Discovery of a Glueball-like Particle X(2370)

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第八届强子谱和强子结构研讨会
桂林，2025年7月12日

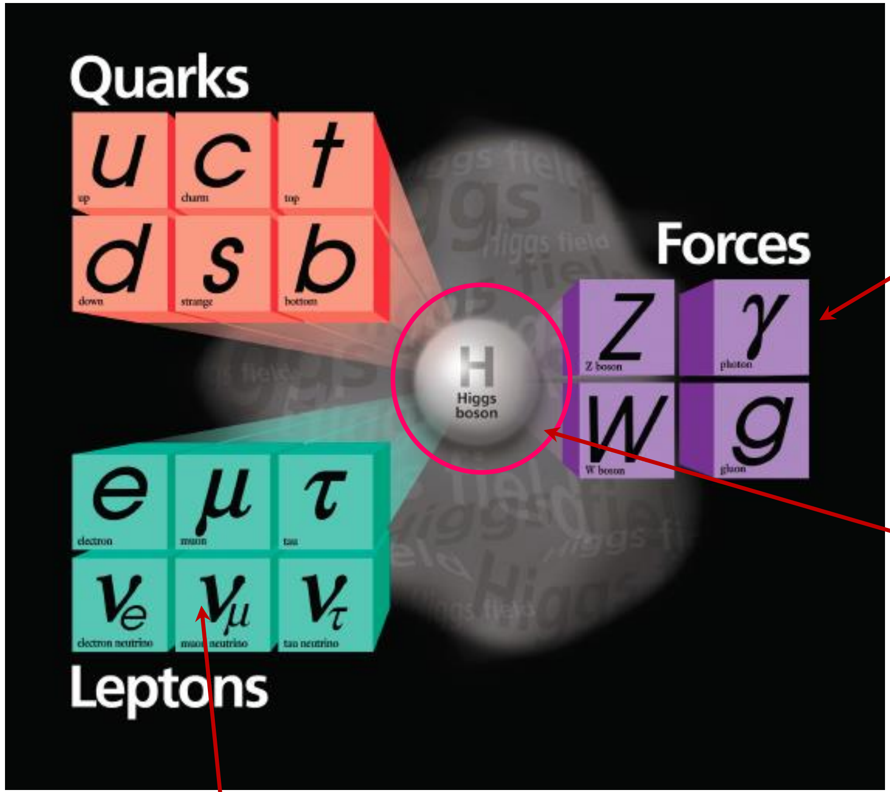
报告内容说明

- 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 发表于 International Journal of Modern Physics A (IJMPA)。【IJMPA Vol: 40 Iss: 19，2530007（2025）】

  arxiv: 2503.13286

标准模型是粒子物理基本理论，描述了自然界物质最基本的结构和电、弱、强三种相互作用



电弱、强相互作用都由规范场传播

- 胶子是强相互作用的传播子
- γ/W/Z传播电弱相互作用

Higgs粒子解释了质量的起源

夸克和轻子是组成物质的最基本粒子

QCD及其重要基本预言

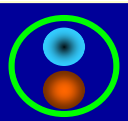
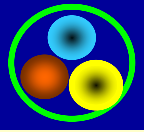
QCD —— SU(3)非阿贝规范理论：

- 高能下，耦合常数α_s running，已被实验证实，获Nobel Prize
- 低能下，胶子存在自相互作用 —— 胶球

Multi-quark States, Hybrids and Glueballs

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

Naive Quark Model：

Meson（ q $\bar{q}$ ）	
Baryon（q q q）	

- **New forms of hadrons:（基于夸克模型的语言和对普通夸克模型的突破）**
  - **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!

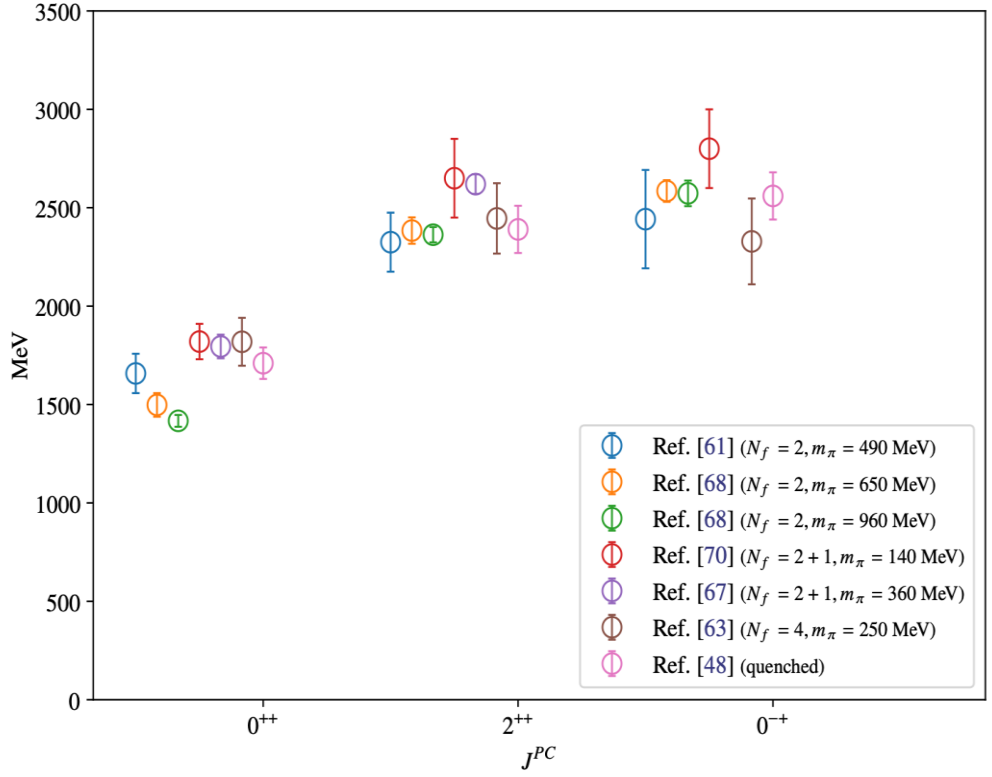
Glueballs

- 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. (Frank Close 1995)

→ 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

- 直接证明胶子的自相互作用——QCD非阿贝尔规范性的直接证明
- Unique particle made of pure force （bosons）
（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

Signatures of Glueballs

- Production:

  high production rate in gluon-rich environment

- Decay:

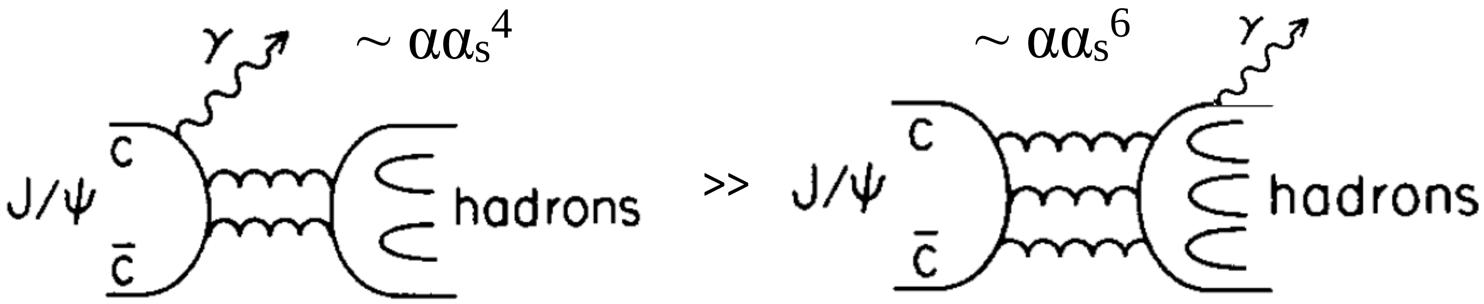
  via gluons

- Flavor singlet:

  contain no quark flavor

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^{-+}…

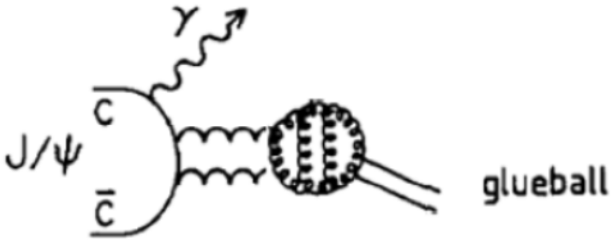
→Clean environment

very different from proton-antiproton collision processes

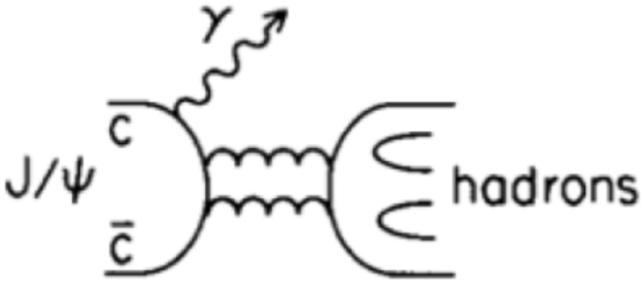
→ Ideal place to search for glueballs

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.



$\sim \alpha\alpha_s^2$

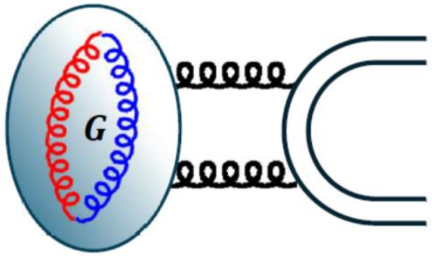


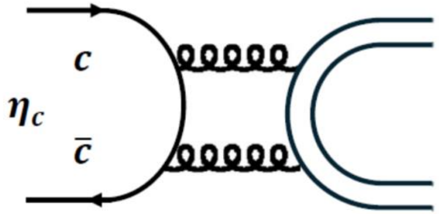
$\sim \alpha\alpha_s^4$

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

Gueball Decays

- via gluons – flavor singlet: important feature of a glueball
  - flavor symmetric decays
- No rigorous predictions on decay patterns and their branching ratios.
- The glueball decays should have similar decay patterns to the charmonium families since they all decay via gluons.（何祚庥、赵光达）
  - 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.

2024.5.9 美国 Newsweek 记者 Ian Randall 的 good questions

- 为什么实验上胶球一直很难找到？
- 现在情况有什么不同？

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 $\Gamma(f_0(1710) \rightarrow$

- $B(J/\psi \rightarrow \gamma f_0(1710) \rightarrow \gamma\pi\pi) = (4.01 \pm 1.0) \times 10^{-4}$
  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)

f0(1710)两点困难：详见 2503.13286

1. **衰变味道不对称 KK>pipi**
2. **4pi mode还未观测到**

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).

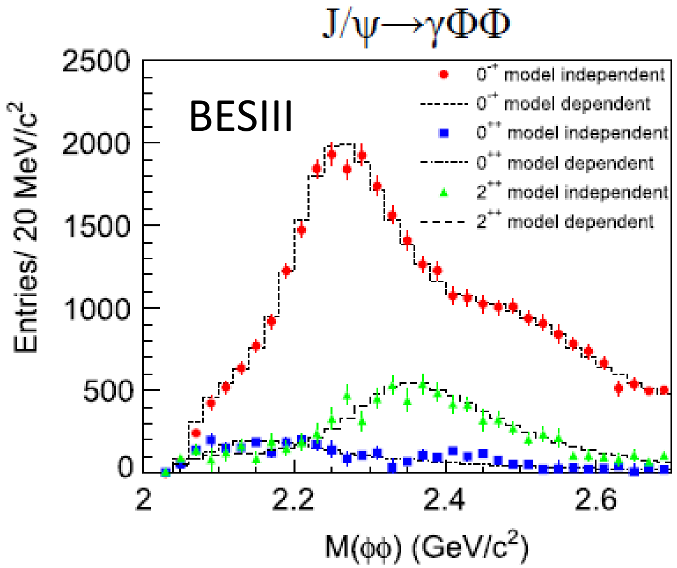
BESIII:

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

0++胶球寻找困难：
在J/psi辐射衰变中
1.5GeV-1.8GeV区域
太多的0++

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. (×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

2++胶球寻找主要困难：J/psi辐射衰变中2.0-2.4GeV区域多个2++

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

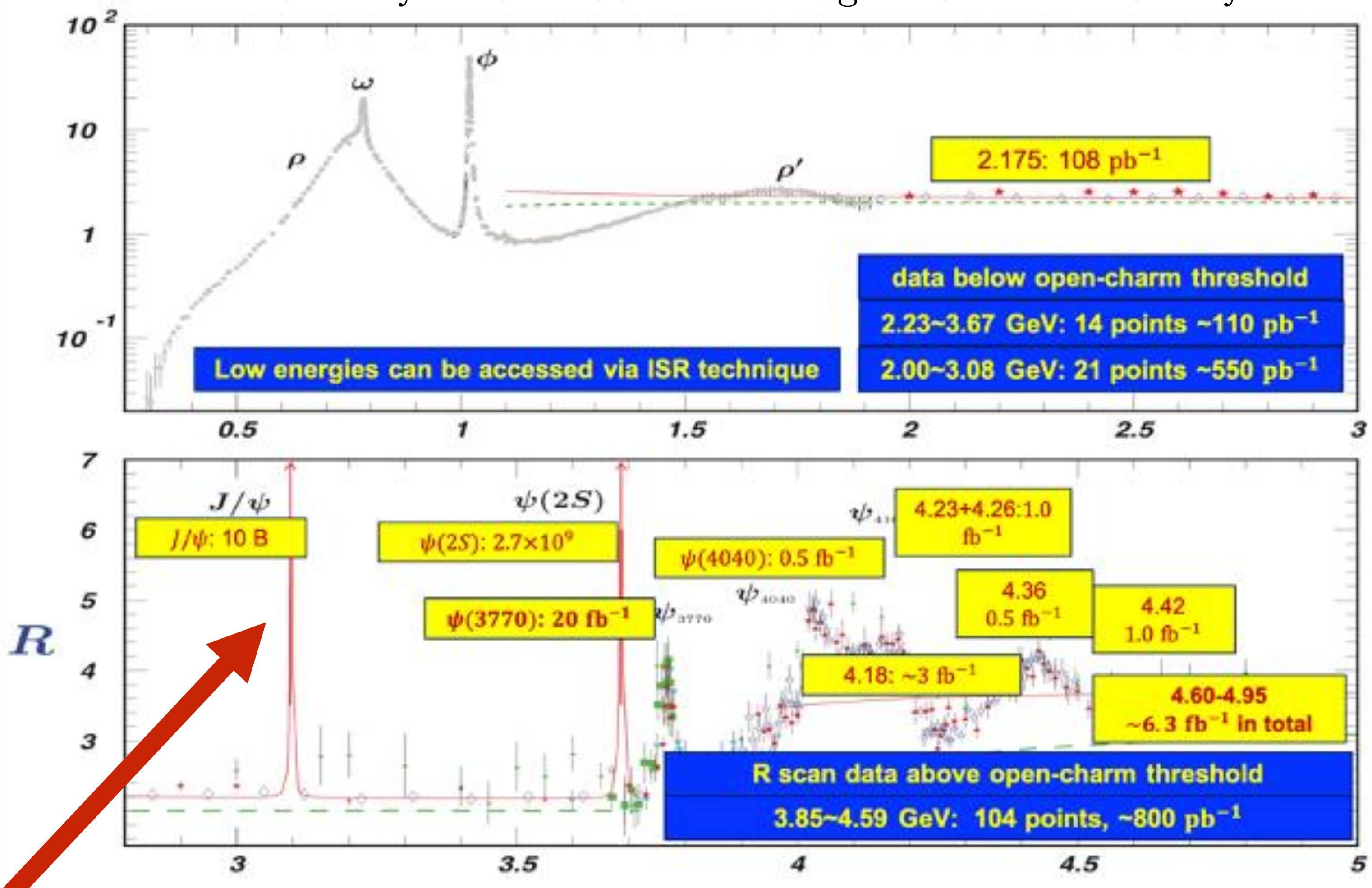
BESIII Data samples

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

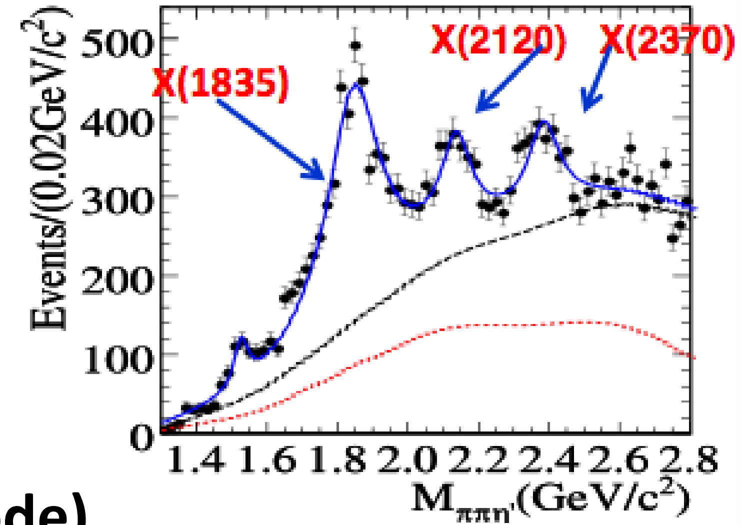
→ We started to find the answer…

X(2370)

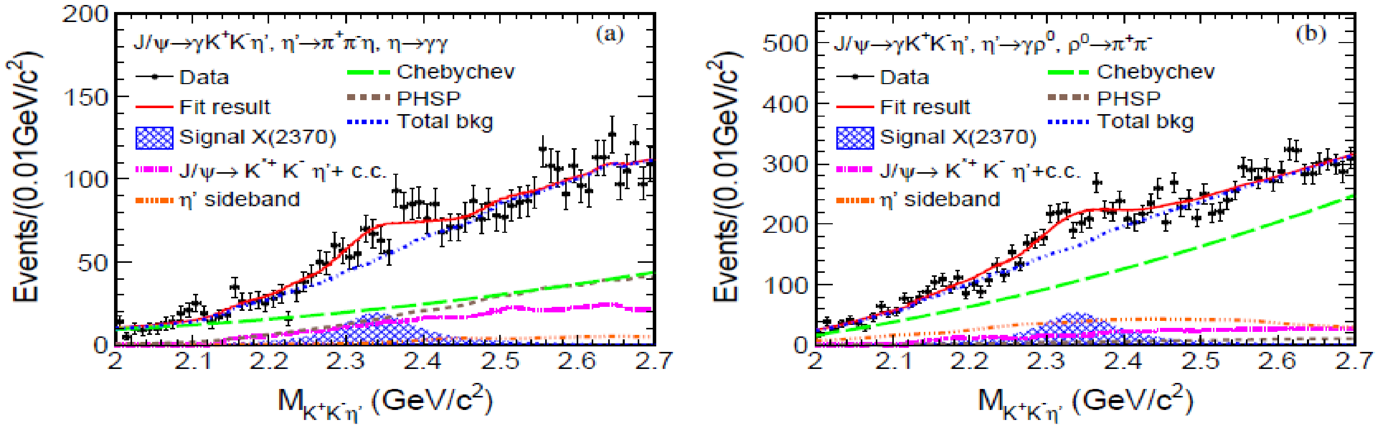
- **Discovered by BESIII in J/ψ→γπ⁺π⁻η′ in 2011.**

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

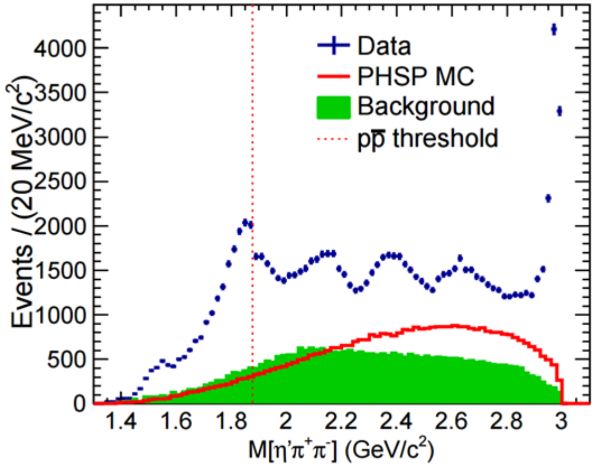
PRL106, 072002 (2011)



- **Confirmed by BESIII in J/ψ→γπ⁺π⁻η′, γKKη′ (new mode)**



EPJC (2020) 80:746



PRL 117, 042002 (2016)

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

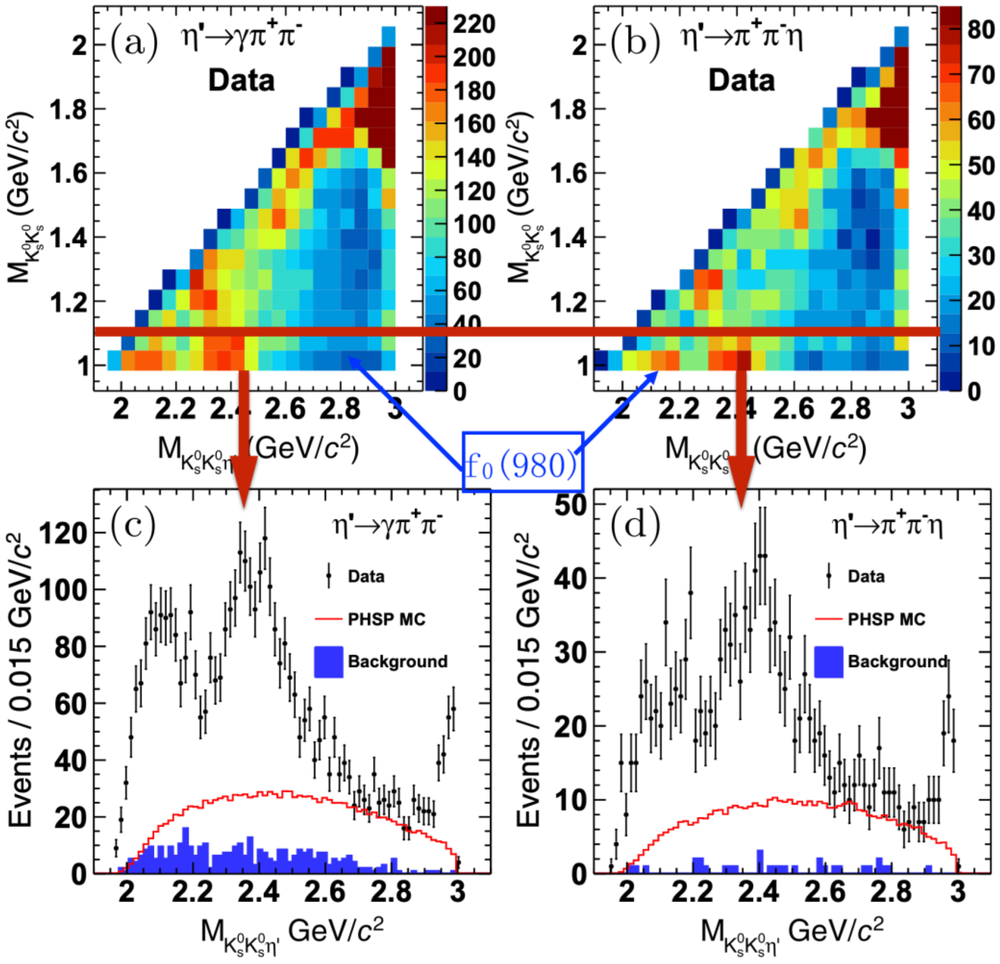
- Its mass is consistent with LQCD prediction on the 0^{-+} glueball.

- 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

$B(J/\psi\rightarrow\gamma X(2370))B(X(2370)\rightarrow f_0(980)\eta')B(f_0(980)\rightarrow K^0_s K^0_s)$

$= (1.31 \pm 0.22^{+2.85}_{-0.84})\times 10^{-5}$

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

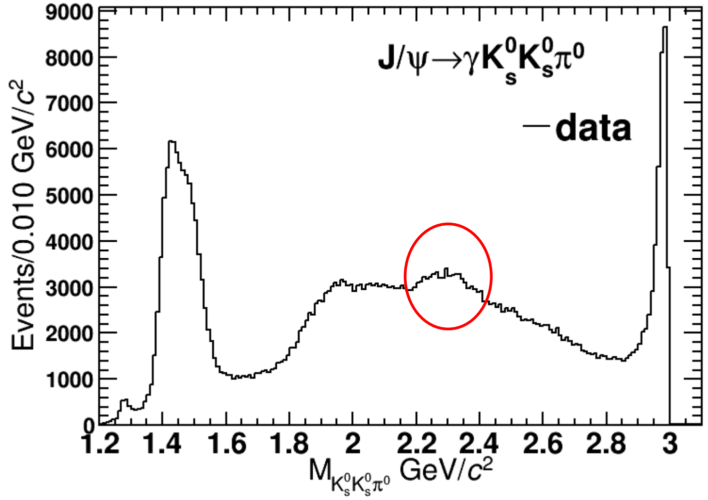
$M = 2395 \pm 14$ MeV

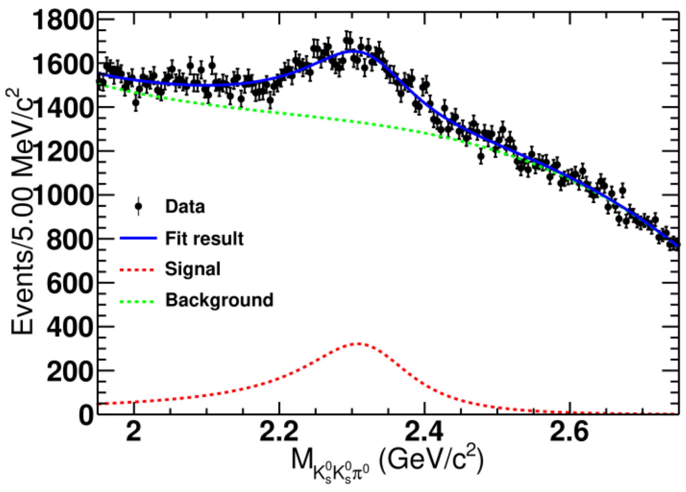
$B(J/\psi\to\gamma G_{0-+}) = (2.31 \pm 0.80) \times 10^{-4}$

- 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: $X(2370) \to K_S^0 K_S^0 \pi^0$



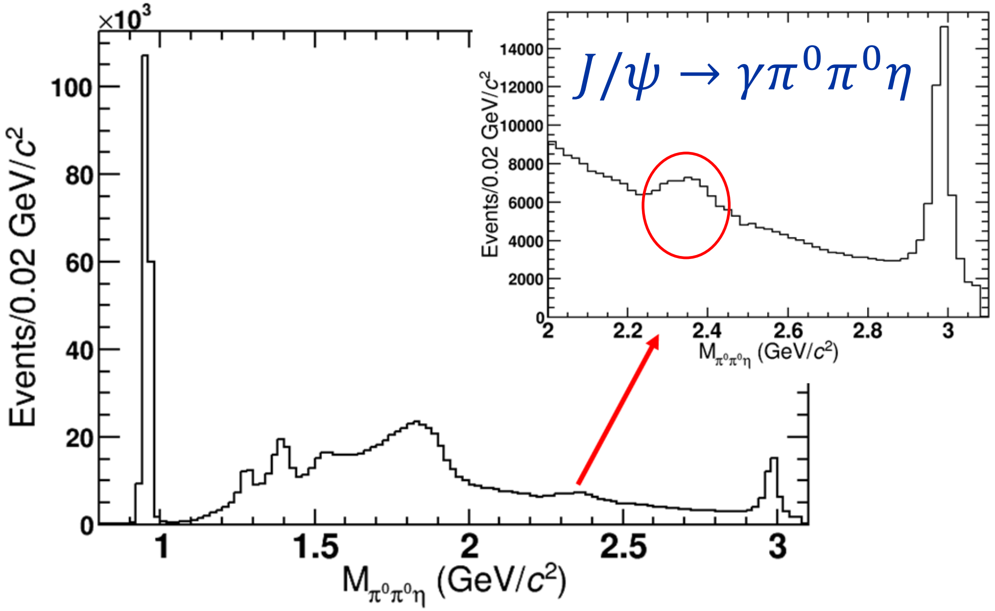


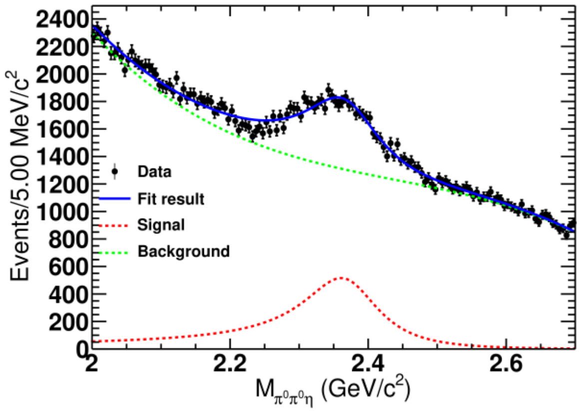
- Almost background free channel
- 1D mass spectrum fit
- Statistical significance：> > 5σ
- Mass and width

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

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

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



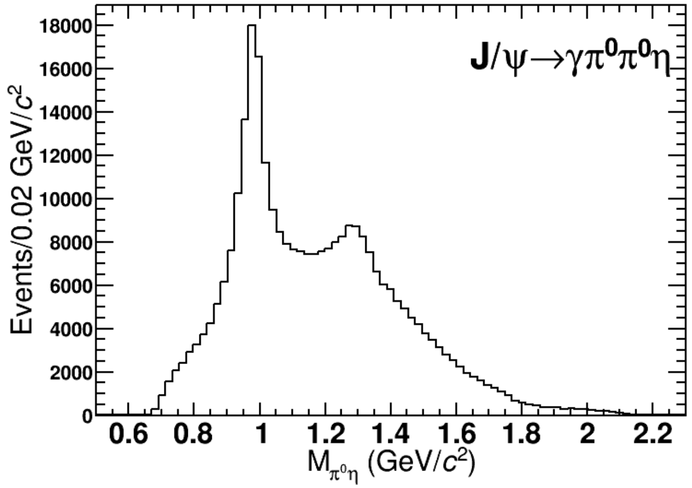


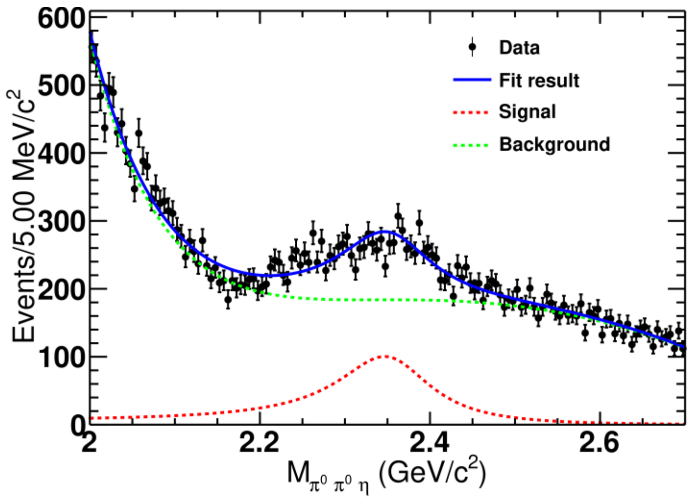
- Almost background free channel
- 1D mass spectrum fit
- Statistical significance：> > 5σ
- Mass and width

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

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

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





$a_0(980)$ 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

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

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

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.

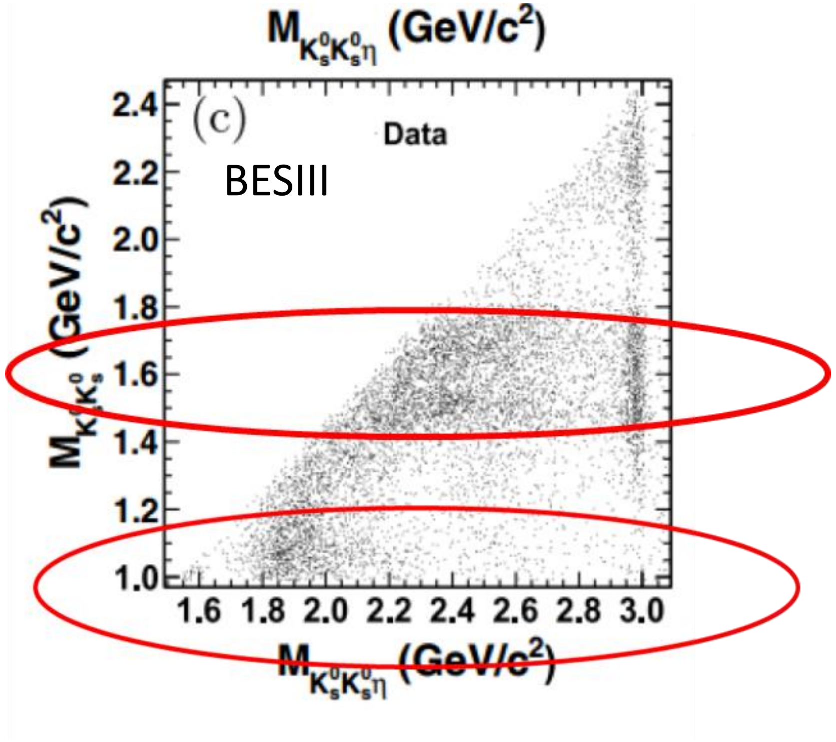
Evidence of X(2370), $\eta_c \to f_0(1500)\eta$, $f_0(1710)\ \eta$

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

Suppression of X(2370),$\eta_c \to f_0(980)\eta$

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

PRL 115,091803 (2015)



X(2370) →$f_0(1500)\eta$ indicate it could be the same as $\eta(2320)$ observed by B.S.Zou et al in pp collision.

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

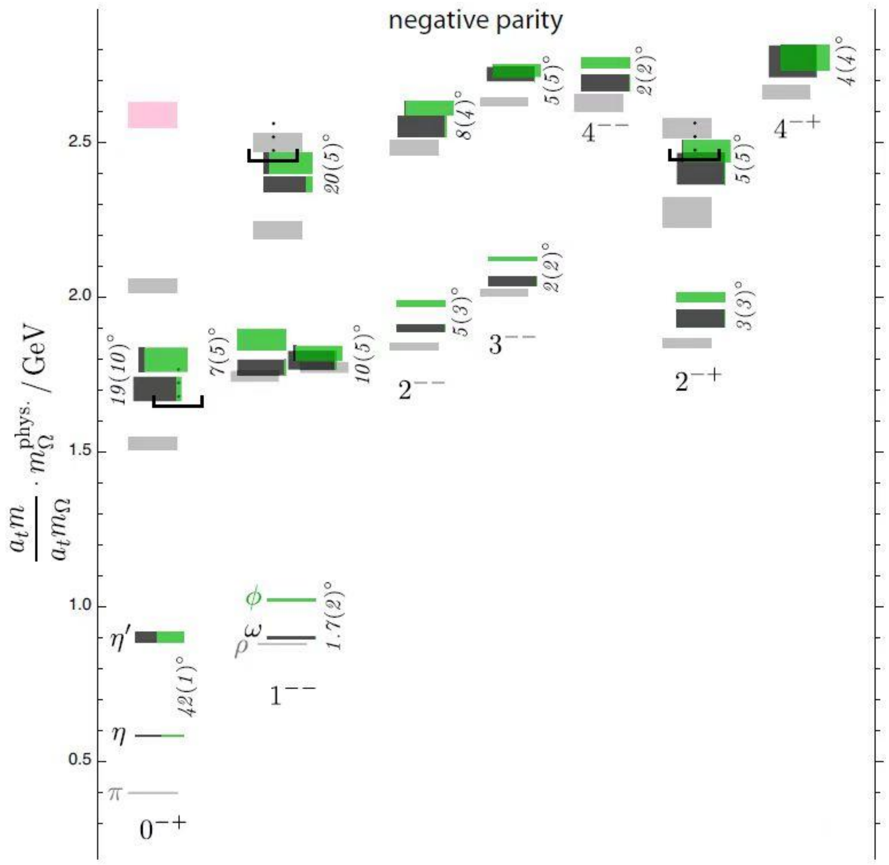
Γ_{34}	$K\overline{K}\pi$	(7.0 ±0.4) %
Γ_{35}	$K\overline{K}\eta$	(1.32±0.15) %
Γ_{36}	$\eta\pi^+\pi^-$	(1.7 ±0.5) %

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 (η’ππ, η’KK, ηππ, ηKK, KKπ) with different quark flavor combinations.
  - e.g., LQCD calculation (PRD 83 (2011) 11502) shows that mixing between nnbar and ssbar components 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

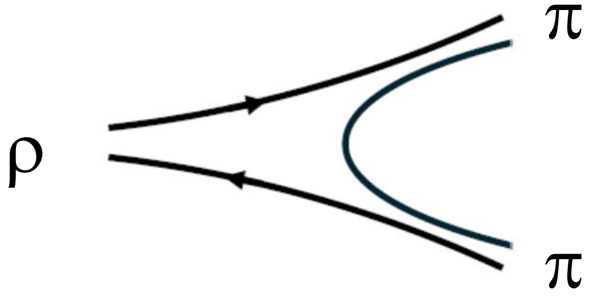


PRD 83 (2011) 11502

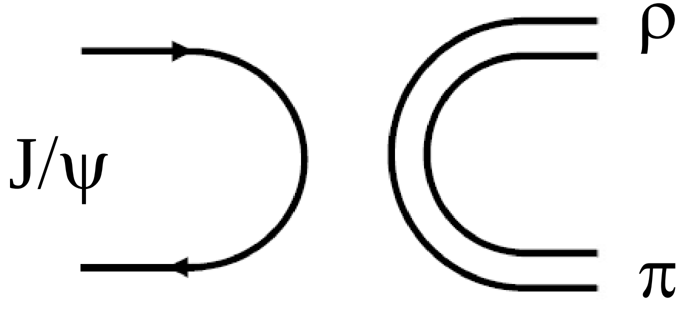
Narrow Deacy Partial Widths of X(2370)!

- 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:

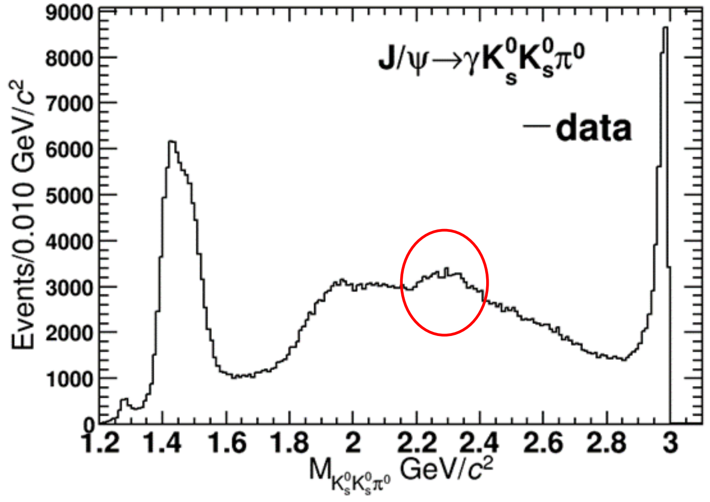
→their widths are very narrow and they have no dominant decay modes – signature of gluon decays.

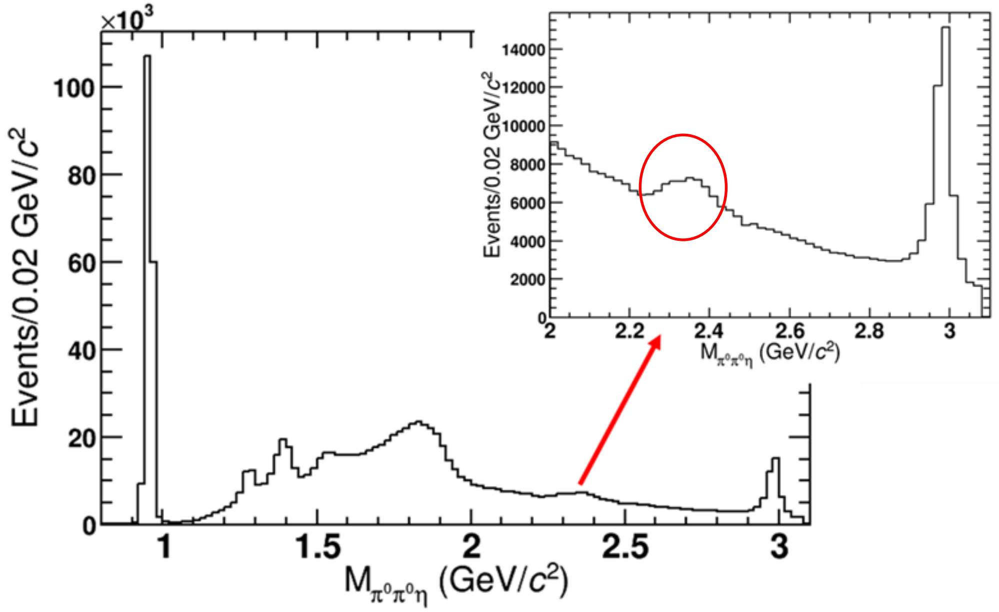
Discussion on X(2370) properties — Production

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

- BR(J/ψ→γX(2370)) = $3 \times 10^{-4} \sim 3 \times 10^{-3}$ 产额排除了 ΛΛbar 分子态等解释
  - cf： BR(J/ψ→γΛΛbar)< 1×10^{-4} @90%CL （ PDG ）

X(2370) production: Unique evident mass peak above 2GeV in $J/\psi \rightarrow \gamma K_s K_s \pi^0$, $\gamma \pi^0 \pi^0 \eta$





Discussion on X(2370) properties — Production

- 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++ candidates!!!

（回答了Newsweek记者的第二个问题，现在与以前状况的最大不同）

→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

唯一性

- X(2370) 粒子是在 J/ψ 辐射衰变中 $>10^{-4}$ 产额的唯一一个与 0^{-+} 胶球质量一致、与粲偶素η_c衰变性质高度相似的粒子

→ 唯一一个与胶球产生、衰变性质都一致的0^{-+}粒子

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 which is one of the most important features of a glueball.
  - Generalized G-parity conservation requires the 0-+ glueball→K*K is forbidden!
  - c.f.: 1. Theoretical calculations shows for normal 0-+ mesons around 2.3GeV, the partial width to K*K is about 20~200MeV (PRD83,114007; PRD96, 034103)
  - c.f.: 2. K*K is one of the dominant decay modes of η(1405)/η(1475), their partial widths to K*K may be ~10-20MeV (close to K*K threshold and in p-wave!), for η excitations around 2.3 GeV, the phase space is much larger than η(1405)/η(1475), i.e., the partial widths to K*K should be much larger than 20MeV.

→Suppression of K*K mode is a distinctive signature of 0-+ glueball.

BESIII X(2370)成果入选
PRL 2024 年度最重要成果

- BESIII首个入选成果
- 2024年强子物理领域唯一一个入选成果

backup

Q&A： 0-+ glueball decay partial width ?

- A: sqrt(OZI rule)

  $\Gamma_{G\to\pi\pi\eta} = \mathrm{sqrt}(\Gamma_{\eta c\to\pi\pi\eta} * \Gamma_{\text{OZI-allowed}})$

  $= \mathrm{sqrt}(0.3\mathrm{MeV} * 20\text{-}100\mathrm{MeV})$

  $\sim$ 2-5MeV

Q&A：

- Sea quark的影响

不仅胶球中含有sea quark，所有强子中都有，但是PDG数据告诉我们，sea quark对强子的特性没有显著影响，比如虽然J/psi和ηc粒子中含有sea quark，但是它们很窄的宽度和衰变模式几乎看不到受影响。

Q&A：

- 是否存在pure glueball?

Pure glueball 理解（或定义）有两种：

1. Yang-Mills胶球（不含夸克圈的贡献）quenched in LQCD，当然也不与qqbar介子混合
2. 含夸克圈的贡献的 （unquenched in LQCD）胶球，但是不与qqbar介子混合

LQCD计算已经告诉我们，虽然各个LQCD组计算结果有系统误差的差别，但是无论quenched或unquenched, 都存在胶球解。即胶球的本征态解是理论必须的，或者说LQCD预言了胶球的存在。当然unquenched解更接近真实物理世界。

我们现在的多夸克态、胶球、混杂态等都是基于夸克模型的语言。夸克模型是粒子物理的重要基石之一！

胶球混合问题主要来自于历史上寻找0++、2++胶球的困难，现在0-+胶球情况简单多了，当然仍然可以问类似的问题。

实验上，是否存在不与qqbar混合的纯胶球，这个问题与是否存在 pure ccbar charmonium一样难以或容易回答，因为实验永远没法证明混合绝对为零，最多说“可能有，但很小”。但是不影响我们研究charmonium

Q&A：进一步回答理论上胶球解是否存在？

- 胶球概念来源于胶子自相互作用可以形成束缚态粒子，即所谓的Yang-Mills胶球，quenched LQCD也得到了这些胶球解。
- 尽管unquenched LCD已计算了quark圈的贡献得到胶球解，仍然有人认为quark衰变可能对以上的解形成很大不确定性地干扰，这些干扰是否真的影响胶球解的存在？

- **物理学是以实验为基础的科学，关键问题需要由实验回答:**

X(2370)粒子的独特产生衰变性质已经从实验上说明需要具有0-+胶球性质的粒子解的存在，即胶子自相互作用可以形成束缚态粒子的基本结论并不受上述因素干扰影响。

Q&A续

- 胶球的实验确认依赖于理论上严格计算清楚？

理论与实验的结合非常重要，理论计算多多益善。目前各大LQCD组的质量计算已经足够好的给与胶球质量范围限制。对胶球的产额也有比较好的预言。

但是QCD的困难大家都很清楚，**至今质子理论上严格算清楚了吗**？质子的自旋问题、质量起源问题都回答清楚了吗？但是这些影响质子的在基本夸克模型中的确认吗？类似的是J/psi的ccbar解释。

一般的实验发现确认新型粒子的逻辑链：

发现新粒子（质量与已知粒子不一致）→新粒子性质很难用已知类型解释 → 与某一种新型粒子特性相符合没有任何矛盾。

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 $M(K_S K_S) < 1.1\ \mathrm{GeV}/c^2$

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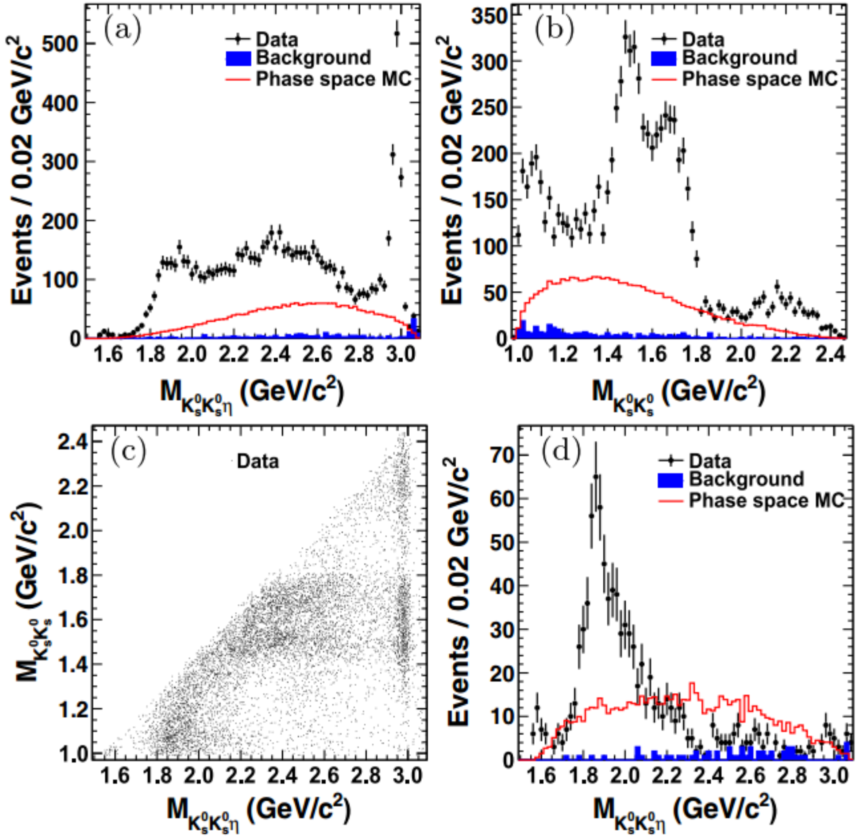
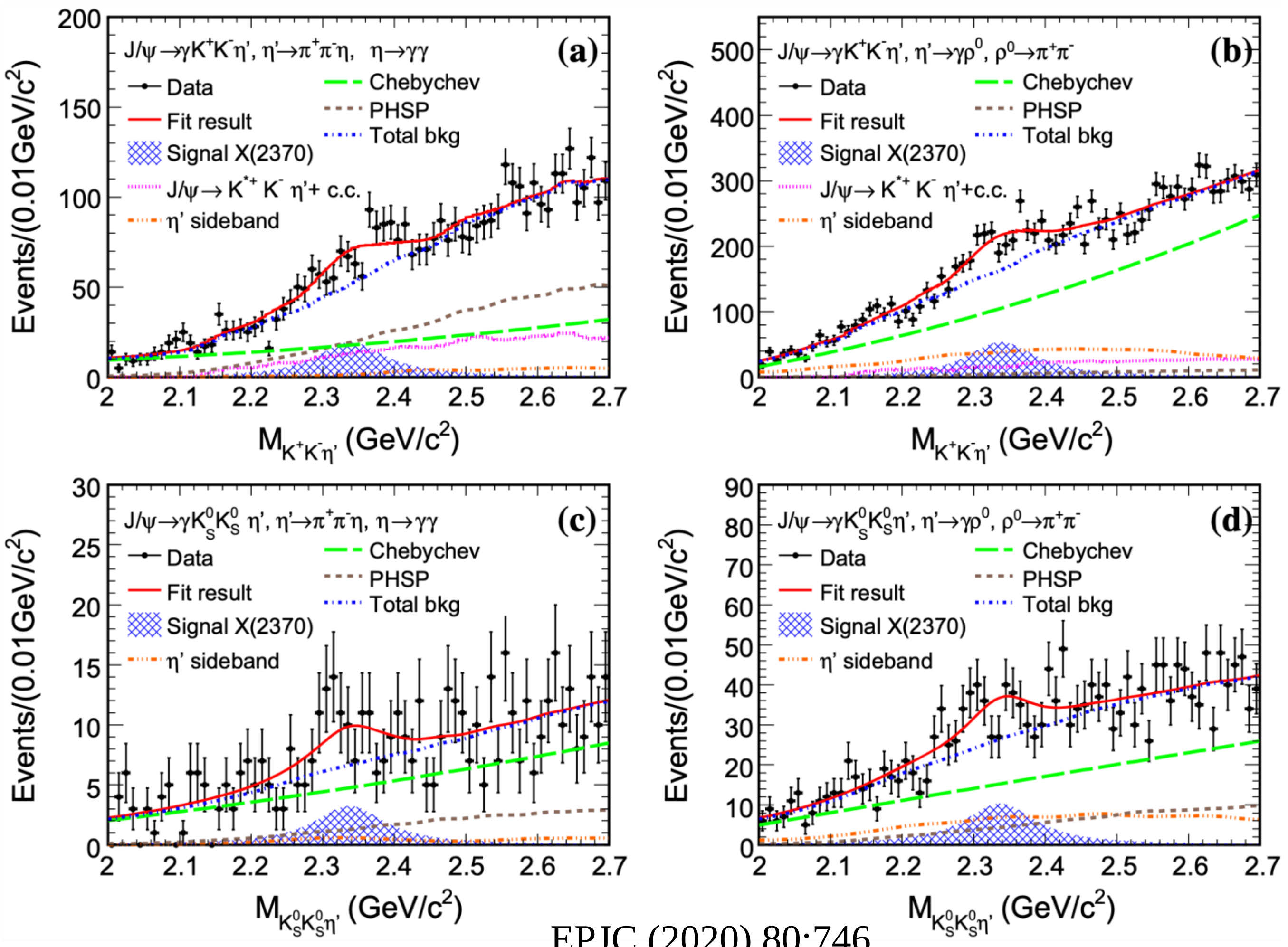


Confirmation of the X(2370) in J/ψ→γKKη'



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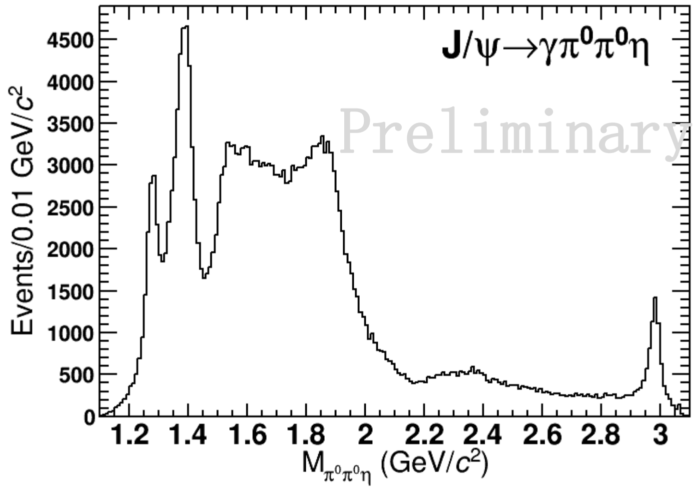
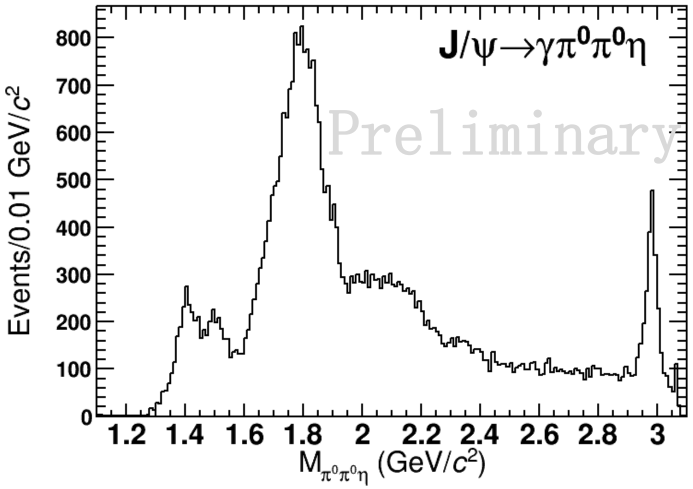
- **Combination with 1.31×10^9 J/ψ events**
  - **J/ψ→γK$^+$K$^-$η' and J/ψ→γK$_s$K$_s$η'**
  - **η' →γππ and η'→ππη**
- **Confirmation of the X(2370) with 8.3σ**
  - **M = 2341.6±6.5(stat.)±5.7(syst.) MeV**
  - **Γ = 117±10(stat.)±8(syst.) MeV**
  - **Br(J/ψ→γX(2370)→γK$^+$K$^-$η')=(1.79±0.23±0.65)×10^{-5}**
  - **Br(J/ψ→γX(2370)→γKsKsη')=(1.18±0.32±0.39)×10^{-5}**

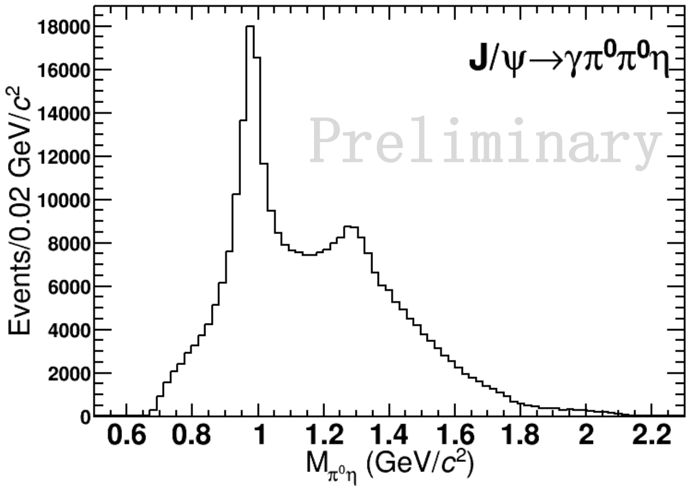
Observation: X(2370) new decay mode of KKη'

$\pi^0\pi^0\eta$ 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

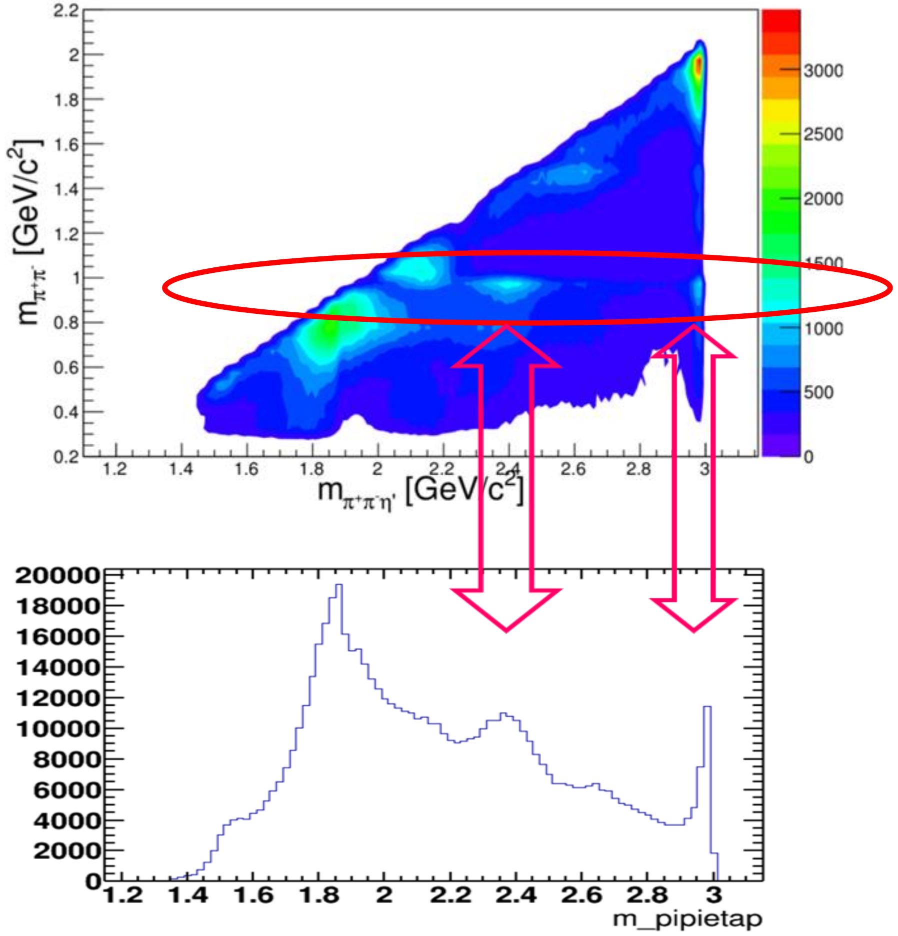
$a_0(980)$ sideband region
$0.2 < |m_{\pi^0\eta} - 0.98| < 0.25$ GeV

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

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

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

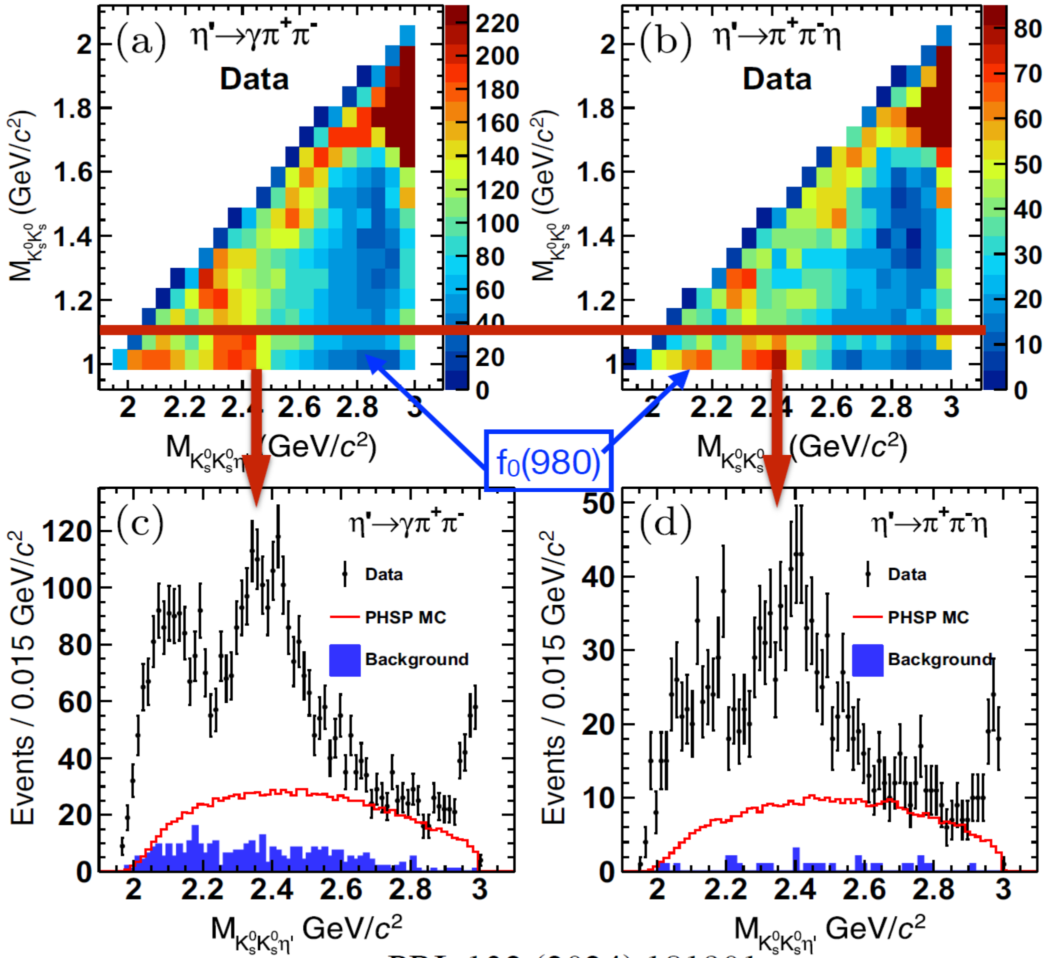
$M_{\pi^+\pi^-}$ vs $M_{\pi^+\pi^-\eta'}$



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

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

- 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)η'
  - η_c → KKη' dominantly via X(1800) η'
  - NO phase space for X(2370)→X(1800) η'



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