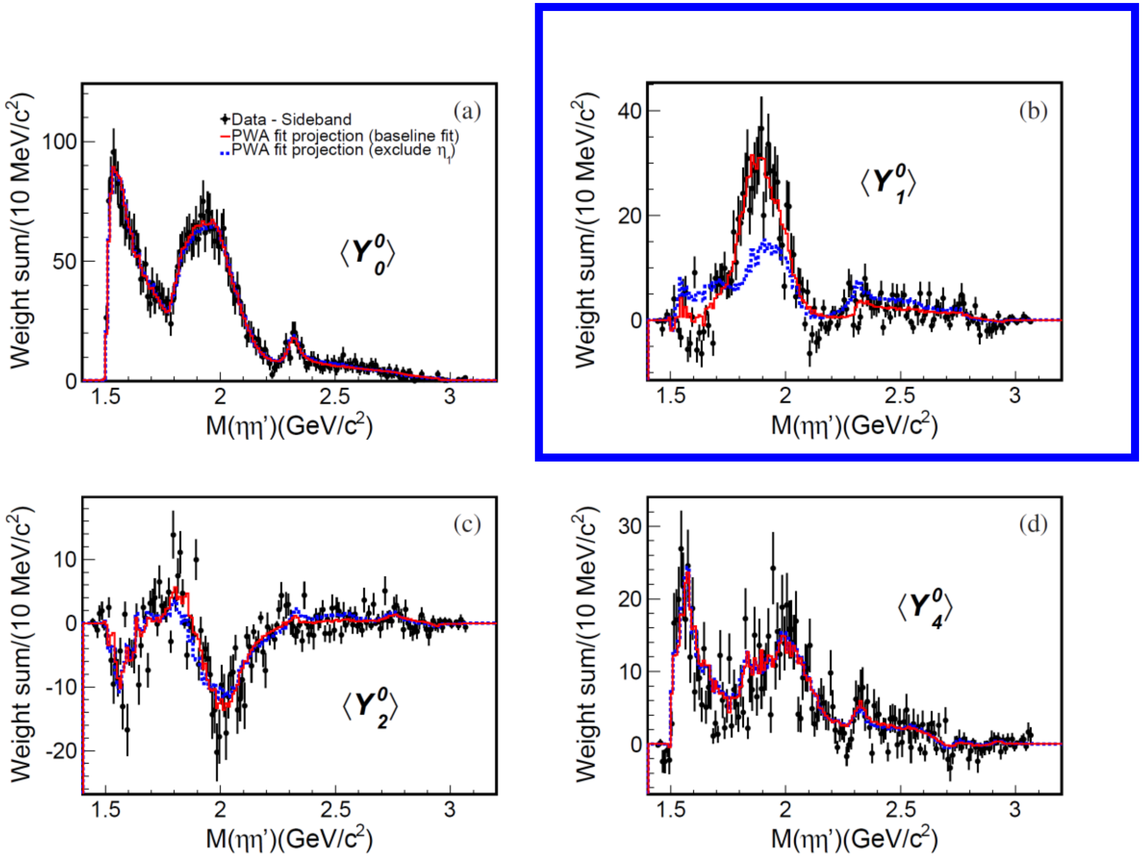
Observation of **An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$**

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

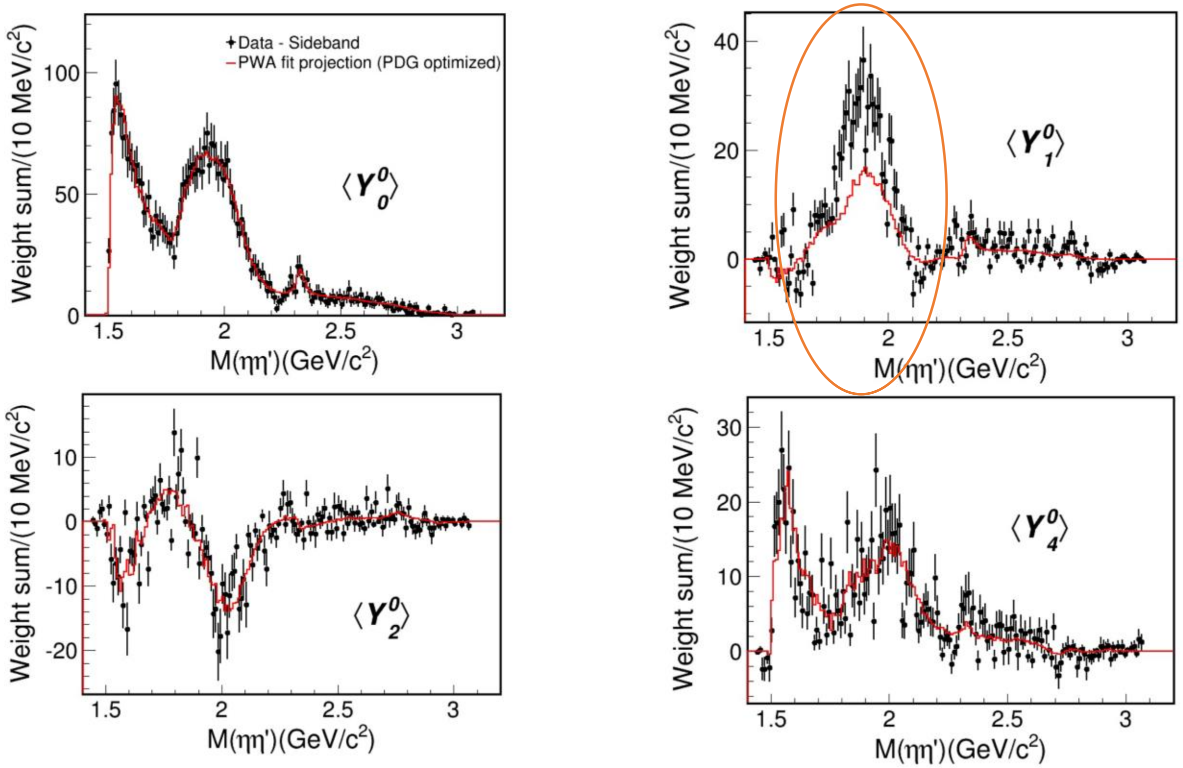
For comparison

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

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



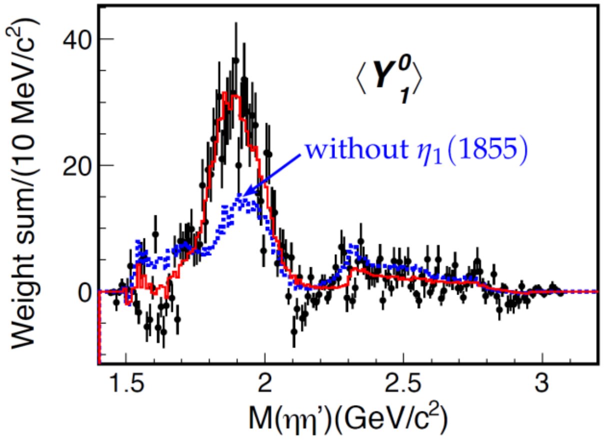
Baseline set of amplitudes



PDG-optimized set of amplitudes

Observation of **An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$**

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

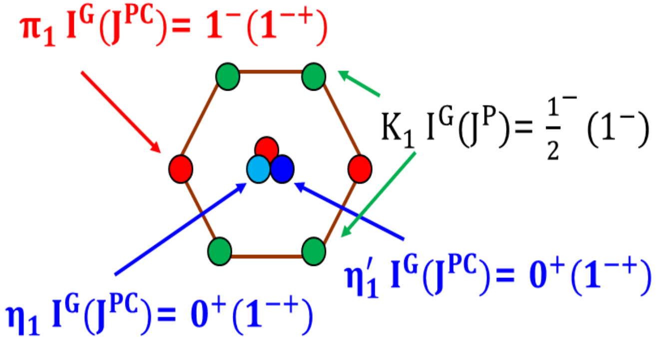


- **Opens a new direction to completing the picture of spin-exotics**
- **Inspired many interpretations:**

PRD 107 074028 (2023) ;
Rept.Prog.Phys. 86 026201(2023);
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) ; …

Hybrid?
$K\bar{K}_1$ Molecule?
Tetraquark?

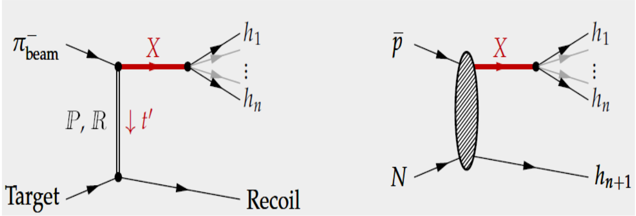
Snowmass 2021: Summary of Topical Group (RF07) & 4 white papers
NSAC Long range plan cold QCD whitepaper: NPA 1047 122874 (2024)

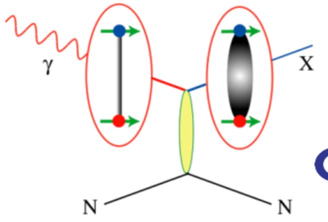


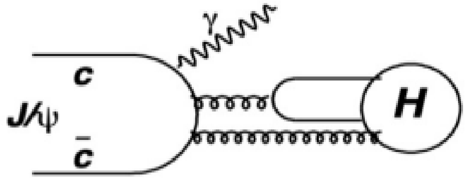
"Here, the result by the BESIII experiment of a possible observation of an $\eta_1(1855)$ state could be a breakthrough."

—— 50 years of QCD: Exotic mesons [EPJ.C 83 (2023) 1125]

Prospects of spin-exotics at BESIII







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

Charmonium decays provide a new path

Isoscalar: $\eta_1(1855)$

- **Decay properties**
  - $J/\psi \to \gamma + \pi a_1, \eta f_1, K_1\bar{K}, VV,$ ……
- **Production properties**
  - $J/\psi \to \omega\eta\eta'$, $\phi\eta\eta'$, ……
  - $\chi_{c1} \to \eta + \eta\eta'$, ……
- **Where is $\eta_1^{(\prime)}$**
- **Other partners: 2^{+-} , ……**
- **Analog in $\bar{c}c$**

Isovector: $\pi_1(1600)$

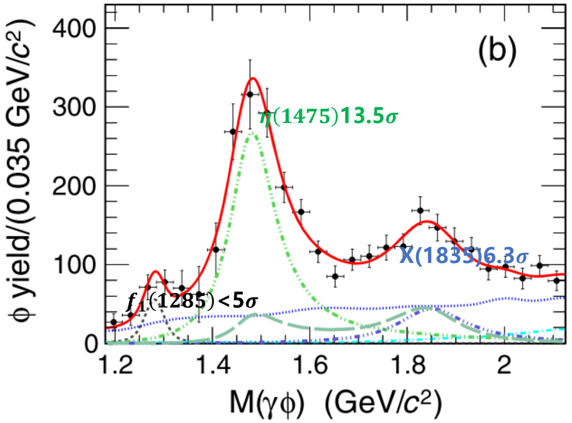
- $J/\psi \to \rho\eta'\pi$, ……
- $\chi_{c1} \to \pi + \pi b_1, \pi f_1$, $\pi\eta'$, ……

$J/\psi \to \gamma\gamma\phi$, a $s\bar{s}$ flavor filter

New

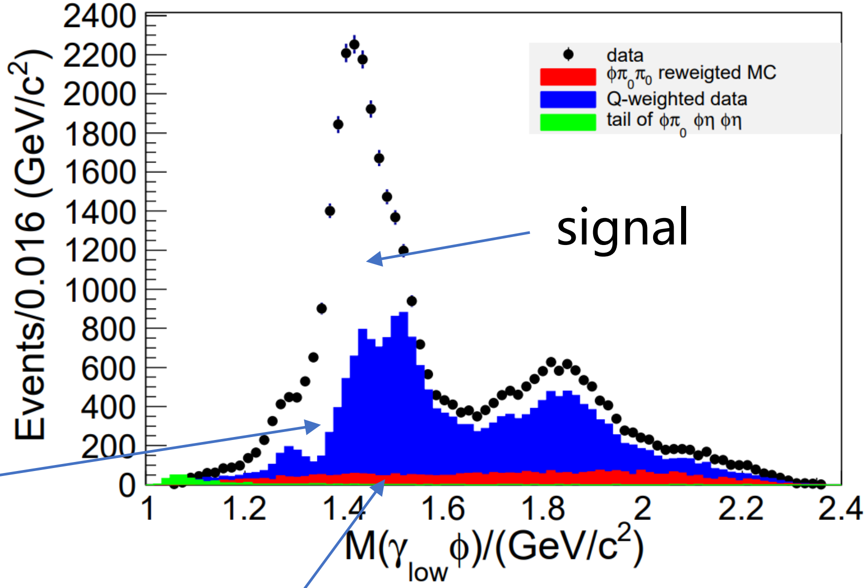
arXiv: 2401.00918

PR D97 051101 (2018)



←Fit to mass spectrum

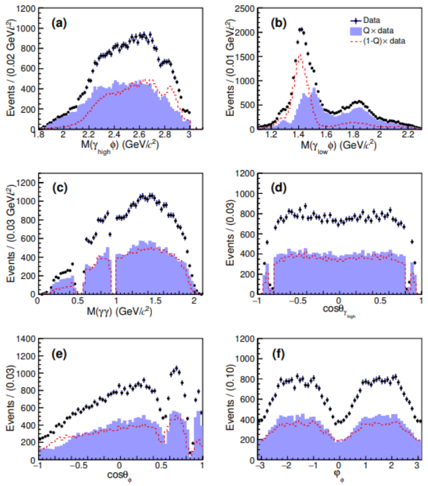
Amplitude analysis with advanced techniques for background subtraction



Subtraction of non-ϕ backgrounds

Multi-dimensional quality factor method

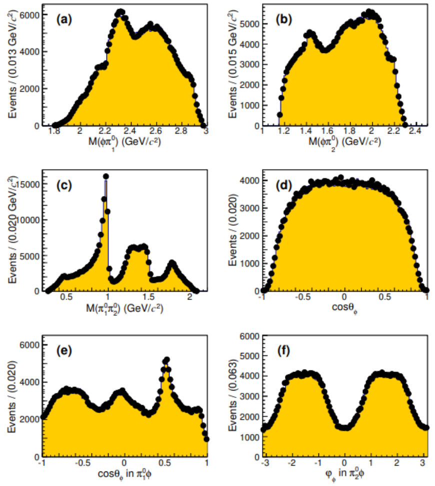
JINST 4, P10003 (2009).



Modeling the dominant ϕ background: $J/\psi \to \pi^0\pi^0\phi$

ML-based reweighting

EPJ Web Conf. 214, 06033 (2019).

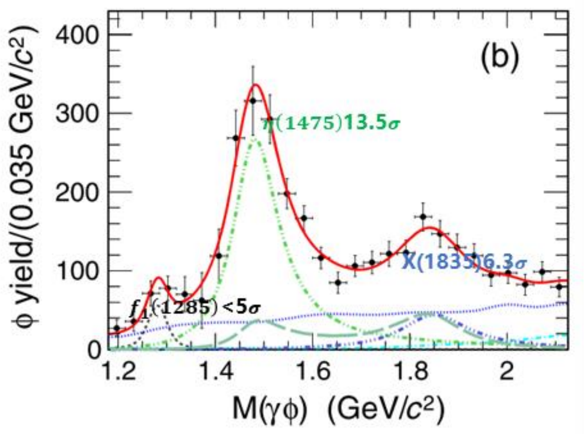


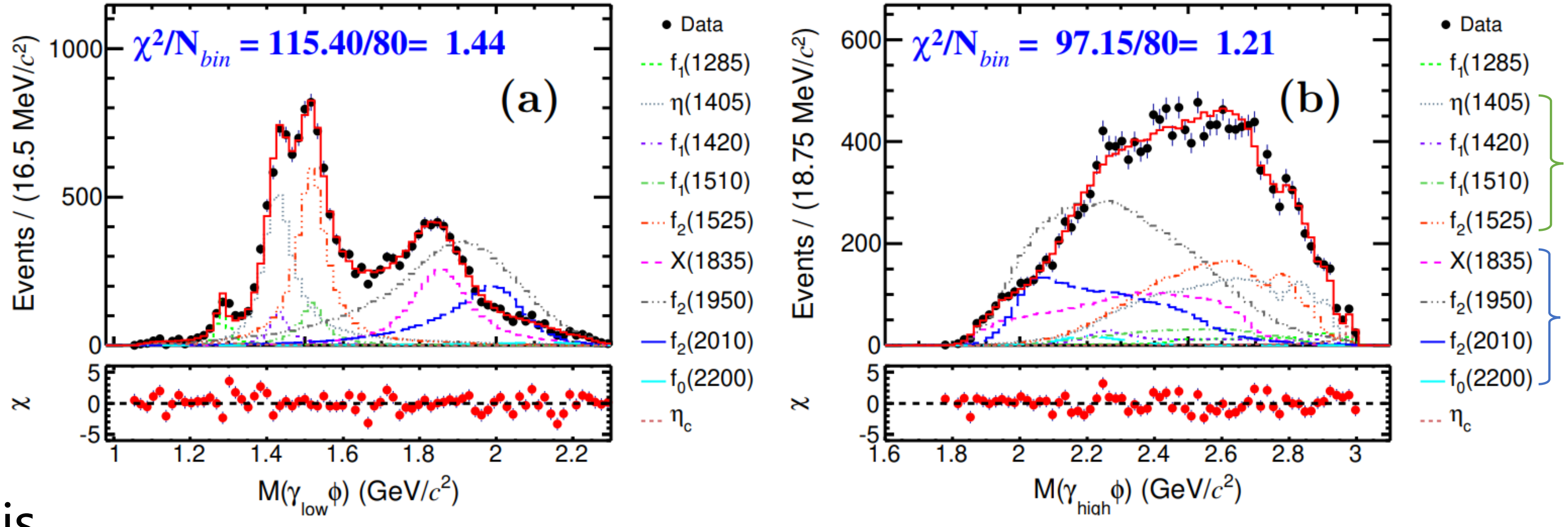
$J/\psi \to \gamma\gamma\phi$, a $s\bar{s}$ flavor filter

New

arXiv: 2401.00918

PR D97 051101 (2018)





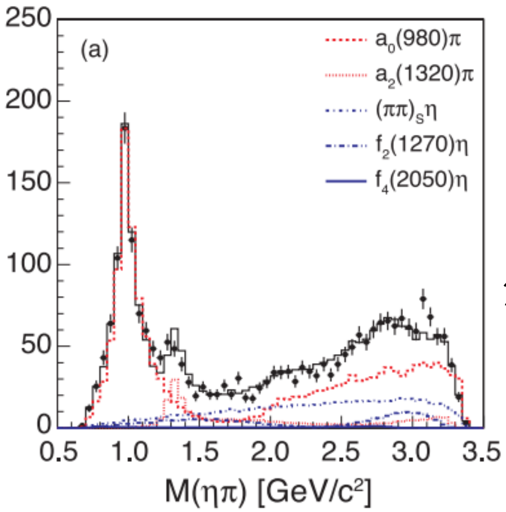
From the amplitude analysis,

- $\eta(1405)$ is observed, while $\eta(1475)$ can not be excluded
- **$X(1835) \to \gamma\phi$ suggests its assignment of η' excitation**
- **$\eta_c \to \gamma\phi$ are observed. The very first radiative decay mode of η_c**
- **Observation of $f_2(1950)$ and $f_0(2200) \to \gamma\phi$ unfavored their glueball interpretations**
  [PRD 108, 014023, arXiv: 2404.01564]
- **No evidence of $\eta_1(1855)$, well consistent with the predictions for hybrid** [NPA 1037, 122683]

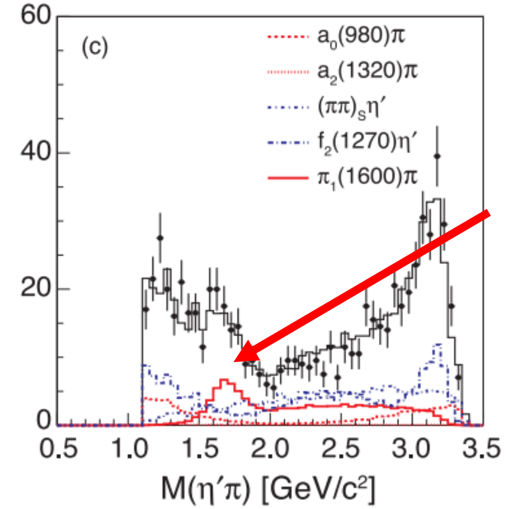
$\chi_{c1} \to \pi^+\pi^-\eta^{(\prime)}$

PR D84 112009 (2011)

$\mathbf{2.6 \times 10^7}$ ψ(3686) @CLEO − c



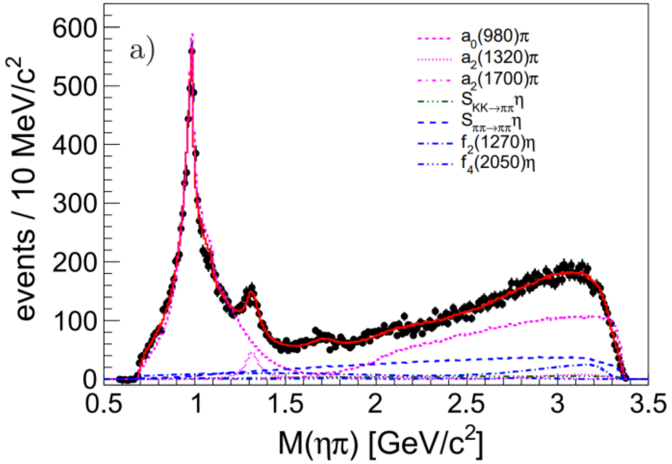
No evidence of $\pi_1 \to \eta\pi$



Evidence of $\pi_1 \to \eta'\pi$ (without significant BW phase motion)

PR D95 032002(2017)

44.8×10^7 ψ(3686) @BESIII



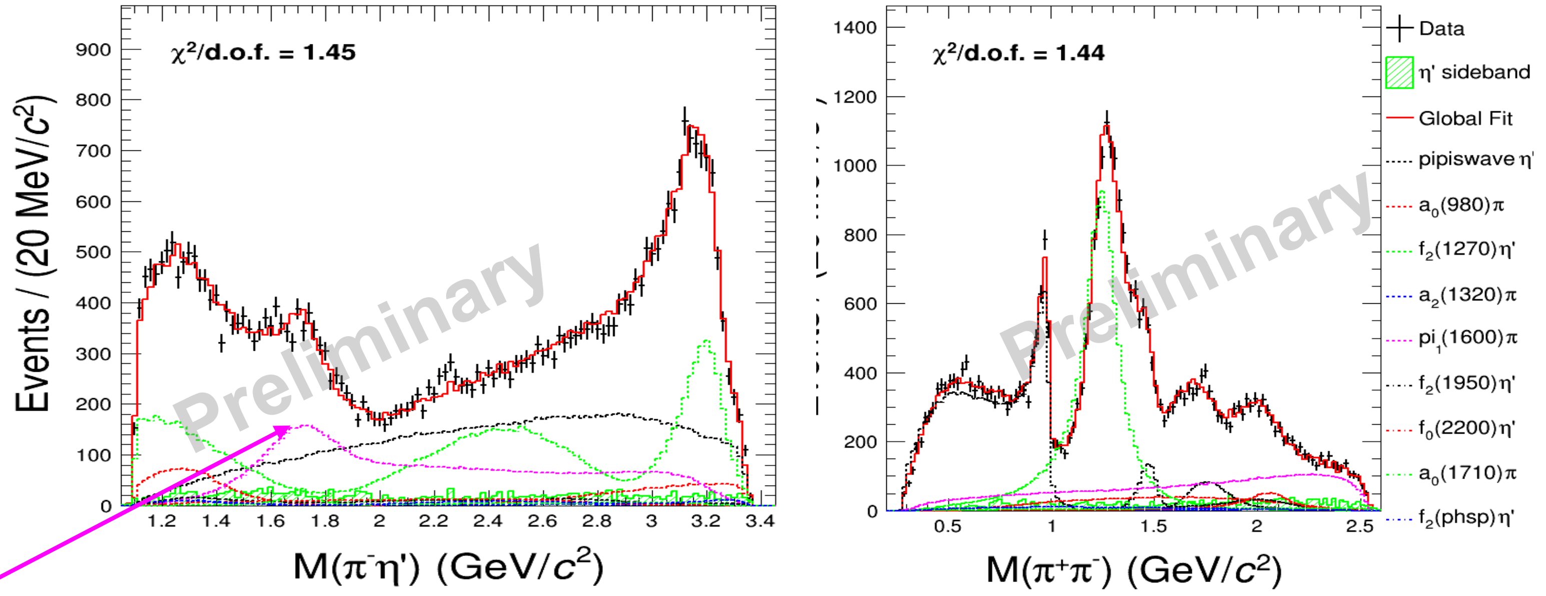
No evidence of $\pi_1 \to \eta\pi$

Observation of $\pi_1(1600)$ in $\chi_{c1} \to \eta'\pi^+\pi^-$

New

2.7×10^9 $\psi(3686)$@BESIII [preliminary]

state	J^{PC}	Decay mode	Significance
$\pi_1(1600)$	1^{-+}	$\pi^\pm\eta'$	$>> 10\sigma$
$(\pi\pi)_{S-wave}$	0^{++}	$\pi^\pm\eta'$	$>> 10\sigma$
$a_0(980)$	0^{++}	$\pi^\pm\eta'$	$> 10\sigma$
$f_2(1270)$	2^{++}	$\pi^+\pi^-$	$>> 10\sigma$
$a_2(1320)$	2^{++}	$\pi^\pm\eta'$	$> 5\sigma$
$f_2(1950)$	2^{++}	$\pi^+\pi^-$	$> 10\sigma$
$f_0(2200)$	0^{++}	$\pi^+\pi^-$	$> 10\sigma$
$a_0(1710)$	0^{++}	$\pi^\pm\eta'$	$> 10\sigma$
$f_2(PHSP)$	2^{++}	$\pi^+\pi^-$	$> 5\sigma$



- **$\pi_1(1600)$ observed $>10\sigma$, with a significant BW phase motion**
- **$J^{PC} = 1^{-+}$, better than other assignments well over 10σ**
  - Evidence of $\pi_1 \to \eta'\pi$ at CLEO-c is confirmed [PR D84 112009 (2011)]

Story thus far

$\eta_1(1855)$

- Production
  - Observed in $J/\psi \to \gamma\eta_1$
  - Not observed in photon-production yet
- Decay
  - Observed in $\eta\eta'$, not observed in $\gamma\phi$, more to be found
- LQCD

  PRD 107, 054511(2023), arXiv:2409.14410

$\pi_1(1600)$

- Mass of $\pi_1(1600)$: 1661^{+15}_{-11} MeV.
- Decay channels of $\pi_1(1600)$: $\rho\pi$, $b_1(1235)\pi$, $\eta'\pi$, and $f_1(1285)\pi$.
- Total width of $\pi_1(1600)$: 240 ± 50 MeV.
- The ratio of the branching ratios of the $\pi_1(1600) \to b_1(1235)\pi$ channel in $\ell = 2$ and $\ell = 0$ channels: $\frac{BR(\pi_1 \to b_1\pi)_{\ell=2}}{BR(\pi_1 \to b_1\pi)_{\ell=0}} = 0.3 \pm 0.1$ [7].
- Ratio of the partial widths of $\pi_1(1600)$ decaying into $f_1(1285)\pi$ and $\eta'\pi$: $\frac{\Gamma_{f_1\pi}}{\Gamma_{\eta'\pi}} = 3.80 \pm 0.78$ [8].
- Ratio of the partial widths of $\pi_1(1600)$ decaying into $\eta\pi$ and $\eta'\pi$: $\frac{\Gamma_{\eta'\pi}}{\Gamma_{\eta\pi}} = 5.54 \pm 1.1^{+1.8}_{-0.27}$ [9].
- Mass of $\pi_1(1400)$: 1354 ± 25 MeV.
- Decay channels of $\pi_1(1400)$: $\eta\pi$.
- Total width of $\pi_1(1400)$: 330 ± 35 MeV.

- LQCD

$\Gamma_{\pi_1 \to b_1\pi}$: 139 − 529 MeV, $\Gamma_{\pi_1 \to \eta'\pi}$: 0 − 12 MeV

- Where is $\eta_1^{(\prime)}$?
- How to discriminate hybrid/molecule/tetraquark ?
  - $f_1\eta$, K_1K are important for $\eta_1^{(\prime)}$
  - Production in $J/\psi \to \omega/\phi + \eta_1'$
- Why η' is the observation channel?
  - $U_1(A)$ anomaly?
  - Dominate decay modes not yet been examined
- Analog in $\bar{c}c$?
- How to identify K_1^{hybrid}, hybrid baryon ?

Stay tuned ...

Synergies in new era of precision spectroscopy

- From serendipitous discoveries of new states to the systematic study of spectral properties and patterns
- High statistics → emergence of new properties/phenomena
- Test QCD with various probes

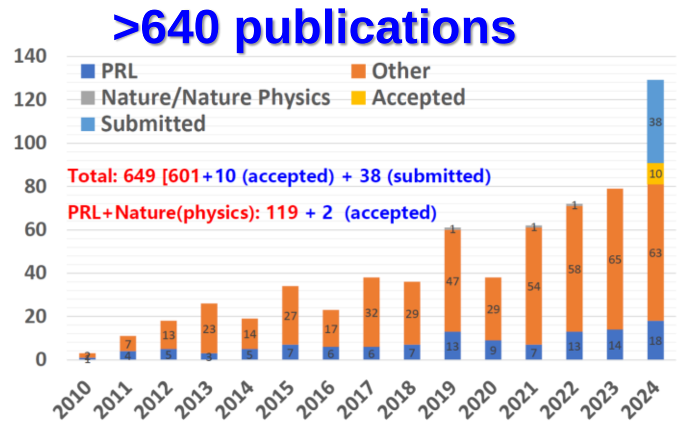
Heavy ⟷ Light

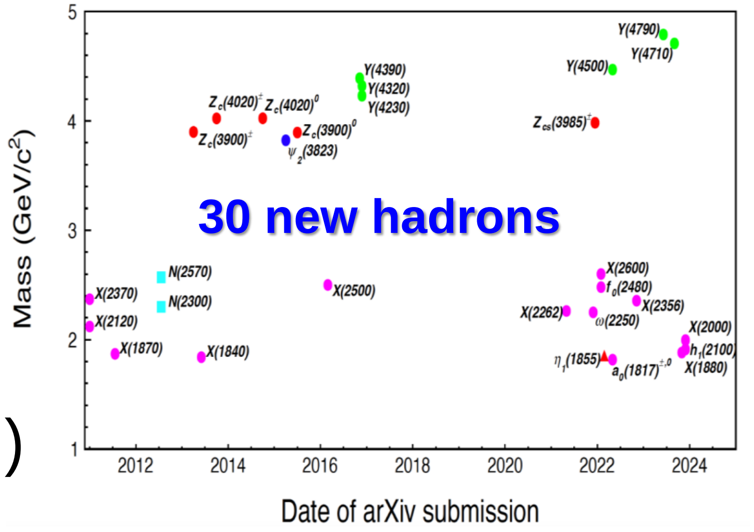
EM probe: e^+e^-: Belle II, BESIII | γp: EIC, GlueX, CLAS12

Hadronic probe: pp: LHCb, CMS, ATLAS | $\bar{p}p$: panda | πp: COMPASS, AMBER

Summary

- Fruitful progress in light QCD exotics at BESIII
- Great potential to be fully explored
  - $50\ \mathrm{fb}^{-1}$ data on disk, including $10 \times 10^9\ J/\psi$ and $2.7 \times 10^9\ \psi'$
  - Running until ~2030
  - Upgrade in this summer
    - $\mathcal{L} \times 3$ @$\sqrt{s}$=4.7 GeV
    - $\sqrt{s} \rightarrow 5.6\ \mathrm{GeV}$, starting from 2028
    - CGEM inner tracker (just finished the installation)
- Close experiment-theory collaboration is essential





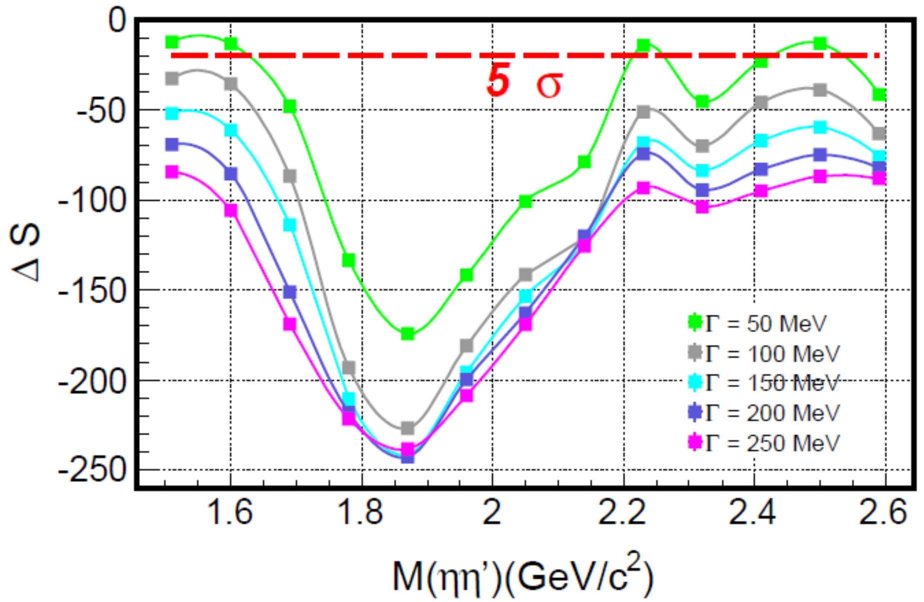
Thank you for your attention

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

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

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

- Significant $f_0(1500)$

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

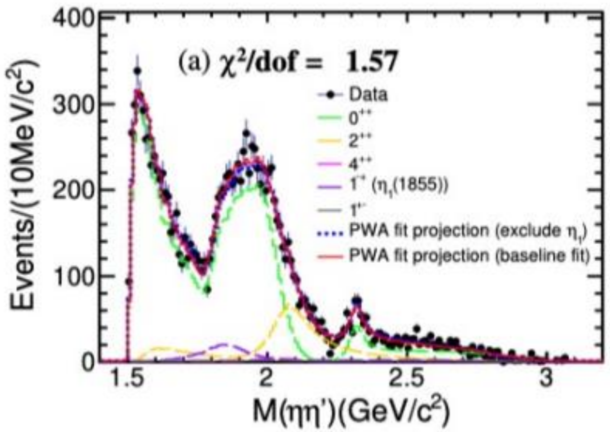
consistent with PDG

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

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

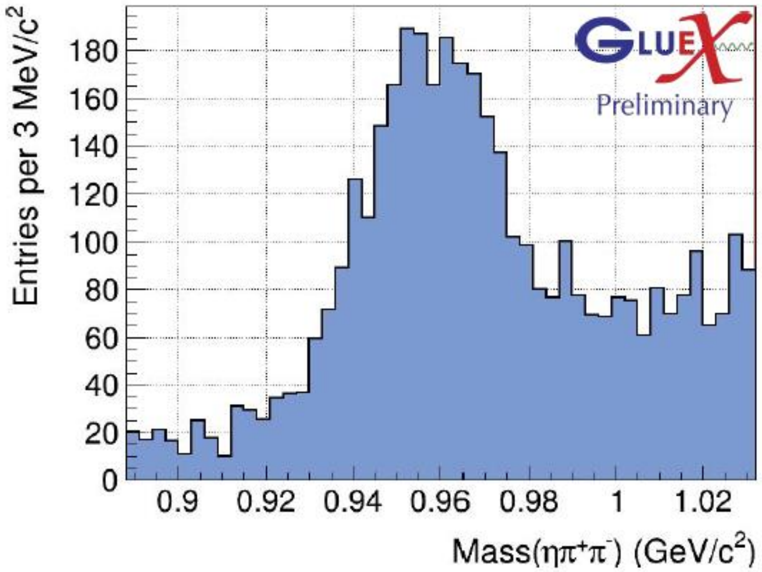
➢Supports to the hypothesis that $f_0(1710)$ overlaps with the ground state scalar glueball

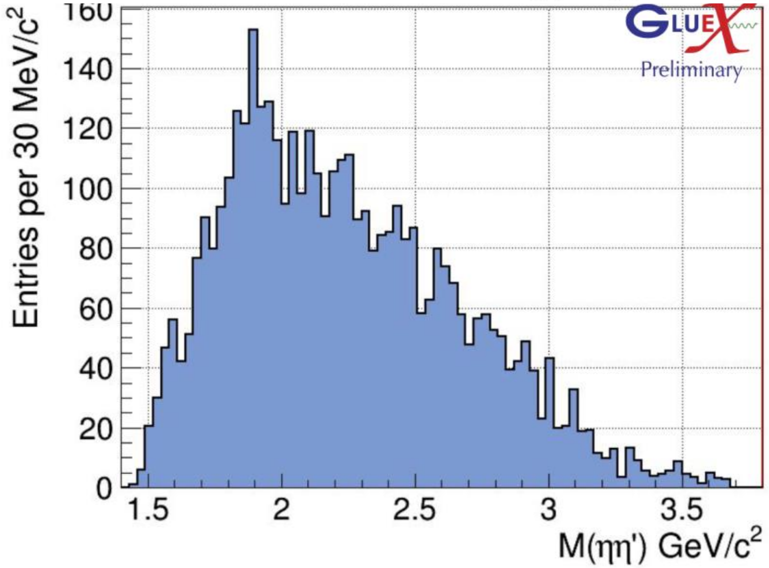
- Scalar glueball expected to be suppressed $B(G\to\eta\eta')/B(G\to\pi\pi) < 0.04$



Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	M_{PDG} (MeV/c^2)	Γ_{PDG} (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi\to\gamma X\to\gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg30\sigma$
	$f_0(1810)$	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

APS DNP October 2022



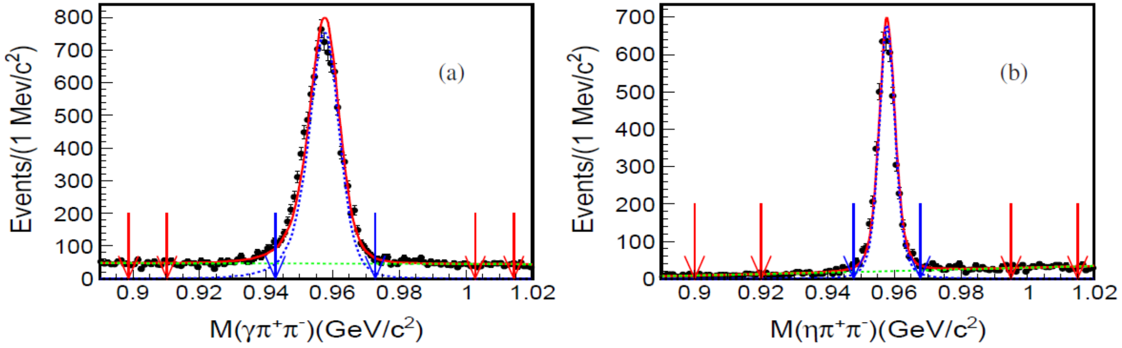


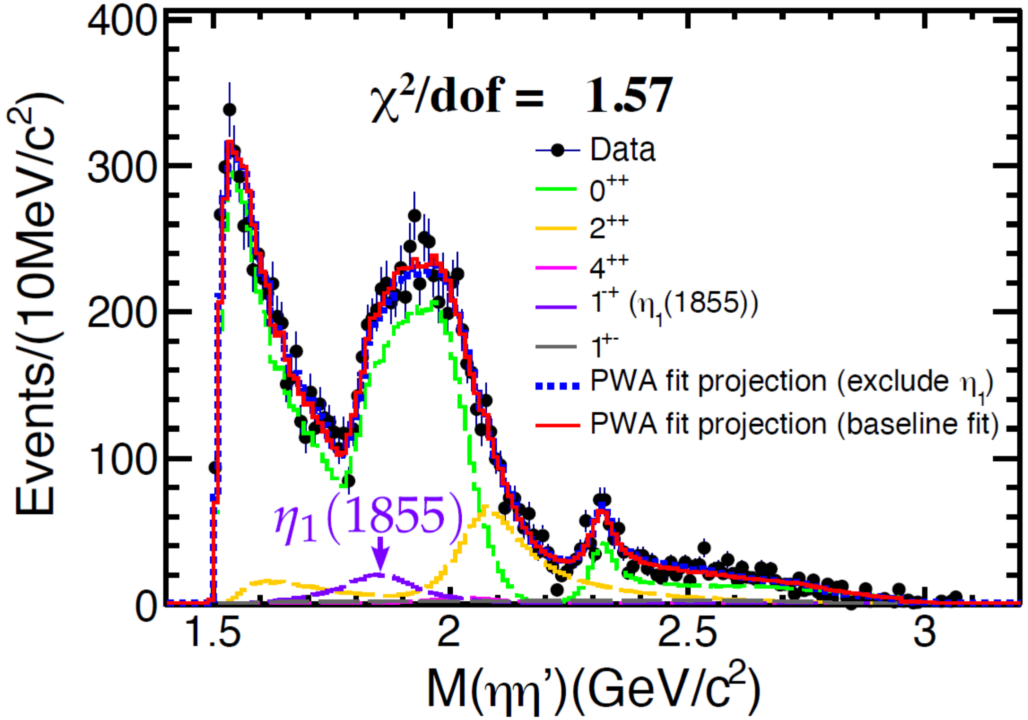
2000 $\eta\eta'$ events

~3 or 4 times increase with GlueX II

In comparison, with 10B J/ψ

~15000 $J/\psi \rightarrow \gamma\eta\eta'$ events





BESIII, PRL **129** (2022) 192002

BESIII, PRD **106** (2022) 072012