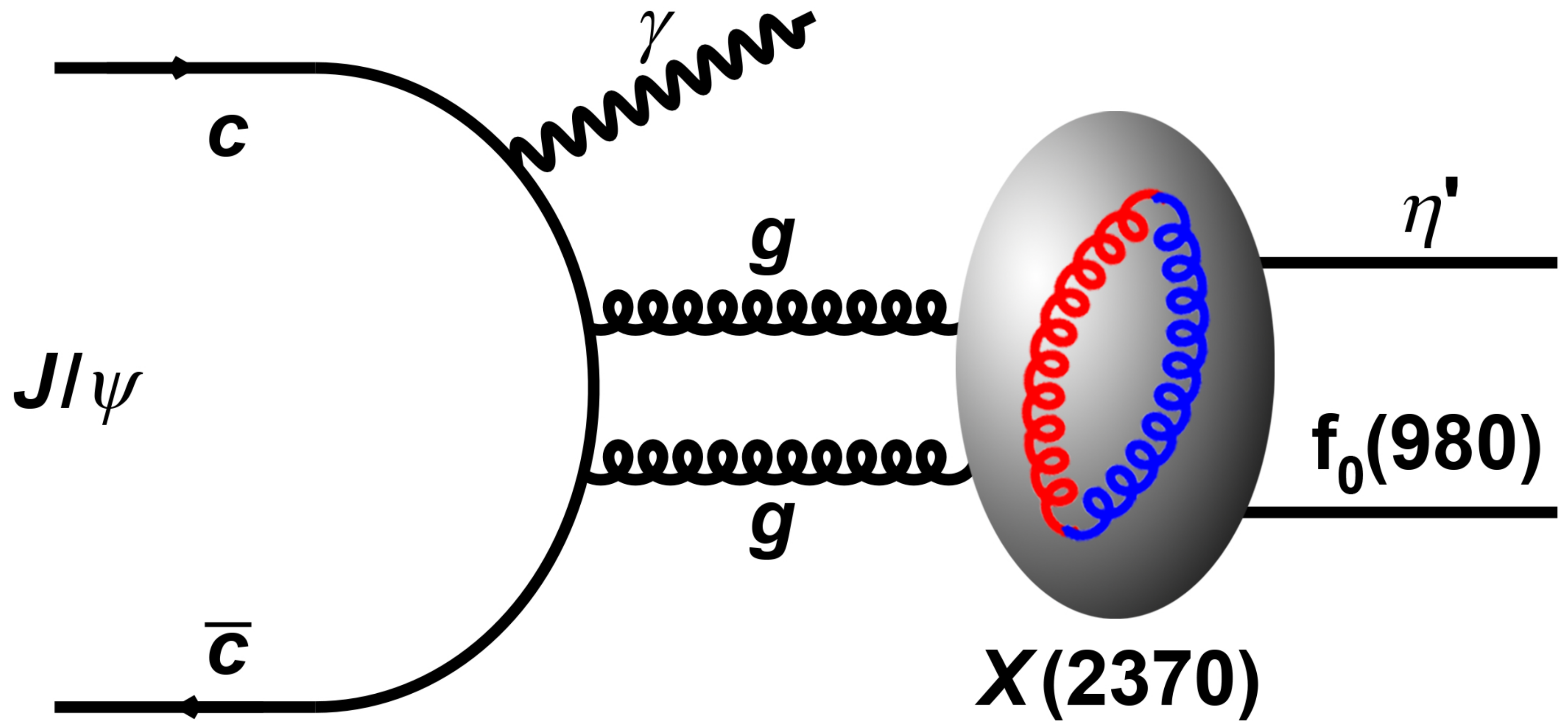
# Discovery of a Glueball-like particle X(2370) @ BESIII





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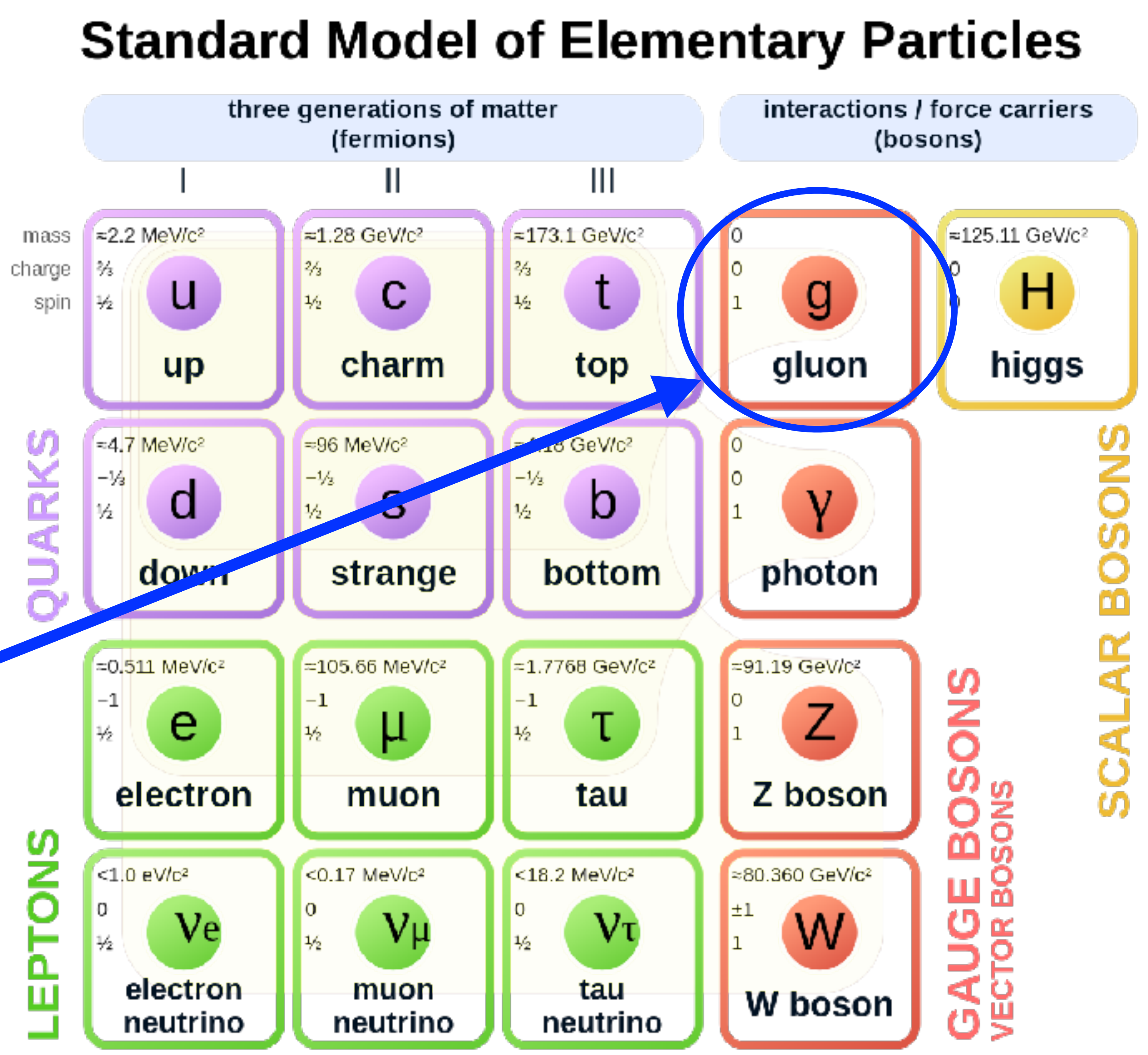
(On behalf of the BESIII Collaboration)


June 14th, 2024

# The Standard Model

- The Standard Model gives a description of the elementary particles and their interactions.
  - **Building blocks of matters (elementary particles)**
    - **6 quarks, 6 leptons, 4 force carriers**
  - **Forces hold them together (3 interactions)**
    - **Weak interaction, electromagnetic interaction, Strong interaction**




**Gluons are the force carriers of the strong interactions**

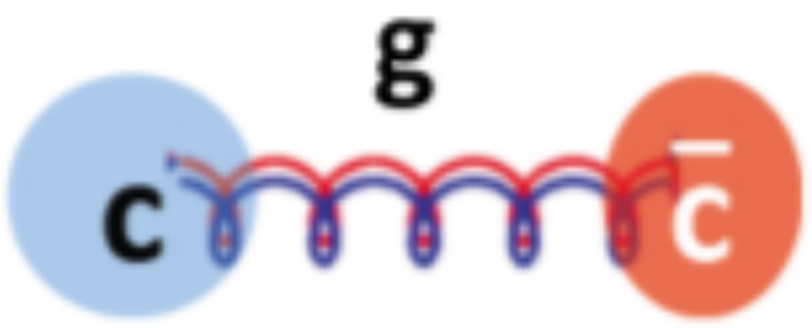
# Forms of hadrons

- **In quark model:**

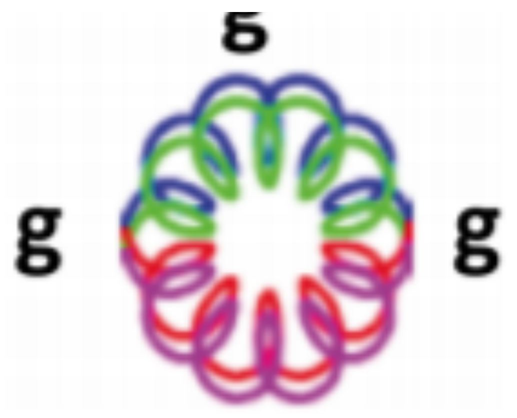


- **Other forms of hadrons：**
  - **Multi-quark:** quark number >= 4

  - **Hybrid state:** the mixture of quark and gluon



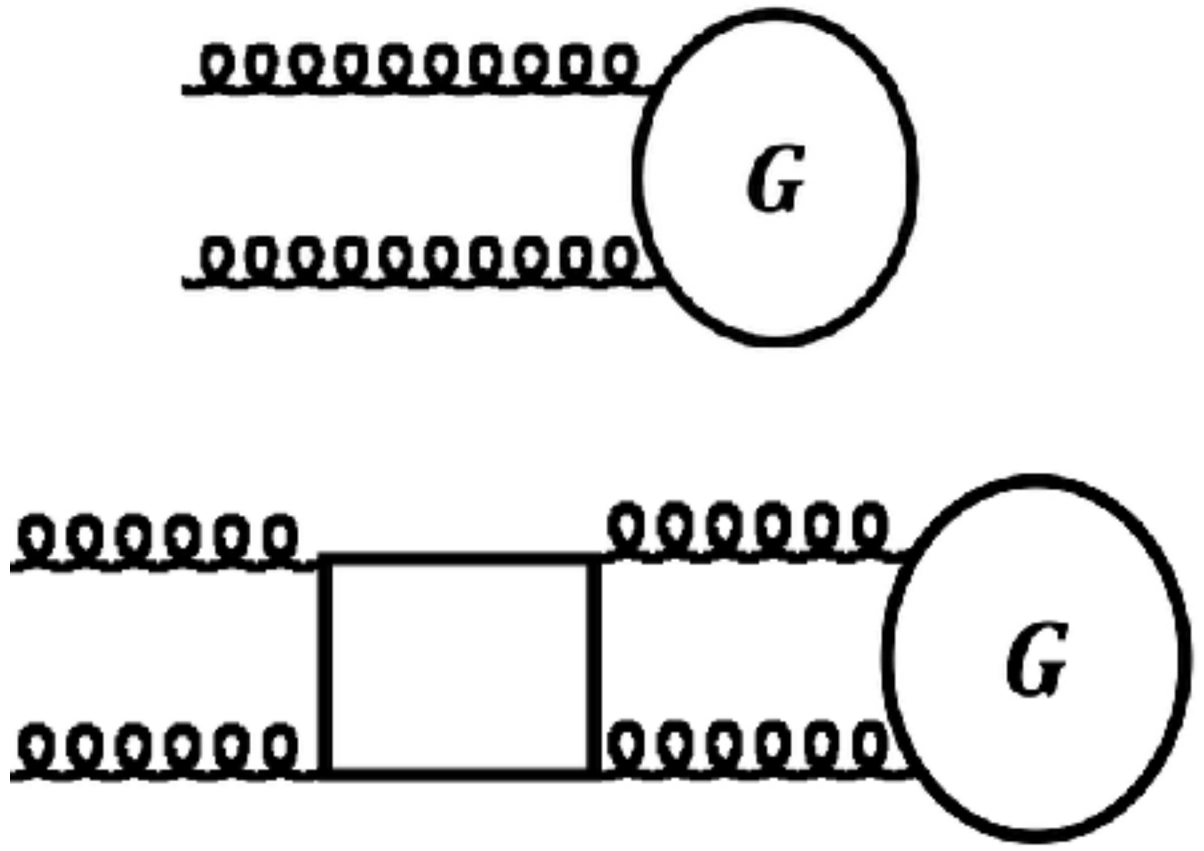

  - **Glueball:** composed of gluons (**gg, ggg, gggg ….**)

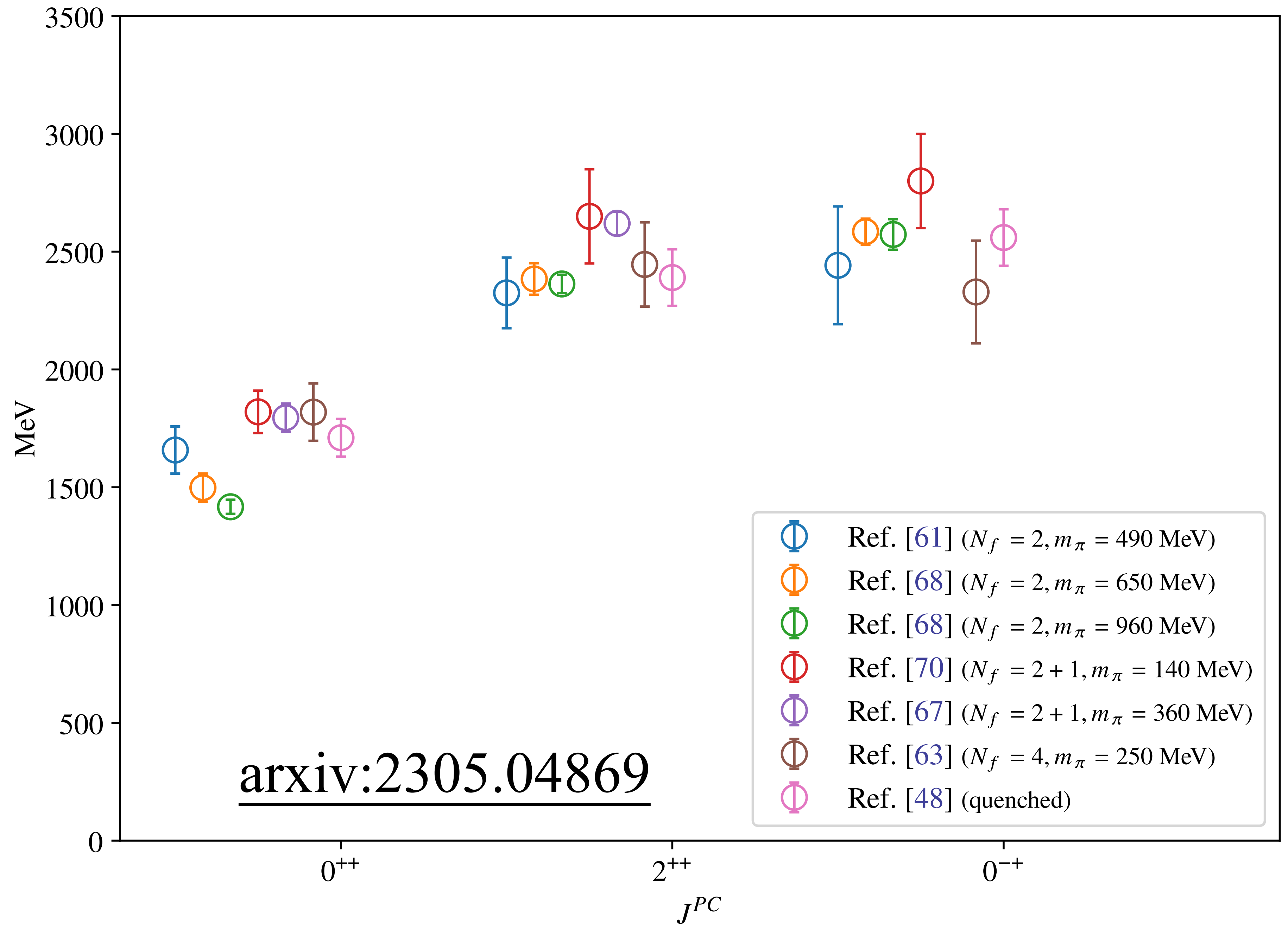



- **The basic theory for strong interactions is quantum chromodynamics (QCD)**
  - **Gluon self-interaction: prediction of non-Abelian Gauge SU(3) QCD theory**
  - **Glueballs are unique particles via self-interactions and formed with force carriers**

# Theoretical Prediction

- **Lattice QCD** (LQCD) is a non-perturbative method from the first principles in theory.
  - **Quenched LQCD**: quantum loops of fermions in Feynman diagrams are neglected
  - **Different lattice QCD groups** (including lattice simulations with dynamical quarks) now **have consistent results**
  - The predictions of **masses and production rates** of pure glueballs are 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/$c^2$



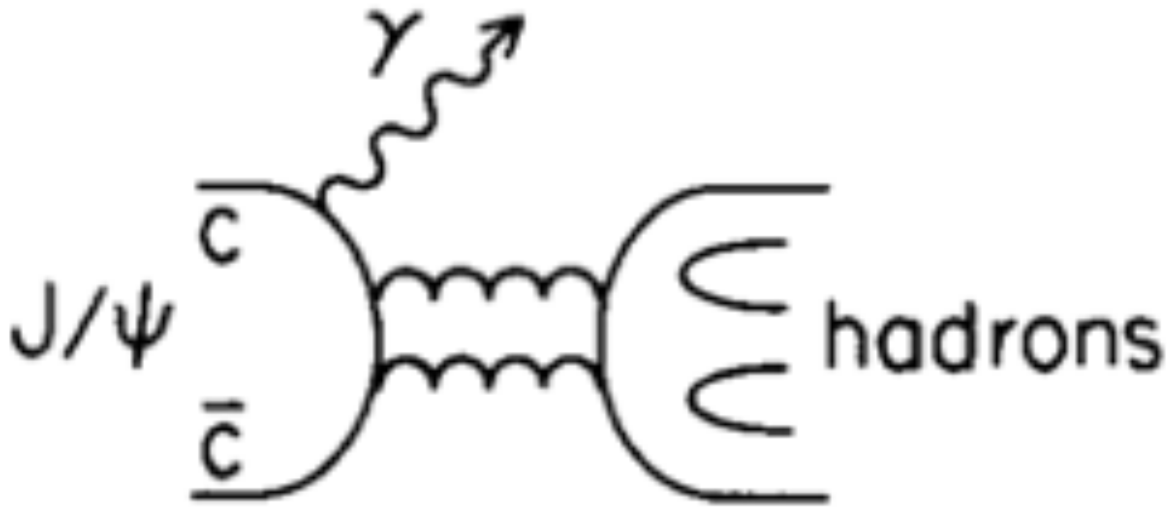



# Glueball Search

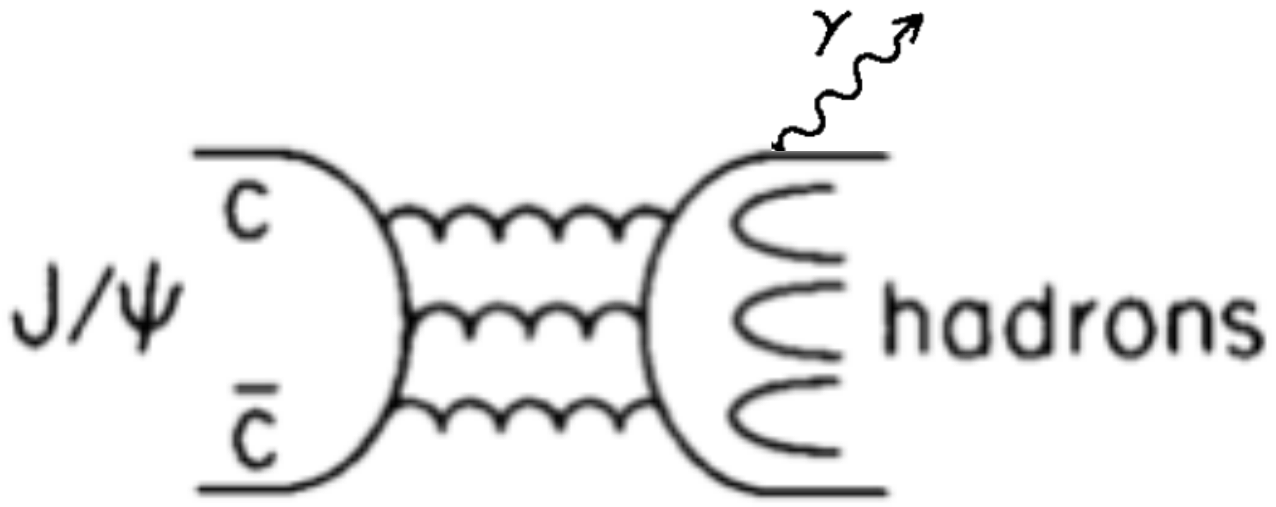
- **Many experiments searched for glueballs over the past 4 decades.**
- **Glueball production in** J/ψ radiative decays
- **Glueball decays**
- **Many historical glueball candidates**, but also some **difficulties**
  - **Scalar Glueball candidate ($0^{++}$)**： $f_0(1500)$, $f_0(1710)$
  - **Tensor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

# J/ψ radiative decays

- **Gluon rich environment**




$\sim \alpha\alpha_s^4$




$\sim \alpha\alpha_s^6$

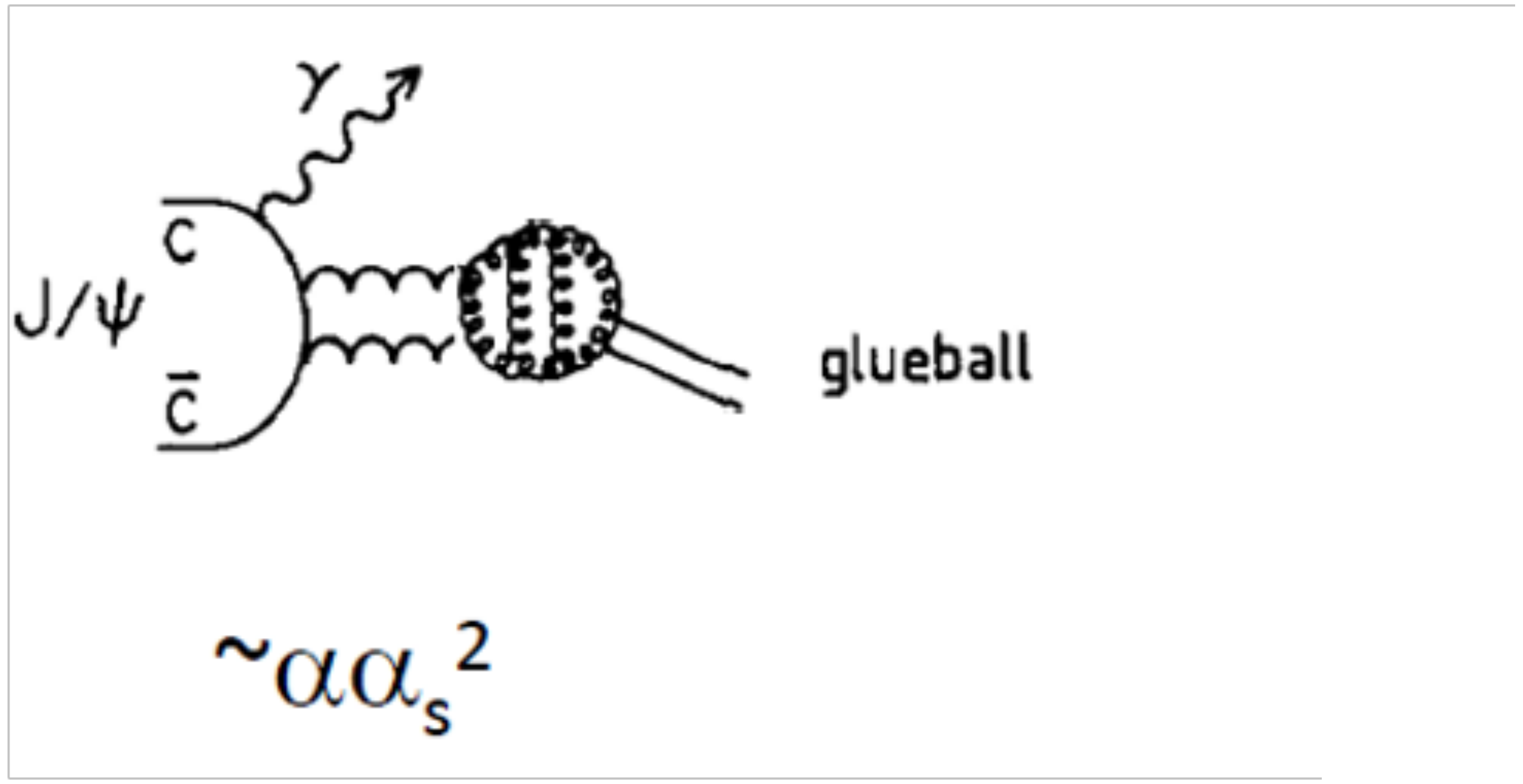
- **Isospin filter:** final states dominated by **I=0** processes
- **Spin-parity filter: C parity must be +**, so $J^{pc}=0^{-+}, 0^{++}, 1^{++}, 2^{++}, 2^{-+} \ldots$
- **Clean environment in electron-positron collision:** very different from **proton-proton collision**

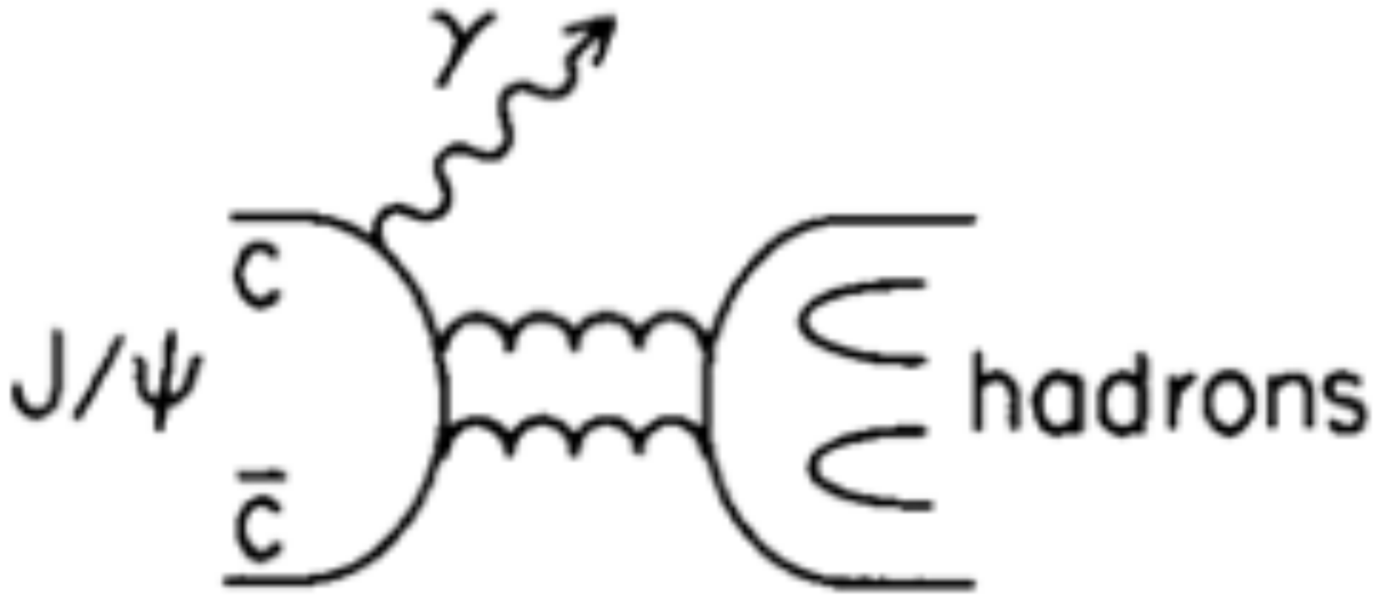
➡ **Ideal place to search for glueballs**

# Glueball Production in J/ψ radiative decays

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

- ✦ Glueball production rate in J/ψ radiative decays could be higher than normal hadrons
- ✦ **A glueball could be easier produced than a conventional $q\bar{q}$ meson with the same $J^{PC}$**




$\sim \alpha\alpha_s^4$

# Glueball Decays

◆ **No rigorous predictions on decay patterns and their branching ratios**

◆ **The glueball decays could have similar decays to the Charmonium families since both of them can only decay via gluons**

$\pi^+\pi^-K^+K^-$.[12] For a glueball, say, a $J^{PC} = 2^{++}$ glueball, which is made of two gluons, its decay proceeds via the two-gluon hadronization, which is similar to the second step of the $\chi_{c2}$ decay. The difference between the $2^{++}$ glueball and $\chi_{c2}$ in their decays is that the two gluons are hadronized at different energy scales, and consequently in the two cases the branching ratio for a given final state can be different. At the higher energy scale like the $\chi_{c2}$

**From Kuang-Ta Chao 1995 Commu. Theor. Phys. 24.373**

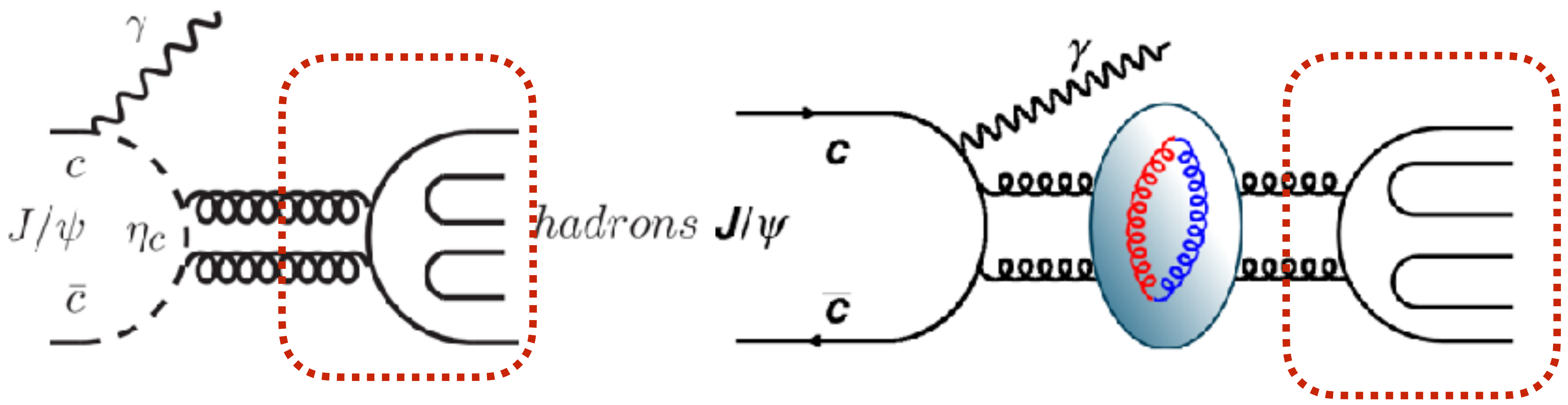
ple equally to all flavors. Since there has been no glueball confirmed by experiments, the best way looking into the flavor symmetry should be to study the decay processes which proceed through a two gluon intermediate state [10]. Fortunately, a lot of experiments have already studied such processes as the decays of charmonium family. One example is, the two

it is worth noticing that there are not any other particles showing such properties [12] as $\xi$ except for the particles with pure OZI suppressed decay modes such as $J/\psi$, $\chi_{c0}$, $\chi_{c2}$, etc. The flavor-symmetric couplings

The knowledge [12] about the hadronic decays of $J/\psi$, $\eta_c$, $\chi_{c0}$ and $\chi_{c2}$ which proceed through pure gluon intermediate state suggests that the glueballs

**From Tao Huang, Kuang-Ta Chao et al. PLB 380 (1996) 189-192**

# $0^{-+}$ Glueball Decays




- **The glueball decays could have similar decays to the Charmonium families since both of them can only decay via gluons**
  - The $0^{-+}$ glueball could have similar decays of $\eta_c$
  - One of the favorite decay modes of $\eta_c$ is $\pi\pi\eta'$, so $J/\psi \to \gamma\, \pi\pi\eta'$ could be a good place to search for the $0^{-+}$ glueball
- **Different energy scales between the charmonium and glueballs**
  - Different decay branching ratios
  - The $\eta_c$ has larger phase space region than a $0^{-+}$ glueball with lower mass

# Glueball Search

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- **Many historical glueball candidates**, but also some **difficulties**
  - **Scalar Glueball candidate ($0^{++}$)**： $f_0(1500)$, $f_0(1710)$
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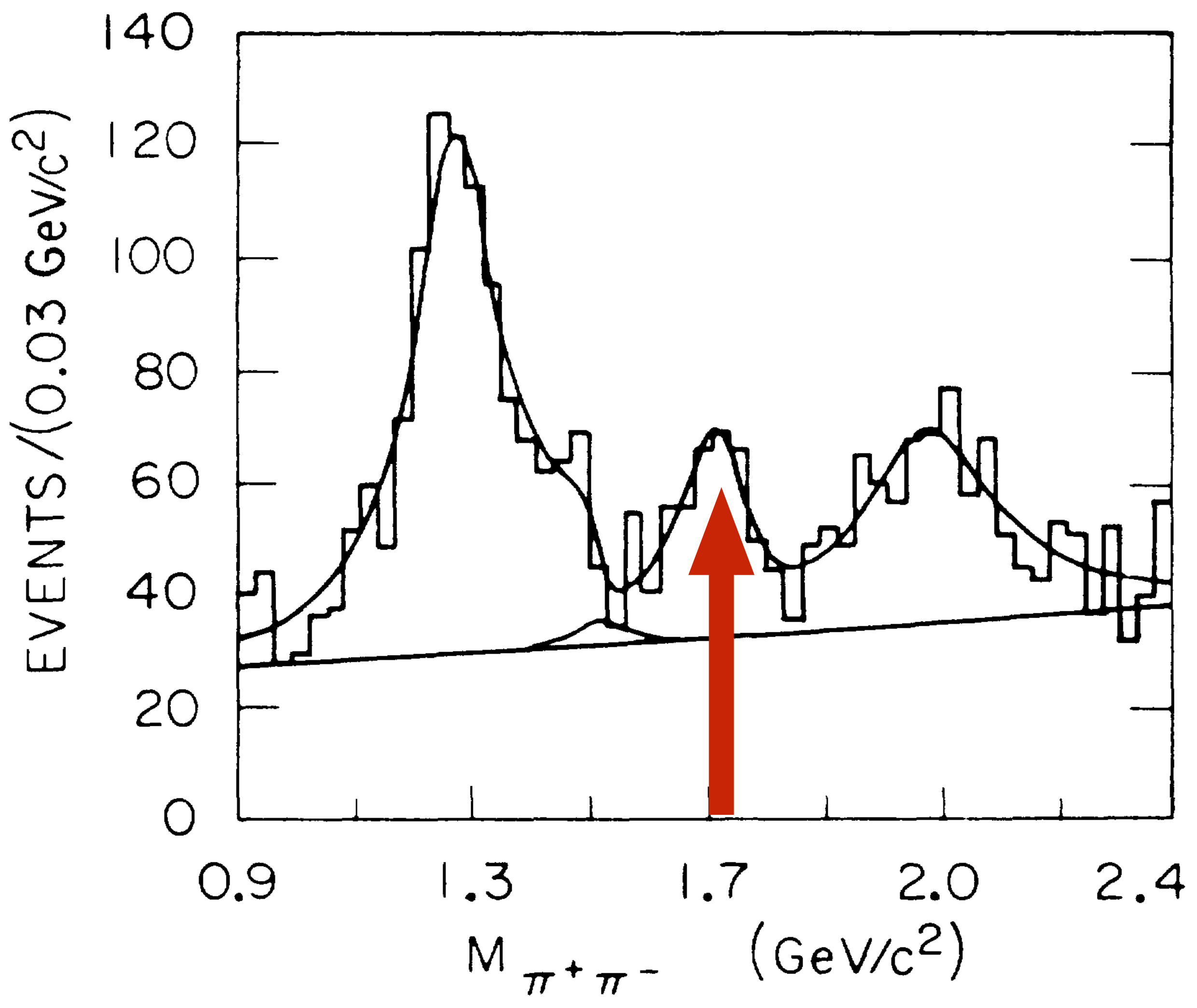
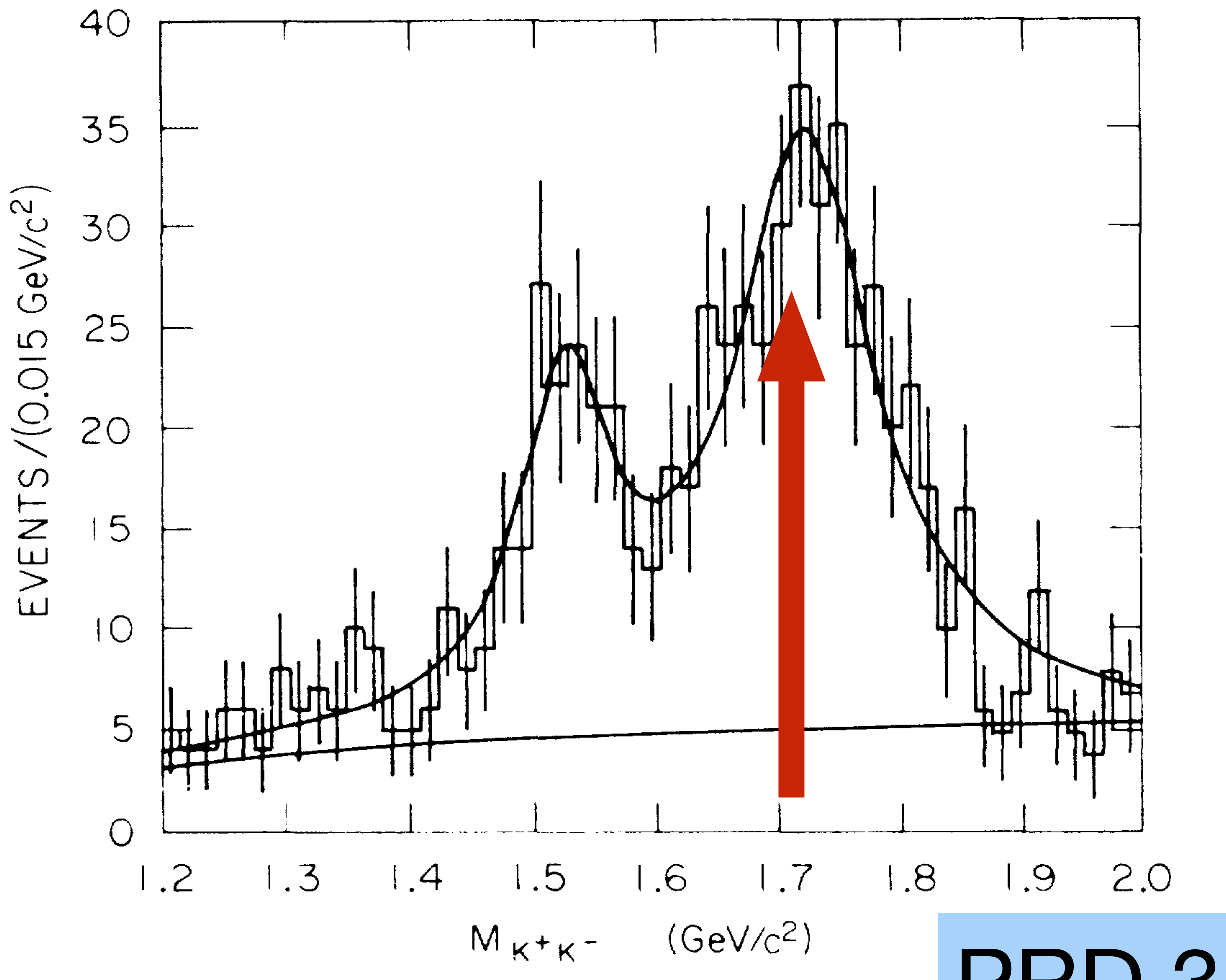
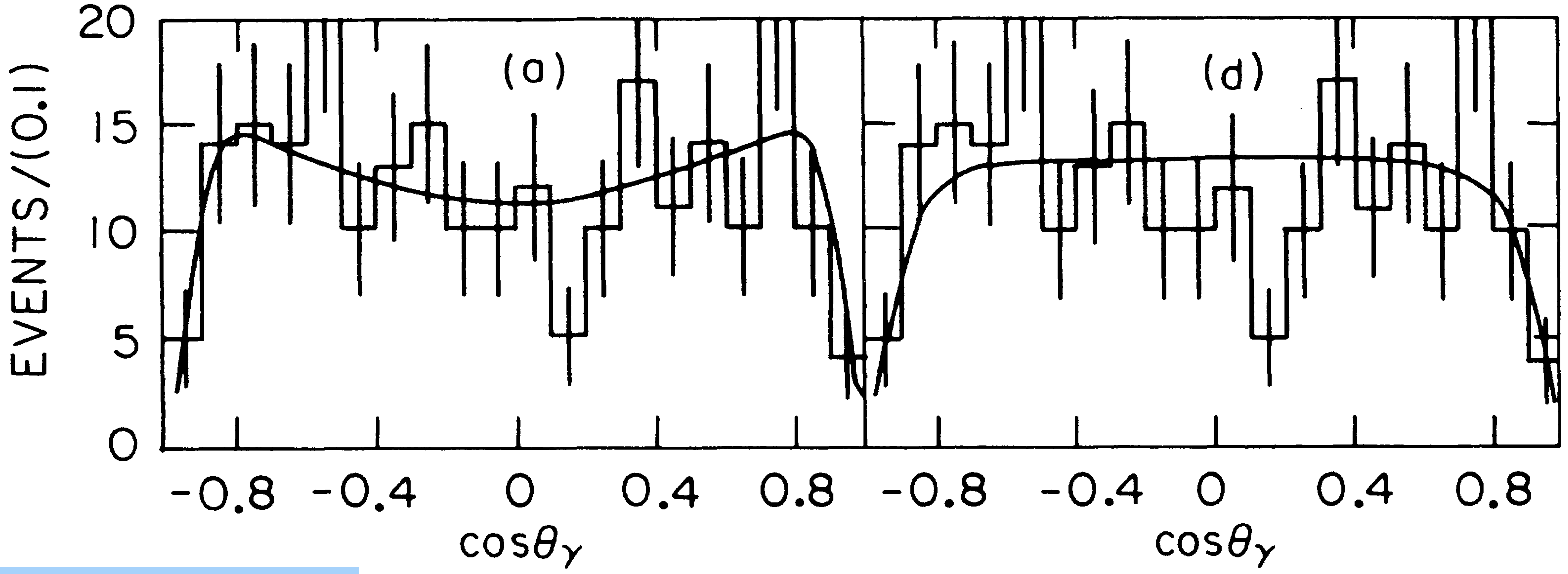
# Historical Glueball Candidates — Scalar $f_0(1710)$



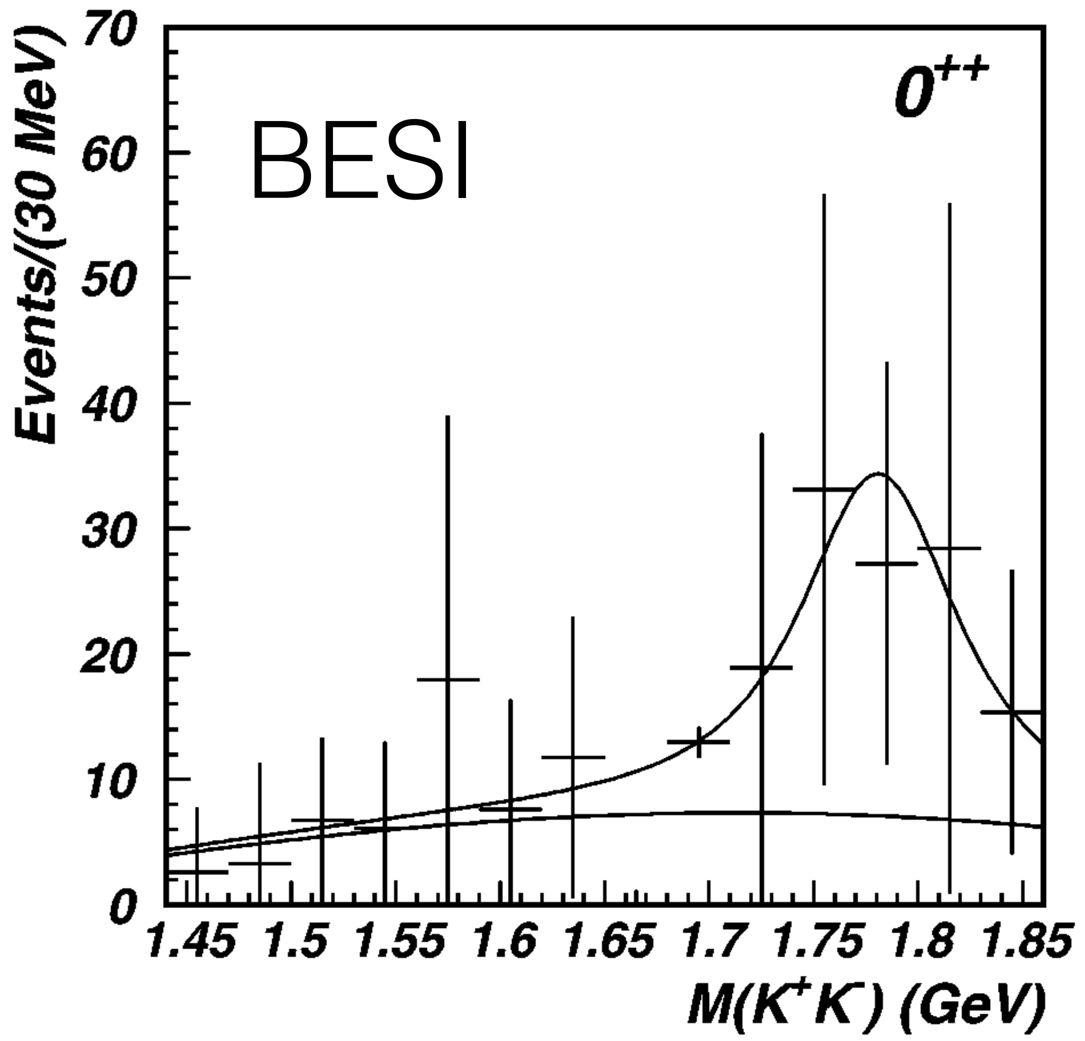



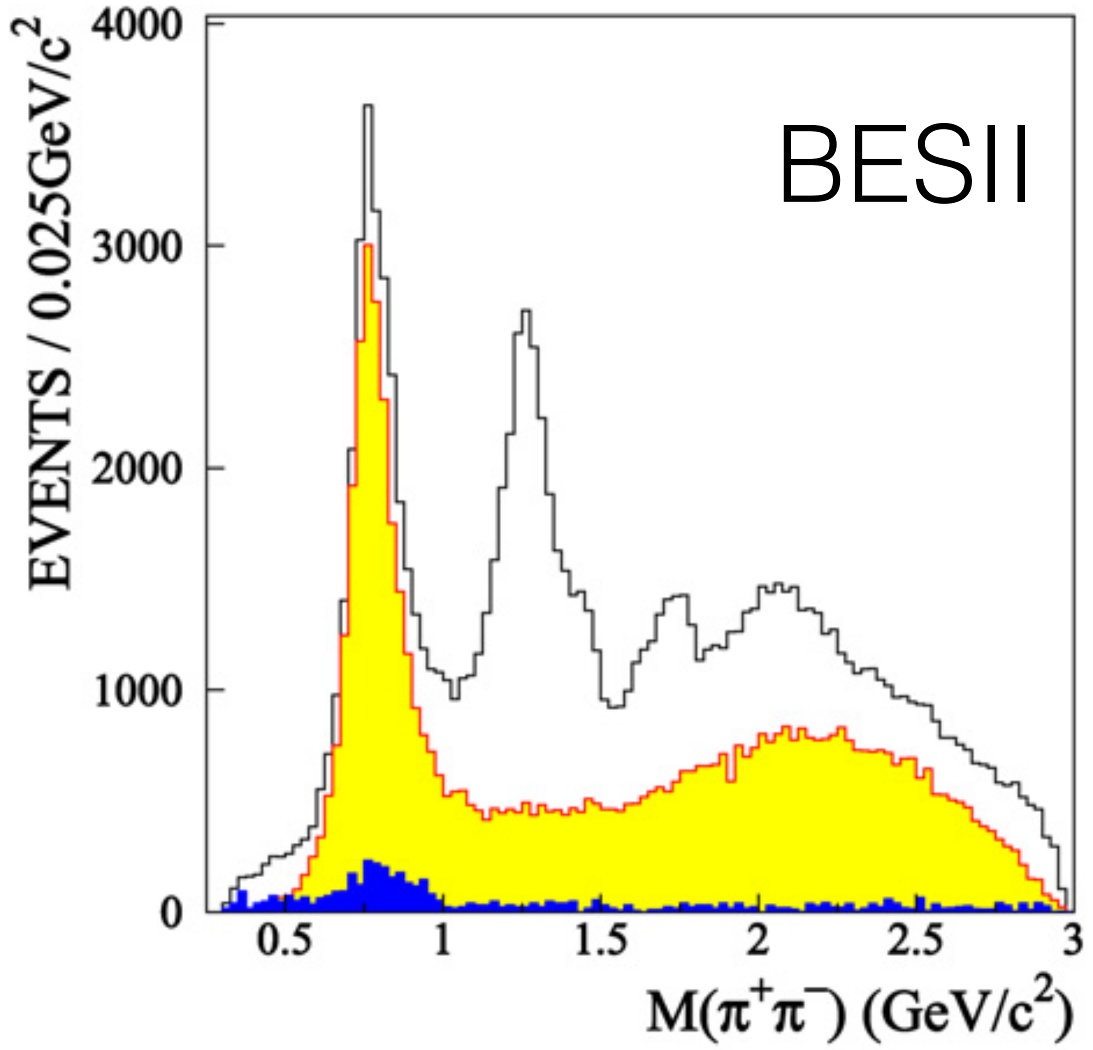

PRD 35 (1987) 2077

- 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**
- Lots of studies at MarkII, DM2, BESI,BESII, BESIII

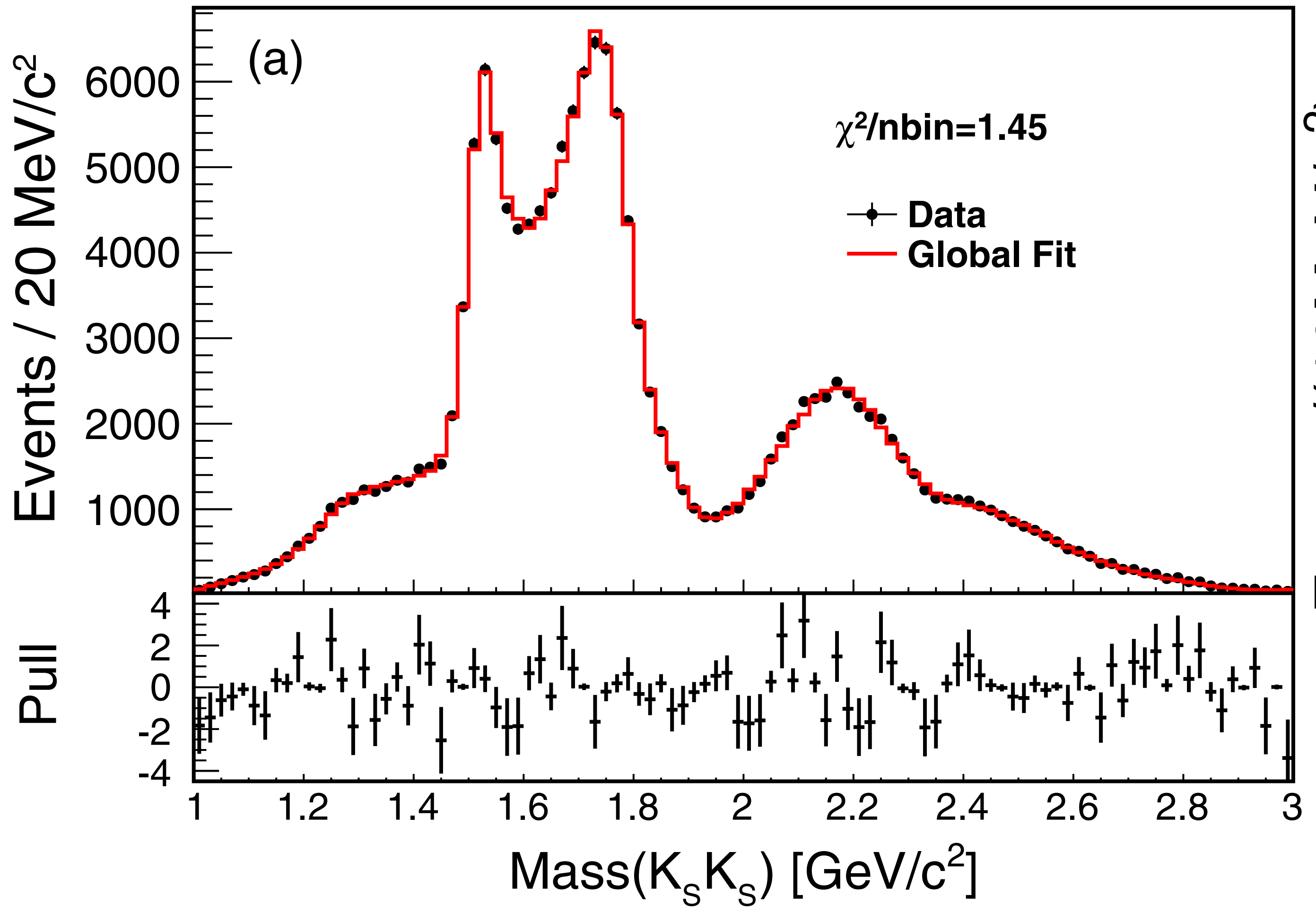
# Historical Glueball Candidates — Scalar $f_0(1710)$



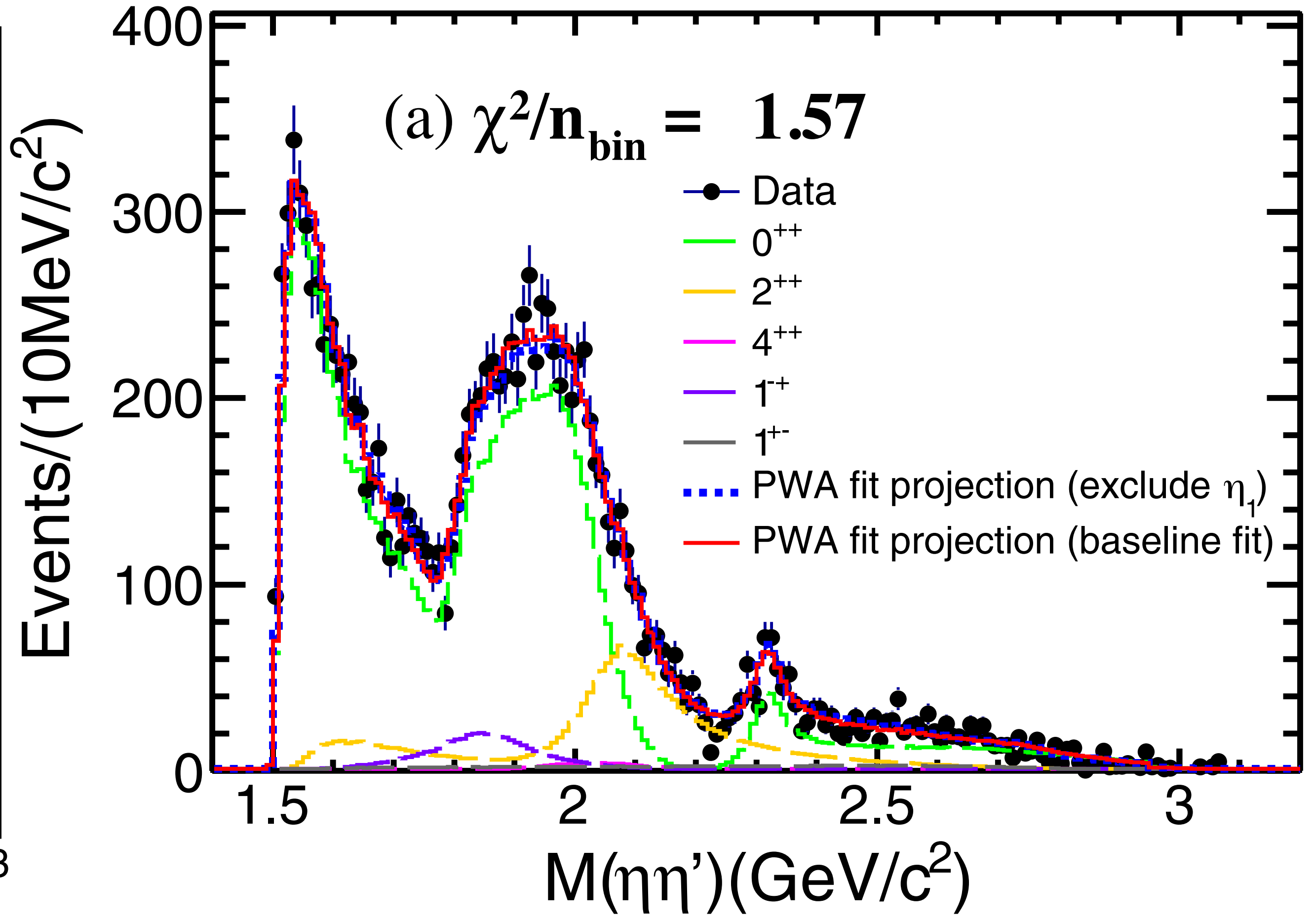
PRL 77(1996) 19



PLB 642 (2006) 441



PRD 98 (2018) 072003



PRD 106 (2022) 072012

- The $f_0(1710)$ **was firstly changed to be $0^{++}$** on a full PWA of J/ψ→ γKK @ BESI
- The $f_0(1710)$ favors to be **a scalar glueball or large glueball content** if it is a mixture of glueball and normal meson

✦ **High production rate of $J/\psi \to \gamma f_0(1710)$**

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

BESII: PLB 642 (2006) 441

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

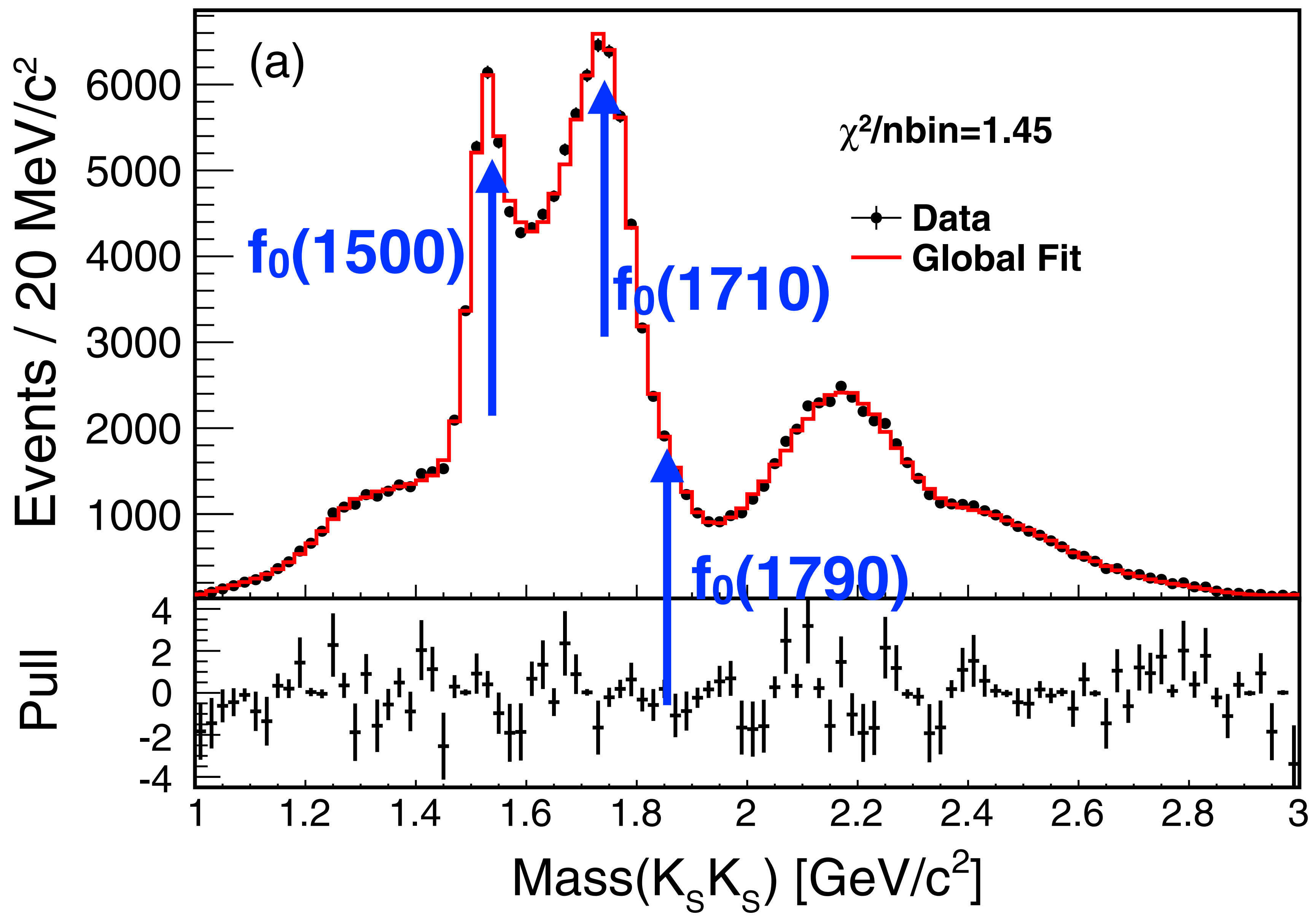
BESIII: PRD 98 (2018) 072003

✦ **Decay suppression in $f_0(1710) \to \eta\eta'$**

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

BESIII: PRD 106 072012(2022)

# Historical Glueball Candidates — Scalar $f_0(1710)$




PRD 98 (2018) 072003

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

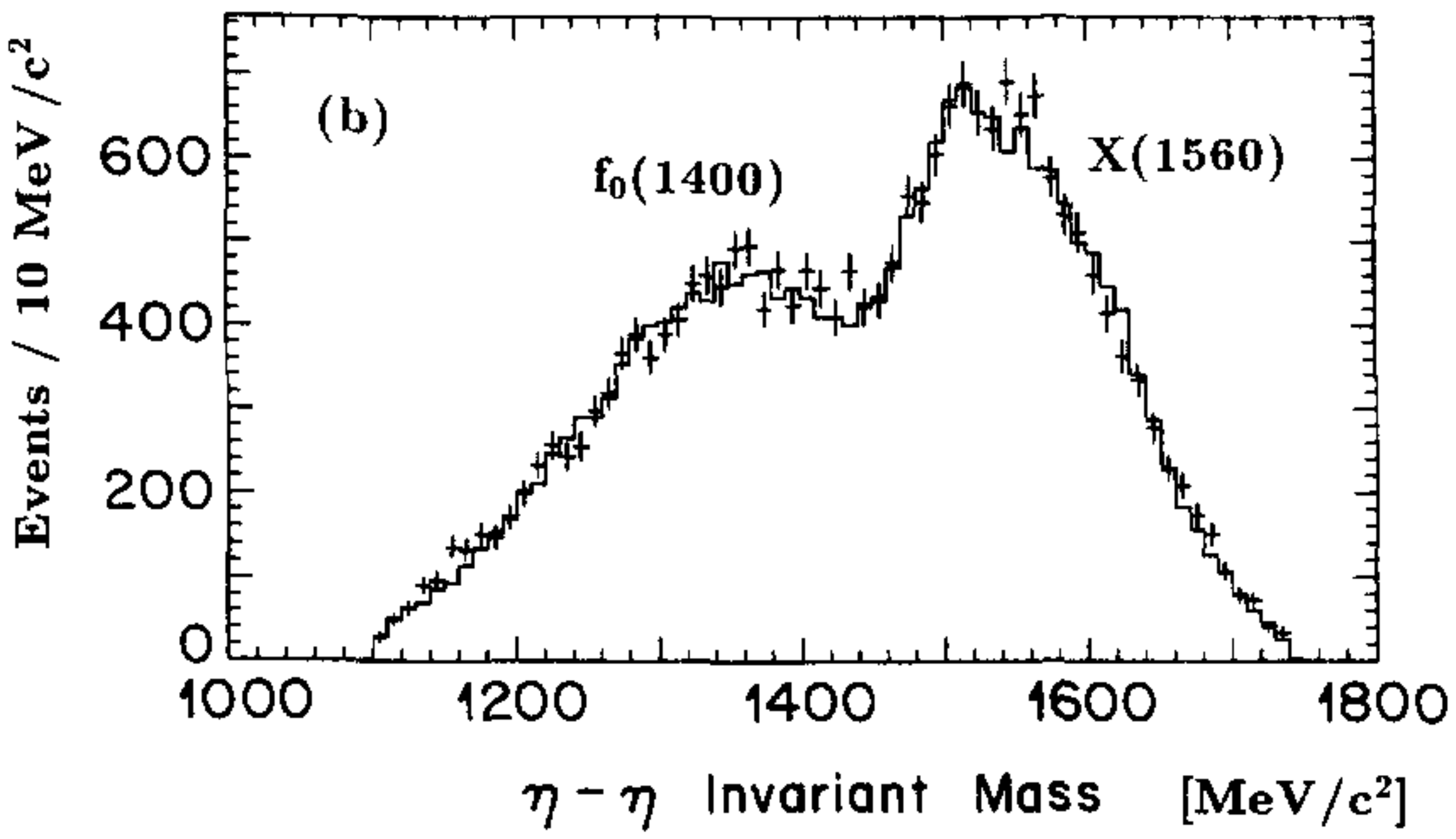
BESII: PLB 642 (2006) 441

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

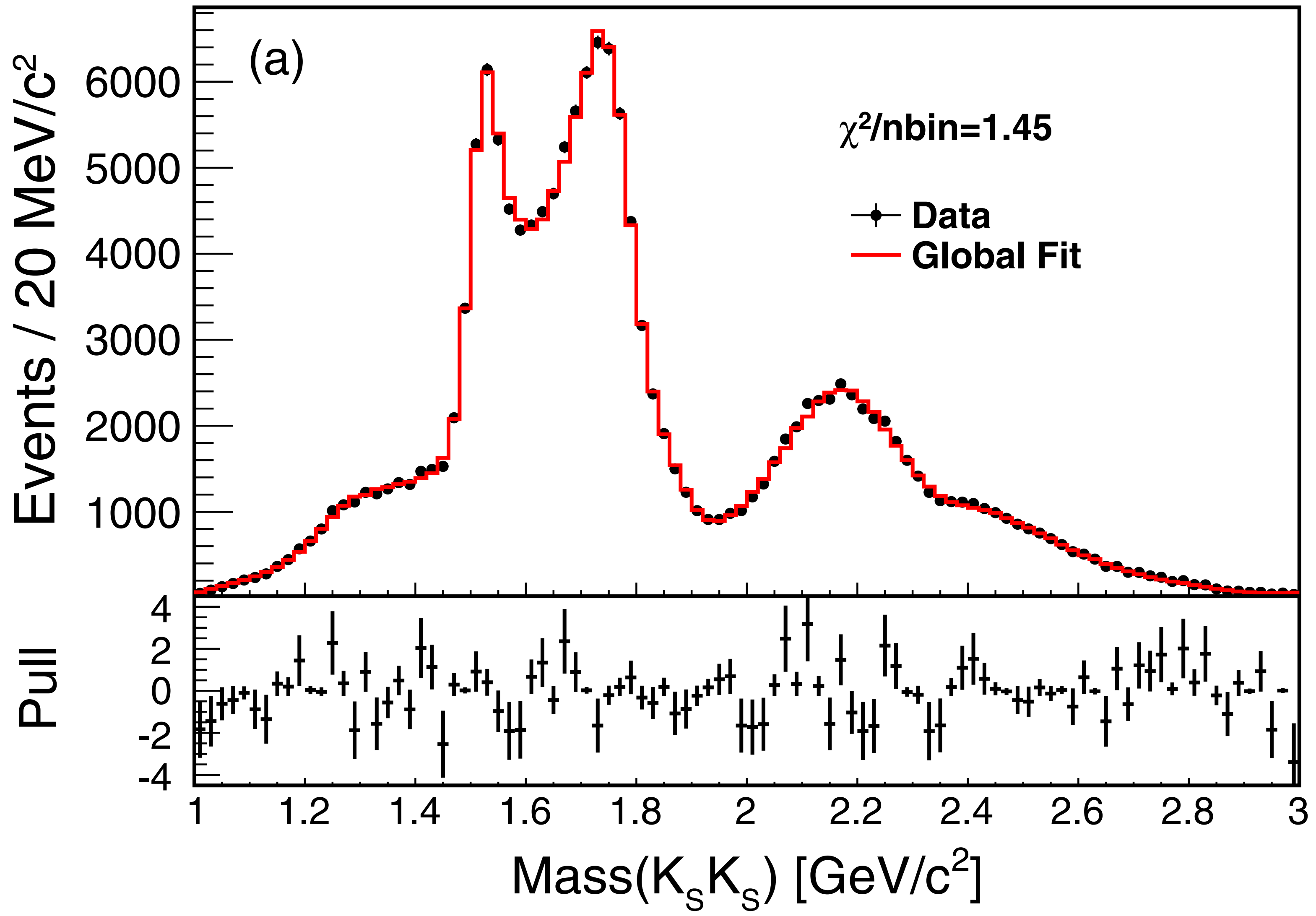
BESIII: PRD 98 (2018) 072003

- **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 $f_0(1790)$

# 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 as a scalar glueball**
  - ✦ **Lower production rate of $J/\psi \to \gamma f_0(1500)$**

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

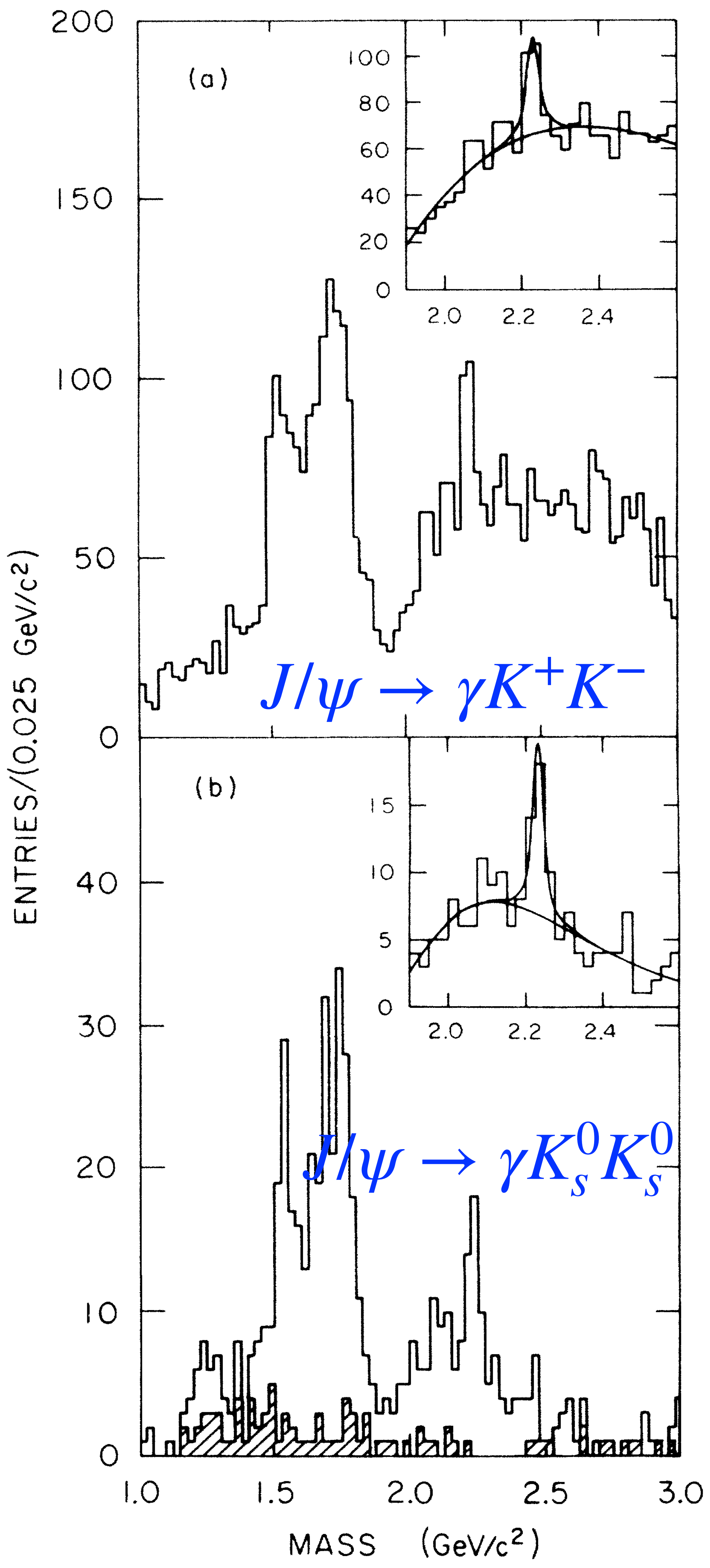
BESIII: PRD 98 (2018) 072003

  - ✦ **No strong suppression in $f_0(1500) \to \eta\eta'$**

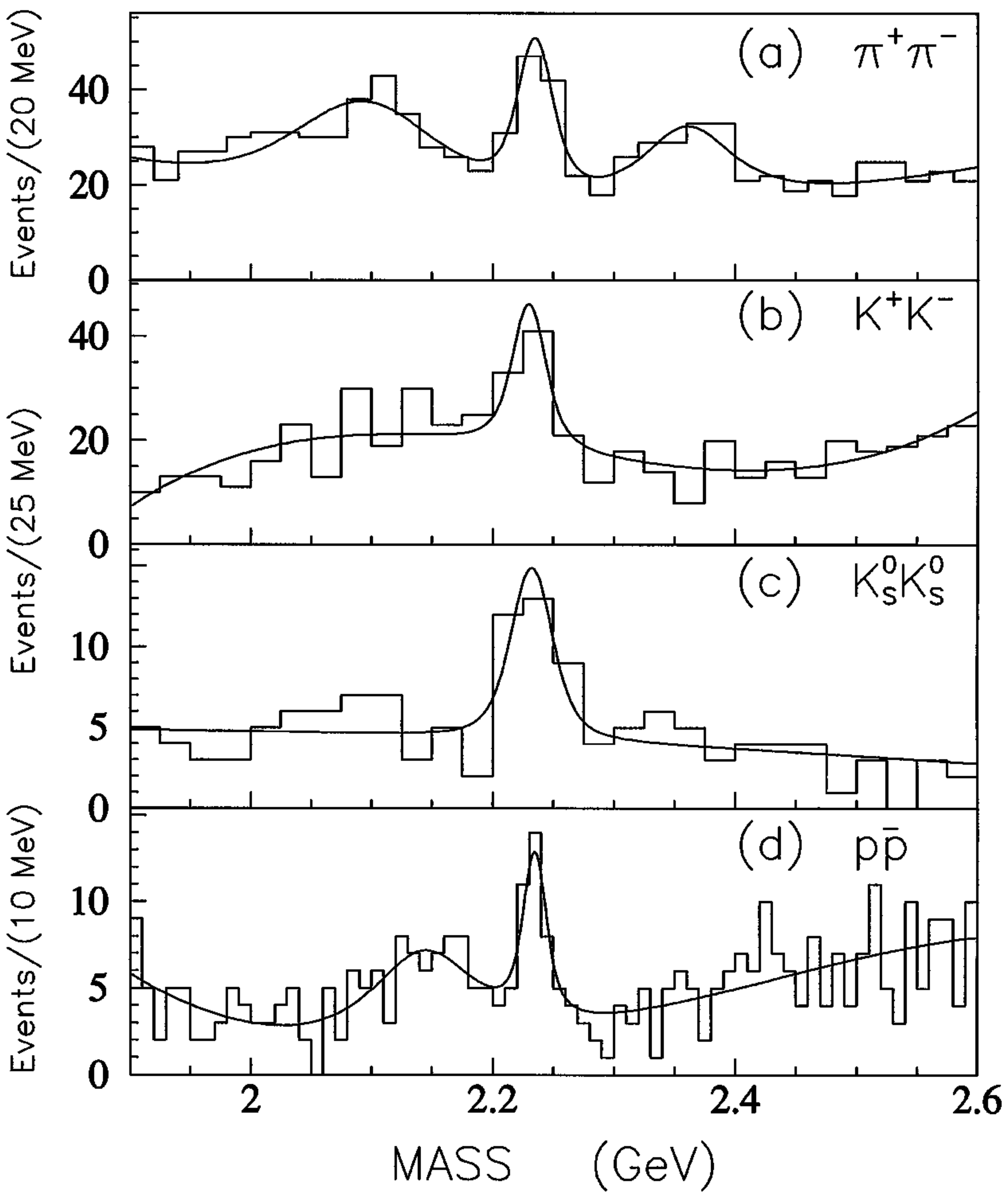
$$B[f_0(1500) \to \eta\eta' / f_0(1500) \to \pi\pi] = (1.66 \pm^{+0.42}_{-0.40}) \times 10^{-1}$$
$$B[f_0(1710) \to \eta\eta' / f_0(1710) \to \pi\pi] < (2.9 \pm^{+1.1}_{-0.9}) \times 10^{-3}$$

BESIII: PRD 106 072012(2022)

# Historical Glueball Candidates — Tensor ξ(2230)




PRL 56 (1986) 107

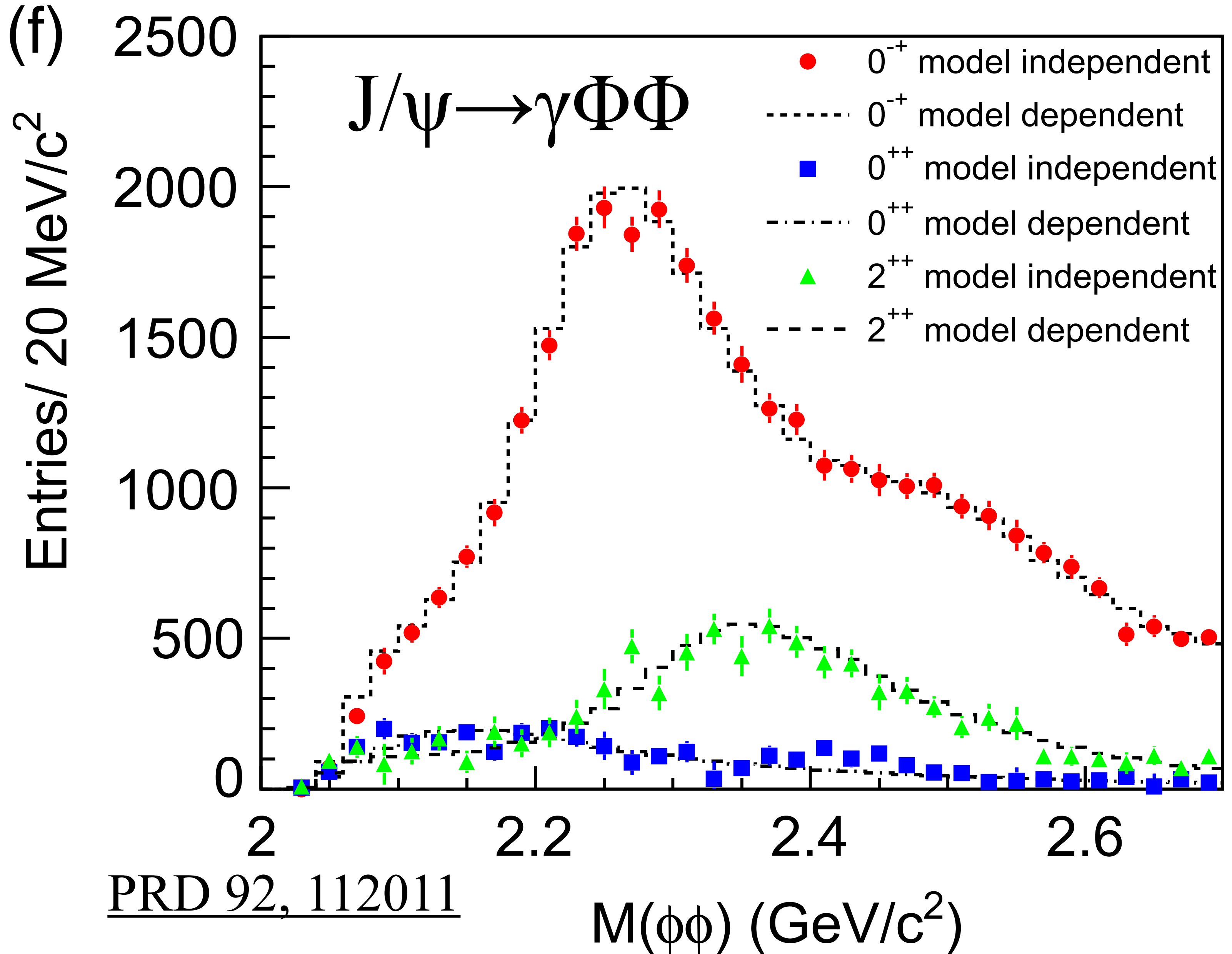



PRL 76 (1996) 3502

- First observed by MarkIII is J/ψ→ γKK in 1980's, then by BESI in 1990's in J/ψ → γKK, γππ, 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 with much higher statistics.

# Historical Glueball Candidates — Tensor $f_2(2340)$

- Its large production rate in J/ψ→γ(KK/ηη/η’η’/ϕϕ) favors its interpretation as a tensor glueball .
- **Difficulty:**
  - **Many wide $f_2$ mesons  and large overlaps in the mass region of 2.3GeV** ($2^{++}$ glueball mass from the LQCD predictions)
    - **no clear mass peak of these $f_2$ mesons**.
  - **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.




PRD 92, 112011

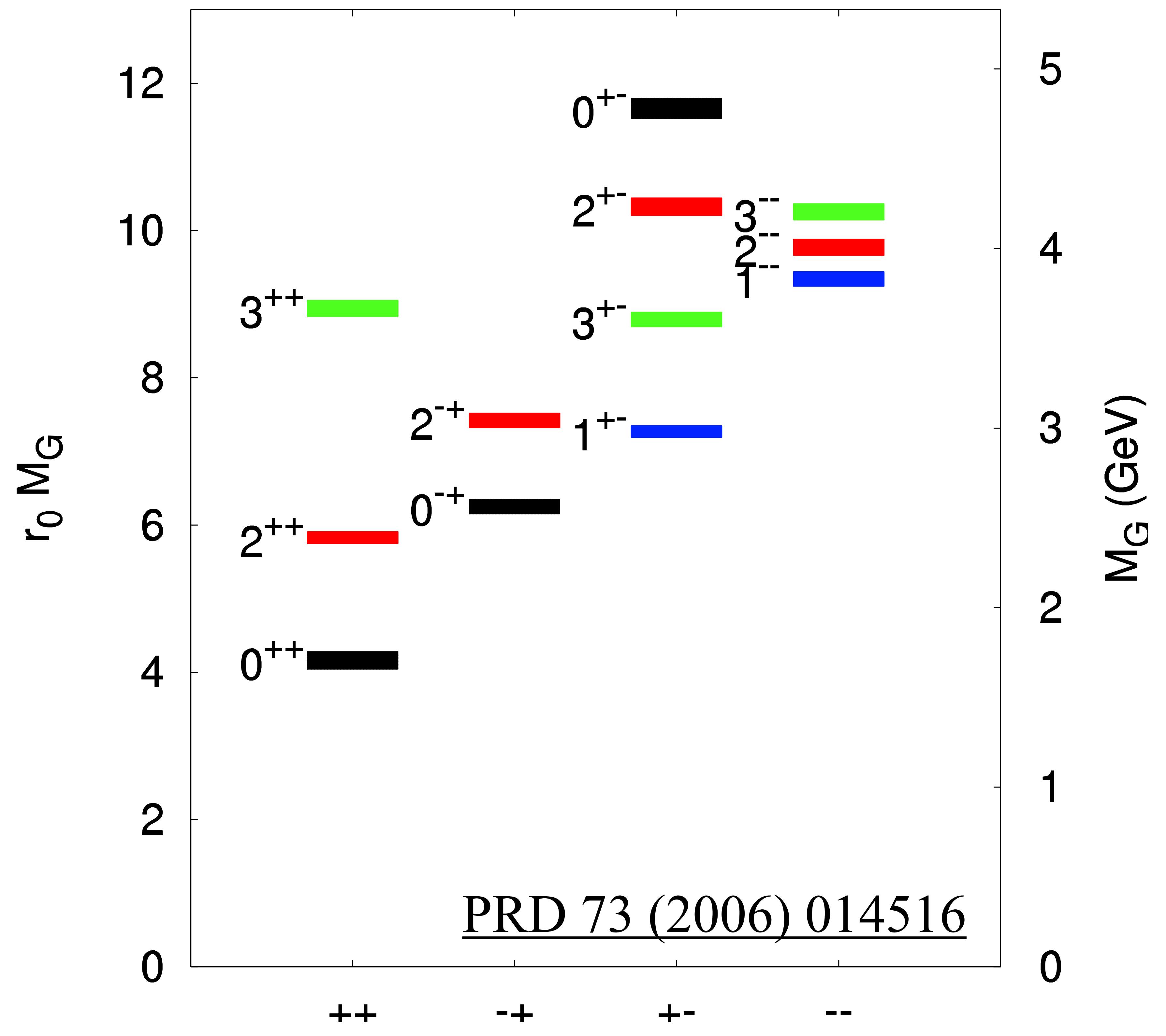
| Resonance | M (MeV/$c^2$) | Γ (MeV/$c^2$) | B.F. ($\times 10^{-4}$) | Sig. |
|---|---|---|---|---|
| $\eta(2225)$ | $2216^{+4+21}_{-5-11}$ | $185^{+12+43}_{-14-17}$ | $(2.40 \pm 0.10^{+2.47}_{-0.18})$ | $28\sigma$ |
| $\eta(2100)$ | $2050^{+30+75}_{-24-26}$ | $250^{+36+181}_{-30-164}$ | $(3.30 \pm 0.09^{+0.18}_{-3.04})$ | $22\sigma$ |
| $X(2500)$ | $2470^{+15+101}_{-19-23}$ | $230^{+64+56}_{-35-33}$ | $(0.17 \pm 0.02^{+0.02}_{-0.08})$ | $8.8\sigma$ |
| $f_0(2100)$ | 2101 | 224 | $(0.43 \pm 0.04^{+0.24}_{-0.03})$ | $24\sigma$ |
| $f_2(2010)$ | 2011 | 202 | $(0.35 \pm 0.05^{+0.28}_{-0.15})$ | $9.5\sigma$ |
| $f_2(2300)$ | 2297 | 149 | $(0.44 \pm 0.07^{+0.09}_{-0.15})$ | $6.4\sigma$ |
| $f_2(2340)$ | 2339 | 319 | $(1.91 \pm 0.14^{+0.72}_{-0.73})$ | $11\sigma$ |
| $0^{-+}$ PHSP | | | $(2.74 \pm 0.15^{+0.16}_{-1.48})$ | $6.8\sigma$ |

# Historical Glueball Candidates — Pseudoscalar η(1405)

- first discovered by MarkII in 1980's, named as η(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**

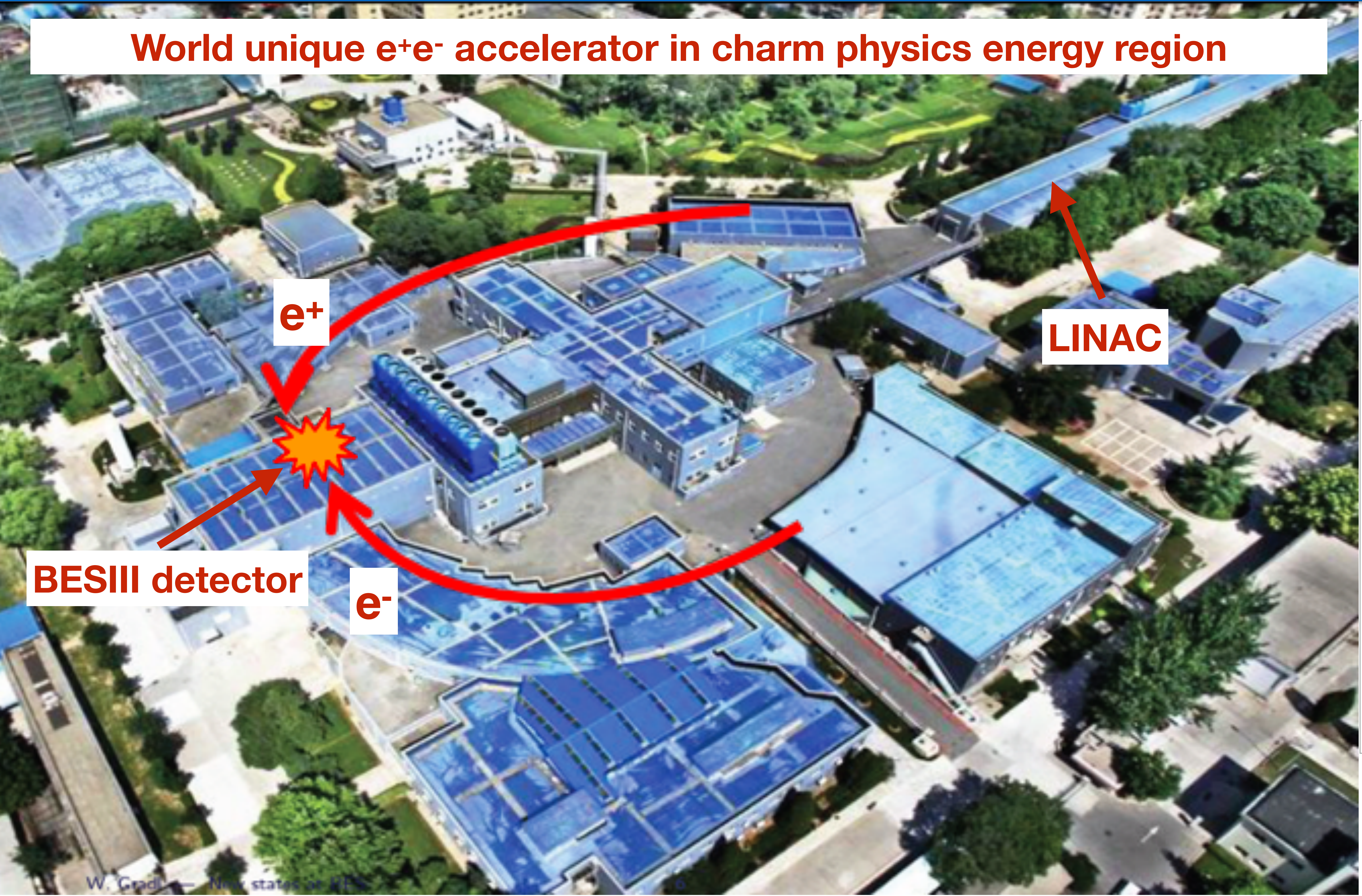
- No longer to be $0^{-+}$ glueball candidate due to its large different mass from LQCD prediction.



# Historical Difficulties in Glueball Searches

- **Experimentally:**
  - Data sample was not big enough
  - No good way **modeling background** in many cases.
  - **Interference among mesons** makes the analysis more complicated:
    - **PWA is a must, but it is complicated and takes a quite long time.**
- **Theoretically:**
  - **Very rare prediction on the glueball production rate** $\Gamma(J/\psi \to \gamma G)$
  - **No rigorous predictions on decay patterns and branching ratios so far (even the order)**
  - **Mix** with qqbar mesons or even with 4q, qqg, mesons? **Mixing dynamics**?

# Beijing Electron Positron Collider (BEPCII)




**2004: Construction**

- Double rings
- Beam energy:

  1.0 - 2.3 (2.45)GeV
- Designed luminosity:

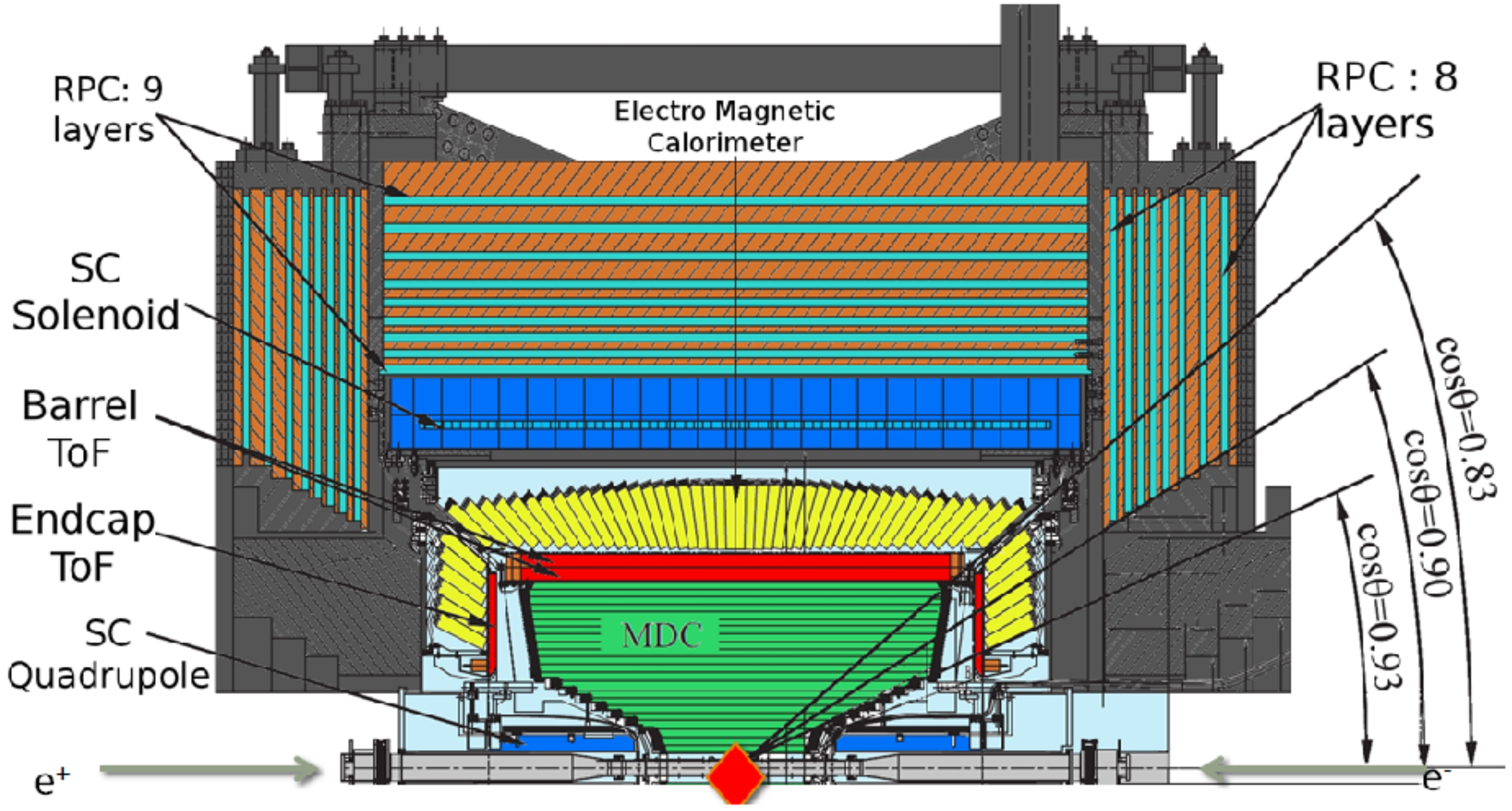
  $1 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

**2008：test run**

**2009-now: BESIII physics runs**

# BESIII detector

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




Total weight 730 ton,
~40,000 readout channel
Data rate: 5kHz, 50Mb/s

- Magnet: 1T Super conducting
- 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
  - ΔE/E = 2.5% @ 1GeV - Barrel
  - ΔE/E = 5% @ 1GeV - Endcap
- Muon ID: 9 layer RPC

**Has been in full operation since 2008, all sub-detectors are in very good status!**

# BESIII Collaboration


**Europe (17/115)**

Germany (6): Bochum University, GSI Darmstadt, Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, Universitaet Giessen, University of Münster

Italy (3): Ferrara University, INFN, University of Torino

Netherlands (1): KVI/University of Groningen

Russia (2): Budker Institute of Nuclear Physics, Dubna JINR

Sweden (1): Uppsala University

Turkey (1): Turkish Accelerator Center Particle Factory Group

UK (2): University of Manchester, University of Oxford

Poland (1) National Centre for Nuclear Research

**Asia (6/10)**

Pakistan (2): COMSATS Institute of Information Technology University of the Punjab, University of Lahore

Mongolia (1): Institute of Physics and Technology

Korea (1): Chung-Ang University

India (1): Indian Institute of Technology madras

Thailand (1): Suranaree University of Technology

**USA(4/8)**

Carnegie Mellon University
Indiana University
University of Hawaii
University of Minnesota

**South America (1/1)**

Chile: University of Tarapaca

**China (60/367)**

Institute of High Energy Physics (146), other units(221): Beijing Institute of Petro-chemical Technology, Beihang University, China Center of Advanced Science and Technology, Fudan University, Guangxi Normal University, Guangxi University, Hangzhou Normal University, Henan Normal University, Henan University of Science and Technology, Huazhong Normal University, Huangshan College, Hunan University, Hunan Normal University, Henan University of Technology Institute of modern physics, Jilin University, Lanzhou University, Liaoning Normal University, Liaoning University, Nanjing Normal University, Nanjing University, Nankai University, North China Electric Power University, Peking University, Qufu normal university, Shanxi University, Shanxi Normal University, Sichuan University, Shandong Normal University, Shandong University, Shanghai Jiaotong Univeristy, Soochow University, South China Normal University, Southeast University, Sun Yat-sen University, Tsinghua University, University of Chinese Academy of Sciences, University of Jinan, University of Science and Technology of China, University of Science and Technology Liaoning, University of South China, Wuhan University, Xinyang Normal University, Zhejiang University, Zhengzhou University, YunNan University , China University of Geosciences

BESIII

**~600 members**
**(more than 130 from outside of China)**
**From 89 institutions in 17 countries**

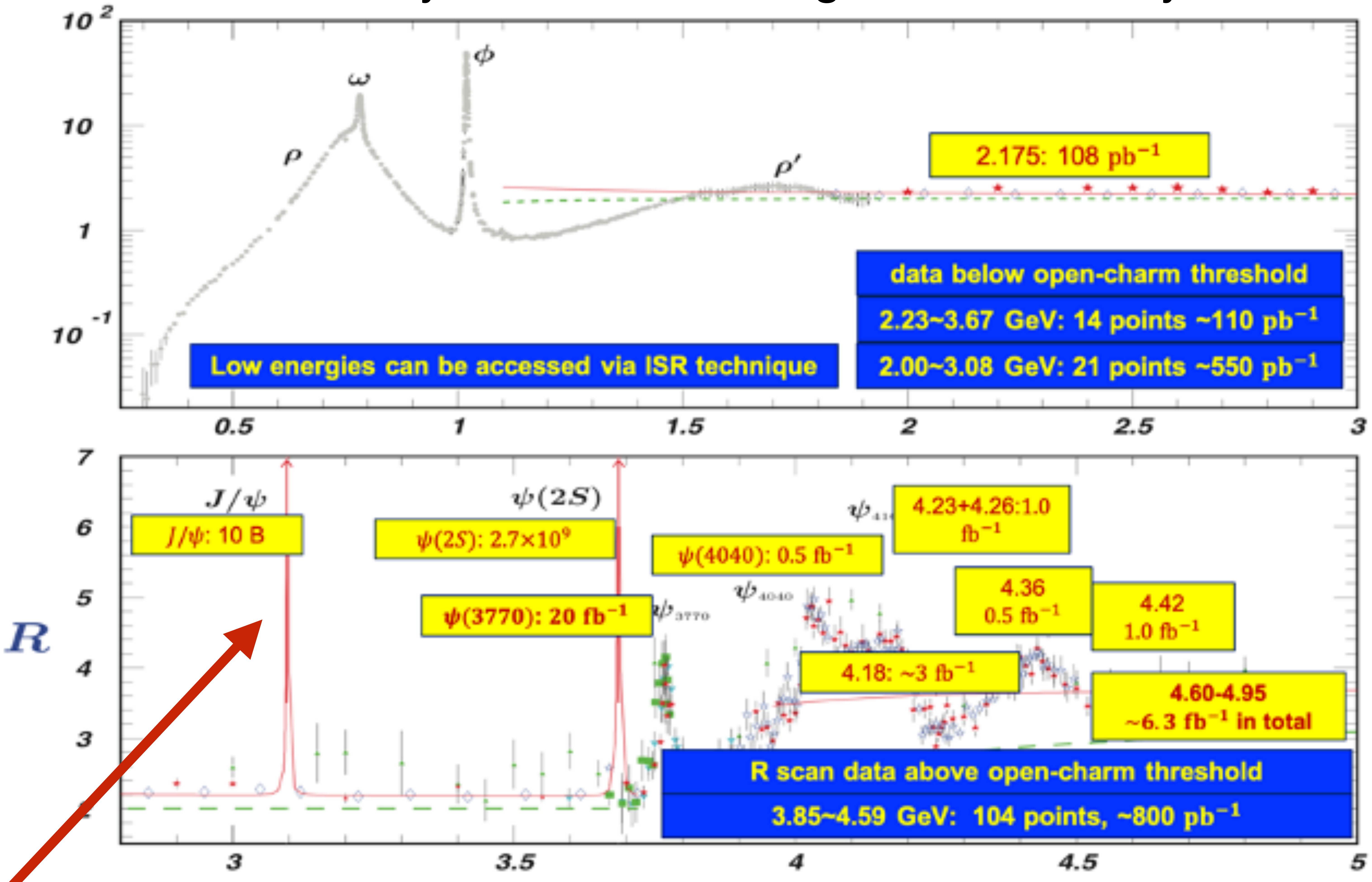
# BESIII Data samples

Totally about 50fb$^{-1}$ integrated luminosity

Data sets collected so far include

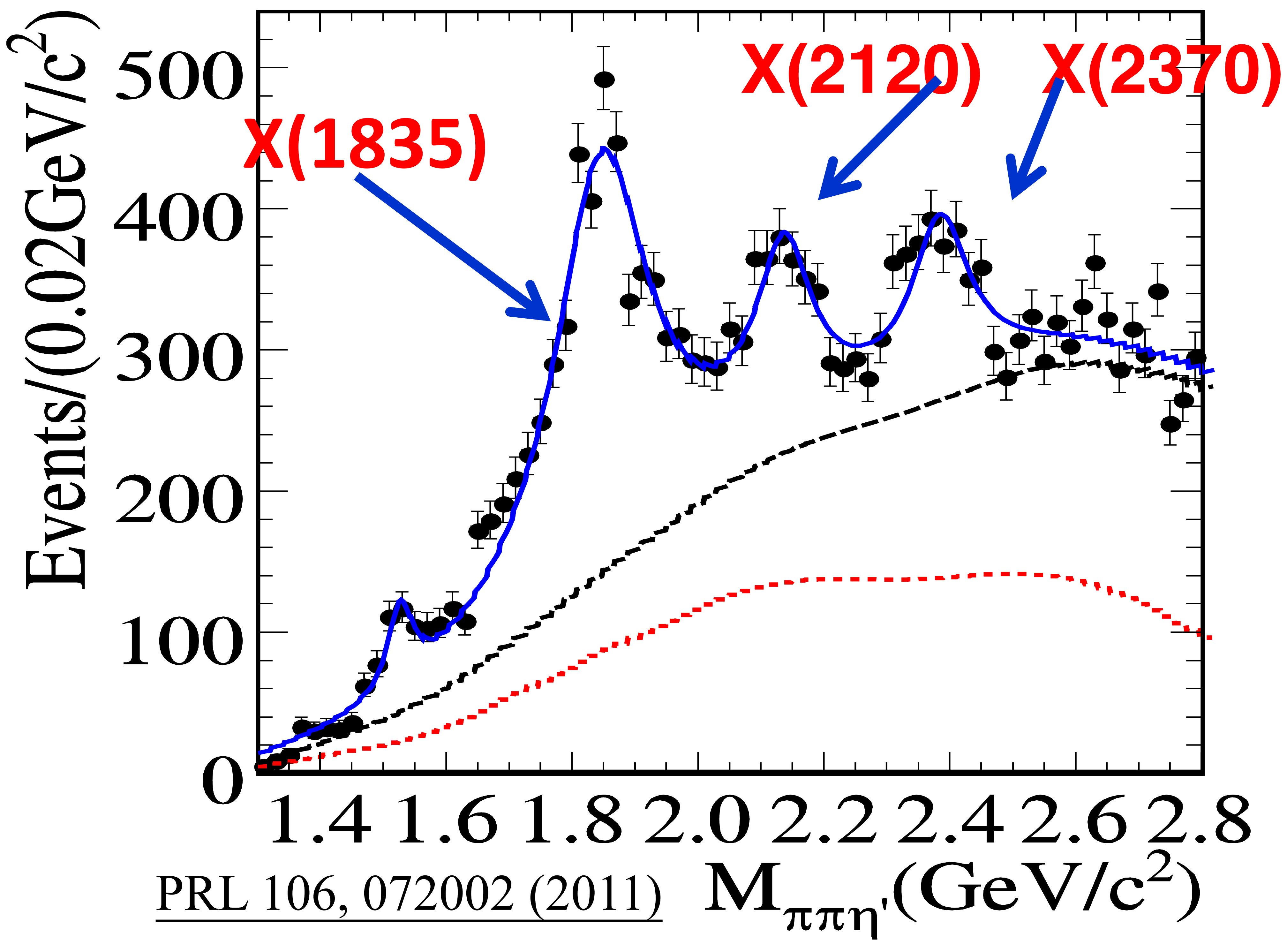
- ✦ 10×10$^{9}$ J/ψ events
- ✦ 2.7×10$^{9}$ ψ(2S) events
- ✦ 20 fb$^{-1}$ ψ(3770)
- ✦ Scan data between 2.0 and 3.08 GeV, and above 3.74GeV
- ✦ Large datasets for XYZ studies:

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




**World largest J/ψ data sample : ~10 billion**

# Observation of the X(2370) in 2011



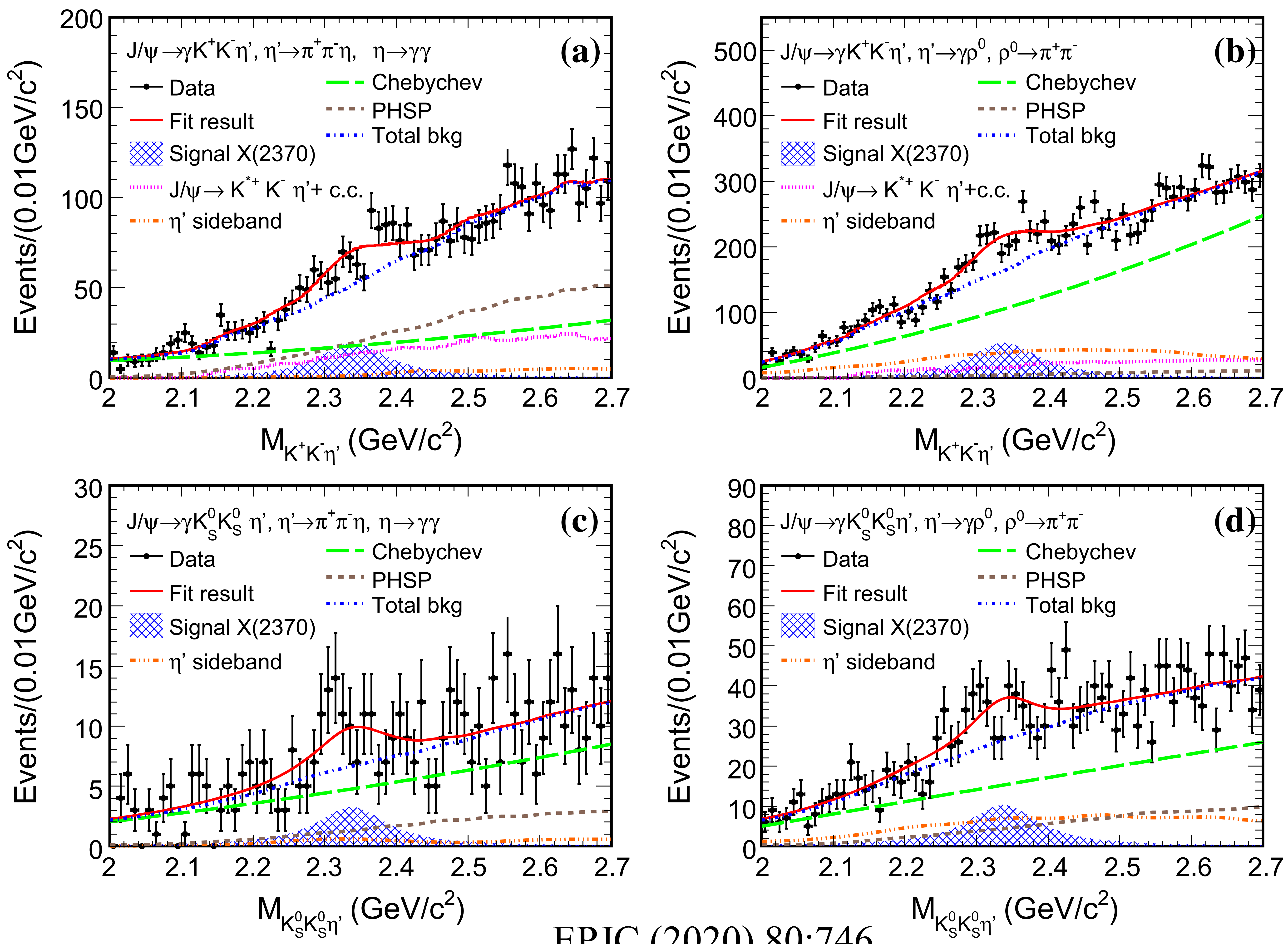

PRL 106, 072002 (2011)

**$J/\psi \to \gamma\pi^+\pi^-\eta'$ With ~225M $J/\psi$ events**

| | 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 |

- **Discovery of X(2370) in $J/\psi \to \gamma\pi^+\pi^-\eta'$ with the statistic significance of 6.4σ**
- **First observation of one particle: a good candidate for $0^{-+}$ glueball**
  - **Mass, production and decay property are consistent with the LQCD prediction**

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



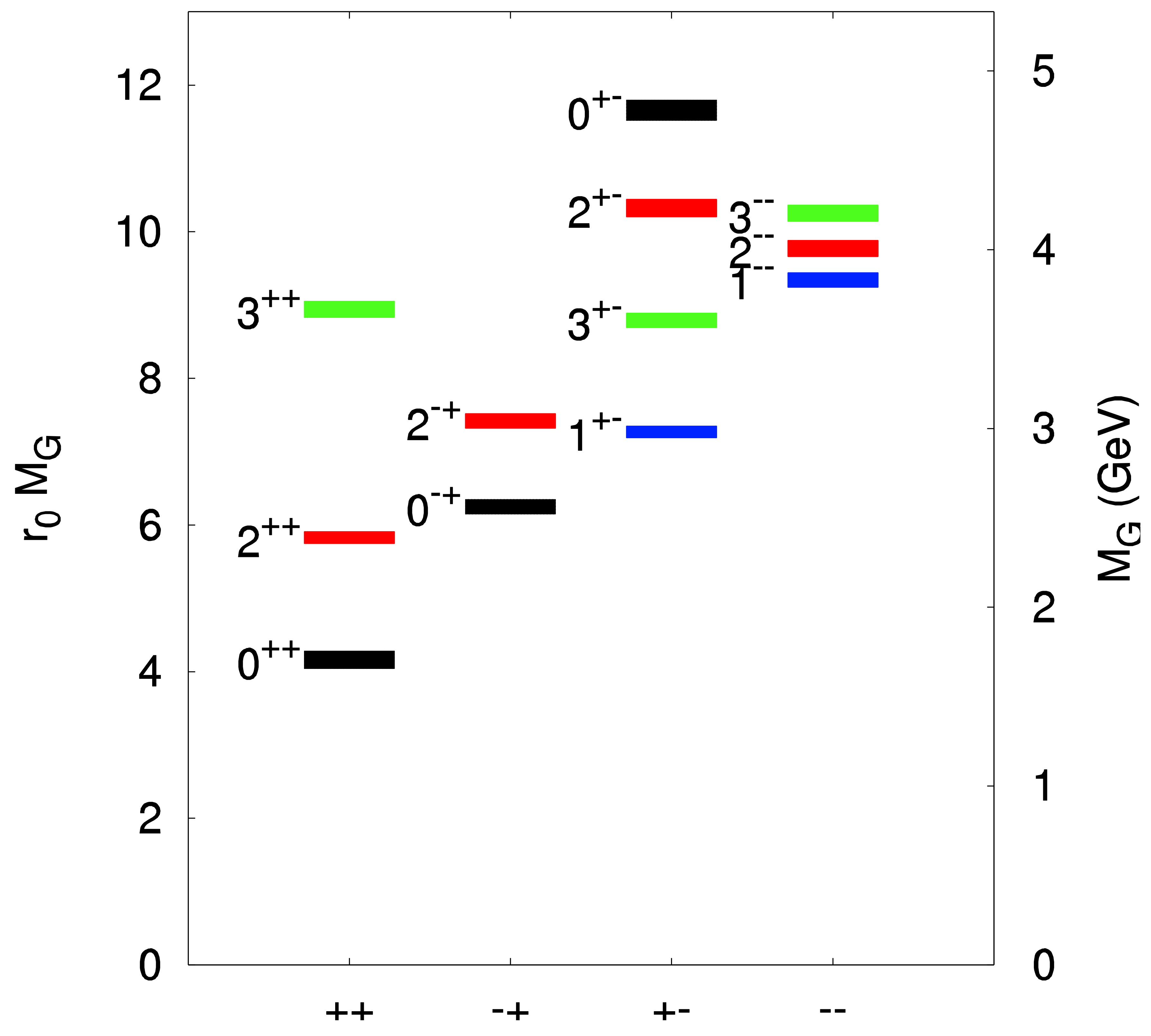

EPJC (2020) 80:746

- ◈ **Combination with $1.31\times10^9$ 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’)=$(1.79\pm0.23\pm0.65)\times10^{-5}$**
  - **Br(J/ψ→γX(2370)→γKsKsη’)=$(1.18\pm0.32\pm0.39)\times10^{-5}$**

**Observation: X(2370) new decay mode of KKη’**

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

- Its mass is consistent with LQCD prediction on the $0^{-+}$ glueball
- Observed in flavor symmetric decay modes of $\pi^+\pi^-\eta'$ and $K\bar{K}\eta'$ — favorite decay modes of $0^{-+}$ glueball
- We need to know its spin-parity



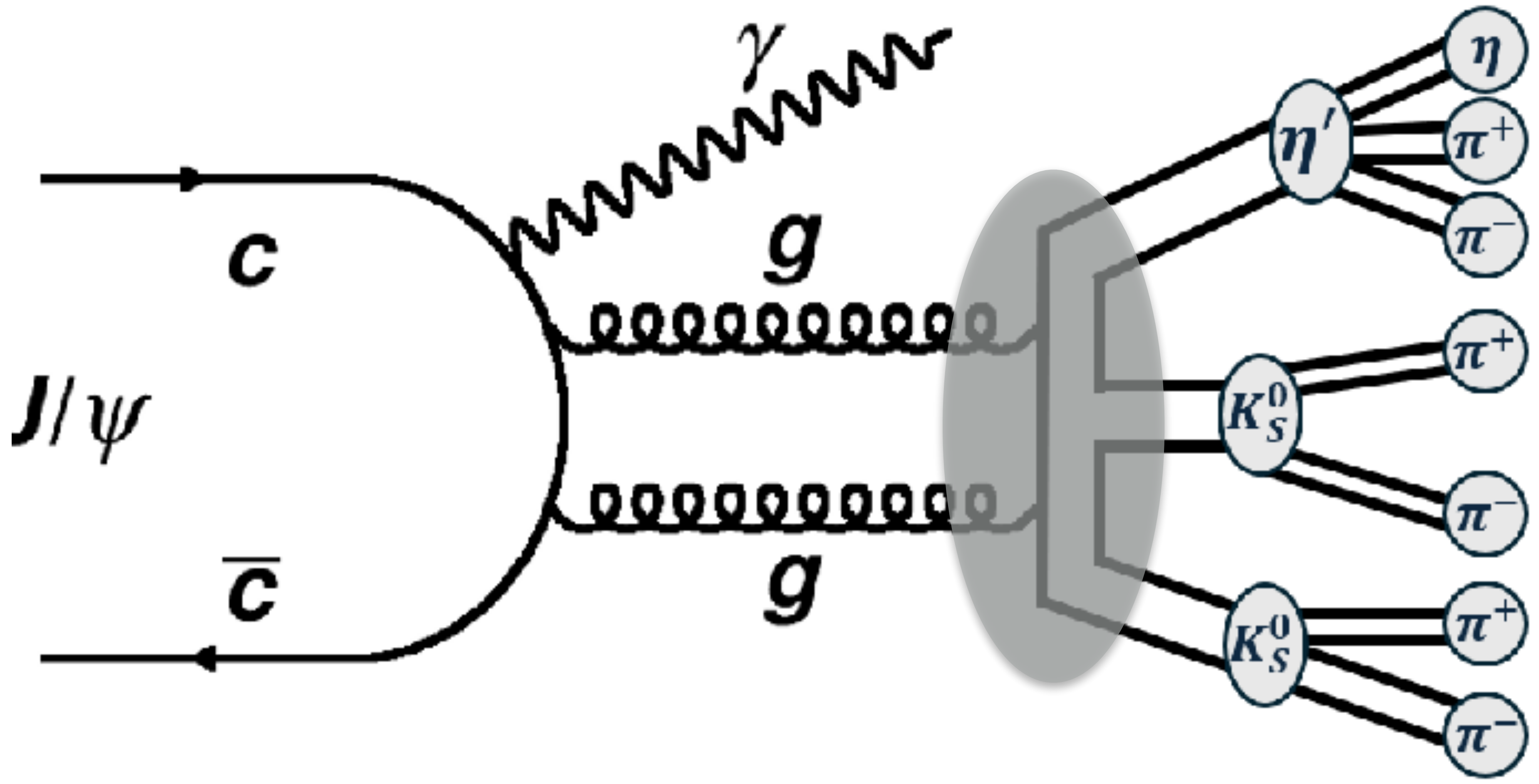
# Spin-Parity determination of the X(2370) in $J/\psi \to \gamma K^0_s K^0_s \eta'$

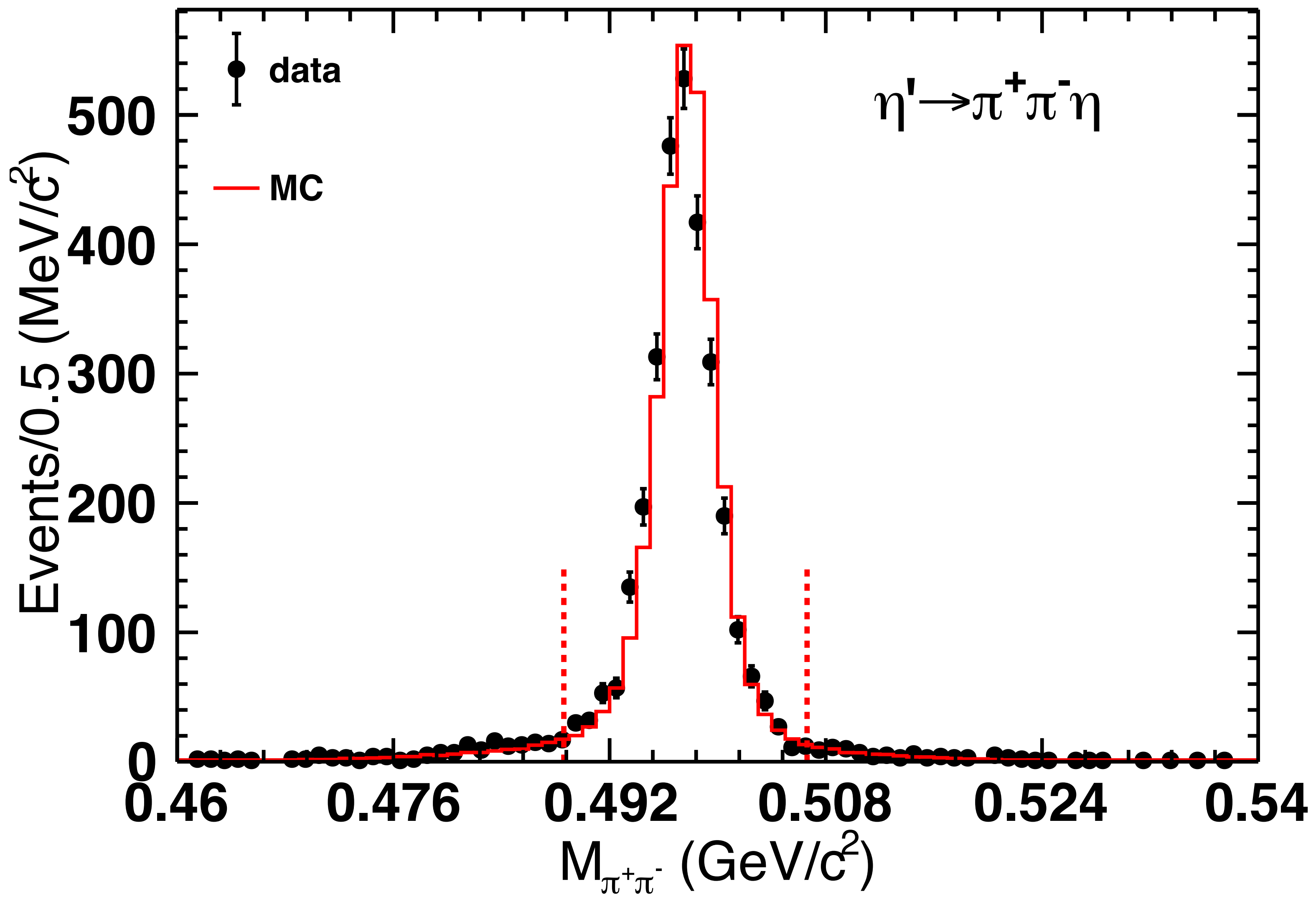
Make use of four advantages:

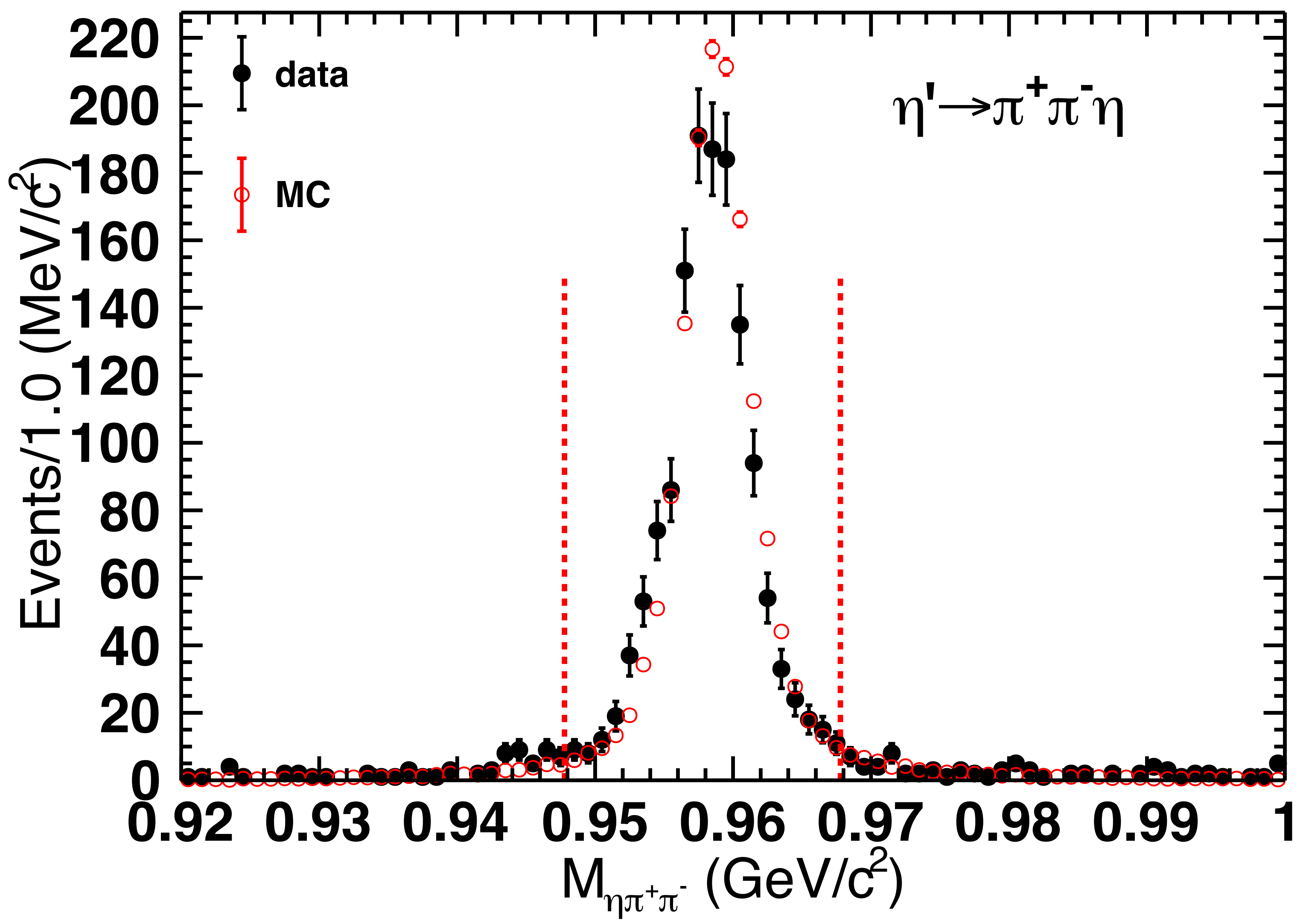
- **Clean $J/\psi \to \gamma K_s^0 K_s^0 \eta'$ process**
  - **Almost no background:** possible dominant background processes of $J/\psi \to \pi^0 K_s^0 K_s^0 \eta'$ and $J/\psi \to K_s^0 K_s^0 \eta'$ are forbidden by **exchange symmetry and C-parity conservation.**
- **~10B clean $J/\psi$ events**
- **High efficiency and precise resolution of charged particles and photons:** good reconstruction for $K_s^0/\eta$
- **Two dominant decay modes of $\eta' \to \gamma\pi^+\pi^-$ and $\eta' \to \pi^+\pi^-\eta$**: good reconstruction for $\eta'$

# Selection for $J/\psi \to \gamma K_s^0 K_s^0 \eta', \eta' \to \pi^+\pi^-\eta$

- **Signal selection:**
  - At least 3 charged pairs + 3 photons
  - Constraint kinematic fit with energy-momentum conservation
  - $K^0_s$ reconstruction: $|M_{\pi\pi} - m_{Ks}| < 9$ MeV/c²
  - η' reconstruction: $|M_{\pi\pi\eta} - m_{\eta'}| < 10$ MeV/c²
- **Background veto:**
  - $\pi^0$ veto: $|M_{\gamma\gamma} - m_{\pi 0}| > 20$MeV/c²



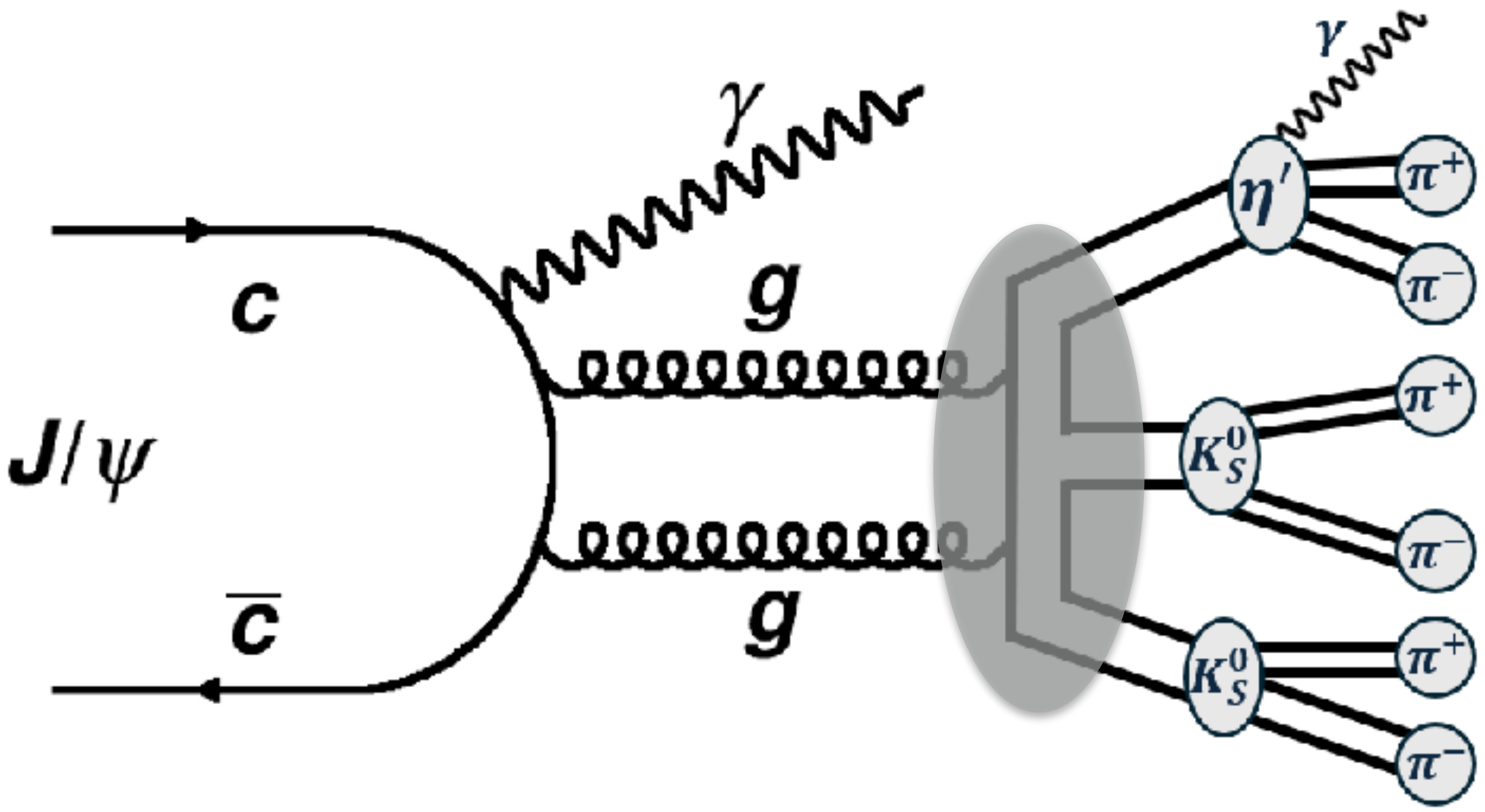



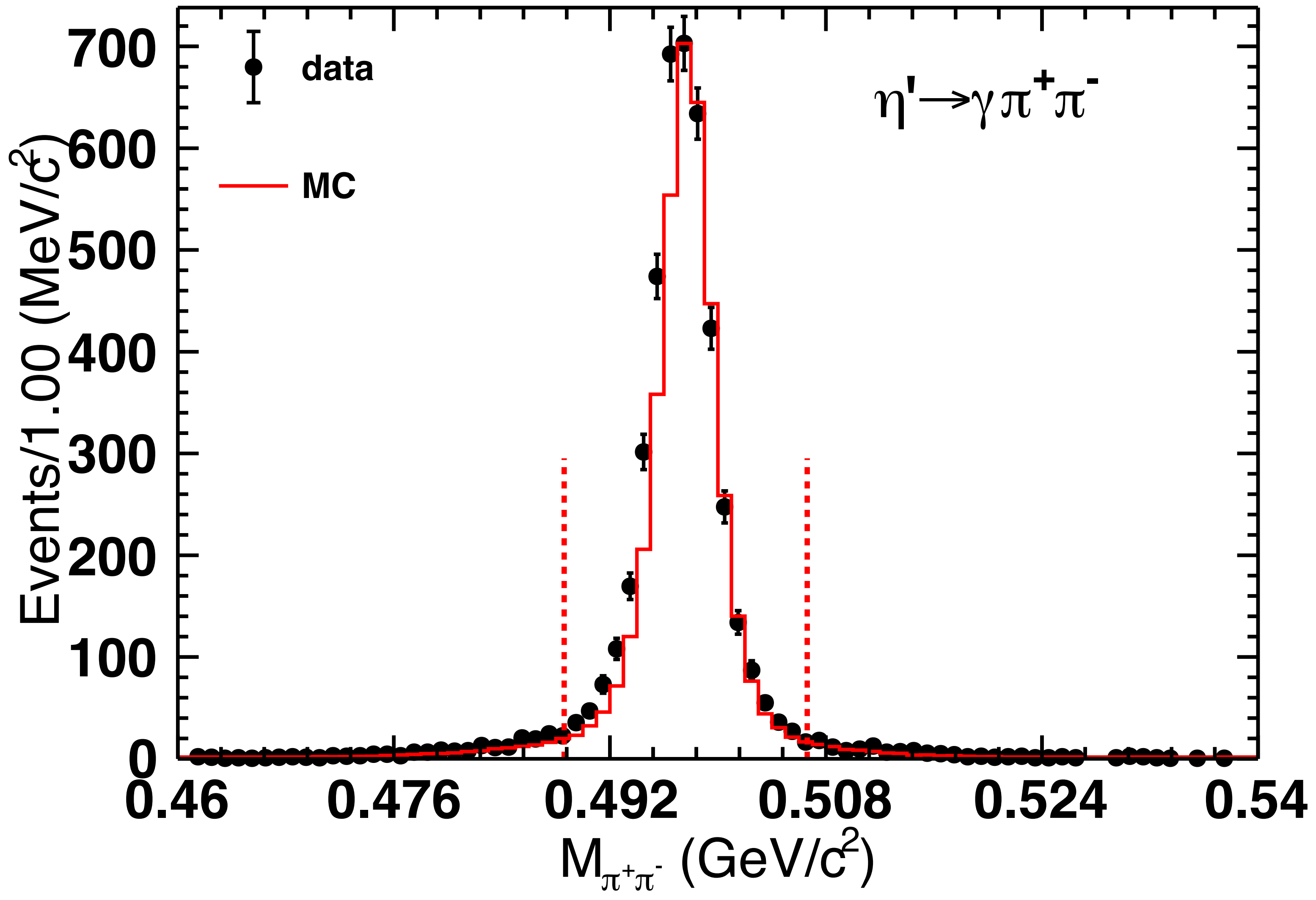



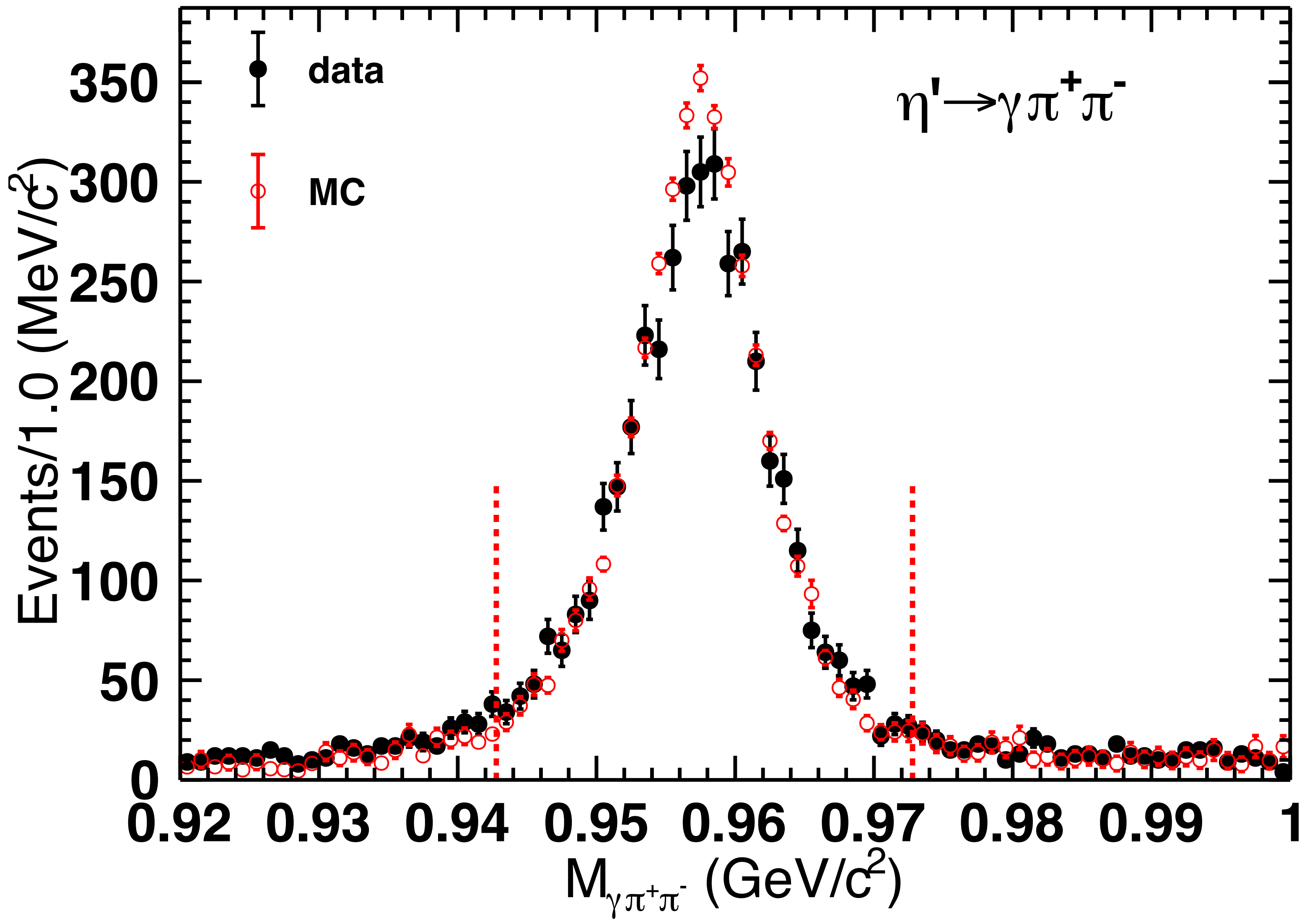

Clean $K^0_s$ and η' Signal

# Selection for $J/\psi \to \gamma K_s^0 K_s^0 \eta', \eta' \to \gamma\pi^+\pi^-$

- **Signal selection:**
  - At least 3 charged pairs + 2 photons
  - Constraint kinematic fit with energy-momentum conservation
  - $K^0_s$ reconstruction: $|M_{\pi\pi} - m_{Ks}| < 9$ MeV/$c^2$
  - η' reconstruction: $|M_{\pi\pi\eta} - m_{\eta'}| < 15$ MeV/$c^2$
- **Background veto:**
  - $\pi^0/\eta$ veto: $|M_{\gamma\gamma} - m_{\pi 0}| > 20$MeV/$c^2$, $|M_{\gamma\gamma} - m_{\eta}| > 30$MeV/$c^2$



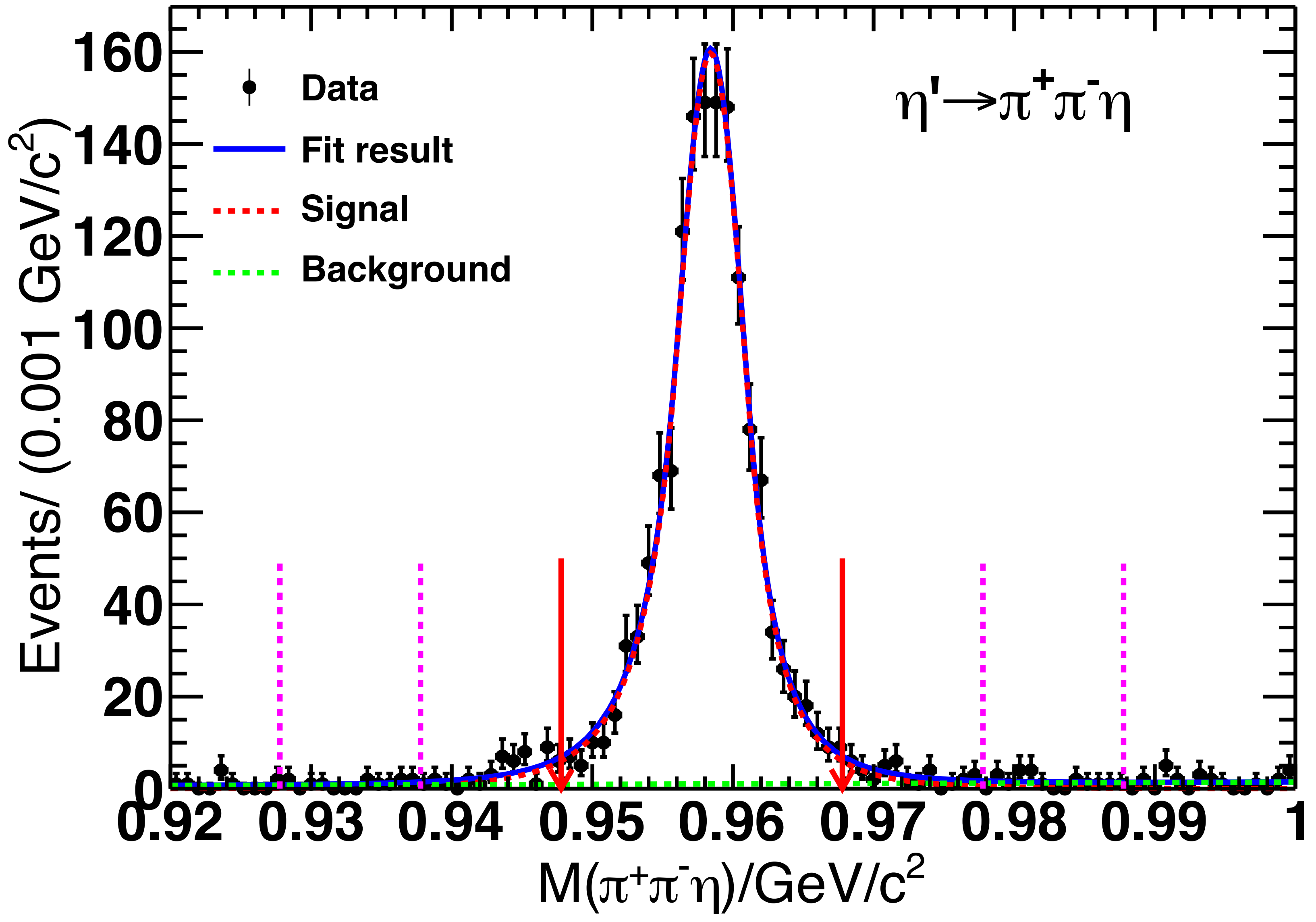



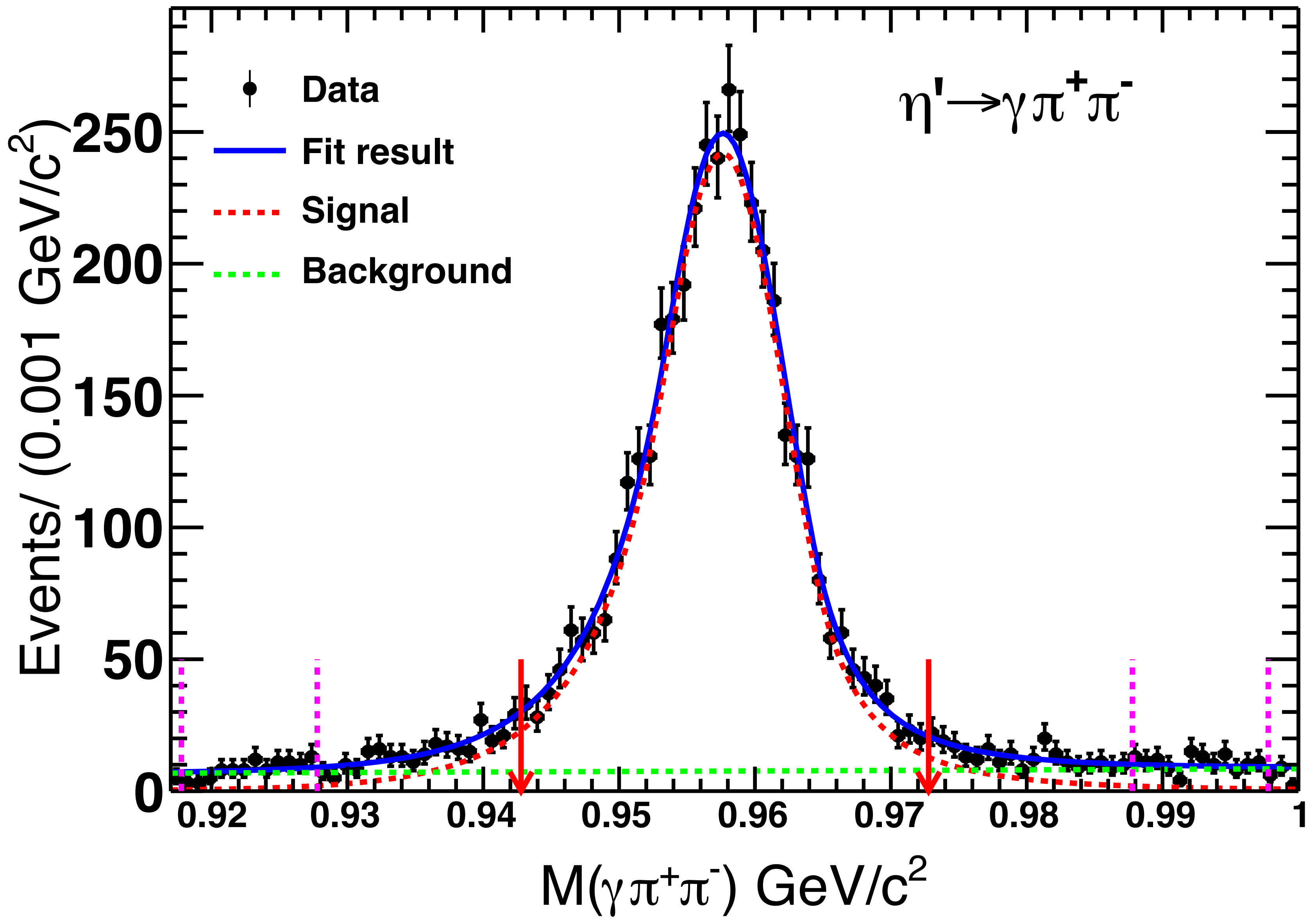




Clean $K^0_s$ and η' Signal

# Background estimation

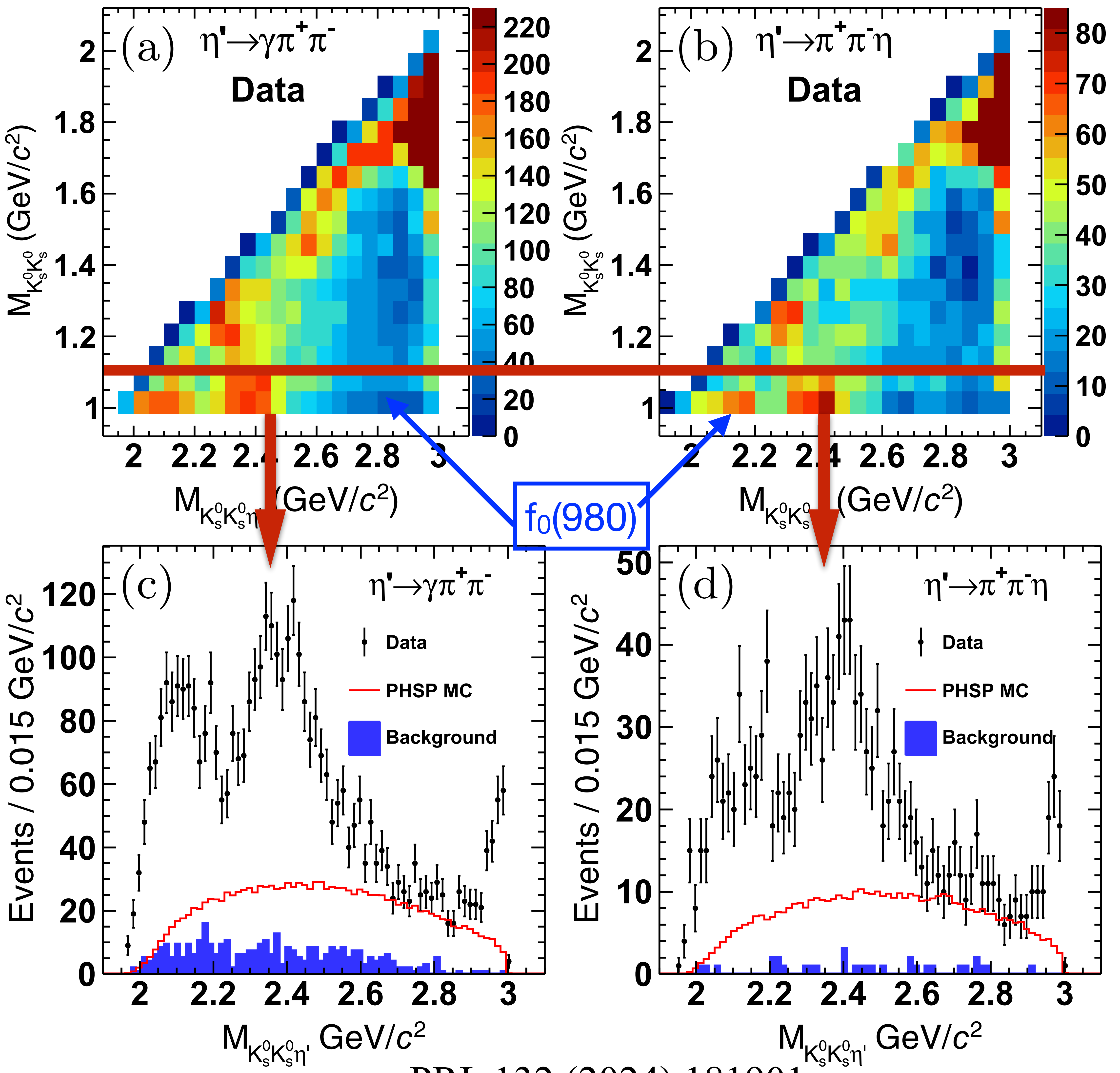
- **Negligible mis-combination for $K^0_S$ reconstruction ( <0.1%)**
- **No background from $J/\psi \to \pi^0 K^0_S K^0_S \eta'$:** further validation directly from data
- **Little background from non-η' processes:** estimated directly from η' mass sideband region:
  - No peaking background
  - **Non-η'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




**The process with almost no background is suitable for the PWA**

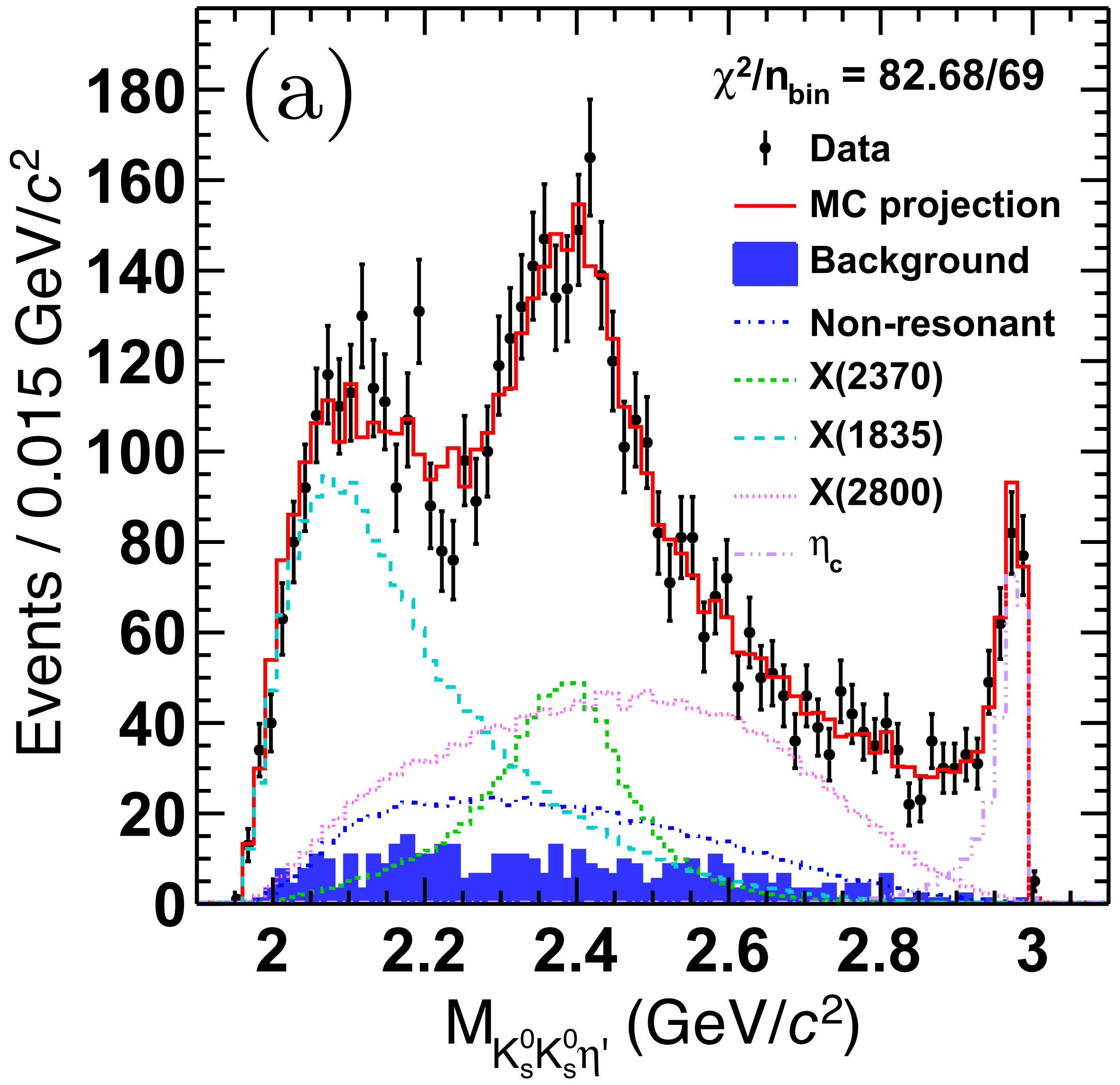
# Mass spectrum after final selection

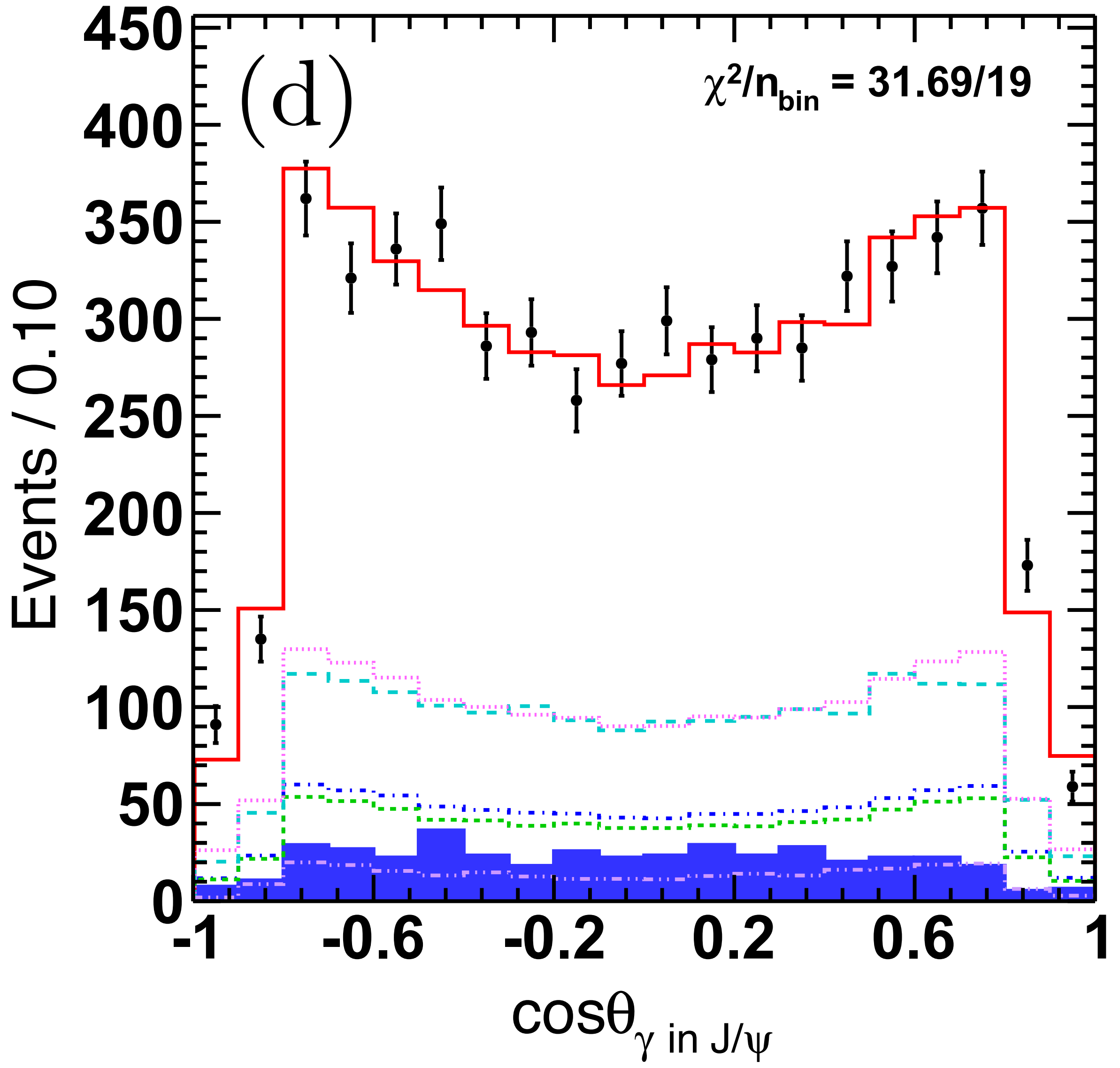



PRL 132 (2024) 181901

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

# PWA Fit




PRL 132 (2024) 181901

- Best fit can well describe the data including resonances (>5σ): **X(1835), X(2370), X(2800), $\eta_c$**
  - **Spin-parity of the X(2370) is determined to be $0^{-+}$** with significance larger than **9.8σ w.r.t. other $J^{PC}$ assumptions**
  - X(2800): a broad structure for the effective contributions from possible high mass resonances

| state | $J^{PC}$ | Decay mode | Mass $(MeV/c^2)$ | Width $(MeV/c^2)$ | Significance |
|---|---|---|---|---|---|
| X(2370) | $0^{-+}$ | $f_0(980)\eta'$ | $2395^{+11}_{-11}$ | $188^{+18}_{-17}$ | $14.9\sigma$ |
| X(1835) | $0^{-+}$ | $f_0(980)\eta'$ | 1844 | 192 | $22.0\sigma$ |
| X(2800) | $0^{-+}$ | $f_0(980)\eta'$ | $2799^{+52}_{-48}$ | $660^{+180}_{-116}$ | $16.4\sigma$ |
| $\eta_c$ | $0^{-+}$ | $f_0(980)\eta'$ | 2983.9 | 32.0 | $> 20.0\sigma$ |
| PHSP | $0^{-+}$ | $\eta'(K_S^0 K_S^0)_{S-wave}$ | $---$ | $---$ | $9.0\sigma$ |
| | | $\eta'(K_S^0 K_S^0)_{D-wave}$ | $---$ | $---$ | $16.3\sigma$ |

# PWA Validations

- **Additional decay modes: significance <3σ and impact is ignored**
  - **$J^{PC}$ and decay modes for each components**: $f_0(1500)\eta'$, $f_2(1270)\eta'$, $K^*(1410)K_s^0$, $K_0^*(1430)K_s^0$, $K_0^*(1430)K_s^0$, $K_2^*(1430)K_s^0$, $K_0^*(1680)K_s^0$, $(K_s^0K_s^0)_S\eta'$, $(K_s^0K_s^0)_D\eta'$, $(K_s^0\eta')_PK_s^0$, $(K_s^0\eta')_DK_s^0$
- **Additional resonance checks: significance <5σ**
  - No evidence of the **X(2120)** in the $K_sK_s$ mass threshold region for $J/\psi\to\gamma K_sK_s\eta'$ only
  - The significance of **$X(2600)\to f_0(980)\eta'$** is 4.2σ
  - Impact from the X(2120) and X(2600) is taken into account as systematic uncertainty
- **The X(2800)** with a mass of 2799 MeV and width of 660 MeV:
  - Used to described **effective contributions from high mass region**
  - **Strongly reply on the description of $\eta_c$ lineshape:** different variations are included into the systematic uncertainty
  - **Statistical uncertainties of the X(2800) mass and width** are included in the systematic uncertainties on the X(2370) measurements

# Final results

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

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

**M = 2395 ±11$^{+26}_{-94}$ MeV**

**Γ = 188$^{+18}_{-17}$$^{+124}_{-33}$ MeV**

**$B(J/\psi\to\gamma X(2370))B(X(2370)\to f_0(980)\eta')B(f_0(980)\to K^0_S K^0_S)$**
**$= (1.31 \pm 0.22^{+2.85}_{-0.84})\times10^{-5}$**

**LQCD prediction on lightest pseudoscalar glueball:**

**$J^{PC}$ = $0^{-+}$**

**M = 2395 ±14 MeV**

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

- 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 ~5% decay rate, $B(J/\psi\to\gamma X(2370)) = (10.7^{+22.8}_{-7})\times10^{-4}$)

# 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 $\eta_c$ 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

# Study in $J/\psi \to \gamma K^0_s K^0_s \eta$

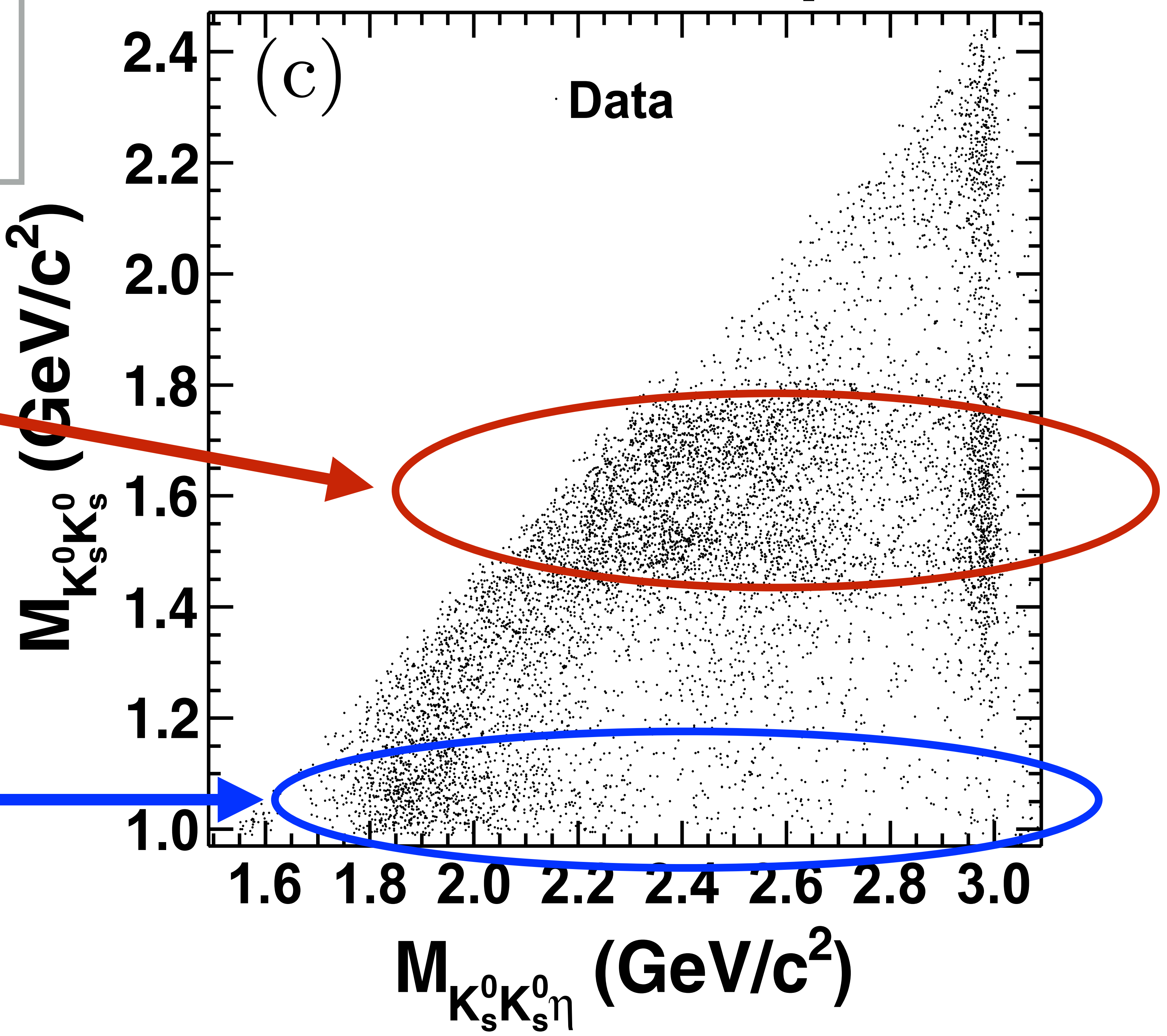
Observation and Spin-Parity Determination of the $X(1835)$ in $J/\psi \to \gamma K^0_S K^0_S \eta$

**Qualitatively, we can clearly observe: same decay modes between the X(2370) and $\eta_c$ if phase space allows**

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

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

**With $1.31\times10^9$ $J/\psi$ events**




PRL 115 (2015) 091803

**Such high similarity between the X(2370) and $\eta_c$ decay modes strongly supports the glueball interpretation of the X(2370)**

# Interpretation

| | X(2370) | $\eta_c$ | 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 ($\eta_c$ dominant decays) and suppressed decay modes are consistent between the X(2370) and $\eta_c$
  - **A good agreement with the glueball interpretation**
- **The X(2370) production properties observed:**
  - richly produced in $J/\psi$ radiative decays as the glueball expectation
  - In the mass region larger than 2GeV, the only particle X(2370) for the $0^{-+}$ glueball candidate in $J/\psi$ radiative decays and two golden decay modes ($\pi\pi\eta'$ and $K\bar{K}\eta'$)
- **Mass, spin-parity:** consistent with $0^{-+}$ glueball prediction

# 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) is the first particle that matches the theoretical expectations for a glueball**
  - ✦ **Spin-parity quantum numbers** are determined to be $J^{pc} = 0^{-+}$
  - ✦ Measurements and predictions on **mass and production rate** are consistent within errors
  - ✦ **production and decay properties:** the X(2370) is observed in J/ψ radiative decay and flavor symmetric decay modes (favorite decay modes of $0^{-+}$ glueball)

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

**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**

# Prospects

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

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

**Decays involving hadronic resonances**

| | | | |
|---|---|---|---|
| $\Gamma_1$ | $\eta'(958)\pi\pi$ | $(1.87\pm0.26)$ % | PRL 106, 072002 (2011) PRL 132 (2024) 181901 |
| $\Gamma_2$ | $\eta'(958)K\bar{K}$ | $(1.61\pm0.25)$ % | EPJC (2020) 80:746 |

**Decays into stable hadrons**

| | | | |
|---|---|---|---|
| $\Gamma_{34}$ | $K\bar{K}\pi$ | $(7.0\ \pm0.4\ )$ % | |
| $\Gamma_{35}$ | $K\bar{K}\eta$ | $(1.32\pm0.15)$ % | PRL 115 (2015) 091803 |
| $\Gamma_{36}$ | $\eta\pi^+\pi^-$ | $(1.7\ \pm0.5\ )$ % | |

Ongoing, aiming for publication @ICHEP2024 (→ $\Gamma_{34}$, $\Gamma_{36}$)

- **Improve the measurements on the mass, width, branching ratio and production rates of the X(2370)**
  - Need to have better ways to understand and control the interferences in PWA.
- **Close collaboration between theory and experiment. Looking forward to more reliable LQCD studies on the glueball properties**