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

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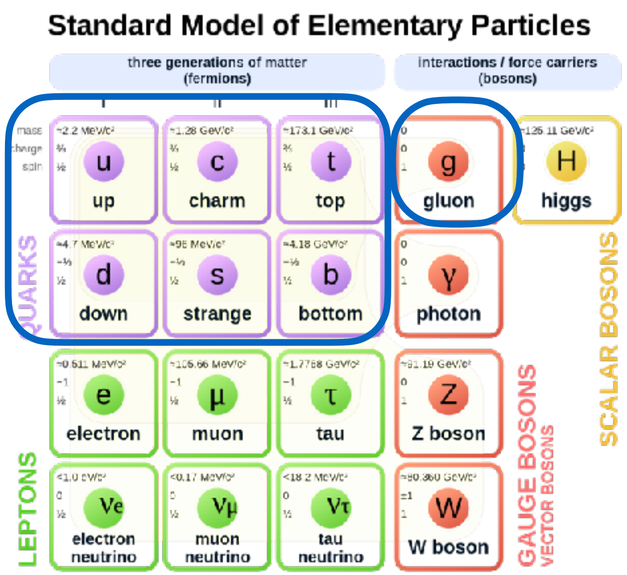
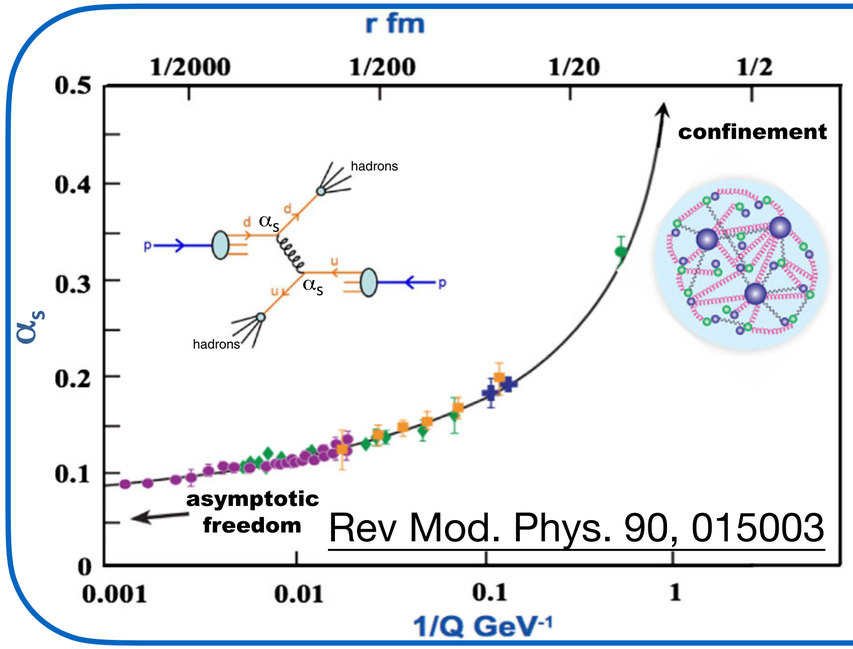
30th Sep. 2025, Mini-Workshop on light hadrons

Fundamental Structure of Matters



- **SM well describes fundamental structure of Matters, including EW and strong interactions**
  - **Gluons mediate strong interactions**
  - **QCD (SU(3) non-Abel gauge theory) is the basic theory for strong interaction**
- **Hadron spectroscopy can provide us clues for the understanding of fundamental structure via the hadron property study**



Rev Mod. Phys. 90, 015003

QCD predictions

- **High Energy:**
  - α_s running, widely confirmed experimentally (Nobel Prize 2004)
- **Low Energy:**
  - Self-interaction of gluons → **Glueballs**

Glueballs

◈ **Special Importance of Glueballs**： **Glueballs to QCD is just as important as Higgs Boson to EW**

- ✦ **Unique particle made of pure force (bosons)**
- ✦ **Direct proof of self-interactions of gluons — Direct proof of non-Abel gauge interactions of QCD**
- ✦ **Direct proof of origin of mass from strong interactions**

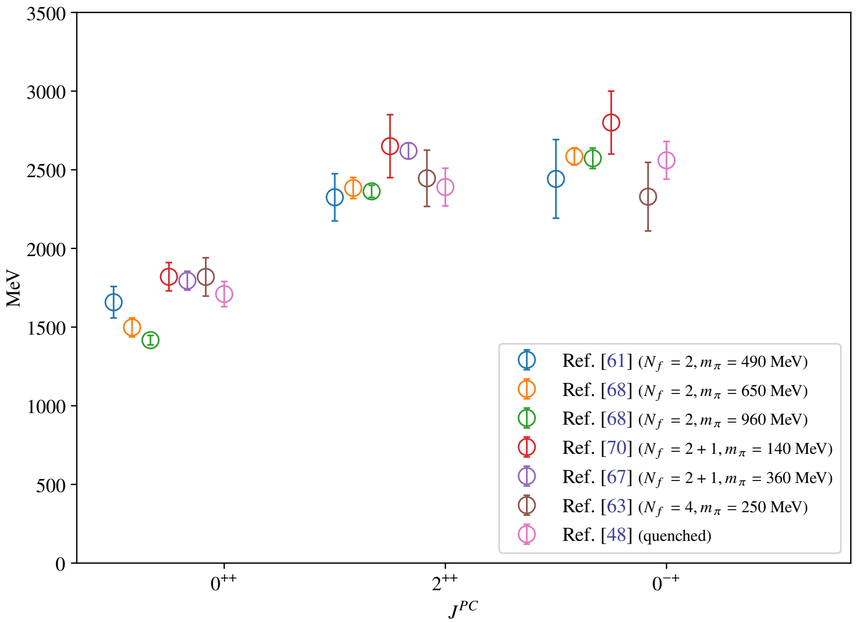
◈ **Lattice QCD** (LQCD) is a non-perturbative method from the first principles in theory.

◈ **Different lattice QCD groups** (including lattice simulations with dynamical quarks)

- ✦ Predictions on **masses and production rates** of pure glueballs
- ✦ Consistent results and expected to be reliable.

◈ **Lattice QCD predictions on glueball masses:**

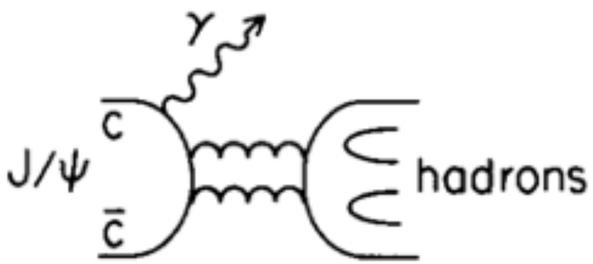
- ✦ **0^{++} ground state:** 1.5 - 1.7 GeV/c^2
- ✦ **2^{++} ground state:** 2.3 - 2.4GeV/c^2
- ✦ **0^{-+} ground state:** 2.3 - 2.6GeV/c^2



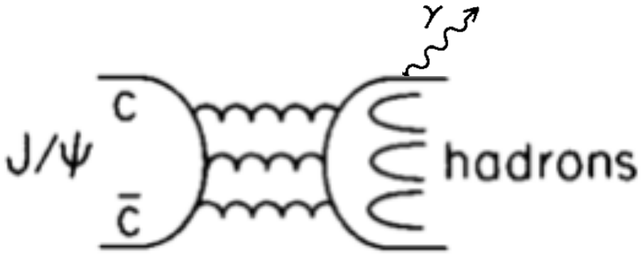
arxiv:2305.04869

Glueball production in J/ψ Radiative decay

◈ **Gluon rich environment**



$\sim \alpha\alpha_s^4$



$\sim \alpha\alpha_s^6$

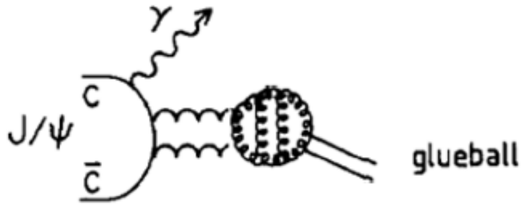
◈ **Isospin filter:** final states dominated by **I=0** processes

◈ **Spin-parity filter:** **C parity must be +**, so $J^{pc}=0^{-+}, 0^{++}, 1^{++}, 2^{++}, 2^{-+}$ …

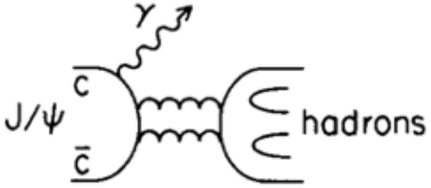
◈ **Clean environment in e^+e^- collision:** very different from **p-p collision**

◈ **Rich glueball production in J/ψ radiative decays:**

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



$\sim \alpha\alpha_s^2$

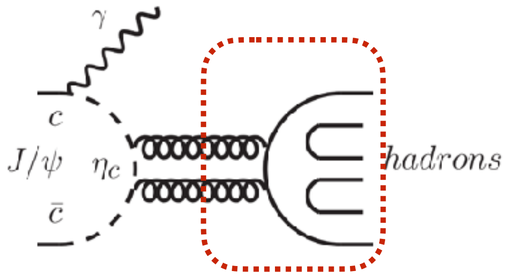


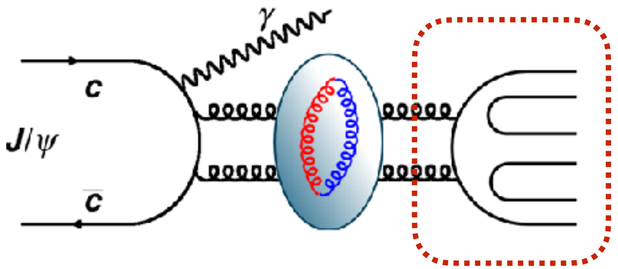
$\sim \alpha\alpha_s^4$

➡ **J/ψ Radiative decay is an ideal place to search for glueballs**

Glueball Decays

- **Flavor symmetric decays**
- **No rigorous predictions on decay patterns and their branching ratios**
- The glueball decays could be the analogy to **Charmonium decays** since they all decay via gluons (OZI suppression) [PLB 380 189(1996), Commu. Theor. Phys. 23.373 (1995)]
  - e.g. the 0^{-+} glueball could have similar decays of η_c

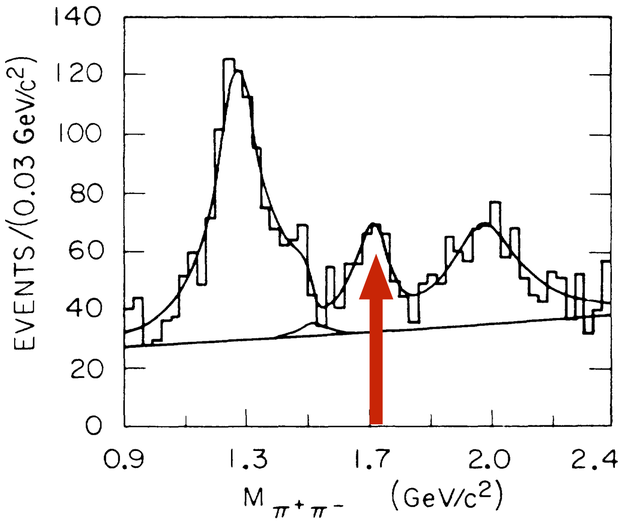


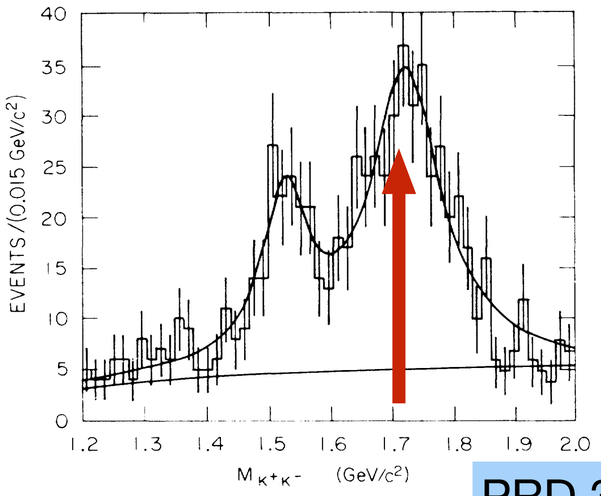


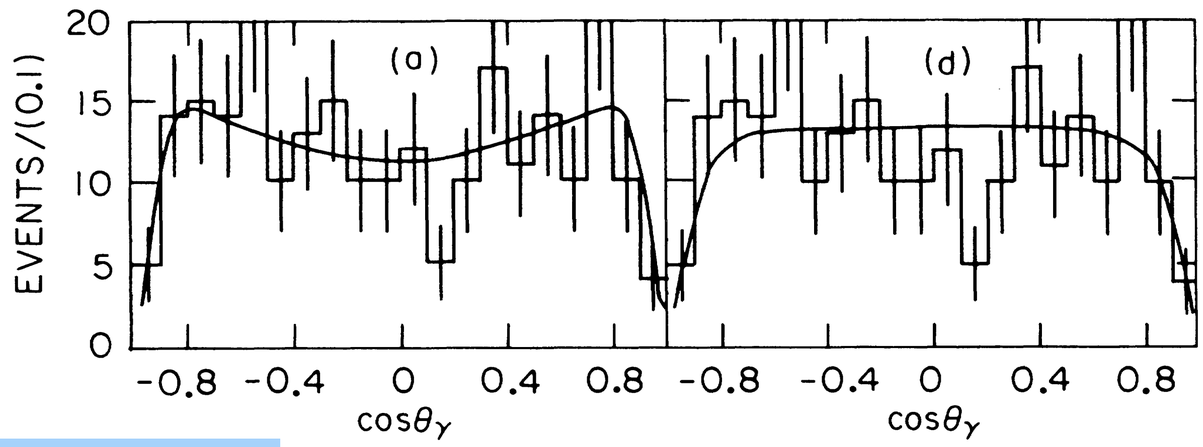
Historical Glueball Candidates

- **Many experiments searched for glueballs over the past 4 decades**
- **Many historical glueball candidates**, but with some **difficulties/controversies.**
  - **Scalar Glueball candidate (0^{++})**： $f_0(1500)$, $f_0(1710)$
  - **Tensor Glueball candidate (2^{++})**: $f_2(2340)$
  - **Pseudoscalar Glueball candidate (0^{-+}):** $\eta(1405)$

Historical Glueball Candidates — Scalar $f_0(1710)$



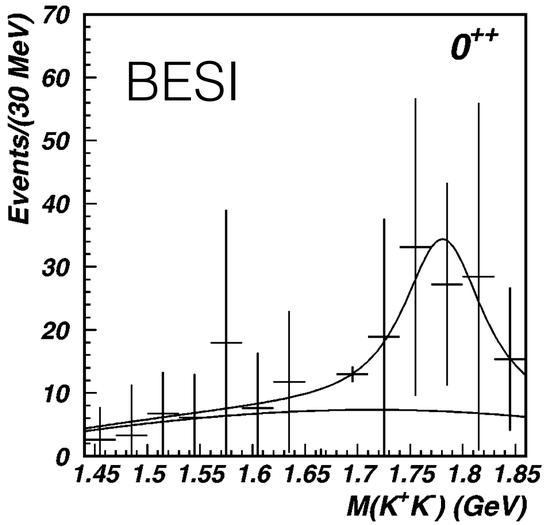




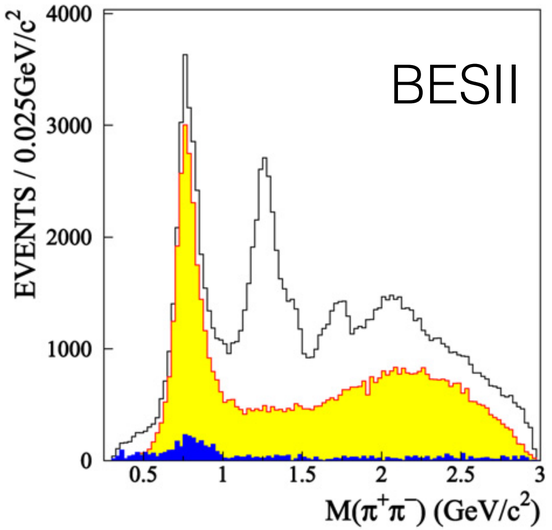
PRD 35 (1987) 2077

- The $f_0(1710)$ was discovered in **$J/\psi \to \gamma\pi^+\pi^-$ and $J/\psi \to \gamma K^+K^-$ by MarkIII** in 1987 as $\theta_2(1720)$
  - **$J^{pc} = 2^{++}$ from a simple fit to the angular distribution**
  - **The significance of 2^{++} state is ~3σ better than 0^{++} assumption**

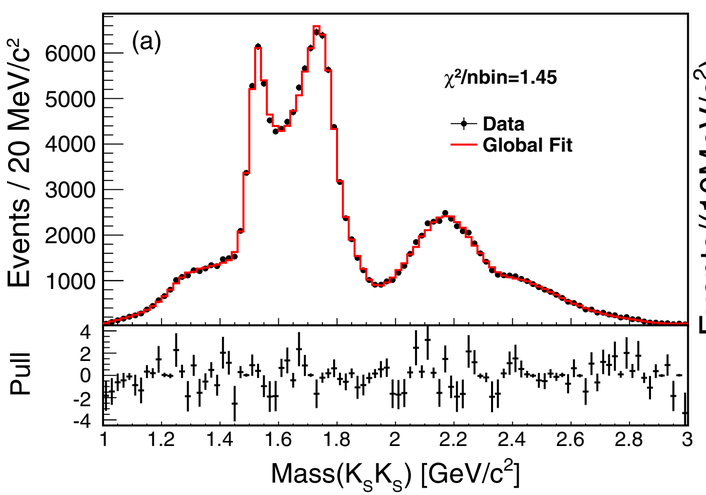
Historical Glueball Candidates — Scalar $f_0(1710)$



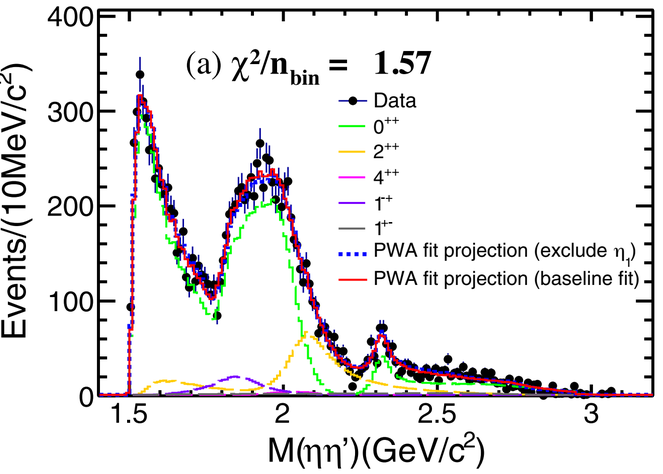
PRL 77(1996) 19



PLB 642 (2006) 441



PRD 98 (2018) 072003



PRD 106 (2022) 072012

- The $f_0(1710)$ **was firstly changed to be 0^{++}** from a full PWA of J/ψ→ γKK @ BESI. Lots of studies at MarkII, DM2, BESI,BESII, BESIII
- The $f_0(1710)$ favors to be **a scalar glueball or large glueball content**: **controversy of dynamic mixing mechanism**

✦ **High production rate of J/ψ→ γ$f_0(1710)$**

$$B[J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi] = (4.0 \pm 1.0) \times 10^{-4}$$

BESII: PLB 642 (2006) 441

$$B[J/\psi \to \gamma f_0(1710) \to \gamma K_s^0 K_s^0] = (2.00^{+0.03}_{-0.02}\ ^{+0.31}_{-0.10}) \times 10^{-4}$$

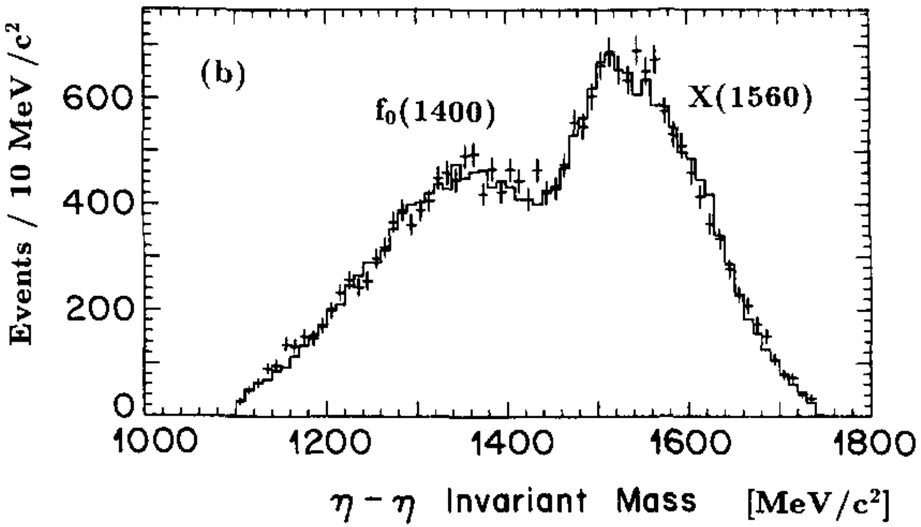
BESIII: PRD 98 (2018) 072003

✦ **Decay suppression in $f_0(1710)$→ ηη'**

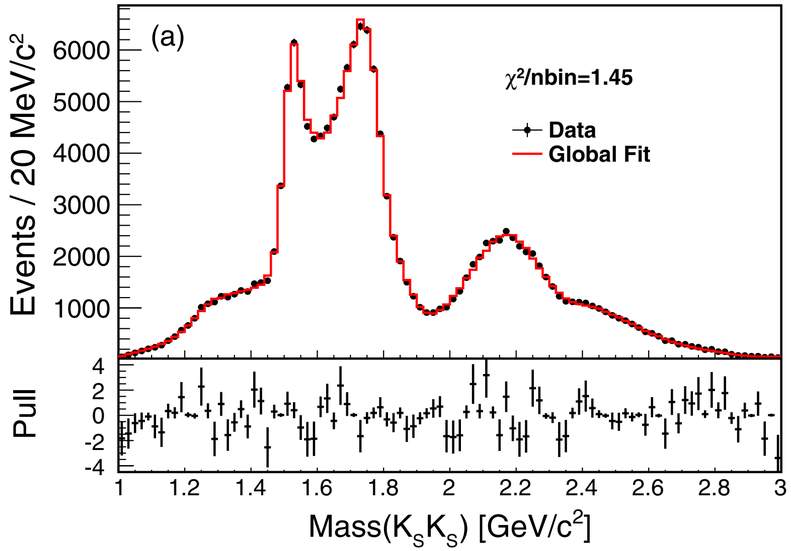
$$B[f_0(1710) \to \eta\eta'/f_0(1710) \to \pi\pi] < (2.9 \pm^{+1.1}_{-0.9}) \times 10^{-3}$$

BESIII: PRD 106 072012(2022)

Historical Glueball Candidates — Scalar $f_0(1500)$



PLB 291 (1992) 347



PRD 98 (2018) 072003

- The $f_0(1500)$ was discovered by Crystal Barrel in 1992
  - An unique 0^{++} candidate since $f_0(1710)$ was f_2 at that time
- **Disfavors to its interpretation of a scalar glueball**

Lower production rate of J/ψ→ γ$f_0(1500)$

$$B[J/\psi \to \gamma f_0(1500) \to \gamma K_s^0 K_s^0] = (1.59^{+0.16\ +0.18}_{-0.16\ -0.56}) \times 10^{-5}$$
$$B[J/\psi \to \gamma f_0(1710) \to \gamma K_s^0 K_s^0] = (2.00^{+0.03\ +0.31}_{-0.02\ -0.10}) \times 10^{-4}$$

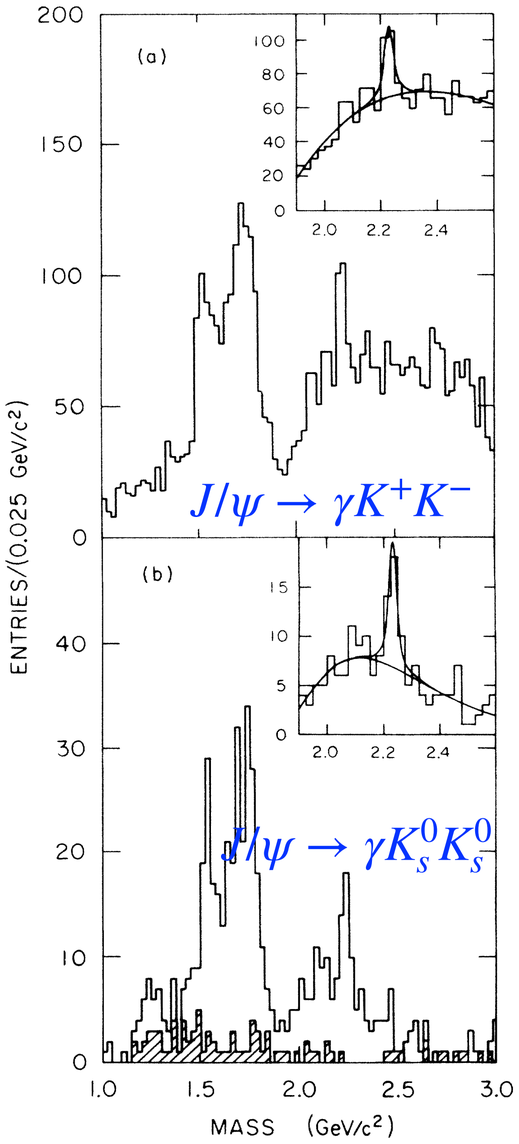
BESIII: PRD 98 (2018) 072003

No strong suppression in $f_0(1500)$→ ηη'

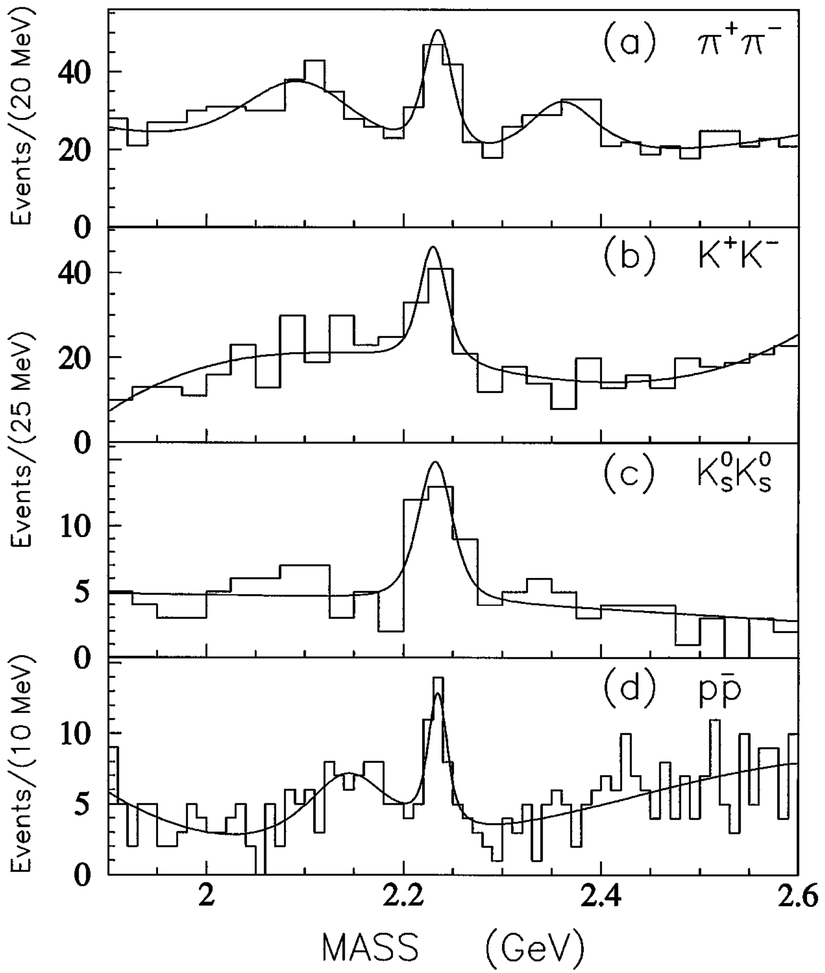
$$B[f_0(1500) \to \eta\eta'/f_0(1500) \to \pi\pi] = (1.66 \pm^{+0.42}_{-0.40}) \times 10^{-1}$$
$$B[f_0(1710) \to \eta\eta'/f_0(1710) \to \pi\pi] < (2.9 \pm^{+1.1}_{-0.9}) \times 10^{-3}$$

BESIII: PRD 106 072012(2022)

Historical Glueball Candidates — Tensor ξ(2230)



PRL 56 (1986) 107



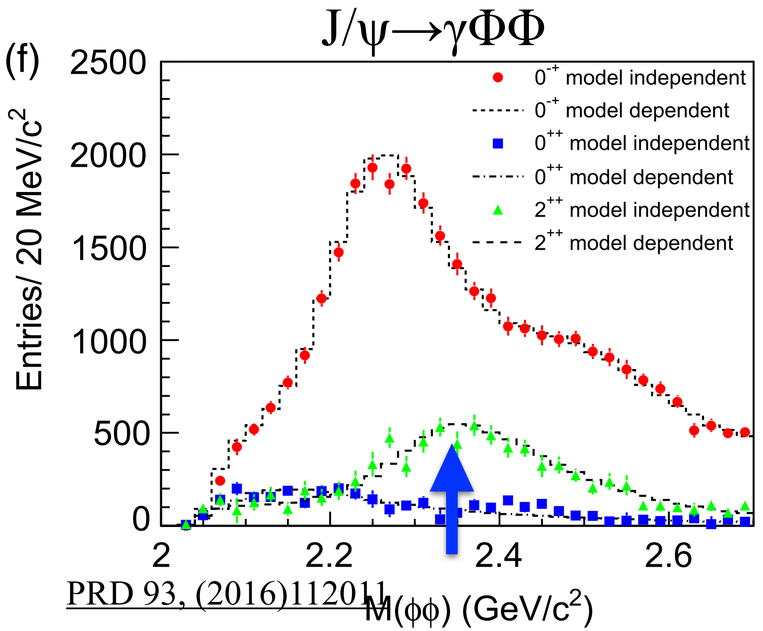
PRL 76 (1996) 3502

- First observed by MarkIII is J/ψ→ γKK in 1980's, then by BESI in 1990's in J/ψ → γKK, γππ, $\gamma p\bar{p}$ with very narrow mass peak.
- It was a tensor glueball candidate due to good flavor symmetric decay property.
- Difficulty: it was not confirmed by BESII, nor BESIII with much higher statistics.

Historical Glueball Candidates — Tensor $f_2(2340)$

$$\Gamma(J/\psi \to \gamma G_{2^+}) = 1.01(22) keV$$
$$\Gamma(J/\psi \to \gamma G_{2^+})/\Gamma_{tot} = 1.1 \times 10^{-2}$$

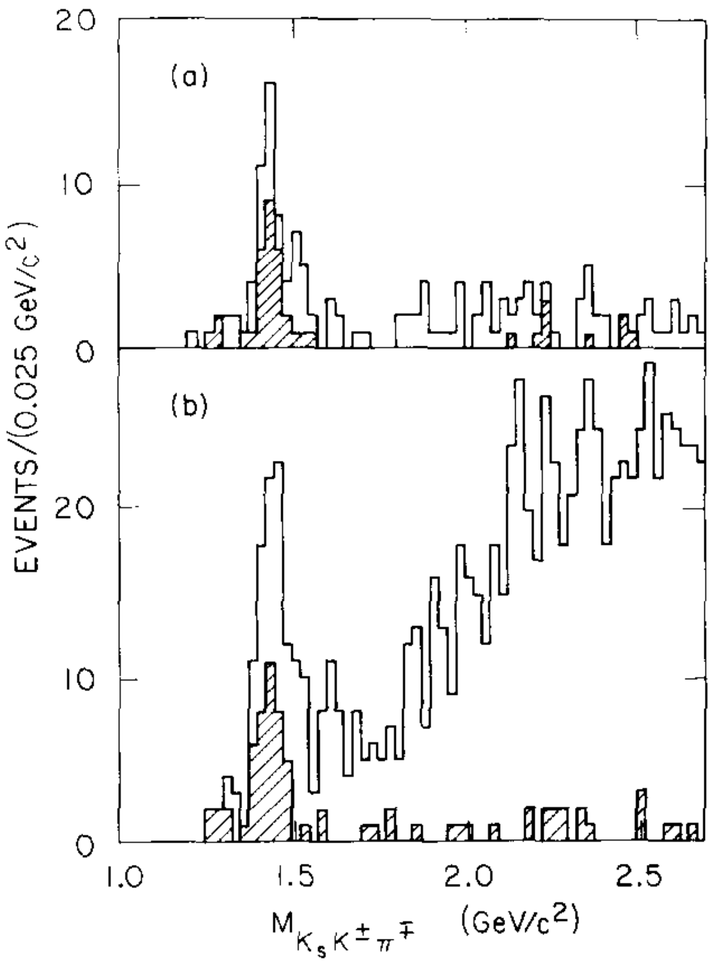
CLQCD, Phys. Rev. Lett. 111, 091601 (2013)



- **Large production rate of $f_2(2340)$ in** J/ψ→γ(KK/ηη/η'η'/φφ)**:** substantially lower than the LQCD prediction for tensor glueball
  - B(J/ψ→$\gamma f_2(2340)$→$\gamma\eta\eta$) = $(3.8^{+0.62}_{-0.66}\ ^{+2.37}_{-2.07}) \times 10^{-5}$ (PRD 87,2013,092009)
  - B(J/ψ→$\gamma f_2(2340)$→$\gamma\phi\phi$) =$(1.91 \pm 0.14^{+0.72}_{-0.73} \times 10^{-4}$ (PRD 93,2016,112011)
  - B(J/ψ→$\gamma f_2(2340)$→$\gamma K_s K_s$) =$(5.54^{+0.34}_{-0.40}\ ^{+3.82}_{-1.49} \times 10^{-5}$ (PRD 98,2018,072003)
  - B(J/ψ→$\gamma f_2(2340)$→$\gamma\eta'\eta'$) =$(8.67 \pm 0.70^{+0.16}_{-1.67} \times 10^{-6}$(PRD 105,2022,072002)
- **Difficulty: Many wide tensor mesons and large overlaps in the mass region of 2.3GeV** (2^{++} glueball mass from the LQCD predictions)
  - Studies are strongly model dependent.

Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. ($\times 10^{-4}$)	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

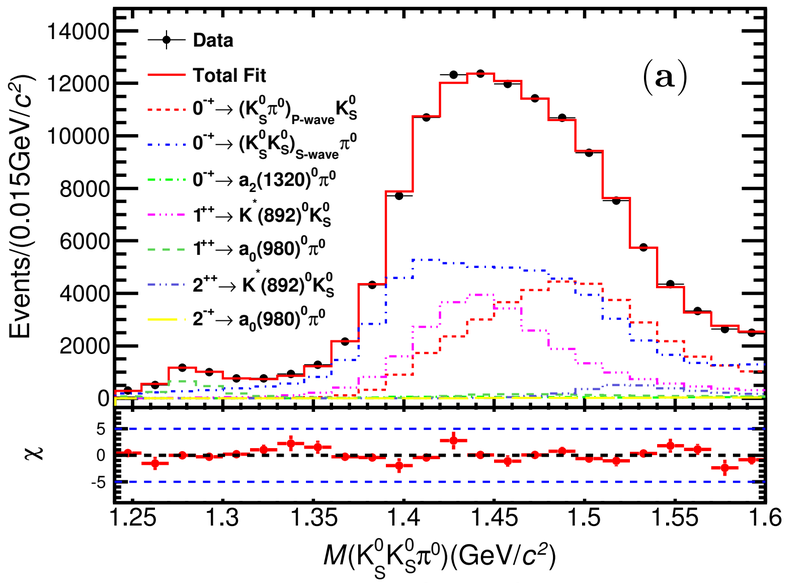
Historical Glueball Candidates — Pseudoscalar η(1405)



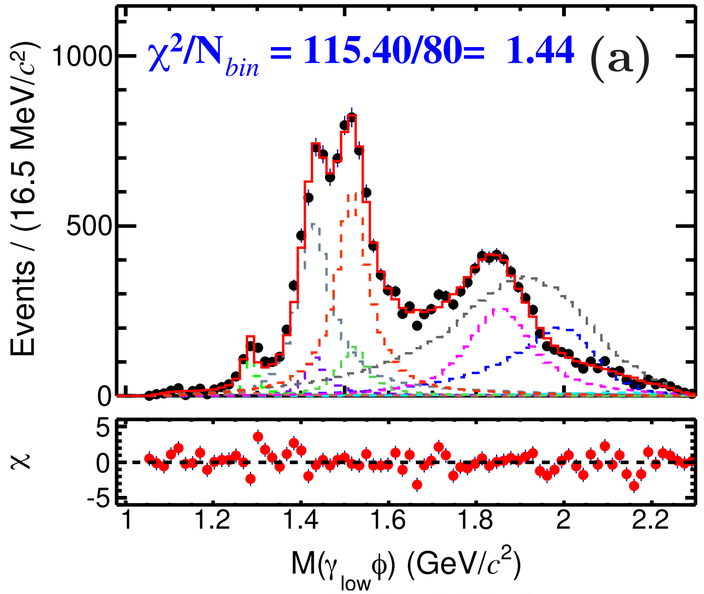
Phys. Lett. 97B (1980) 2

- First discovered by MarkII in 1980, named as η(1440) with complicated structures.
  - Believed as the first glueball candidate due to its large production rate in J/ψ radiative decays
- Lots of studies at MarkII, MarkIII, DM2 and BES:
  - **No longer a 0^{-+} glueball candidate due to its large different mass from latest LQCD prediction** (Lack of reliable LQCD predictions in 1980's)

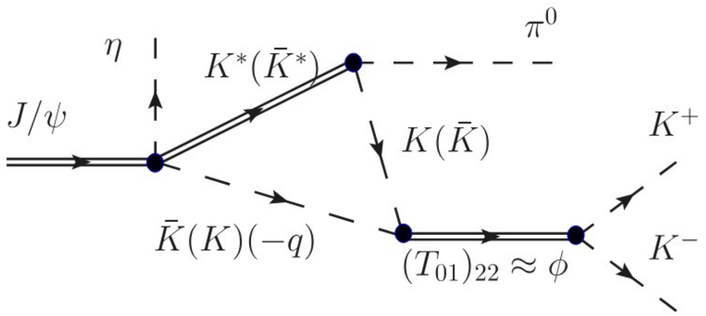
Shed new lights on $\eta(1405)/\eta(1475)$ puzzle



JHEP 03 (2023) 121



arxiv: 2401.00918



Triangle sigularity?

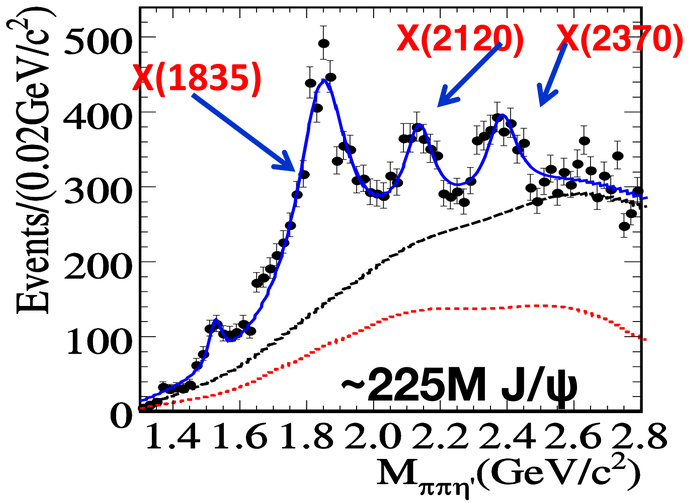
- η(1295) and η(1475) are generally assigned to be the first radial excitation of the ground states of η and η'
  - η(1405) - η(1475) puzzle :Whether or not the η(1405) - η(1475) are 1 or 2 states?
- PWA of J/ψ→γKsKsπ⁰: Two isoscalar states η(1405) and η(1475) around 1.4GeV can well fit data
- PWA of J/ψ→γγΦ： observed η(1405) with 18.9σ, while η(1475) can not be excluded (3.9σ)

X(2370)

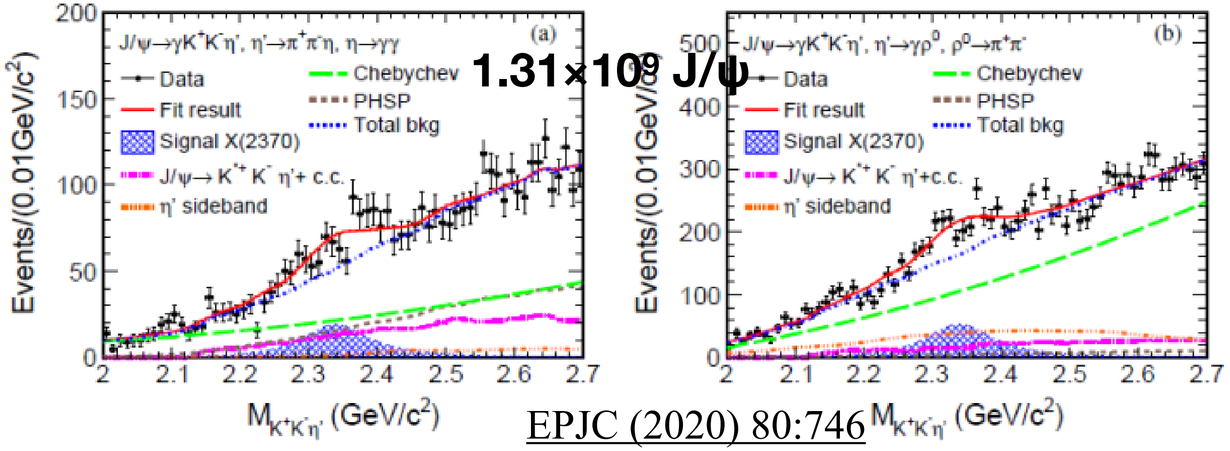
- **Discovered by BESIII in $J/\psi \to \gamma\pi^+\pi^-\eta'$ in 2011**

	M(MeV/c²)	Γ(MeV/c²)	Sig.
X(1835)	$1836.5\pm3.0^{+5.6}_{-2.1}$	$190.1\pm9.0^{+38}_{-36}$	>20σ
X(2120)	$2122.4\pm6.7^{+4.7}_{-2.7}$	$83\pm16^{+31}_{-11}$	7.2σ
X(2370)	$2376.3\pm8.7^{+3.2}_{-4.3}$	$83\pm17^{+44}_{-6}$	6.4σ

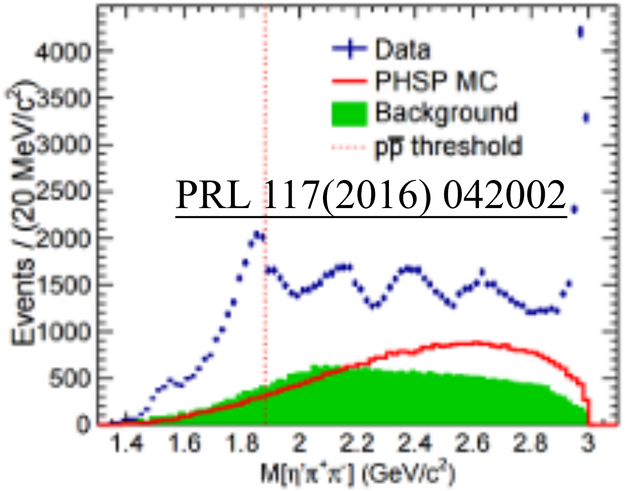
PRL 106, 072002 (2011)



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



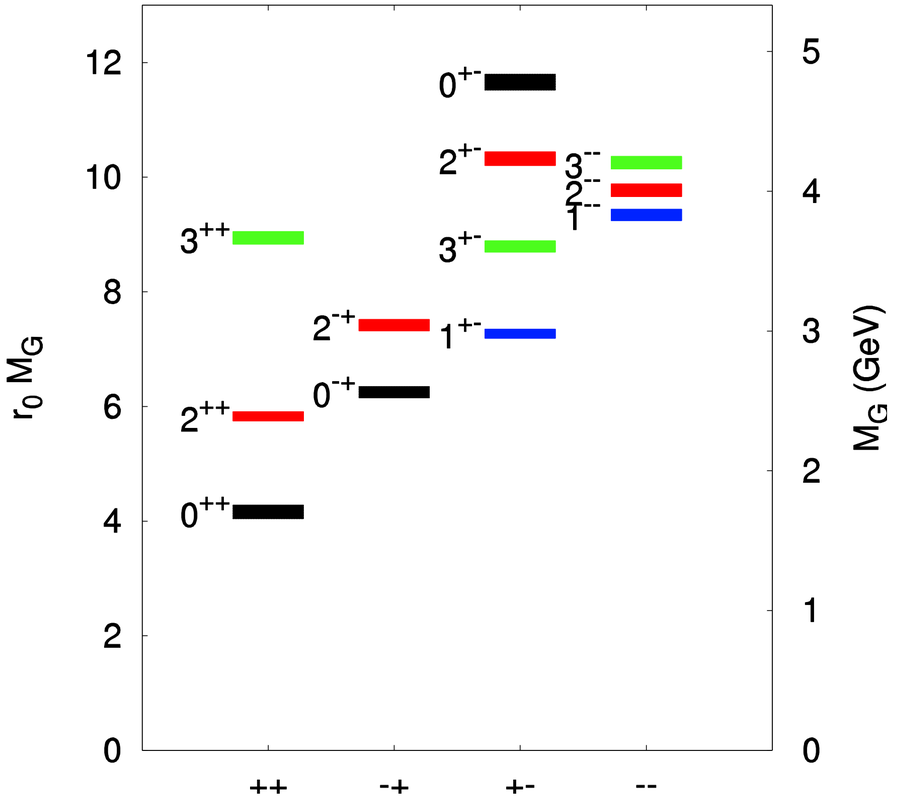
EPJC (2020) 80:746



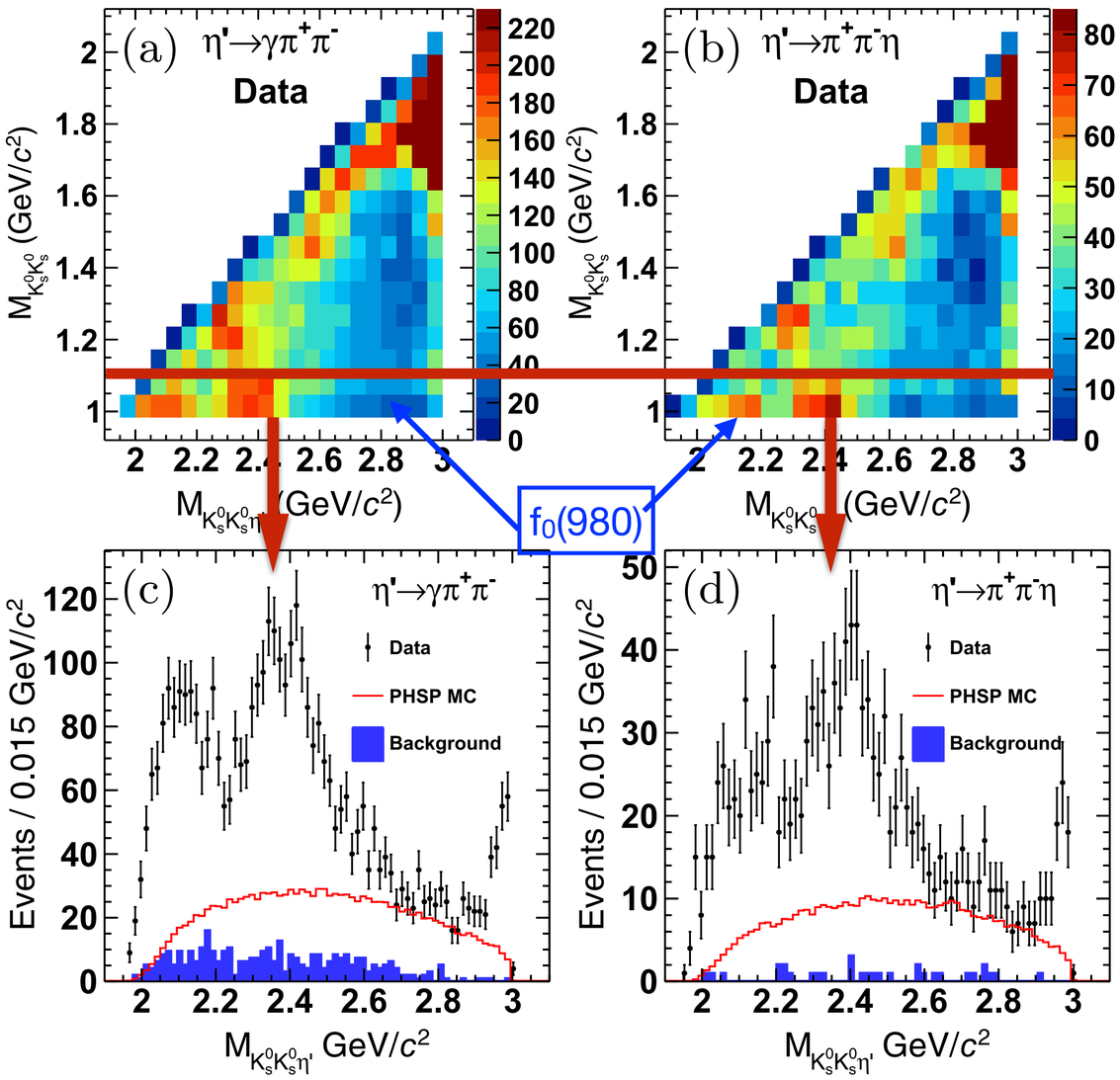
PRL 117(2016) 042002

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

- Its mass is consistent with LQCD prediction on the 0^{-+} glueball
- Produced in the gluon-rich J/ψ radiative decays
- Observed in 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



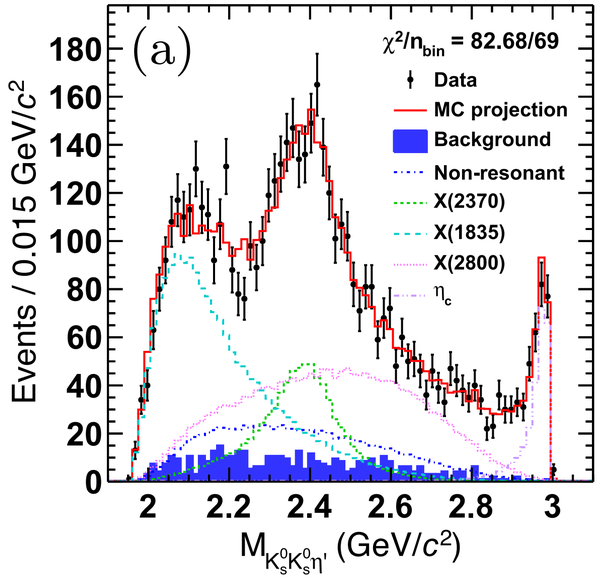
Spin-Parity determination of the X(2370) in $J/\psi\to\gamma K^0_S K^0_S \eta'$



PRL 132 (2024) 181901

- Analysis advantage of $J/\psi\to\gamma K^0_S K^0_S \eta'$:
  - Almost background free channel (exchange symmetry and C-parity conservation)
  - 10billion J/ψ data
  - Very good BESIII detector performance
- Similar structures in $\eta'\to\pi^+\pi^-\eta$ / $\gamma\pi^+\pi^-$ modes:
  - Evident $f_0(980)$ in $K^0_S K^0_S$ mass threshold
  - Clear signal of X(1835),X(2370),η_c with $f_0(980)$ selection
- Best PWA fit can well describe the data:
  - **Spin-parity of the X(2370) is determined to be 0^{-+}** with significance larger than **9.8σ w.r.t. other J^{PC} assumptions**

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



PRL 132 (2024) 181901

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Compared with LQCD prediction on Lightest 0^{-+} Glueball

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

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

$M = 2395 \pm 11^{+26}_{-94}$ MeV

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

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

LQCD prediction on lightest pseudoscalar glueball:

$J^{pc} = 0^{-+}$

$M = 2395 \pm 14$ MeV

$B(J/\psi\to\gamma G_{0^{-+}}) = (2.31 \pm 0.80)\times 10^{-4}$ PRD 100 (2019) 054511

- The measurements are in a good agreement 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 in a good agreement with LQCD predictions**
  - The estimation on $B(J/\psi\to\gamma X(2370))$ and prediction on $B(J/\psi\to\gamma G_{0^{-+}})$ are consistent within errors (assuming ~5% decay rate, $B(J/\psi\to\gamma X(2370)) = (10.7^{+22.8}_{-7})\times 10^{-4}$)

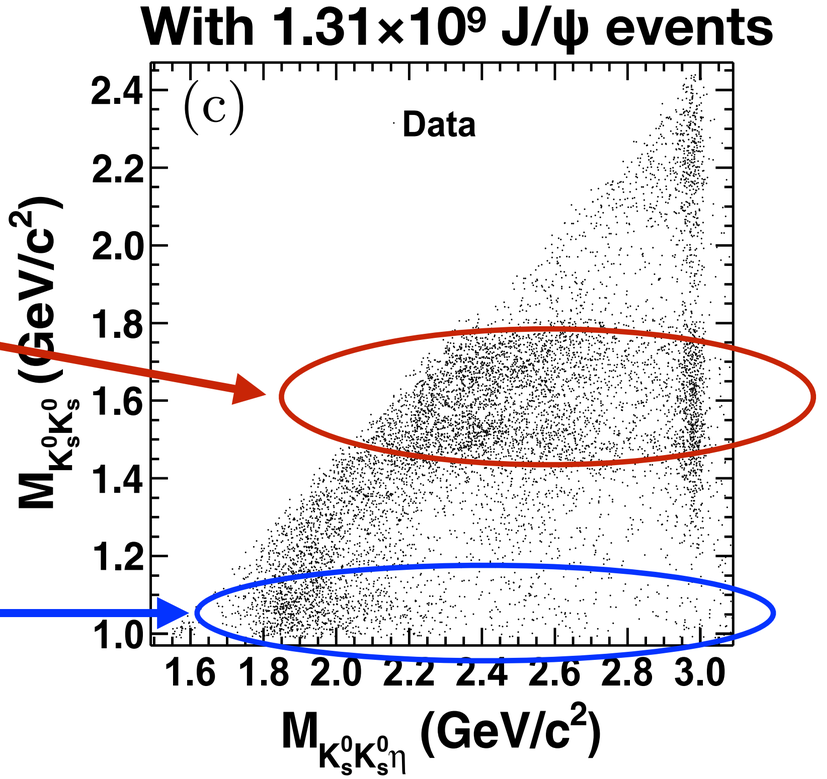
X(2370) in $J/\psi \to \gamma K^0_s K^0_s \eta$

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

Qualitatively, we can clearly observe: similar decay patterns of the X(2370) and η_c if phase space allows

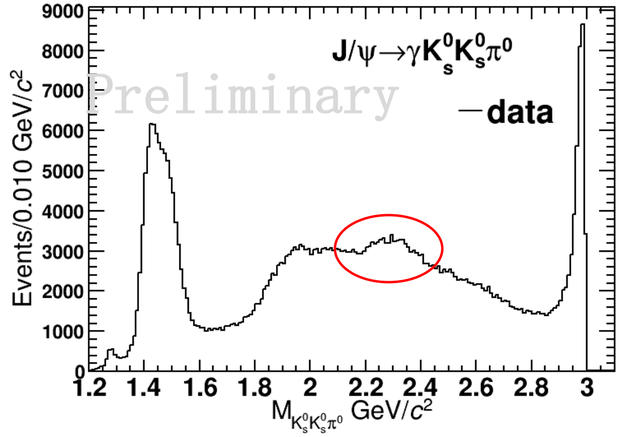
In the upper KK mass band of 1.5-1.7GeV range, clear signals of both X(2370) and η_c

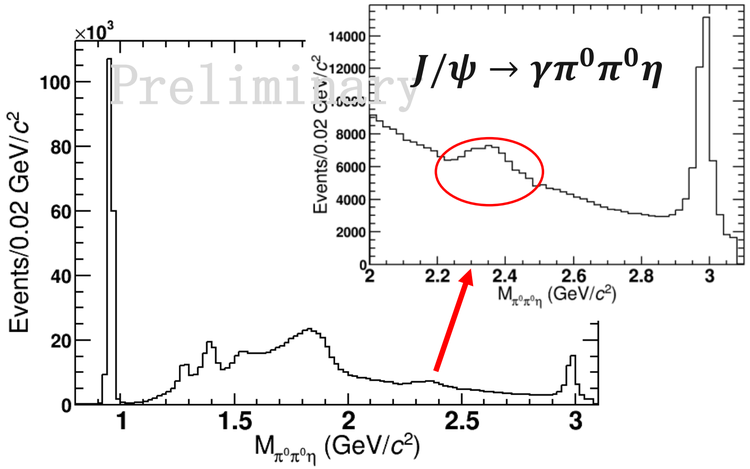
In the lower KK mass band of $f_0(980)$, no X(2370), nor η_c

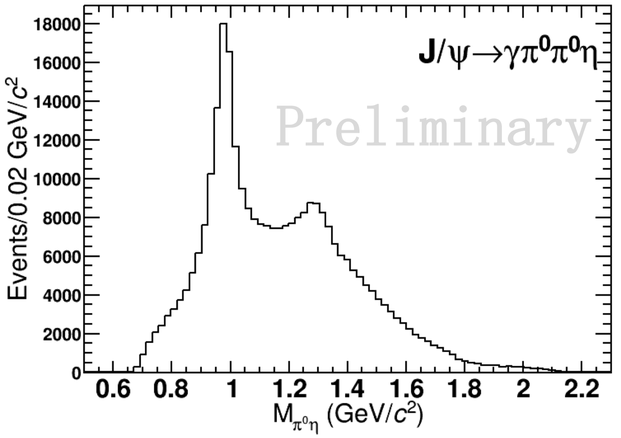


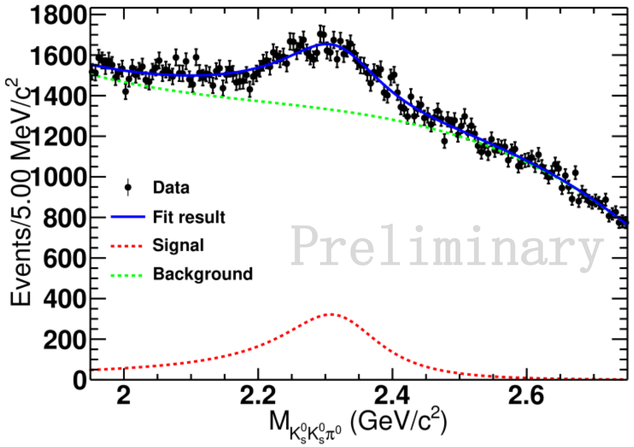
PRL 115 (2015) 091803

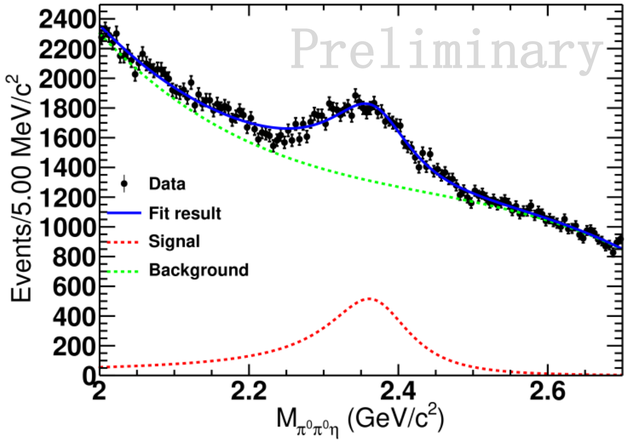
Observation of new decay modes of the X(2370)

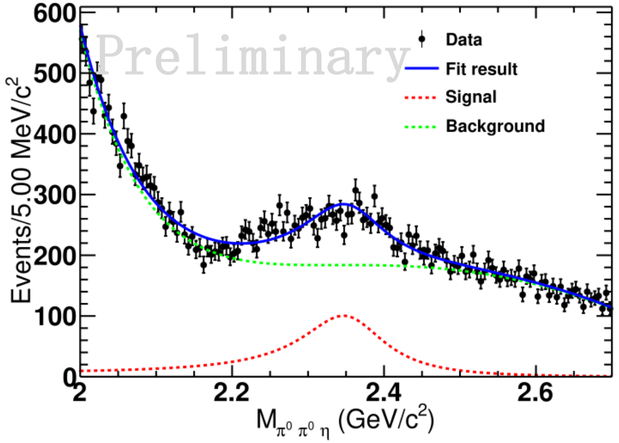












First observation of $X(2370) \to K_s^0 K_s^0 \pi^0$, $X(2370) \to \pi^0\pi^0\eta$ and $X(2370) \to a(980)\eta$ with **significances >> 5σ and accompanied with η_c**

Observation of the X(2370) in the 5 golden decay modes

5 major η_c decay modes (from PDG)
— 5 "Golden" modes in 0^{-+} glueball traditional 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) %

- **The 0^{-+} glueball decays could be the analogy to η_c decays**
  - **Decay modes of X(2370)$\rightarrow\pi\pi\eta'$,$K\bar{K}\eta'$,$K\bar{K}\pi$, $\pi\pi\eta$, $K\bar{K}\eta$, $a(980)\pi$ observed, consistent with 0^{-+} glueball**

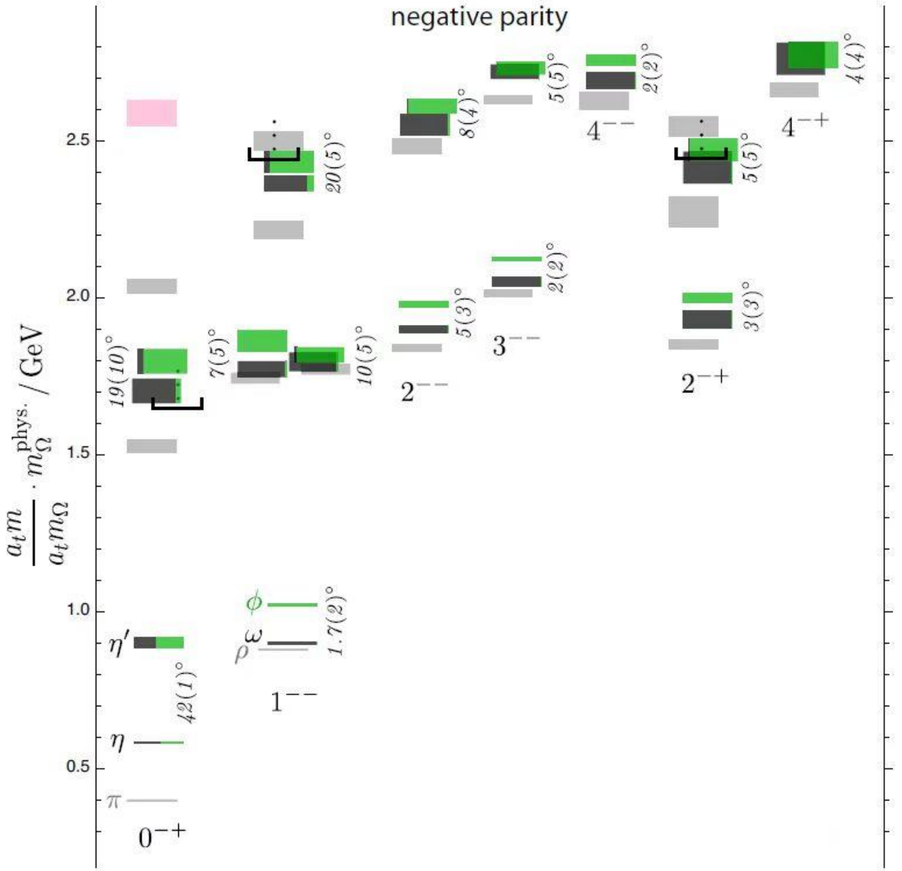
Such high similarity between the X(2370) and η_c decay modes strongly supports the glueball interpretation of the X(2370)

Discussion on X(2370) decay properties

- **Normal $q\bar{q}$ mesons, hybrids and multiquark states can hardly explain all 5 decay modes ($\pi\pi\eta'$, $KK\eta'$, $\pi\pi\eta$, $KK\eta$,$KK\pi$) with different quark flavor combinations.**

  - e.g., LQCD calculation shows that mixing between $u\bar{u} + d\bar{d}$ and $s\bar{s}$ components should be very small for 0^{-+} $q\bar{q}$ meson at ~ 2GeV

- **The high similarities between X(2370) and η_c decay modes strongly suggest it decays via gluons**



PRD 83 (2011) 11502

Narrow Decay Partial Widths of the X(2370)

- **For 5 golden PPP decay modes: similar number of events under the X(2370) peak**
  - **No dominant decay modes, similar to η_c**

- **Naive estimation on the BR of each mode ~5-10%, i.e., partial width of each decay modes is ~10MeV**

- **This would be very hard to be explained if there were quark content ($q\bar{q}$, qqg, multiquark) in X(2370) for OZI allowed decays**

  - Typically OZI allowed decay partial width ~100MeV

  - OZI allowed decays usually have dominant decay modes

- **X(2370) decays should be OZI suppressed decays as η_c, i.e., via gluons!**

Discussion on X(2370) properties — Production

- Richly produced in J/ψ radiative decays — just as glueball expectation

- In the above 2.3GeV mass region as LQCD 0^{-+} glueball prediction, X(2370) is the unique 0^{-+} particle produced in these “5 golden modes” and in J/ψ radiative decays, i.e., no other 0^{-+} particles in this mass region can be called as “richly produced” if they have not shown up in 10 billion such a huge J/ψ data sample.

  - **The production property shows that we only have one qualified candidate X(2370) for 0^{-+} glueball**

  - **We are facing a situation: Either we finally identify X(2370) as 0-+ glueball, or LQCD may face a big challenge in the glueball predictions —— similar to the situation before the Higgs boson discovery**

Summary

- **Glueballs are important predictions from LQCD:**
  - **Unique particles formed** by gluons (force carriers) due to non-Abelian Gauge self-interactions of gluons
- **The X(2370) observed in J/ψ radiative decays is the first particle consistent with 0^{-+} glueball**
  - **Spin-parity quantum numbers** are determined to be $J^{PC} = 0^{-+}$
  - Measurements and predictions on **mass and rich production rate** are consistent within errors
  - **Decay properties:** observation of 5 golden decay modes of $\pi\pi\eta', K\bar{K}\eta', K\bar{K}\pi, \pi\pi\eta, K\bar{K}\eta, a(980)\pi$ (in analogy to η_c)
  - — **Glueball-like particle, X(2370) is discovered by BESIII**

Golden decay modes in 0^{-+} glueball search

- **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^{++} meson decays — spin-parity filter
- **PP (2 pseudoscalar mesons) modes are mostly forbidden for 0^{-+} mesons**
- **VV (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

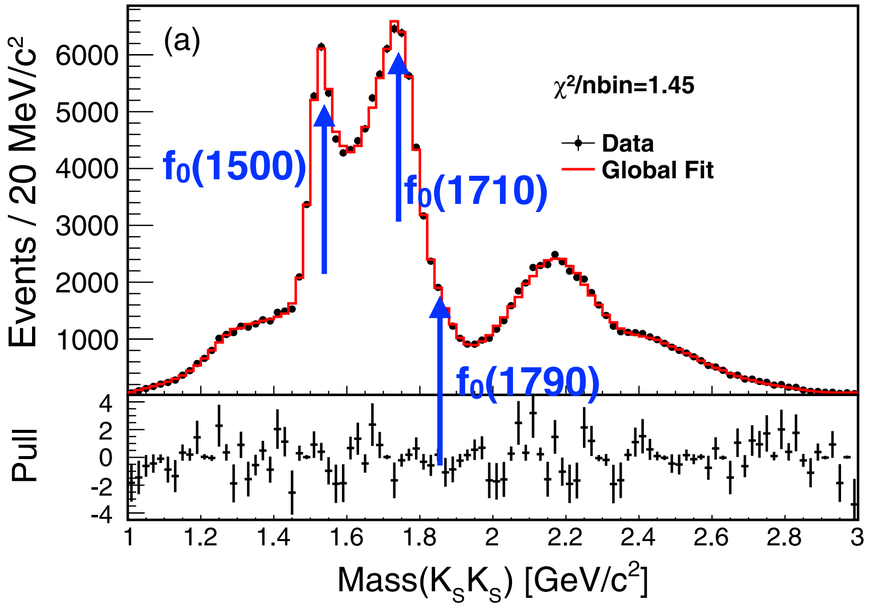
Interpretation

	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
- **Mass, spin-parity:** consistent with 0^{-+} glueball prediction

In the mass region larger than 2GeV, the only particle X(2370) for the 0^{-+} glueball candidate in J/ψ radiative decays and five golden decay modes ($\pi\pi\eta'$,$K\bar{K}\eta'$,$K\bar{K}\pi$,$\pi\pi\eta$, $K\bar{K}\eta$)

Historical Glueball Candidates — Scalar $f_0(1710)$



PRD 98 (2018) 072003

$$B[J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi] = (4.0 \pm 1.0) \times 10^{-4}$$

BESII: PLB 642 (2006) 441

$$B[J/\psi \to \gamma f_0(1710) \to \gamma K_S^0 K_S^0] = (2.00^{+0.03\ +0.31}_{-0.02\ -0.10}) \times 10^{-4}$$

BESIII: PRD 98 (2018) 072003

- **Controversy:** with PS subtraction, **$\Gamma(f_0(1710)\to\pi\pi:KK)=1:2.43$**, in contrast to the flavor symmetry property of a pure glueball
- **Difficulty:** needs to be understood from **first principle of QCD** (not just phenomenological understanding)
  - What causes the **flavor symmetric breaking**?
  - **Dynamic mixing mechanism**: mixing between $f_0(1500)$/$f_0(1710)$, or even with $f_0(1790)$

Improved situation in Glueball Searches

◈ **Experimentally:**

- ✦ **World largest J/ψ data sample : ~10 billion**
- ✦ **Physics channels with few background**
- ✦ **GPU technique helps to speed up PWA** [J.Phys.Conf. Ser. 219, 042031]
  - ✦ It takes a long time in PWA for the complicated interference and comprehensive test of different combinations

◈ **Theoretically:**

- ✦ **Guidance from η_c decays**
- ✦ Now we have prediction on **glueball production rate from LQCD:** $B(J/\psi \to \gamma G_{0^{-+}}) = 2.31 \pm 0.80 \times 10^{-4}$
- ✦ Luckily, for the X(2370), there is **no other 0^{-+} resonance nearby** (in ~200MeV range) in J/ψ radiative decays

Many thanks to the efficient work:
The BESIII detector maintenance and offline software teams, computing center
The BEPCII accelerator operation team which provide stable detector operation