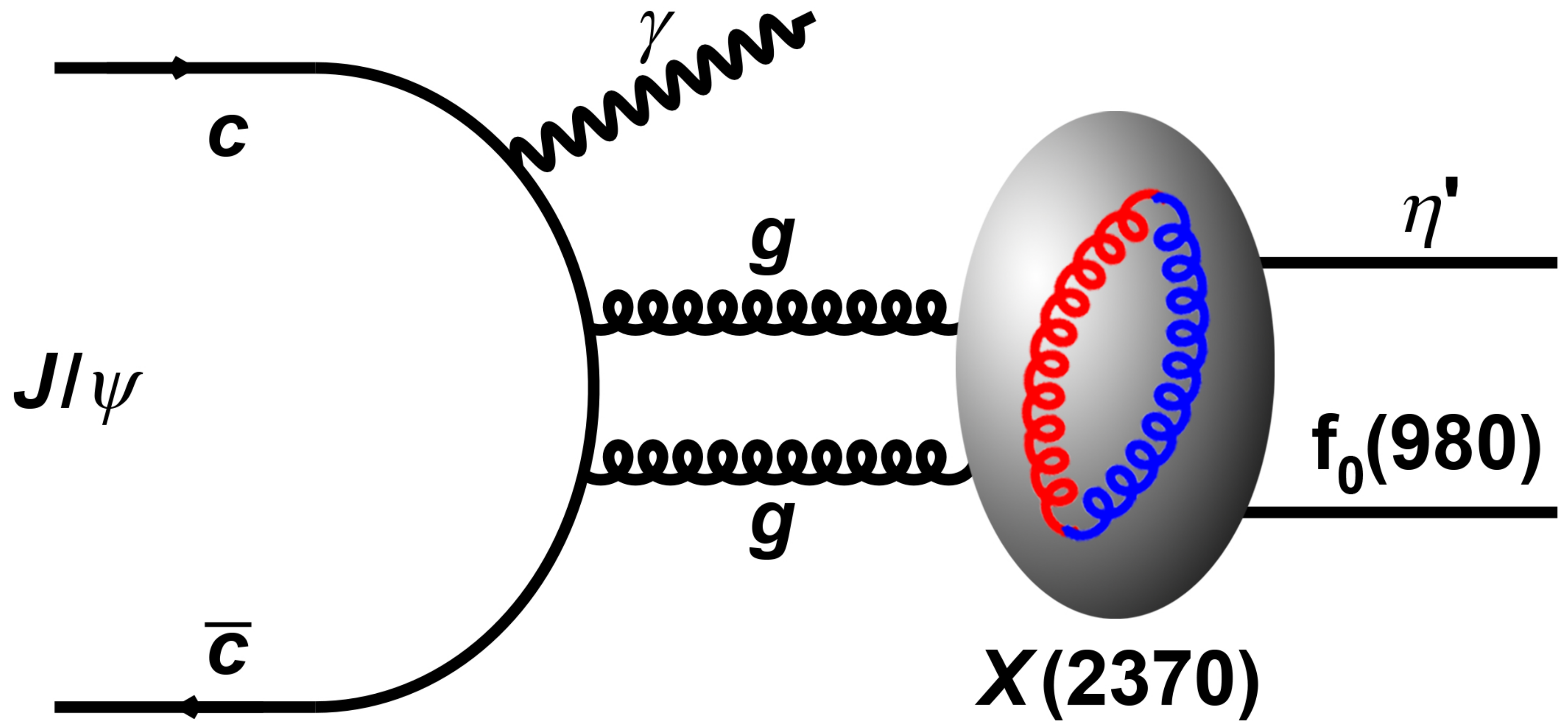
# Discovery of a Glueball-like particle X(2370) @ BESIII





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(On behalf of the BESIII Collaboration)


July 1st, 2024

# Forms of hadrons

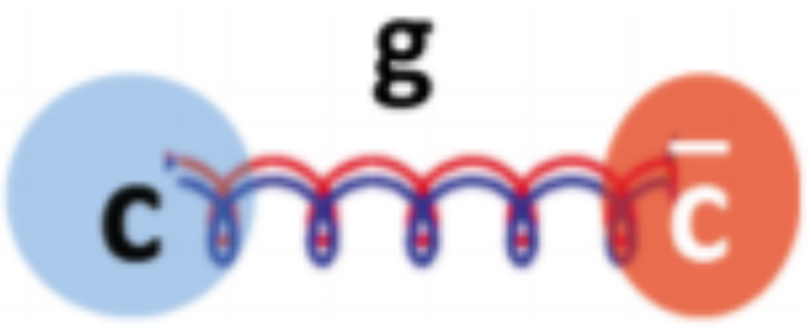
◈ **In quark model:**



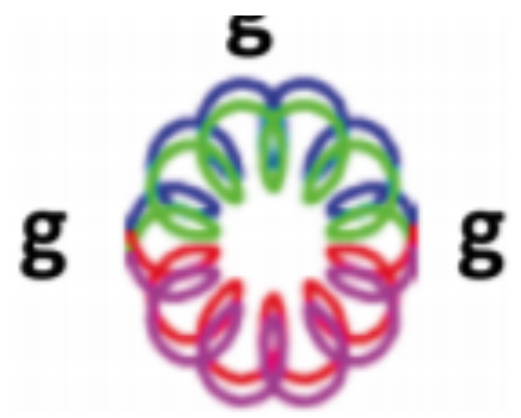
◈ **Other forms of hadrons：**

- ✦ **Multi-quark:** quark number >= 4

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



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

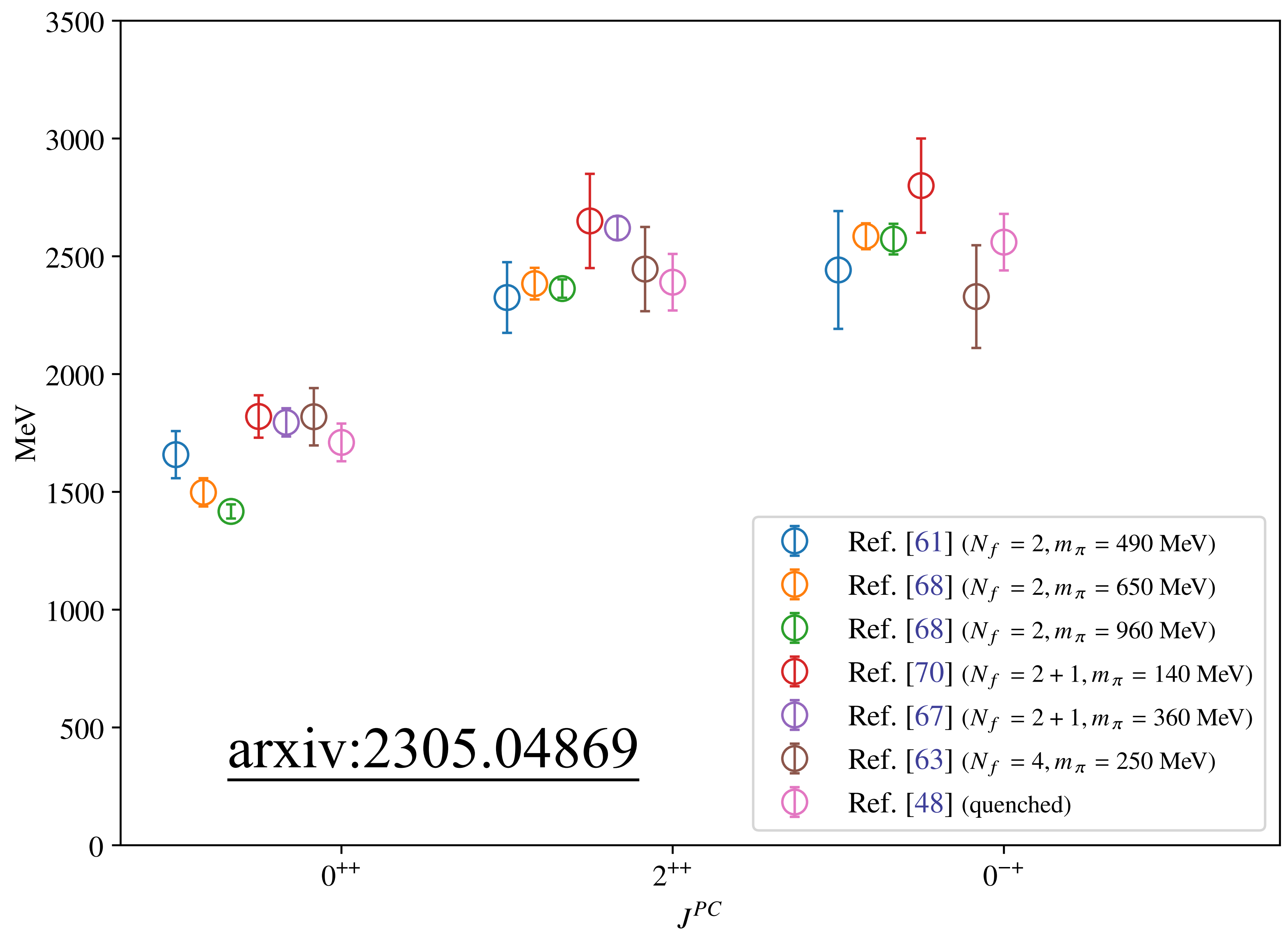


**The basic theory for strong interactions is quantum chromodynamics (QCD)**

# Glueball

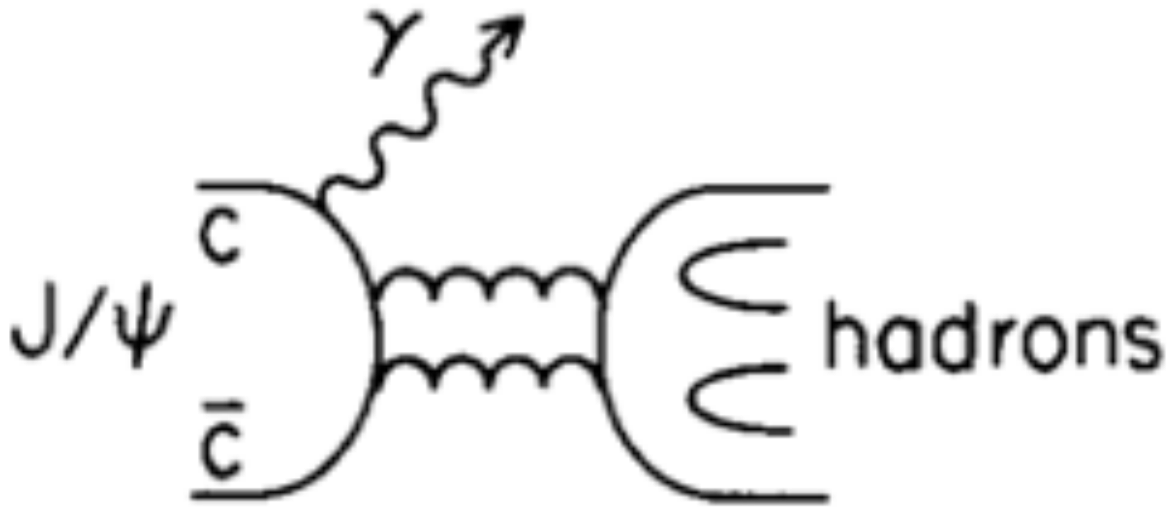
**Glueballs are unique particles via self-interactions and formed with force carriers**

- **Lattice QCD** (LQCD) is a non-perturbative method from the first principles in theory.
  - **Different lattice QCD groups** (including lattice simulations with dynamical quarks) now **have consistent predictions on** the **masses and production rates of pure glueballs**.
- 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/$c^2$

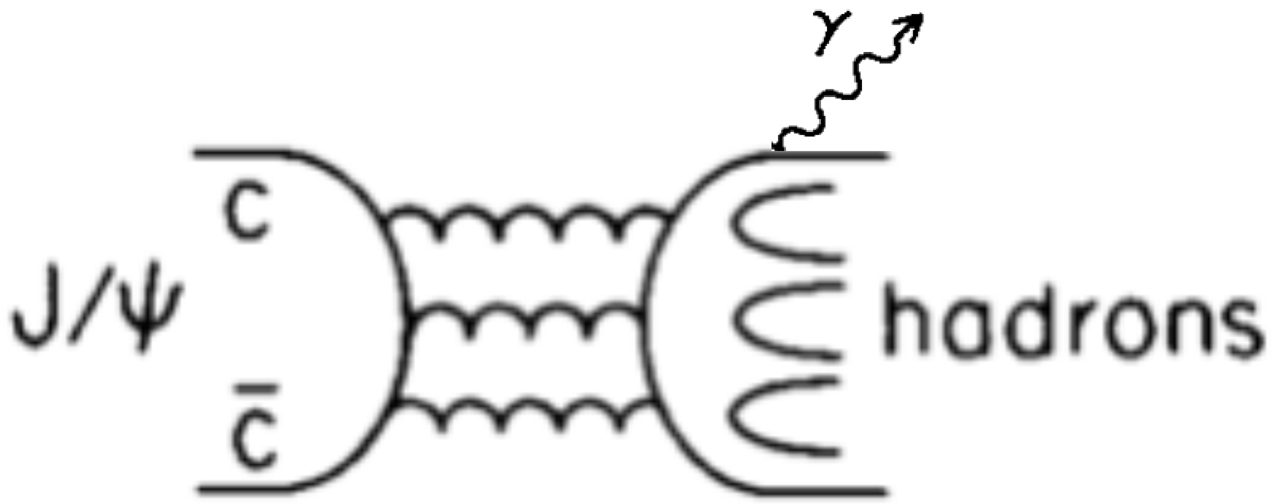


# J/ψ radiative decays

- **Gluon rich environment**




$\sim \alpha\alpha_s^4$




$\sim \alpha\alpha_s^6$

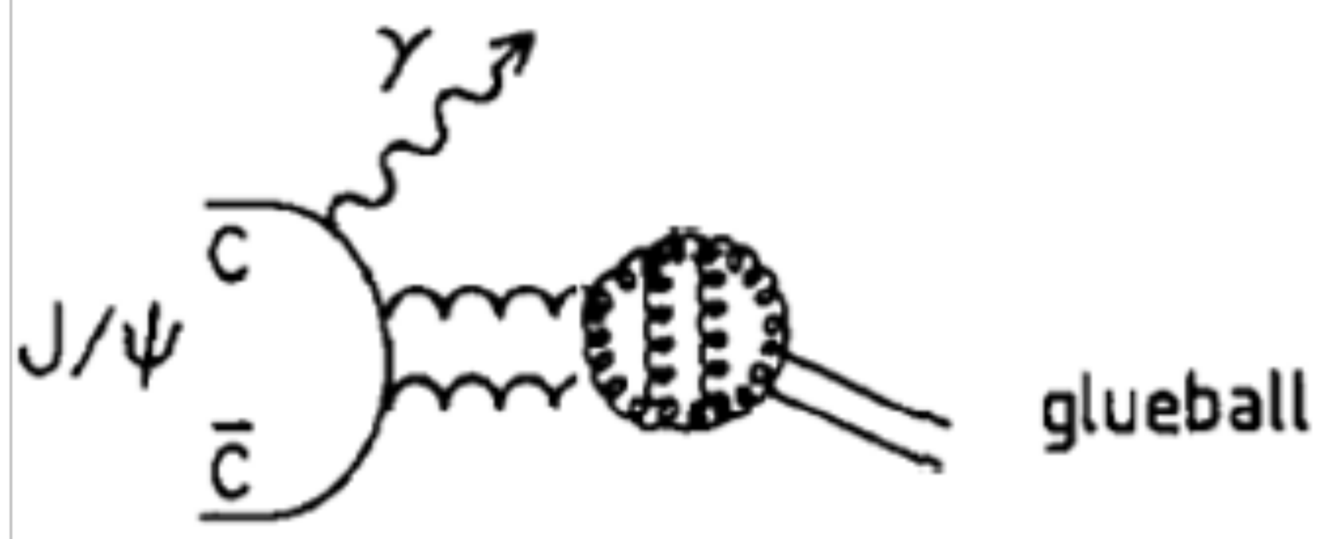
- **Isospin filter:** final states dominated by **I=0** processes
- **Spin-parity filter: C parity must be +**, so $J^{pc}=0^{-+}, 0^{++}, 1^{++}, 2^{++}, 2^{-+} \ldots$
- **Clean environment in electron-positron collision:** very different from **proton-proton collision**

➡ **Ideal place to search for glueballs**

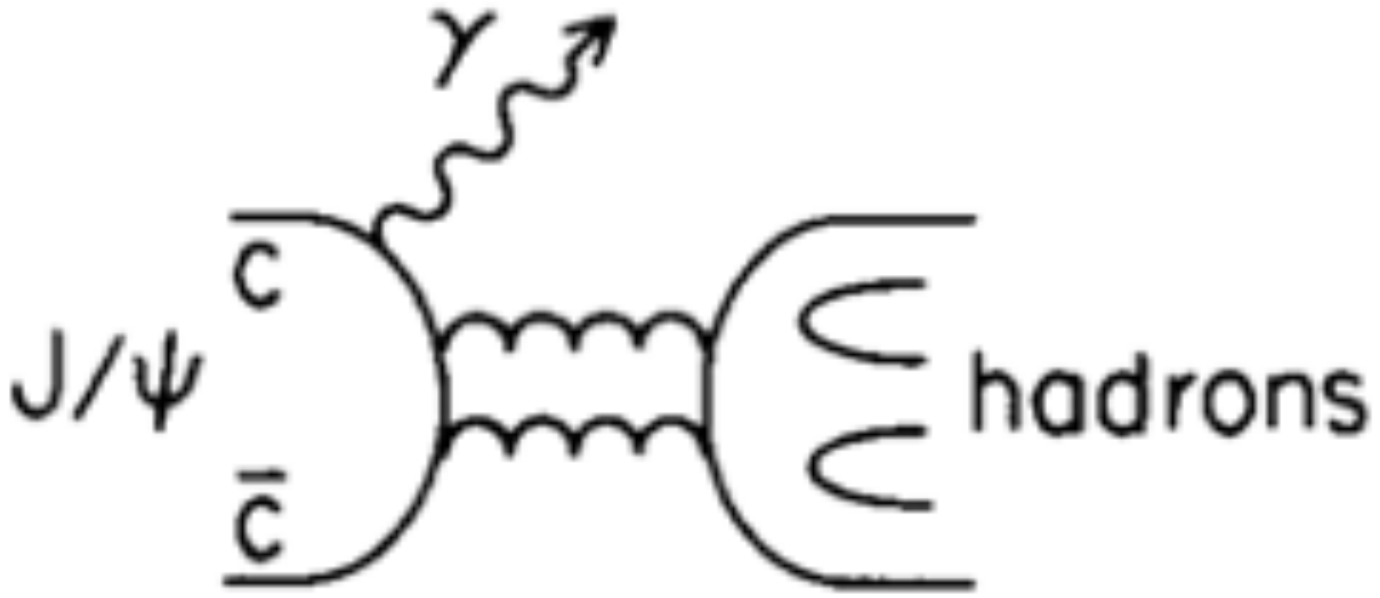
# Glueball Production in J/ψ radiative decays

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

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




$\sim \alpha\alpha_s^2$




$\sim \alpha\alpha_s^4$

# 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**

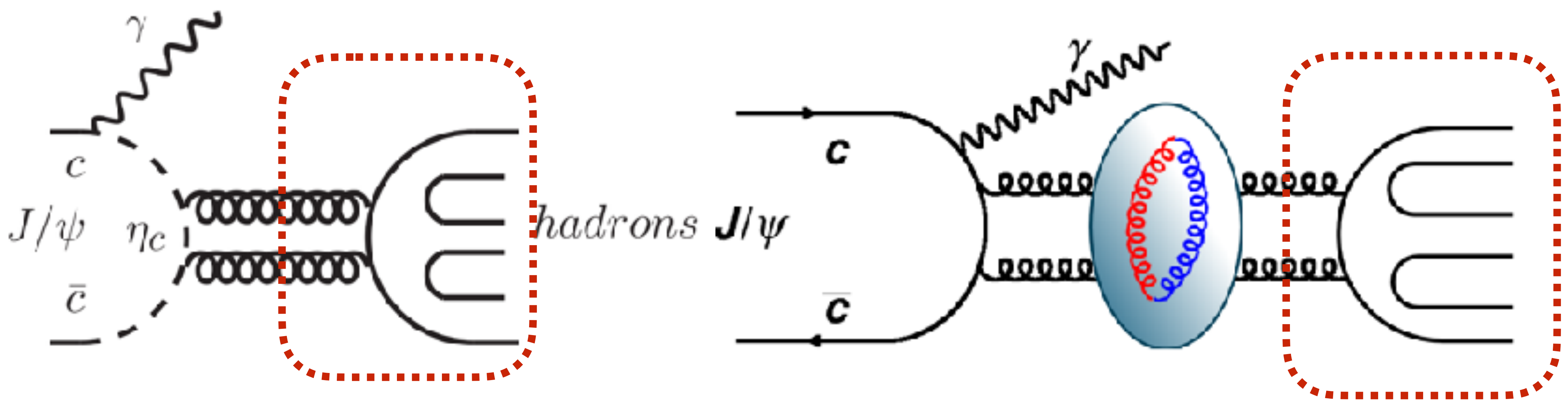
ple equally to all flavors. Since there has been no glueball confirmed by experiments, the best way looking into the flavor symmetry should be to study the decay processes which proceed through a two gluon intermediate state [10]. Fortunately, a lot of experiments have already studied such processes 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 $0^{-+}$ 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

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

- **Typically, PPP (3 pseudoscalar mesons, such as $\pi\pi\eta$, $\pi\pi\eta'$, $KK\pi$) modes are believed as golden decay modes in $0^{-+}$ glueball searches**
  - S wave decays for $0^{-+}$ mesons, no suppression factor, dominant decay modes
  - PPP modes are strongly suppressed in $0^{++}$, $2^{++}$ meson decays — spin-parity filter
- **PP (2 pseudoscalar mesons) modes are mostly forbidden for $0^{-+}$ mesons**
- **VV (2 vector mesons, such as $\omega\omega$, $\phi\phi$, $\rho\rho$, K*K*)**
  - P wave decays for $0^{-+}$ mesons — suppressed decays, especially near mass threshold
  - All $J^{PC}$ mesons allowed, not a spin-parity filter
- **Baryon modes**
  - All $J^{PC}$ mesons allowed, not a spin-parity filter

# Glueball Search

- **Many experiments searched for glueballs over the past 4 decades.**

- **Many historical glueball candidates**, but also some **difficulties/controversy.**

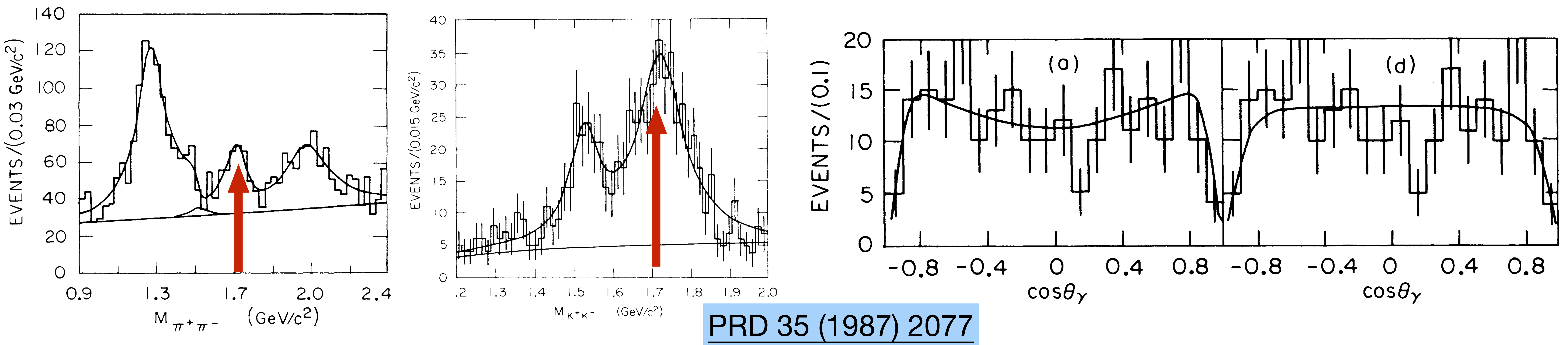
  - **Scalar Glueball candidate ($0^{++}$)**：$f_0(1710)$

  - **Tensor Glueball candidate ($2^{++}$)**: $f_2(2340)$

  - **Pseudoscalar Glueball ($0^{-+}$)**: $\eta(1405)$

More details in Beijing's talk

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

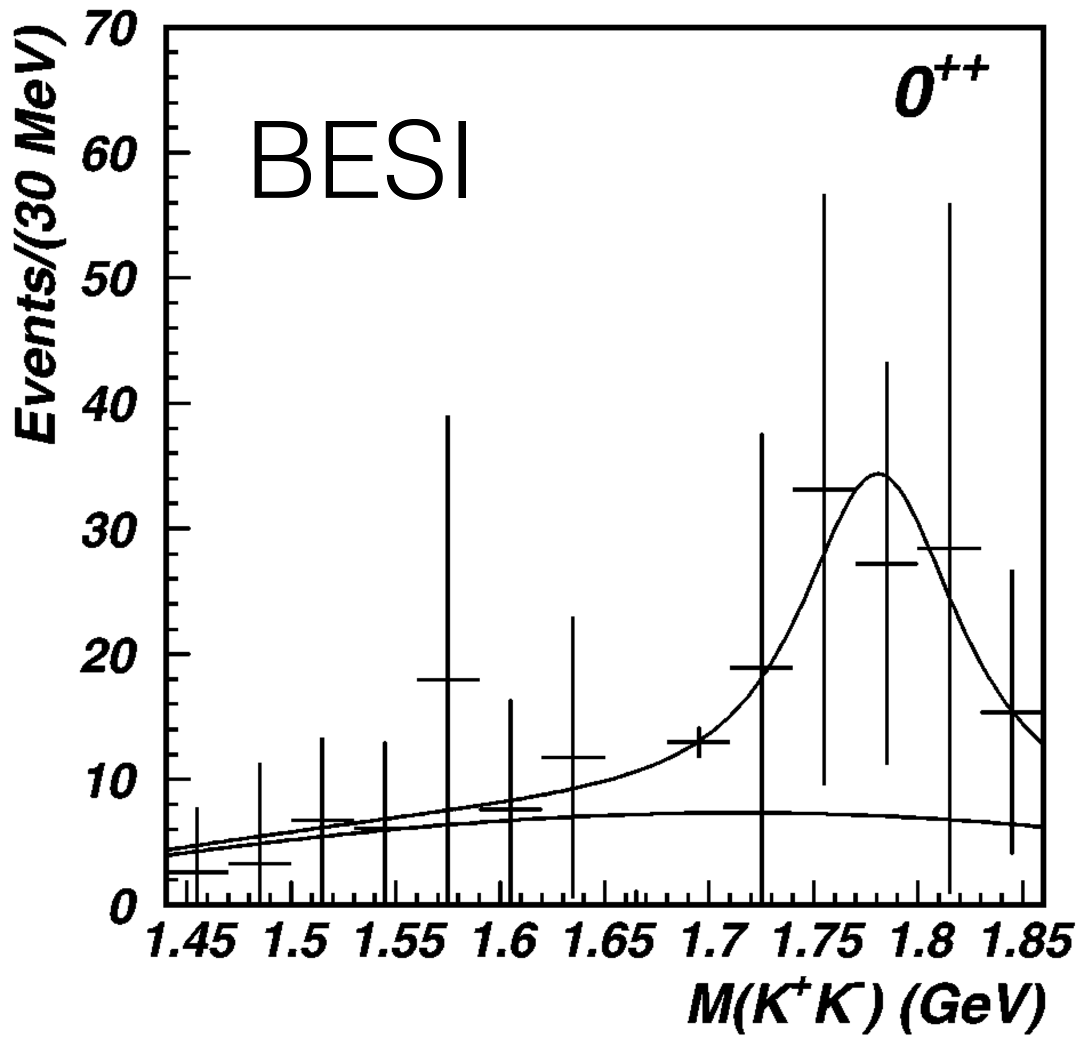



PRD 35 (1987) 2077

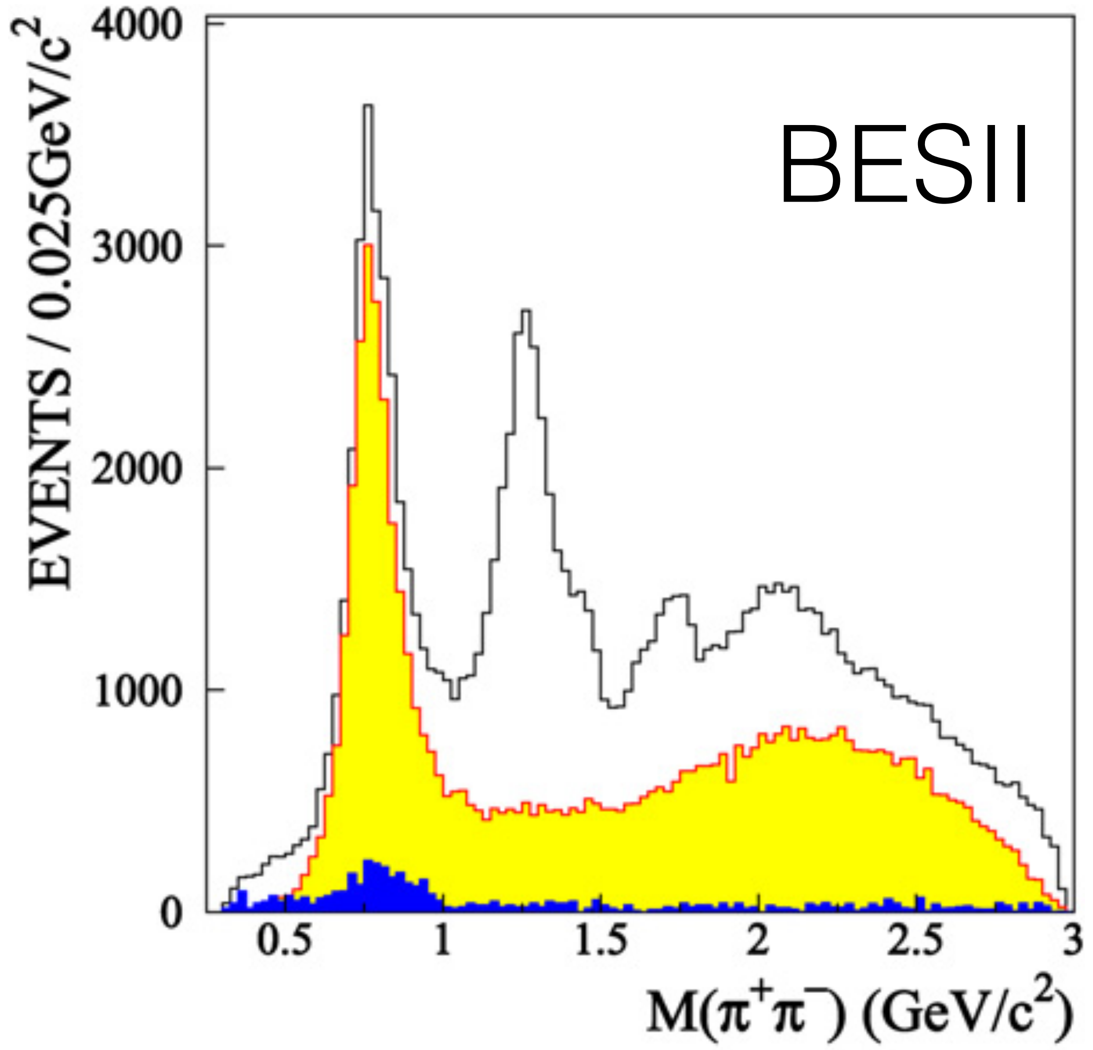
◈ The $f_0(1710)$ was discovered in **$J/\psi \to \gamma \pi^+\pi^-$ and $J/\psi \to \gamma K^+K^-$ by MarkIII** in 1987 as $\theta_2(1720)$

- **$J^{pc} = 2^{++}$ from a simple fit to the angular distribution**
- **The significance of $2^{++}$ state is ~3σ better than $0^{++}$ assumption**

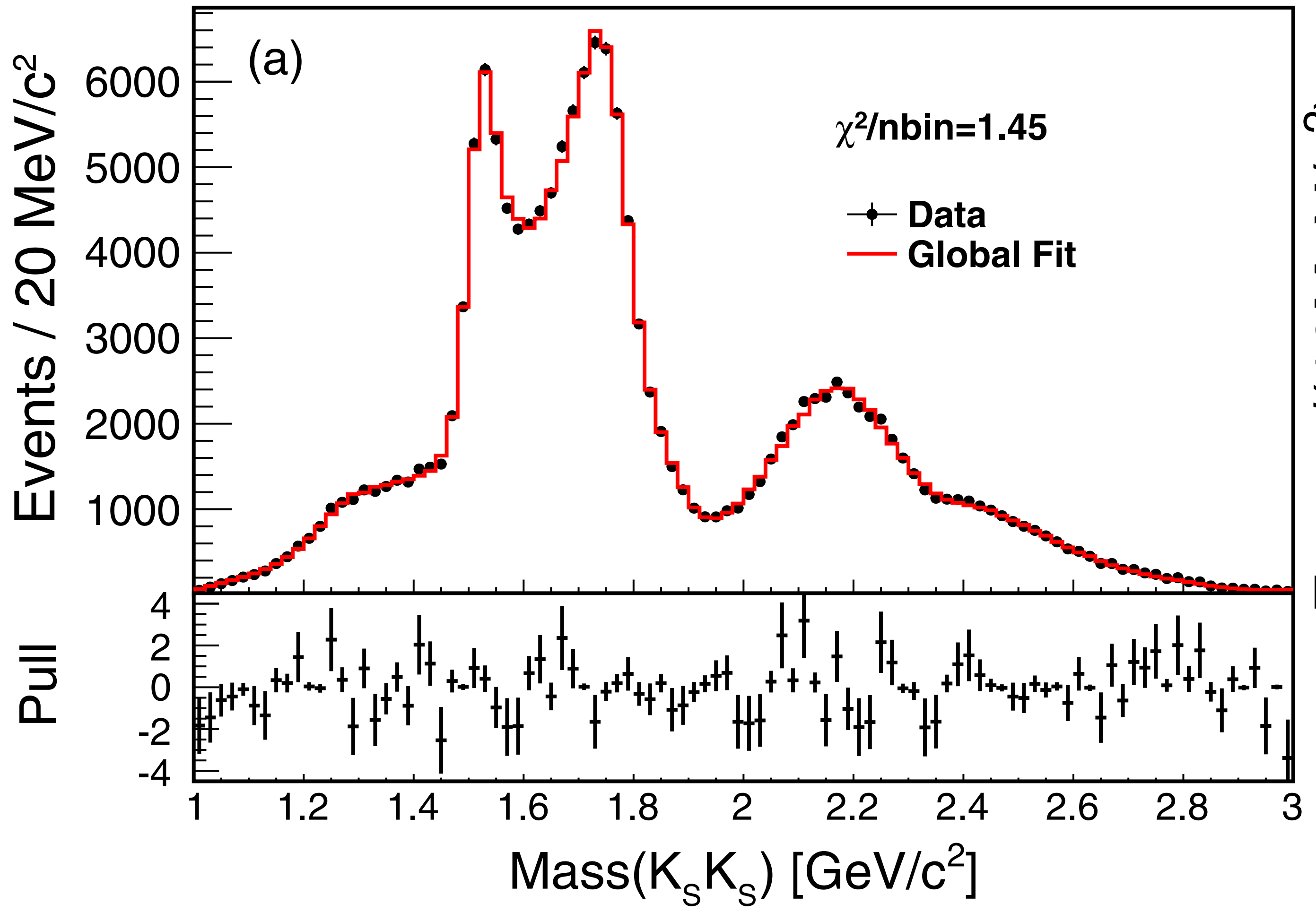
# Historical Glueball Candidates — Scalar $f_0(1710)$



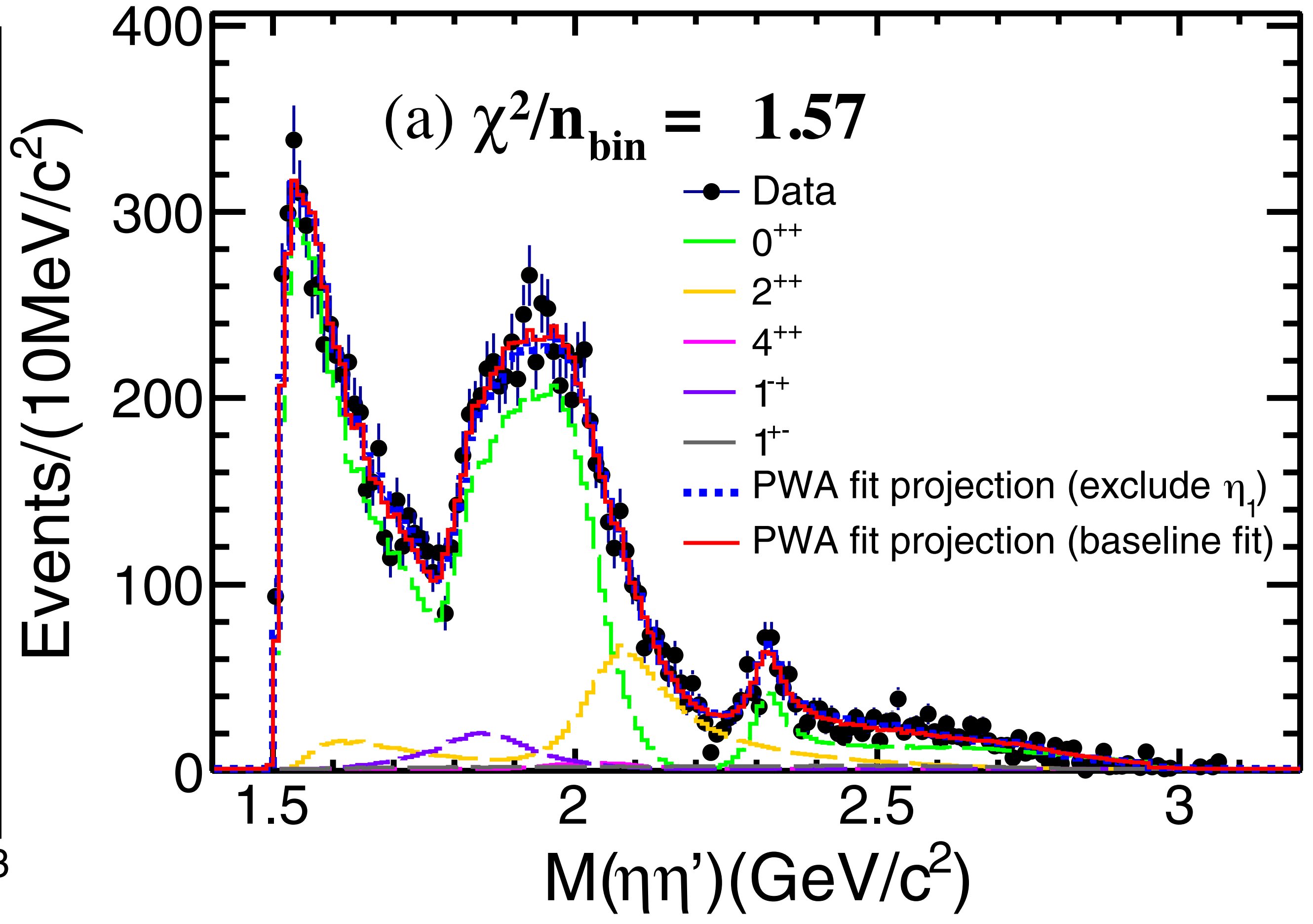

PRL 77(1996) 19




PLB 642 (2006) 441




PRD 98 (2018) 072003




PRD 106 (2022) 072012

- The $f_0(1710)$ **was firstly changed to be $0^{++}$** on a full PWA of $J/\psi \to \gamma KK$ @ BESI. Lots of studies at MarkII, DM2, BESI,BESII, BESIII
- 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

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

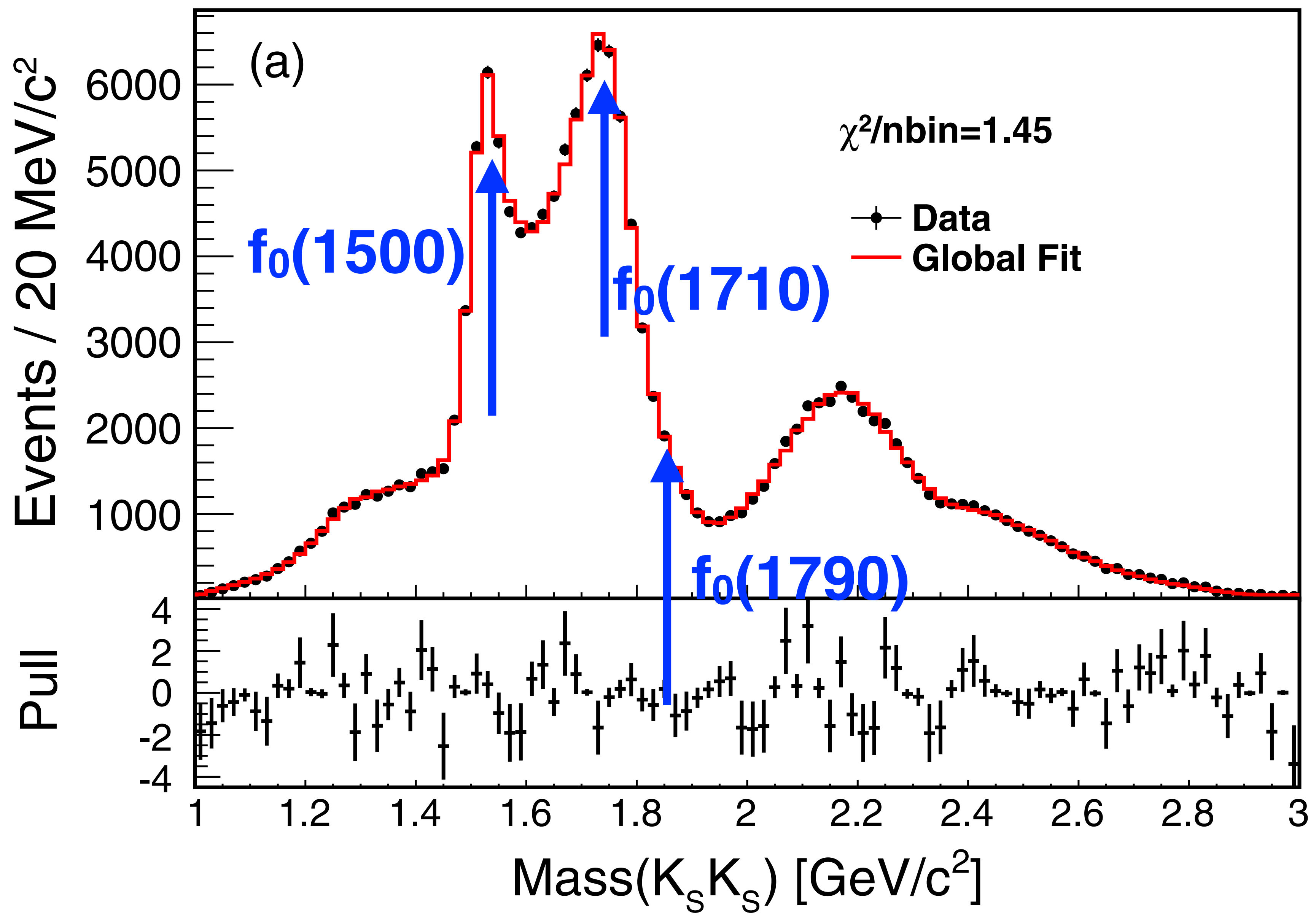
BESIII: PRD 98 (2018) 072003

**✦ 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

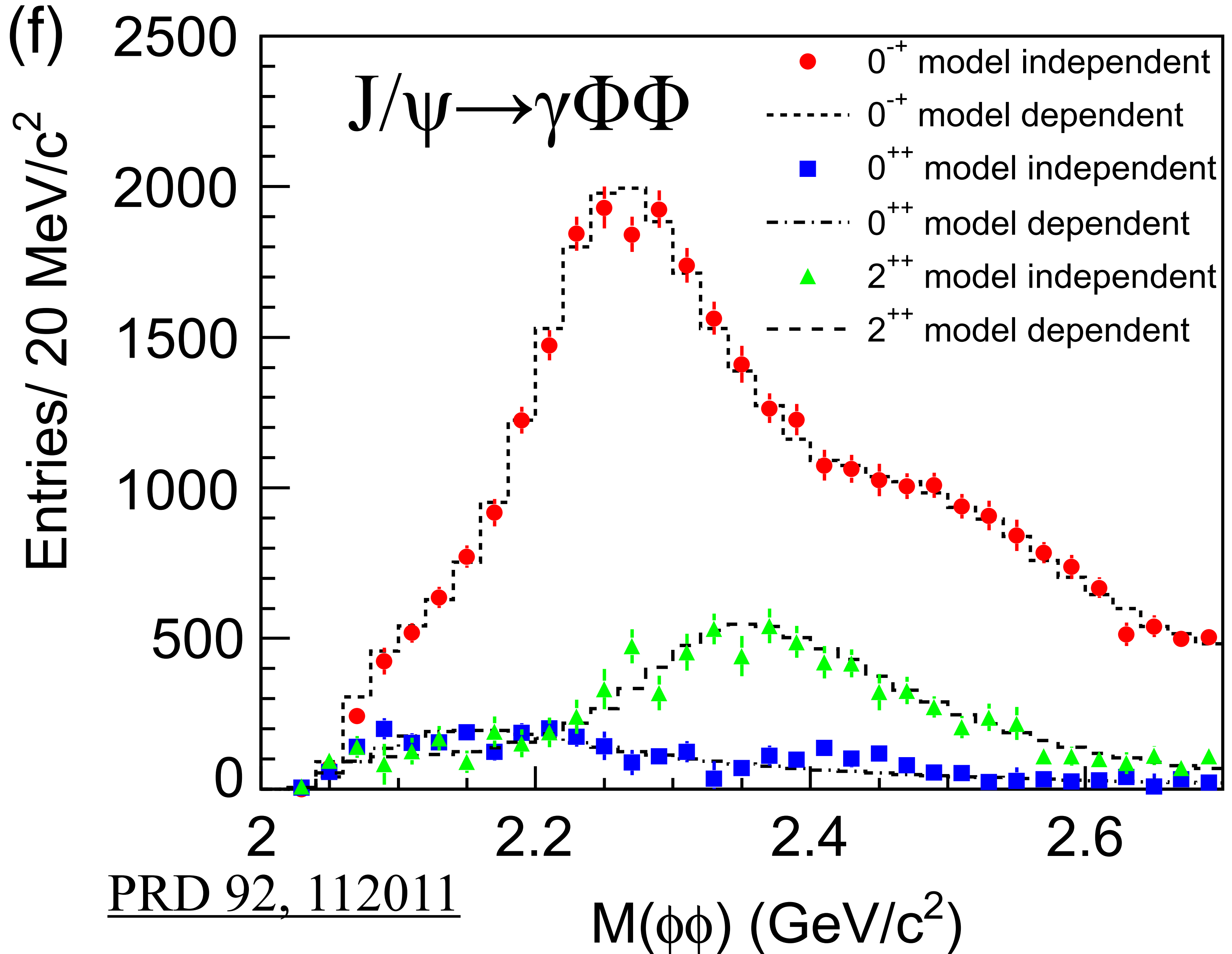
$$B[J/\psi \to \gamma f_0(1710) \to \gamma K_s^0 K_s^0] = (2.00^{+0.03}_{-0.02}\,{}^{+0.31}_{-0.10}) \times 10^{-4}$$

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 — Tensor $f_2(2340)$

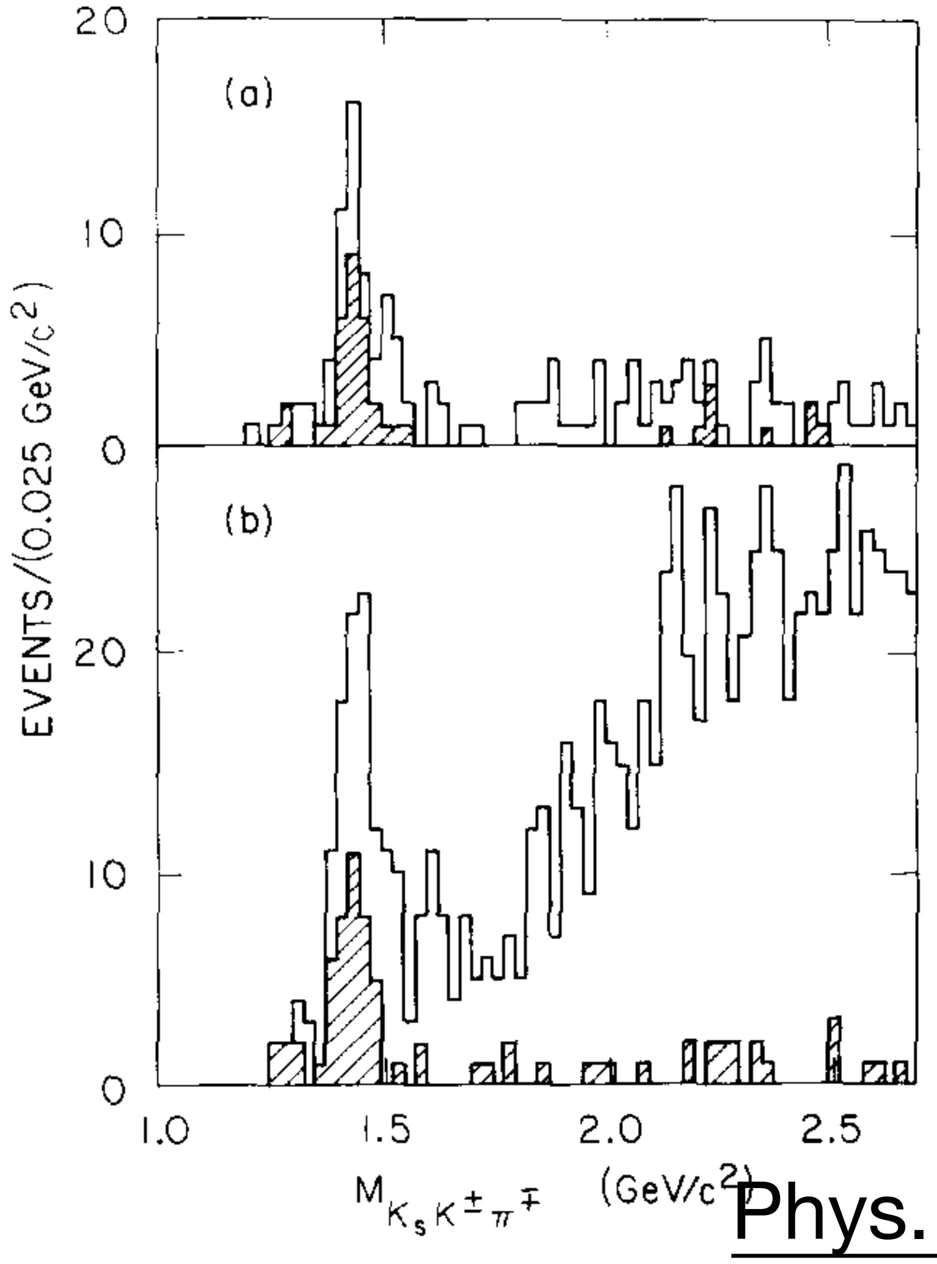
- Its large production rate in $J/\psi \to \gamma(KK/\eta\eta/\eta'\eta'/\phi\phi)$ : inconsistent with LQCD prediction on a tensor glueball .
- **Difficulty:**
  - **Many wide $f_2$ mesons and large overlaps in the mass region of 2.3GeV** ($2^{++}$ glueball mass from the LQCD predictions)
    - **no 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.



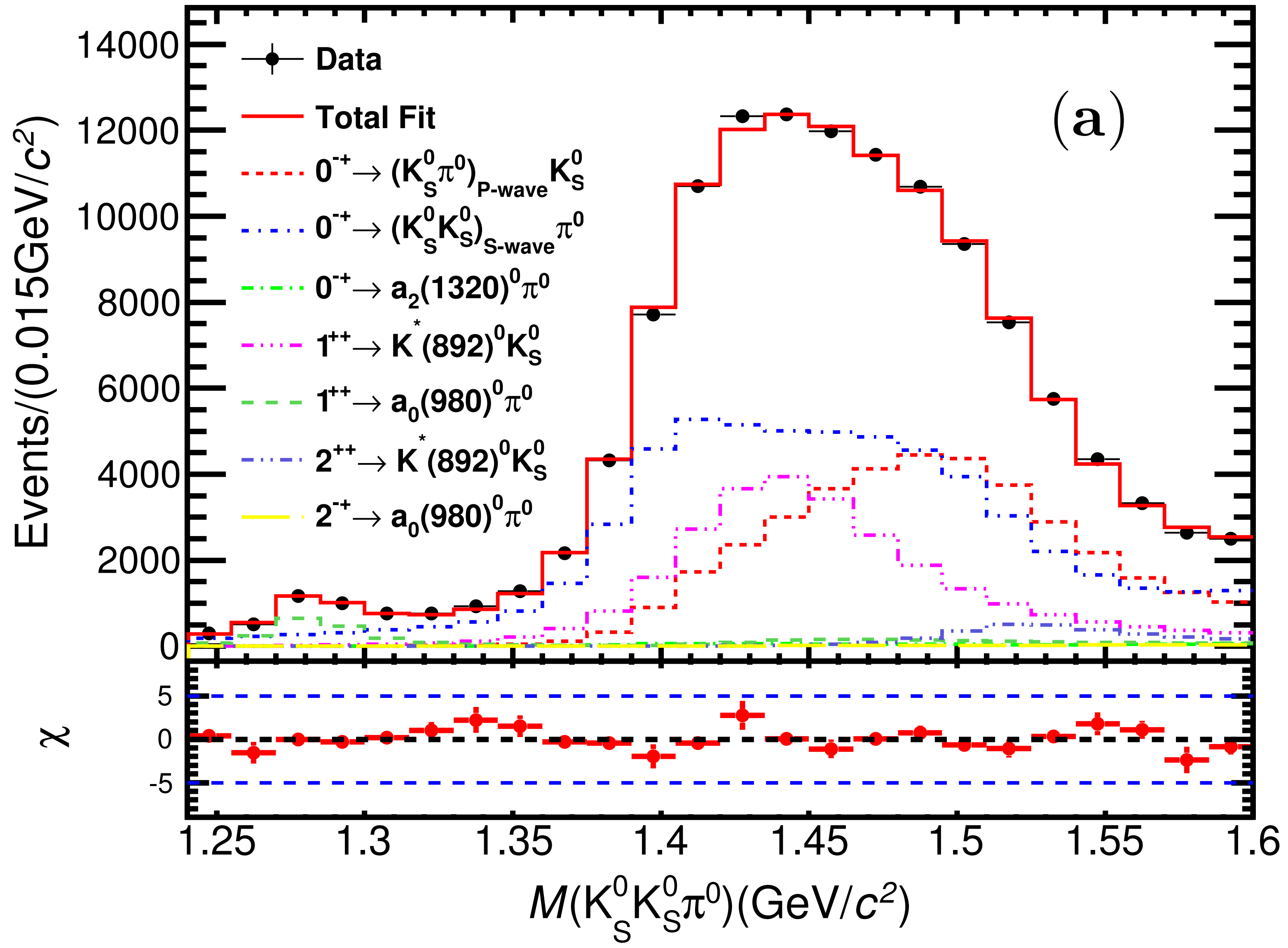

PRD 92, 112011

| 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 | | | $(2.74 \pm 0.15^{+0.16}_{-1.48})$ | $6.8\sigma$ |

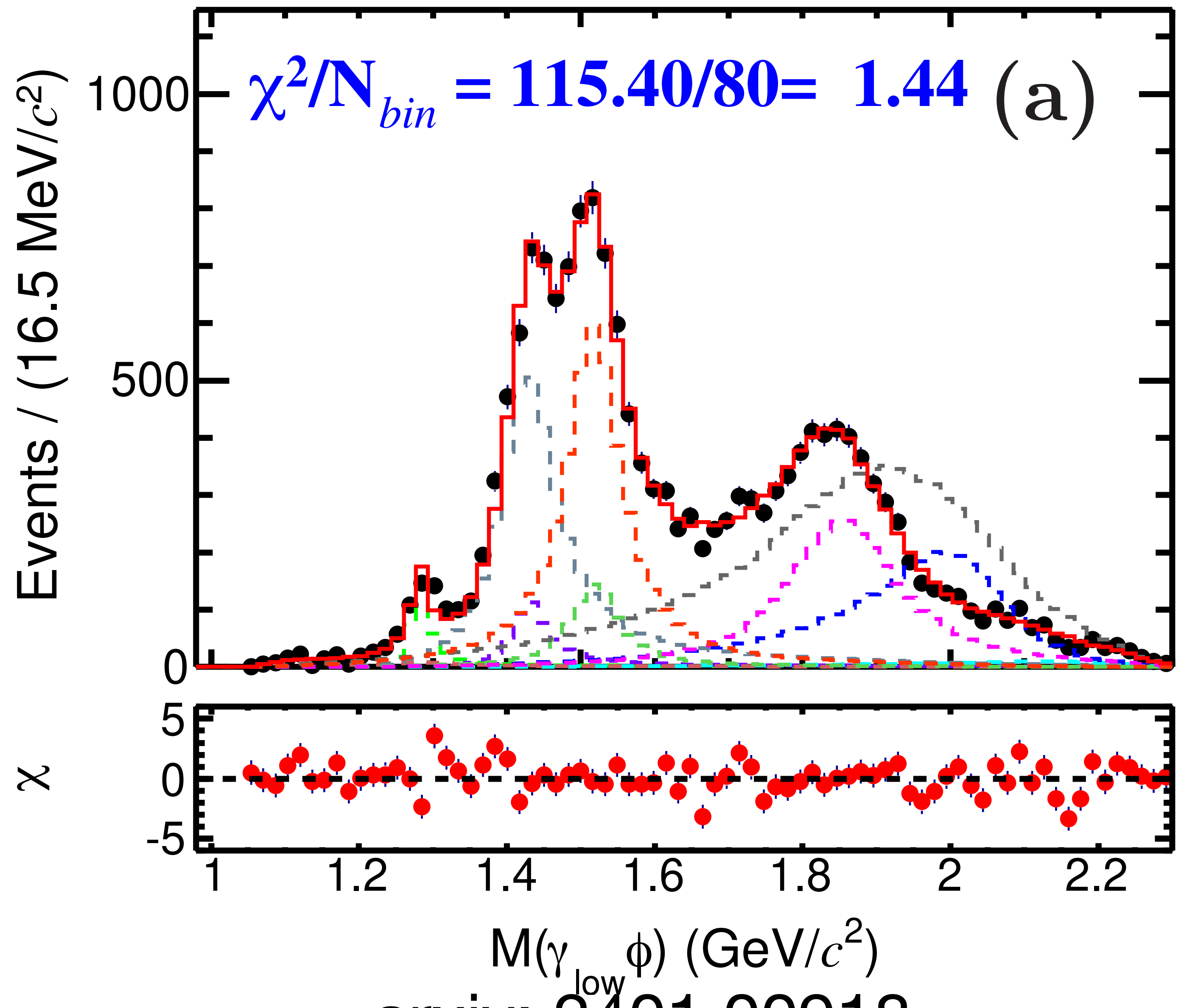
# Historical Glueball Candidates — Pseudoscalar η(1405)




Phys. Lett. 97B (1980) 2



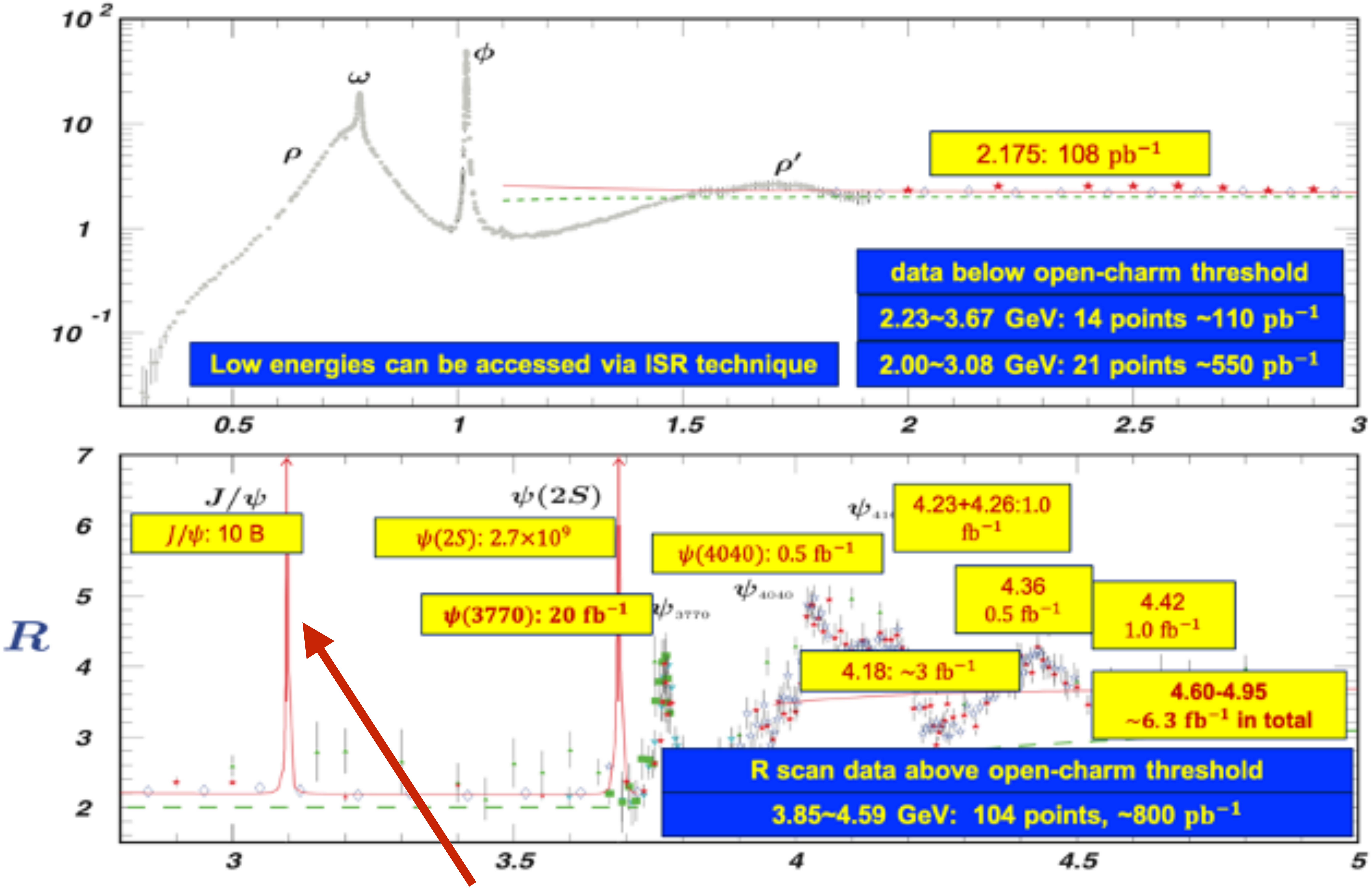

JHEP 03 (2023) 121




arxiv: 2401.00918

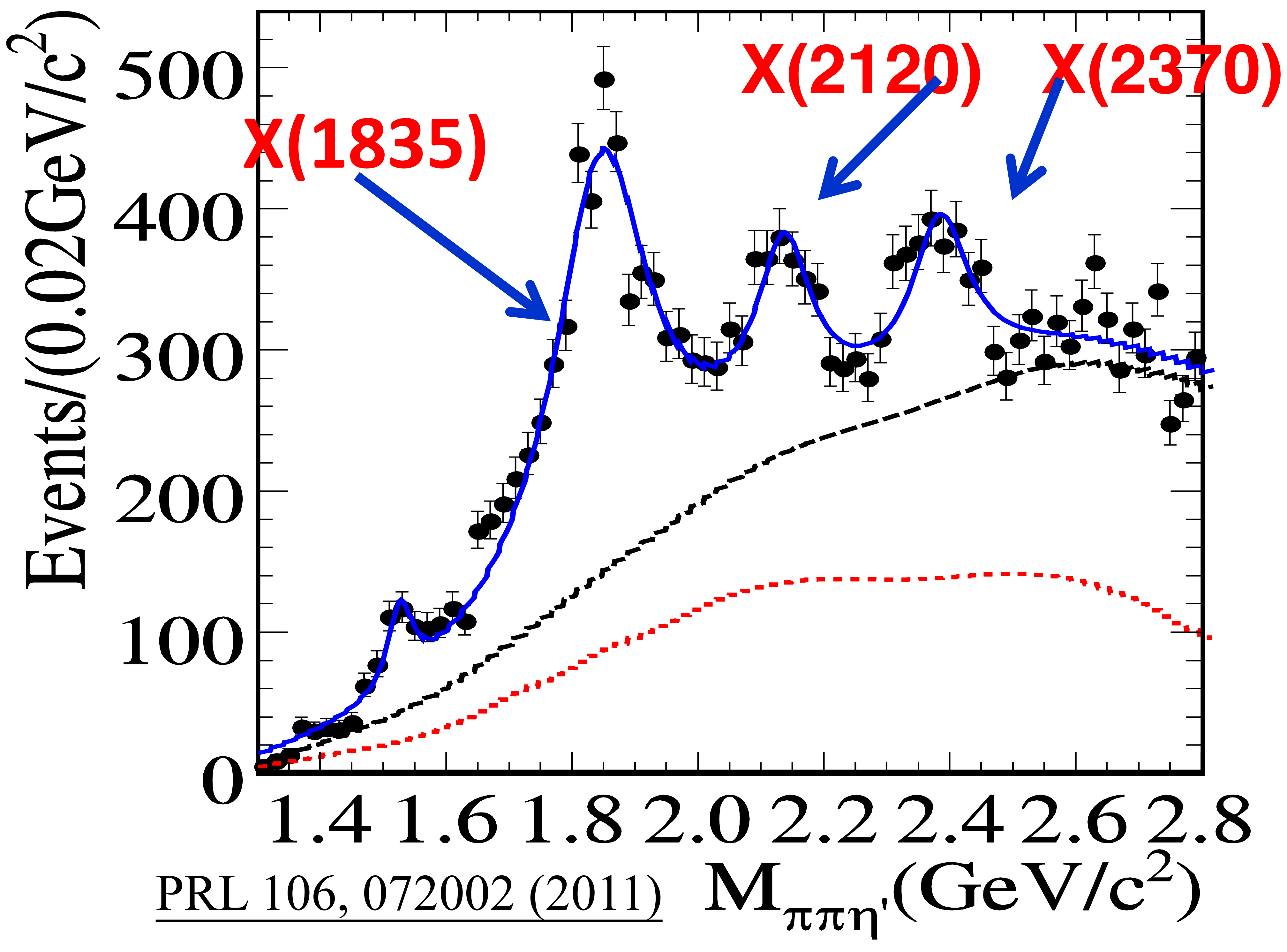
- first discovered by MarkII in 1980, named as η(1440) with complicated structures.
  - Believed as the first glueball candidate due to its large production rate in J/ψ radiative decays
- Lots of studies at MarkII, MarkIII, DM2 and BES:
  - **No longer to be 0⁻⁺ glueball candidate due to its large different mass from LQCD prediction** (Lack of reliable LQCD predictions in 1980's)
  - $J/\psi \to \gamma K_s K_s \pi$: 2 isoscalar states η(1405) and η(1475) around 1.4GeV
  - $J/\psi \to \gamma\gamma\phi$: observed η(1405) with 18.9σ and no significance of η(1475)

# BESIII Data samples




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

# Observation of the X(2370) in 2011



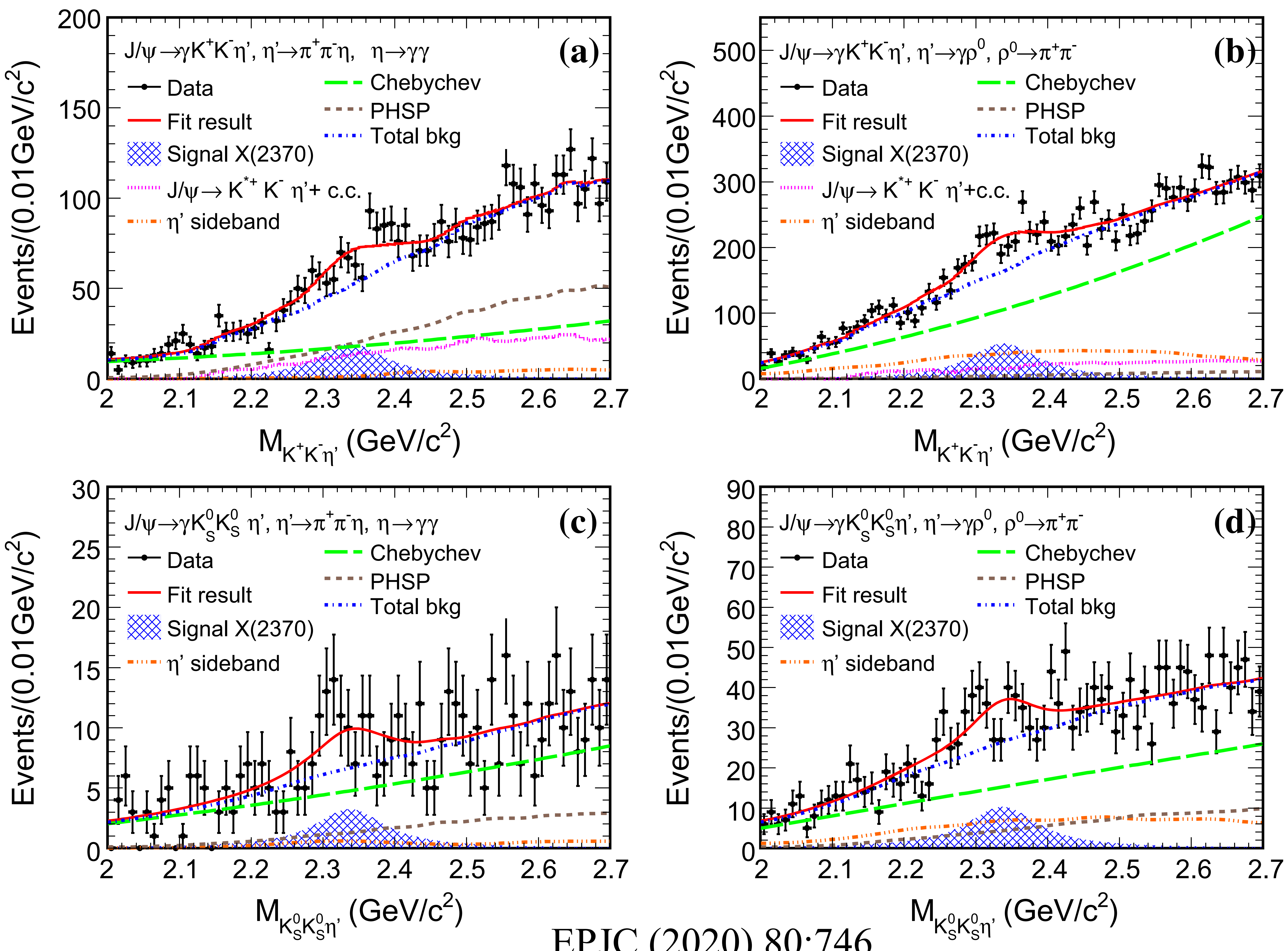

PRL 106, 072002 (2011)

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

| | M(MeV/c²) | Γ(MeV/c²) | Sig. |
|---|---|---|---|
| X(1835) | $1836.5 \pm 3.0^{+5.6}_{-2.1}$ | $190.1 \pm 9.0^{+38}_{-36}$ | >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 |

- ◈ **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'



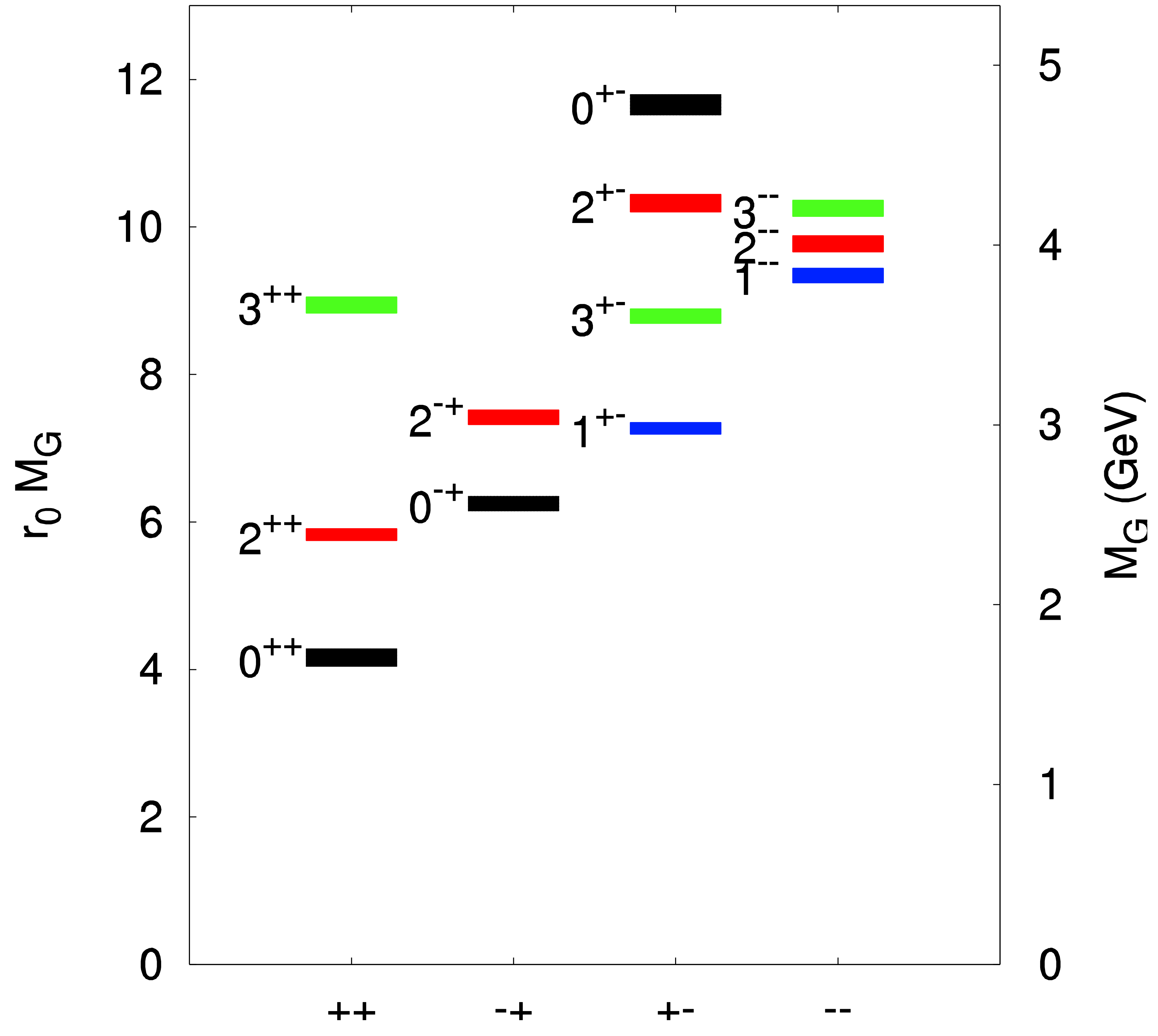

EPJC (2020) 80:746

- **Combination with 1.31×10⁹ J/ψ events**
  - **J/ψ→γK⁺K⁻η' and J/ψ→γKₛKₛη'**
  - **η' →γππ and η'→ππη**
- **Confirmation of the X(2370) with 8.3σ**
  - **M = 2341.6±6.5(stat.)±5.7(syst.) MeV**
  - **Γ = 117±10(stat.)±8(syst.) MeV**
  - **$Br(J/\psi\to\gamma X(2370)\to\gamma K^+K^-\eta')=(1.79\pm0.23\pm0.65)\times10^{-5}$**
  - **$Br(J/\psi\to\gamma X(2370)\to\gamma K_SK_S\eta')=(1.18\pm0.32\pm0.39)\times10^{-5}$**

**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



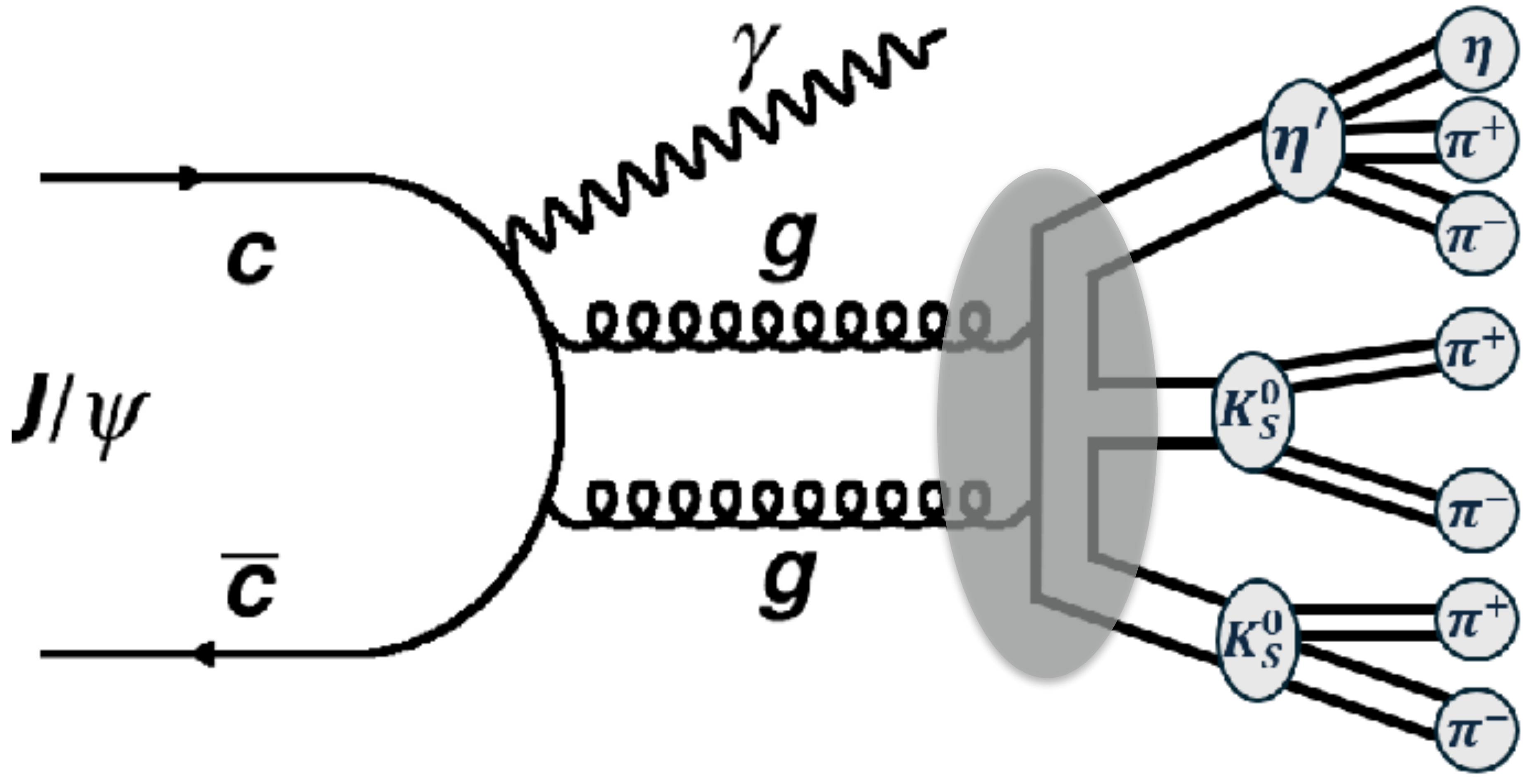
# Spin-Parity determination of the X(2370) in $J/\psi \rightarrow \gamma K^0_s K^0_s \eta'$

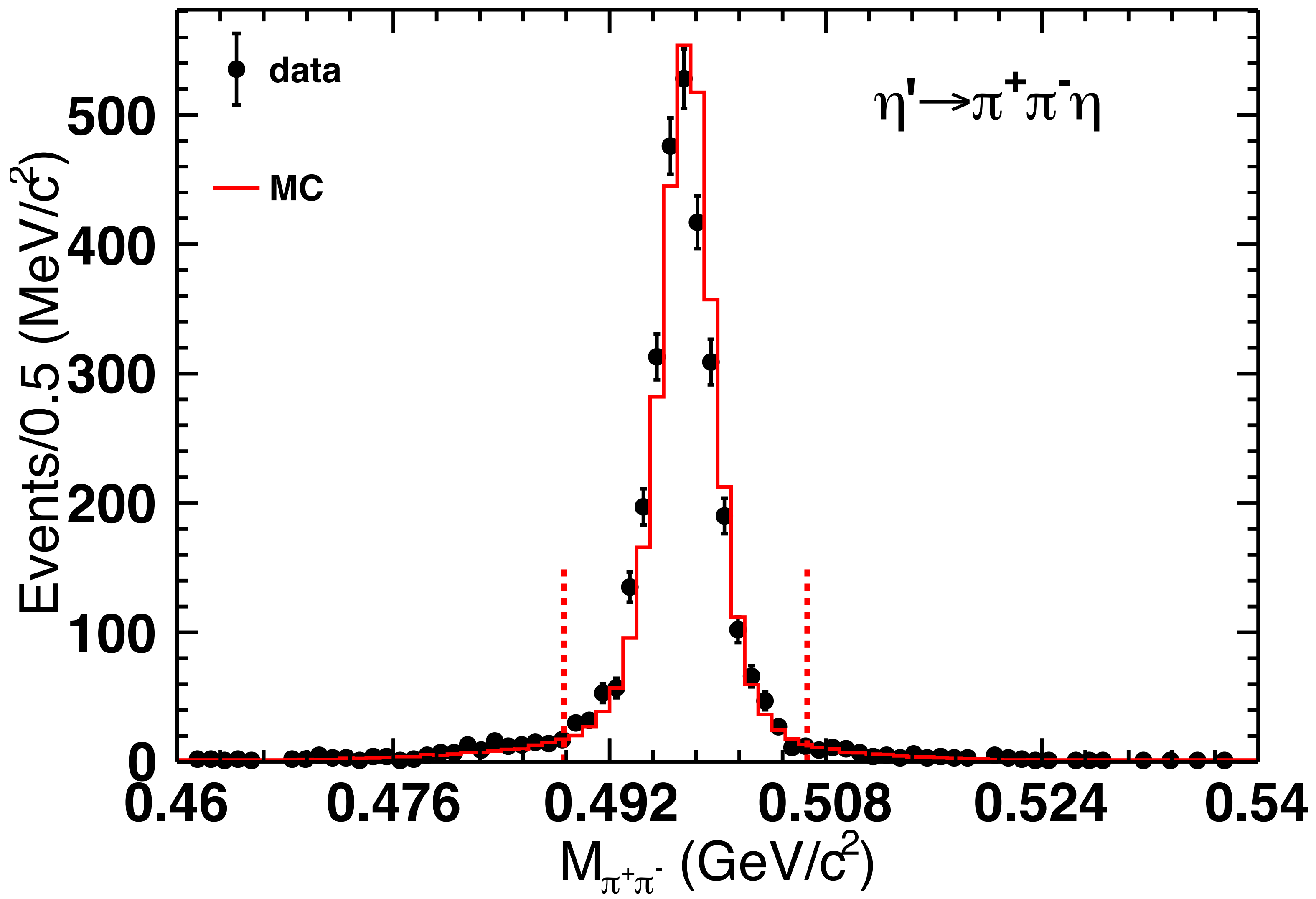
Make use of four advantages:

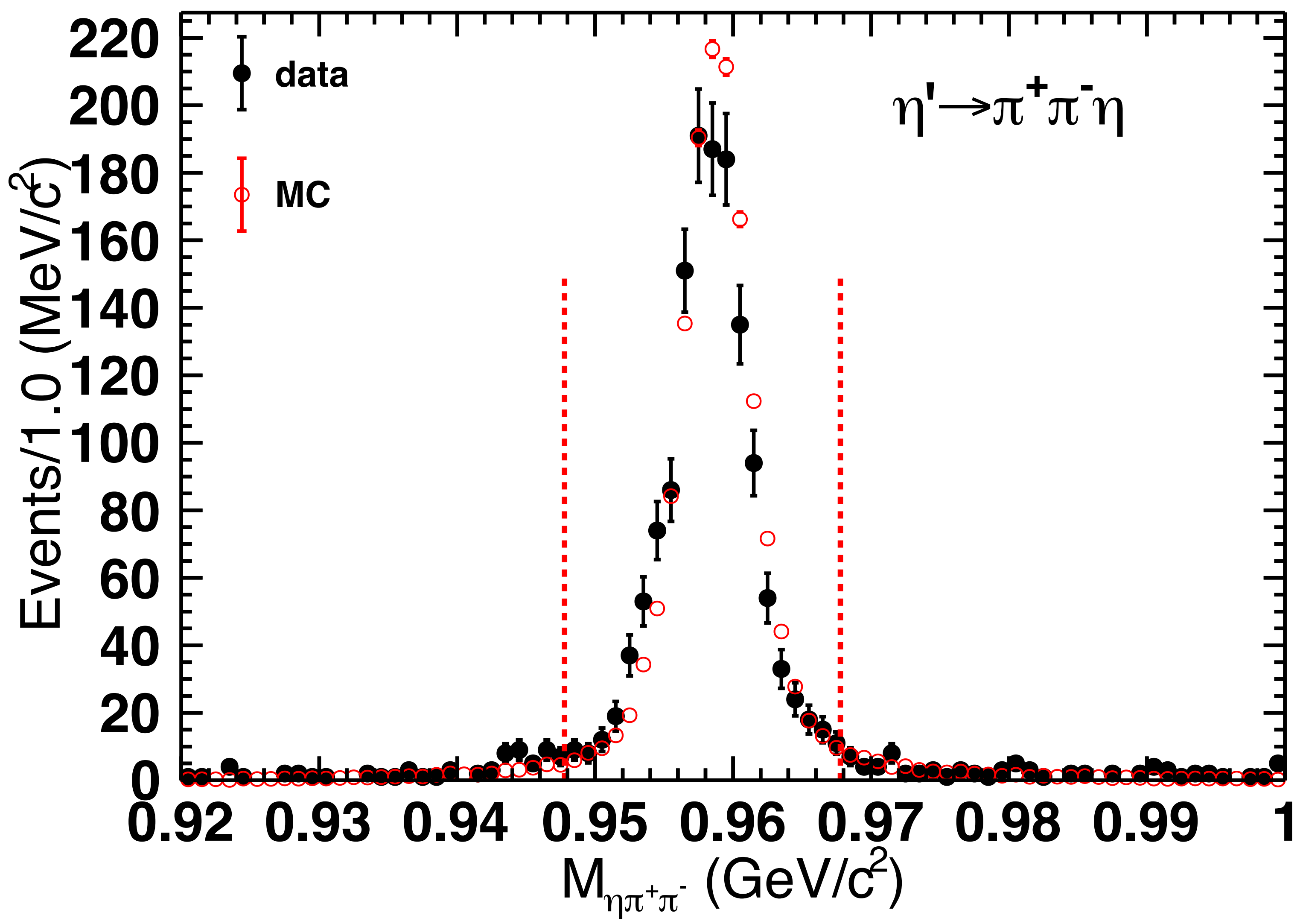
- ◈ **Clean $J/\psi \rightarrow \gamma K_s^0 K_s^0 \eta'$ process**
  - ✦ **Almost no background:** possible dominant background processes of $J/\psi \rightarrow \pi^0 K_s^0 K_s^0 \eta'$ and $J/\psi \rightarrow K_s^0 K_s^0 \eta'$ are forbidden by **exchange symmetry and C-parity conservation.**
- ◈ **~10B 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 $\eta' \rightarrow \gamma \pi^+ \pi^-$ and $\eta' \rightarrow \pi^+ \pi^- \eta$:** 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/$c^2$
  - η' reconstruction: $|M_{\pi\pi\eta} - m_{\eta'}| < 10$ MeV/$c^2$
- **Background veto:**
  - $\pi^0$ veto: $|M_{\gamma\gamma} - m_{\pi 0}| > 20$MeV/$c^2$



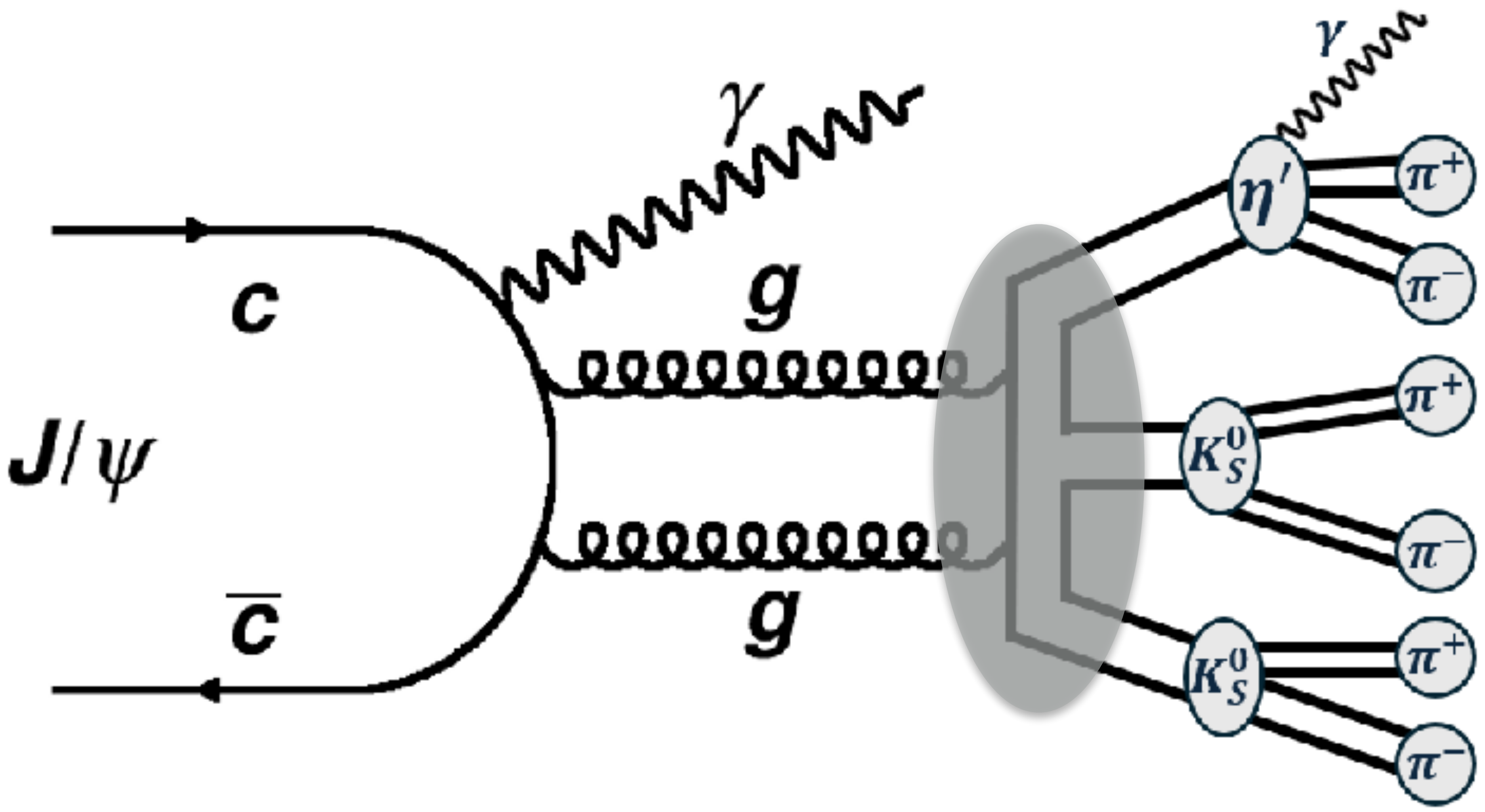



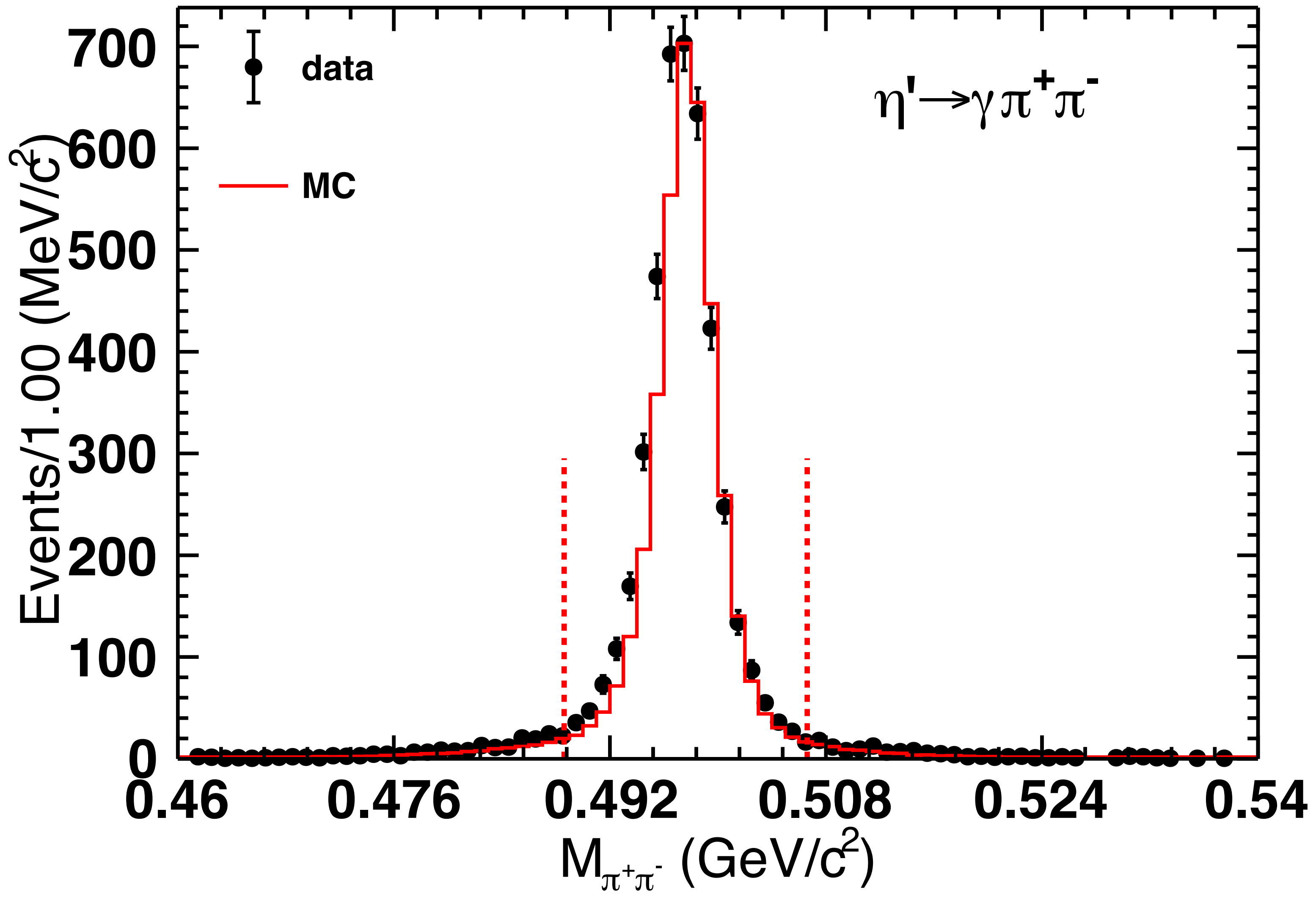



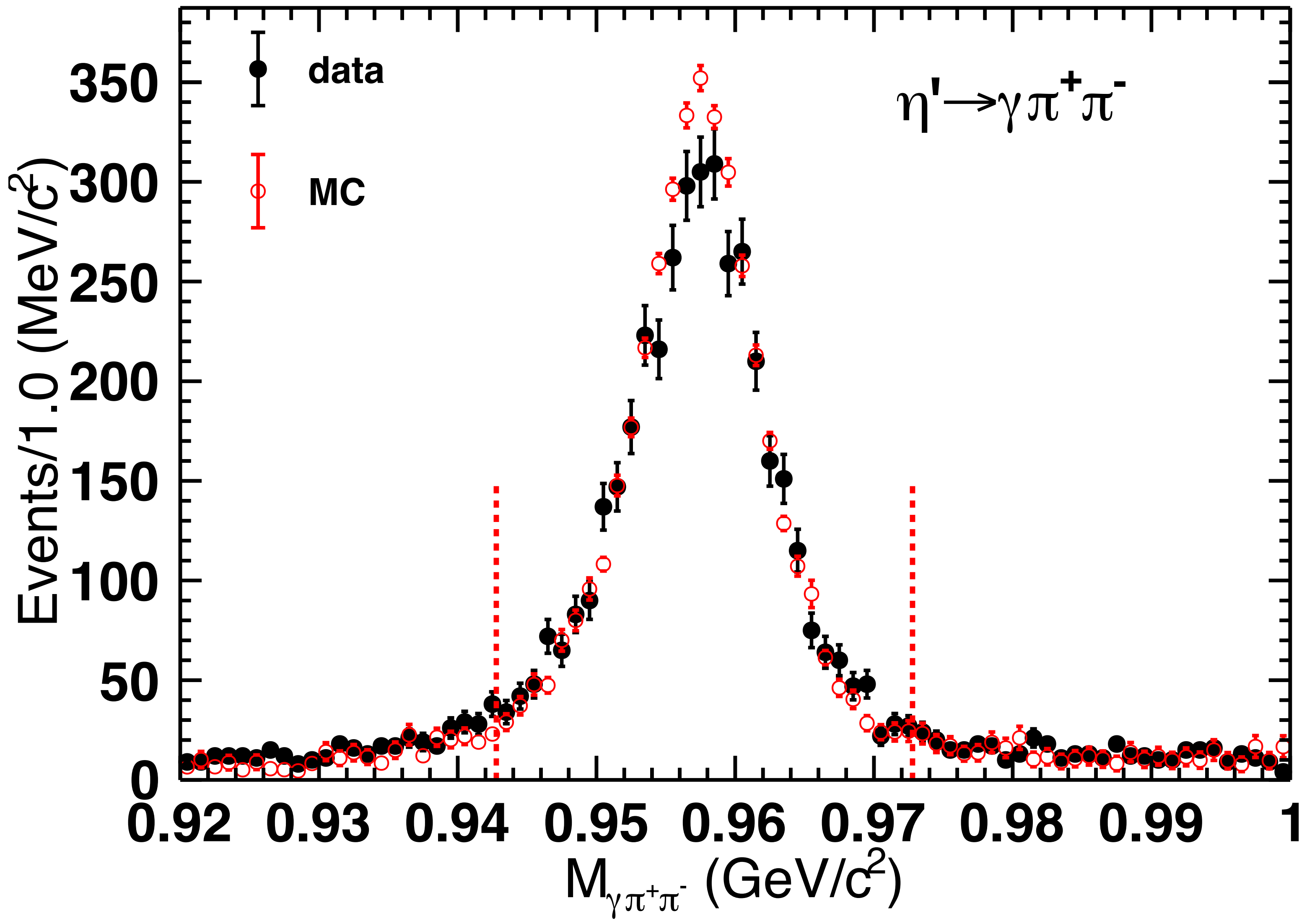

Clean $K^0_s$ and η' Signal

# 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/$c^2$



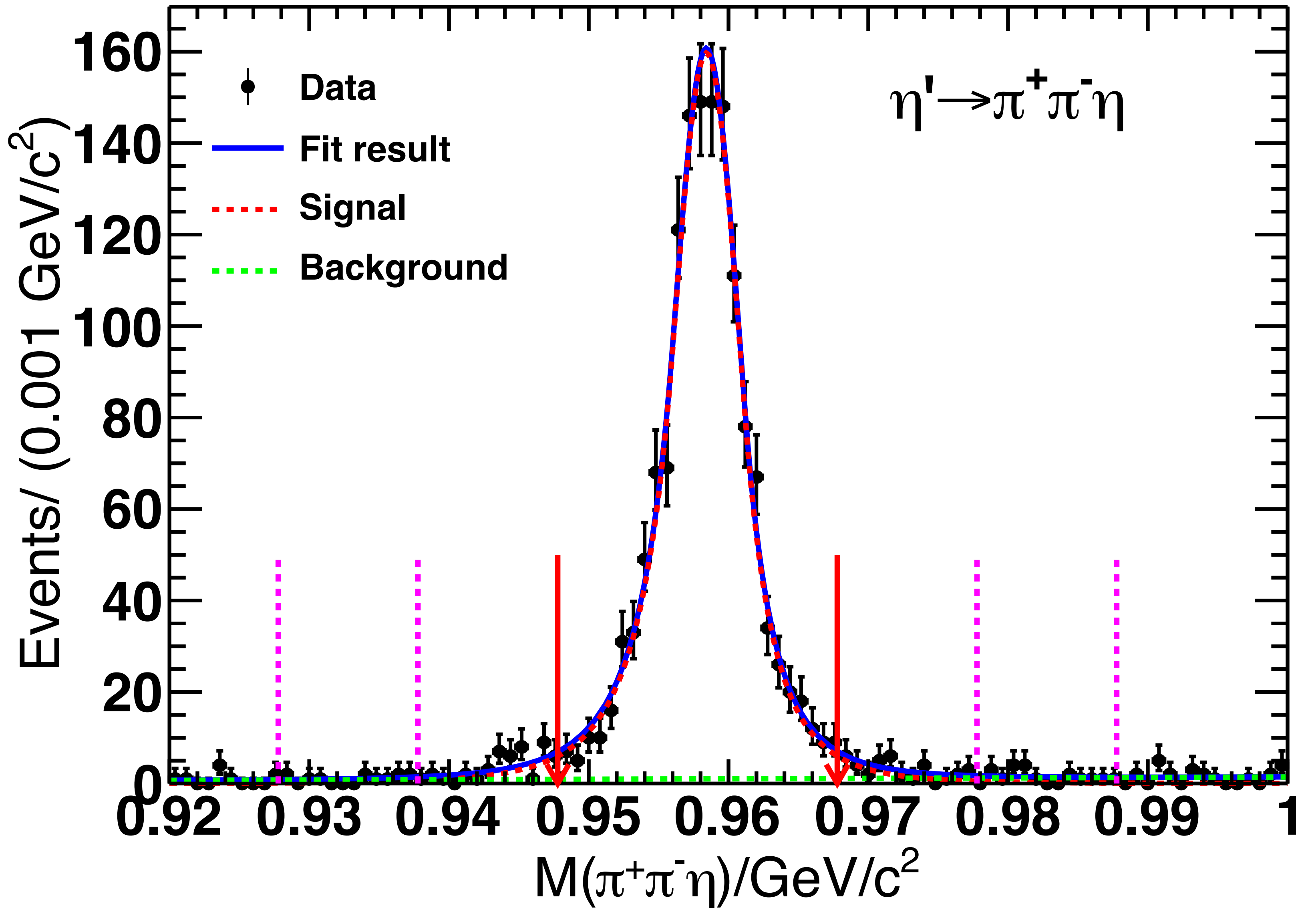



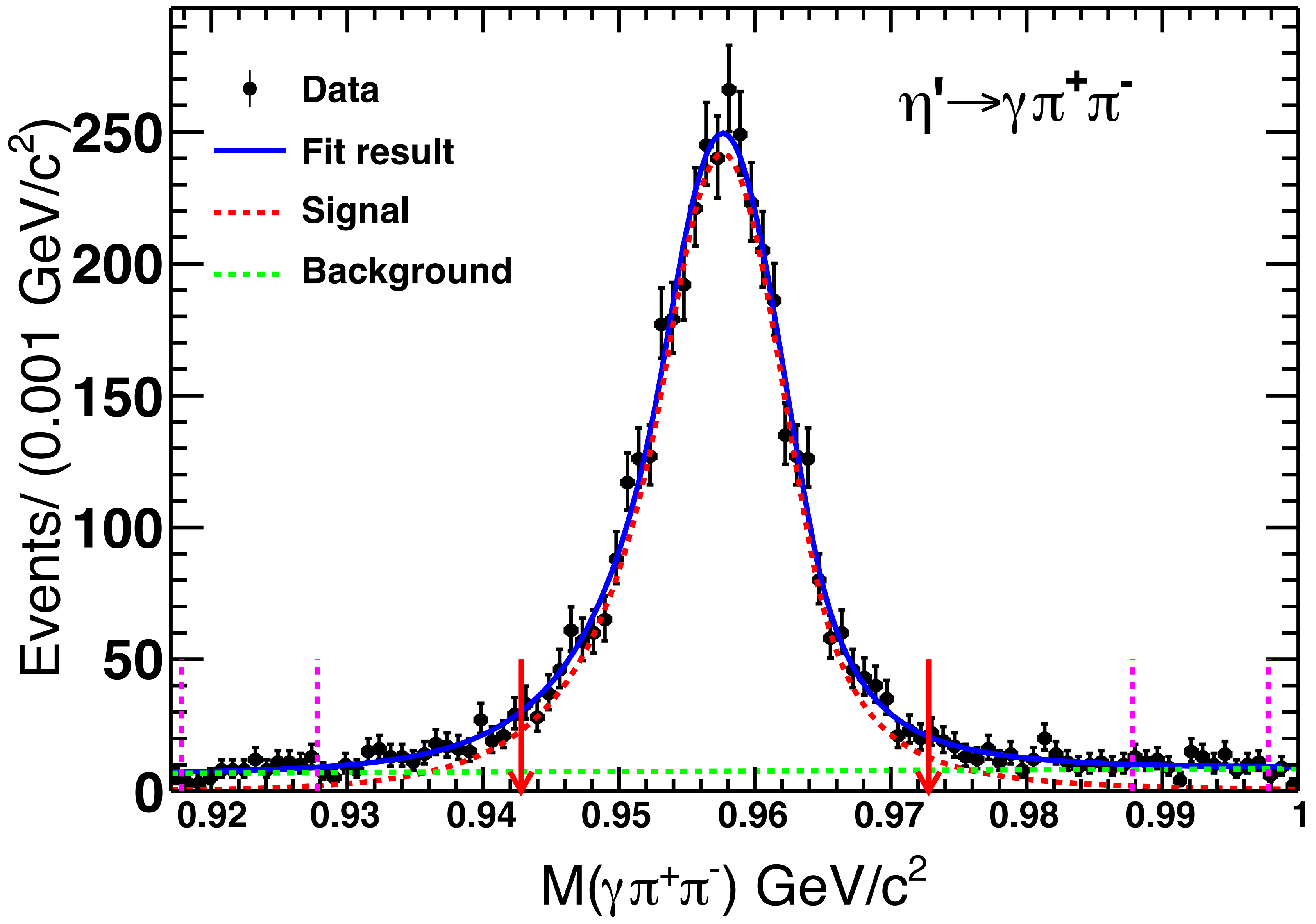




Clean $K^0_s$ and η’ Signal

# Background estimation

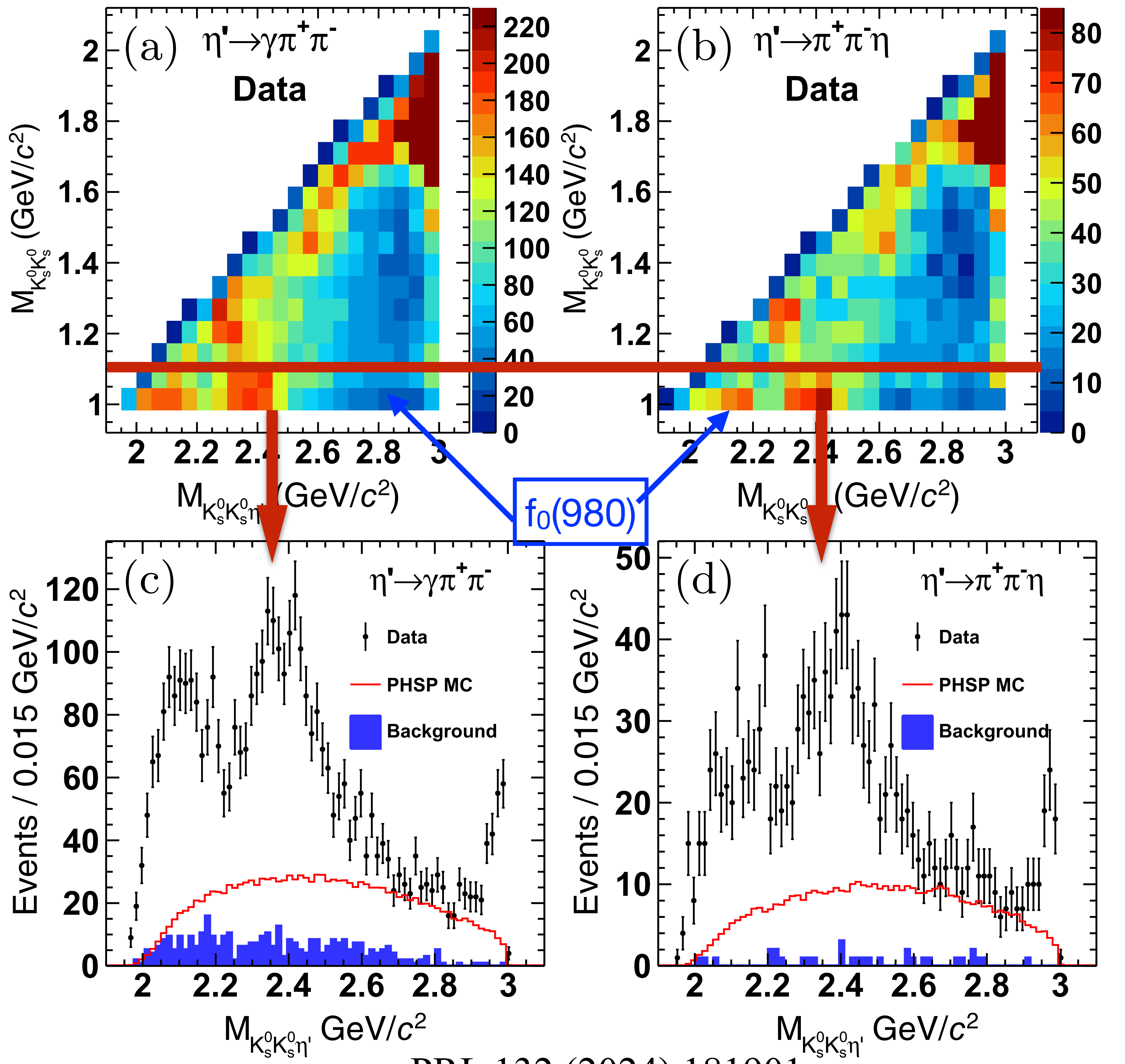
- **Negligible mis-combination for $K^0_s$ reconstruction ( <0.1%)**
- **No background from $J/\psi \to \pi^0 K^0_s K^0_s \eta'$:** further validation directly from data
- **Little background from non-η' processes:** estimated directly from η' mass sideband region:
  - No peaking background
  - **Non-η'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

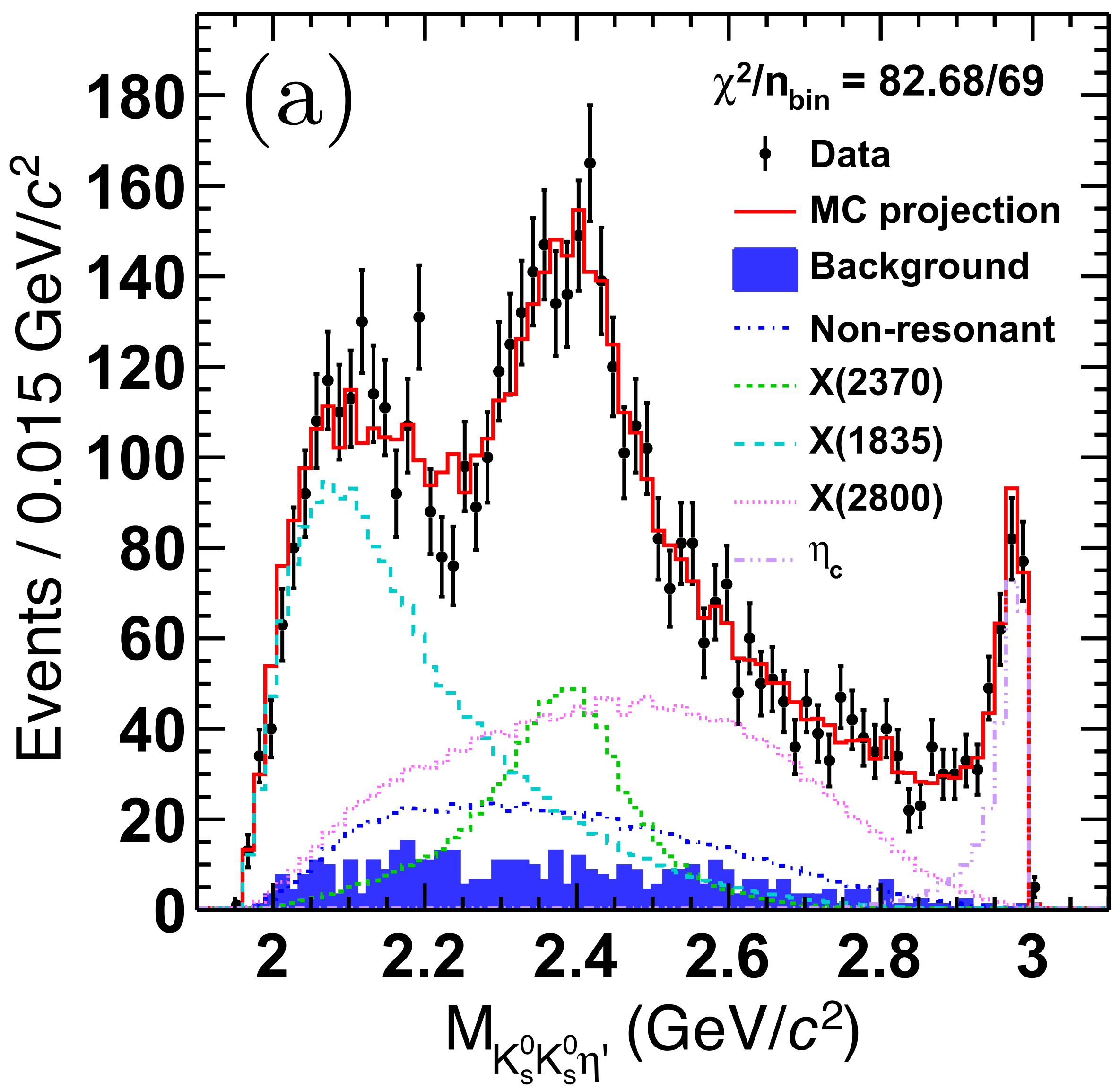
# Mass spectrum after final selection

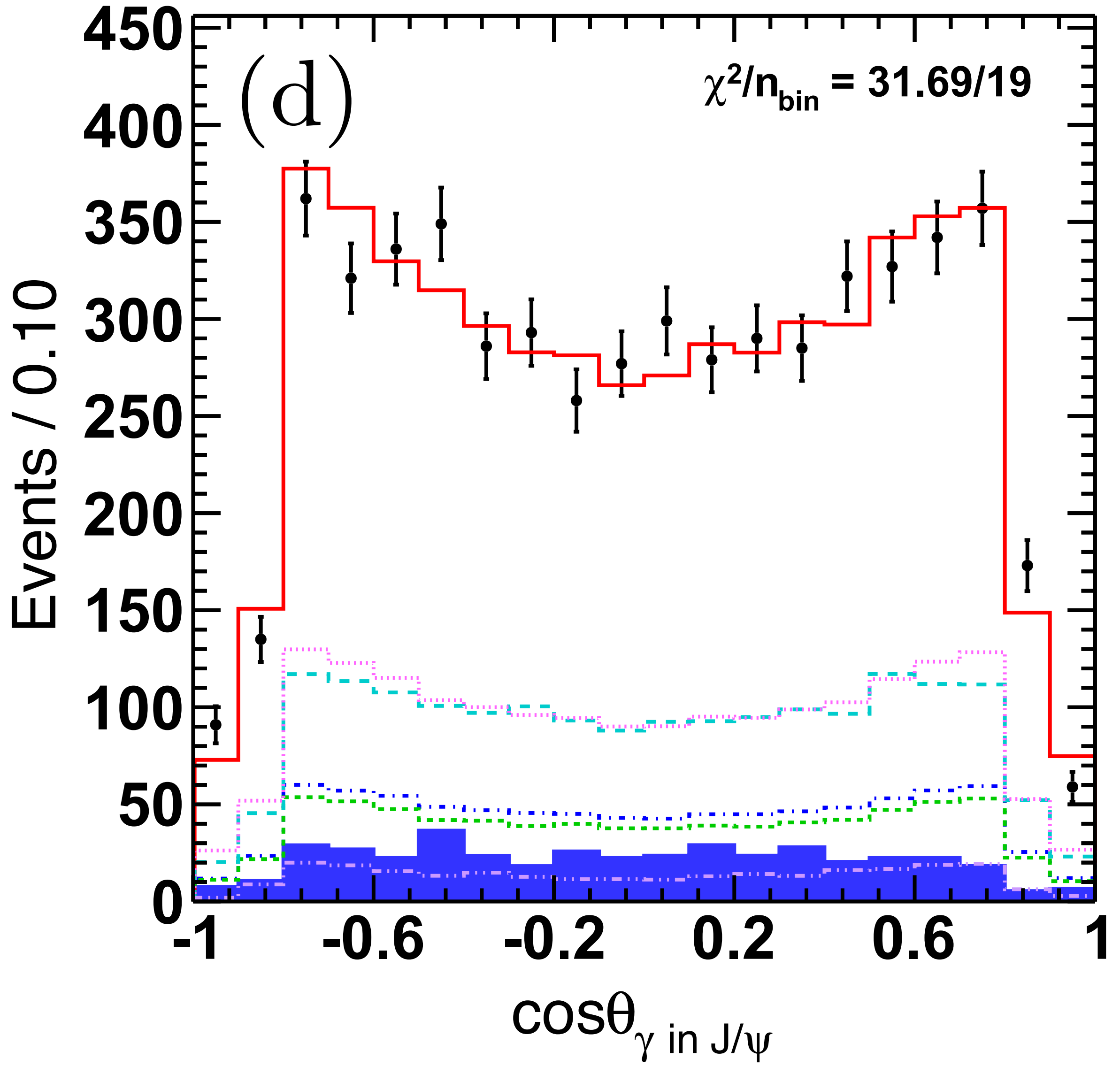



PRL 132 (2024) 181901

- 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 $M(K^0_sK^0_s) < 1.1\,\mathrm{GeV}/c^2$
  - Clear signal of the X(2370) and $\eta_c$
  - Reduce PWA complexities from additional intermediate processes

# PWA Fit

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- 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 | $0^{-+}$ | $\eta'(K_S^0K_S^0)_{S-wave}$ | $---$ | $---$ | $9.0\sigma$ |
| | | $\eta'(K_S^0K_S^0)_{D-wave}$ | $---$ | $---$ | $16.3\sigma$ |

# 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)→$f_0$(980)η'** 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**

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

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

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

**LQCD prediction on lightest pseudoscalar glueball:**

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

**$M = 2395 \pm 14$ MeV**

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

- The measurements are in a agreement with the predictions on **lightest pseudoscalar glueball**
  - **The spin-parity of the X(2370) is determined to be $0^{-+}$ for the first time**
  - **Mass is in a good agreement with LQCD predictions**
  - The estimation on $B(J/\psi \to \gamma X(2370))$ and prediction on $B(J/\psi \to \gamma G_{0^{-+}})$ are consistent within errors (assuming ~5% decay rate, $B(J/\psi \to \gamma X(2370)) = (10.7^{+22.8}_{-7}) \times 10^{-4}$)

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

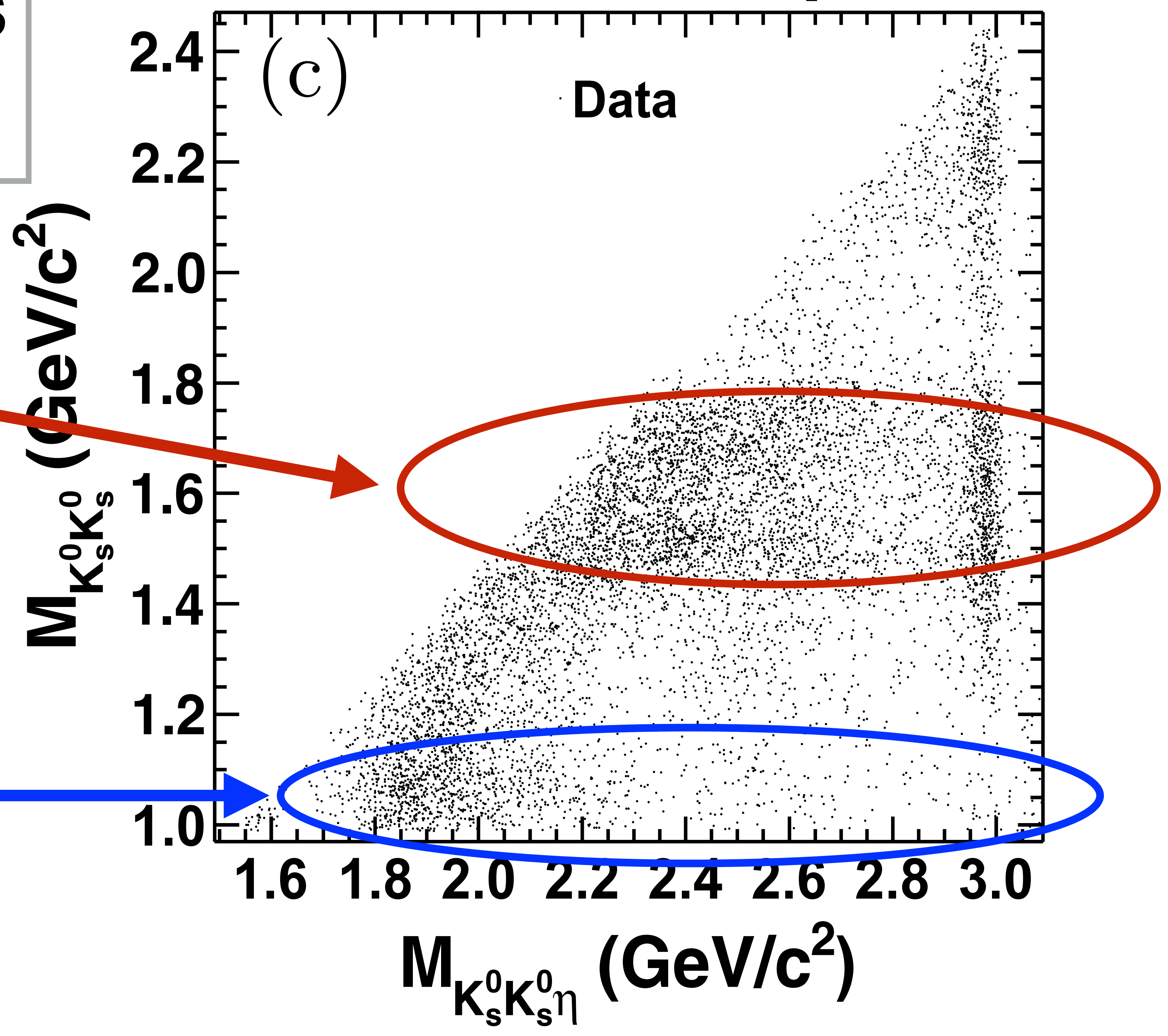
Observation and Spin-Parity Determination of the $X(1835)$ in $J/\psi \to \gamma K^0_S K^0_S \eta$

**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

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

# X(2370) Properties

| | 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**:
  - Major decay mode $f_0(980)\eta'$ with large $s\bar{s}$ component: disfavor the pure $u\bar{u} + d\bar{d}$ meson interpretation
  - Major decay mode $f_0(1500)\eta$ with large $u\bar{u} + d\bar{d}$ component: disfavor the pure $s\bar{s}$ meson interpretation
  - The suppression of $f_0(980)\eta$ mode: disfavor the pure $s\bar{s}$ meson interpretation
  - **The high similarities between X(2370) and $\eta_c$ decay modes strongly support the $0^{-+}$ glueball interpretation**
- **The X(2370) production properties:**
  - richly produced in $J/\psi$ radiative decays as the glueball expectation
  - In the mass region larger than 2.3GeV, the unique particle X(2370) for the $0^{-+}$ glueball candidate in $J/\psi$ radiative decays and two golden decay modes ($\pi\pi\eta'$ and $K\bar{K}\eta'$)

# 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**

# 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 |
| $\Gamma_2$ | $\eta'(958)K\overline{K}$ | $(1.61\pm0.25)$ % | EPJC (2020) 80:746 |

**Decays into stable hadrons**

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

Ongoing, aiming for publication @ICHEP2024

- **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**

# 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**?

# Glueball-like particle: X(2370)

- **X(2370) is a UNIQUE particle** with **mass**, **spin-parity**, **production rate** and **decay property** consistent with $0^{-+}$ glueball expectation

  - Unique $0^{-+}$ particle produced above 2.3GeV in $J/\psi$ radiative decays in the golden $0^{-+}$ glueball decay modes

  - Unique $0^{-+}$ particle with decay modes highly similar to $\eta_c$ (even only with qualitative observations)

- **The reasonable interpretation of X(2370) is the lightest $0^{-+}$ glueball**