# Lightest $0^{-+}$ Glueball as Dominant Constituent of $X(2370)$


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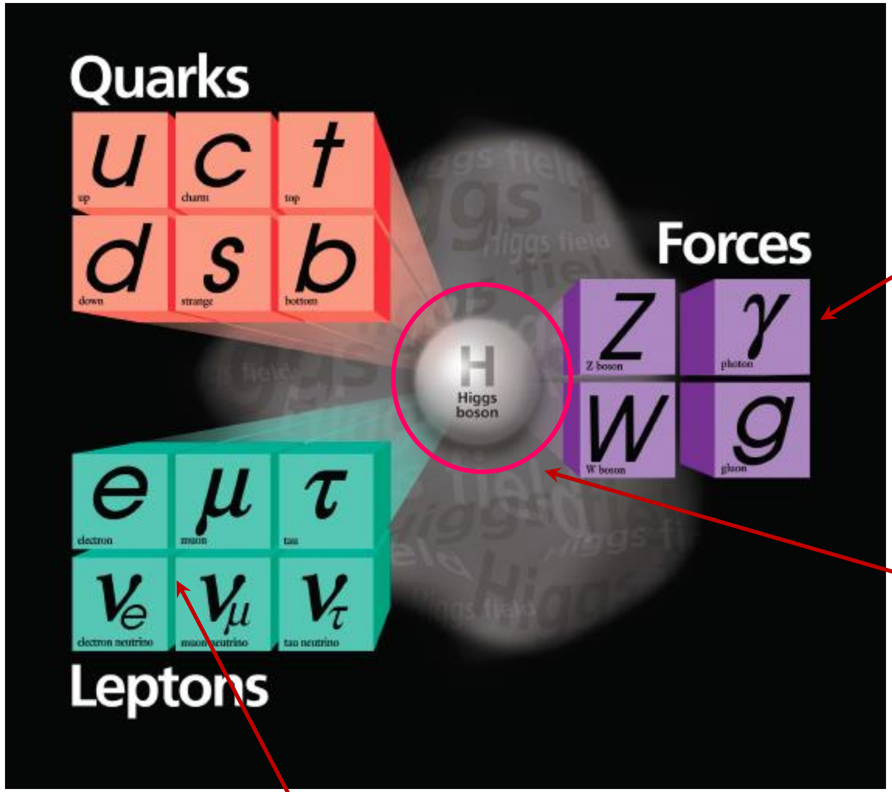
# Standard Model （Gauge Theory） describes EW and Strong interactions




**EW and strong interactions are mediated by gauge bosons:**
- **EW interaction by $\gamma/W/Z$**
- **Strong interaction by Gluons**

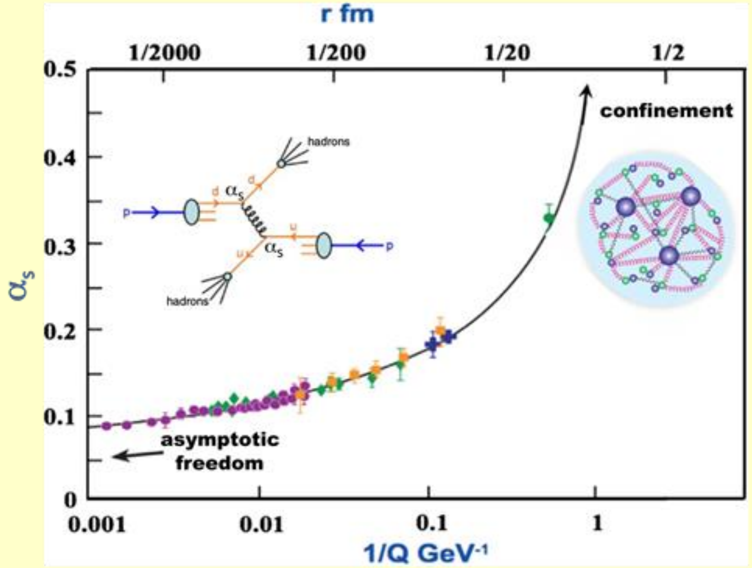
**Higgs Boson – origin of mass**

**Matter is made of leptons and quarks**

# QCD and its important predictions

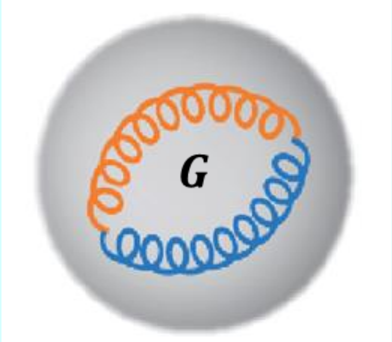
## QCD —— SU(3) non-Abelian gauge theory:

### At high energy




- $\alpha_s$ running, widely confirmed experimentally (Nobel Prize 2004)

### At low energy



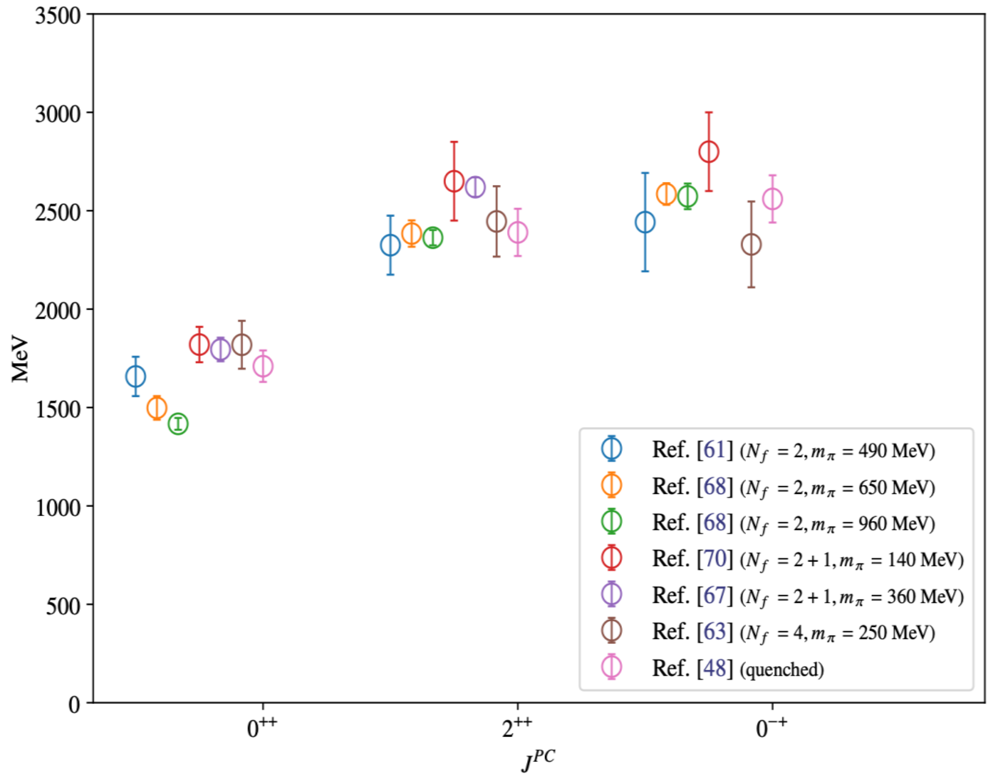

- self-interaction of gluons → bound states of gluons —— Glueballs
- Many candidates, not established yet

# Glueballs

- **Unique particles formed by gauge bosons due to non-Abelian self-interactions**
  - **Unique kind of matter made of pure force (unlike usual matter formed by fermions)**
- **Lattice QCD predictions**
  - $0^{++}$ **ground state:** $1.3\sim2\ \mathrm{GeV}/c^2$
  - $2^{++}$ **ground state:** $2.3\sim2.8\ \mathrm{GeV}/c^2$
  - $0^{-+}$ **ground state:** $2.3\sim3\ \mathrm{GeV}/c^2$

**→ All LQCD calculations predict the existence of glueballs.**

arxiv:2305.04869



# Unique Importance of Glueballs

- Direct proof of self-interactions of gluons — Direct proof of non-Abelian gauge interactions of QCD

- Unique particle/matter made of pure force （bosons）

（ called **‘force particle’,** ‘forcion?’ —— named by Yifang Wang, IHEP former Director）

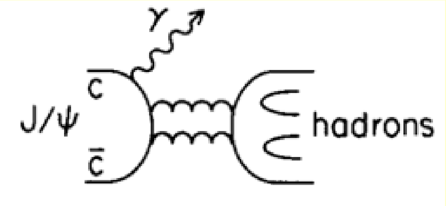
- Direct proof of origin of mass from strong interaction

# Glueball production and decays

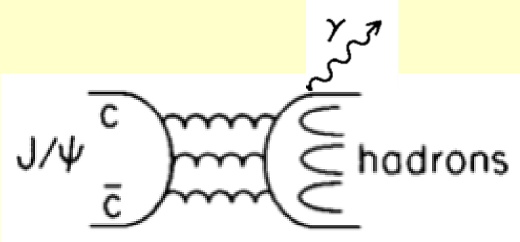
## — **Signatures of glueballs**

# Glueball production in J/ψ radiative decays

- **Gluon rich environment**



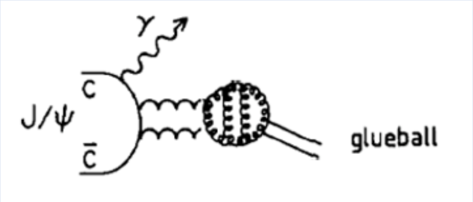

$\sim \alpha\alpha_s^4$



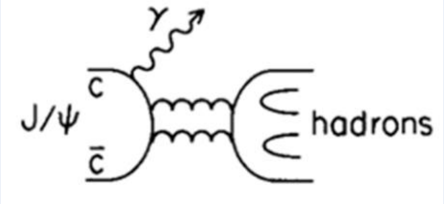

$\sim \alpha\alpha_s^6$

- **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




$\sim \alpha\alpha_s^2$




$\sim \alpha\alpha_s^4$

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

# LQCD Predictions on $B(J/\psi \to \gamma G_{0^{-+}})$

**LQCD prediction on lightest pseudoscalar glueball:**

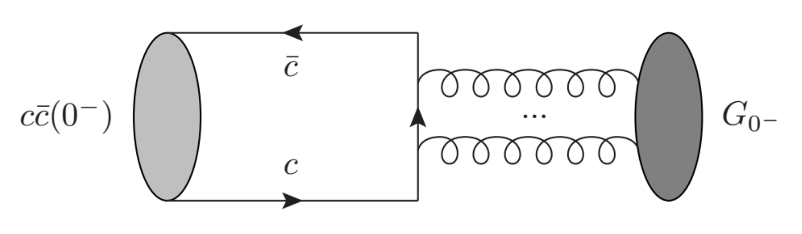
$$M = 2395 \pm 14\ \mathrm{MeV}$$

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

PRD 100 (2019) 054511

- LQCD also predicts the mixing mechanism between $0^{-+}$ $c\bar{c}$ and $0^{-+}$ glueball.

PLB 827 (2022) 136960




- Such a mixing mechanism can significantly increase the production rate of the mixture $0^{-+}$ particle to $(2\sim20) \times 10^{-3}$

  even with tiny mixing angle $2^o \sim 5^o$

arXiv: 2605.01757

→ High production rate is expected for $0^{-+}$ glueball in $J/\psi$ radiative decays.

# Glueball Decays ——
## flavor-singlet and decay pattern similarities to charmonium decays

**No rigorous predictions, but physics pictures are quite clear:**

**Glueballs** contain no quark flavor — **flavor-singlet states**

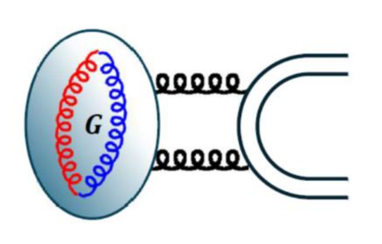
- Most important feature for glueballs
- Flavor symmetric decays into light hadrons
- For $0^{-+}$ glueball, $\boldsymbol{K^{*}\bar{K}}$ **mode is forbidden** due to generalized G-parity conservation.

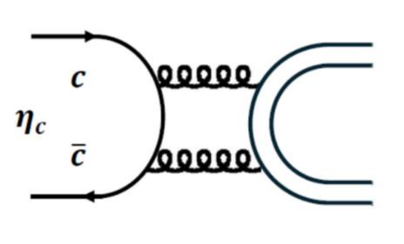
PLB 106 (1981) 114

PLB 109 (1982) 326

Phys. Rep. 454 (2007) 1

The glueball decays should have similar decay patterns to the charmonium families $(0^{++}-\chi_{c0}, 2^{++}-\chi_{c2}, 0^{-+}-\eta_c)$ since they all decay via gluons.

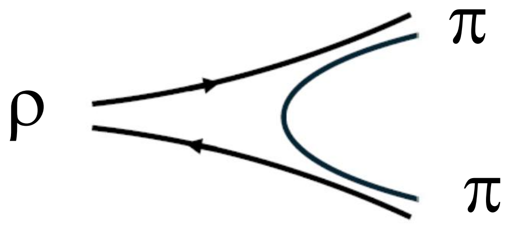


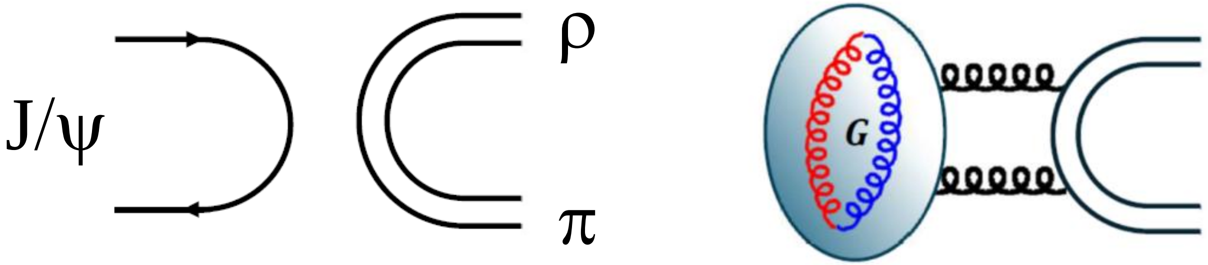

Commun.Theor.Phys. 24 (1995) 373 (hep-ph/9502408 )

PLB 380 (1996) 189

# Glueball Decays —
## OZI Forbidden decays and narrow partial widths



OZI allowed decays



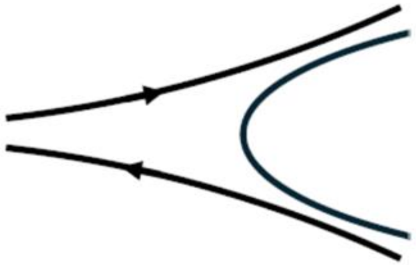
OZI forbidden decays

- Most light meson decays are OZI allowed decays:
  → Typical partial widths > 100MeV, and usually have dominant decay modes.
- $J/\psi$ and $\eta_c$ decays are all OZI forbidden decays:
  → Partial decay widths should be very **narrow** and have **no dominant** decay modes
  ➔ signature of gluon decays. ← Glueballs decay similarly

# Narrow partial decay width of $0^{-+}$ glueball

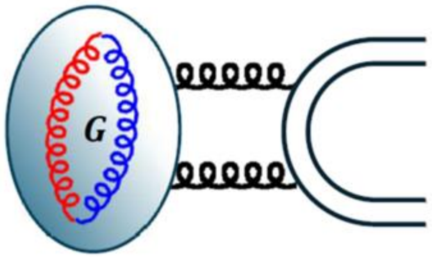
- Glueball width ~ $\sqrt{\text{OZI}}$ rule [Nucl. Phys. B 130 (1977) 328-348]

$$\Gamma(G_{0^{-+}} \to \pi\pi\eta) = \sqrt{\Gamma(\text{OZI allowed}) \times \Gamma(\eta_c \to \pi\pi\eta)}$$
$$= \sqrt{(100 \sim 200)\text{MeV} \times 0.5\text{MeV}}$$
$$\sim \text{a few MeV}$$

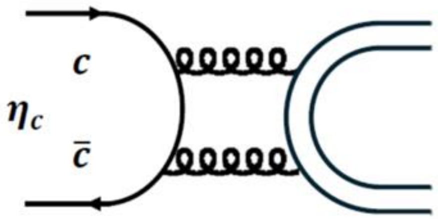


$\alpha_s^0$

OZI allowed decays




$\alpha_s^2$




$\alpha_s^4$

# Glueball Decays —

## suppressions of G $\rightarrow$ $\gamma\omega$, $\gamma\phi$

- $\gamma\omega$, $\gamma\phi$ decay modes are regarded as tags of $u\bar{u} + d\bar{d}$ and $s\bar{s}$ contents inside a meson, and are also called flavor filters. (PLB 164 (1985) 379, PRD 67 (2003) 074031)

- Glueballs contain no quarks, and gluons have no direct interaction with photons

  G $\rightarrow$ $\gamma\omega$, $\gamma\phi$ should be strongly suppressed

- $J/\psi \rightarrow \gamma\gamma\omega$, $\gamma\gamma\phi$ are good places to study this property.

# Expected Signatures of Glueball

- Production:

  high production rate in $J/\psi$ radiative decays

- Decay: via gluons
  - flavor-singlet state
  - decay pattern similarities to charmonium decays
  - narrow partial decay width to each mode
  - suppressions of $\gamma\omega$, $\gamma\phi$ decay modes

The combination of these signatures enable us to identify whether a particle is a glueball or not.

# PPP Modes — Golden Decay Modes for $0^{-+}$ Glueball Searches

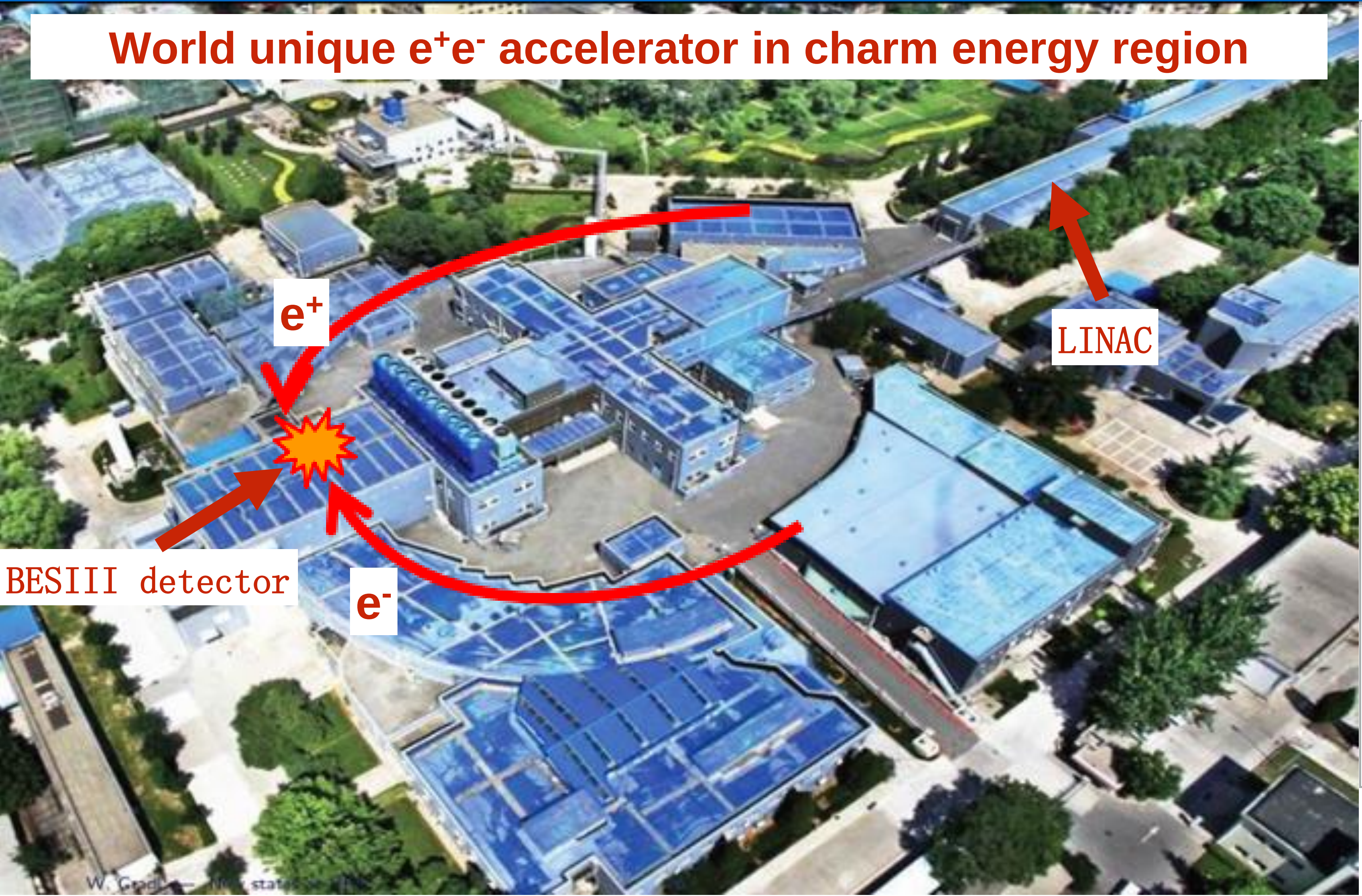


- Typically, $PPP$ (3 pseudoscalar mesons, such as $\pi\pi\eta, \pi\pi\eta', K\bar{K}\pi$) modes are believed as golden decay modes in $0^{-+}$glueball searches.
  - $S$ –wave decays for $0^{-+}$ mesons, no suppression factor, major decay modes
  - $PPP$ modes are either forbidden or strongly suppressed in $0^{++}$or $2^{++}$ 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 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 two-body sequential decays, i.e., mainly via $f_2(1270)$, $a_1(1260)$ pair intermediate states — $0^{-+}$ glueball mass may not be high enough, i.e., $PS$ is not allowed.

Low Sensitivity

# BESIII Studies on X(2370)

# Beijing Electron Positron Collider (BEPCII)



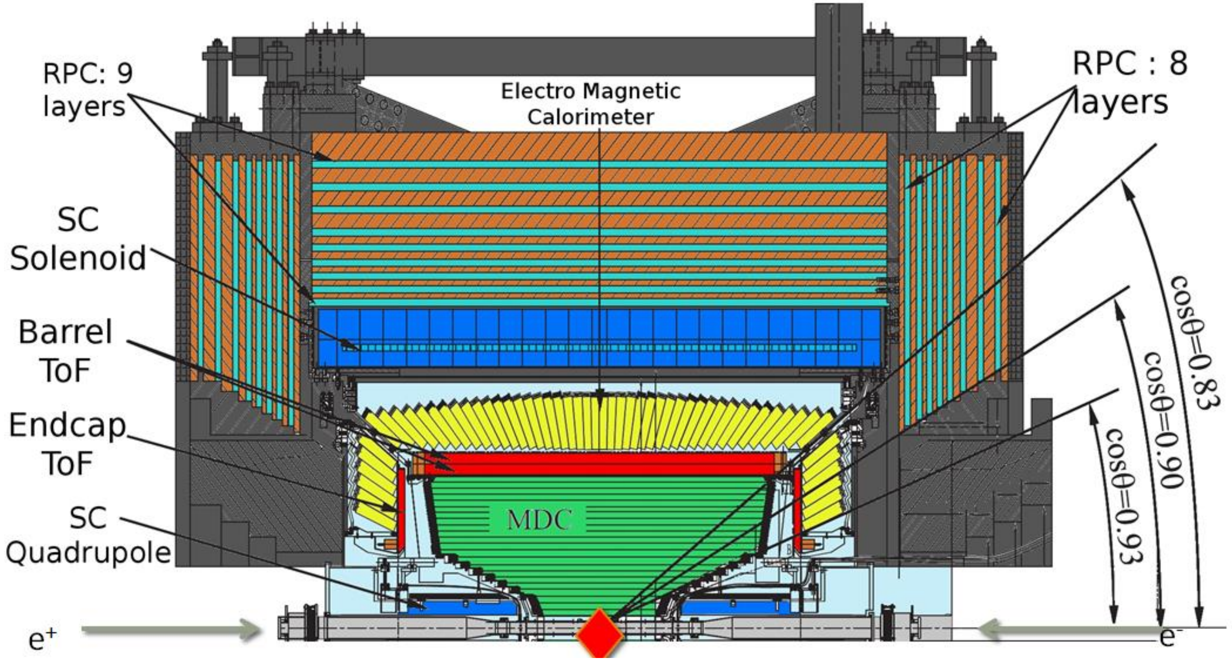

2004-2008: Construction

- Double rings
- Beam energy:
  1.0 – 2.3 (2.45) GeV
- Designed luminosity:
  $1 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

2009-now: BESIII physics runs

# BESIII detector

Designed for neutral and charged particles with excellent resolution, PID, and large coverage




Total weight 730 tons,
~40,000 readout channels
Data rate: 5k Hz, 50 Mb/s

- MDC: small cell & He gas
  - $\sigma_{xy}$ = 130 μm
  - $\sigma_p/p$=0.5% @1GeV
  - dE/dx = 6%
- TOF: plastic scintillator/MRPC
  - $\sigma_T$ = 80 ps Barrel
  - $\sigma_T$ = 110 (60) ps Endcap
- EMC: CsI crystals
  - $\Delta E/E$ = 2.5% @ 1GeV - Barrel
  - $\Delta E/E$ = 5% @ 1GeV - Endcap
- Muon ID: 9 layer RPC
- Magnet: 1T Superconducting

**In full operation since 2008, all sub-detectors are in a very good condition!**

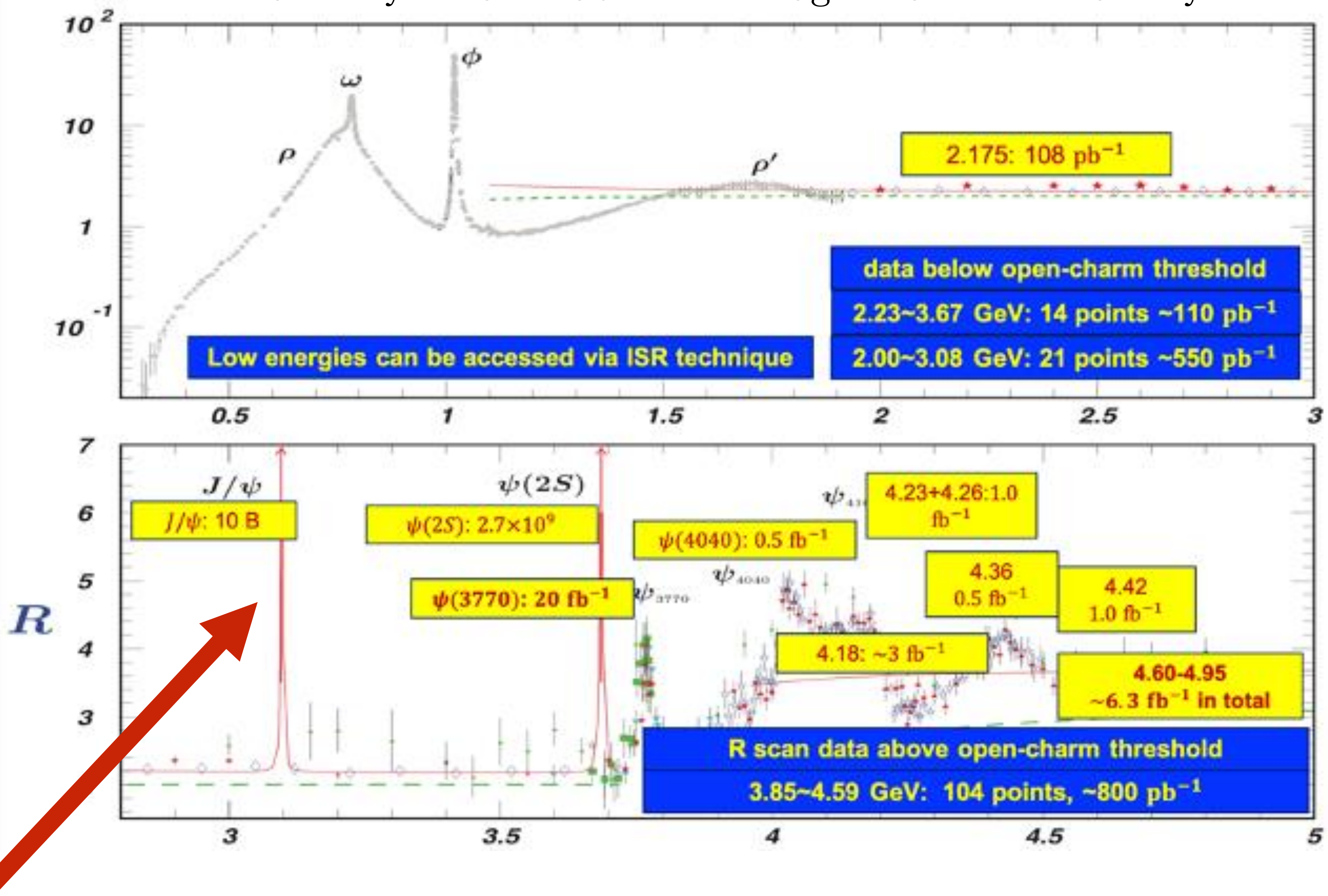
# BESIII Data samples

Data sets collected so far:

- ✦ $10\times10^{9}$ J/ψ events
- ✦ $2.7\times10^{9}$ ψ(2S) events
- ✦ 20 $fb^{-1}$ ψ(3770)
- ✦ Scan data between 1.8 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 50$fb^{-1}$ integrated luminosity




**Huge 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 $J/\psi$ data, we should be able to answer this key question — either we find them, or exclude them.
  - BESIII Physics Yellow Book

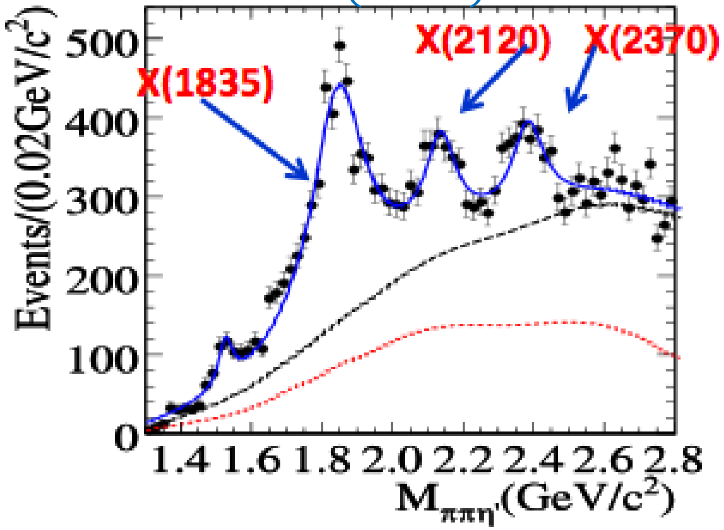
→ We started to find the answer…

# Discovery of $X(2370)$

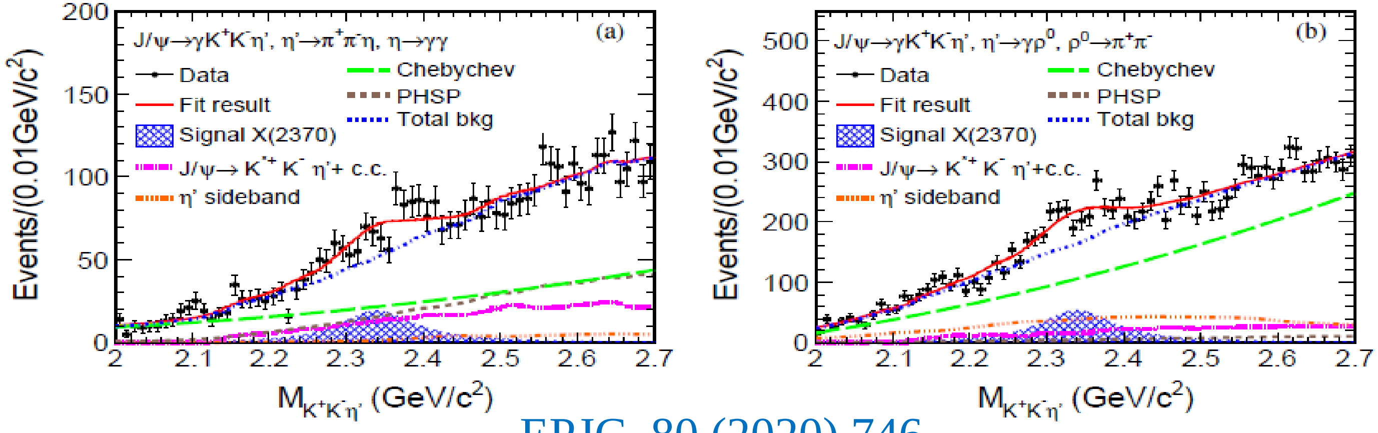
- **Discovered by BESIII in $J/\psi \to \gamma\pi^+\pi^-\eta'$ in 2011.**

| 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 |

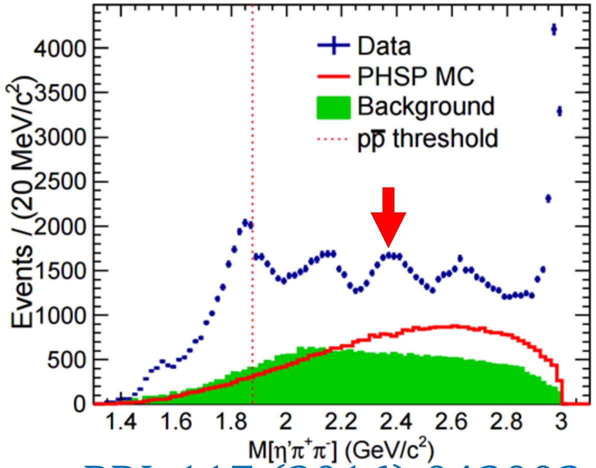
PRL106 (2011) 072002




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

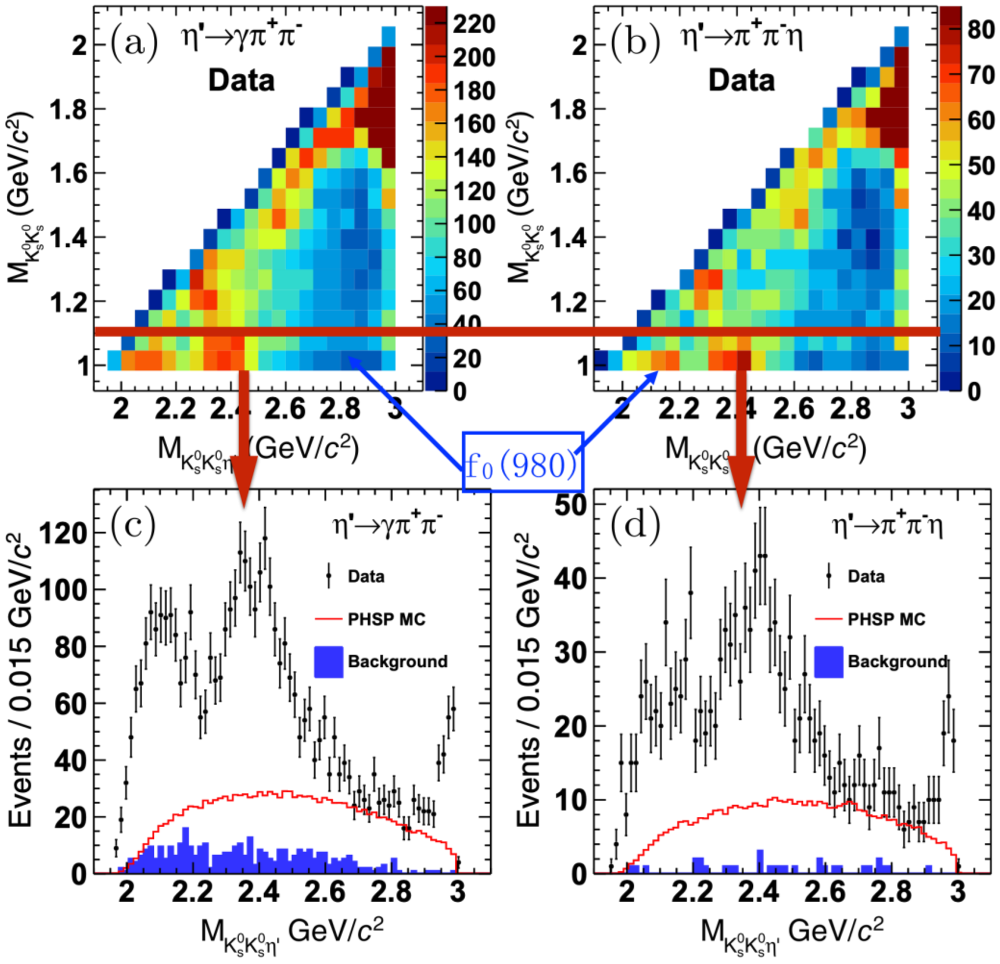



EPJC 80 (2020) 746




PRL 117 (2016) 042002

# Spin-parity Determination of $X(2370)$ in J/ψ→$\gamma K_S^0 K_S^0 \eta'$




[PRL 132 (2024) 181901](PRL 132 (2024) 181901)

- Almost background free channel
- 10 billion $J/\psi$ data
- Very good BESIII detector performance

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

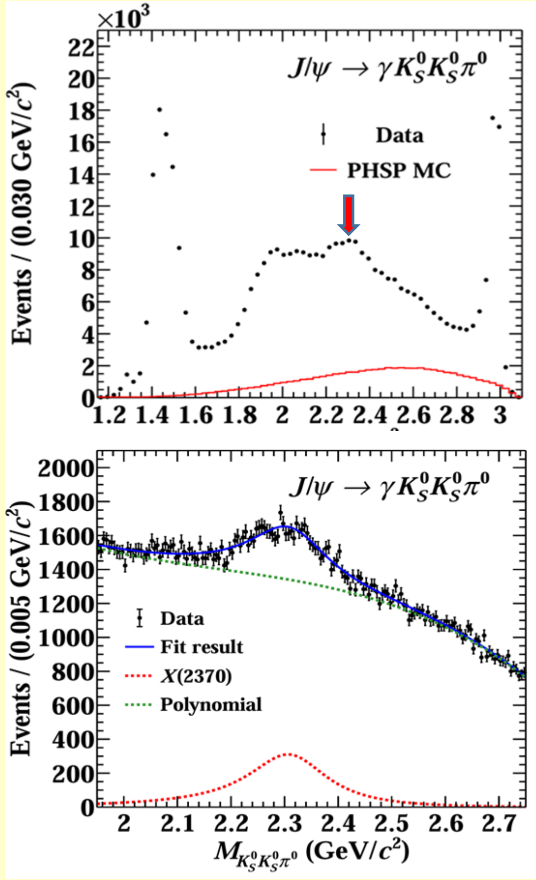
$$M = 2395 \pm 11^{+26}_{-94}\ \mathrm{MeV}$$

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

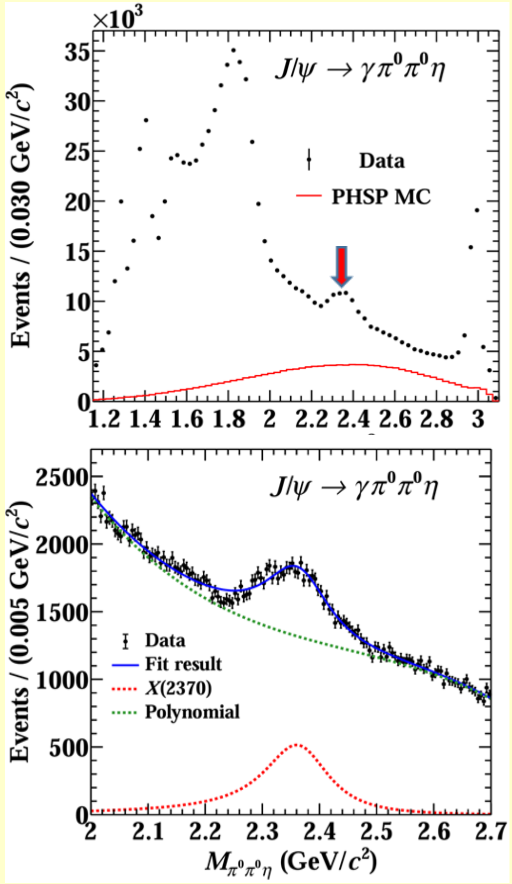
$$B\big(J/\psi \to \gamma X(2370)\big) \times B(X(2370) \to f_0(980)\eta') \times B\big(f_0(980) \to K_S^0 K_S^0\big) = \big(1.31 \pm 0.22 \pm^{+2.85}_{-0.84}\big) \times 10^{-5}$$

# New decay modes: X(2370) $\rightarrow K_S^0 K_S^0 \pi^0$, $\pi^0\pi^0\eta$, $a_0(980)\pi^0$

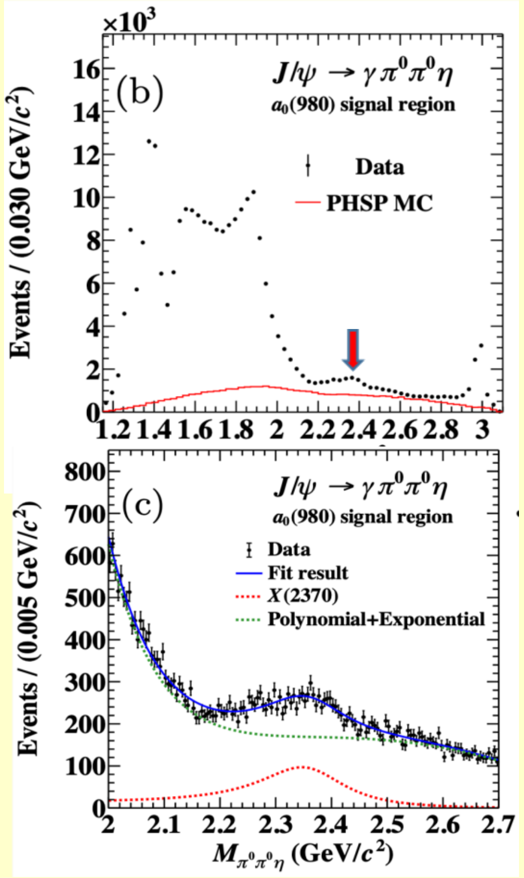
Observed X(2370) decay modes show strong similarities to those of $\eta_c$




$X(2370) \rightarrow K_S^0 K_S^0 \pi^0$ $(> 14\sigma)$




$X(2370) \rightarrow \pi^0\pi^0\eta$ $(> 20\sigma)$

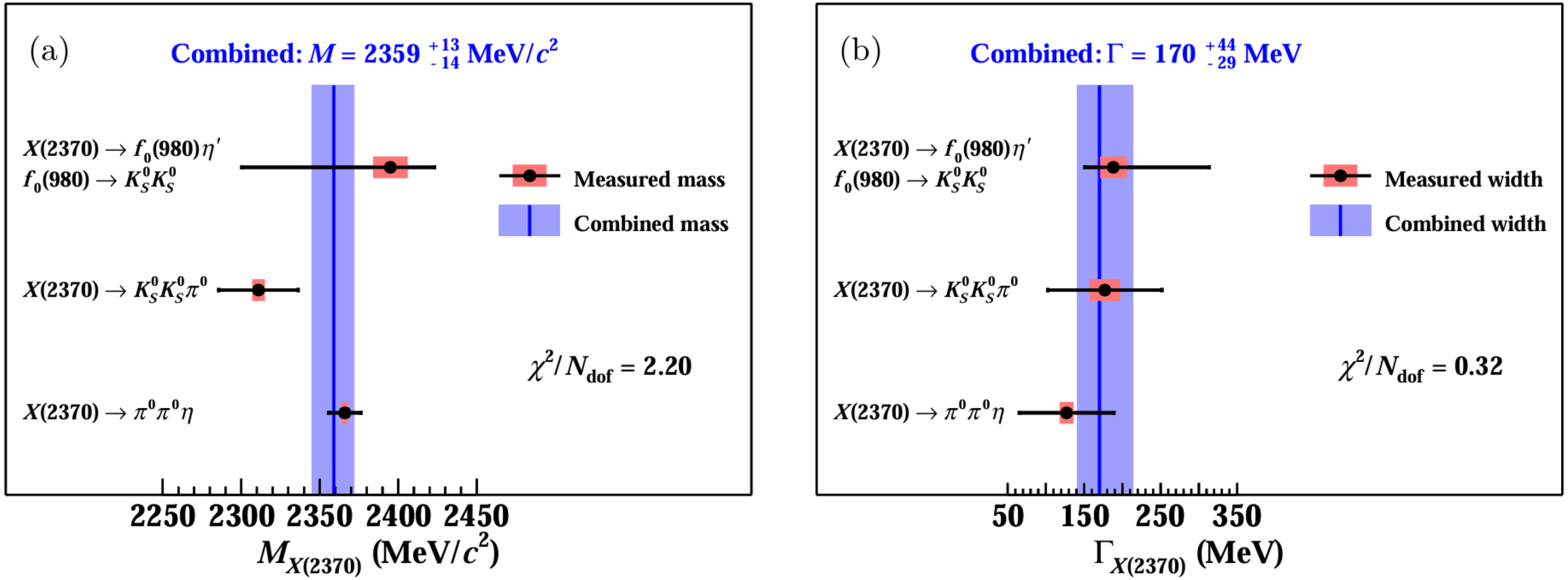



$X(2370) \rightarrow a_0(980)\pi^0$ $(> 9\sigma)$

arxiv:2605.26495

# $X(2370)$ Combined Mass and Width

arxiv：2605.26495




Combined result:

$$M_{X(2370)} = 2359^{+13}_{-14}\mathrm{MeV}/c^2$$

$$\Gamma_{X(2370)} = 170^{+44}_{-29}\mathrm{MeV}$$

# High production rate of $B(J/\psi \to \gamma X(2370))$

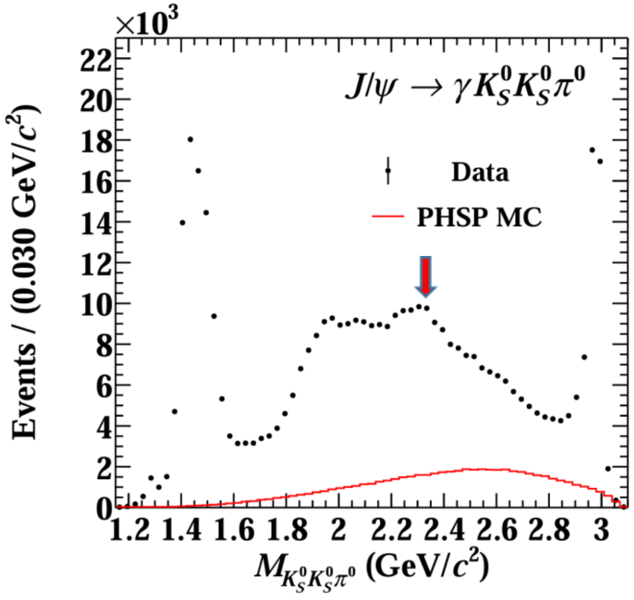
| Decay channel | $\mathcal{B}$ $(\times 10^{-4})$ |
|---|---|
| $J/\psi \to \gamma X(2370) \to \gamma K\bar{K}\pi$ | $3.25 \pm 0.25^{+0.73}_{-0.75}$ |
| $J/\psi \to \gamma X(2370) \to \gamma\pi\pi\eta$ | $3.2 \pm 0.1^{+0.9}_{-1.0}$ |
| $J/\psi \to \gamma X(2370) \to \gamma\pi\pi\eta'$ | $1.94 \pm 0.04^{+0.33}_{-0.88}$ |
| $J/\psi \to \gamma X(2370) \to \gamma K\bar{K}\eta'$ | $0.39 \pm 0.05 \pm 0.10$ |

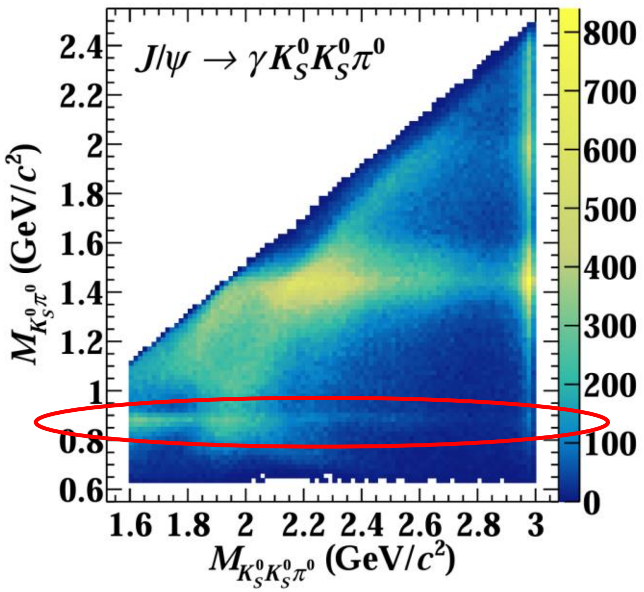
- The total sum from the left table is $\sim 0.9 \times 10^{-3}$
- Considering other unmeasured decay modes, it is reasonable to conclude:

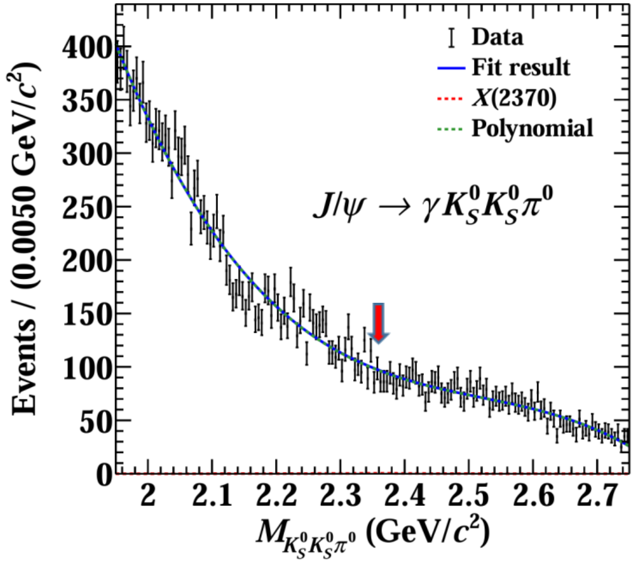
$$B(J/\psi \to \gamma X(2370)) > 1 \times 10^{-3}$$

# Flavor-singlet state: non-observation of $X(2370) \to K^*(892)\bar{K} + \text{c.c.}$

Forbidden by Generalized G-parity conservation




Significance of the $X(2370) = 0.1\sigma$

$$\mathcal{B}[J/\psi \to \gamma X(2370)] \times \mathcal{B}\left[X(2370) \to K^*(892)^0 K_S^0 + \text{c.c.} \to K_S^0 K_S^0 \pi^0\right] < 2.7 \times 10^{-6} \text{ @90\% C.L.}$$

$$\frac{\mathcal{B}[X(2370) \to K^*(892)^0 K_S^0 + \text{c.c.} \to K_S^0 K_S^0 \pi^0]}{\mathcal{B}[X(2370) \to K_S^0 K_S^0 \pi^0]} < 0.081 \text{ @90\% C.L.}$$

X(2370) is a flavor-singlet state, the first observed above 1 GeV.

# Narrow partial decay widths of X(2370)

| Decay channel | $\mathcal{B}$ $(\times 10^{-4})$ |
|---|---|
| $J/\psi \to \gamma X(2370) \to \gamma K\bar{K}\pi$ | $3.25 \pm 0.25^{+0.73}_{-0.75}$ |
| $J/\psi \to \gamma X(2370) \to \gamma\pi\pi\eta$ | $3.2 \pm 0.1^{+0.9}_{-1.0}$ |
| $J/\psi \to \gamma X(2370) \to \gamma\pi\pi\eta'$ | $1.94 \pm 0.04^{+0.33}_{-0.88}$ |
| $J/\psi \to \gamma X(2370) \to \gamma K\bar{K}\eta'$ | $0.39 \pm 0.05 \pm 0.10$ |

- These processes are dominated by S-wave two-body decay process, with flavor symmetry

a) $K\bar{K}\eta'$ : $f_0(980)\eta'$

b) $\pi\pi\eta'$ : $f_0(980)\eta'$, $f_0(500)\eta'$

c) $\pi\pi\eta$ : $a_0(980)\pi^0$, $f_0(500)\eta$, $f_0(1500)\eta$, $f_0(1710)\eta$

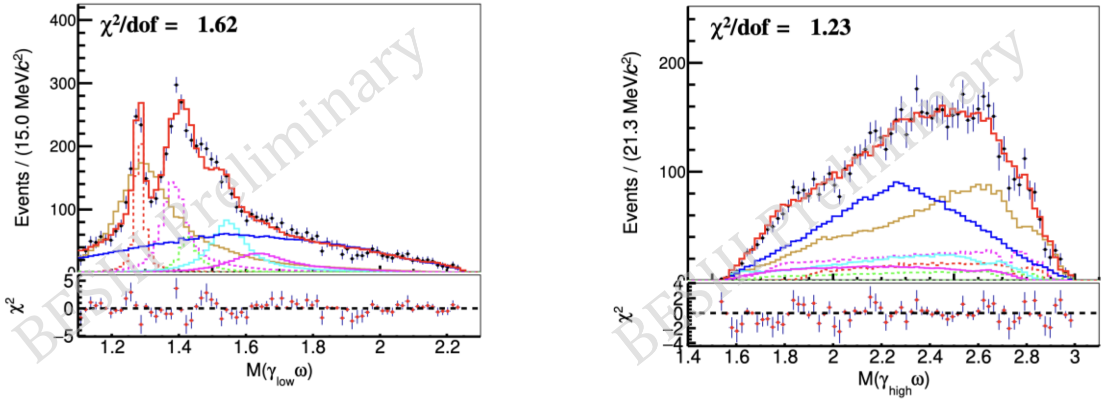
d) $K\bar{K}\pi$: $K_0^*(1430)\bar{K}$, $K_0^*(800)\bar{K}$, $a_0(980)\pi^0$, many more isospin combinations

- There may be other unmeasured decay modes of X(2370) , such as VV, multi-pion modes

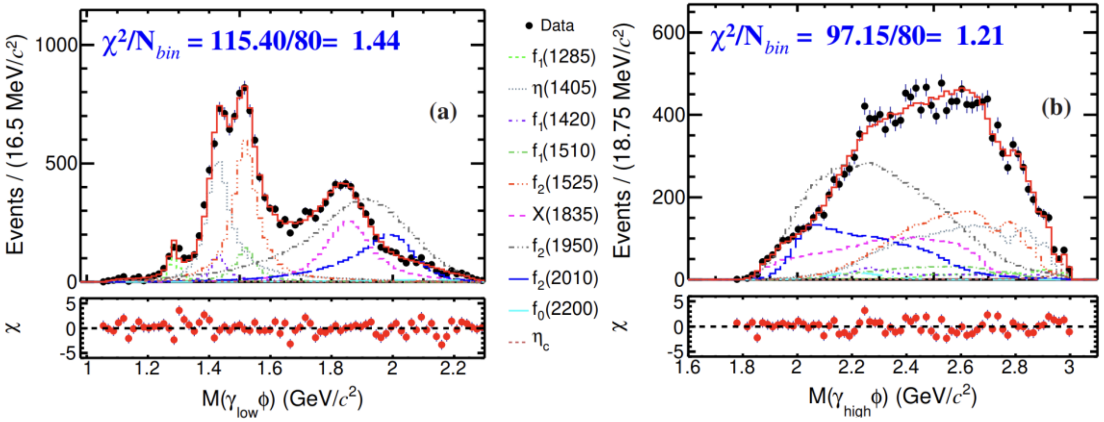
→ Each above S-wave two-body decay mode has a BR 1~10%, corresponding to a partial width ~ a few MeV, since X(2370) total width is only ~150MeV

# Suppressions of X(2370) → γω, γϕ

J/ψ → γγω




J/ψ → γγϕ




PRD 111(2025) 052011

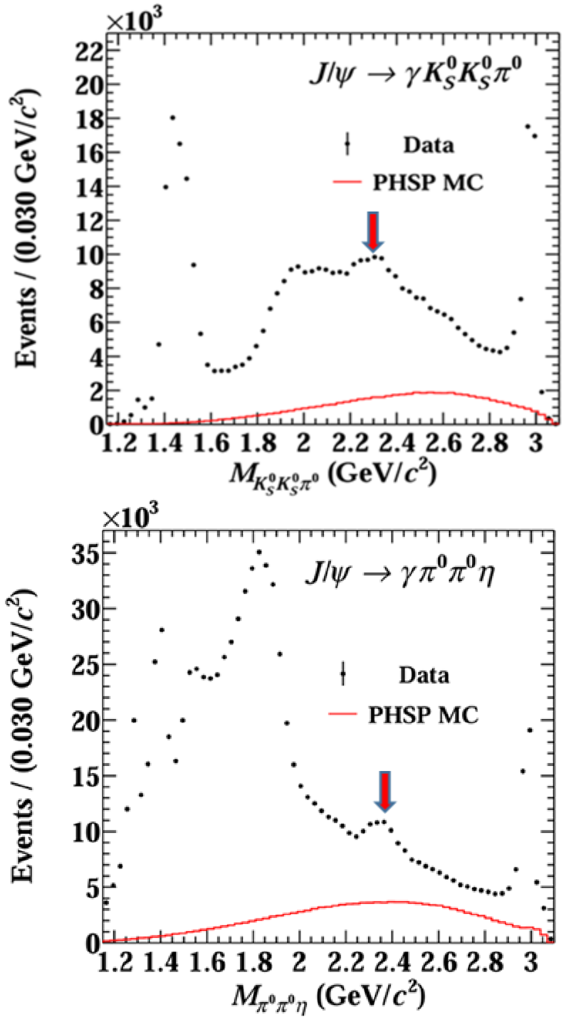
- J/ψ → γγω, γγϕ have been studied with amplitude analysis at BESIII

| Resonance $R$ | $J/\psi \to \gamma R \to \gamma\gamma\omega$ $(\times 10^{-6})$ [29] | $J/\psi \to \gamma R \to \gamma\gamma\phi$ $(\times 10^{-6})$ [30] |
|---|---|---|
| $\eta(1405)$ | $3.54 \pm 0.20^{+0.65}_{-0.24}$ | $3.57 \pm 0.18^{+0.59}_{-0.61}$ |
| $X(1835)$ | $< 0.11$ | $3.37 \pm 0.19^{+0.78}_{-1.10}$ |
| $X(2370)$ | $< 0.04$ | $< 0.11$ |

- With $B\big(J/\psi \to \gamma X(2370)\big) > 1 \times 10^{-3}$, these suppressions are very strong

# Examine consistencies of X(2370) with glueballs and other interpretations

# High production rate of $B(J/\psi \to \gamma X(2370))$




$$B(J/\psi \to \gamma X(2370)) > 1 \times 10^{-3}$$

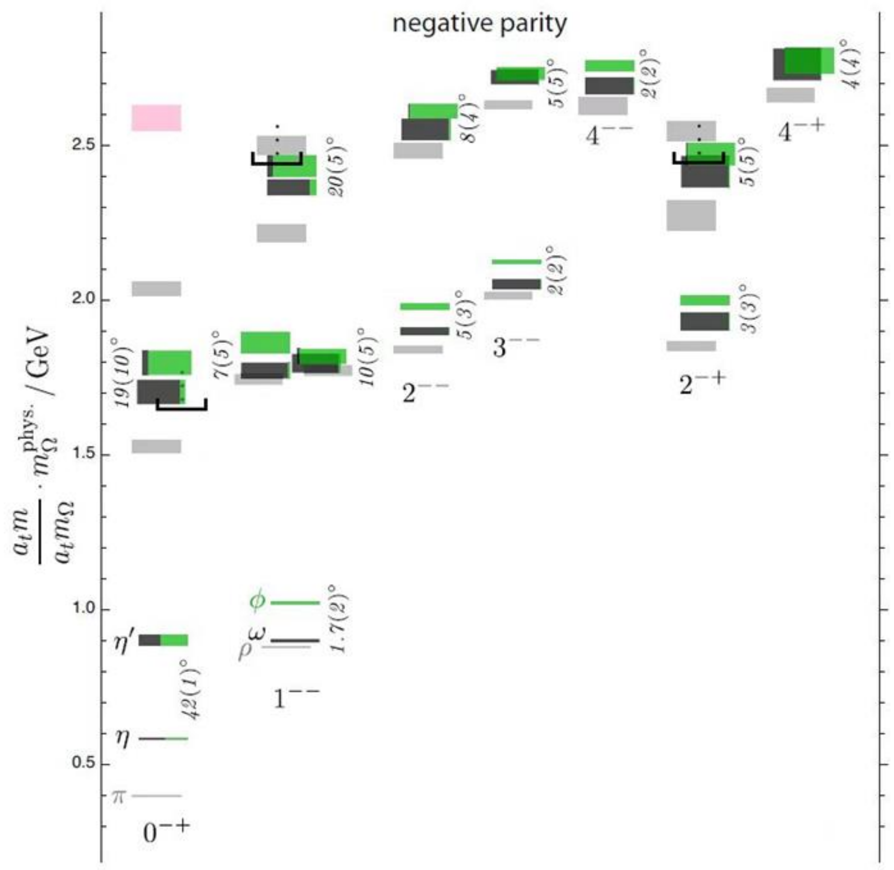
- High production rate is expected by glueball+$c\bar{c}$ mixing mechanism

- X(2370) is unique between 2.3GeV and $\eta_c$ as seen in left plots

→Other $0^{-+}$ mesons either with much lower production rates or with much broader widths than X(2370)

- Disfavor baryonium-like states, given (PDG 2026):
  - $B(J/\psi \to \gamma \Lambda\bar{\Lambda}) < 1.3 \times 10^{-4}$ @ 90% C.L.
  - $B(J/\psi \to \gamma p\bar{p}) = (3.8 \pm 1.0) \times 10^{-4}$

# X(2370) is flavor-singlet




PRD 83 (2011) 111502

Most important glueball expectation

Disfavor $q\bar{q}$ interpretation

- LQCD prediction: no flavor-singlet from $u\bar{u} + d\bar{d}$ and $s\bar{s}$ mixing above 1GeV
  - PDG data support this prediction

Hybrid and multiquark states can hardly form flavor-singlet states

# X(2370) decays similar to $\eta_c$

- Expected for $0^{-+}$ glueball

- Other interpretations can hardly explain this, e.g., full strange tetraquark states cannot have such similarities.

# Narrow partial decay widths of X(2370)

- Expected for glueball decays
  - Estimated from $\sqrt{\mathrm{OZI}}$ rule ~ a few MeV

- Disfavor $q\bar{q}$ , multi-quark or hybrid states (with $q\bar{q}$ inside them )
  - They are all dominated by OZI allowed decays (typical decay width ~ 100MeV)

# Strong suppressions of X(2370) $\rightarrow \gamma\omega, \gamma\phi$

- Expected for $0^{-+}$ glueball

- Light $q\bar{q}$ content inside X(2370) should be very small

# Summary

- Properties of $X(2370)$ :
  - high production rate in $J/\psi$ radiative decays
  - flavor-singlet state
  - decay pattern similarities to $\eta_c$
  - narrow partial decay widths
  - strong suppressions of $\gamma\omega$, $\gamma\phi$ decays
- These properties are fully consistent with the expected signatures of glueball.
  - Other interpretations can hardly explain all of them simultaneously
- The lightest $0^{-+}$ glueball is needed for a natural and complete explanation of X(2370) properties measured by BESIII.

**→ The lightest $0^{-+}$ glueball is the dominant constituent of X(2370)**

# Summary

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  - high production rate in J/ψ radiative decays
  - flavor-singlet state
  - decay pattern similarities to $\eta_c$
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**→ The lightest $0^{-+}$ glueball is the dominant constituent of X(2370)**

Thanks!

backup

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

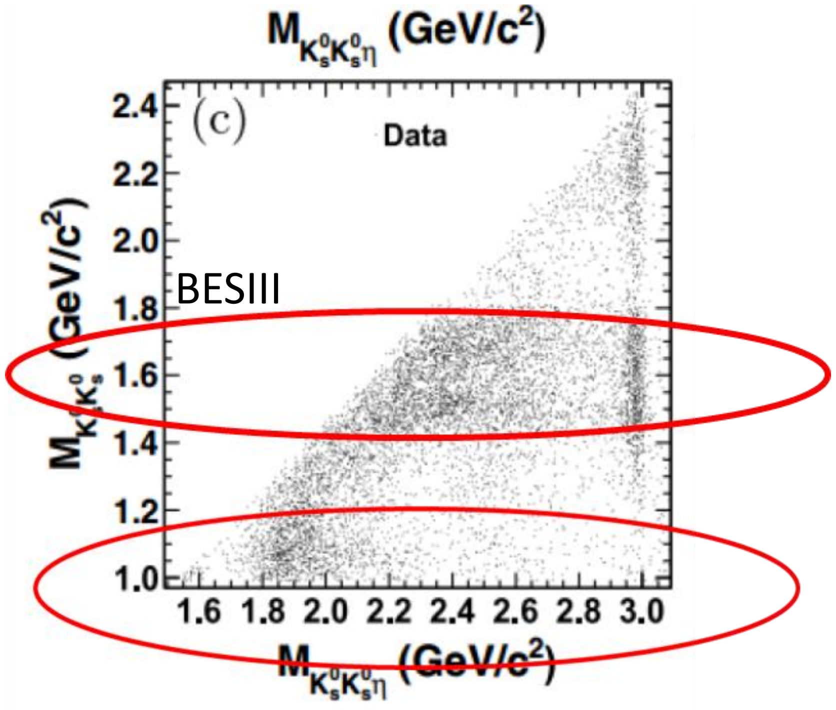
In the 2D mass plot of $M_{K_S^0 K_S^0}$ $vs.$ $M_{K_S^0 K_S^0 \eta}$ in the BESIII paper on the spin-parity determination of the $X(1835)$, qualitatively, we can clearly observe:

- 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 $\eta_c$.

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

- In the lower $M_{K_S^0 K_S^0}$ mass band of $f_0(980)$, no $X(2370)$, nor $\eta_c$.

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




PRL 115, 091803 (2015)

**→High similarities between $X(2370)$ and $\eta_c$ decays!**

# 5 major $\eta_c$ decay modes（from PDG）— 5 “Golden” modes in $0^{-+}$ glueball traditional searches

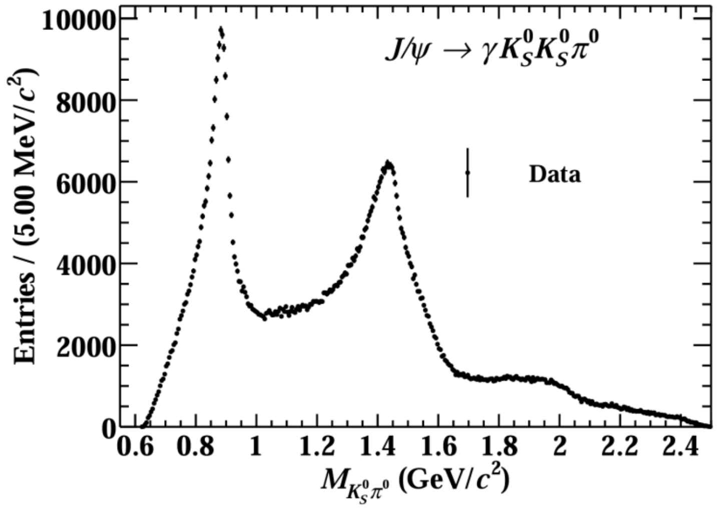
| Decays involving hadronic resonances | |
|---|---|
| $\eta'(958)\pi\pi$ | $(2.0 \pm 0.4)$ % |
| $\eta'(958)K\overline{K}$ | $(1.73 \pm 0.35)$ % |

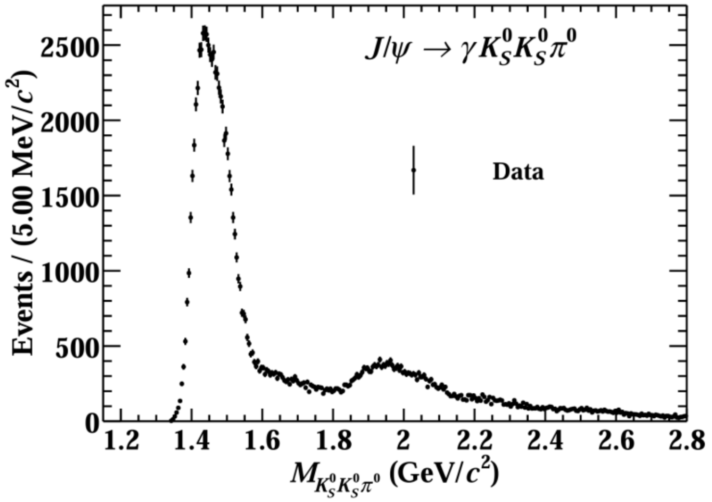
| Decays into stable hadrons | |
|---|---|
| $K\overline{K}\pi$ | $(7.1 \pm 0.4)$ % |
| $K\overline{K}\eta$ | $(1.32 \pm 0.15)$ % |
| $\eta\pi^+\pi^-$ | $(1.6 \pm 0.4)$ % |

$X(2370)$ is observed in all 5 modes

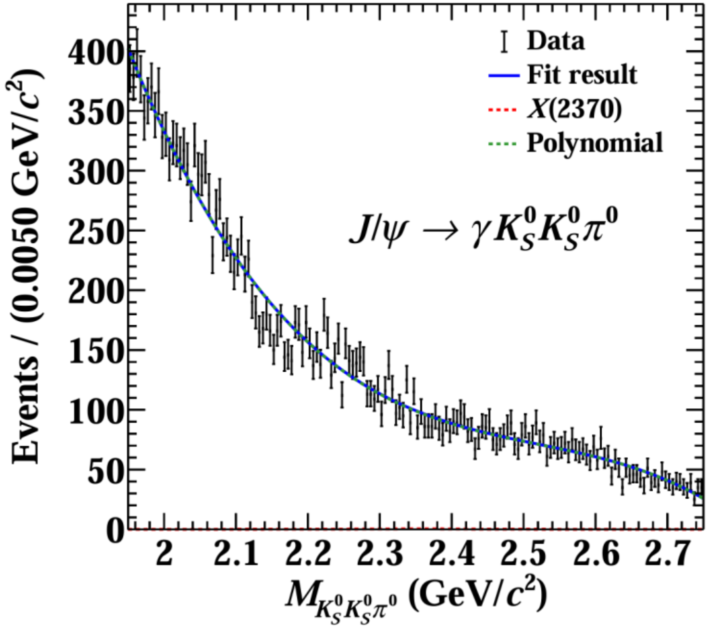
→ High similarities between $X(2370)$ and $\eta_c$ decays

# Searching for $X(2370) \to K^*(892)\bar{K} + \mathrm{c.c.} \to K_S^0 K_S^0 \pi^0$




Significance of the $X(2370) = 0.1\sigma$




$$\mathcal{B}[J/\psi \to \gamma X(2370)] \times \mathcal{B}[X(2370) \to K^*(892)^0 K_S^0 + \mathrm{c.c.} \to K_S^0 K_S^0 \pi^0]$$
$$= (0.1 \pm 1.2(\mathrm{stat}) \pm 1.1(\mathrm{syst})) \times 10^{-6}$$

$$\mathcal{B}[J/\psi \to \gamma X(2370)] \times \mathcal{B}\left[X(2370) \to K^*(892)^0 K_S^0 + \mathrm{c.c.} \to K_S^0 K_S^0 \pi^0\right]$$
$$< 2.7 \times 10^{-6}\ @90\%\ \mathrm{C.L.}$$

$$\frac{\mathcal{B}[X(2370) \to K^*(892)^0 K_S^0 + \mathrm{c.c.} \to K_S^0 K_S^0 \pi^0]}{\mathcal{B}[X(2370) \to K_S^0 K_S^0 \pi^0]} = 0.003 \pm 0.040(\mathrm{stat}) \pm 0.026(\mathrm{syst})$$

$$\frac{\mathcal{B}[X(2370) \to K^*(892)^0 K_S^0 + \mathrm{c.c.} \to K_S^0 K_S^0 \pi^0]}{\mathcal{B}[X(2370) \to K_S^0 K_S^0 \pi^0]} < 0.081\ @90\%\ \mathrm{C.L.}$$

# Estimation of constraint on normal $q\bar{q}$ contribution inside $X(2370)$ based on $K^*\bar{K}$ upper limit

- Theoretical calculations on the partial width of normal $q\bar{q} \to K^*\bar{K}$ is about 20~200 MeV
- $Br(X(2370) \to K^*\bar{K} + \mathrm{c.c.})/Br(X(2370) \to KK\pi) < 0.08$
- Reasonable assumption: $Br(X(2370) \to KK\pi) < 10\%$
- Then we have $Br(X(2370) \to K^*\bar{K} + \mathrm{c.c.}) < 0.008$

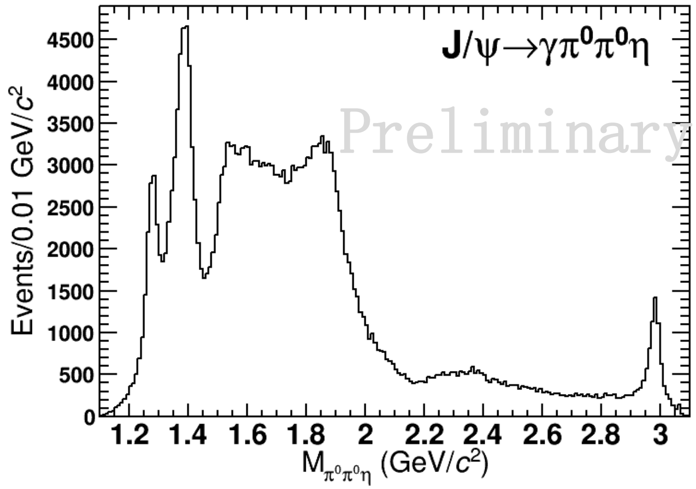
  → partial width of $X(2370) \to K^*\bar{K} < 2MeV$

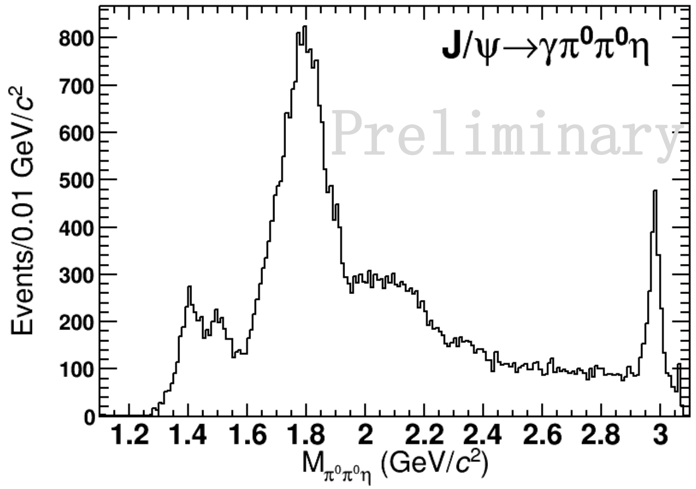
So the normal $q\bar{q}$ contribution in $X(2370) < 10\%$~$1\%$

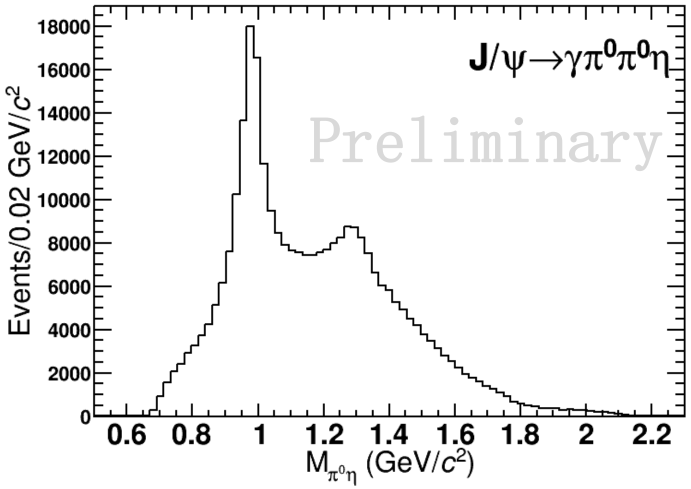
→ normal $q\bar{q}$ contribution inside $X(2370)$ is very small!

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

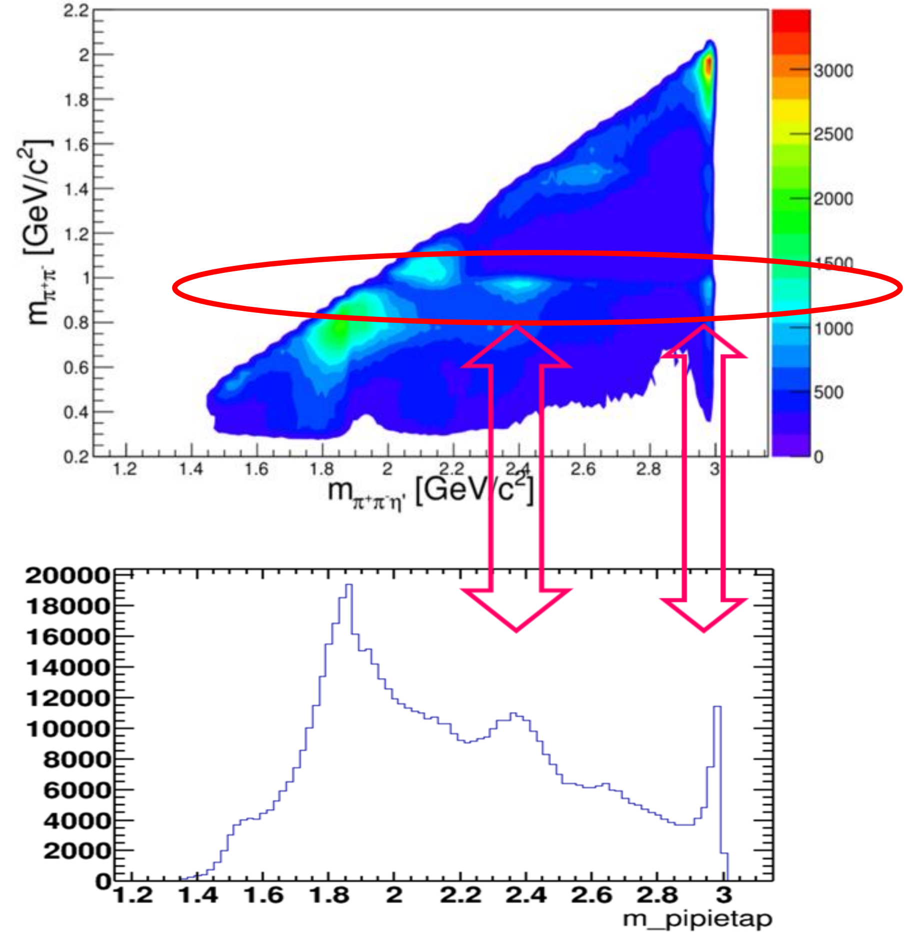
$a_0(980)$ sideband region
$0.2 < |m_{\pi^0\eta} - 0.98| < 0.25$ GeV

$M(\pi^0\pi^0\eta) > 2$ 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 $\eta_c$
- Additional important information:
  - $X(2370) \to \pi\pi\eta'$ almost 100% via $f_0(980)\eta'$
  - $\eta_c \to \pi\pi\eta'$ dominantly via $X(1800)\eta'$
  - NO phase space for $X(2370) \to X(1800)\eta'$

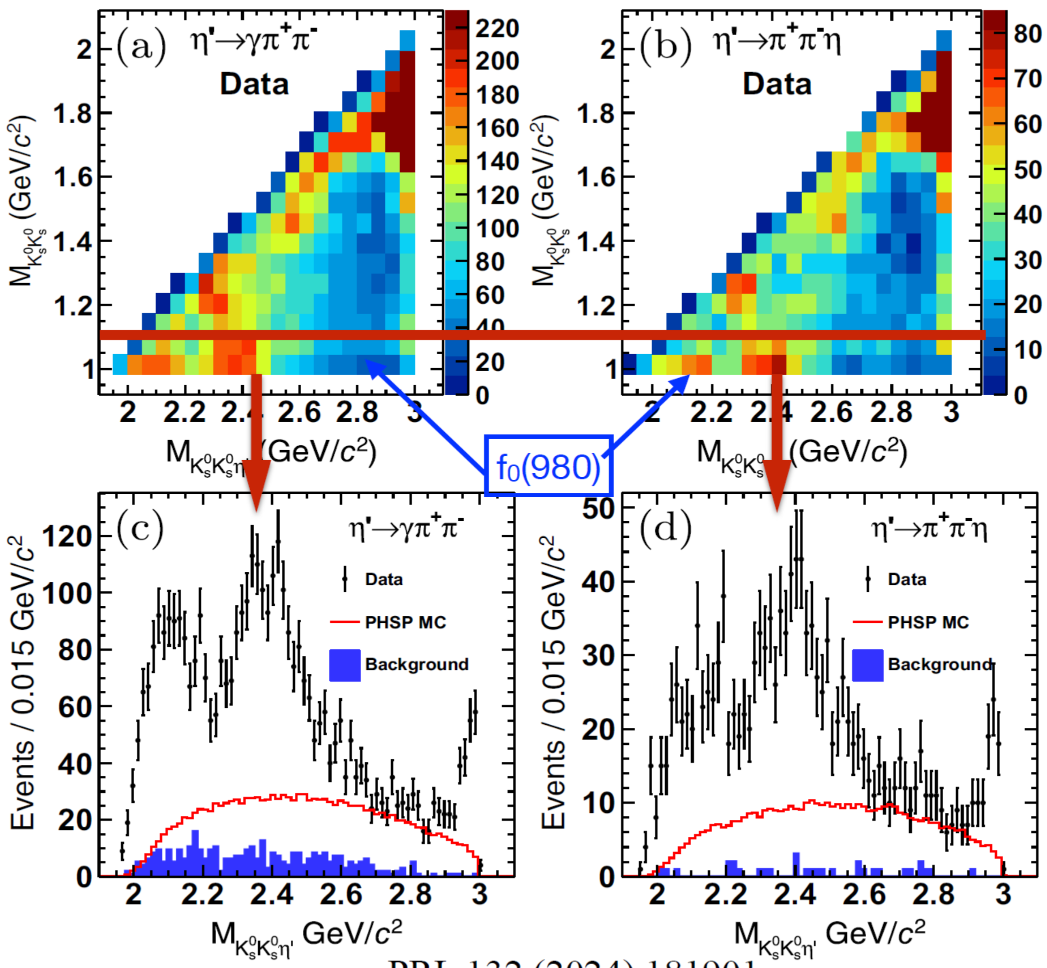
$M_{\pi^+\pi^-}$ vs $M_{\pi^+\pi^-\eta'}$




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

# $J/\psi \to \gamma K_S^0 K_S^0 \eta'$

- In the $f_0(980)$ mass band of $K_S^0 K_S^0$ mass, clear signals of both $X(2370)$ and $\eta_c$
- Additional important information:
  - $X(2370) \to K\bar{K}\eta'$ almost 100% via $f_{0(980)}\eta'$
  - $\eta_c \to KK\eta'$ dominantly via $X(1800)\eta'$
  - NO phase space for $X(2370) \to X(1800)\eta'$

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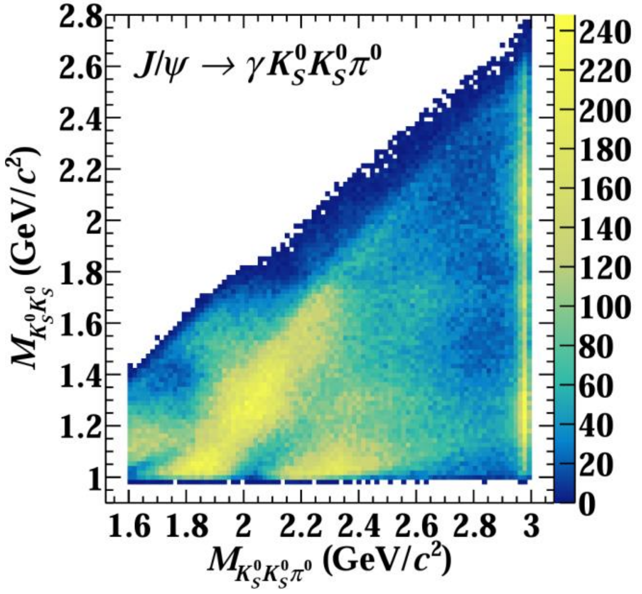
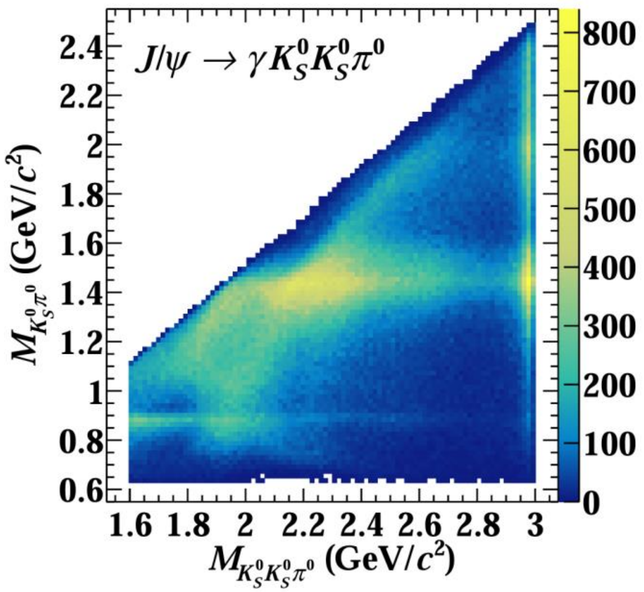
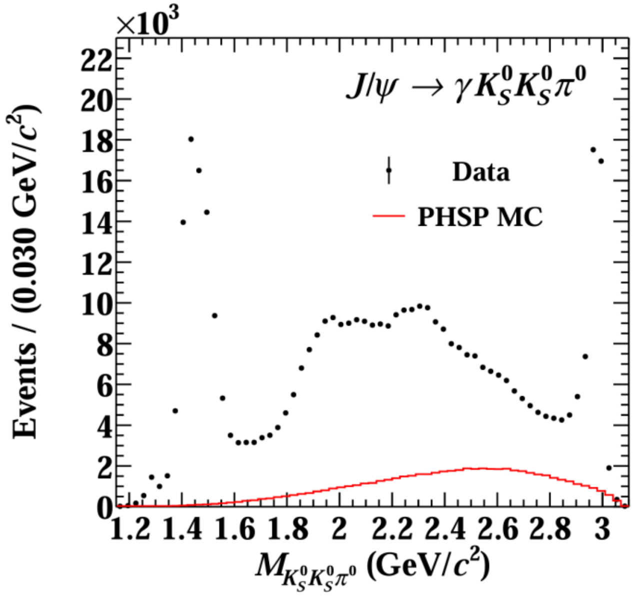
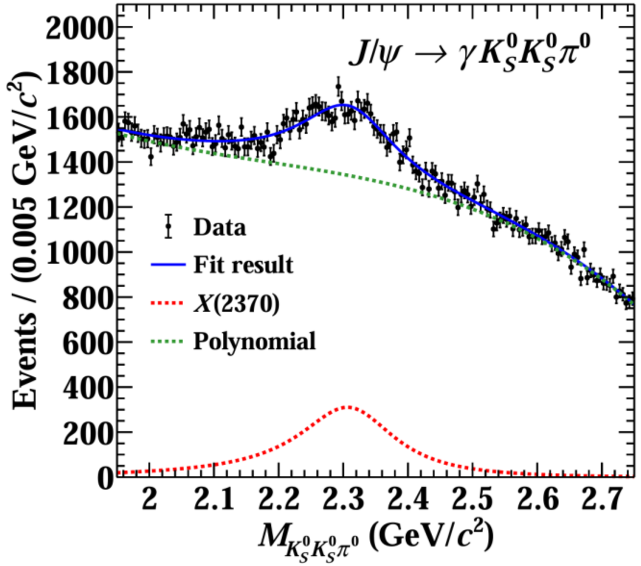
# $J/\psi \to \gamma K_S^0 K_S^0 \pi^0$



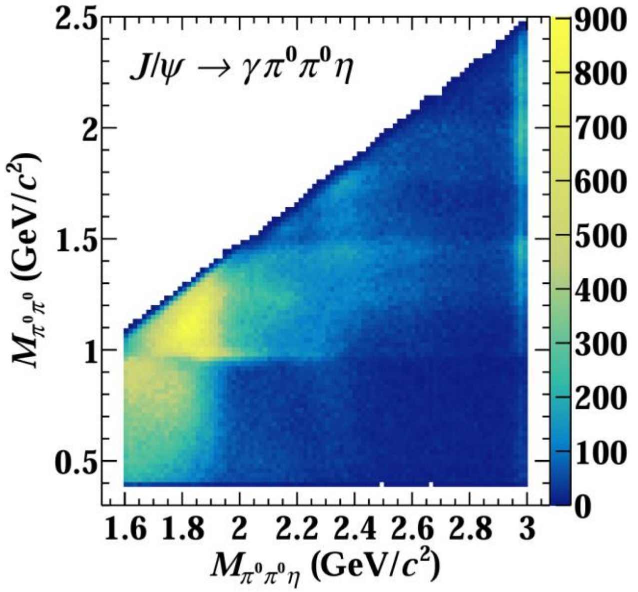

Final result:

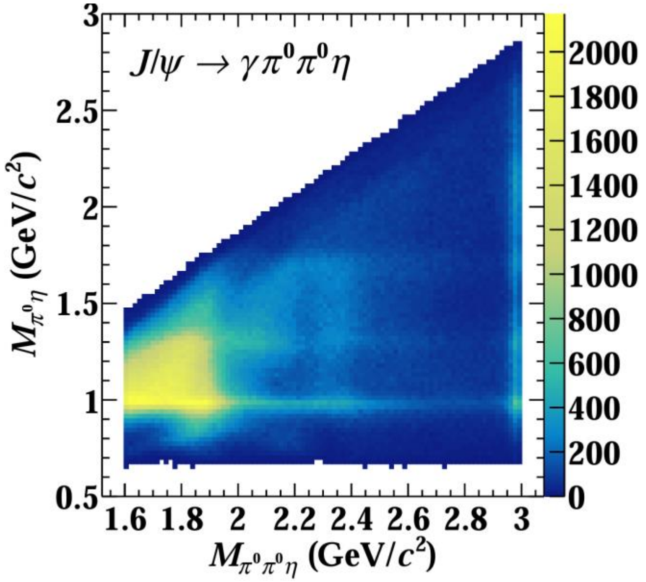
$M_{X(2370)} = 2311 \pm 4(\text{stat}) \pm 25(\text{syst})$ MeV$/c^2$

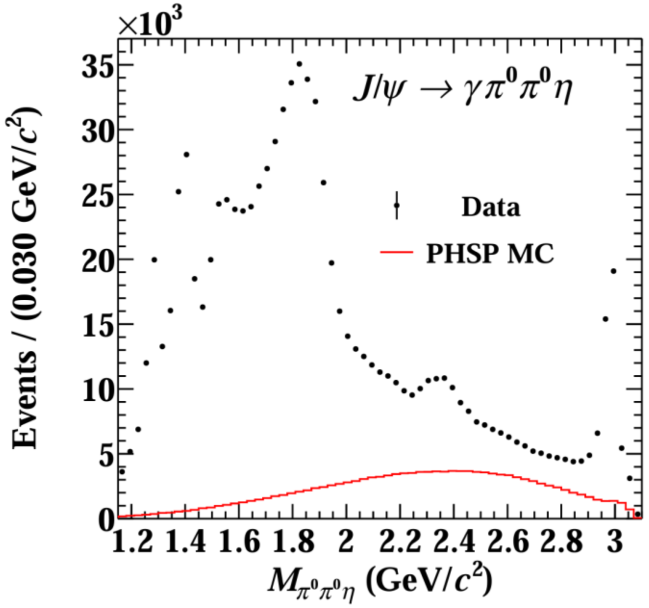
$\Gamma_{X(2370)} = 177 \pm 20(\text{stat}) \pm 72(\text{syst})$ MeV

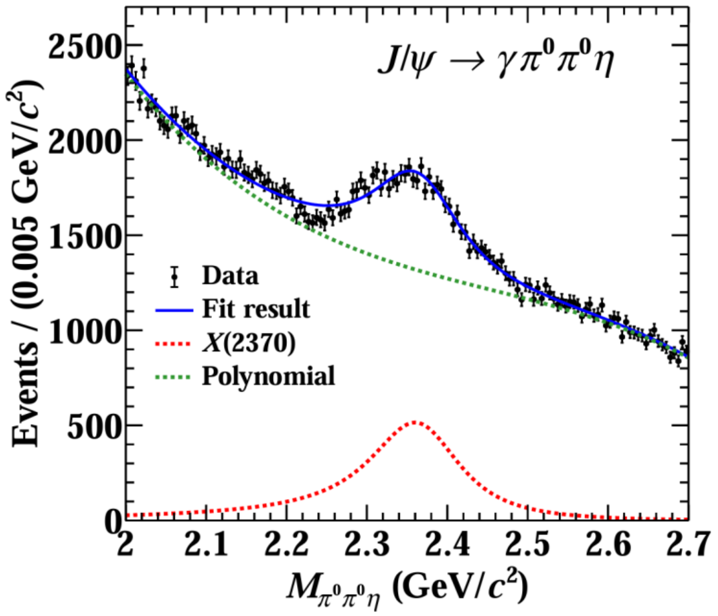
Significance of the $X(2370) > 14\sigma$

# $J/\psi \to \gamma\pi^0\pi^0\eta$



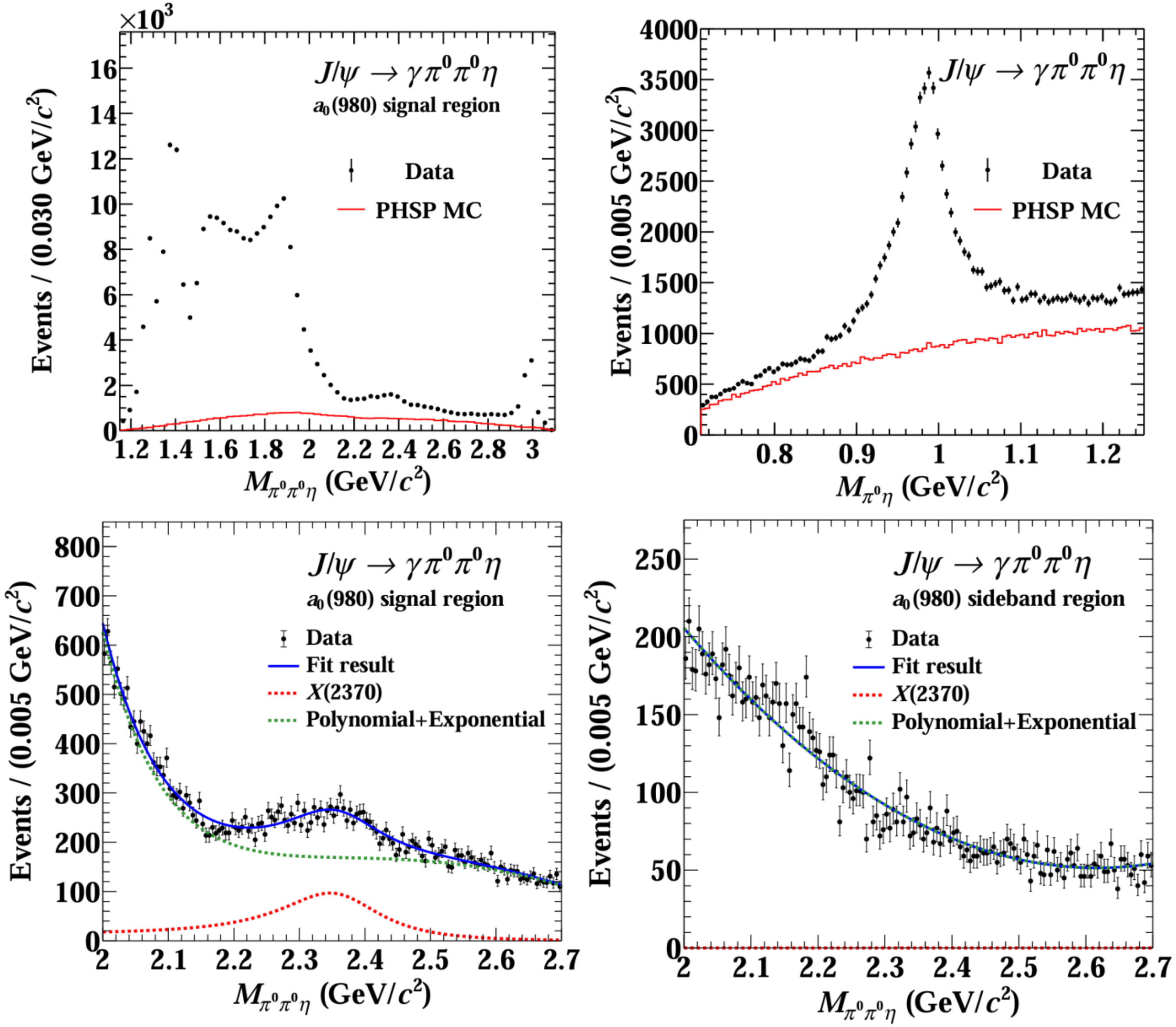

Final result:

$M_{X(2370)} = 2366 \pm 2(\text{stat}) \pm 10(\text{syst})\ \text{MeV}/c^2$

$\Gamma_{X(2370)} = 127 \pm 9(\text{stat}) \pm 61(\text{syst})\ \text{MeV}$

Significance of the $X(2370) > 20\sigma$

# $J/\psi \to \gamma a_0^0 \pi^0 \to \gamma \pi^0 \pi^0 \eta$



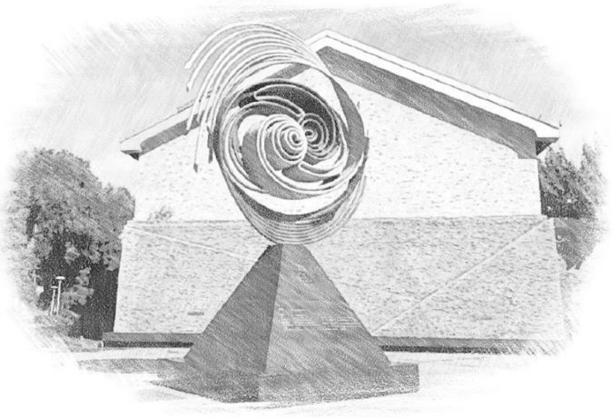

Final result:

$M_{X(2370)} = 2358 \pm 5(\text{stat}) \pm 9(\text{syst})\ \text{MeV}/c^2$

$\Gamma_{X(2370)} = 180 \pm 20(\text{stat}) \pm 58(\text{syst})\ \text{MeV}$

Significance of the $X(2370) > 9\sigma$

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



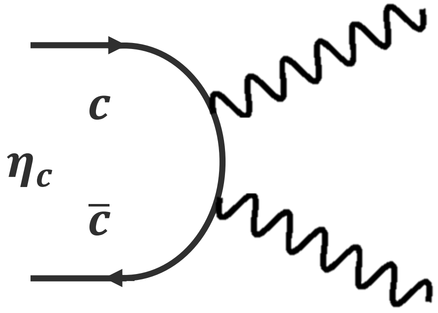
中国高等科学技术中心
China Center of Advanced Science and Technology

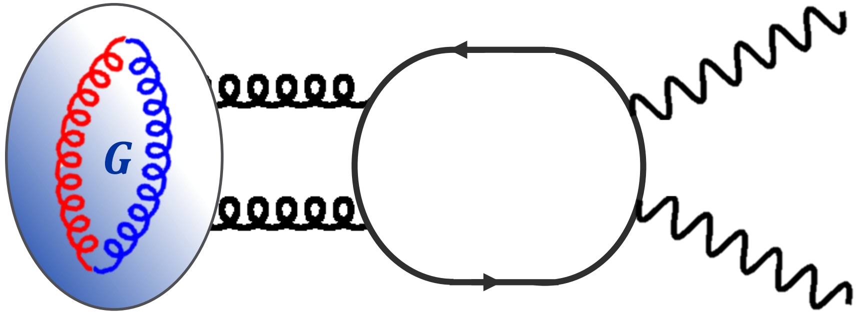
BESIII

# Search for the $X(2370)$ in $\gamma\gamma \rightarrow \pi^+\pi^-\eta'$ using Belle data

# Feynman diagram of the two-photon process

- The $\eta_c$ and glueball decay to two photons



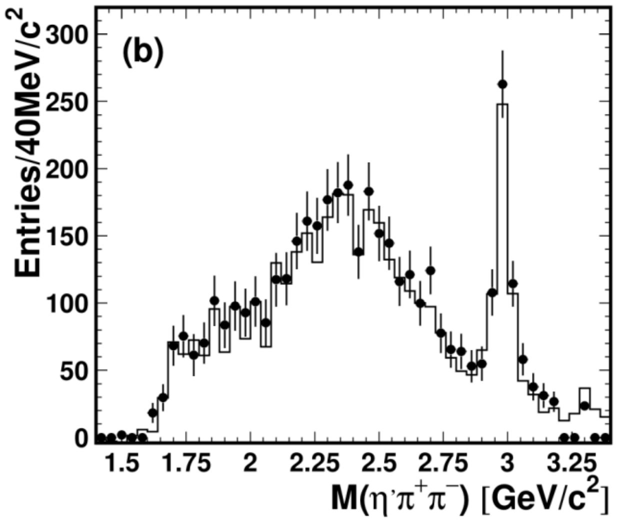

Compared with $\eta_c$ suppressed: $\alpha_s^2$ ~0.1

$$\frac{\Gamma_{X(2370)\to\gamma\gamma}}{\Gamma_{\eta_c\to\gamma\gamma}} \sim 0.1$$

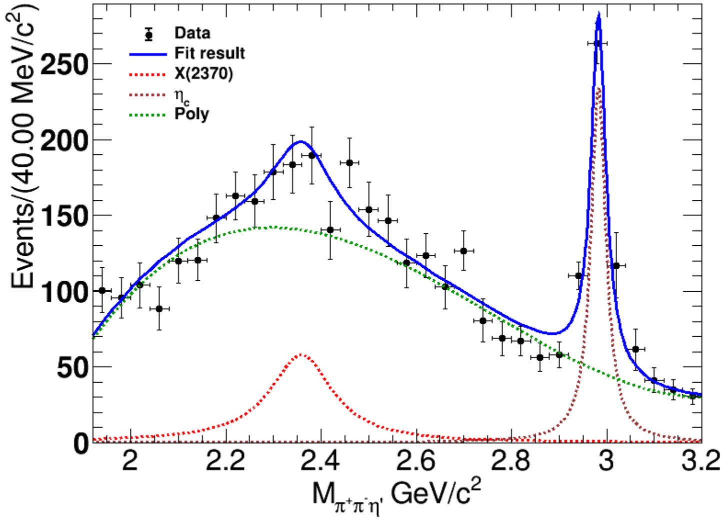
# Search for $\gamma\gamma \to X(2370)$ with $\pi^+\pi^-\eta'$ final state

➢ Perform a $\chi^2$ fit to the $\pi^+\pi^-\eta'$ mass spectrum extracted from PRD 86, 052002 (2012)

- No PWA yet. Conservatively assuming that all events in the plot are from 0-+, fix the X (2370) peak and width to BESIII value
- Significance of the $X(2370)$ ~3σ




PRD 86, 052002 (2012)
(Belle Data)




$N_{\eta_c}$ = 330 ± 21
$N_{X(2370)}$ = 324 ± 101
$N_{X(2370)}/N_{\eta_c}$ = 0.98 ± 0.33

# $Event\ rate\ and\ \Gamma_{X(2370)\to\gamma\gamma}/\Gamma_{\eta_c\to\gamma\gamma}$

➢ For two photon process

$$\frac{N_{X(2370)}}{N_{\eta_c}} = \frac{\Gamma_{X(2370)\to\gamma\gamma} B\left[X(2370)\to\pi^+\pi^-\eta'\right]}{\Gamma_{\eta_c\to\gamma\gamma} B[\eta_c\to\pi^+\pi^-\eta']}$$

- Since $\eta_c$ has much larger phase space than X(2370) so as to have many more decay modes than X(2370), so naively, we may have $B[X(2370) \to \pi^+\pi^-\eta']/B[\eta_c \to \pi^+\pi^-\eta']$ ~5-10

- So, $\frac{\Gamma_{X(2370)\to\gamma\gamma}}{\Gamma_{\eta_c\to\gamma\gamma}}$ = (1/5-1/10) * $\frac{N_{X(2370)}}{N_{\eta_c}}$ = (0.1-0.2)*(0.98+/-0.33) ~ 0.1-0.2, as expected from $\alpha_s^2$ ~0. 1

- Without considering sys. errors, $\Gamma_{X(2370)\to\gamma\gamma}$ rate is not inconsistent with glueball within 2 σ