Light exotic hadron at BESIII

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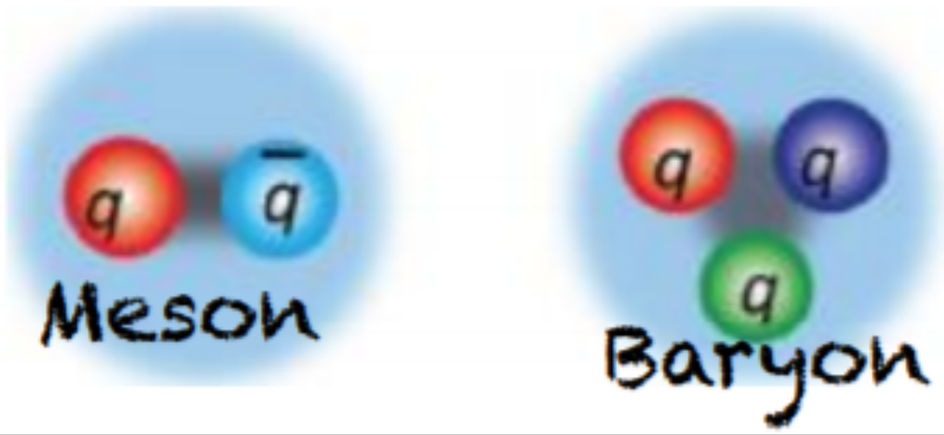
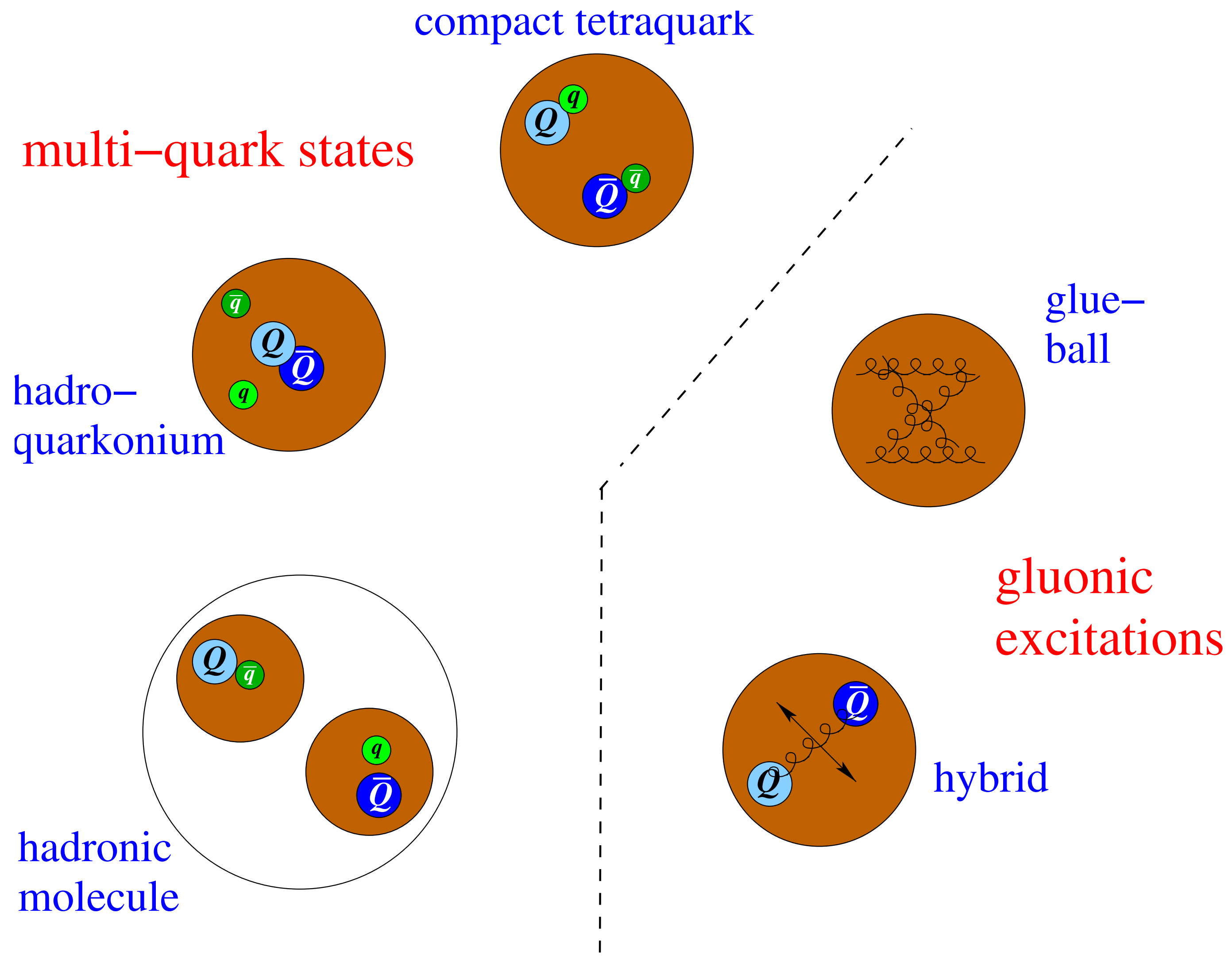
Opportunities and Ideas at the QCD Frontier, 2025.4.9

Forms of hadrons

Quark model



New forms of hadrons



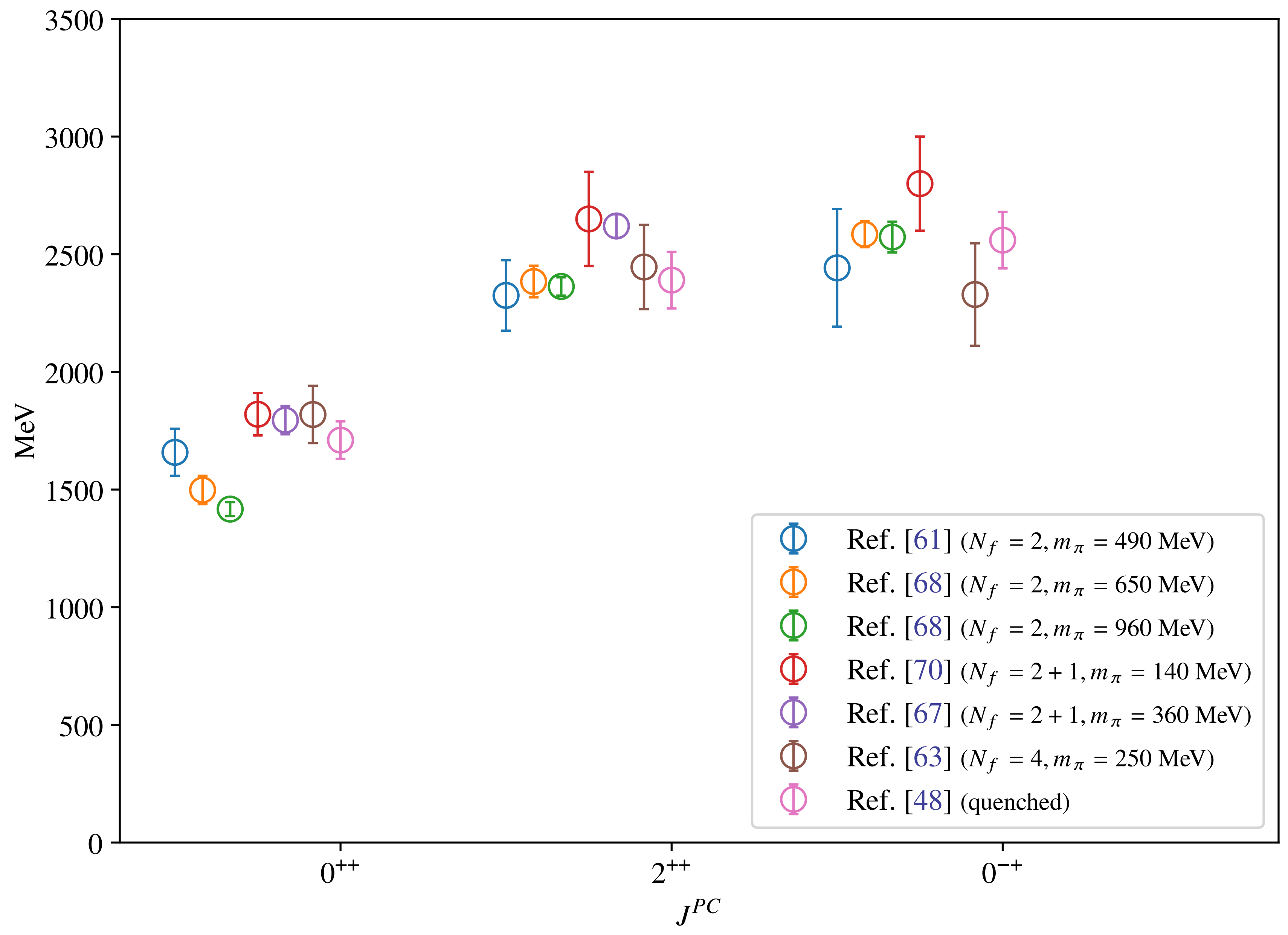
Physics report 873 (2020) 1-154

- **Quark model (QM)**
  - Identify hadrons as compound objects consisting of quarks and antiquarks
  - Dynamics description inside hadrons
- **New form of hadrons:**
  - **Multi-quark:** quark number >= 4
  - **Hybrid state:** the mixture of quark and gluon
  - **Glueball:** composed of gluons
- **Understanding of fundamental structure via hadron spectroscopy:** challenge identification from QM
  - **Exotic quantum states**
  - **Crypto exotic with particular properties**

Glueballs

- ◈ **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 formed with force carriers via self-interactions**
  - ✦ **Glueballs to QCD is just as important as Higgs Boson to EW**

- ◈ **Lattice QCD** (LQCD) is a non-perturbative method from the first principles in theory.
- ◈ **Different lattice QCD groups** (including lattice simulations with dynamical quarks)
  - ✦ Predictions on **masses and production rates** of pure glueballs
  - ✦ Consistent results and expected to be reliable.
- ◈ Lattice QCD predictions on pure 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

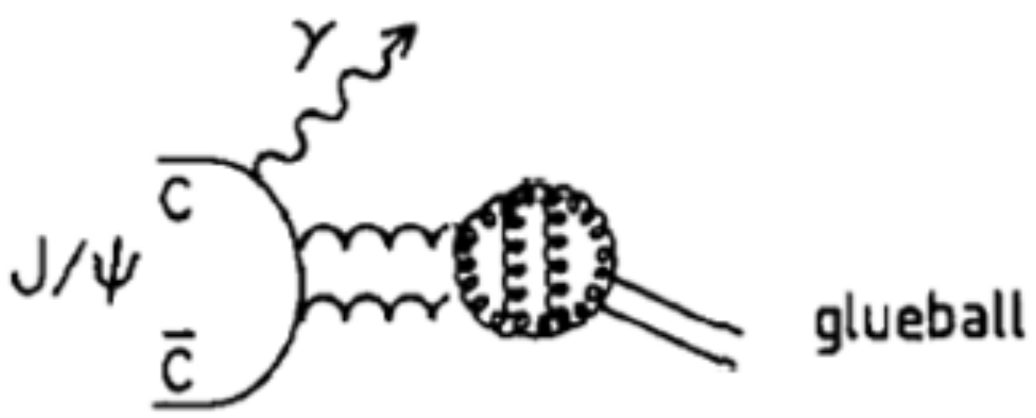


arxiv:2305.04869

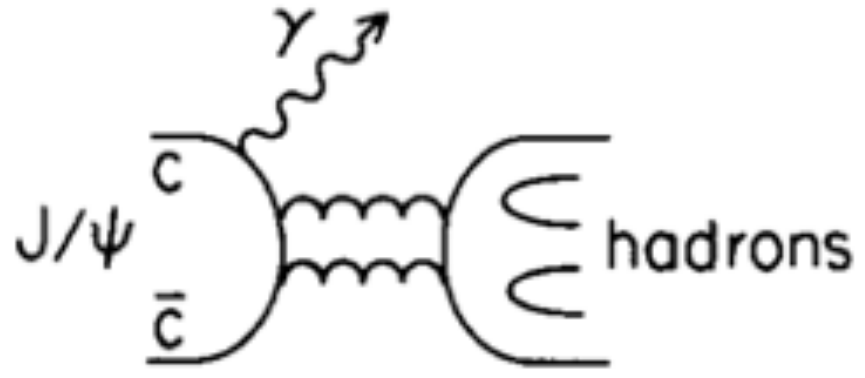
Glueball production in J/ψ Radiative decay

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

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

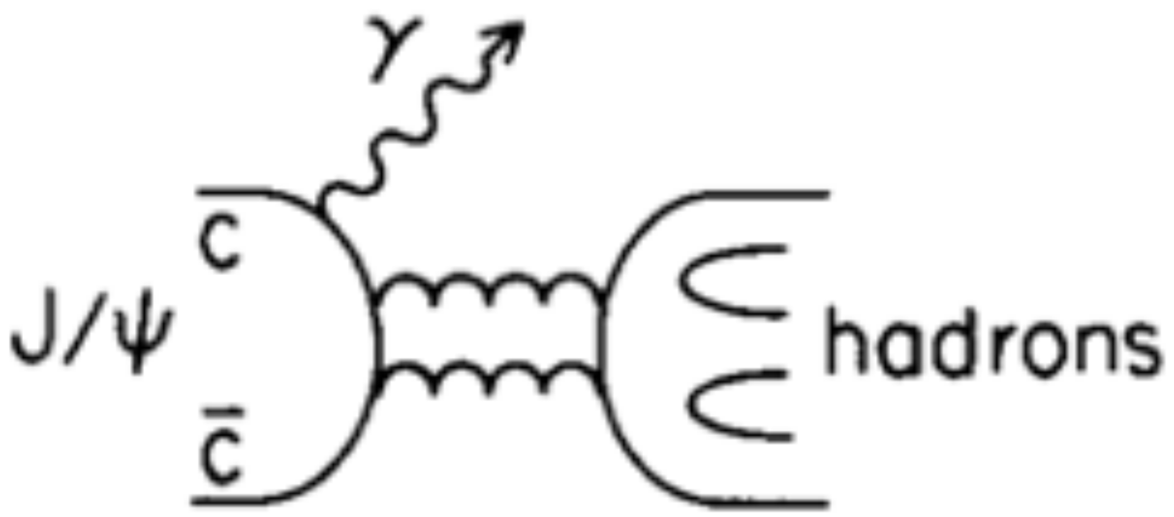


$\sim \alpha\alpha_s^2$

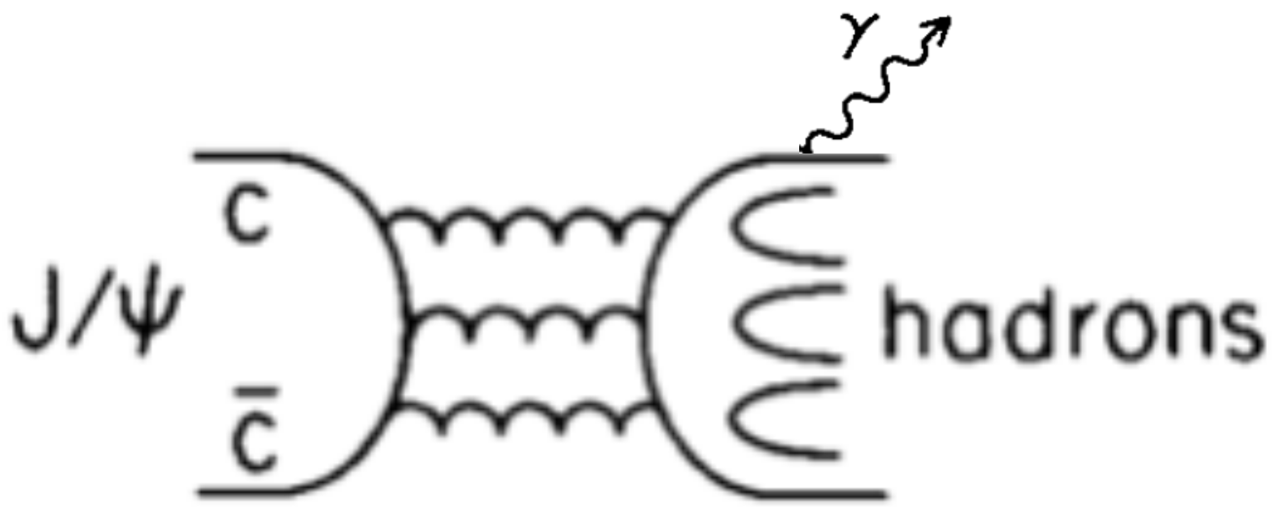


$\sim \alpha\alpha_s^4$

◈ **Clean environment**



$\sim \alpha\alpha_s^4$



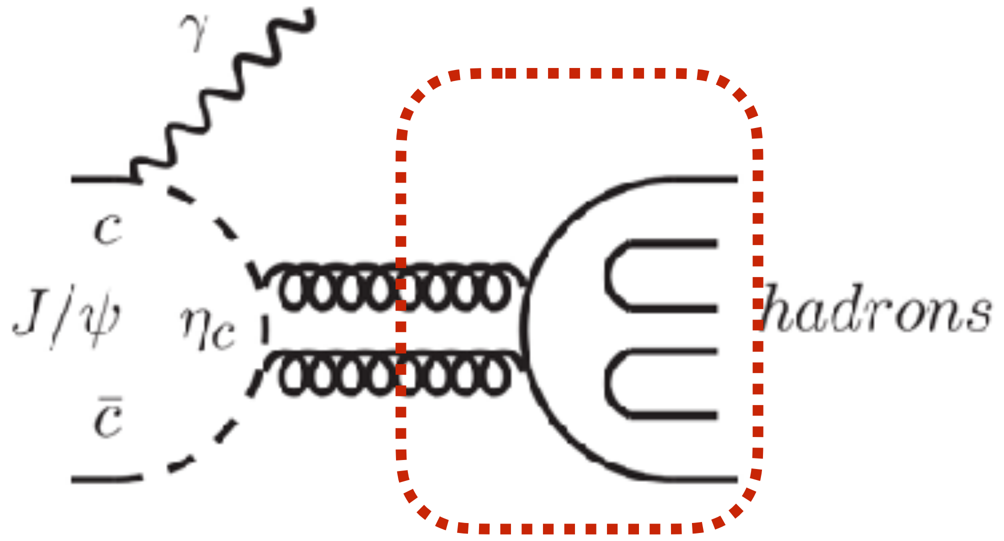
$\sim \alpha\alpha_s^6$

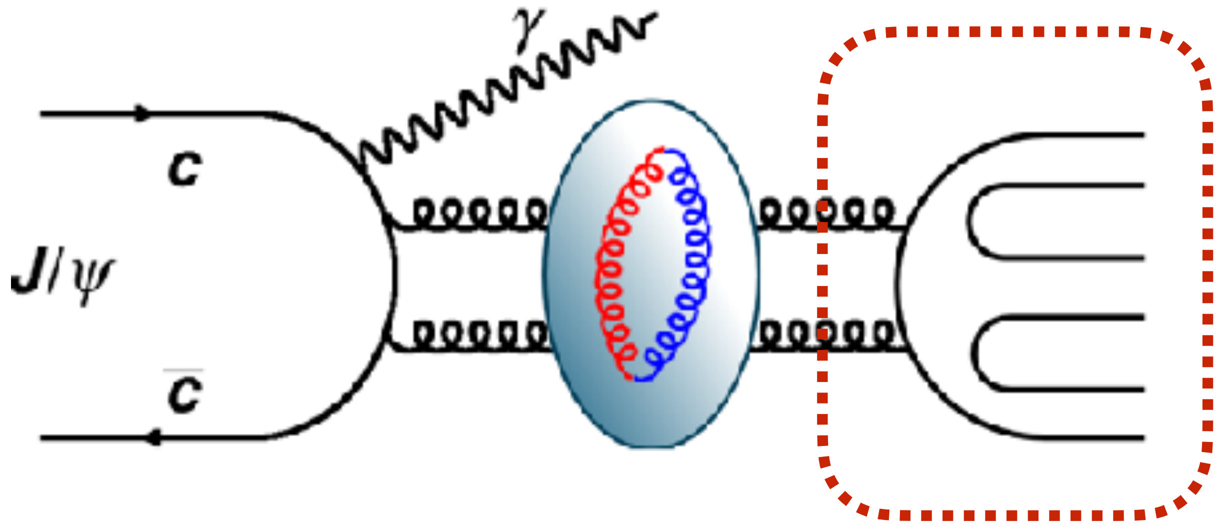
- **Isospin filter:** final states dominated by **I=0** processes
- **Spin-parity filter: C parity must be +**, so $J^{PC}=0^{-+}, 0^{++}, 1^{++}, 2^{++}, 2^{-+}$ …
- **Clean environment in e^+e^- collision:** very different from **p-p collision**

➡ J/ψ Radiative decay is an ideal place to search for glueballs

Glueball Decays

- **Flavor symmetric decays**
- **No rigorous predictions on decay patterns and their branching ratios**
- The glueball decays could be the analogy to **Charmonium decays** since they all decay via gluons (OZI suppression) [PLB 380 189(1996), Commu. Theor. Phys. 23.373 (1995)]
  - e.g. the 0^{-+} glueball could have similar decays of η_c





Historical Glueball Candidates

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

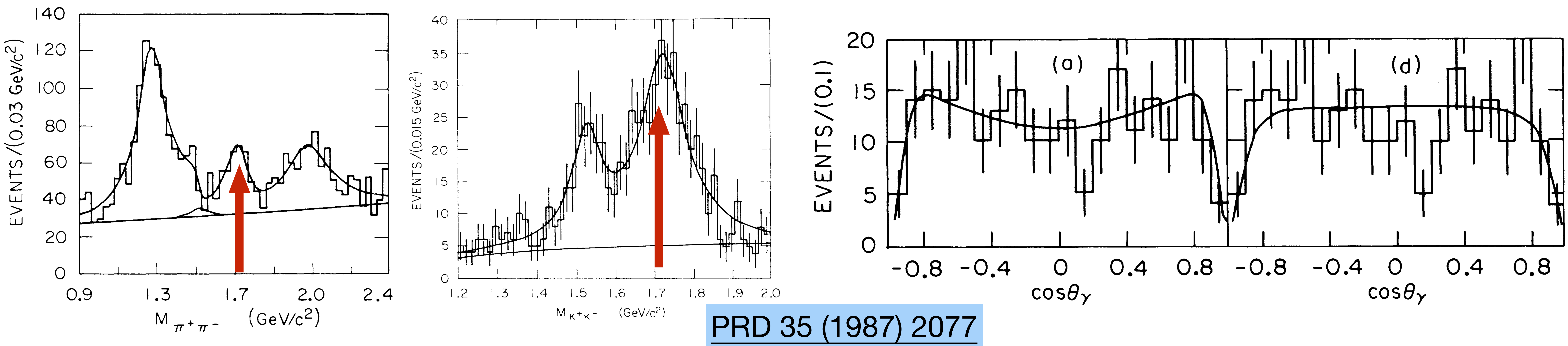
- **Many historical glueball candidates**, but with some **difficulties/controversies.**

    - **Scalar Glueball candidate (0^{++})**： $f_0(1500)$, $f_0(1710)$

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

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

Historical Glueball Candidates — Scalar $f_0(1710)$

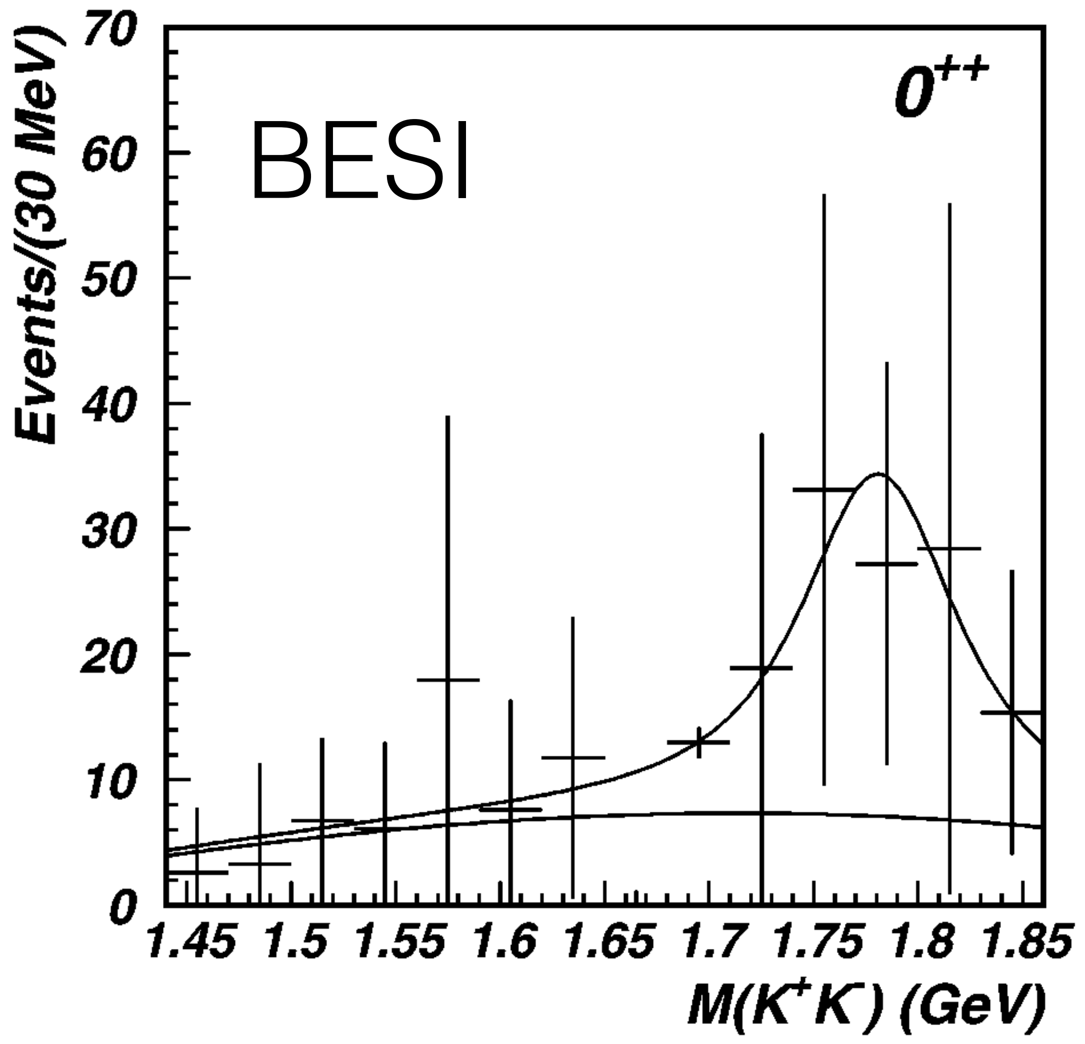


PRD 35 (1987) 2077

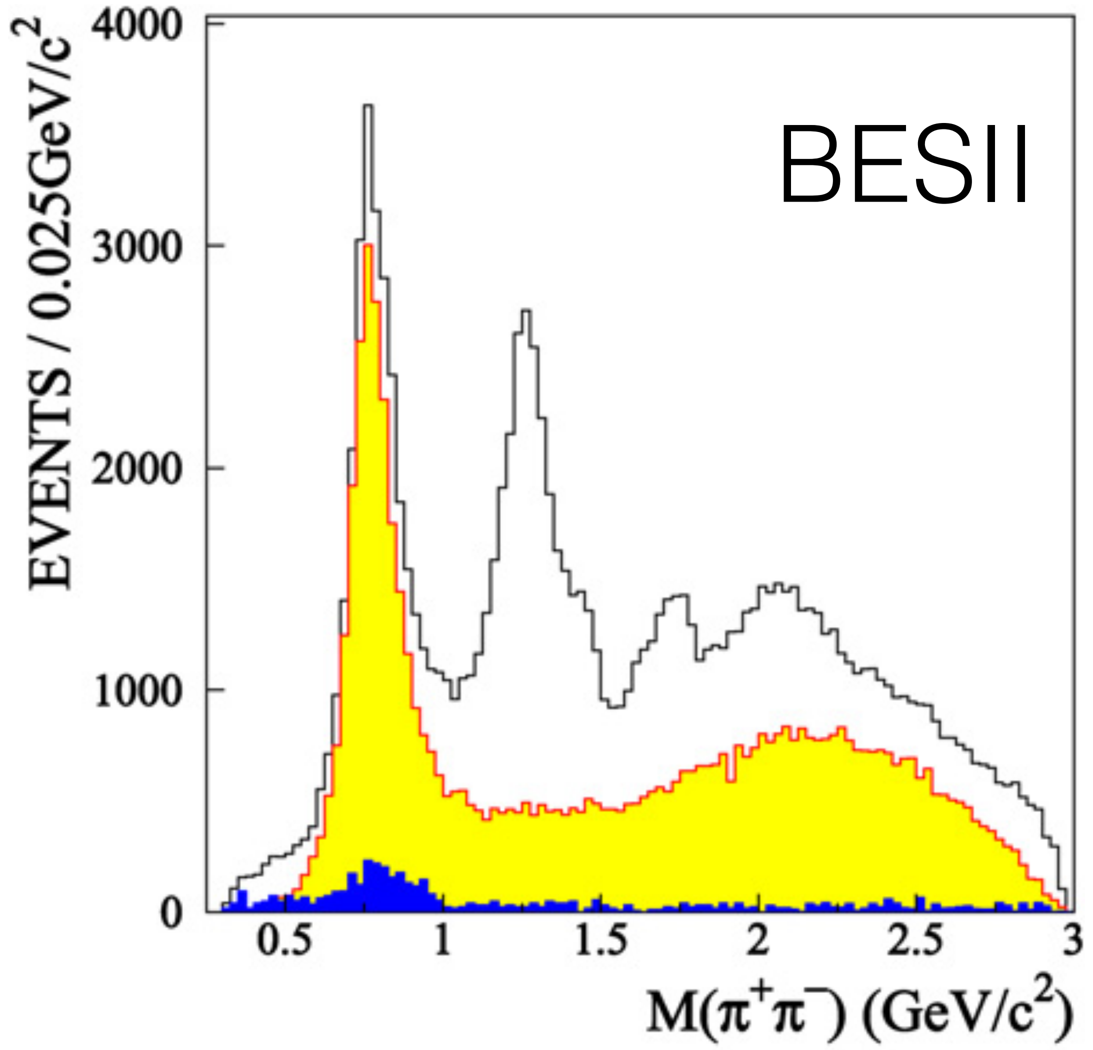
◈ The $f_0(1710)$ was discovered in **$J/\psi \to \gamma\pi^+\pi^-$ and $J/\psi \to \gamma K^+K^-$ by MarkIII** in 1987 as $\theta_2(1720)$

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

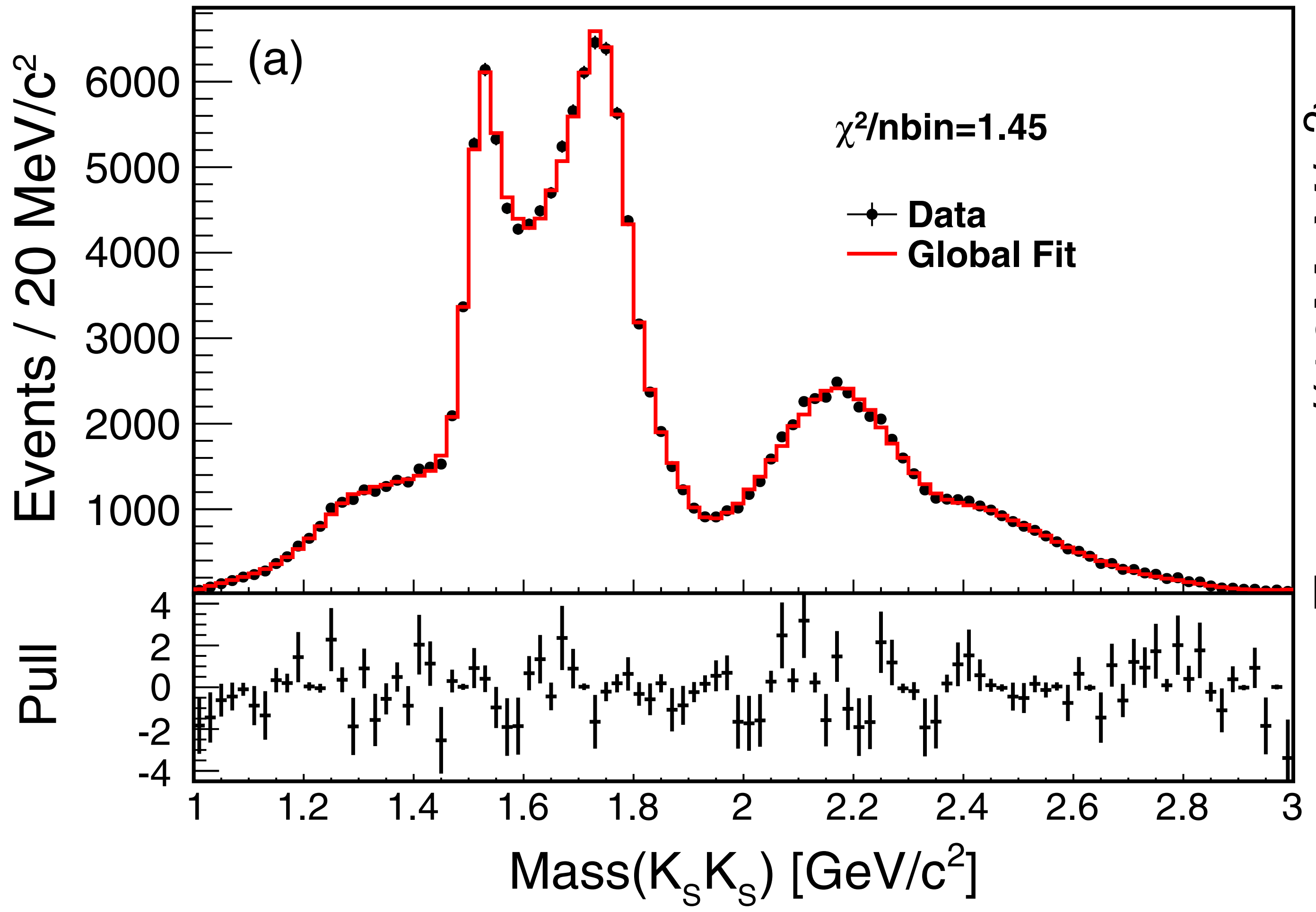
Historical Glueball Candidates — Scalar $f_0(1710)$



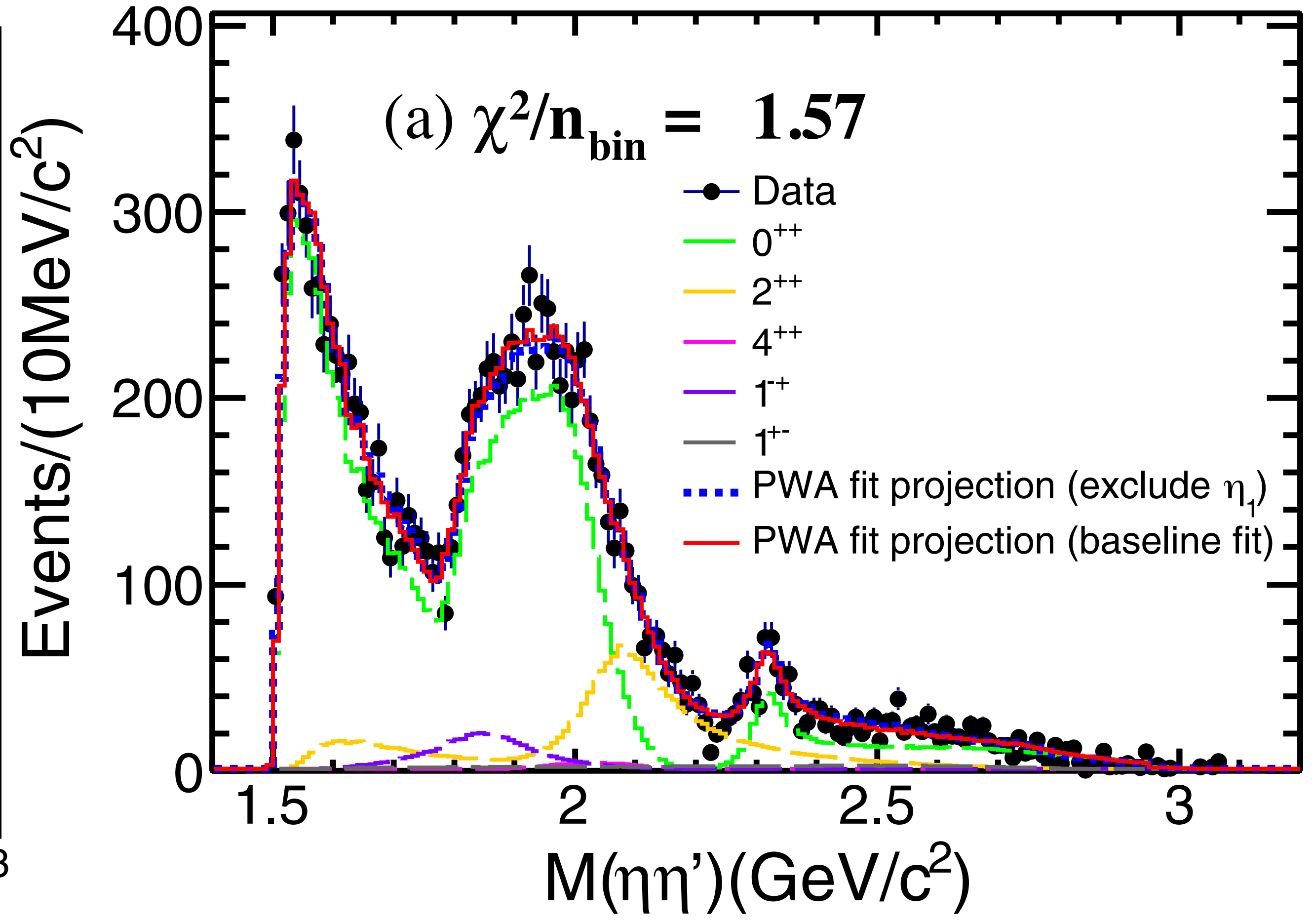
PRL 77(1996) 19



PLB 642 (2006) 441



PRD 98 (2018) 072003



PRD 106 (2022) 072012

- The $f_0(1710)$ **was firstly changed to be 0^{++}** from 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**: **controversy of dynamic mixing mechanism**

✦ **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

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

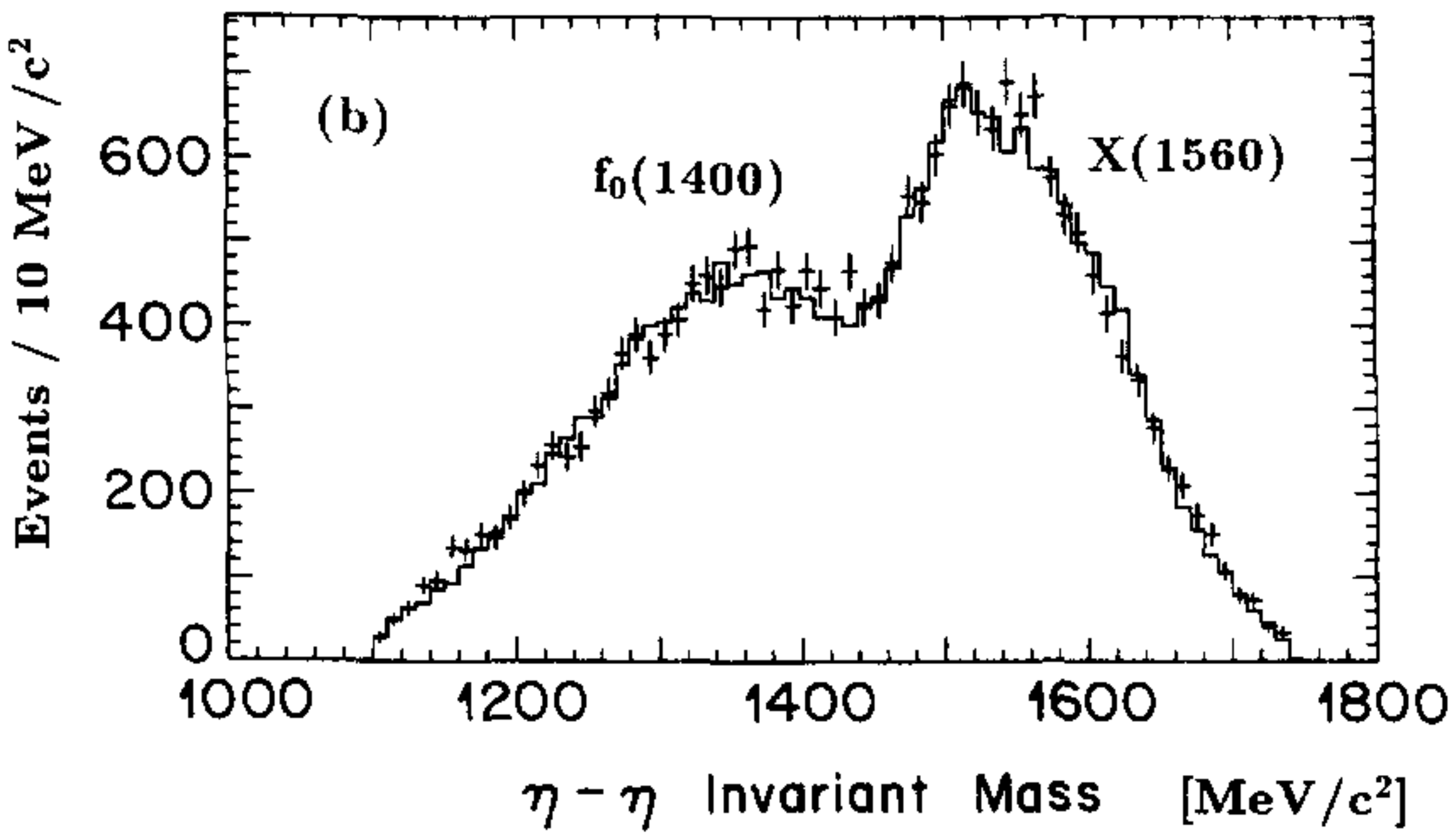
BESIII: PRD 98 (2018) 072003

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

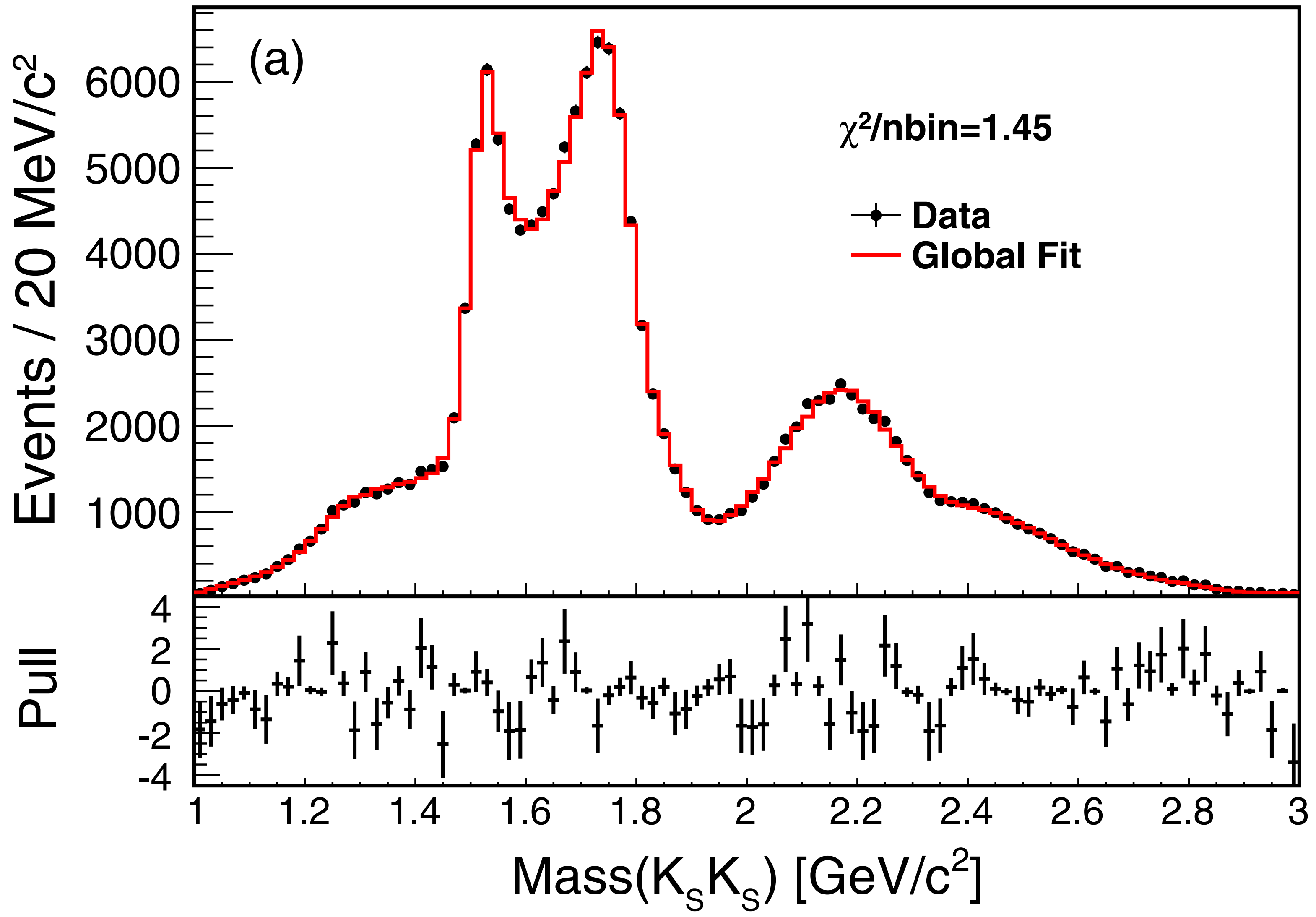
$$B[f_0(1710) \to \eta\eta' / f_0(1710) \to \pi\pi] < (2.9 \pm^{+1.1}_{-0.9}) \times 10^{-3}$$

BESIII: PRD 106 072012(2022)

Historical Glueball Candidates — Scalar $f_0(1500)$



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

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

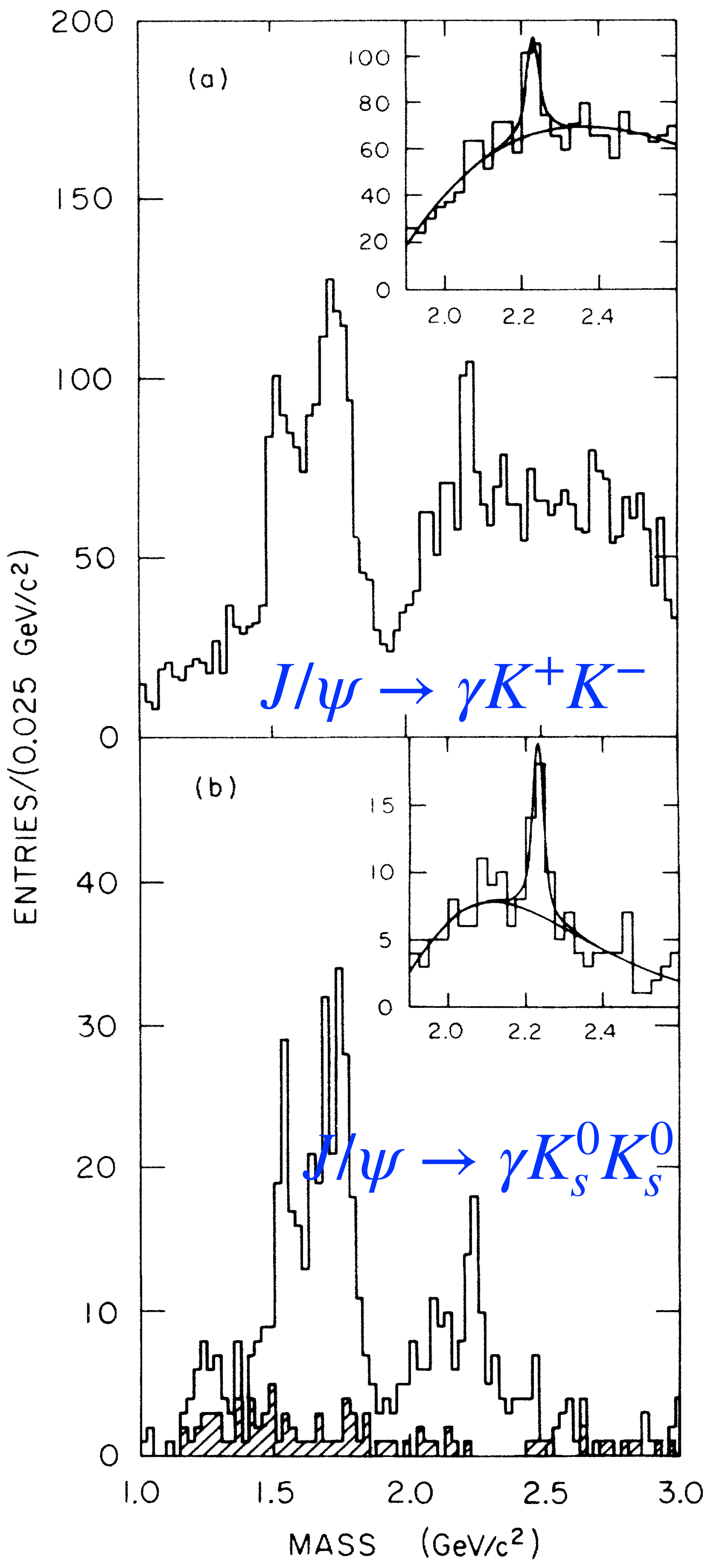
BESIII: PRD 98 (2018) 072003

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

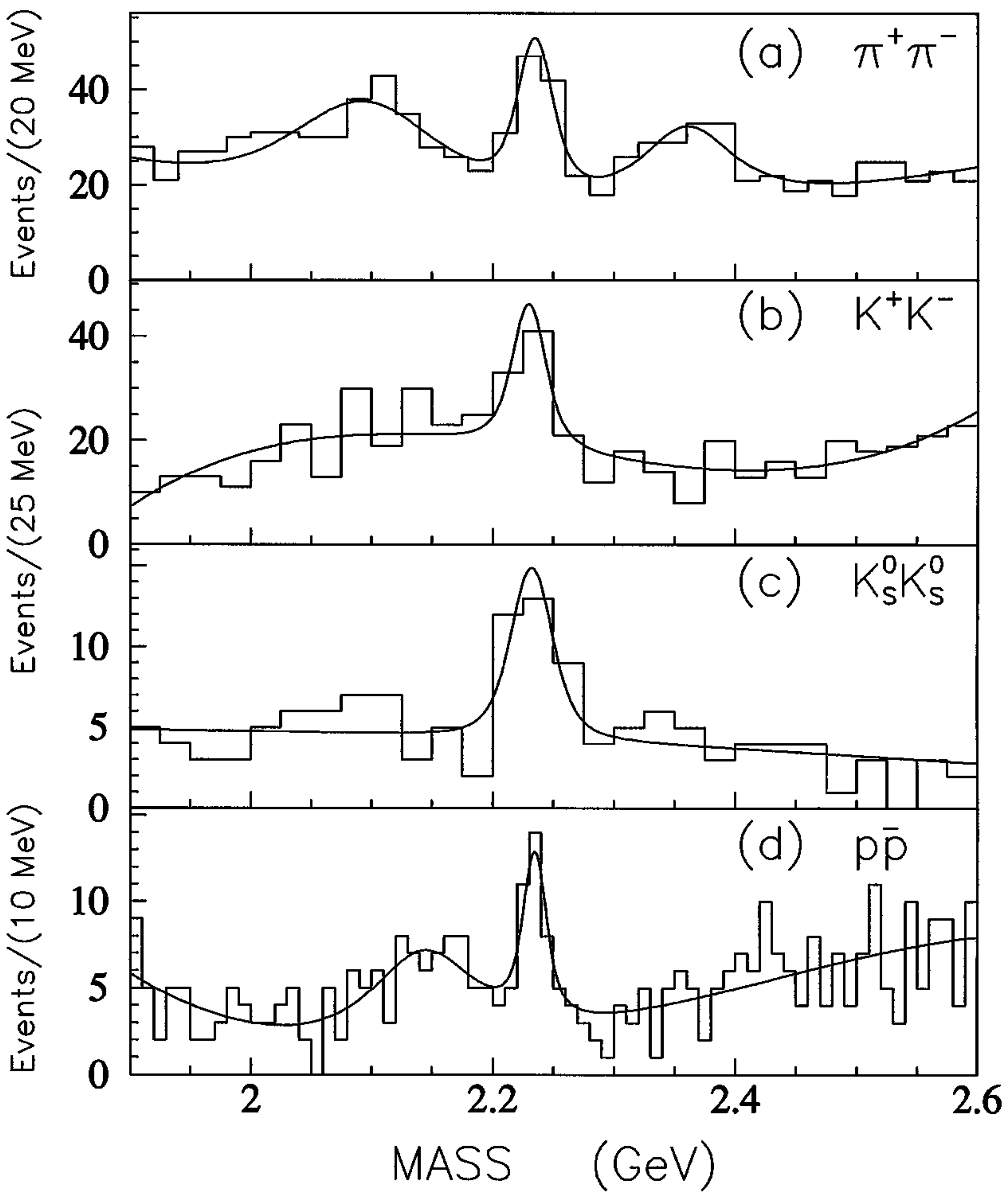
$$B[f_0(1500) \to \eta\eta' / f_0(1500) \to \pi\pi] = (1.66 \pm^{+0.42}_{-0.40}) \times 10^{-1}$$
$$B[f_0(1710) \to \eta\eta' / f_0(1710) \to \pi\pi] < (2.9 \pm^{+1.1}_{-0.9}) \times 10^{-3}$$

BESIII: PRD 106 072012(2022)

Historical Glueball Candidates — Tensor ξ(2230)



PRL 56 (1986) 107



PRL 76 (1996) 3502

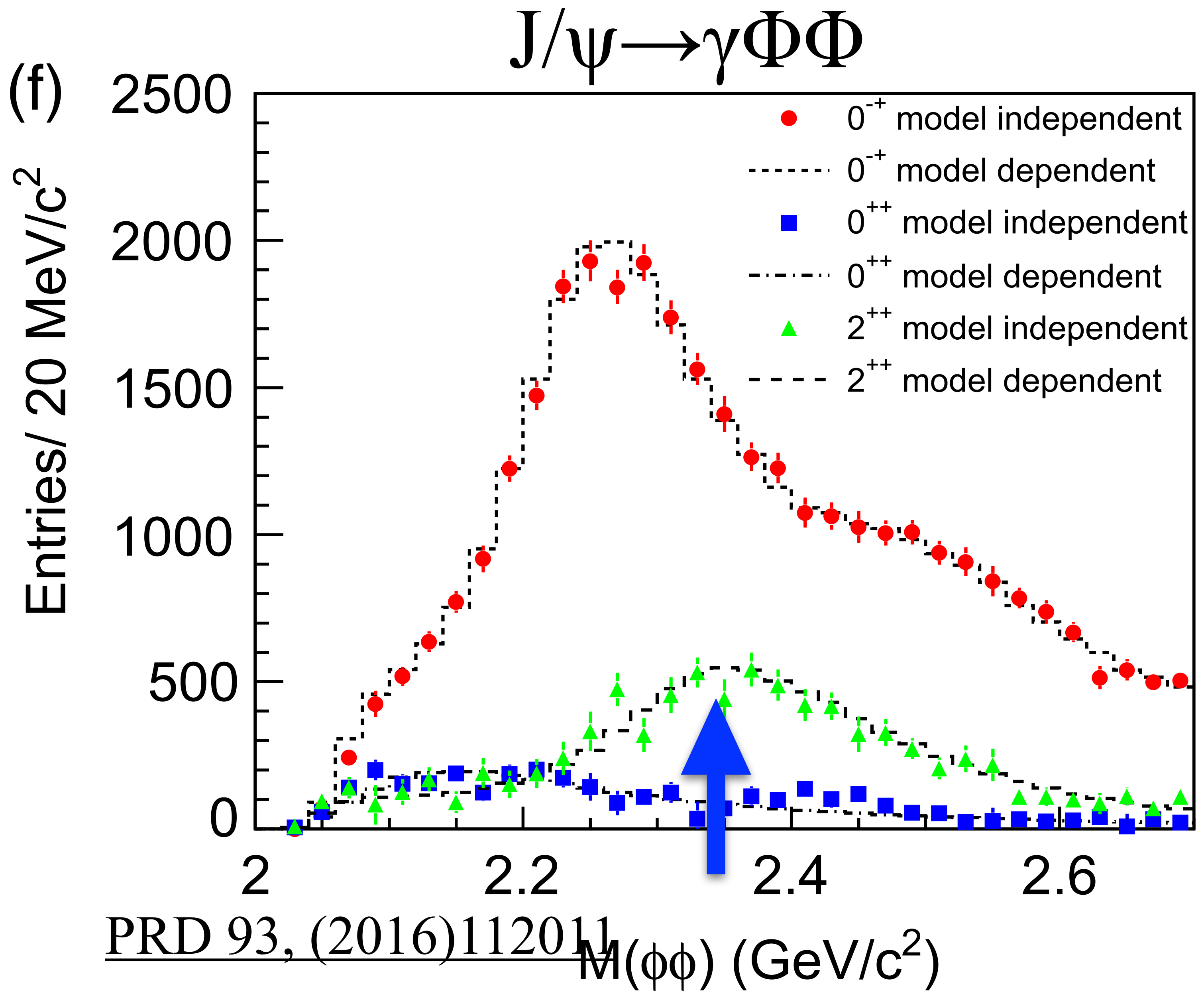
- First observed by MarkIII is J/ψ→ γKK in 1980's, then by BESI in 1990's in J/ψ → γKK, $\gamma\pi\pi$, $\gamma p\bar{p}$ with very narrow mass peak.
- It was a tensor glueball candidate due to good flavor symmetric decay property.
- Difficulty: it was not confirmed by BESII, nor BESIII with much higher statistics.

Historical Glueball Candidates — Tensor $f_2(2340)$

$$\Gamma(J/\psi \to \gamma G_{2+}) = 1.01(22)keV$$
$$\Gamma(J/\psi \to \gamma G_{2+})/\Gamma_{tot} = 1.1 \times 10^{-2}$$

CLQCD, Phys. Rev. Lett. 111, 091601 (2013)

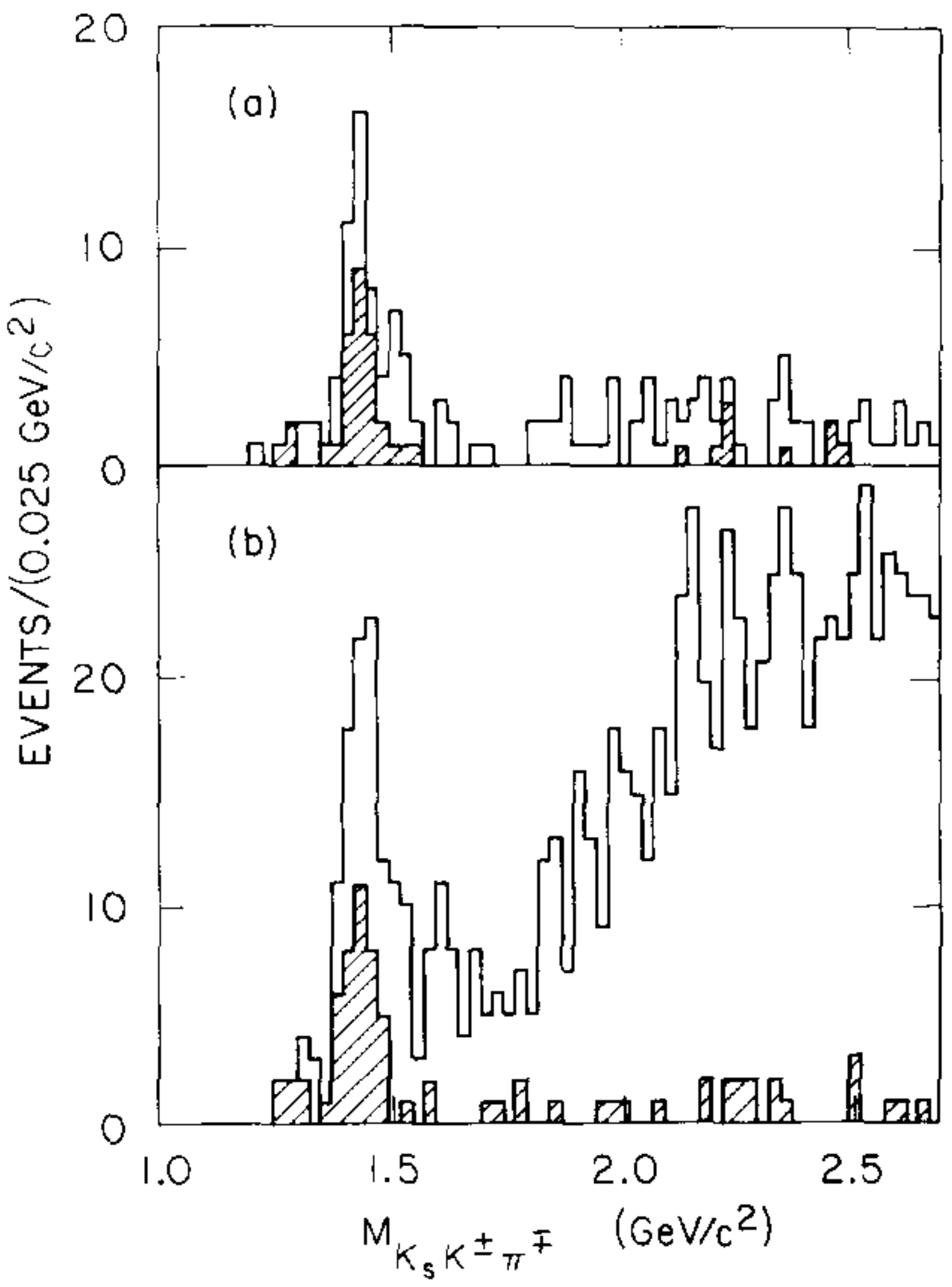
- **Large production rate of $f_2(2340)$ in** J/ψ→γ(KK/ηη/η'η'/ϕϕ)**:** substantially lower than the LQCD prediction for tensor glueball
  - B(J/ψ→$\gamma f_2(2340)\to\gamma\eta\eta$) = $(3.8^{+0.62}_{-0.66}\ {}^{+2.37}_{-2.07}) \times 10^{-5}$ (PRD 87,2013,092009)
  - B(J/ψ→$\gamma f_2(2340)\to\gamma\phi\phi$) =$(1.91 \pm 0.14^{+0.72}_{-0.73} \times 10^{-4}$ (PRD 93,2016,112011)
  - B(J/ψ→$\gamma f_2(2340)\to\gamma K_s K_s$) =$(5.54^{+0.34}_{-0.40}\ {}^{+3.82}_{-1.49} \times 10^{-5}$ (PRD 98,2018,072003)
  - B(J/ψ→$\gamma f_2(2340)\to\gamma\eta'\eta'$) =$(8.67 \pm 0.70^{+0.16}_{-1.67} \times 10^{-6}$(PRD 105,2022,072002)
- **Difficulty: Many wide tensor mesons and large overlaps in the mass region of 2.3GeV** (2^{++} glueball mass from the LQCD predictions)
  - Studies are strongly model dependent.



PRD 93, (2016)112011

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

Historical Glueball Candidates — Pseudoscalar η(1405)



Phys. Lett. 97B (1980) 2

- 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 a 0^{-+} glueball candidate due to its large different mass from latest LQCD prediction** （Lack of reliable LQCD predictions in 1980’s）

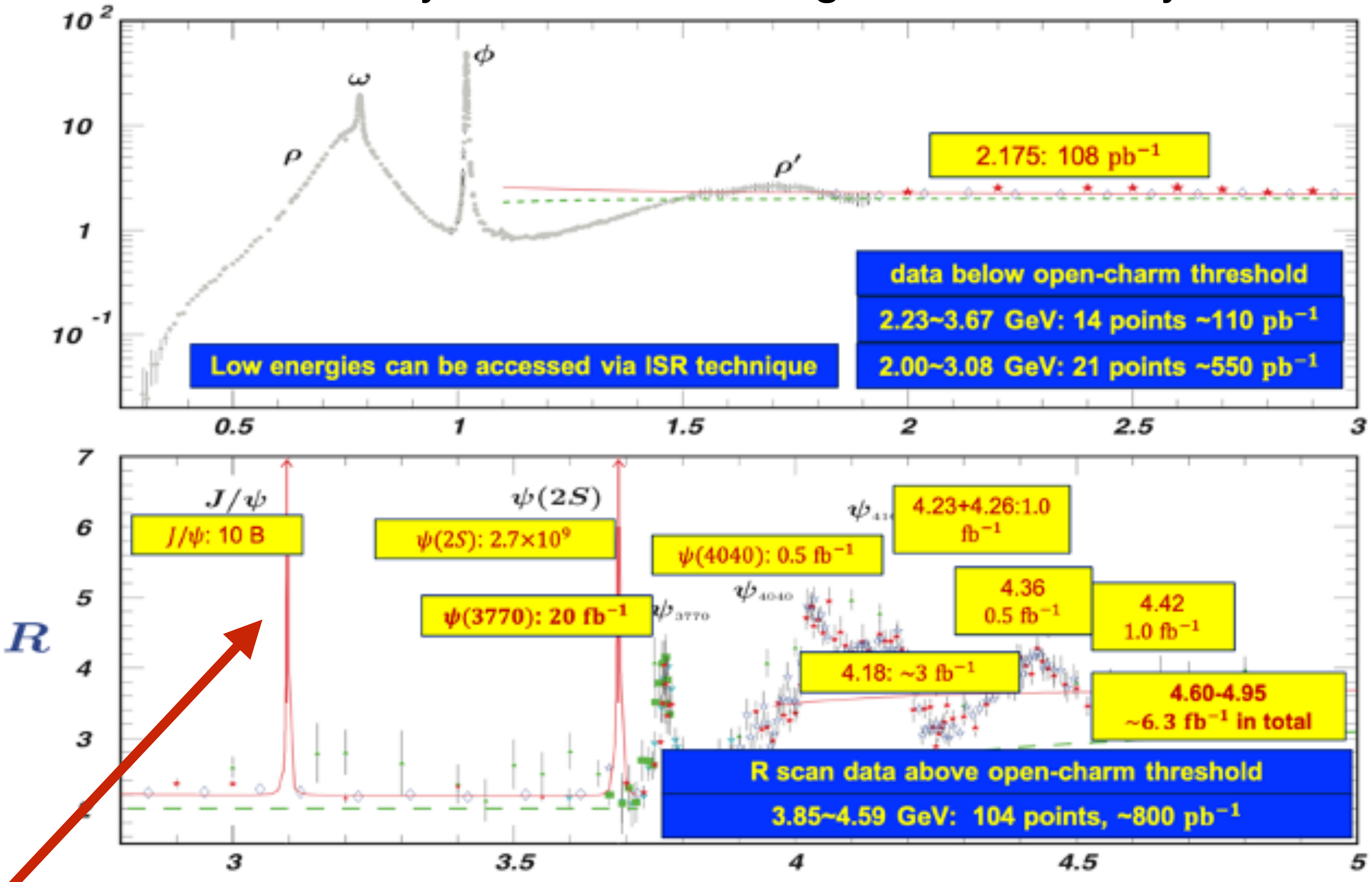
BESIII Data samples

Data sets collected so far include

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



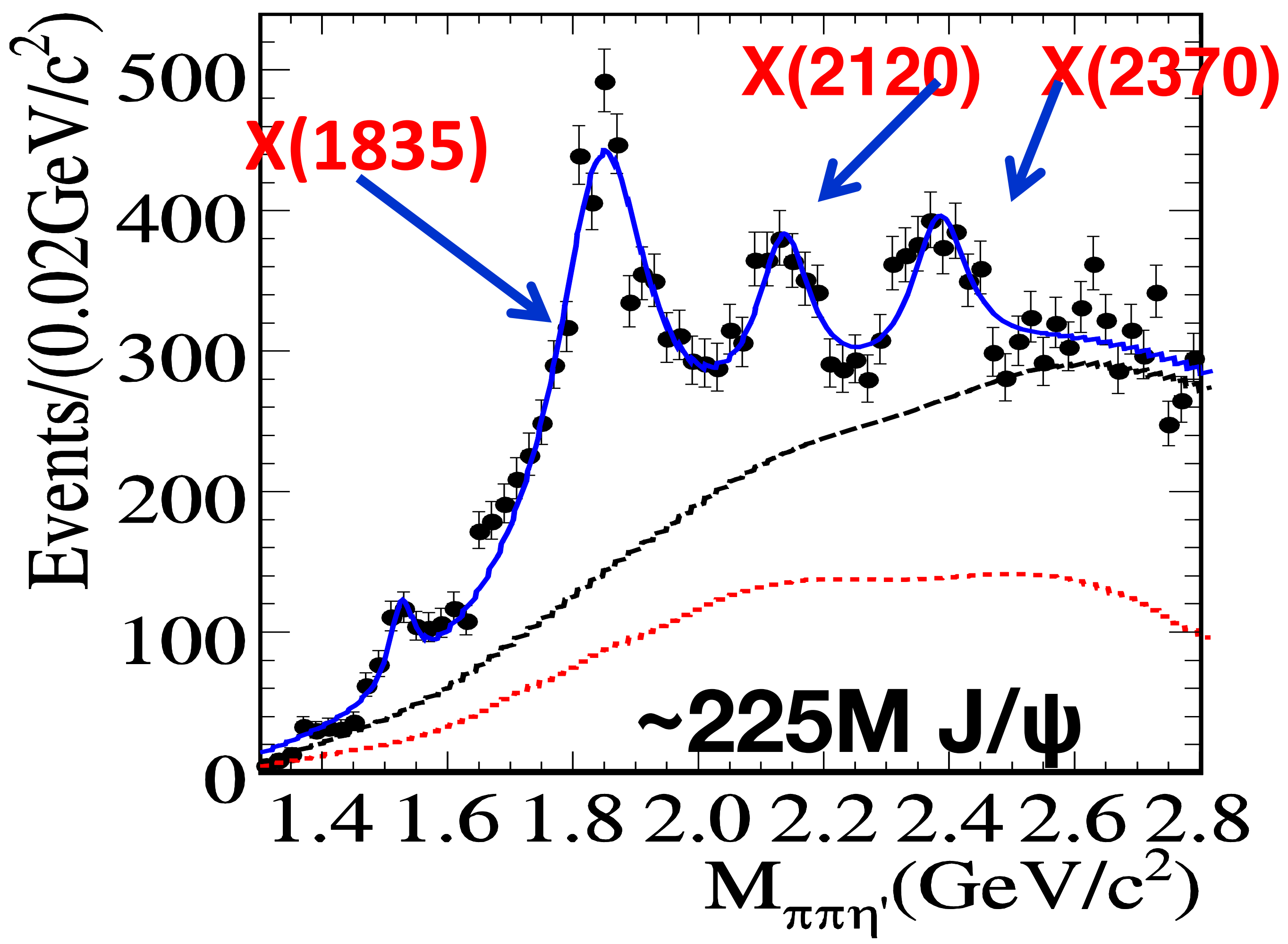
World largest J/ψ data sample : ~10 billion

X(2370)

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

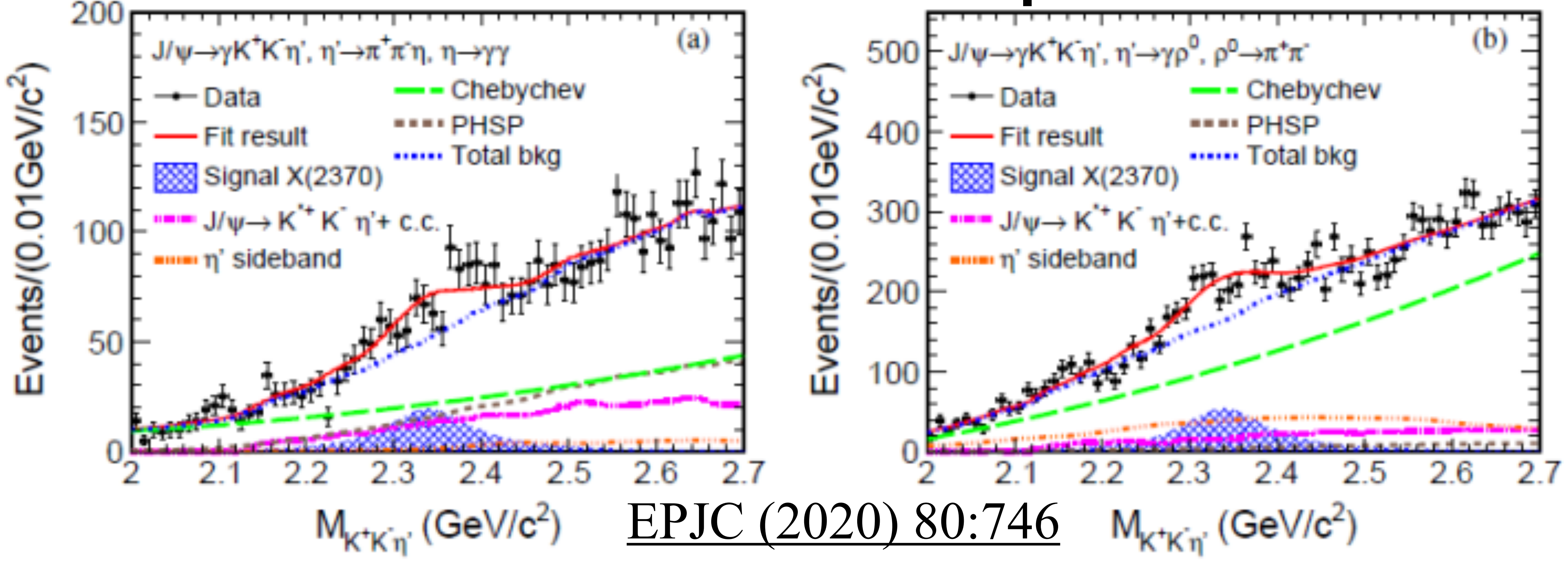
	M(MeV/c²)	Γ(MeV/c²)	Sig.
X(1835)	$1836.5\pm3.0^{+5.6}_{-2.1}$	$190.1\pm9.0^{+38}_{-36}$	>20σ
X(2120)	$2122.4\pm6.7^{+4.7}_{-2.7}$	$83\pm16^{+31}_{-11}$	7.2σ
X(2370)	$2376.3\pm8.7^{+3.2}_{-4.3}$	$83\pm17^{+44}_{-6}$	6.4σ

PRL 106, 072002 (2011)

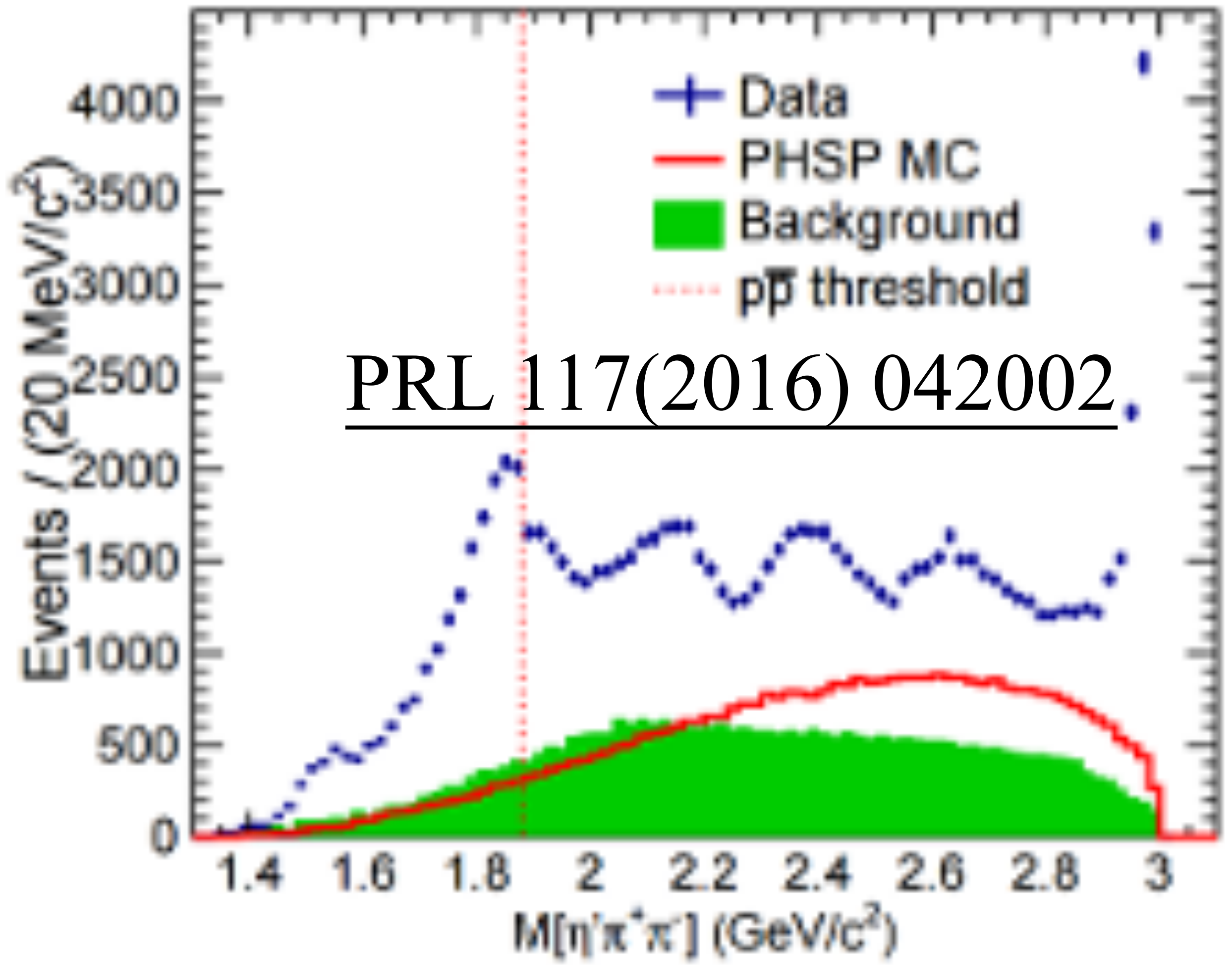


◈ **Confirmed by BESIII in $J/\psi \to \gamma\pi^+\pi^-\eta'$ and $J/\psi \to \gamma K\bar{K}\eta'$ (new mode)**

1.31×10⁹ J/ψ



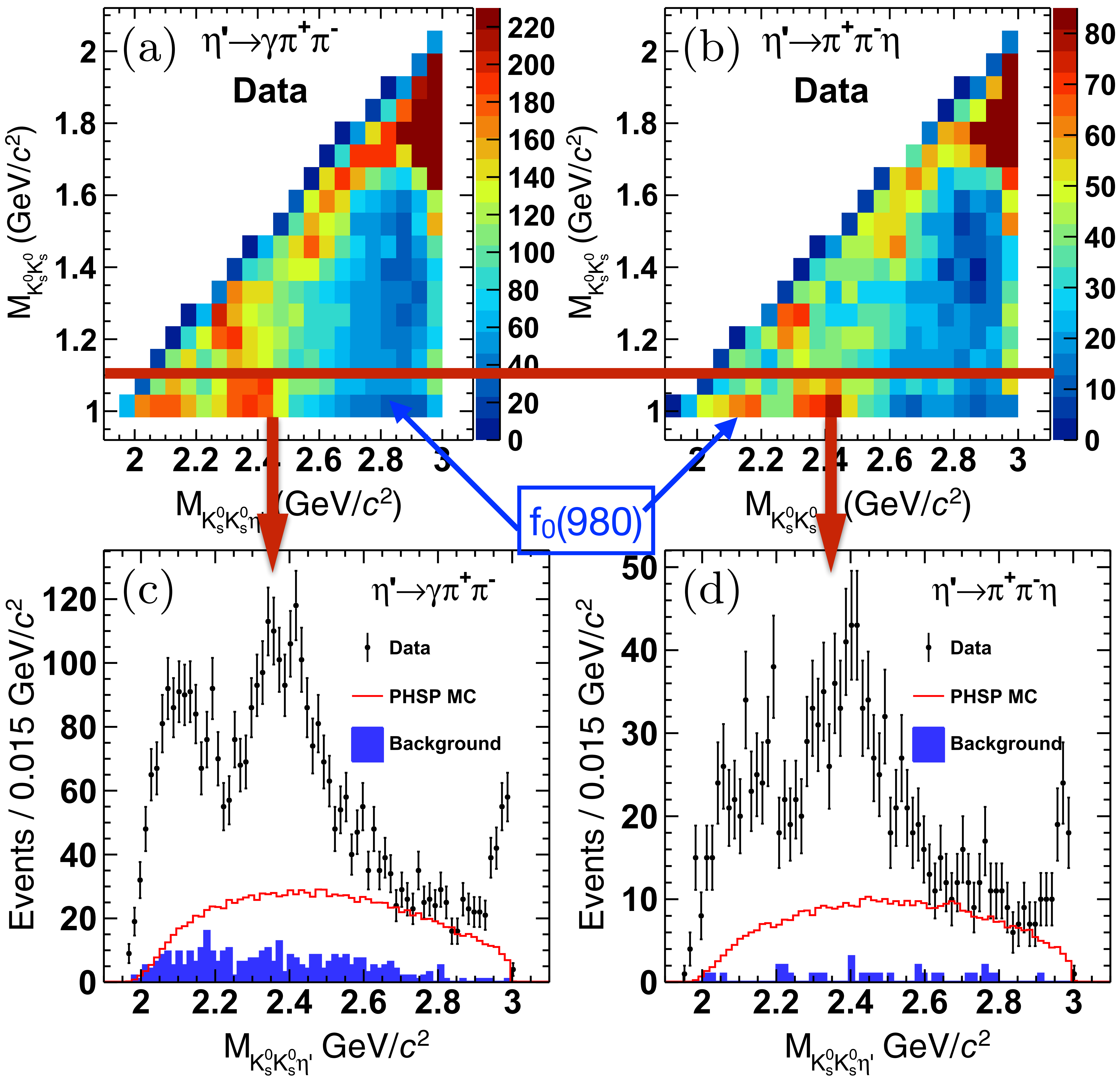
EPJC (2020) 80:746



PRL 117(2016) 042002

Observation of the flavor symmetry decay of the X(2370)

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



PRL 132 (2024) 181901

- Analysis advantage of $J/\psi\to\gamma K^0_sK^0_s\eta'$:
  - Almost background free channel (exchange symmetry and C-parity conservation)
  - 10billion J/ψ data
  - Very good BESIII detector performance
- Similar structures in $\eta'\to\pi^+\pi^-\eta$ / $\gamma\pi^+\pi^-$ modes:
  - Evident $f_0(980)$ in $K^0_sK^0_s$ mass threshold
  - Clear signal of X(1835),X(2370),η_c with $f_0(980)$ selection
- Best PWA fit can well describe the data:
  - **Spin-parity of the X(2370) is determined to be 0^{-+}** with significance larger than **9.8σ w.r.t. other J^{PC} assumptions**

Glueball-like Particle X(2370)

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 pure 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 good 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, $B(J/\psi \to \gamma X(2370)) = (10.7^{+22.8}_{-7}) \times 10^{-4}$)

PRL 132 (2024) 181901

X(2370) in $J/\psi \to \gamma K^0_s K^0_s \eta$

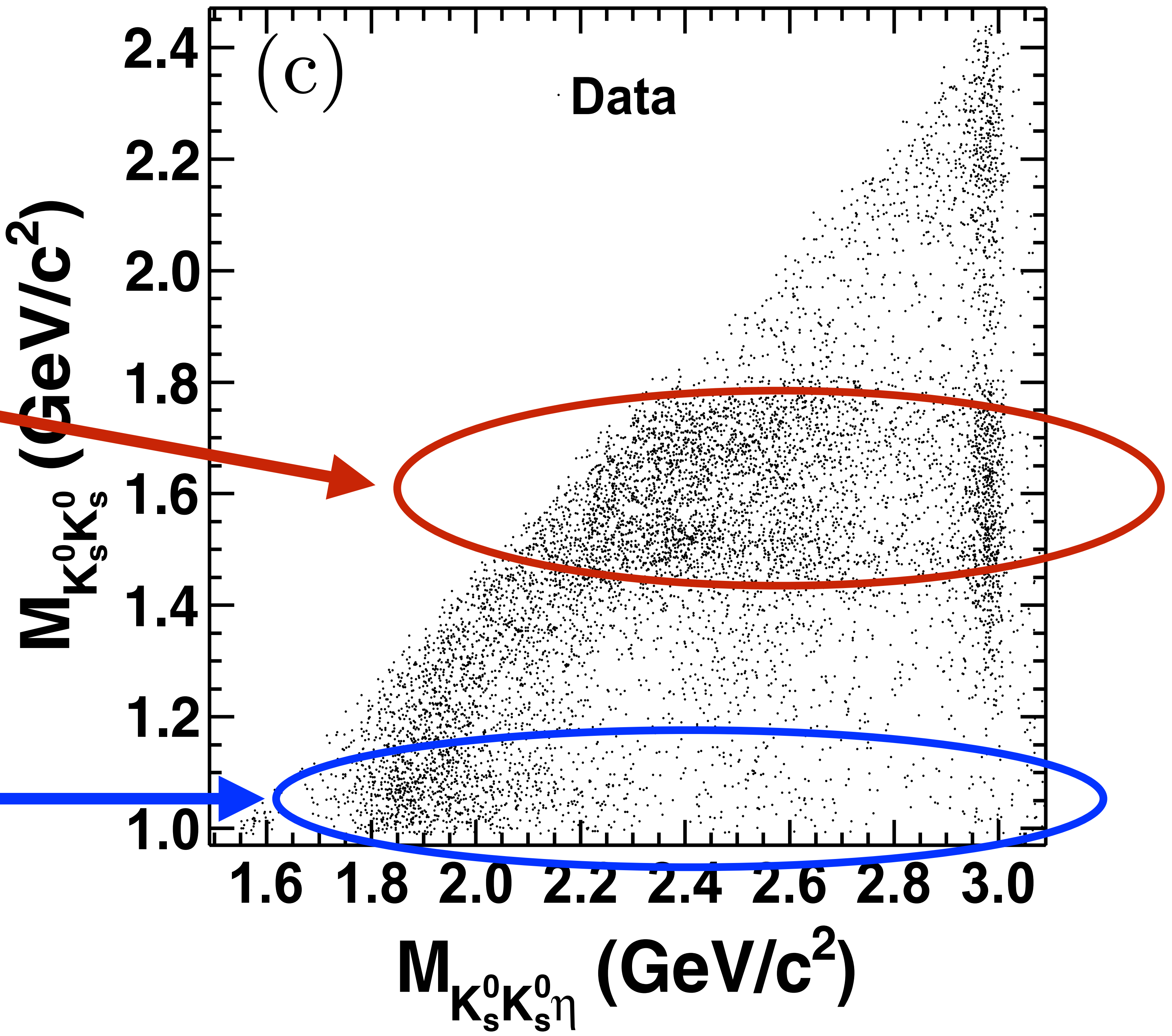
Observation and Spin-Parity Determination of the $X(1835)$ in $J/\psi \to \gamma K^0_S K^0_S \eta$

Qualitatively, we can clearly observe: similar decay patterns of the X(2370) and η_c if phase space allows

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

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

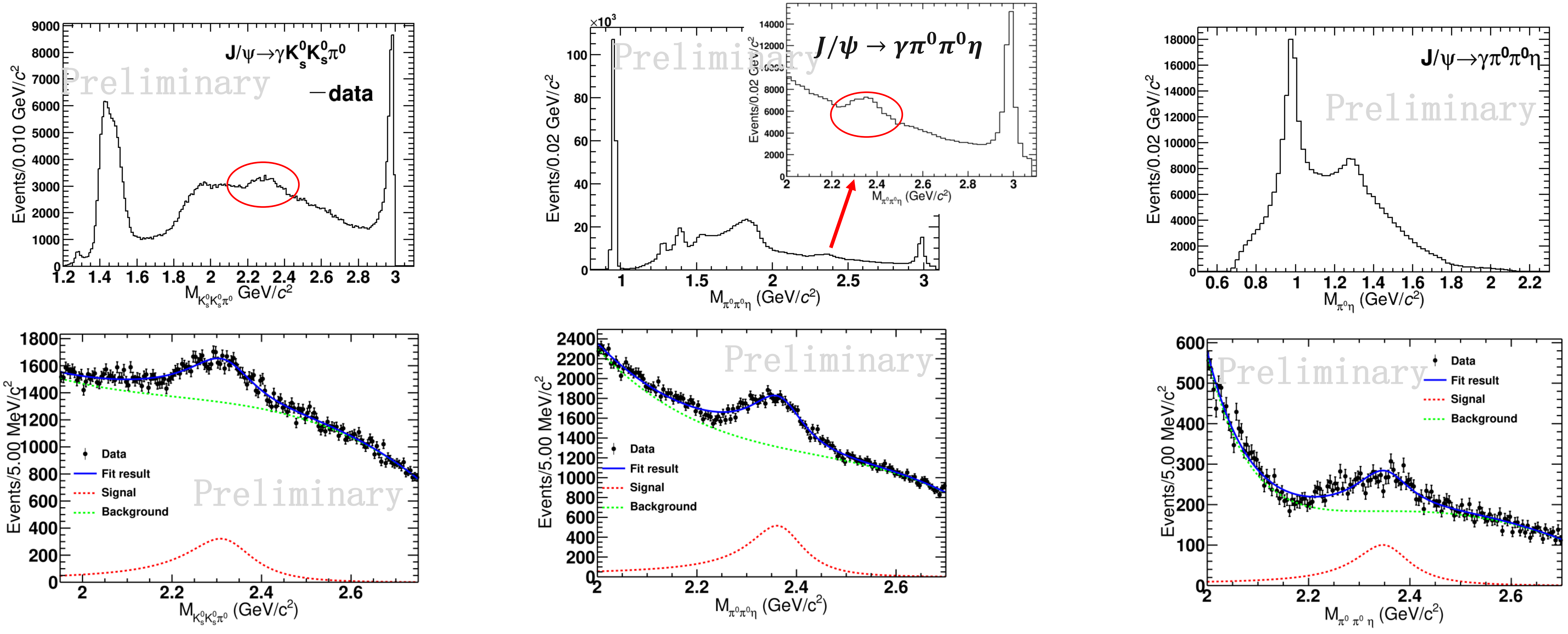
With 1.31×10^9 J/ψ events



PRL 115 (2015) 091803

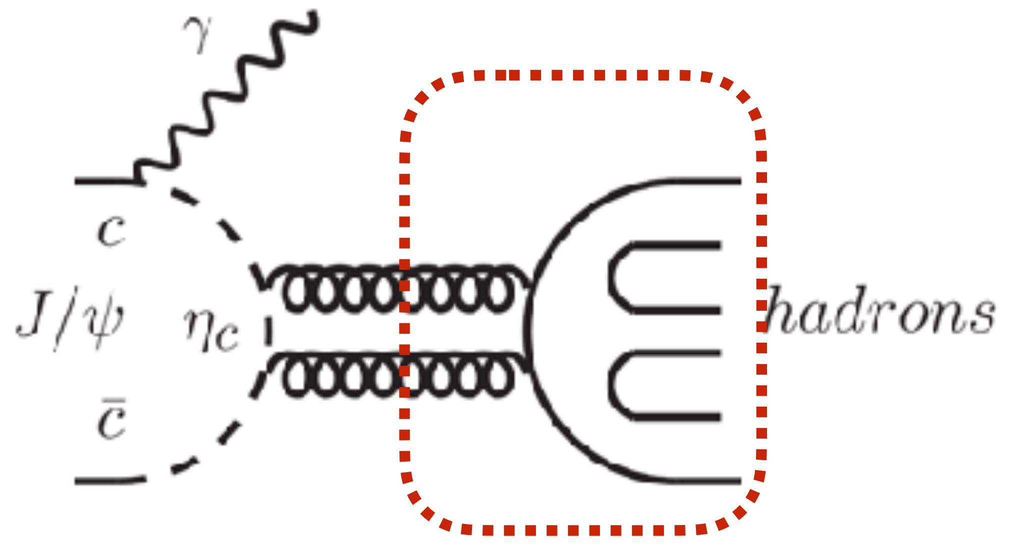
Such high similarity between the X(2370) and η_c decay modes

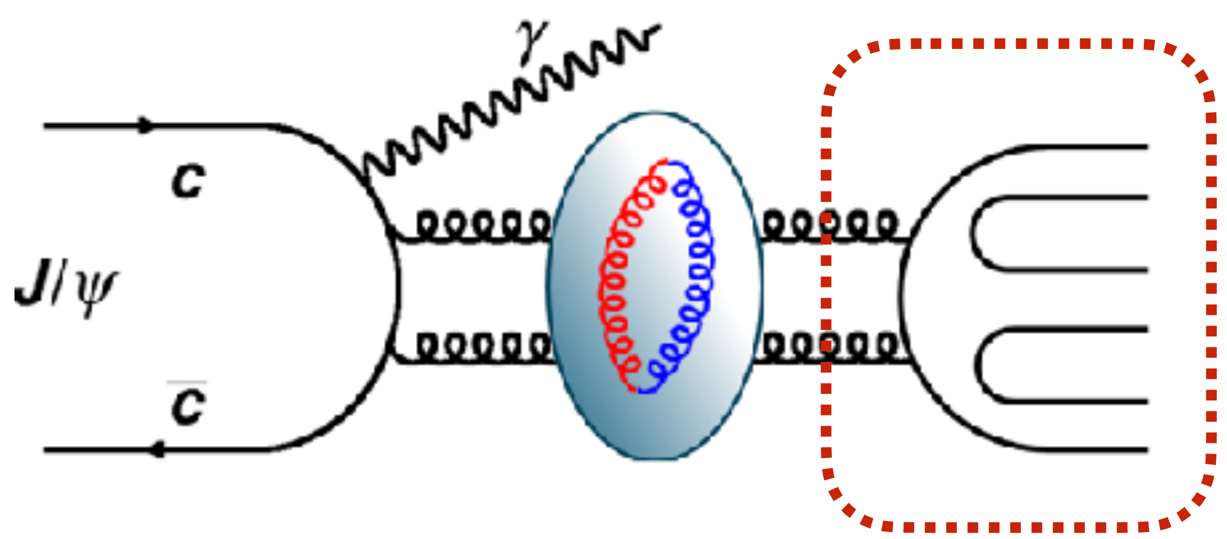
Observation of new decay modes of the X(2370)



First observation of $X(2370) \to K_s^0 K_s^0 \pi^0$, $X(2370) \to \pi^0 \pi^0 \eta$ and $X(2370) \to a(980)\pi$ with **significances >> 5σ and accompanied with η_c**

Observation of the X(2370) in the 5 golden decay modes





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

Decays involving hadronic resonances

Γ_1	$\eta'(958)\pi\pi$	(1.87±0.26) %
Γ_2	$\eta'(958)K\overline{K}$	(1.61±0.25) %

Decays into stable hadrons

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

- **The 0^{-+} glueball decays could be the analogy to η_c decays**
  - **Decay modes of X(2370)→$\pi\pi\eta'$,$K\bar{K}\eta'$,$K\bar{K}\pi$, $\pi\pi\eta$, $K\bar{K}\eta$, $a(980)\pi$ observed, consistent with 0^{-+} glueball**

Such high similarity between the X(2370) and η_c decay modes strongly supports the glueball interpretation of the X(2370)

Discussion on X(2370) decay properties

	X(2370)	η_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	
$f_0(1500)\eta$	√	√	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**
- Normal $q\bar{q}$ mesons, hybrids and multi-quark states can hardly explain all 5 decays modes ($\pi\pi\eta'$,$KK\eta'$,$\pi\pi\eta$,$KK\eta$,$KK\pi$) with different quark flavor combinations
- **The high similarities between X(2370) and η_c decay modes strongly suggest it decays via gluons**
- **Narrow Decay Partial Widths of X(2370)**: **X(2370) decays should be OZI suppressed decays as η_c, i.e. via gluons**
  - Naive estimation on the BR of each mode ~5-10%, i.e., partial width of each decay mode is ~10MeV
  - This would be very hard to explained if there were quark content in X(2370) for OZI allowed decays

Discussion on X(2370) Production Properties

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

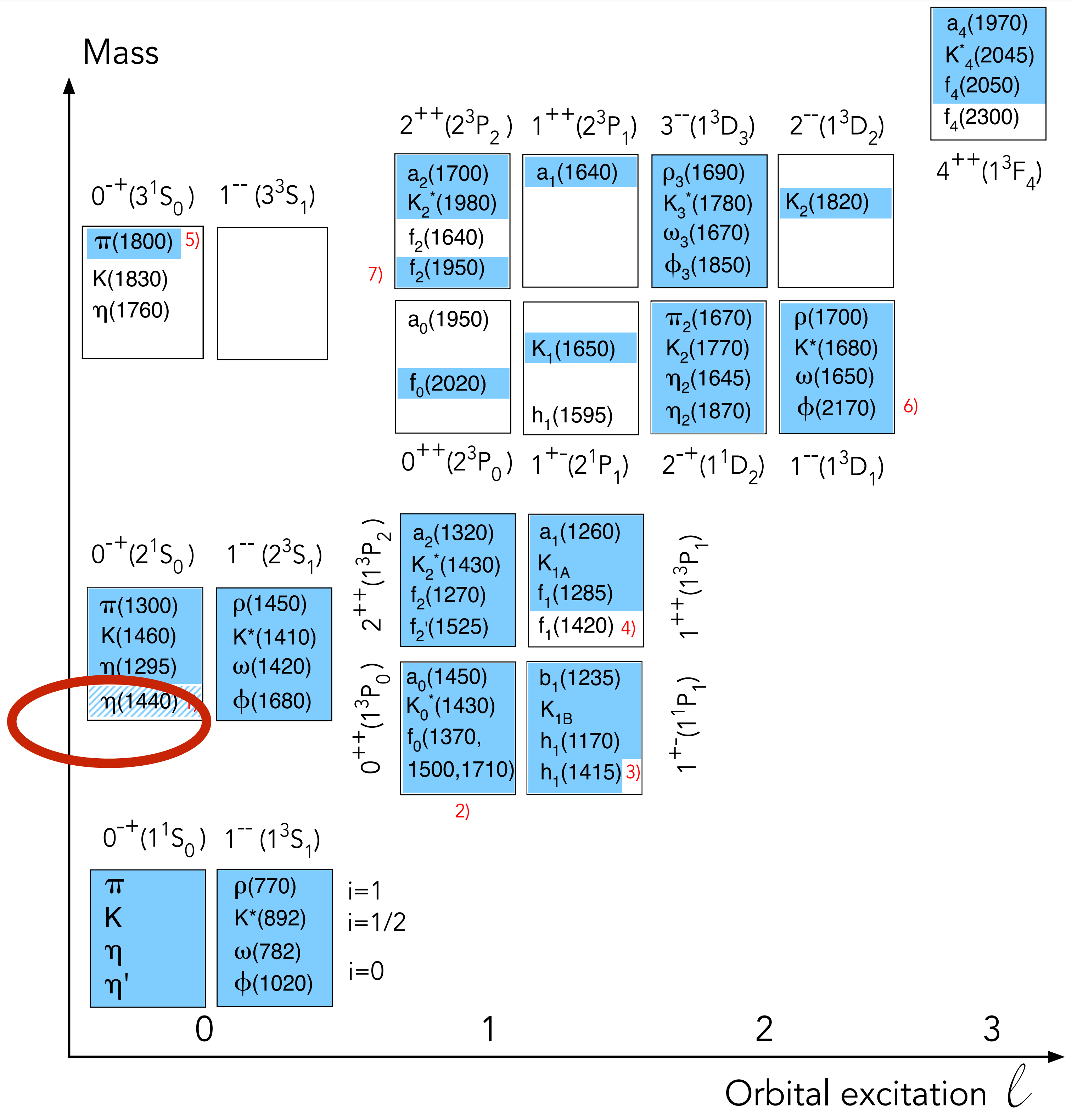
- In the above 2.3GeV mass region as LQCD 0^{-+} glueball prediction:

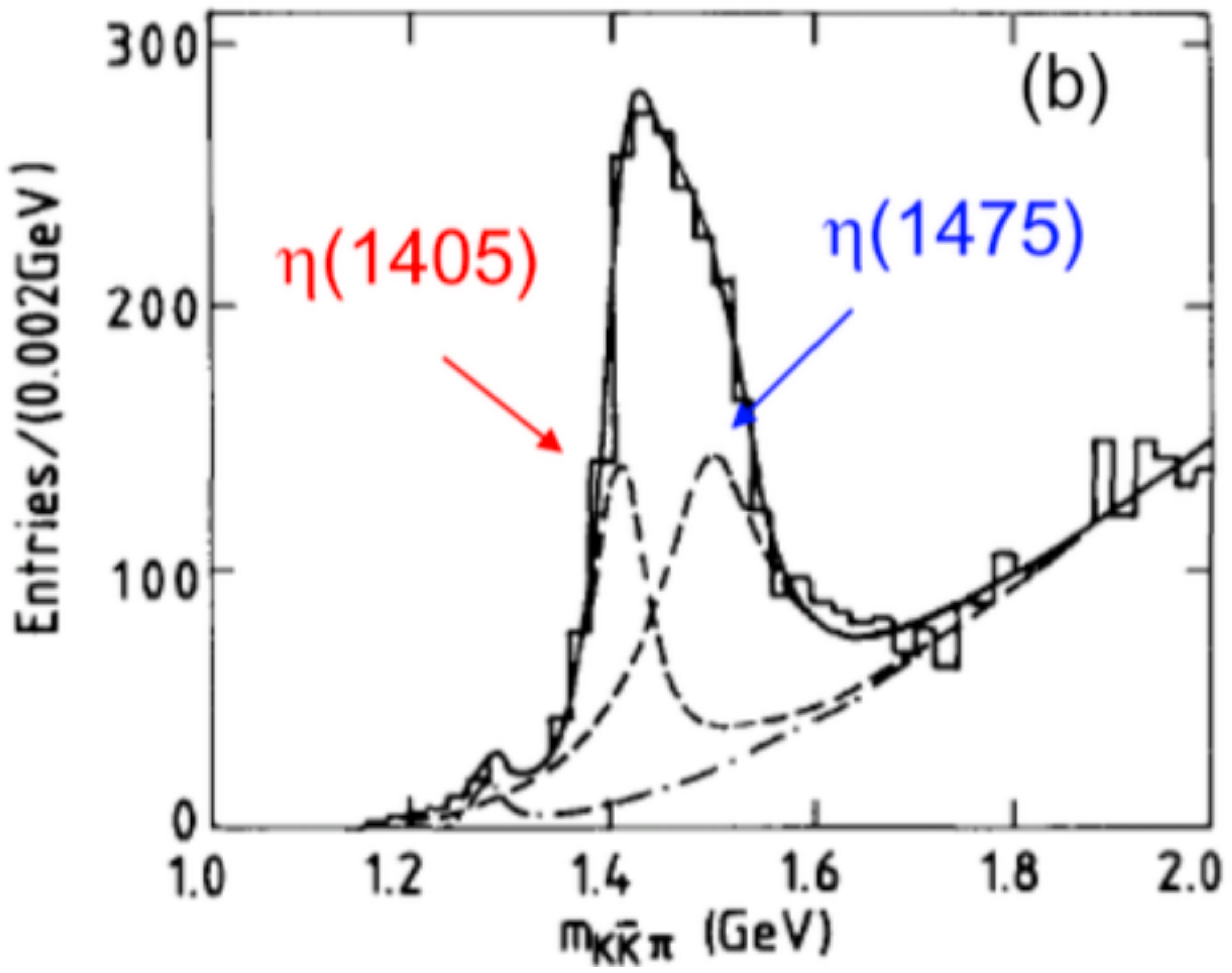
  - The X(2370) is the **unique** 0^{-+} particle produced in these **“5 golden modes”** and in J/ψ **radiative decays**, i.e., no other 0^{-+} particles in this mass region can be called as “richly produced” if they have not shown up **in 10 billion such a huge J/ψ data sample**.

- We are facing a situation: Either we finally identify X(2370) as 0^{-+} glueball, or LQCD may face a big challenge in the glueball predictions

➡ Similar to the situation before the Higgs Boson discovery

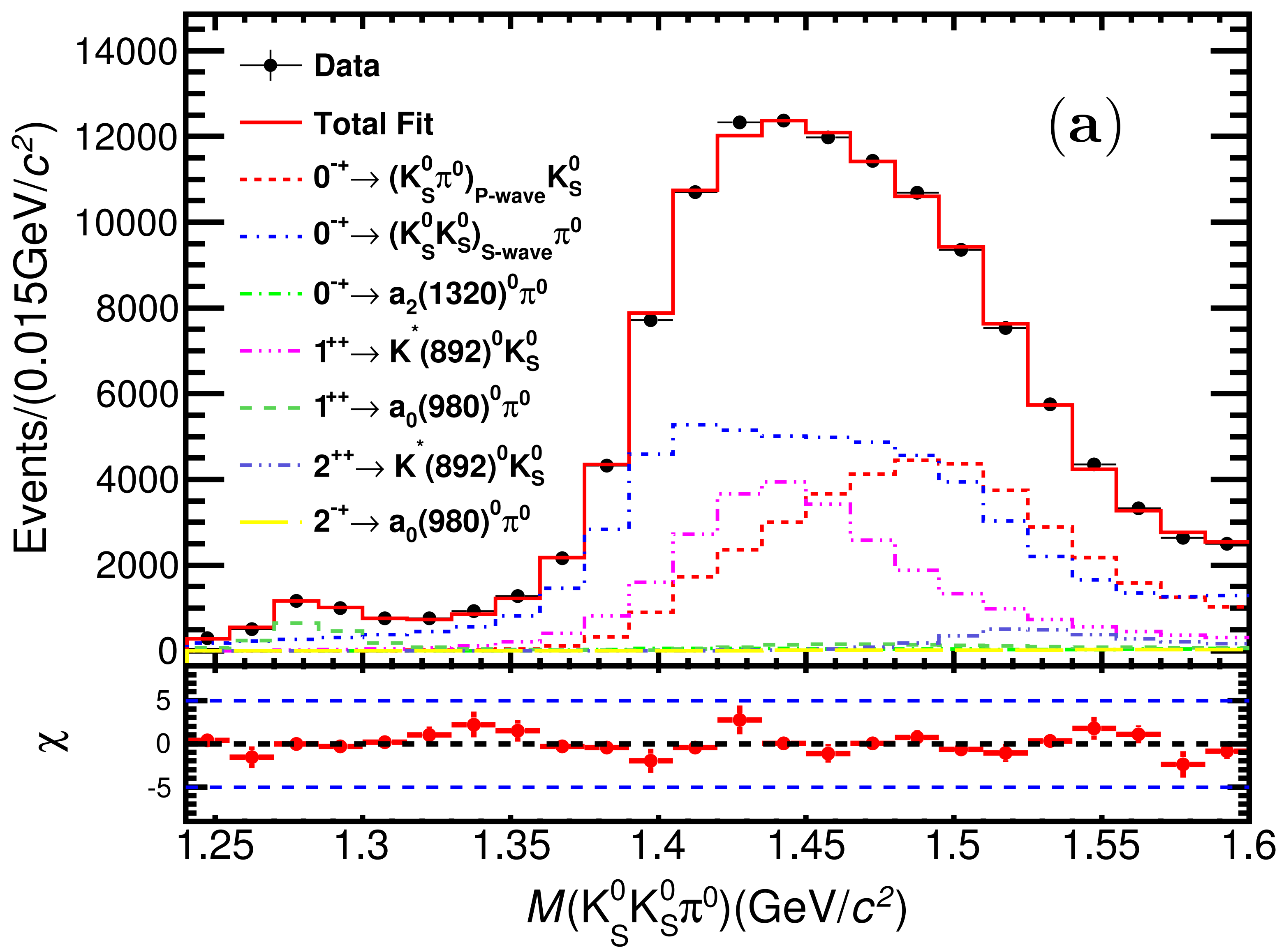
E-ι puzzle



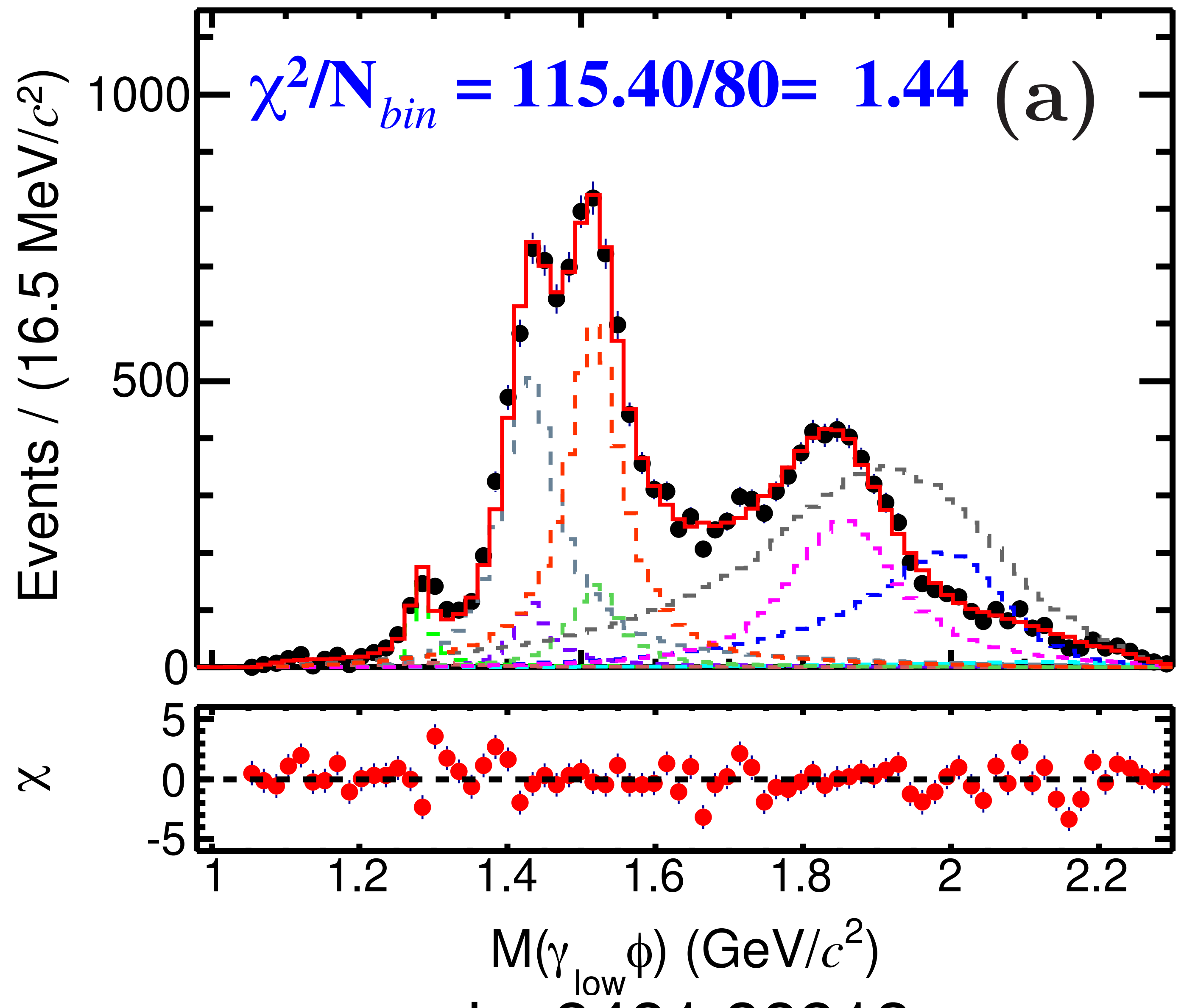


- An isoscalar state, η(1440) as a glueball candidate
- η(1295) and η(1440) are generally assigned to be the first radial excitation of the ground states of η and η’
- Two isoscalars observed in the mass region
  - η(1405) mainly into a_0(980) π. , η(1475) mainly into K*(892)K

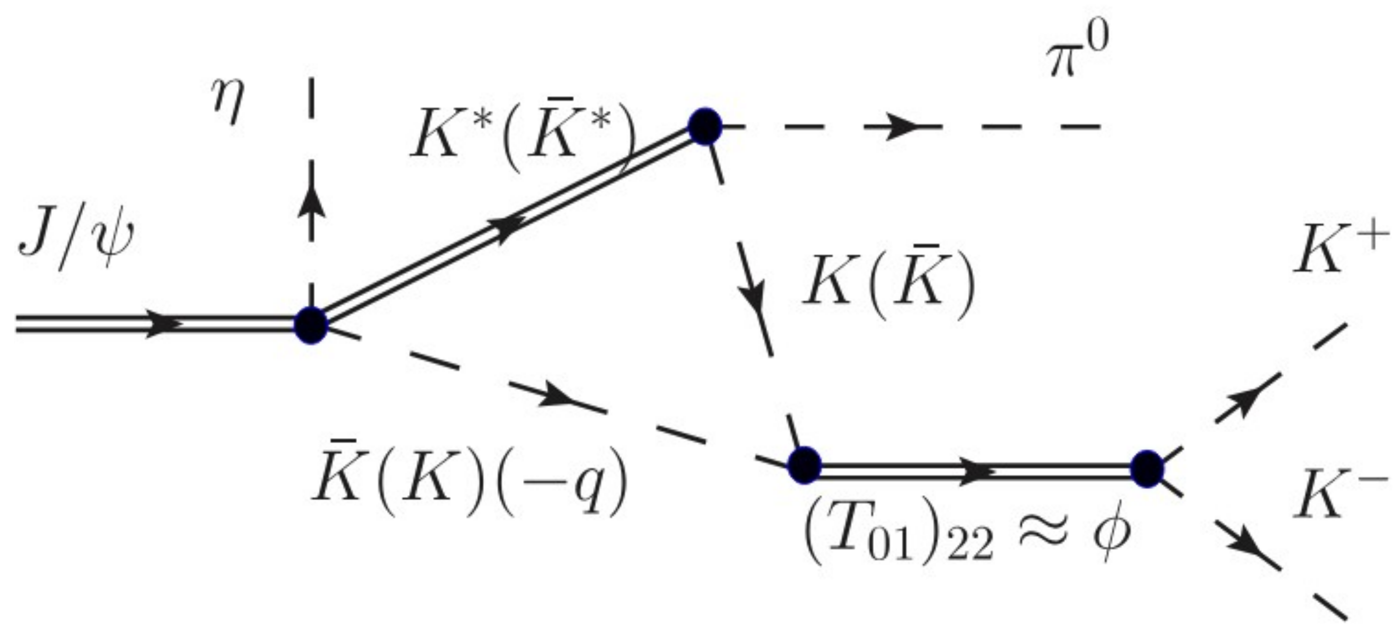
Shed new lights on $\eta(1405)/\eta(1475)$ puzzle



JHEP 03 (2023) 121



arxiv: 2401.00918



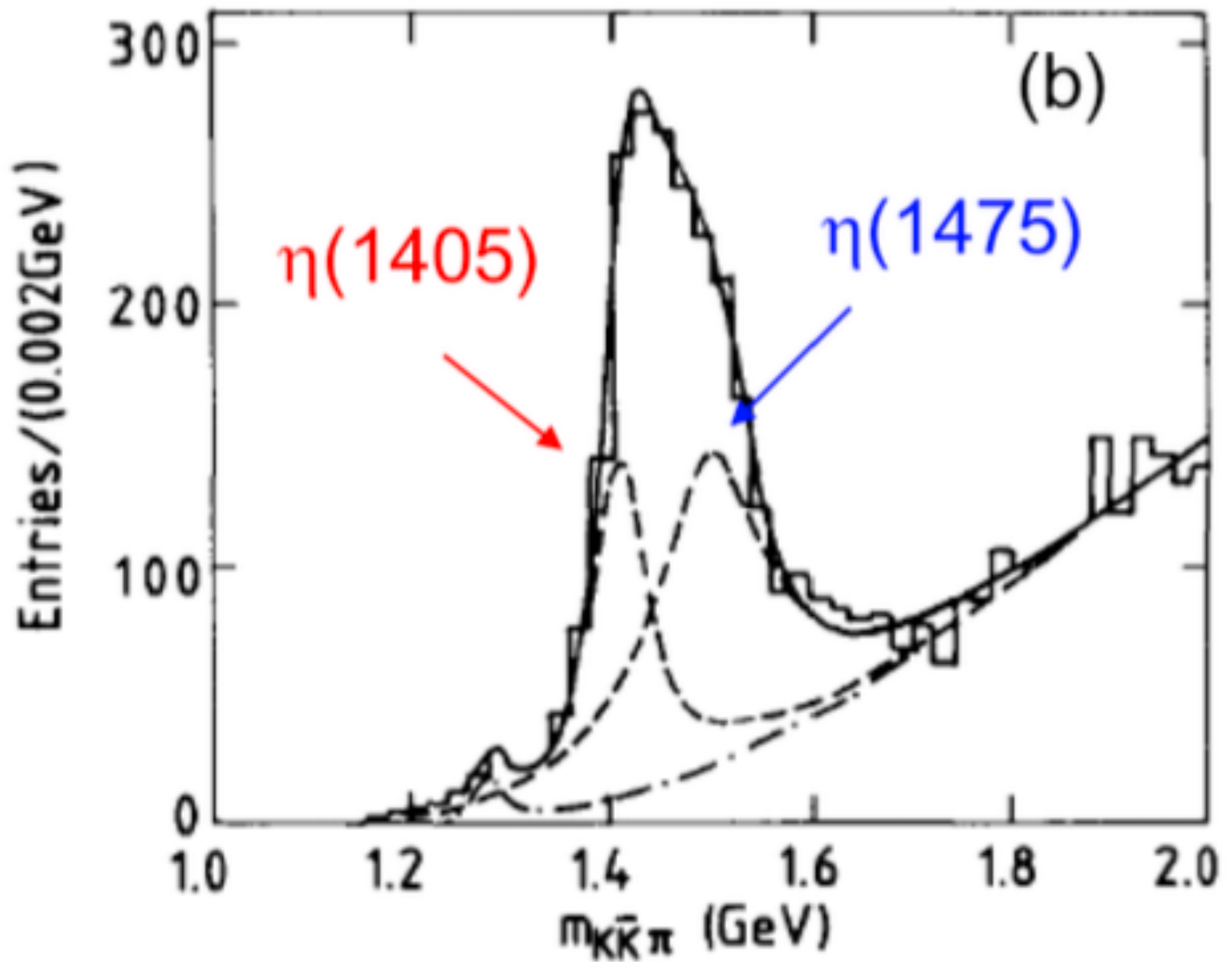
Triangle singularity?

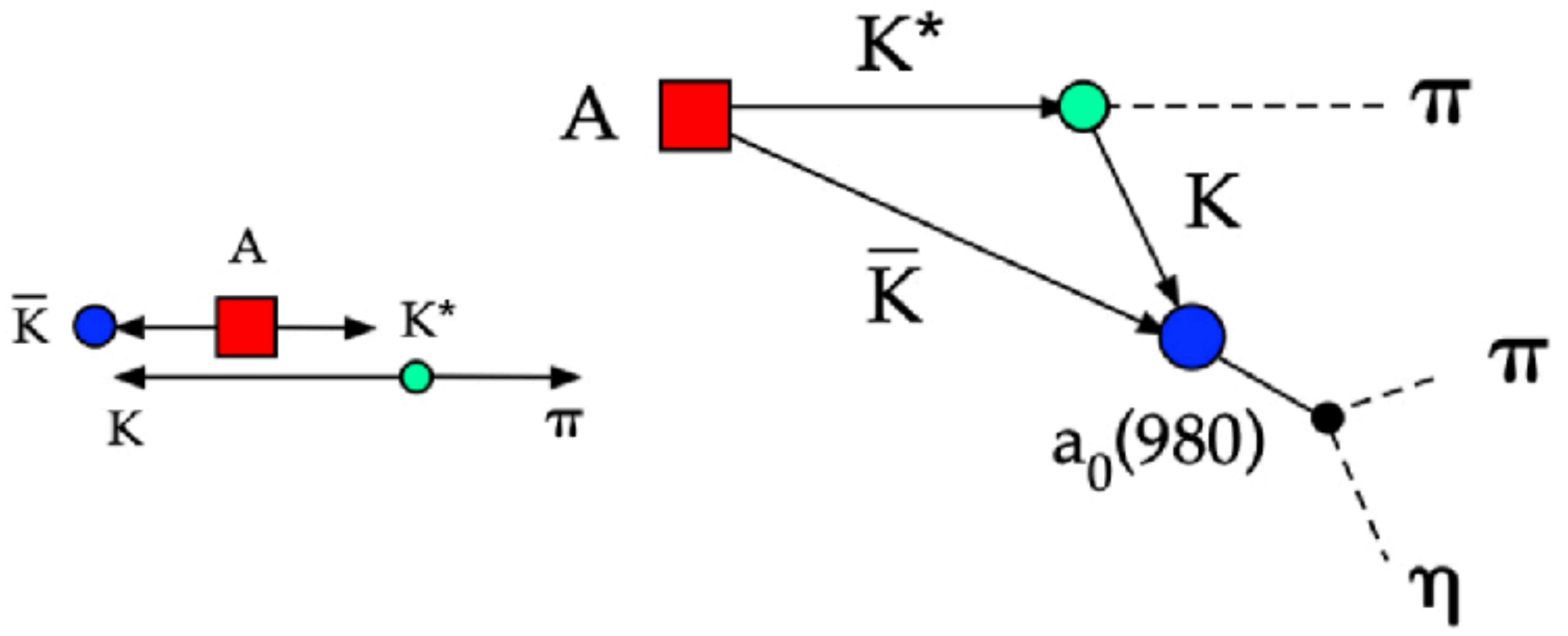
- PWA of J/ψ→γKsKsπ⁰: Two isoscalar states η(1405) and η(1475) around 1.4GeV can well fit data

- PWA of J/ψ→γγΦ: observed η(1405) with 18.9σ, while η(1475) can not be excluded (3.9σ)

- **η(1405) - η(1475) puzzle : whether or not the η(1405) - η(1475) are 1 or 2 states?**

Some thoughts on η(1440)



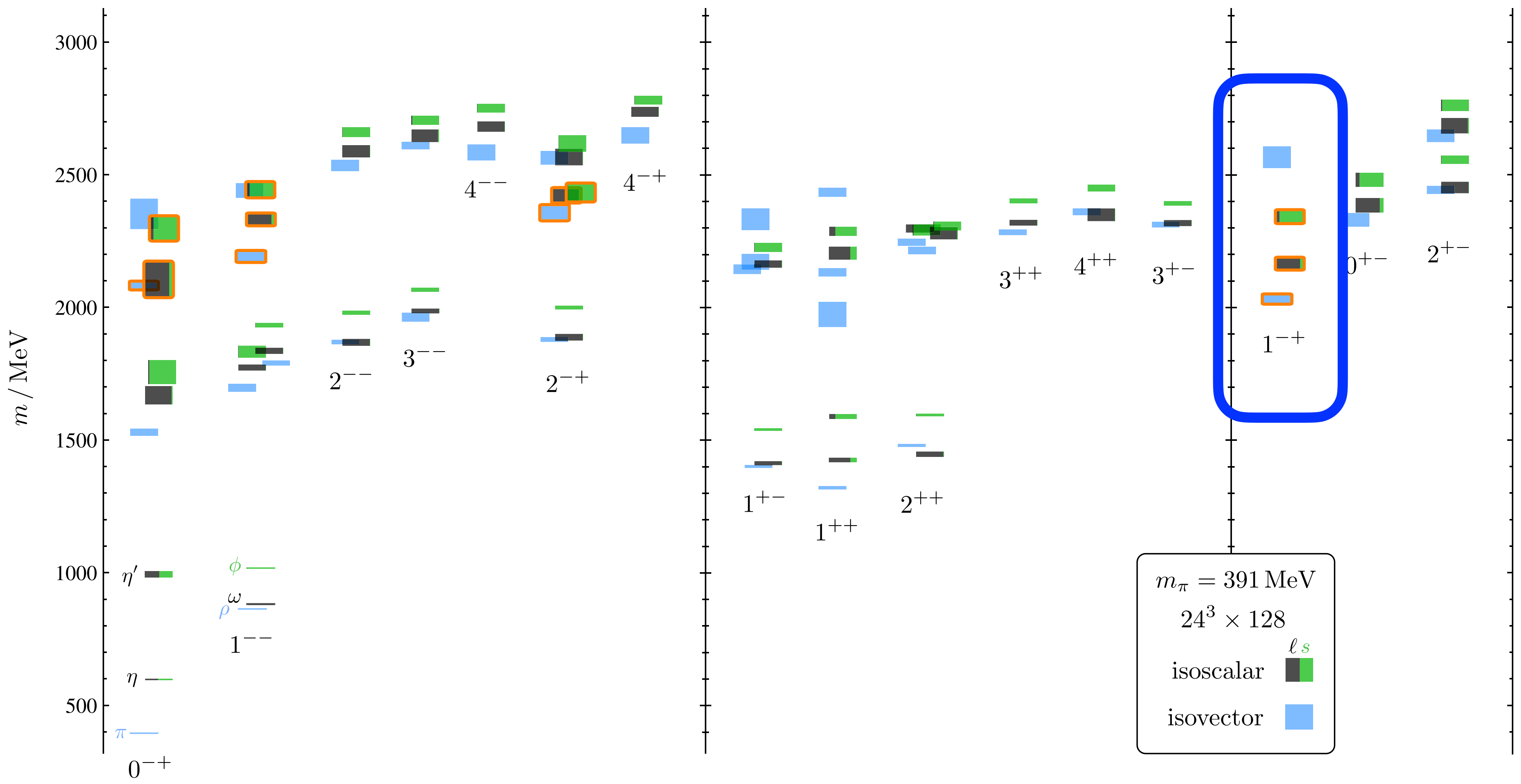


◈ The broad structure ~1.4GeV: η(1405) and η(1475) / Triangle singularity

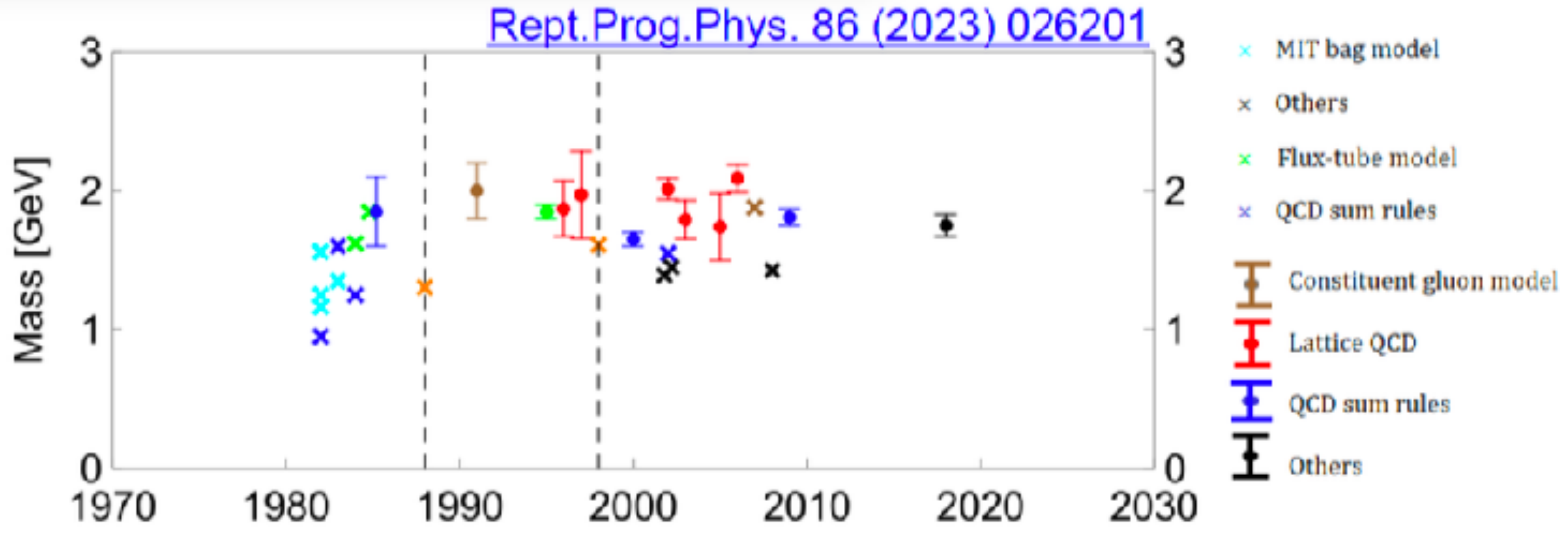
- ✦ Probe the quark constitute and triangle singularity effect via ω/ϕ associated production
- ✦ Probe the triangle singularity via the ratio between $a_0(980)$ and $f_0(980)$
  - ✦ Need to check the complexity of $\pi^+\pi^-\pi^0$ decay mode
  - ✦ Need to expected ratio: measurement and prediction

Exotic 1^{-+} state

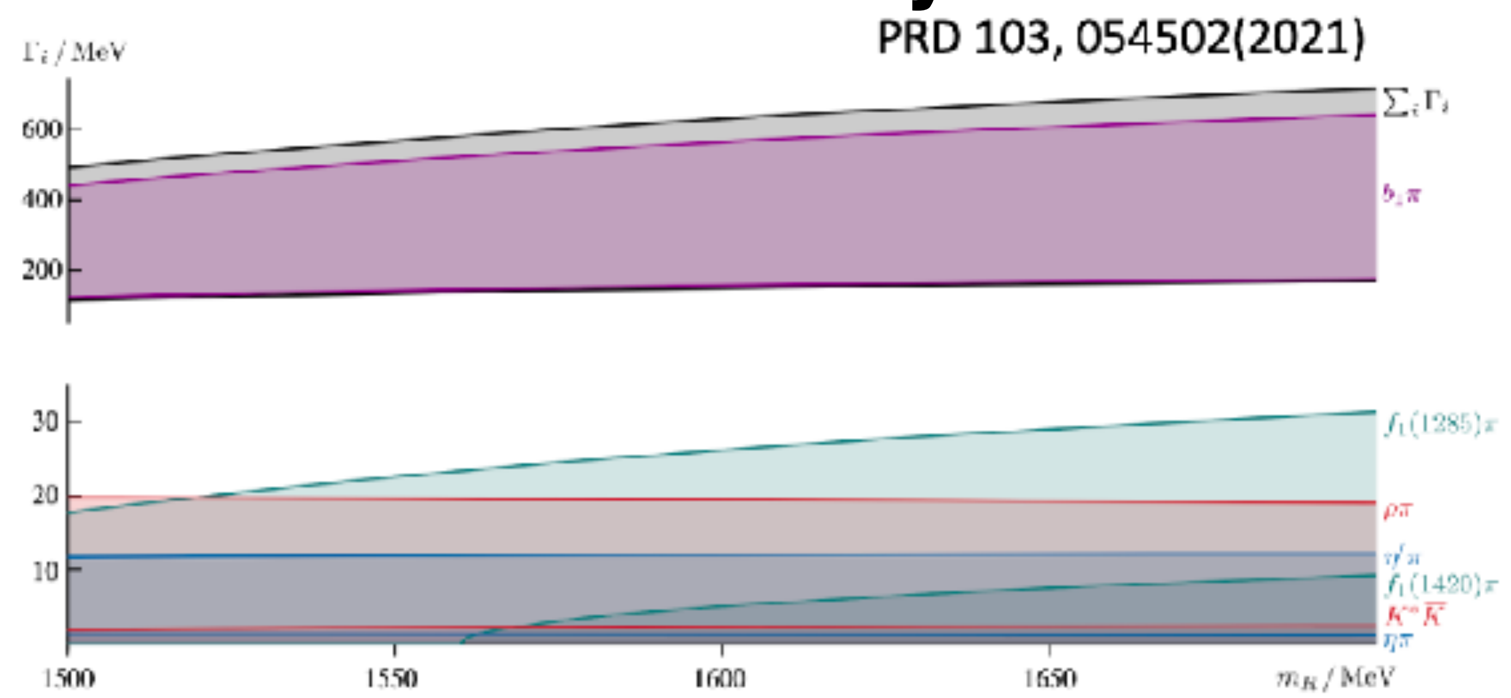
J^{PC}	$q\bar{q}$
0^{++}	yes
0^{+-}	–
0^{-+}	yes
0^{--}	–
1^{++}	yes
1^{+-}	yes
1^{-+}	–
1^{--}	yes
2^{++}	yes
2^{+-}	–
2^{-+}	yes
2^{--}	yes
3^{++}	yes
3^{+-}	yes
3^{-+}	–
3^{--}	yes



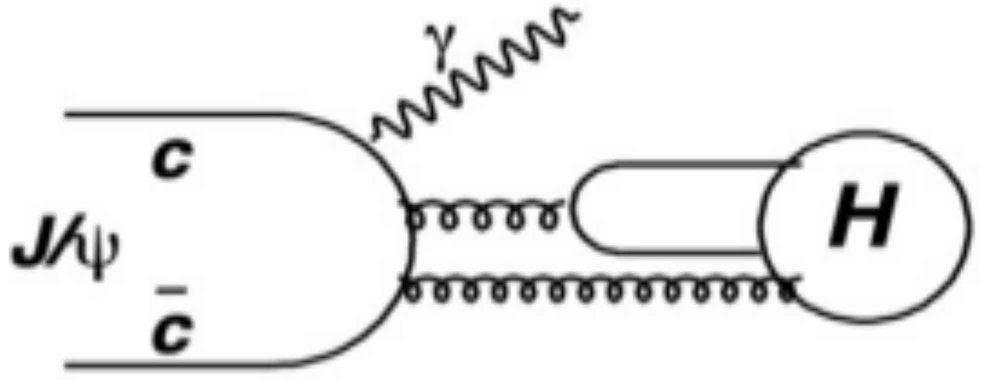
PRD 88 094505(2013)



Mass of 1^{-+} hybrid



Width of 1^{-+} hybrid

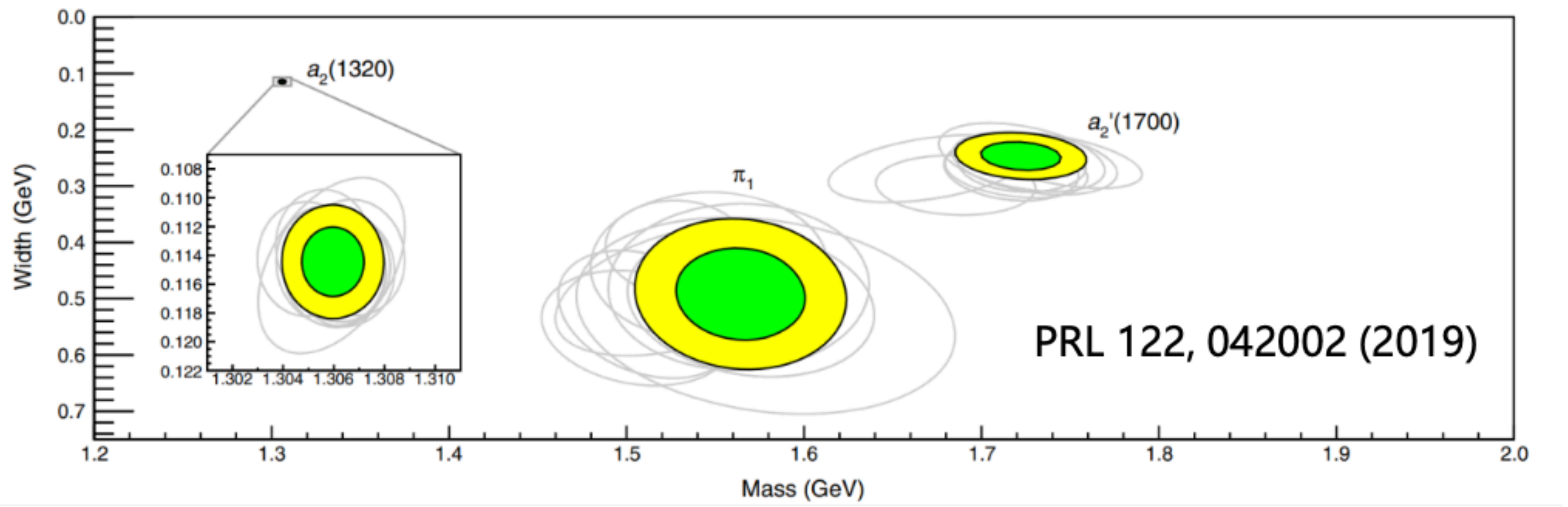


$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$

- **Spin-exotic state of 1^{-+} :** forbidden in conventional quark model
- Exotic state **1^{-+} provide an unique way for hybrid search:**
- LQCD predicts the **lightest nonet of 1^{-+} hybrids**: 1.7 - 2.1GeV
  - **Can be produced in the gluon-rich charmonium decays**

Spin-exotic mesons

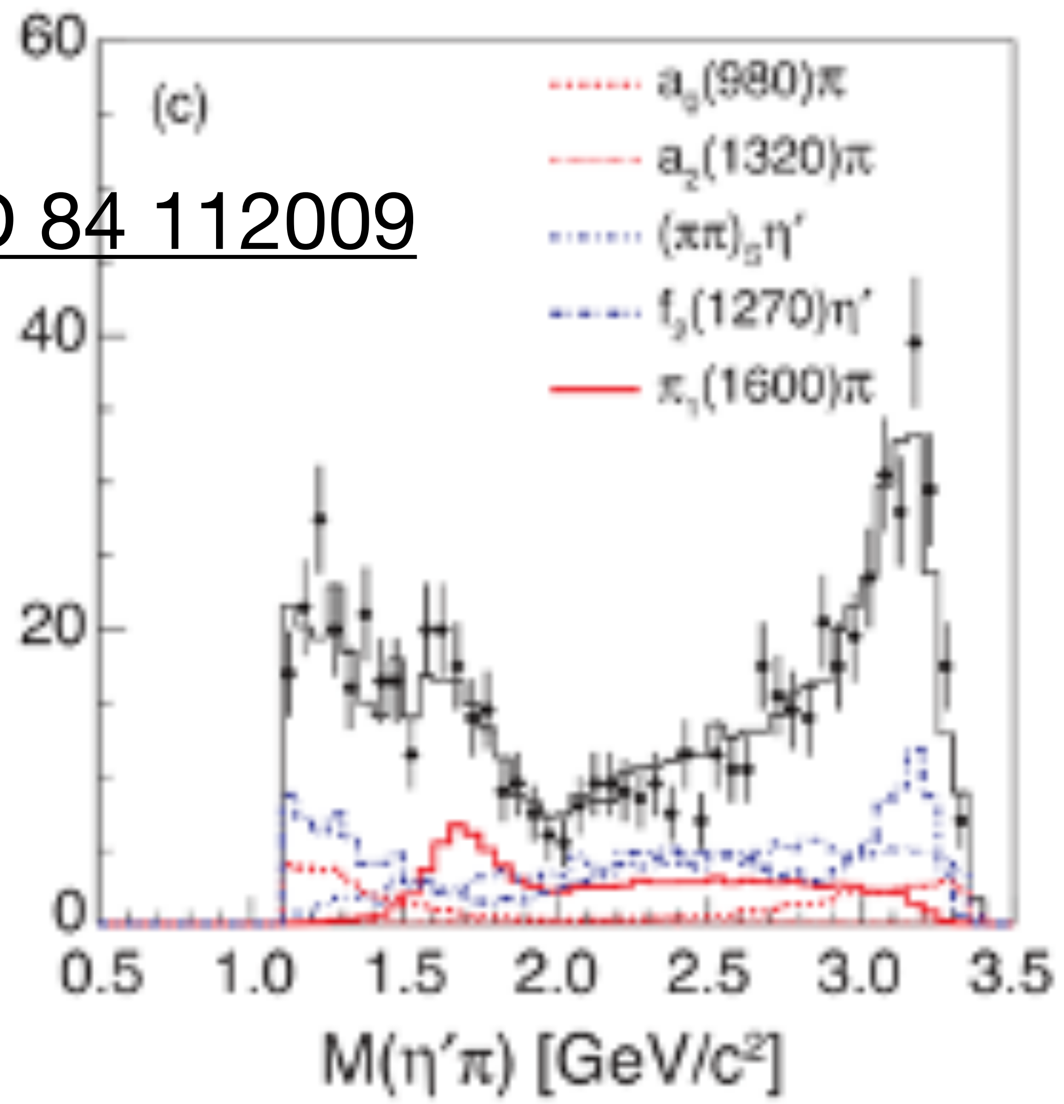
- Over 3 decades, experimental evidence for 3 candidates with 1^{-+} state:
  - All 1^{-+} iso-vectors
  - $\pi_1(1400)$: seen in $\eta\pi$
  - $\pi_1(1600)$: seen in $\rho\pi$, $\eta'\pi$, $b_1\pi$, $f_1\pi$
  - $\pi_1(2015)$: seen in $b_1\pi$ and $f_1\pi$
- Some claims are controversial
- $\pi_1(1400)$ and $\pi_1(1600)$ can be one pole

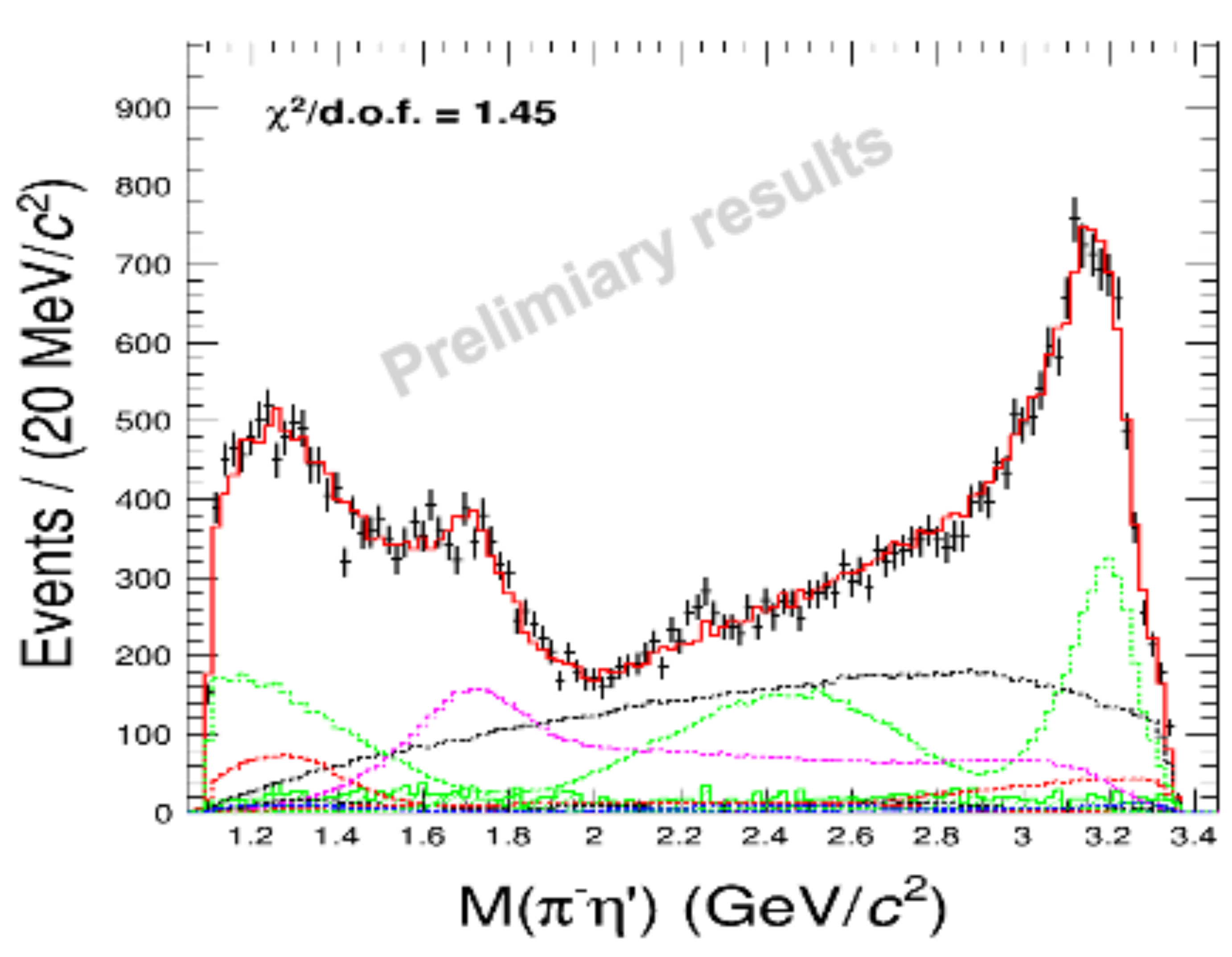


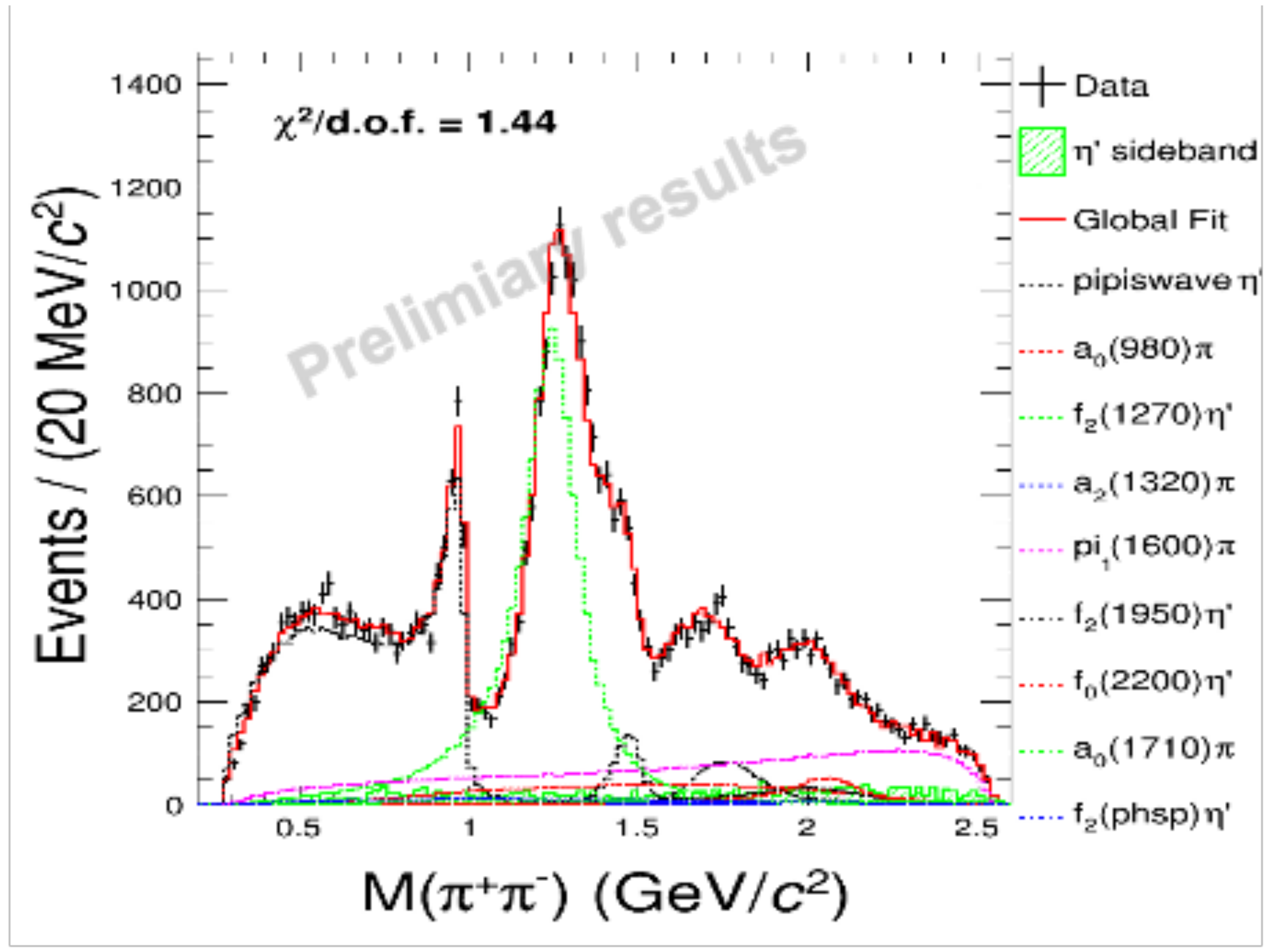
	Decay mode	Reaction	Experiment
$\pi_1(1400)$	$\eta\pi$	$\pi^-p\to\pi^-\eta p$ $\pi^-p\to\pi^0\eta n$ $\pi^-p\to\pi^-\eta p$ $\pi^-p\to\pi^0\eta n$ $\bar{p}n\to\pi^-\pi^0\eta$ $\bar{p}p\to\pi^0\pi^0\eta$	GAMS KEK E852 E852 CBAR CBAR
	$\rho\pi$	$\bar{p}p\to 2\pi^+2\pi^-$	Obelix
$\pi_1(1600)$	$\eta'\pi$	$\pi^-Be\to\eta'\pi^-\pi^0Be$ $\pi^-p\to\pi^-\eta'p$	VES E852
	$b_1\pi$	$\pi^-Be\to\omega\pi^-\pi^0Be$ $\bar{p}p\to\omega\pi^+\pi^-\pi^0$ $\pi^-p\to\omega\pi^-\pi^0p$	VES CBAR E852
	$\rho\pi$	$\pi^-Pb\to\pi^+\pi^-\pi^-X$ $\pi^-p\to\pi^+\pi^-\pi^-p$	COMPASS E852
	$f_1\pi$	$\pi^-p\to p\eta\pi^+\pi^-\pi^-$ $\pi^-A\to\eta\pi^+\pi^-\pi^-A$	E852 VES
$\pi_1(2015)$	$f_1\pi$	$\pi^-p\to\omega\pi^-\pi^0p$	E852
	$b_1\pi$	$\pi^-p\to p\eta\pi^+\pi^-\pi^-$	

Observation of Exotic 1-+ Isovector state $\pi(1600)$

PRD 84 112009



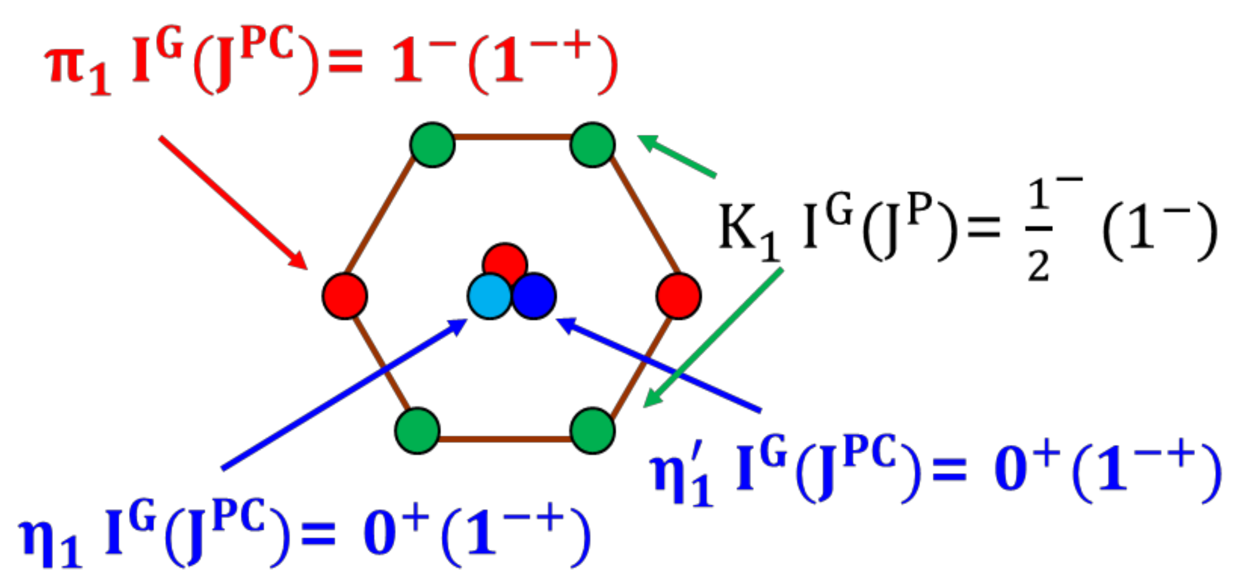


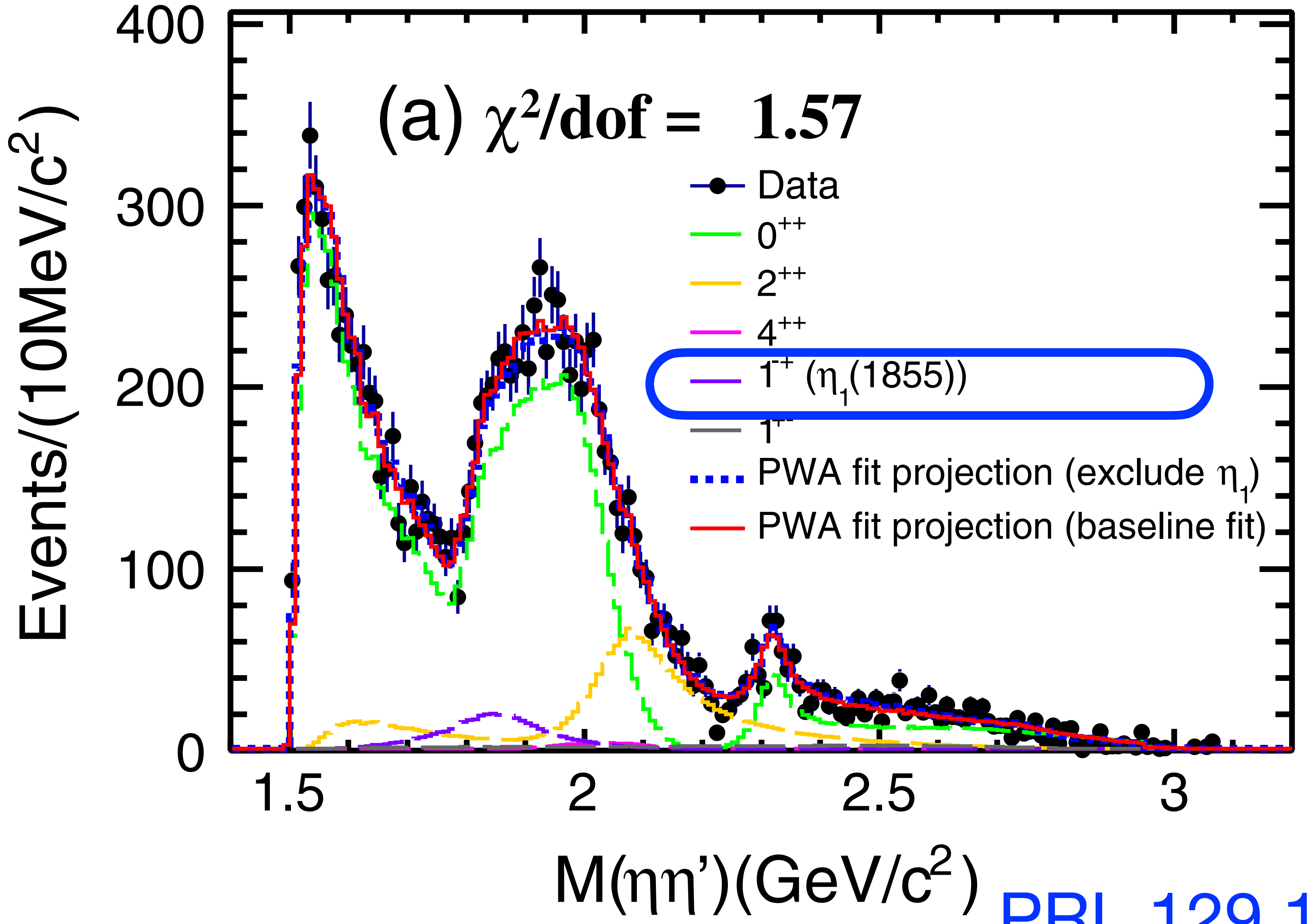


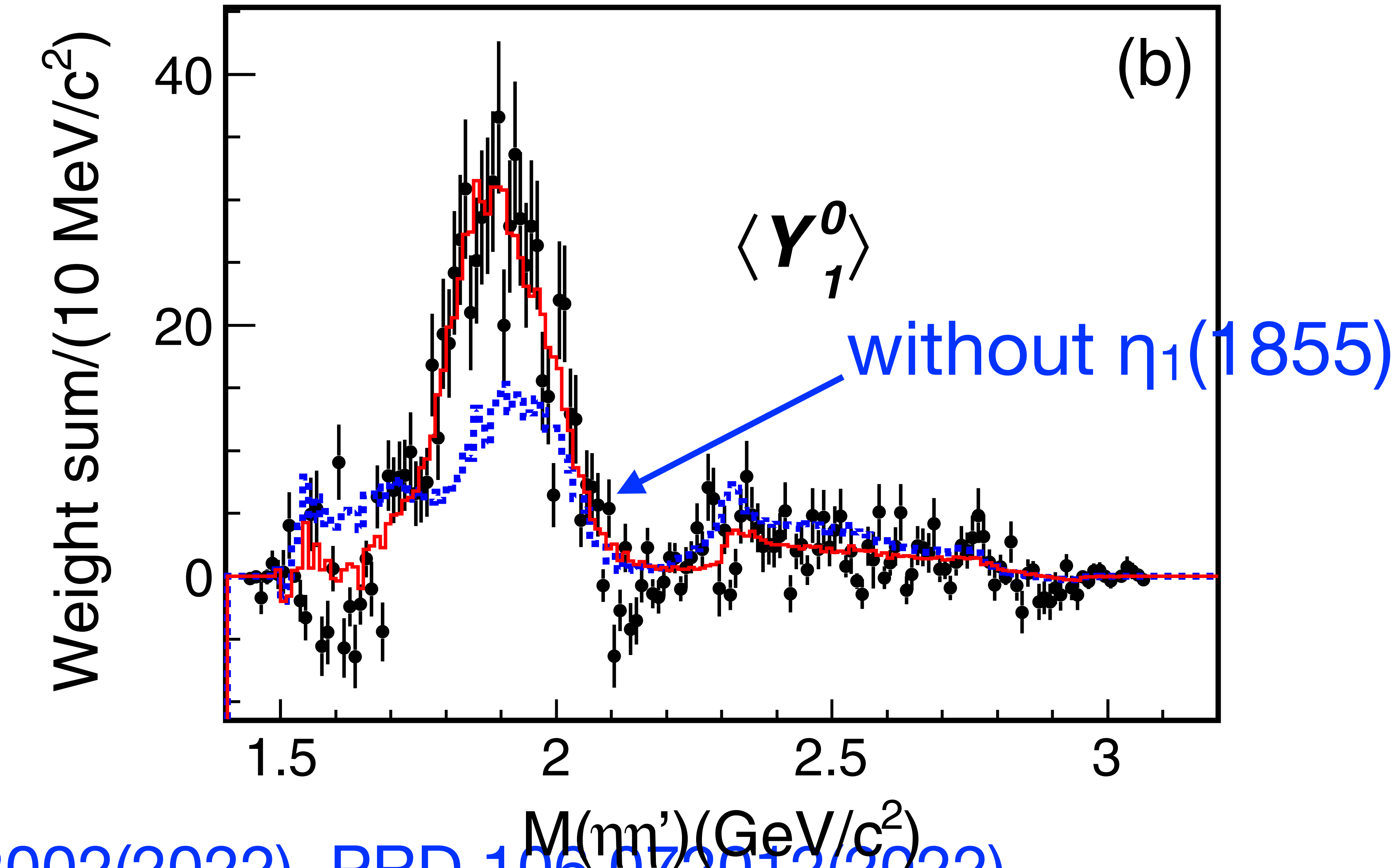
- CLEO-c results: evidence of an exotic P-wave $\eta'\pi$ amplitude with 4σ and but no significant phase motion
- PWA in $\psi' \to \gamma\chi_{c1}(\chi_{c1} \to \pi^+\pi^-\eta')$ with higher ψ' data sample @ BESIII:
  - **First observation of Exotic 1-+ Isovector state $\pi(1600)$ with a significance >10σ better than other J^{PC} assumption**
  - **The significance of phase motion is also greater than 10σ**

Observation of An Exotic 1^{-+} Isoscalar $\eta_1(1855)$

Isoscalar (1^{-+}) is critical to establish the nonet hybrid multiplet: partners for the Isovector (1^{-+})





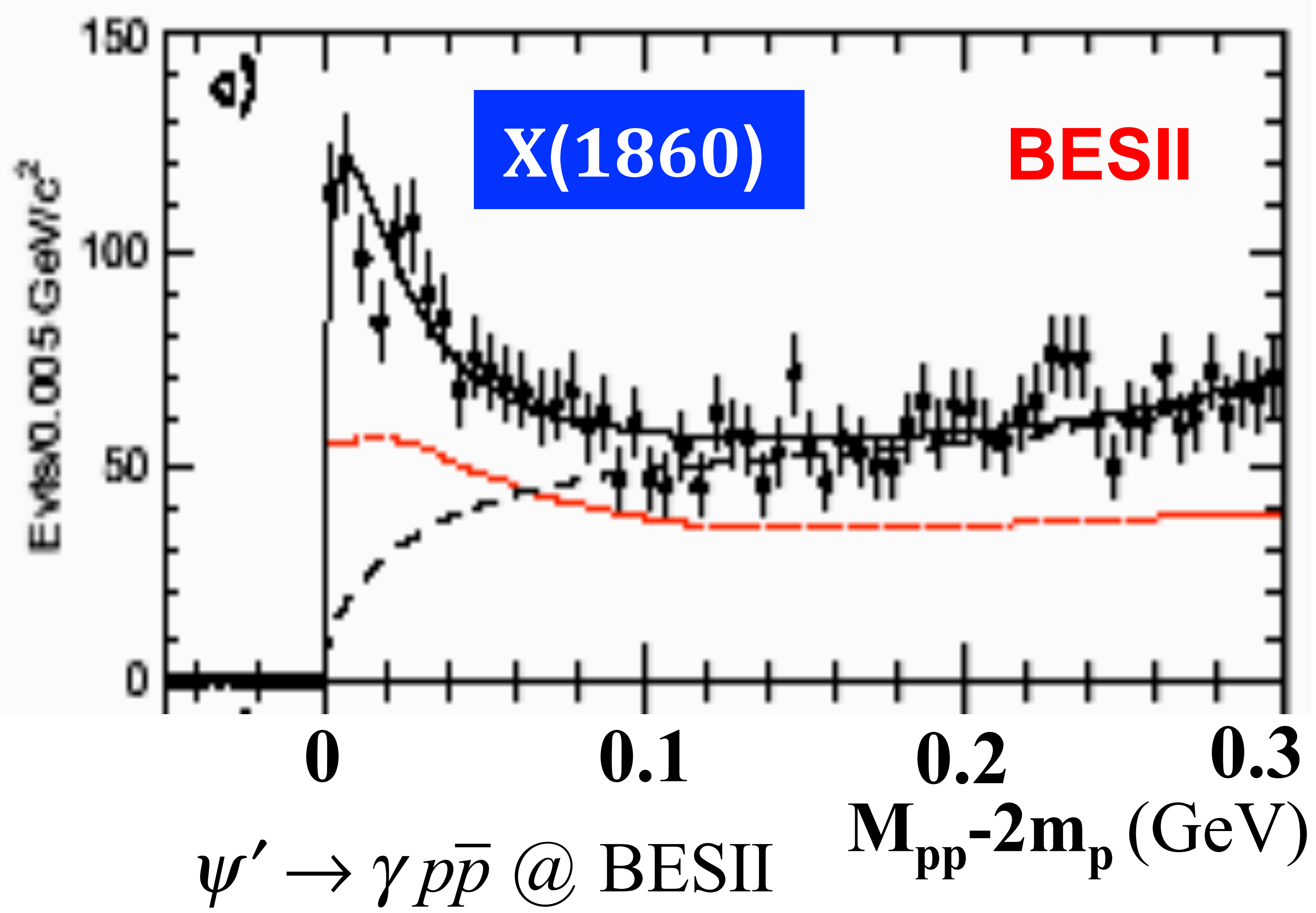


PRL 129 192002(2022), PRD 106 072012(2022)

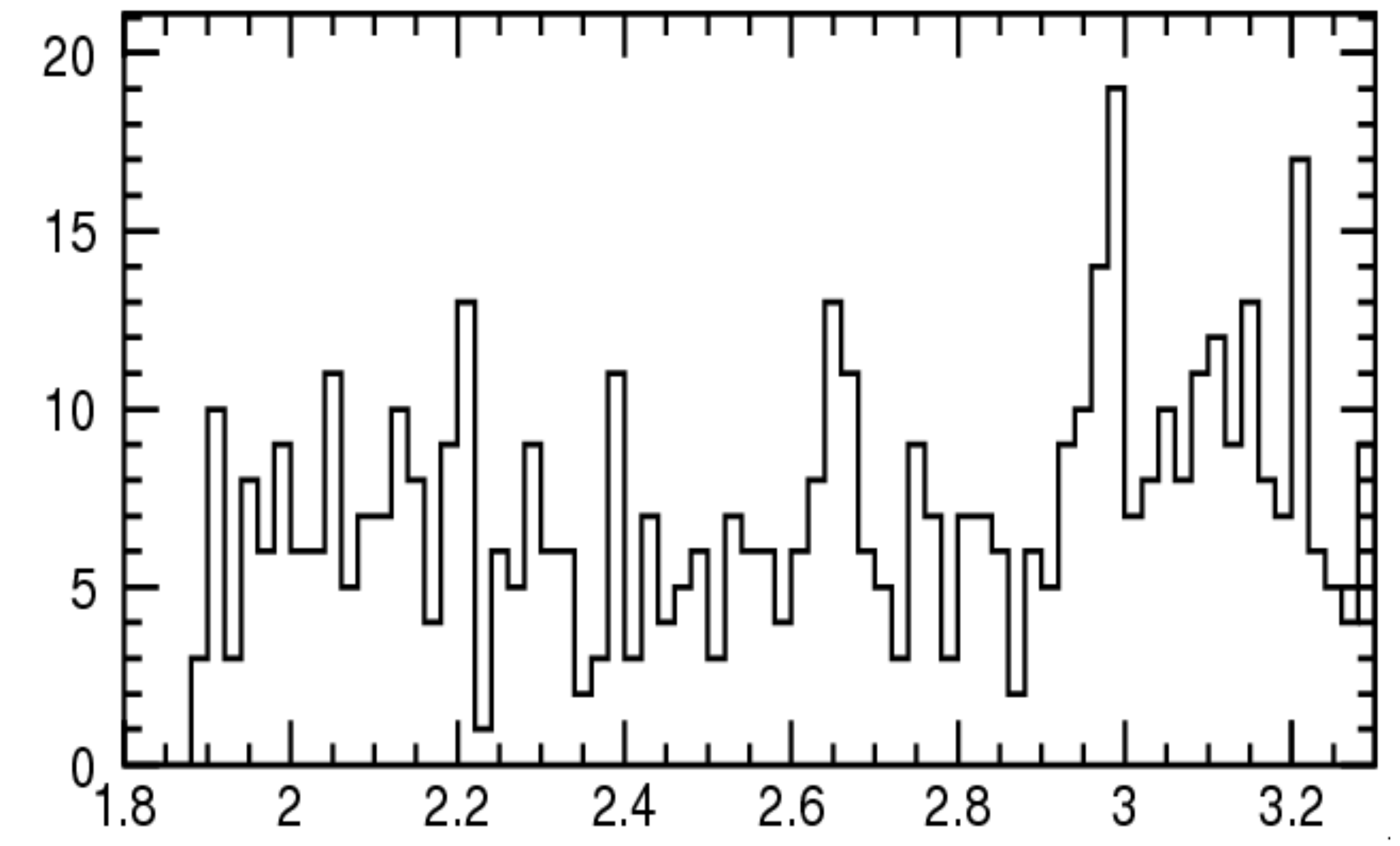
- **J/ψ→γηη' is a good channel for $\eta_1(1^{-+})$ search**
- **Observation of an isoscalar 1^{-+} $\eta_1(1855)$ in J/ψ→γηη' (>19σ)**
  - PWA: quasi two-body decay amplitudes in the sequential decay processes with covariant tensor formalism
  - $M= 1855\pm9^{+6}_{-1}$ MeV, $\Gamma=188\pm18^{+3}_{-8}$ MeV, $B(J/\psi\to\gamma\eta_1(1855)\to\gamma\eta\eta')=(2.70\pm0.41^{+0.16}_{-0.35})\times10^{-6}$
- **Mass consistent with hybrid on LQCD, and more interpretations** (KK Molecule/Tetraquark)

Observation of M_{ppb} threshold enhancement — X(ppb)

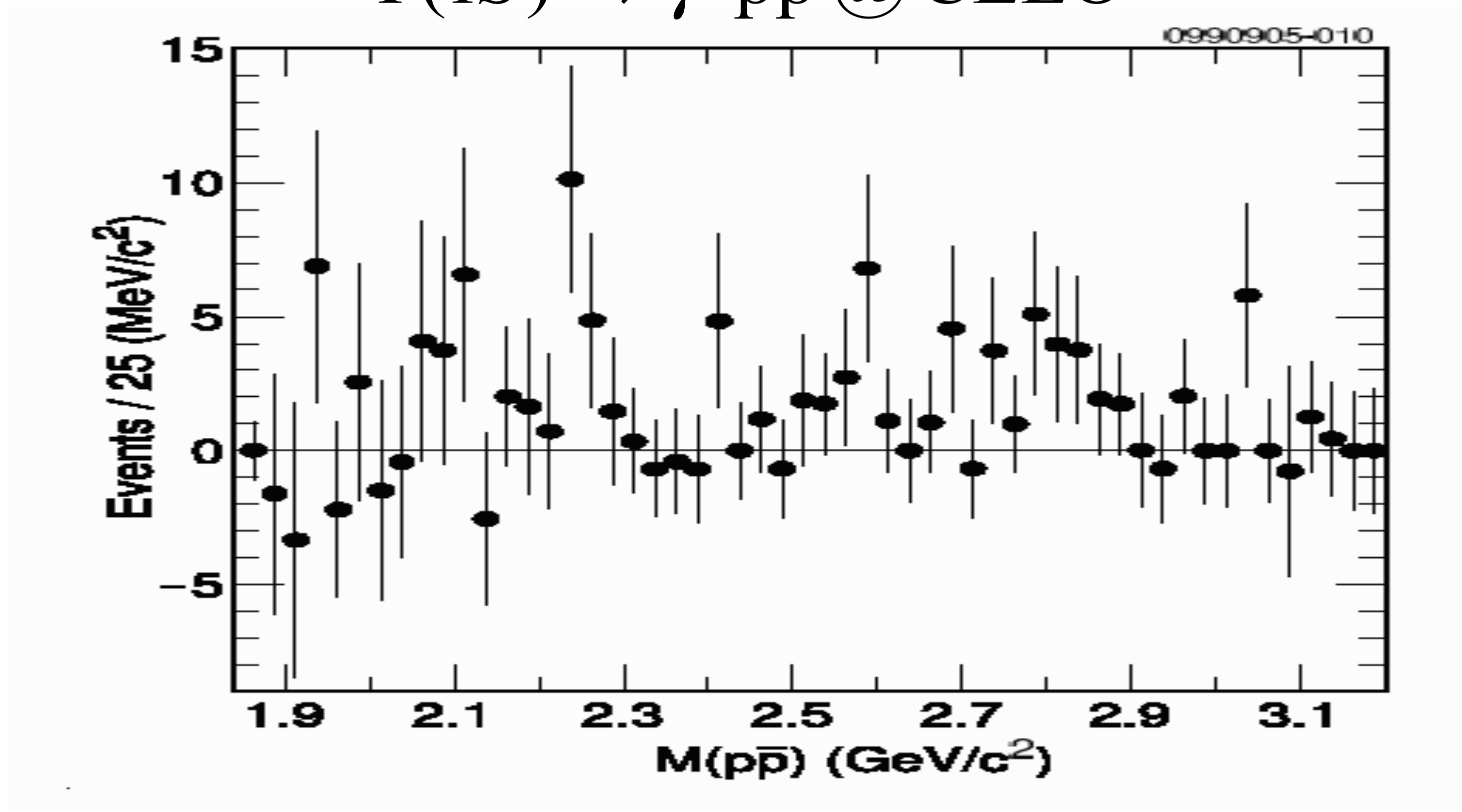
$J/\psi \to \gamma p\bar{p}$



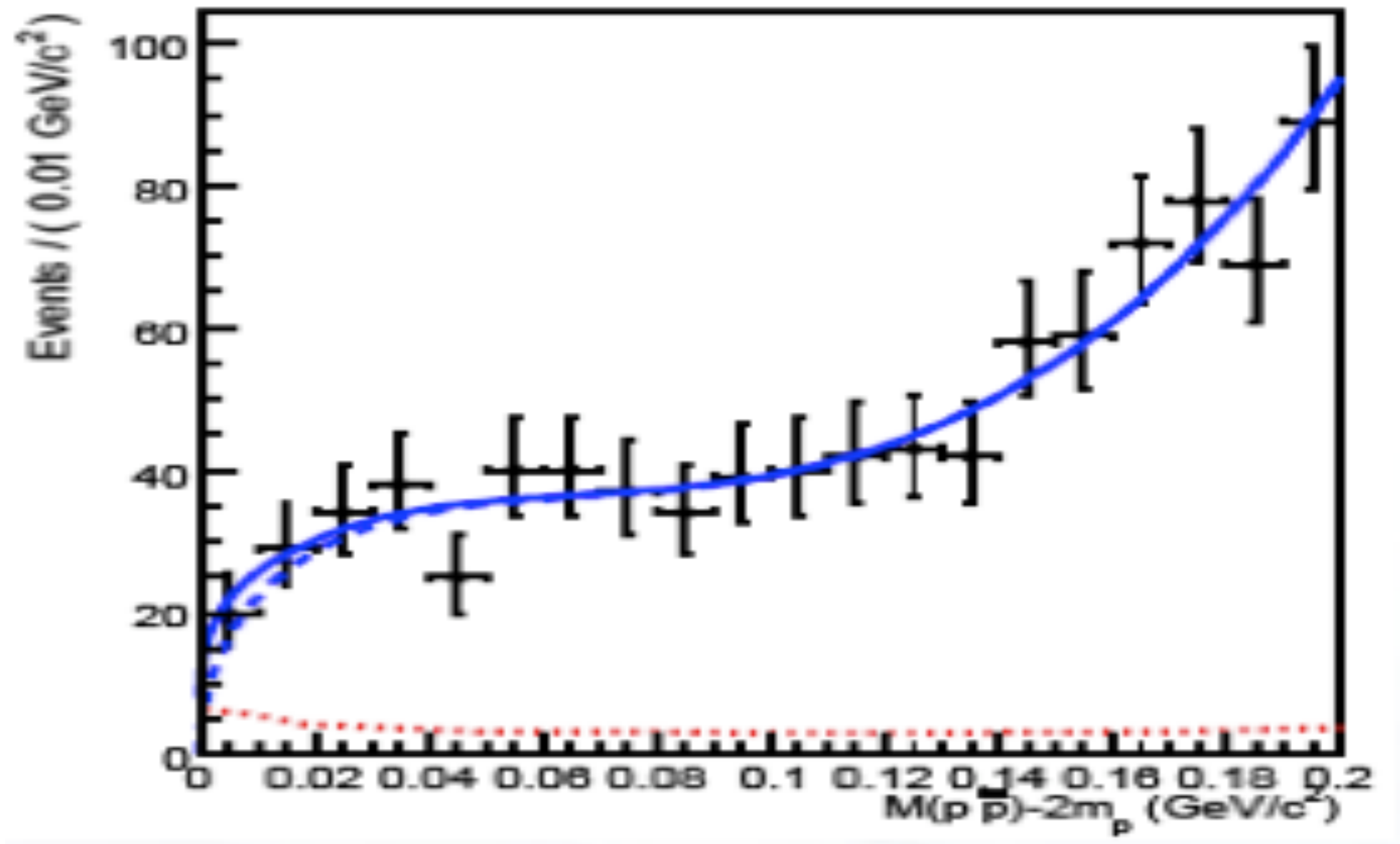
$\psi' \to \gamma p\bar{p}$ @ BESII



$\Upsilon(1S) \to \gamma\ p\bar{p}$ @ CLEO



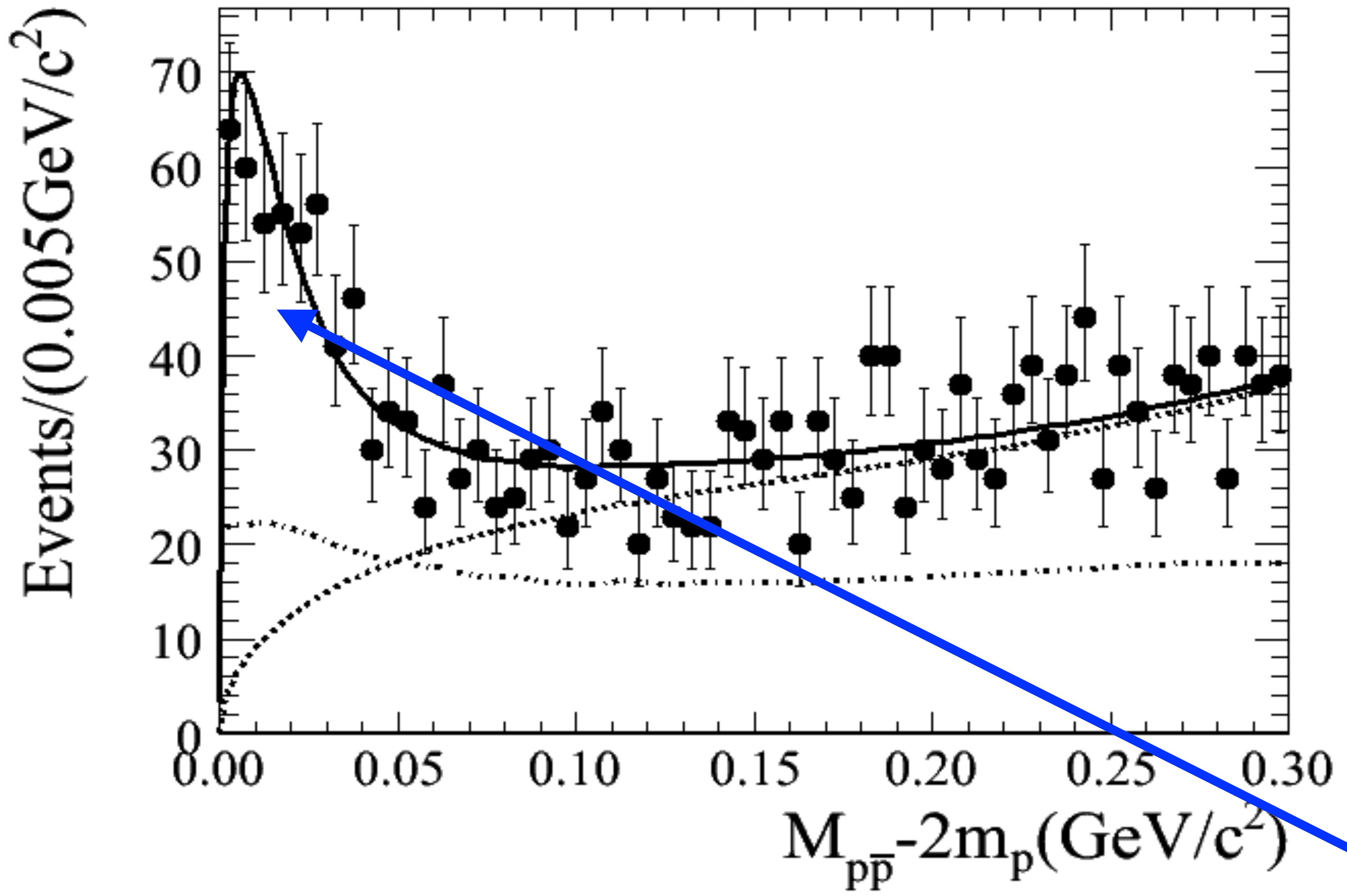
$J/\psi \to \omega\ p\bar{p}$ @ BESII

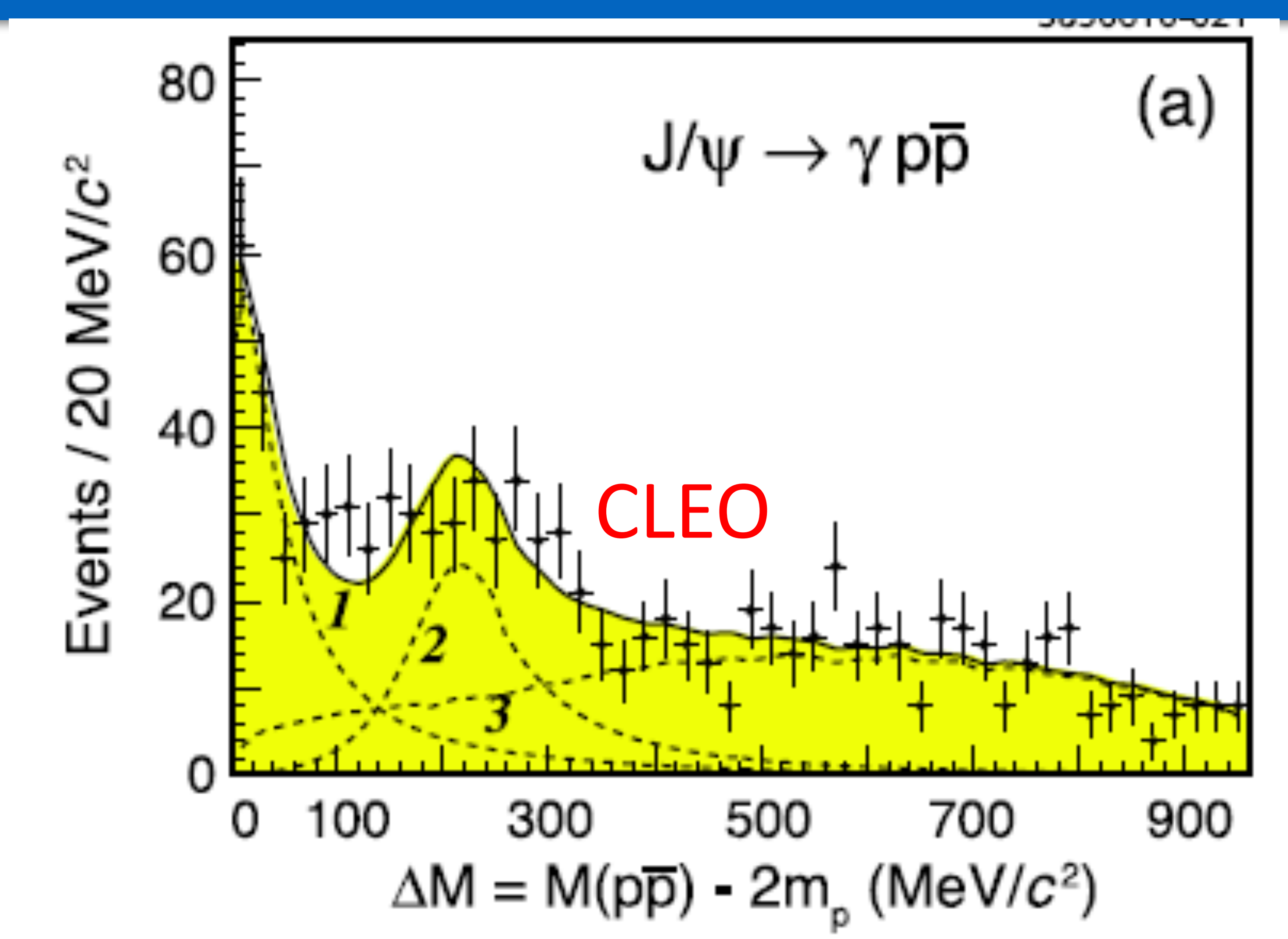


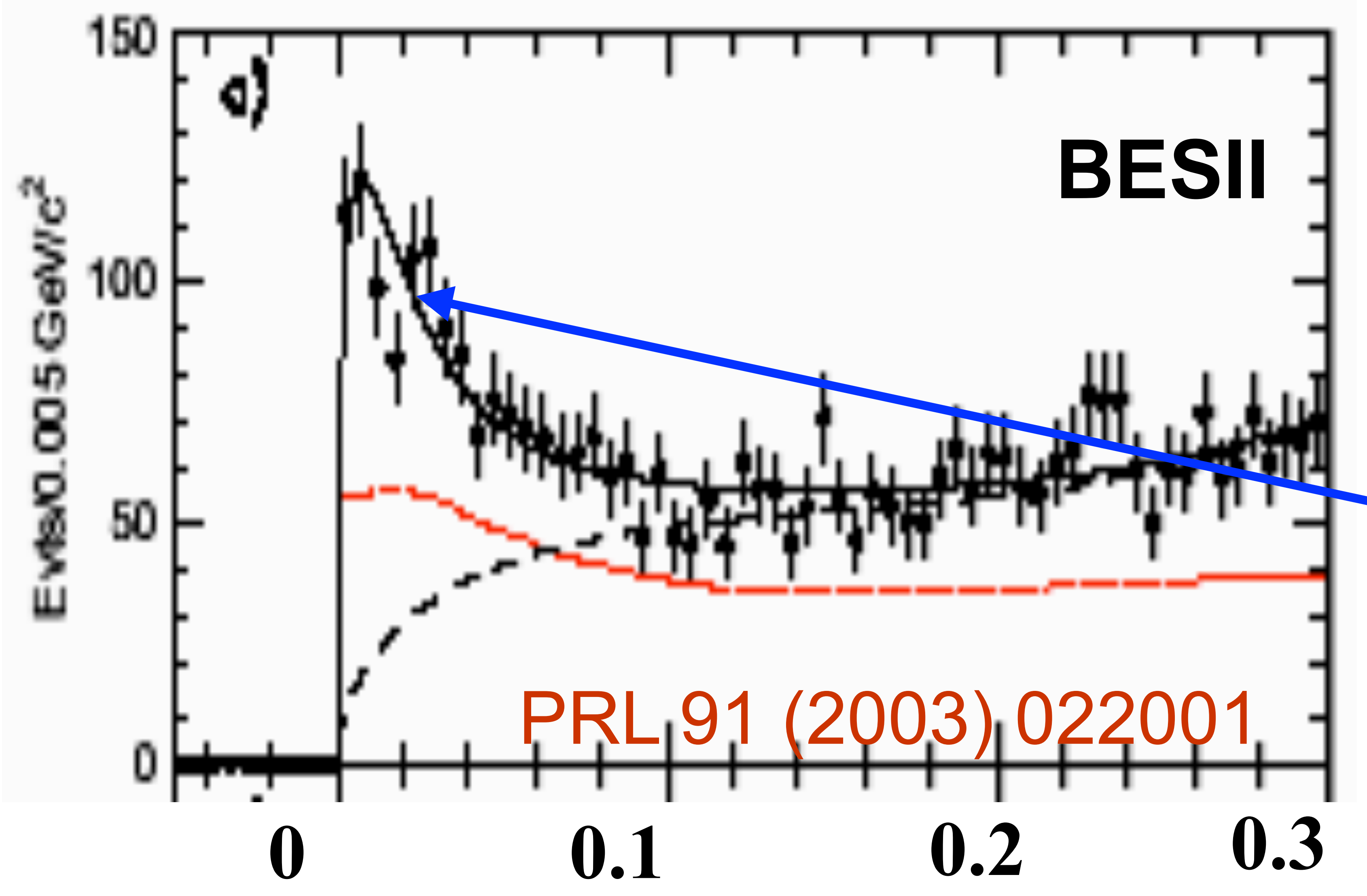
◈ **First observation of ppb mass threshold enhancement**

◈ **No similar threshold structure in other channels → It can not be pure FSI effect**

Confirmation of $M_{pp\bar{b}}$ threshold enhancement







$M=1859 \,{}^{+3}_{-10}\,{}^{+5}_{-25}$ MeV/c^2

$\Gamma < 30$ MeV/c^2 (90% CL)

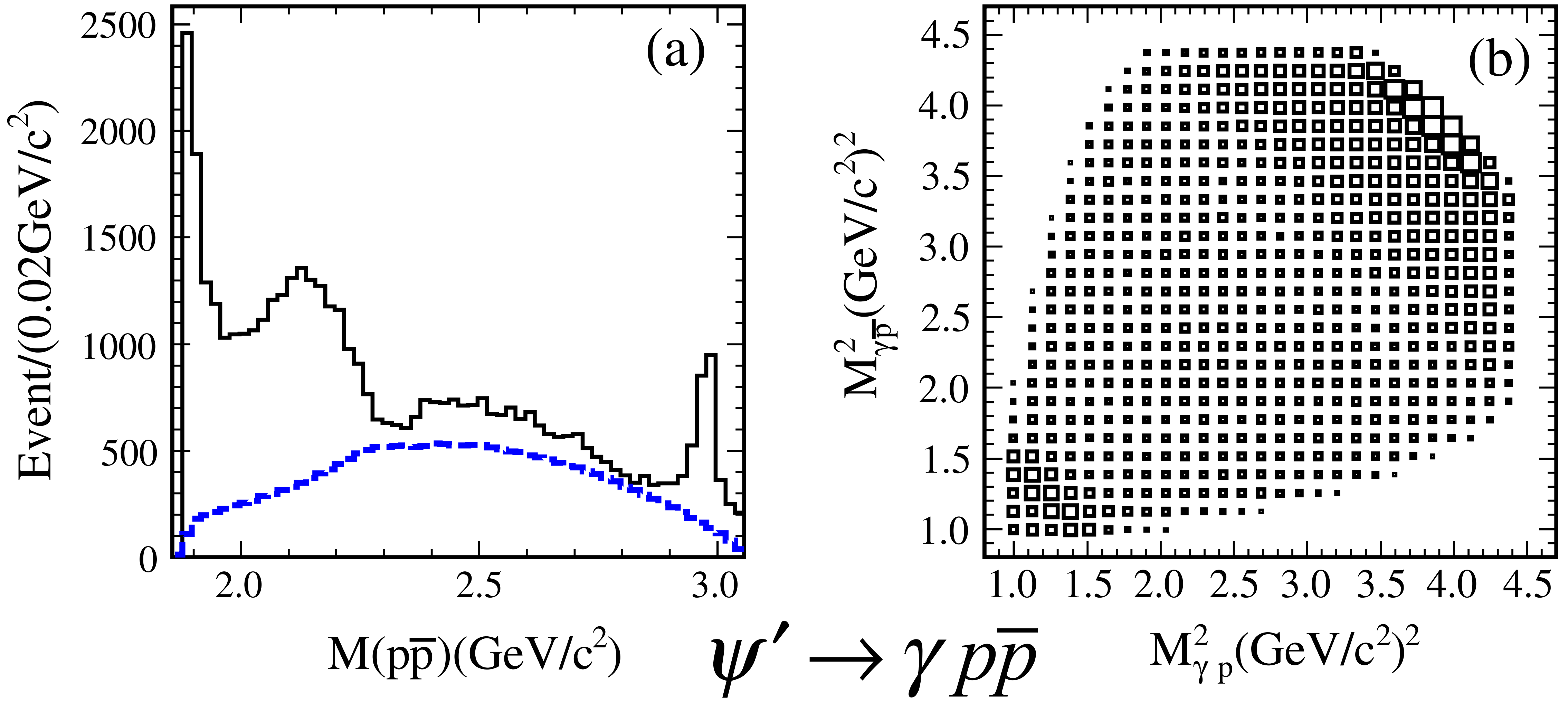
$M=1861 \,{}^{+6}_{-13}\,{}^{+7}_{-26}$ MeV/c^2

$\Gamma < 38$ MeV/c^2 (90% CL)

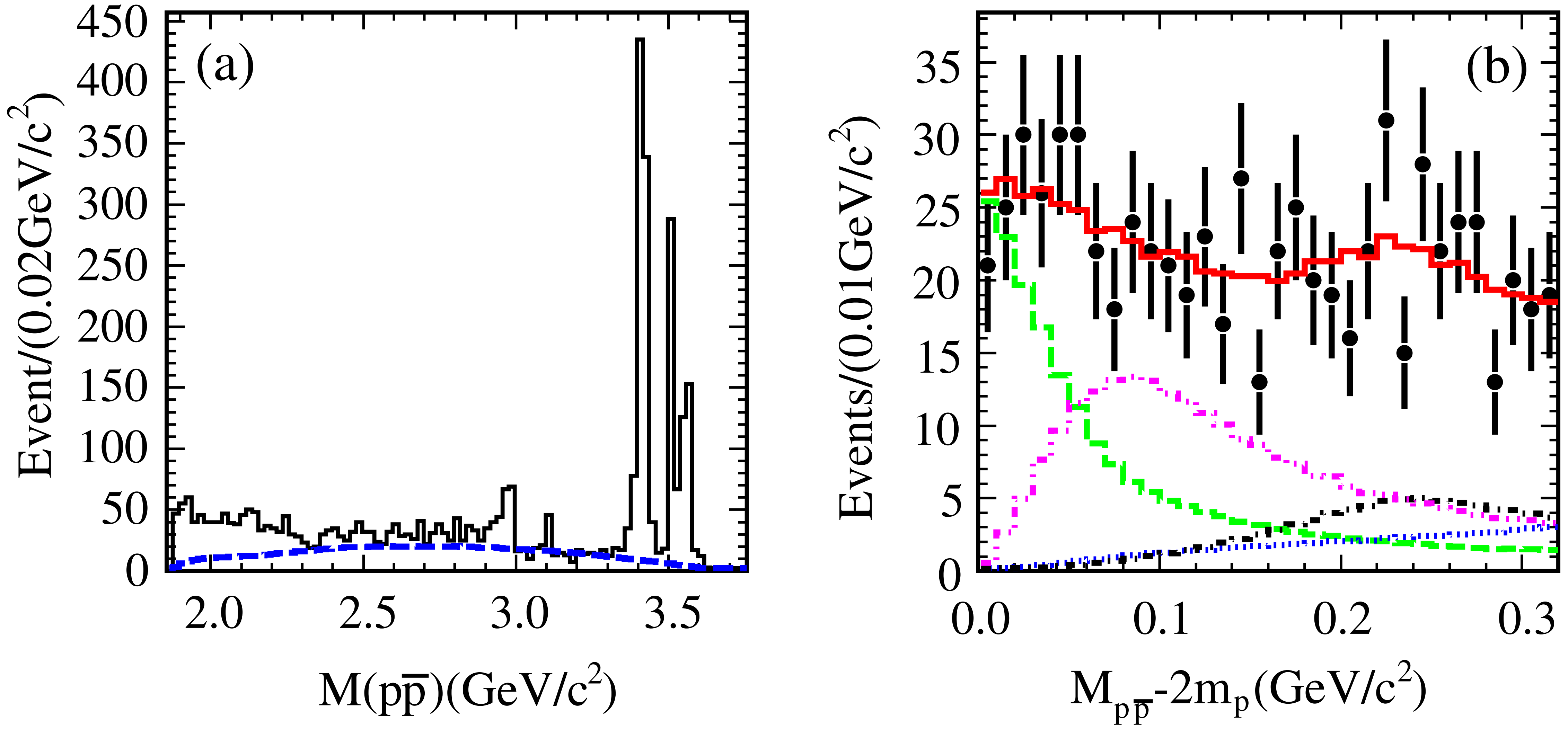
Good agreement on the mass and width measurements which indicated that the confirmation of the $M_{pp\bar{b}}$ threshold enhancement

More precise measurements with PWA

$J/\psi \to \gamma p\bar{p}$



$\psi' \to \gamma p\bar{p}$



Favor to 0^{-+} with the significance >6.8σ larger than others

M = 1861±1$^{+13}_{-4}$MeV

Γ = 1±6$^{+18}_{-1}$MeV (<32MeV @90% CL)

B(J/ψ→γX(1860))B(X(1860)→pp)

=8.6$^{+0.3}_{-0.2}$$^{+2.4}_{-3.5}$×10^{-5}

X(pp) significance >6.9σ

Production ratio:

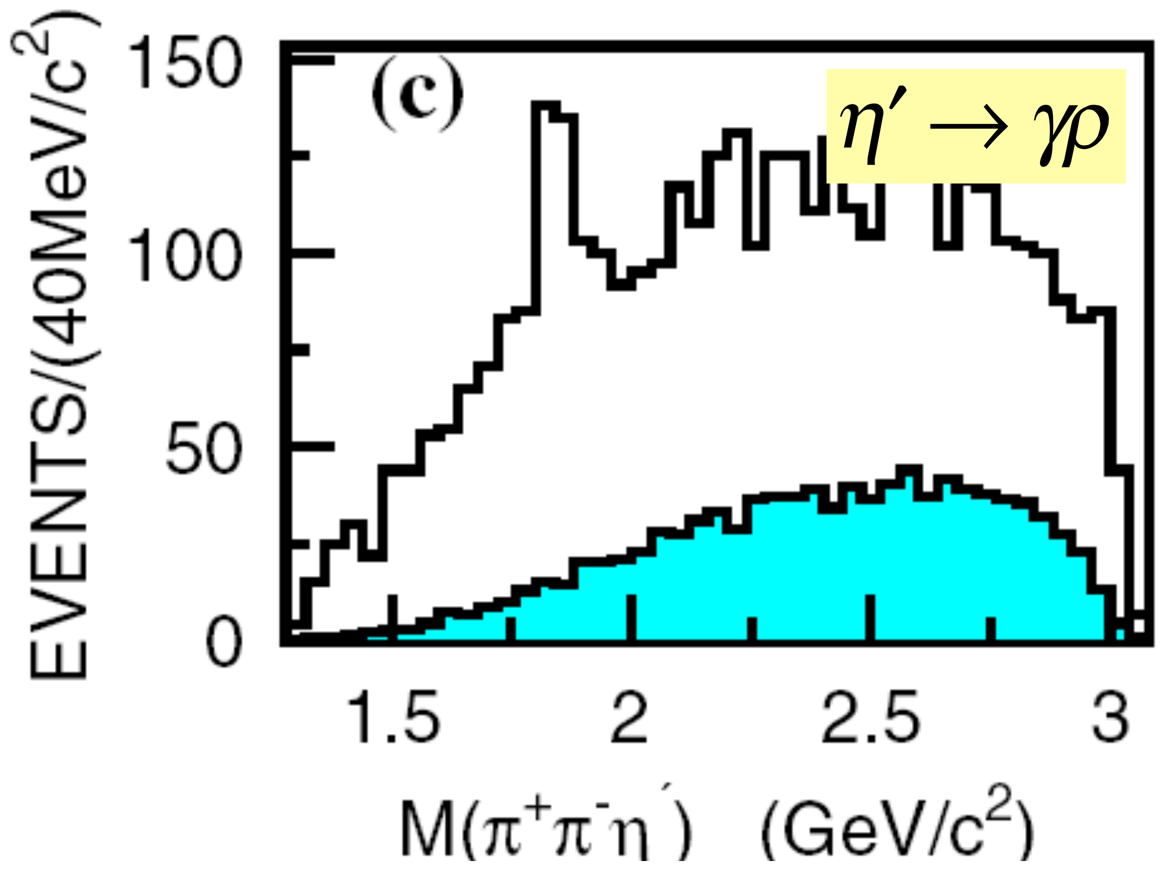
R = 5.08±0.56$^{+0.64}_{-3.09}$±0.12%

Evident suppression w.r.t. "12%rule"

What's the source: ppb bound state, multi-quark state?

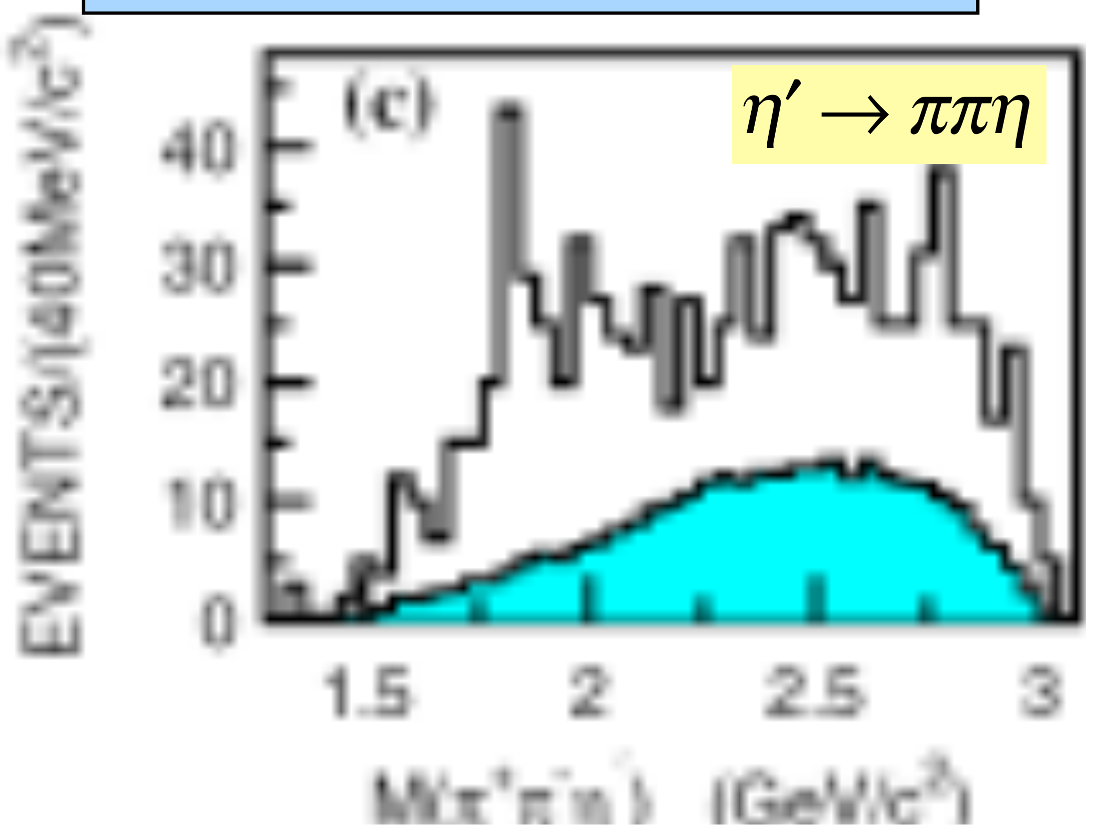
Observation of the X(1835)/X(2120)/X(2370) in J/ψ→γππη’

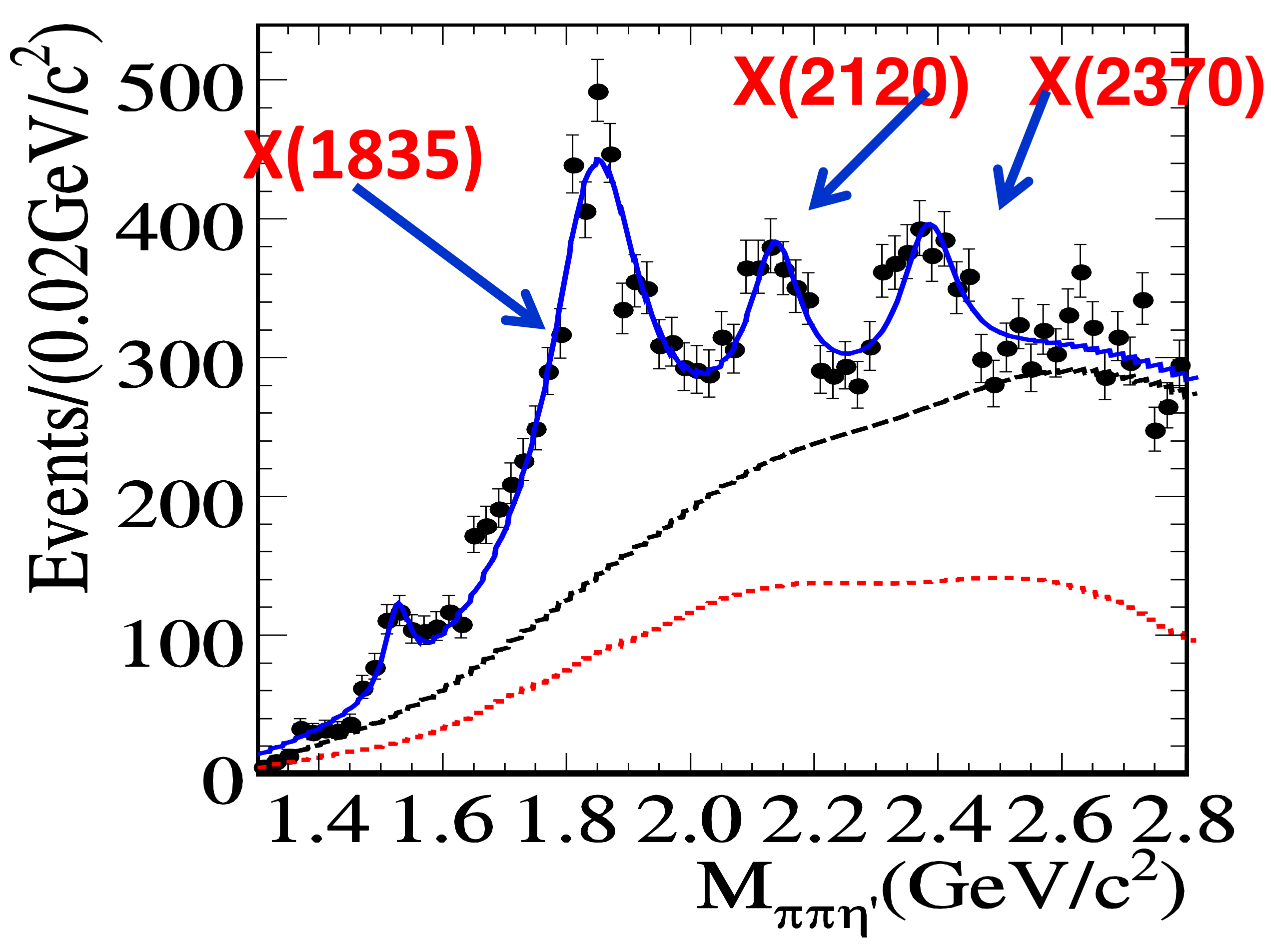
Statistical Significance ~ 6σ

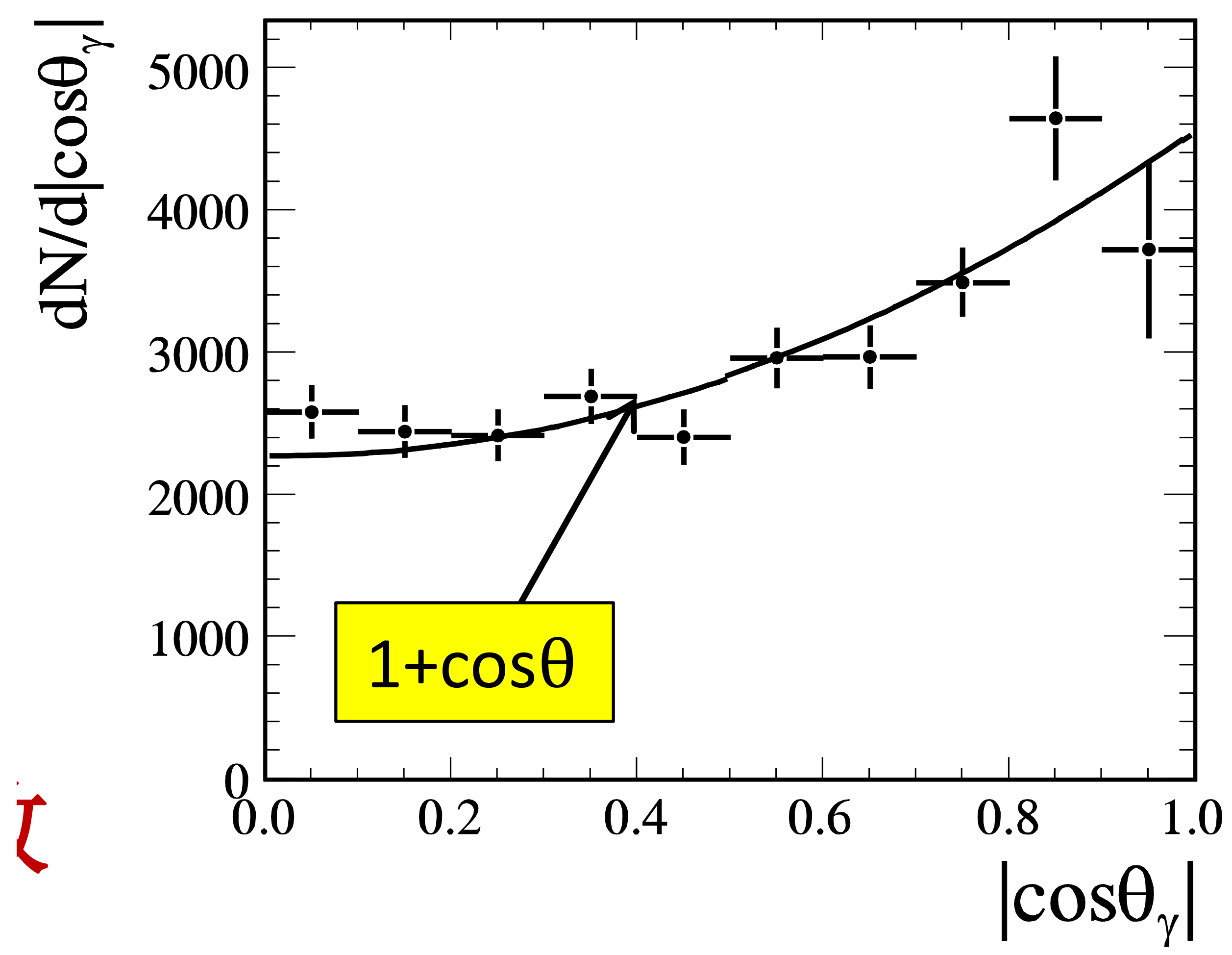


PRL 95,262001(2005)

Statistical Significance ~ 5.1σ

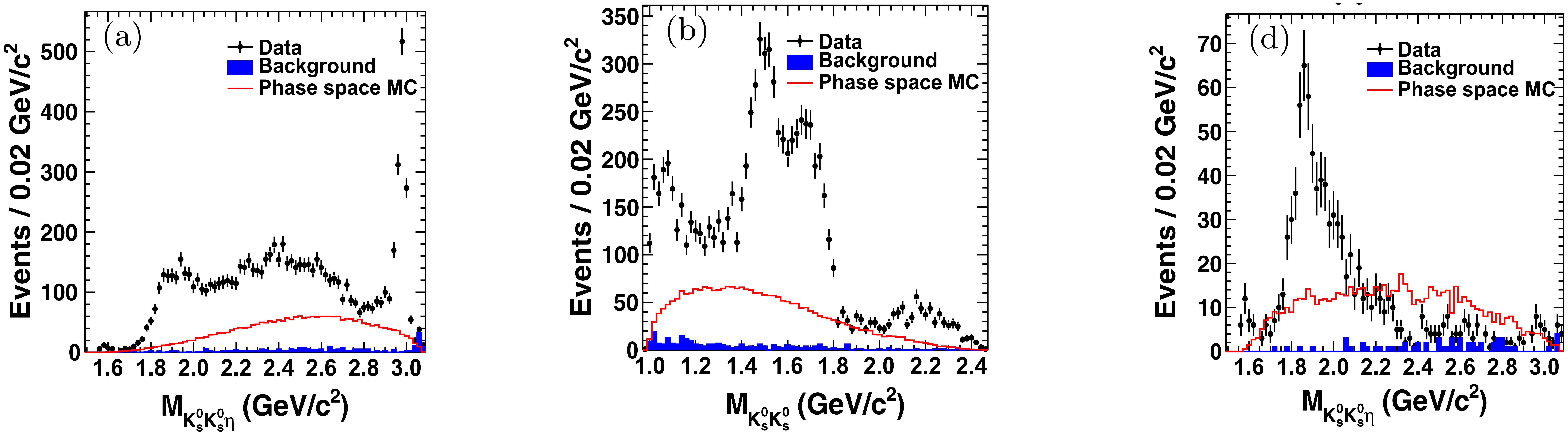






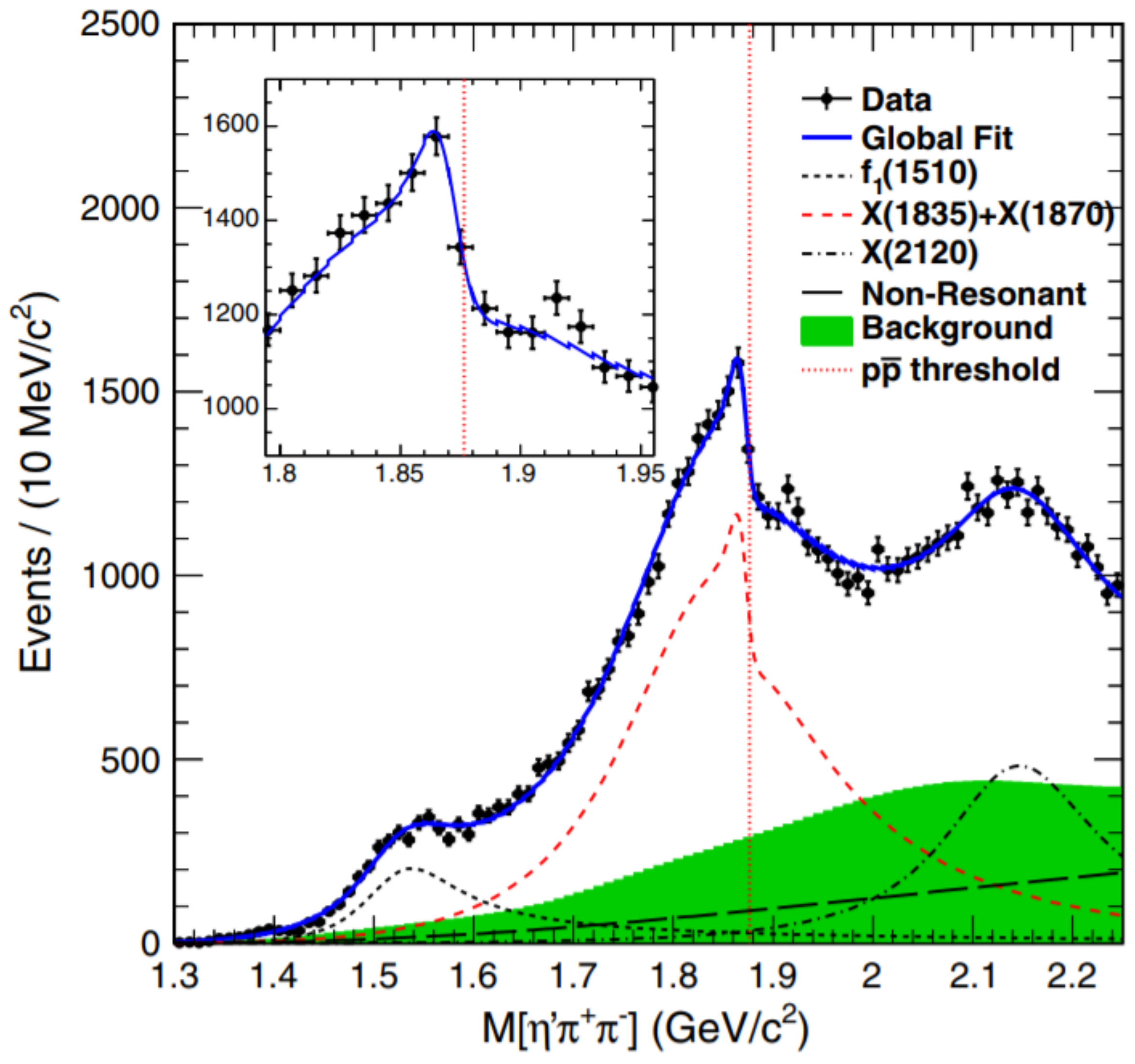
- ◈ First observation of the X(1835) @ BESII
- ◈ Confirmation of the X(1835) and observation of the two new resonances (X(2120) and X(2370)) @ BESIII

Spin-Parity determination of the X(1835) in $J/\psi \to \gamma K_s K_s \eta$

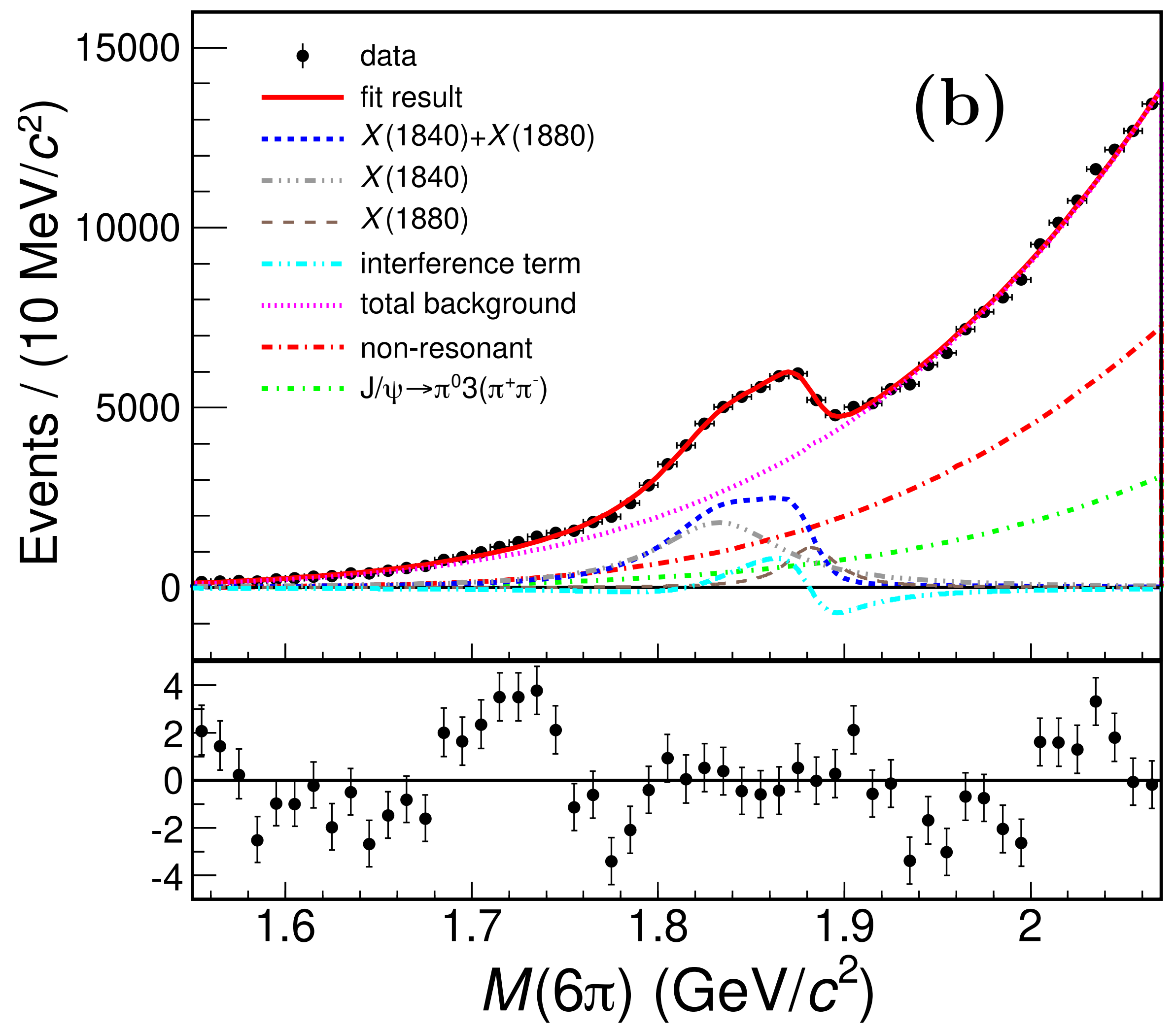


- $X(1835) \to K_s K_s \eta$ is dominated by the $f_0(980)$ production with the significance >12.9σ.
- The spin-parity is determined to be 0^{-+}
  - $M = 1844 \pm 9^{+16}_{-25}$ MeV, $\Gamma = 192^{+20}_{-17}{}^{+62}_{-43}$ MeV
  - $B(J/\psi \to \gamma X(1835)) B(X(1835) \to f_0(980)\eta) = 3.31^{+0.33}_{-0.30}{}^{+1.96}_{-1.29} \times 10^{-5}$

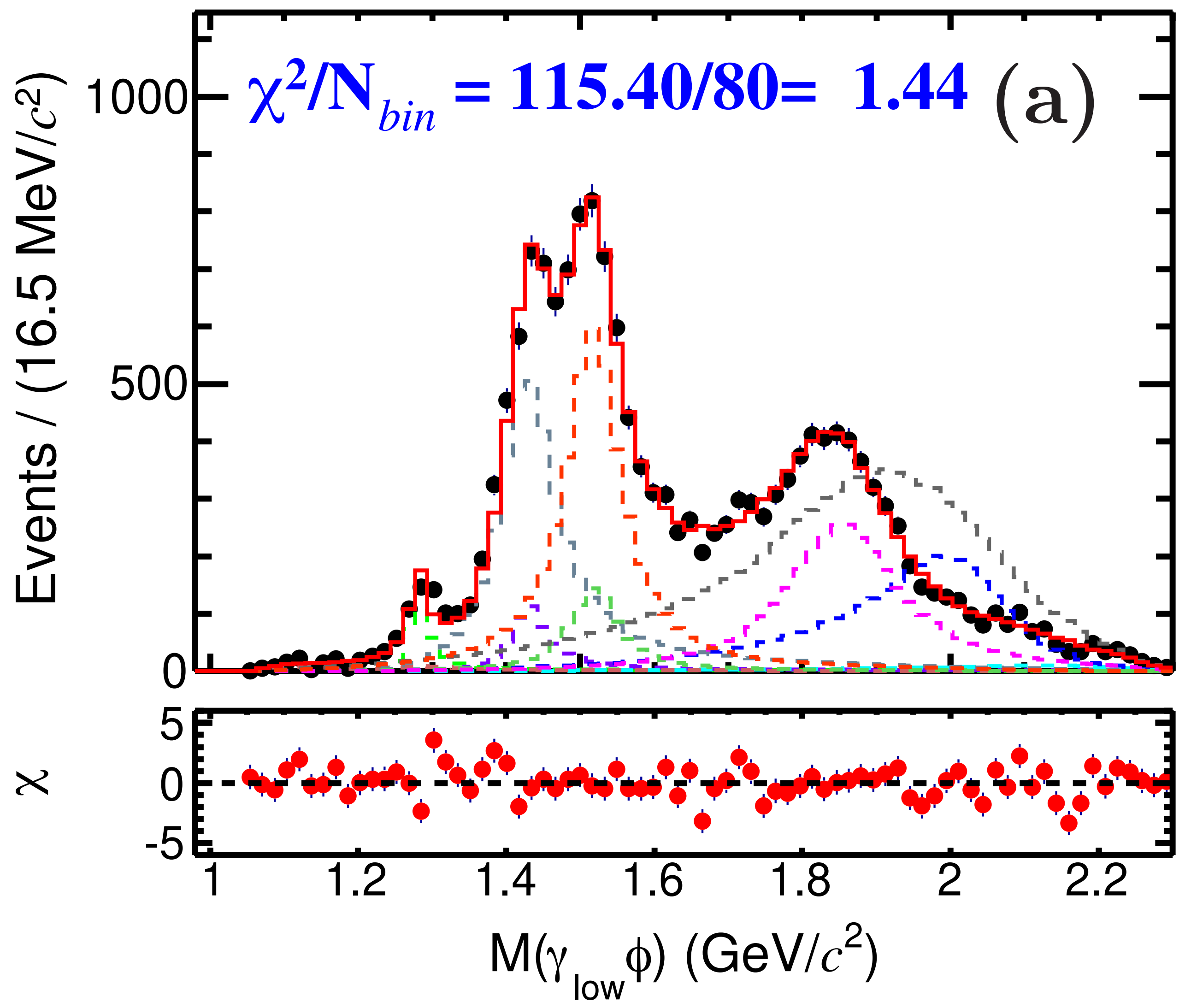
Direct link between the X($p\bar{p}$) and X(1835)



[PRL 117, 042002](#)



[PRL 132 (2024) 151901](#)



[arxiv:2401.00918](#)

- ◈ **Anomalous $\pi\pi\eta'$ line shape near $M_{p\bar{p}}$ threshold: first establish the direct link between the X(1835) and X($p\bar{p}$)**
  - ✦ Two models (Flatte formula/2-resonance) can fit data well: **interpretations of $p\bar{p}$ mass threshold as a molecule state or a bound state**
- ◈ **Anomalous shape observed in $J/\psi \to \gamma 3(\pi\pi)$ near $M_{p\bar{p}}$ threshold**
  - ✦ **Two structures of X(1840) and X(1880) give a good description on data: interpretation of a bound state**
- ◈ **Mass and width of the X(1835) in $J/\psi \to \gamma\gamma\phi$** are consistent with those in $J/\psi \to \gamma K_s K_s \eta$:
  - ✦ **X(1835) contains a sizable $s\bar{s}$ component**

Summary

- A set of interesting and important results from the light hadron spectroscopy achieved:
  - **Discovery of a glueball-like particle: X(2370)**
  - Strong correlation between the X(1835) and $M_{p\bar{p}}$ threshold enhancement. A molecule state or a bound state?
  - Observation of An Exotic 1^{-+} Isoscalar state $\eta_1(1855)$ and Isovector state $\pi(1600)$
  - …
- With the more data, the more extensive and intensive investigation are ongoing, looking forward to new results in the near future.

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