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

金　山

for the BESIII Collaboration

南京大学

第四届强子与重味物理理论与实验联合研讨会

March 23, 2025

报告内容说明

- 与"J粒子发现50周年纪念大会"邀请报告内容基本一致

- 作为 Invited Review Article 刚刚投送 International Journal of Modern Physics A (IJMPA)

  arxiv: 2503.13286

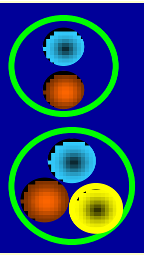
Multi-quark State, Glueball and Hybrid

- **Hadrons consist of 2 or 3 quarks：**

Naive Quark Model：

Meson（ q $\bar{q}$ ）

Baryon（q q q）



- **New forms of hadrons:**
  - **Multi-quark states： Number of quarks >= 4**
  - **Hybrids： q$\bar{q}$g， qqqg …**
  - **Glueballs： gg， ggg …**

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

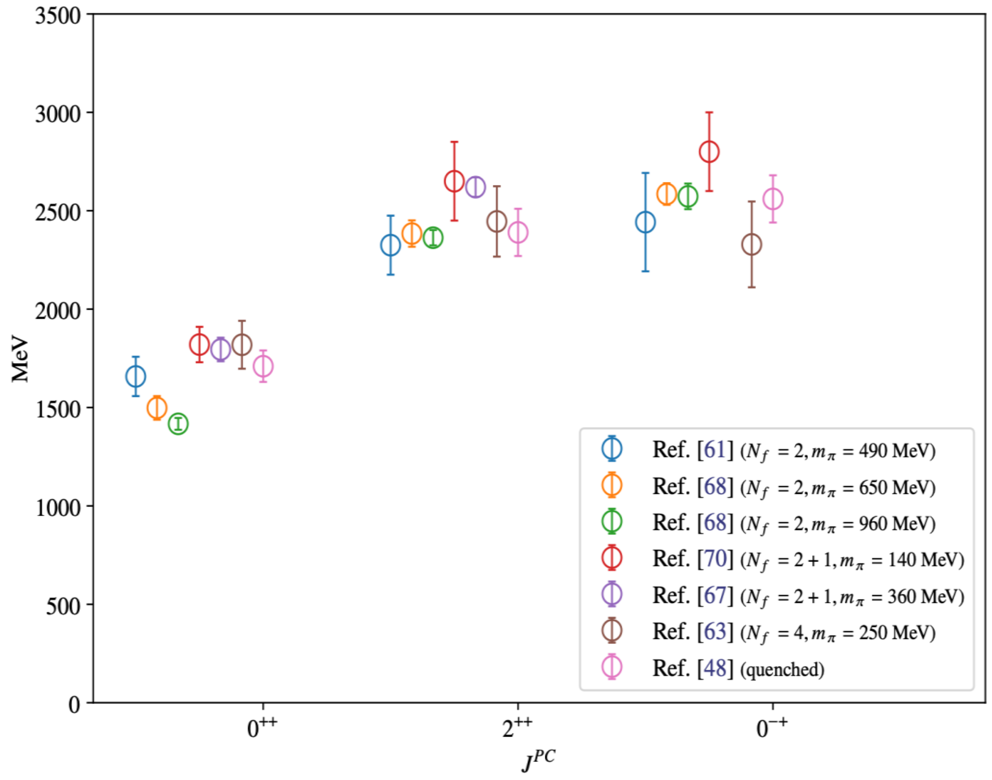
Glueballs

- **Unique particles formed by gauge bosons due to non-Abel self-interactions**
  - **Unique kind of matter made of pure force (usually matter formed by fermions)**
  - **Glueballs to QCD is just as important as Higgs boson to EW.**

→ Direct test of QCD and SM

- **Lattice QCD predictions**
  - **0^{++} ground state: 1.3~2 GeV/c^2**
  - **2^{++} ground state: 2.2~2.8 GeV/c^2**
  - **0^{-+} ground state: 2.3~2.8 GeV/c^2**

arxiv:2305.04869

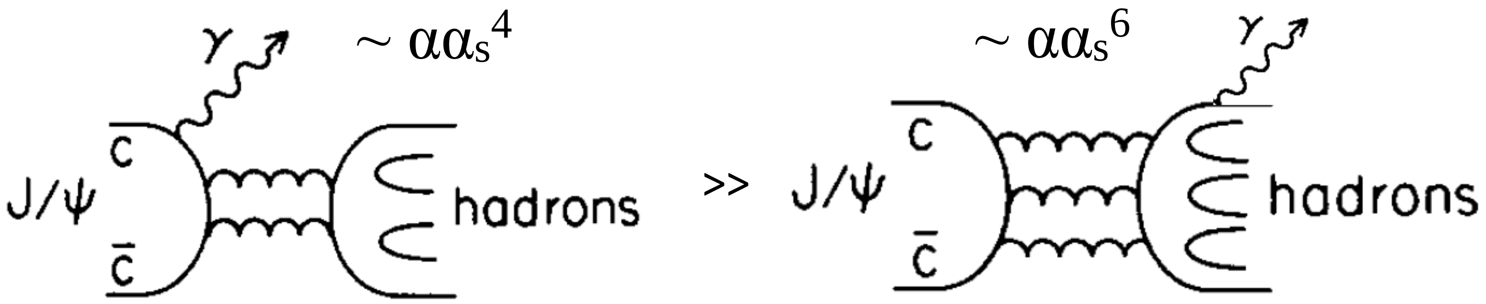


胶球的独特意义

- 唯一由玻色子组成的物质
- Unique particle made of pure force
  （简称“force particle”“力子”—— named by 王贻芳）
- 可见物质质量强相互作用起源的直接证明

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^{-+}…

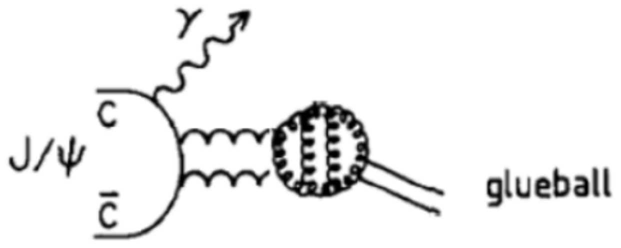
→Clean environment

very different from proton-antiproton collision processes

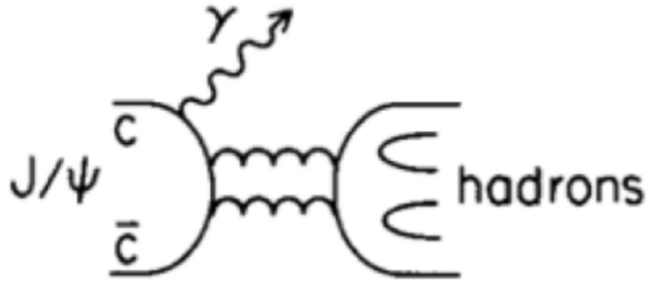
→ Ideal place to search for glueballs

Gueball Productions in J/ψ radiative decays

- Rich production in J radiative decays — glueball production rate in J radiative decays could be higher than normal hadrons.



$\sim \alpha \alpha_s^2$

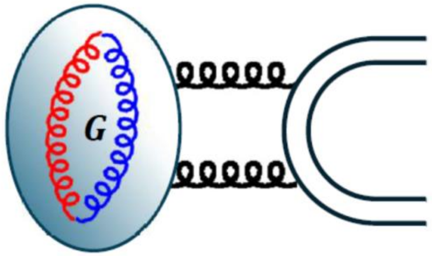


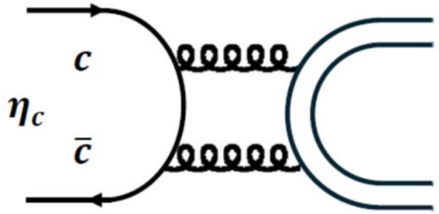
$\sim \alpha \alpha_s^4$

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

Gueball Decays

- via gluons
  - flavor symmetric decays
- No rigorous predictions on decay patterns and their branching ratios.
- The glueball decays could have similar decay patterns to the charmonium families since they all decay via gluons.
  - e.g. the 0^{-+} glueball could have similar decays to η_c
  - One of the largest decay modes of η_c is $\eta'\pi+\pi-$, so $J/\psi\rightarrow\gamma\eta'\pi+\pi-$ could be a good place to search for the 0^{-+} glueball.





Golden Decay Modes for 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, major decay modes
  - PPP modes are either forbidden or strongly suppressed in 0^{++}, 2^{++} mesons decays — spin-parity filter
- PP (2 pseudoscalar mesons) modes are 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
- Multi-pion modes
  - All J^{PC} mesons allowed, not a spin-parity filter
  - 0-+ mesons decay mainly via 2 body sequential decays, i.e., mainly via f2(1270), a1(1260) pair intermediate states — 0-+ glueball mass may not be high enough, i.e., PS is not allowed.

Historical Glueball Candidates

- 0^{++} scalar glueball candidates
  - $f_0(1710)$
    - Discovered by MarkII in 1980's as $\theta_2(1720)$ at beginning, only based on a fit to the angular distribution. Lots of studies at MarkII, DM2, BESI.
    - J^{pc} was fisrtly changed to 0^{++} at BESII based on a full PWA in $J/\psi \rightarrow \gamma KK$
    - With PWA, it was carefully studied at BESIII in $J/\psi \rightarrow \gamma KK, \gamma\pi\pi, \gamma\eta\eta, \gamma\eta\eta'$.
    - The high production rate of $J/\psi \rightarrow \gamma f_0(1710)$ and the suppression of $f0(1710) \rightarrow \gamma\eta\eta'$ measured from BESIII strongly support its interpretation as a scalar glueball or it has large glueball content if it is a mixture of glueball and normal meson.
    - Difficulty: With phase space subtracted, from BESII and BESIII measurements, we obtained $\Gamma(f_0(1710) \rightarrow \pi\pi : K\bar{K}) = 1:2.43$, which should be 1:1 for a pure glueball decays. What causes the flavor symmetry breaking needs to be understood from the first principles of QCD (not just phenomenological understanding).

- $B(J/\psi \rightarrow \gamma f_0(1710) \rightarrow \gamma\pi\pi) = (4.01 \pm 1.0) \times 10^{-4}$
  BESII: PLB 642 441 (2006)
- $B(J/\psi \rightarrow \gamma f_0(1710) \rightarrow \gamma K_s K_s) = (2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$
  BESIII: PRD 98 072003 (2018)
- $B(f_0(1500) \rightarrow \eta\eta')/B(f_0(1500) \rightarrow \pi\pi) = (1.66^{+0.42}_{-0.40}) \times 10^{-1}$
- $B(f_0(1710) \rightarrow \eta\eta')/B(f_0(1710) \rightarrow \pi\pi) < (2.9^{+1.1}_{-0.9}) \times 10^{-3}$
  BESIII: PRD 106 072012(2022)

两点困难：详见 2503.13286

Historical Glueball Candidates

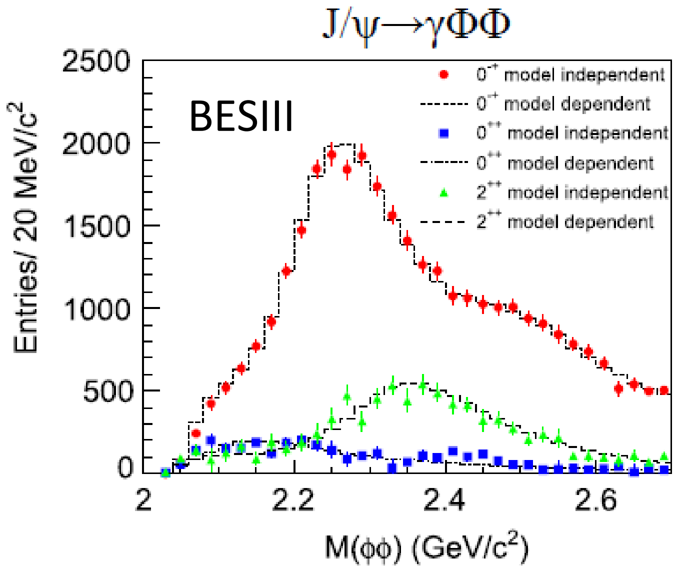
- 0^{++} scalar glueball candidates
  - $f_0(1500)$
    - Discovered by Crystal Barrel in 1990's as a unique 0^{++} candidate since $f_0(1710)$ was f_2 at that time.
    - Difficulty: compared with $f_0(1710)$, much lower production rate than $f_0(1710)$ disfavors its interpretation as a scalar glueball.
  - Mixing between f0(1500)/f0(1710), or even with f0(1790)?
    - Difficulty: dynamic mixing mechanism needs to be understood from the first principle of QCD (not just phenomenological understanding).

BESIII:

$$B(J/\psi \to \gamma f_0(1500)) \sim 0.29 \times 10^{-3}$$
$$B(J/\psi \to \gamma f_0(1710)) \sim 2.2 \times 10^{-3}$$

Historical Glueball Candidates

- 2^{++} Tensor Glueball Candidates
  - ξ(2230)
    - First observed by MarkIII is J/ψ → γKK in 1980's, then by BESI in 1990's in J/ψ → γKK, γππ, γppbar 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.
  - $f_2(2340)$
    - Many wide f_2 mesons in the mass region of 2.3 GeV from the LQCD predictions
    - 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. They can only be seen as PWA components.
    - $f_2(2340)$: its large production rate in J/ψ radiative decays favors its interpretation as a tensor glueball candidate.
    - More PWA studies are needed to check the consistency among various decays modes. However, due to large overlaps again, no independent mass and width scan can be performed in PWA, i.e., the masses and widths of these f_2 mesons have to be fixed to previous measurements.



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

- 0^{-+} Pseudoscalar Glueball Candidate
  - η(1405) first discovered by MarkII in 1980's, named as ι(1440) with complicated structures. Lots of studies at MarkII, MarkIII, 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 1980's
  - No longer to be believed as 0^{-+} glueball candidate due to its large different mass from LQCD prediction.

Until 2011， no good 0-+ glueball candidate above 2.3GeV

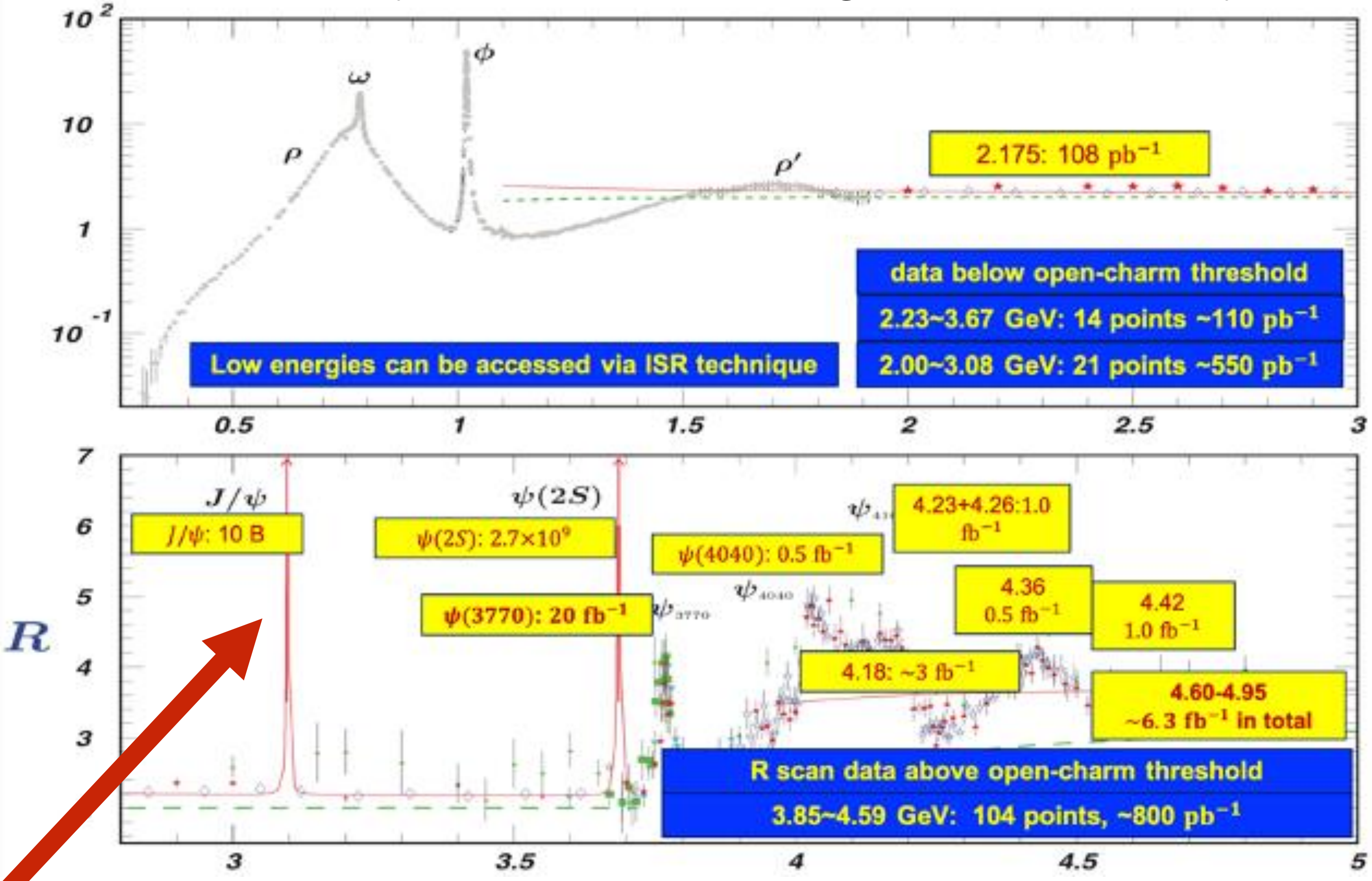
BESIII Data samples

Data sets collected so far include

- ✦ 10×10^9 J/ψ events
- ✦ 2.7×10^9 ψ(2S) events
- ✦ 20 fb^{-1} ψ(3770)
- ✦ Scan data between 2.0 and 3.08 GeV, and above 3.74GeV
- ✦ Large datasets for XYZ studies:

Scan with >500pb-1 per energy point space 10-20MeV apart

Totally about 50fb^{-1} integrated luminosity



World largest J/ψ data sample : ~10 billion

Key scientific question to be answered at BESIII: Glueballs exist or not?

- Searching for glueballs has been the top physics goal of BEPC and BEPCII for about 40 years!

- With 10 billion J/ψ data, we should be able to answer this key question — Either we find them, or exclude them.
  - BESIII Physics Yellow Book

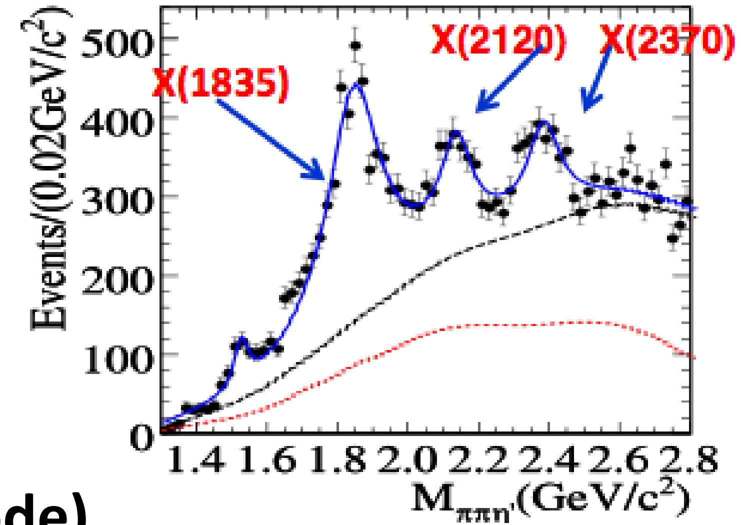
→ We started to find the answer…

X(2370)

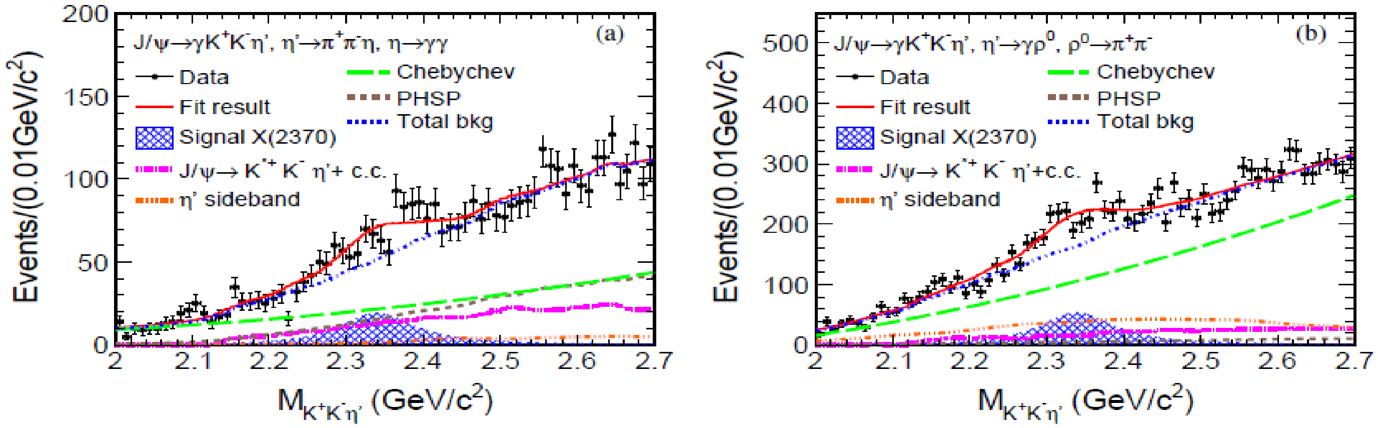
- **Discovered by BESIII in $J/\psi \to \gamma\pi^+\pi^-\eta'$ in 2011.**

Resonance	M(MeV/c²)	Γ(MeV/c²)	Stat.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

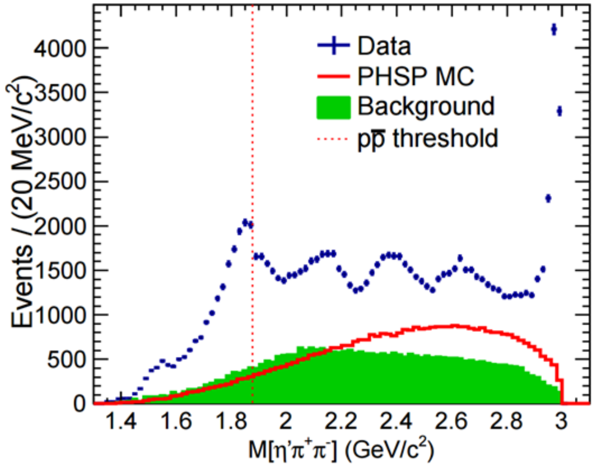
PRL106, 072002 (2011)



- **Confirmed by BESIII in $J/\psi \to \gamma\pi^+\pi^-\eta'$, $\gamma KK\eta'$ (new mode)**



EPJC (2020) 80:746



PRL 117, 042002 (2016)

X(2370) — good candidate of 0^{-+} glueball when it was first observed at beginning

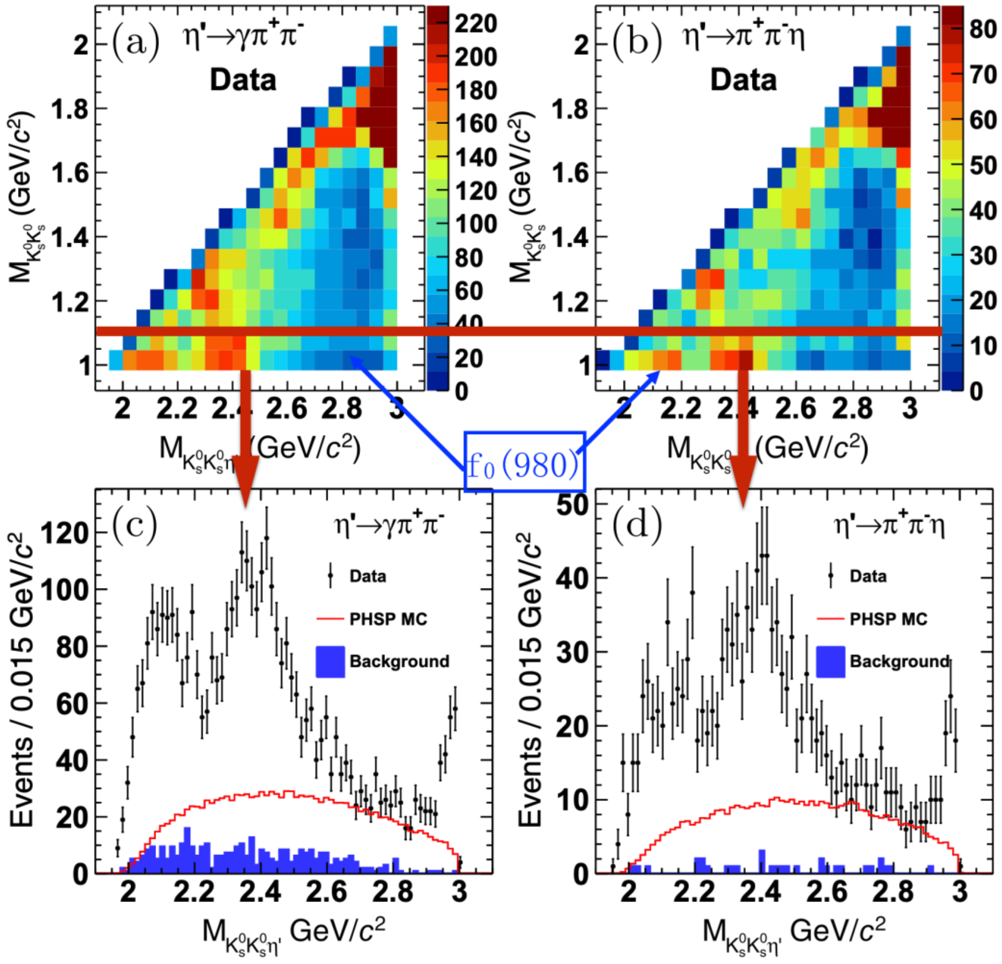
- Its mass is consistent with LQCD prediction on the 0^{-+} glueball.

- Observed in the best place to search for the 0^{-+} glueball:
  - In J/ψ radiative decays
  - In golden decays modes of 0-+ glueball seaaches: first in $\pi\pi\eta'$ & later in $KK\eta'$

- Flavor symmetric decay — observed in both $\pi^+\pi^-\eta'$ and $KK\eta'$ decay modes.

→ Determination of its spin-parity is crucial!

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



PRL 132 (2024) 181901

- Almost background free channel
- 10 billion J/ψ data
- Very good BESIII detector performance

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

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

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

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

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:

$J^{PC} = 0^{-+}$ PRD 100 (2019) 054511

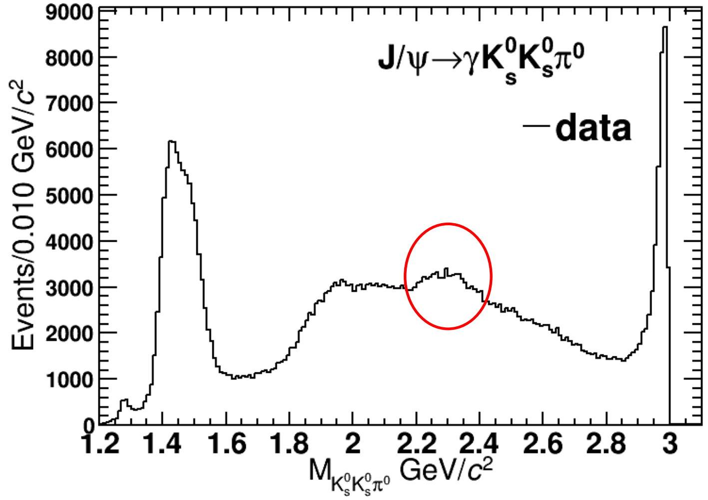
$M = 2395 \pm 14$ MeV

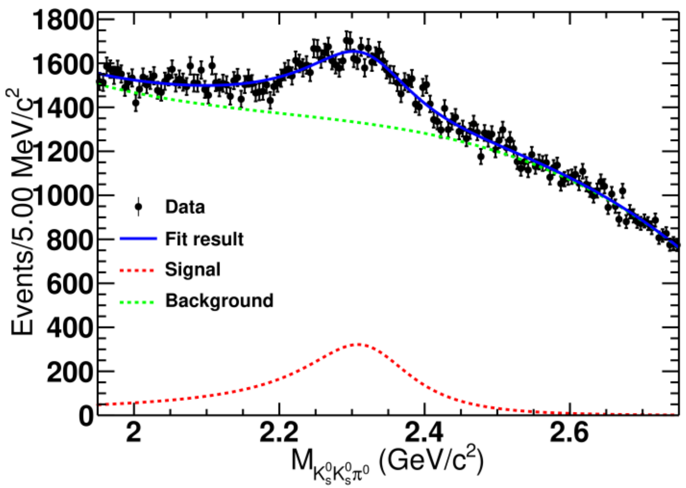
$B(J/\psi\to\gamma G_{0-+}) = (2.31 \pm 0.80) \times 10^{-4}$

- The measurements are in a 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 $B(X(2370)\to f_0(980)\eta')$ ~5% decay rate, $B(J/\psi\to\gamma X(2370)) = (10.7^{+22.8}_{-7})\times10^{-4}$)

New (preliminary) results on X(2370) at ICHEP2024

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



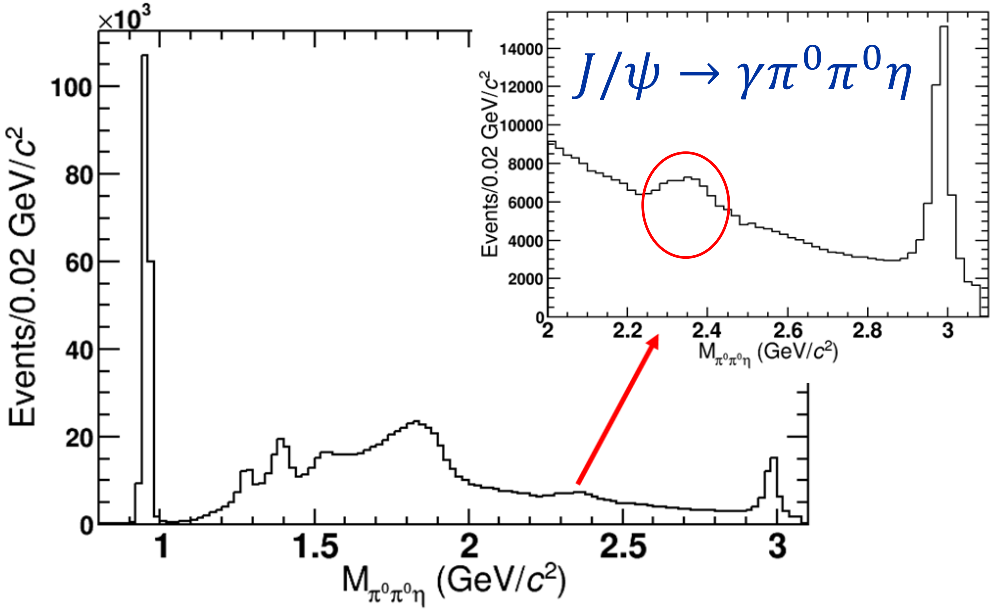


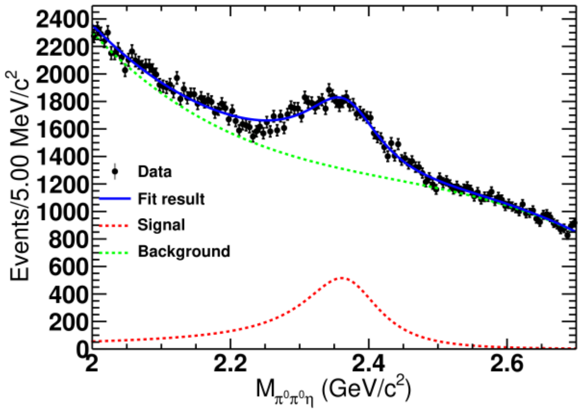
- Almost background free channel
- 1D mass spectrum fit
- Statistical significance：> > 5σ
- Mass and width

$$M_{X(2370)} = 2321 \pm 4(stat) \pm 65(syst.)\ \text{MeV}$$

$$\Gamma_{X(2370)} = 182 \pm 16(stat) \pm 59(syst.)\ \text{MeV}$$

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



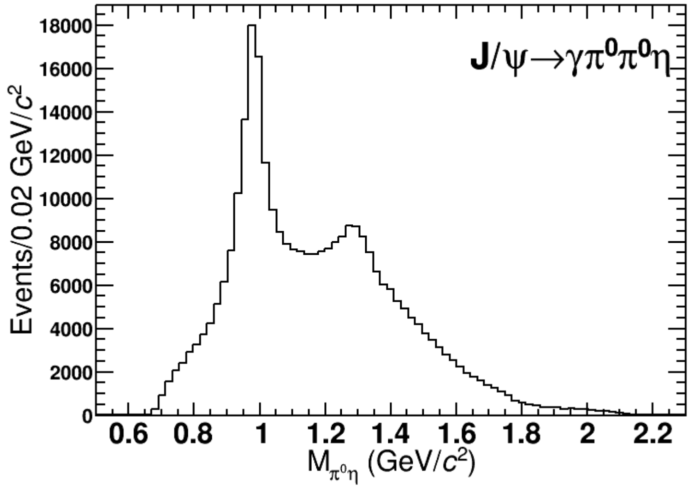


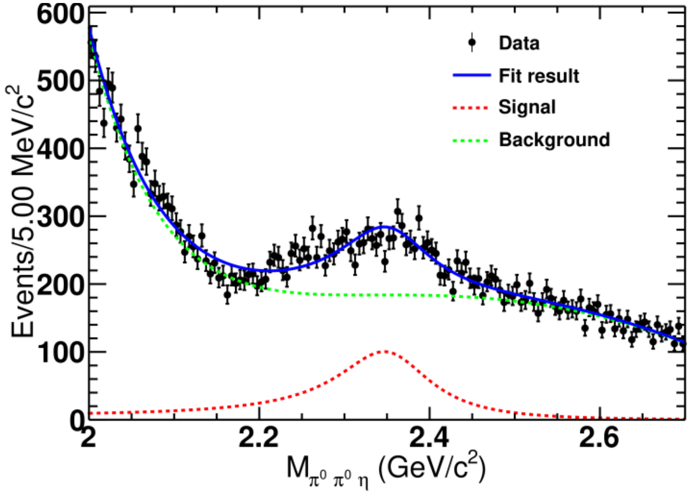
- Almost background free channel
- 1D mass spectrum fit
- Statistical significance：> > **5σ**
- Mass and width

$$M_{X(2370)} = 2370 \pm 2(stat) \pm 52(syst.)\ \text{MeV}$$

$$\Gamma_{X(2370)} = 134 \pm 8(stat) \pm 30(syst.)\ \text{MeV}$$

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





$a_0(980)$ signal region
$|m_{\pi^0\eta} - 0.98| < 0.05$ GeV

- Clear $a_0(980)$ signal in $M_{\pi\eta}$ spectrum
- 1D mass spectrum fit
- Statistical significance : >> 5σ
- Mass and width

$$M_{X(2370)} = 2352 \pm 3(stat) \pm 74(syst.)\ \text{MeV}$$
$$\Gamma_{X(2370)} = 134 \pm 4(stat) \pm 62(syst.)\ \text{MeV}$$

$J/\psi \rightarrow \gamma K_S K_S \eta$

In the 2D mass plot of M_{KK} vs. $M_{KK\eta}$ in the BESIII paper on the spin-parity determination of the X(1835), qualitatively, we can clearly observe:

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

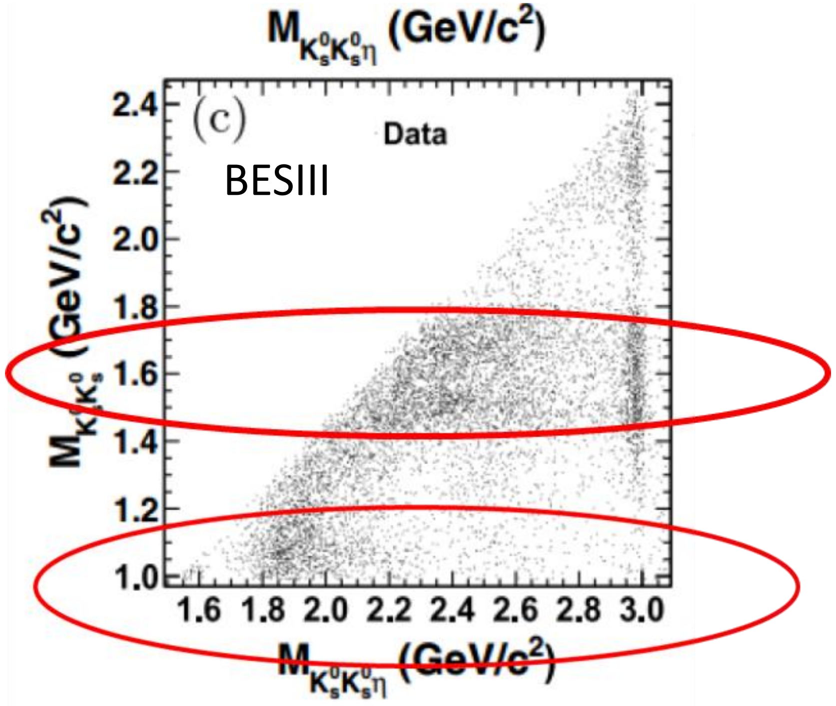
Evidence of X(2370), hc→$f_0(1500)\eta$, $f_0(1710)\ \eta$

- In the lower M_{KK} mass band of $f_0(980)$, no X(2370), nor η_c.

Suppression of X(2370),η_c→$f_0(980)\eta$

→High similarities between X(2370) and η_c decays!

PRL 115,091803 (2015)



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) %

X(2370) is observed in all 5 modes

→ High similarities between X(2370) and η_c decays

Discussion on X(2370) properties — Decays

- Normal qqbar mesons, hybrids and multiquark states can hardly explain all 5 decay modes ($\eta'\pi\pi$, η'KK, $\eta\pi\pi$, ηKK, Kπ) with different quark flavor combinations.
  - e.g., LQCD calculation (PRD 83 (2011) 11502) shows that mixing between nnbar and ssbar comppnents should be very small for 0-+ qqbar mesons at 2GeV.

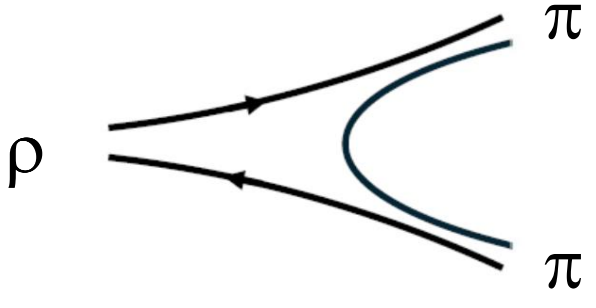
- The high similarities between X(2370) and η_c decay modes strongly suggest it decays via gluons.

- Narrow decay partial widths → next page

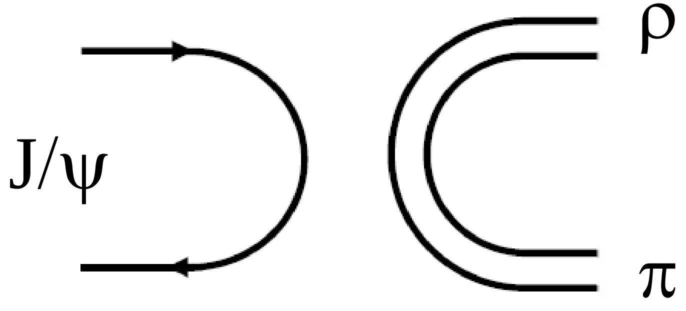
Narrow Deacy Partial Widths of X(2370)!

- For 5 golden PPP decay modes: similar number of events under the X(2370) peak — No dominant decay modes, similar to η_c!
- Naïve estimation on the BR of each mode ~ 5-10%, i.e., partial width of each decay mode is ~ 10MeV!
- This would be very hard to be explained if there were quark content (qqbar, qqg, or 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!

OZI Rule



OZI allowed decays



OZI forbidden decays

- OZI allowed decay rates are much higher than OZI forbidden decays rates.
- Most light meson decays are OZI allowed decays:

→their typical widths>100MeV and usually they have dominant decays modes.

- J/ψ and η_c decays are all OZI forbidden decays:

→their widths are very narrow and they have no dominant decay modes – signature of gluon decays.

Discussion on X(2370) properties — Production

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

- In the above 2.3 GeV 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 → very different from 0++, 2++ candidate!!!

→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

Conclusions

- BESIII discovers a glueball like particle X(2370) — The mass, spin-parity quantum numbers, production and decay properties of X(2370) are fully consistent with the features of the lightest pseudoscalar glueball.

- Only glueball interpretation can naturally explain all of the decay and production properties of X(2370) observed at BESIII without any difficulties/contradictions.

Outlook

- More decay modes of X(2370) will be searched for and studied using 10 biollion J/psi data sample.

- Searching for X(2370)→K*K is of special importance since it will provide a crucial test whether X(2370) is a flavor singlet as an expectation of a glueball.

→ Generalized G-parity conservation requires the X(2370)→K*K is forbidden!

Outlook

- More decay modes of X(2370) will be searched for and studied using 10 biollion J/psi data sample.

- Searching for X(2370)→K*K is of special importance since it will provide a crucial test whether X(2370) is a flavor singlet state as an expectation of a glueball.

→ Generalized G-parity conservation requires the X(2370)→K*K is forbidden if it is a flavor singlet state!

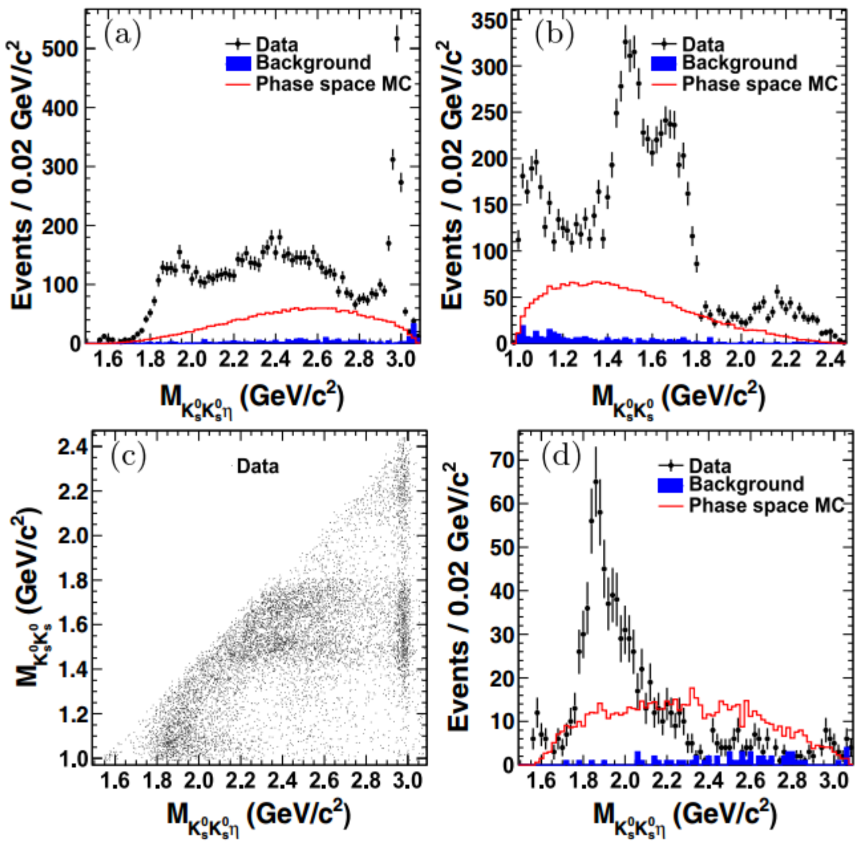
Thanks!

backup

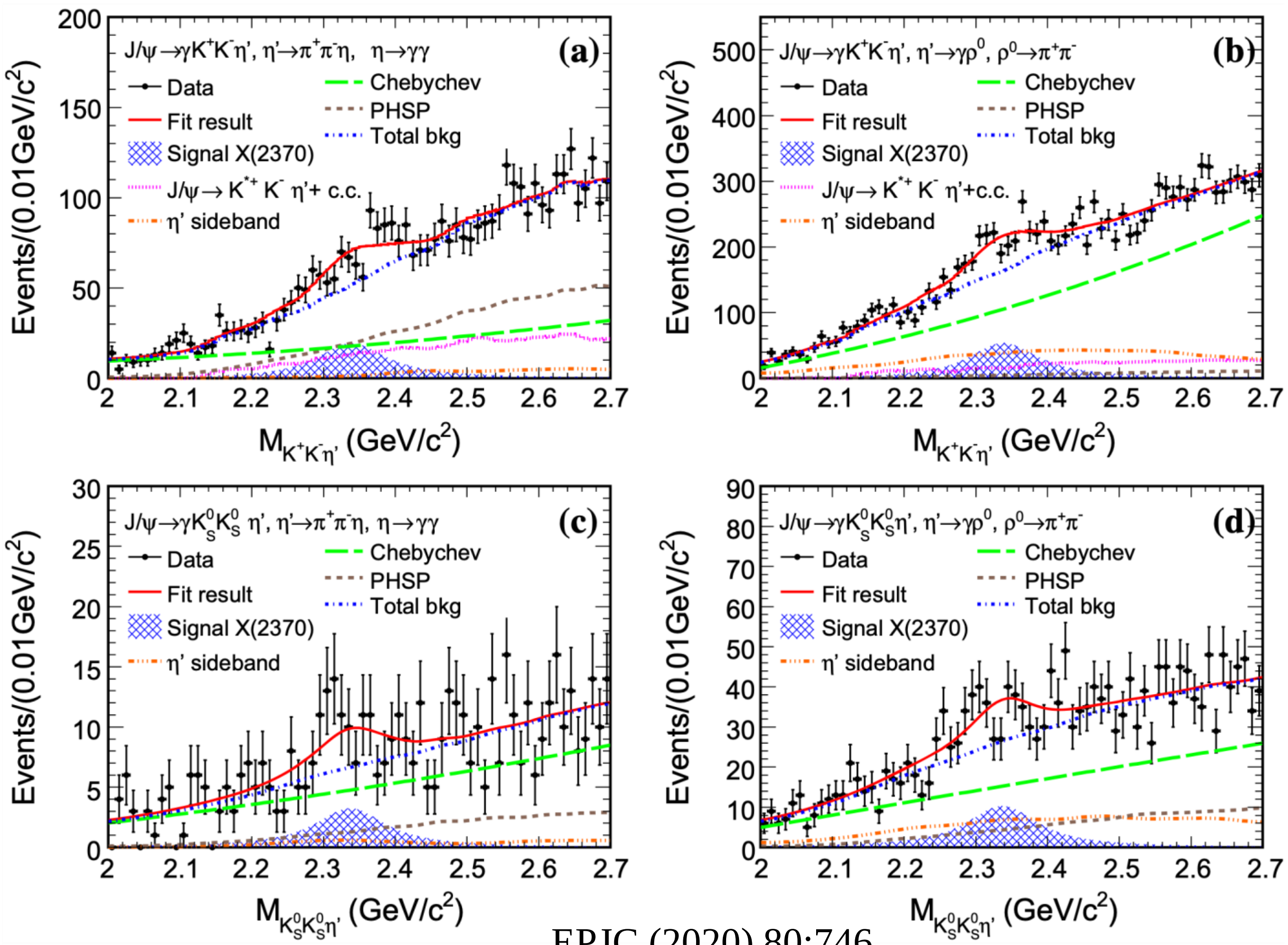
Observation of X(1835) in $J/\psi \rightarrow \gamma K_S K_S \eta$

- Use 1.3×10^9 J/ψ events collected by BESIII in 2009 and 2012
- Clear structure on mass spectrum of $K_S K_S \eta$ around 1.85 GeV$/c^2$
- Strongly correlated to $f_0(980)$
- PWA for $M(K_S K_S) < 1.1$ GeV$/c^2$

PRL 115, 091803 (2015)



Confirmation of the X(2370) in J/ψ→γKKη'



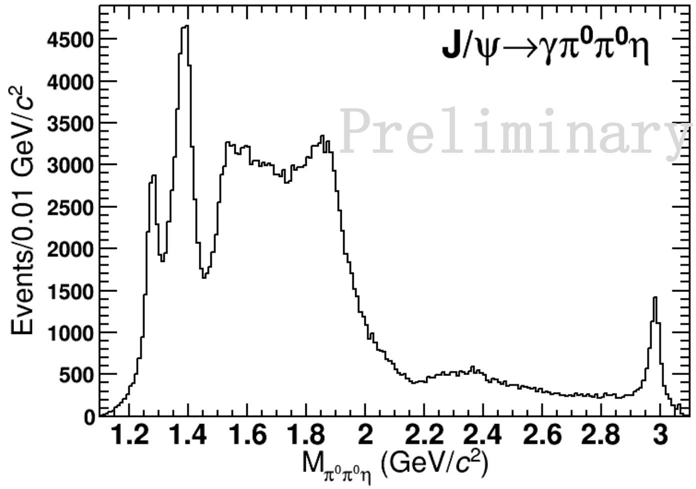
EPJC (2020) 80:746

- **Combination with 1.31 ×10⁹ J/ψ events**
  - **J/ψ→γK⁺K⁻η' and J/ψ→γKₛKₛη'**
  - **η' →γππ and η'→ππη**
- **Confirmation of the X(2370) with 8.3σ**
  - **M = 2341.6 ±6.5(stat.) ±5.7(syst.) MeV**
  - **Γ = 117 ±10(stat.) ±8(syst.) MeV**
  - **Br(J/ψ→γX(2370)→γK⁺K⁻η')=(1.79 ±0.23 ±0.65) ×10⁻⁵**
  - **Br(J/ψ→γX(2370)→γKsKsη')=(1.18 ±0.32 ±0.39) ×10⁻⁵**

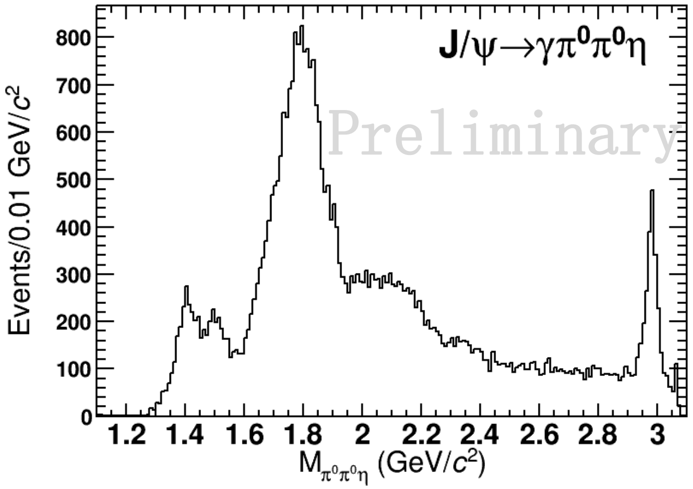
Observation: X(2370) new decay mode of KKη'

$\pi^0\pi^0\eta$ invariant mass spectrum in $a_0(980)$ signal region

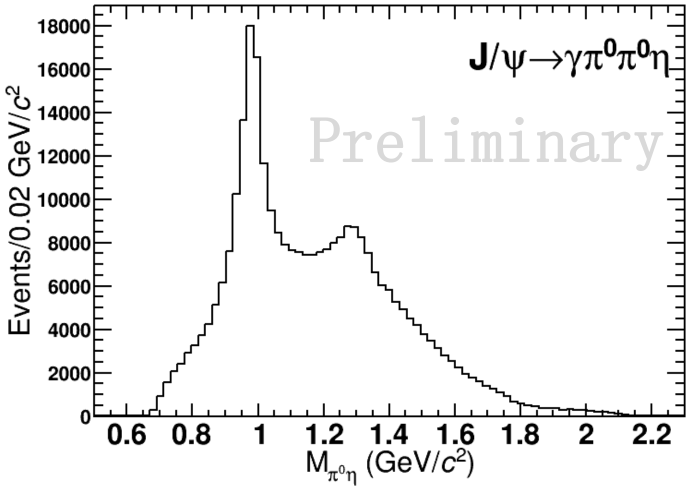
- After requiring $|m_{\pi^0\pi^0} - 1.5| > 0.15$ GeV to veto $f_0(1500)$ signal, there is the clear $X(2370)$ signal in the $a_0(980)$ signal region, but not in the $a_0(980)$ sideband region.



$a_0(980)$ signal region
$|m_{\pi^0\eta} - 0.98| < 0.05$ GeV



$a_0(980)$ sideband region
$0.2 < |m_{\pi^0\eta} - 0.98| < 0.25$ GeV

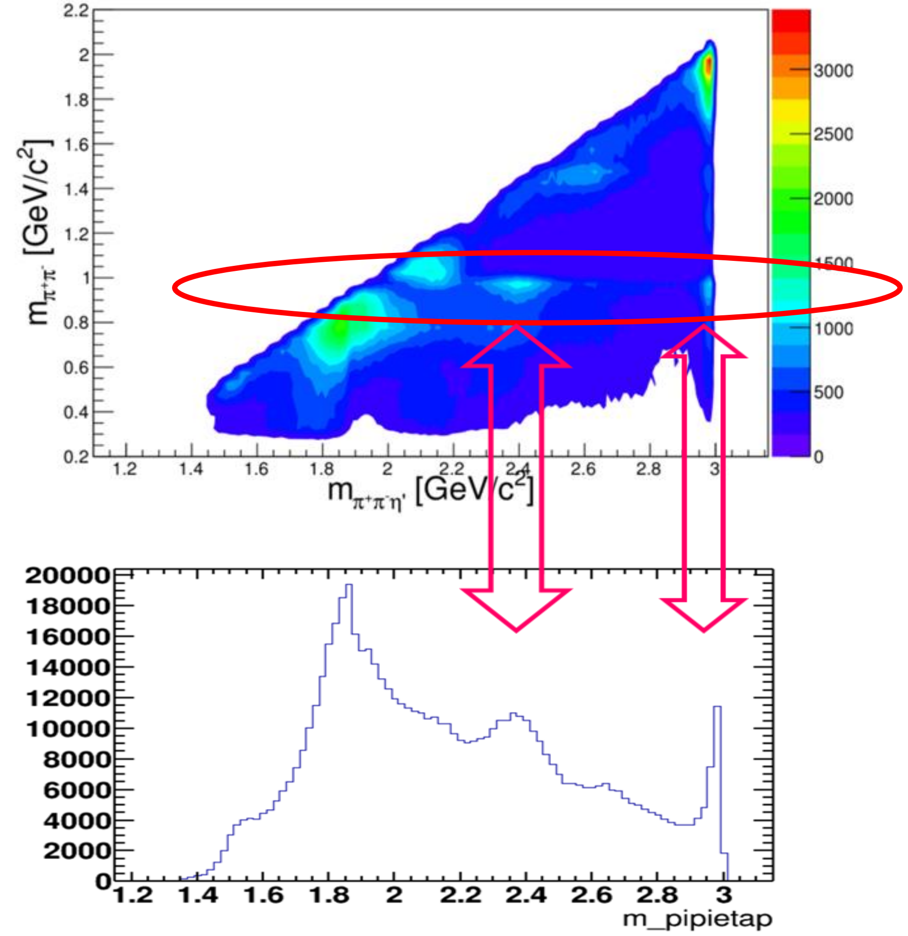


$M(\pi^0\pi^0\eta)$>2 GeV

$J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$

- $\pi^+\pi^-\eta'$ is the first mode to discover the X(2370)
- In the 2D plot of $M_{\pi\pi}$.vs. $M_{\pi\pi\eta'}$, in the $f_0(980)$ mass band, clear signals of both X(2370) and η_c
- Additional important information:
  - X(2370)→ππη' almost 100% via $f_0(980)\eta'$
  - η_c → ππη' dominantly via X(2000) η'
  - NO phase space for X(2370)→X(2000) η'

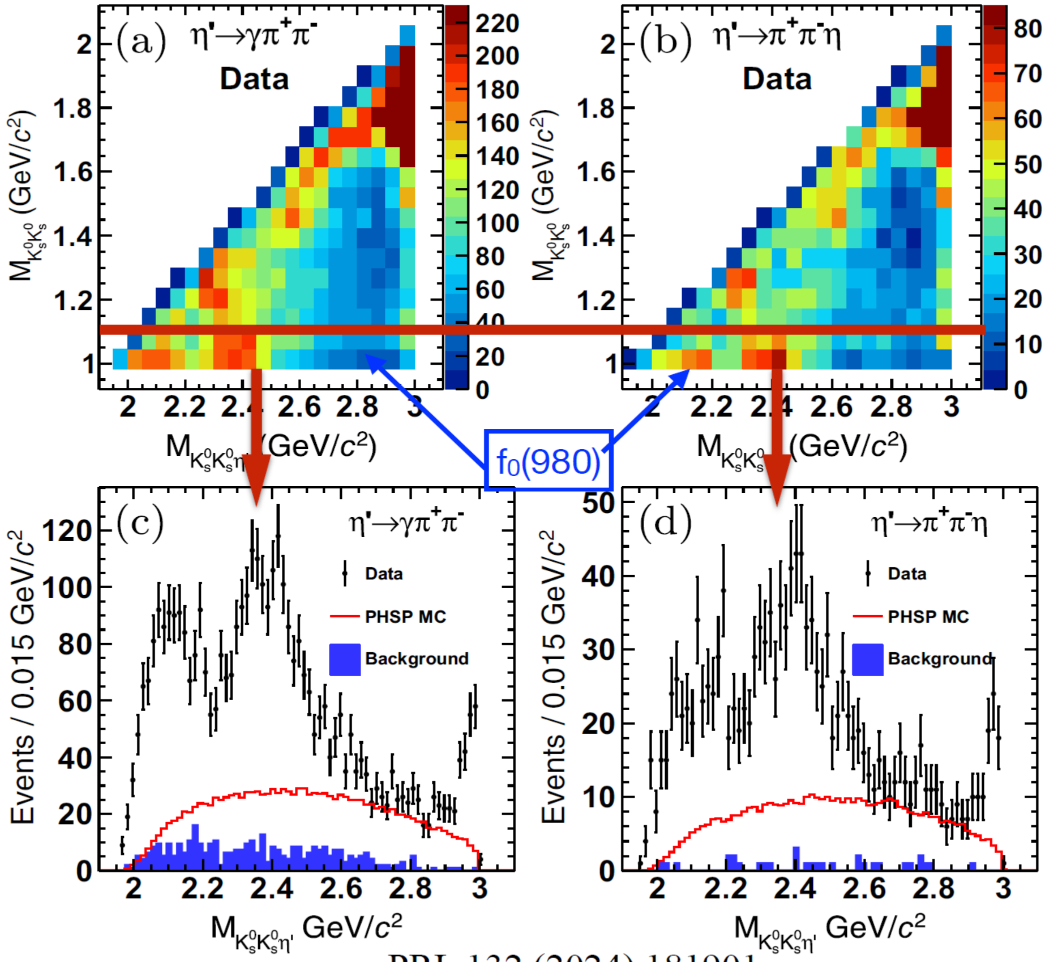
$M_{\pi^+\pi^-}$ vs $M_{\pi^+\pi^-\eta'}$



$M_{\pi^+\pi^-}$ < 1.0

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

- In the f0(980) mass band of KsKs mass, clear signals of both X(2370) and η_c
- Additional important information:
  - X(2370)→KKη' almost 100% via $f_0(980)\eta'$
  - η_c → KKη' dominantly via X(1800) η'
  - NO phase space for X(2370)→X(1800) η'



PRL 132 (2024) 181901