Light QCD exotics at BESIII

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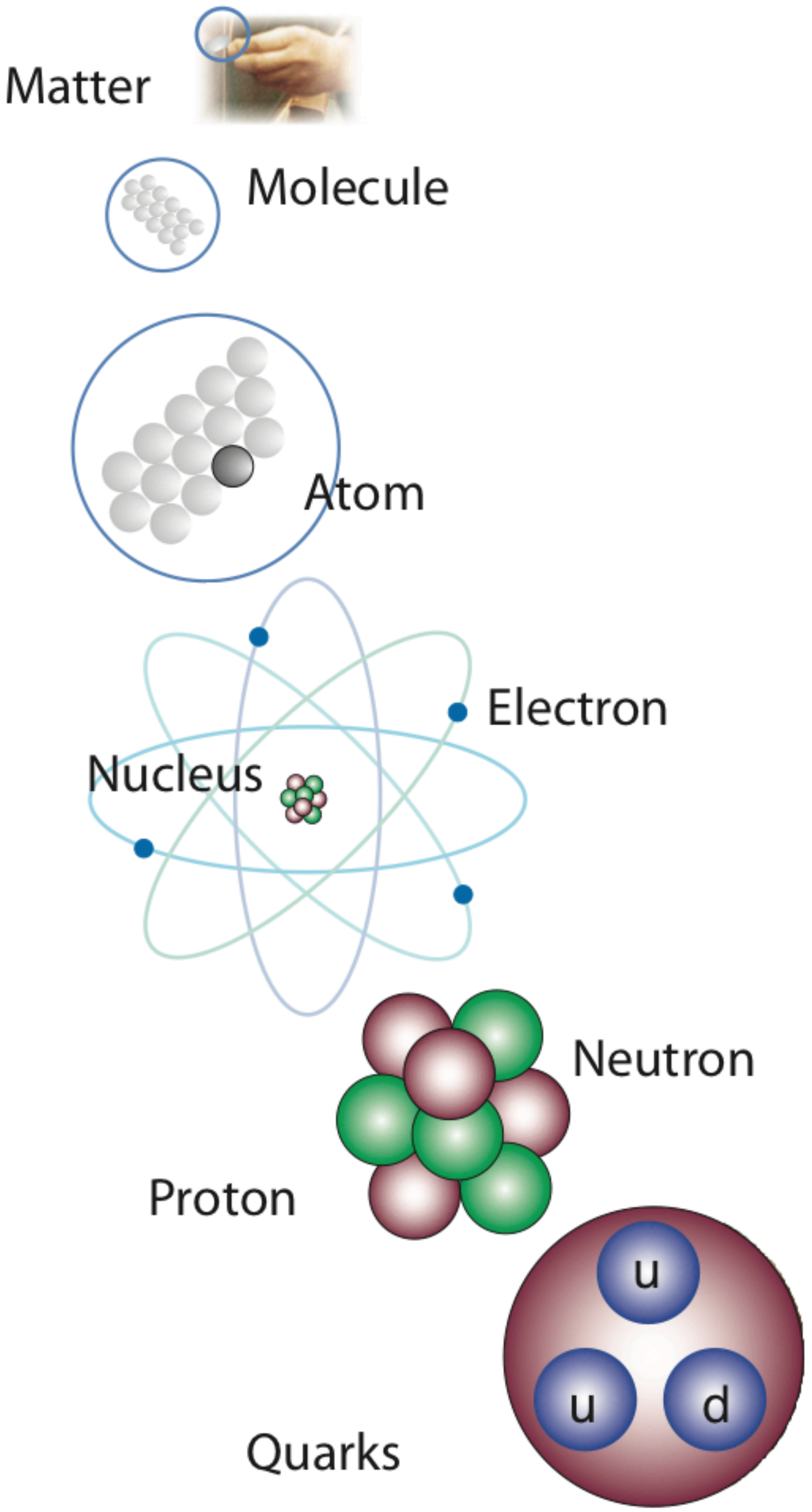
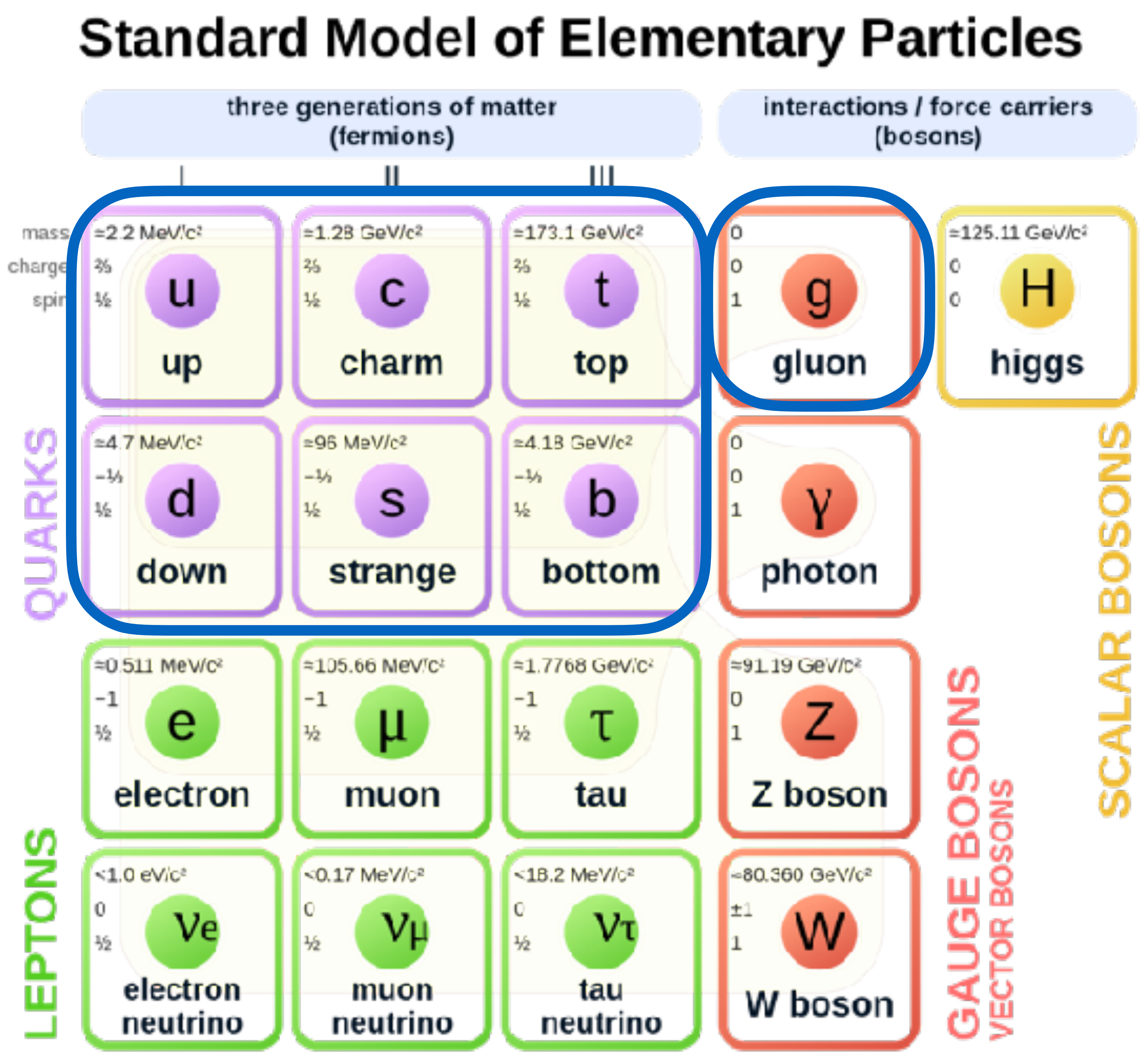
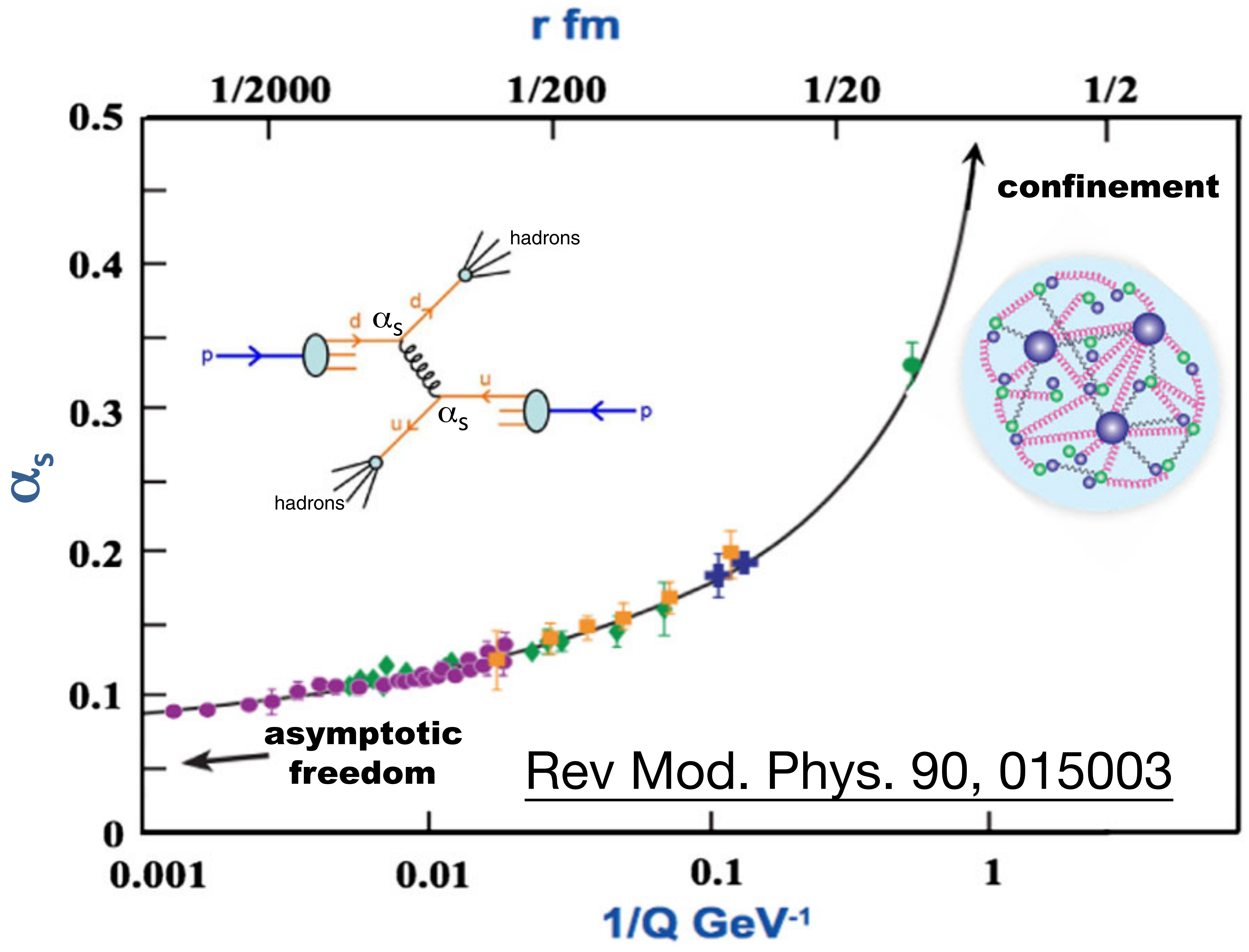
Fundamental Structure of Matters



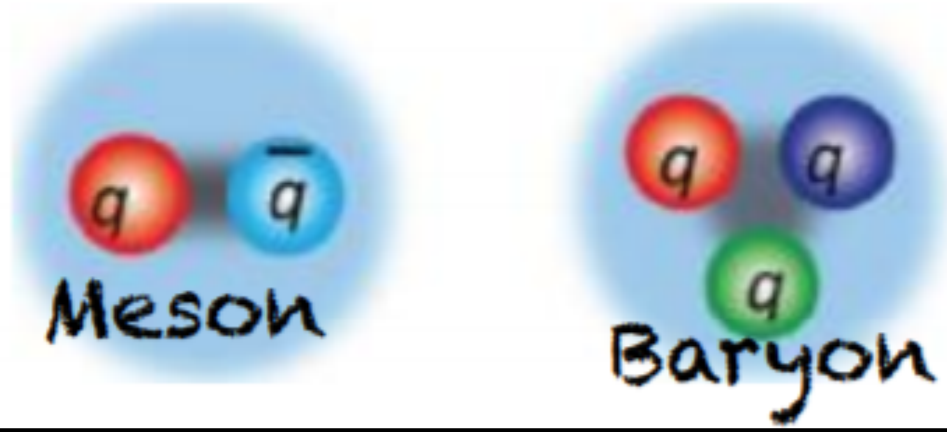




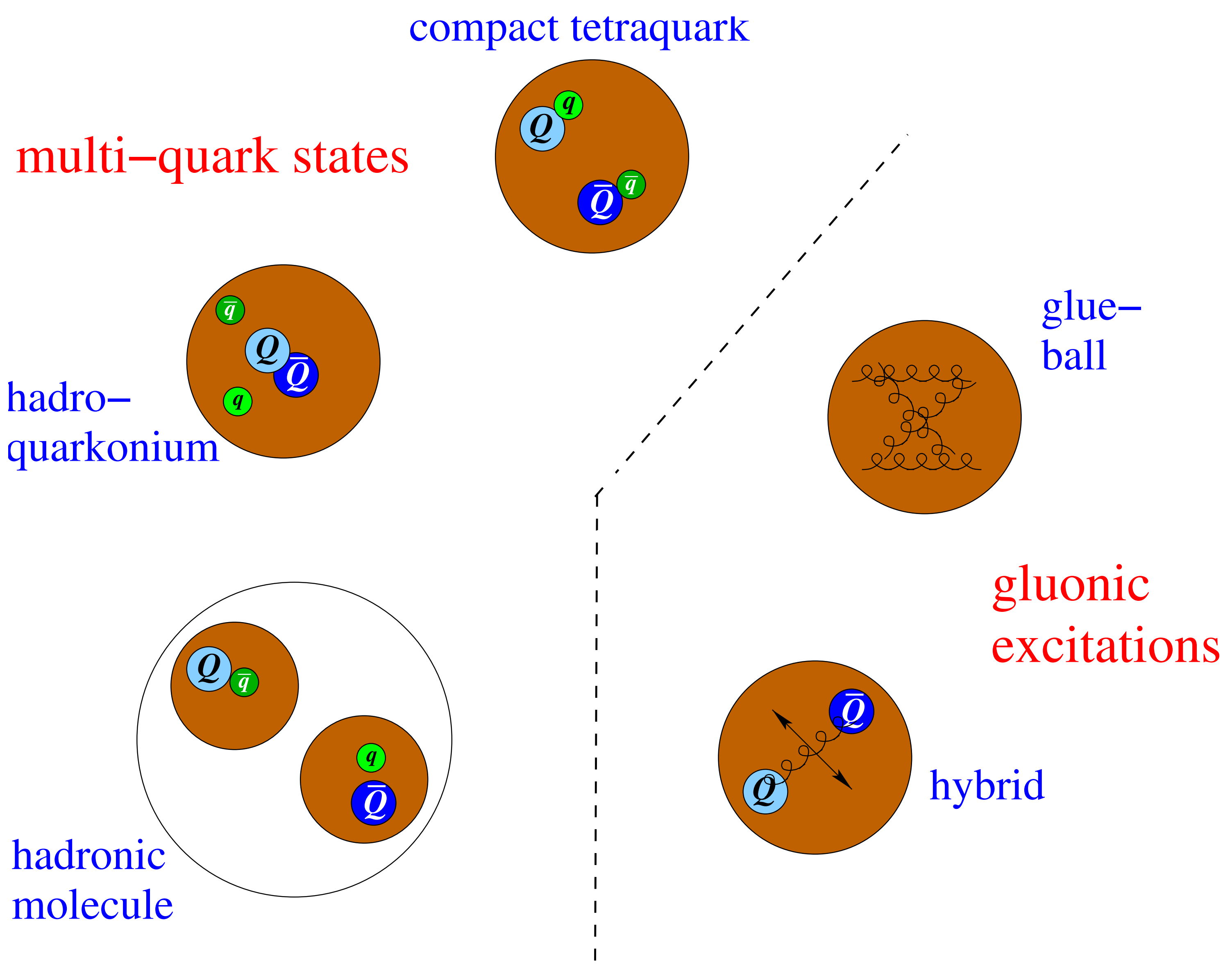
Hadron spectroscopy can provide us clues for the understanding of fundamental structure via the hadron property study

Forms of hadrons

Quark model



New forms of hadrons



Physics report 873 (2020) 1-154

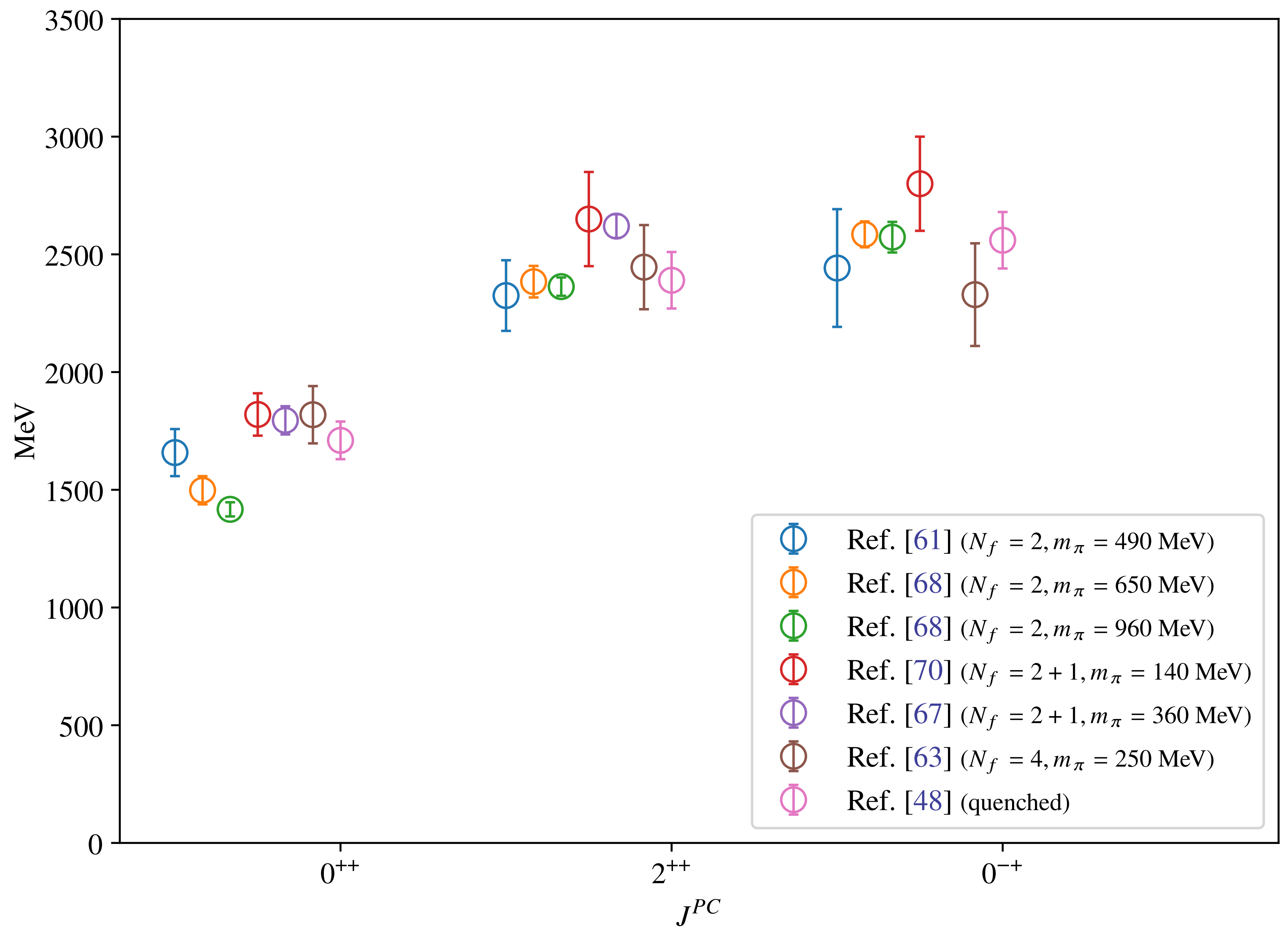
- ◈ **Quark model (QM)**
  - ✦ Identify hadrons as compound objects consisting of quarks and antiquarks
  - ✦ Dynamics description inside hadrons
- ◈ **New form of hadrons:**
  - ✦ **Multi-quark:** quark number >= 4
  - ✦ **Hybrid state:** the mixture of quark and gluon
  - ✦ **Glueball:** composed of gluons
- ◈ **Identification from QM:** challenging
  - ✦ **Exotic quantum states**
  - ✦ **Crypto exotic with particular properties**

Many candidates, but no unambiguous hadrons with nonstandard structure have established

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**

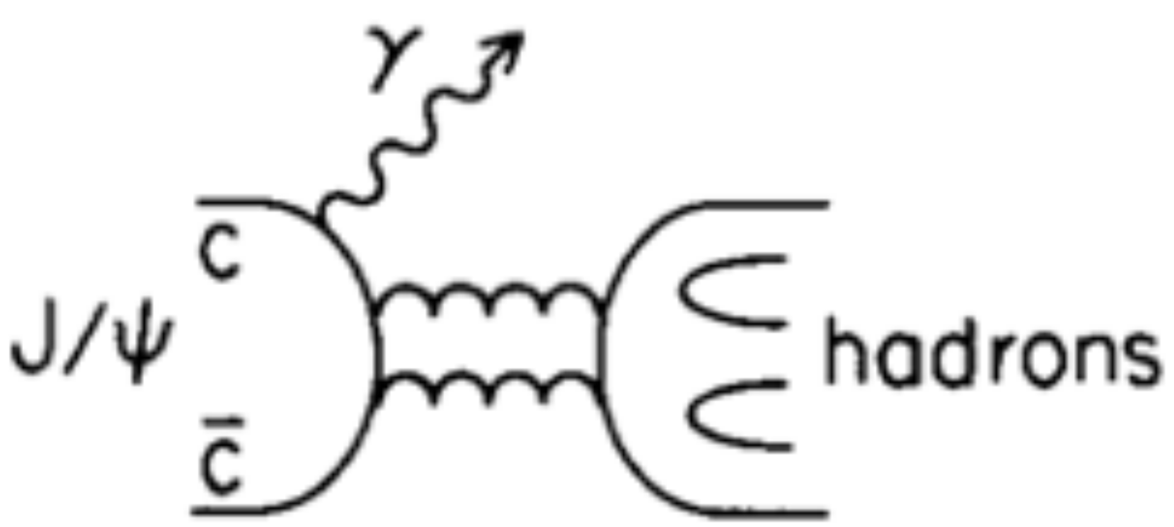
- **Lattice QCD** (LQCD) is a non-perturbative method from the first principles in theory.
- **Different lattice QCD groups** (including lattice simulations with dynamical quarks)
  - Predictions on **masses and production rates** of pure glueballs
  - Consistent results and expected to be reliable.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



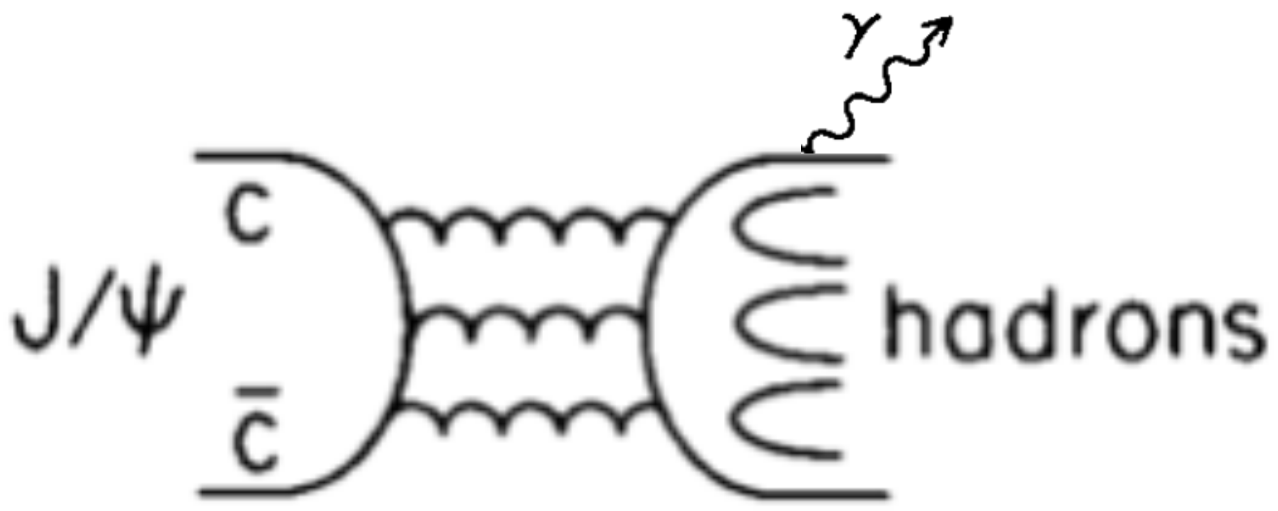
arxiv:2305.04869

Glueball production in J/ψ Radiative decay

◈ **Gluon rich environment**



$\sim \alpha\alpha_s^4$



$\sim \alpha\alpha_s^6$

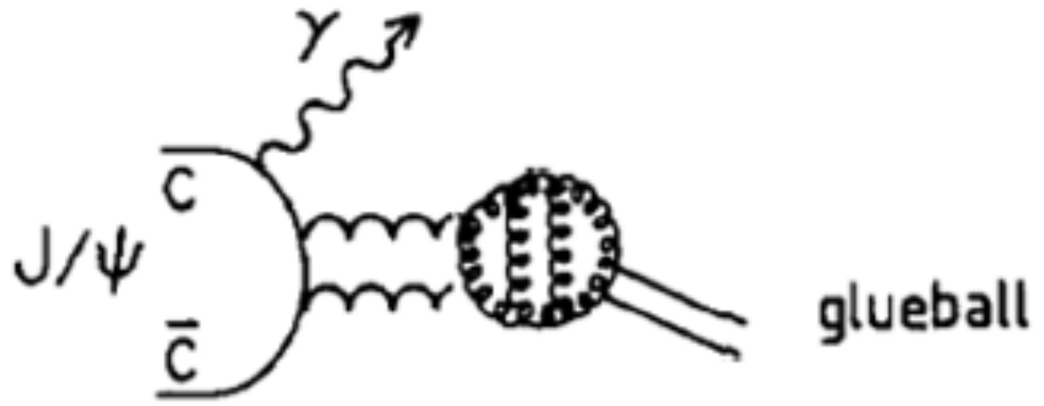
◈ **Isospin filter:** final states dominated by **I=0** processes

◈ **Spin-parity filter:** **C parity must be +**, so $J^{PC}=0^{-+}, 0^{++}, 1^{++}, 2^{++}, 2^{-+}$ …

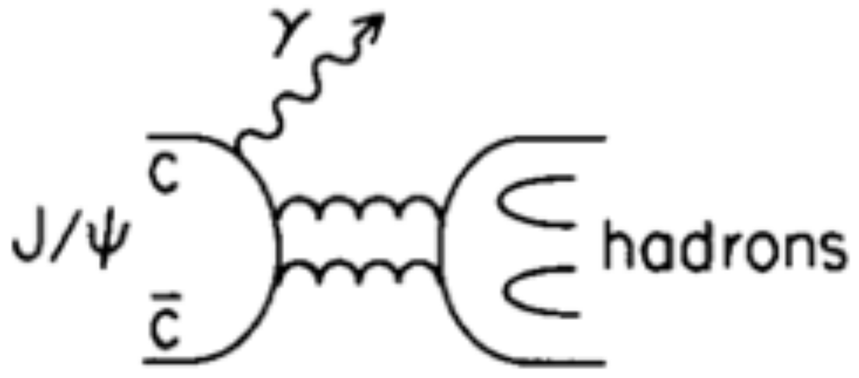
◈ **Clean environment** **in e^+e^- collision:** very different from **p-p collision**

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

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



$\sim \alpha\alpha_s^2$

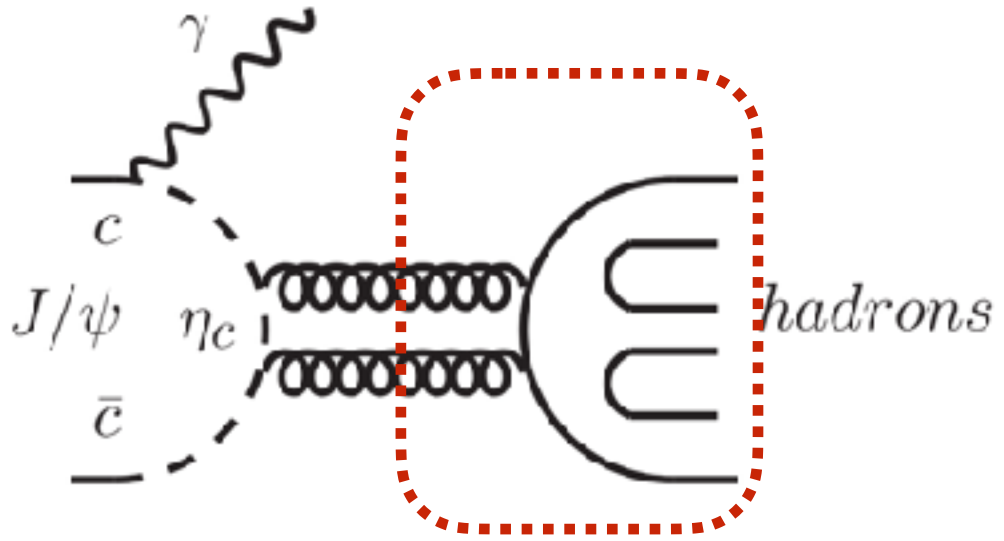


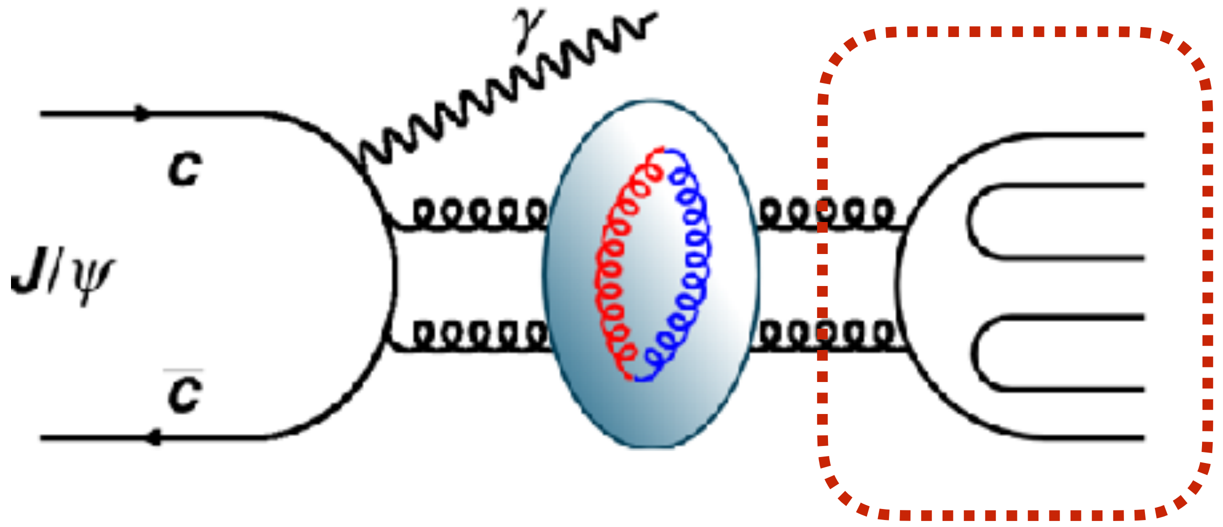
$\sim \alpha\alpha_s^4$

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

Glueball Decays

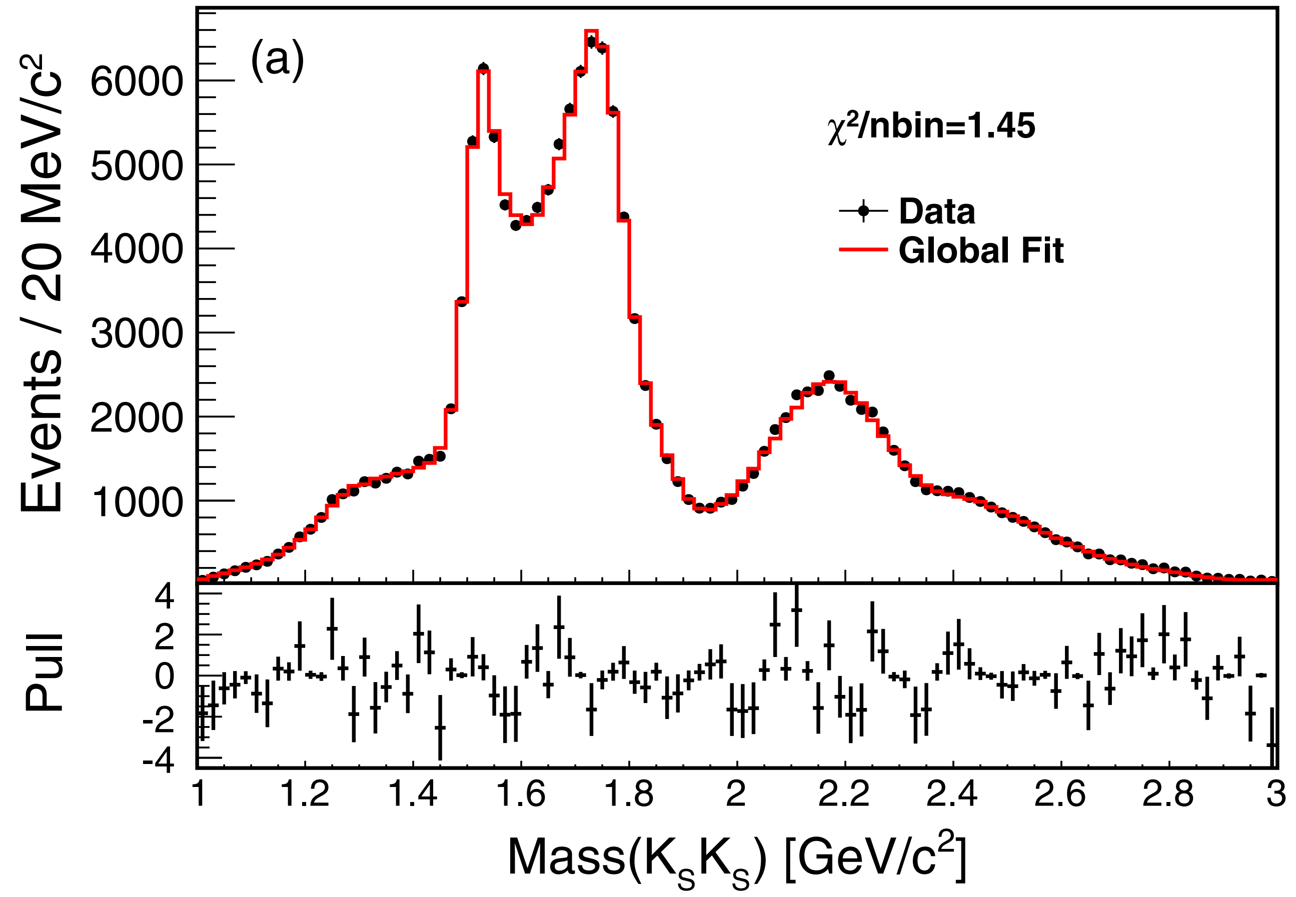
- Flavor symmetric decays
- No rigorous predictions on decay patterns and their branching ratios
- The glueball decays could be the analogy to **Charmonium decays** since they all decay via gluons (OZI suppression) [PLB 380 189(1996), Commu. Theor. Phys. 23.373 (1995)]
  - e.g. the 0^{-+} glueball could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





Historical Glueball Candidates

0^{++}: $f_0(1710)$



High production rate in J/ψ→ γf₀(1710):

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

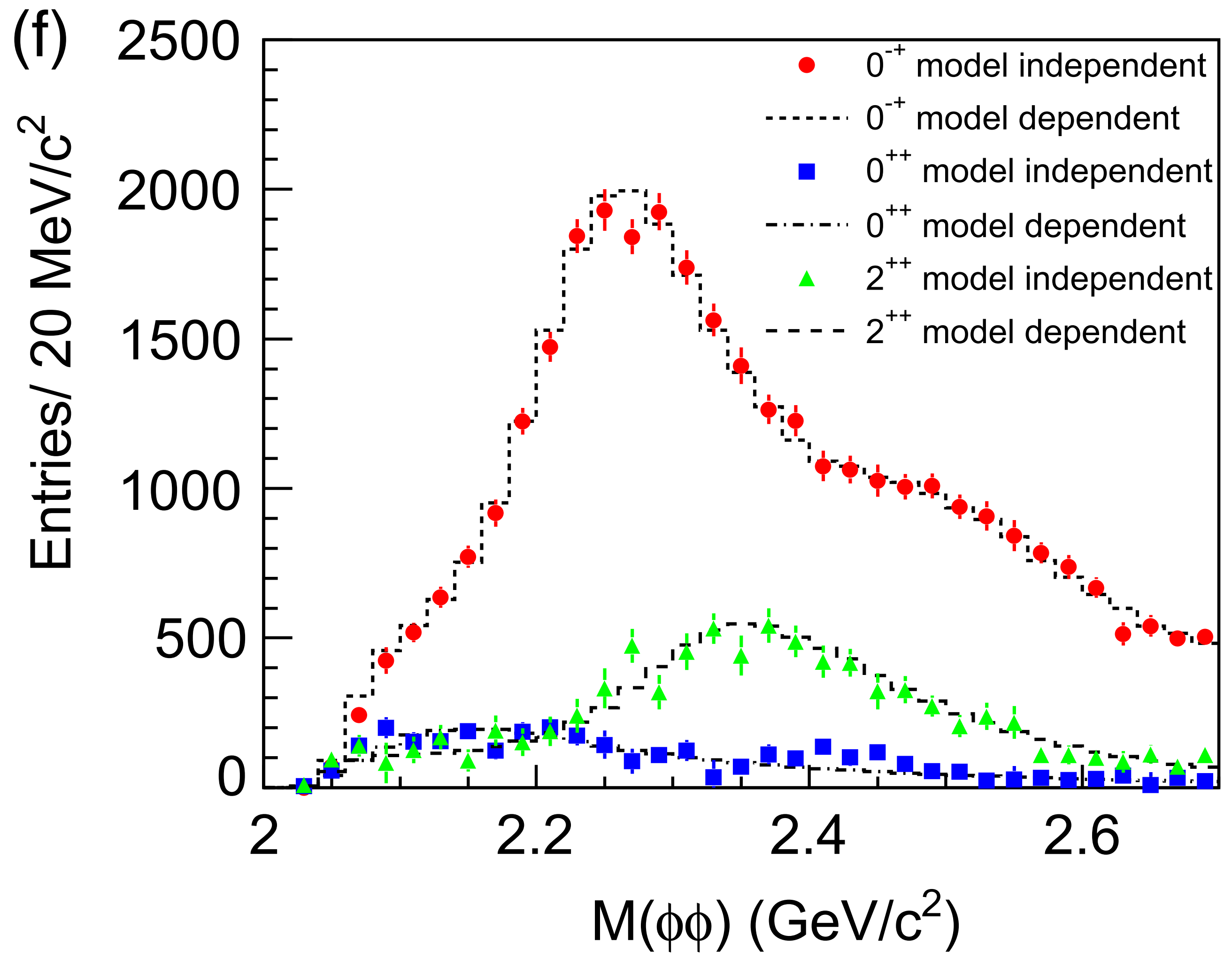
$$B[J/\psi \to \gamma f_0(1710) \to \gamma K_s^0 K_s^0] = (2.00^{+0.03}_{-0.02}\ {}^{+0.31}_{-0.10}) \times 10^{-4}$$

Decay suppression in $f_0(1710)$→ ηη':

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

$f_0(1710)$ favors to be a scalar glueball or large glueball content (mixing mechanism)

2^{++}: $f_2(2340)$



High production rate in J/ψ→ γf₂(2340):

B($J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta$) = $(3.8^{+0.62}_{-0.66}\ {}^{+2.37}_{-2.07}) \times 10^{-5}$

B($J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi$) =$(1.91 \pm 0.14^{+0.72}_{-0.73} \times 10^{-4}$

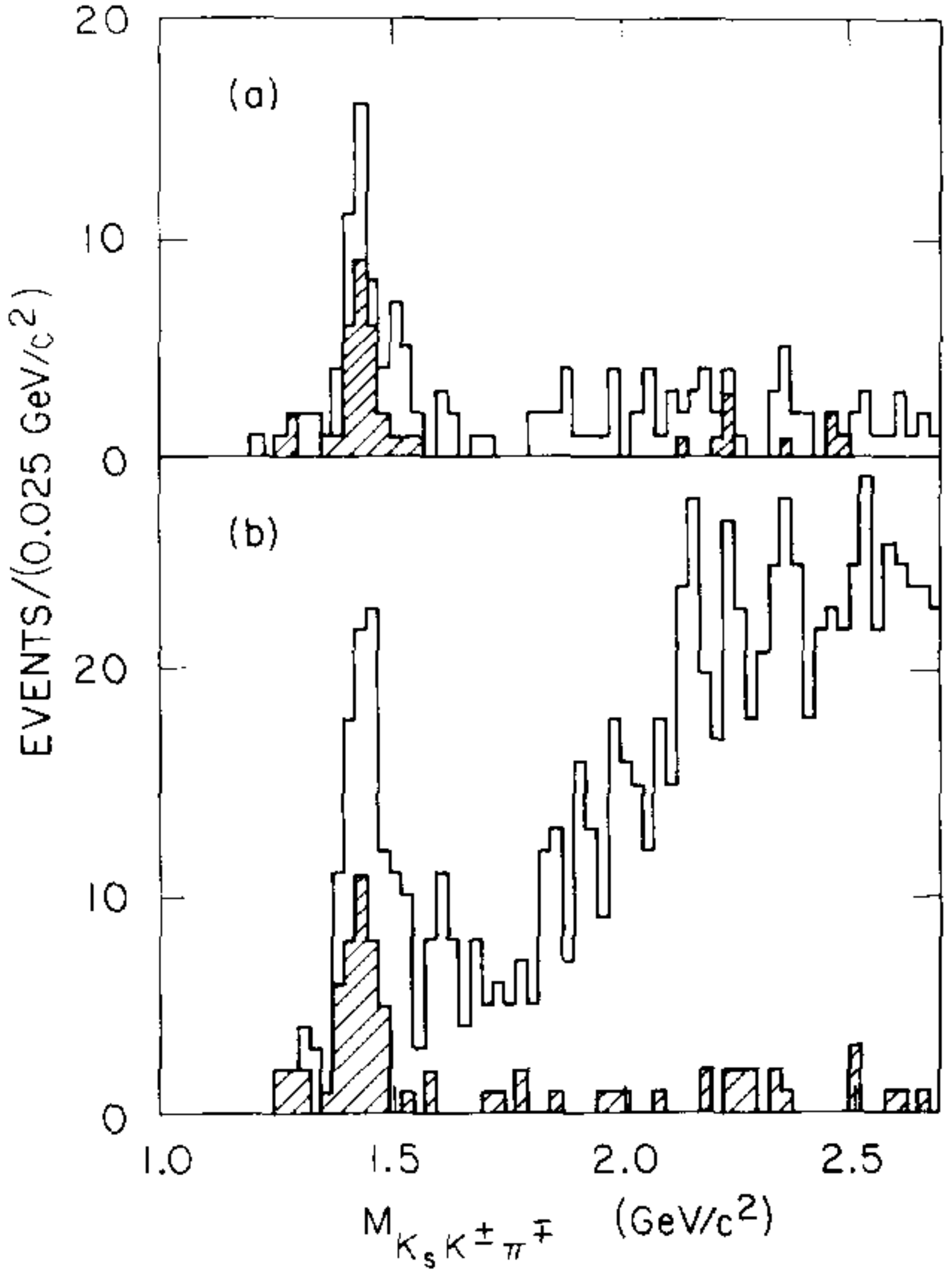
B($J/\psi \to \gamma f_2(2340) \to \gamma K_s K_s$) =$(5.54^{+0.34}_{-0.40}\ {}^{+3.82}_{-1.49} \times 10^{-5}$

B($J/\psi \to \gamma f_2(2340) \to \gamma\eta'\eta'$) =$(8.67 \pm 0.70^{+0.16}_{-1.67} \times 10^{-6}$

Production rate lower than LQCD prediction

Large overlaps between many broad tensor meson cause the its measurement difficulty

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



No longer a 0^{-+} glueball candidate due to its large mass difference from latest LQCD prediction

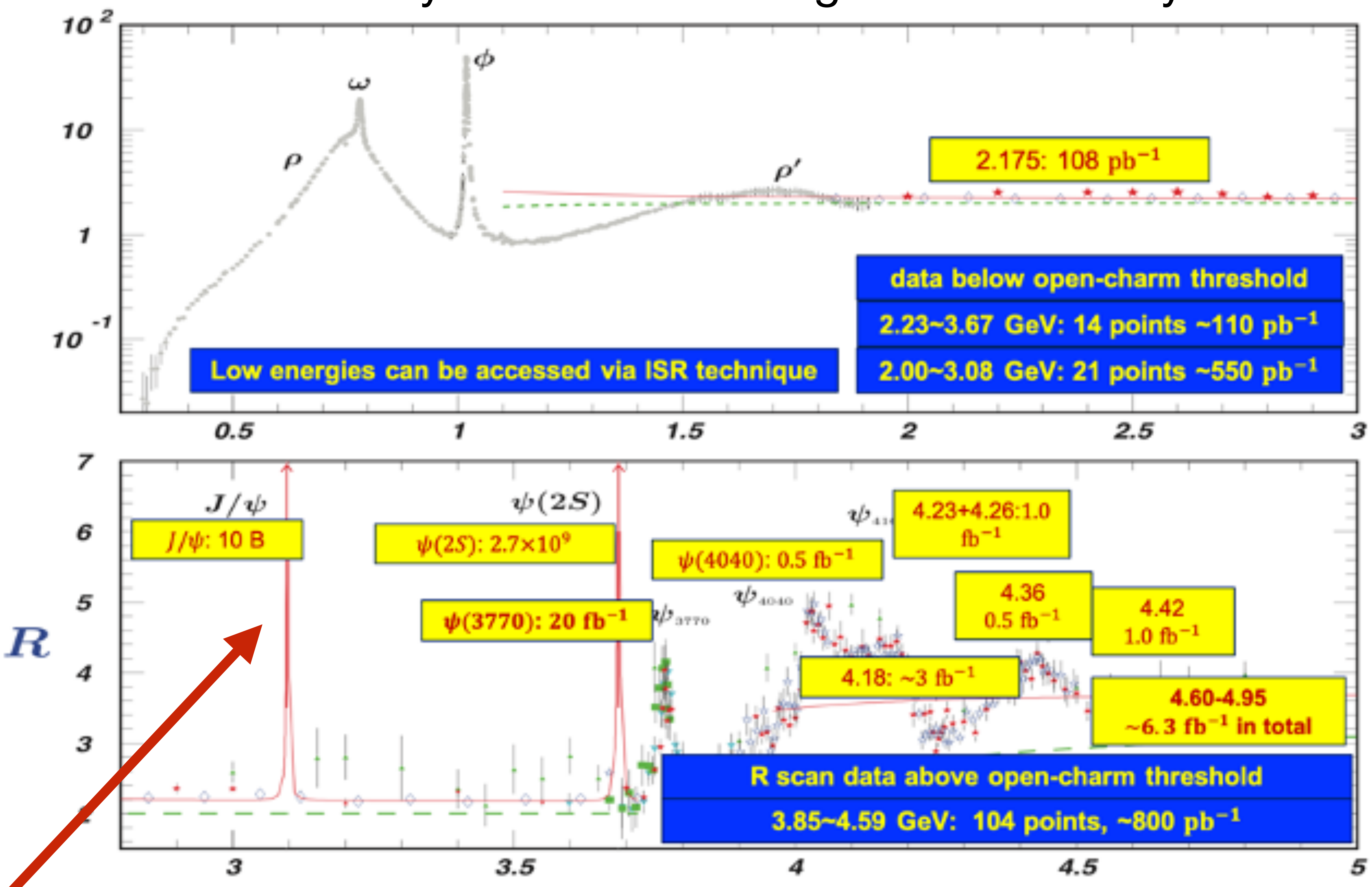
BESIII Data samples

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



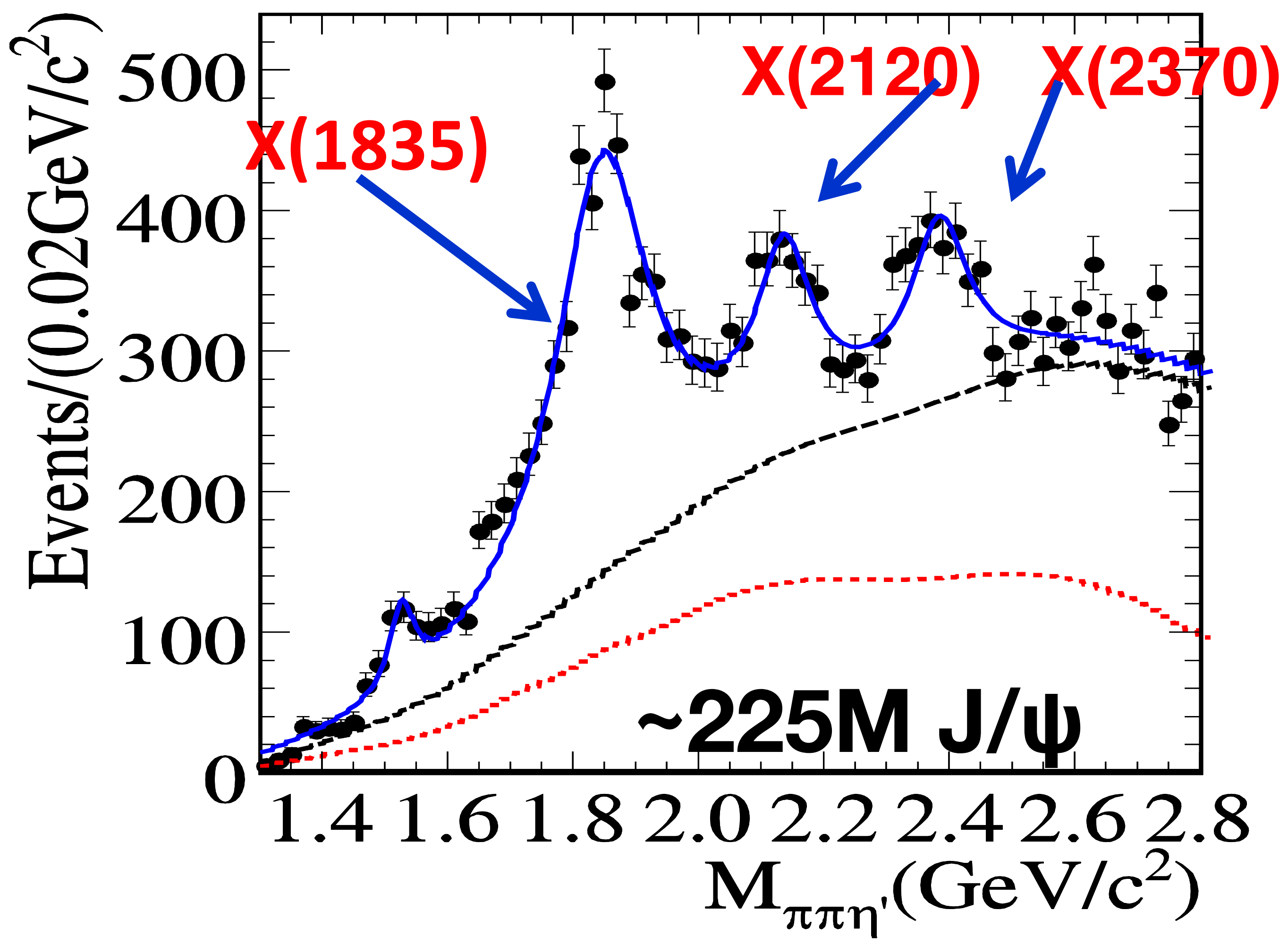
World largest J/ψ data sample : ~10 billion

X(2370)

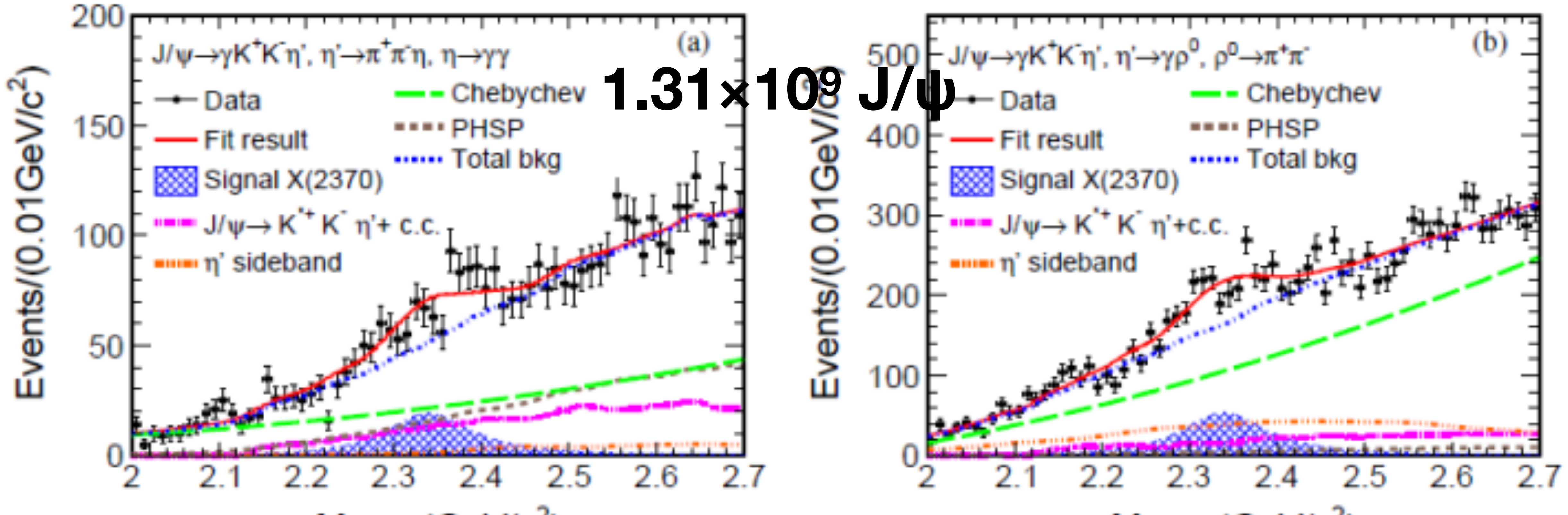
- **Discovered by BESIII in $J/\psi \to \gamma\pi^+\pi^-\eta'$ in 2011**

	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

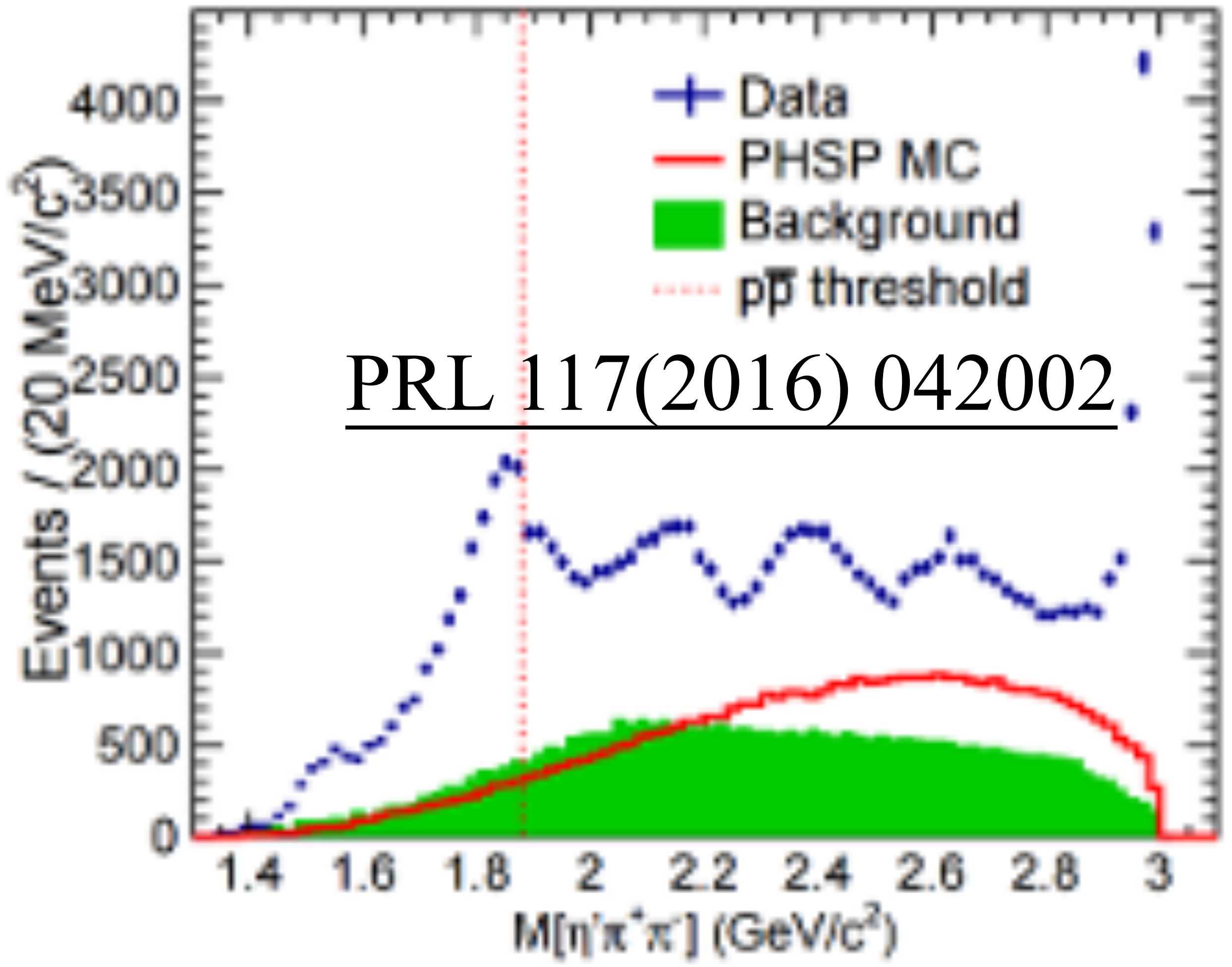
PRL 106, 072002 (2011)



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

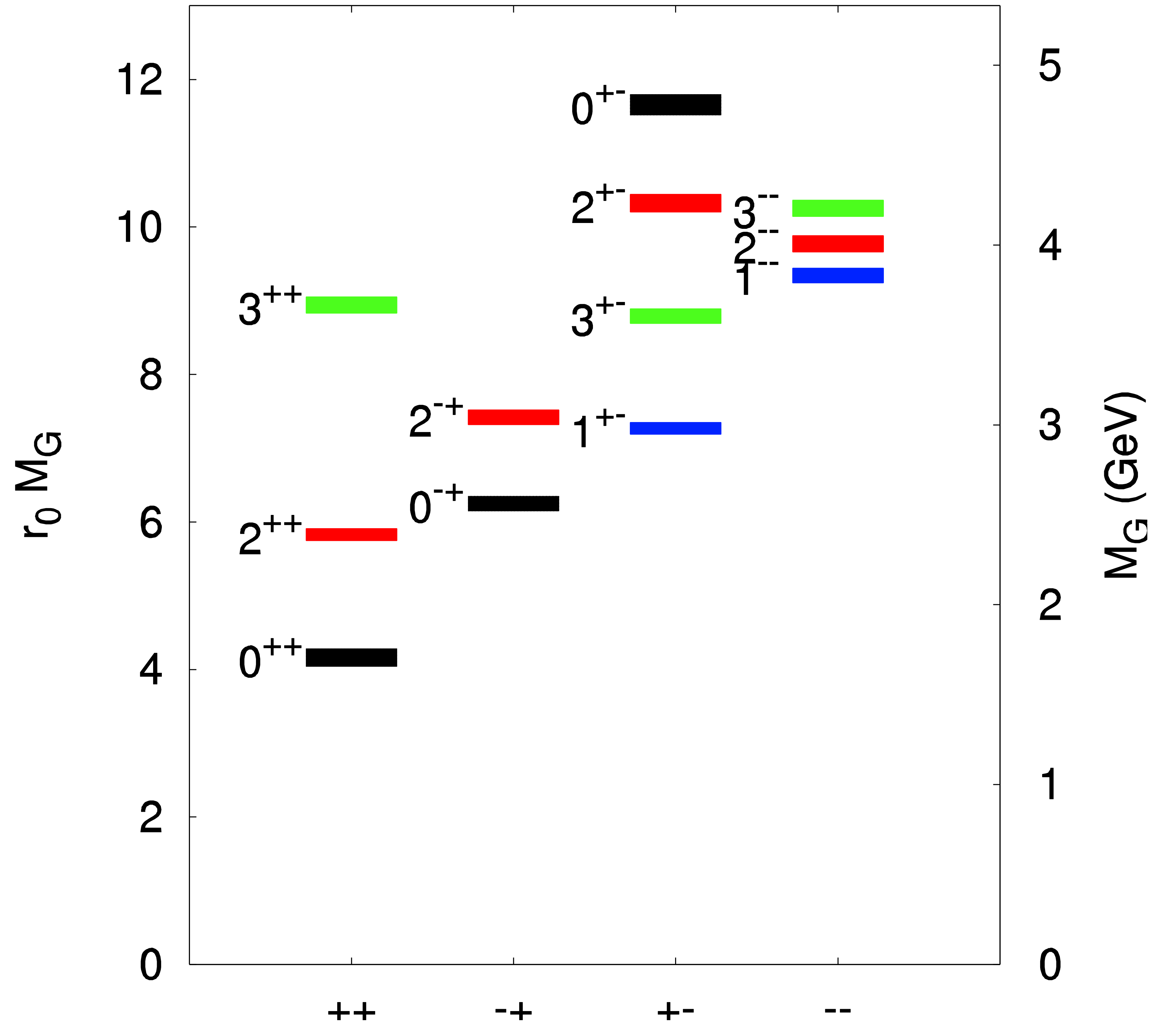


EPJC (2020) 80:746

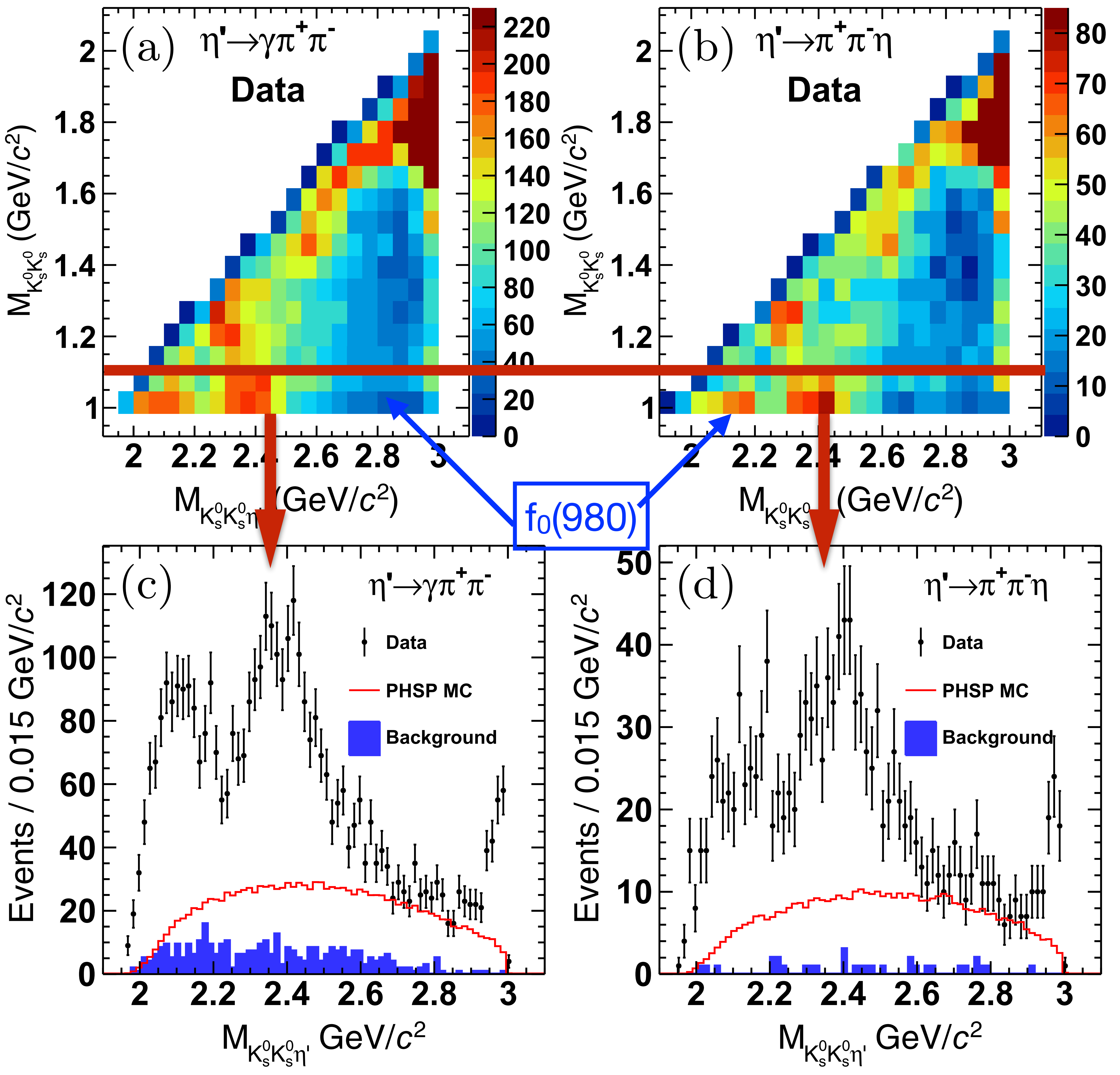


X(2370) - good candidate of 0^{-+} glueball

- Its mass is consistent with LQCD prediction on the 0^{-+} glueball
- Produced in the gluon-rich J/ψ radiative decays
- Observed in flavor symmetric decay modes of $\pi^+\pi^-\eta'$ and $K\bar{K}\eta'$ — favorite decay modes of 0^{-+} glueball
- Determination of its spin-parity is crucial



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



PRL 132 (2024) 181901

- Analysis advantage of $J/\psi \to \gamma K^0_s K^0_s \eta'$:
  - 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 $K^0_s K^0_s$ 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**

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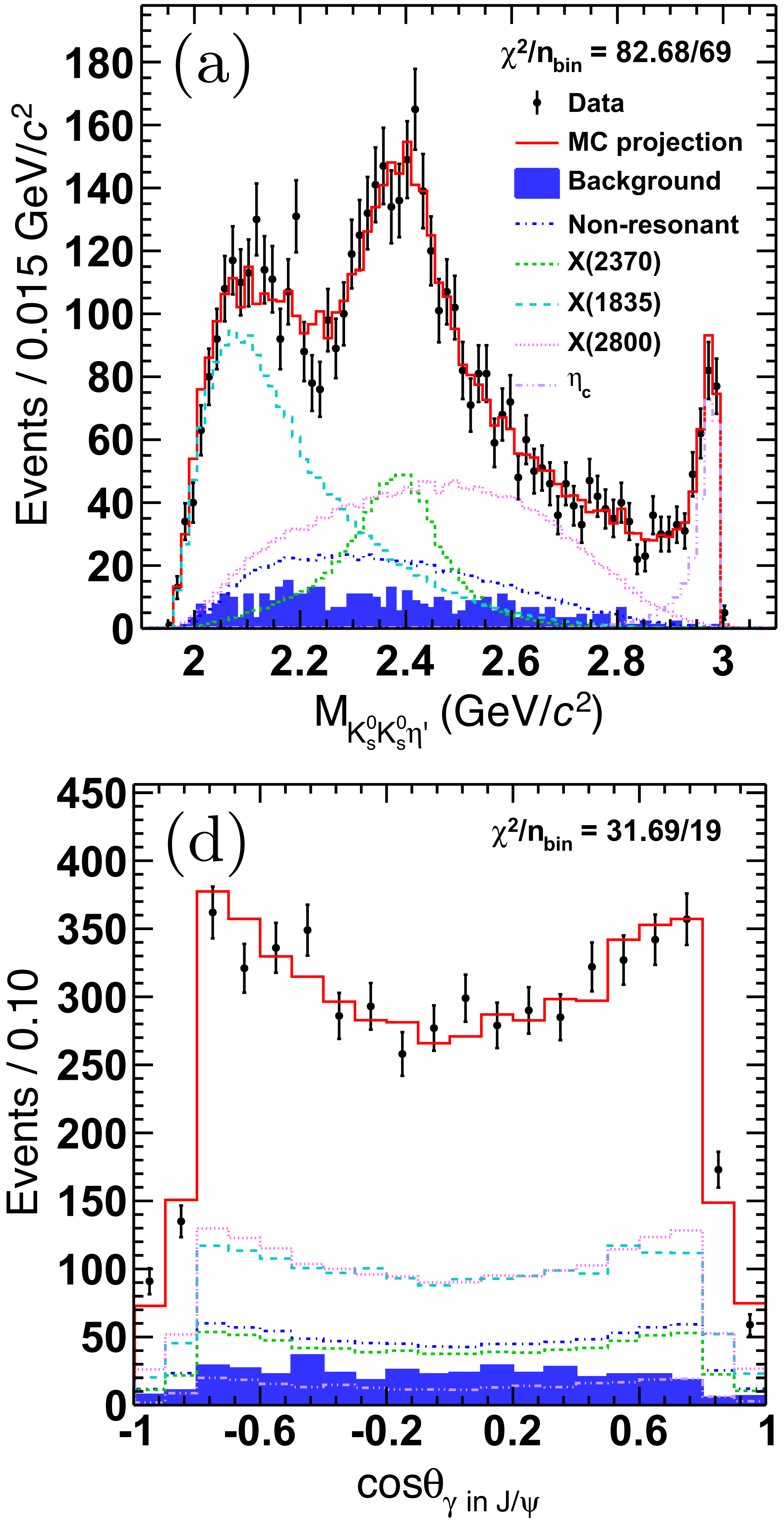

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Compared with LQCD prediction on Lightest 0^{-+} Glueball

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

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

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

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

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

LQCD prediction on lightest pseudoscalar glueball:

$J^{pc} = 0^{-+}$

$M = 2395 \pm 14$ 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, $B(J/\psi \to \gamma X(2370)) = (10.7^{+22.8}_{-7}) \times 10^{-4}$)

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

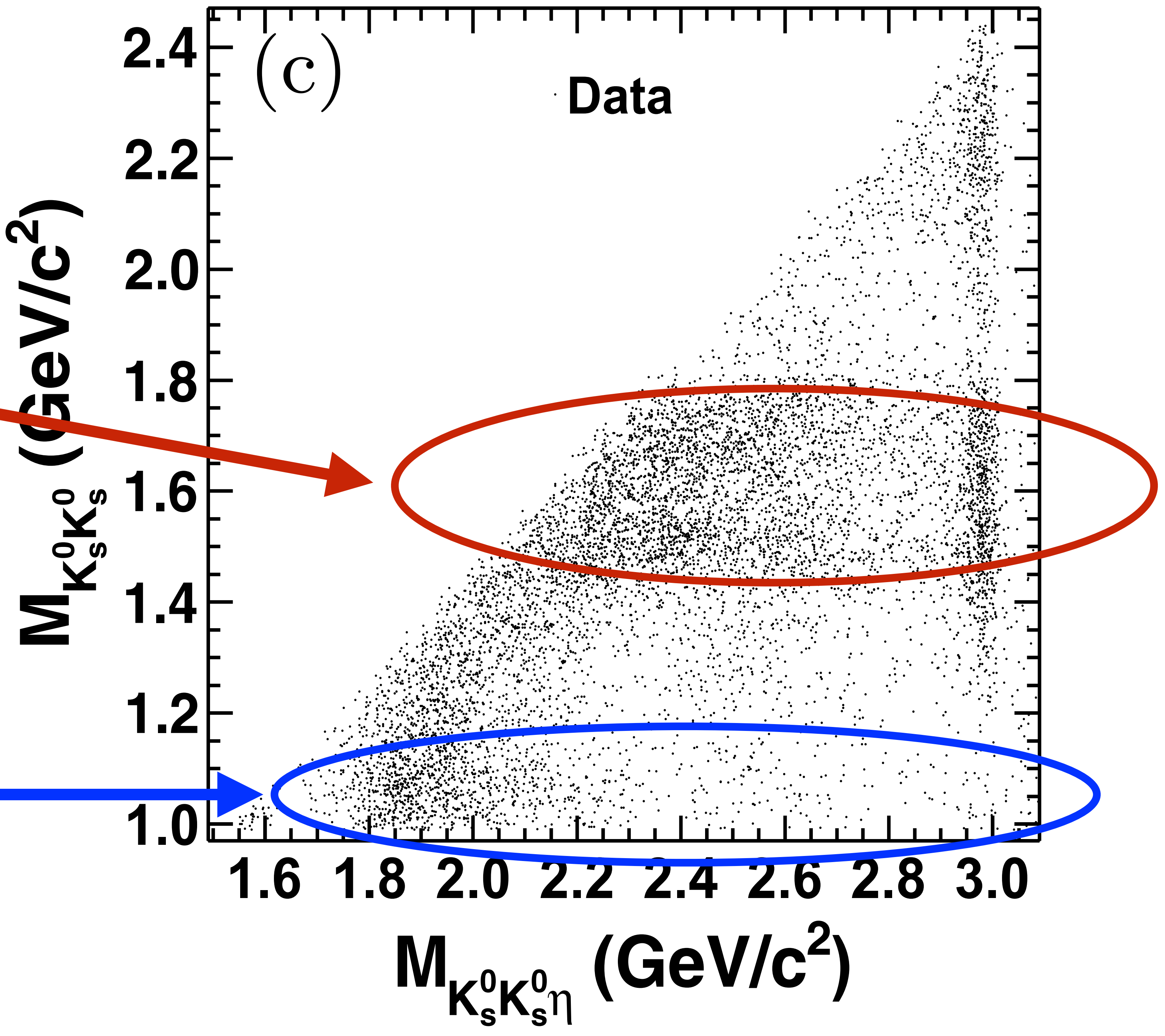
Observation and Spin-Parity Determination of the $X(1835)$ in $J/\psi \to \gamma K^0_S K^0_S \eta$

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

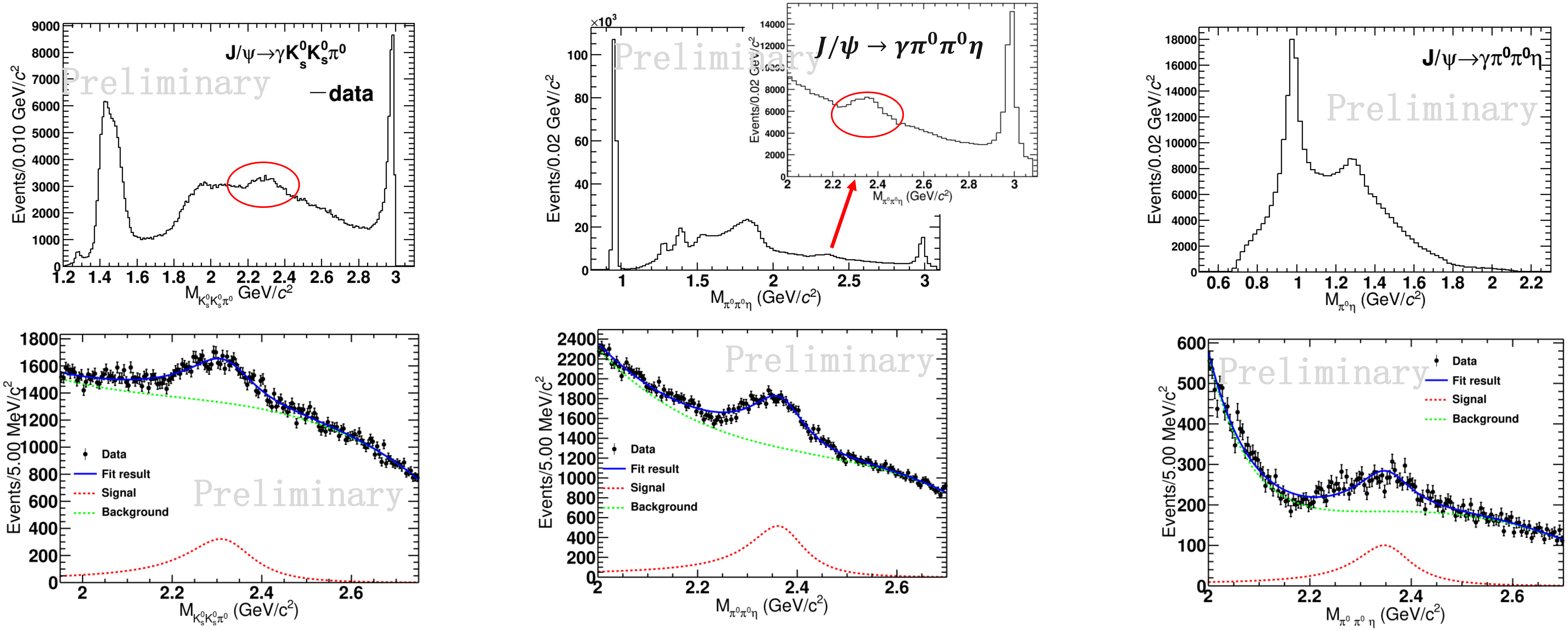
In the lower KK mass band of $f_0(980)$, no X(2370), nor η_c

With 1.31×10^9 J/ψ events



PRL 115 (2015) 091803

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 $X(2370) \to a(980)\eta$ 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)

Key scientific question: Glueballs exist or not?

- With 10 billion J/ψ data, we should be able to answer this key question — Either we find them or exclude them

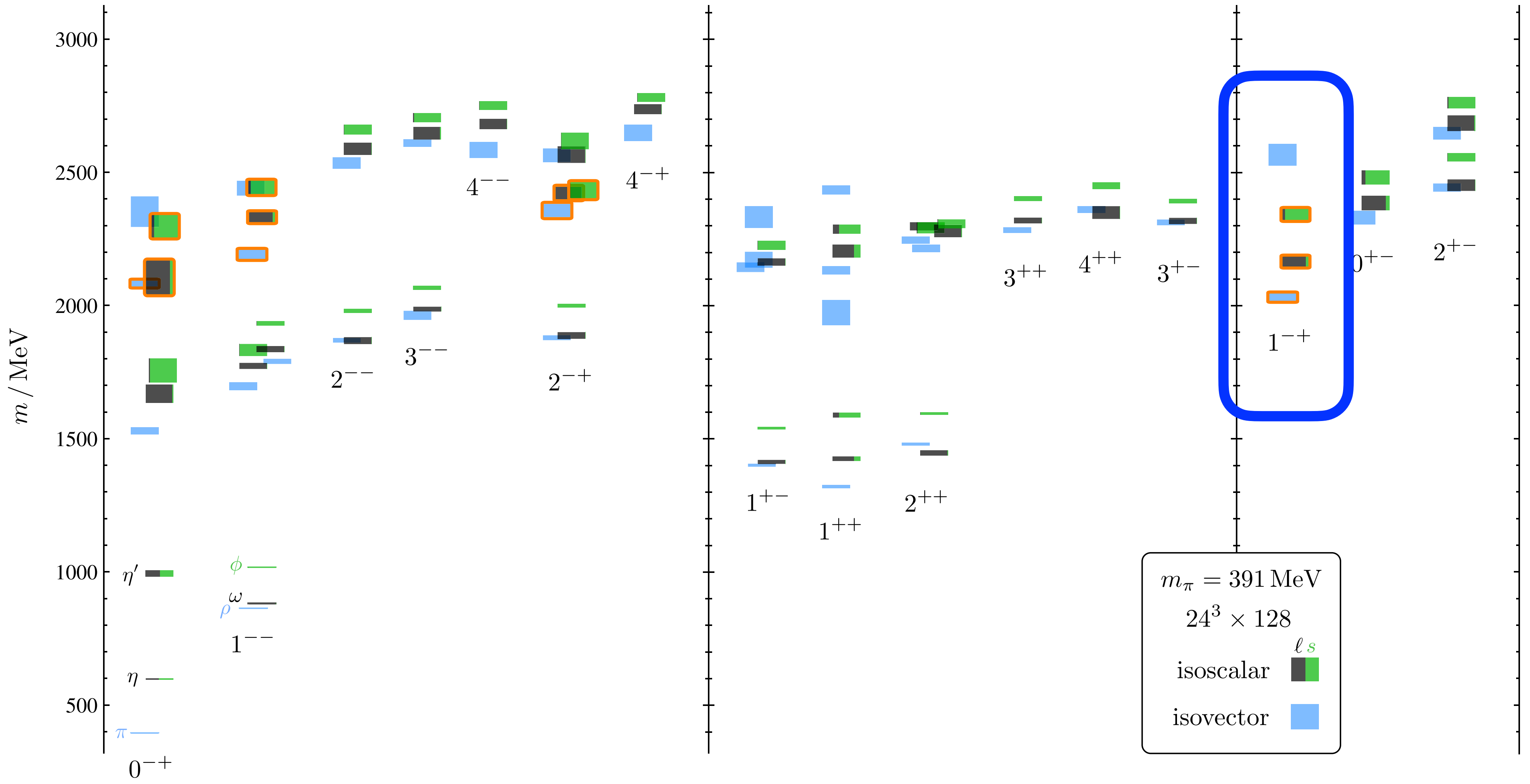
  - In the above 2.3 GeV mass region as LQCD 0-+ glueball prediction

  - X(2370) is the unique 0-+ particle produced in these "5 golden modes" and in J/ψ radiative decays

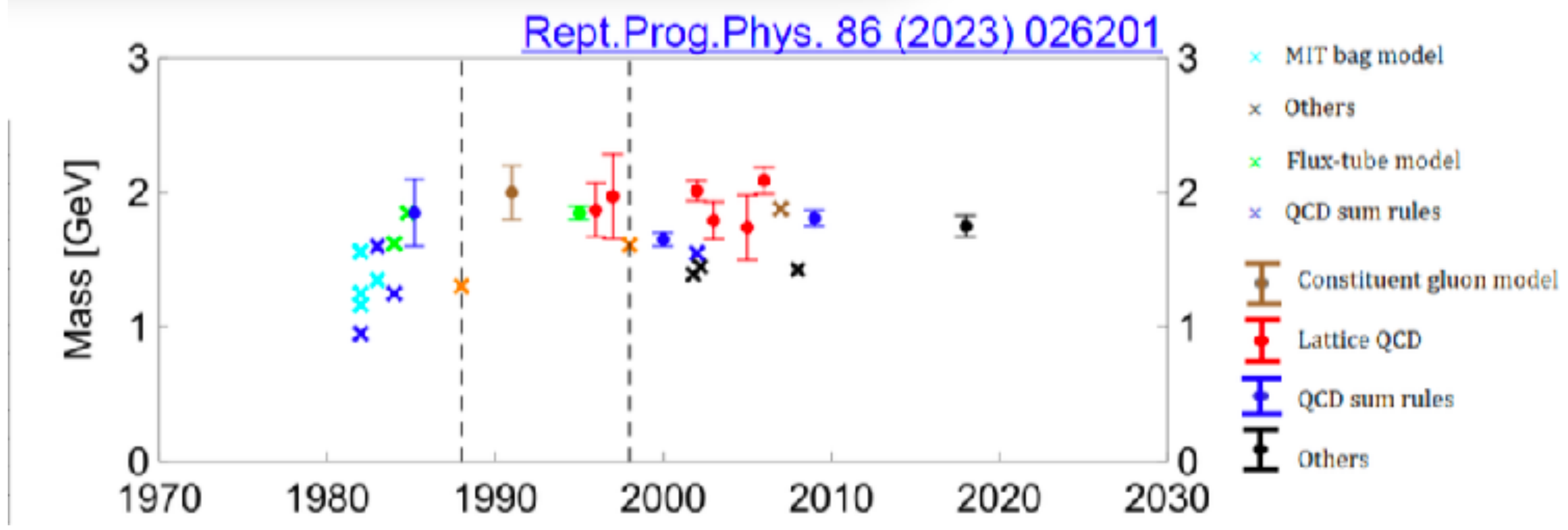
➡ 10 billion J/ψ data make us face a situation: Either we finally identify X(2370) as 0-+ glueball, or LQCD may face a big challenge in the glueball predictions

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

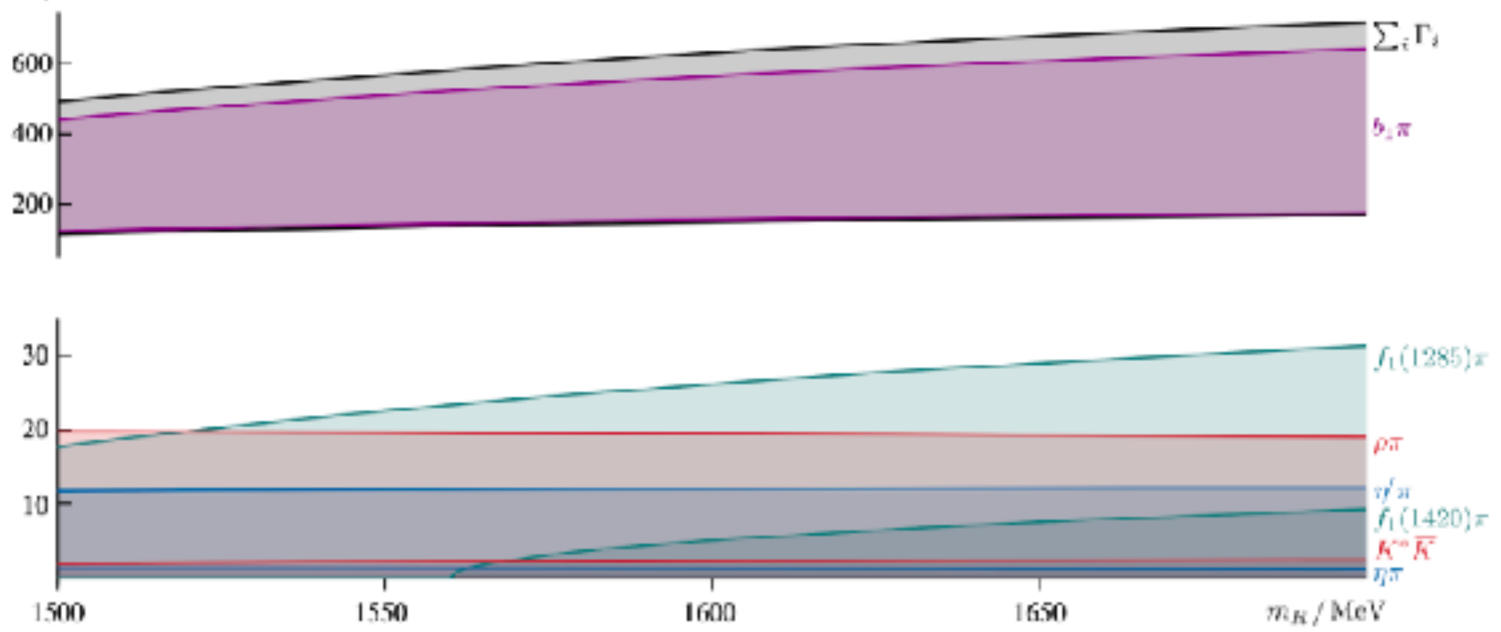


PRD 88 094505(2013)

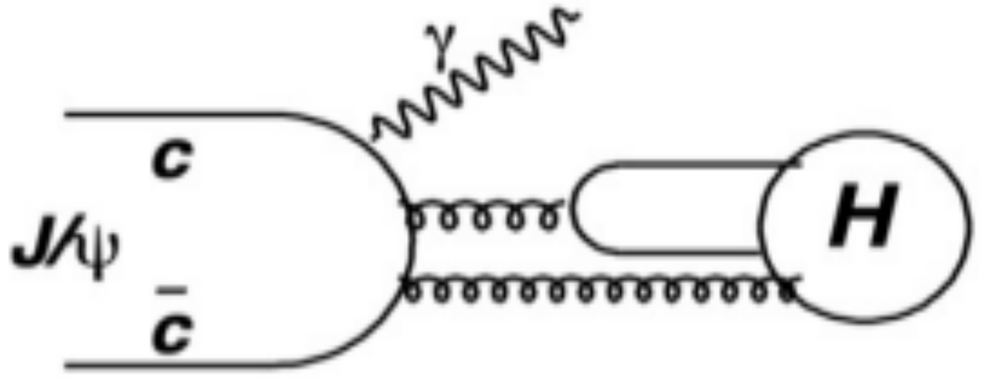


Mass of 1^{-+} hybrid

PRD 103, 054502(2021)



Width of 1^{-+} hybrid

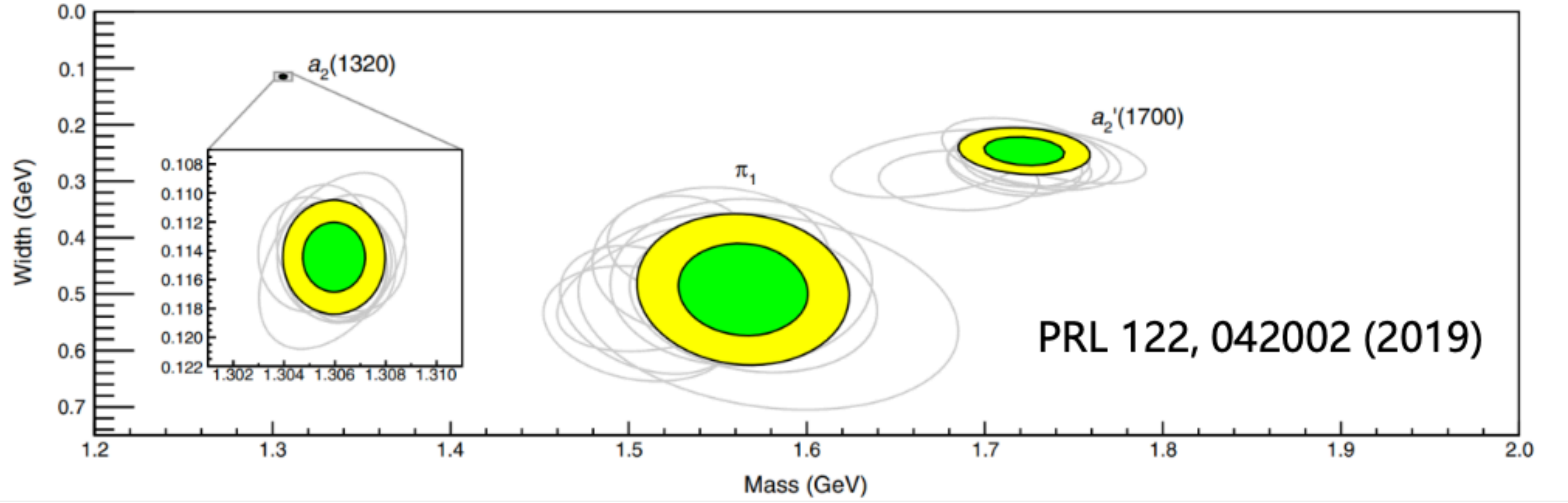


$$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$$

- **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

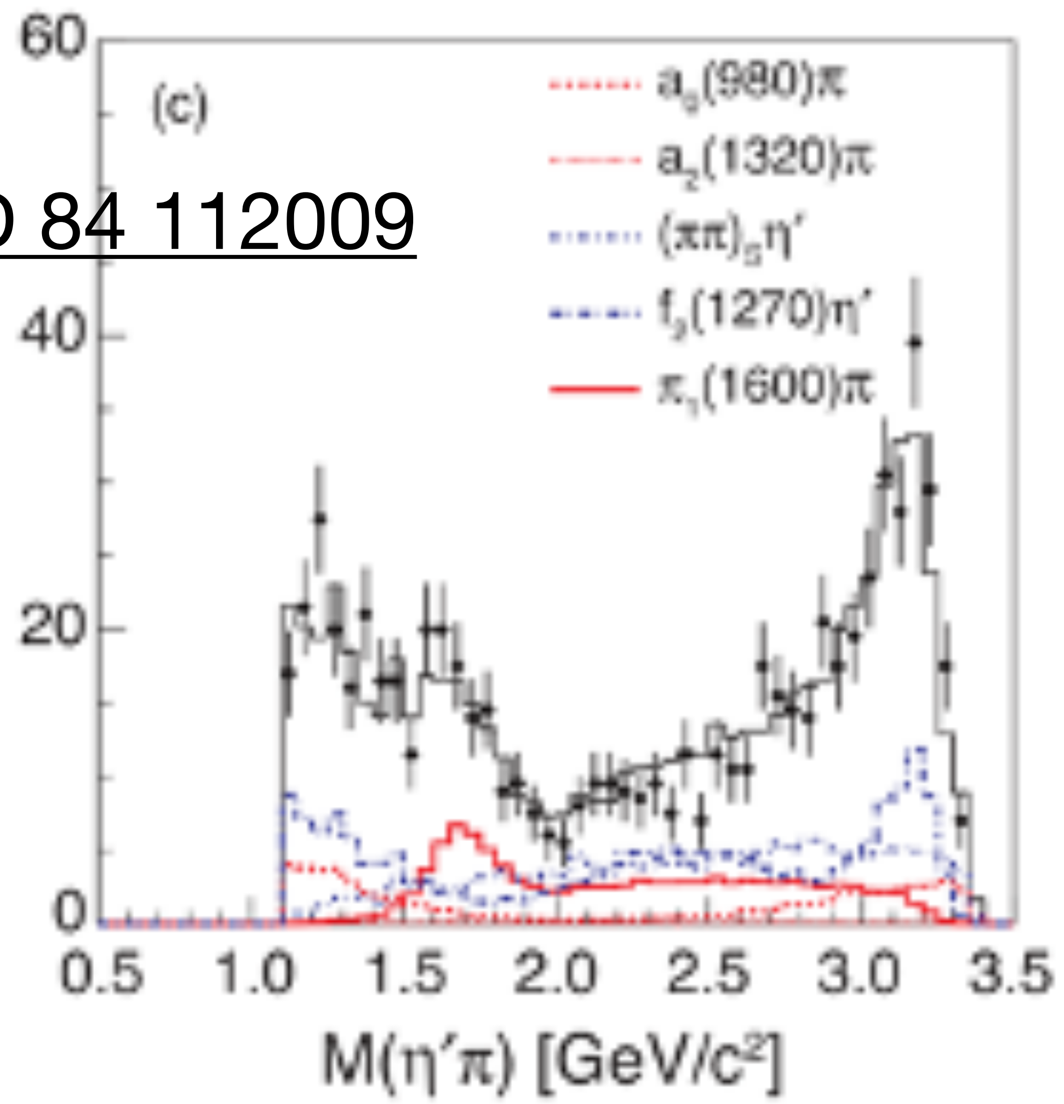
- Over 3 decades, experimental evidence for 3 candidates with 1^{-+} state:
  - All 1^{-+} iso-vectors
  - $\pi_1(1400)$: seen in $\eta\pi$
  - $\pi_1(1600)$: seen in $\rho\pi$, $\eta'\pi$, $b_1\pi$, $f_1\pi$
  - $\pi_1(2015)$: seen in $b_1\pi$ and $f_1\pi$
- Some claims are controversial
- $\pi_1(1400)$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

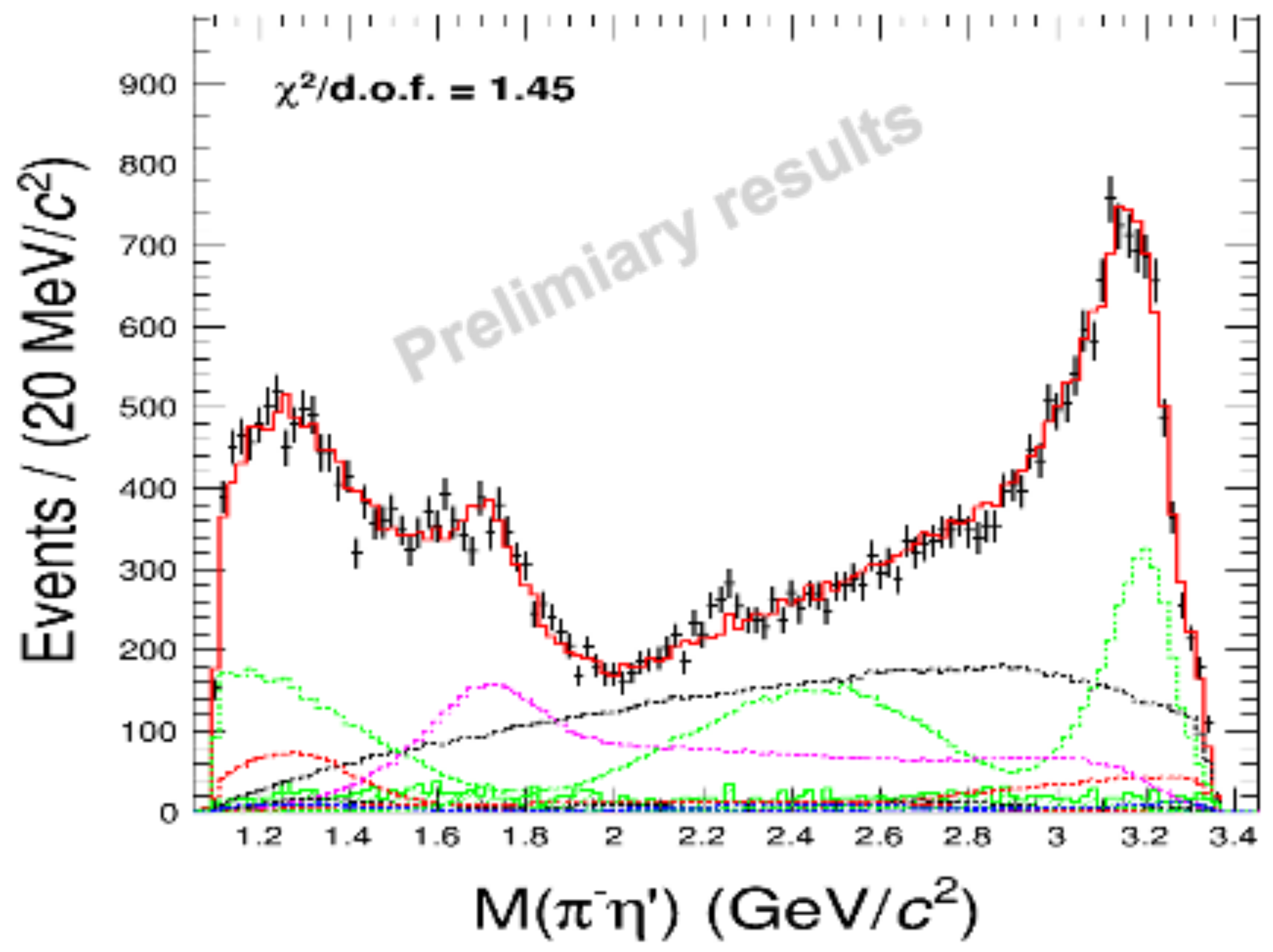


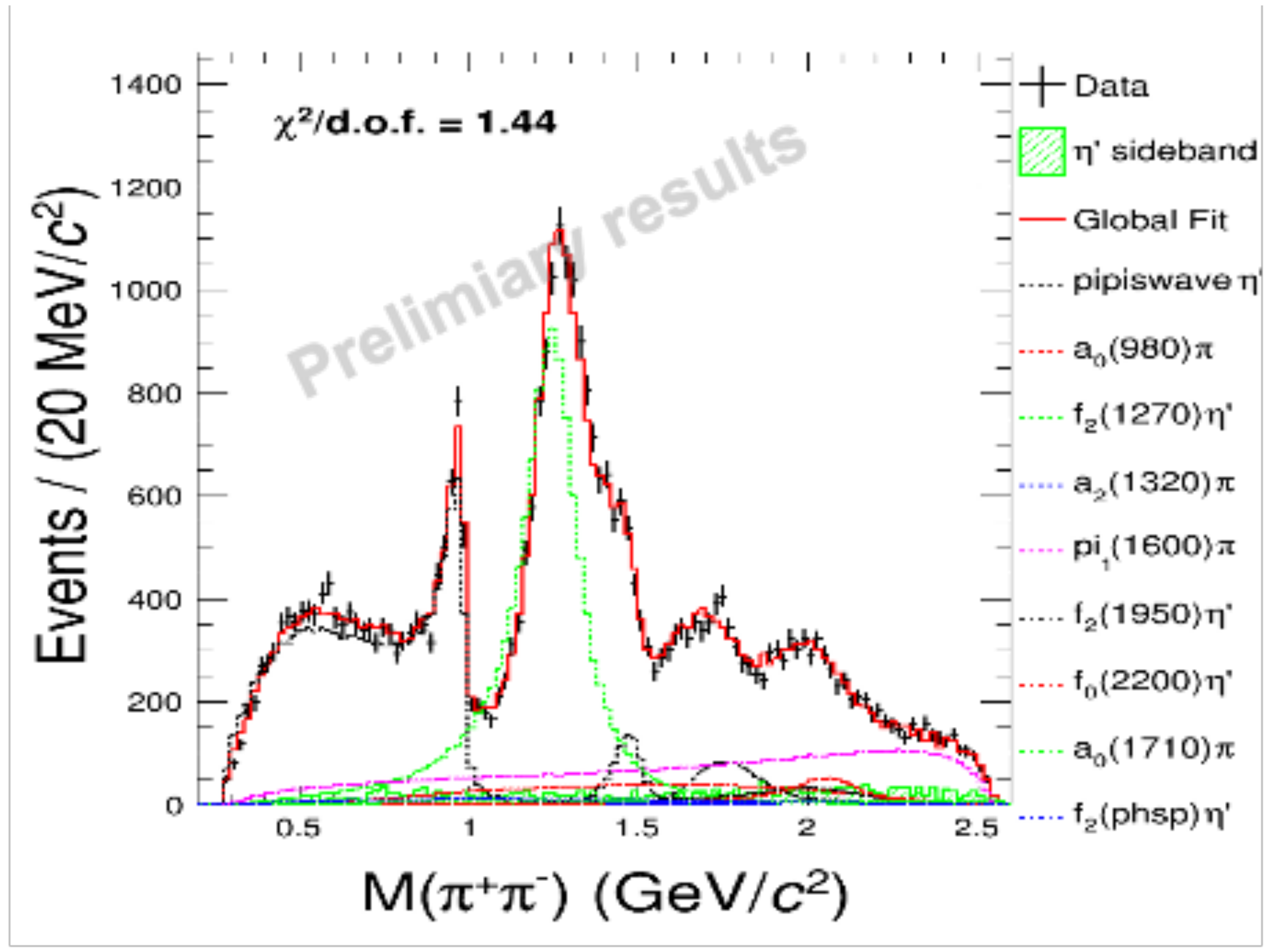
	Decay mode	Reaction	Experiment
$\pi_1(1400)$	$\eta\pi$	$\pi^- p \to \pi^- \eta p$	GAMS
		$\pi^- p \to \pi^0 \eta n$	KEK
		$\pi^- p \to \pi^- \eta p$	E852
		$\pi^- p \to \pi^0 \eta n$	E852
		$\bar{p} n \to \pi^- \pi^0 \eta$	CBAR
		$\bar{p} p \to \pi^0 \pi^0 \eta$	CBAR
	$\rho\pi$	$\bar{p} p \to 2\pi^+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

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

PRD 84 112009



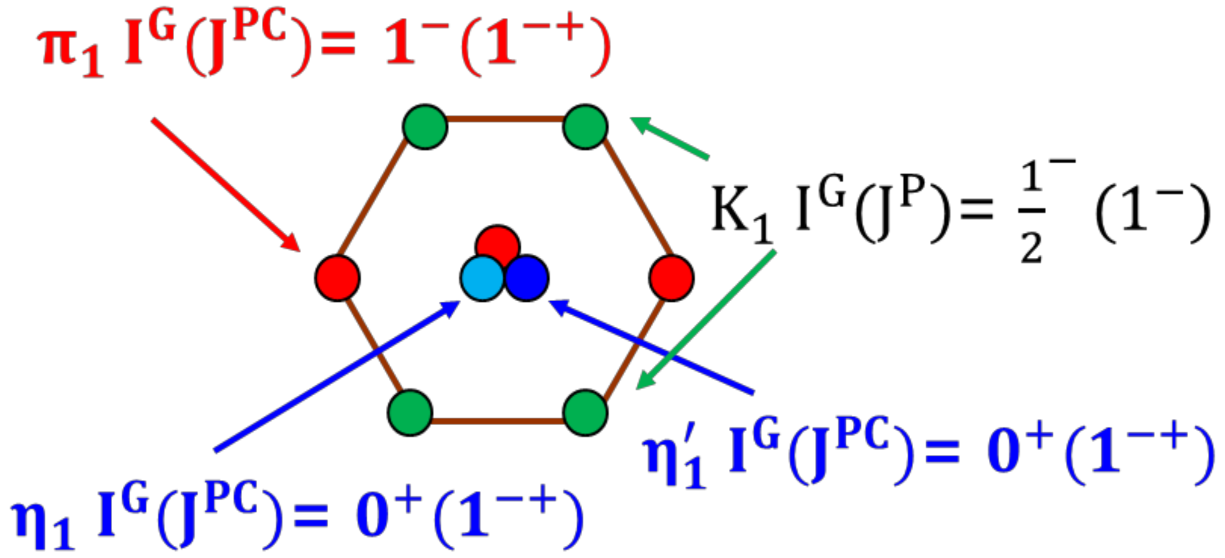


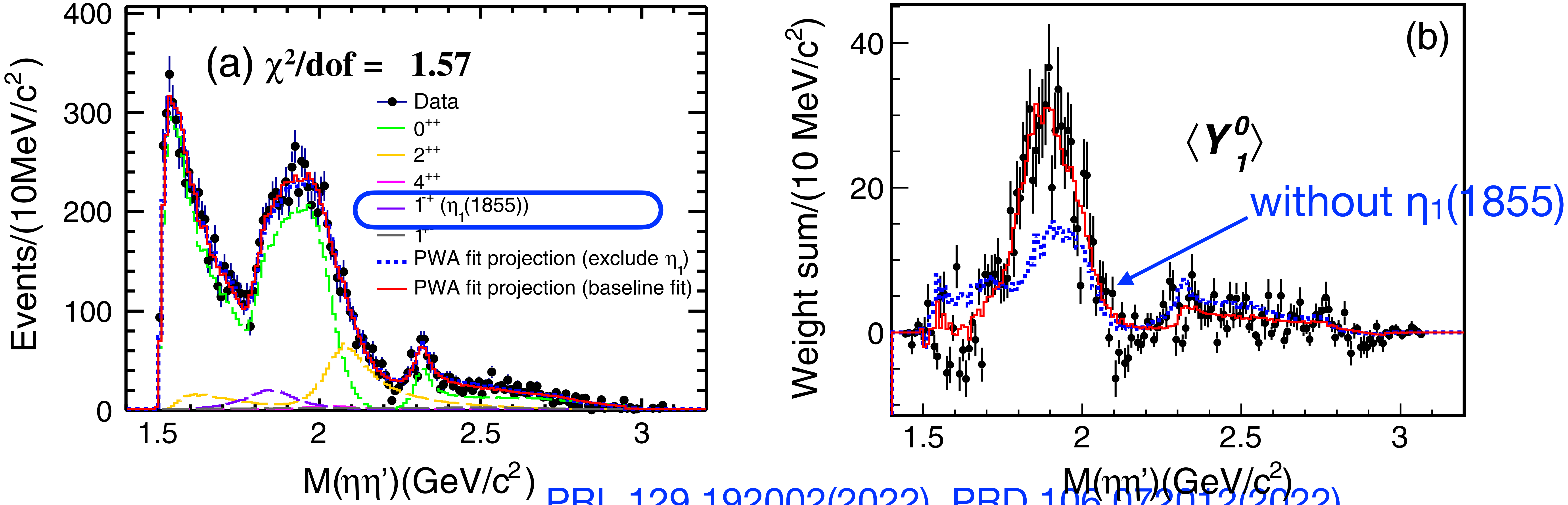


- CLEO-c results: evidence of an exotic P-wave $\eta'\pi$ amplitude with 4σ and but no significant phase motion
- PWA in $\psi' \to \gamma\chi_{c1}(\chi_{c1} \to \pi^+\pi^-\eta')$ with higher ψ' data sample @ BESIII:
  - **First observation of Exotic 1^{-+} Isovector state $\pi(1600)$ with a significance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

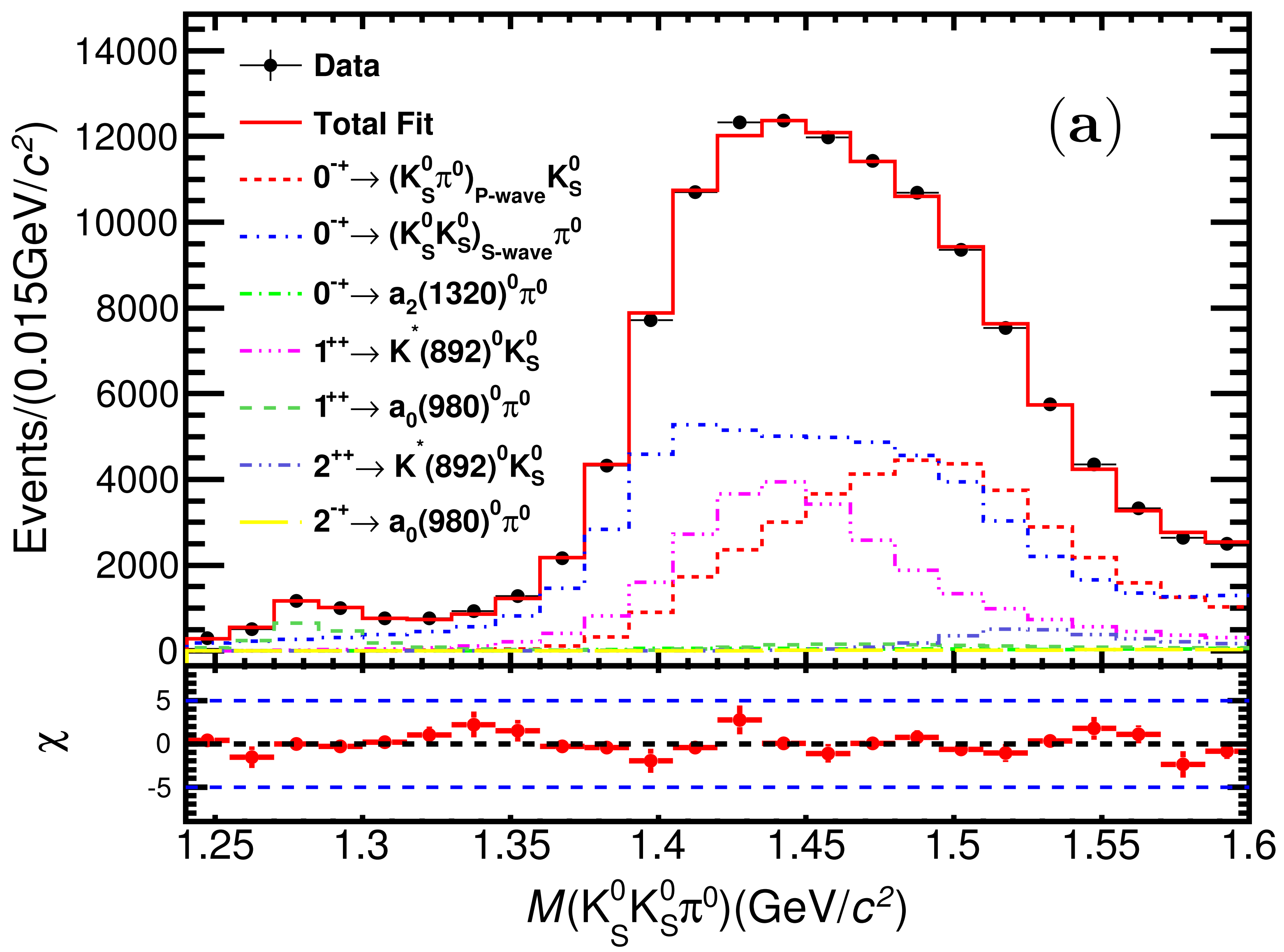




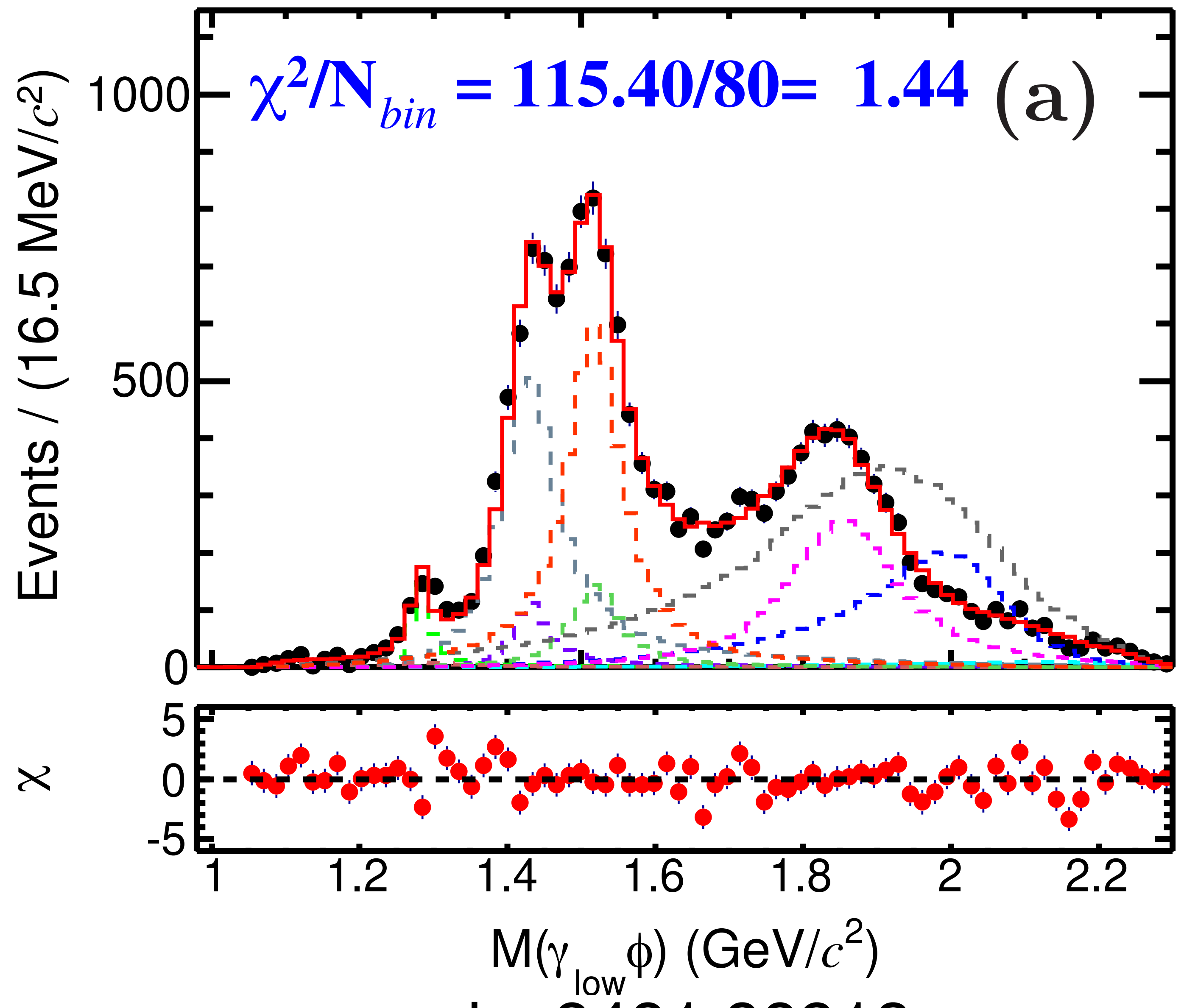
PRL 129 192002(2022), PRD 106 072012(2022)

- **$J/\psi \to \gamma\eta\eta'$ is a good channel for $\eta_1(1^{-+})$ search**
- **Observation of an isoscalar 1^{-+} $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$ (>19σ)**
  - PWA: quasi two-body decay amplitudes in the sequential decay processes with covariant tensor formalism
  - $M = 1855 \pm 9^{+6}_{-1}$ MeV, $\Gamma = 188 \pm 18^{+3}_{-8}$ MeV, $B(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$
- **Mass consistent with hybird on LQCD, and more interpretations** (KK Molecule/Tetraquark)

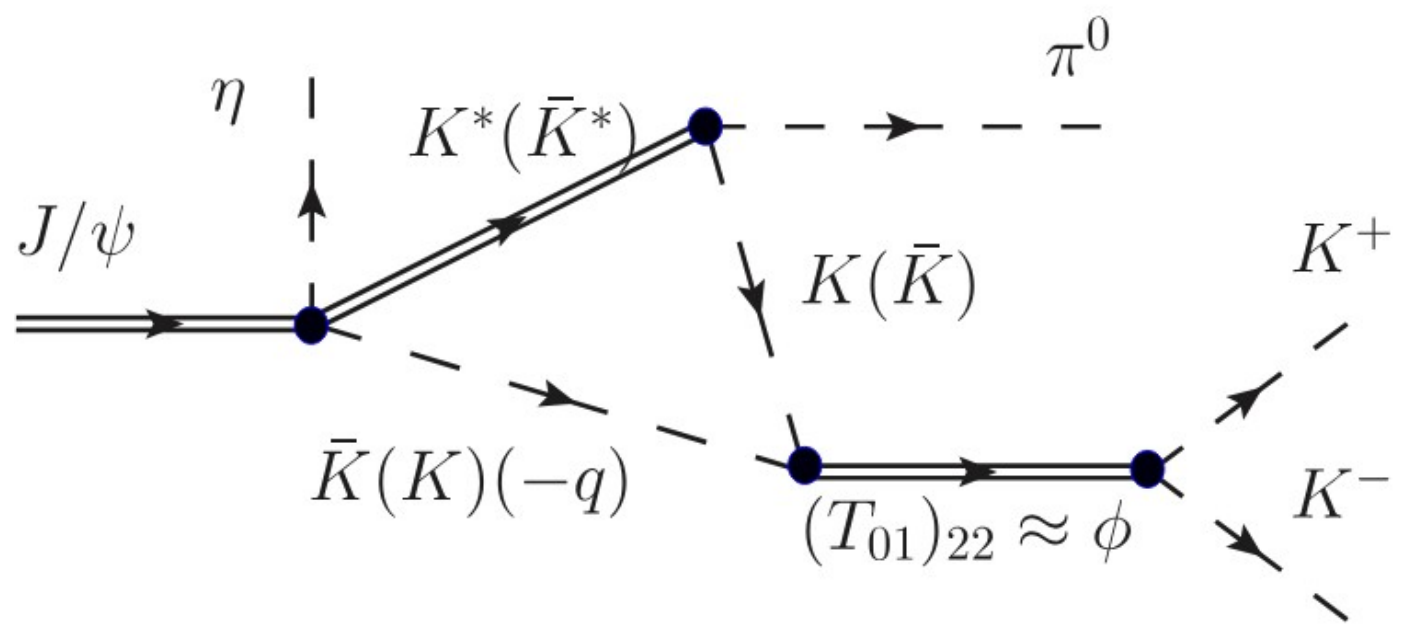
Shed new lights on $\eta(1405)/\eta(1475)$ puzzle



JHEP 03 (2023) 121



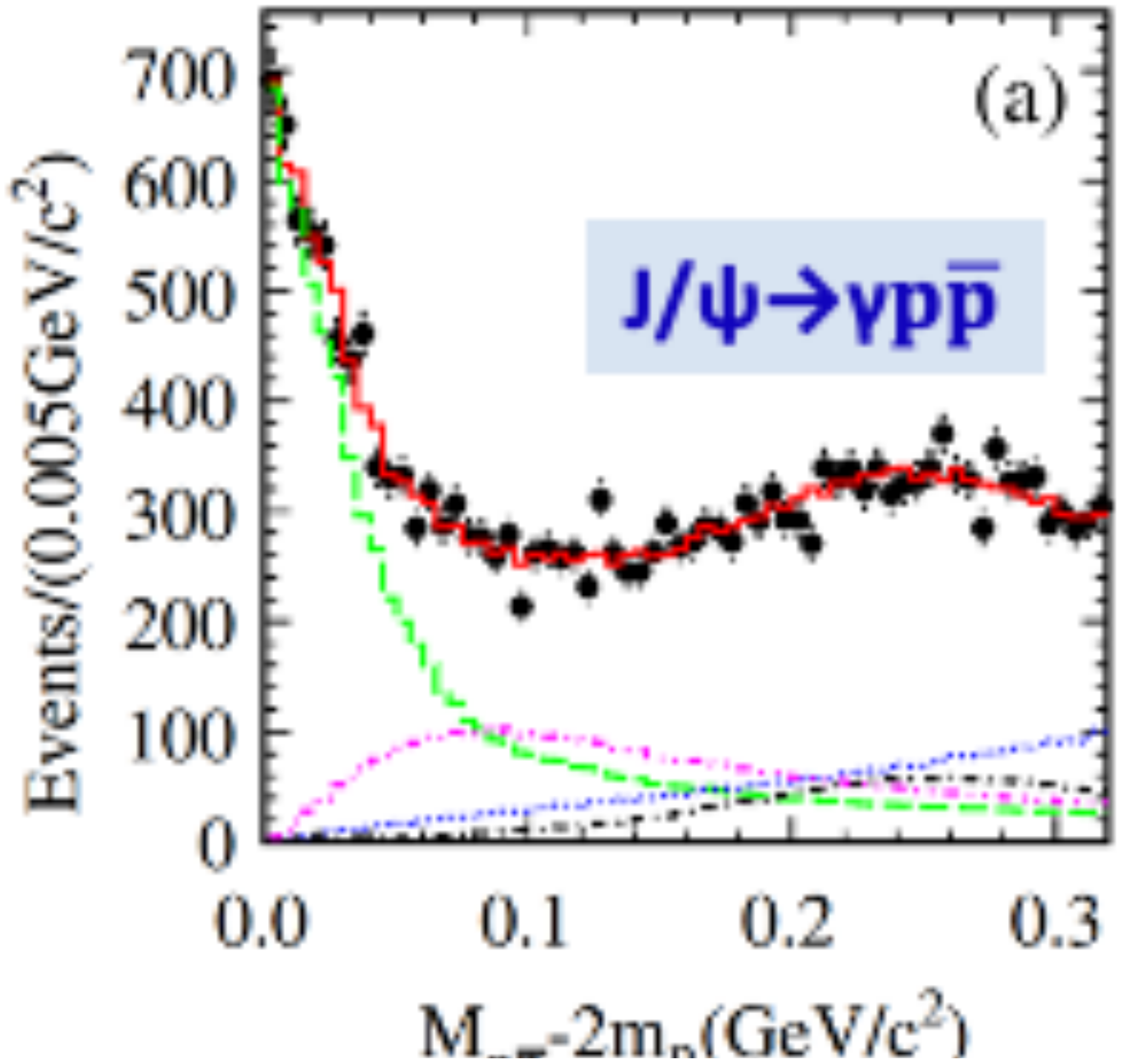
arxiv: 2401.00918



Triangle sigularity?

- ◈ η(1295) and η(1475) are generally assigned to be the first radial excitation of the ground states of η and η’
  - ✦ η(1405) - η(1475) puzzle :Whether or not the η(1405) - η(1475) are 1 or 2 states?
- ◈ PWA of $J/\psi \to \gamma K_s K_s \pi^0$: Two isoscalar states η(1405) and η(1475) around 1.4GeV can well fit data
- ◈ PWA of $J/\psi \to \gamma\gamma\Phi$： observed η(1405) with 18.9σ, while η(1475) can not be excluded (3.9σ)

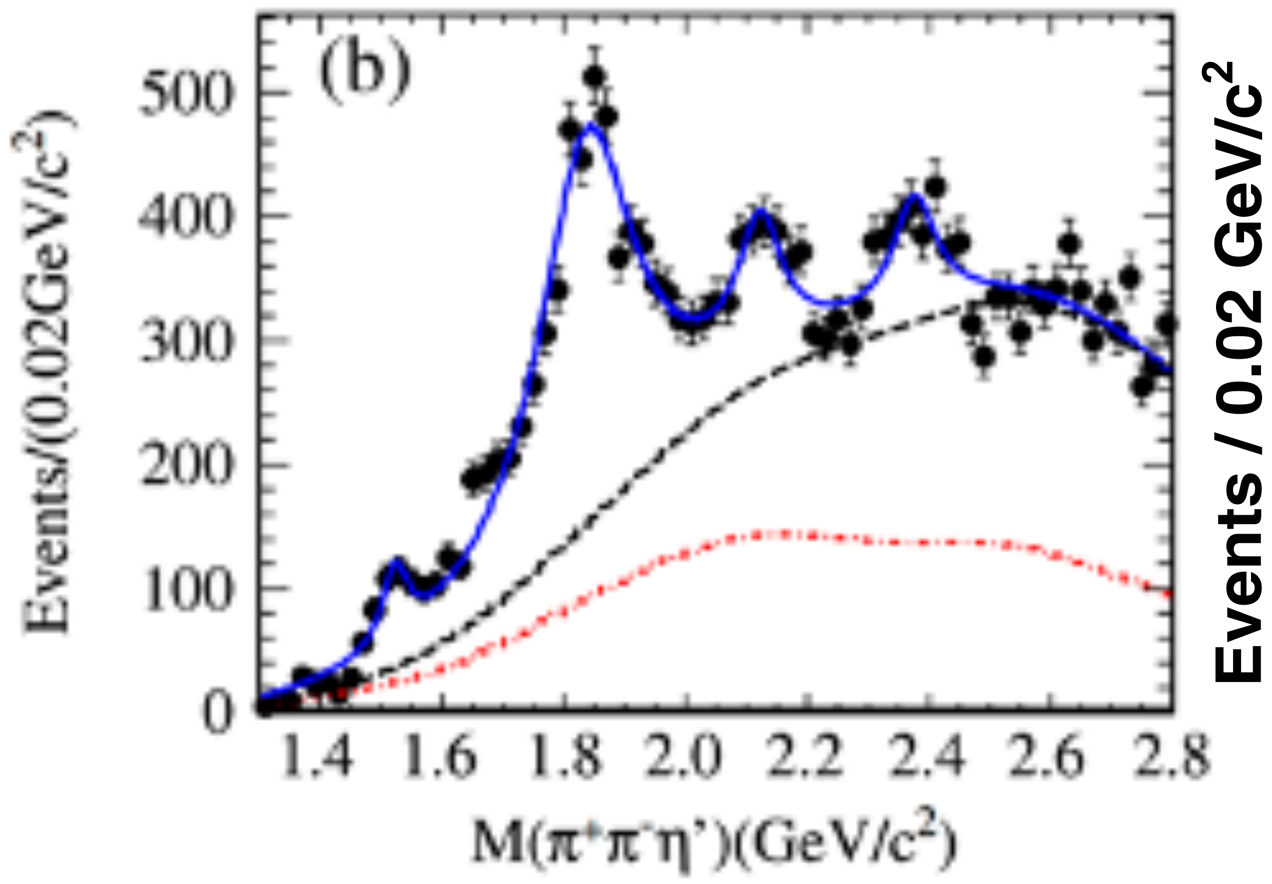
Observation of X($p\bar{p}$) and X(1835)



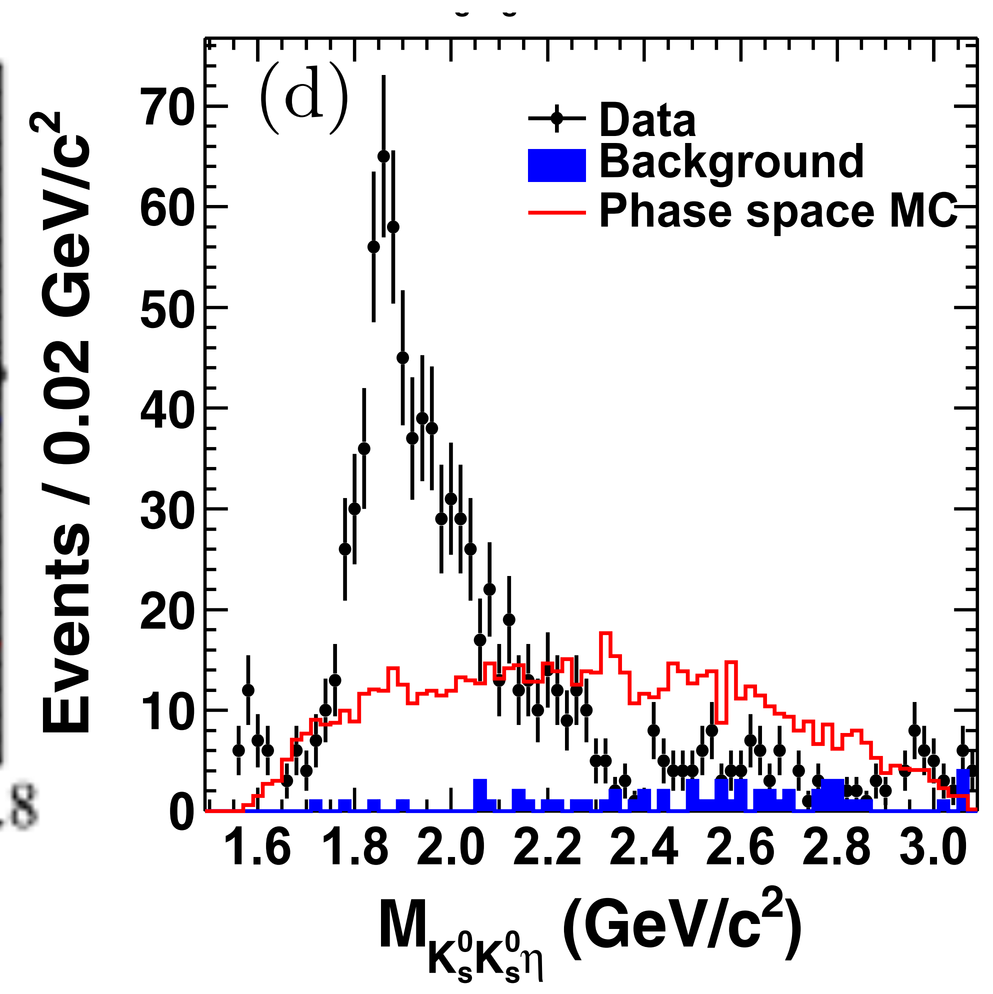
PRL 108 (2012)112003

- $p\bar{p}$ mass threshold enhancement X($p\bar{p}$) :
  - Discovered in $J/\psi \to \gamma p\bar{p}$ by BESII in 2003 and confirmed by BESIII and CLEO-c
  - Further determination of Spin-parity to be 0-+
  - No similar threshold structure in other channels → It can not be pure FSI effect

M= $1832^{+19}_{-5}{}^{+18}_{-17}\pm19$ MeV/c^2, Γ=13±19MeV/c^2 (<76MeV/c^2@90% C.L.)



PRL 106 (2011)072002



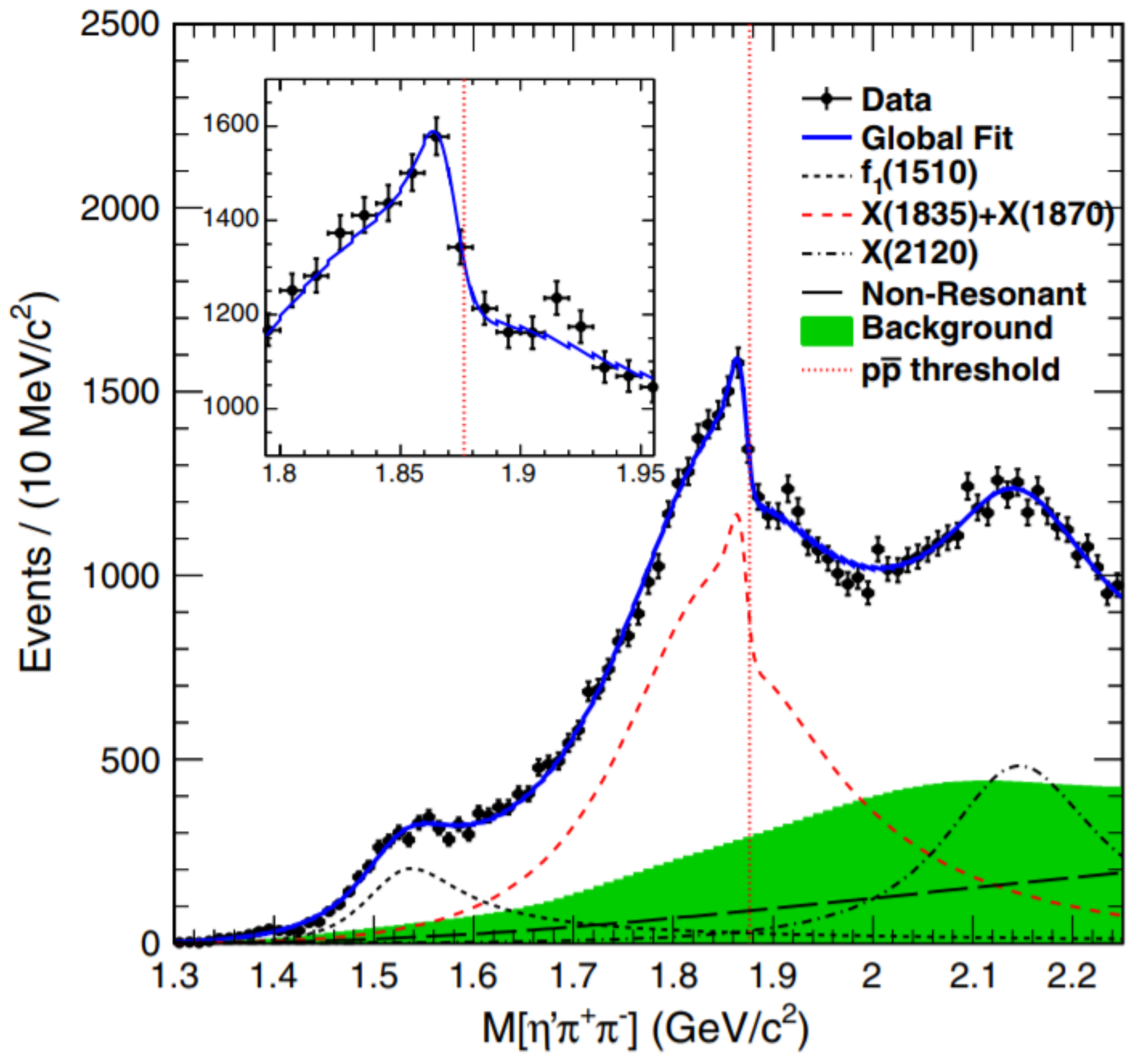
PRL 115 091803

- X(1835) :
  - Discovered by BESII and confirmed by BESIII in $J/\psi \to \gamma\pi\pi\eta'$
  - Determination of Spin-parity to be 0-+ in $J/\psi \to \gamma K_s K_s \eta$

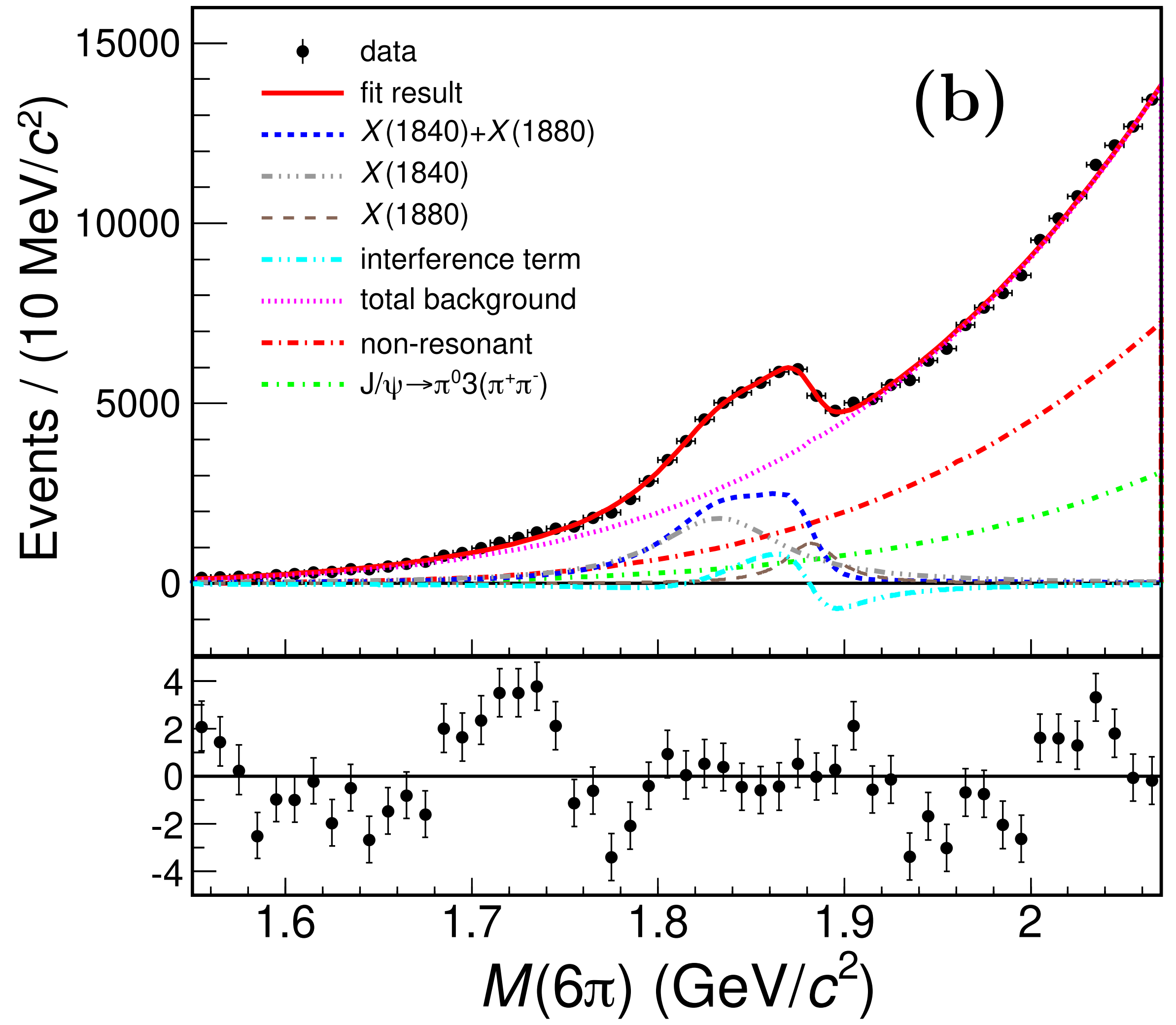
M= $1844\pm9^{+16}_{-25}$ MeV/c^2

Γ=$192^{+20}_{-17}{}^{+62}_{-43}$ MeV/c^2

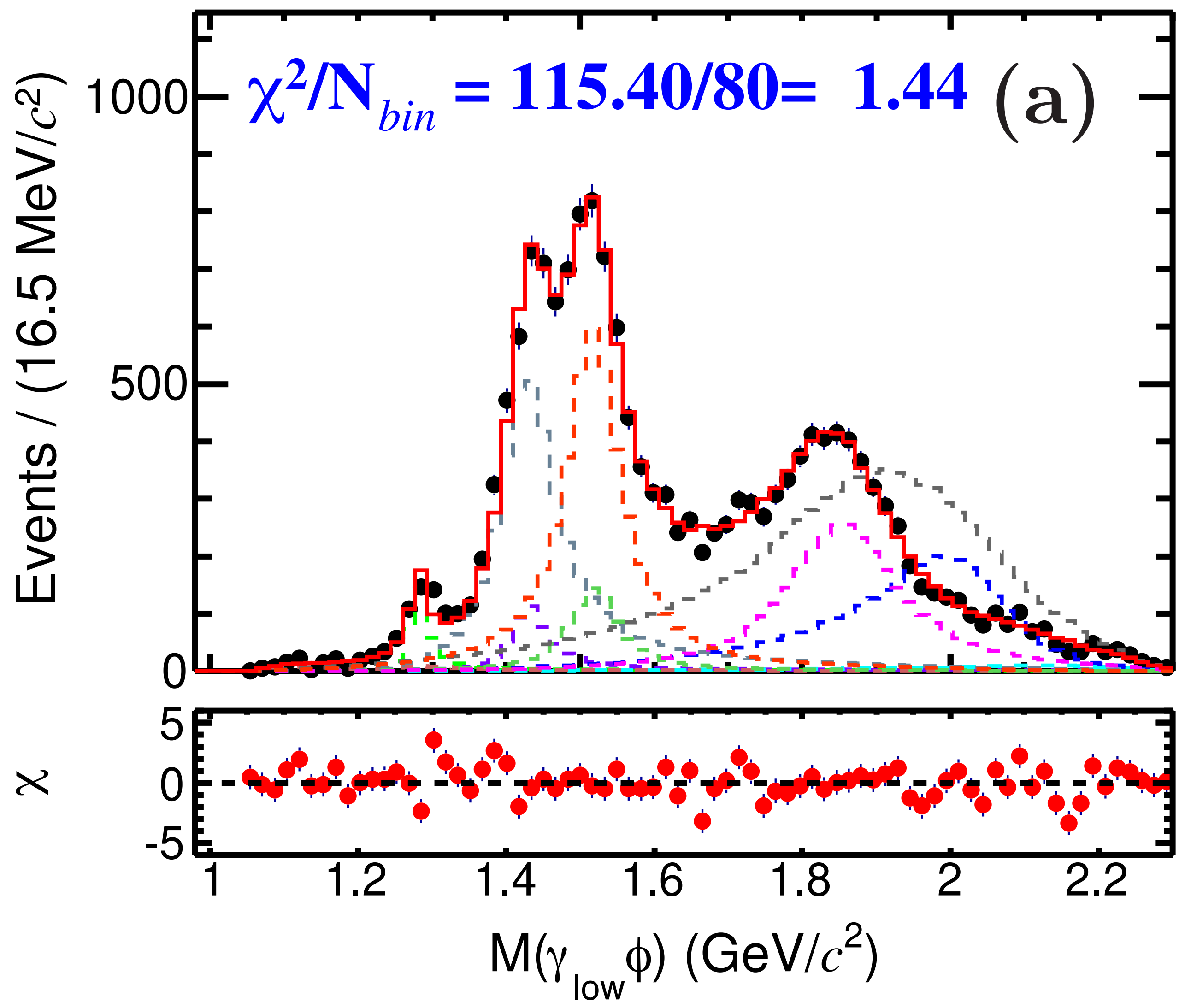
Direct link between the X($p\bar{p}$) and X(1835)



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.

Interpretation

	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	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 (η_c dominant decays) and suppressed decay modes are consistent between the X(2370) and η_c
  - **A good agreement with the glueball interpretation**
- **The X(2370) production properties observed:**
  - richly produced in J/ψ radiative decays as the glueball expectation
- **Mass, spin-parity:** consistent with 0^{-+} glueball prediction

In the mass region larger than 2GeV, the only particle X(2370) for the 0^{-+} glueball candidate in J/ψ radiative decays and five golden decay modes ($\pi\pi\eta'$, $K\bar{K}\eta'$, $K\bar{K}\pi$, $\pi\pi\eta$, $K\bar{K}\eta$)