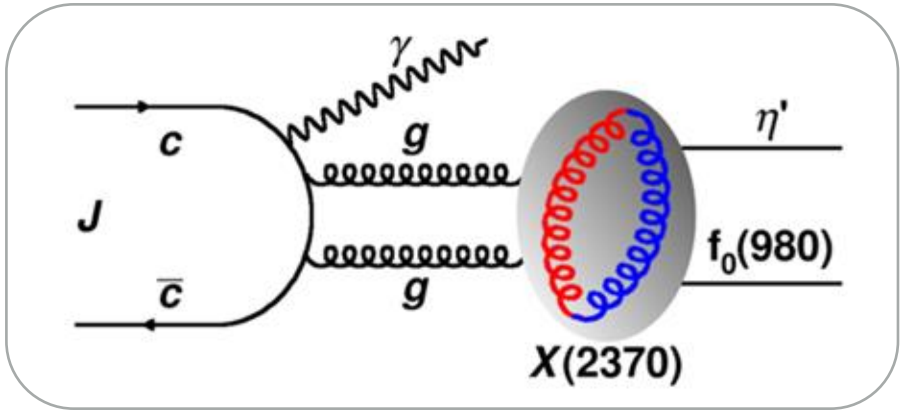

Study of $X(2370)$ at BESIII

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On behalf of the BESIII Collaboration

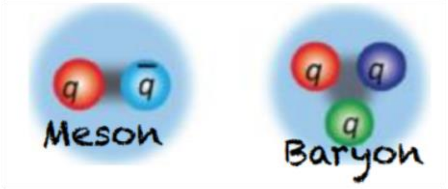
The XVIth Quark Confinement and the Hadron Spectrum Conference (QCHSC2024)

Aug 21, 2024, Cairns, Australia

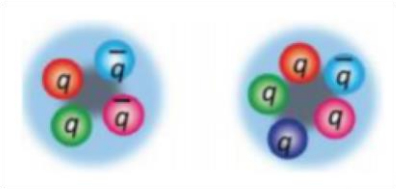
Forms of hadrons

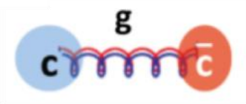
- The basic theory for strong interactions is quantum chromodynamics (QCD). Hadrons are the bound states of QCD

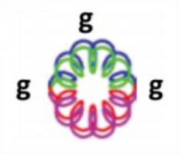
- Hadrons consist of 2 or 3 quarks in conventional quark model
  - Mesons (quark-antiquark states)
  - Baryons (3-quark states)



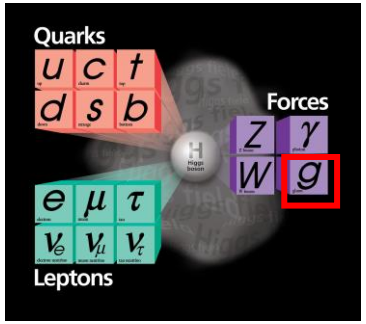
- New forms of hadrons allowed by QCD：
  - **Multi-quark**: quark number >= 4
  - **Hybrid state**: the mixture of quark and gluon
  - **Glueball**: composed of gluons (gg, ggg, gggg ….)

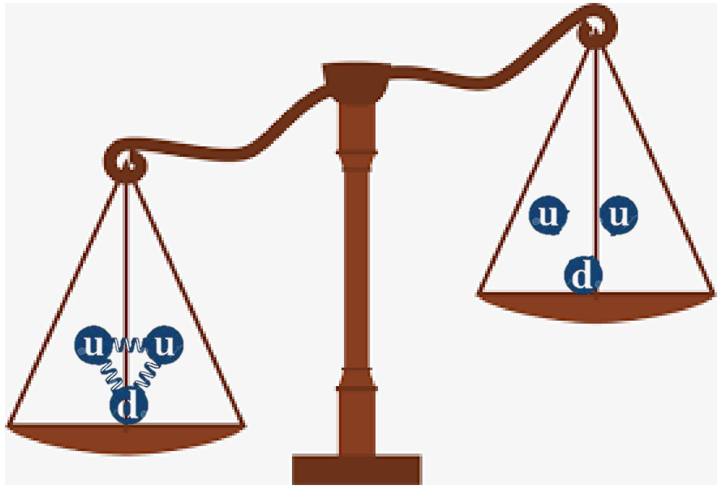






Glueball



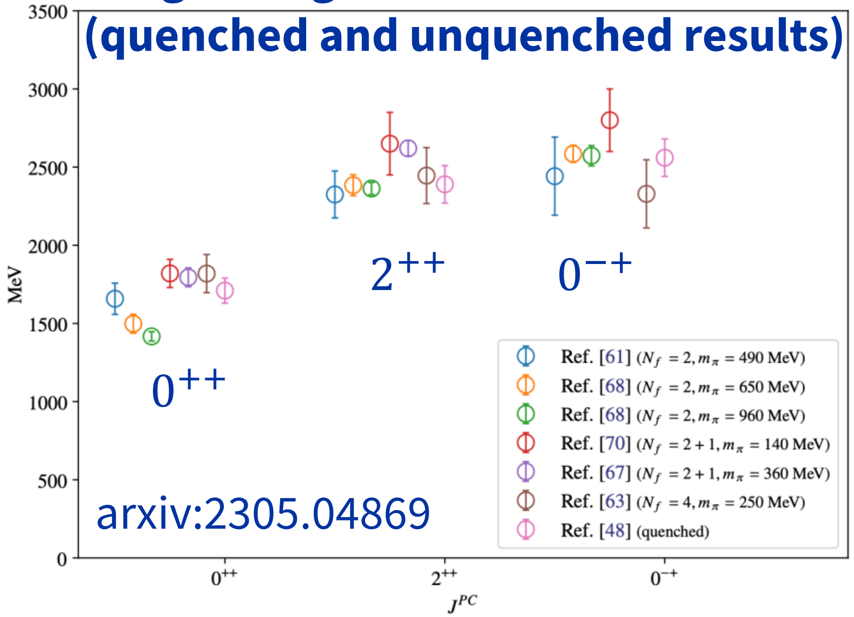


dynamics of gluons
~ 99% of proton mass

- The self interaction of **gluons** —— gauge bosons of strong interactions, is unique property of QCD.
- **Glueball** formed by self-interacted gluons.
- Many candidates but have not been established yet!

➔ **Direct test of QCD**

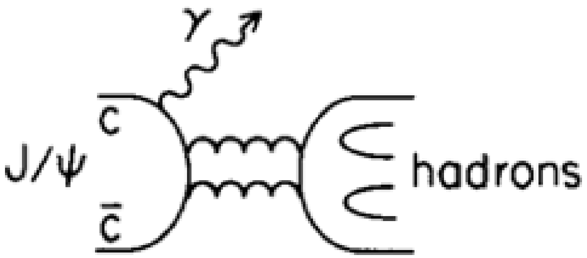
Yang-Mills glueballs on lattice (quenched and unquenched results)



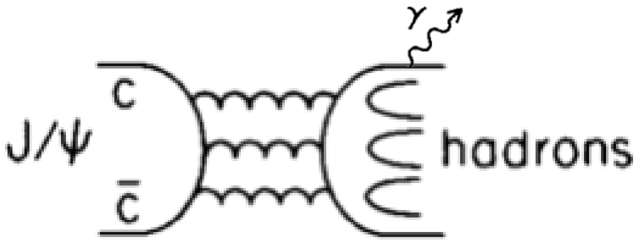
- Theoretical predictions on glueball masses from lattice QCD and QCD-inspired models mostly consistent
  - Light-mass glueball with ordinary J^{PC}: $0^{++}, 2^{++}, 0^{-+}$

J/ψ radiative decays

- **Gluon rich environment**
- **Isospin filter**: final states dominated by I=0 processes
- **Spin-parity filter**: C parity must be +, so $J^{PC} = 0^{-+}, 0^{++}, 1^{++}, 2^{-+}, 2^{++} \ldots$
- **Clean environment** in electron-positron collision
  - very different from proton-antiproton collision



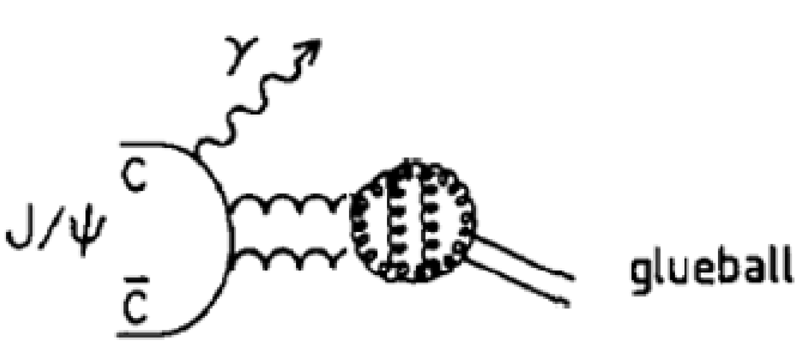
$\sim \alpha \alpha_s^4$



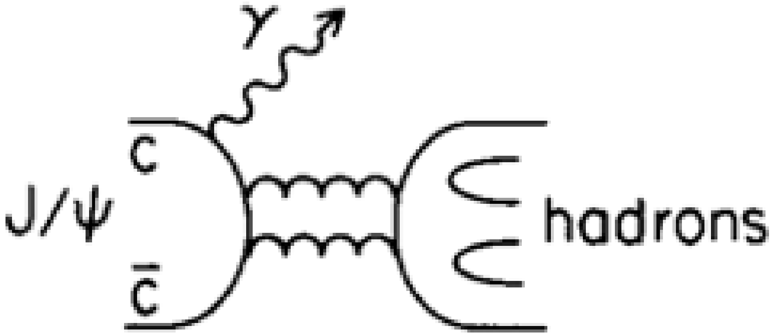
$\sim \alpha \alpha_s^6$

Glueball Production in J/ψ radiative decays

- Glueball: strongly produced in gluon-rich processes
- Rich production in J/ψ radiative decays
  - Glueball production rate in J/ψ radiative decays could be higher than normal hadrons



$\sim\alpha\alpha_s^2$

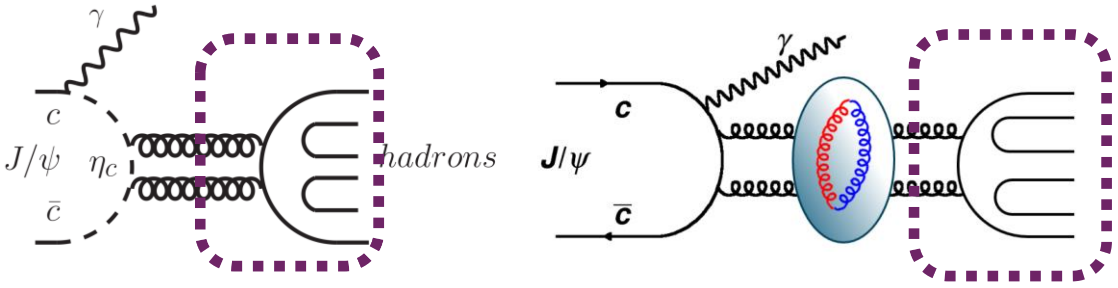


$\sim\alpha\alpha_s^4$

➔J/ψ radiative decays are believed to be an ideal place to search for glueballs.

Glueball Decays

- Via gluons (gluon is flavor-blind) —— flavor symmetric decays
- No rigorous predictions on glueballs' decay patterns and their branching fractions
- The decay patterns of glueballs may resemble those of the Charmonium family, as they also decay through gluons [PLB 380 189(1996), Commu. Theor. Phys. 24.373(1995)].
  - e.g.: The 0^{-+} glueball could have similar decays of η_c



- Different energy scales between the charmonium and glueballs
  - Different decay branching ratios
  - η_c has larger phase space region than a 0^{-+} glueball with lower mass

Glueball Search

- Many experiments searched for glueballs over the past 4 decades.

- Many historical glueball candidates, but also some **difficulties/controversies**.
  - Scalar Glueball candidate (0^{++}): $f_0(1710)$
  - Tensor Glueball candidate (2^{++}): $f_2(2340)$
  - Pseudoscalar Glueball candidate (0^{-+}): $\eta(1405)$

Scalar glueball candidate

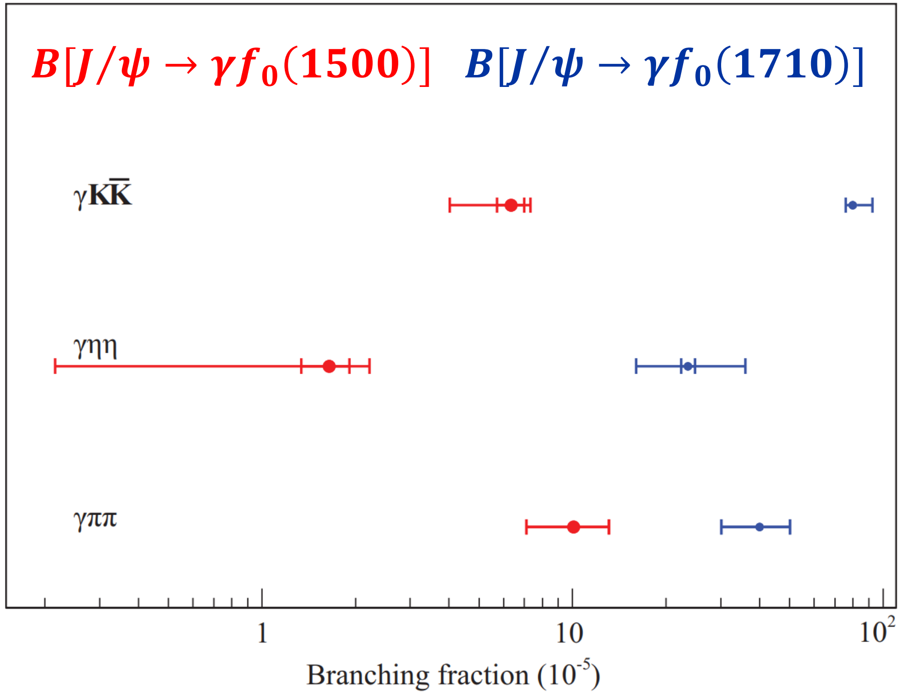
- Expected production rate of scalar glueball in J/ψ radiative decays
  - $B[J/\psi \to \gamma G_{0^{-+}}] = 3.8(8) \times 10^{-3}$ @ LQCD

- Observed $B[J/\psi \to \gamma f_0(1710)]$ is x10 larger than $f_0(1500)$ @ BESIII

- The high production rate of $J/\psi \to \gamma f_0(1710)$ and the suppression of $f_0(1710) \to \eta\eta'$ supports that
  - $f_0(1710)$ has a large overlap with glueball [PRD 106 072012(2022)]

still await undisputed confirmations

$\mathcal{B}(J/\psi \to \gamma f_0(1500))$ (10^{-3})	$\mathcal{B}(J/\psi \to \gamma f_0(1710))$ (10^{-3})	$\mathcal{B}(J/\psi \to \gamma$ scalar glueball) (LQCD calculation) (10^{-3})
~0.29	~2.2	3.8 (8)



Natl. Sci. Rev. 8, no.11, nwab198 (2021)

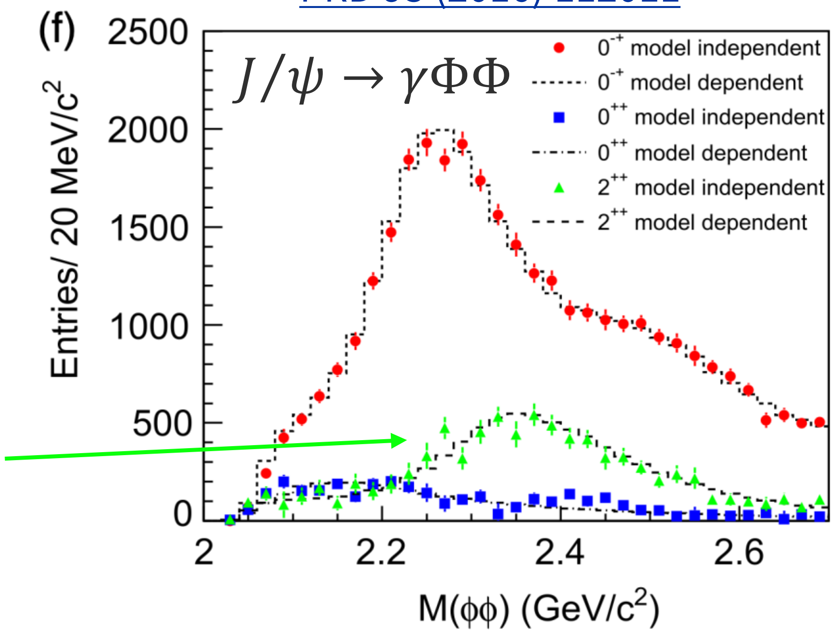
Tensor glueball candidate

PRD 93 (2016) 112011

- Expected production rate of tensor glueball
  - $B[J/\psi \to \gamma G_{2^{++}}] = 1.1 \times 10^{-2}$ @ LQCD [PRL 111 (2013) 091601]

- Observed $f_2(2340)$ @ BESIII:
  - $B[J/\psi \to \gamma f_2(2340) \to \gamma \Phi\Phi] = 1.91 \pm 0.14^{+0.72}_{-0.73} \times 10^{-4}$

- Difficulty: no clear mass peak of these f_2 mesons can be directly observed in J/ψ radiative decays due to large overlaps among various wide resonances.

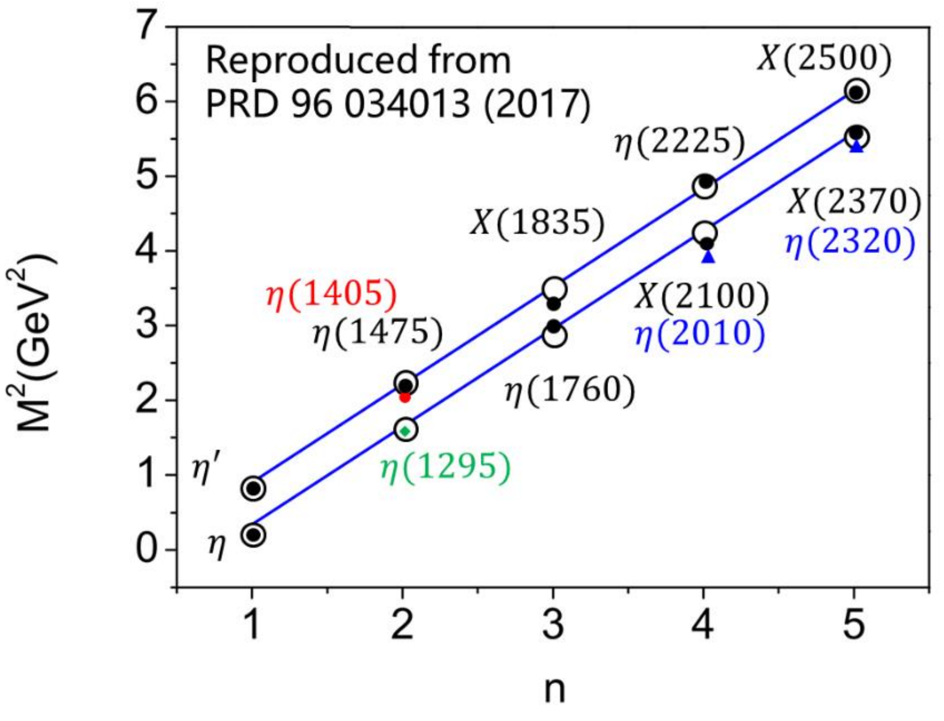


Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. (×10^{-4})	Sig.
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28σ
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	22σ
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2101	224	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24σ
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$	9.5σ
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$	6.4σ
$f_2(2340)$	2339	319	$(1.91 \pm 0.14^{+0.72}_{-0.73})$	11σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ

It is desired to study more decay modes

Pseudoscalar glueball candidate

- Pseudoscalar meson spectrum
  - Only η and η' (& radial excitations) from quark model
  - A promising window to search for extra states
- Expected mass @LQCD: 2.3~2.6 GeV
  - The first glueball candidate: ι(1440) (split into $\eta(1405)$ and $\eta(1475)$), whose mass is incompatible with LQCD
  - Little experimental information above 2 GeV
- Where is Pseudoscalar glueball?
  - The 0^{-+} glueball could have similar decays of η_c
  - 3 pseudoscalar final state is a good place to search for



5 typical $\eta_c \to 3P$ decay modes in PDG ——
5 "Golden" modes in 0^{-+} glueball searches

Decays involving hadronic resonances

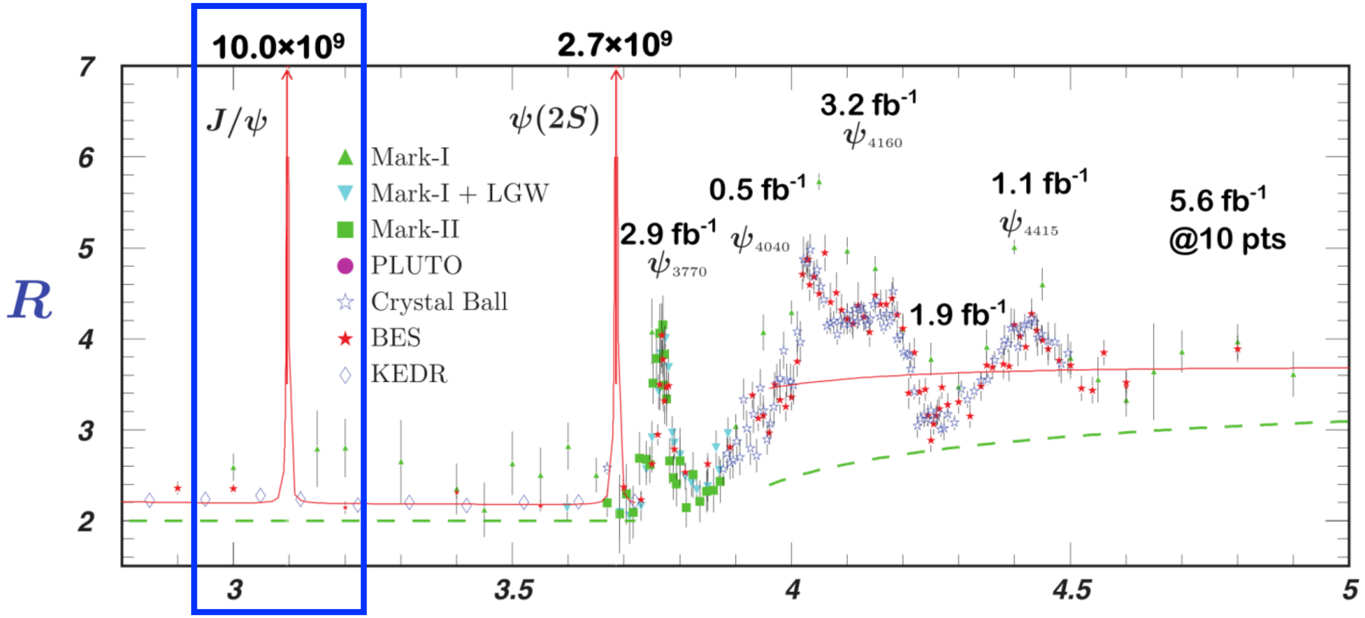
Γ_1	$\eta'(958)\pi\pi$	(1.87 ± 0.26) %
Γ_2	$\eta'(958)K\overline{K}$	(1.61 ± 0.25) %

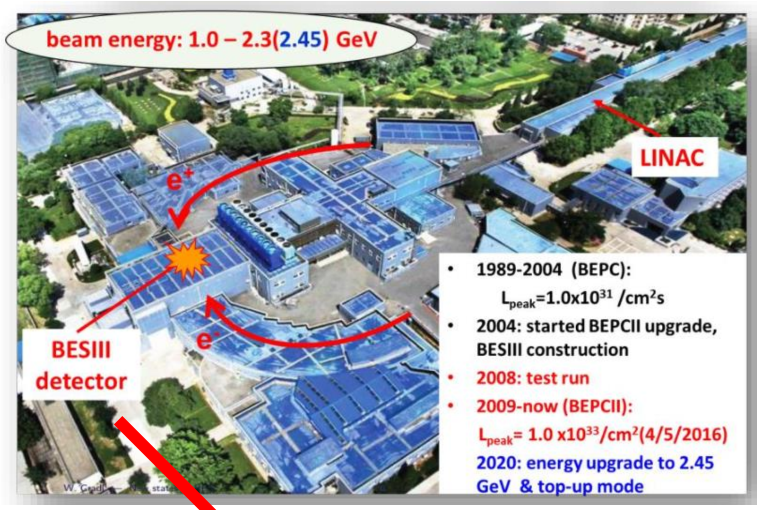
Decays into stable hadrons

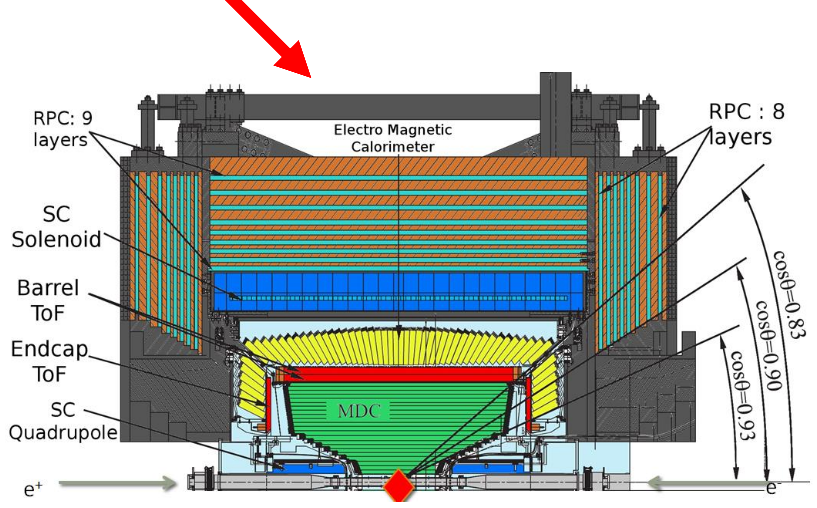
Γ_{34}	$K\overline{K}\pi$	(7.0 ± 0.4) %
Γ_{35}	$K\overline{K}\eta$	(1.32 ± 0.15) %
Γ_{36}	$\eta\pi^+\pi^-$	(1.7 ± 0.5) %

BESIII data collections

BEPCII and BESIII
The Experimental facility







World largest J/ψ data sample : ~10 billion.
- Well defined initial and final states
- Low background

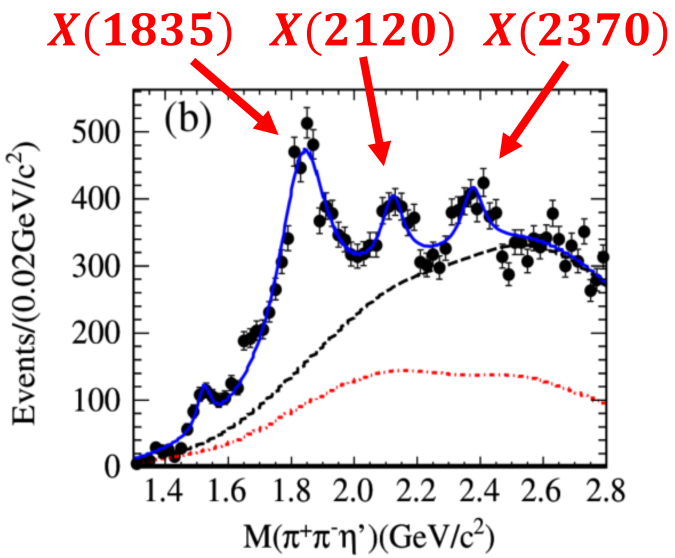
Provide a good opportunity to search for glueball!

Study of $X(2370)$ at BESIII

$X(2370)$

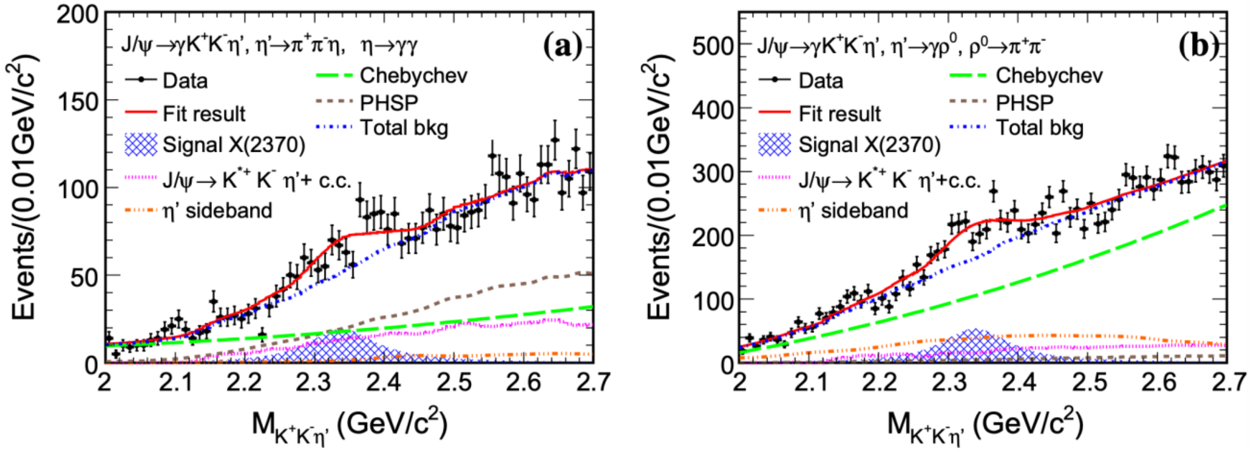
- First observation by BESIII of the $X(2370)$ in $J/\psi \to \gamma\pi^+\pi^-\eta'$

	M(MeV/c²)	Γ(MeV)	Sig.
X(1835)	$1836.5 \pm 3.0^{+5.6}_{-2.1}$	$190.1 \pm 9.0^{+38}_{-36}$	>20σ
X(2120)	$2122.4 \pm 6.7^{+4.7}_{-2.7}$	$83 \pm 16^{+31}_{-11}$	7.2σ
X(2370)	$2376.3 \pm 8.7^{+3.2}_{-4.3}$	$83 \pm 17^{+44}_{-6}$	6.4σ

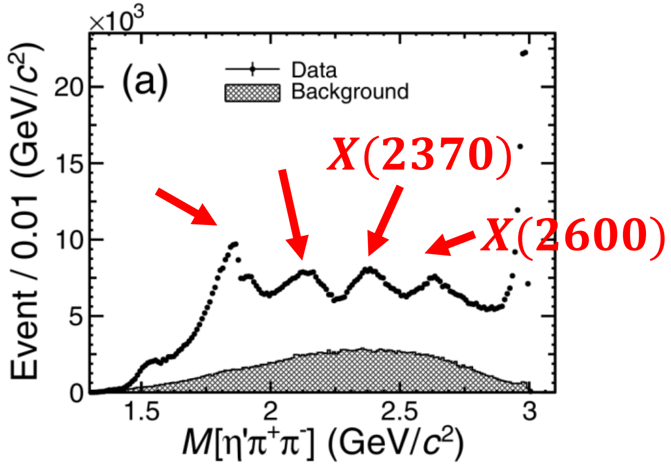


RPL 106 (2011) 072002

- Confirmed by BESIII in $J/\psi \to \gamma K\bar{K}\eta'$ (new mode), $\gamma\pi^+\pi^-\eta'$



Eur. Phys. J. C 80, 746 (2020)



PRL 129 (2022) 042001

$X(2370)$ —— good candidate of 0^{-+} glueball

- Its mass is consistent with LQCD prediction on the lightest 0^{-+} glueball
- Observed in the best place to search for the 0^{-+} glueball:
  - Produced in the gluon-rich J/ψ radiative decays
  - Flavor symmetric decay modes of $\pi^+\pi^-\eta'$ and $K\bar{K}\eta'$ —— favorite decay modes of 0^{-+} glueball

➔Determination of its spin-parity is crucial

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

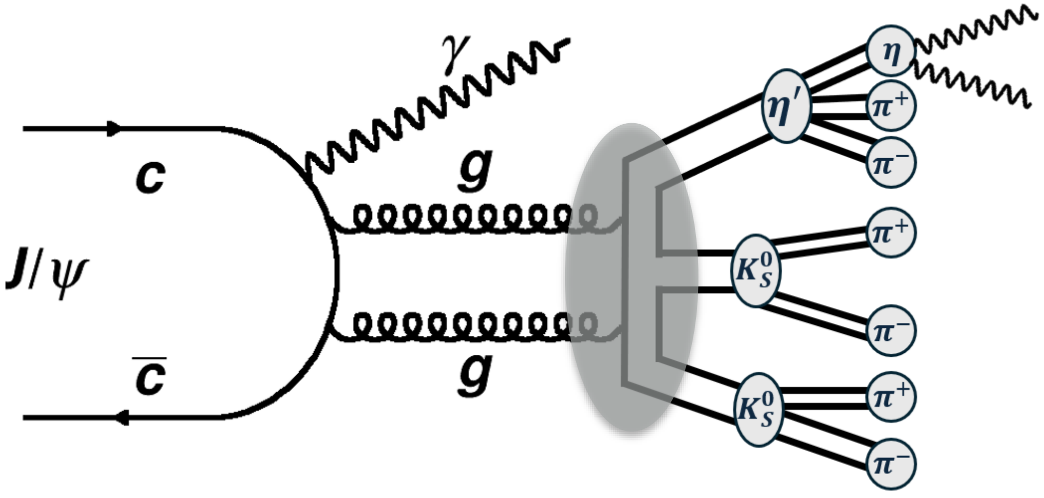
Journal: Phys. Rev. Lett. 132 (2024) 181901

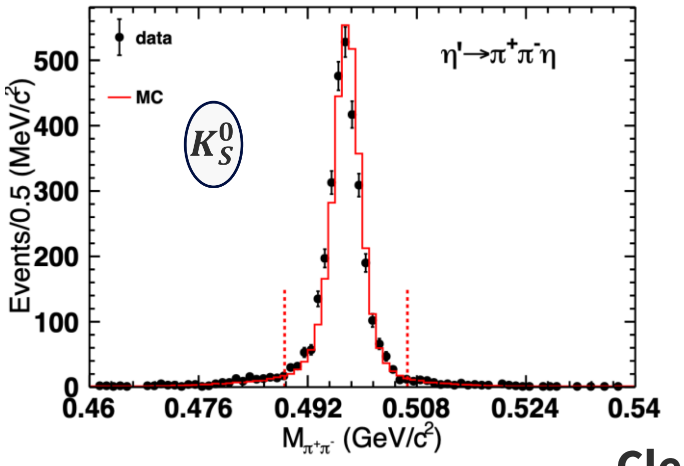
Advantages of this channel:

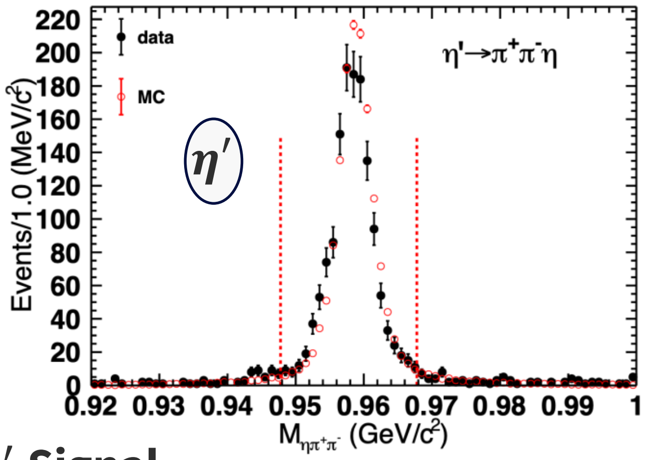
- ~10B clean J/ψ events
- Almost no background:
  - Possible dominant background processes of $J/\psi \to \pi^0 K_S^0 K_S^0 \eta'$ and $J/\psi \to K_S^0 K_S^0 \eta'$ are forbidden by exchange symmetry and C-parity conservation.
- High efficiency and precise resolution of charged particles and photons:
  - good reconstruction for K_S^0 and η
  - good reconstruction for η' for two dominant decay modes of $\eta' \to \gamma\pi^+\pi^-$ and $\eta' \to \pi^+\pi^-\eta$

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

- **Signal selection:**
  - At least 3 charged pairs + 3 photons
  - Constraint kinematic fit with energy-momentum conservation
  - K_S^0 reconstruction: $|M_{\pi^+\pi^-} - M_{K_S^0}| < 9\ \mathrm{MeV/c^2}$
  - η' reconstruction: $|M_{\pi^+\pi^-\eta} - M_{\eta'}| < 10\ \mathrm{MeV/c^2}$
- **Background veto:**
  - π^0 veto: $|M_{\gamma\gamma} - M_{\pi^0}| > 20\ \mathrm{MeV/c^2}$



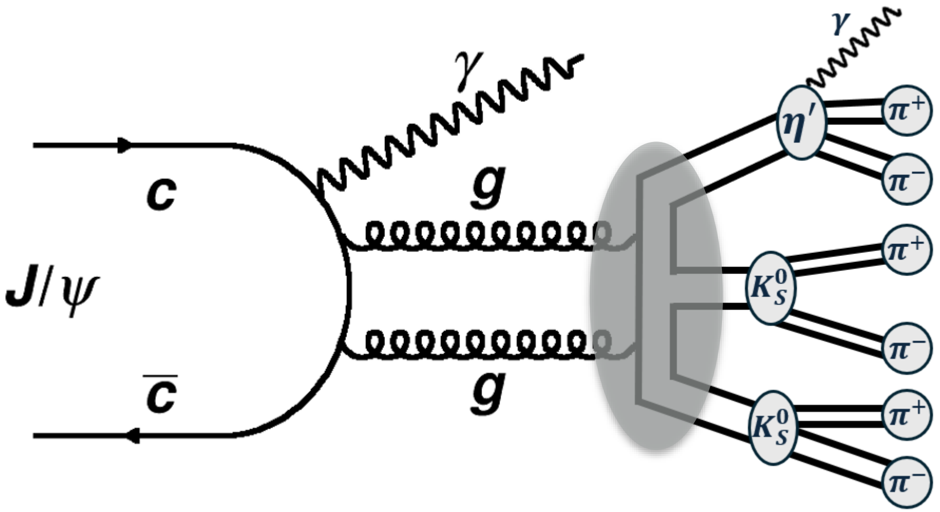


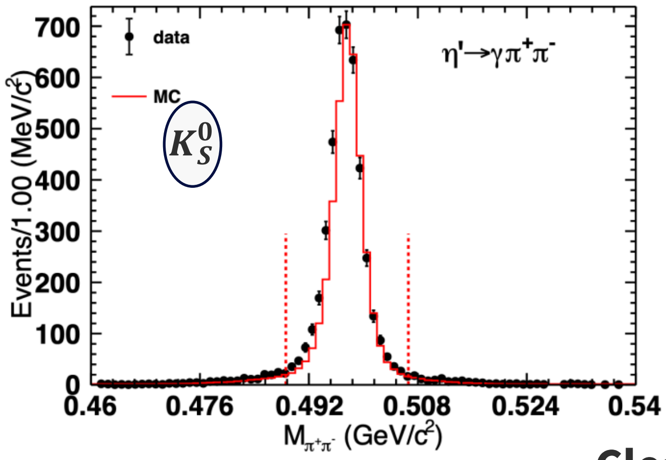


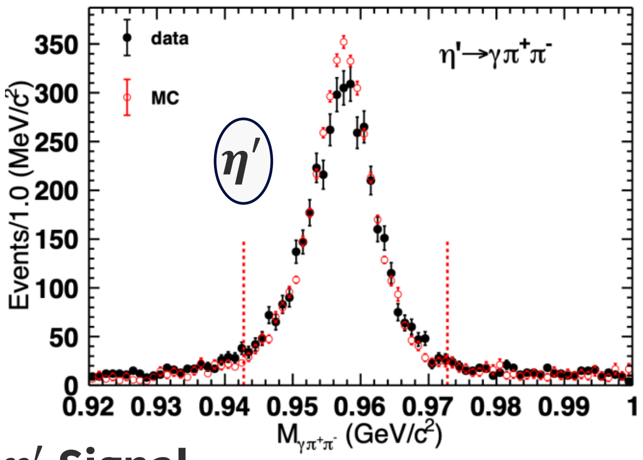
Clean K_S^0 and η' Signal

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

- **Signal selection:**
  - At least 3 charged pairs + 2 photons
  - Constraint kinematic fit with energy-momentum conservation
  - K_S^0 reconstruction: $|M_{\pi^+\pi^-} - M_{K_S^0}| < 9\ \mathrm{MeV/c^2}$
  - η' reconstruction: $|M_{\gamma\pi^+\pi^-} - M_{\eta'}| < 15\ \mathrm{MeV/c^2}$
- **Background veto:**
  - π^0/η veto: $|M_{\gamma\gamma} - M_{\pi^0}| > 20\ \mathrm{MeV/c^2}$, $|M_{\gamma\gamma} - M_{\eta}| > 30\ \mathrm{MeV/c^2}$



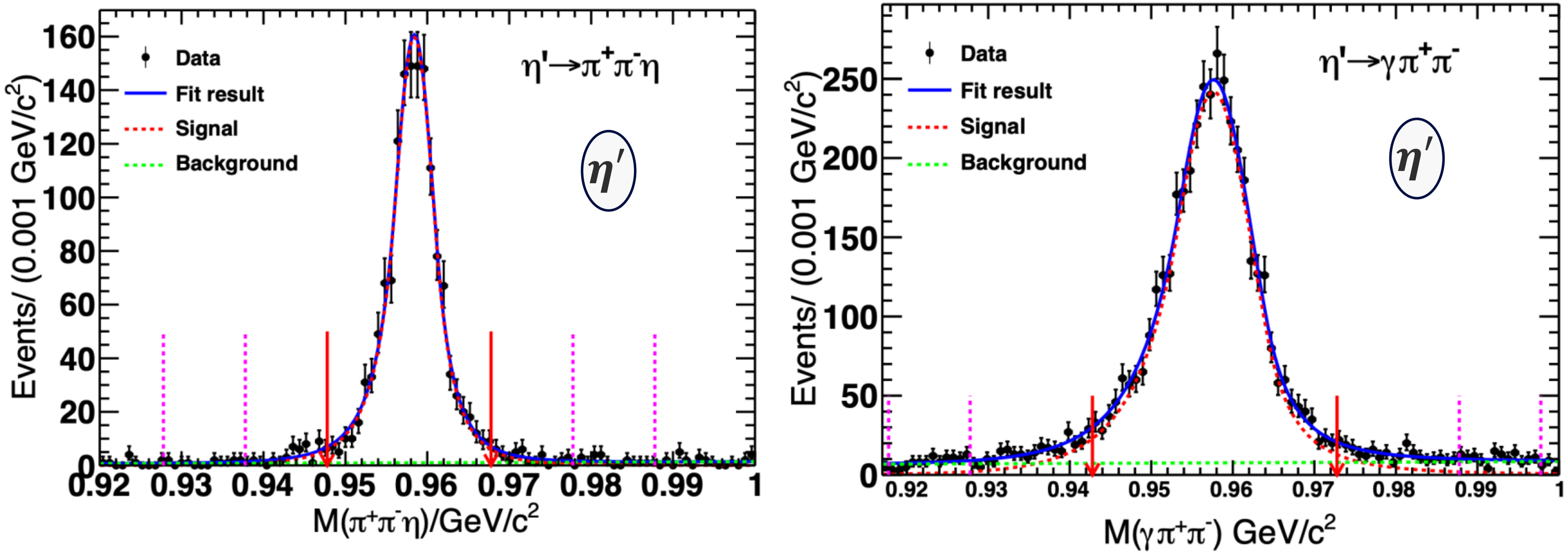




Clean K_S^0 and η' Signal

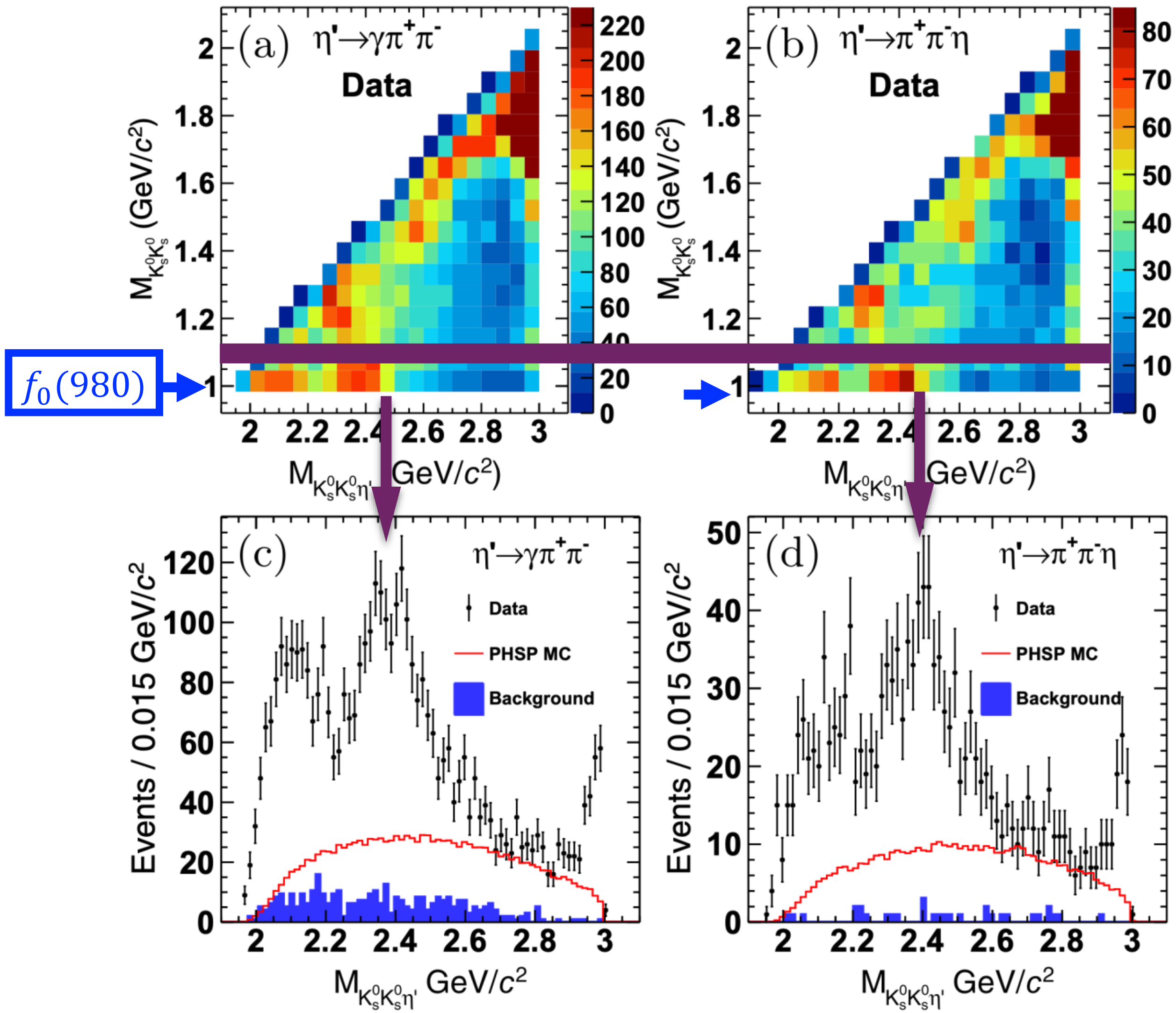
Background estimation

- Negligible mis-combination for K_S^0 reconstruction (<0.1%)
- No background from $J/\psi \to \pi^0 K_S^0 K_S^0 \eta'$: further validation directly from data
- Little background from non-η' processes: estimated directly from η' mass sideband region:
  - No peaking background
  - Non-η' background fraction: 1.8% for $\eta' \to \pi^+\pi^-\eta$; 6.8% for $\eta' \to \gamma\pi^+\pi^-$



Spin-Parity determination benefits from low background level

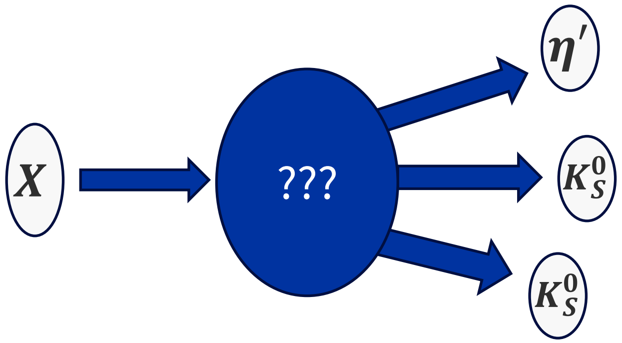
Mass spectra after final selection



PRL 132 (2024) 181901

- Similar structures in $\eta' \to \pi^+\pi^-\eta$ and $\eta' \to \gamma\pi^+\pi^-$ modes
  - Evident $f_0(980)$ in $K_S^0 K_S^0$ mass threshold
  - A clear connection between the $f_0(980)$ and $X(2370)$
- $f_0(980)$ in selection with $M_{K_S^0 K_S^0} < 1.1$ GeV/c^2
  - Clear signal of the $X(2370)$ and η_c
  - Reduce PWA complexities from additional intermediate processes

Partial wave analysis (PWA)



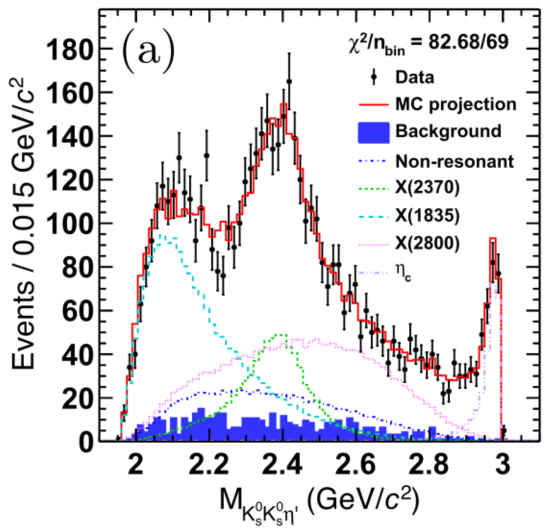
- PWA is a key tool to hadron spectroscopy
  - Input: four-momenta of the final-state particles
  - Measure the resonances' **spin-parity**, resonance parameters, production and decay properties, …

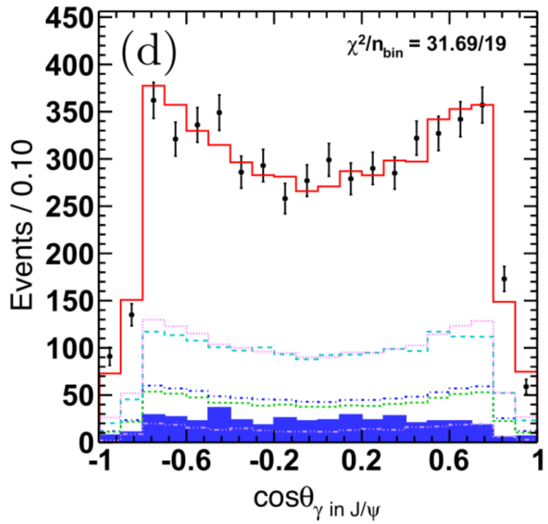
- PWA of $J/\psi \to \gamma K_S^0 K_S^0 \eta'$ is performed using **covariant tensor formalism** [1] . The signal amplitudes are parametrized as quasi-sequential two-body decays:
  - $J/\psi \to \gamma X, X \to Y\boldsymbol{\eta}', Y \to \boldsymbol{K_S^0 K_S^0}$ or $X \to Z\boldsymbol{K_S^0}, Z \to \boldsymbol{K_S^0 \eta}'$
    - ✓ K_S^0 and η' constructed with daughter particles as they are unstable states
  - Differential cross section is observable: $\omega(\xi, \alpha) = \frac{d\sigma}{d\Phi} = \left|\sum_j A_j\right|^2$

- An unbinned maximum likelihood fit is performed on the data.

[1] Zou & Bugg, Eur. Phys. J. A 16, 537–547 (2003)

PWA Fit





PRL 132 (2024) 181901

- Best fit can well describe the data including resonances (>5σ): $X(1835), X(2370), X(2800), \eta_c$
  - Spin-parity of the $X(2370)$ is determined to be 0^{-+} with significance larger than 9.8σ w.r.t. other J^{PC} assumptions
  - $X(2800)$: a broad structure for the effective contributions from possible high mass resonances

state	J^{PC}	Decay mode	Mass (MeV/c^2)	Width (MeV)	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

PWA Validations

- Intermediate process: significance <3σ and impact is ignored
  - J^{PC} and decay modes for each components: $f_0(1500)\eta'$, $f_2(1270)\eta'$, $K^*(1410)K_S^0$, $K_0^*(1430)K_S^0$, $K_2^*(1430)K_S^0$, $K^*(1680)K_S^0$, $(K_S^0K_S^0)_S\eta'$, $(K_S^0K_S^0)_D\eta'$, $(K_S^0\eta')_PK_S^0$, $(K_S^0\eta')_DK_S^0$
- Additional resonance checks: significance <5σ
  - No evidence of the $X(2120)$ in the $K_S^0K_S^0$ mass threshold region for $J/\psi \to \gamma K_S^0K_S^0\eta'$ only
  - The significance of $X(2600) \to f_0(980)\eta'$ is 4.2σ
  - Impact from the $X(2120)$ and $X(2600)$ is considered as systematic uncertainty
- The $X(2800)$ with a mass of 2799 MeV and width of 660 MeV:
  - Used to described **effective contributions from high mass region**
  - **Strongly reply on the description of η_c lineshape**: different variations are included into the systematic uncertainty
  - **Statistical uncertainties of the $X(2800)$ mass and width** are included in the systematic uncertainties on the $X(2370)$ measurements

Results

$X(2370)$ measurements: PRL 132 (2024) 181901

- $J^{PC} = 0^{-+}$ with significance > 9.8σ
- $M = 2395^{+11}_{-11}(stat.)^{+26}_{-94}(syst.)$ MeV/c^2
- $\Gamma = 188^{+18}_{-17}(stat.)^{+124}_{-33}(syst.)$ MeV
- $B[J/\psi \to \gamma X(2370)] \cdot B[X(2370) \to f_0(980)\eta'] \cdot B[f_0(980) \to K_S^0 K_S^0] = 1.31^{+0.22}_{-0.22}(stat.)^{+2.85}_{-0.84}(syst.) \times 10^{-5}$

LQCD prediction on lightest pseudoscalar glueball:

- $J^{PC} = 0^{-+}$
- $M = 2395 \pm 14$ MeV/c^2
- $B[J/\psi \to \gamma G_{0^{-+}}] = (2.31 \pm 0.80) \times 10^{-4}$

PRD 100 (2019) 054511

- The measurements **agree with the predictions on lightest pseudoscalar glueball**
  - The spin-parity of the $X(2370)$ is determined to be 0^{-+} for the first time
  - Mass is consistent with LQCD predictions
  - The estimation on $B[J/\psi \to \gamma X(2370)]$ and prediction on $B[J/\psi \to \gamma G_{0^{-+}}]$ are at the same level

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

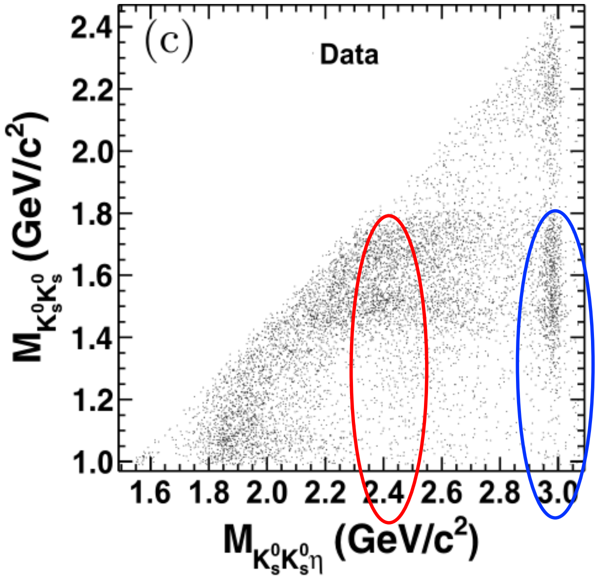
Journal: Phys. Rev. Lett. 115 (2015) 091803

- In the 2D scatter plot of $M(K_S^0 K_S^0)$ vs. $M(K_S^0 K_S^0 \eta)$, **qualitatively**, we can clearly observe same decay patterns between the $X(2370)$ and η_c if phase space allows

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

With 1.31B J/ψ events

- In the upper $M(K_S^0 K_S^0)$ mass band of 1.5-1.7 GeV range, clear signals of both $X(2370)$ and η_c.
- In the lower $M(K_S^0 K_S^0)$ mass band of $f_0(980)$, no $X(2370)$, nor η_c.

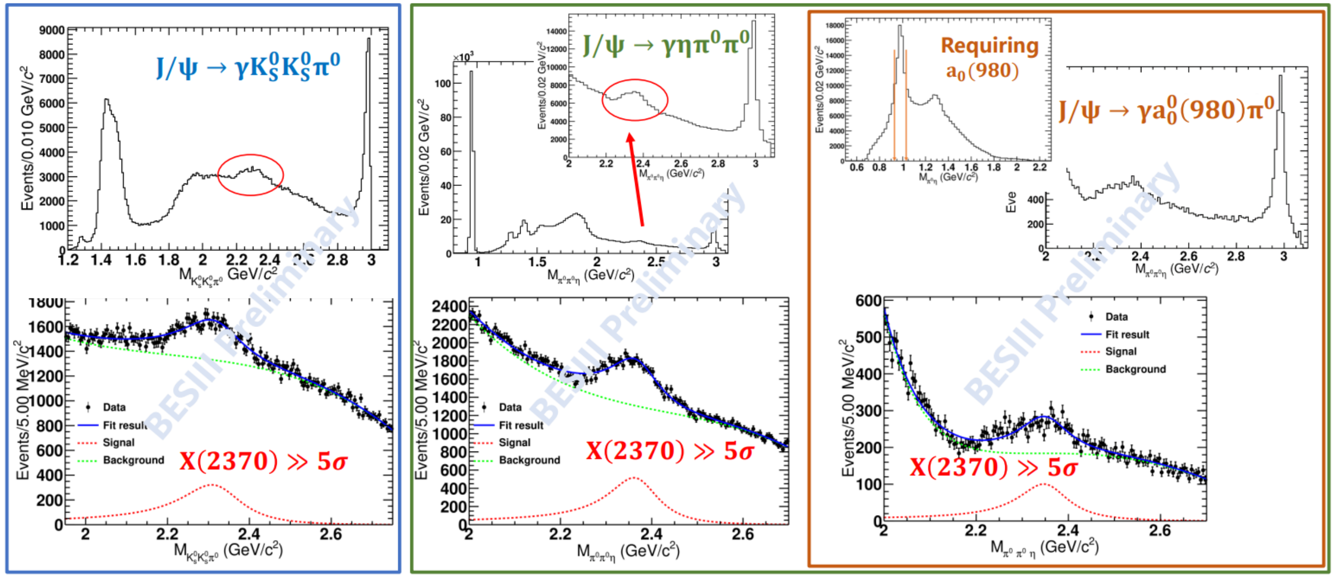


- The similarity between the $X(2370)$ and η_c decay modes supports the glueball interpretation of the $X(2370)$

Observation of new decay modes of $X(2370)$

[1] $f_0(980) \to K_S^0 K_S^0$
[2] $a_0^0(980) \to \pi^0\eta$

- New decay modes



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

Summary of decay modes of $X(2370)$

Decay mode	Significance	Ref
$\pi^+\pi^-\eta'$	6.4σ	RPL 106 (2011) 072002
$K_S^0K_S^0\eta$	seen	PRL 115 (2015) 091803
$K\bar{K}\eta'$	8.3σ	EPJC 80, 746 (2020)
$f_0(980)\eta'$ [1]	11.7σ	PRL 132 (2024) 181901
$K_S^0K_S^0\pi^0$	$\gg 5\sigma$	ICHEP2024 BESIII Preliminary
$\pi^0\pi^0\eta$	$\gg 5\sigma$	
$a_0^0(980)\pi^0$ [2]	$\gg 5\sigma$	
$\gamma\phi$	No evidence	arXiv:2401.00918
$\eta\eta\eta'$	No evidence	PRD 103 (2021) 1, 012009

- $X(2370)$ has been observed in above typical $\eta_c \to 3P$ decay modes. (Good similarities with η_c)
- Upper limits of $B[X(2370) \to \gamma\phi]$ and $B[X(2370) \to \eta\eta\eta']$ are well consistent with the predictions of 0^{-+} glueball.

Summary

- Glueballs are important predictions from QCD:
  - Unique particles formed by gluons (force carriers) due to self-interactions of gluons

- The $X(2370)$ is observed in the gluon-rich J/ψ radiative decay:
  - J^{PC} determined to be 0^{-+}
  - Measurements and predictions on mass and production rate are consistent within uncertainties
  - flavor symmetric decay modes meet expectation

——The $X(2370)$ is a glueball-like particle

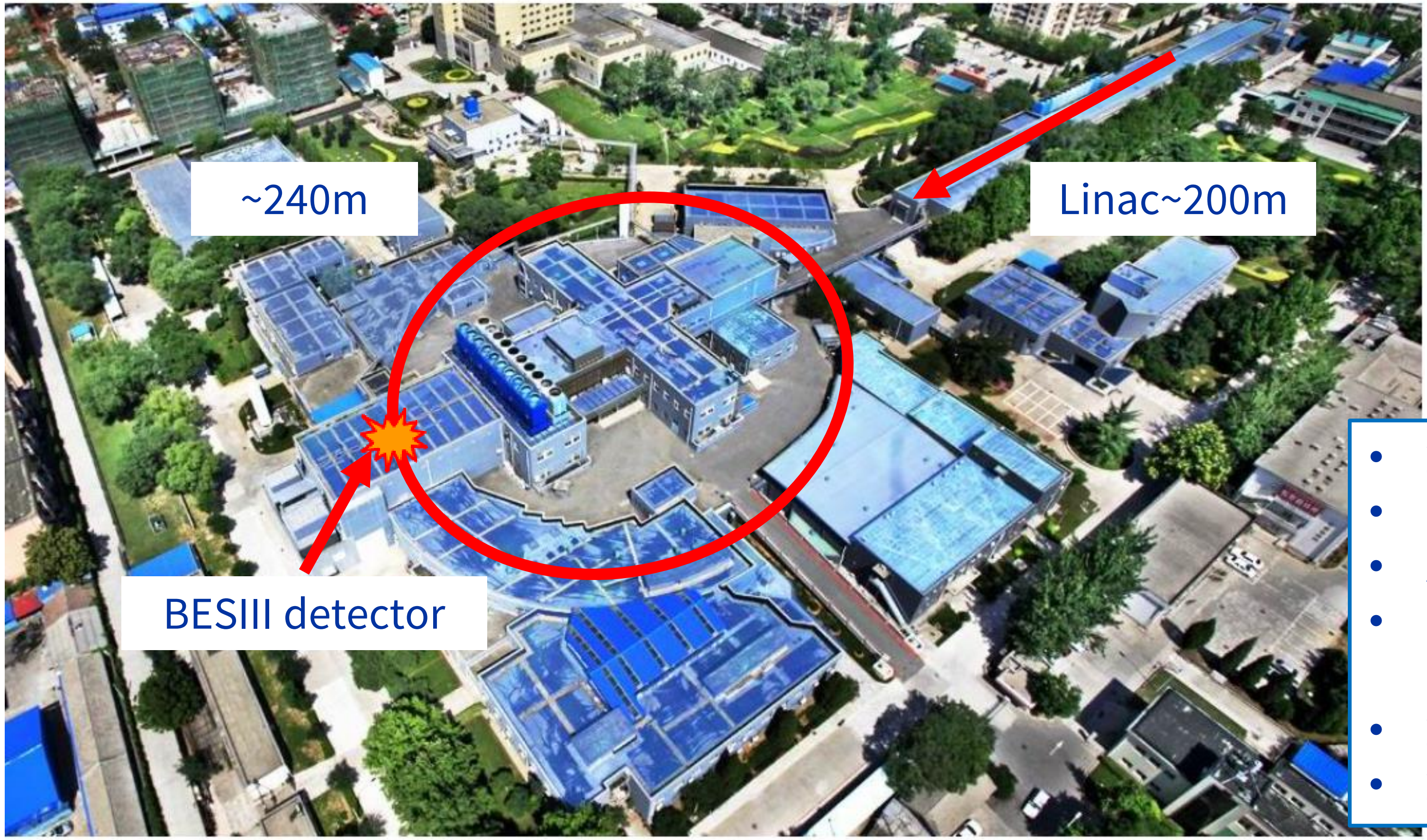
- Looking forward to further experimental + theoretical efforts, which are essential to improve our understanding of this particle.

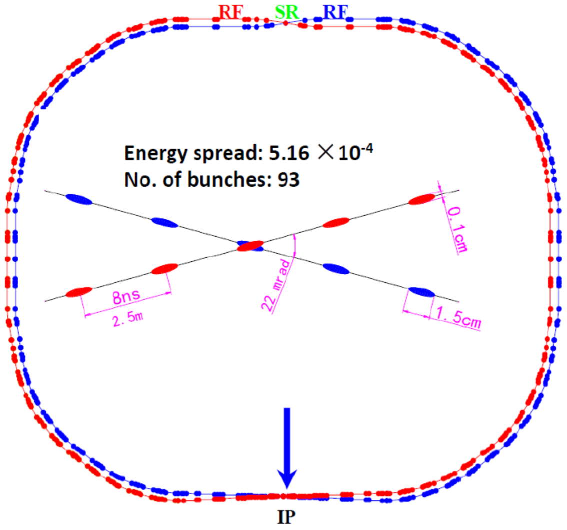
Thanks!

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Beijing Electron Positron Collider (BEPCII)

World unique e^+e^- accelerator in charm physics energy region



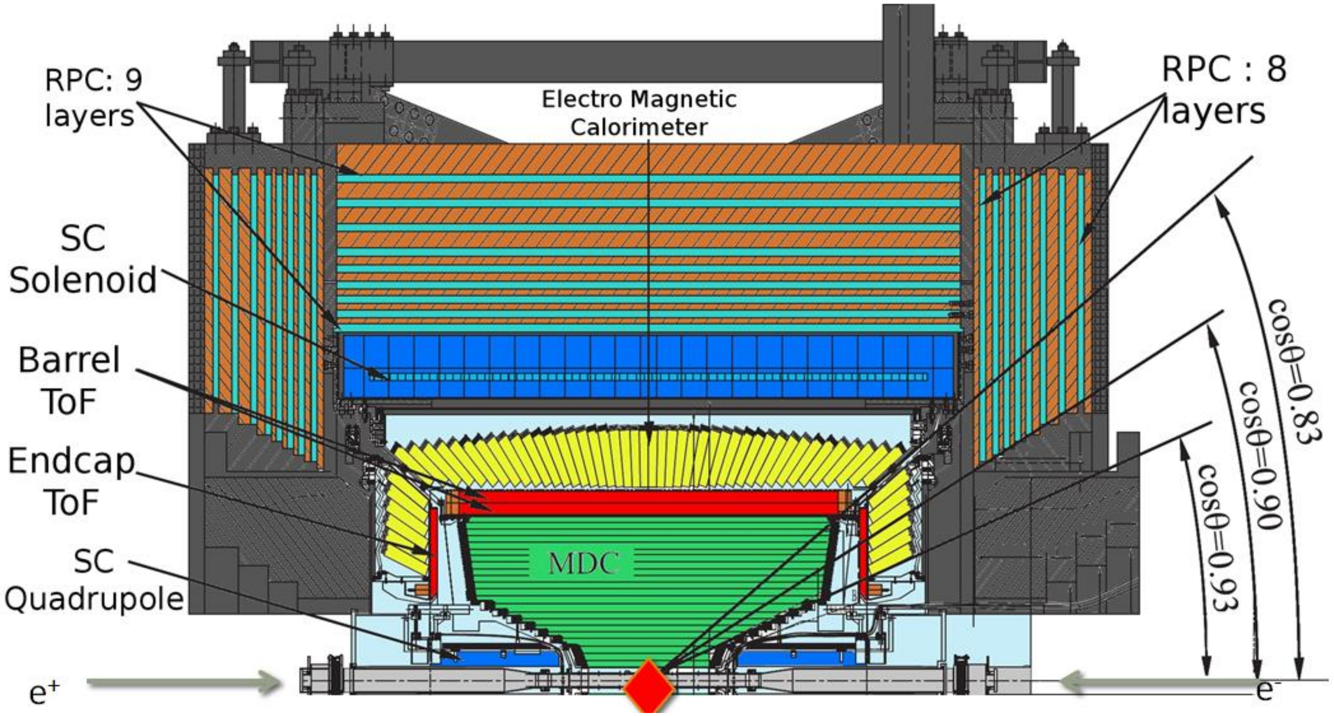


- 2004: started BEPCII/BESIII construction
- Double rings
- $E_{cm} = 2.0\sim4.6$ (4.9 since 2019) GeV
- Design luminosity: $1 \times 10^{33} cm^{-2} s^{-1}$ (reached 2016 @$E_{cm} = 3.77$ GeV)
- 2008: test run
- 2009~ today: BESIII physics runs

BESIII detector

Totally about 50 fb^{-1} integrated luminosity. Data sets collected so far include:

- 10×10^9 J/ψ events
- 2.7×10^9 $\psi(2S)$ events
- 20 fb^{-1} $\psi(3770)$



Nucl. Instr. Meth. A614, 345 (2010)

Multilayer Drift Camber (MDC)

σ_p/p <0.5% @1GeV (1T)

$\sigma_{xy} \sim 130\ \mu m$

$dE/dx \sim 6\%$

Time Of Flight (TOF)

$\sigma_t < 68ps$ (barrel)

$\sigma_t < 60ps$ (endcap)

Electromagnetic Calorimeter (EMC)

σ_E/E <2.5% @ 1 GeV (barrel)

σ_E/E < 5% @ 1 GeV (endcap)

$\sigma_{xy} \sim 6mm$ @ 1 GeV

Muon Counter

$\sigma_{spatial} < 2cm$

Glueball Decays

- The decay modes of glueballs may resemble those of the Charmonium family decays, as both can only decay via gluons.

$\pi^+\pi^-K^+K^-$.[12] For a glueball, say, a $J^{PC} = 2^{++}$ glueball, which is made of two gluons, its decay proceeds via the two-gluon hadronization, which is similar to the second step of the χ_{c2} decay. The difference between the 2^{++} glueball and χ_{c2} in their decays is that the two gluons are hadronized at different energy scales, and consequently in the two cases the branching ratio for a given final state can be different. At the higher energy scale like the χ_{c2}

From Kuang-Ta Chao 1995 Commu. Theor. Phys. 24.373

ple equally to all flavors. Since there has been no glueball confirmed by experiments, the best way looking into the flavor symmetry should be to study the decay processes which proceed through a two gluon intermediate state [10]. Fortunately, a lot of experiments have already studied such processes as the decays of charmonium family. One example is, the two

it is worth noticing that there are not any other particles showing such properties [12] as ξ except for the particles with pure OZI suppressed decay modes such as J/ψ, χ_{c0}, χ_{c2}, etc. The flavor-symmetric couplings

The knowledge [12] about the hadronic decays of J/ψ, η_c, χ_{c0} and χ_{c2} which proceed through pure gluon intermediate state suggests that the glueballs

From Tao Huang, Kuang-Ta Chao et al. PLB 380 (1996) 189-192

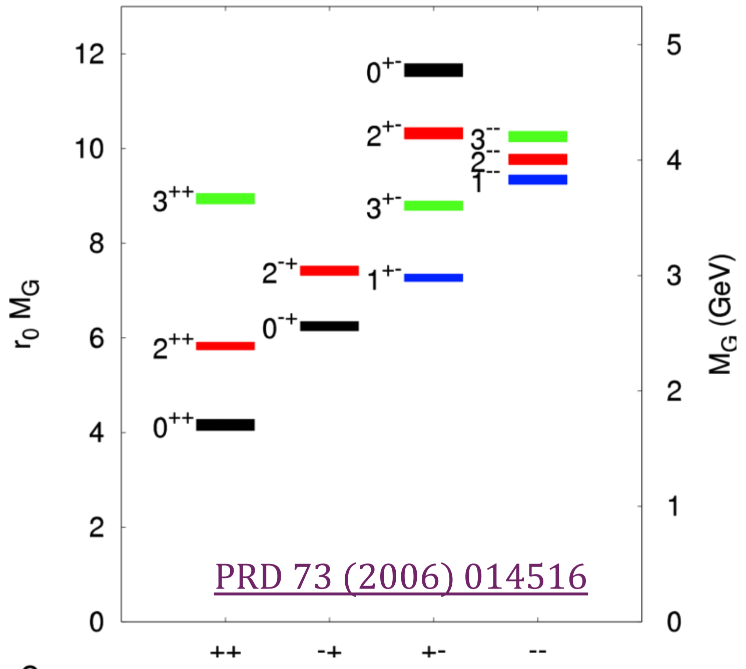
Lattice QCD predictions for glueball masses and BR:

- 0^{++} ground state: 1.5-1.7 GeV/c²; $B[J/\psi \to \gamma G_{0^{++}}] = (3.8 \pm 0.9) \times 10^{-3}$.
- 2^{++} ground state: 2.3-2.4 GeV/c²; $B[J/\psi \to \gamma G_{2^{++}}] = (1.1 \pm 0.2) \times 10^{-2}$.
- 0^{-+} ground state: 2.3-2.6 GeV/c² ; $B[J/\psi \to \gamma G_{0^{++}}] = (2.31 \pm 0.80) \times 10^{-4}$.

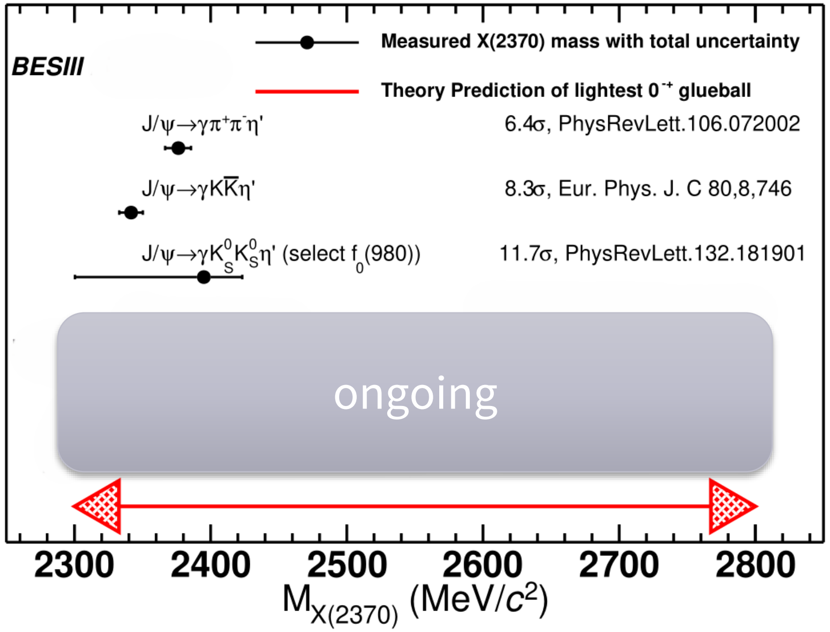
TABLE I. Branching ratios for the decay of the pseudoscalar glueball $\tilde{G}$ into three pseudoscalar mesons.

Quantity	Case (i): $M_{\tilde{G}} = 2.6$ GeV	Case (ii): $M_{\tilde{G}} = 2.37$ GeV
$\Gamma_{\tilde{G}\to KK\eta}/\Gamma_{\tilde{G}}^{\mathrm{tot}}$	0.049	0.043
$\Gamma_{\tilde{G}\to KK\eta'}/\Gamma_{\tilde{G}}^{\mathrm{tot}}$	0.019	0.011
$\Gamma_{\tilde{G}\to \eta\eta\eta}/\Gamma_{\tilde{G}}^{\mathrm{tot}}$	0.016	0.013
$\Gamma_{\tilde{G}\to \eta\eta\eta'}/\Gamma_{\tilde{G}}^{\mathrm{tot}}$	0.0017	0.00082
$\Gamma_{\tilde{G}\to \eta\eta'\eta'}/\Gamma_{\tilde{G}}^{\mathrm{tot}}$	0.00013	0
$\Gamma_{\tilde{G}\to KK\pi}/\Gamma_{\tilde{G}}^{\mathrm{tot}}$	0.47	0.47
$\Gamma_{\tilde{G}\to \eta\pi\pi}/\Gamma_{\tilde{G}}^{\mathrm{tot}}$	0.16	0.17
$\Gamma_{\tilde{G}\to \eta'\pi\pi}/\Gamma_{\tilde{G}}^{\mathrm{tot}}$	0.095	0.090

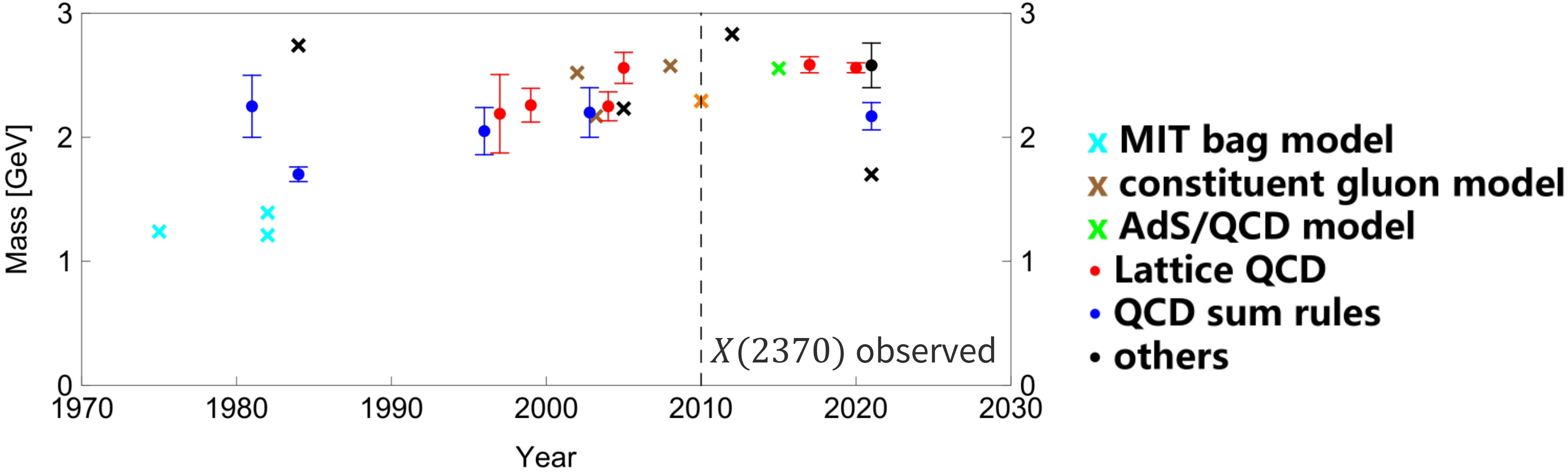
PhysRevD.87.054036



0+-
2+-
3--
2--
1--
3++
3+-
2-+
1+-
0-+
2++
0++
PRD 73 (2006) 014516
$r_0 M_G$
M_G (GeV)
++
-+
+-
--



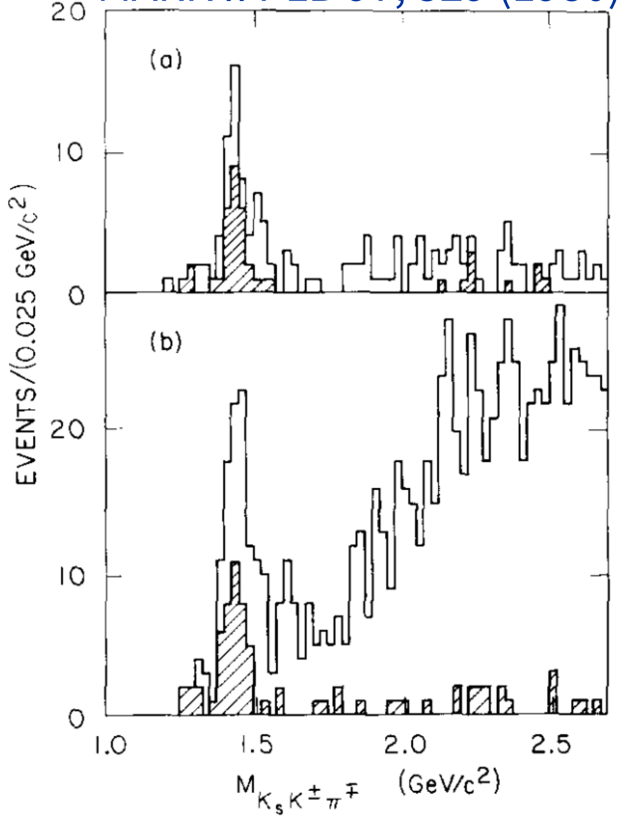
BESIII
Measured X(2370) mass with total uncertainty
Theory Prediction of lightest 0^{-+} glueball
$J/\psi \to \gamma\pi^+\pi^-\eta'$
6.4σ, PhysRevLett.106.072002
$J/\psi \to \gamma K\bar{K}\eta'$
8.3σ, Eur. Phys. J. C 80,8,746
$J/\psi \to \gamma K_S^0 K_S^0 \eta'$ (select $f_0(980)$)
11.7σ, PhysRevLett.132.181901
ongoing
2300
2400
2500
2600
2700
2800
$M_{X(2370)}$ (MeV/c^2)



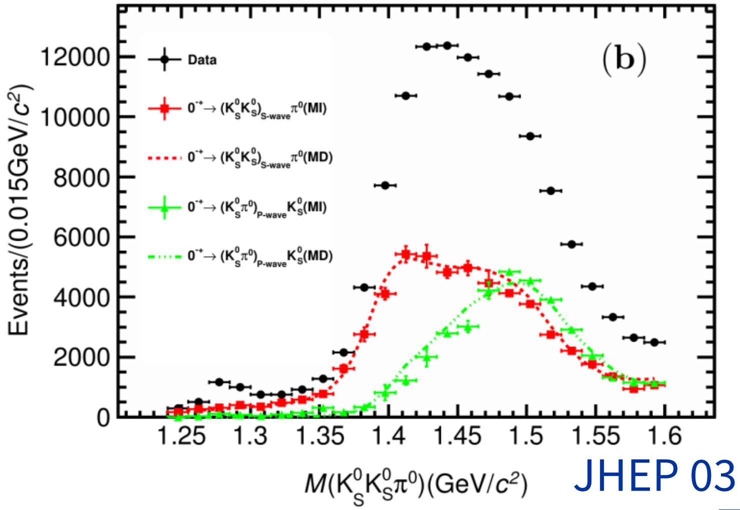
Mass [GeV]
Year
$X(2370)$ observed
x MIT bag model
x constituent gluon model
x AdS/QCD model
• Lattice QCD
• QCD sum rules
• others

Pseudoscalar glueball candidate

MARK II PLB 97, 329 (1980)



- $\boldsymbol{\eta(1405)}$ / $\boldsymbol{\eta(1475)}$ puzzle
  - ι(1440), split into $\eta(1405)$ and $\eta(1475)$, first discovered by MARK II in 1980s. Lots of studies at MARK II, MARK III, DM2 and BES.
  - Believed as the first glueball candidate due to its large production rate in J/ψ radiative decays and lack of reliable LQCD predictions in 1980s
  - No longer to be believed as 0^{-+} glueball candidate due to its large differen mass from LQCD prediction.

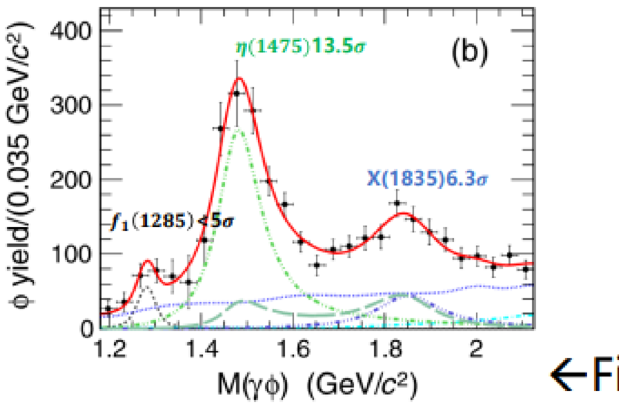


JHEP 03 121(2023)

- Recent BESIII's study in $J/\psi \to \gamma K^0_S K^0_S \pi^0$
  - Consistency between MI and MD results
  - Dominated by 0 -+
  - Two BWs around 1.4 GeV is needed

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

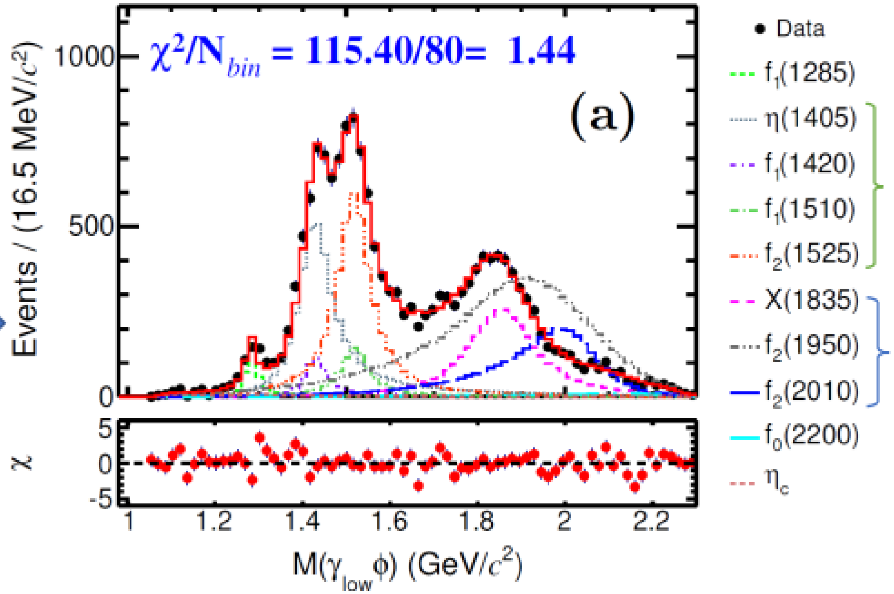
PR D97 051101 (2018)



←Fit to mass spectrum

Amplitude analysis with advanced techniques for background subtraction

arXiv: 2401.00918

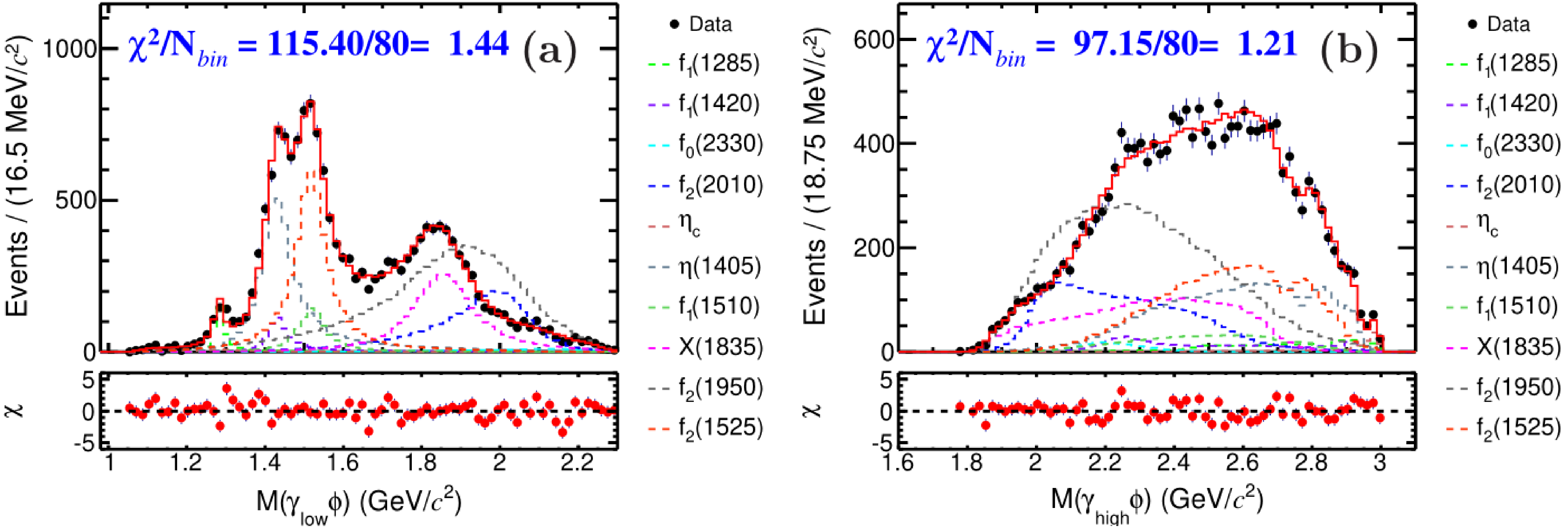


From the amplitude analysis,

- $\eta(1405)$ 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]

PWA of $J/\psi \rightarrow \gamma\gamma\phi$

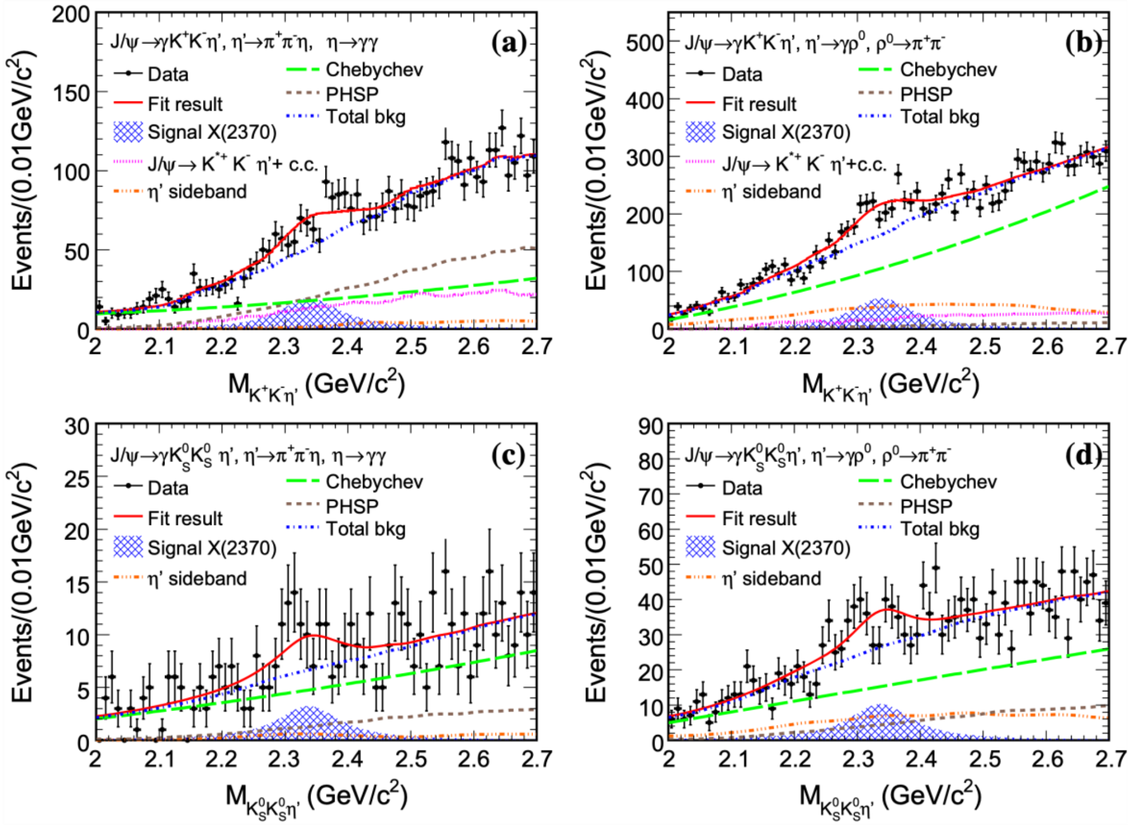
- No evidence for the η(1295), η(1475), η1(1855),and X(2370) in the γφ system.



Confirmation of the $X(2370)$ in $J/\psi \to \gamma K\bar{K}\eta'$

- $J/\psi \to \gamma K\bar{K}\eta'$ channel was analyzed with ~1.31B J/ψ events

Eur. Phys. J. C 80, 746 (2020)



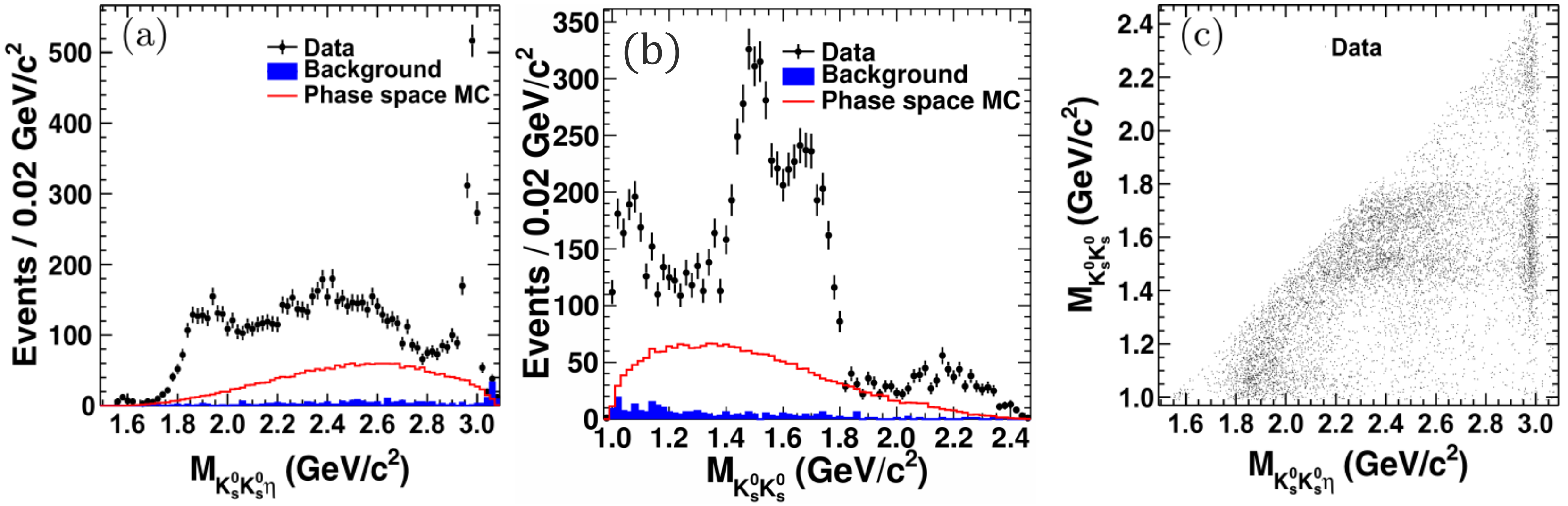
- Combined following channels
  - $J/\psi \to \gamma K^+K^-\eta'$ and $J/\psi \to \gamma K_S^0 K_S^0 \eta'$
  - $\eta' \to \gamma\pi^+\pi^-$ and $\eta' \to \pi^+\pi^-\eta$
- Confirmation of the $X(2370)$ with 8.3σ
  - $\mathrm{M} = 2341.6 \pm 6.5(\mathrm{stat.}) \pm 5.7(\mathrm{syst.})\ \mathrm{MeV}/c^2$
  - $\Gamma = 117 \pm 10(\mathrm{stat.}) \pm 8(\mathrm{syst.})\ \mathrm{MeV}$

Observation: X(2370) new decay mode of $K\bar{K}\eta'$

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

➢ Mass spectra

With 1.31B J/ψ events

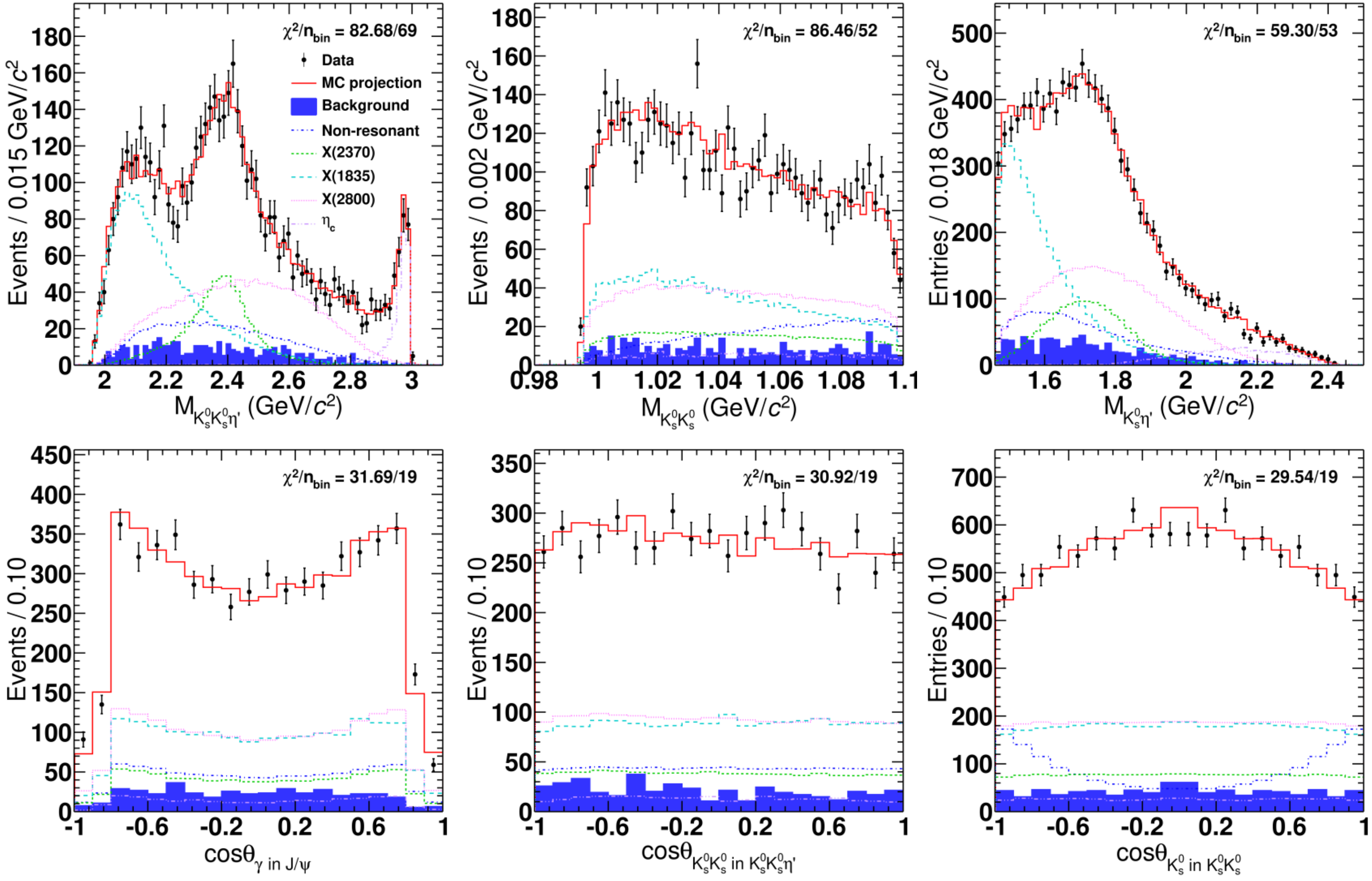


PRL 115 (2015) 091803

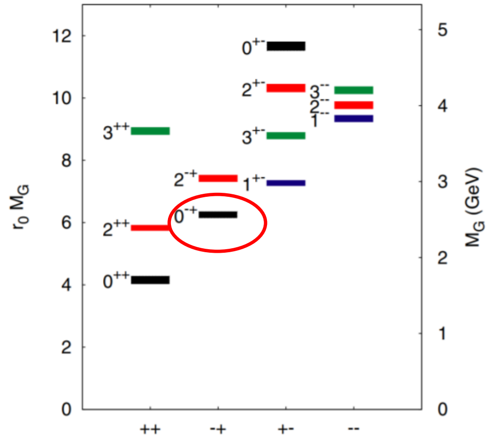
Observation and Spin-Parity Determination of the $X(1835)$ in $J/\psi \to \gamma K_S^0 K_S^0 \eta$

$X(2370)$ observed in $J/\psi \to \gamma K_S^0 K_S^0 \eta'$

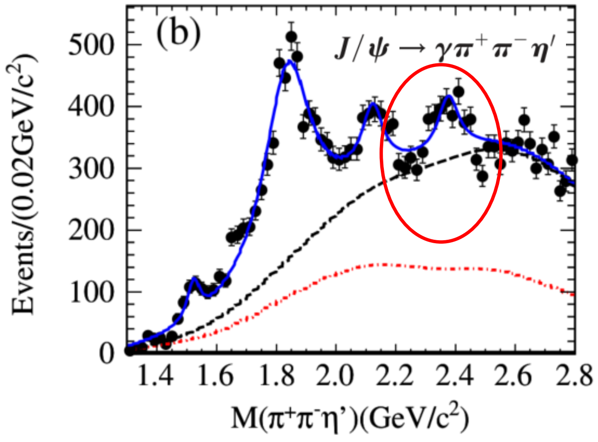
PWA projections



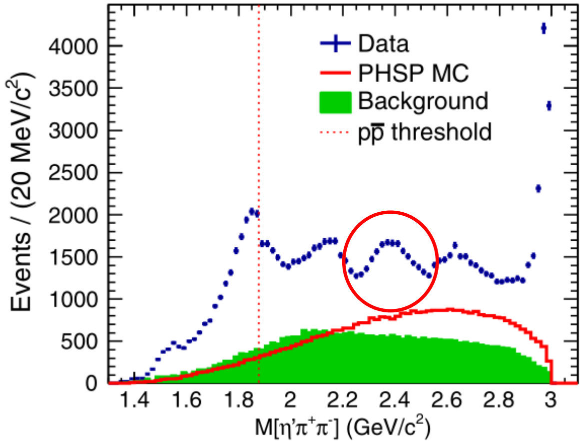
Overview



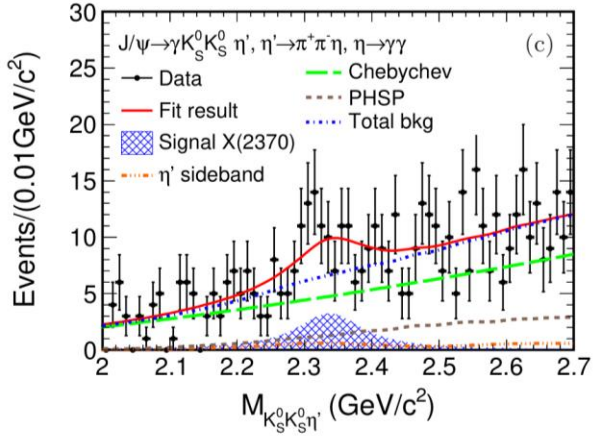
PRD 73 (2006) 014516



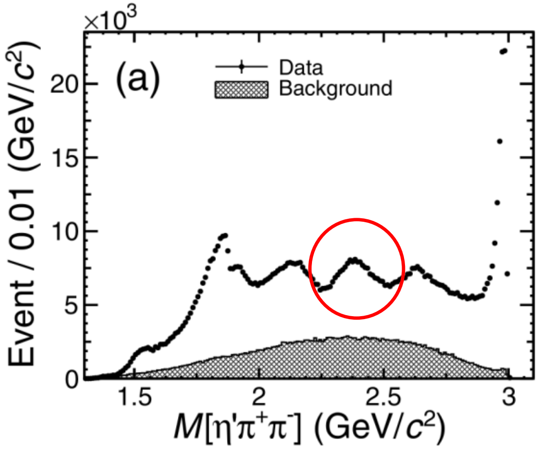
RPL 106 (2011) 072002



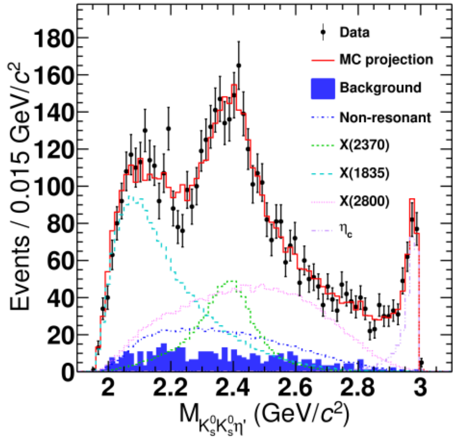
PRL 117 (2016) 042002



Eur. Phys. J. C 80, 746 (2020)



PRL 129 (2022) 042001



PRL 132 (2024) 181901

- The $X(2370)$ was first observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$ channel and confirmed in $J/\psi \to \gamma K\bar{K}\eta'$ channel. The J^{PC} of X(2370) is determined to be 0^{-+} in $J/\psi \to \gamma K_S^0 K_S^0 \eta'$channel.
- The mass, spin-parity, production and decay properties of the $X(2370)$ are consistent with the features of the lightest pseudoscalar glueball.

Systematic uncertainty

Sources	ΔM (MeV/c^2)	$\Delta\Gamma$ (MeV)	$\Delta\mathcal{B}/\mathcal{B}(\%)$
Event selection	...	...	± 4.8
Background estimation	$+2$	$^{+4}_{-4}$	$^{+3.7}_{-5.1}$
$f_0(980)$ parametrization	-6	$+7$	± 5.3
X(1835) parametrization	$^{+15}_{-12}$	$^{+24}_{-11}$	$^{+20.2}_{-8.3}$
η_c parametrization	-13	-8	-14.5
Breit-Wigner formula	-1	$+6$	-8.3
Broad 0^{-+} structure	-88	$^{+111}_{-21}$	$^{+211.8}_{-56.5}$
Additional resonances	$^{+22}_{-25}$	$^{+48}_{-21}$	$^{+41.9}_{-20.8}$
Total	$^{+26}_{-94}$	$^{+124}_{-33}$	$^{+217.0}_{-63.7}$

Interpretation

	X(2370)	η_c	Interpertation on the X(2370)
$f_0(980)\eta'$	√	√	Disfavors $q\bar{q}$ meson with pure $u\bar{u}/d\bar{d}$ component
$f_0(980)\eta$	Suppressed	Suppressed	Disfavors $q\bar{q}$ meson with pure $s\bar{s}$ component
$f_0(1500)\eta$	√	√	Disfavors $q\bar{q}$ meson with pure $s\bar{s}$ component

- **The X(2370) decay properties observed**: **disfavor the interpretation of $q\bar{q}$ meson**
  - Observed decay modes (η_c dominant decays) and suppressed decay modes are consistent between the $X(2370)$ and η_c
  - **A good agreement with the glueball interpretation**
- **The X(2370) production properties observed:**
  - richly produced in J/ψ radiative decays as the glueball expectation
  - In the mass region larger than 2 GeV, the only particle $X(2370)$ for the 0^{-+} glueball candidate in η_c radiative decays and two golden decay modes $\pi\pi\eta'$ and $K\bar{K}\eta'$
- **Mass, spin-parity:** consistent with 0^{-+} glueball prediction

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

- 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
- PP (2 pseudoscalar mesons) modes are mostly forbidden for 0^{-+} mesons
- 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

Possible intermediate states

Table 8: Possible waves for the decay of $Y \to K_s^0 K_s^0$ and $Z \to K_s^0 \eta'$.

Decays	$f_0 \to K_s^0 K_s^0$	$f_2 \to K_s^0 K_s^0$	$K^* \to K_s^0 \eta'$	$K_0^* \to K_s^0 \eta'$	$K_2^* \to K_s^0 \eta'$
L	0	2	1	0	2

Table 6: Possible waves for the decay of $J/\psi \to \gamma X$. L is the quantum number of the orbital angular momentum.

Decays	$J/\psi \to \gamma 0^{-+}$	$J/\psi \to \gamma 1^{++}$	$J/\psi \to \gamma 2^{-+}$	$J/\psi \to \gamma 2^{++}$
L	1	0, 2	1, 3	0, 2

Table 7: Possible waves for the decay of $X \to Y\eta'$ or $X \to ZK_s^0$ with different J^{PC} of X. Label "$--$" means that this decay is forbidden.

L \ Decays / J^{PC}	$X \to f_0\eta'$	$X \to f_2\eta'$	$X \to K^* K_s^0$	$X \to K_0^* K_s^0$	$X \to K_2^* K_s^0$
0^{-+}	0	2	1	0	2
1^{++}	1	1, 3	0, 2	1	1, 3
2^{-+}	2	0	$--$	2	0
2^{++}	$--$	1, 3	$--$	$--$	1, 3