Discovery of a Glueball-like particle X(2370) @ BESIII

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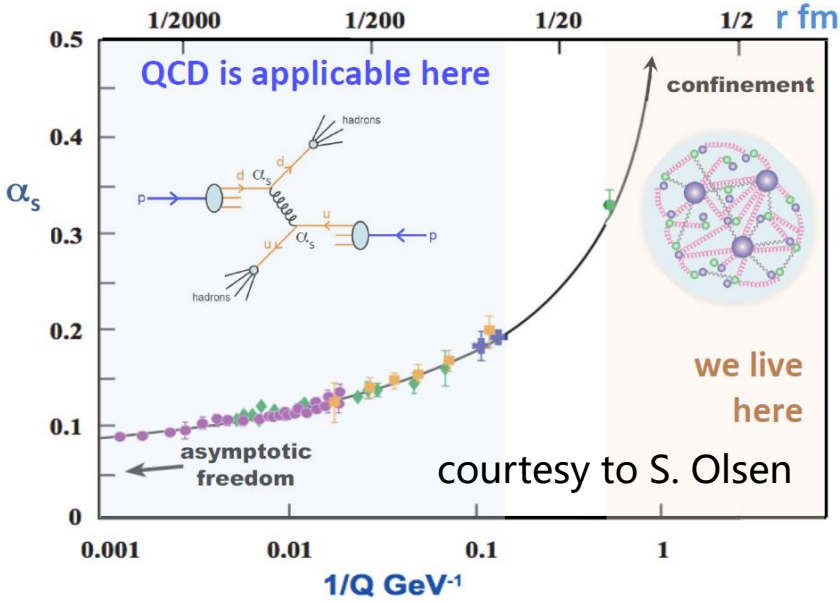
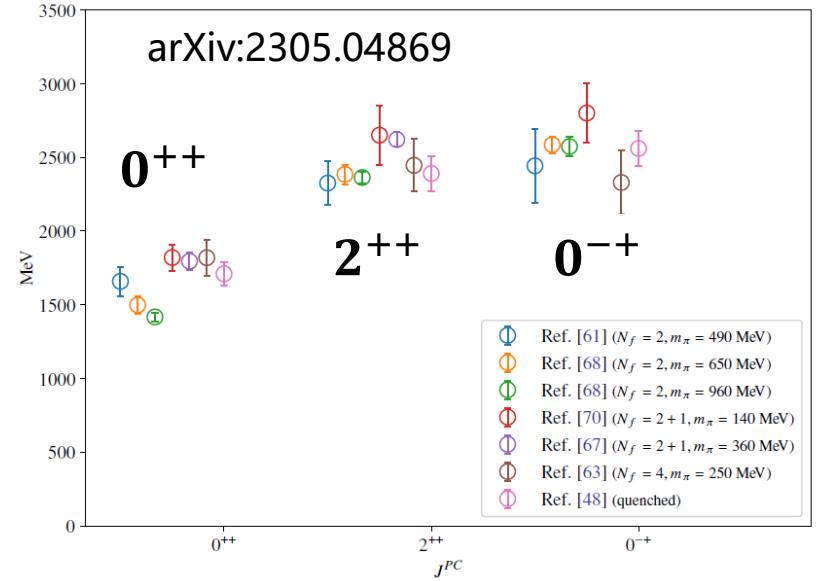
ichep2024.org

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: $J^{PC} = 0^{++}, 2^{++}, 0^{-+}$



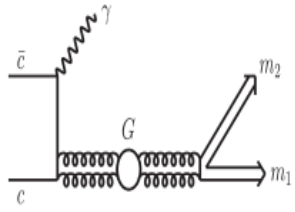


Yang-Mills glueballs on lattice (quenched and unquenched results)

Glueball hunting for over 40 years

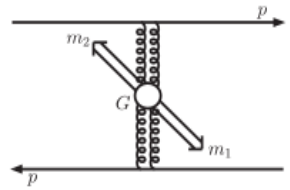
- **Supernumerary states** that do not fit into $\mathbf{q\bar{q}}$ multiplets
  - A priori, mixed with nearby $\mathbf{q\bar{q}}$
  - Assignment of some $\mathrm{q\bar{q}}$ multiplets difficult
- Production: Strongly produced in **gluon-rich processes**
- Decay: **gluon is flavor-blind**
  - No dominate 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]



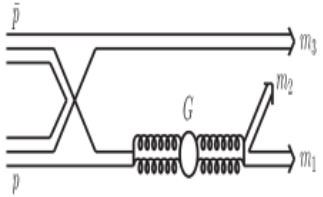
Charmonium decays:

BESIII, MRKIII…



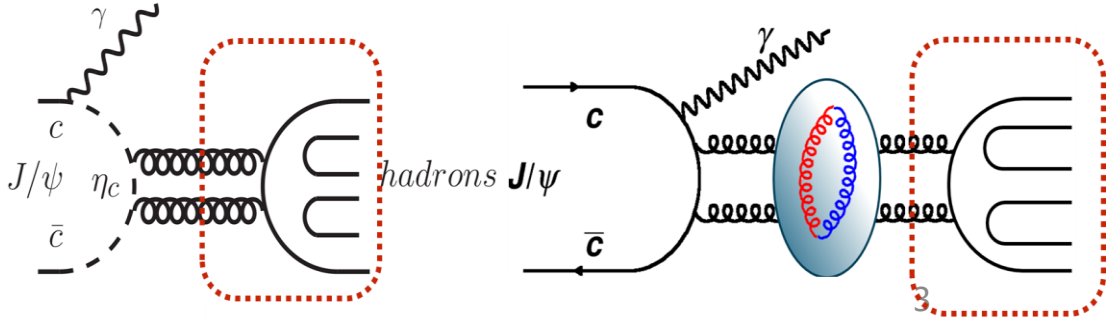
pp double-Pomeron exchange:

WA102, GAMS…

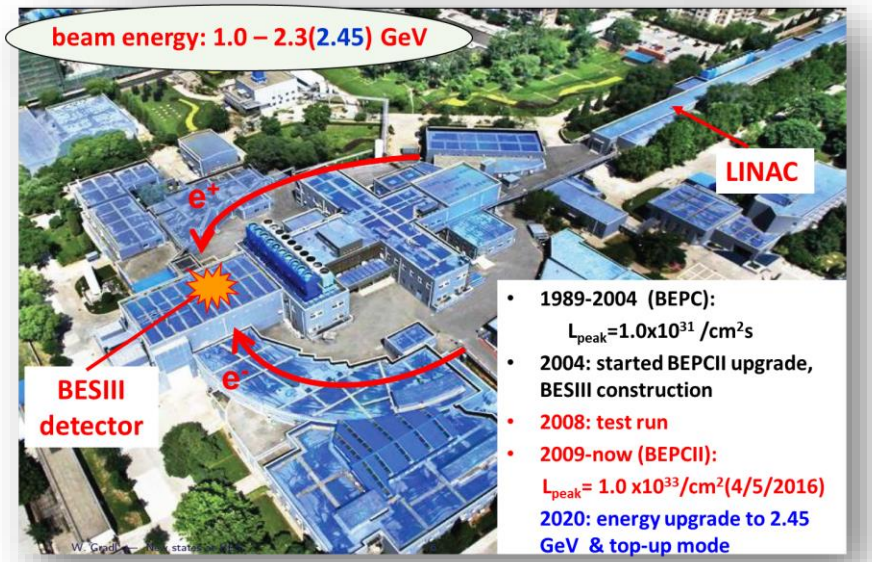


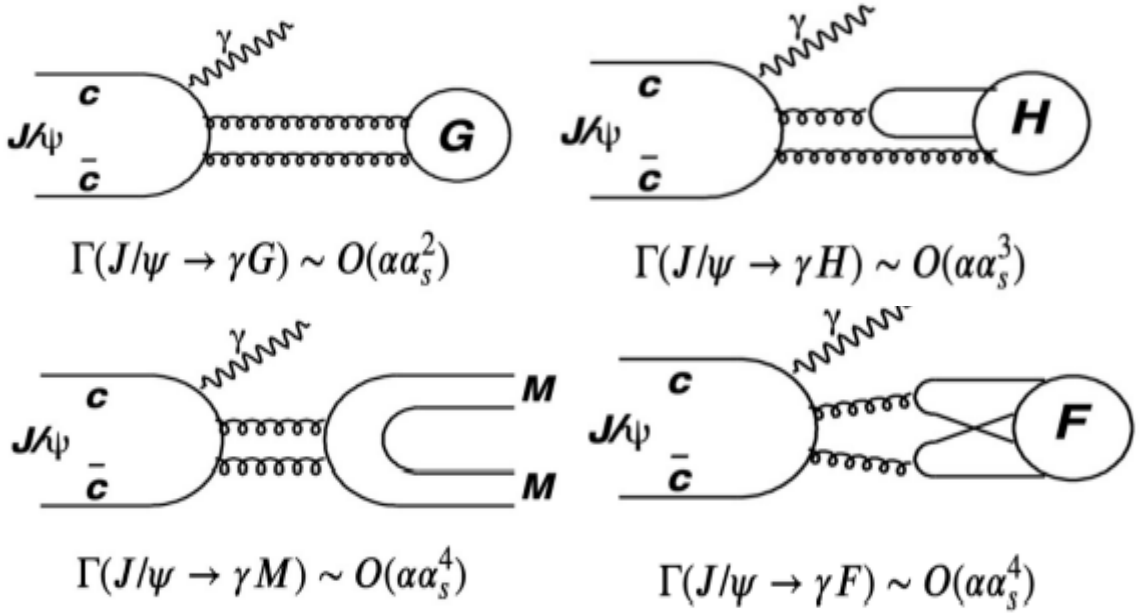
$\mathbf{p\bar{p}}$ annihilation:

Crystal barrel, OBELIX…



Beijing Electron Positron Collider (BEPCII)





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

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

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

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

Charmonium decays provide an ideal lab for glueballs

- 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

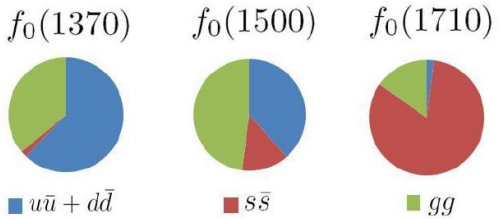
- **Supernumerary scalars** suggest additional degrees of freedom
  - However, mixing scenarios are controversial
- Measured $B(J/\psi \to \gamma f_0(1710))$ is **x10 larger** than $f_0(1500)$

  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**

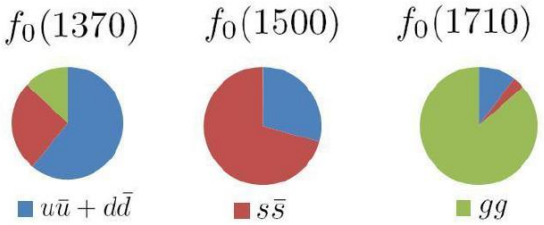
  [PLB 816, 136227 (2021), EPJC 82, 80 (2022), PLB 826, 136906 (2022)]
- **Further more, suppression of $f_0(1710) \to \eta\eta'$ supports $f_0(1710)$ has a large overlap with glueball**

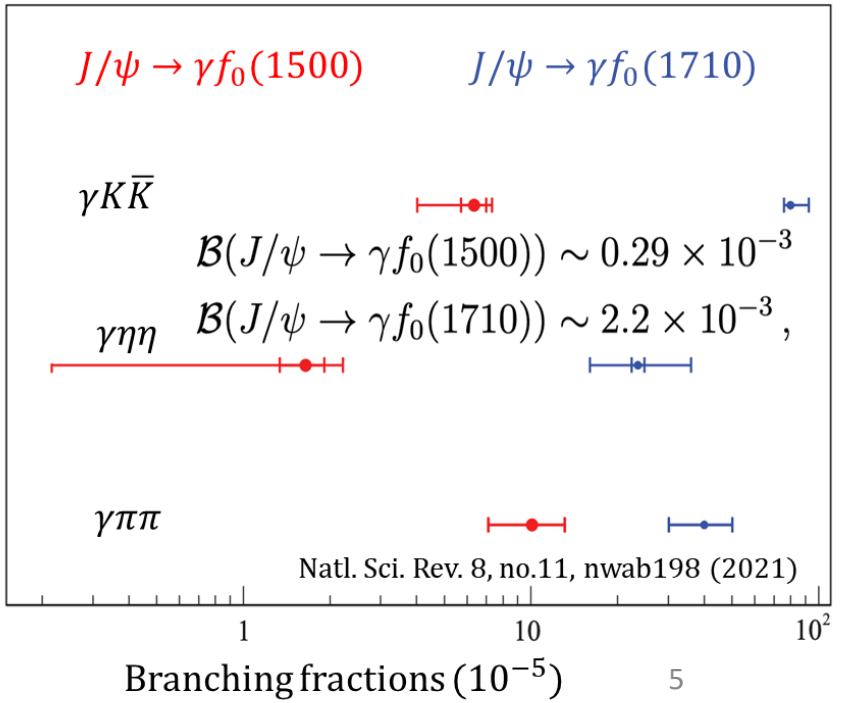
BESIII [PRD 106 072012(2022)]

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



Cheng *et al*, Phys. Rev. D**74** (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

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

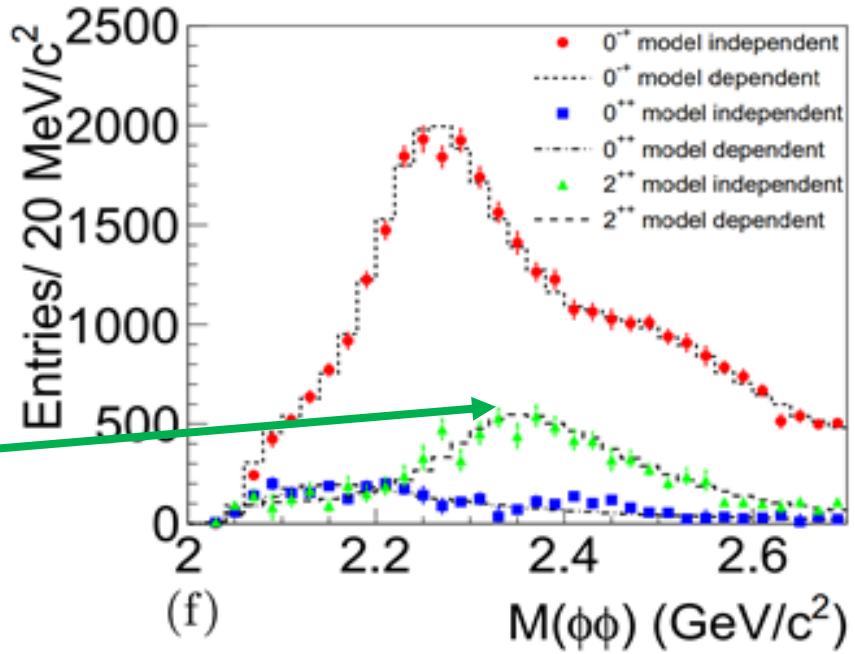
$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = \left(1.91 \pm 0.14^{+0.72}_{-0.73}\right) \times 10^{-4}}$
BESIII PRD 93, 112011 (2016)

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

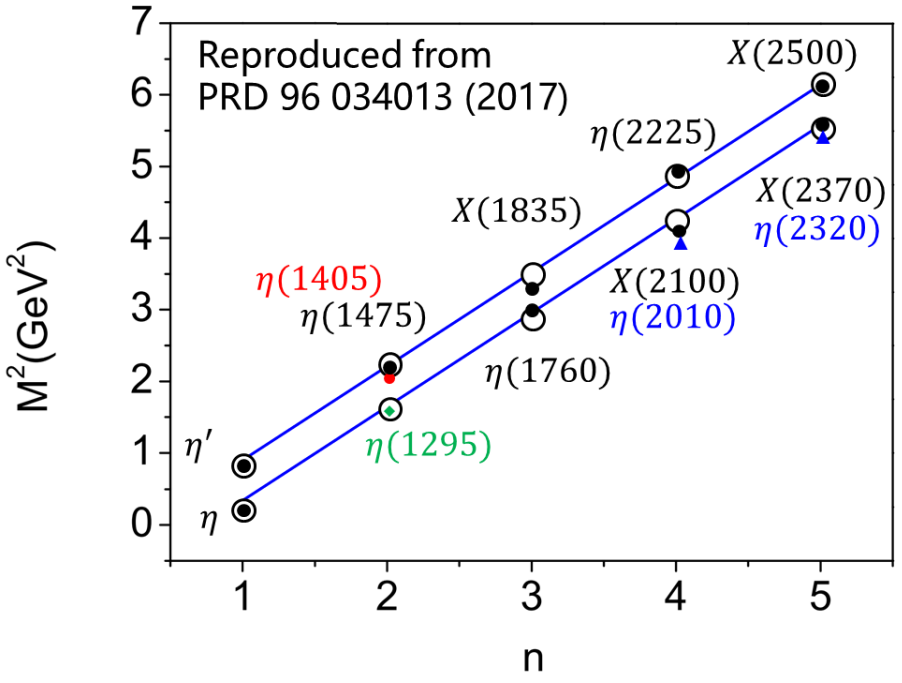


- $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ in πp reactions are all observed in $\mathbf{J/\psi \to \gamma\phi\phi}$ with a **strong production of $f_2(2340)$**
- Consistent with **double-Pomeron exchange** from WA102@CERN

More complicated due to the large number of tensor states

Where is the 0^{-+} glueball

- Pseudoscalar sector, a promising window
  - Only η, η' (& radial excitations) from quark model
- Mass
  - LQCD: 0^{-+} glueball (2.3~2.6 GeV)
  - The first glueball candidate: $\iota(1440)$ (Split into $\eta(1405)$ and $\eta(1475)$)
    - Mass incompatible with LQCD
  - Little experimental information above 2 GeV
- Production
  - LQCD: $\Gamma(J/\psi \to \gamma G_{0^-})/\Gamma_{\text{total}} = 2.31(80) \times 10^{-4}$, 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

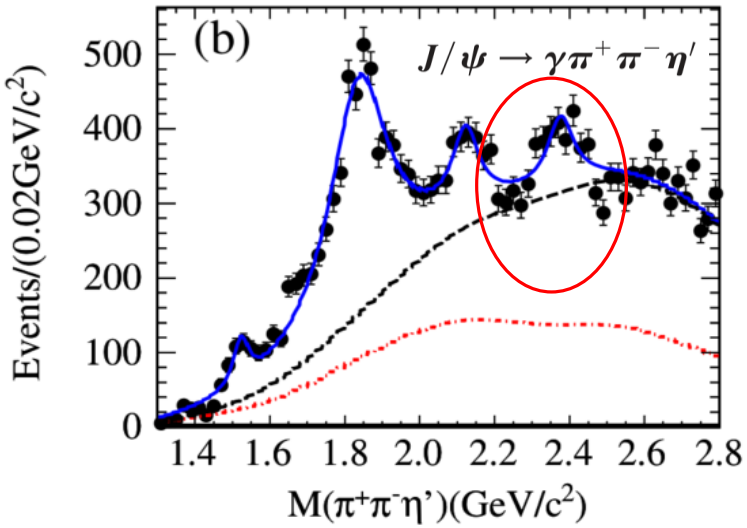
Γ_1	$\eta'(958)\pi\pi$	(1.87±0.26) %
Γ_2	$\eta'(958)K\overline{K}$	(1.61±0.25) %
	Decays into stable hadrons	
Γ_{34}	$K\overline{K}\pi$	(7.0 ±0.4) %
Γ_{35}	$K\overline{K}\eta$	(1.32±0.15) %
Γ_{36}	$\eta\pi^+\pi^-$	(1.7 ±0.5) %

- No dominant decay
- Flavor symmetric

Observation of $X(2370)$

- **Discovered by BESIII in $J/\psi \to \gamma\eta'\pi\pi$ in 2011**
- Confirmed by BESIII in $J/\psi \to \gamma\eta'\pi\pi, \gamma\eta'KK$
  - 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

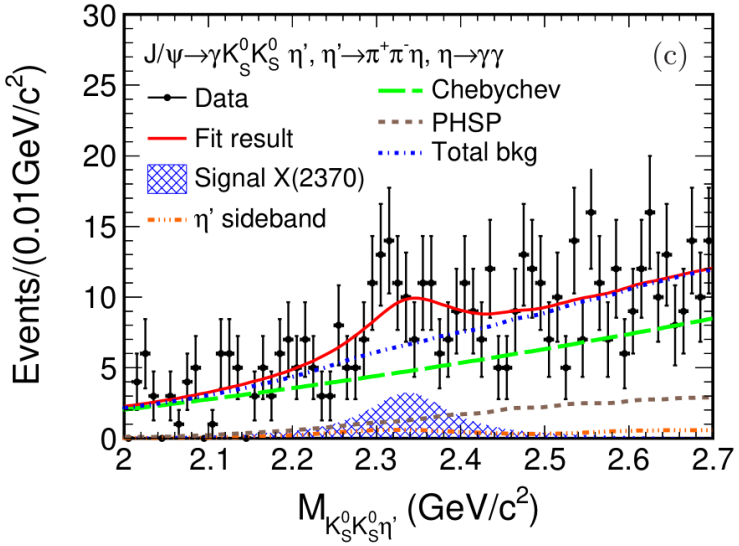
$J/\psi \to \gamma\eta'\pi\pi$



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

- **A good candidate for 0^{-+}glueball**
- Mass is consistent with LQCD predictions
- Produced in the gluon-rich J/ψ radiative decays
- Observed in both $\eta'\pi\pi$ and $\eta'KK$

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



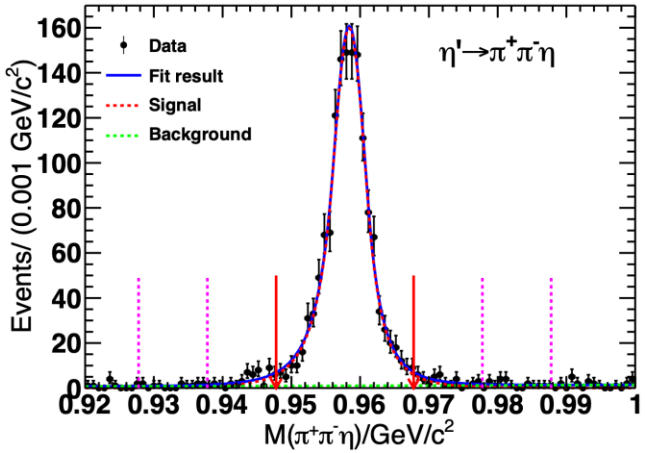
BESIII EPJC 80 746(2020)

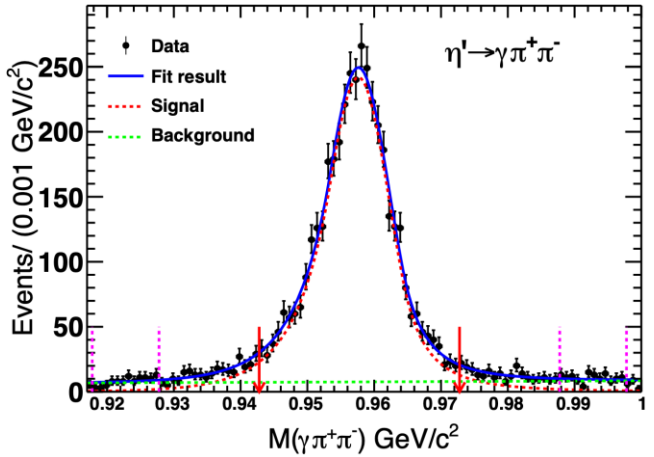
→ Determination of its spin-parity is crucial

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

- 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 $J/\psi \to \pi^0\eta' K_S^0 K_S^0$ 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 $\eta' \to \eta\pi^+\pi^-$, 6.8% for $\eta' \to \gamma\pi^+\pi^-$**

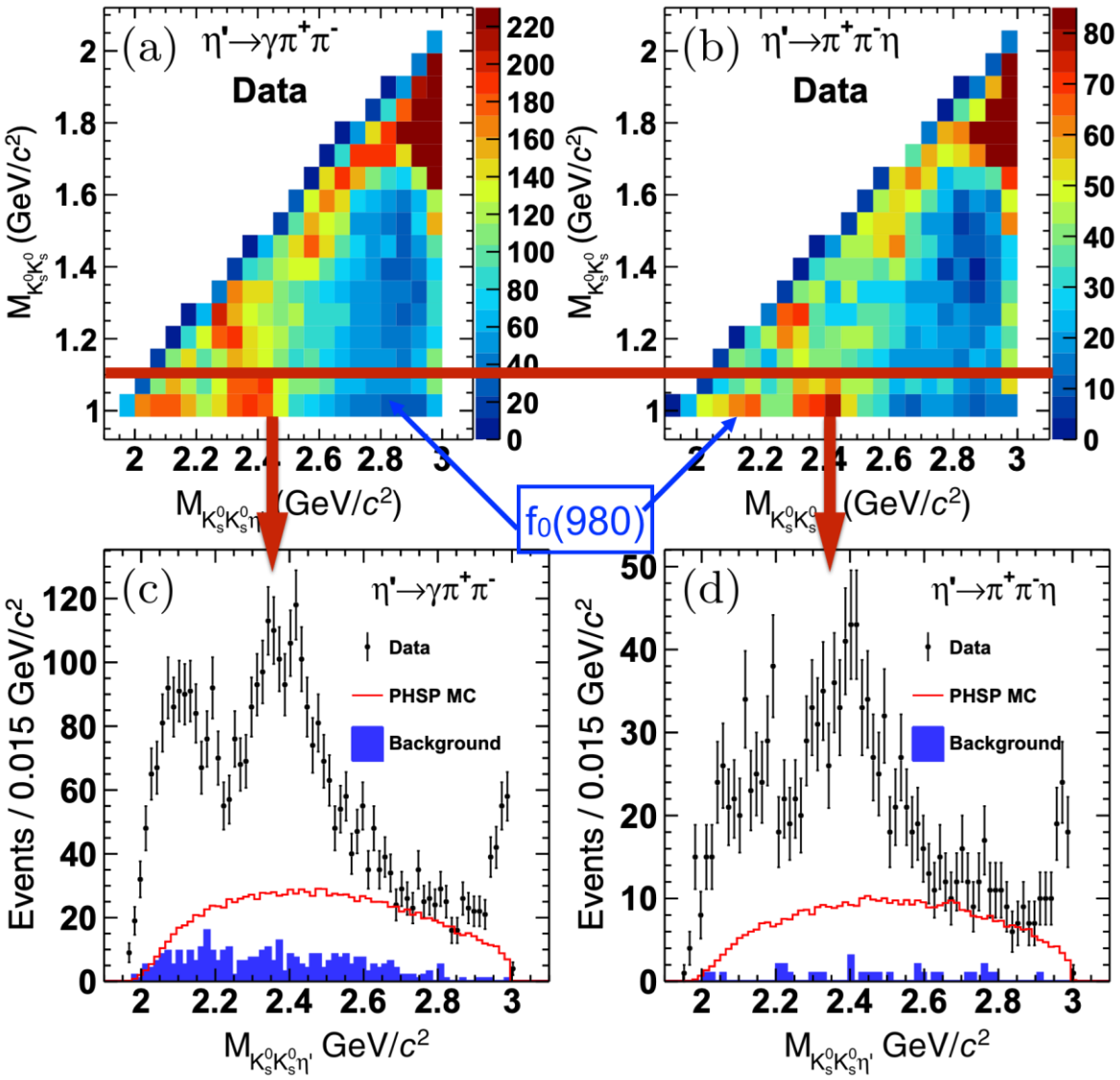
BESIII PRL 132 181901(2024)





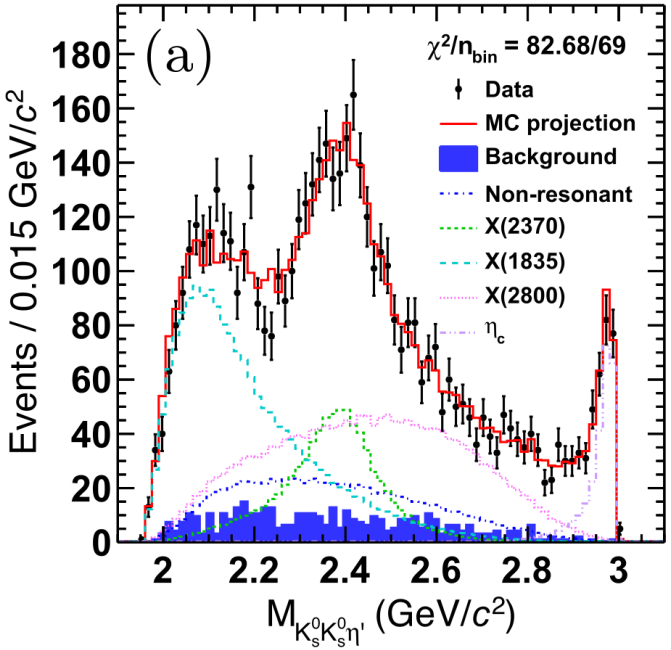
Spin-parity Determination of $X(2370)$ in $J/\psi \to \gamma\eta' K_S^0 K_S^0$

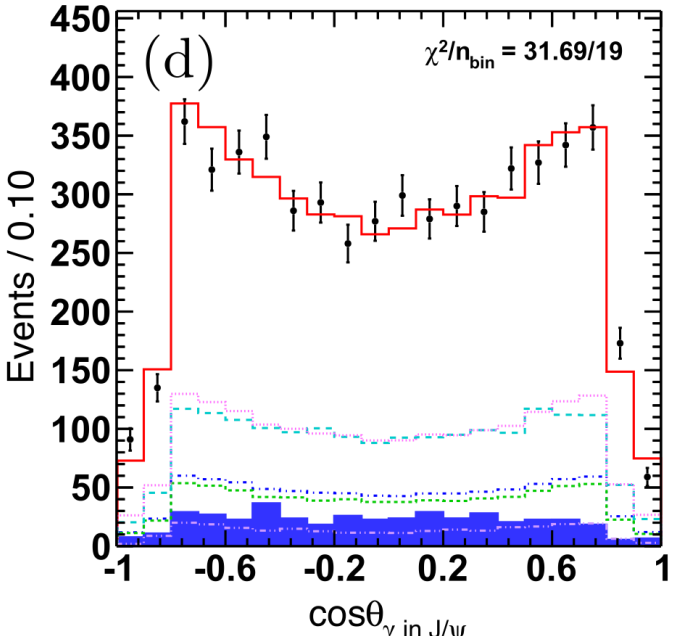
BESIII PRL 132 181901(2024)



- A clear connection between the $f_0(980)$ and $X(2370)/\eta_c$
  - $f_0(980)$ selection with $M(K_S^0 K_S^0) < 1.1\,\mathrm{GeV}/c^2$
  - 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 $J/\psi \to \gamma\eta' K_S^0 K_S^0$





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^{-+}	$\eta'(K_S^0K_S^0)_{S-wave}$	− − −	− − −	9.0σ
		$\eta'(K_S^0K_S^0)_{D-wave}$	− − −	− − −	16.3σ

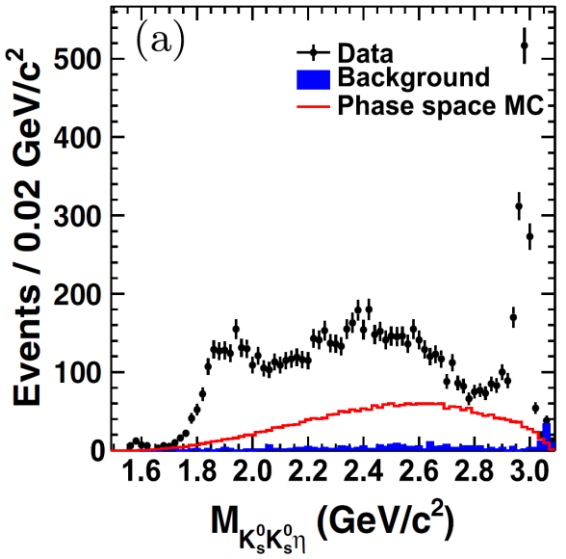
- **$X(2370)$'s $J^{PC} = 0^{-+}$ with 9.8 σ**
- Product branching fraction:

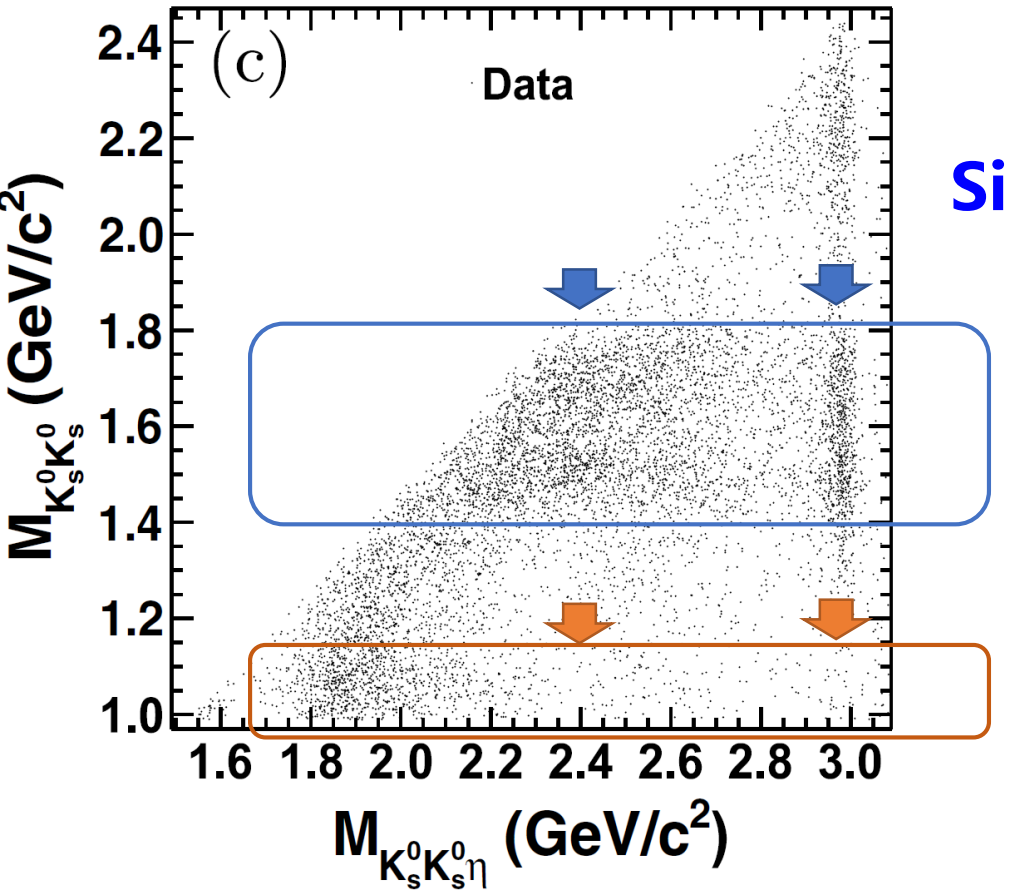
$$B(J/\psi \to \gamma X(2370) B(X(2370) \to \eta' K_S^0 K_S^0) B(f_0(980) \to K_S^0 K_S^0) = \left(1.31 \pm 0.22^{+2.85}_{-0.84}\right) \times 10^{-5}$$

$X(2370)$ 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)



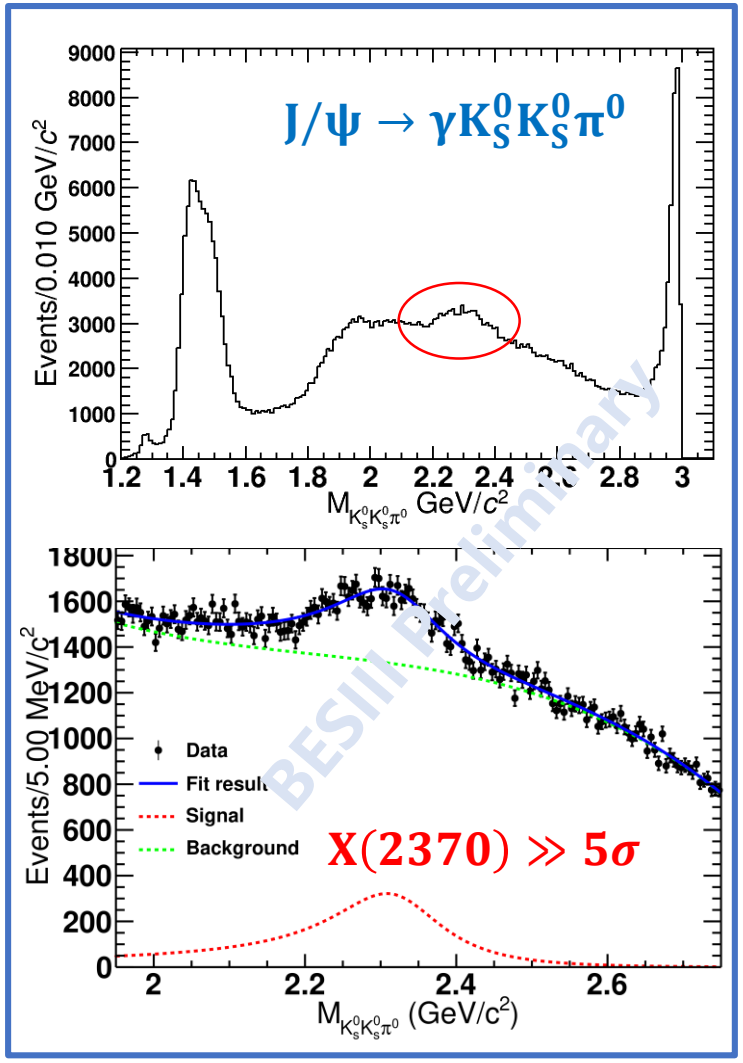


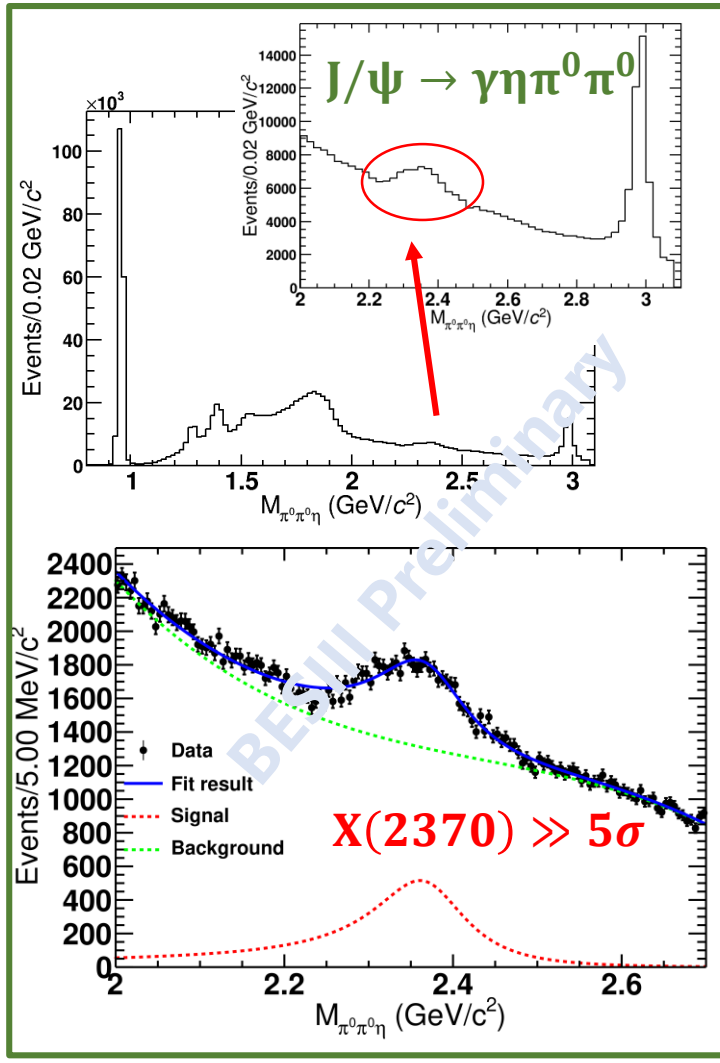
Similar decay patterns of the $X(2370)$ and η_c

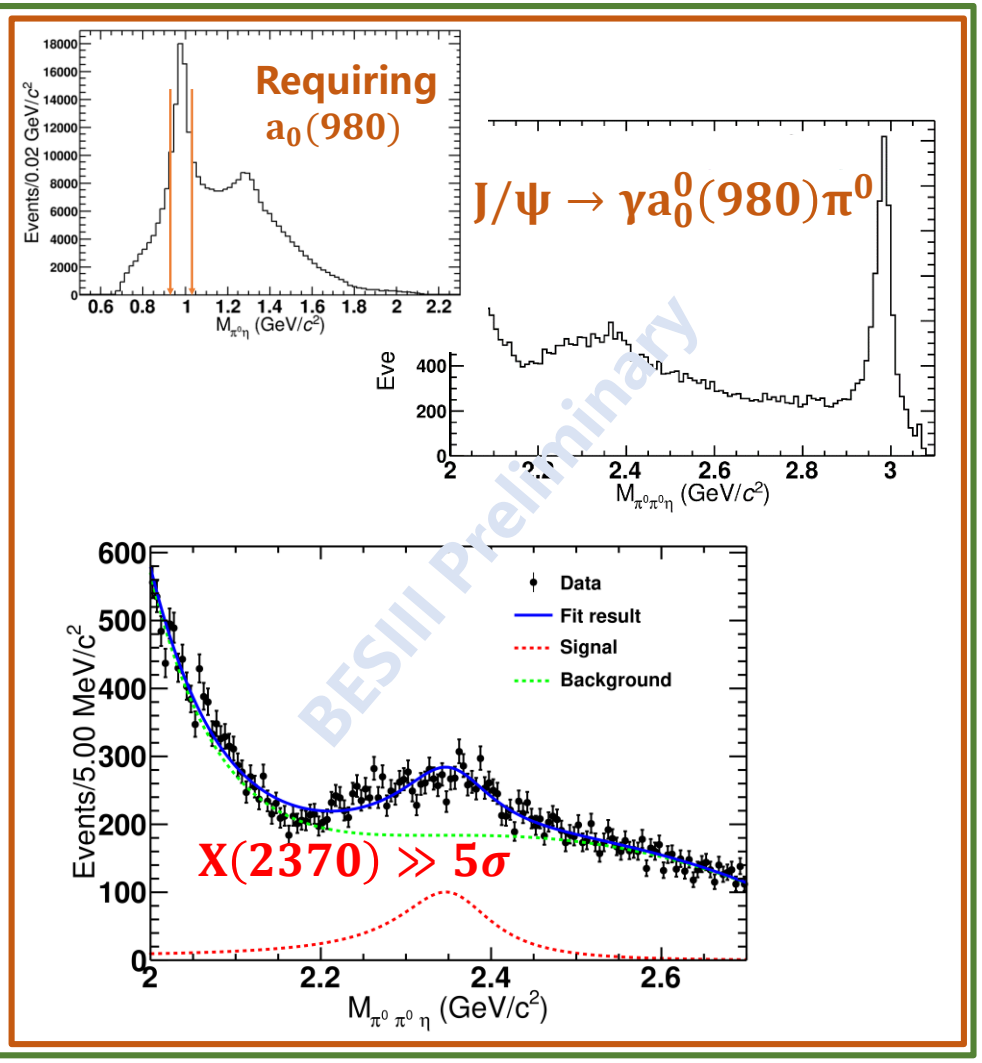
clear $X(2370)$ AND η_c signals

no $X(2370)$ OR η_c signal

Observation of new decay modes of X(2370)







- $X(2370) \to K_S^0 K_S^0 \pi^0$, * $\eta\pi^0\pi^0$, $a_0^0(980)\pi^0$ firstly observed, all accompanied with η_c

* $\eta(2320) \to \eta\eta\eta, \eta\pi\pi$ [PL B496 145(2000)] could be the current X(2370) at BESIII

Summary

- BESIII has a rich program of light QCD exotic studies
  - 10×10^9 J/ψ and 2.7×10^9 ψ′ on disk
  - Running until ~2030
- **$X(2370)$ observed in the gluon-rich J/ψ radiative decays**
  - **J^{PC} determined to be 0^{-+}**
  - **Mass and production rate consistent with LQCD**
  - **Decay modes $X(2370) \to \eta'\pi\pi, \eta' KK, K_S^0 K_S^0 \eta, K_S^0 K_S^0 \pi^0, \eta\pi^0\pi^0$, $a_0^0(980)\pi^0$ observed, in analog to η_c**

  } Consistent with 0^{-+} glueball
- Further experimental + theoretical efforts essential to improve our understanding of glueballs

Thank you for your attention

Backup slides

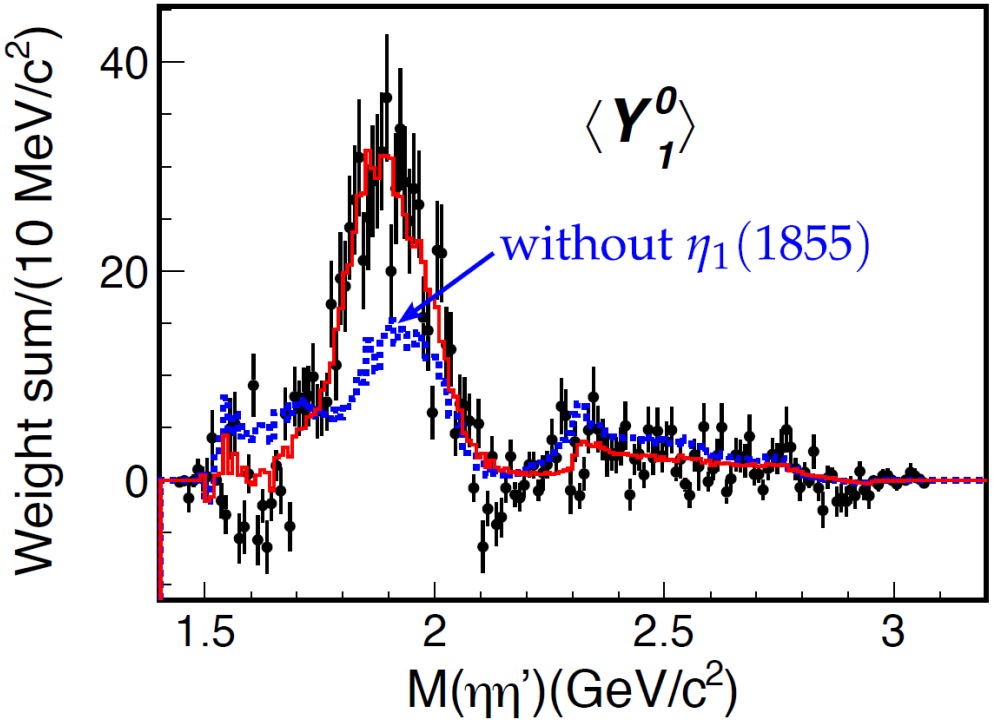
Observation of An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$

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

- **Unambiguous signature for exotics**
  - **J^{PC} forbidden for $q\bar{q}$: 0^{--}, even^{+-}, odd^{-+}**
- **An isoscalar 1^{-+} , $\eta_1(1855)$, has been observed in $J/\psi \to \gamma\eta\eta'$ (>19σ)**

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

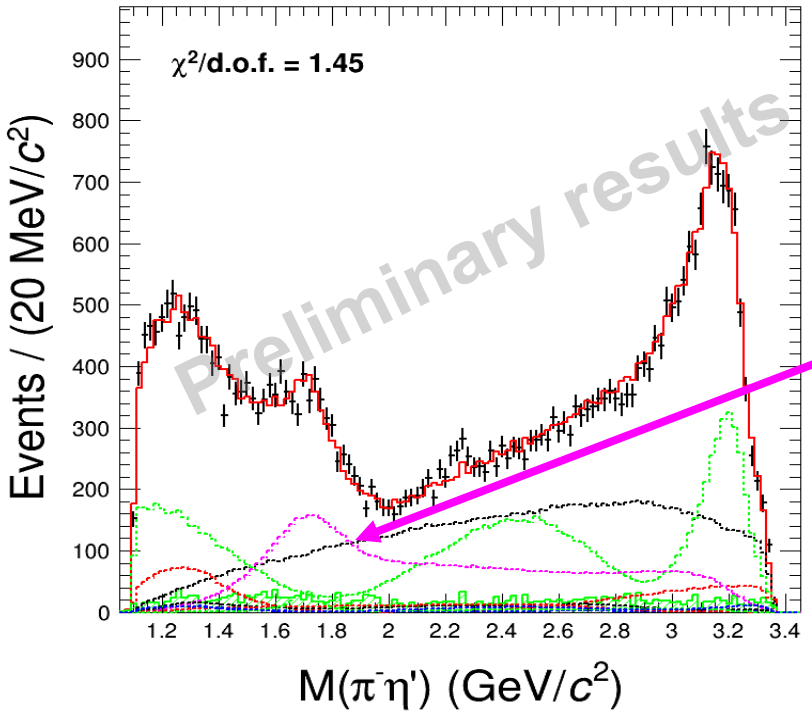
  $B(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$
  - **Mass consistent with hybrid on LQCD**
- **Inspired many interpretations:**
  Hybrid/$K\bar{K}_1$ Molecule/Tetraquark?



Opens a new direction to completing the picture of spin-exotics

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

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

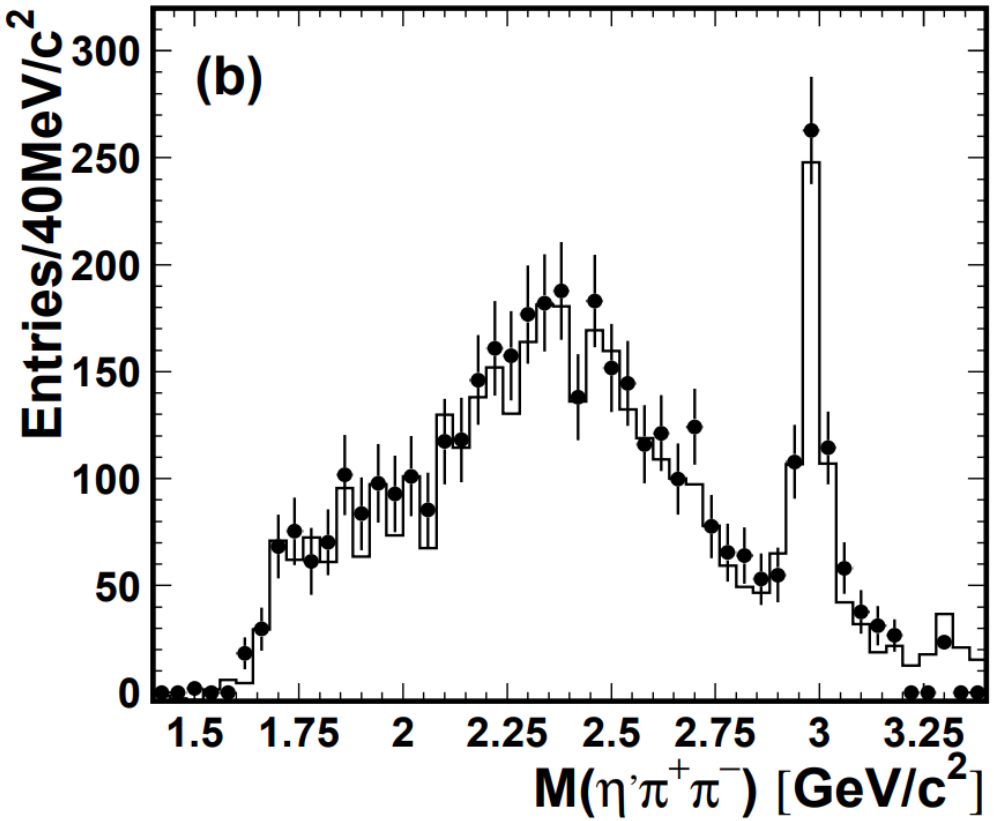


- **Amplitude analysis of $\chi_{c_1} \to \eta'\pi^+\pi^-$ is performed**
- **$\pi_1(1600)$ observed>10σ**
- **with a significant BW phase motion**
- **$J^{PC}= 1^{-+}$, better than other assignments well over 10σ**
  - Evidence of $\pi_1 \to \eta'\pi$ at CLEO-c is confirmed [PR D84 112009 (2011)]

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

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

Belle PRD 86 052002(2012)



What we have learned before

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

e^+e^- annihilation

$p\bar{p}$ annihilation

central exclusive production

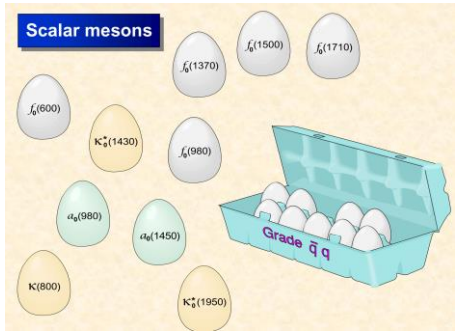
charge-exchange reactions

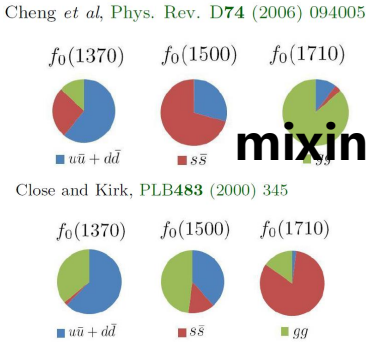
Scalar: 1 nonet in quark model, f_0 & f_0'

Exp: **overpopulation**

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

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





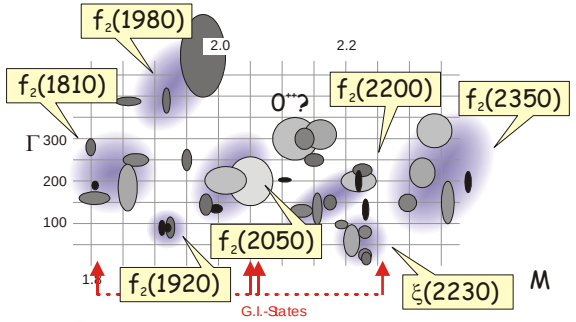
mixing schemes

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

Exp: **large uncertainty**

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

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

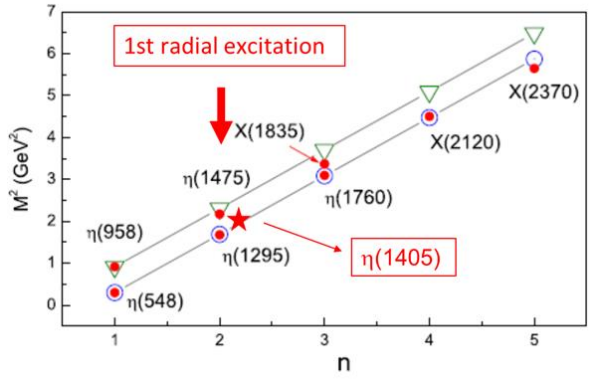


Pseudoscalar: η & η' , "simple"

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

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

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



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 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 $f_0(1710)$**

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

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

- Scalar glueball expected to be suppressed

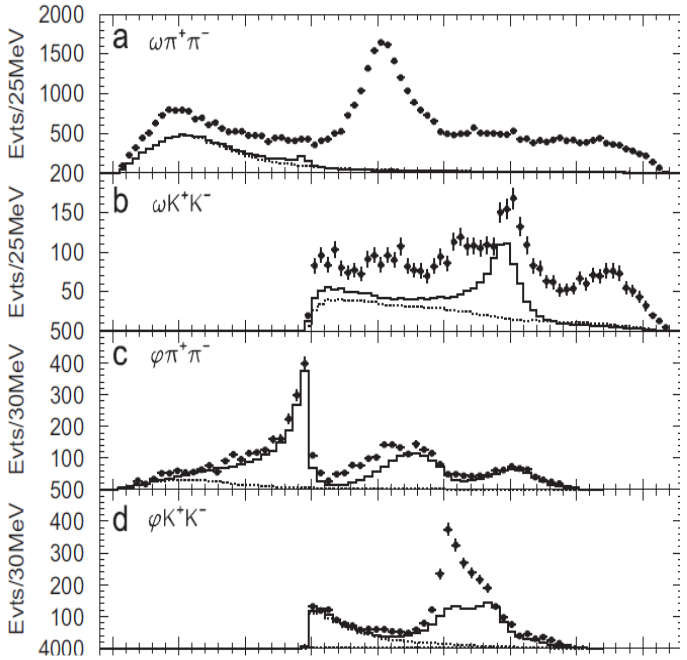
$$B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$$

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

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

More scalars

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

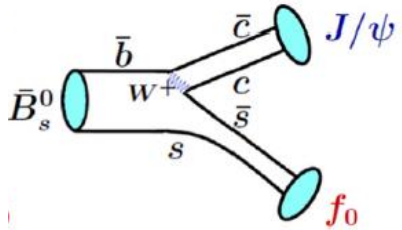


ωK^+K^- ➔ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

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

ϕK^+K^- ➔ No peak around 1700 MeV/c^2

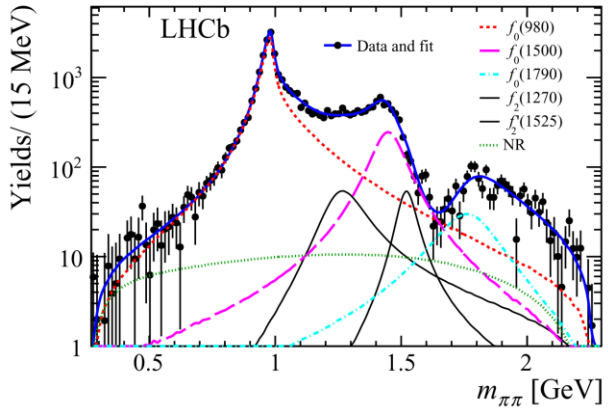
$f_0(1800)$

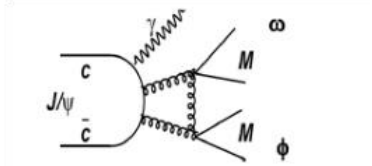


selective for $s\bar{s}$

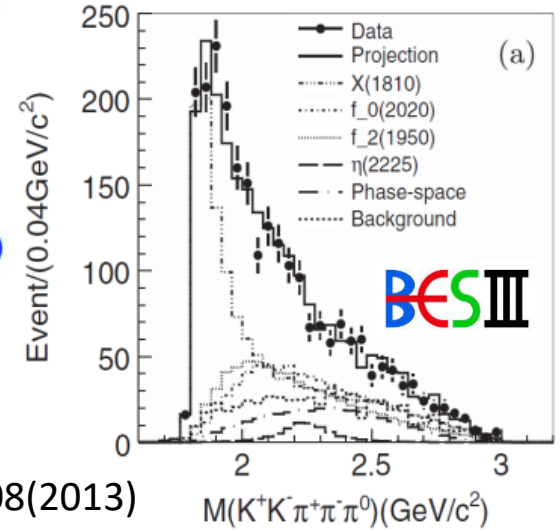
$B_s \to J/\psi f_0$

PLB 797 (2019) 134789





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



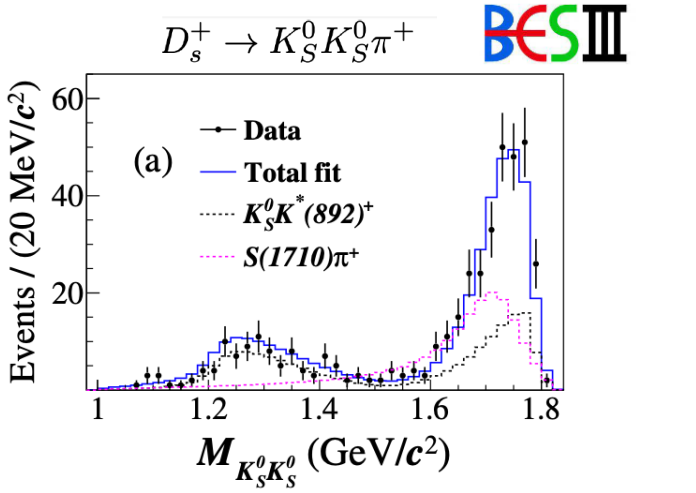
PRD 87, 032008(2013)

$a_0(1817)$

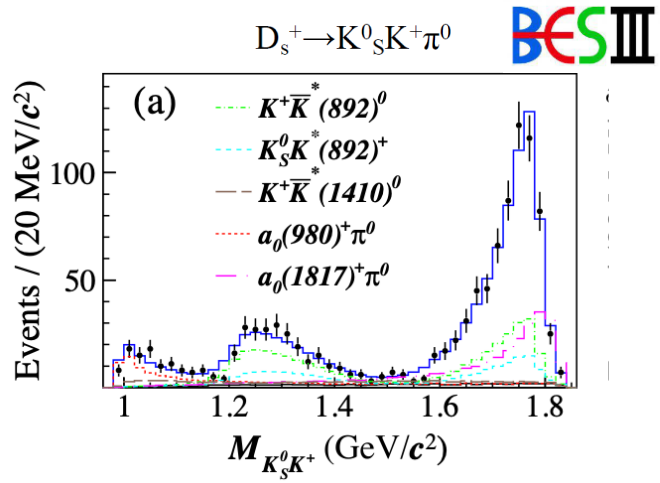
Isovector partner of $f_0(1800)$?

[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

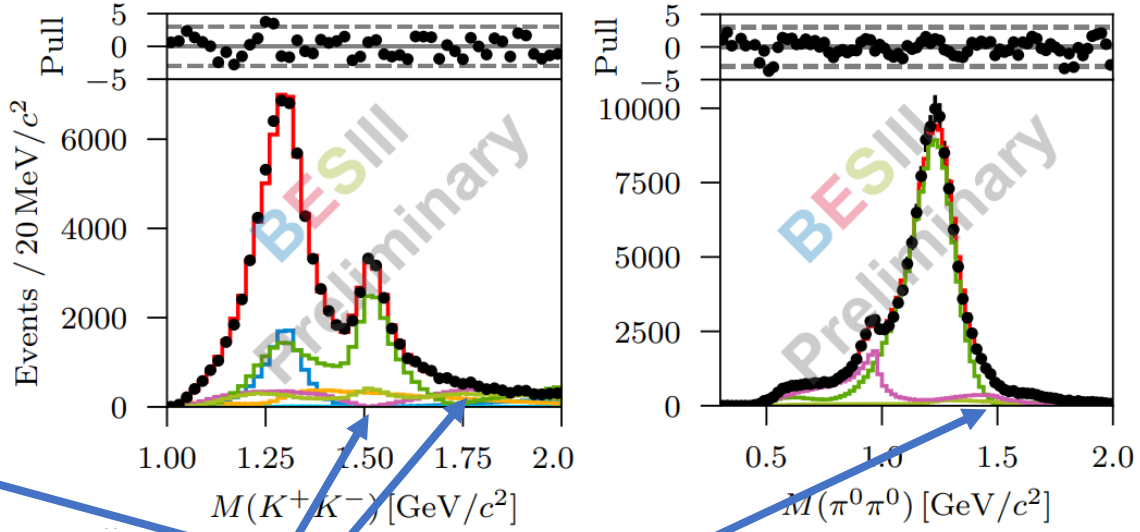
Parameter	$f_0(1710)$ fit			
	fit-H	fit-L	H,L combined	PDG
χ^2/ndf	694.2/585	701.6/585	–	–
Mass(f_J) (MeV/c^2)	1750^{+5+29}_{-6-18}	1749^{+5+31}_{-6-42}	1750^{+6+29}_{-7-18}	1720 ± 6
$\Gamma_{\rm tot}(f_J)$ (MeV)	138^{+12+96}_{-11-50}	145^{+11+31}_{-10-54}	139^{+11+96}_{-12-50}	135 ± 6
$\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})_{f_J}$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

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

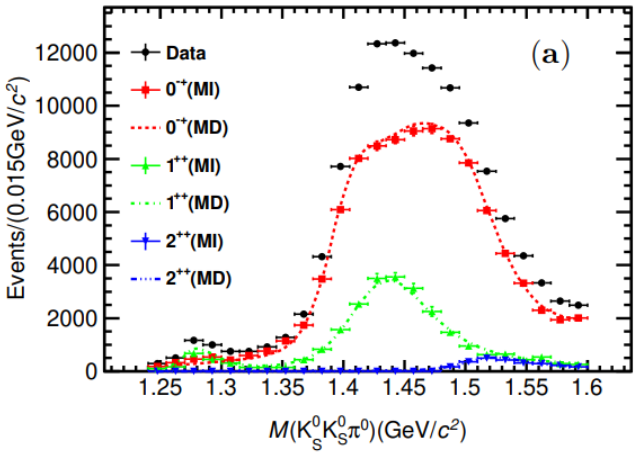
$$J/\psi \to \gamma K_S K_S \pi^0$$

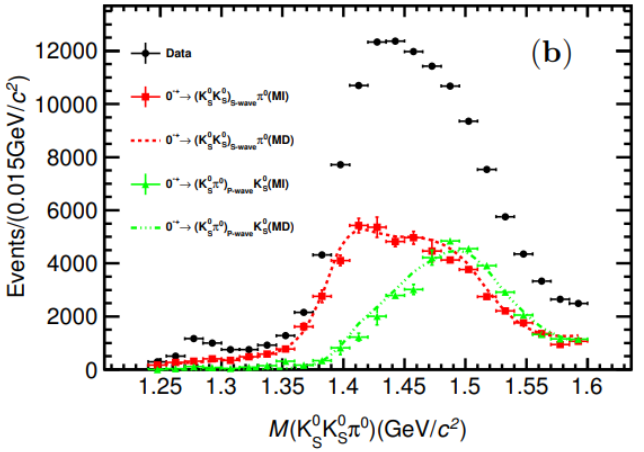
BESIII JHEP 03 121(2023)

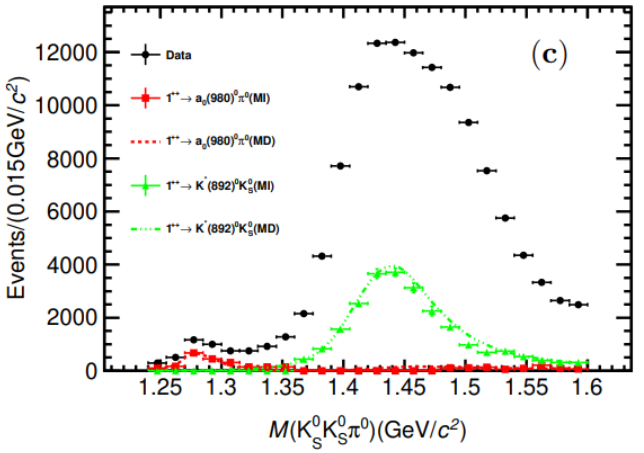
- **M**ass **I**ndependent PWA in bins of M($K_S K_S \pi^0$) to detangle J^{PC} components
  - **Valuable inputs to develop models**
- **M**ass **D**ependent PWA with BW to extract resonances
- **Consistency between MI and MD results**

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

- $\eta(1405)/\eta(1475)$ poles in coupled-channel analysis
  - PRD 107, L091505 (2023) ; PRD 109, 014021 (2024)

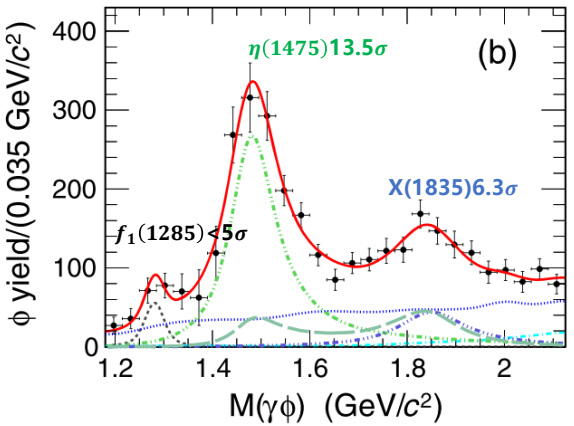






$J/\psi \to \gamma\gamma\phi$, a $s\bar{s}$ flavor filter

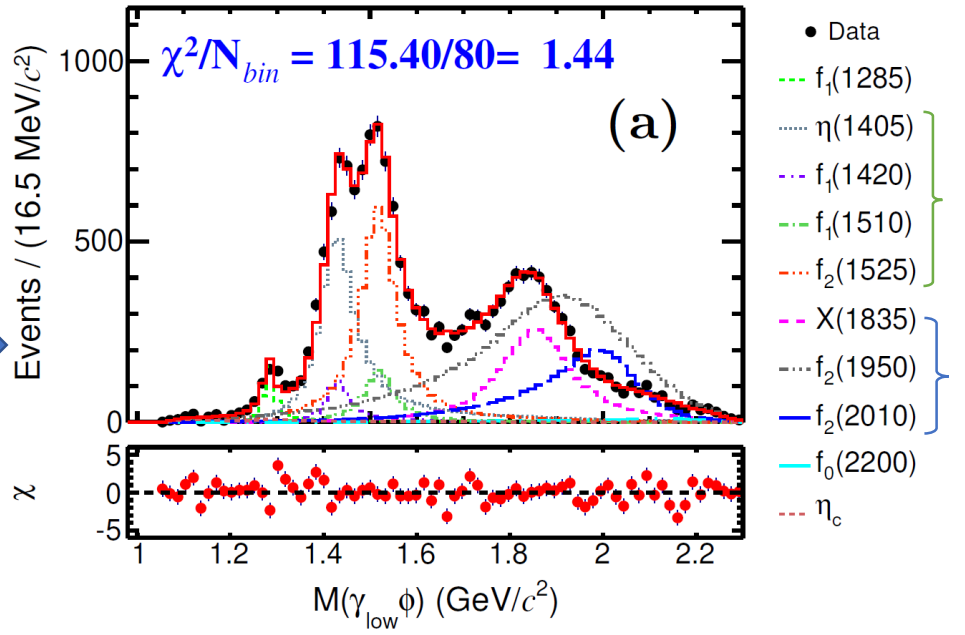
PR D97 051101 (2018)



←Fit to mass spectrum

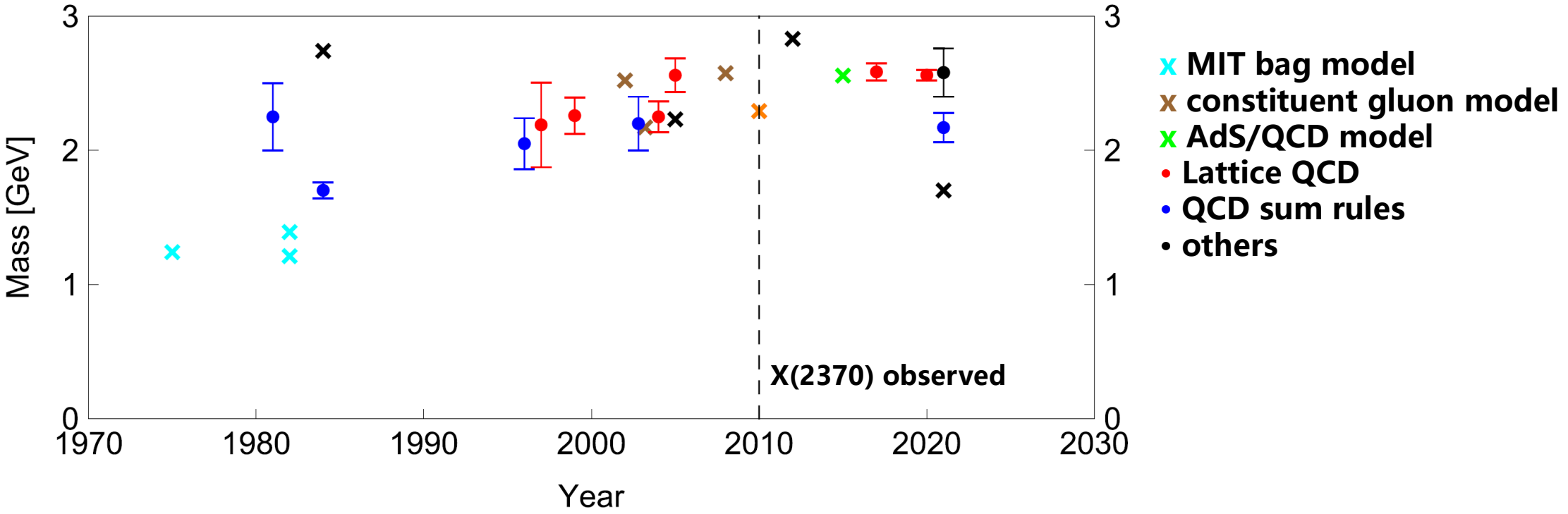
Amplitude analysis with advanced techniques for background subtraction

arXiv: 2401.00918

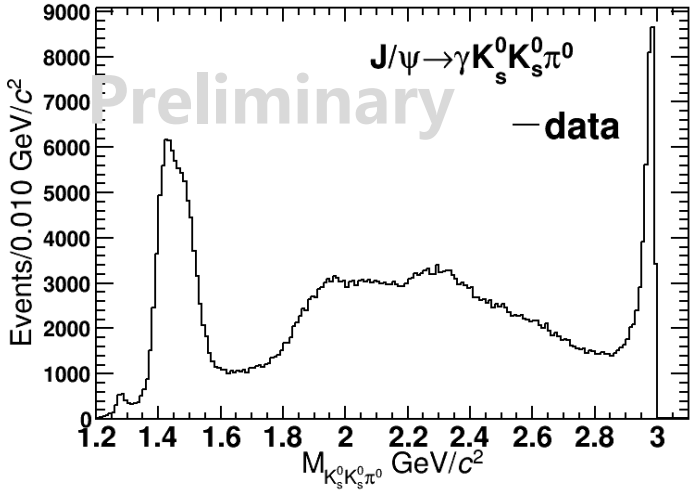


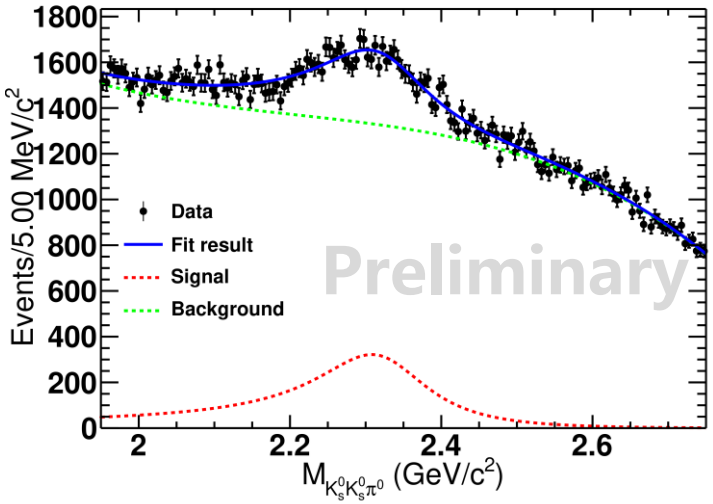
From the amplitude analysis,

- $\eta(1405)$ 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]


Mass [GeV]
Year
0
1
2
3
1970
1980
1990
2000
2010
2020
2030
X(2370) observed
x MIT bag model
x constituent gluon model
x AdS/QCD model
• Lattice QCD
• QCD sum rules
• others

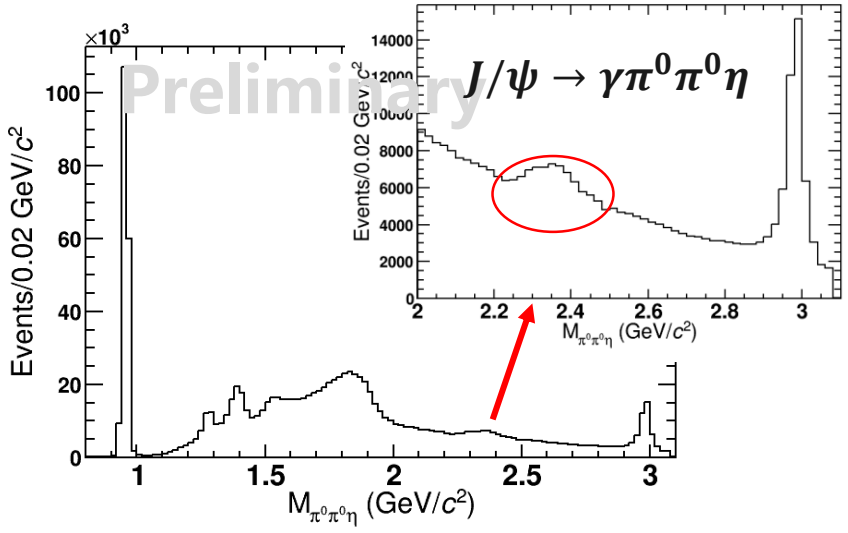
Observation of new decay mode: $X(2370) \to K_S^0 K_S^0 \pi^0$

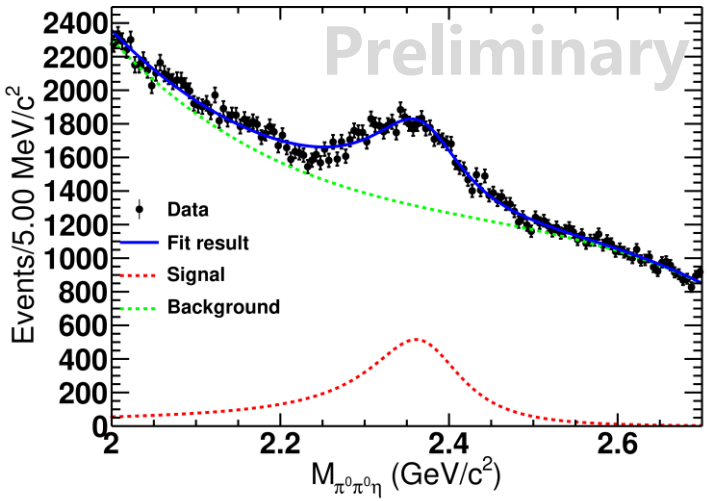




- Almost background free channel
- 1D mass spectrum fit
  - Signal: efficiency weighted BW × PHSP(J/ψ→γX) factor
  - Background: Chebyshev polynomial
- Statistical significance: >>5σ
- Mass and width (preliminary):
  - $M_{X(2370)} = 2321 \pm 4(stat) \pm 65(syst.)$ MeV/c^2
  - $\Gamma_{X(2370)} = 182 \pm 16(stat) \pm 59(syst.)$ MeV
- Syst. errors sources:
  - fit range, background shapes, intermediate states, possible interference

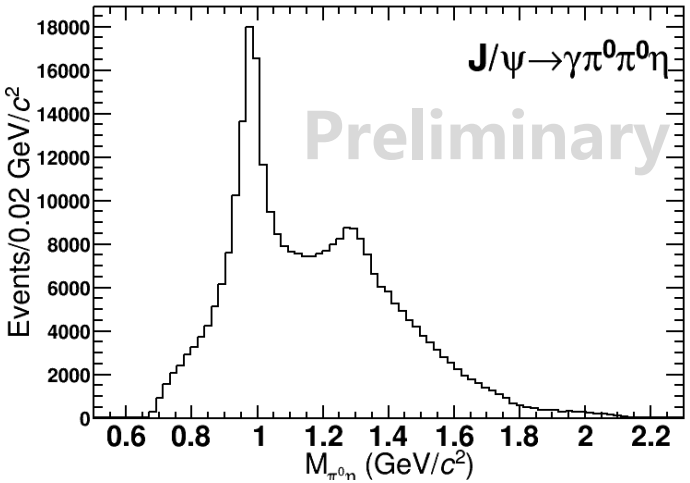
Observation of new decay mode: $X(2370) \to \eta\pi^0\pi^0$

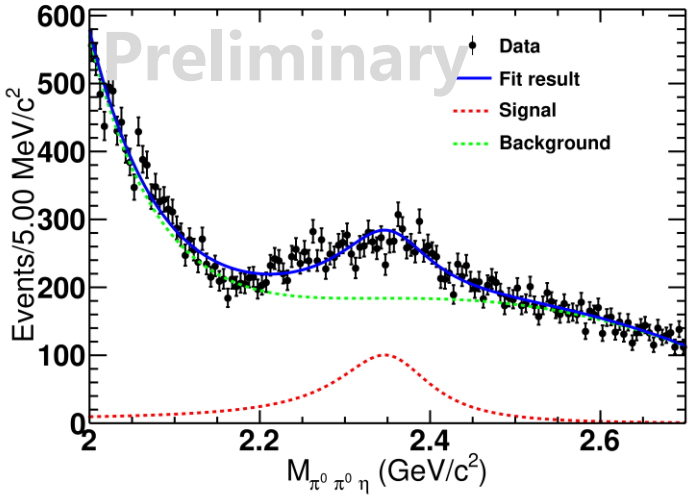




- Almost background free channel
- 1D mass spectrum fit
  - Signal: efficiency weighted BW × PHSP(J/ψ→γX) factor
  - Background: Chebyshev polynomial
- Statistical significance: >>5σ
- Mass and width (preliminary):
  - $M_{X(2370)} = 2370 \pm 2(stat) \pm 52(syst.)$ MeV/c^2
  - $\Gamma_{X(2370)} = 134 \pm 8(stat) \pm 30(syst.)$ MeV
- Syst. errors sources:
  - fit range, background shapes, intermediate states, possible interference

Observation of new decay mode: $X(2370) \to a_0^0(980)\pi^0$





$a_0(980)$ signal region

$\left|m_{\pi^0\eta} - 0.98\right| < 0.05$ GeV

- Clear $a_0(980)$ signal in $m_{\pi^0\eta}$ spectrum
- 1D mass spectrum fit
  - Signal: efficiency weighted BW × PHSP(J/ψ→γX) factor × PHSP(X→$a_0^0(980)\pi^0$) factor
  - Background: Chebyshev polynomial
- Statistical significance: >>5σ
- Mass and width (preliminary):
  - $M_{X(2370)} = 2352 \pm 3(stat) \pm 74(syst.)$ MeV/c^2
  - $\Gamma_{X(2370)} = 134 \pm 4(stat) \pm 62(syst.)$ MeV
- Syst. errors sources:
  - fit range, background shapes, possible interference

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

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

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

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

Golden Decay Modes in 0^{-+} Glueball Searches

- PP (2 pseudoscalar mesons) modes are mostly forbidden for 0^{-+} mesons
- Typically, PPP (3 pseudoscalar mesons, such as $\pi\pi\eta$, $\pi\pi\eta'$, $KK\pi$) modes are believed as golden decay modes in 0^{-+} glueball searches.
  - S wave decays for 0^{-+} mesons, no suppression factor, dominant decay modes
  - PPP modes are strongly suppressed in 0^{++}, 2^{++} mesons decays — spin-parity filter
- VV modes (2 vector mesons, such as $\omega\omega$, $\phi\phi$, $\rho\rho$, K*K*)
  - P wave decays for 0^{-+} mesons — suppressed decays, especially near mass threshold
  - All J^{PC} mesons allowed, not a spin-parity filter
- Baryon modes
  - All J^{PC} mesons allowed, not a spin-parity filter