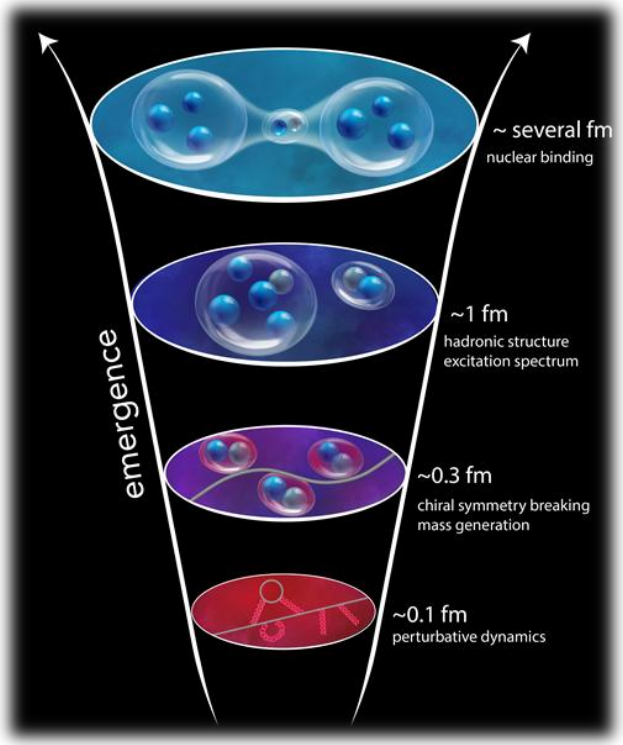
Light QCD exotics at BESIII

Beijiang Liu
Institute of High Energy Physics, Chinese Academy of Sciences

ECT* workshop: Glueballs and Charmonium: Lattice QCD, Experiment and Phenomenology
March 2-6, 2026

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

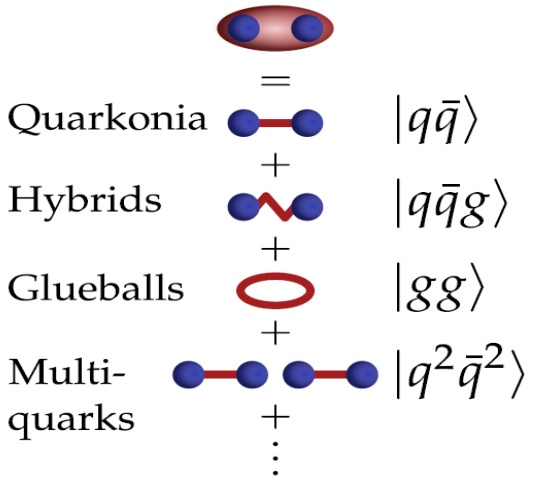


Eur.Phys.J.A 60 (2024) , 173

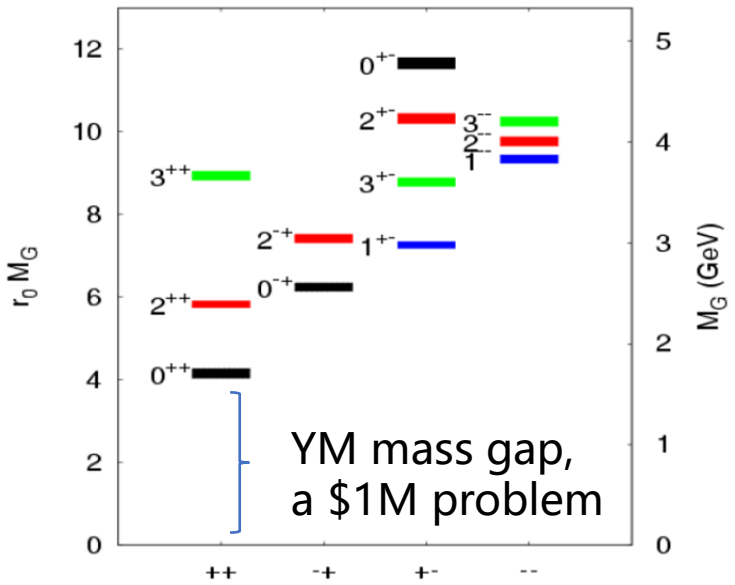
Glueballs

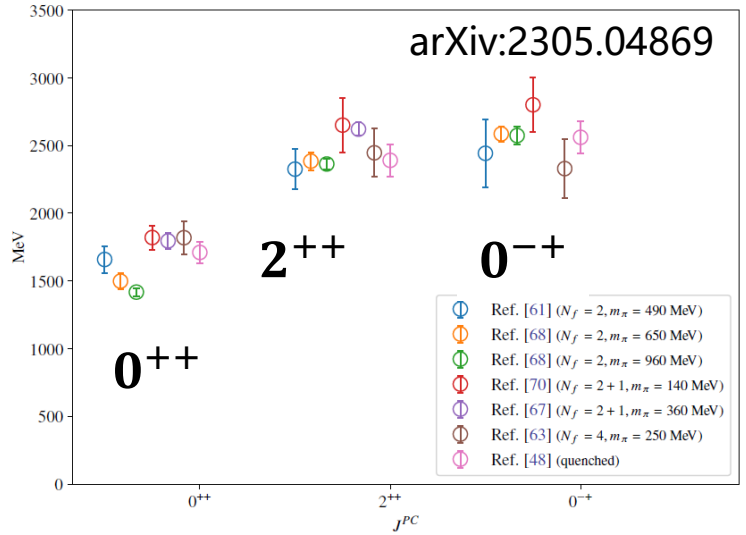
- Glueballs are the most direct prediction of QCD
  - Color singlets emerge as a consequence of the gluon self-interactions
  - Unique particles formed by gauge bosons (force)
  - Essential for understanding of confinement and mass dynamical generation
- Theoretical predictions from lattice QCD and QCD-inspired models mostly consistent
  - Light-mass glueballs: $J^{PC} = 0^{++}, 2^{++}, 0^{-+}$

non-$\mathbf{q\bar{q}}$ nature with ordinary quantum numbers is difficult to establish



PRD 73 014516 (2006)



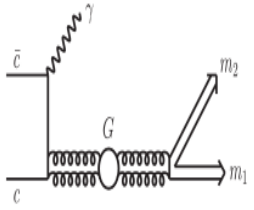


Yang-Mills glueballs on lattice (quenched and unquenched)

Glueball hunting for over 40 years

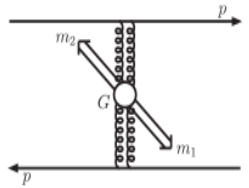
- **Supernumerary states** w.r.t. quark model
  - A priori, mixed with nearby $\mathbf{q\bar{q}}$
  - Assignment of some $q\bar{q}$ multiplets is difficult
- Detailed and accurate information about couplings to production and decay channels is required
- Strongly produced in **gluon-rich processes**
- Decay: **gluon is flavor-blind**
  - $SU(3)_{flavor}$ symmetry expected, but differing quark masses leads exceptions
  - No rigorous predictions on decay patterns
  - Could be analogy to **OZI suppressed** decays of charmonium, as they all decay via gluons [PLB 380 189(1996), Commu. Theor. Phys. 24.373(1995)]

gluon-rich processes [Phys. Rept. 454 1]



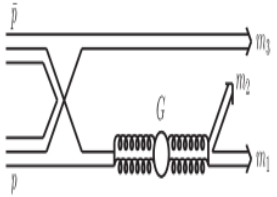
Charmonium decays:

BESIII, MRKIII…



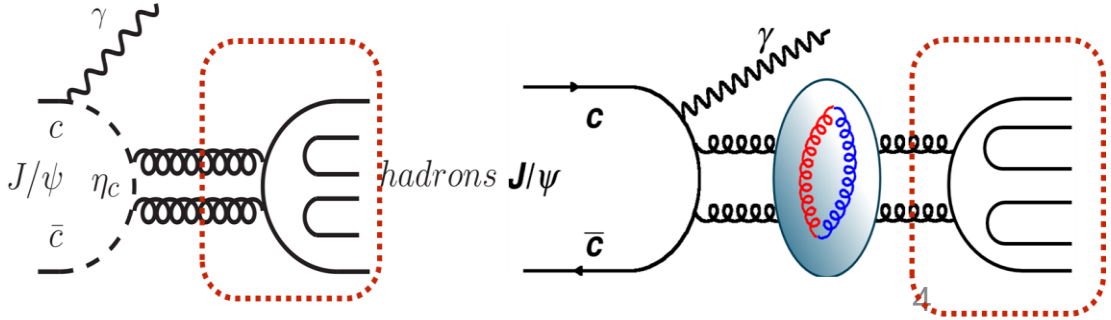
pp double-Pomeron exchange:

WA102, GAMS…



$p\bar{p}$ annihilation:

Crystal barrel, OBELIX…



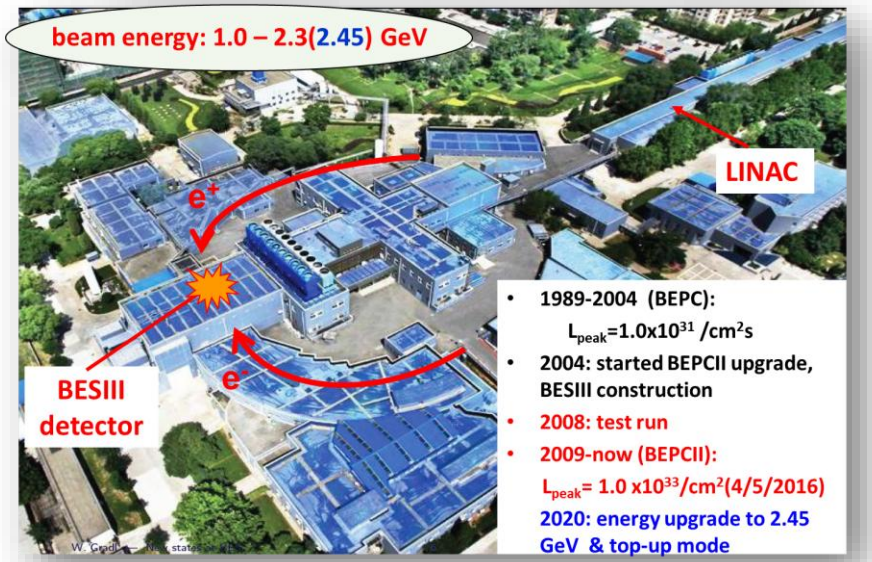
Some glueball candidates in the past

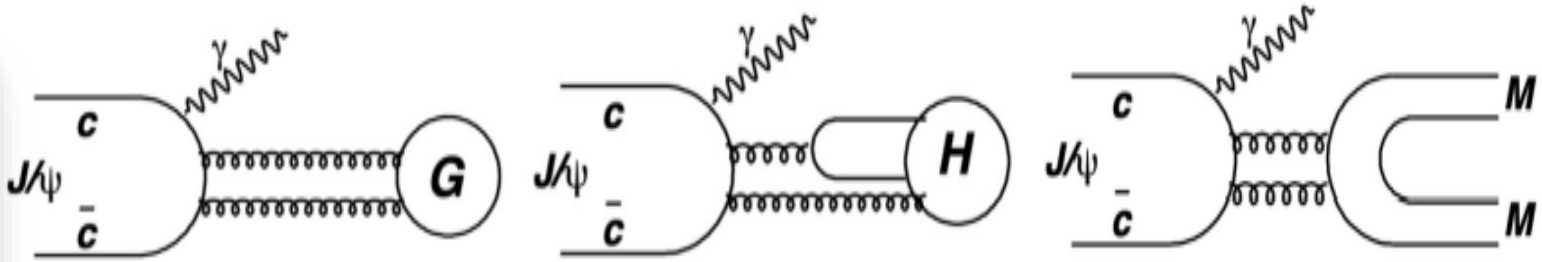
- The first glueball candidate, $\iota(1440)$, observed in J/ψ radiative decays in 1980s
- Scalar candidates $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ (MarkII in1980s, Crystal Barrel in 1990s)
- Narrow tensor glueball candidate $\xi(2230)$ (MarkIII in 1980s/BESI in 1990s)
  - Not confirmed by CLEO, BESII nor BESIII with much higher statistics

And,

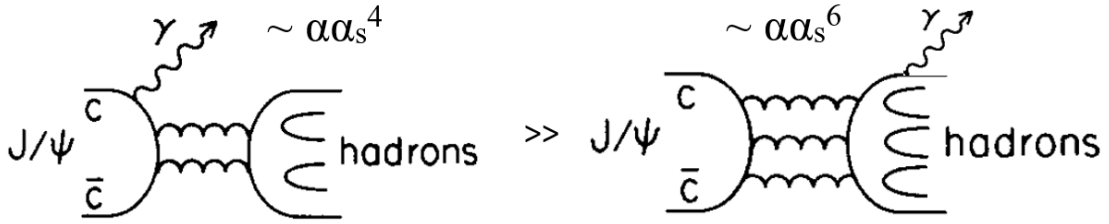
- Odderon (odd C-parity) from D0 and TOTEM (2021)

Beijing Electron Positron Collider (BEPCII)





$$\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2) \; > \; \Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3) \; > \; \Gamma(J/\psi \to \gamma M) \sim O(\alpha\alpha_s^4)$$



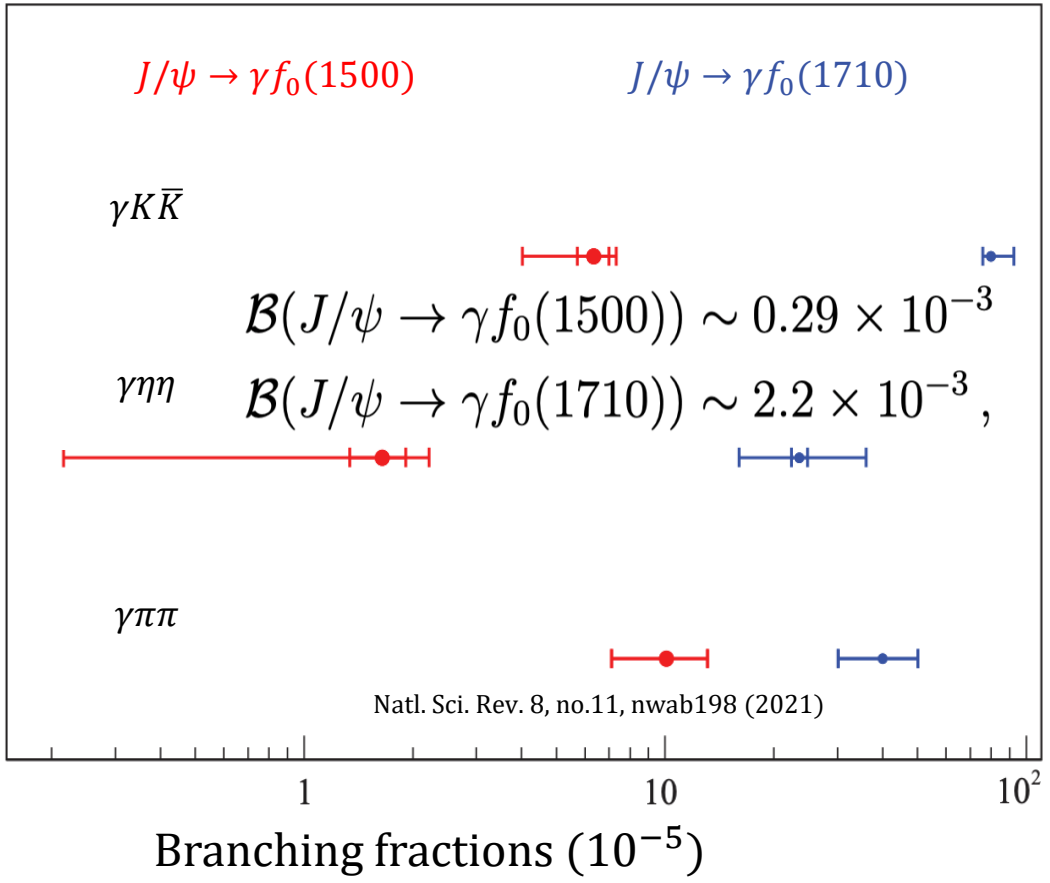
Charmonium decays provide an ideal lab for Gluonic Excitations

- **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**

Scalar glueball candidate: **production properties**

- **Scalar glueball is expected to have a large production in $\mathbf{J/\psi}$ radiative decays**:
  - LQCD: $\Gamma(\mathrm{J/\psi} \to \gamma \mathrm{G_{0+}})/\Gamma_{total} = 3.8(9) \times 10^{-3}$
    - $\Gamma(\mathrm{J/\psi} \to \gamma \mathrm{G_{0+}})/\Gamma_{total} = 6.2(9) \times 10^{-3}$
  - Observed $\mathrm{B}(\mathrm{J/\psi} \to \gamma \mathrm{f_0}(1710))$ is x10 larger than $\mathrm{f_0}(1500)$

➢ **BESIII: $\mathbf{f_0(1710)}$ largely overlapped with scalar glueball**



BESIII PRD 87 092009 (2013)
BESIII PRD 92 052003 (2015)
BESIII PRD 98 072003 (2018)

Scalar glueball candidate: **decay properties**

Flavor-blindness of glueball decays

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

*with chiral suppression

PRL 95 172001 , PRL 98 149103

Expectation:

$$\Gamma(G \to \pi\pi)/\Gamma(G \to K\bar{K}) \approx \frac{f_\pi^4}{f_K^4} \approx 0.48$$

Measured:

$$\frac{1}{P.S.}\Gamma(G \to \pi\pi : K\bar{K} : \eta\eta) \approx 1.3 : 3.16 : 1$$

New inputs from $J/\psi \to \gamma\eta\eta'$

[BESIII PRL 129 192002(2022) , PRD 106 072012(2022]

- 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

$$B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$$

[PR D 92, 121902; PR D 92, 114035]

Bottom line: Predictions on mixing scheme and decay property of glueball are model-dependent

Identification of scalar glueball with coupled-channel analyses based on BESIII data

Scalar isoscalar mesons and the scalar glueball from radiative J/ψ decays

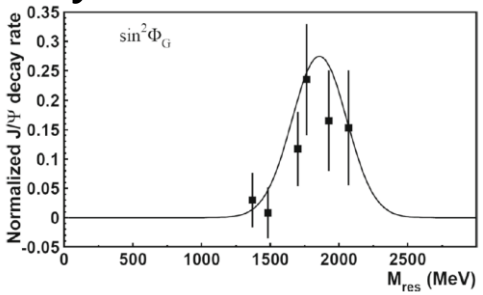
A.V. Sarantsev[a,b], I. Denisenko[c], U. Thoma[a], and E. Klempt[a]

[a] Helmholtz–Institut für Strahlen– und Kernphysik, Universität Bonn, Germany
[b] NRC "Kurchatov Institute", PNPI, Gatchina 188300, Russia
[c] Joint Institute for Nuclear Research, Joliot-Curie 6, 141980 Dubna, Moscow region, Russia

Abstract

A coupled-channel analysis of BESIII data on radiative J/ψ decays into $\pi\pi$, $K\bar{K}$, $\eta\eta$ and $\omega\phi$ has been performed. The partial-wave amplitude is constrained by a large number of further data. The analysis finds ten isoscalar scalar mesons. Their masses, widths and decay modes are determined. The scalar mesons are interpreted as mainly SU(3)-singlet and mainly octet states. Octet isoscalar scalar states are observed with significant yields only in the 1500-2100 MeV mass region. Singlet scalar mesons are produced over a wide mass range but their yield peaks in the same mass region. The peak is interpreted as scalar glueball. Its mass and width are determined to $M = 1865 \pm 25^{+10}_{-30}$ MeV and $\Gamma = 370 \pm 50^{+30}_{-20}$ MeV, its yield in radiative J/ψ decays to $(5.8 \pm 1.0)\,10^{-3}$.

Phys.Lett.B 816, 136227 (2021)
Eur.Phys.J.C 83 1125(2023)



Production rate: $5.8(1) \times 10^{-3}$

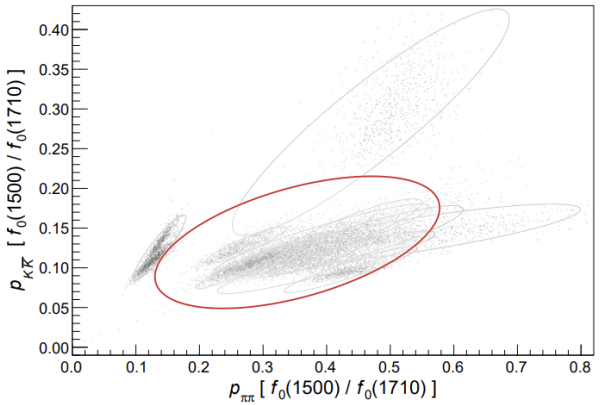
Scalar and tensor resonances in J/ψ radiative decays

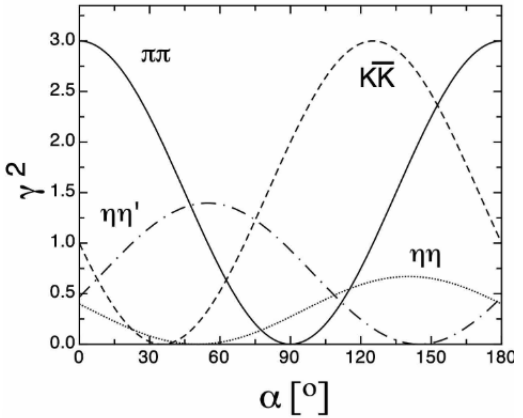
A. Rodas,[1,2,*] A. Pilloni,[3,4,5,†] M. Albaladejo,[6] C. Fernández-Ramírez,[7] V. Mathieu,[8,9] and A. P. Szczepaniak[2,10,11]
(Joint Physics Analysis Center)

[1] Department of Physics, College of William and Mary, Williamsburg, VA 23187, USA
[2] Theory Center, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
[3] INFN Sezione di Roma, I-00185 Roma, Italy
[4] Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, Università degli Studi di Messina, I-98166 Messina, Italy
[5] INFN Sezione di Catania, I-95123 Catania, Italy
[6] Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Universidad de Valencia, Institutos de Investigación de Paterna, Aptd. 22085, E-46071 Valencia, Spain
[7] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad de México 04510, Mexico
[8] Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, E08028, Spain
[9] Departamento de Física Teórica, Universidad Complutense de Madrid and IPARCOS, E-28040 Madrid, Spain
[10] Physics Department, Indiana University, Bloomington, IN 47405, USA
[11] Center for Exploration of Energy and Matter, Indiana University, Bloomington, IN 47403, USA

We perform a systematic analysis of the $J/\psi \to \gamma\pi^0\pi^0$ and $\to \gamma K^0_S K^0_S$ partial waves measured by BESIII. We use a large set of amplitude parametrizations to reduce the model bias. We determine the physical properties of seven scalar and tensor resonances in the 1–2.5 GeV mass range. These include the well known $f_0(1500)$ and $f_0(1710)$, that are considered to be the primary glueball candidates. The hierarchy of resonance couplings determined from this analysis favors the latter as the one with the largest glueball component.

Eur.Phys.J.C 82, 80 (2022)

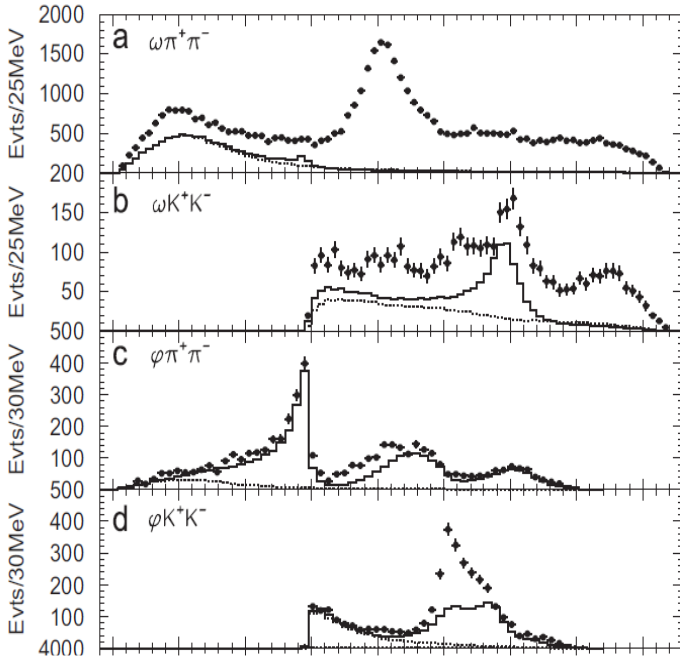




$f_0(1710)$ largely overlapped with scalar glueball

At least 2 scalars around 1.7 GeV

$f_0(1710)/f_0(1800)$?



ωK^+K^- ➔ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

$\phi\pi^+\pi^-$ ➔ Enhancement at 1790 MeV/c^2

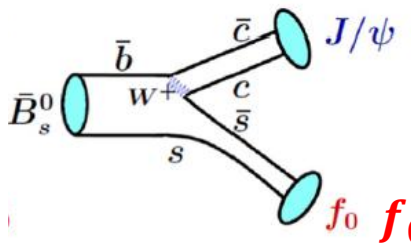
ϕK^+K^- ➔ No peak around 1700 MeV/c^2

$f_0(1800)$

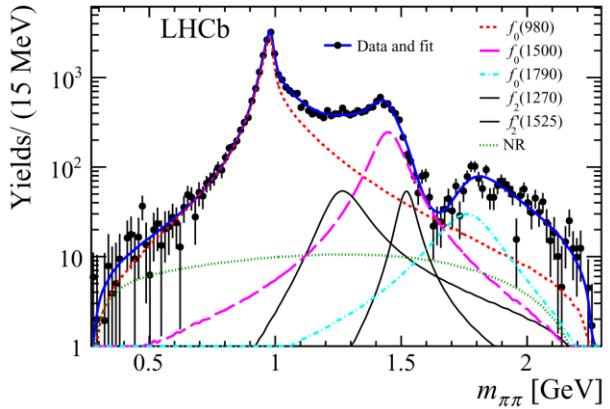
selective for $s\bar{s}$

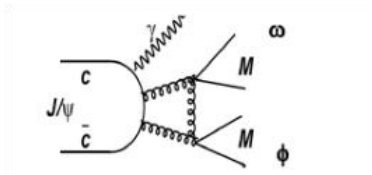
$B_s \to J/\psi f_0$

PLB 797 (2019) 134789



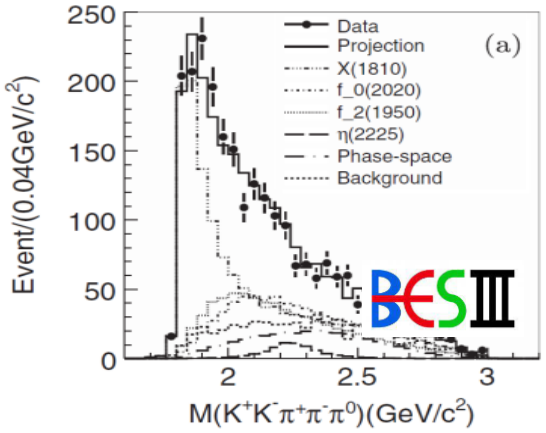
$f_0(1800)$, no $f_0(1710)$





$J/\psi \to \gamma\omega\phi$ **(DOZI)**

$f_8 \to \omega\phi$



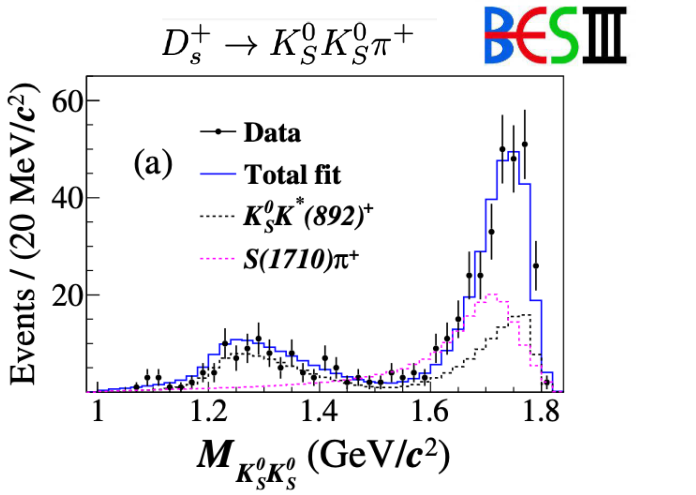
PRD 87, 032008(2013)

$a_0(1817)$

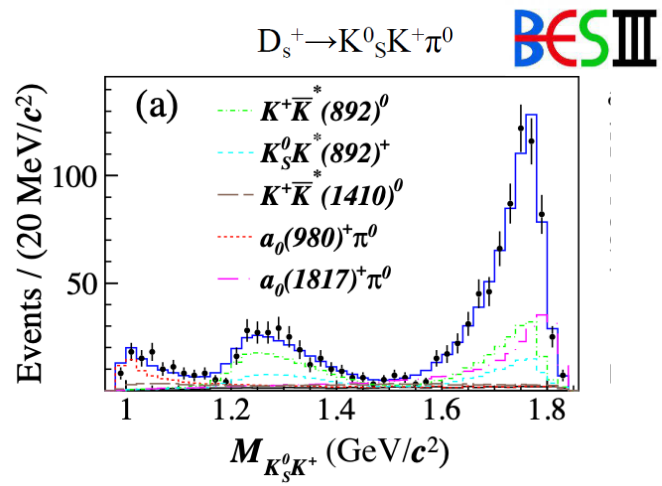
Isovector partner of $f_0(1800)$?

[Shulei 's talk]

PRD105, L051103 (2022)



PRL129, 182001 (2022)



Indications of tensor glueball

$$\Gamma(J/\psi \to \gamma G_{2^+}) = 1.01(22) keV$$
$$\Gamma(J/\psi \to \gamma G_{2^+})/\Gamma_{tot} = 1.1 \times 10^{-2}$$

CLQCD, Phys. Rev. Lett. 111, 091601 (2013)

Experimental results

$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = \left(3.8^{+0.62+2.37}_{-0.65-2.07}\right) \times 10^{-5}}$
BESIII PRD 87,092009 (2013)

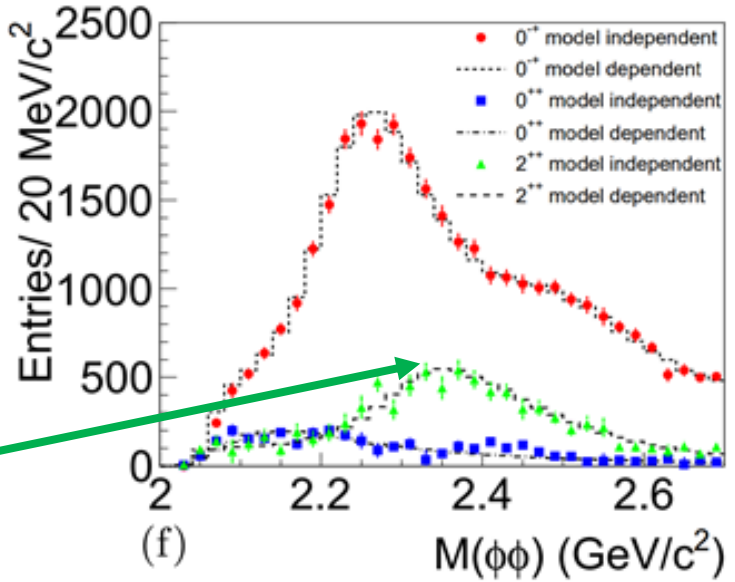
$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = \left(1.91 \pm 0.14^{+0.72}_{-0.73}\right) \times 10^{-4}}$
BESIII PRD 93, 112011 (2016)

$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma K_S K_S) = \left(5.54^{+0.34+3.82}_{-0.40-1.49}\right) \times 10^{-5}}$
BESIII PRD 98,072003 (2018)

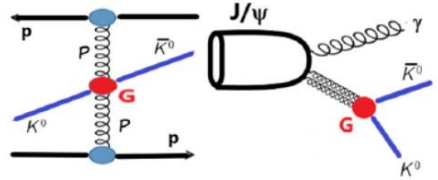
$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta'\eta') = \left(8.67 \pm 0.70^{+0.16}_{-1.67}\right) \times 10^{-6}}$
BESIII PRD 105,072002 (2022)

still desired to study more decay modes

BESIII $J/\psi \to \gamma\phi\phi$ [PRD 93, 112011 (2016)]



- $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ in πp reactions are all observed in $\mathbf{J/\psi \to \gamma\phi\phi}$ with a **strong production of $f_2(2340)$**
- Consistent with **double-Pomeron exchange** from WA102@CERN



More complicated due to the large number of tensor states

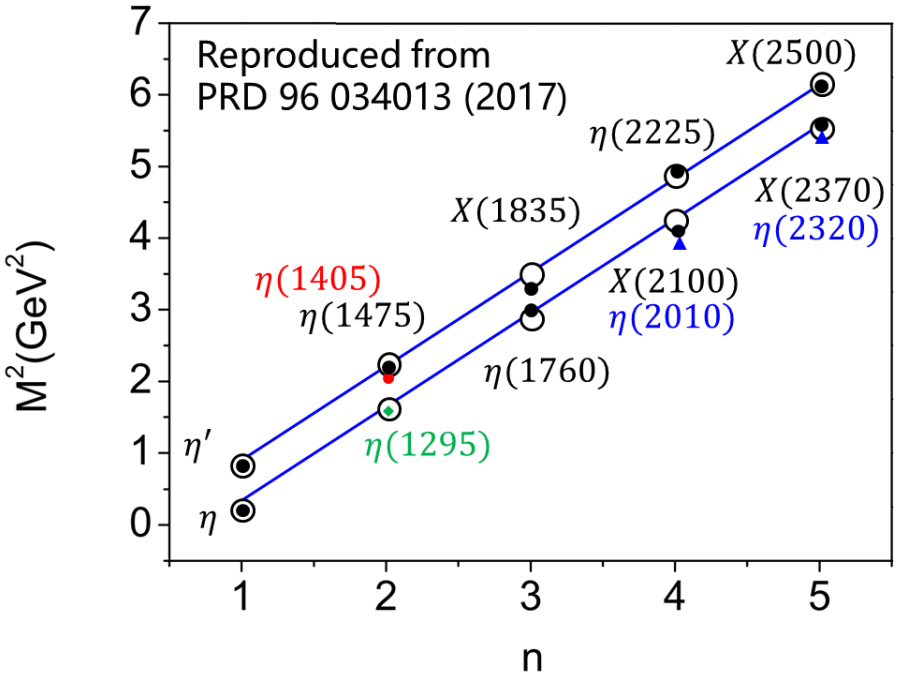
Where is the 0^{-+} glueball

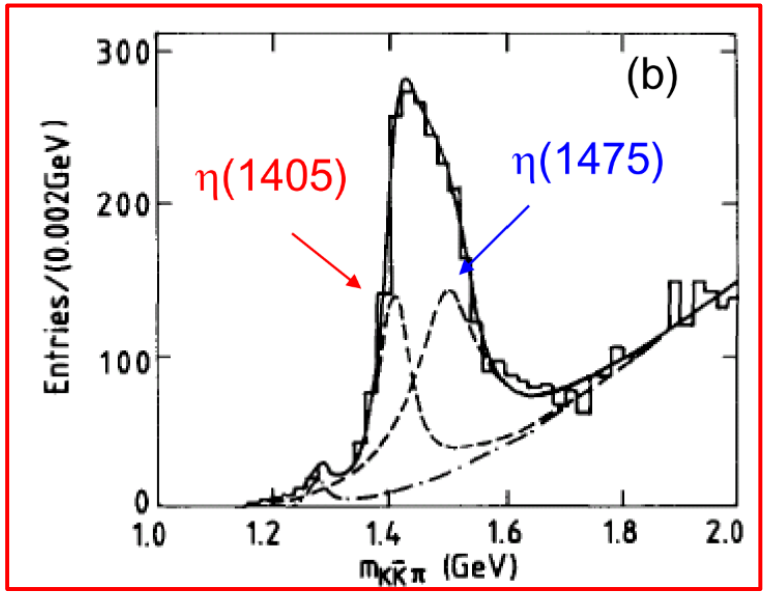
- Pseudoscalar sector, a promising window

  [Future Physics Programme of BESIII(2020), CPC 44, 040001]

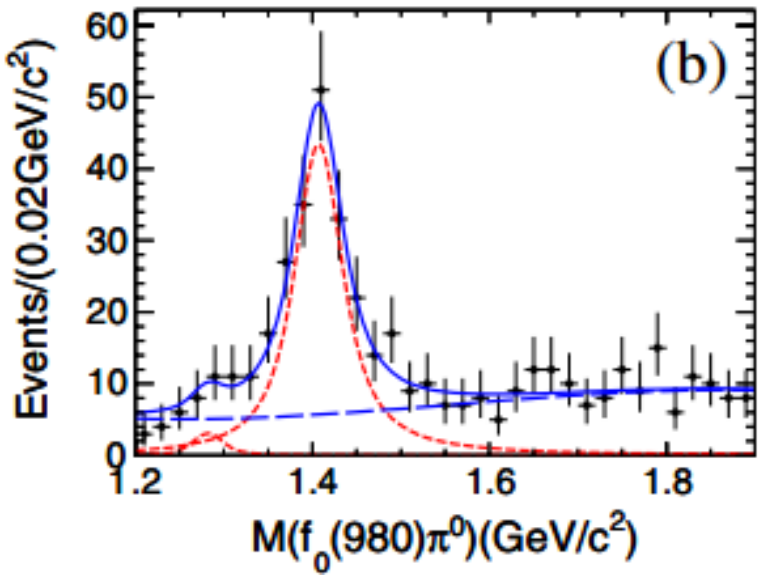
  - Only η, η' (& radial excitations) from quark model

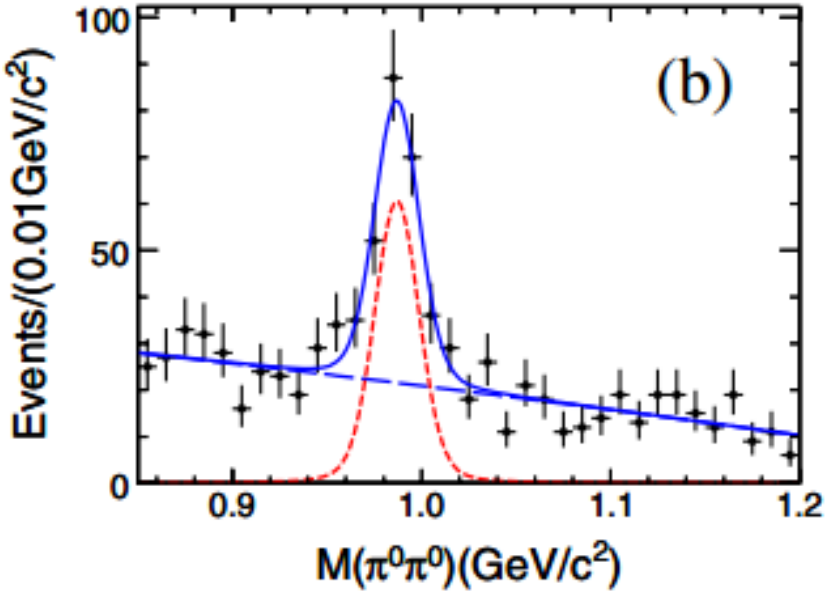
- Mass spectrum
  - LQCD: 0^{-+} glueball (2.3~2.6 GeV)
  - Little experimental information above 2 GeV
  - What's the nature of the outnumbered $\eta(1405)$? $\eta(1295)$ exists?
    - Will affect the trajectory

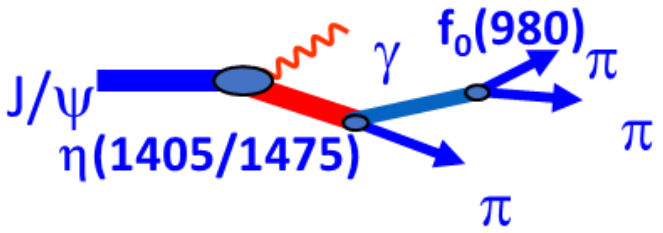




Isospin-violating decay of $\eta(1405) \to f_0(980)\pi^0$







BESIII PRL 108 182001(2012)

f0(980) is extremely narrow: Γ ≅ 10 MeV.

PDG: Γ(f0(980)) ≅ 40~100 MeV.

Anomalously large isospin violation:

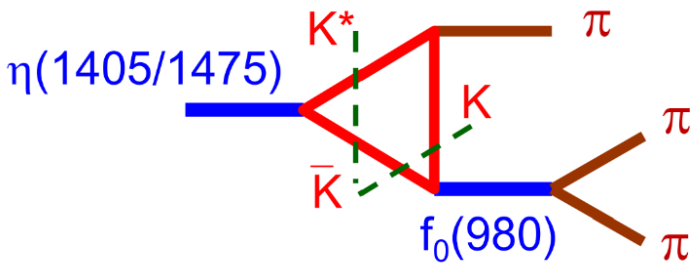
$$\frac{Br(\eta(1405) \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\eta(1405) \to a_0^0(980)\pi^0 \to \eta\pi^0\pi^0)} \cong (17.9 \pm 4.2)\%$$

$$\xi_{af} = \frac{Br(\chi_{c1} \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\chi_{c1} \to a_0(980)\pi^0 \to \eta\pi^0\pi^0)} < 1\%(90\%\ C.L.)$$

PRD, 83(2100)032003

Triangle singularity mechanism has been proposed
- Manifested in many near-threshold structures

PRL 108 081803 (2012)



Shed new lights on the $\eta(1405)/\eta(1475)$ puzzle

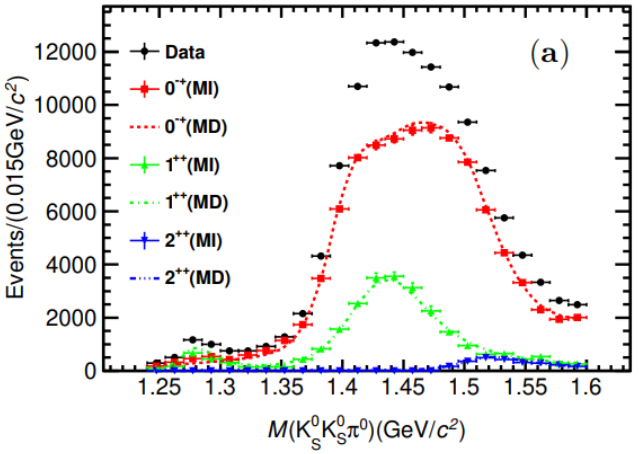
$$J/\psi \to \gamma K_S K_S \pi^0$$

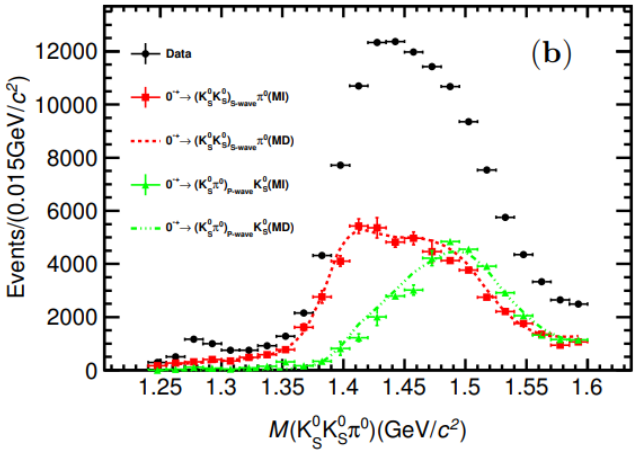
BESIII JHEP 03 121(2023)

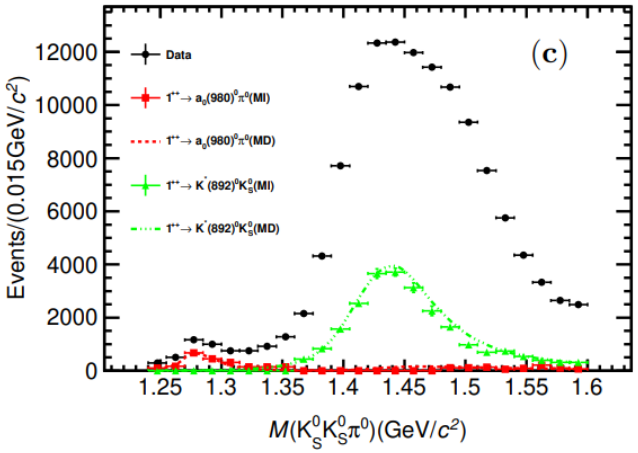
- **M**ass **I**ndependent PWA in bins of $M(K_S K_S \pi^0)$ to detangle J^{PC} components
  - **Valuable inputs to develop models**
- **M**ass **D**ependent PWA with BW to extract resonances
- **Consistency between MI and MD results**

- **Dominated by 0^{-+}**
  - **Two BWs around 1.4 GeV is needed**

- Coupled-channel analysis
  - PRD 107, L091505
  - PRD 109, 014021
  - PRD 111, 114015



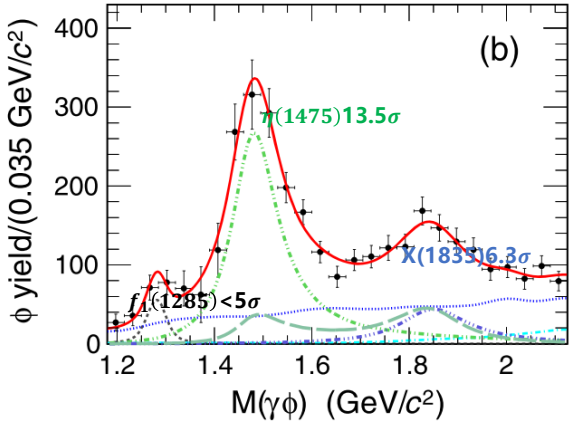




$J/\psi \to \gamma\gamma\phi$, a $s\bar{s}$ flavor filter

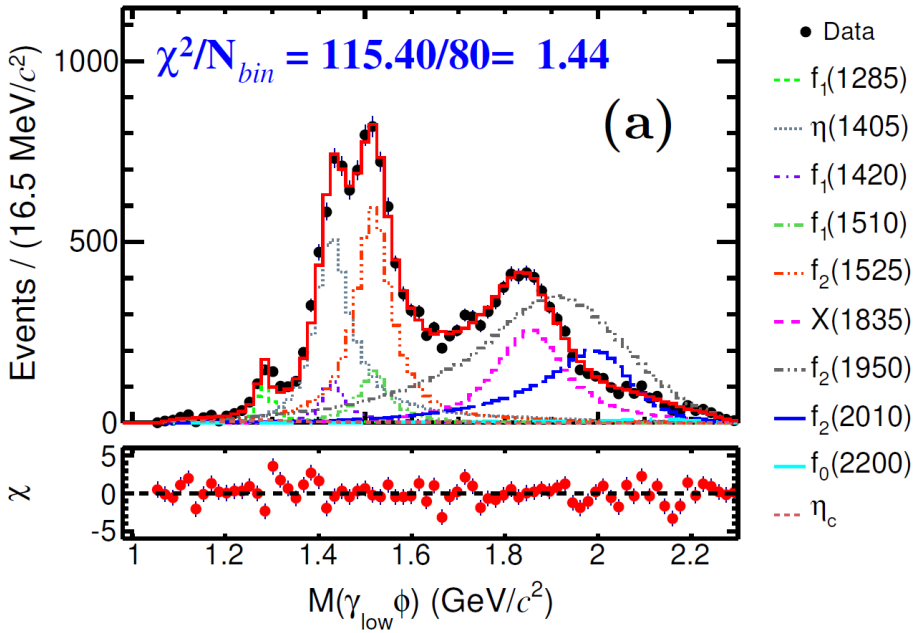
BESIII PhysRevD.111.052011(2025)

PR D97 051101 (2018)



Amplitude analysis with ML techniques for background subtraction

←Fit to mass spectrum

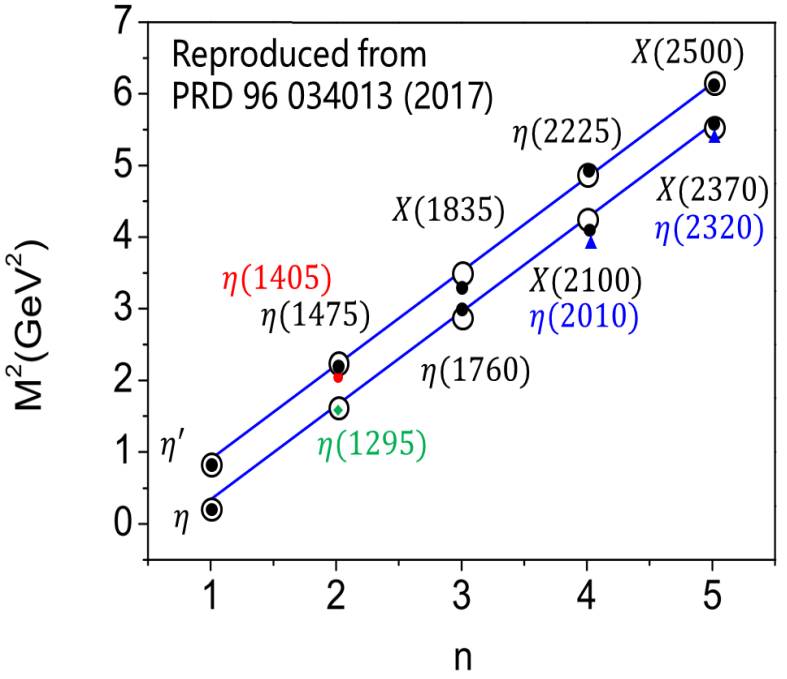


From the amplitude analysis,

- $\eta(1405)$ 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]

Where is the 0^{-+} glueball

- Pseudoscalar sector, a promising window
  - [Future Physics Programme of BESIII(2020), CPC 44, 040001]
  - Only η, η' (& radial excitations) from quark model
- Mass
  - LQCD: 0^{-+} glueball (2.3~2.6 GeV)
  - Puzzles remain in low mass region
- Production
  - LQCD: $\Gamma(J/\psi \to \gamma G_{0^-})/\Gamma_{total} = 2.31(80) \times 10^{-4}$, at the same level as 0^{-+} mesons [PRD.100.054511(2019)]
- **Decays**
  - **Possible guidance: OZI suppressed decays of η_c**
  - $0^{-+} \to 3P$ **is a good place to look for**
    - $0^{-+} \to 2P$ is forbidden
    - $0^{-+} \to 3P$ can via S-wave, while 0^+ or 2^+ is suppressed



$\eta_c \to 3P$ in PDG

Decays involving hadronic resonances

Γ_1	$\eta'(958)\pi\pi$	(1.87±0.26) %
Γ_2	$\eta'(958)K\overline{K}$	(1.61±0.25) %

Decays into stable hadrons

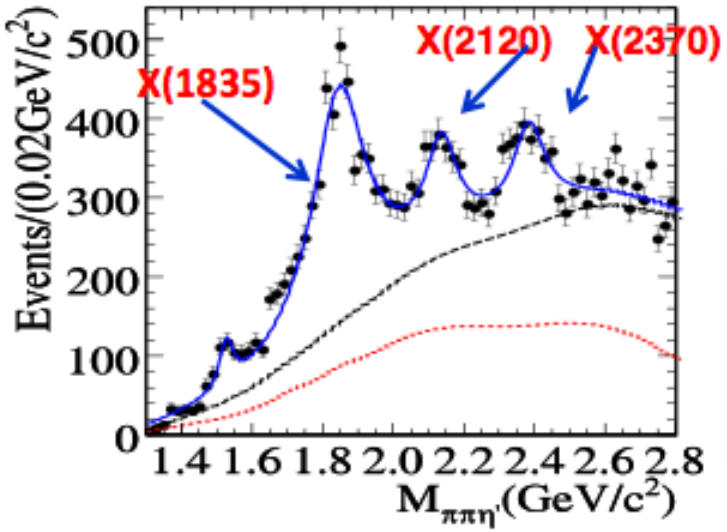
Γ_{34}	$K\overline{K}\pi$	(7.0 ±0.4) %
Γ_{35}	$K\overline{K}\eta$	(1.32±0.15) %
Γ_{36}	$\eta\pi^+\pi^-$	(1.7 ±0.5) %

- No dominant decay
- Flavor symmetric

A glueball-like state $X(2370)$

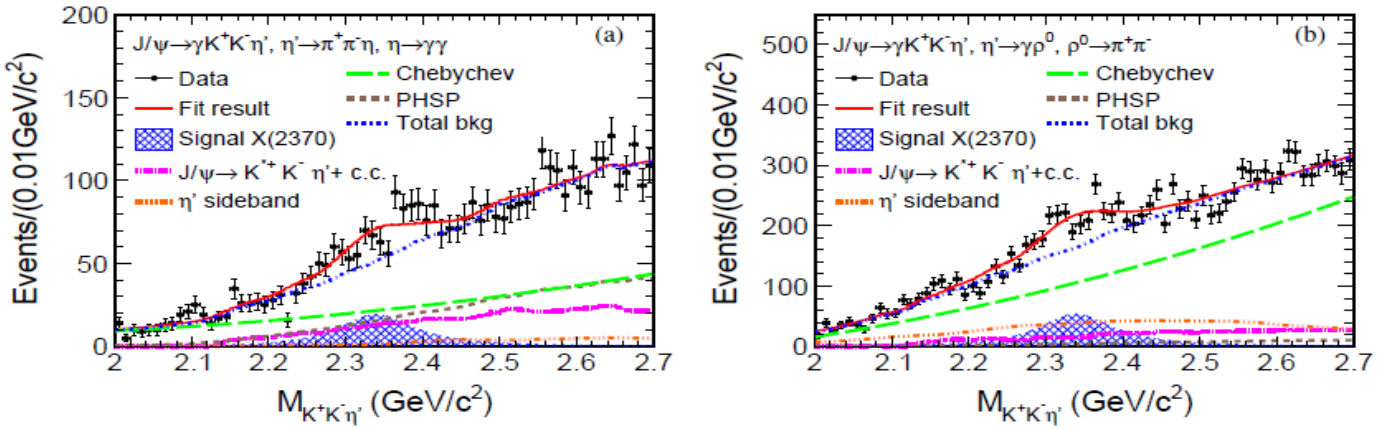
- **Discovered by BESIII in $J/\psi \to \gamma\eta'\pi\pi$ in 2011**
- Confirmed by BESIII in $J/\psi \to \gamma\eta'\pi\pi$, **$\gamma\eta'KK$ (new mode)**
  - Not seen in $J/\psi \to \gamma\eta'\eta\eta$ [BESIII PRD 103 012009 (2021)], $J/\psi \to \gamma\gamma\phi$ [BESIII PRD.111.052011(2025)]. Upper limits of BF are well consistent with predictions of 0^{-+}glueball
- **Mass consistent with LQCD prediction for 0^{-+} glueball**

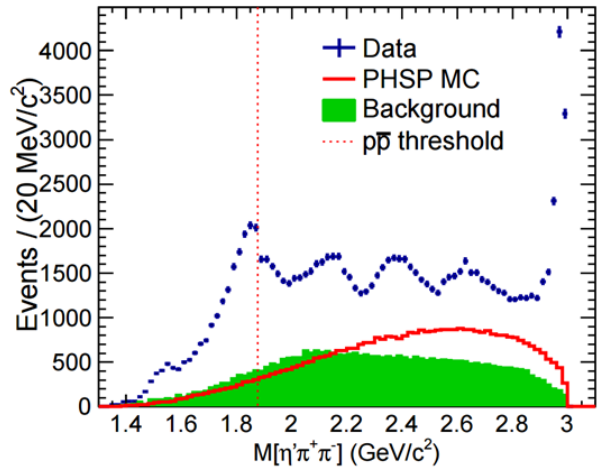
$J/\psi \to \gamma\eta'\pi\pi$



BESIII PRL 106, 072002(2011)

$J/\psi \to \gamma\eta'KK$ BESIII EPJC 80 746(2020)



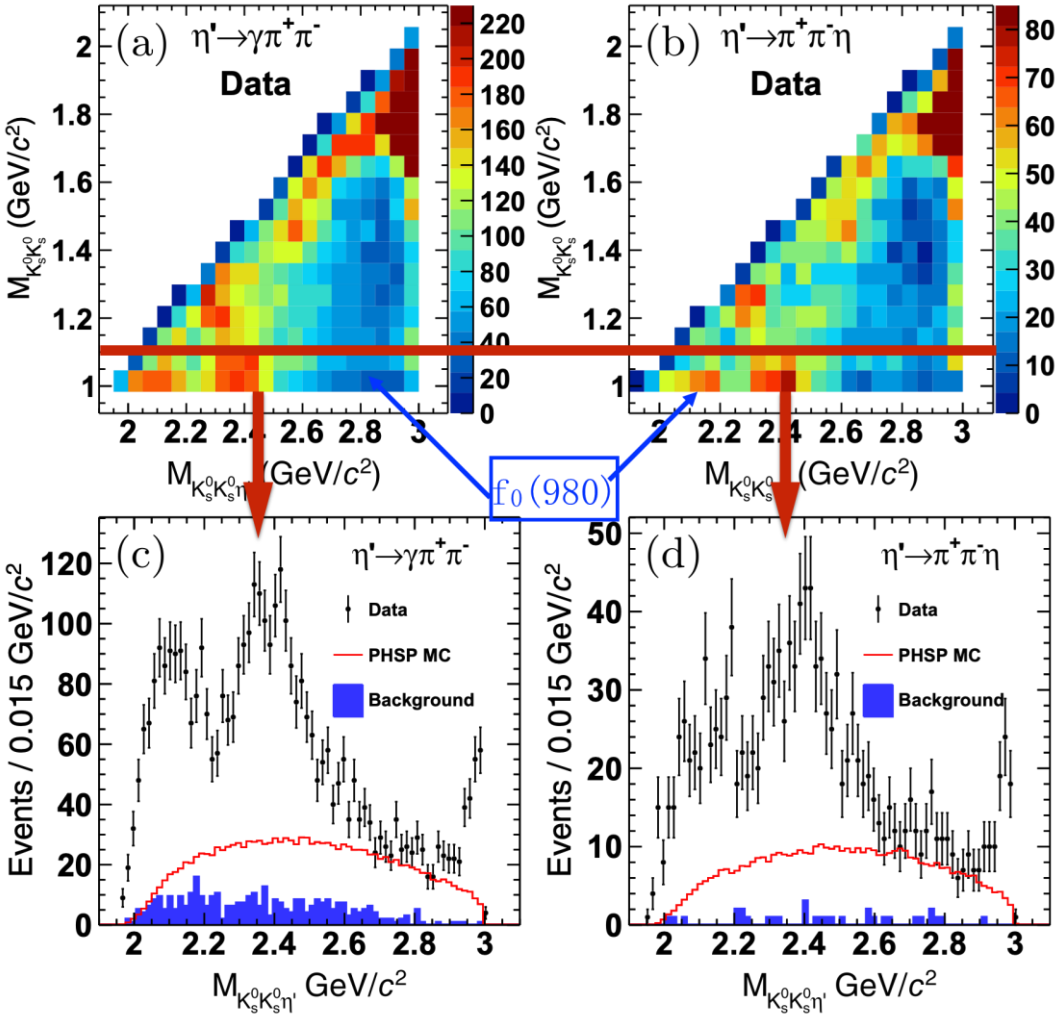


BESIII PRL 117, 042002 (2016)

A glueball-like state $X(2370)$

- **Spin-parity determined to be 0^{-+}**

$J/\psi \to \gamma\eta' K^0_S K^0_S$ **BESIII PRL 132, 181901(2024)**



$J^{PC} = 0^{-+}$ with significance >9.8σ

$M = 2395 \pm 11^{+26}_{-94}$ MeV

$\Gamma = 188^{+18}_{-17}{}^{+124}_{-33}$ MeV

$B(J/\psi \to \gamma X(2370))B(X(2370) \to f_0(980)\eta')B(f_0(980) \to K^0_S K^0_S)$
$= 1.31 \pm 0.22^{+2.85}_{-0.84} \times 10^{-5}$

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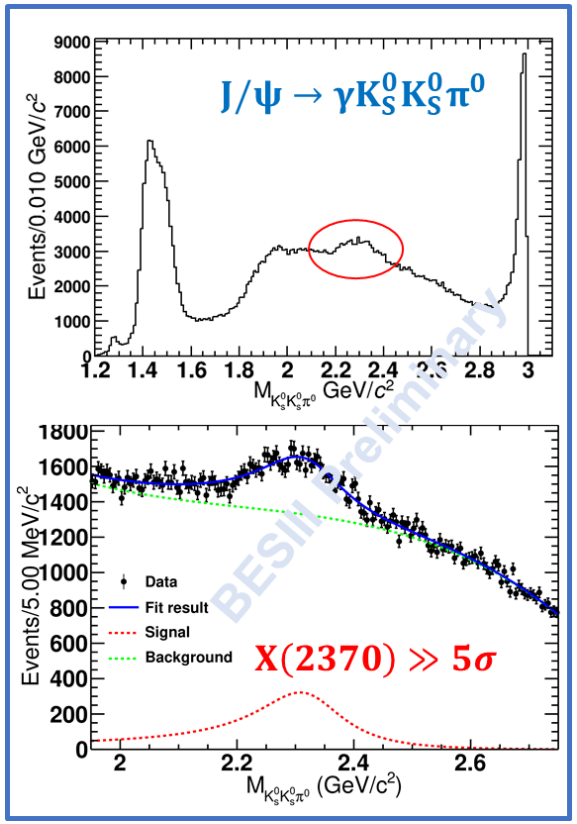
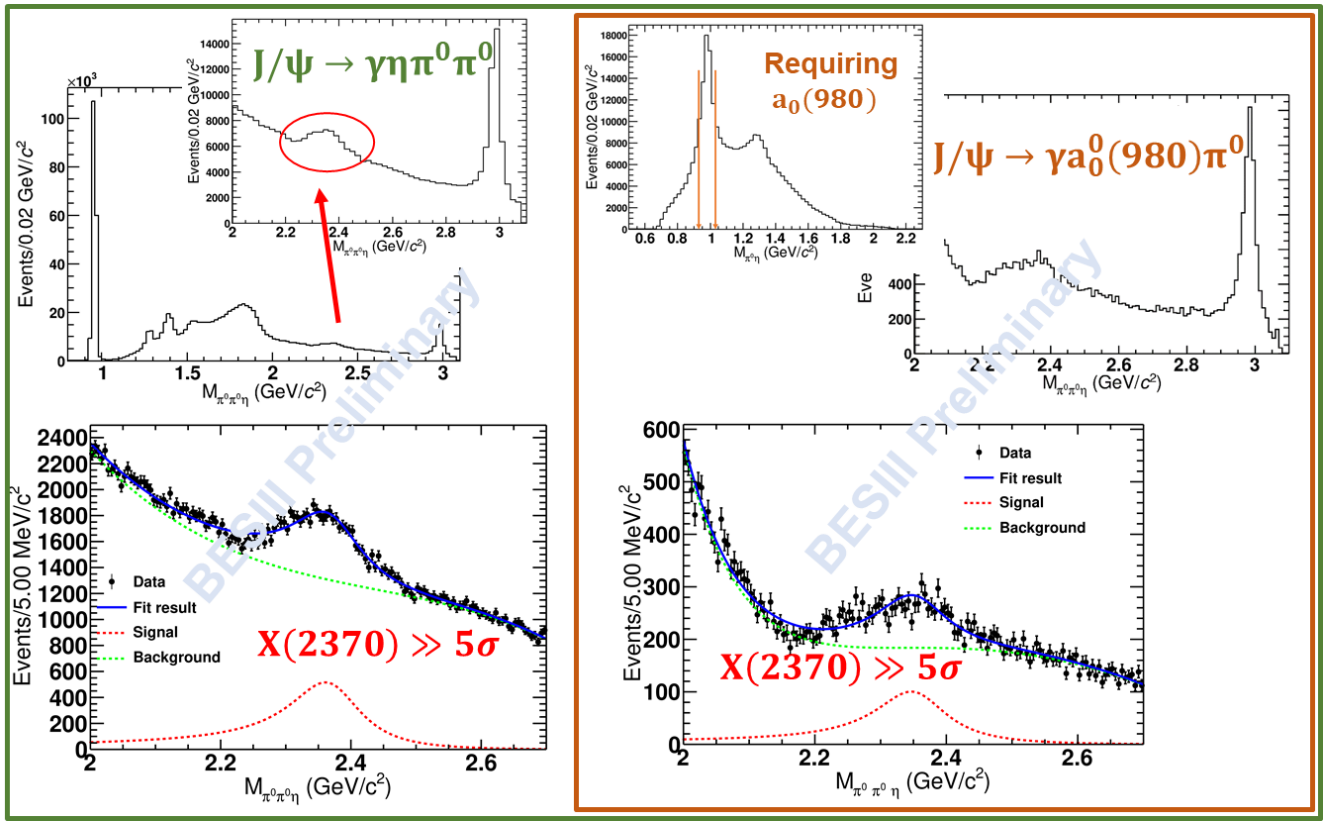
PRL 2024 COLLECTION

Highlights of ICHEP2024





*$\eta(2320) \to \eta\eta\eta, \eta\pi\pi$ [PL B496 145(2000)] could be the same state

$X(2370)$ observed in the gluon-rich J/ψ radiative decays

- **A first-time determination of $J^{PC}=0^{-+}$**
- **Mass and production rate consistent with LQCD**
- **Decay modes $X(2370) \to \eta'\pi\pi, \eta'KK, K_S^0K_S^0\eta, K_S^0K_S^0\pi^0, \eta\pi^0\pi^0$, $a_0^0(980)\pi^0$, in analog to η_c with OZI-suppressed style**
  - **i.e. flavor symmetric AND narrow partial width**

Qualitatively consistent with 0^{-+} glueball

Landscape of glueballs has been updated with BESIII' s inputs

Scalar: 1 nonet in quark model, f_0 & f_0'

Exp: overpopulation

LQCD : ground state 0^+ glueball ~1.7 GeV;

$$\Gamma(J/\psi \to \gamma G_{0+})/\Gamma_{total} = 3.8(9) \times 10^{-3}$$

Tensor: 2 nonets($^3P_2$,$^3F_2$), complicated

Exp: large uncertainty

LQCD: 2^{++}(2.3~2.4 GeV);

$$\Gamma(J/\psi \to \gamma G_{2+})/\Gamma_{total} = 1.1(2) \times 10^{-2}$$

Pseudoscalar: η & η' , "simple"

Exp: lacking of info. above 2 GeV; puzzles $\eta(1295)$? $\eta(1405/1475)$?

LQCD: 0^{-+}(2.3~2.6 GeV)

$$\Gamma(J/\psi \to \gamma G_{0-})/\Gamma_{total} = 2.31(80) \times 10^{-4}$$

✓**$B(J/\psi \to \gamma f_0(1710))$ is x10 larger than $f_0(1500)$; suppression of $f_0(1710) \to \eta\eta'$**

➔ **Large gluonic component**

BESIII [PRD 87 092009, PRD 92 052003, PRD 98 072003, PRD 106 072012]

✓**Large production rate of $f_2(2340)$ in J/ψ radiative decays**

BESIII [PRD 87,092009, PRD 93, 112011, PRD 98,072003, PRD 105,072002]

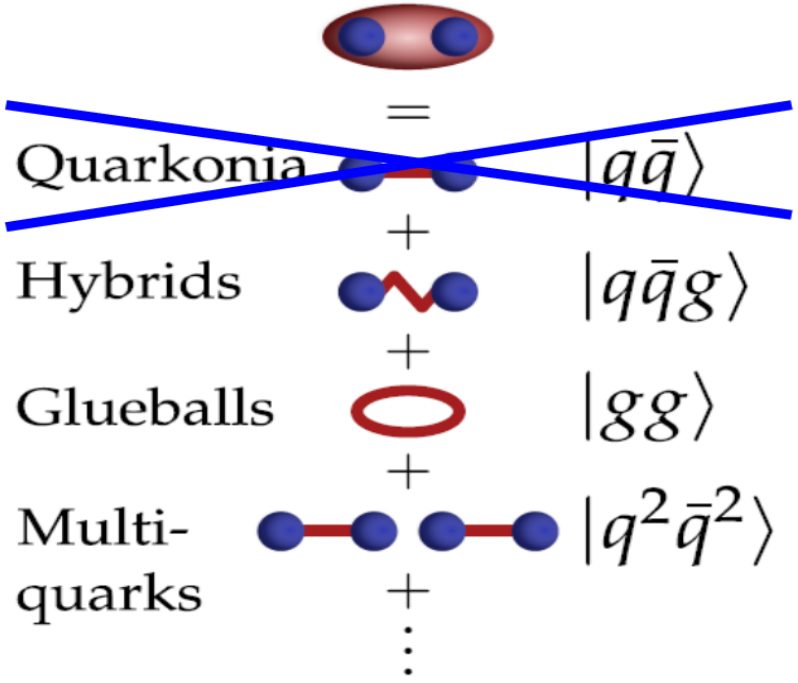
✓**$X(2370)$: a good candidate with analogy decay pattern as η_c**

BESIII [PRL 106, 072002, PRL 117, 042002, EPJC 80 746, PRL 132, 181901, PoS ICHEP2024 490]

definitively manifest the gluonic excitation yet?

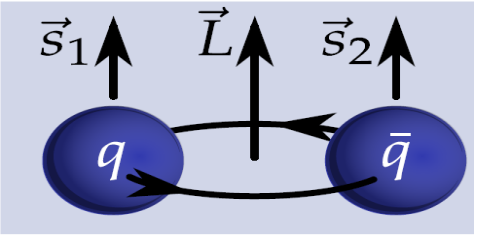
Light hadrons with exotic quantum numbers

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



Experiments:

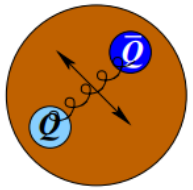
- **Hadroproduction:** GAMS, VES, E852, COMPASS, AMBER
- **$p\bar{p}$ annihilation:** Crystal Barrel, OBELIX, PANDA
- **Photoproduction:** GlueX(2017-), CLAS

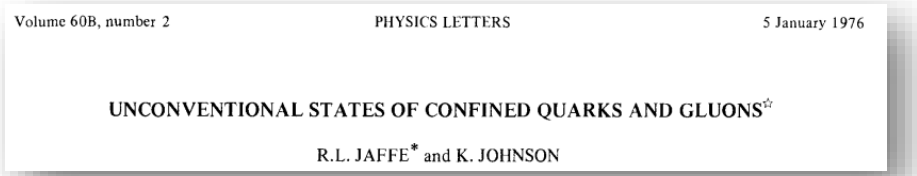


$\vec{J} = \vec{L} + \vec{S}$ $P = (-1)^{L+1}$ $C = (-1)^{L+S}$

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

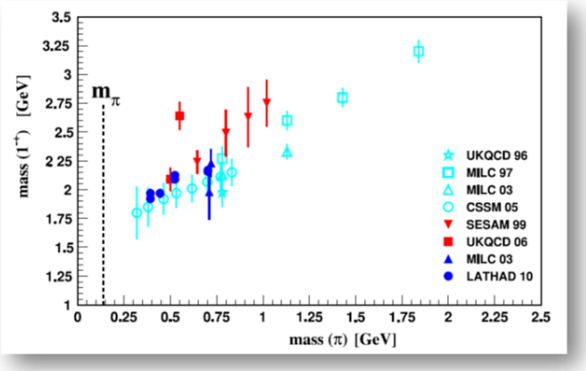
Predictions



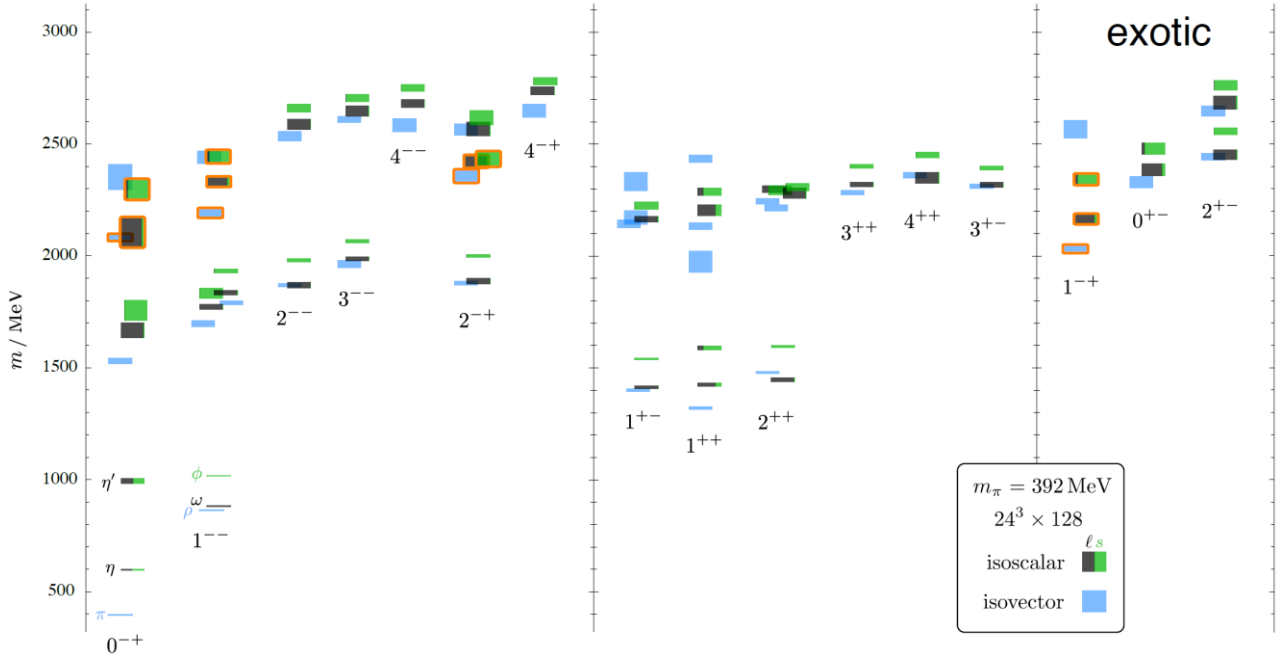

Volume 60B, number 2 PHYSICS LETTERS 5 January 1976

UNCONVENTIONAL STATES OF CONFINED QUARKS AND GLUONS☆

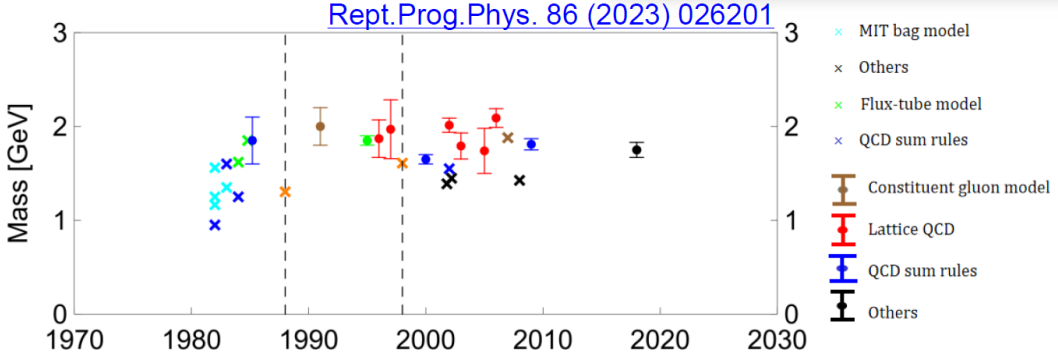
R.L. JAFFE* and K. JOHNSON



PRD 88 094505(2013)

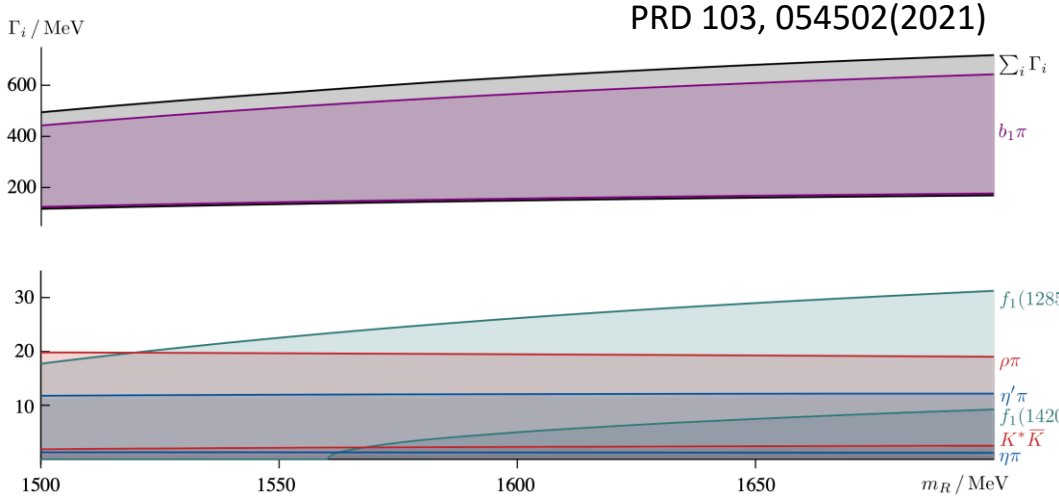


Rept.Prog.Phys. 86 (2023) 026201



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

PRD 103, 054502(2021)



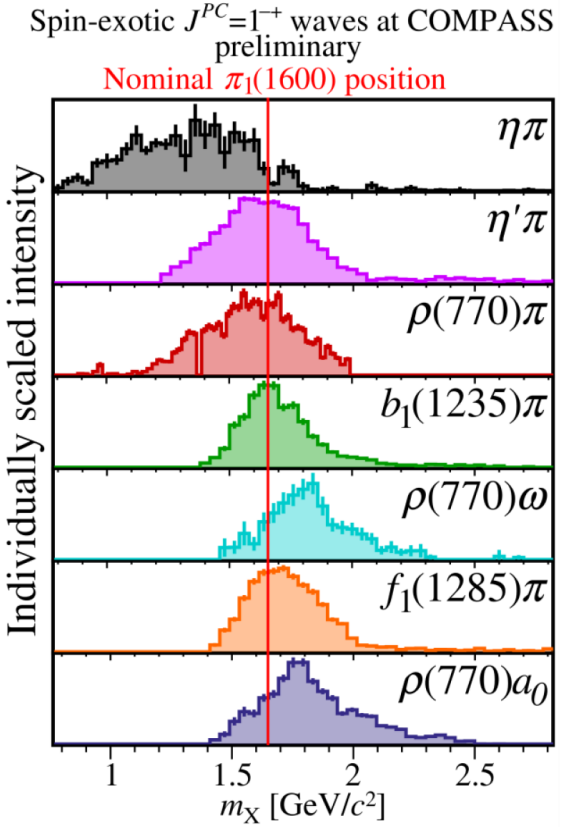
Decay width of $\mathbf{1^{-+}}$ hybrid π_1

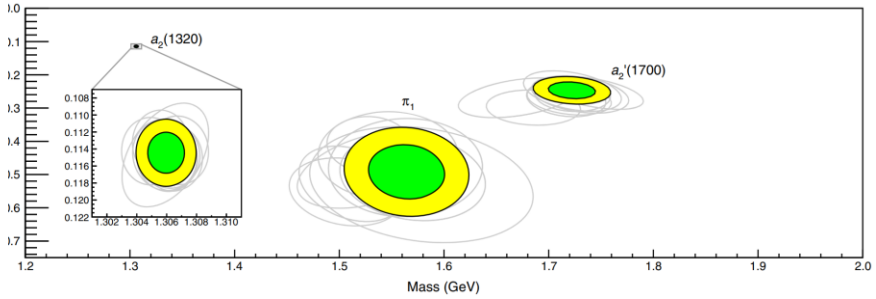
On lattice,

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

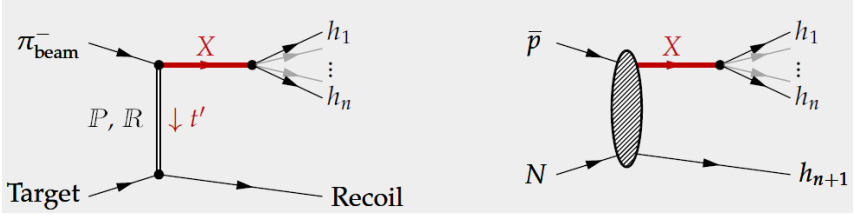
Spin-exotic mesons

- 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)]

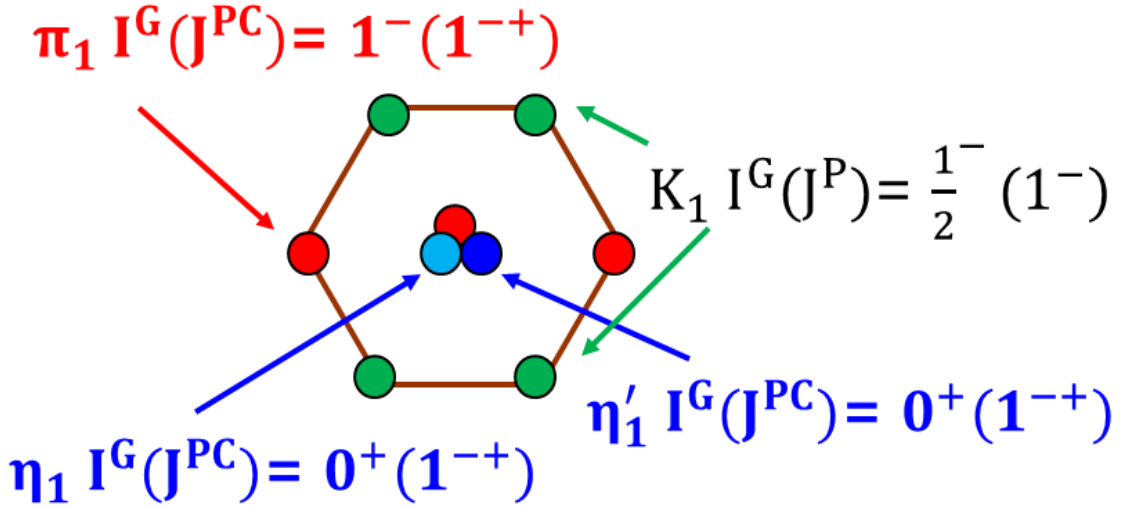


Review: PRC 82, 025208 (2010), PPNP 82, 21 (2015), EPJC 83 (2023) 1125

	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
	$b_1\pi$	$\pi^-p \to p\eta\pi^+\pi^-\pi^-$	

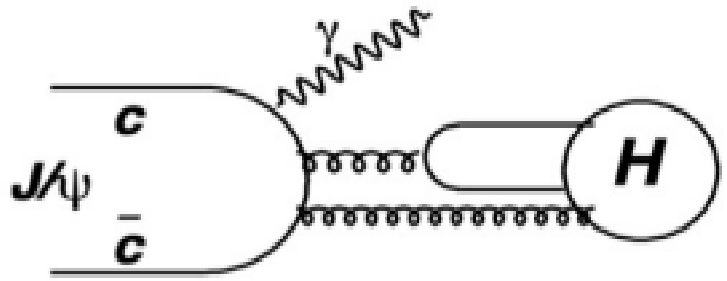
1^{-+} Hybrids

- **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)

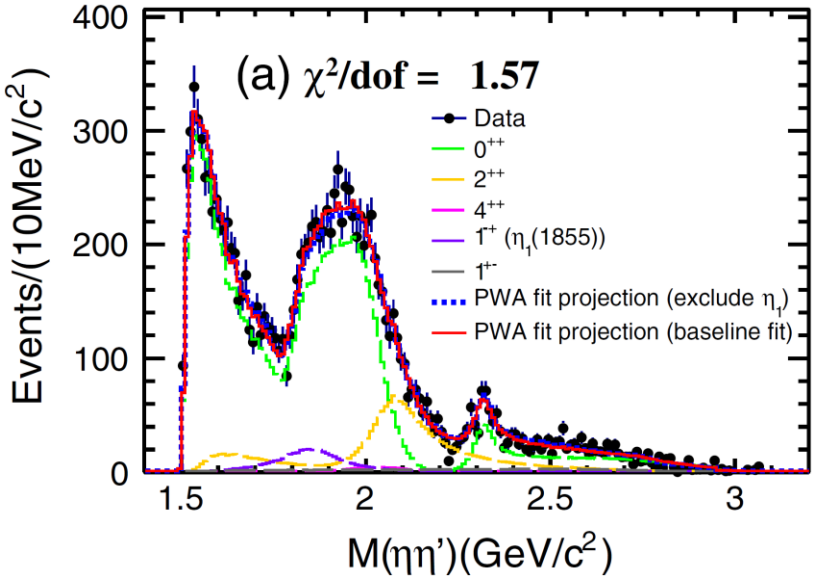
- **An isoscalar 1^{-+} , $\eta_1(1855)$, has been observed in $J/\psi \to \gamma\eta\eta'$ (>19σ)**

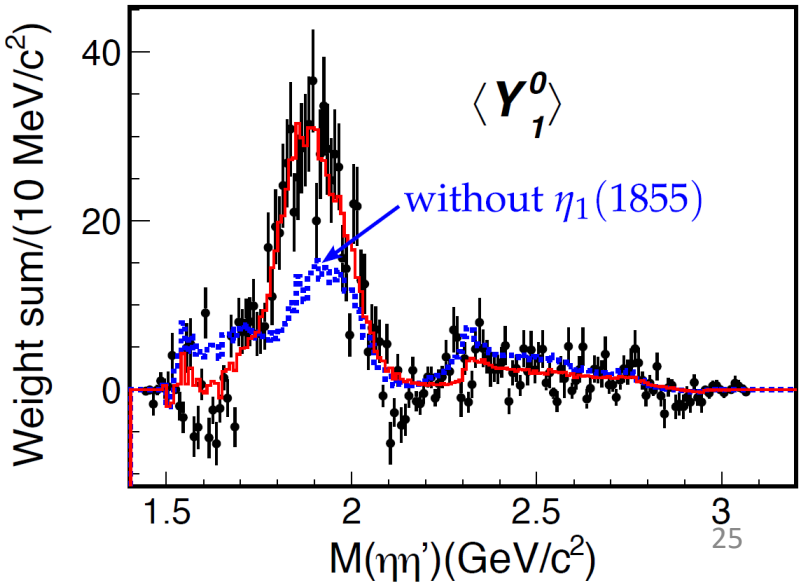
  $M = (1855 \pm 9^{+6}_{-1})\ \mathrm{MeV/c^2}$, $\Gamma = (188 \pm 18^{+3}_{-8})\ \mathrm{MeV/c^2}$

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

  - **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)

- 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:

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

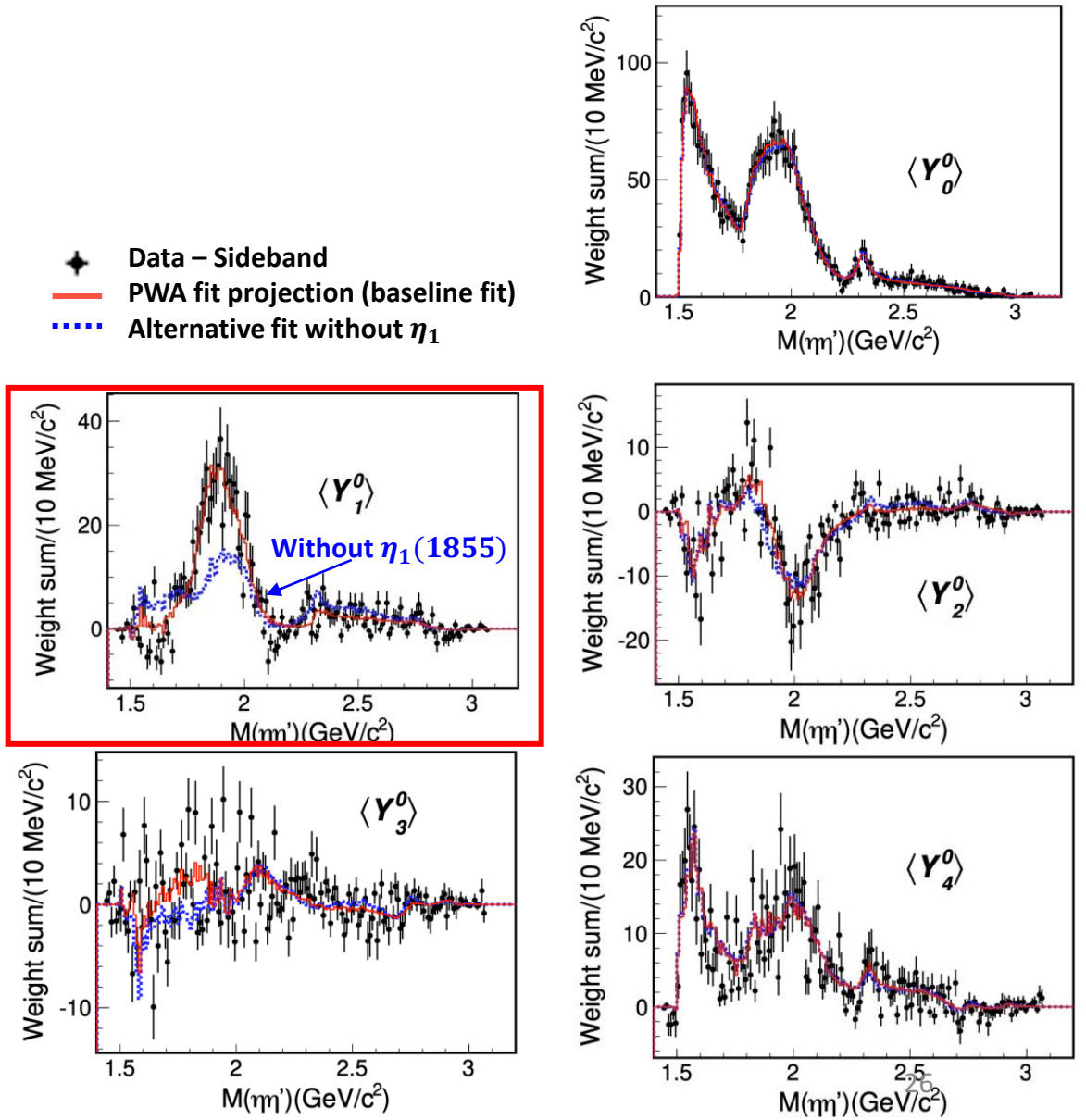
$$\sqrt{4\pi}\langle Y_1^0\rangle = 2S_0P_0\cos\phi_{P_0} + \frac{2}{\sqrt{5}}(2P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) + \sqrt{3}P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

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

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

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

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



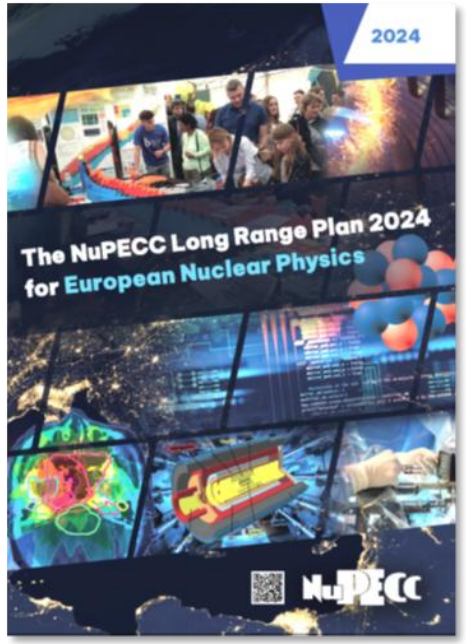
Observation of An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$

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

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

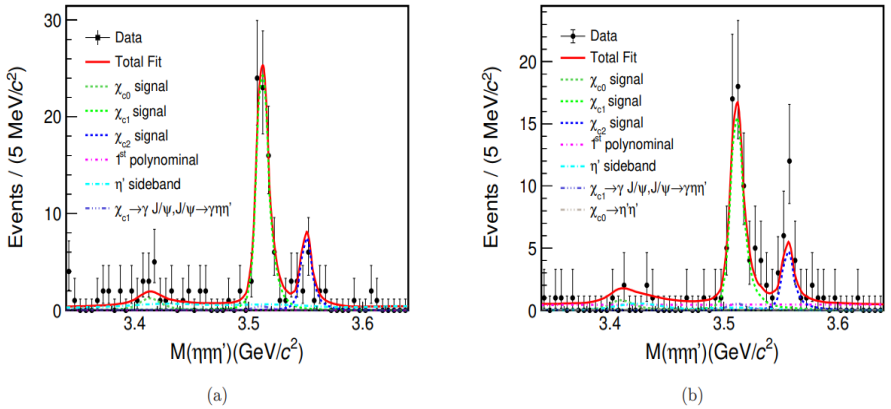
  NPA 1047 122874(2024); Rept.Prog.Phys. 86 (2023) 026201; PRD 107 (2023) 7, 074028; SCPMA 65 (2022) 6, 261011; CPC 46 , 051001(2022); CPL 39, 051201 (2022); PLB 834, 137478(2022); PRD 106 , 074003(2022); PRD 106, 036005(2022) ;...

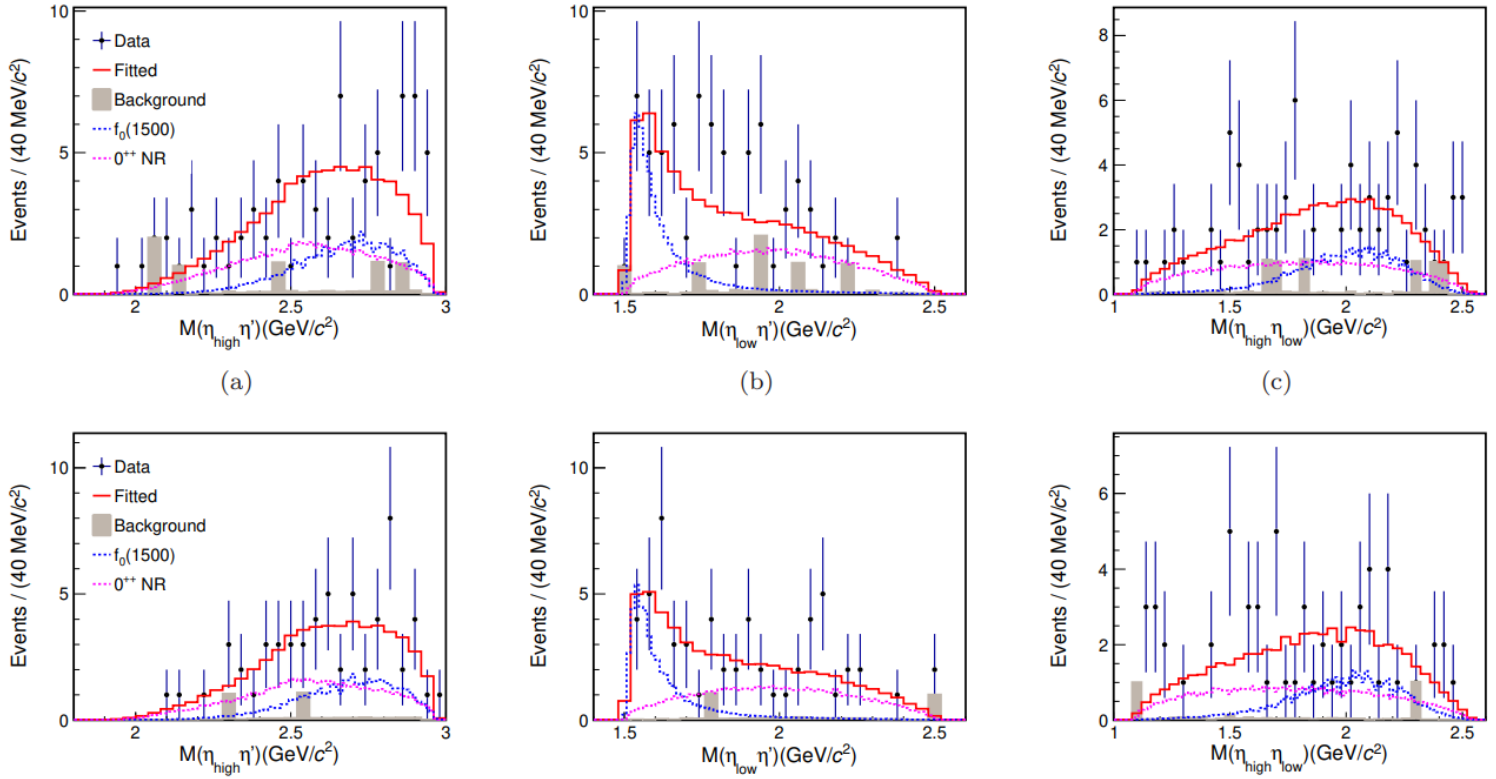
- Opens a new direction to completing the picture of spin-exotics
  - As a "recent achievements and highlights" in hadron spectroscopy in the NuPECC LRP
  - 50 years of QCD: Exotic mesons, "observation of an $\eta_1(1855)$ state could be a breakthrough" [EPJ.C 83 (2023) 1125]



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

BESIII CPC 49, 10 (2025)





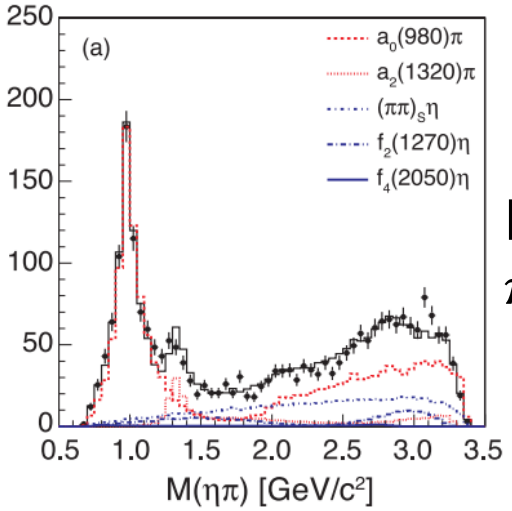
$$\mathcal{B}(\chi_{c1} \to \eta\eta\eta') = (1.39 \pm 0.13(\text{stat.}) \pm 0.09(\text{sys.})) \times 10^{-4}$$

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

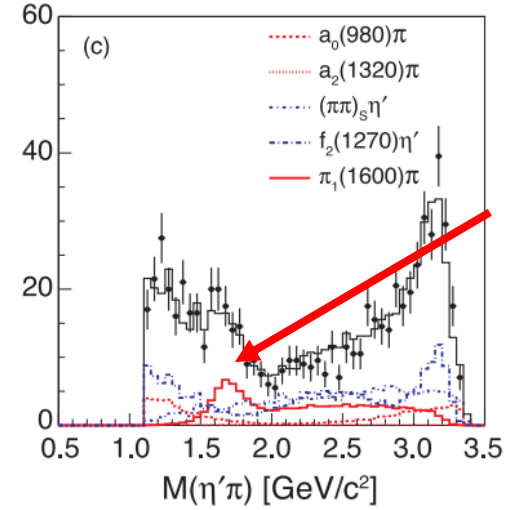
Studies of π_1 in $\chi_{c1} \to \pi^+\pi^-\eta^{(\prime)}$

PR D84 112009 (2011)

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



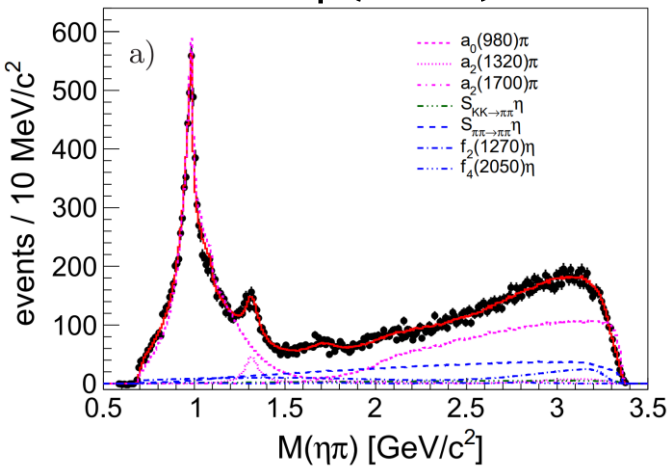
No evidence of $\pi_1 \to \eta\pi$



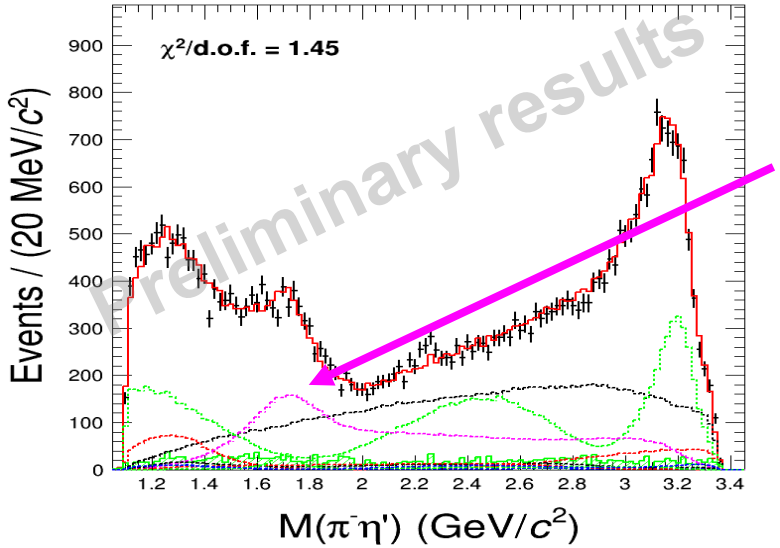
Evidence of $\pi_1 \to \eta'\pi$ (without significant BW phase motion)

PR D95 032002(2017)

44.8×10^7 $\psi(3686)$@BESIII

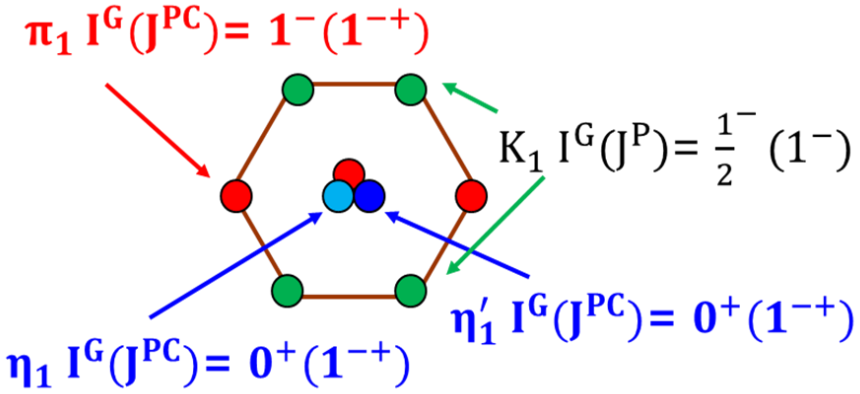


$\mathbf{2.7 \times 10^9}$ $\psi(3686)$@BESIII [New]



- $\pi_1(1600)$ observed>10σ
- with a significant BW phase motion
- $J^{PC}= 1^{-+}$, better than other assignments well over 10σ

What about K_1 ?



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

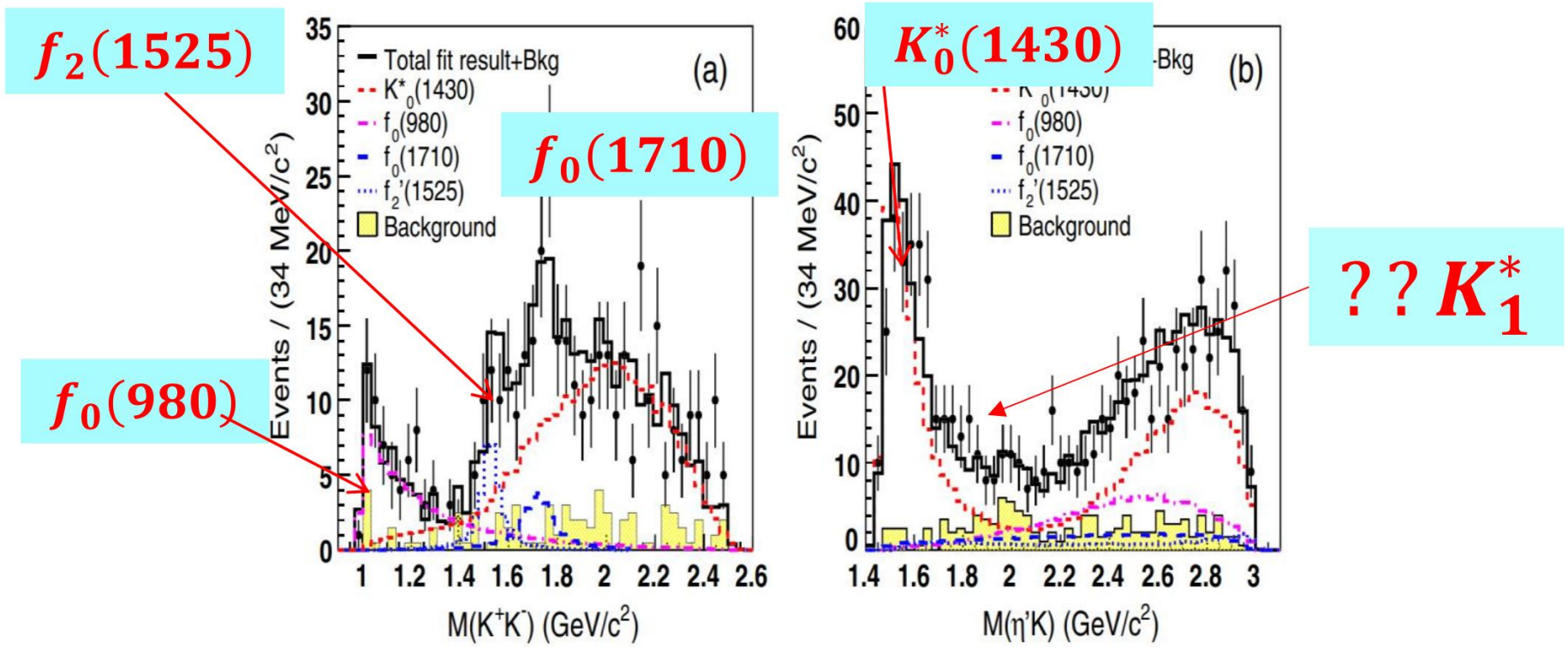
Decay property is the key

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

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

PWA with 106 million $\psi(3686)$

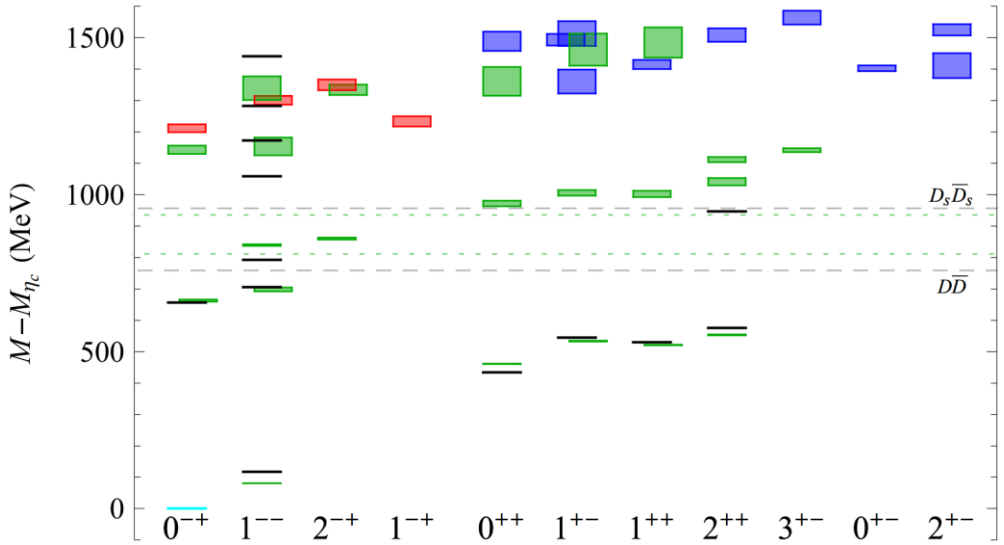
PhysRevD.89.074030



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

$\bar{c}cg$ hybrids

LQCD predicts similar supermultiplet as light hybrids



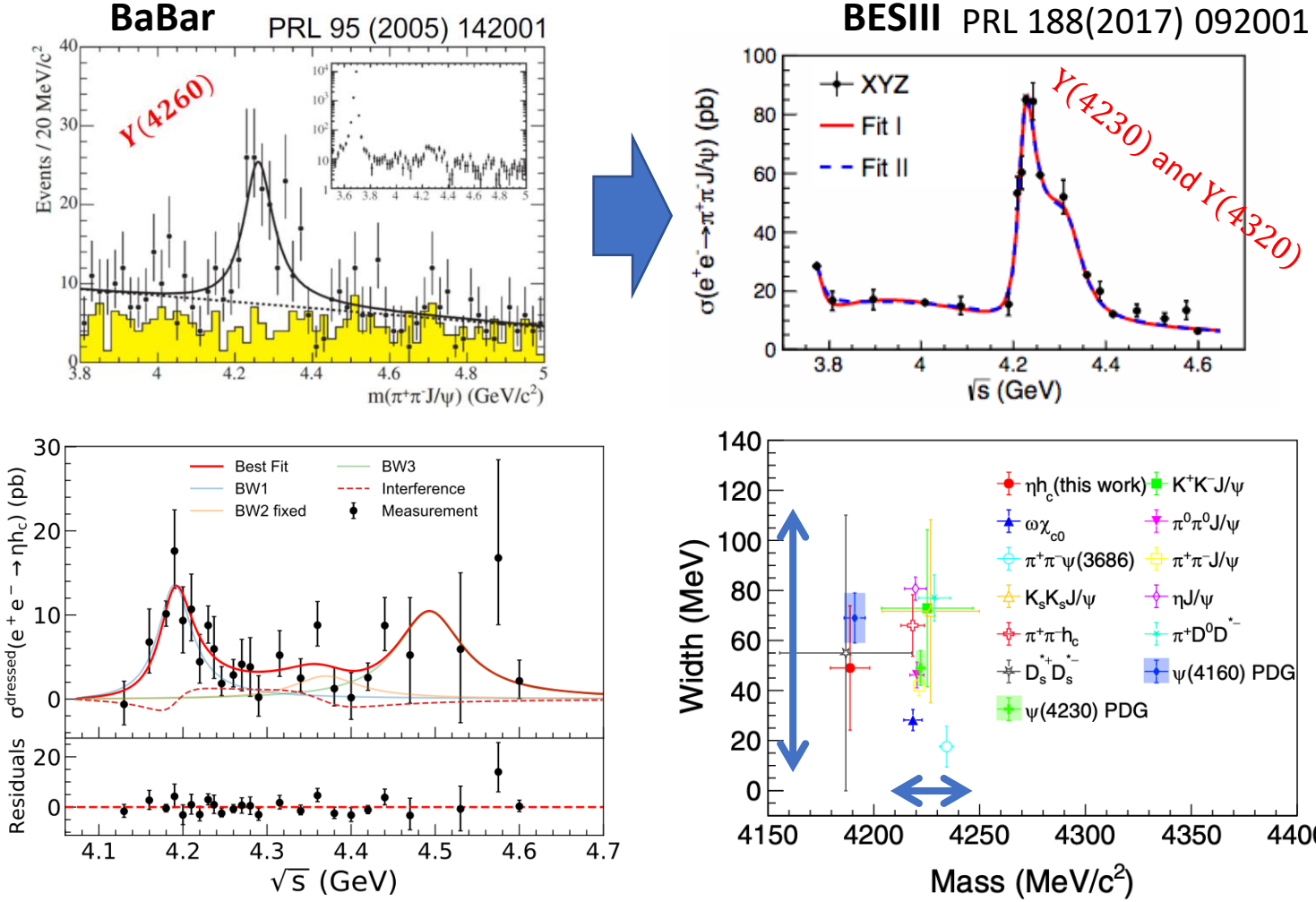
JHEP 07 (2012), 126

- 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

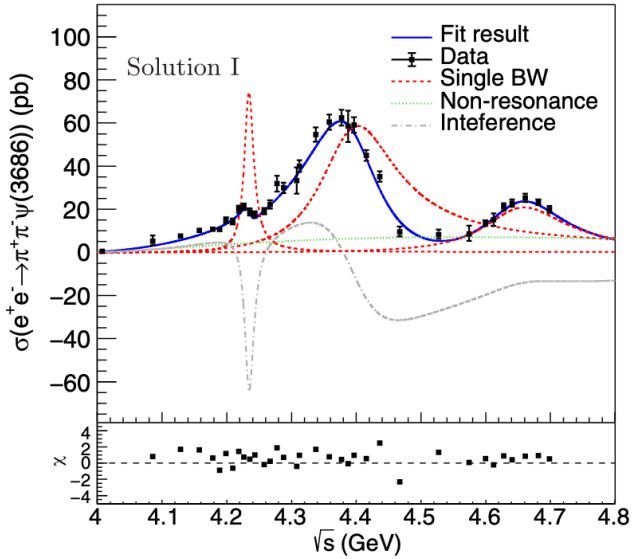
Vector states: Y(4260) → Y(4230)

- Y(4260) firstly seen by BaBar, afterwards split into two states $\mathrm{Y}(4230)$ and $\mathrm{Y}(4320)$ by BESIII
  - Inconsistent with simple $c\bar{c}$ scenario
  - Candidates for exotics:
    - Hybrid ($gc\bar{c}$)?
    - Hadronic molecule ?
    - Tetraquark ?
- Seen in more than ten decay modes at BESIII
  - With consistent mass, not width



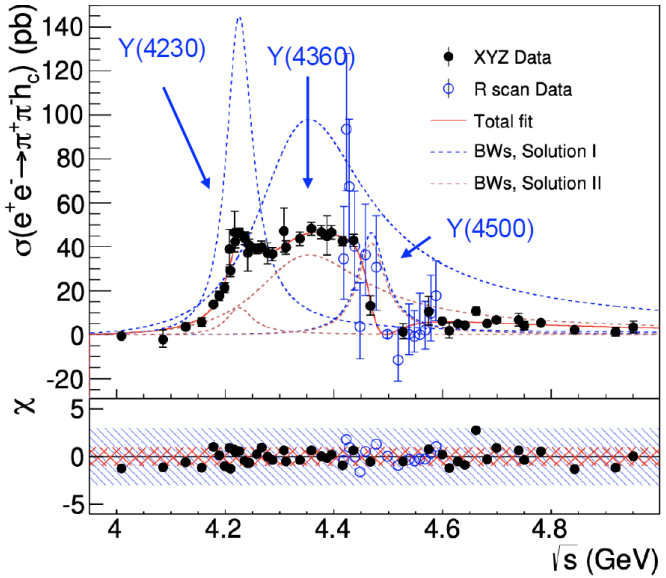
BESIII, Phys.Rev.D 111 (2025) 1, L011101

Vector states: at higher masses



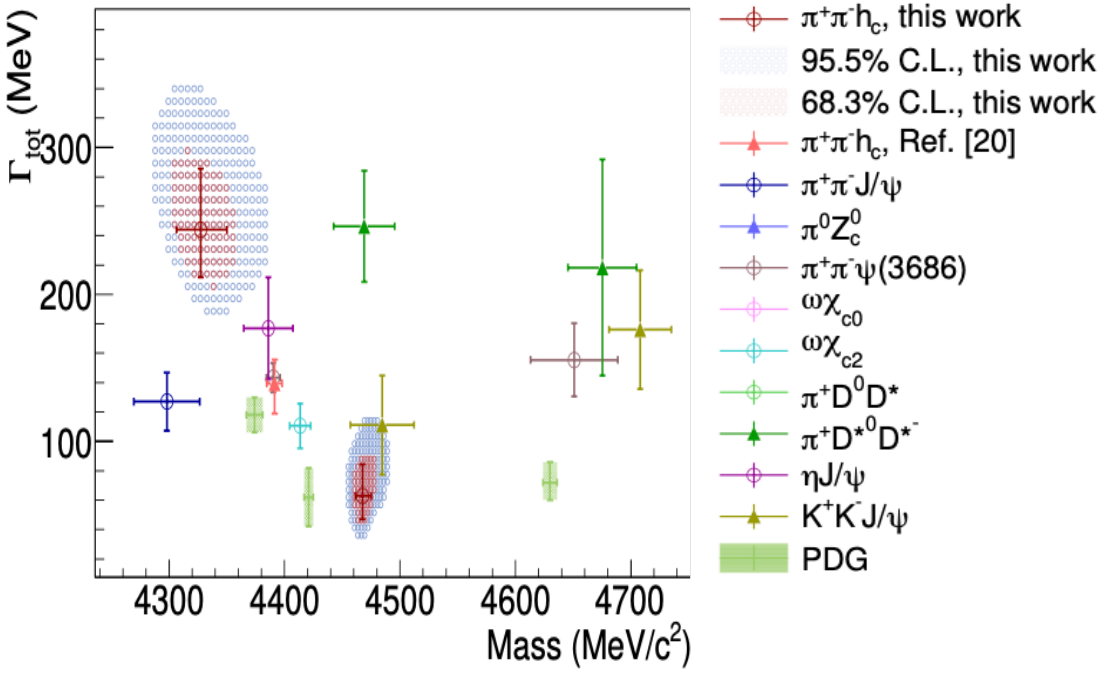
$e^+e^- \to \pi\pi\psi(3686)$

BESIII, PRD 104 (2021), 052012



$e^+e^- \to \pi\pi h_c$

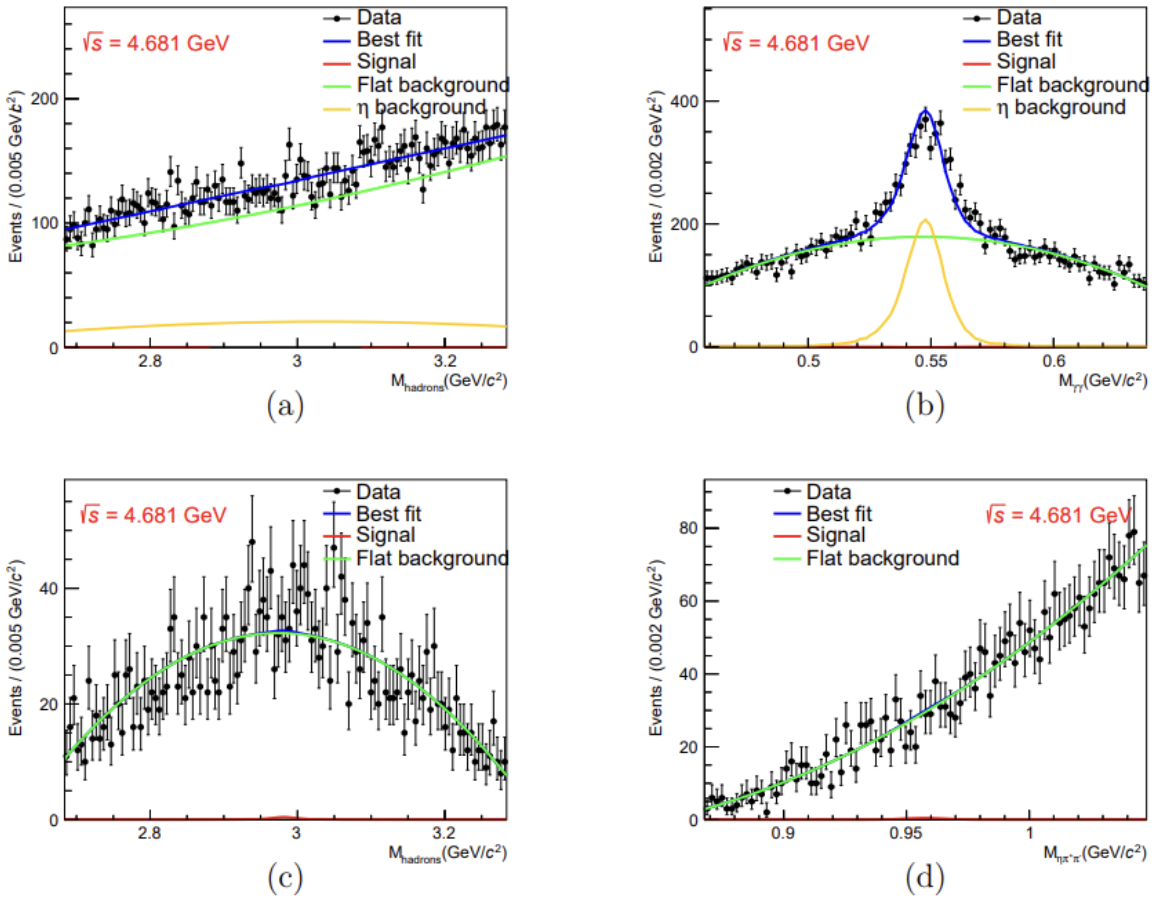
BESIII, arXiv: 2504.04096



Less consistency between exclusive channels

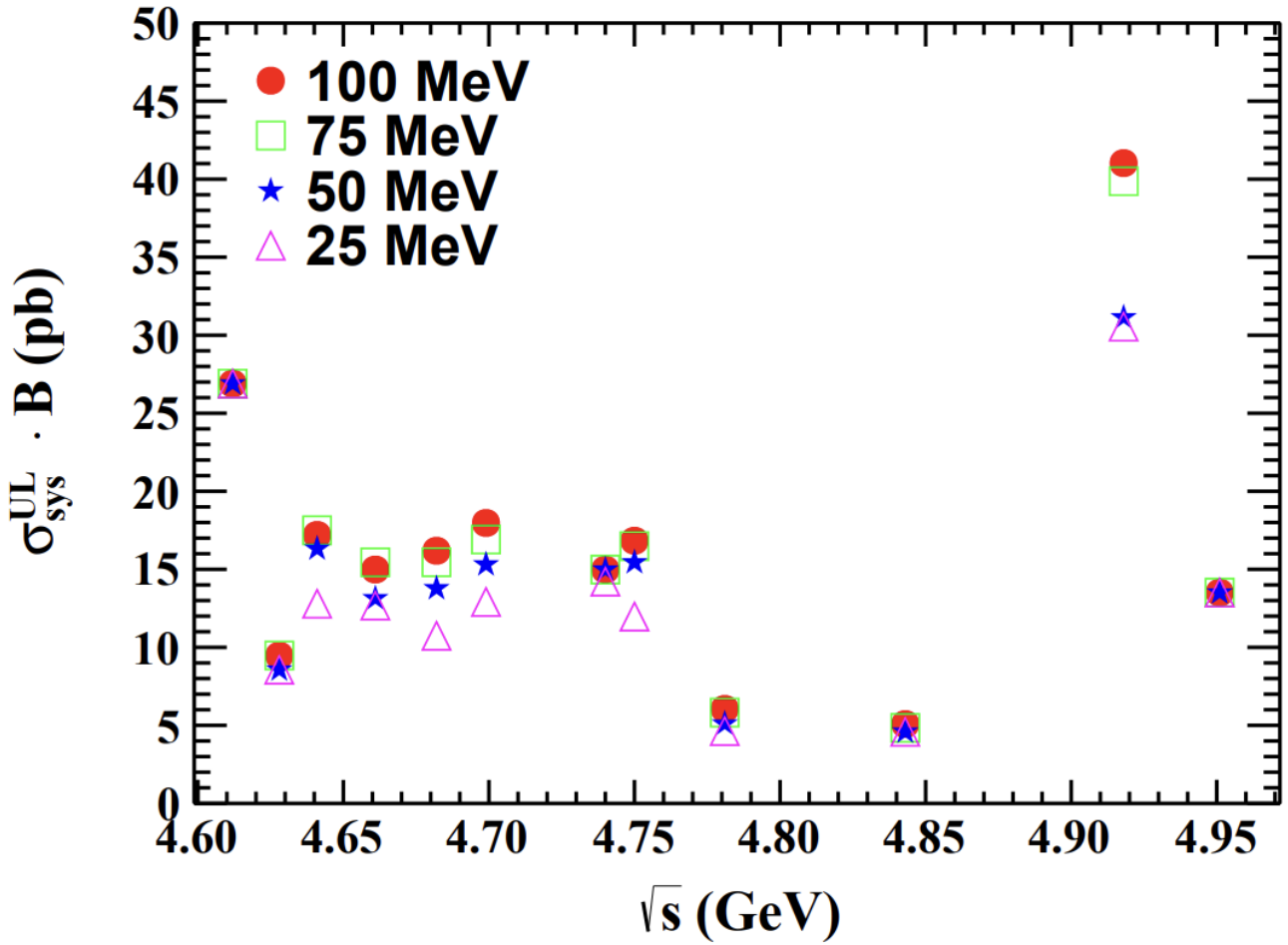
Search for 1^{-+} charmonium-like hybrid via $e^+e^- \to \gamma\eta^{(\prime)}\eta_c$ at center-of-mass energies between 4.258 and 4.681 GeV

BESIII PR D 111, 112007 (2025)



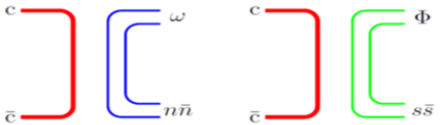
Search for a 1^{-+} molecular state via $e^+e^- \to \gamma D_s^+ D_{s1}^-(2536) + c.c.$

BESIII PRD 112, 032002(2025)

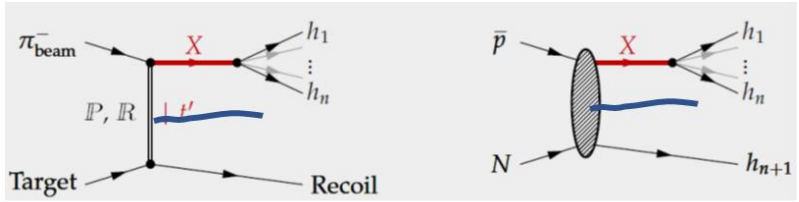


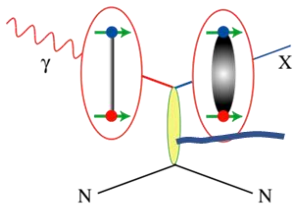
1^{-+} Hybrids

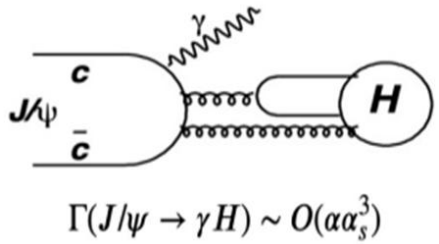
- How to discriminate hybrid/molecule/tetraquark?
  - $\eta_1(1855) \to f_1\eta$, K_1K are important
  - $\Gamma_{\pi_1\to b_1\pi}/\Gamma_{\pi_1\to\eta'\pi}$ is not available yet
- Where is the $\boldsymbol{\eta_1^{(\prime)}}$? $J/\psi \to \omega\eta\eta'$, $\phi\eta\eta'$ to access quark contents



- 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**





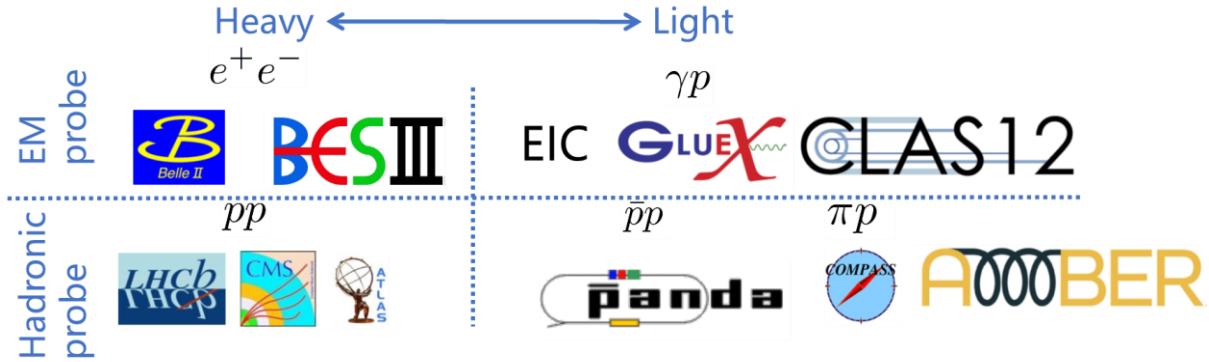


Outlook

- Having established the existence of new forms of hadrons is only the starting point
  - Measure their properties
  - Establish the multiplets

  } Underlying physics responsible for the rich spectrum

- Global efforts with various probes in running and planned experiments
  - BESIII plays a leading role in the studies of glueballs and hybrids



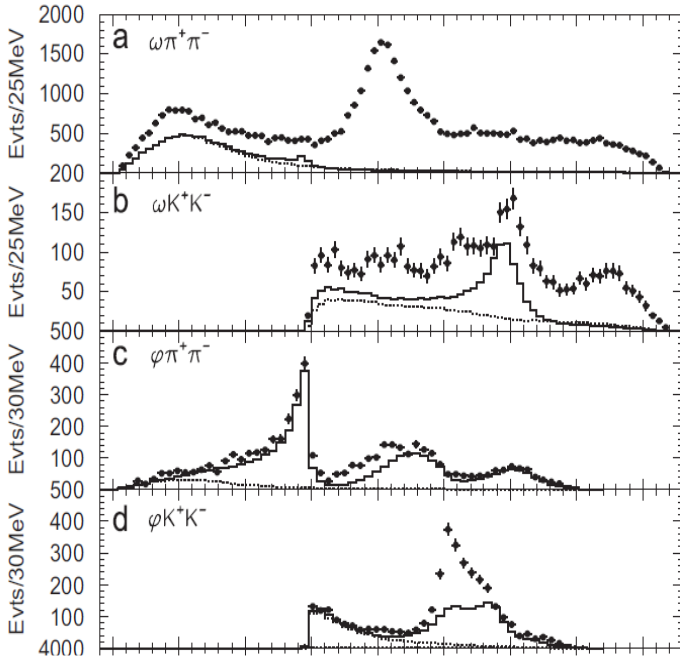
- Leveraging the high precision of current and future data requires
  - Advanced analysis techniques
  - Close theory-experiment collaboration

Thank you for your attention

backup

At least 2 scalars around 1.7 GeV

$f_0(1710)/f_0(1790)$?

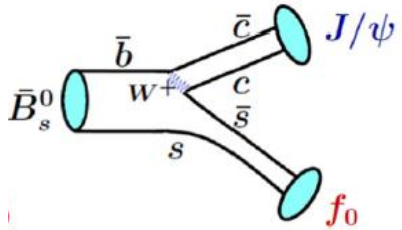


ωK^+K^- ➜ Peak around 1700 MeV/c^2
(OZI rule: $n\bar{n}$ structure)

$\phi\pi^+\pi^-$ ➜ Enhancement at 1790 MeV/c^2

ϕK^+K^- ➜ No peak around 1700 MeV/c^2

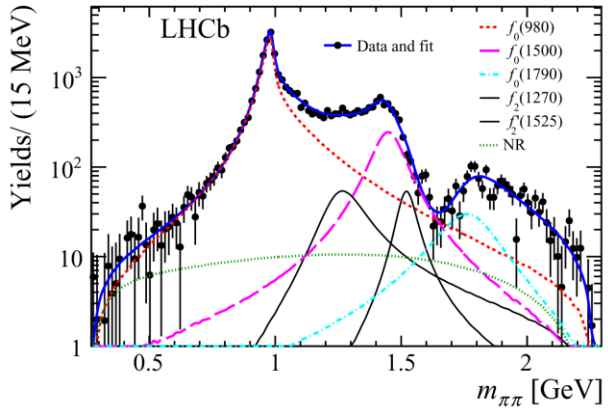
$f_0(1800)$

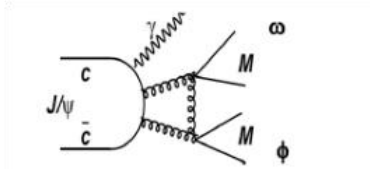


selective for $s\bar{s}$

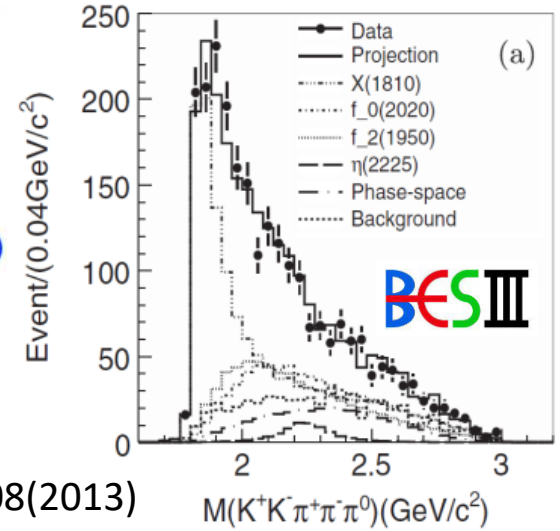
$B_s \rightarrow J/\psi f_0$

PLB 797 (2019) 134789





$J/\psi \rightarrow \gamma\omega\phi$ **(DOZI)**



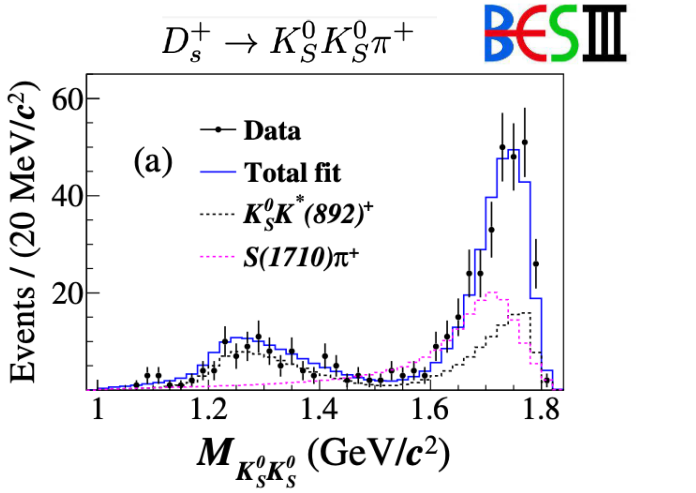
PRD 87, 032008(2013)

$a_0(1817)$

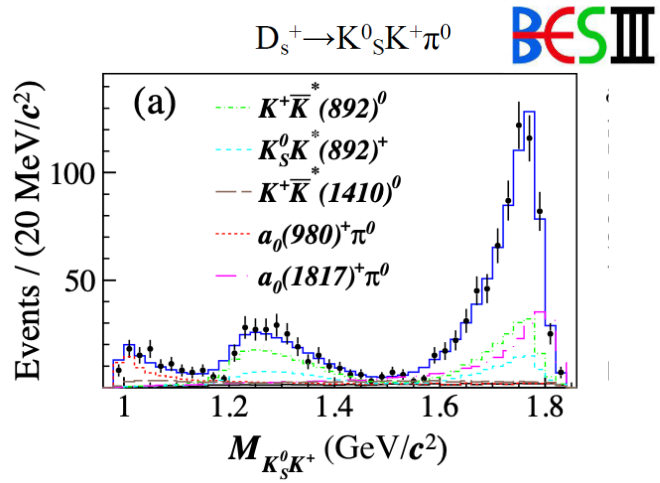
Isovector partner of $f_0(1800)$?

[Shulei 's talk]

PRD105, L051103 (2022)



PRL129, 182001 (2022)



Two photon couplings

$\gamma\gamma \to K_S K_S$

Belle PTEP 2013 (2013) 12, 123C01

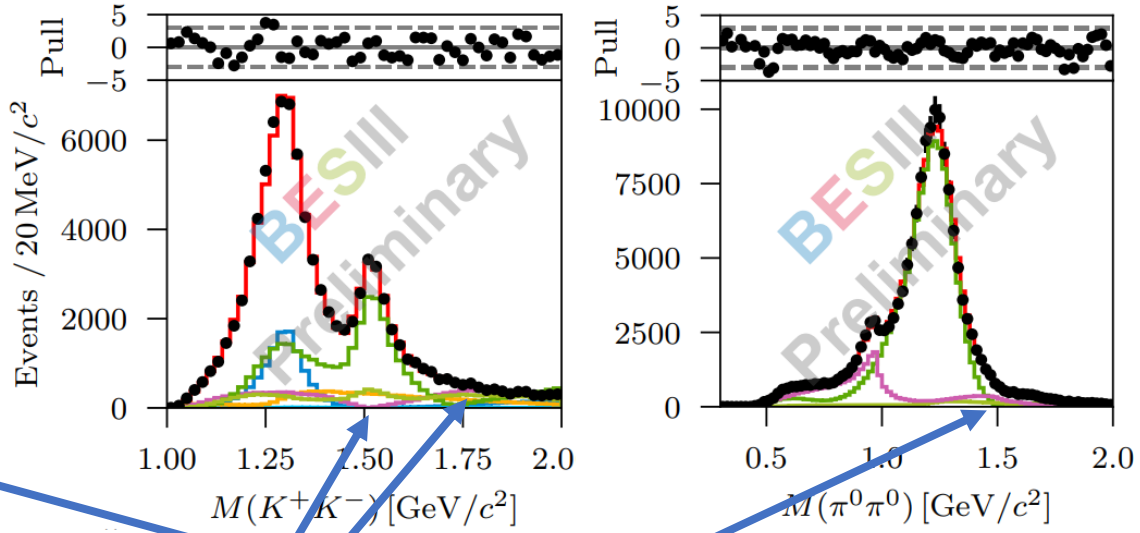
Parameter	$f_0(1710)$ fit			
	fit-H	fit-L	H,L combined	PDG
χ^2/ndf	694.2/585	701.6/585	–	–
Mass(f_J) (MeV/c^2)	1750^{+5+29}_{-6-18}	1749^{+5+31}_{-6-42}	1750^{+6+29}_{-7-18}	1720 ± 6
$\Gamma_{\rm tot}(f_J)$ (MeV)	138^{+12+96}_{-11-50}	145^{+11+31}_{-10-54}	139^{+11+96}_{-12-50}	135 ± 6
$\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})_{f_J}$ (eV)	12^{+3+227}_{-2-8}	21^{+6+38}_{-4-26}	12^{+3+227}_{-2-8}	unknown

$\gamma\gamma \to \pi^0\pi^0$

Belle PRD 78 (2008) 052004

Parameter	Nominal	$r_{02} = 0$	No $f_0(Y)$	Unit
Mass($f_0(980)$)	982.2 ± 1.0	980.2 ± 1.0	$983.7^{+1.5}_{-1.0}$	MeV/c^2
$\Gamma_{\gamma\gamma}(f_0(980))$	$285.5^{+17.2}_{-17.1}$	$297.0^{+14.2}_{-13.7}$	$370.5^{+20.2}_{-18.7}$	eV
$g_{f_0(980)\pi\pi}$	1.82 ± 0.03	1.79 ± 0.03	1.89 ± 0.03	GeV
Mass($f_0(Y)$)	1469.7 ± 4.7	1466.8 ± 0.6	–	MeV/c^2
$\Gamma(f_0(Y))$	$89.7^{+8.1}_{-6.6}$	$422.4^{+18.4}_{-19.8}$	–	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(f_0(Y) \to \pi^0\pi^0)$	$11.2^{+5.0}_{-4.0}$	$6780.2^{+626.5}_{-574.7}$	0 (fixed)	eV

BESIII preliminary



$f_0(1710)?$ $f_0(1800)?$

$f_0(1500)?$

Proper assignment requires **more sophisticated model**

Two photon couplings

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

Belle PRD 86 052002(2012)

