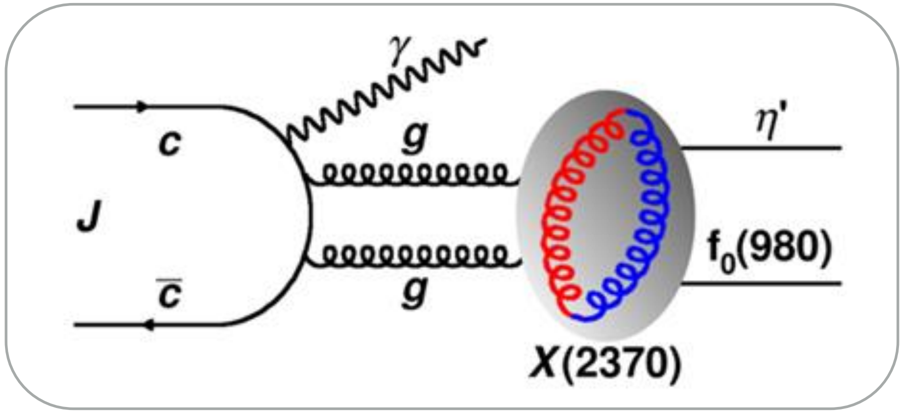

Discovery of a Glueball-like particle $X(2370)$

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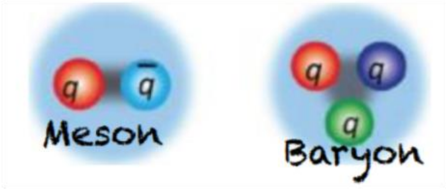
(On behalf of the BESIII Collaboration)

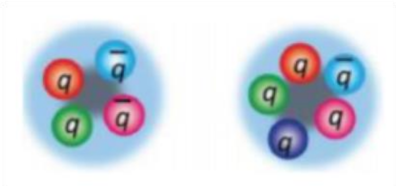
29th PASCOS, July 7-13, 2024, Quy Nhon, Vietnam

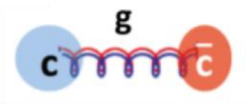
Reminder: Forms of hadrons

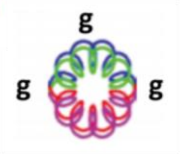
- The basic theory for strong interactions is quantum chromodynamics (QCD). Hadrons are the bound states of QCD
- Hadrons consist of 2 or 3 quarks in conventional quark model
  - Mesons (quark-antiquark states)
  - Baryons (3-quark states)



- 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 ….)







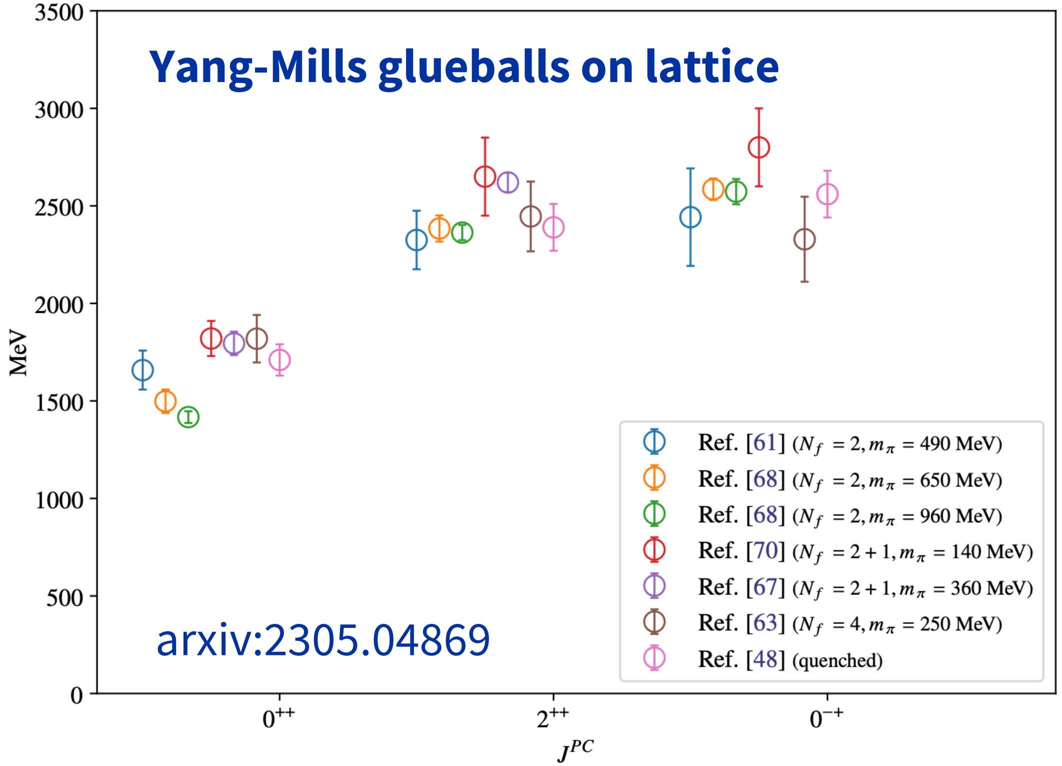
Lots of candidates, but new forms of hadrons have not been established yet!

Glueball

- The self interaction of gluons —— gauge bosons of strong interactions, is unique property of QCD. Glueball formed by self-interacted gluons.

➔Direct test of QCD

- Lattice QCD predictions on glueball masses:
  - 0^{++} ground state: 1.3 ~ 2 GeV/c²
  - 2^{++} ground state: 2.2 ~ 2.8 GeV/c²
  - 0^{-+} ground state: 2.3 ~ 2.8 GeV/c²



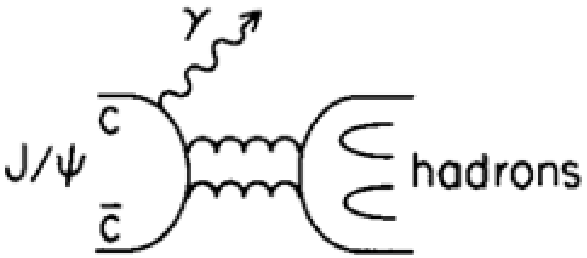
Light-mass glueball: 0^{++}, 2^{++}, 0^{-+}

J/ψ radiative decays

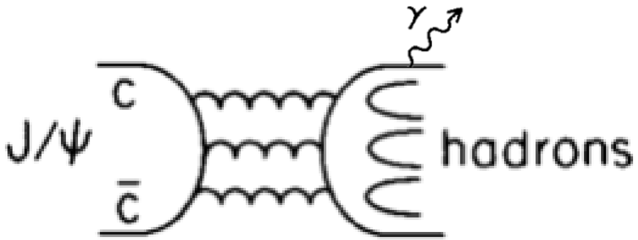
- **Gluon rich environment**
- **Isospin filter**: final states dominated by I=0 processes
- **Spin-parity filter**: C parity must be +, so $J^{PC} = 0^{-+}, 0^{++}, 1^{++}, 2^{-+}, 2^{++} \ldots$

$C(X) = + \text{ for } J/\psi \to \gamma X$

- **Clean environment** in electron-positron collision
  - very different from proton-antiproton collision



$\sim\alpha\alpha_s^4$

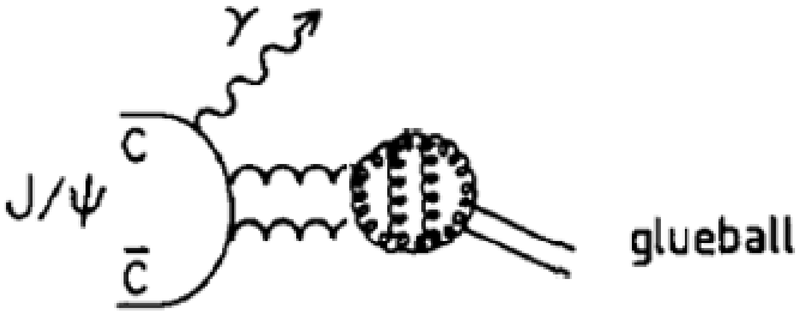


$\sim\alpha\alpha_s^6$

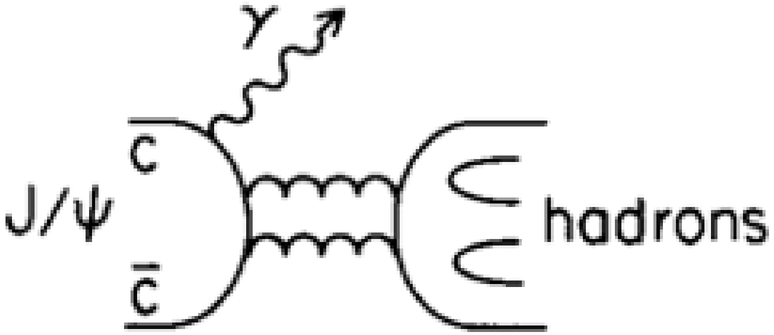
Glueball Production in J/ψ radiative decays

➢ Rich production in J/ψ radiative decays

- Glueball production rate in J/ψ radiative decays could be higher than normal hadrons



$\sim \alpha \alpha_s^2$

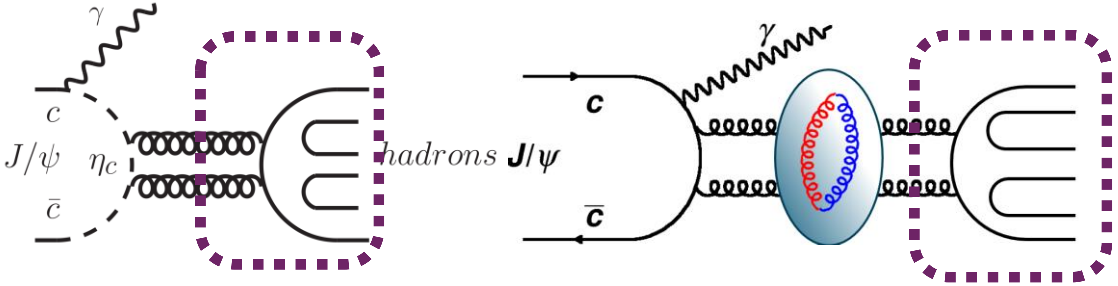


$\sim \alpha \alpha_s^4$

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

Glueball Decays

- Via gluons —— 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.
  - The 0^{-+} glueball could have similar decays of η_c
  - One of the largest decay modes of η_c is $\pi\pi\eta'$, so $J/\psi \to \gamma\pi\pi\eta'$ could be a good place to search for the 0^{-+} glueball



- 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/controversy**.
  - 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

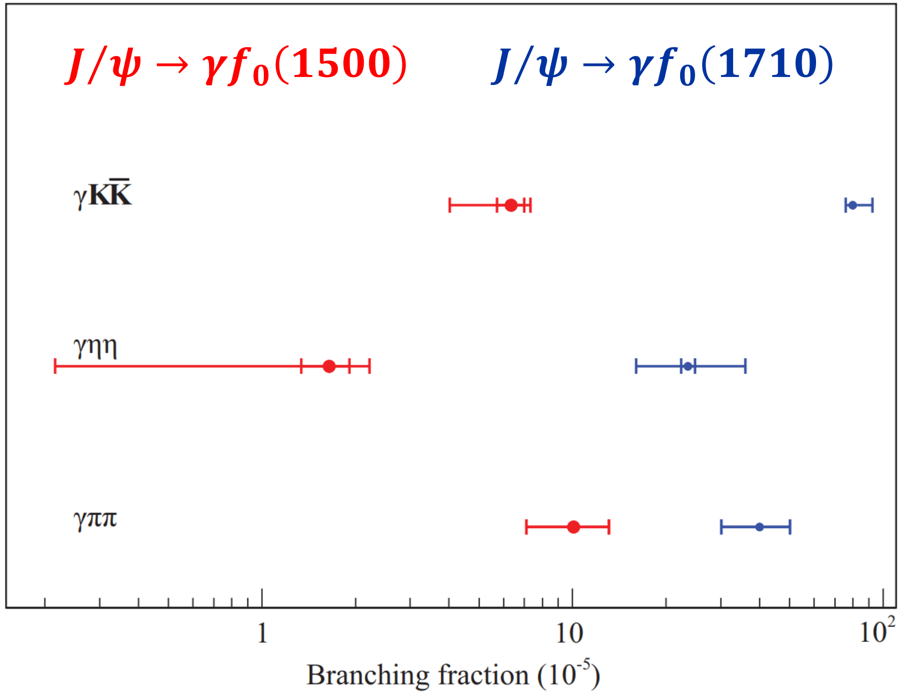
- $B[J/\psi \rightarrow \gamma G_{0^{-+}}] = 3.8(8) \times 10^{-3}$ @ LQCD

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

➢ The high production rate of $J/\psi \rightarrow \gamma f_0(1710)$ and the suppression of $f_0(1710) \rightarrow \eta\eta'$ supports that

- $f_0(1710)$ has a large overlap with glueball [PRD 106 072012(2022)]

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



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

still await undisputed confirmations

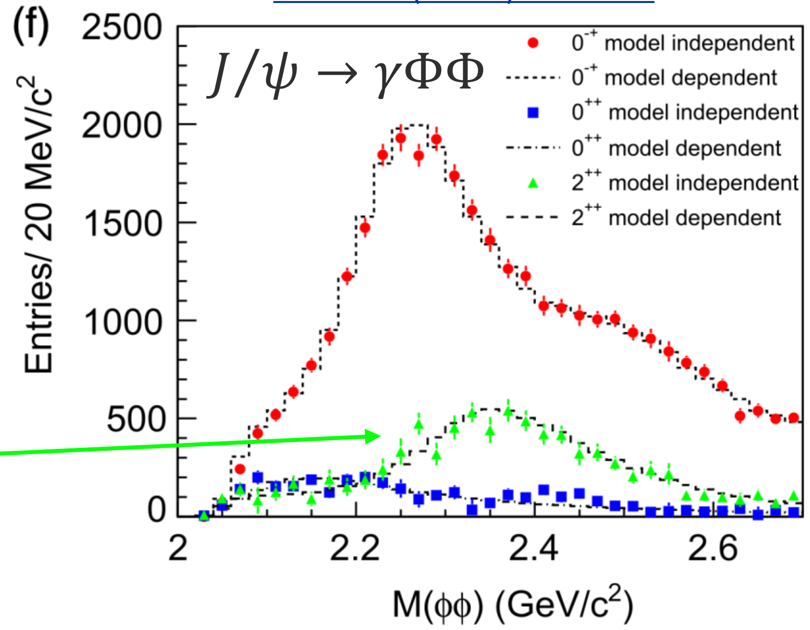
Tensor glueball candidate

- 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.

PRD 93 (2016) 112011

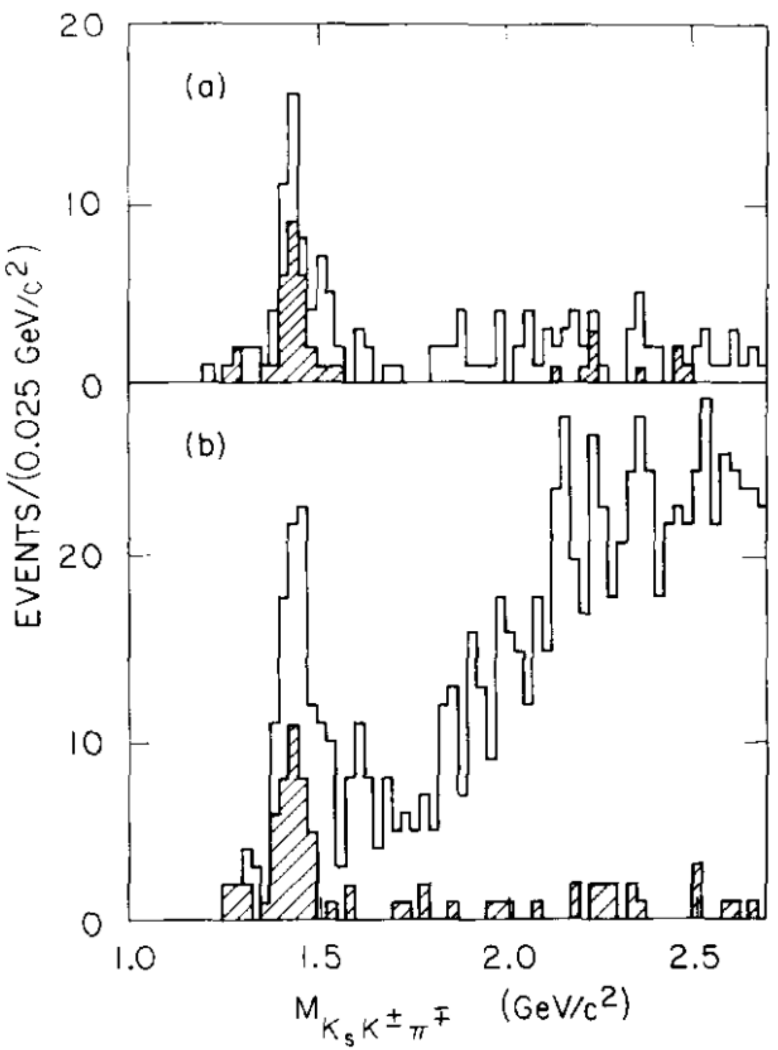


Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. (×10^{-4})	Sig.
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28σ
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	22σ
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	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

Pseudoscalar glueball candidate

- Expected mass @LQCD: 2.3~2.8 GeV

- Pseudoscalar $\eta(1405)$
  - $\eta(1405)$ first discovered by MARK II in 1980's, named as ι(1440). 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 different mass from LQCD prediction.



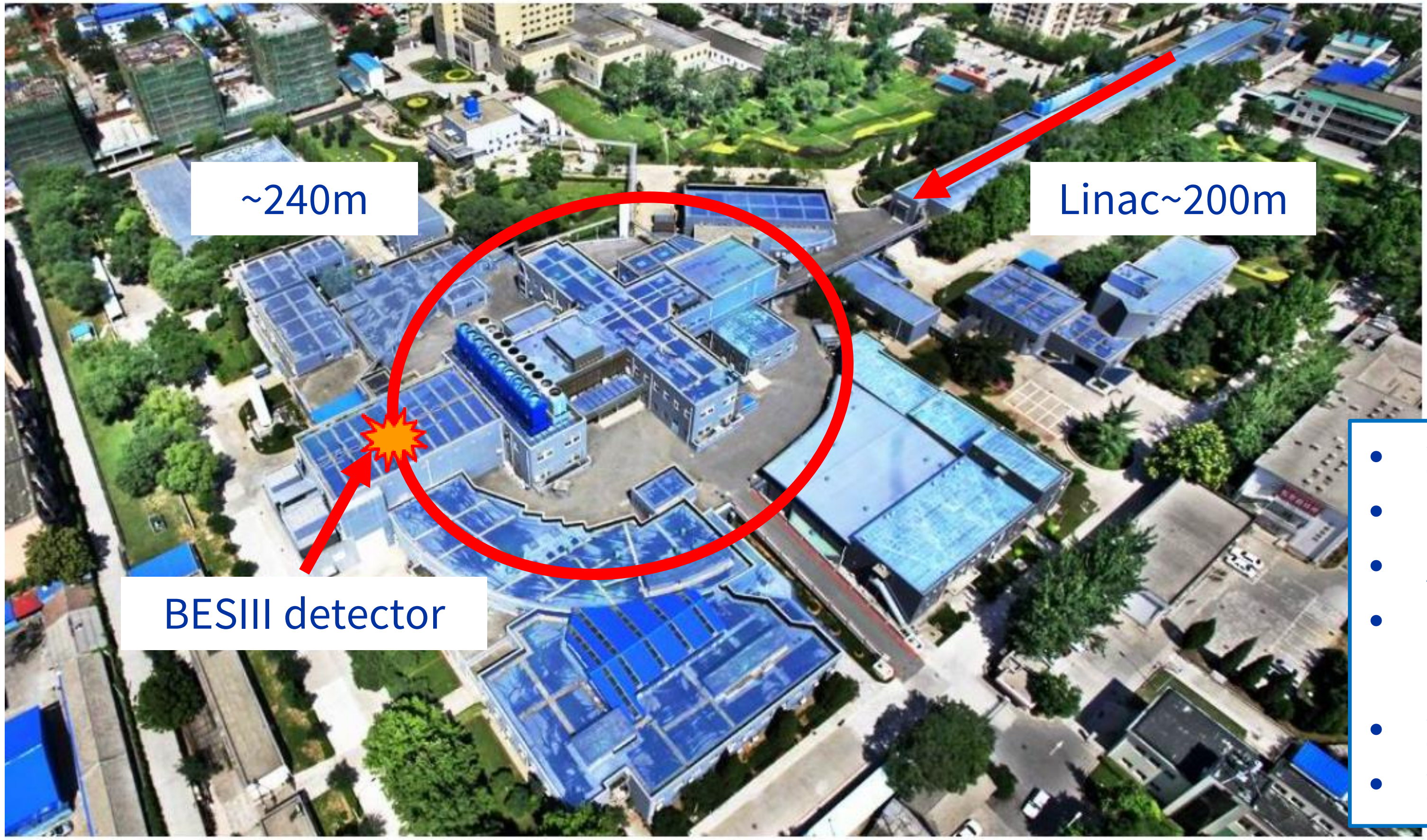
MARK II PLB 97, 329 (1980)

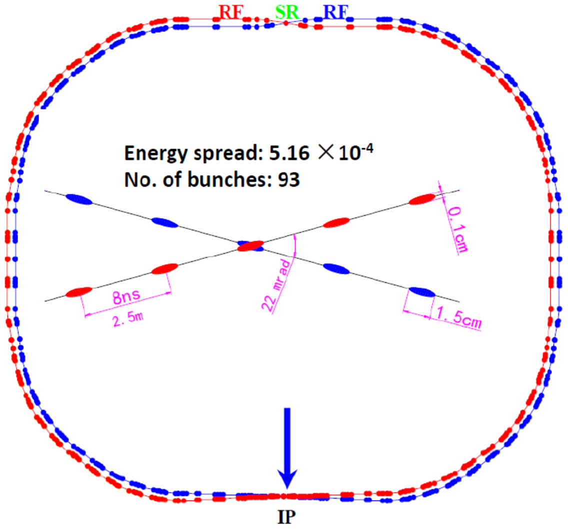
BEPCII and BESIII

The Experimental facility

Beijing Electron Positron Collider (BEPCII)

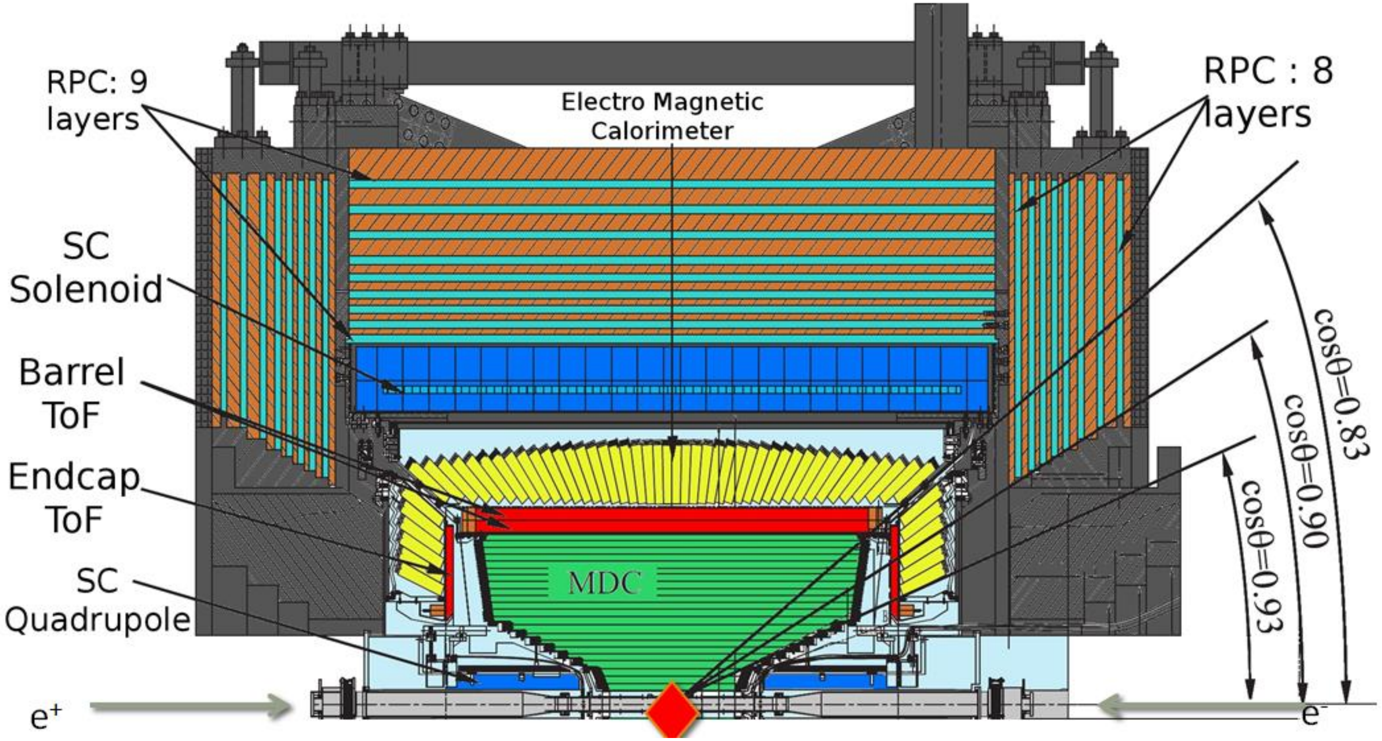
World unique e^+e^- accelerator in charm physics energy region





- 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



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

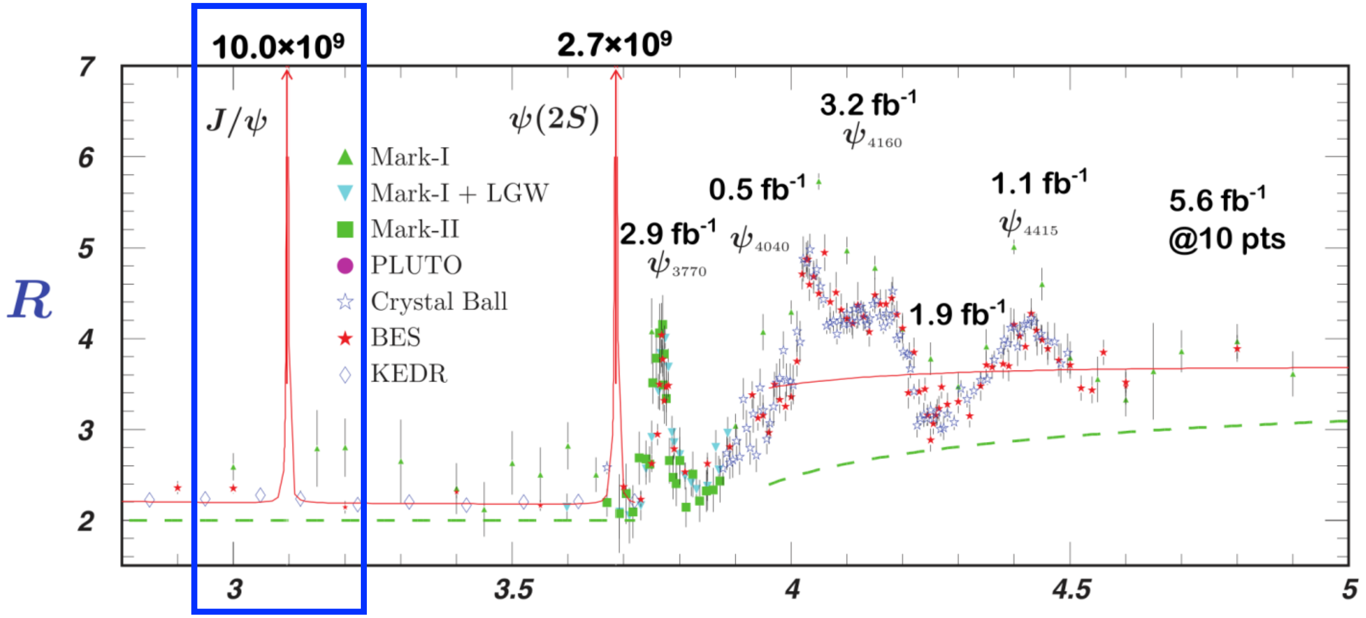
Muon Counter

$\sigma_{\text{spatial}} < 2cm$

BESIII data collections

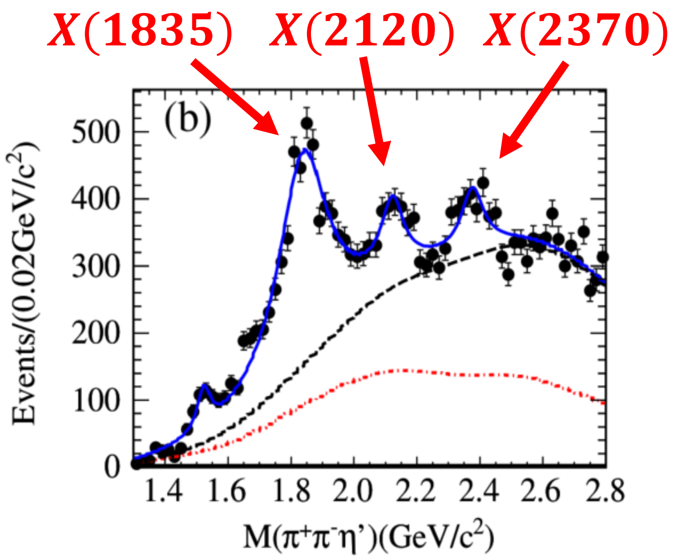
- Totally about 50 fb^{-1} integrated luminosity. Data sets collected so far include
  - 10×10^9 J/ψ events
  - 2.7×10^9 ψ(2S) events
  - 20 fb^{-1} ψ(3770)
  - …

World largest J/ψ data sample : ~10 billion.
Provide a good opportunity to search for glueball



Discovery of $X(2370)$ on BESIII

$X(2370)$

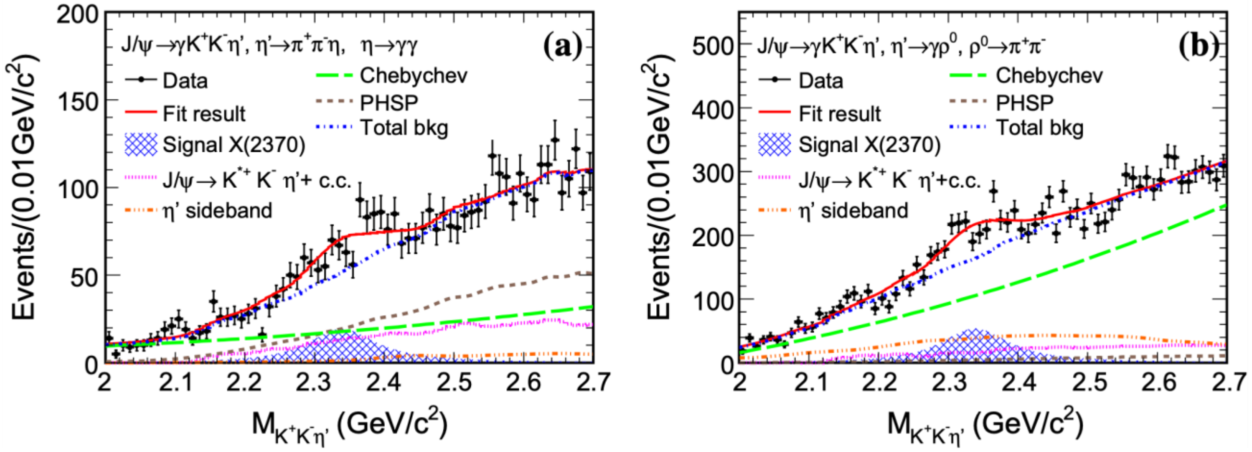


RPL 106 (2011) 072002

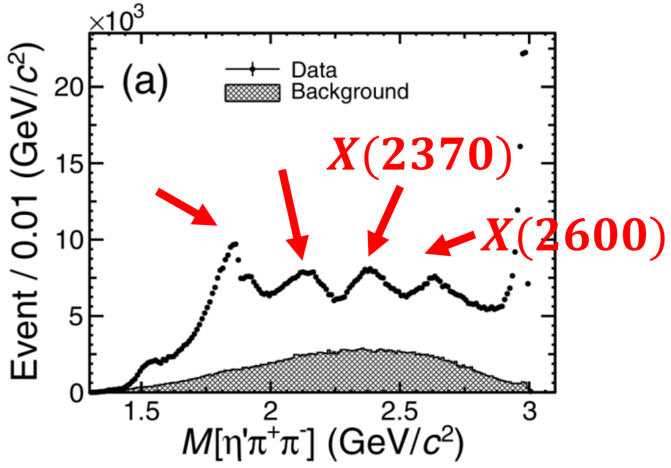
- First observation by BESIII of the $X(2370)$ in $J/\psi \to \gamma\pi^+\pi^-\eta'$

	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

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

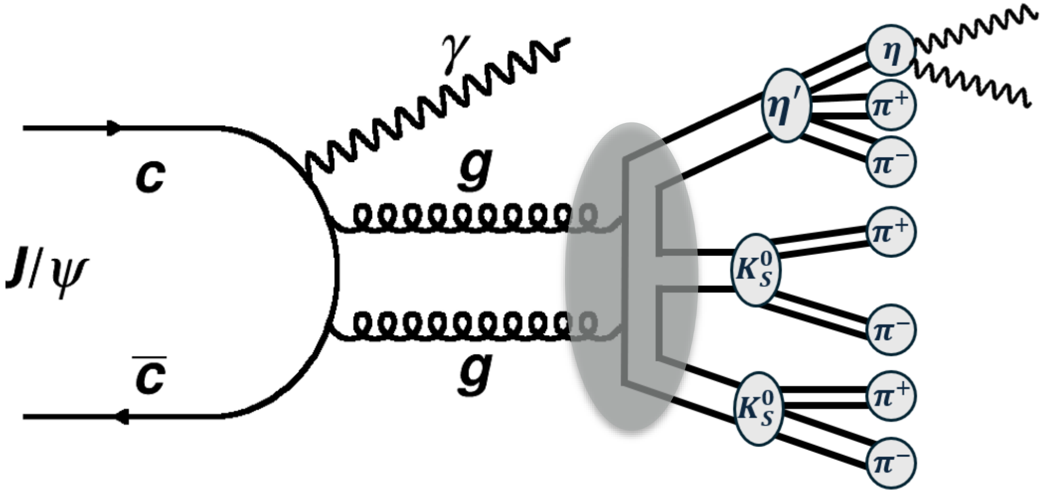
Journal: Phys. Rev. Lett. 132 (2024) 181901

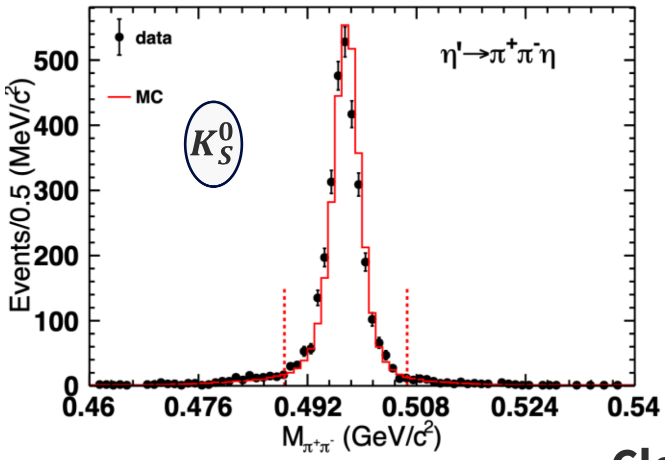
Advantages of this channel:

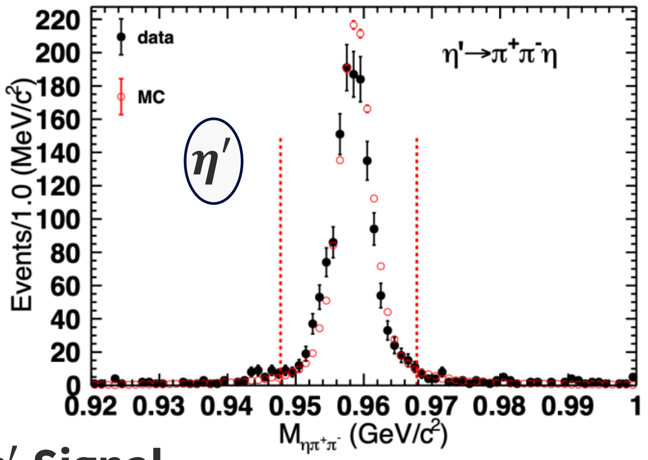
- ~10B clean J/ψ events
- Almost no background:
  - Possible dominant background processes of $J/\psi \to \pi^0 K_S^0 K_S^0 \eta'$ and $J/\psi \to K_S^0 K_S^0 \eta'$ are forbidden by exchange symmetry and C-parity conservation.
- High efficiency and precise resolution of charged particles and photons:
  - 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: $\left|M_{\pi^+\pi^-} - M_{K_S^0}\right| < 9\ \mathrm{MeV/c^2}$
  - η' reconstruction: $\left|M_{\pi^+\pi^-\eta} - M_{\eta'}\right| < 10\ \mathrm{MeV/c^2}$
- **Background veto:**
  - π^0 veto: $\left|M_{\gamma\gamma} - M_{\pi^0}\right| > 20\ \mathrm{MeV/c^2}$



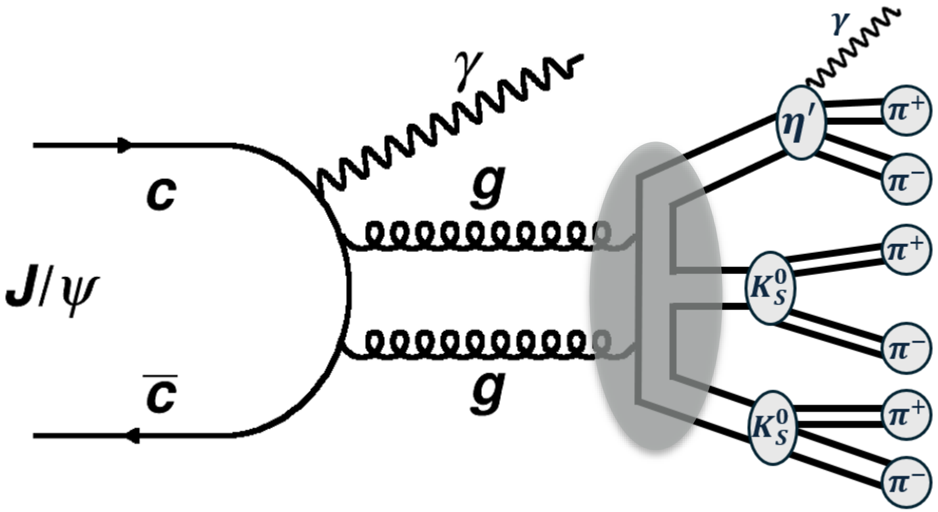


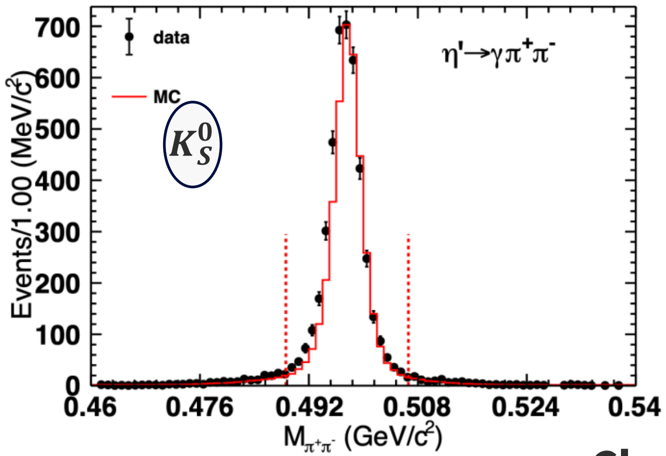


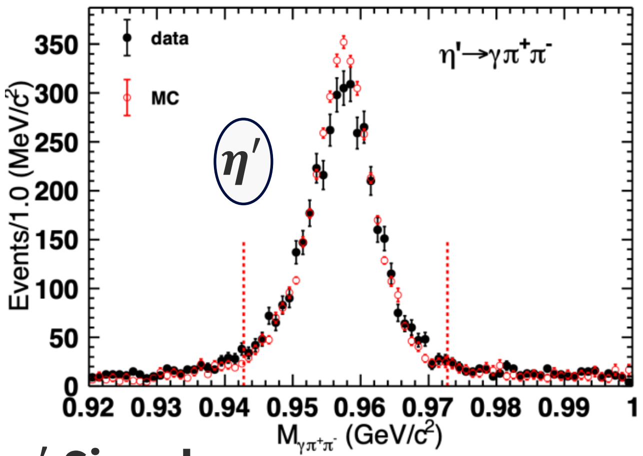
Clean K_S^0 and η' Signal

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: $|M_{\gamma\gamma} - M_{\pi^0}| > 20\ \mathrm{MeV/c^2}$, $|M_{\gamma\gamma} - M_{\eta}| > 30\ \mathrm{MeV/c^2}$



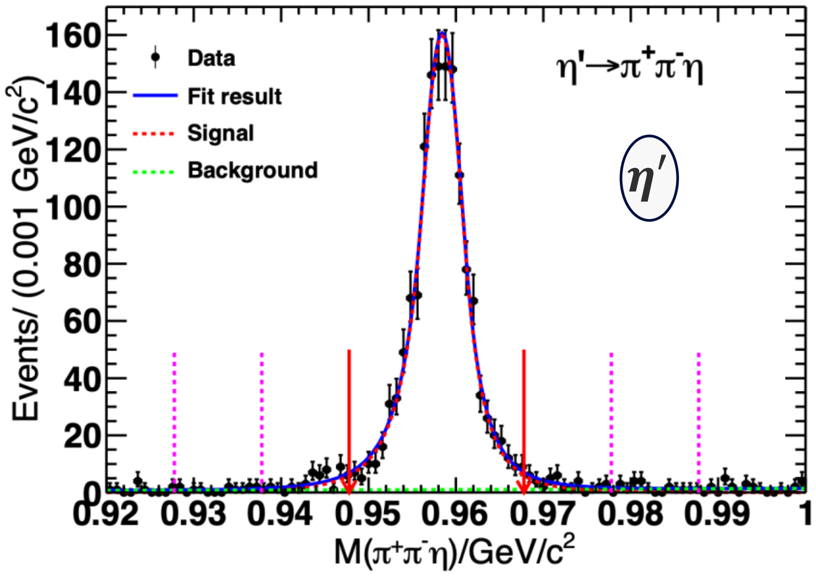


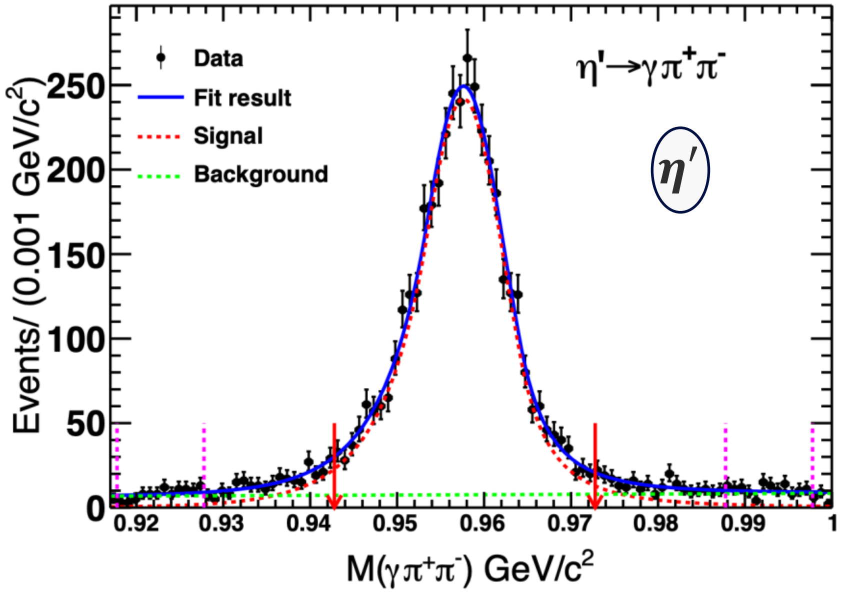


Clean K_S^0 and η' Signal

Background estimation

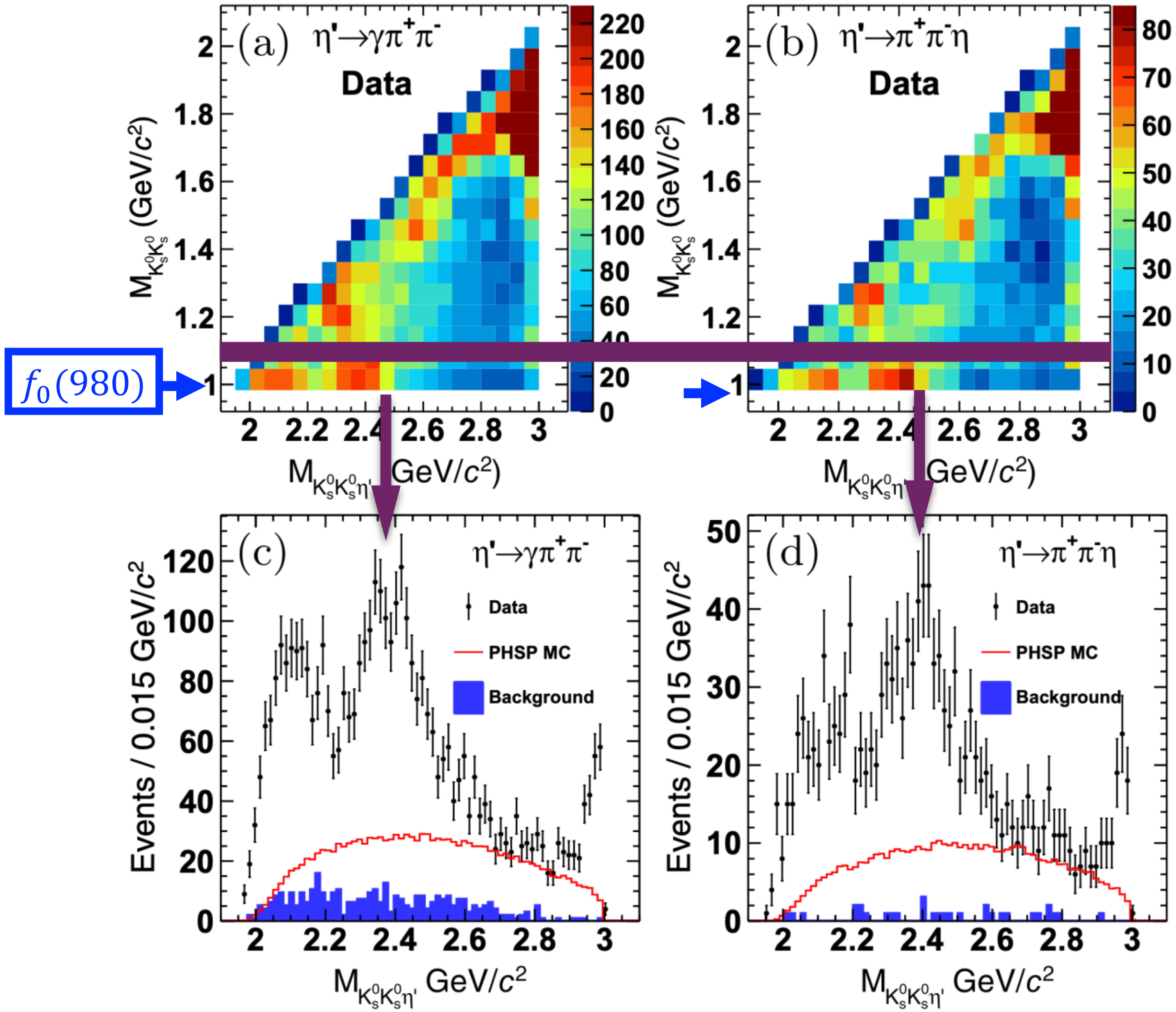
- Negligible mis-combination for K_S^0 reconstruction (<0.1%)
- No background from $J/\psi \to \pi^0 K_S^0 K_S^0 \eta'$: further validation directly from data
- Little background from non-η' processes: estimated directly from η' mass sideband region:
  - No peaking background
  - Non-η' background fraction: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





Spin-Parity determination benefits from low background level

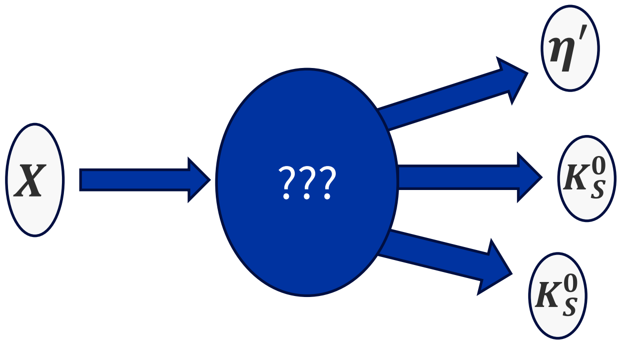
Mass spectra after final selection



[PRL 132 (2024) 181901]

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

Partial wave analysis (PWA)



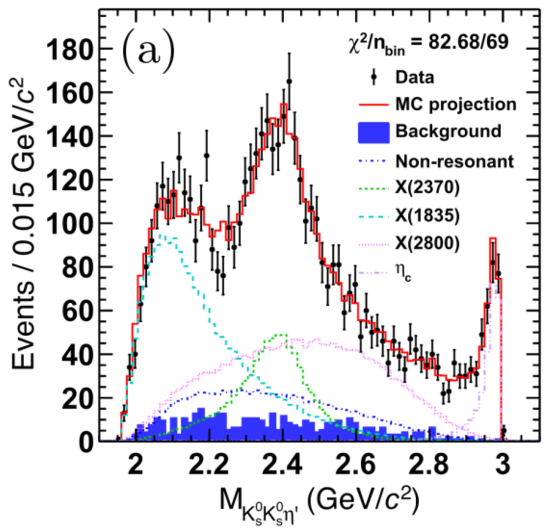
- PWA is a key tool to hadron spectroscopy
  - Input: four-momenta of the final-state particles
  - Measure the resonances' **spin-parity**, resonance parameters, production and decay properties, …

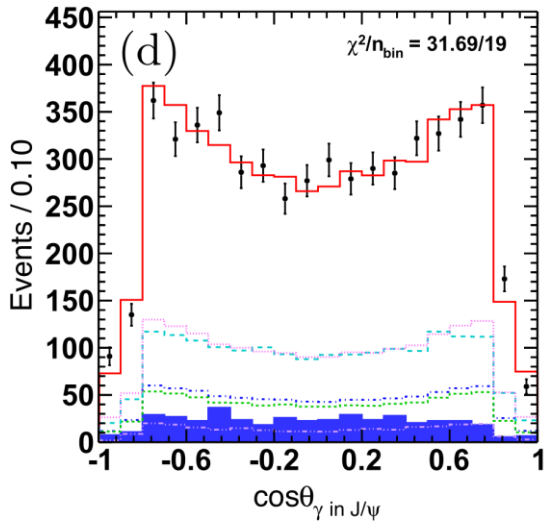
- PWA of $J/\psi \to \gamma K_S^0 K_S^0 \eta'$ is performed using **covariant tensor formalism** [1] . The signal amplitudes are parametrized as quasi-sequential two-body decays:
  - $J/\psi \to \gamma X, X \to Y\boldsymbol{\eta}', Y \to \boldsymbol{K_S^0 K_S^0}$ or $X \to Z\boldsymbol{K_S^0}, Z \to \boldsymbol{K_S^0 \eta}'$
    - ✓ 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^{-+}	$\eta'(K^0_S K^0_S)_{S-wave}$	− − −	− − −	9.0σ
		$\eta'(K^0_S K^0_S)_{D-wave}$	− − −	− − −	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:

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

LQCD prediction on lightest pseudoscalar glueball:

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

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

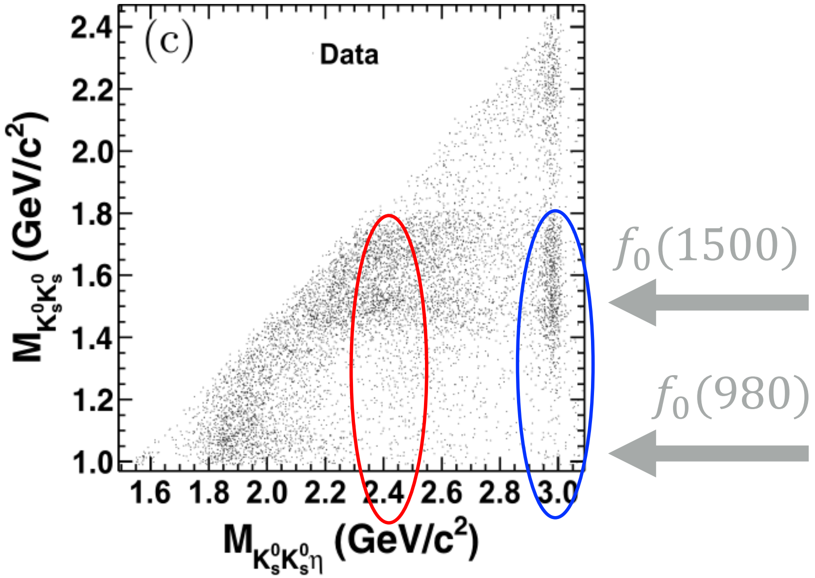
Journal: Phys. Rev. Lett. 115 (2015) 091803

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

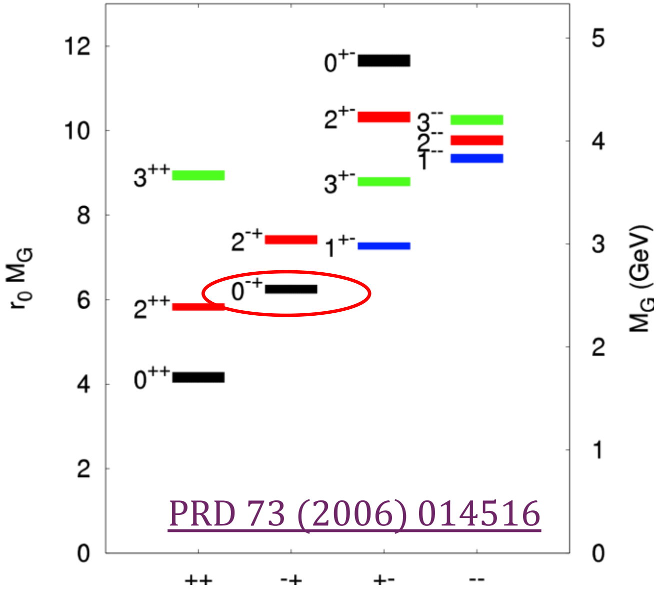
With 1.31B J/ψ events

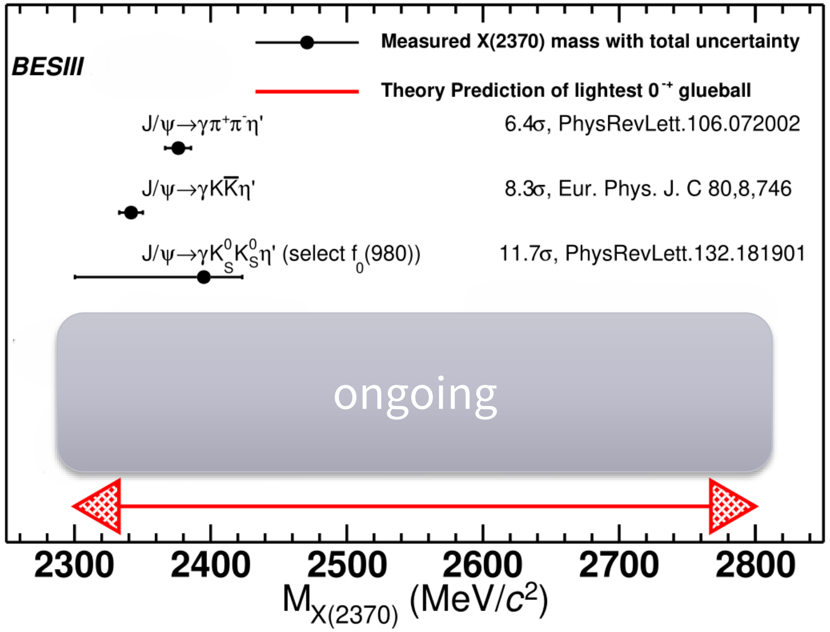
- In the upper $M(K_S^0 K_S^0)$ mass band of 1.5-1.7 GeV range, clear signals of both $X(2370)$ and η_c.
- In the lower $M(K_S^0 K_S^0)$ mass band of $f_0(980)$, no $X(2370)$, nor η_c.



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

Discovery of a Glueball-like Particle: $X(2370)$





- **Only one 0^{-+} resonance observed** with mass, spin-parity, production rate and decay property consistent to 0^{-+} glueball expectation
  - In the mass range of 2.3 - 2.8GeV: consistent with LQCD prediction
  - Production rate in the J/ψ **radiative decays**: : consistent with LQCD prediction
  - Decay property like η_c: two **favorite decay modes** decay modes of $\pi^+\pi^-\eta'$ and $K\bar{K}\eta'$

Summary

➢ Glueballs are important predictions from LQCD:

- Unique particles formed by gluons (force carriers) due to self-interactions of gluons

➢ The $X(2370)$ is the first particle that matches the theoretical expectations for a glueball

- $J^{PC} = 0^{-+}$
- Measurements and predictions on mass are consistent within uncertainties
- observed in J/ψ radiative decay and its production rate meets expectation
- flavor symmetric decay modes (favorite decay modes of 0^{-+} glueball)

——Glueball-like particle, $X(2370)$ is discovered by BESIII

Prospects

- More decay modes of the $X(2370)$: check the similarities with η_c to understand the decay pattern of this glueball-like particle

5 typical η_c decay modes (from PDG) ——
5 "Golden" modes in 0^{-+} glueball searches

Decays involving hadronic resonances

Γ_1	$\eta'(958)\pi\pi$	(1.87 ± 0.26) %	Observed: RPL 106 (2011) 072002; Eur. Phys. J. C 80, 746 (2020); PRL 132 (2024) 181901
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) %	Ongoing
Γ_{35}	$K\overline{K}\eta$	(1.32 ± 0.15) %	Seen PRL 115 (2015) 091803
Γ_{36}	$\eta\pi^+\pi^-$	(1.7 ± 0.5) %	Ongoing

- Improve the measurements on $X(2370)$'s mass, width, branching ratio and production rates
- Close collaboration between theory and experiment. Looking forward to more reliable LQCD studies on the glueball properties and Light Meson spectroscopy

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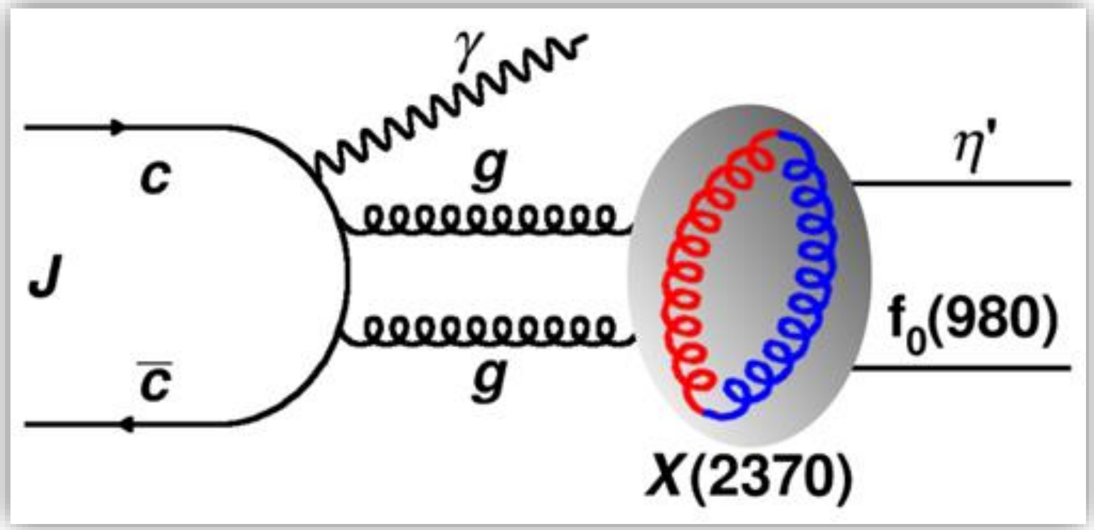

Thanks!

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