Light QCD exotics at BESIII

Beijiang Liu
(on behalf of BESIII)

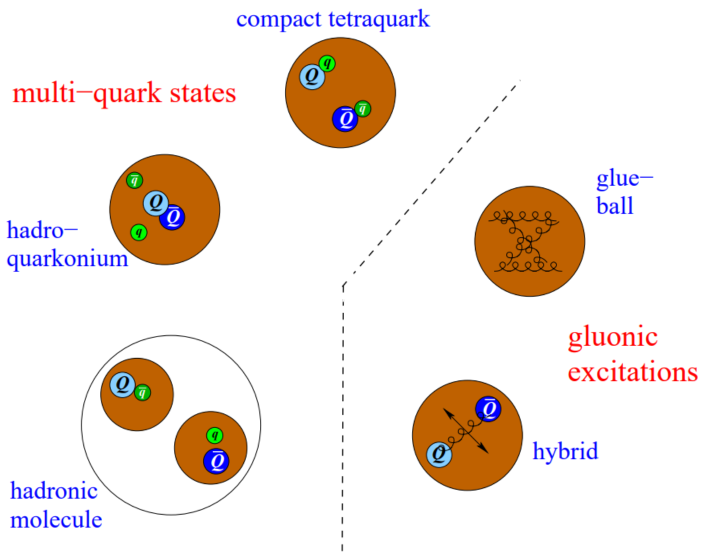
Institute of High Energy Physics, Chinese Academy of Sciences

XVIth Quark Confinement and the Hadron Spectrum
18–24 Aug 2024, Cairns, Queensland, Australia

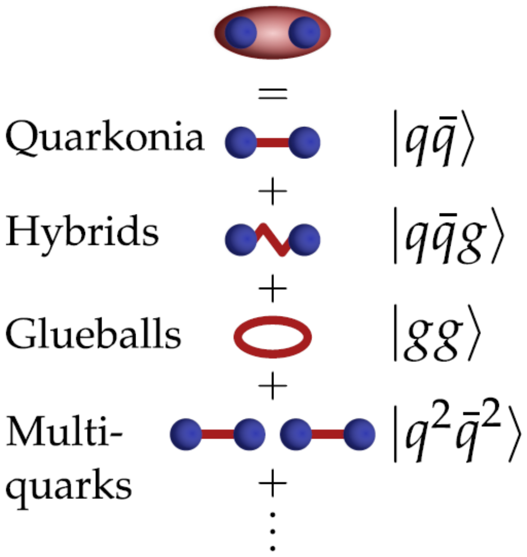
Hadron spectroscopy

- **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 $q\bar{q}$

Supernumerary states

Abnormal properties

+ Kinematic effects

Light QCD exotics

Light sector is even harder

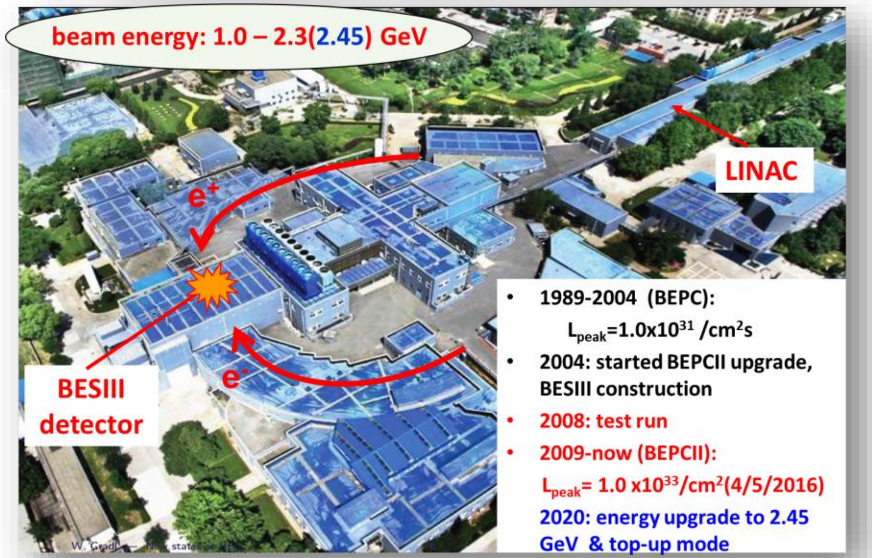
- **Light flavor-exotic hard to establish**
- **Assignment of some $SU(3)_{flavor}\ |q\bar{q}>$ nonets difficult**

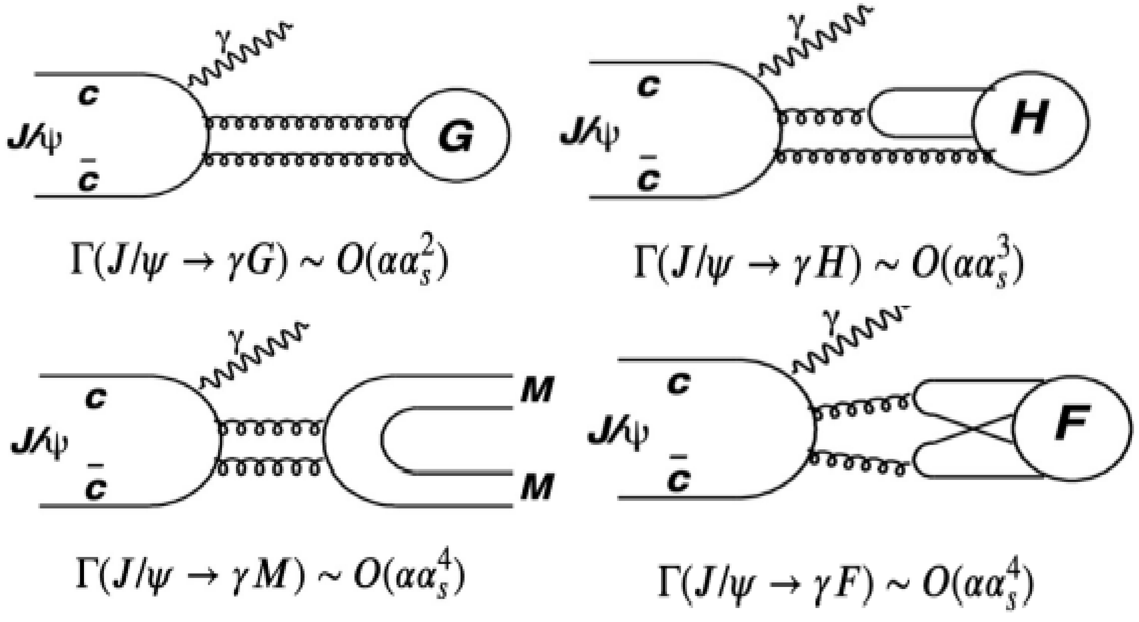
- **Role of gluons:**
  - Gluons mediate the strong force
  - Gluons' unique self-interacting property

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

Critical to confinement and mass dynamical generation

Beijing Electron Positron Collider (BEPCII)



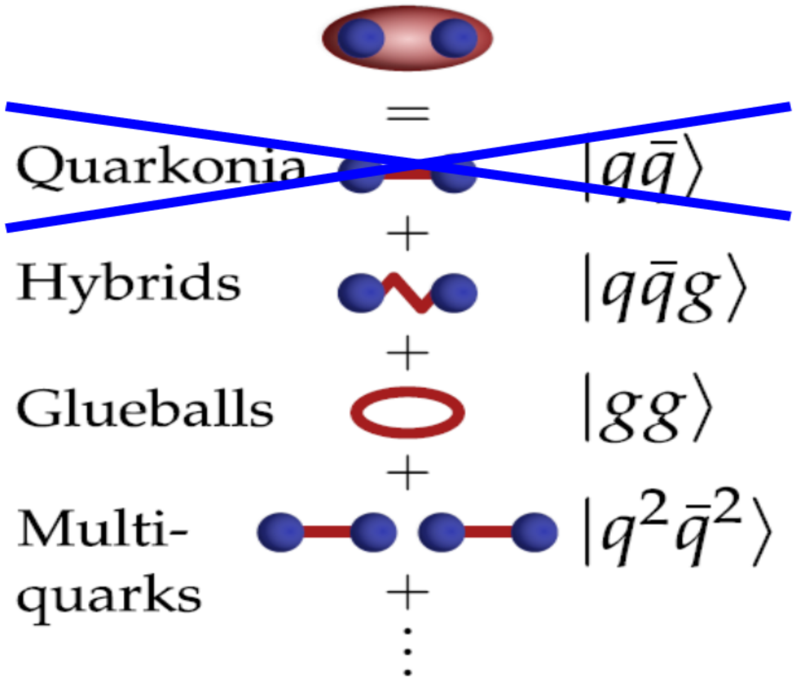


Charmonium decays provide an ideal lab for Gluonic Excitations

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

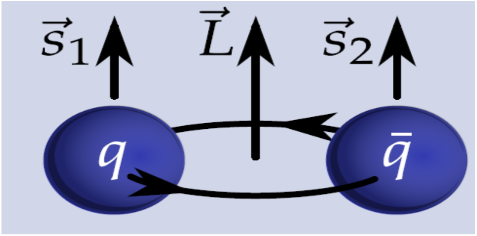
Light hadrons with exotic quantum numbers

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



Experiments:

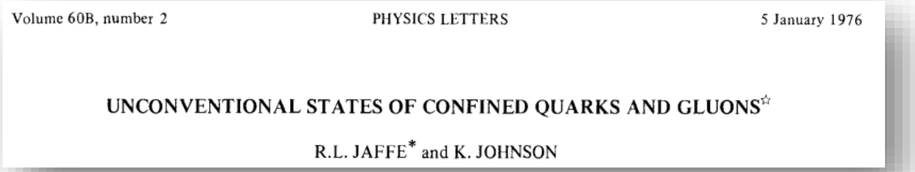
- **Hadroproduction:** GAMS, VES, E852, COMPASS
- **$\mathbf{p\bar{p}}$ annihilation:** Crystal Barrel, OBELIX, PANDA(under construction)
- **Photoproduction:** GlueX(2017-), CLAS



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

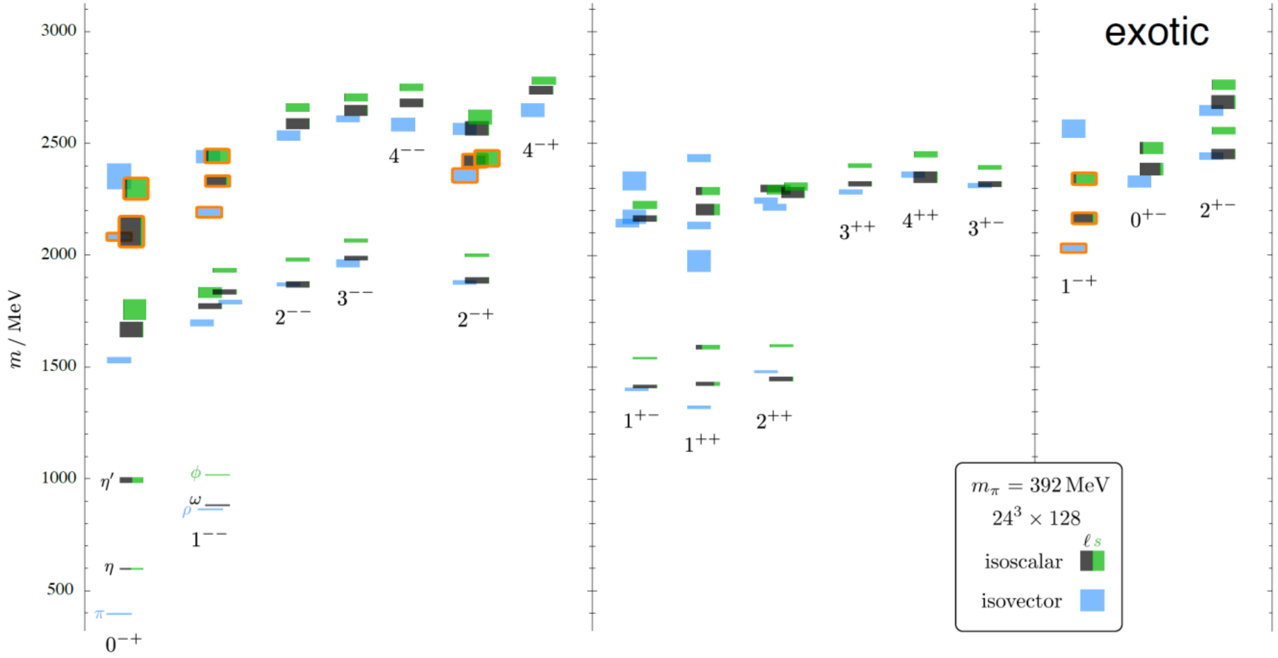
Allowed $\mathbf{J^{PC}}$: $\mathbf{0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots}$

Predictions


Volume 60B, number 2 PHYSICS LETTERS 5 January 1976

UNCONVENTIONAL STATES OF CONFINED QUARKS AND GLUONS☆

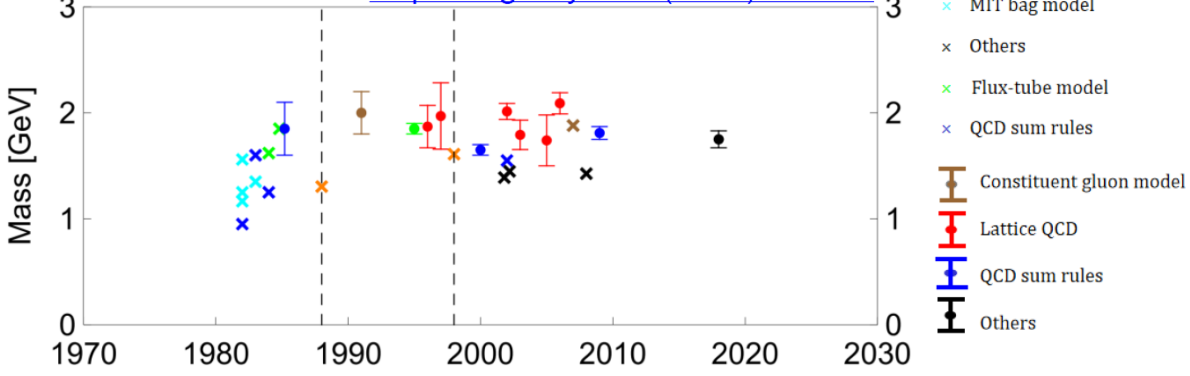
R.L. JAFFE* and K. JOHNSON



PRD 88 094505(2013)

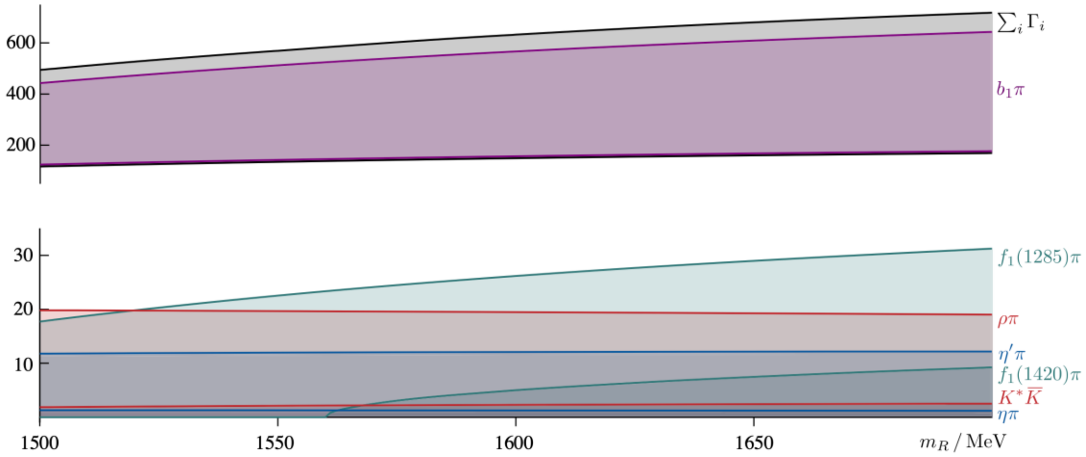
Lightest spin-exotic state in LQCD: **1^{-+} hybrid**

Rept.Prog.Phys. 86 (2023) 026201



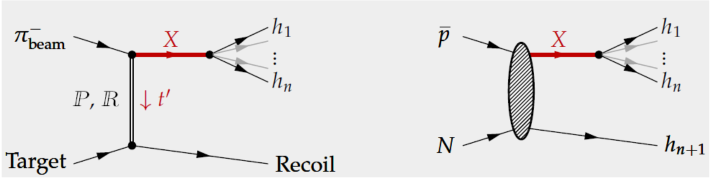
Mass of 1^{-+} hybrid

PRD 103, 054502(2021)



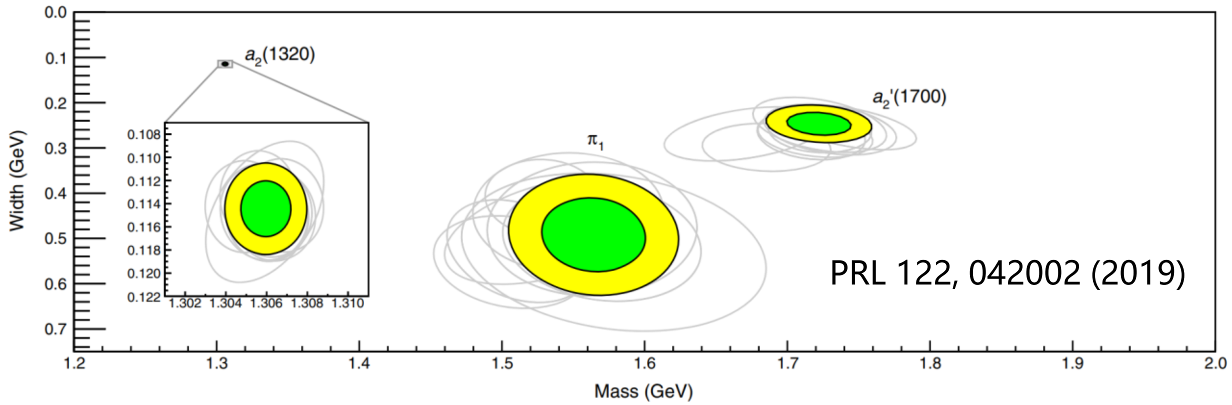
Decay width of 1^{-+} hybrid π_1

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



Spin-exotic mesons

- **Over 3 decades, only 3 candidates so far:** **All 1^{-+} isovectors**
  - $\pi_1(1400)$: seen in ηπ
  - $\pi_1(1600)$: seen in ρπ, η’π, $b_1\pi$, $f_1\pi$
  - $\pi_1(2015)$ (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

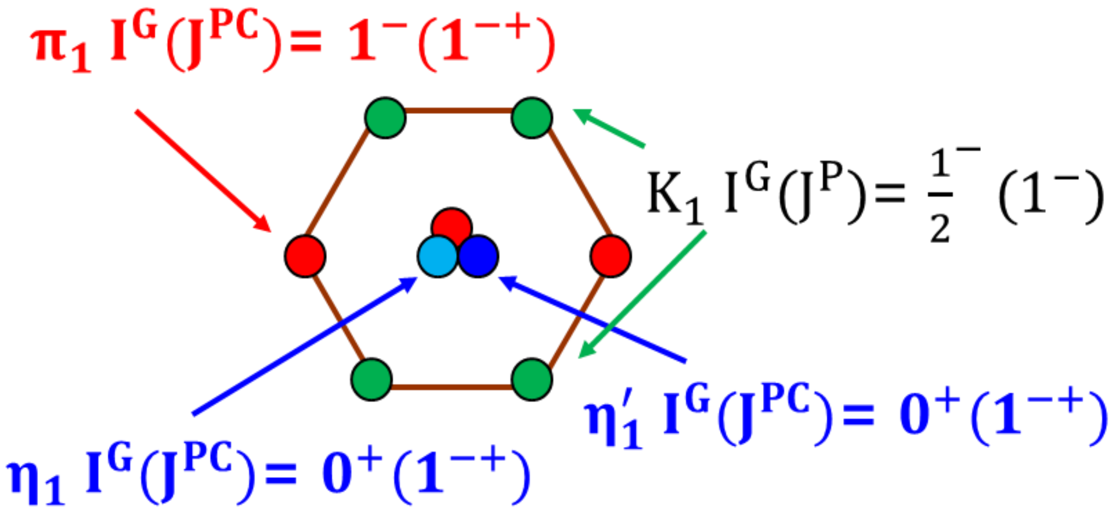


PRL 122, 042002 (2019)

	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
$\pi_1(1600)$	$\eta'\pi$	$\pi^-Be \to \eta'\pi^-\pi^0 Be$ $\pi^-p \to \pi^-\eta' p$	VES E852
	$b_1\pi$	$\pi^-Be \to \omega\pi^-\pi^0 Be$ $\bar{p}p \to \omega\pi^+\pi^-\pi^0$ $\pi^-p \to \omega\pi^-\pi^0 p$	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
	$b_1\pi$	$\pi^-p \to p\eta\pi^+\pi^-\pi^-$	

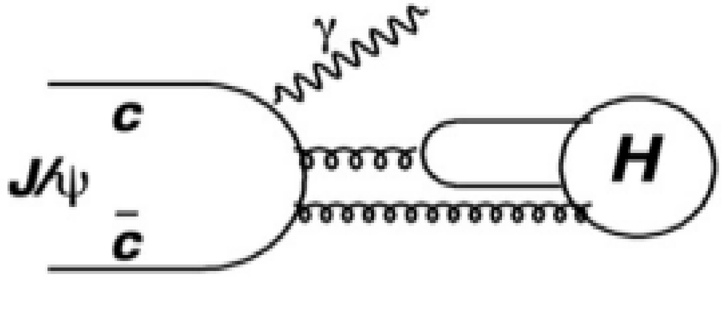
1^{-+} Hybrids

- **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 η_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)] *

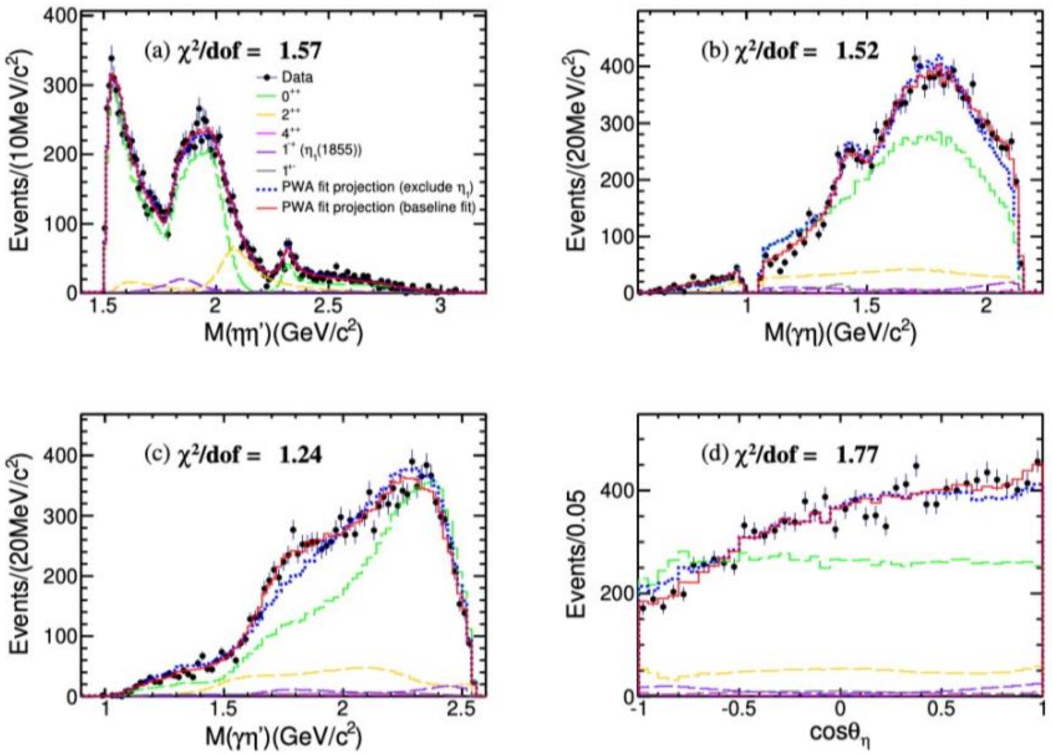
**World's first PWA framework with GPU acceleration*

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

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

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

- **Mass is consistent with LQCD calculation for the 1^{-+} hybrid ($1.7\sim2.1$ 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:

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

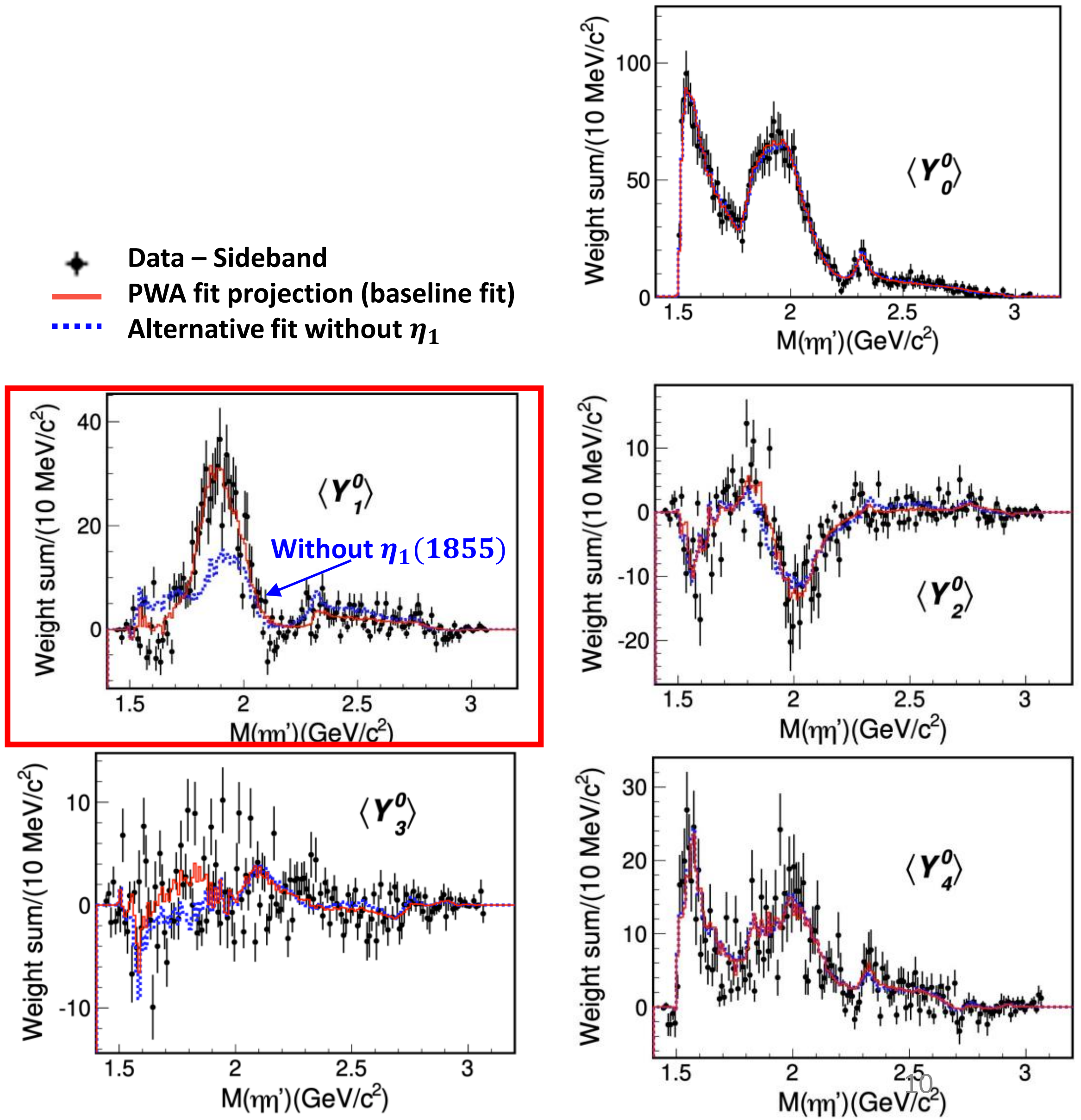
$$\sqrt{4\pi}\langle Y_1^0\rangle = 2S_0P_0\cos\phi_{P_0} + \frac{2}{\sqrt{5}}(2P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) + \sqrt{3}P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

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

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

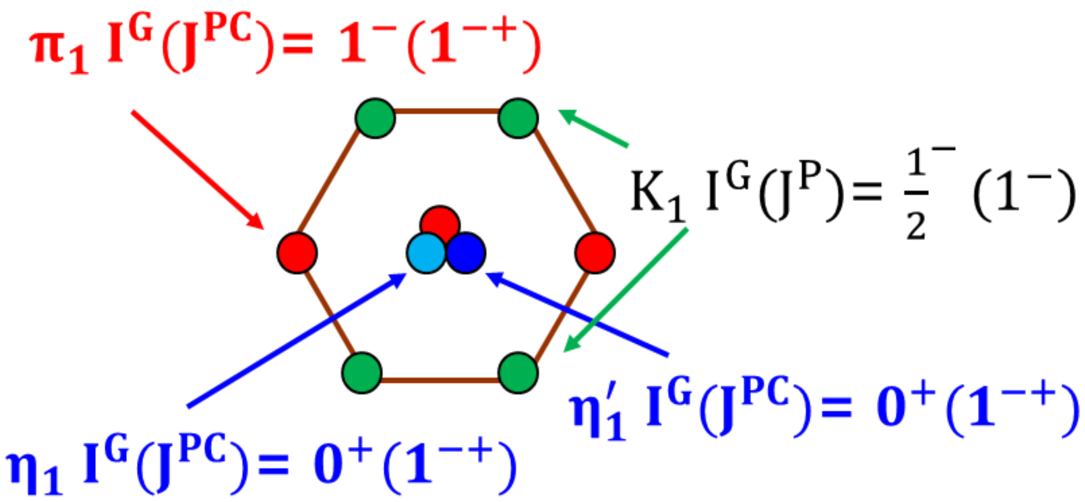
$$\sqrt{4\pi}\langle Y_4^0\rangle = \frac{1}{7}(6D_0^2 - 4D_1^2 + D_2^2).$$

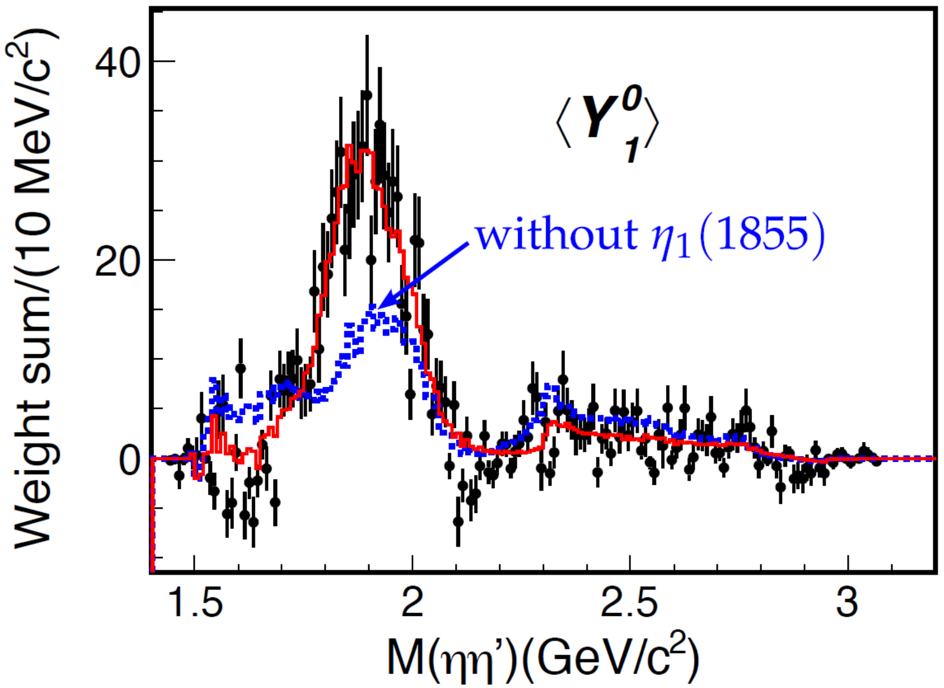
- **Narrow structure** in $\langle Y_1^0 \rangle$
  - ➢ **Cannot be described by resonances in $\gamma\eta(\eta')$**
  - **$\eta_1(1855) \rightarrow \eta\eta'$ needed**



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?**

"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: $\eta_1(1855)$

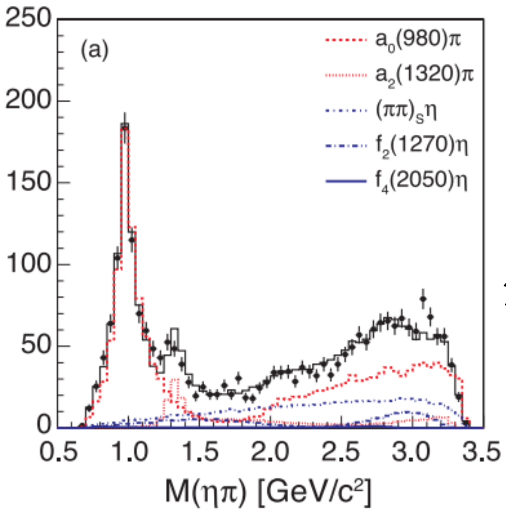
- **Decay properties**
  - $J/\psi \to \gamma + \pi a_1, \eta f_1, K_1\bar{K}, VV$, ……
- **Production properties**
  - $J/\psi \to \omega\eta\eta'$, $\phi\eta\eta'$, ……
  - $\chi_{c1} \to \eta + \eta\eta'$, ……
- **Where is $\eta_1^{(\prime)}$**
- **Other partners: 2^{+-}, ……**
- **Analog in $\bar{c}c$**

Isovector: $\pi_1(1600)$

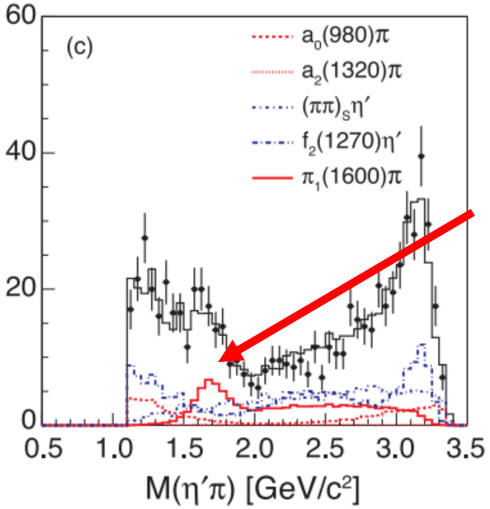
- $J/\psi \to \rho\eta'\pi$, ……
- $\chi_{c1} \to \pi + \pi b_1, \pi f_1$, $\pi\eta'$, ……
  - LQCD predicted major decay modes

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

PR D84 112009 (2011)
2.6×10^7 $\psi(3686)$@CLEO − c

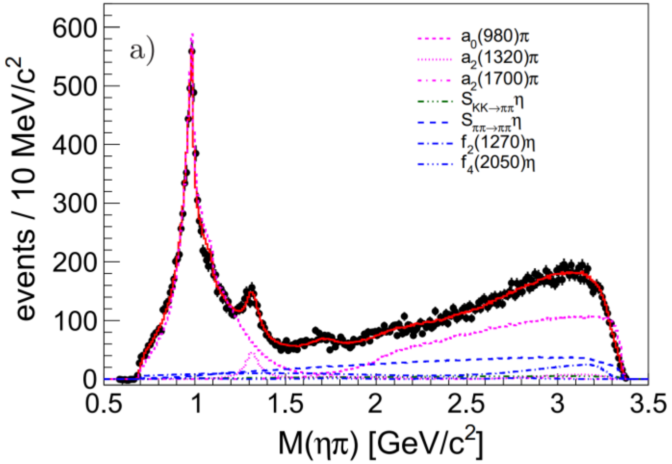


No evidence of $\pi_1 \to \eta\pi$



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

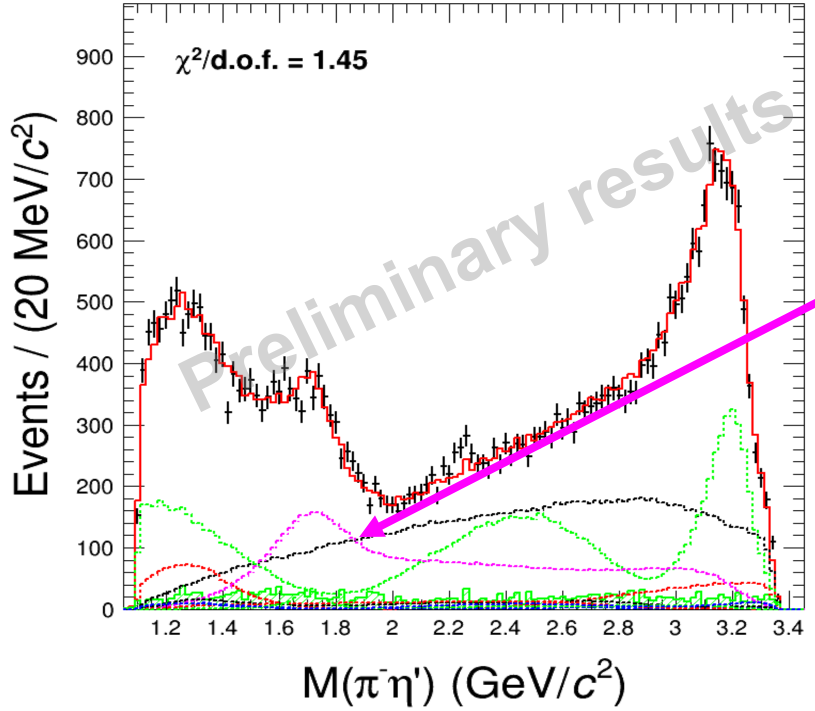
PR D95 032002(2017)
44.8×10^7 $\psi(3686)$@BESIII



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

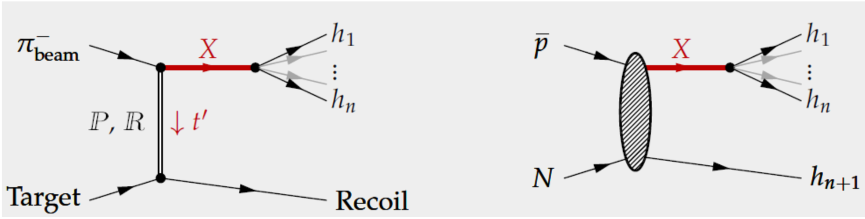
Observation of $\pi_1(1600)$ in $\chi_{c_1} \to \eta'\pi^+\pi^-$ **New**

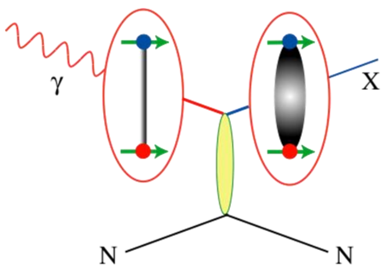
$\mathbf{2.7 \times 10^9}$ $\psi(3686)$@BESIII [preliminary]

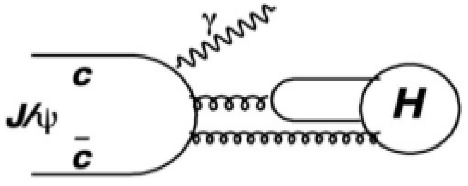


- **Amplitude analysis of $\chi_{c_1} \to \eta'\pi^+\pi^-$ is performed**
- **$\pi_1(1600)$ observed>10σ**
- **with a significant BW phase motion**
- **$J^{PC} = 1^{-+}$, better than other assignments well over 10σ**
  - Evidence of $\pi_1 \to \eta'\pi$ at CLEO-c is confirmed [PR D84 112009 (2011)]

Observations of π_1 and η_1 in charmonium decays provide a new path to study 1^{-+}





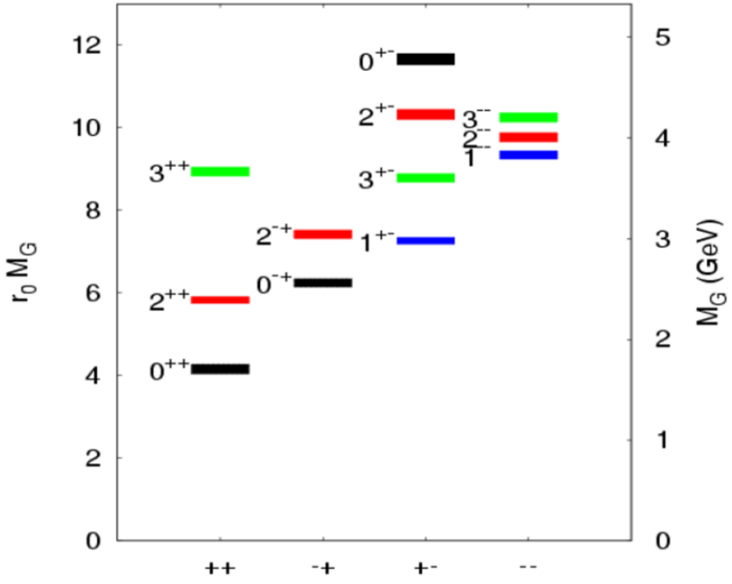


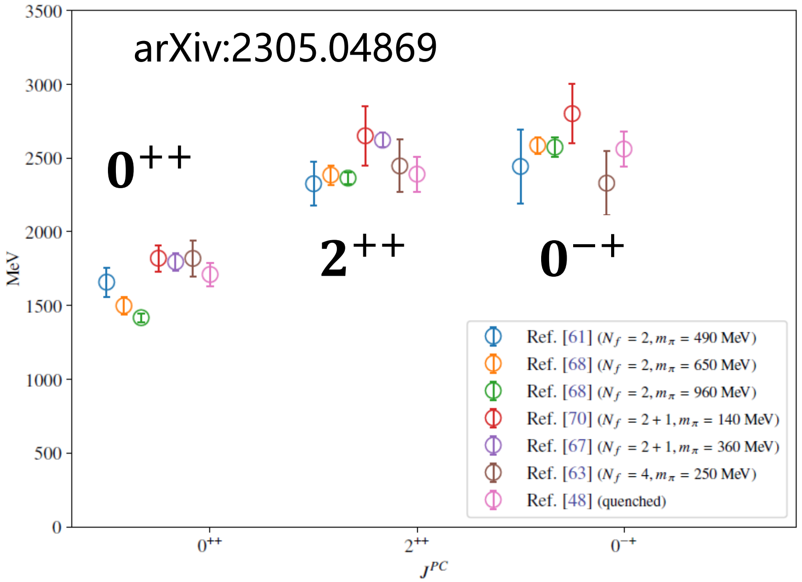
$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$

Glueballs

- Glueballs are the most direct prediction of QCD
  - Color singlets emerge as a consequence of the gluon self-interactions
- Essential for understanding of confinement and mass dynamical generation
  - Gluon degree of freedom in the low energy
- Theoretical predictions from lattice QCD and QCD-inspired models mostly consistent
  - Light-mass glueballs: $J^{PC} = 0^{++}, 2^{++},\ 0^{-+}$

PRD 73 014516 (2006)





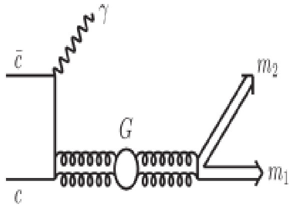
Yang-Mills glueballs on lattice (quenched and unquenched results)

Glueball hunting for over 40 years

- **Supernumerary states** that do not fit into $\mathbf{q\bar{q}}$ multiplets
  - A priori, mixed with nearby $\mathbf{q\bar{q}}$
  - Assignment of some $q\bar{q}$ multiplets difficult
- Production: Strongly produced in **gluon-rich processes**
- Decay: **gluon is flavor-blind**
  - No dominate decay mode
  - $\mathrm{SU(3)_{flavor}}$ symmetry expected
  - No rigorous predictions
    - 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)]

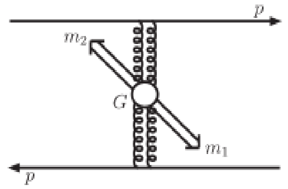
gluon-rich processes

[Phys. Rept. 454 1]



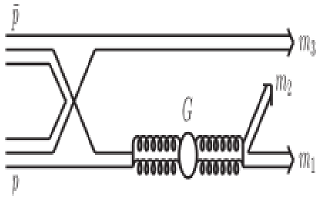
Charmonium decays:

BESIII, MRKIII…



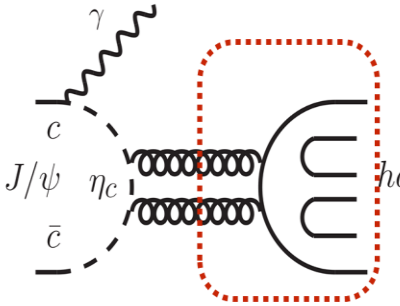
pp double-Pomeron exchange:

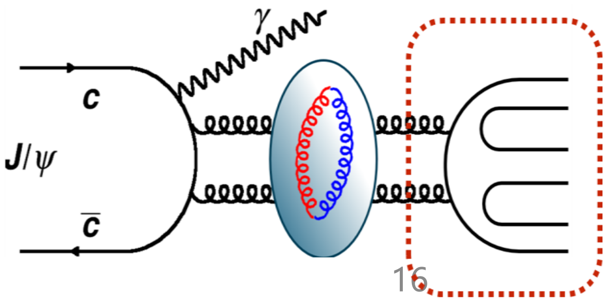
WA102, GAMS…



$\mathbf{p\bar{p}}$ annihilation:

Crystal barrel, OBELIX…





Scalar glueball candidate

- **Supernumerary scalars** suggest additional degrees of freedom
  - However, mixing scenarios are controversial
- Measured $B(J/\psi \to \gamma f_0(1710))$ is **x10 larger** than $f_0(1500)$

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

  - LQCD: $\Gamma(J/\psi \to \gamma G_{0+})/\Gamma_{total} = 3.8(9) \times 10^{-3}$ [PRL 110, 091601(2013)]

  ➢ **BESIII: $f_0(1710)$ largely overlays with the scalar glueball**

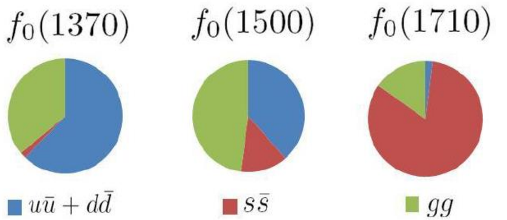
  ➢ **Identification of scalar glueball with coupled-channel analyses based on BESIII data**

  [PLB 816, 136227 (2021), EPJC 82, 80 (2022), PLB 826, 136906 (2022)]

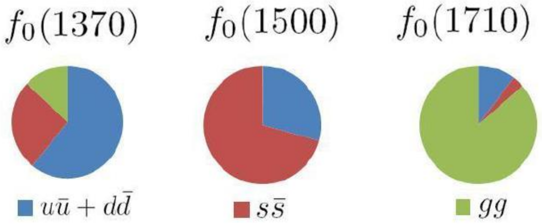
- **Further more, suppression of $f_0(1710) \to \eta\eta'$ supports $f_0(1710)$ has a large overlap with glueball**

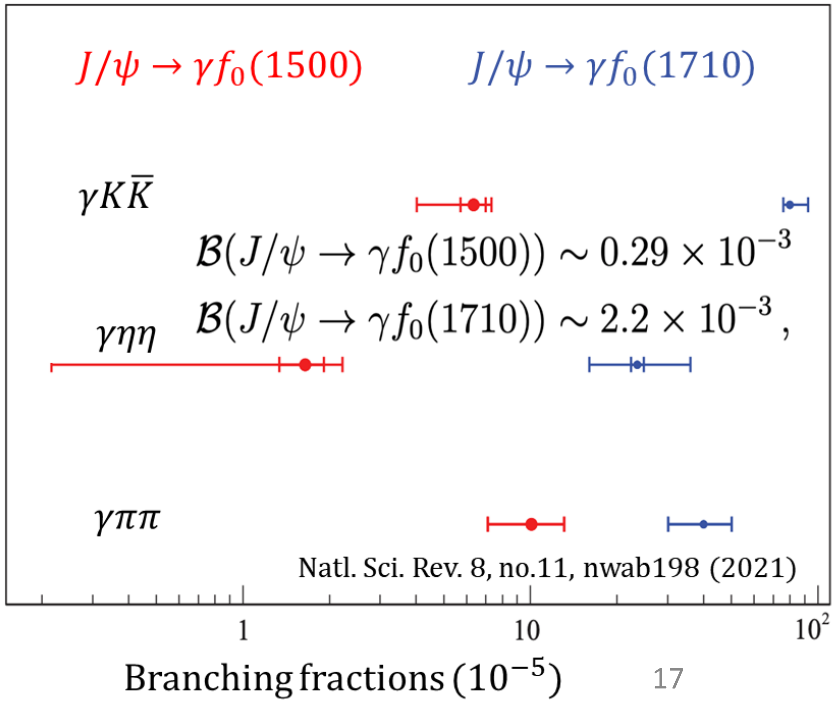
BESIII [PRD 106 072012(2022)]

Close and Kirk, PLB483 (2000) 345



Cheng et al, Phys. Rev. D74 (2006) 094005





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

$$\mathrm{Br}(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = (3.8^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$$

BESIII PRD 87,092009 (2013)

$$\mathrm{Br}(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73}) \times 10^{-4}$$

BESIII PRD 93, 112011 (2016)

$$\mathrm{Br}(J/\psi \to \gamma f_2(2340) \to \gamma K_s K_s) = (5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$$

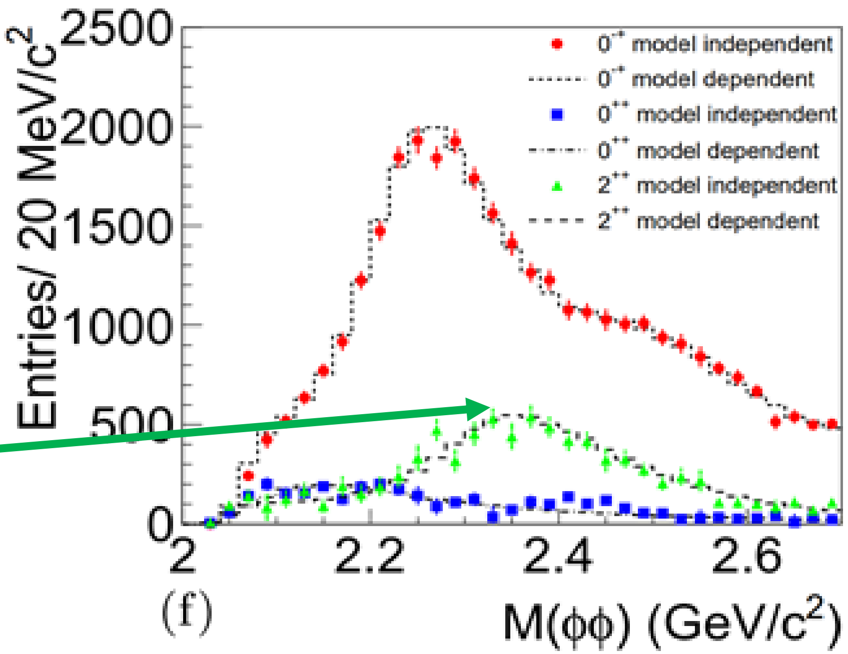
BESIII PRD 98,072003 (2018)

$$\mathrm{Br}(J/\psi \to \gamma f_2(2340) \to \gamma\eta'\eta') = (8.67 \pm 0.70^{+0.16}_{-1.67}) \times 10^{-6}$$

BESIII PRD 105,072002 (2022)

still desired to study more decay modes

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



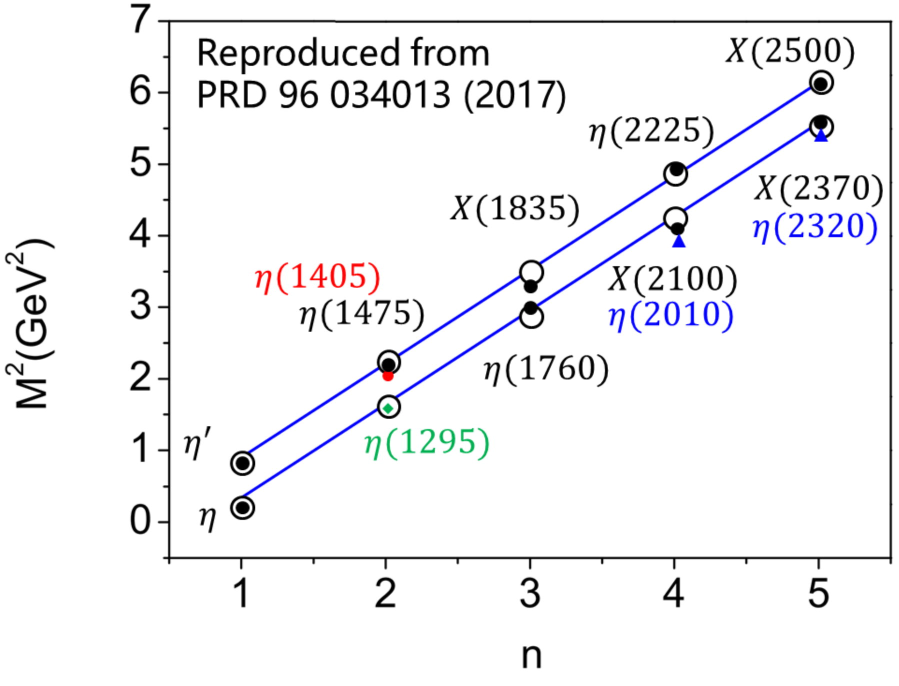
- $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ in πp reactions are all observed in $J/\psi \to \gamma\phi\phi$ with a **strong production of $f_2(2340)$**
- Consistent with **double-Pomeron exchange** from WA102@CERN

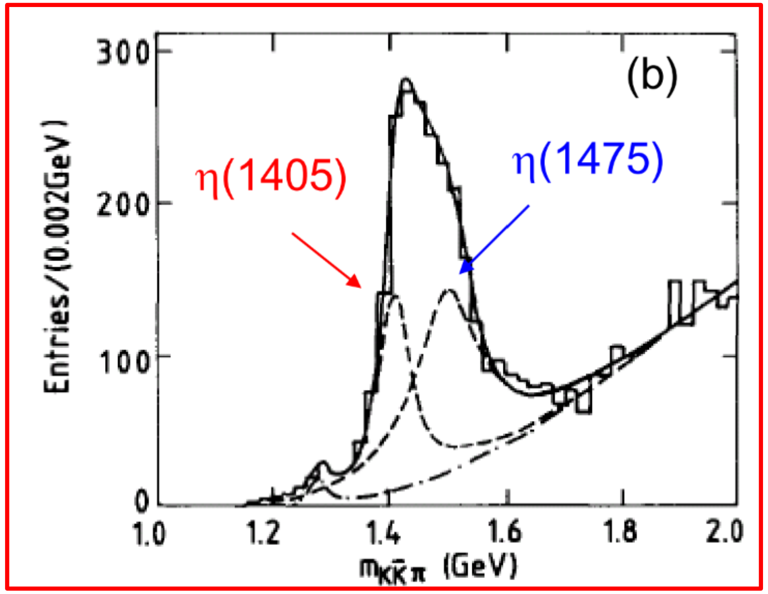
More complicated due to the large number of tensor states

Where is the 0^{-+} glueball

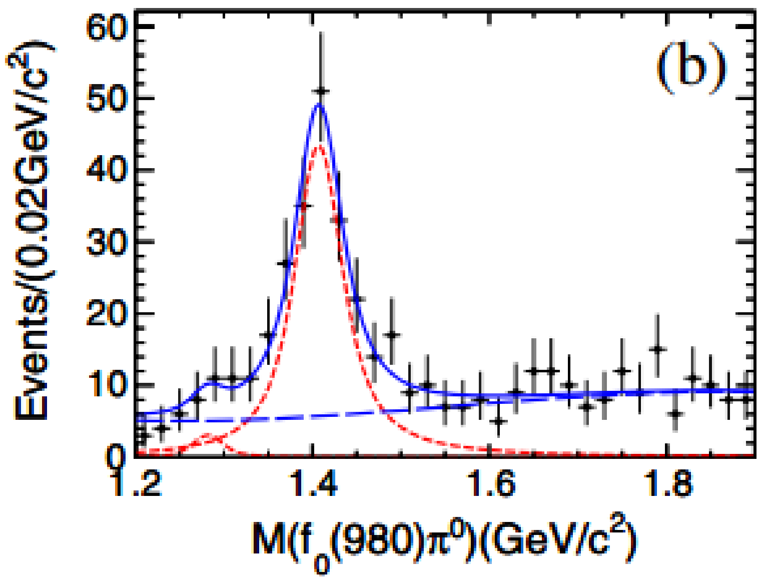
- Pseudoscalar sector, a promising window
  - Only η, η′ (& radial excitations) from quark model
- Mass
  - LQCD： 0^{-+} glueball (2.3~2.6 GeV)
  - The first glueball candidate: ι(1440) (Split into η(1405) and η(1475))
    - Mass incompatible with LQCD
  - Little experimental information above 2 GeV

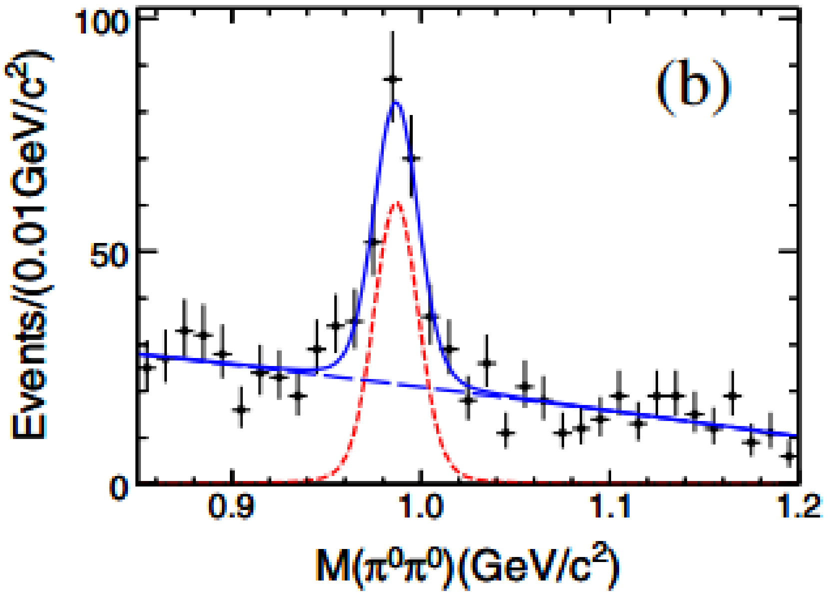
[PRD.100.054511(2019)]

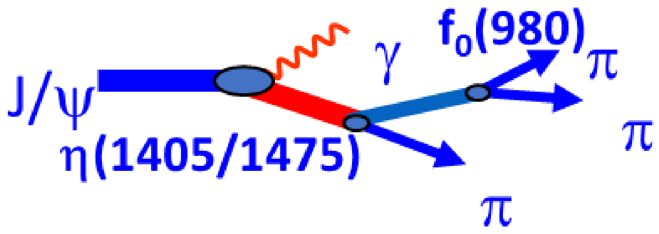




Isospin-violating decay of $\eta(1405) \rightarrow f_0(980)\pi^0$







BESIII PRL 108 182001(2012)

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

PDG: Γ(f0(980)) $\cong$ 40~100 MeV.

Triangle singularity mechanism has been proposed

- Manifested in many near-threshold structures

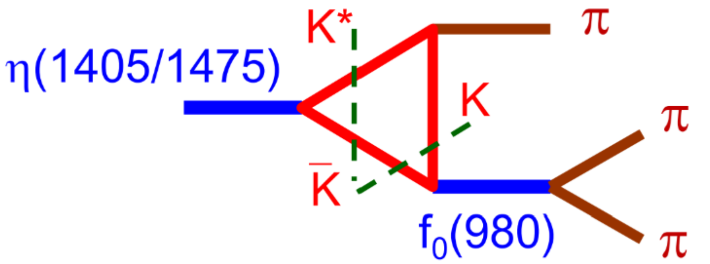
Anomalously large isospin violation:

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

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

PRD, 83(2100)032003

PRL 108 081803 (2012)



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

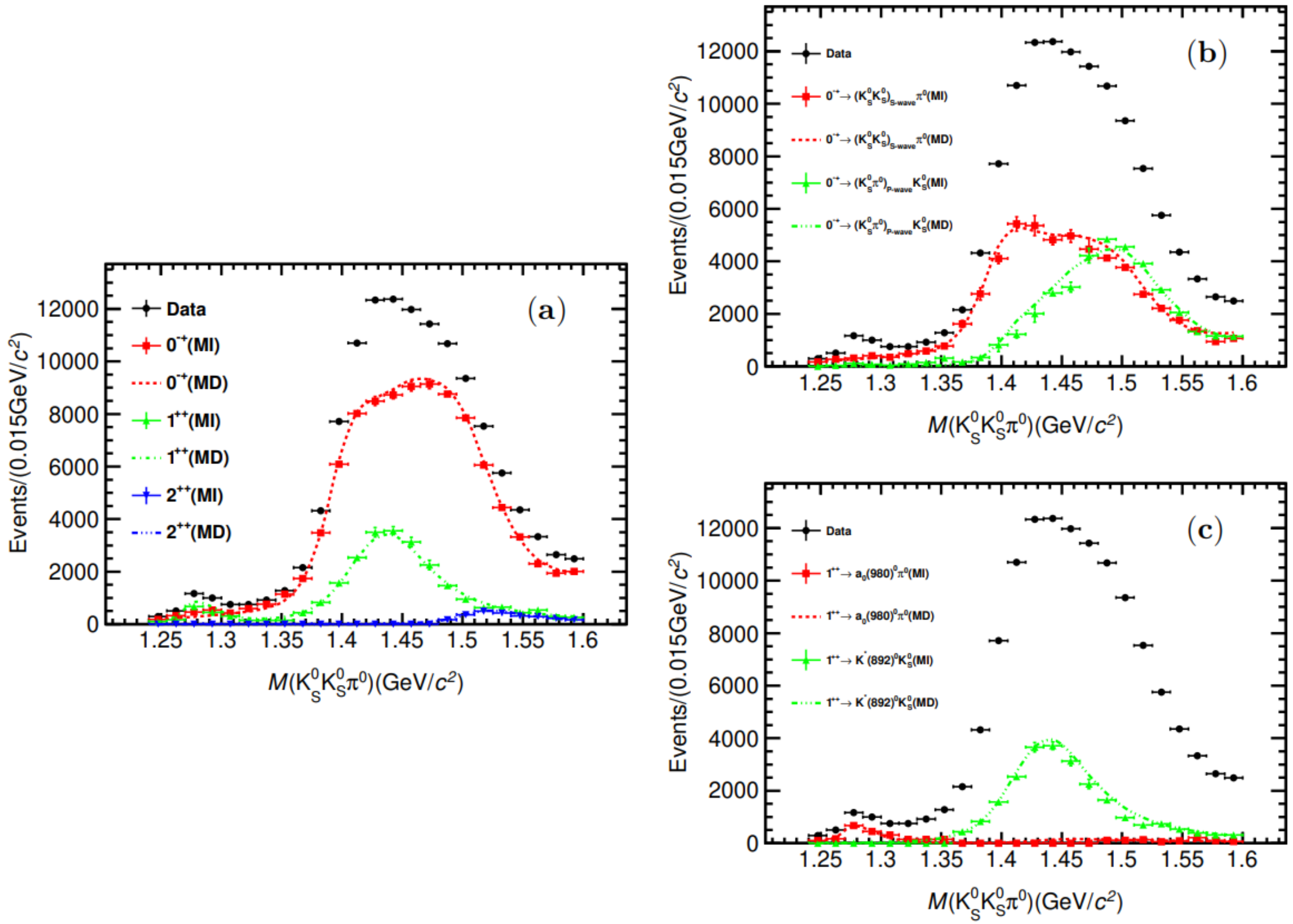
$$J/\psi \to \gamma K_S K_S \pi^0$$

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**

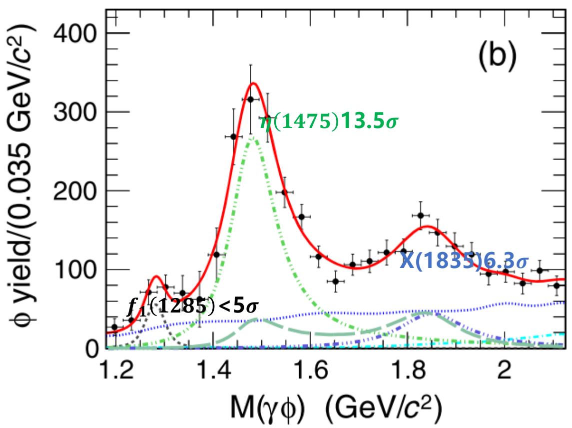
- coupled-channel analysis
  - Two poles: PRD 107, L091505 (2023) ; PRD 109, 014021 (2024)
  - One state: arXiv:2407.10234



J/ψ → γγϕ, a $s\bar{s}$ flavor filter

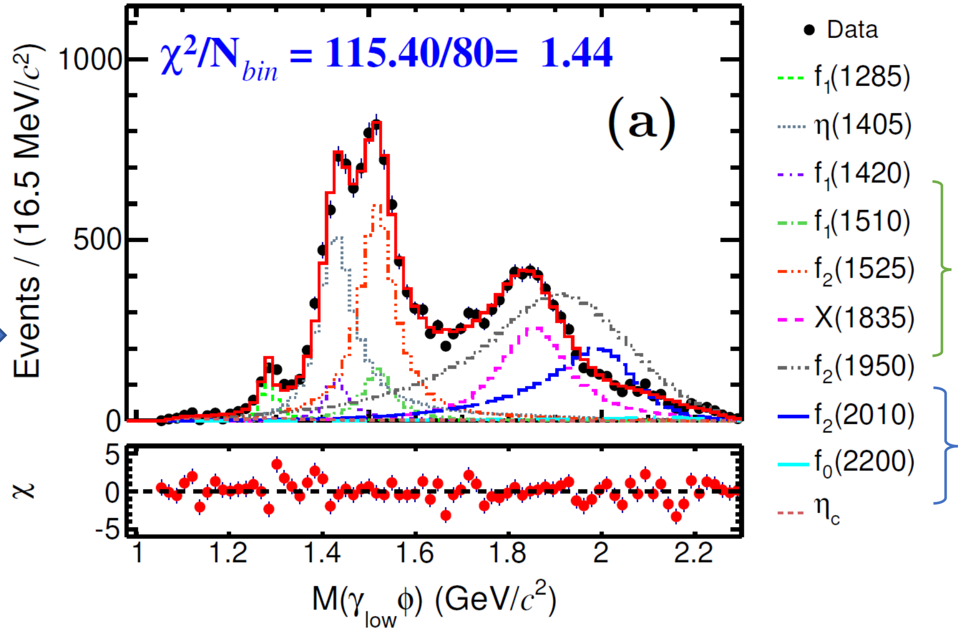
arXiv: 2401.00918

PR D97 051101 (2018)



←Fit to mass spectrum

Amplitude analysis with advanced techniques for background subtraction

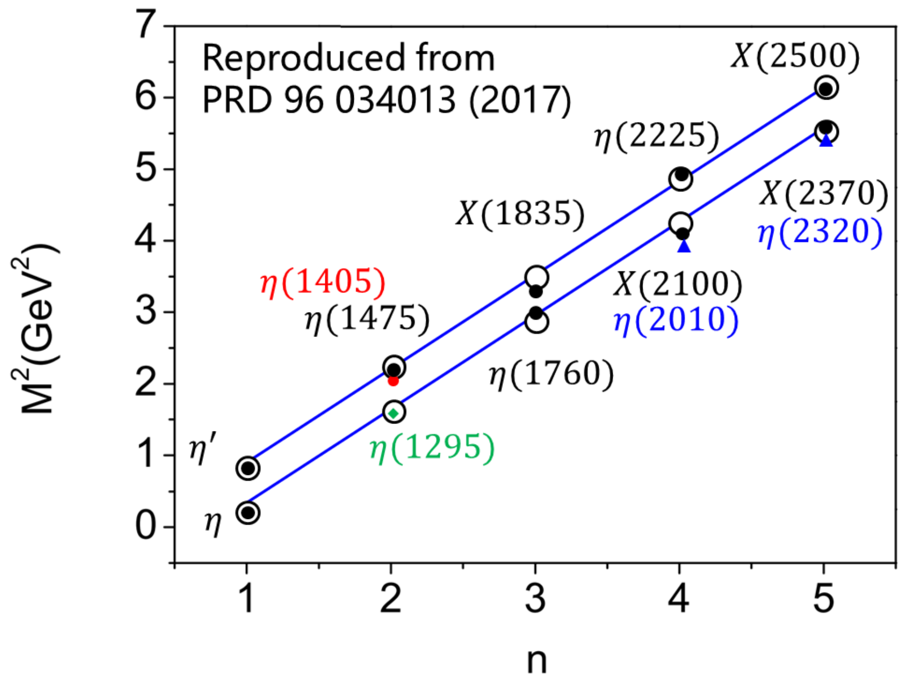


From the amplitude analysis,

- η(1405) is observed, while η(1475) can not be excluded
- **X(1835) → γϕ suggests its assignment of η' excitation**
- **η_c → γϕ 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]

Where is the 0^{-+} glueball

- Pseudoscalar sector, a promising window
  - Only η, η′ (& radial excitations) from quark model
- Mass
  - LQCD: 0^{-+} glueball (2.3~2.6 GeV)
  - The first glueball candidate: ι(1440) (Split into η(1405) and η(1475))
    - Mass incompatible with LQCD
  - Little experimental information above 2 GeV
- 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**
  - **3 pseudoscalar final state is a good place to look for** ($0^{-+} \to 2P$ is forbidden)



$\eta_c \to 3$ P in PDG

Decays involving hadronic resonances

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

Decays into stable hadrons

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

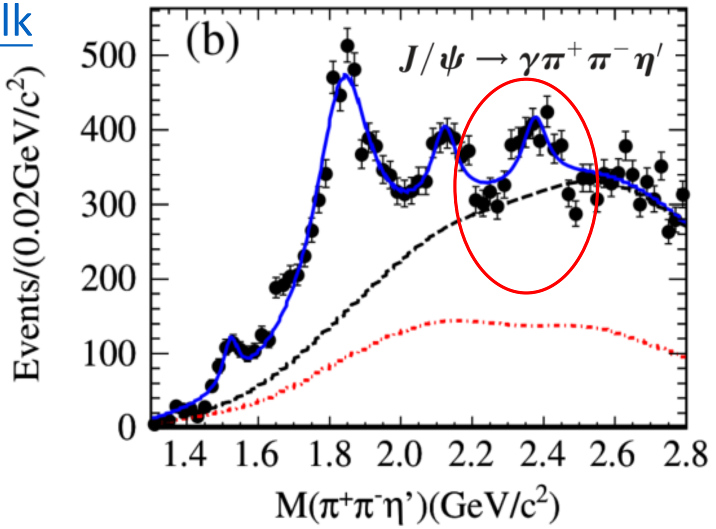
- No dominant decay
- Flavor symmetric

A glueball-like state $X(2370)$

P. Zhang's talk

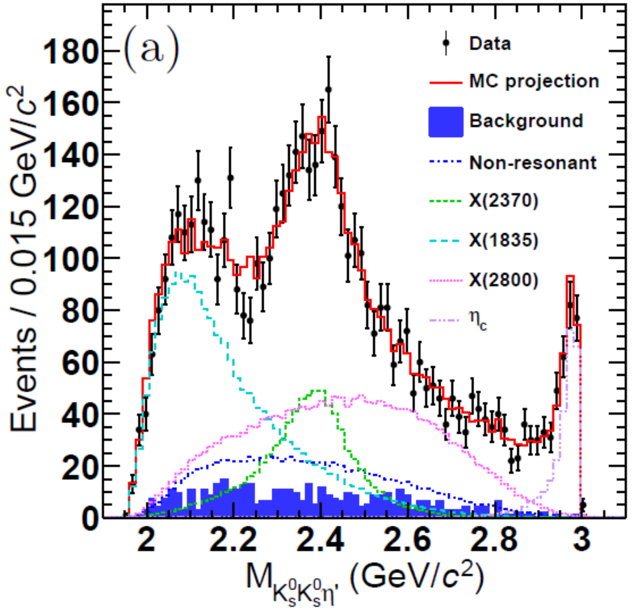
- **Discovered by BESIII in $J/\psi \to \gamma\eta'\pi\pi$ in 2011**
- Confirmed by BESIII in $J/\psi \to \gamma\eta'\pi\pi, \gamma\eta'KK$
  - Not seen in $J/\psi \to \gamma\eta'\eta\eta$ [BESIII PRD 103 012009 (2021)], $J/\psi \to \gamma\gamma\phi$ [BESIII arXiv: 2401.00918]. Upper limits of BF are well consistent with predictions of 0^{-+}glueball
- **Mass consistent with LQCD prediction for 0^{-+} glueball**
- **Spin-parity determined to be 0^{-+}** BESIII PRL 132, 181901(2024)

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



BESIII PRL 106, 072002(2011), PRL 117, 042002 (2016)

$J/\psi \to \gamma\eta' K_S^0 K_S^0$



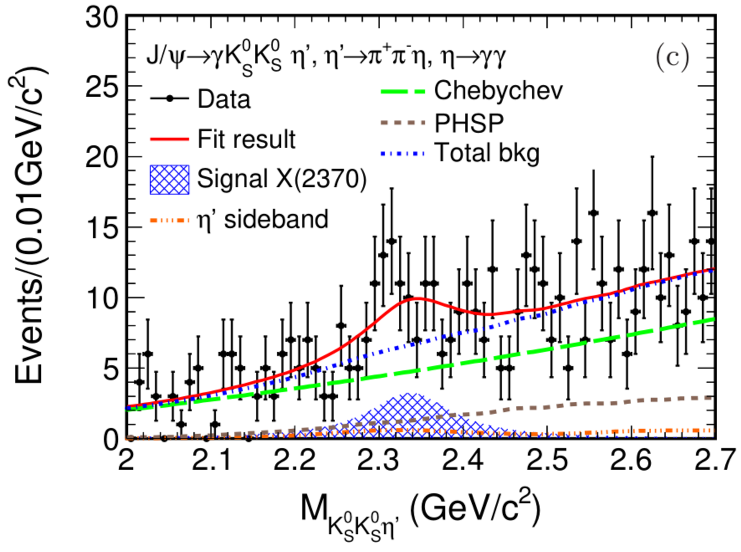
J^{PC} = 0^{-+} with significance >9.8σ

M = 2395 ±11$^{+26}_{-94}$ MeV

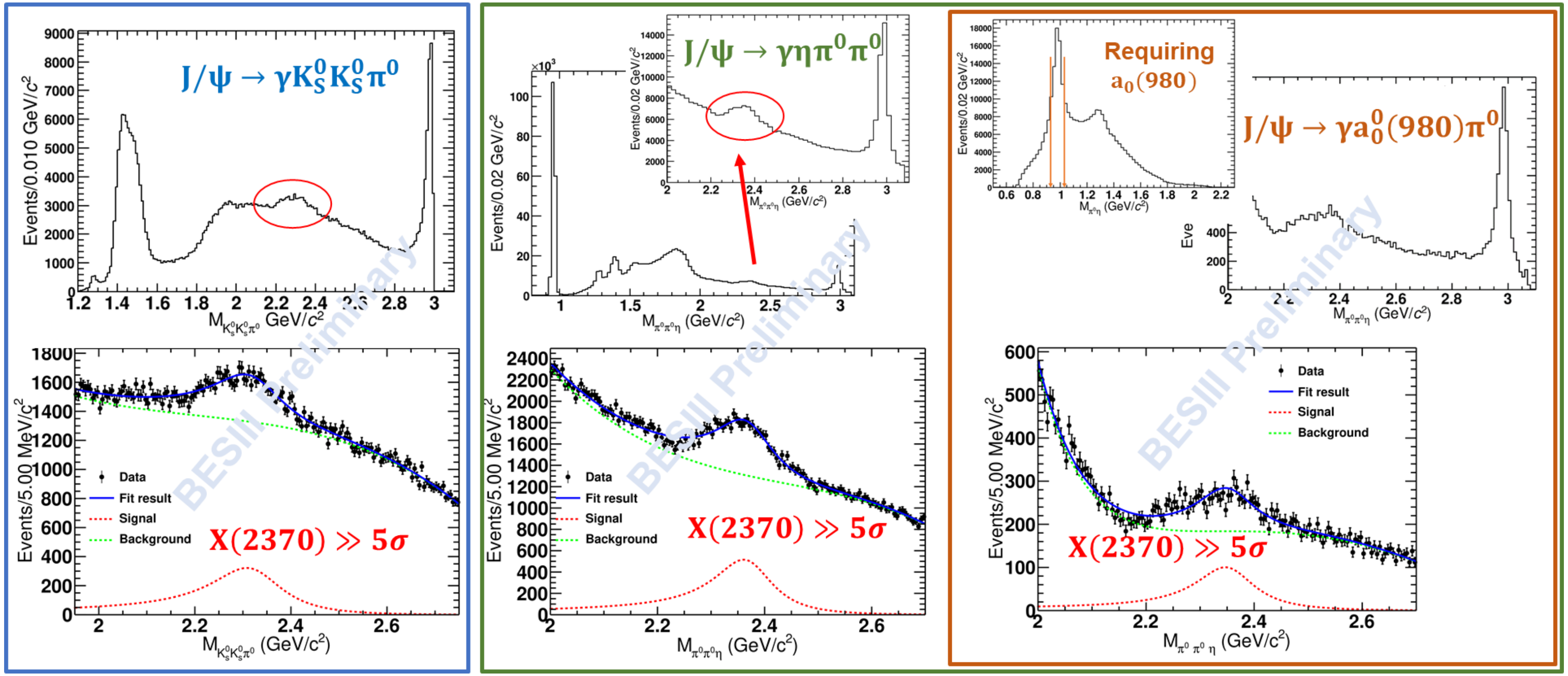
Γ = 188$^{+18}_{-17}$$^{+124}_{-33}$ MeV

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

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



BESIII EPJC 80 746(2020)



New decay modes

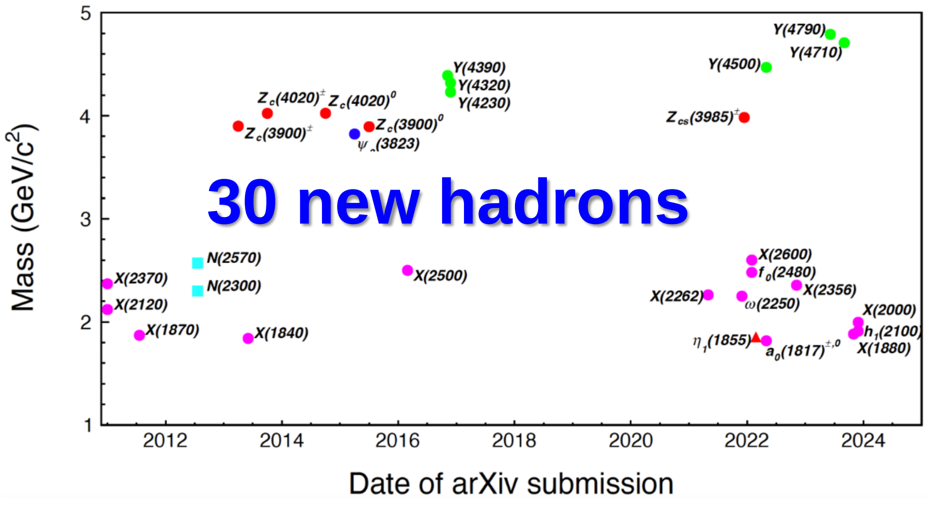
$X(2370)$ observed in the gluon-rich J/ψ radiative decays

- **J^{PC} determined to be 0^{-+}**
- **Mass and production rate consistent with LQCD**
- **Decay modes $X(2370) \to$ $\eta'\pi\pi, \eta' KK, K_S^0K_S^0\eta, K_S^0K_S^0\pi^0, \eta\pi^0\pi^0, a_0^0(980)\pi^0$ observed, in analog to η_c**

Consistent with 0^{-+} glueball

Summary

- BESIII has a rich program of hadron physics
- Lots of progress in light QCD exotics
- Great potential to be fully explored
  - $50\ \mathrm{fb}^{-1}$ data on disk, including $10 \times 10^9\ J/\psi$ and $2.7 \times 10^9\ \psi'$
  - Running until ~2030
  - Upgrade in this summer
    - $\mathcal{L} \times 3$ @$\sqrt{s}$=4.7 GeV
    - $\sqrt{s} \rightarrow 5.6\ GeV$, starting from 2028
    - CGEM inner tracker

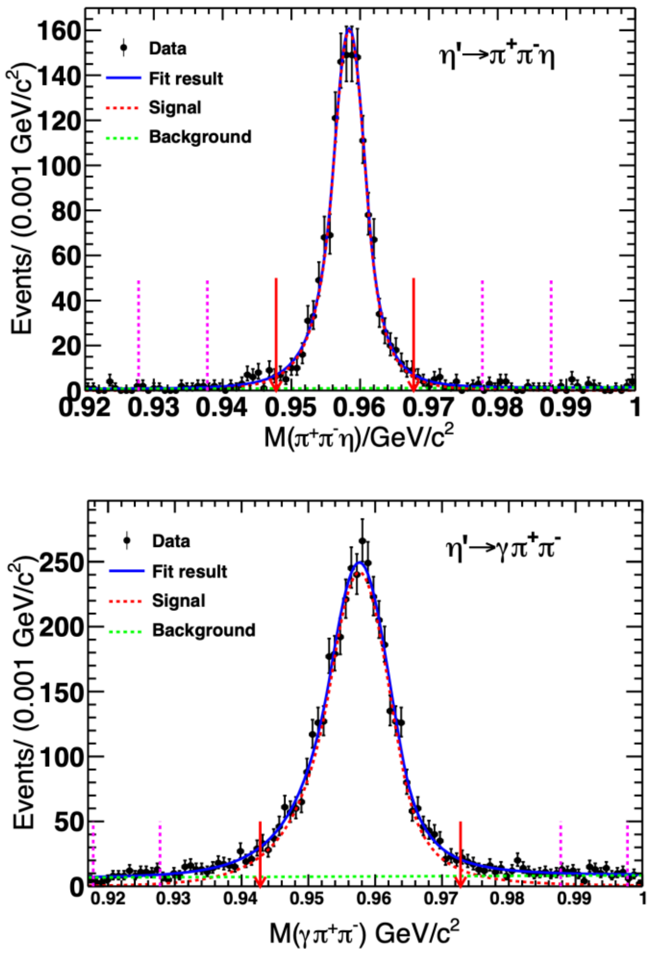


backups

Spin-parity Determination of $X(2370)$ in $J/\psi \rightarrow \gamma\eta' K_S^0 K_S^0$

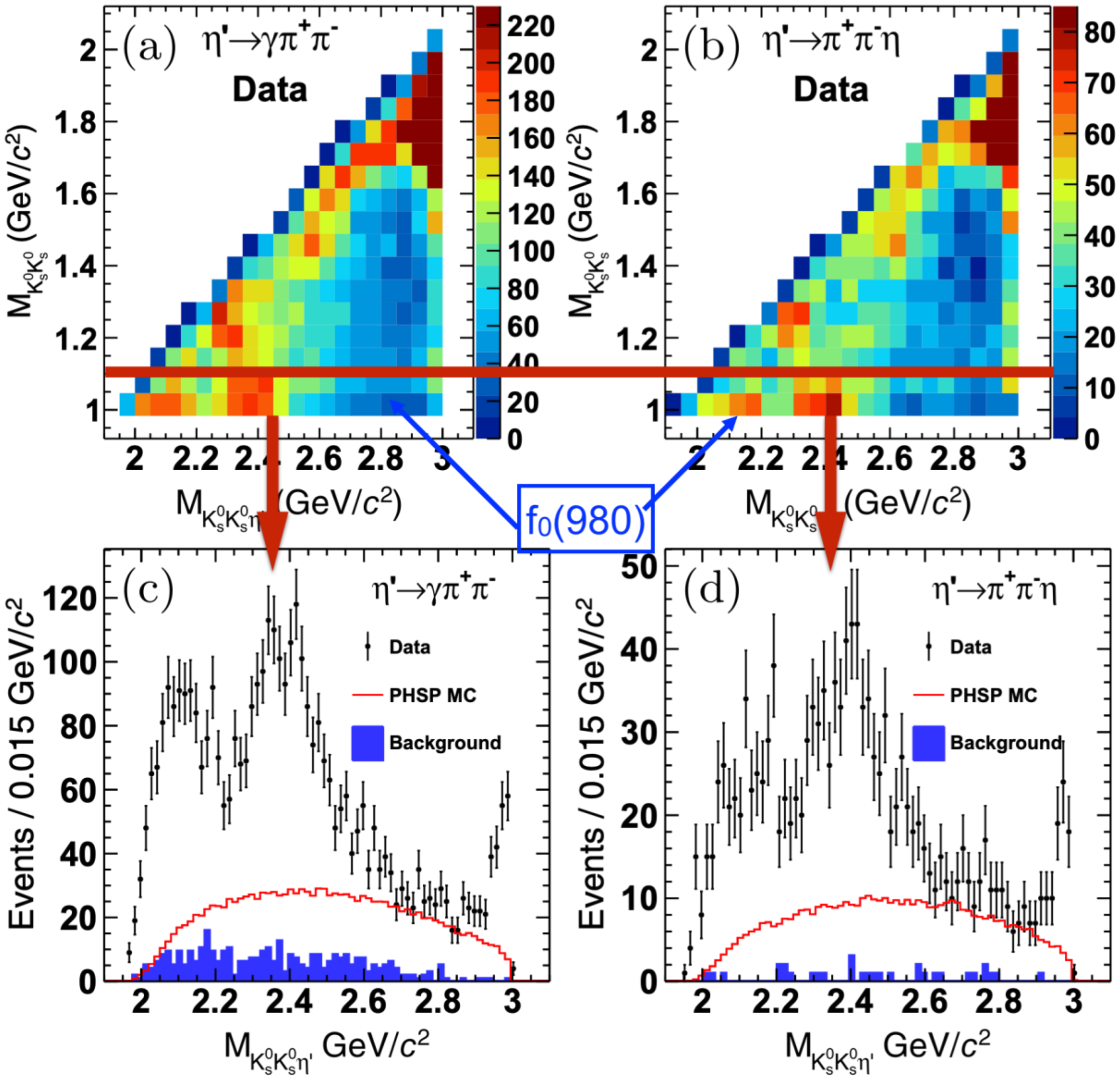
BESIII PRL 132 181901(2024)

- η' reconstructed with $\eta\pi^+\pi^-$ and $\gamma\pi^+\pi^-$
- K_S^0 reconstructed with $\pi^+\pi^-$
- **Almost background free**
  - Negligible mis-combination for K_S^0 (<0.1%)
  - No background from $J/\psi \rightarrow \pi^0\eta' K_S^0 K_S^0$ or $\eta' K_S^0 K_S^0$
    - Forbidden by exchange symmetry and CP conservation
  - No peaking background
  - Little Non- η' backgrounds estimated from η' sidebands
    - **1.8% for $\eta' \rightarrow \eta\pi^+\pi^-$, 6.8% for $\eta' \rightarrow \gamma\pi^+\pi^-$**



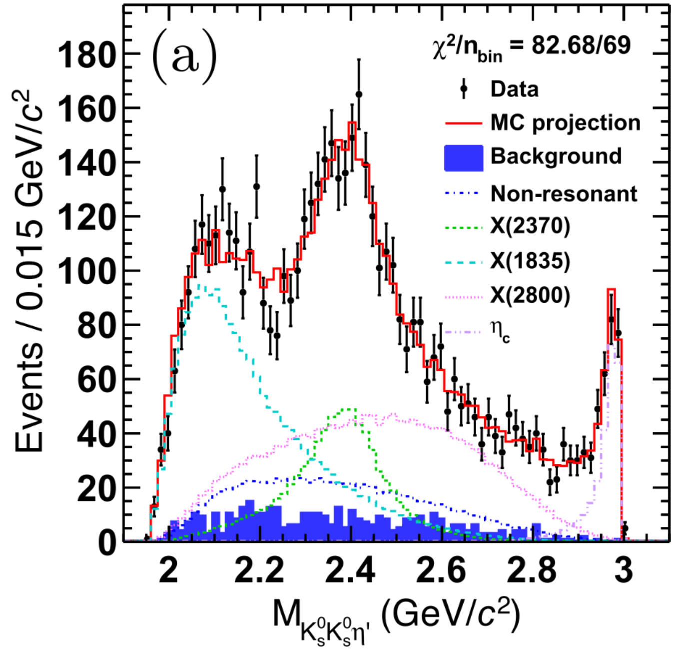
Spin-parity Determination of $X(2370)$ in $J/\psi \to \gamma\eta' K_S^0 K_S^0$

BESIII PRL 132 181901(2024)



- A clear connection between the $f_0(980)$ and $X(2370)/\eta_c$
  - $f_0(980)$ selection with $M(K_S^0 K_S^0) < 1.1 GeV/c^2$
  - Clear signals of the $X(2370)$ and η_c
- Amplitude analysis
  - Quasi two-body decay amplitudes in the sequential decay processes $J/\psi \to \gamma X, X \to Y\eta', Y \to K_S^0 K_S^0$ and $J/\psi \to \gamma X, X \to Z K_S^0, Z \to K_S^0 \eta'$ are constructed using the covariant tensor formalism[Eur. Phys. J. A 16, 537]

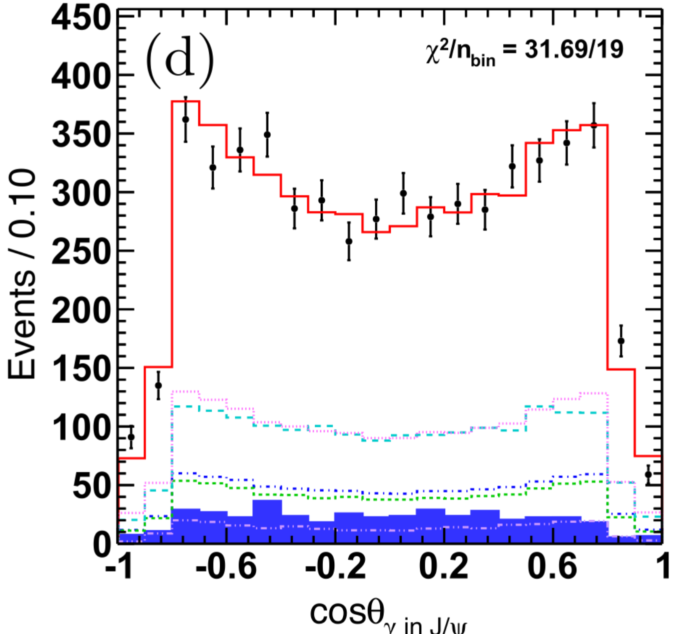
Spin-parity Determination of $X(2370)$ in $J/\psi \rightarrow \gamma\eta' K_S^0 K_S^0$



BESIII PRL 132 181901(2024)

Nominal fit solution

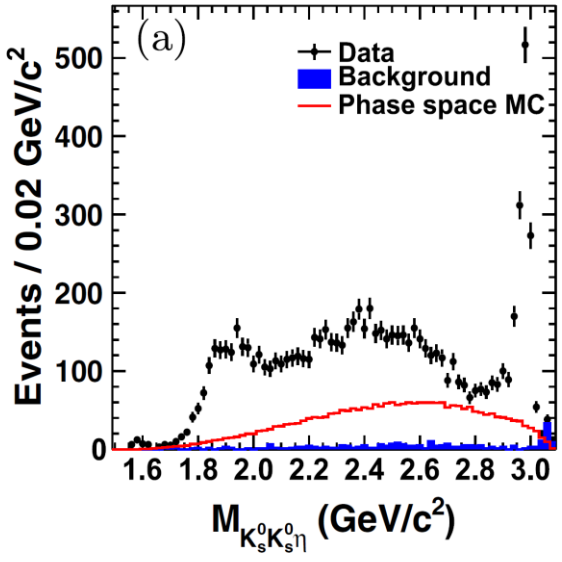
state	J^{PC}	Decay mode	Mass (MeV/c^2)	Width (MeV/c^2)	Significance
X(2370)	0^{-+}	$f_0(980)\eta'$	2395^{+11}_{-11}	188^{+18}_{-17}	14.9σ
X(1835)	0^{-+}	$f_0(980)\eta'$	1844	192	22.0σ
X(2800)	0^{-+}	$f_0(980)\eta'$	2799^{+52}_{-48}	660^{+180}_{-116}	16.4σ
η_c	0^{-+}	$f_0(980)\eta'$	2983.9	32.0	$> 20.0\sigma$
PHSP	0^{-+}	$\eta'(K_S^0 K_S^0)_{S-wave}$	– – –	– – –	9.0σ
		$\eta'(K_S^0 K_S^0)_{D-wave}$	– – –	– – –	16.3σ



- **$X(2370)$'s $J^{PC} = 0^{-+}$ with 9.8 σ**
- Product branching fraction:

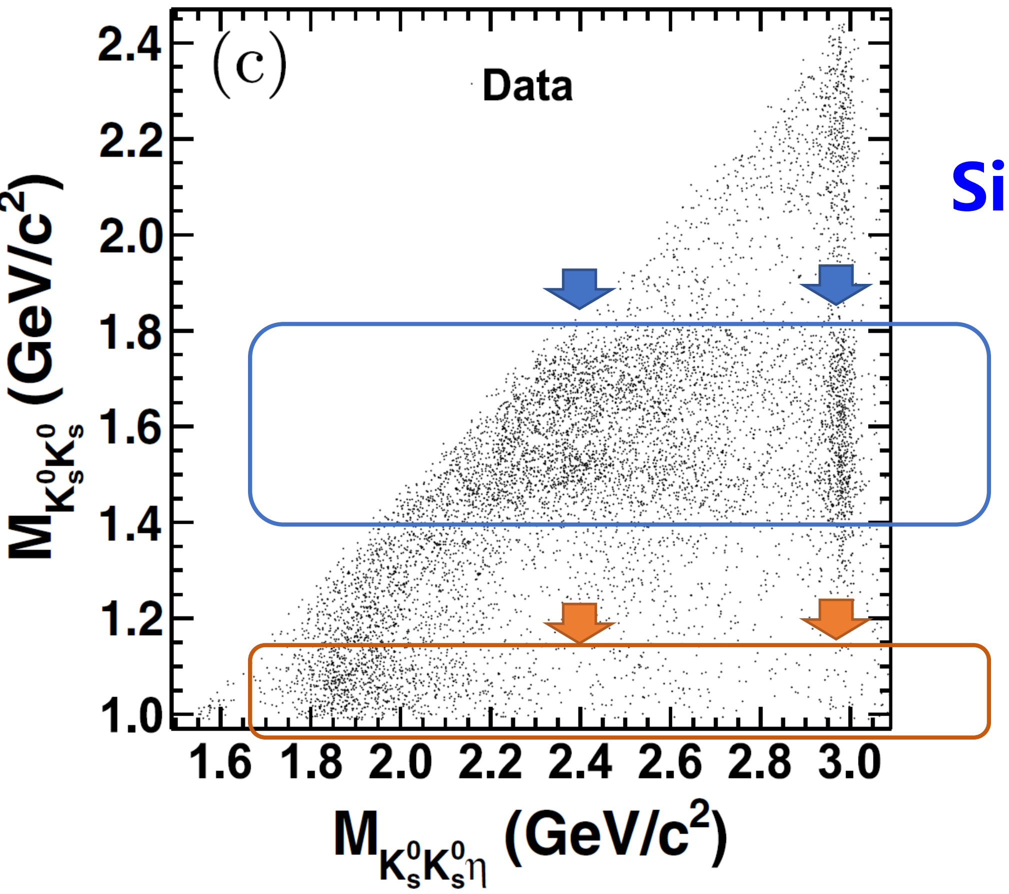
$$B(J/\psi \rightarrow \gamma X(2370)B(X(2370) \rightarrow \eta' K_S^0 K_S^0)B(f_0(980) \rightarrow K_S^0 K_S^0) = (1.31 \pm 0.22^{+2.85}_{-0.84}) \times 10^{-5}$$

$\mathbf{X(2370)}$ seen in $J/\psi \to \gamma K_S^0 K_S^0 \eta$



Observation and Spin-Parity Determination of the $X(1835)$ in $J/\psi \to \gamma K_S^0 K_S^0 \eta$

BESIII PRL 115 091803(2015)



Similar decay patterns of the $X(2370)$ and η_c

clear $X(2370)$ AND η_c signals

no $X(2370)$ OR η_c signal

What we have learned before

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

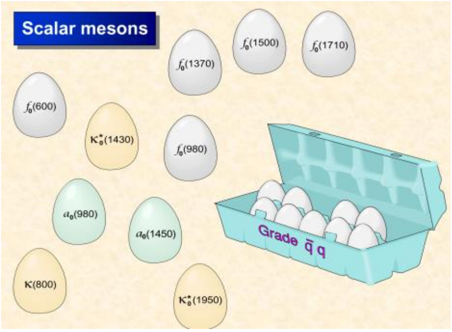
e^+e^- annihilation
$p\bar{p}$ annihilation
central exclusive production
charge-exchange reactions

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

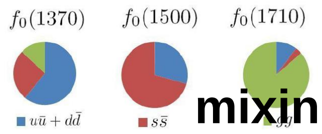
Exp: **overpopulation**

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

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

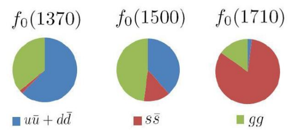


Cheng *et al*, Phys. Rev. D**74** (2006) 094005



mixing schemes

Close and Kirk, PLB**483** (2000) 345

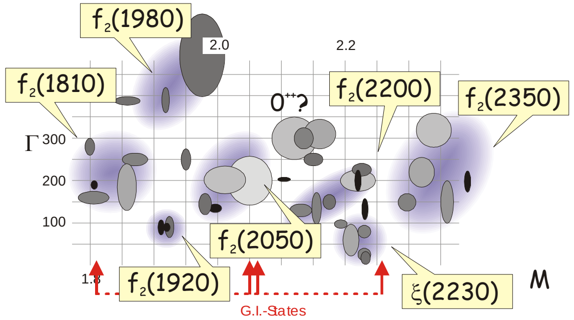


Tensor: 2 nonets($^3P_2$,$^3F_2$), complicated

Exp: **large uncertainty**

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

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

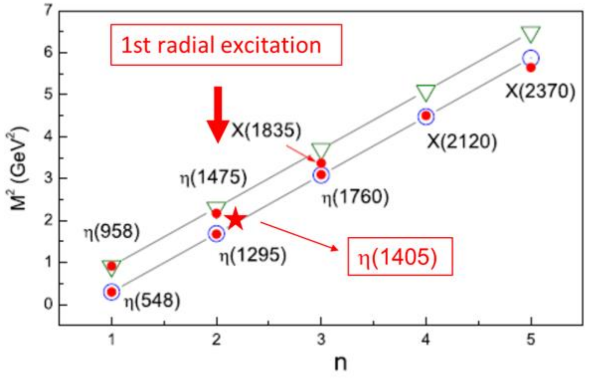


Pseudoscalar: η & η′ , “simple”

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

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

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



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

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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 with analogy decay pattern as η_c**

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 $f_0(1710)$**

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

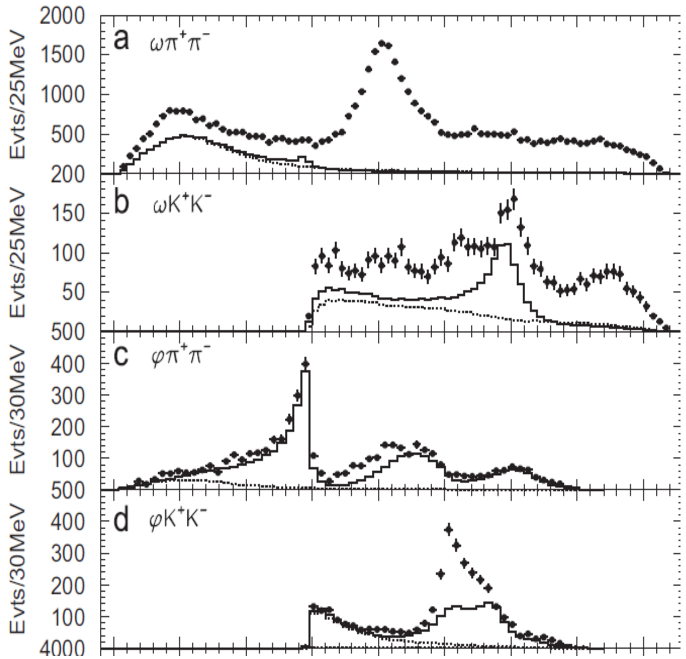
➢ Supports to the hypothesis that $f_0(1710)$ overlaps with the ground state scalar glueball
  - Scalar glueball expected to be suppressed $B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$

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

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

More scalars

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

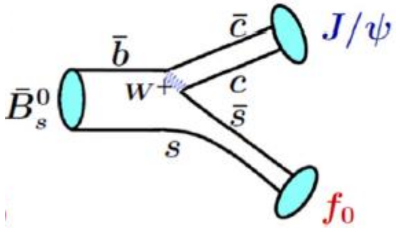


ωK^+K^- ➜ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

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

ϕK^+K^- ➜ No peak around 1700 MeV/c^2

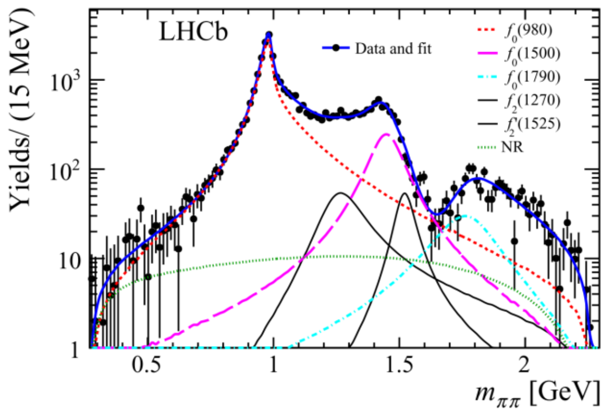
$f_0(1800)$

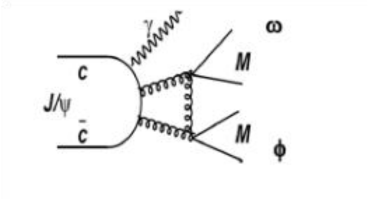


selective for $s\bar{s}$

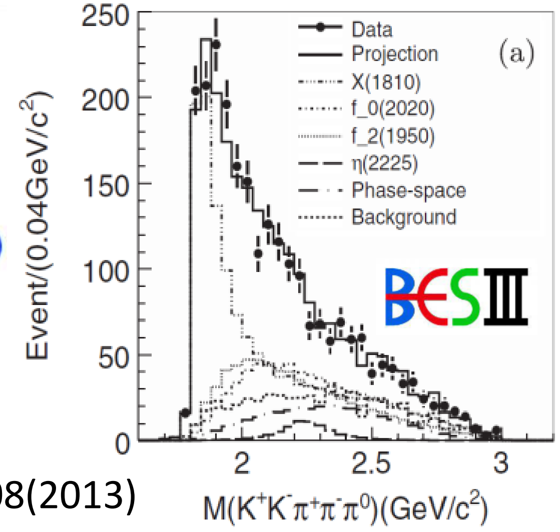
$B_s \to J/\psi f_0$

PLB 797 (2019) 134789





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



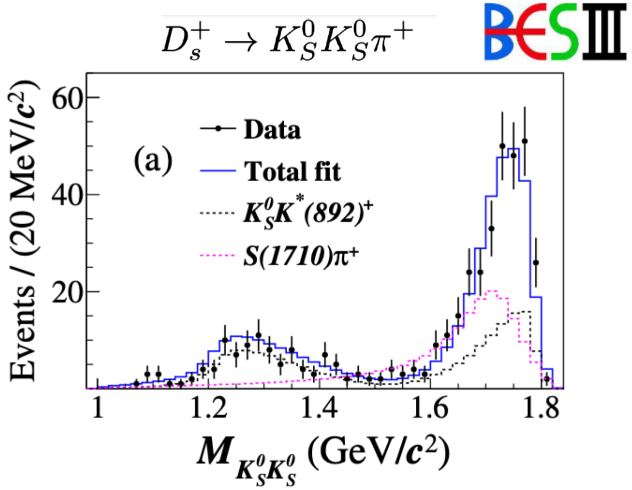
PRD 87, 032008(2013)

$a_0(1817)$

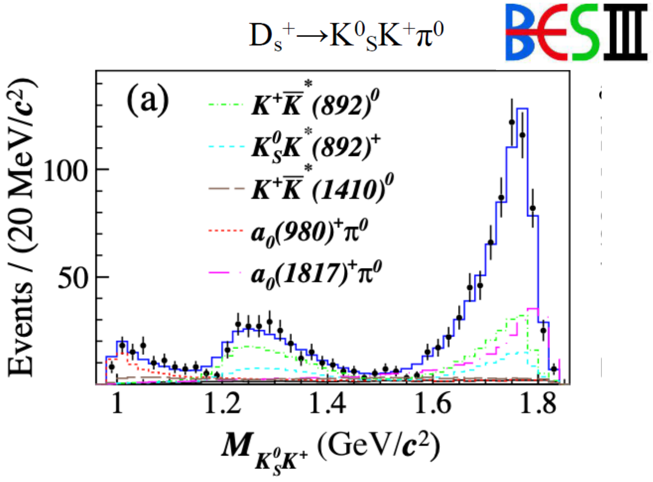
Isovector partner of $f_0(1800)$?

[Shulei 's talk]

PRD105, L051103 (2022)



PRL129, 182001 (2022)



Two photon couplings

$\gamma\gamma \rightarrow K_S K_S$

Belle PTEP 2013 (2013) 12, 123C01

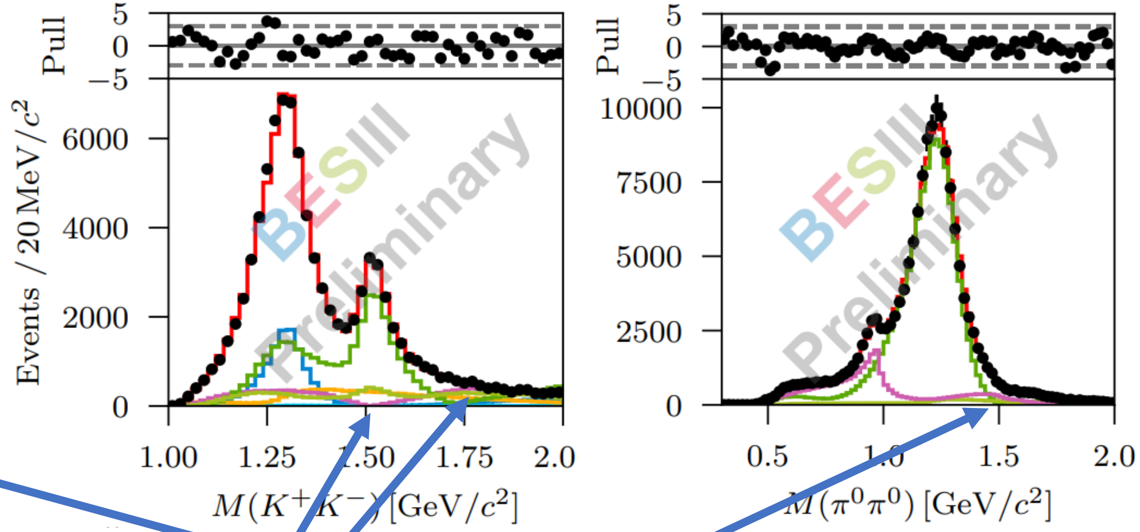
Parameter	$f_0(1710)$ fit			
	fit-H	fit-L	H,L combined	PDG
χ^2/ndf	694.2/585	701.6/585	–	–
Mass(f_J) (MeV/c^2)	1750^{+5+29}_{-6-18}	1749^{+5+31}_{-6-42}	1750^{+6+29}_{-7-18}	1720 ± 6
$\Gamma_{tot}(f_J)$ (MeV)	138^{+12+96}_{-11-50}	145^{+11+31}_{-10-54}	139^{+11+96}_{-12-50}	135 ± 6
$\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})_{f_J}$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

$\gamma\gamma \rightarrow \pi^0\pi^0$

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
$\Gamma_{\gamma\gamma}\mathcal{B}(f_0(Y) \rightarrow \pi^0\pi^0)$	$11.2^{+5.0}_{-4.0}$	$6780.2^{+626.5}_{-574.7}$	0 (fixed)	eV

BESIII preliminary



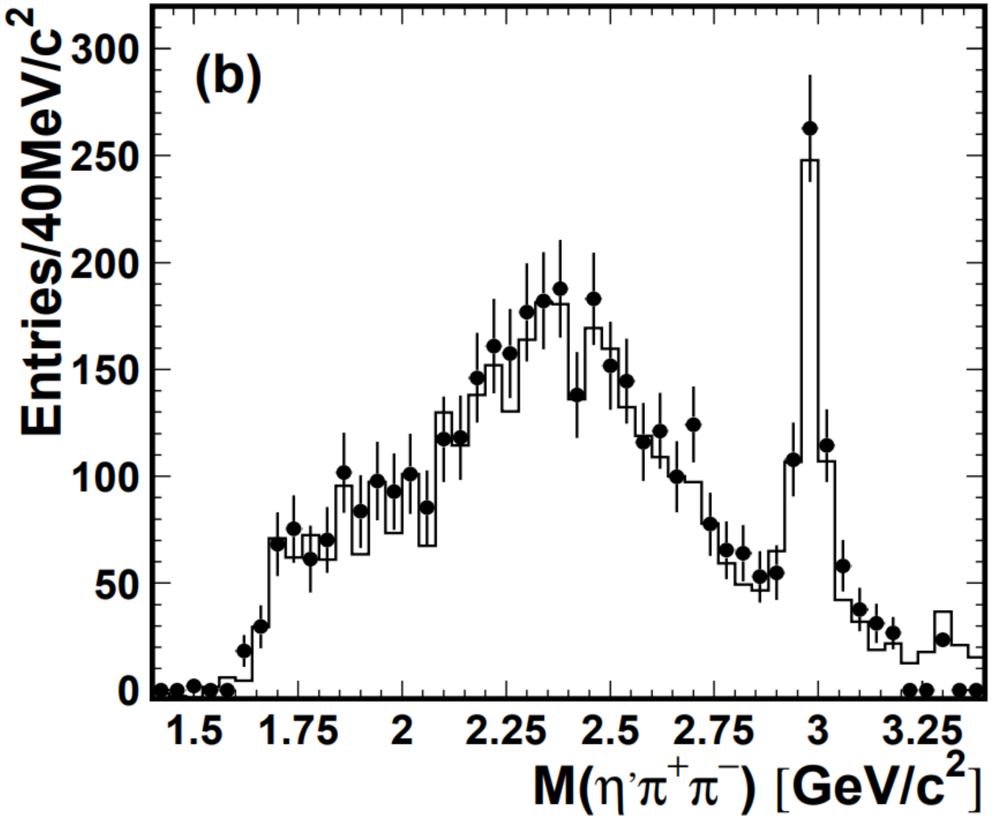
$f_0(1710)$? $f_0(1800)$?

$f_0(1500)$?

Proper assignment requires **more sophisticated model**

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

Belle PRD 86 052002(2012)



Amplitude analysis

Amplitude analysis is a key tool of hadron spectroscopy to disentangle contributions from individual resonances and to extract the resonance's spin-parity, mass, width and decay properties

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

$\ln L = \sum_{n=1}^{N_{data}} \ln(Prob(\xi,\alpha))$

ξ (the four-momenta of the final-state particles),

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

$\epsilon(\xi)$ efficiency

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

For J/ψ radiative decays [Eur. Phys. J. A 16, 537]

$$A = \psi_\mu(m_1)e_\nu^*(m_2)A^{\mu\nu} = \psi_\mu(m_1)e_\nu^*(m_2)\sum_i \Lambda_i U_i^{\mu\nu}$$

e.g. $J/\psi \rightarrow \gamma 0^{-+}, 0^{-+} \rightarrow f_0\eta, f_0\pi\pi$

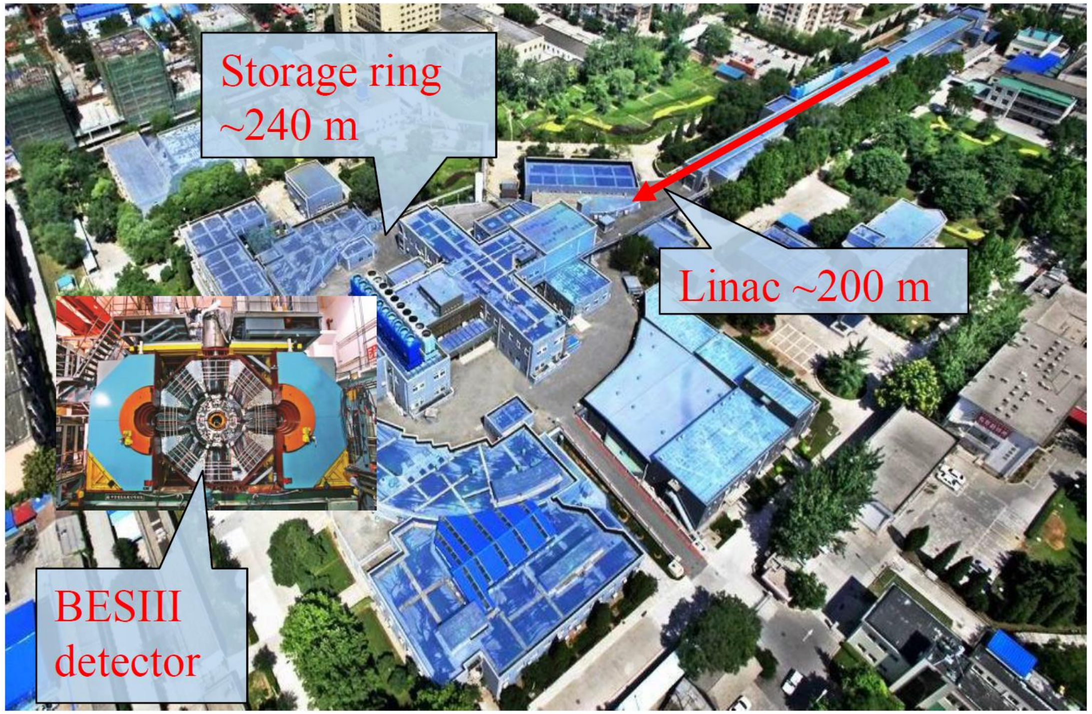
$$\langle\gamma 0^{-+}|(f_0\eta)1\rangle = S_{\mu\nu}B_1(Q_{\psi\gamma X})f_{(12)}^{(f_0)}$$

$$S_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta}p_\psi^\alpha q^\beta$$

$B_1(Q_{\psi\gamma X})$ is Blatt-Weisskopf centrifugal barrier for $J/\psi \rightarrow \gamma X$

BESIII@BECPII

Beijing Electron Positron Collider(BEPCII)



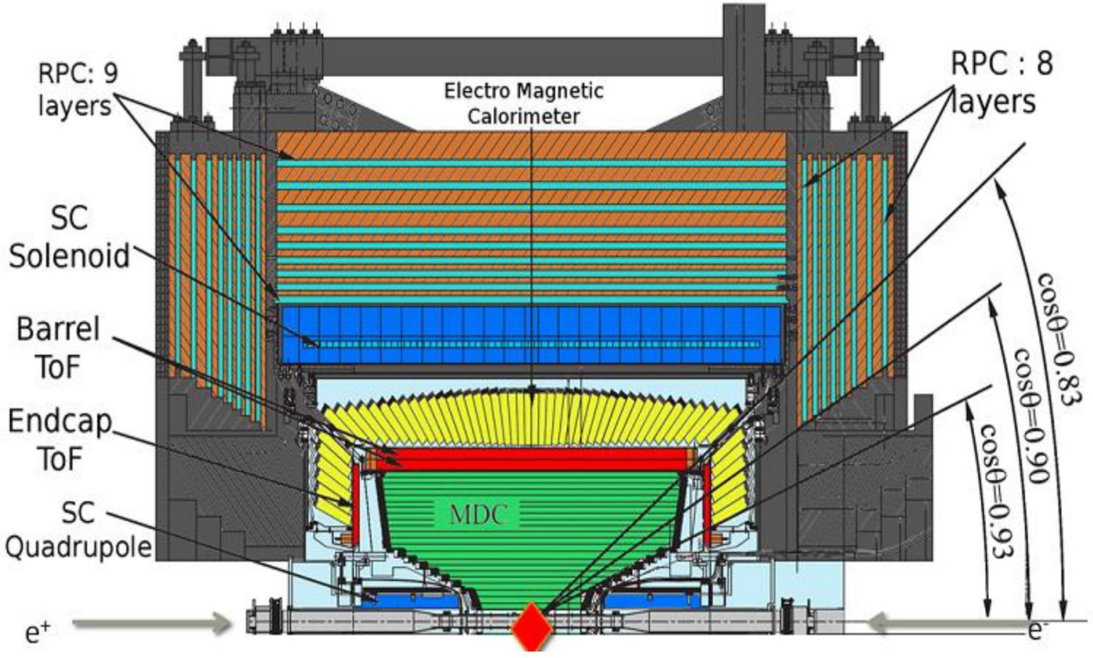
Double-ring, symmetry, multi-bunch $e^+ e^-$ collider

E_{cm}= 1.84 to 4.95 GeV

Energy spread: $\Delta E \approx 5 \times 10^{-4}$

Peak luminosity in continuously operation @E_{cm}= 3.77 GeV: 1.1×10^{33} $cm^{-2}s^{-1}$

Beijing Spectrometer(BESIII)



Main Drift Chamber	Time Of Flight	Electromagnetic Calorimeter	Muon Counter
Small cell, 43 layer	Plastic scintillator	CsI(Tl): L=28 cm	RPC
σ_{xy}=130 μm	σ_T(barrel): 65 ps	Barrel σ_E=2.5%	Barrel: 9 layers
dE/dx~6%	σ_T(endcap): 110 ps	Endcap σ_E=5.0%	Endcap: 8 layers
σ_p/p= 0.5% at 1 GeV	(update to 60 ps with MRPC)		$\sigma_{spatial}$: 1.48 cm

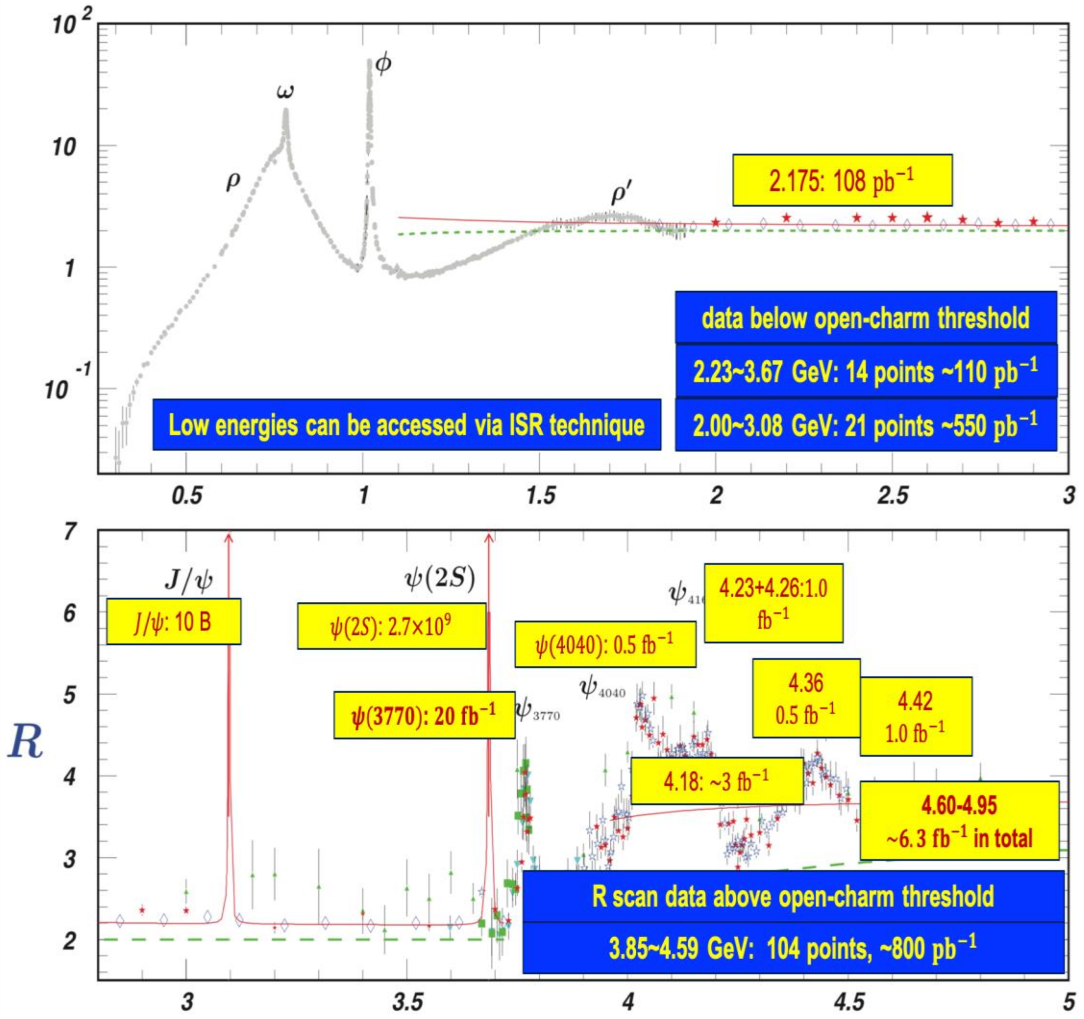
BESIII collaboration: ~600members from 17countries，89 institutions

World's largest $\tau - \mathrm{charm}$ data sets in e^+e^- annihilation

Totally about 50 fb^{-1} from 2.0-4.95 GeV

Data sets collected so far include

- $\mathbf{10 \times 10^9}$ $\mathbf{J/\psi}$ **events**
- $\mathbf{2.7 \times 10^9}$ $\mathbf{\psi(2S)}$ **events**
- **20 fb^{-1}** $\mathbf{\psi(3770)}$
- Scan data [1.84, 3.08] GeV; [3.735, 4.600]GeV, 143 energy points, ~2.0 fb^{-1}
- Large data sets for XYZ study ~22 fb^{-1}
- Entangled hadron pair-productions near thresholds



Rich physics program:

Spectroscopy & decays of light hadrons and charmonium, charm physics, precision measurements of QCD parameters, tests of fundamental symmetry, ……