Studies of 1^{-+} states at BESIII

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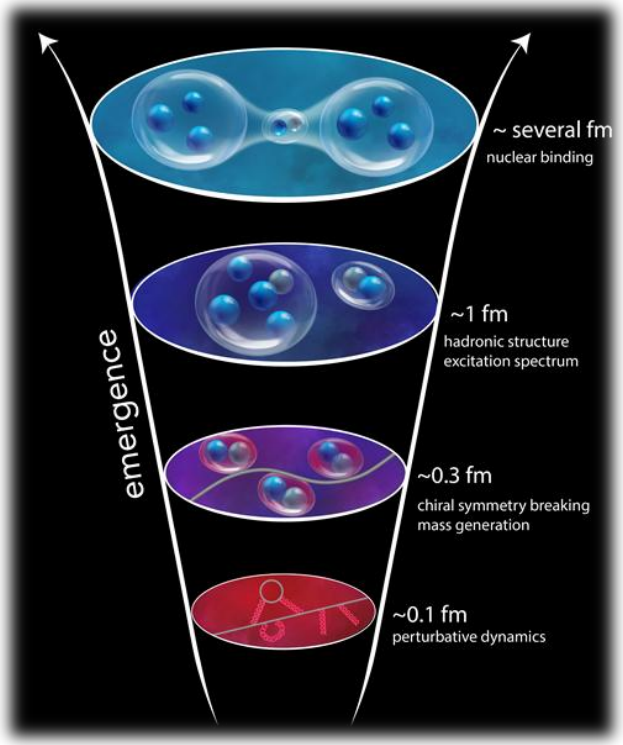
Mysterious gluons

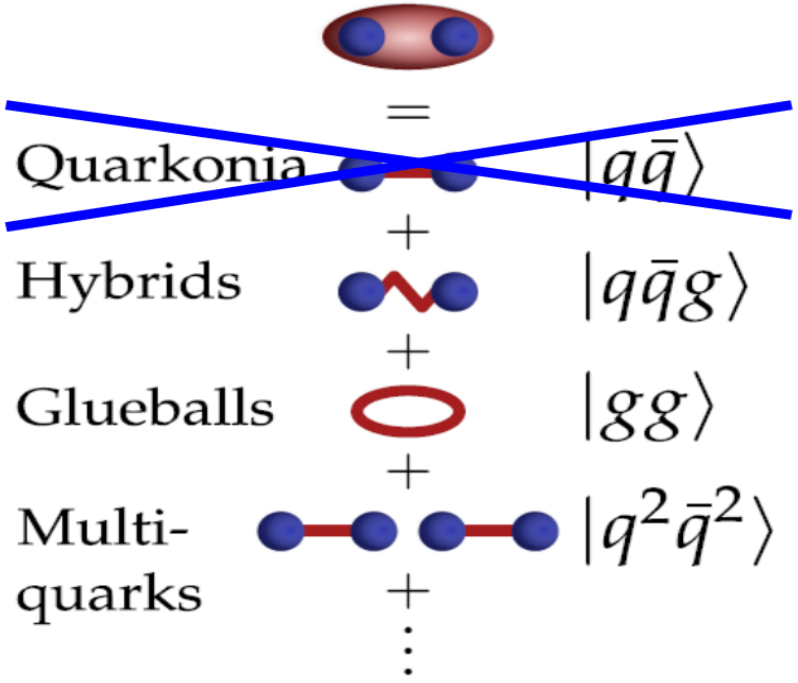
- How does QCD give rise to hadrons?
  - What is the origin of confinement?
  - How is the mass generated in QCD?
- Role of gluons in hadrons
  - How to access soft gluon dynamics
- Key thing to search for: hadrons explicitly manifest the gluonic degrees of freedom
  - Gluonic excitations: Glueballs and hybrids, which provide critical information on the strong force and QCD vacuum



Eur.Phys.J.A 60 (2024) , 173

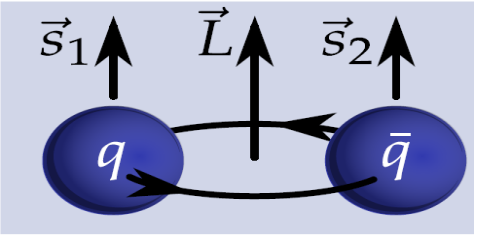
Light hadrons with exotic quantum numbers

- **Finding unambiguous signature for exotics**
  - **Efforts concentrate on Spin-exotic**
    - **Forbidden for $q\bar{q}$:**
      $J^{PC} = 0^{--}, even^{+-}, odd^{-+}$



Experiments:

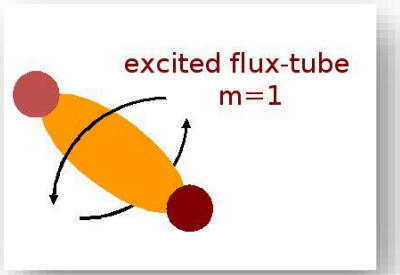
- **Hadroproduction:** GAMS, VES, E852, COMPASS, AMBER
- **$p\bar{p}$ annihilation:** Crystal Barrel, OBELIX, PANDA
- **Photoproduction:** GlueX(2017-), CLAS



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

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

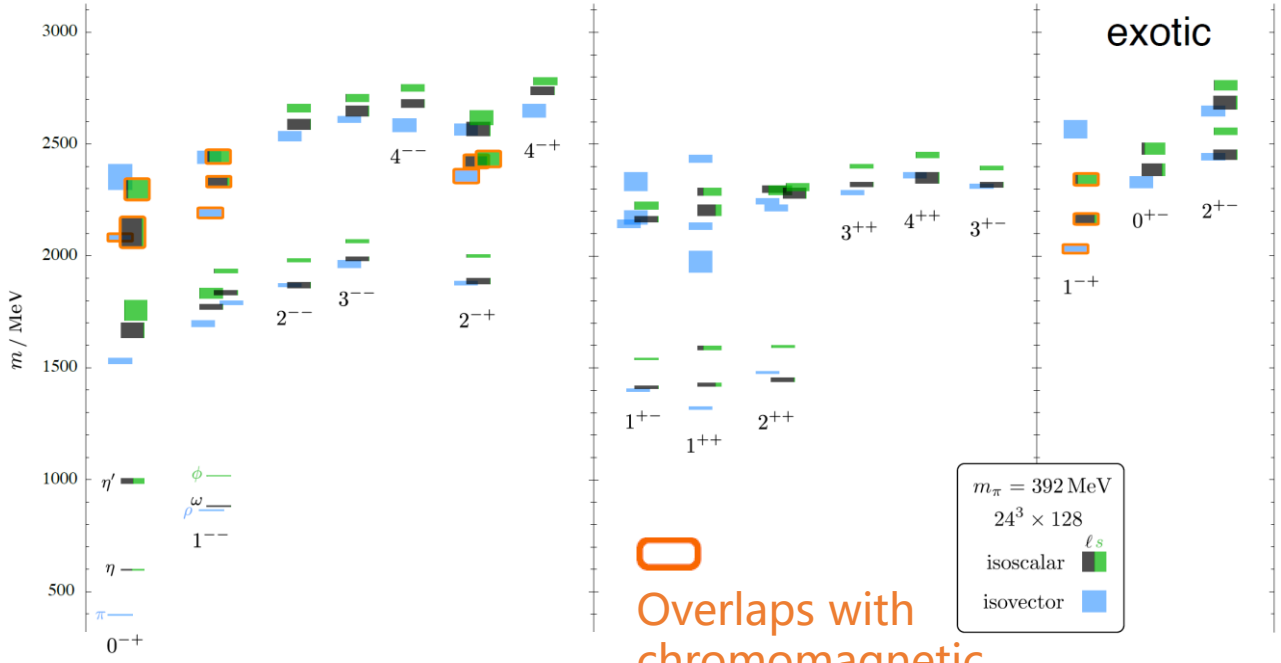
Predictions



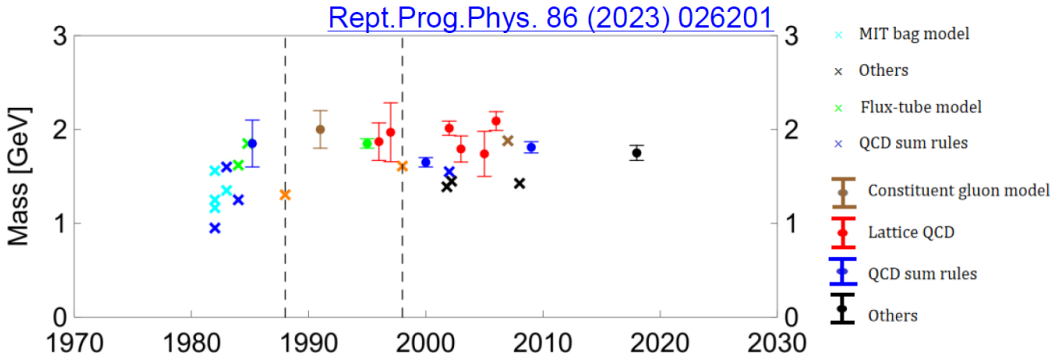
"Constituent gluon"

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

PRD 88 094505(2013)

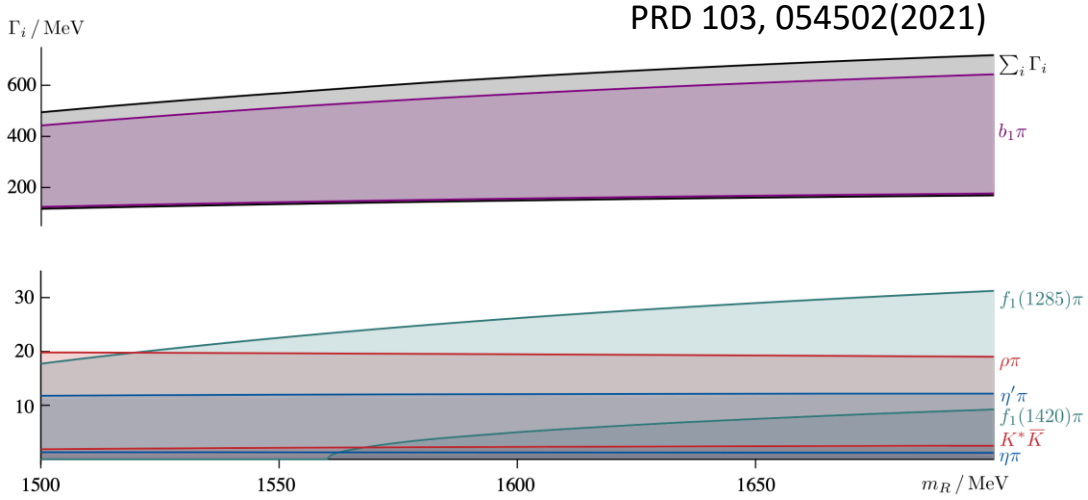


Overlaps with chromomagnetic operators



Mass of 1^{-+} hybrid

PRD 103, 054502(2021)



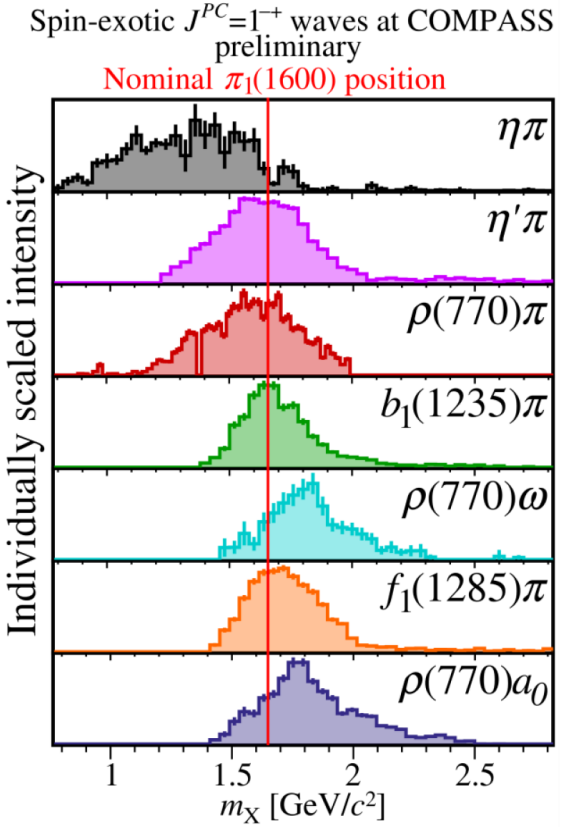
Decay width of 1^{-+} hybrid π_1

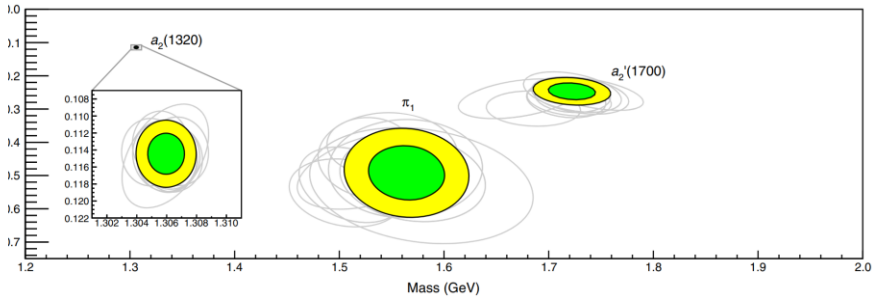
On lattice,

- Meson excitations similar to quark model
- Hybrid supermultiplet: 0^{-+}, 1^{--}, 2^{-+}, 1^{-+}
- Lightest spin-exotic state in LQCD: 1^{-+} hybrid

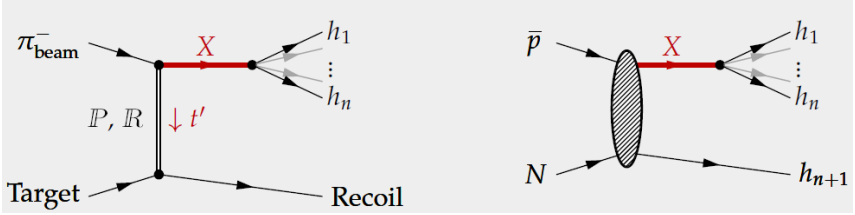
Spin-exotic mesons

- Candidates over 3 decades
  - $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2015)$ (needs confirmation), all isovetors





[PRL 122, 042002 (2019), EPJ C 81, 1056 (2021)]

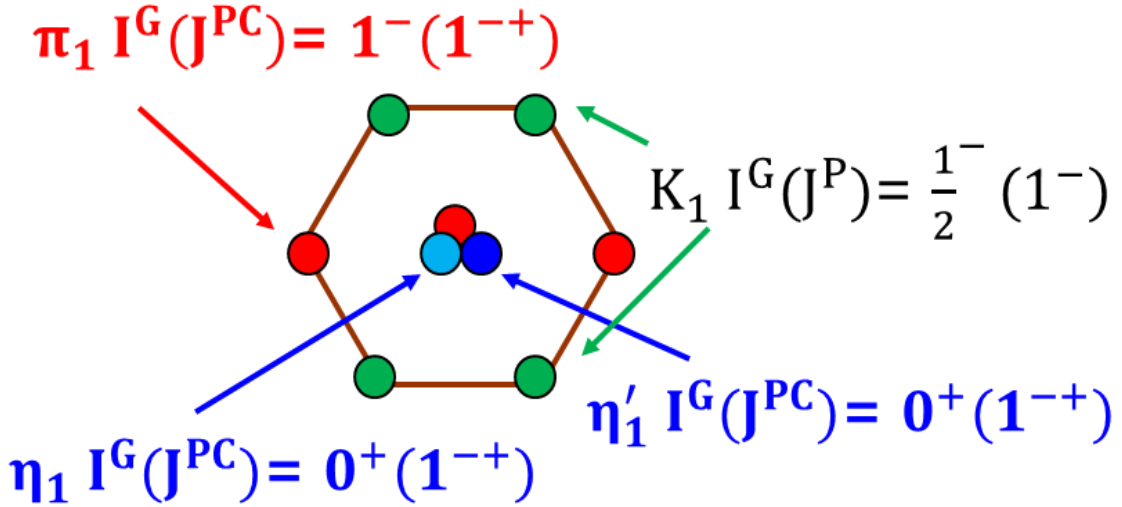


Review: PRC 82, 025208 (2010), PPNP 82, 21 (2015), EPJC 83 (2023) 1125

	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
	$b_1\pi$	$\pi^-Be \to \omega\pi^-\pi^0Be$ $\bar{p}p \to \omega\pi^+\pi^-\pi^0$ $\pi^-p \to \omega\pi^-\pi^0 p$	VES CBAR E852
	$\rho\pi$	$\pi^-Pb \to \pi^+\pi^-\pi^-X$ $\pi^-p \to \pi^+\pi^-\pi^- p$	COMPASS E852
	$f_1\pi$	$\pi^-p \to p\eta\pi^+\pi^-\pi^-$ $\pi^-A \to \eta\pi^+\pi^-\pi^-A$	E852 VES
$\pi_1(2015)$	$f_1\pi$	$\pi^-p \to \omega\pi^-\pi^0 p$	E852
	$b_1\pi$	$\pi^-p \to p\eta\pi^+\pi^-\pi^-$	

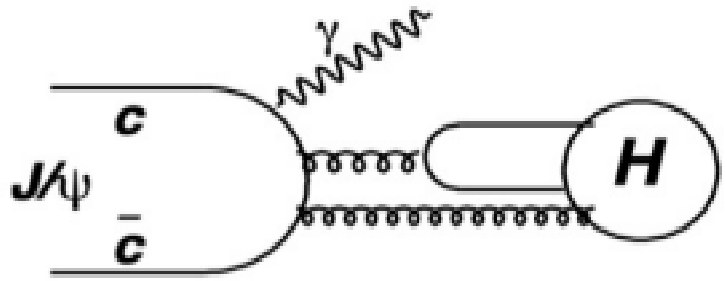
1^{-+} Hybrids

- **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 $J/\psi \to \gamma\eta\eta'$



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

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

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

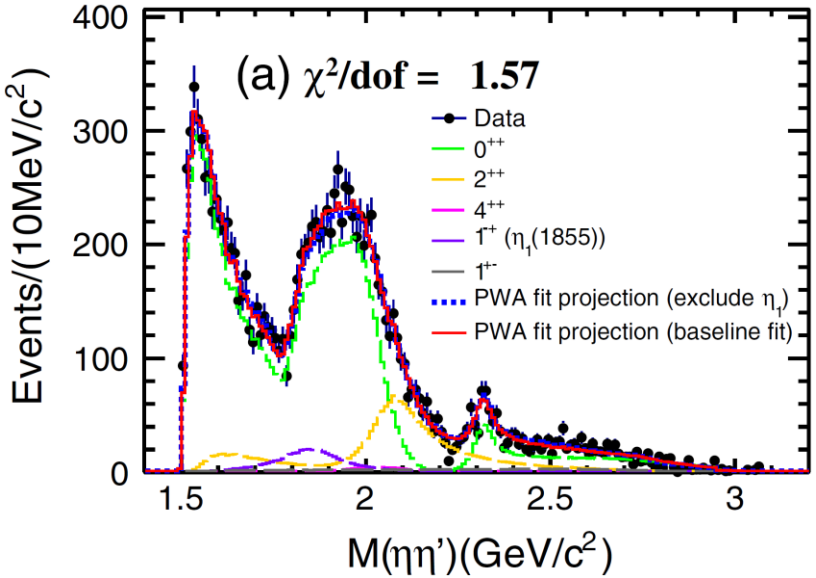
- **An isoscalar 1^{-+} , $\eta_1(1855)$, has been observed in $J/\psi \to \gamma\eta\eta'$ (>19σ)**

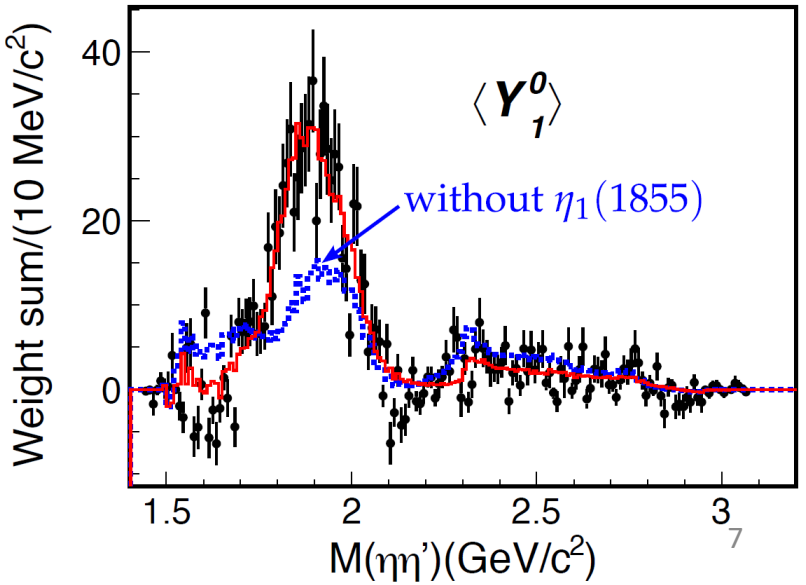
  $M = (1855 \pm 9^{+6}_{-1})\ \mathrm{MeV/c^2}$, $\Gamma = (188 \pm 18^{+3}_{-8})\ \mathrm{MeV/c^2}$

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

  - **Mass consistent with hybrid on LQCD**

- **$\eta\eta'$ in P-waves uniquely indicates 1^{-+} exotic quantum numbers**





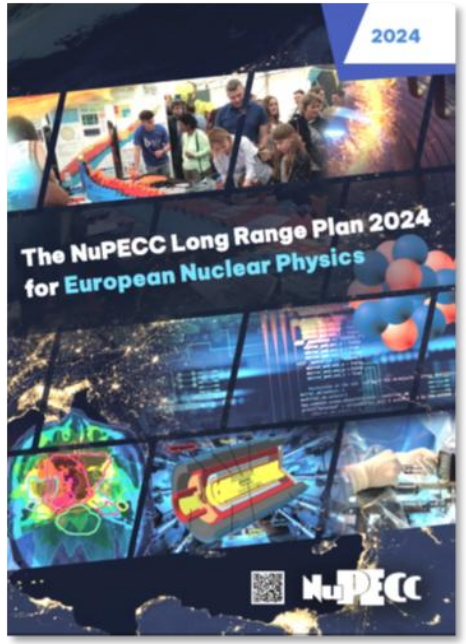
Observation of An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$

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

- Inspired many interpretations: Hybrid/$K\bar{K}_1$Molecule/Tetraquark?

  NPA 1047 122874(2024); Rept.Prog.Phys. 86 (2023) 026201; PRD 107 (2023) 7, 074028; SCPMA 65 (2022) 6, 261011; CPC 46 , 051001(2022); CPL 39, 051201 (2022); PLB 834, 137478(2022); PRD 106 , 074003(2022); PRD 106, 036005(2022) ;...

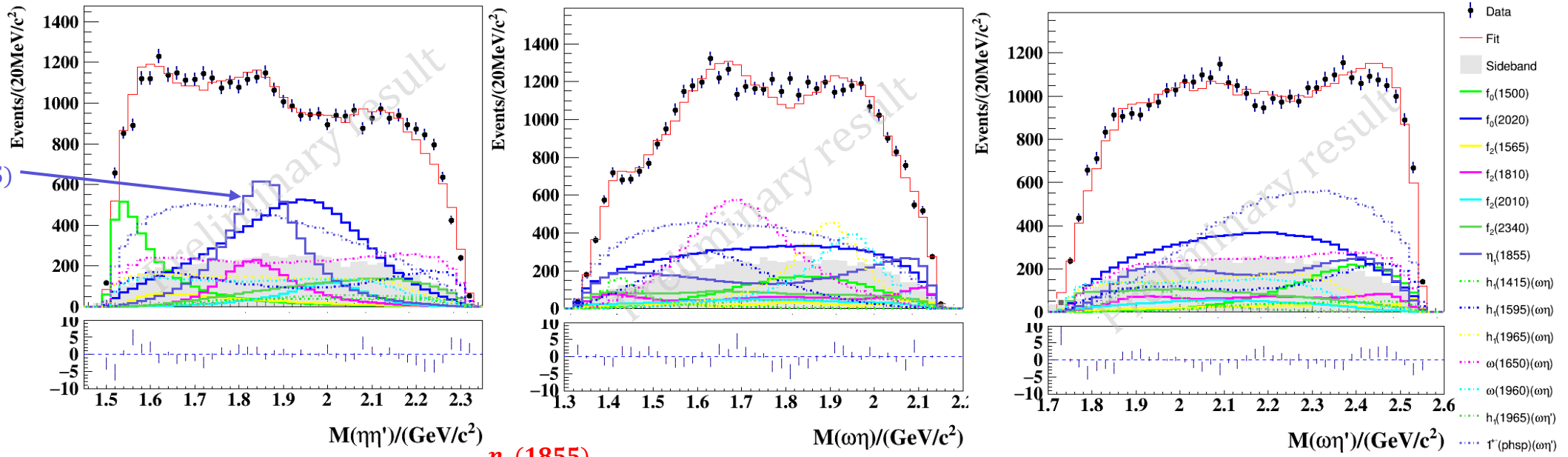
- Opens a new direction to completing the picture of spin-exotics
  - As a "recent achievements and highlights" in hadron spectroscopy in the NuPECC LRP
  - 50 years of QCD: Exotic mesons, "observation of an $\eta_1(1855)$ state could be a breakthrough" [EPJ.C 83 (2023) 1125]



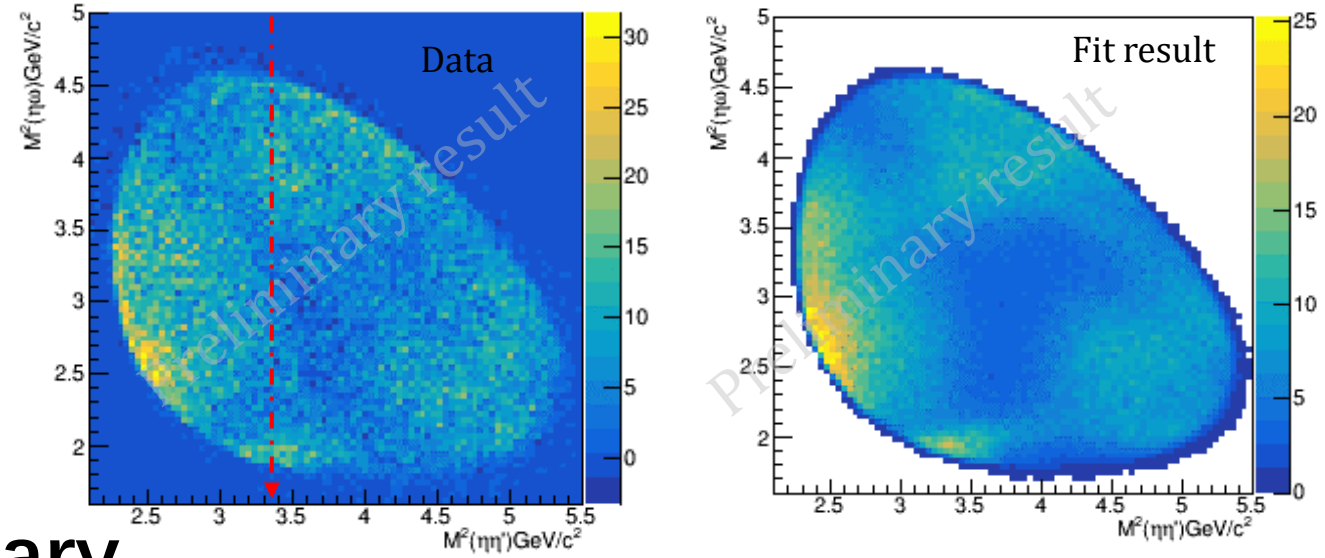
PWA results of $J/\psi \to \omega\eta\eta'$

NEW

$\eta_1(1855)$



$\eta_1(1855)$



BESIII Preliminary

PWA results of $J/\psi \to \omega\eta\eta'$

NEW

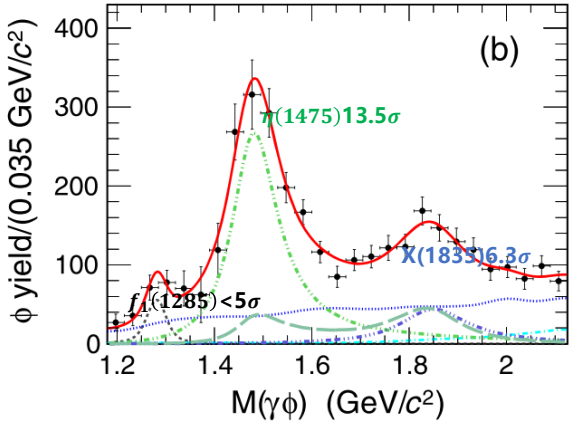
Resonance	J^{PC}	Decay mode	Sig.(σ)	Br
$f_0(1500)$	0^{++}	$\eta\eta'$	14.5	$(4.40 \pm 0.08^{+2.89}_{-2.21}) \times 10^{-5}$
$f_0(2020)$	0^{++}	$\eta\eta'$	21.4	$(2.01 \pm 0.02^{+0.47}_{-1.07}) \times 10^{-4}$
$f_2(1565)$	2^{++}	$\eta\eta'$	8.6	$(1.71 \pm 0.05^{+0.90}_{-0.77}) \times 10^{-5}$
$f_2(1810)$	2^{++}	$\eta\eta'$	12.4	$(4.03 \pm 0.08^{+3.84}_{-0.96}) \times 10^{-5}$
$f_2(2010)$	2^{++}	$\eta\eta'$	6.1	$(2.34 \pm 0.06^{+3.69}_{-1.33}) \times 10^{-5}$
$f_2(2340)$	2^{++}	$\eta\eta'$	8.4	$(5.32 \pm 0.10^{+2.20}_{-2.98}) \times 10^{-5}$
$\eta_1(1855)$	1^{-+}	$\eta\eta'$	23.7	$\left(1.15 \pm 0.01^{+0.10}_{-0.45}\right) \times 10^{-4}$
$h_1(1415)$	1^{+-}	$\omega\eta$	16.7	$(2.09 \pm 0.06^{+0.60}_{-0.72}) \times 10^{-5}$
$h_1(1595)$	1^{+-}	$\omega\eta$	16.3	$\left(7.28 \pm 0.10^{+5.93}_{-3.16}\right) \times 10^{-5}$
$h_1(1965)$	1^{+-}	$\omega\eta$	19.7	$\left(7.43 \pm 0.10^{+1.52}_{-3.13}\right) \times 10^{-5}$
$\omega(1650)$	1^{--}	$\omega\eta$	18.8	$(1.59 \pm 0.02^{+0.34}_{-0.27}) \times 10^{-4}$
$\omega(1960)$	1^{--}	$\omega\eta$	20.0	$(7.48 \pm 0.11^{+1.43}_{-2.78}) \times 10^{-5}$
$h_1(1965)$	1^{+-}	$\omega\eta'$	14.6	$(2.27 \pm 0.06^{+1.04}_{-0.37}) \times 10^{-5}$
$1^{+-}(phsp)$	1^{+-}	$\omega\eta'$	16.6	$\left(2.15 \pm 0.02^{+0.35}_{-0.82}\right) \times 10^{-4}$

BESIII Preliminary

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

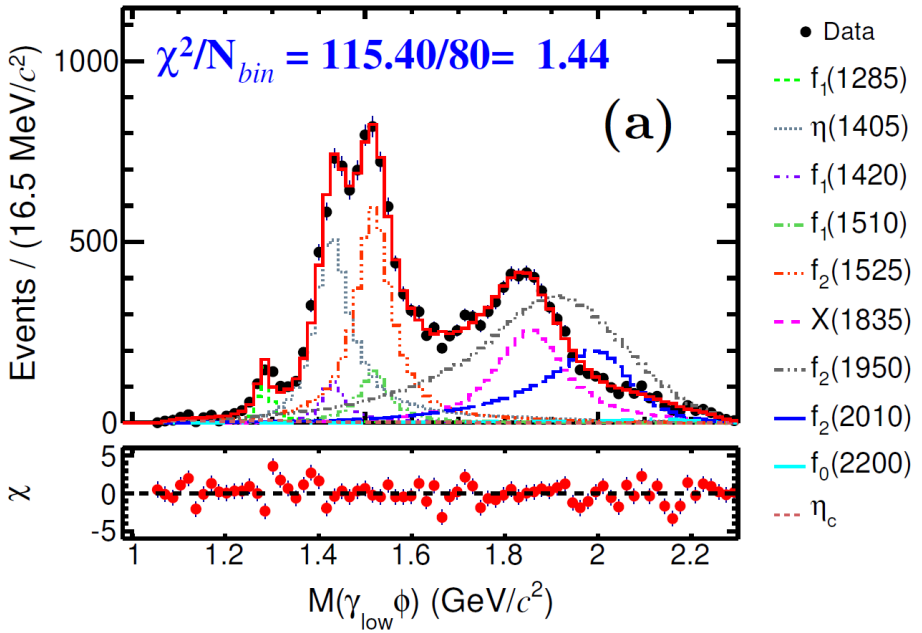
BESIII PhysRevD.111.052011(2025)

PR D97 051101 (2018)



Amplitude analysis with ML techniques for background subtraction

←Fit to mass spectrum

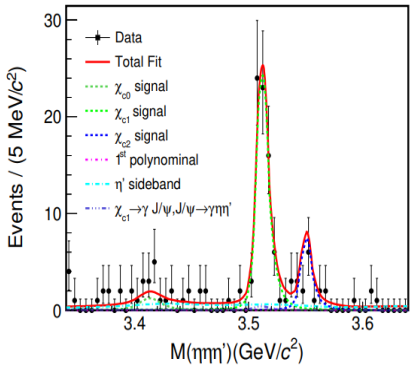


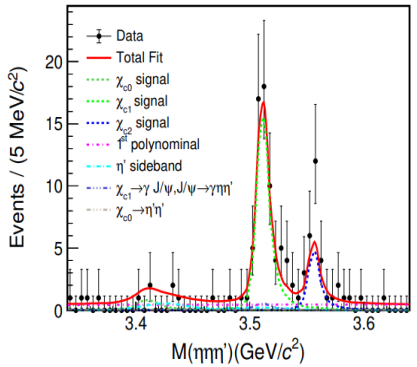
From the amplitude analysis,

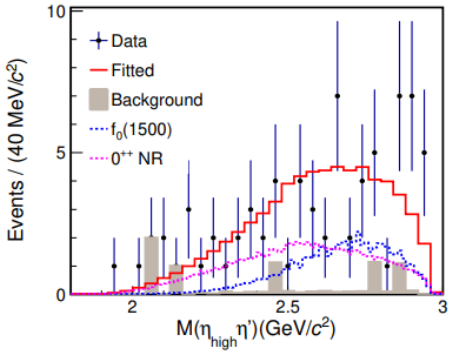
- $\eta(1405)$ is observed, while $\eta(1475)$ can not be excluded
- $X(1835) \to \gamma\phi$ suggests its assignment of η' excitation
- $\eta_c \to \gamma\phi$ are observed. The very first radiative decay mode of η_c
- Observation of $f_2(1950)$ and $f_0(2200) \to \gamma\phi$ unfavored their glueball interpretations [PRD 108, 014023, Sci.China Phys.Mech.Astron. 67 (2024) 11, 111012]
- **No evidence of $X(2370)/\eta_1(1855)$, well consistent with the predictions for glueball/hybrid** [PRD 107, 114020, NPA 1037, 122683]

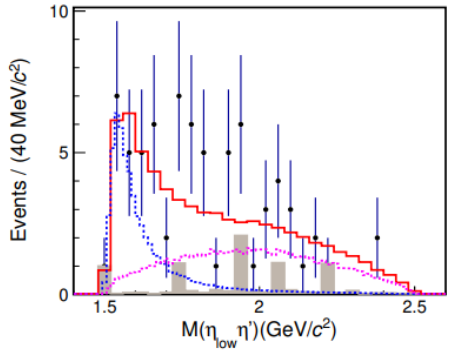
Search for η_1 in $\chi_{c1} \to \eta\eta\eta'$

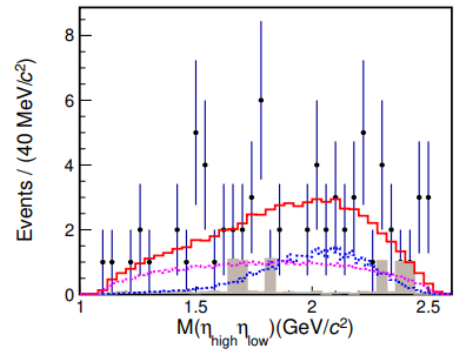
BESIII CPC 49, 10 (2025)

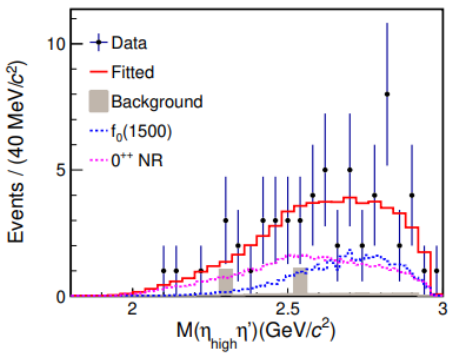


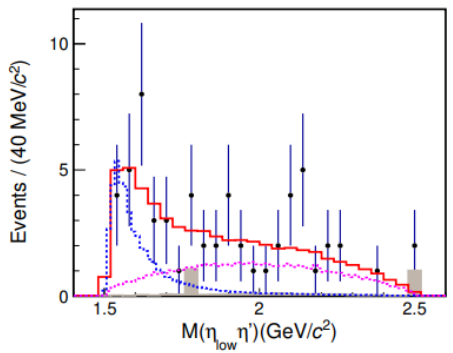


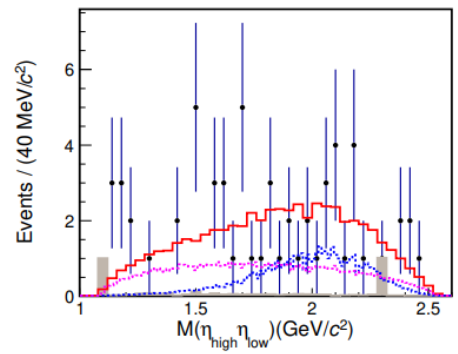












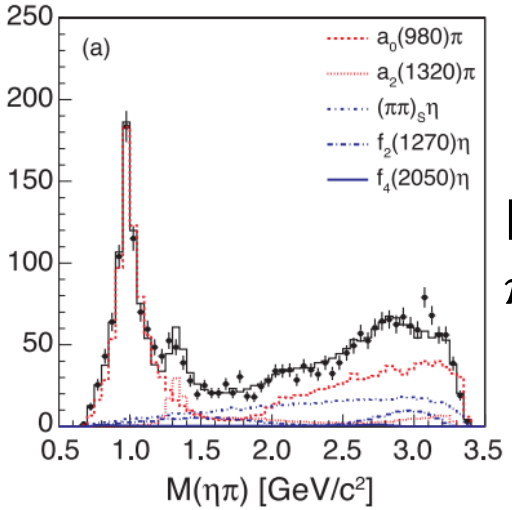
$$\mathcal{B}(\chi_{c1} \to \eta\eta\eta') = (1.39 \pm 0.13(\text{stat.}) \pm 0.09(\text{sys.})) \times 10^{-4}$$

$$\mathcal{B}(\chi_{c1} \to \eta_1(1855)\eta) \cdot \mathcal{B}(\eta_1(1855) \to \eta\eta') < 9.79 \times 10^{-5}$$

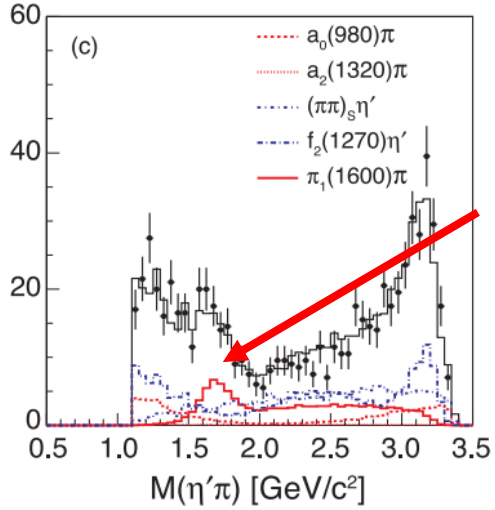
Studies of π_1 in $\chi_{c1} \to \pi^+\pi^-\eta^{(\prime)}$

PR D84 112009 (2011)

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



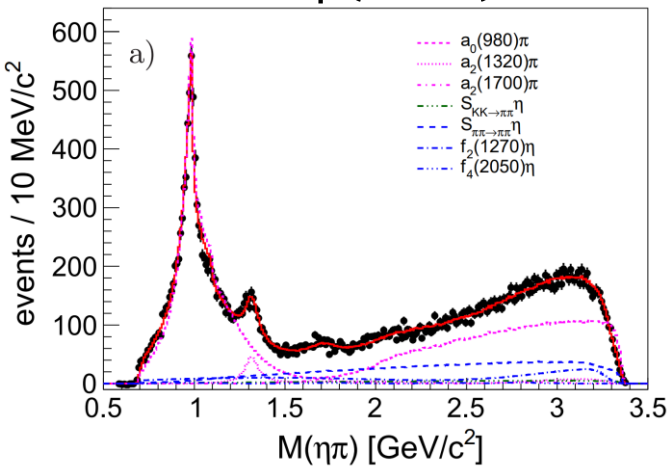
No evidence of $\pi_1 \to \eta\pi$



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

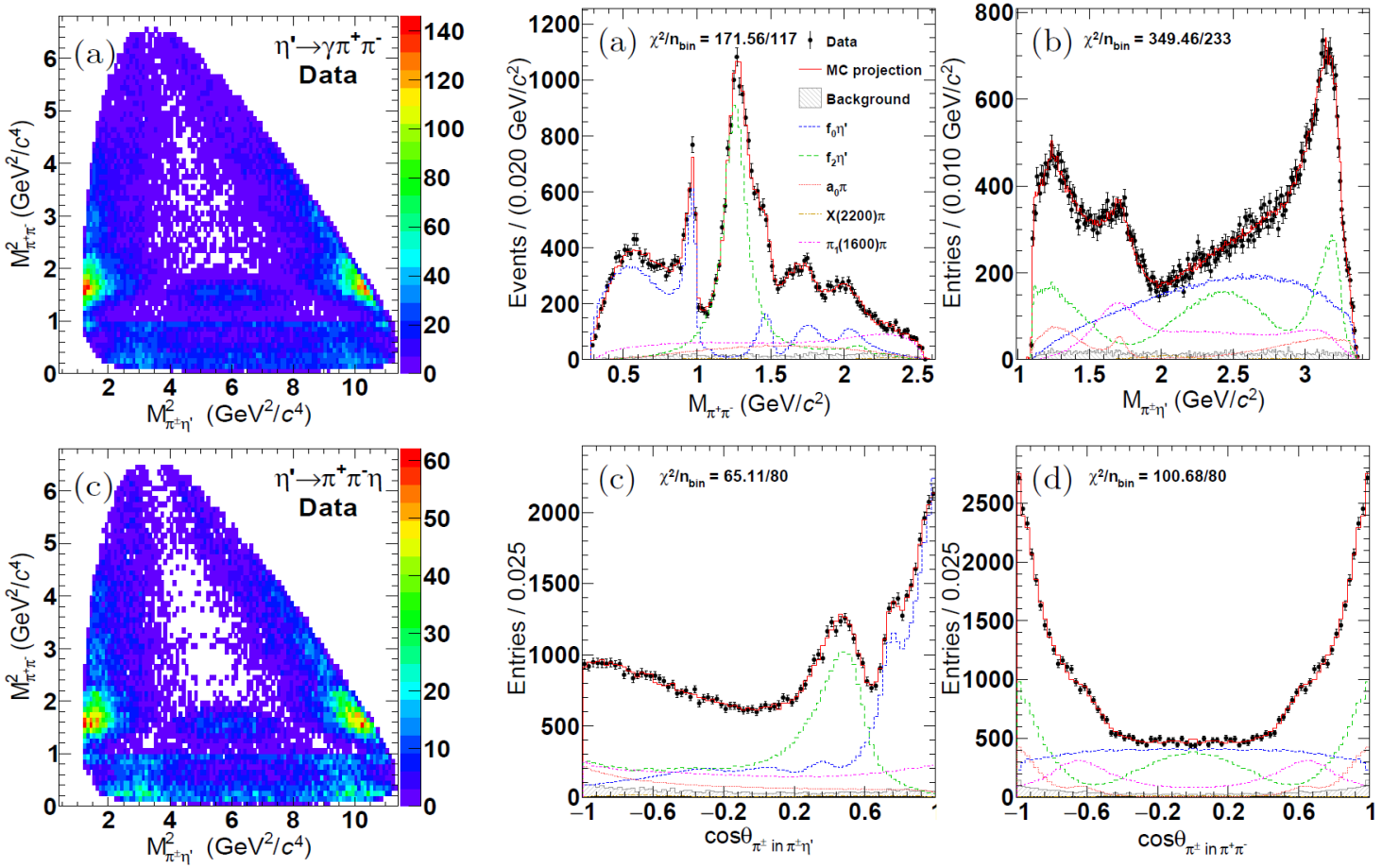
PR D95 032002(2017)

44.8×10^7 $\psi(3686)$@BESIII



NEW arXiv:2604.12524

Observation of π_1 in $\chi_{c1} \to \pi^+\pi^-\eta'$



- $\pi_1(1600)$ **observed>21**σ
- **with a significant BW phase motion > 11**σ
- $\mathbf{J^{PC}= 1^{-+}}$**, better than other assignments > 17**σ

BW with mass-dependent width

$$M = (1828 \pm 8^{+11}_{-33})\ \mathrm{MeV/c^2},$$
$$\Gamma = \left(638 \pm 26^{+35}_{-86}\right)\ \mathrm{MeV/c^2}$$
$$\mathrm{B}\left[\chi_{c1} \to \pi_1(1600)^{\pm}\pi^{\mp}\right] \times B\left[\pi_1(1600)^{\pm} \to \pi^{\pm}\eta'\right] = (4.30 \pm 0.14^{+1.04}_{-1.03}) \times 10^{-4}$$

$\mathbf{pole}: \left(\mathbf{1690 \pm 16^{+36}_{-44}}\right) - \mathbf{i}(\mathbf{217 \pm 5^{+7}_{-19}})\mathbf{MeV}$

BW with constant width

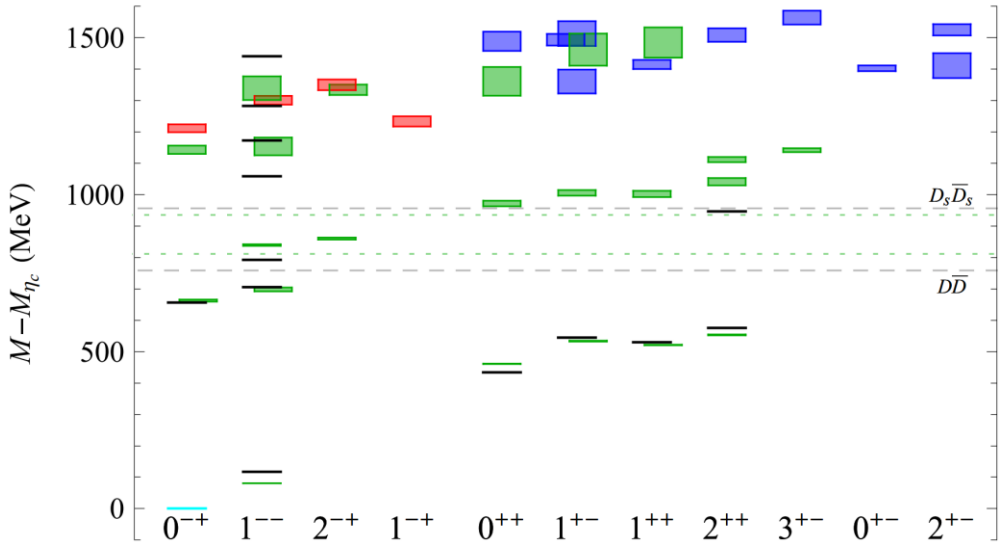
$$M = (1675 \pm 9^{+32}_{-32})\ \mathrm{MeV/c^2},$$
$$\Gamma = \left(443 \pm 15^{+18}_{-56}\right)\ \mathrm{MeV/c^2}$$
$$\mathrm{B}\left[\chi_{c1} \to \pi_1(1600)^{\pm}\pi^{\mp}\right] \times B\left[\pi_1(1600)^{\pm} \to \pi^{\pm}\eta'\right] = (4.27 \pm 0.14^{+0.86}_{-1.32}) \times 10^{-4}$$

$\mathbf{pole}: \left(\mathbf{1689 \pm 10^{+33}_{-35}}\right) - \mathbf{i}(\mathbf{220 \pm 7^{+9}_{-27}})\mathbf{MeV}$

- **Pole position is consistent with CLEO-c, COMPASS and JPAC**

$\bar{c}cg$ hybrids

LQCD predicts similar supermultiplet as light hybrids



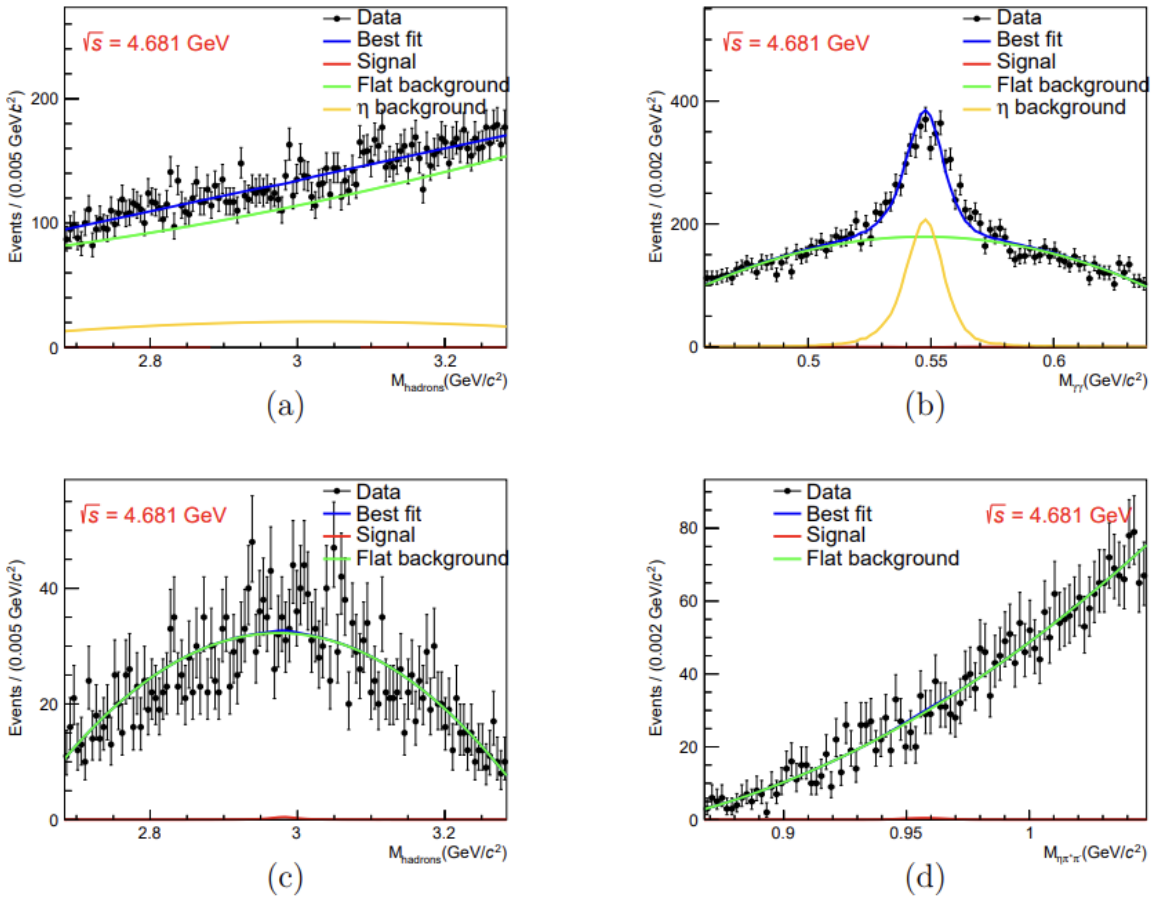
JHEP 07 (2012), 126

- Y(4230)?
  - Seem to be contradicting with the exp. observation: $\sigma(D^*\bar{D}+c.c.) \gg \sigma(D^*\bar{D}^*)$
- Transitions between 1^{--} and $\{0,1,2\}^{-+}$
- Molecule states of 1^{-+} and 1^{--} ?

Further studied at BESIII and Belle II

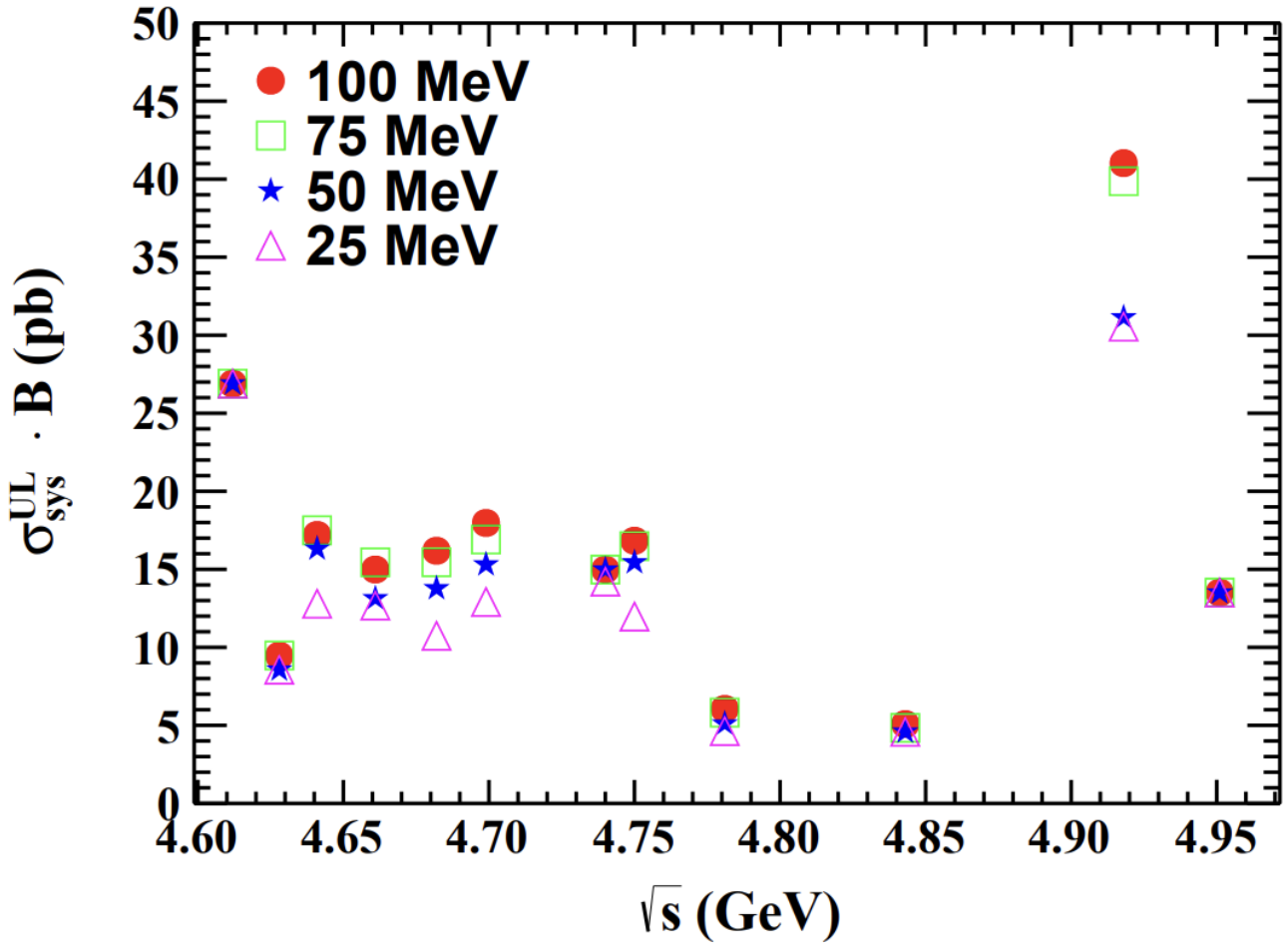
Search for 1^{-+} charmonium-like hybrid via $e^+e^- \to \gamma\eta^{(\prime)}\eta_c$ at center-of-mass energies between 4.258 and 4.681 GeV

BESIII PR D 111, 112007 (2025)



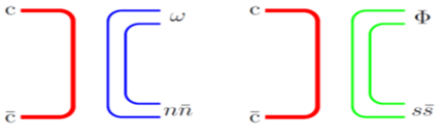
Search for a 1^{-+} molecular state via $e^+e^- \to \gamma D_s^+ D_{s1}^-(2536) + c.c.$

BESIII PRD 112, 032002(2025)

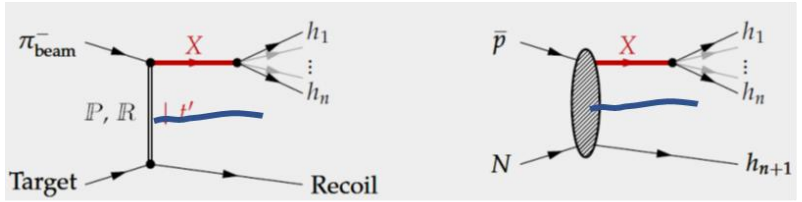


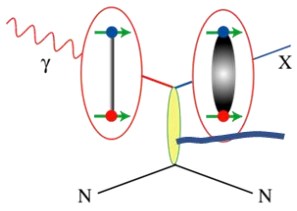
1^{-+} Hybrids

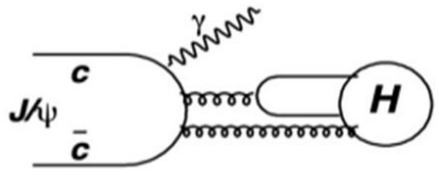
- How to discriminate hybrid/molecule/tetraquark?
  - $\eta_1(1855) \to f_1\eta$, K_1K are important
  - $\Gamma_{\pi_1\to b_1\pi}/\Gamma_{\pi_1\to\eta'\pi}$ is not available yet
- Where is the $\boldsymbol{\eta_1^{(\prime)}}$? $J/\psi \to \omega\eta\eta'$, $\phi\eta\eta'$ to access quark contents



- Why η' is the observation channel for $\boldsymbol{\pi_1(1600)}$ and $\boldsymbol{\eta_1(1855)}$? $U_1(A)$ anomaly?
- Does $\boldsymbol{K_1}$ exist and how to identify it?
- Where are the other $J^{PC} = (0^{--},)\text{even}^{+-}, \text{odd}^{-+}$ states? Analog in $\bar{c}c$ exists?
- New results from COMPASS, AMBER, BESIII, GlueX and PANDA are eagerly awaited. **Stay tuned**







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

Thank you

backup

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:

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

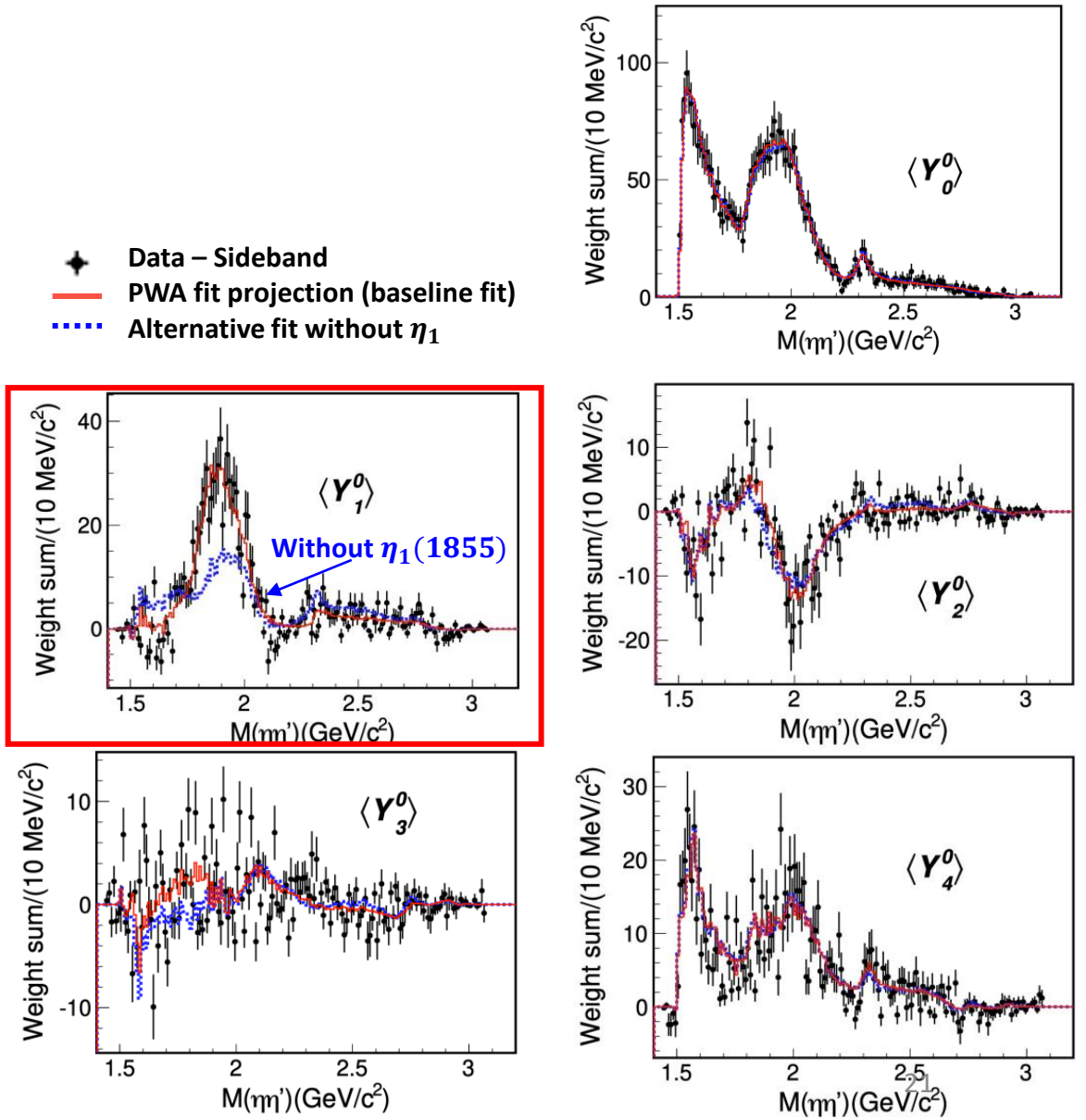
$$\sqrt{4\pi}\langle Y_1^0\rangle = 2S_0P_0\cos\phi_{P_0} + \frac{2}{\sqrt{5}}(2P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) + \sqrt{3}P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

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

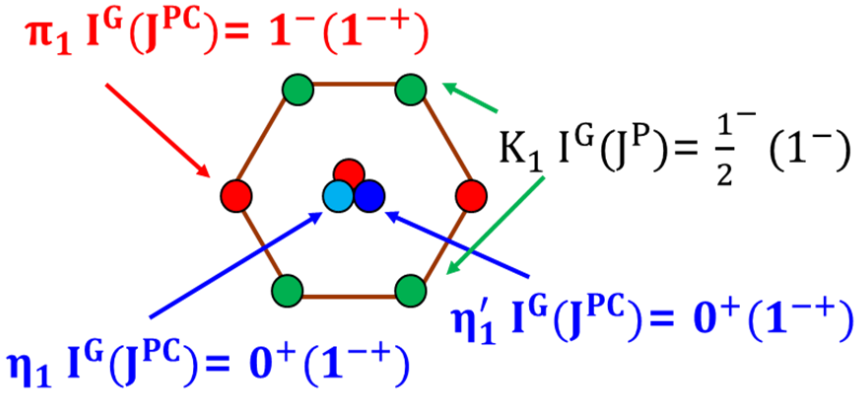
$$\sqrt{4\pi}\langle Y_3^0\rangle = \frac{6}{\sqrt{35}}(\sqrt{3}P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) - P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

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

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



What about K_1 ?



Exotic Kaons are difficult to be established,
because they do not have exotic quantum numbers

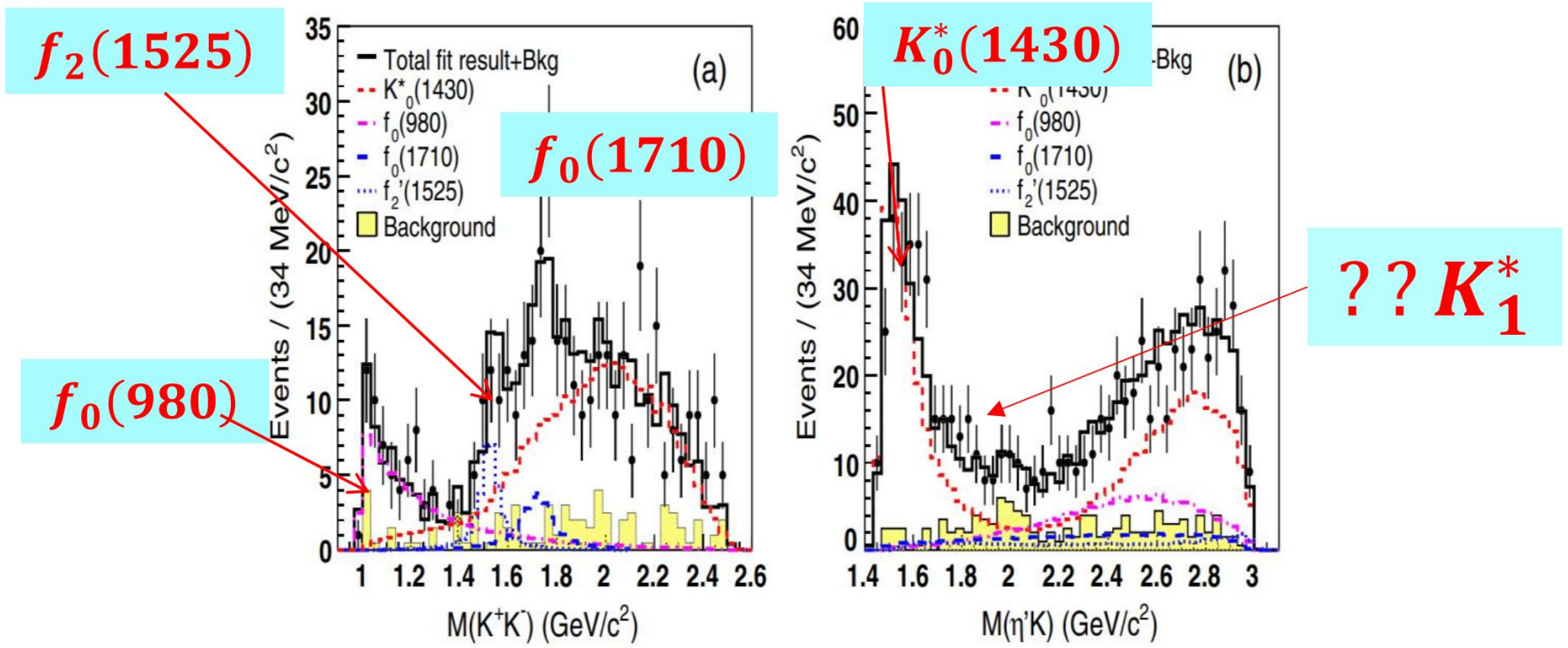
Decay property is the key

- $K_1(1270)$
- $K_1(1400)$
- $K^*(1410)$
- $K_0^*(1430)$
- $K_2^*(1430)$
- $K(1460)$
  $K_2(1580)$
  $K(1630)$
- $K_1(1650)$
- $K^*(1680)$
- $K_2(1770)$
- $K_3^*(1780)$
- $K_2(1820)$
  $K(1830)$
- $K_0^*(1950)$
- $K_2^*(1980)$

$\chi_{c1} \to K^+K^-\eta'$

PWA with 106 million $\psi(3686)$

PhysRevD.89.074030



Now, BESIII has 2.7 billion $\psi(3686)$. An updated analysis is underworking