Light QCD exotics at BESIII

刘北江

中国科学院高能物理研究所

第二届强子物理新发展研讨会 暨 强子物理在线论坛100期特别活动

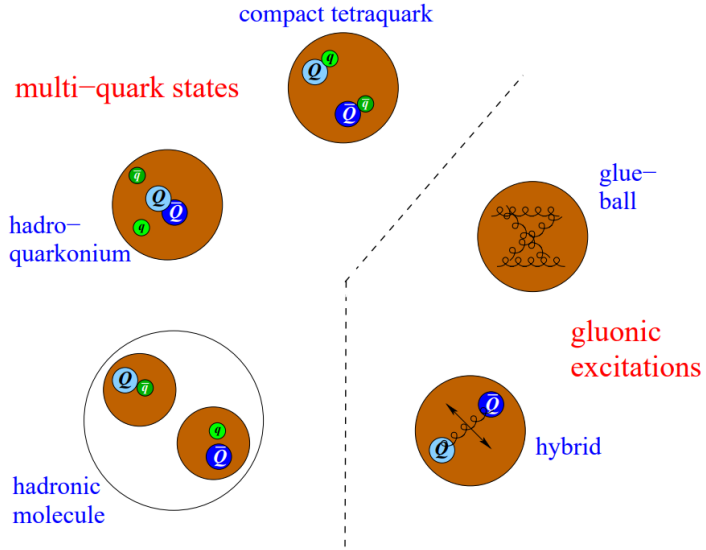
中国科学技术大学，6.30-7.4，2024

Hadron spectroscopy

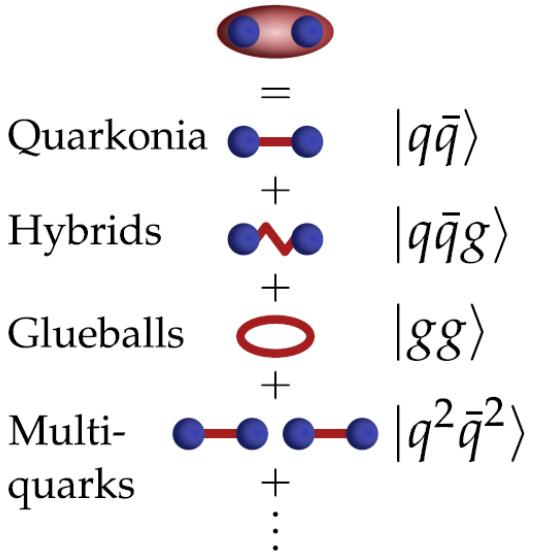
- **How does QCD give rise to hadrons?**
  - **Quark model seems to work really well. Why?**
- **Key things to search for: additional degree of freedom**
  - Strong evidences for multi-quark in heavy quark sector

https://qwg.ph.nat.tum.de/exoticshub/

  - **Evidence for gluonic excitations remains sparse**



Phys.Rept. 873 (2020) 1



Physical meson

A linear superposition of all allowed color-singlet configurations

Identification is challenging

Manifestly exotic: with forbidden QN

Flavor exotic: $Z_c, T_{cc}, T_{\psi\psi}$ ……

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

Crypto exotic: with QN as $\mathbf{q\bar{q}}$

Supernumerary states

Abnormal properties

+ Kinematic effects

Light QCD exotics

Light sector is even harder

- **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

- Spin-exotics
  [HAPOF # 60]

Smoking gun

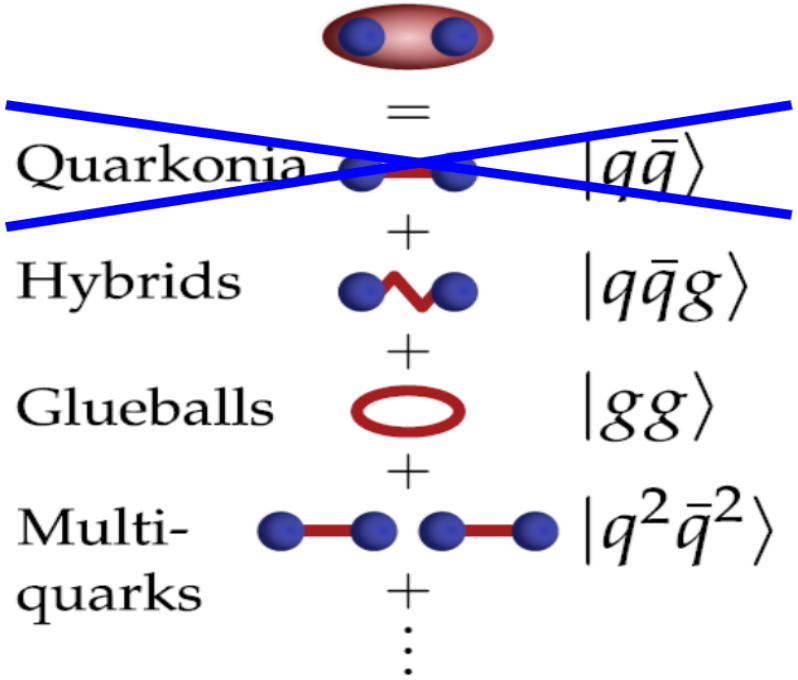
Manifestly exotic

Crypto exotic

- Glueballs (supplemented with more stuff)
  [HAPOF #65, 98]
- Threshold structures (not covered in this talk)
  [HAPOF #76, 80]

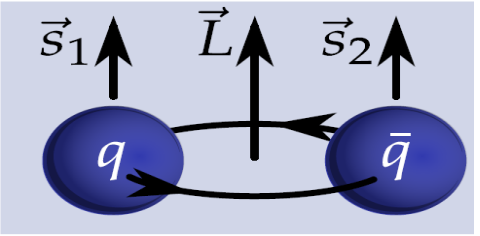
A smoking gun——
Light hadrons with exotic quantum numbers

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



Experiments:

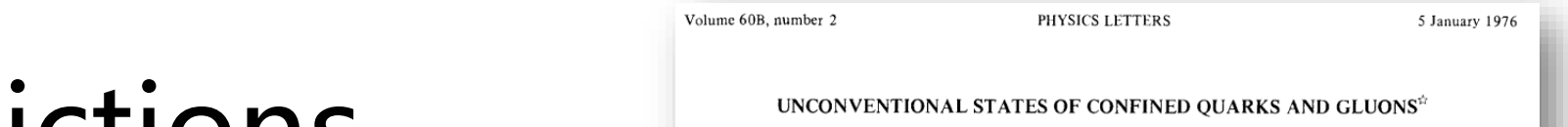
- **Hadroproduction:** GAMS, VES, E852, COMPASS
- **$p\bar{p}$ annihilation:** Crystal Barrel, OBELIX, PANDA(under construction)
- **Photoproduction:** GlueX(2017-), CLAS



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

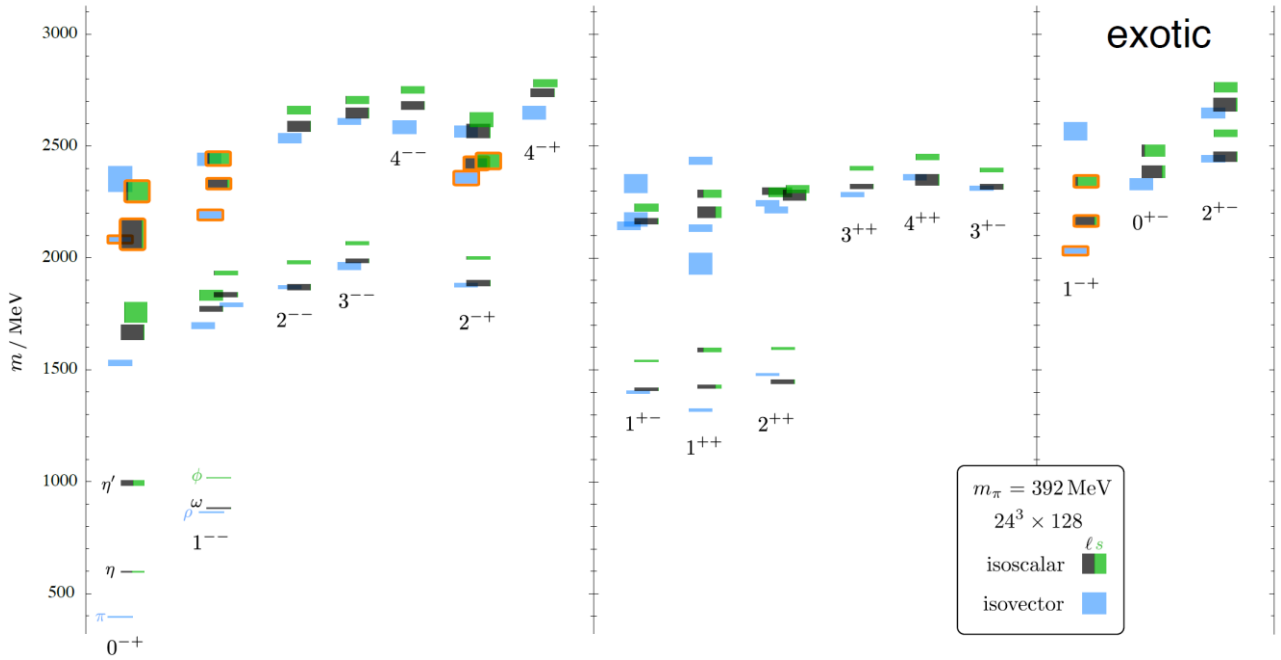
Allowed $\mathbf{J^{PC}}$: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$

Predictions


Volume 60B, number 2 PHYSICS LETTERS 5 January 1976

UNCONVENTIONAL STATES OF CONFINED QUARKS AND GLUONS☆

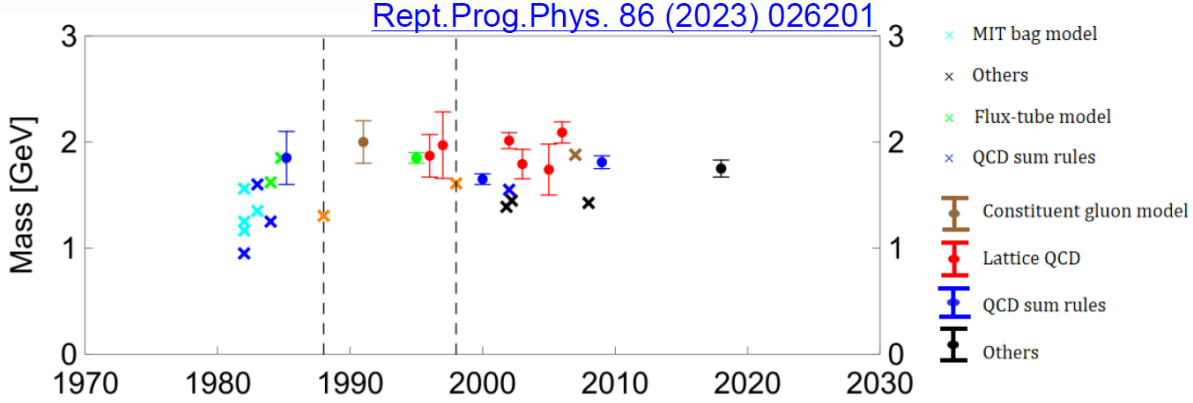
R.L. JAFFE* and K. JOHNSON



PRD 88 094505(2013)

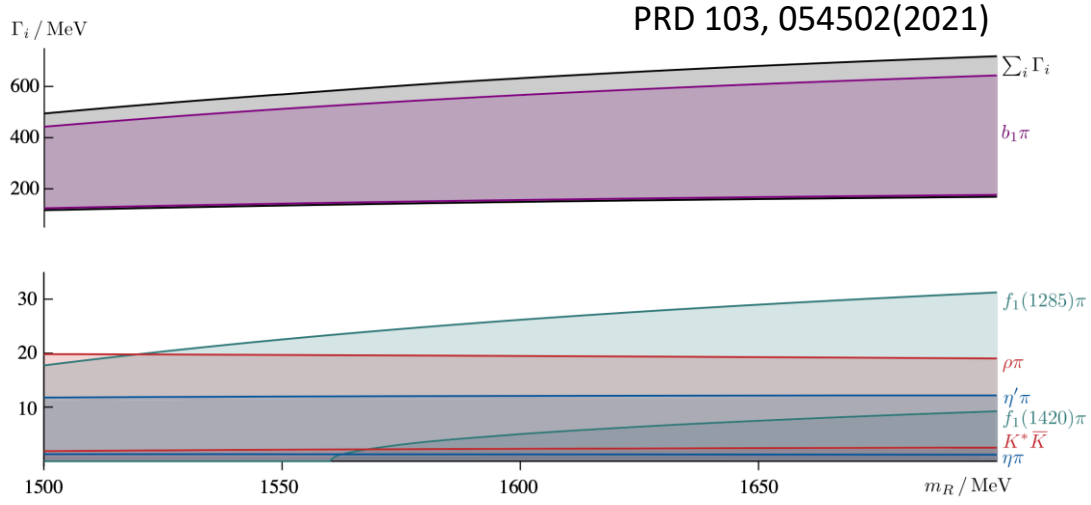
Lightest spin-exotic state in LQCD: 1^{-+} hybrid

Rept.Prog.Phys. 86 (2023) 026201



Mass of 1^{-+} hybrid

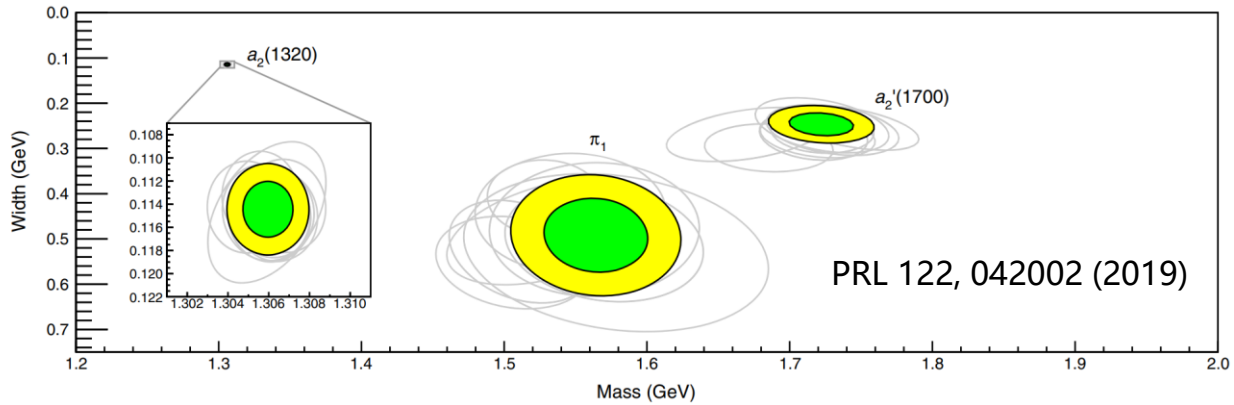
PRD 103, 054502(2021)



Decay width of 1^{-+} hybrid π_1

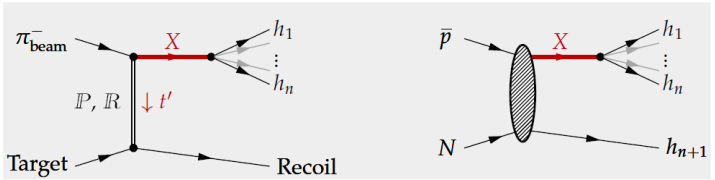
Spin-exotic mesons

- **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 $f_1\pi$
- Some claims are controversial
- $\pi_1(1400)$ & $\pi_1(1600)$ can be one pole



PRL 122, 042002 (2019)

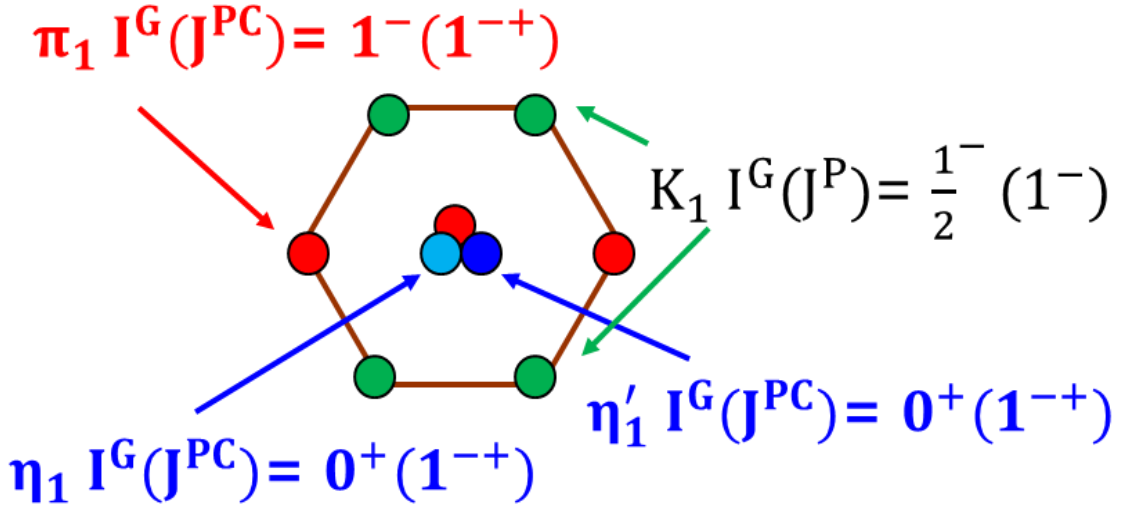
Detailed reviews: PRC 82, 025208 (2010), PPNP 82, 21 (2015)



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

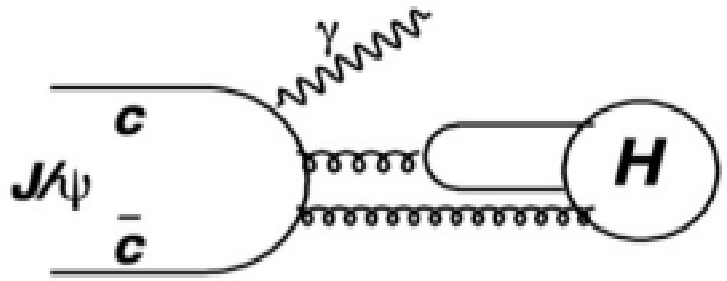
1^{-+} Hybrids

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

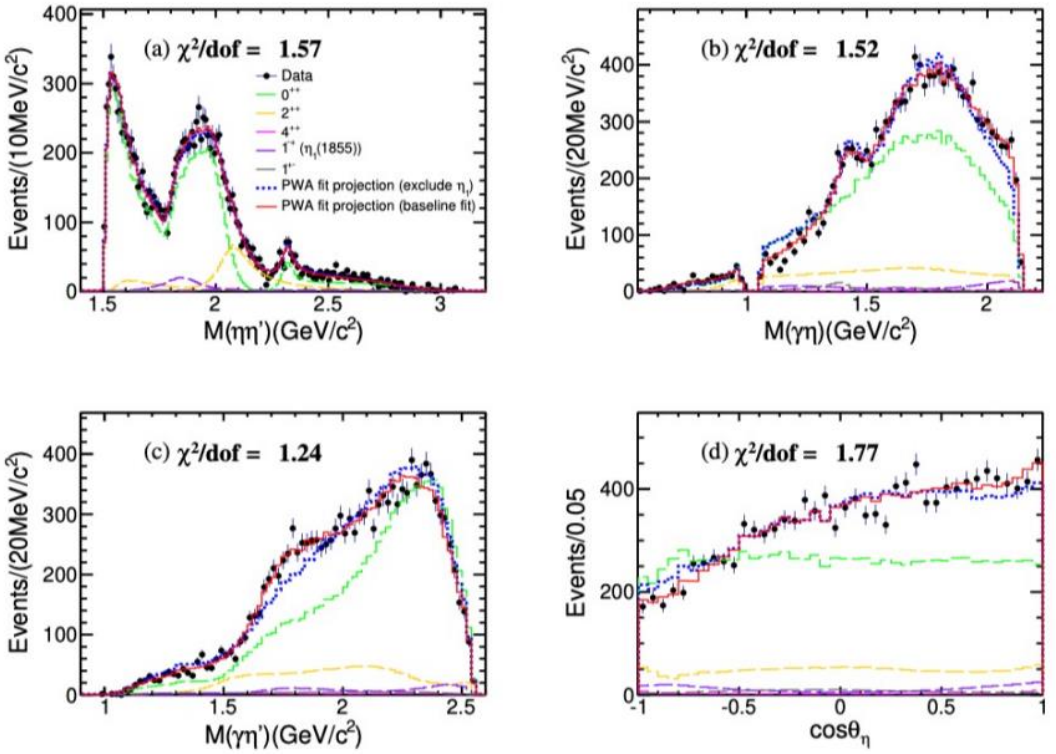


$$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$$

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

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

- The η' is reconstructed from $\gamma\pi^+\pi^-$ & $\eta\pi^+\pi^-$, η from $\gamma\gamma$
- Partial wave analysis of $J/\psi \to \gamma\eta\eta'$
  - Quasi two-body decay amplitudes in the sequential decay processes $J/\psi \to \gamma X, X \to \eta\eta'$ and $J/\psi \to \eta X, X \to \gamma\eta'$ and $J/\psi \to \eta' X, X \to \gamma\eta$ are constructed using the covariant tensor formalism[Eur. Phys. J. A 16, 537] and GPUPWA [J. Phys. Conf. Ser. 219, 042031(2010)] *



World's first PWA framework with GPU acceleration

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

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

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

- **Mass is consistent with LQCD calculation for the 1^{-+} hybrid ($1.7 \sim 2.1$ GeV/c^2)**

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:

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

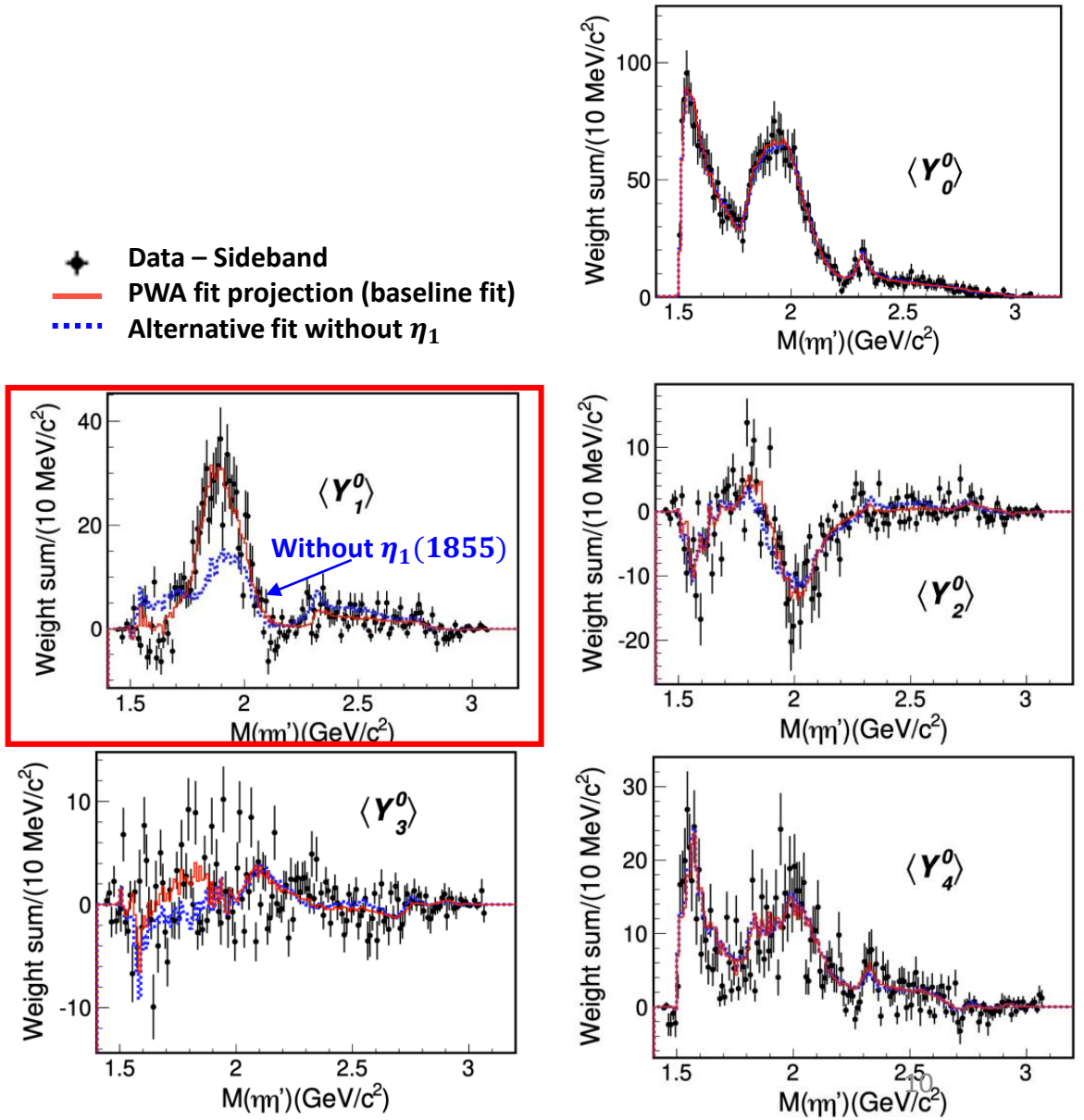
$$\sqrt{4\pi}\langle Y_1^0\rangle = 2S_0P_0\cos\phi_{P_0} + \frac{2}{\sqrt{5}}(2P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) + \sqrt{3}P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

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

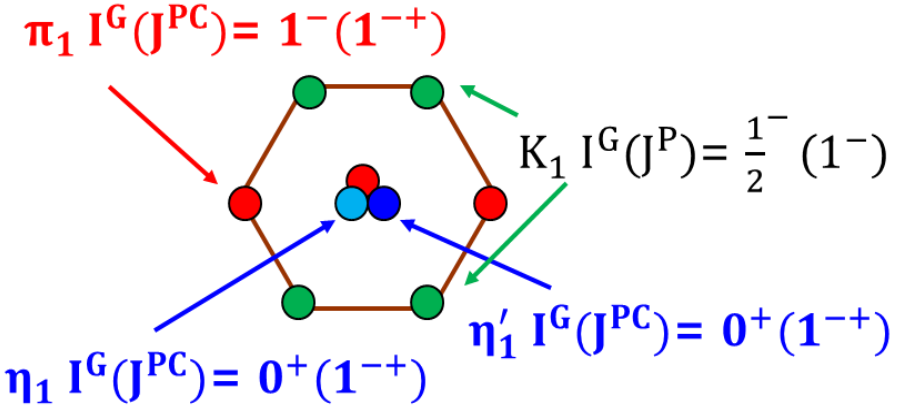
$$\sqrt{4\pi}\langle Y_3^0\rangle = \frac{6}{\sqrt{35}}(\sqrt{3}P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) - P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

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

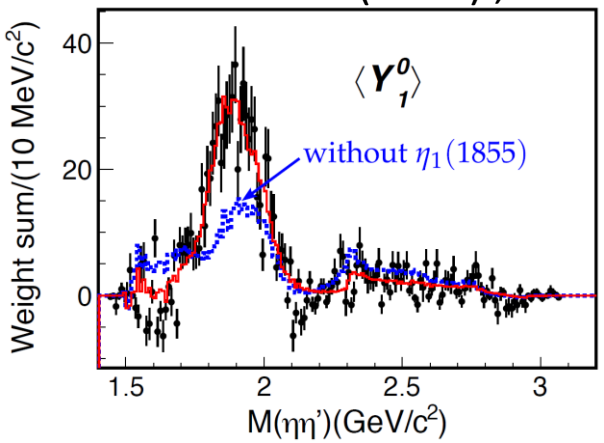
- **Narrow structure** in $\langle Y_1^0 \rangle$
  - **Cannot be described by resonances in $\gamma\eta(\eta')$**
  - **$\eta_1(1855) \to \eta\eta'$ needed**



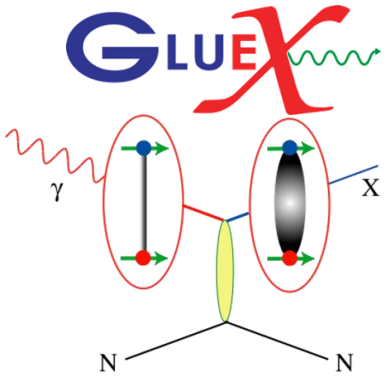
Observation of **An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$**



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



- **Opens a new direction to completing the picture of spin-exotics**
- **Inspired many interpretations: Hybrid/$K\bar{K}_1$Molecule/Tetraquark?**
- **Remarks:**
  - **Snowmass2021: RF7 Summary**
  - **The present and future of QCD (LRP23 whitepaper)** [NPA 1047 122874(2024)]
    - **Significant impact to the research planning of GlueX @JLab**



"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

Uniqueness, enrichment and complementary

- **High statistics gluon-rich environment: 10 B J/ψ, 2.7 B ψ', a lot of χ_{cJ}**

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 $\bar{c}c$**

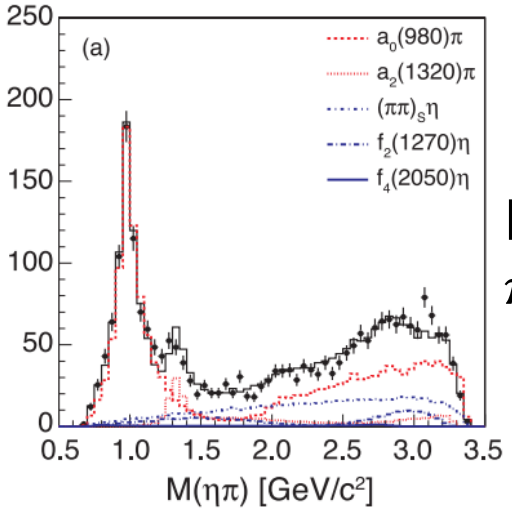
Isovector: $\pi_1(1600)$

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

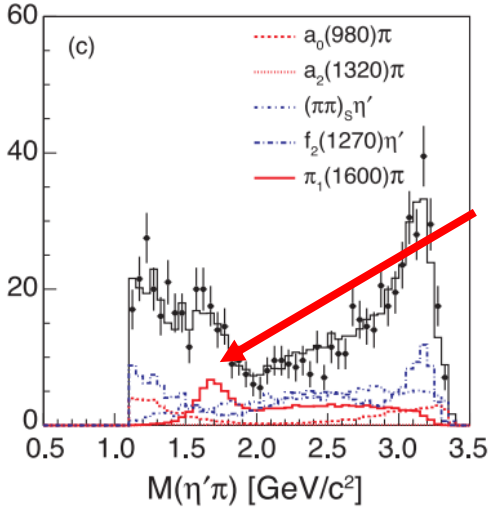
$\chi_{c1} \to \pi^+\pi^-\eta^{(\prime)}$

PR D84 112009 (2011)

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



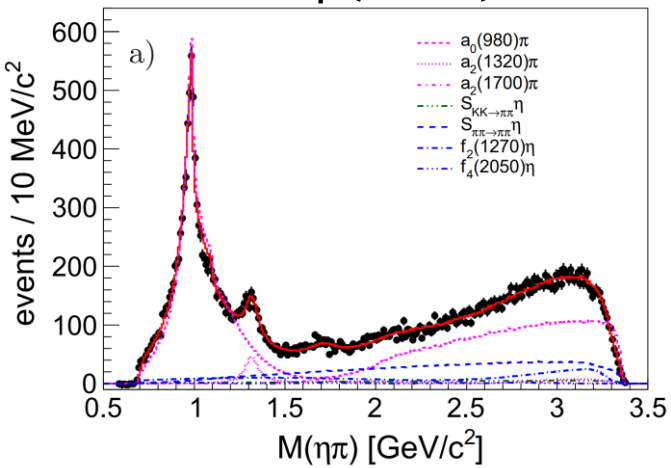
No evidence of $\pi_1 \to \eta\pi$



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

PR D95 032002(2017)

44.8×10^7 ψ(3686)@BESIII



$\mathbf{2.7 \times 10^9}$ ψ(3686)

Stay tuned

- Spin-exotics

- Glueballs

Glueballs

- **Light-mass glueballs with ordinary J^{PC}**

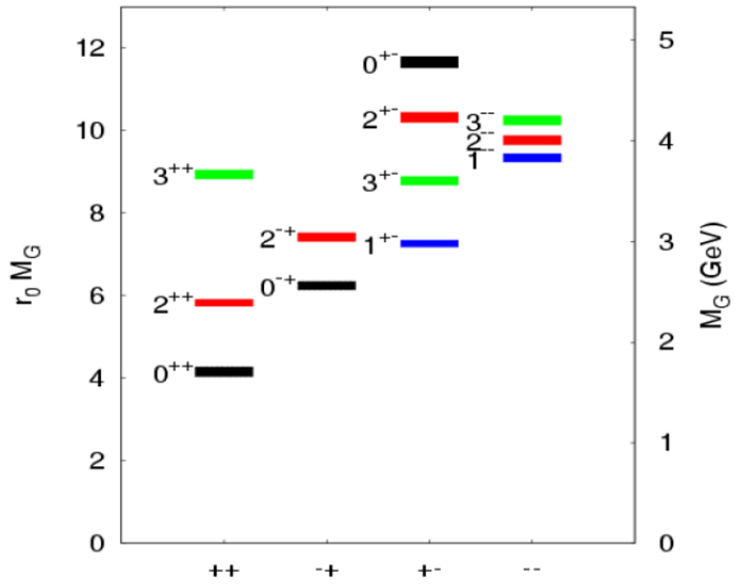
→ **mixing with $q\bar{q}$ mesons**

➢Challenge: reveal the exotic admixture

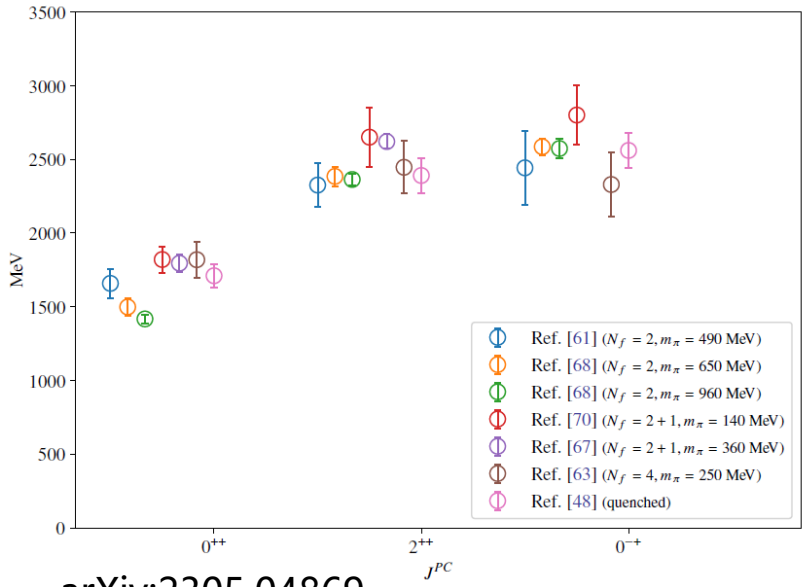
- **Non-$q\bar{q}$ nature difficult to be established**
  - **Overpopulation, but QM assignment is difficult**
  - **Identification is model-dependent**

→ **Requires systematic study**

PRD 73 014516 (2006)



Yang-Mills glueballs on lattice



arXiv:2305.04869

What we have learned before

-- from MarkIII, BES, Crystal barrel, OBELIX, WA102, GAMS, E852, …

e^+e^- annihilation

$p\bar{p}$ annihilation

central exclusive production

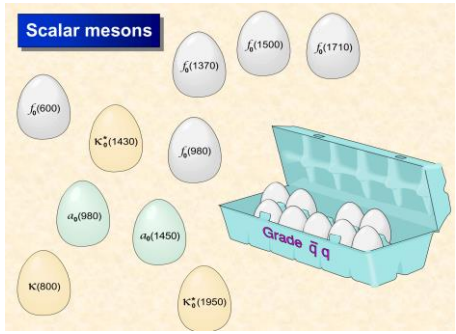
charge-exchange reactions

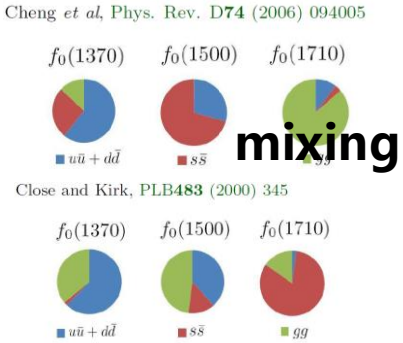
Scalar: 1 nonet in quark model, f_0 & f_0'

Exp: **overpopulation**

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

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





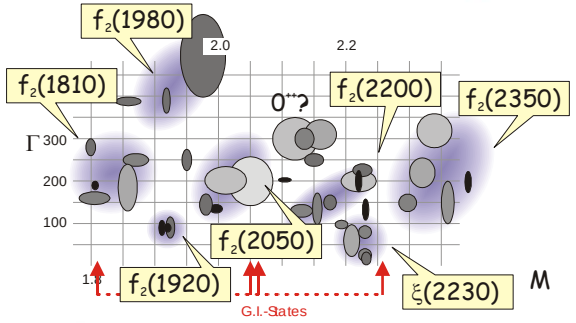
mixing schemes

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

Exp: **large uncertainty**

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

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

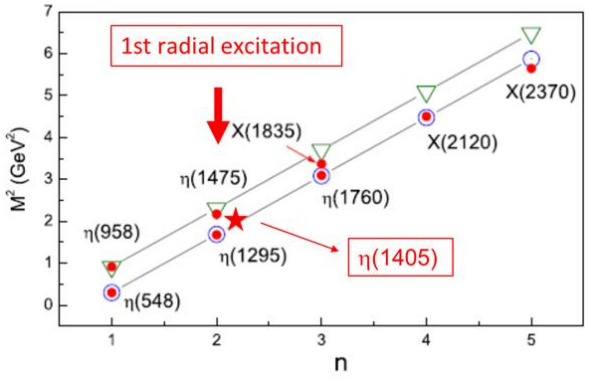


Pseudoscalar: η & η' , "simple"

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

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

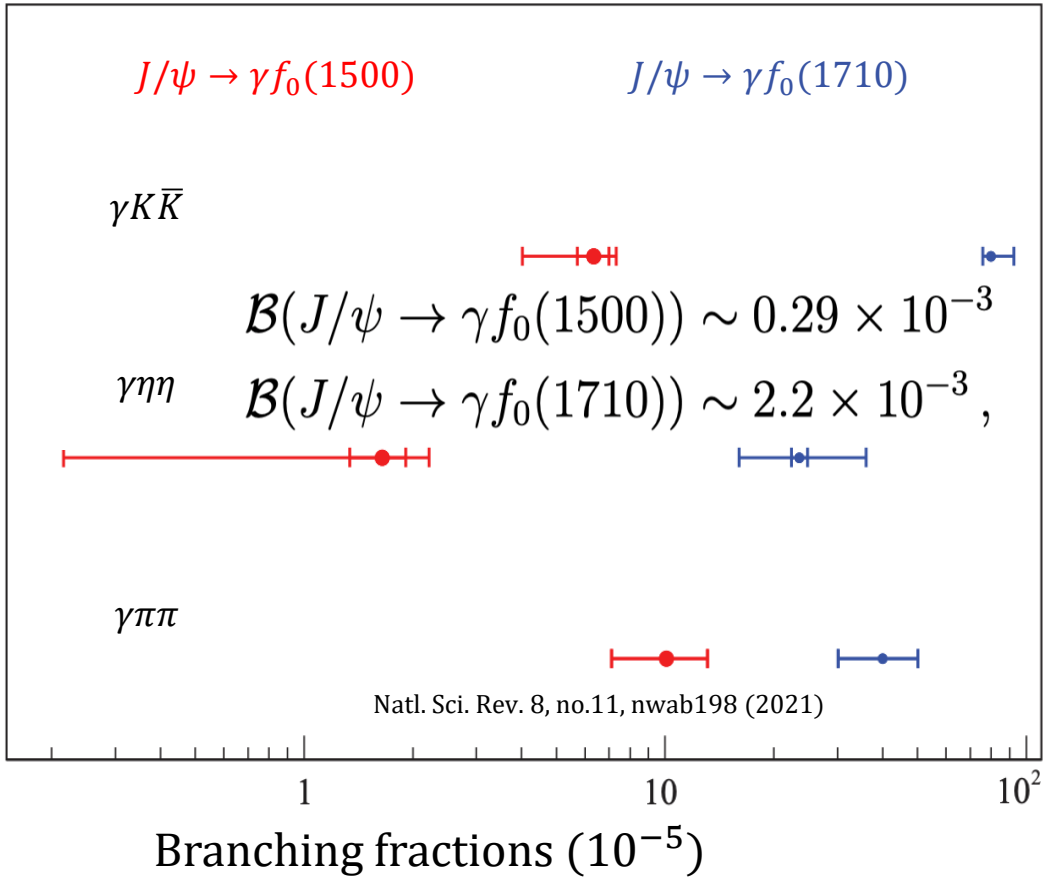
$$\Gamma(J/\psi \to \gamma G_{0-})/\Gamma_{total} = 2.31(80) \times 10^{-4}$$



Scalar glueball candidate: **production properties**

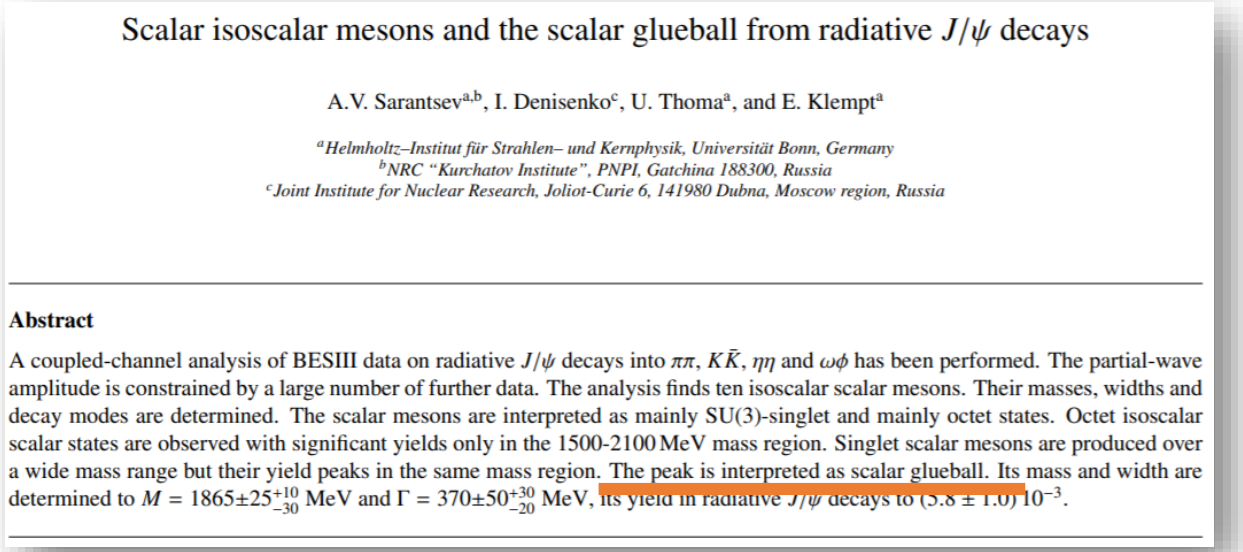
- **Scalar glueball is expected to have a large production in $\mathbf{J/\psi}$ radiative decays**:
  - LQCD: $\Gamma(\mathrm{J/\psi} \to \gamma \mathrm{G_{0+}})/\Gamma_{total} = 3.8(9) \times 10^{-3}$
  - Observed $\mathrm{B}(\mathrm{J/\psi} \to \gamma \mathrm{f_0}(1710))$ is x10 larger than $\mathrm{f_0}(1500)$

➢ **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)

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



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

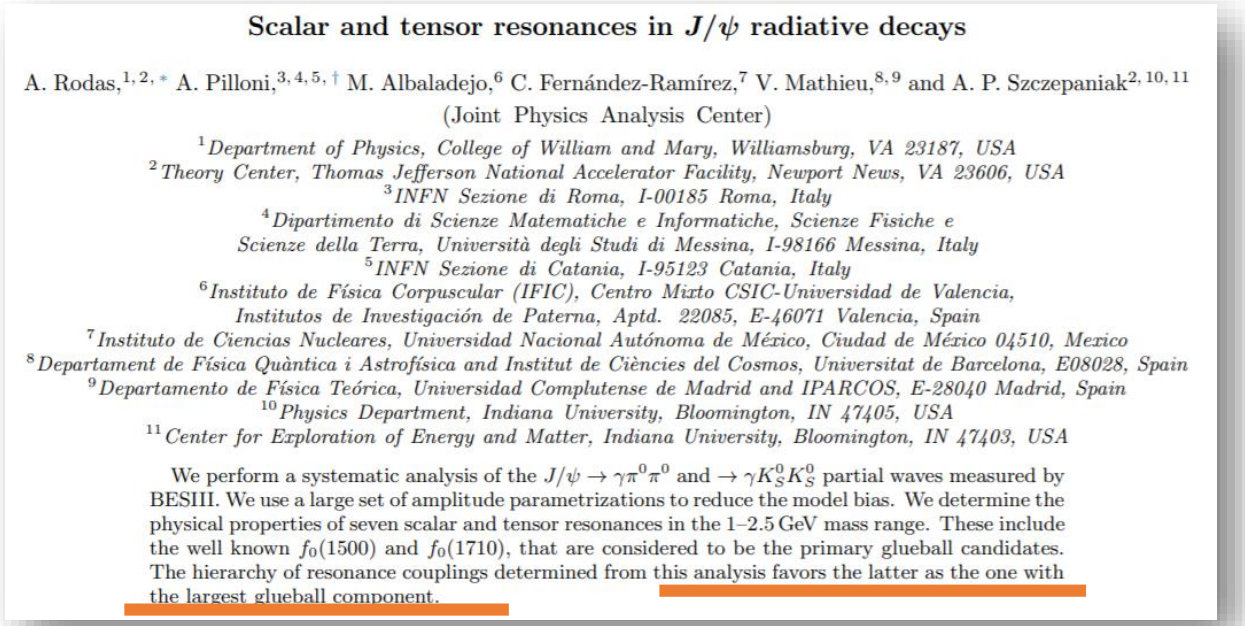
A.V. Sarantsev[a,b], I. Denisenko[c], U. Thoma[a], and E. Klempt[a]

[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)



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

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 $f_0(1500)$

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

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

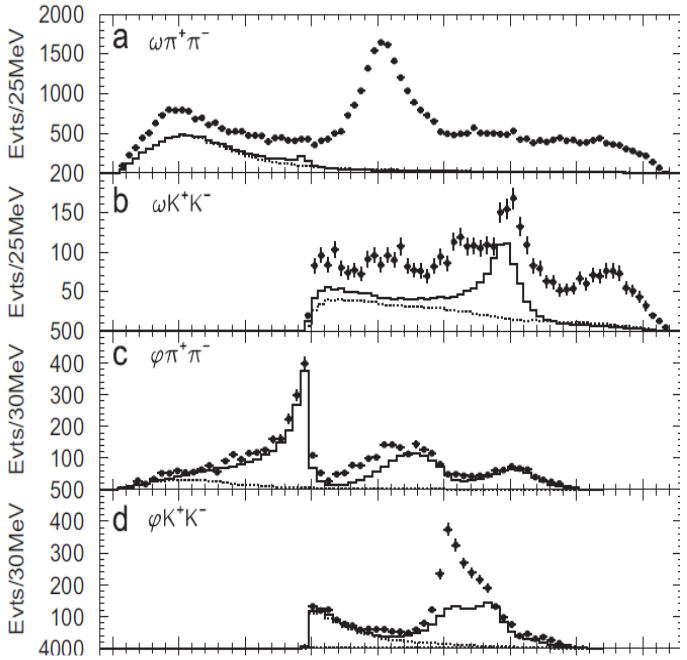
$$B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$$

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

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

More scalars

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

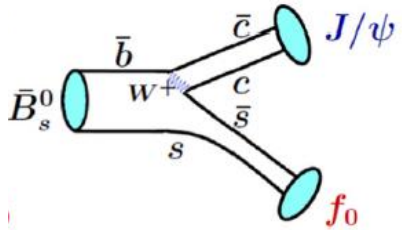


ωK^+K^- ➔ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

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

ϕK^+K^- ➔ No peak around 1700 MeV/c^2

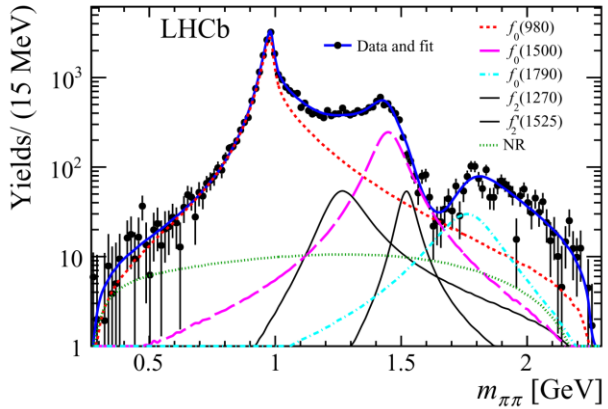
$f_0(1800)$

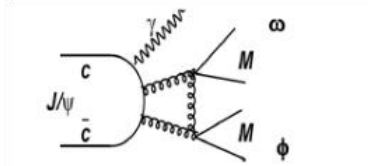


selective for $s\bar{s}$

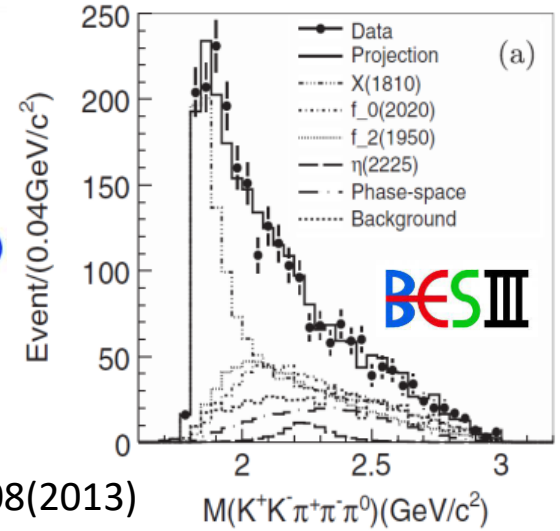
$B_s \to J/\psi f_0$

PLB 797 (2019) 134789





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



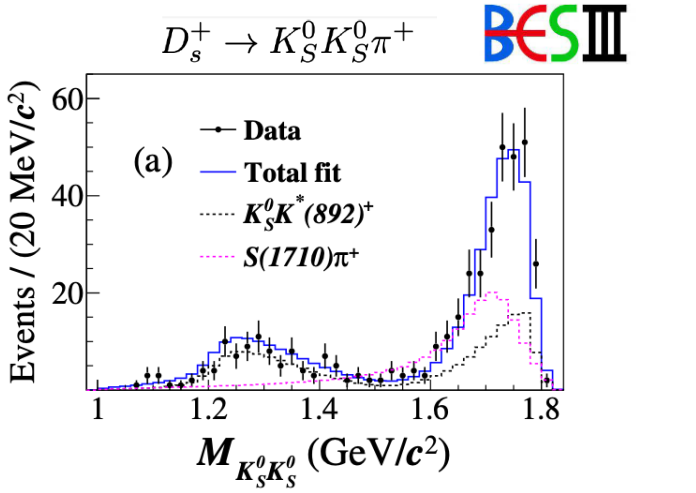
PRD 87, 032008(2013)

$a_0(1817)$

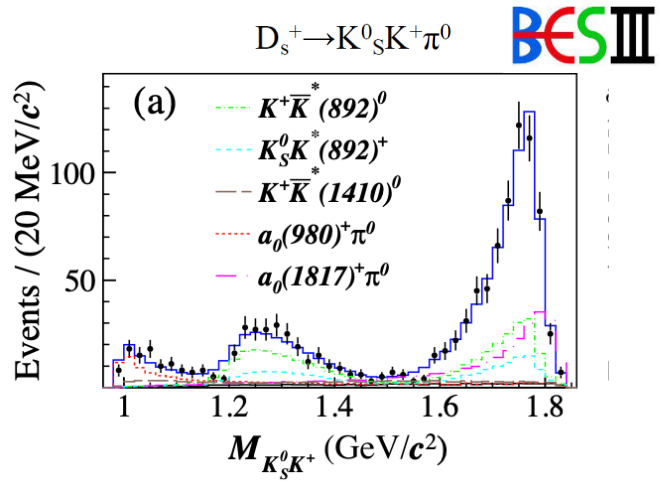
Isovector partner of $f_0(1800)$?

[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

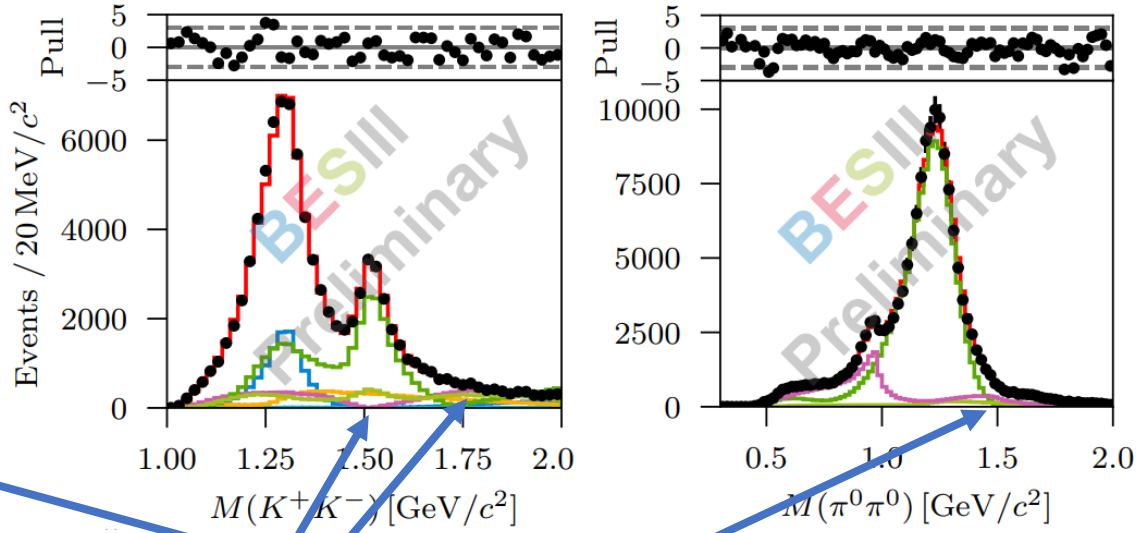
Parameter	$f_0(1710)$ fit			
	fit-H	fit-L	H,L combined	PDG
χ^2/ndf	694.2/585	701.6/585	–	–
Mass(f_J) (MeV/c^2)	1750^{+5+29}_{-6-18}	1749^{+5+31}_{-6-42}	1750^{+6+29}_{-7-18}	1720 ± 6
$\Gamma_{\rm tot}(f_J)$ (MeV)	138^{+12+96}_{-11-50}	145^{+11+31}_{-10-54}	139^{+11+96}_{-12-50}	135 ± 6
$\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})_{f_J}$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

Trace 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)

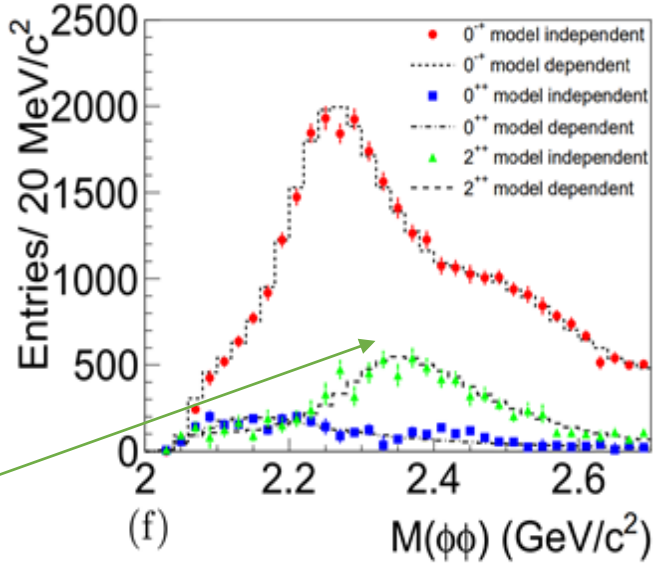
$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = \left(1.91 \pm 0.14^{+0.72}_{-0.73}\right) \times 10^{-4}}$
BESIII PRD 93, 112011 (2016)

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

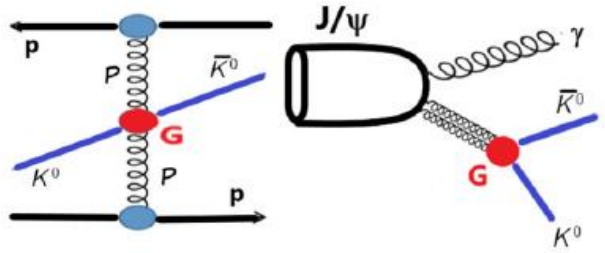
$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta'\eta') = \left(8.67 \pm 0.70^{+0.16}_{-1.67}\right) \times 10^{-6}}$
BESIII PRD 105,072002 (2022)

More decay modes are desired

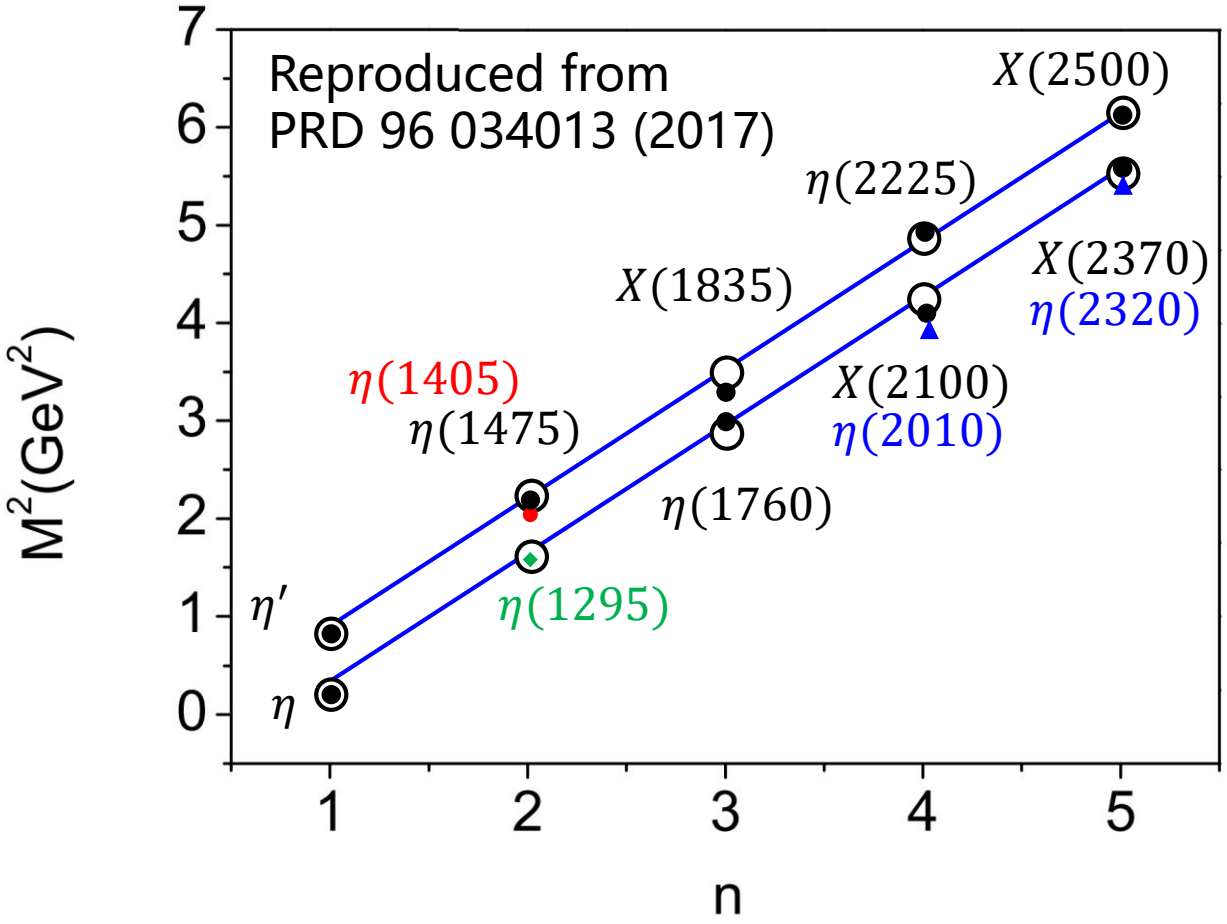
BESIII $J/\psi \to \gamma\phi\phi$ [PRD 93, 112011 (2016)]

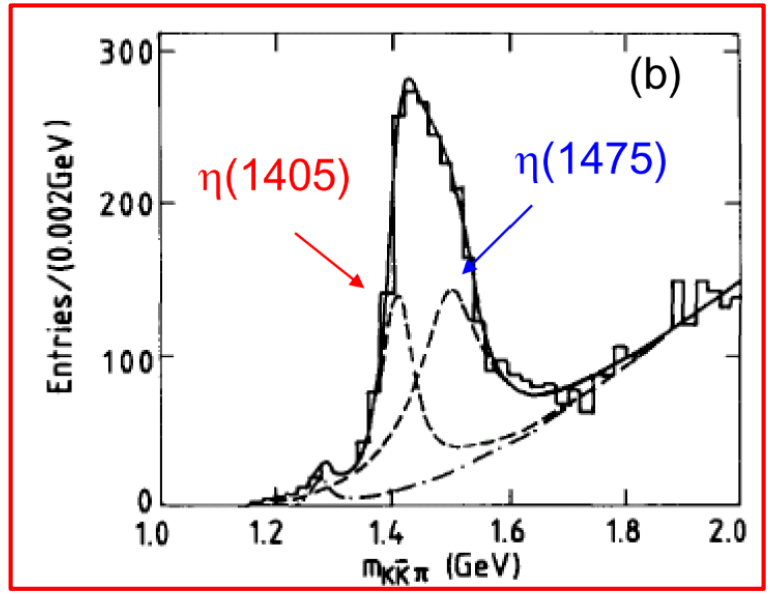


- $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ stated in π^-p reactions are observed with a **strong production of $f_2(2340)$**
- Consist with CEP from WA102@CERN



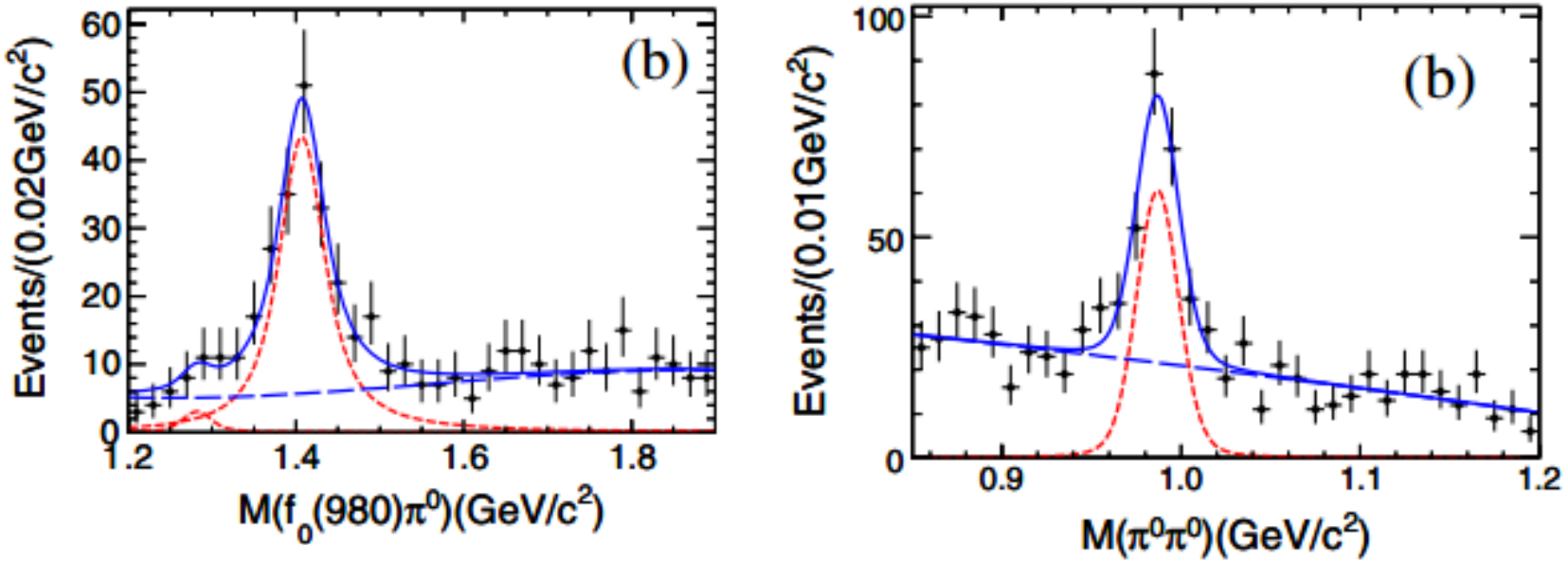
Where is the 0^{-+} glueball

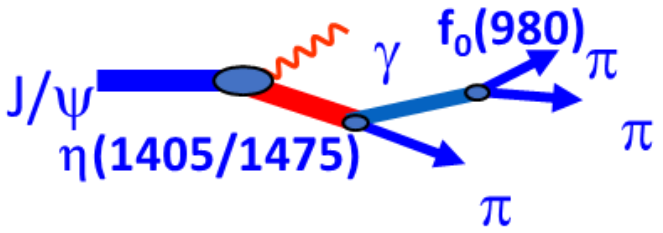




- **LQCD：0^{-+}(2.3~2.6 GeV)**
- **Little experimental information above 2 GeV**
- **What’s the nature of the outnumbered $\eta(1405)$? $\eta(1295)$ exists?**

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





BESIII PRL 108 182001(2012)

f0(980) is extremely narrow: $\Gamma \cong 10$ MeV.

PDG: Γ(f0(980)) $\cong$ 40~100 MeV.

Anomalously large isospin violation:

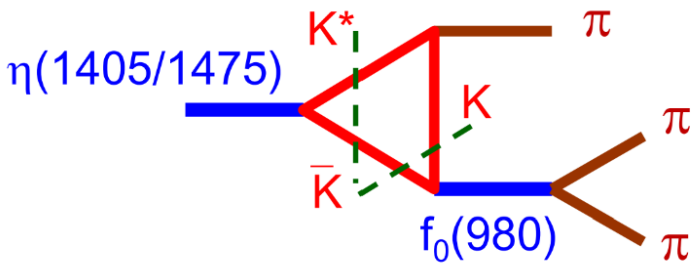
$$\frac{Br(\eta(1405) \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\eta(1405) \to a_0^0(980)\pi^0 \to \eta\pi^0\pi^0)} \cong (17.9 \pm 4.2)\%$$

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

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

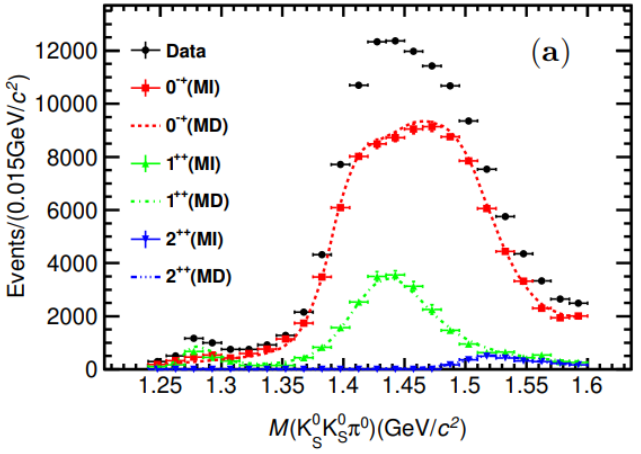
$$J/\psi \to \gamma K_S K_S \pi^0$$

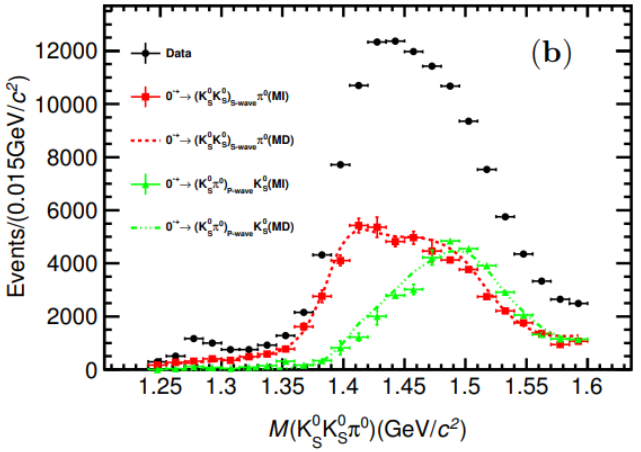
BESIII JHEP 03 121(2023)

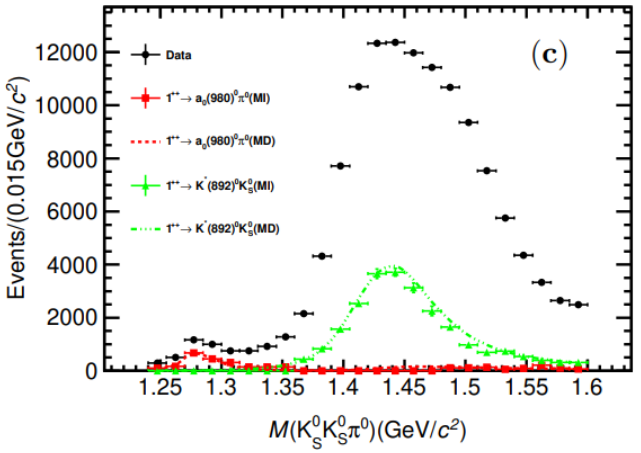
- **M**ass **I**ndependent PWA in bins of M($K_S K_S \pi^0$) to detangle J^{PC} components
  - **Valuable inputs to develop models**
- **M**ass **D**ependent PWA with BW to extract resonances
- **Consistency between MI and MD results**

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

- $\eta(1405)/\eta(1475)$ poles in coupled-channel analysis [Satoshi ' s talk]
  - PRD 107, L091505 (2023) ; PRD 109, 014021 (2024)

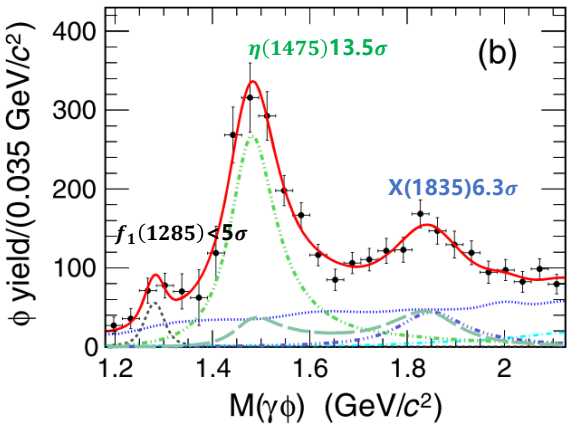






$J/\psi \to \gamma\gamma\phi$, a $s\bar{s}$ flavor filter

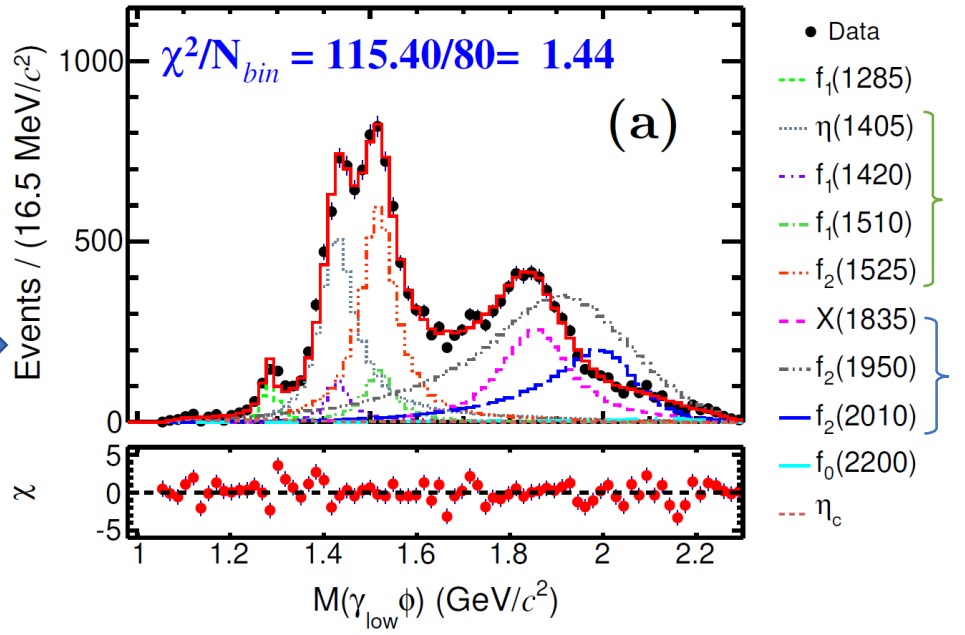
PR D97 051101 (2018)



←Fit to mass spectrum

Amplitude analysis with advanced techniques for background subtraction

arXiv: 2401.00918



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 $X(2370)/\eta_1(1855)$, well consistent with the predictions for glueball/hybrid** [PRD 107, 114020, NPA 1037, 122683]

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)

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

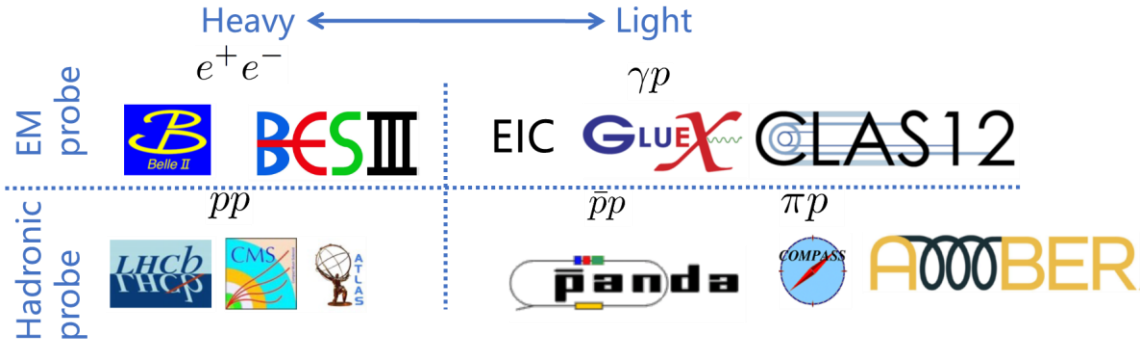
- ✓ **$f_0(1710)$ is largely overlapped with the scalar glueball, according to its production and decay properties**
- ✓ **Large production rate of $f_2(2340)$ in J/ψ radiative decays**
- ✓ **Non-observation of $\eta(1295)$**
- ✓ **Insights of $\eta(1405/1475)$**
- ✓ **$X(2370)$: a good candidate**

[Yanping' s talk]

Summary

To address the outstanding questions in hadron physics,

- Various probes needed to understand the rich patterns of spectroscopy



- Experiment-theory collaboration is critical

- Thanks to JAPOF