Light Hadron Spectroscopy @ BESIII

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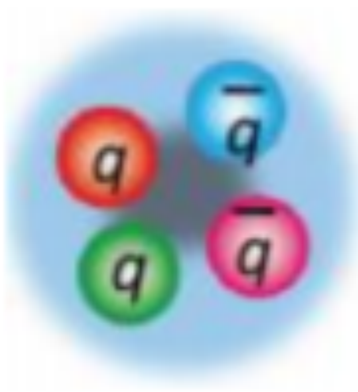
Forms of hadrons

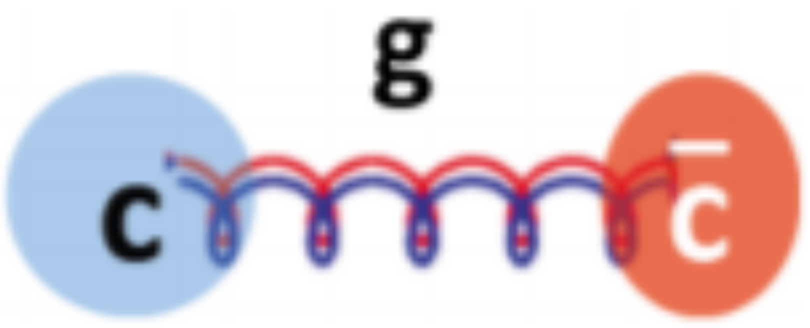
◈ **In quark model:**

◈ **Other forms of hadrons:**

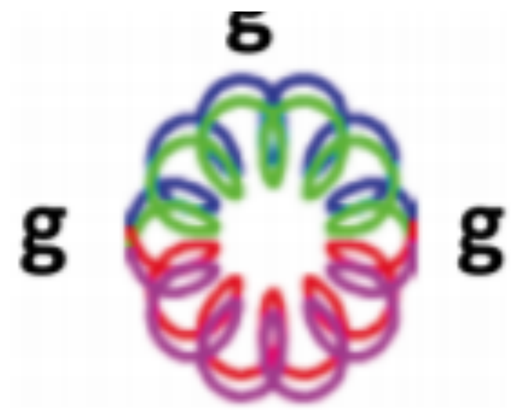
- ✦ **Multi-quark:** quark number >= 4



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



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

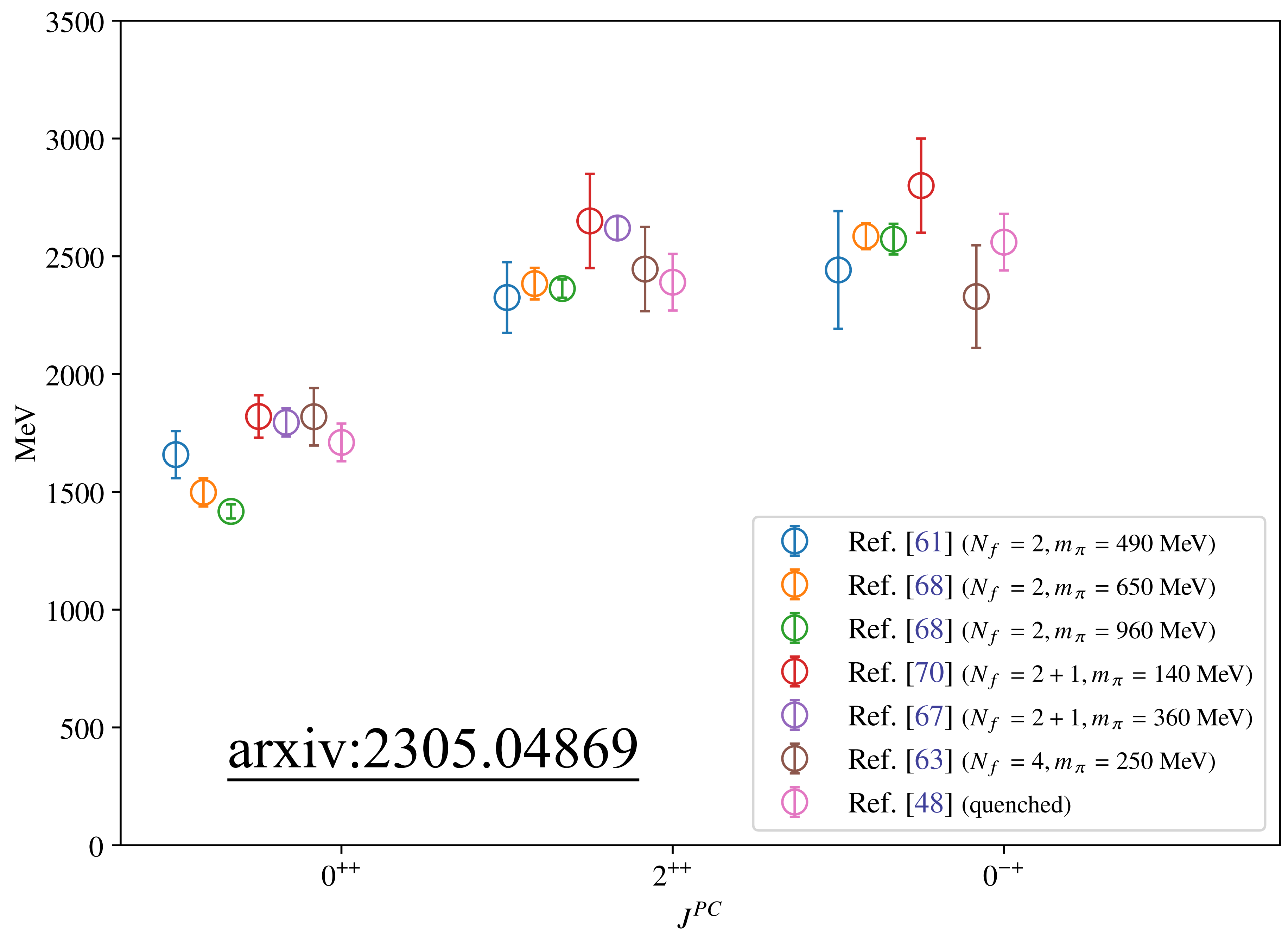


The basic theory for strong interactions is quantum chromodynamics (QCD)

Glueball

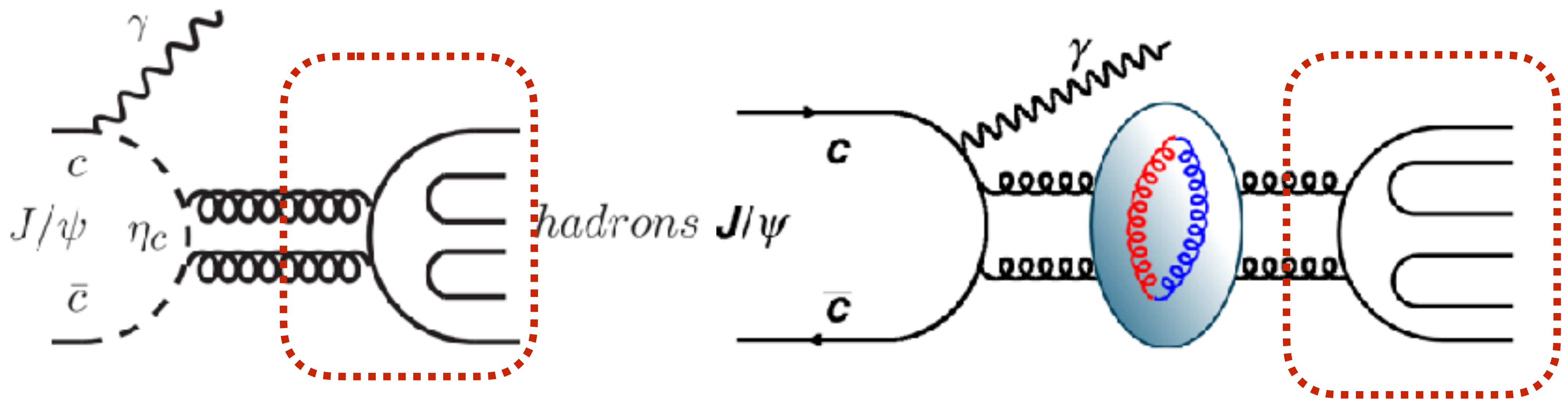
Glueballs are unique particles via self-interactions and formed with force carriers

- **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



Glueball Production and Decay

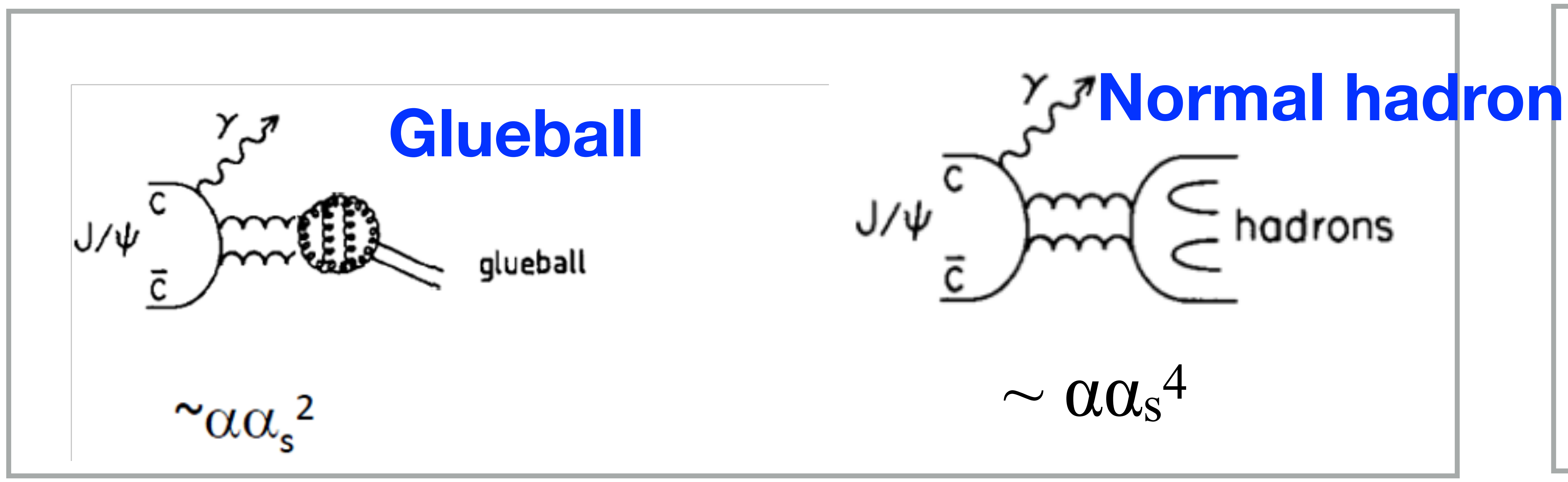
- **Glueball production:**
  - **Strongly produced in gluon-rich processes**
- **Glueball decay:**
  - Gluon is flavor-blind
  - No rigorous predictions on decay patterns and branching ratios
  - **Could have similar decays to the charmonium families** as they all decay via gluons (Theor. Phys. 24.373, PLB 380(1960)189-192)

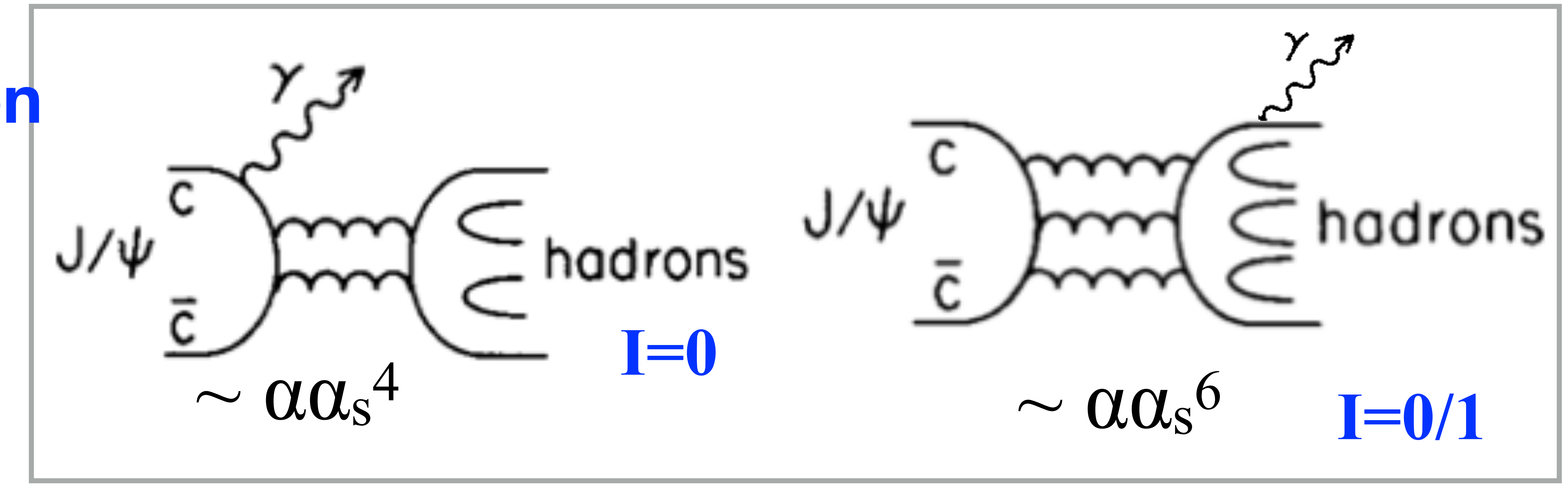


  - The 0^{-+} glueball could have similar decays of η_c
  - One of the favorite decay modes of η_c is $\pi\pi\eta'$, so $J/\psi \to \gamma\, \pi\pi\eta'$ could be a good place to search for the 0^{-+} glueball

J/ψ radiative decays

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

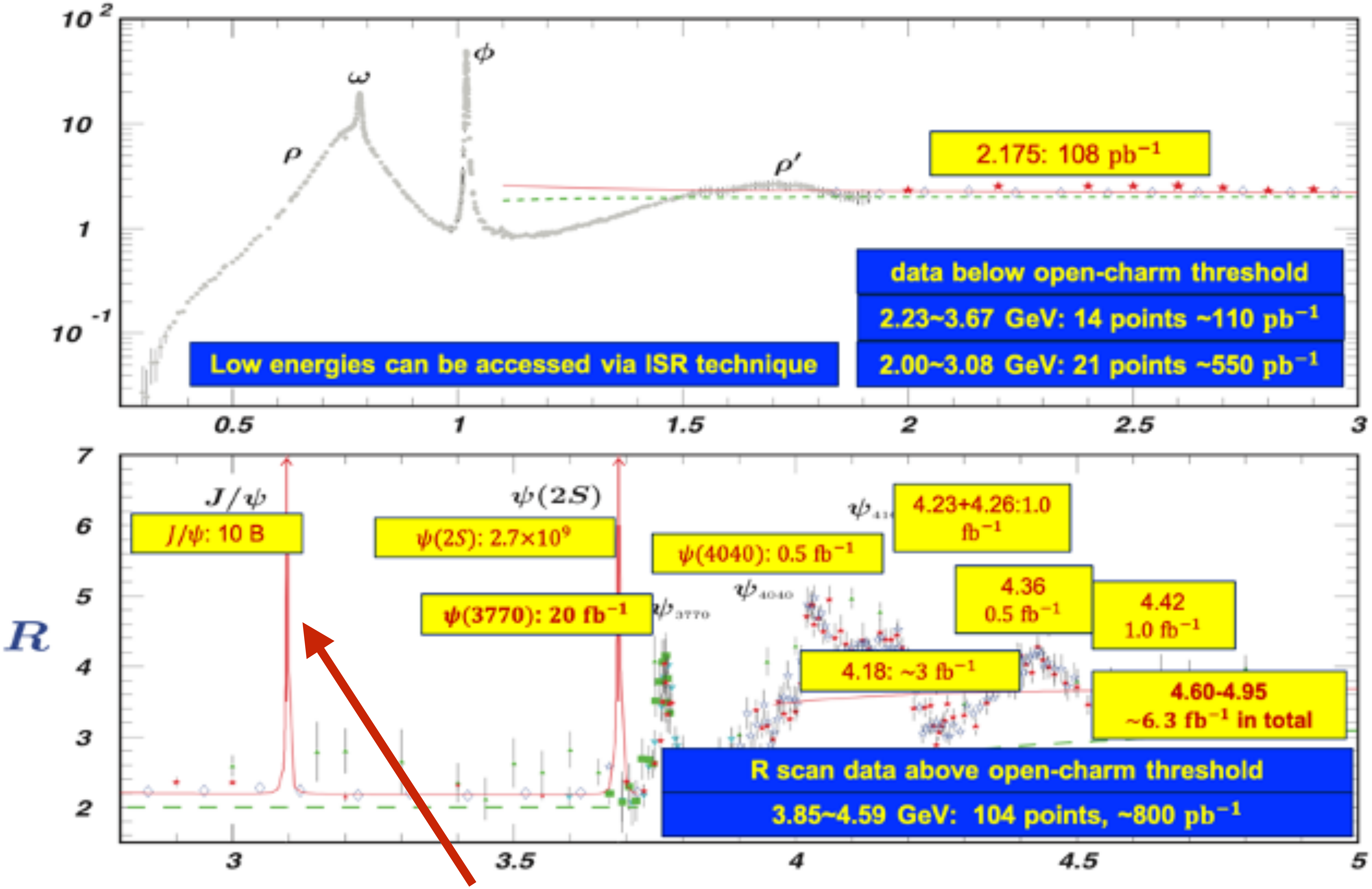




- **Isospin filter:** final states dominated by **I=0** processes
- **Spin-parity filter: C parity must be +**, so $J^{PC}=0^{-+}, 0^{++}, 1^{++}, 2^{++}, 2^{-+}$ …
- **Clean environment in electron-positron collision:** very different from **proton-proton collision**

➡ **Ideal place for glueball search**

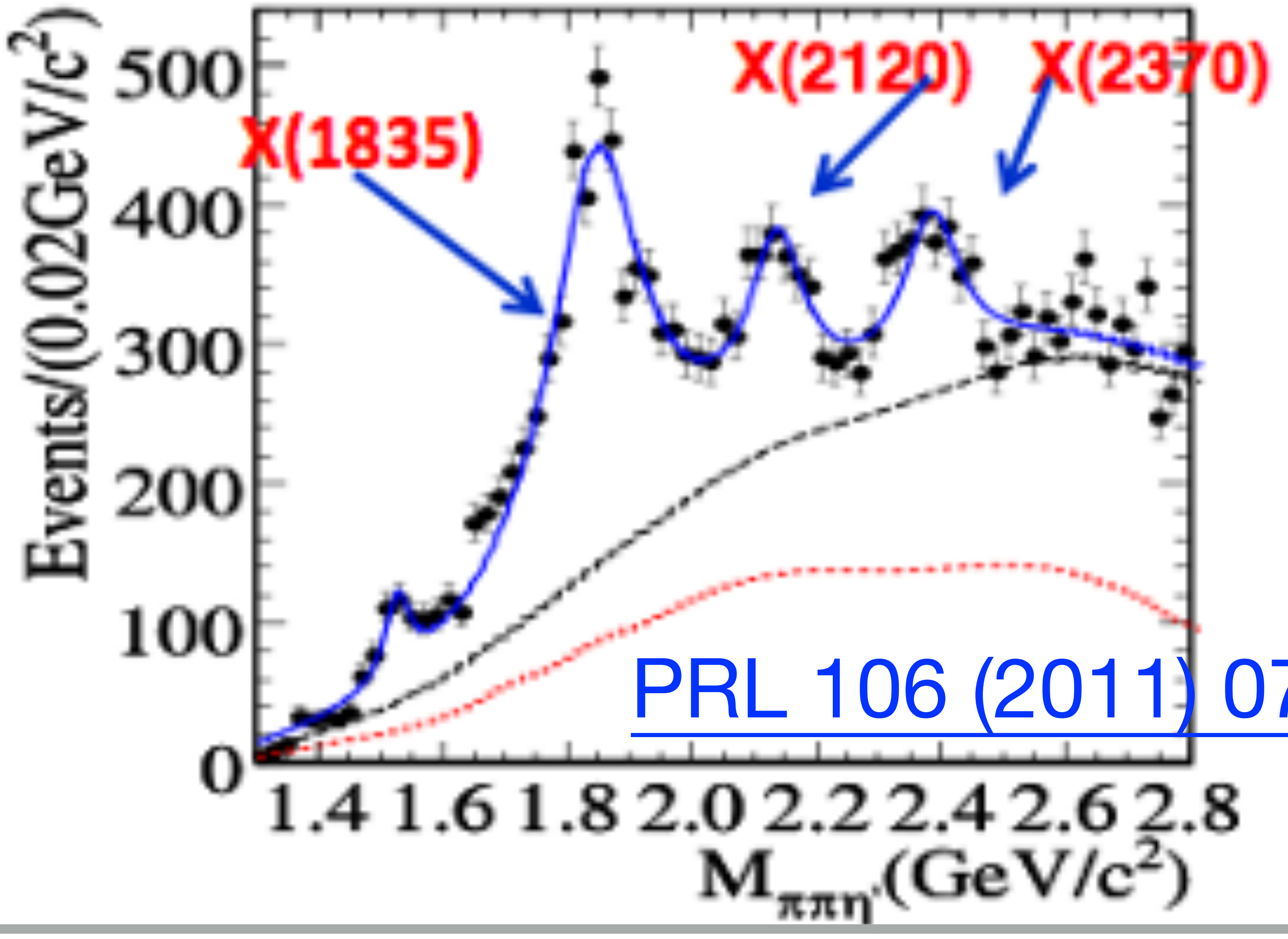
BESIII Data samples



World largest J/ψ data sample : ~10 billion

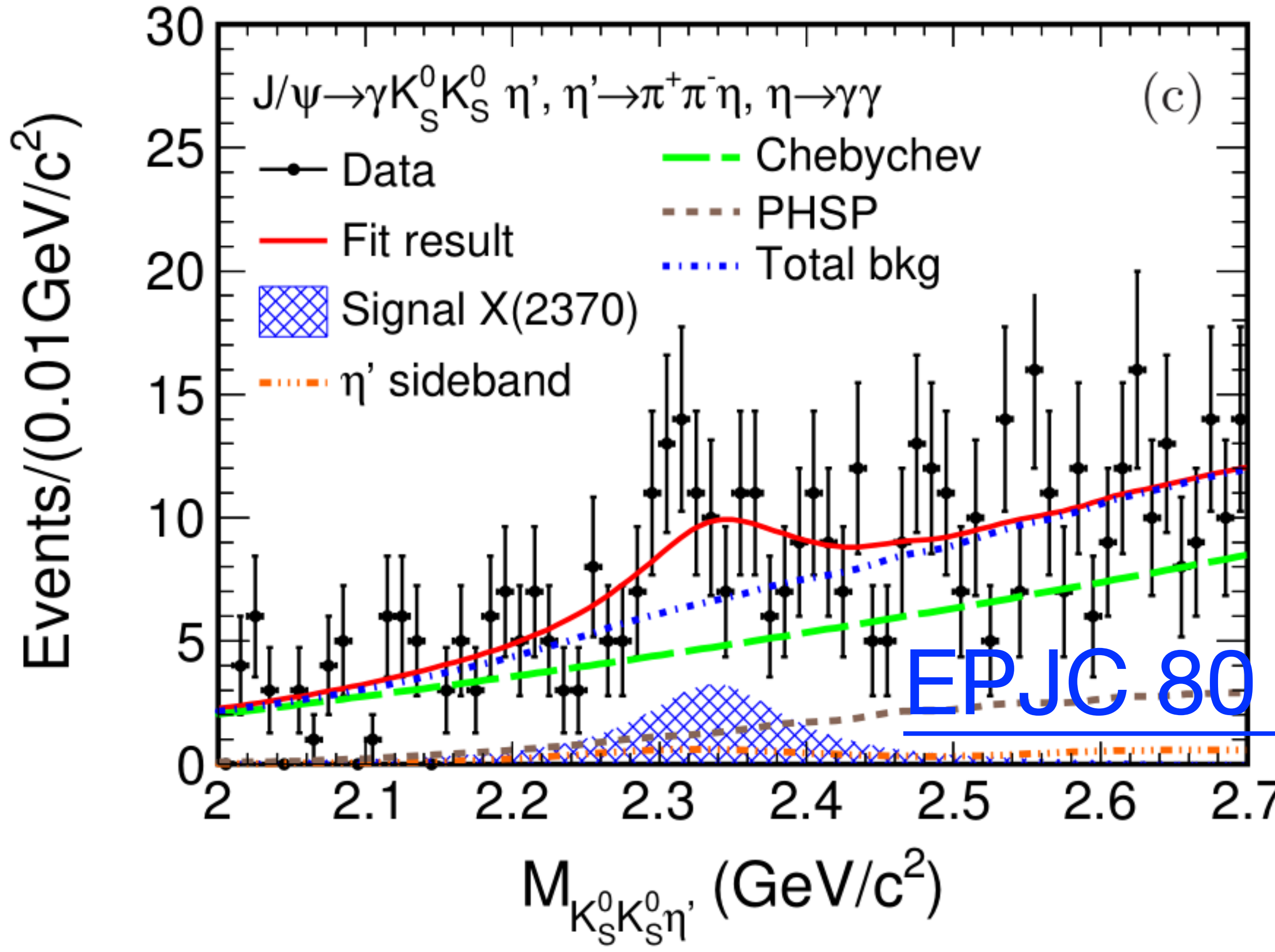
Observation of the X(2370) in J/ψ→γππη’ and J/ψ→γKKη’

J/ψ→γπ⁺π⁻η’ with ~225M J/ψ



PRL 106 (2011) 072002

J/ψ→γKKη’ with 1.31×10⁹ J/ψ events



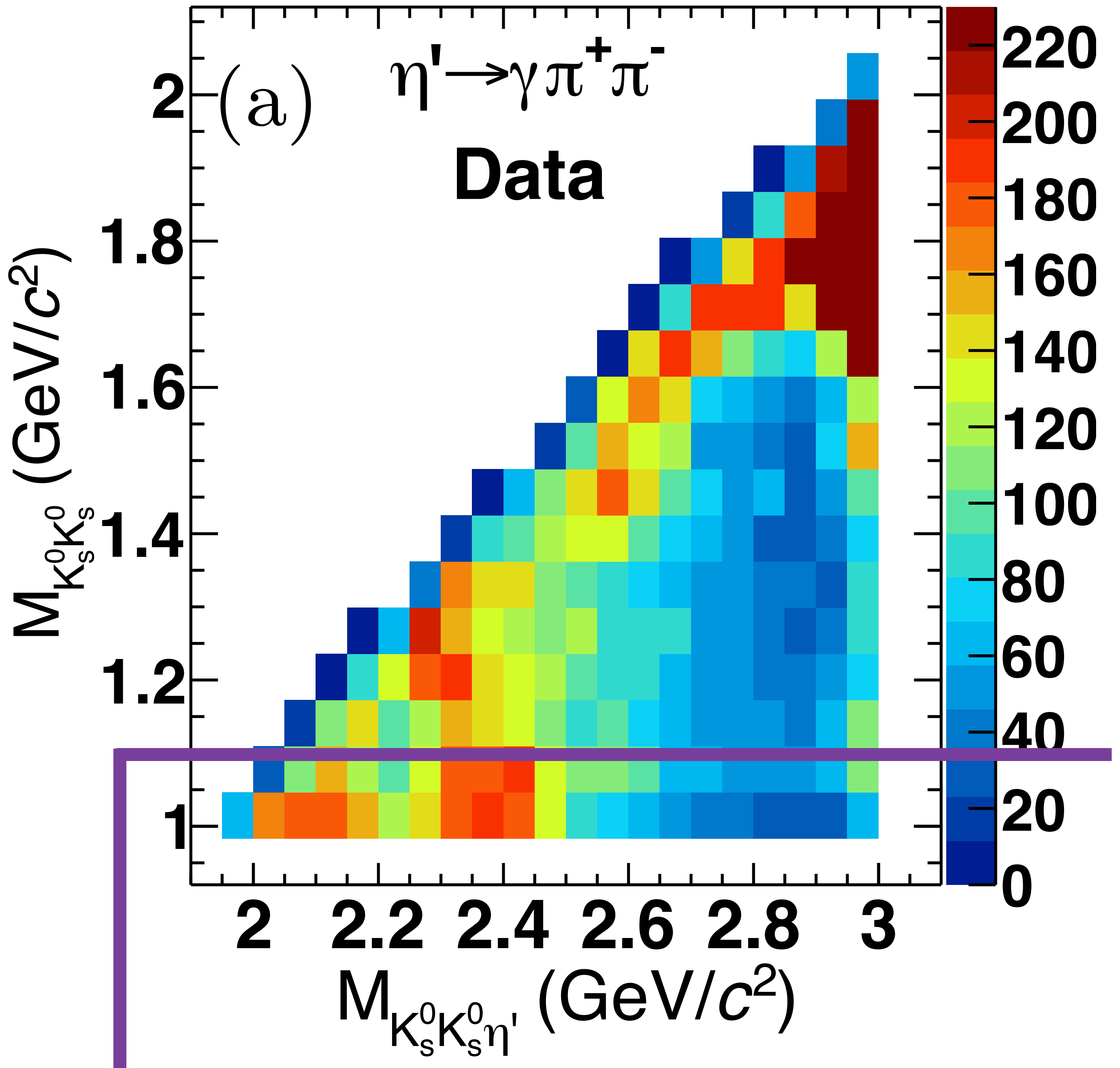
EPJC 80 (2020) 746

- Discovery of the X(2370) by BESIII in J/ψ→γππη’
- Confirmation of the X(2370) in J/ψ→γKKη’ with 8.3σ
- A good candidate for 0^{-+} glueball: first observation of one particle with mass, production and decay property consistent to LQCD prediction
  - Its mass is consistent with LQCD prediction
  - Strongly produced in the gluon-rich J/ψ radiative decays
  - Flavor symmetric decay modes of ππη’ and KKη

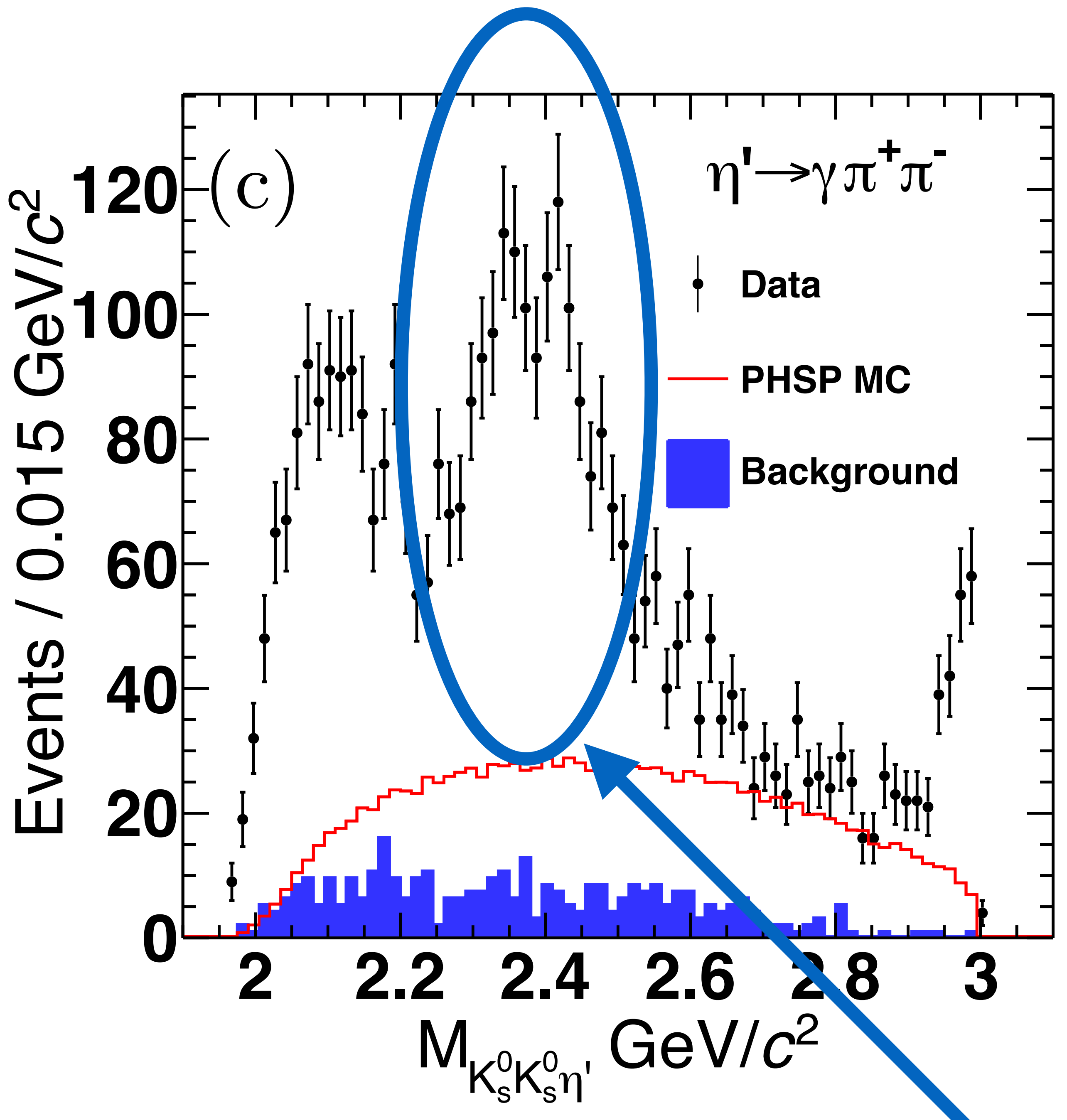
Determination of its spin-parity is crucial !

Spin-parity determination of the X(2370) in J/ψ→γKsKsη'

- **Advantage in $J/\psi\to\gamma K_sK_s\eta'$: almost background free**
  - Due to exchange symmetry and CP conversation, **no background contamination from $J/\psi\to\pi^0K_sK_s\eta'$**
  - **Clean $f_0(980)\to K_sK_s$ signal** in the K_sK_s low mass region
- **Spin-parity of the X(2370) firstly determined to be 0^{-+} with a significance of 10σ greater than alternative J^{PC}**

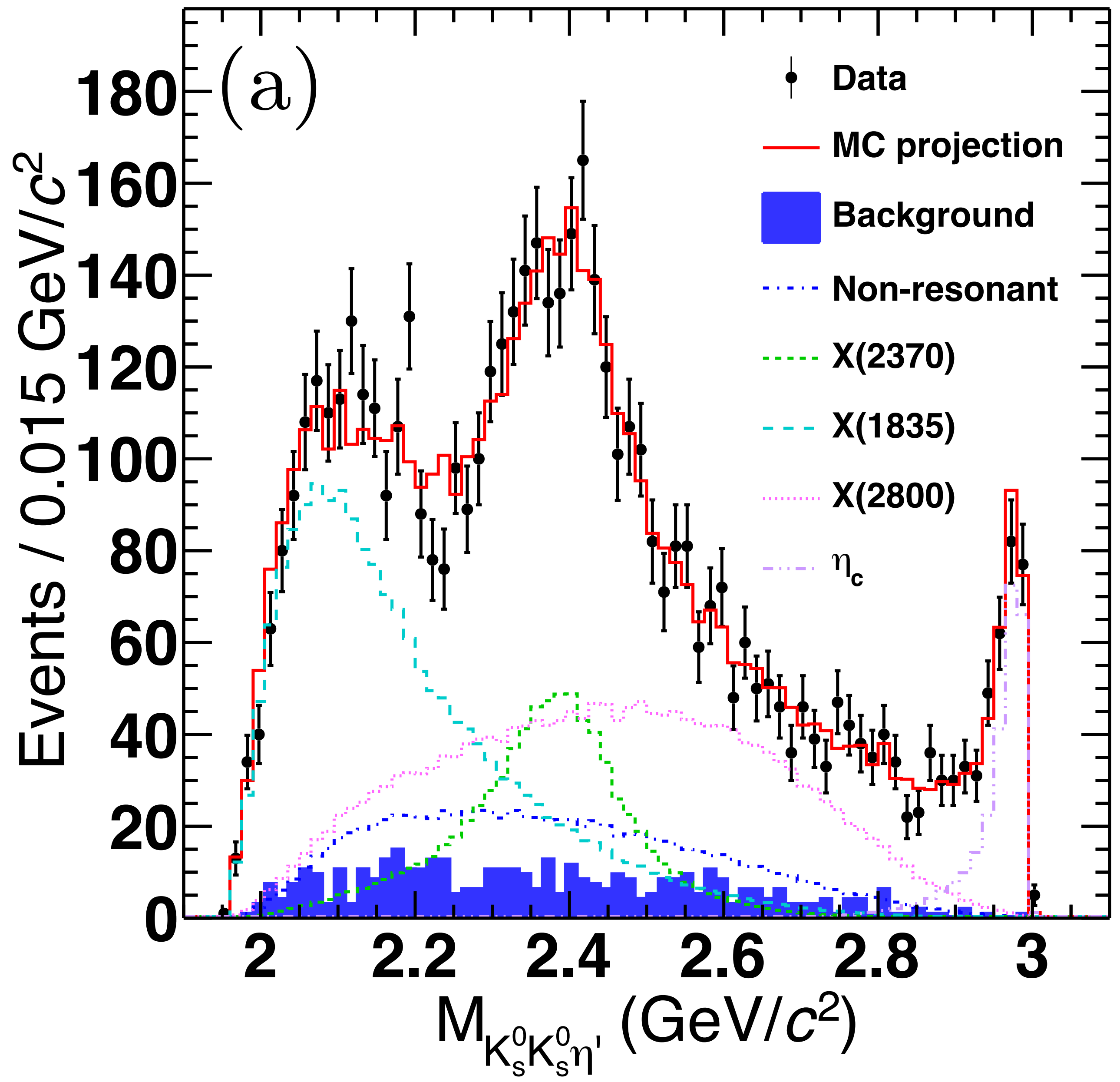


f0(980)



PRL 132 (2024) 181901

X(2370)



η'→γππ and η'→ππη

Final results

X(2370) measurements:

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

M = 2395 ±11$^{+26}_{-94}$ MeV

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

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

PRL 132 (2024) 181901

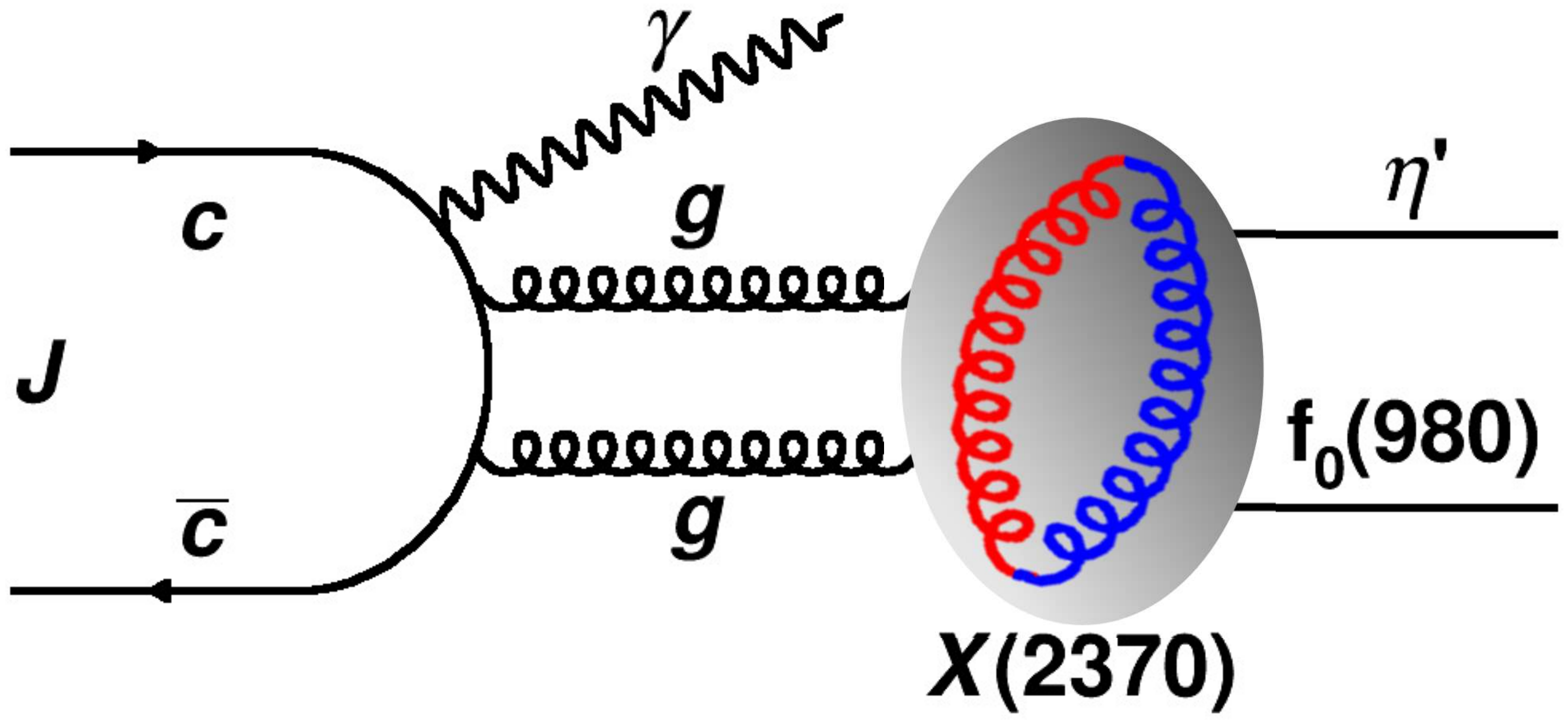
LQCD prediction on lightest pseudoscalar glueball:

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

M = 2395 ±14 MeV

$B(J/\psi\to\gamma G_{0-+}) = (2.31 \pm 0.80) \times10^{-4}$

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

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

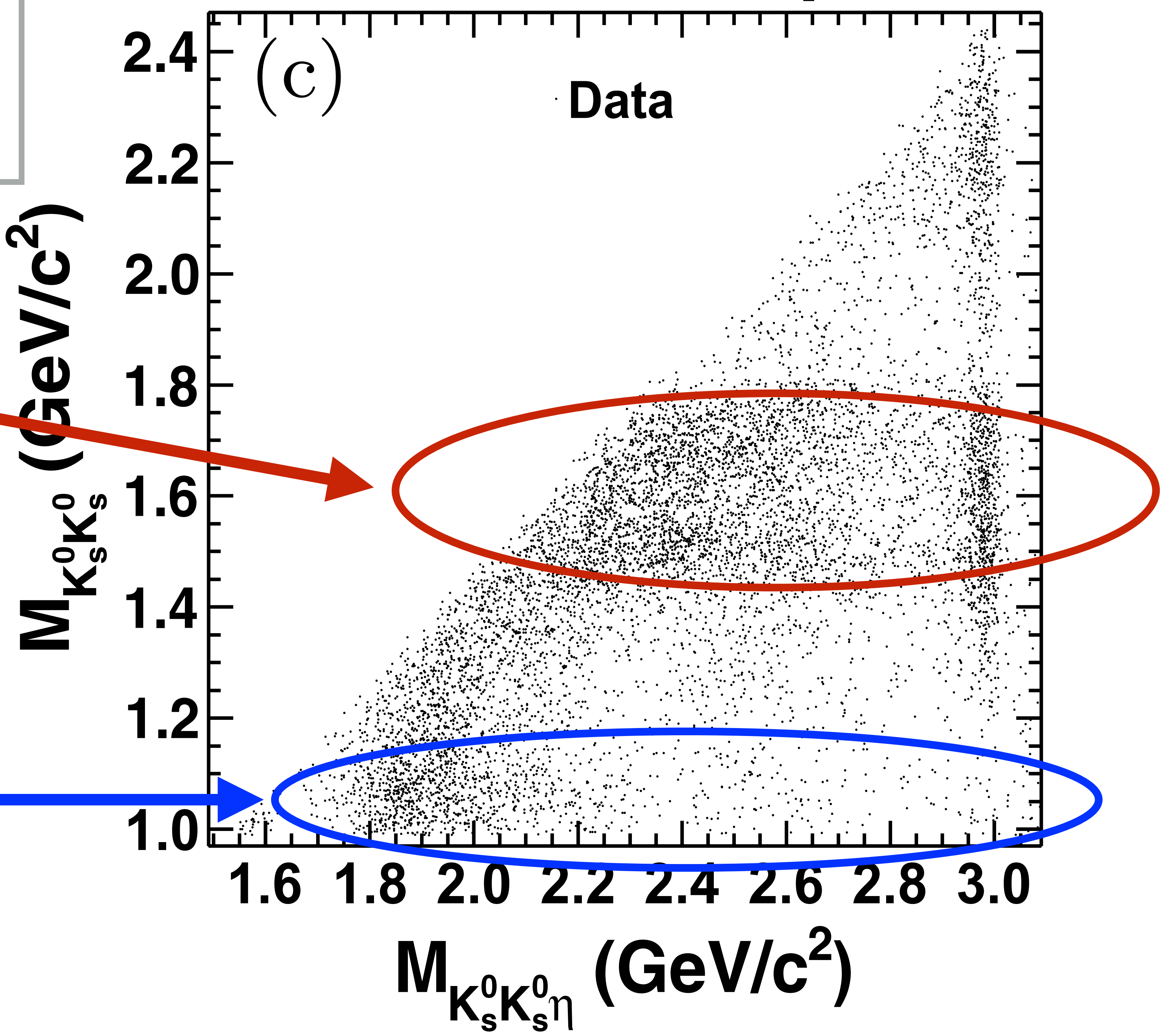
Observation and Spin-Parity Determination of the $X(1835)$ in $J/\psi \to \gamma K^0_S K^0_S \eta$

Qualitatively, we can clearly observe: same decay modes between the X(2370) and 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

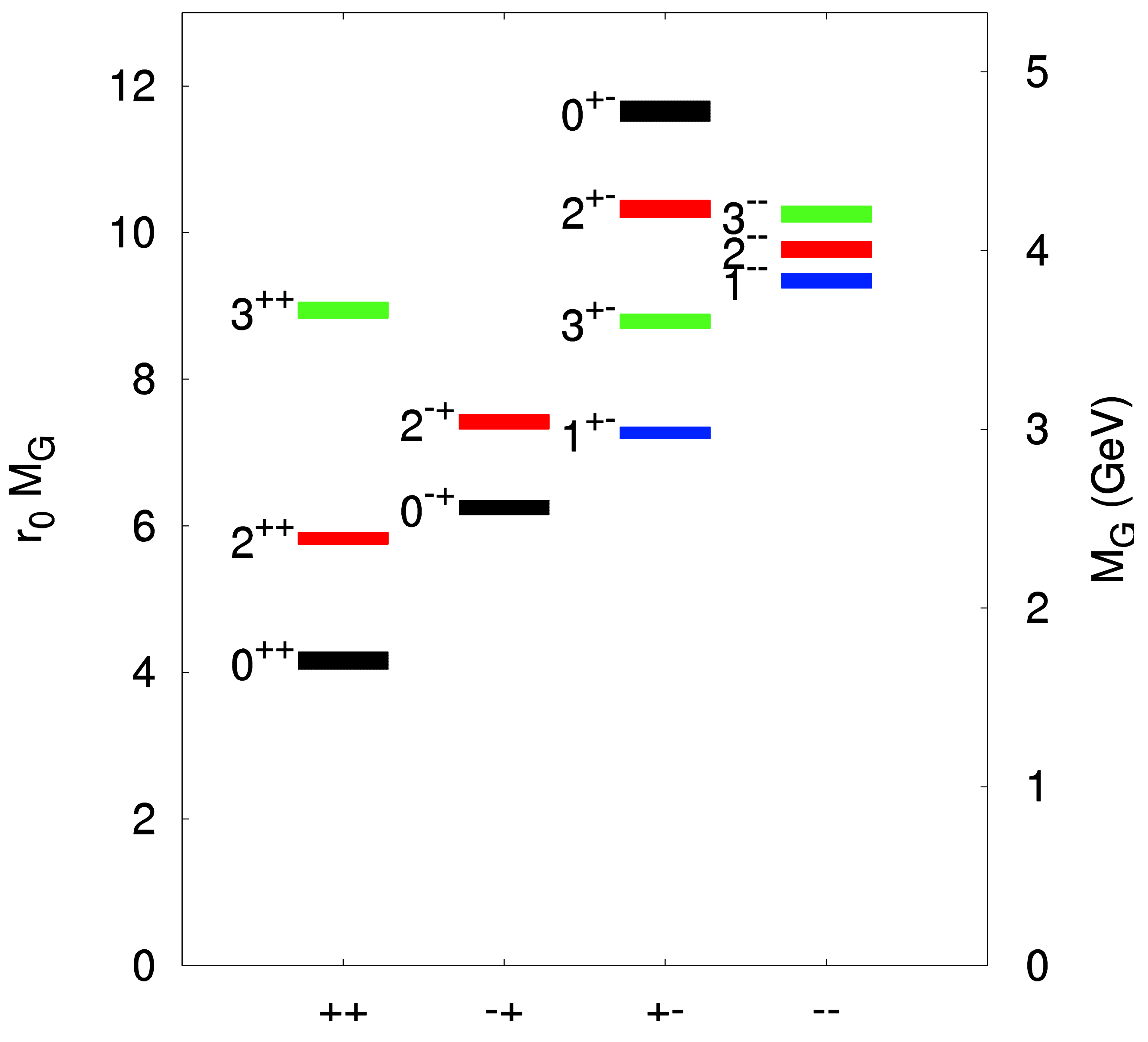
With 1.31×10^9 J/ψ events

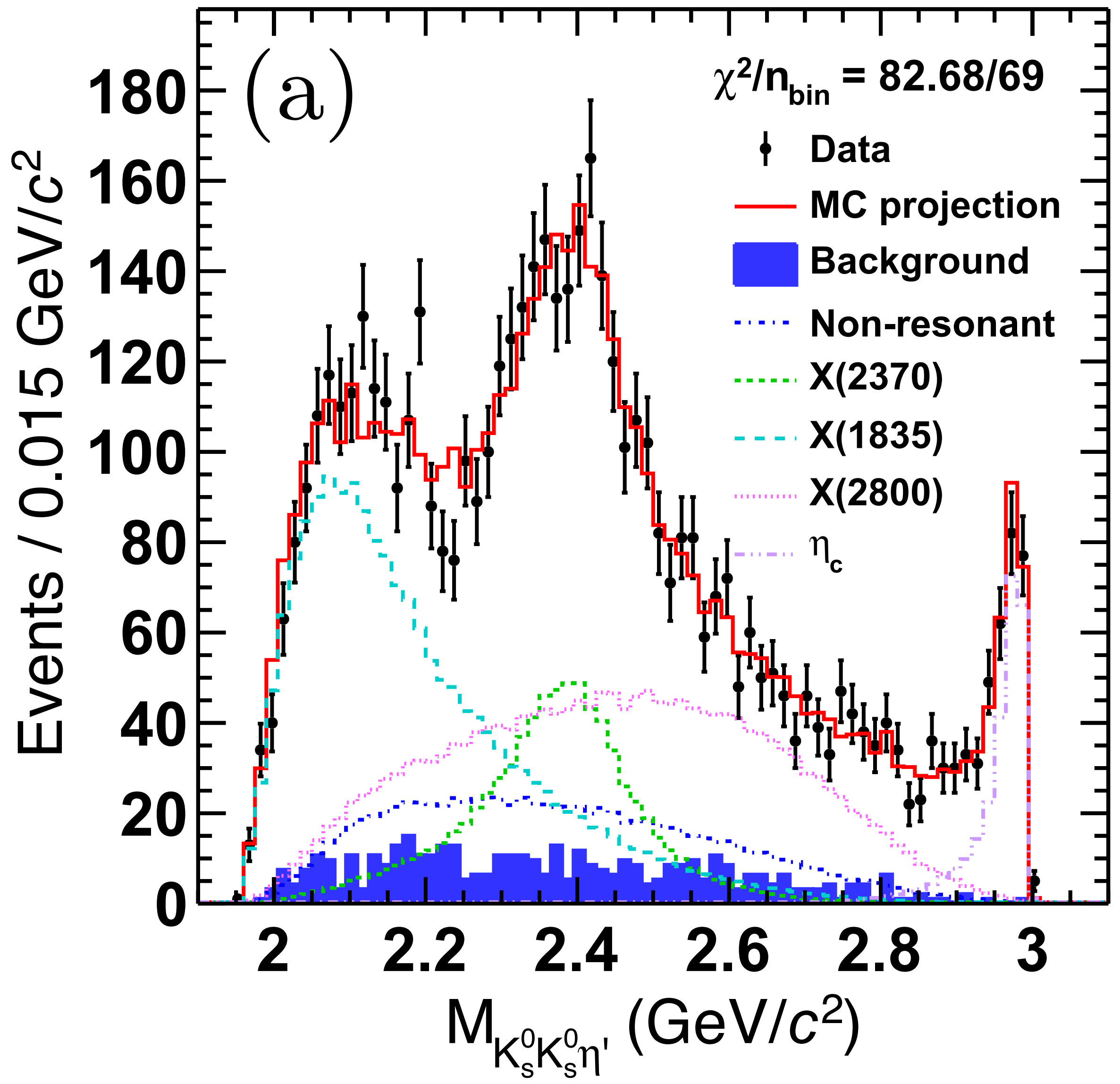


PRL 115 (2015) 091803

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

Discovery of a Glueball-like Particle: X(2370)





- **Only one resonance observed** with **mass**, **spin-parity**, **production rate** and **decay property** consistent to 0^{-+} glueball expectation
  - In the **mass range** of 2.3 - 2.6GeV: consistent with LQCD prediction
  - Production rate in the J/ψ **radiative decays: consistent with LQCD prediction**
  - **Decay property highly similarity to** η_c : two favorite decay modes of $\pi^+\pi^-\eta'$ and $K\bar{K}\eta'$

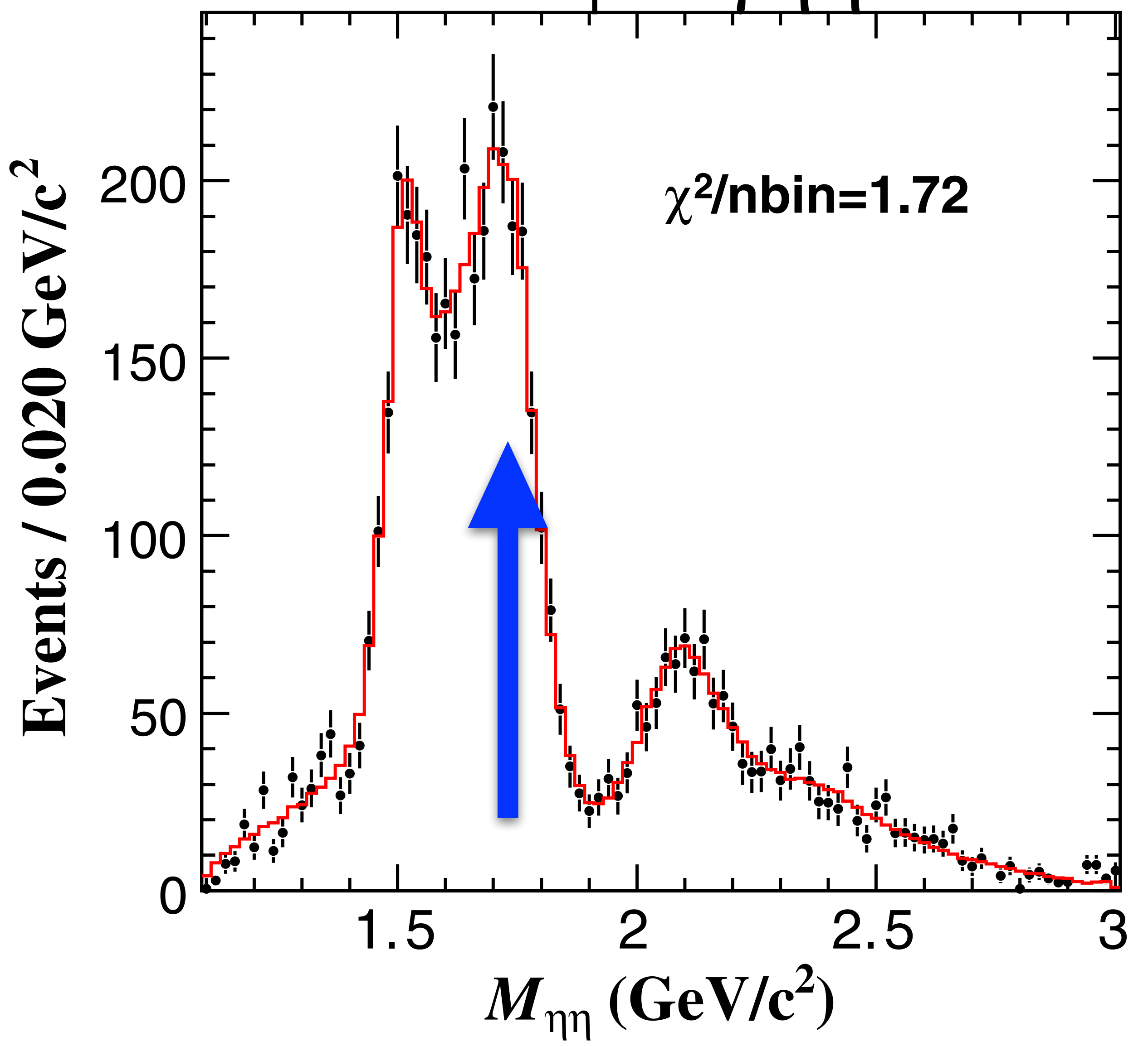
X(2370) Properties

	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	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 η_c decay modes strongly support the 0^{-+} glueball interpretation**
- **The X(2370) production properties:**
  - richly produced in J/ψ 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/ψ radiative decays and two golden decay modes ($\pi\pi\eta'$ and $K\bar{K}\eta'$)

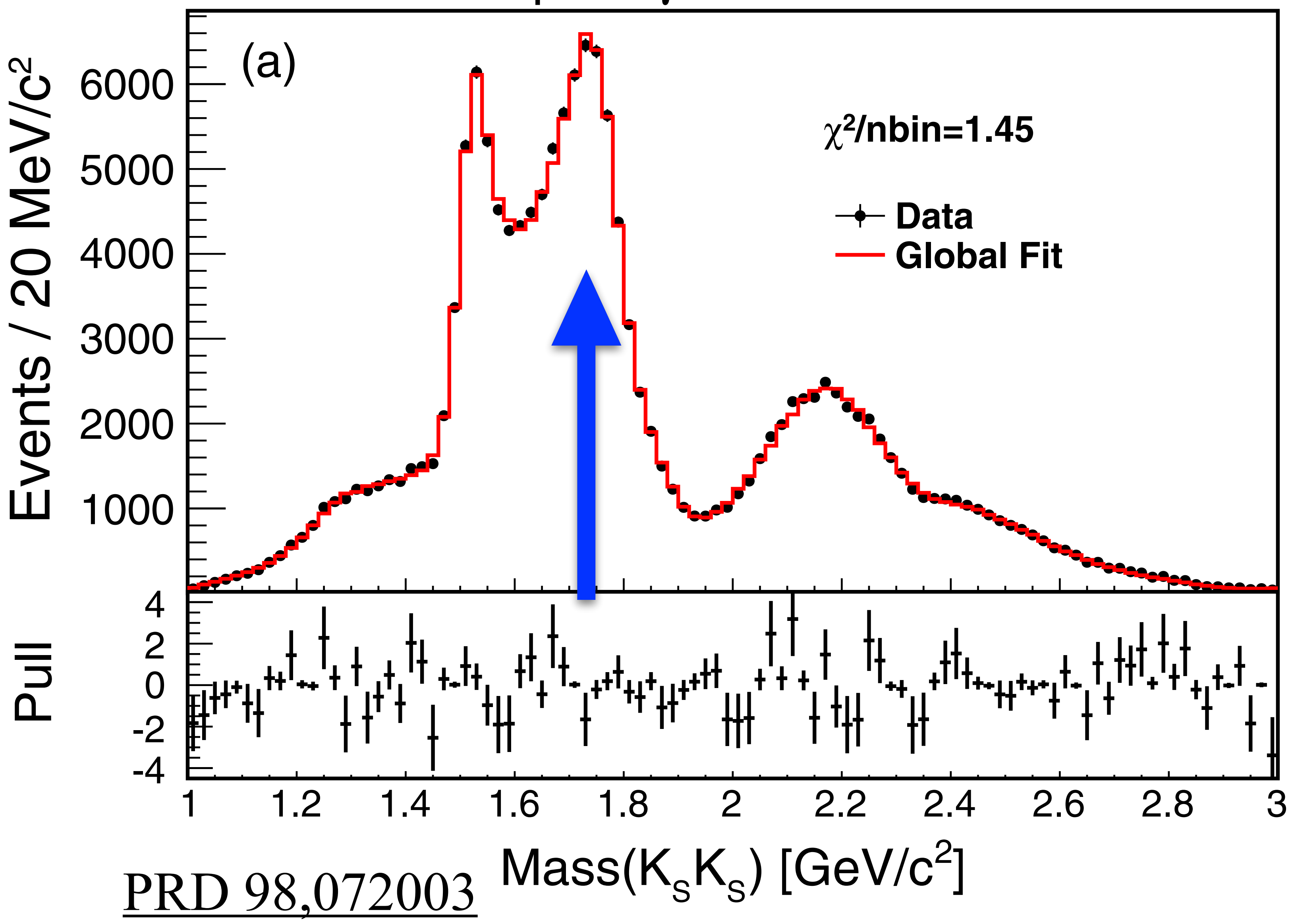
Scalar Glueball Candidates — $f_0(1710)$

$J/\psi \rightarrow \gamma\eta\eta$



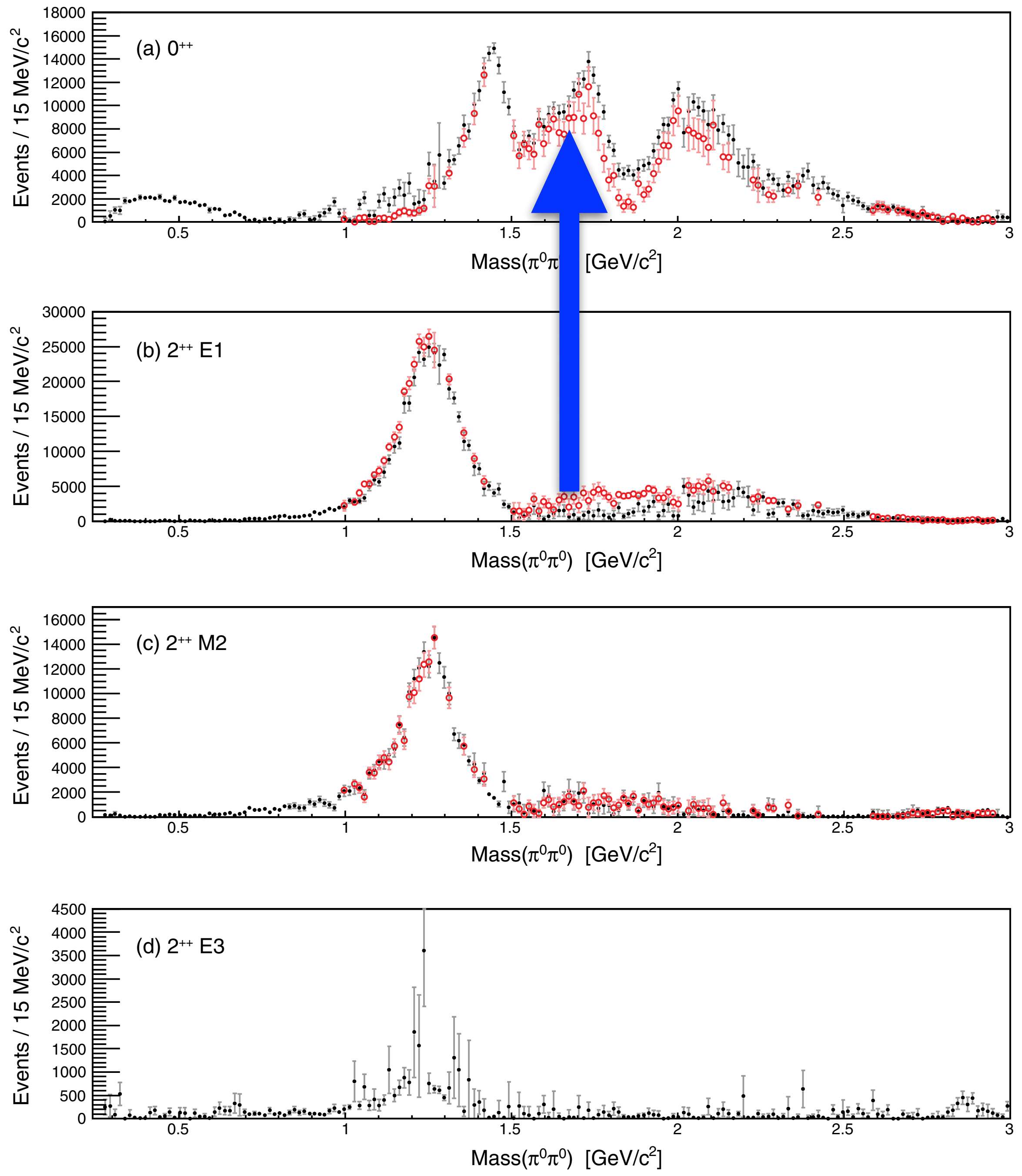
PRD 87,092009

$J/\psi \rightarrow \gamma K_S K_S$



PRD 98,072003

$J/\psi \rightarrow \gamma\pi^0\pi^0$



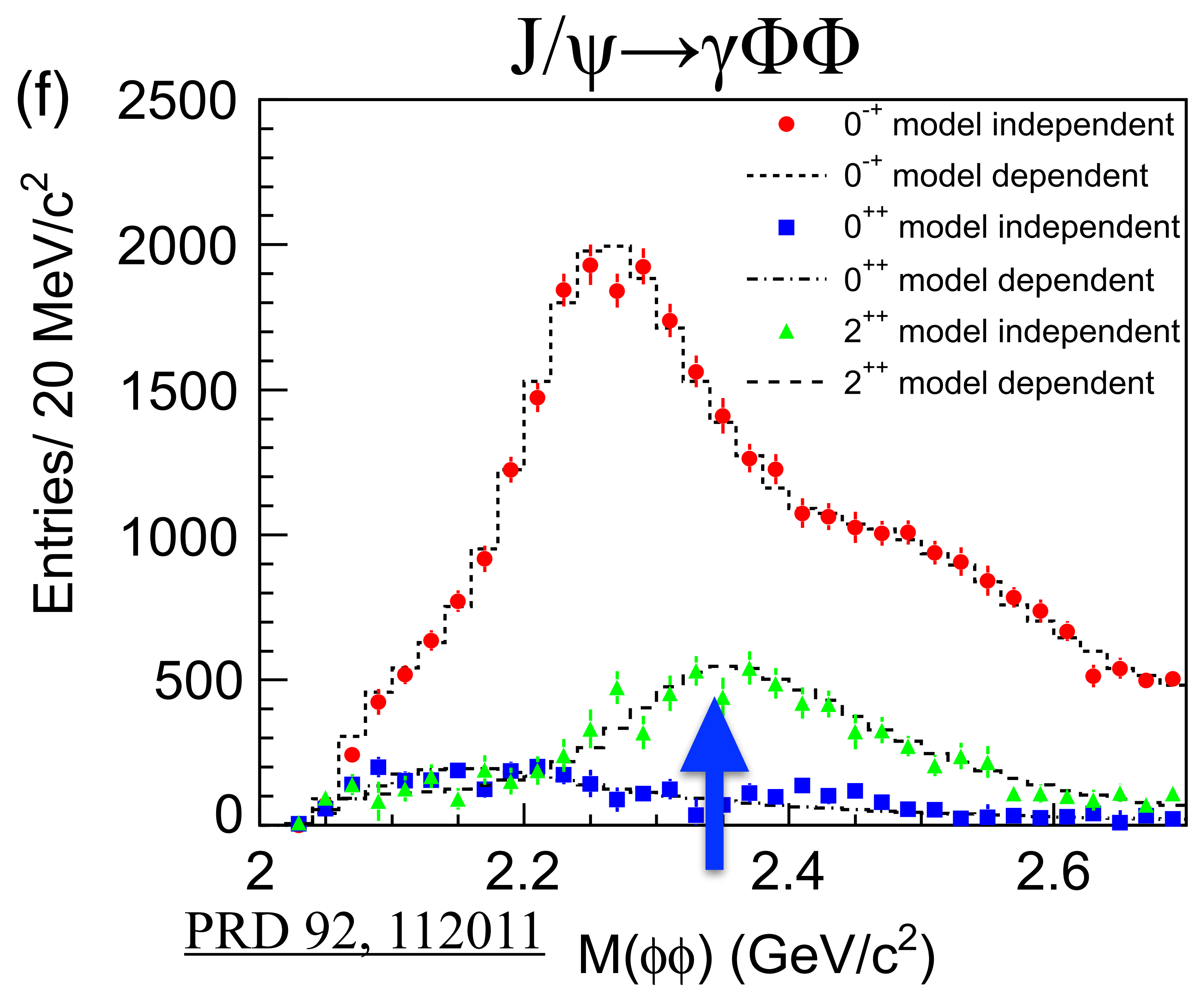
- The $f_0(1710)$ favors to be **a scalar glueball or large glueball content** if it is a mixture of glueball and normal meson
  - **Large production rate:** $B(J/\psi \rightarrow \gamma f_0(1710) \rightarrow \gamma\eta\eta) = 2.35^{+0.13}_{-0.11}{}^{+1.24}_{-0.74} \times 10^{-4}$ $B(J/\psi \rightarrow \gamma f_0(1710) \rightarrow \gamma K_S K_S) = 2.00^{+0.03}_{-0.02}{}^{+0.31}_{-0.10} \times 10^{-4}$
  - **Decay suppression in $\eta\eta'$:** $B[f_0(1710) \rightarrow \eta\eta' / f_0(1710) \rightarrow \pi\pi] < (2.9\pm^{+1.1}_{-0.9}) \times 10^{-3}$
- **Controversy:** Dynamic mixing mechanism?

Tensor Glueball Candidates —$f_2(2340)$

$$\Gamma(J/\psi \to \gamma G_{2^+}) = 1.01(22) keV$$

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

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

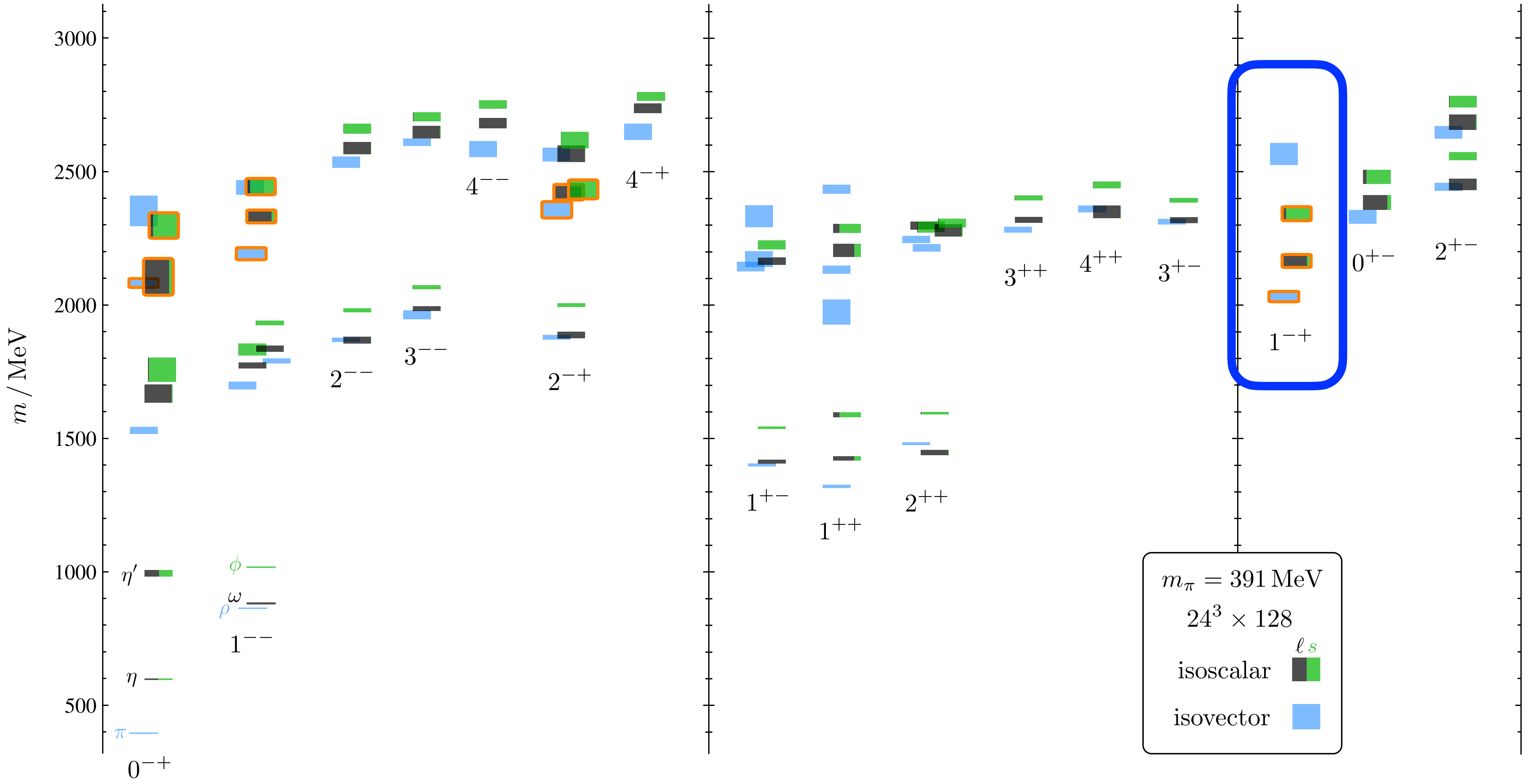


- ◈ **Large production rate of $f_2(2340)$:** substantially lower than the LQCD prediction for tensor glueball
  - ✦ B(J/ψ→γf_2(2340)→$\gamma\eta\eta$) = $(3.8^{+0.62}_{-0.66}\ {}^{+2.37}_{-2.07}) \times 10^{-5}$ (PRD 87,2013,092009)
  - ✦ B(J/ψ→γf_2(2340)→$\gamma\phi\phi$) =$(1.91 \pm 0.14^{+0.72}_{-0.73} \times 10^{-4}$ (PRD 93,2016,112011)
  - ✦ B(J/ψ→γf_2(2340)→$\gamma K_s K_s$) =$(5.54^{+0.34}_{-0.40}\ {}^{+3.82}_{-1.49} \times 10^{-5}$ (PRD 98,2018,072003)
  - ✦ B(J/ψ→γf_2(2340)→$\gamma\eta'\eta'$) =$(8.67 \pm 0.70^{+0.16}_{-1.67} \times 10^{-6}$(PRD 105,2022,072002)
- ◈ **Difficulty: Many wide f_2 mesons and large overlaps in the mass region of 2.3GeV** (2^{++} glueball mass from the LQCD predictions)
  - ✦ Studies are strongly model dependent.

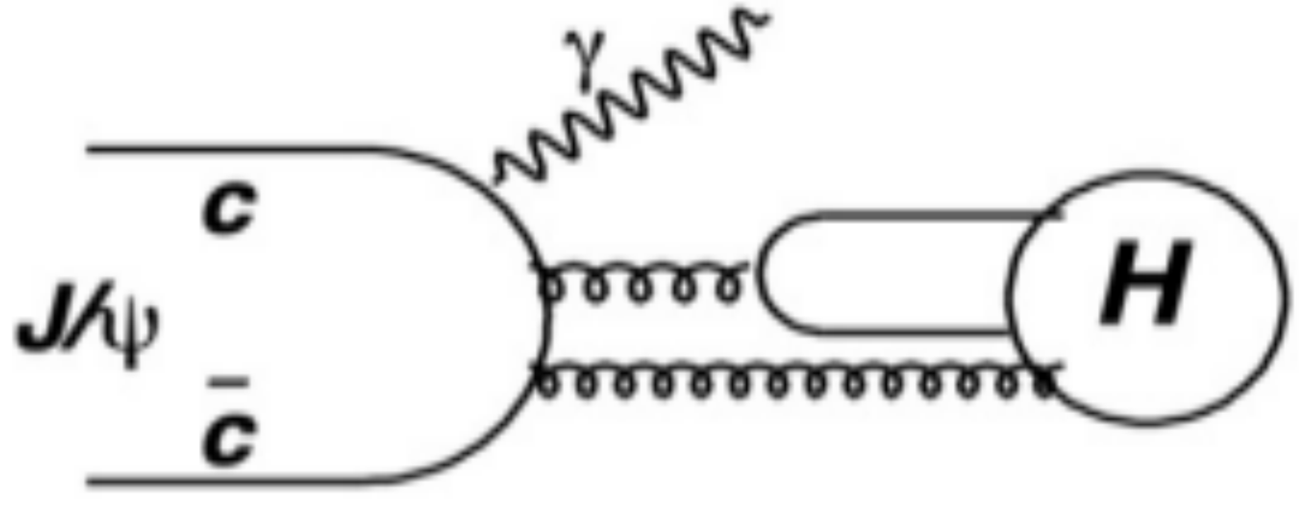
Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. $(\times 10^{-4})$	Sig.
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28σ
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	22σ
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	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

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)

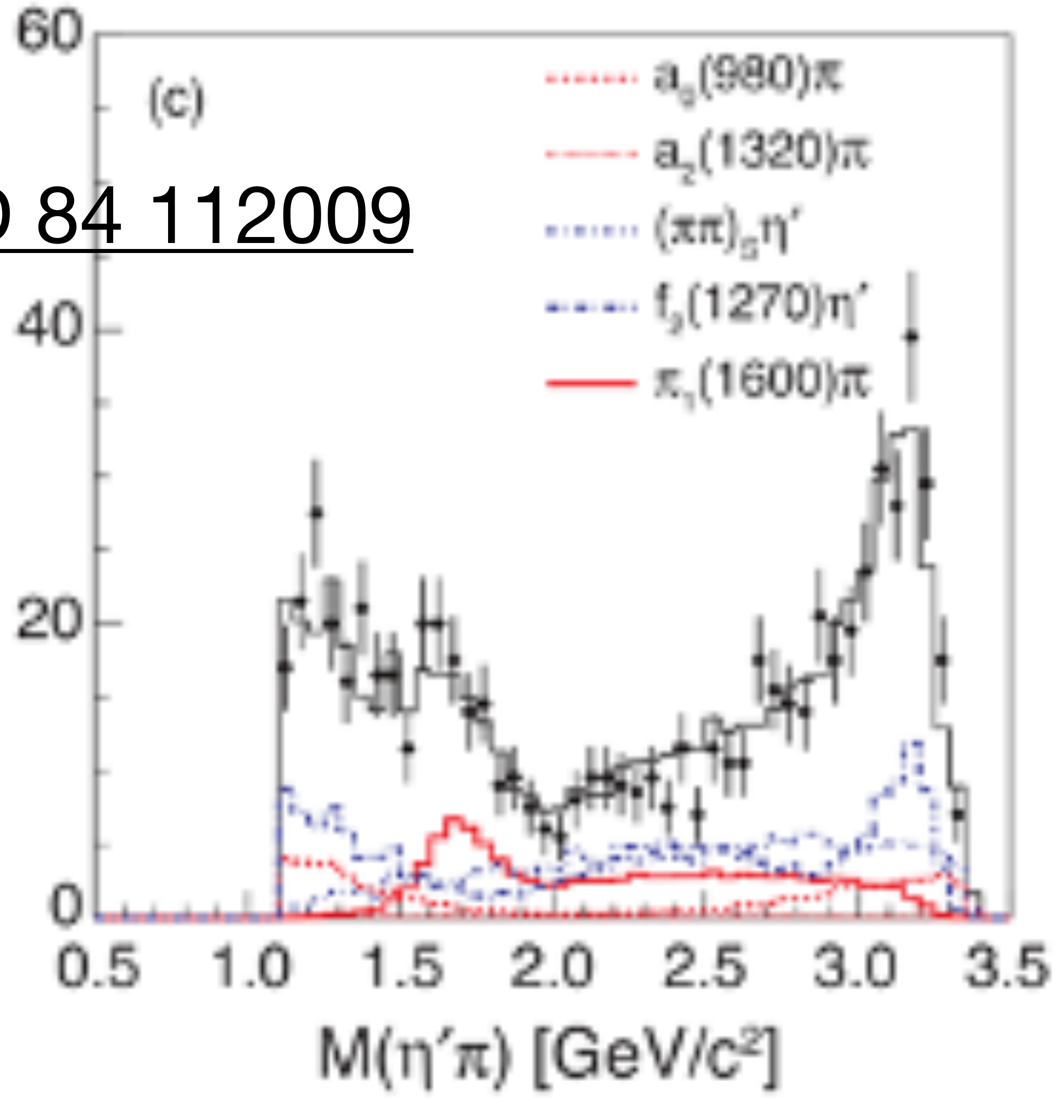


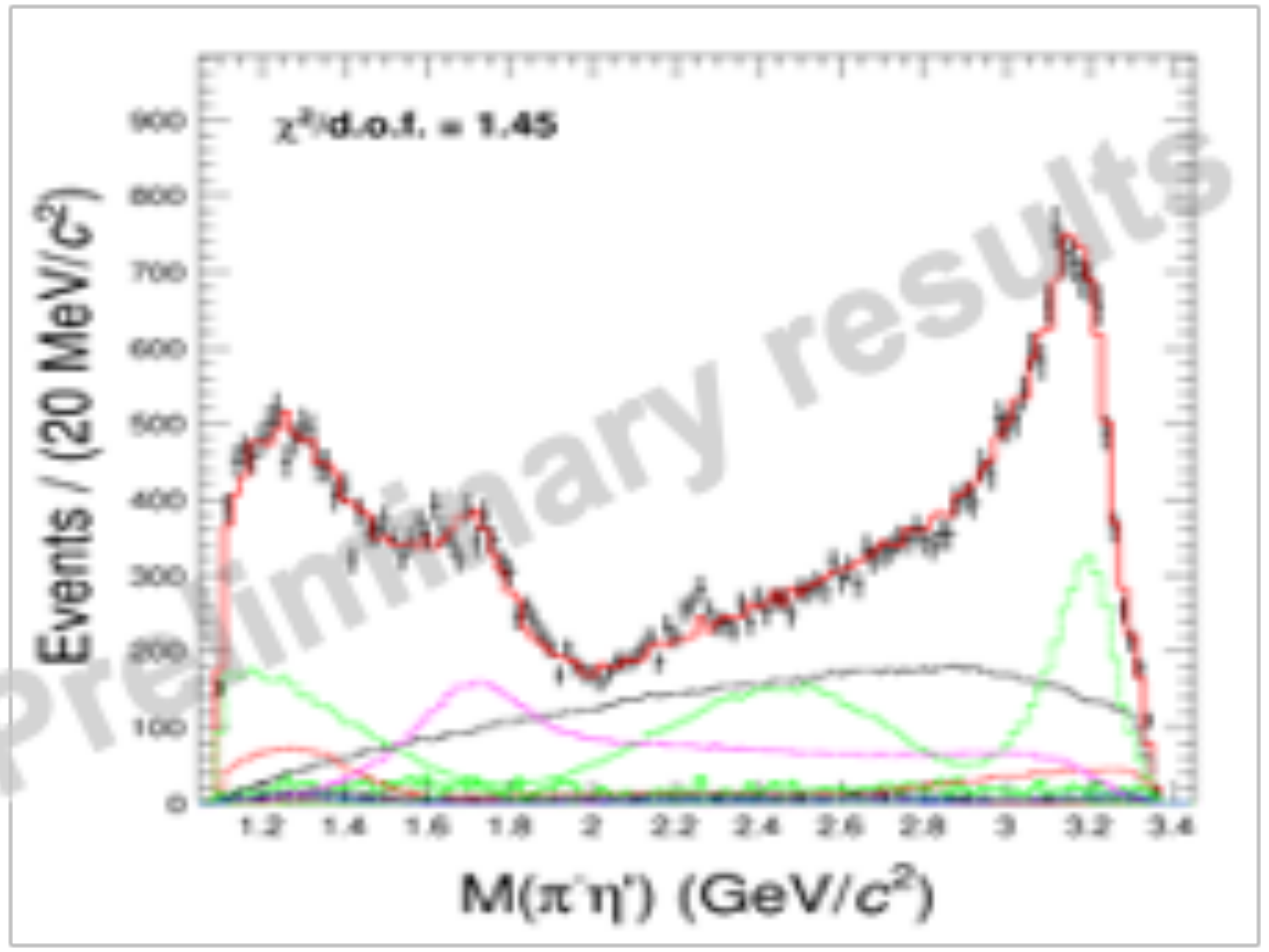
$$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$$

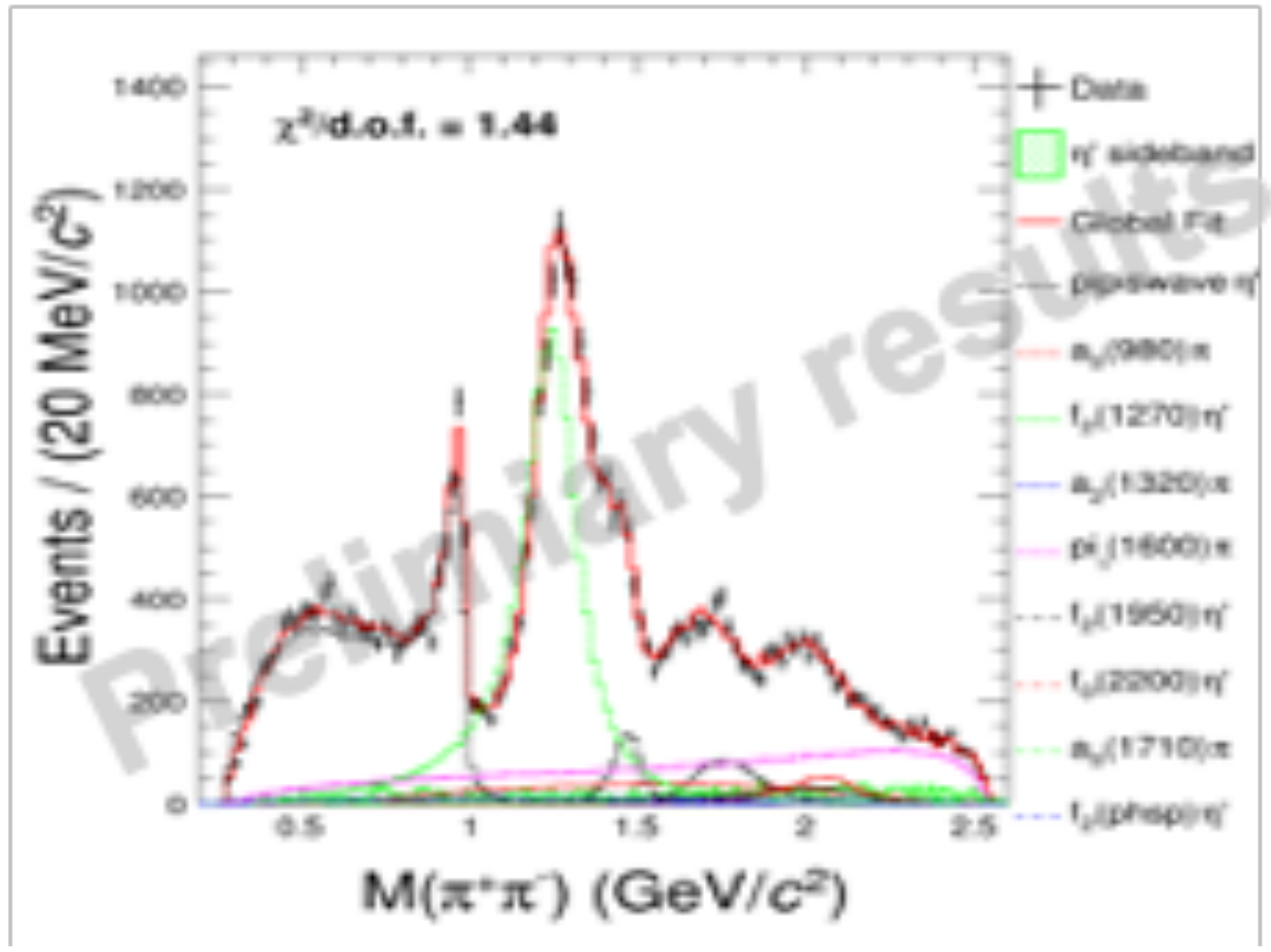
- **Spin-exotic state of 1^{-+} :** forbidden in conventional quark model
- LQCD predicts the **lightest nonet of hybrids**: 1^{--} 0^{-+} **1^{-+}** 2^{-+}
- Exotic state **1^{-+} provide an unique way for hybrid search:**
  - **Can be produced in the gluon-rich charmonium decays**

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

PRD 84 112009





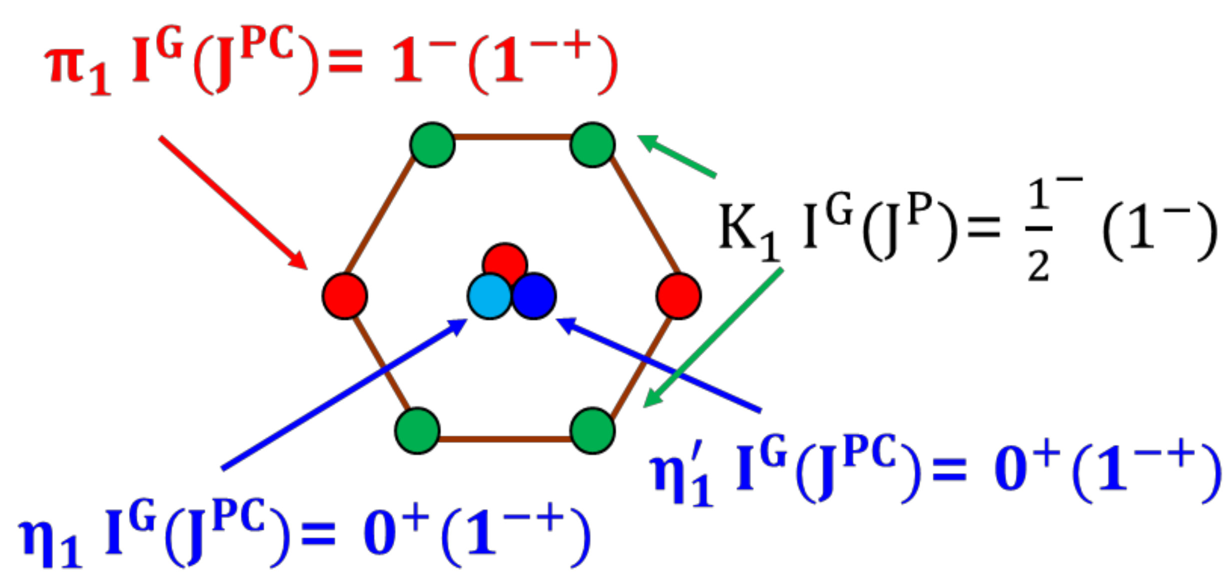


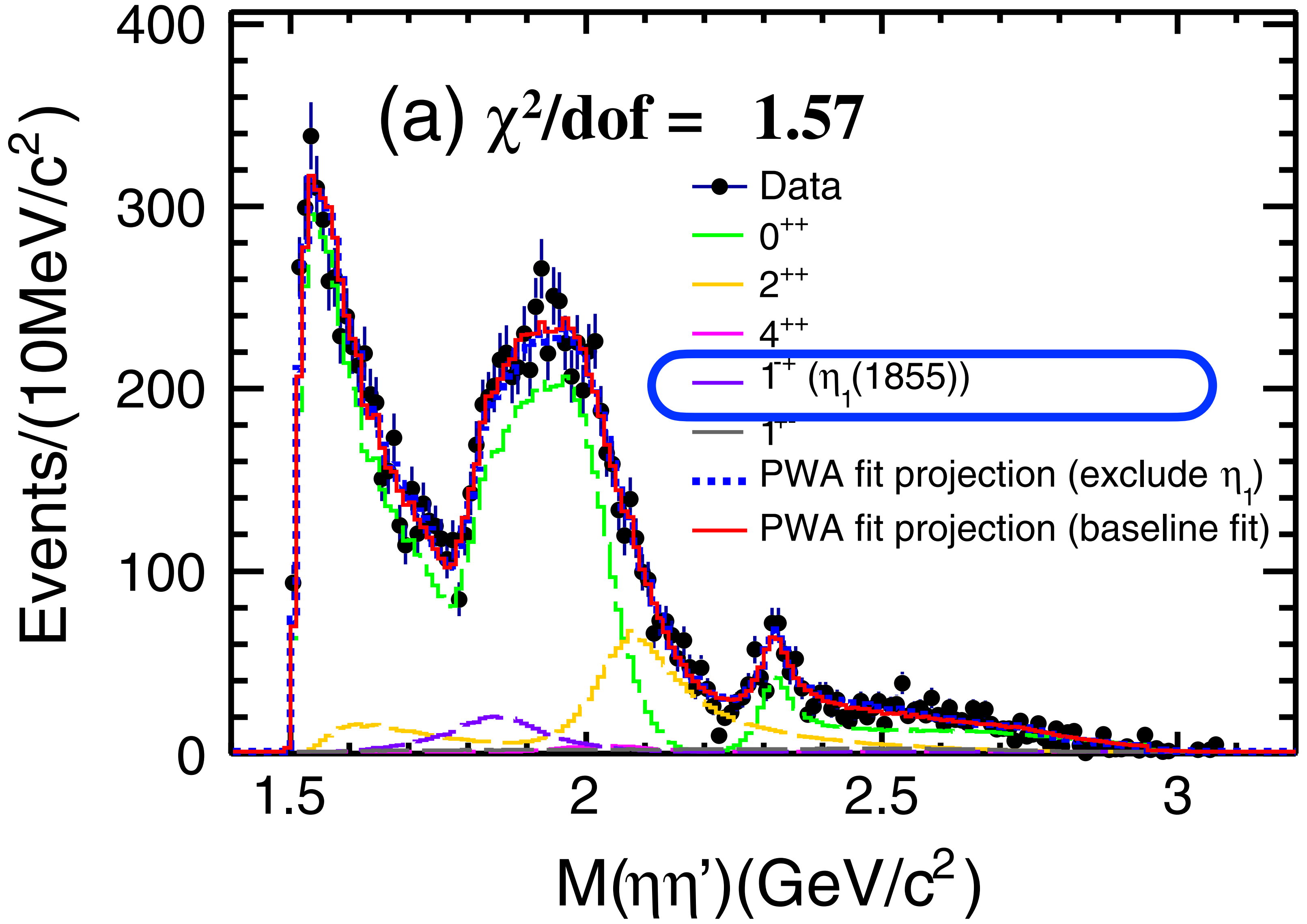
state	J^{PC}	Decay mode	Significance
$\pi_1(1600)$	1^{-+}	$\pi^{\pm}\eta'$	$>> 10\sigma$
$(\pi\pi)_{S-wave}$	0^{++}	$\pi^{\pm}\eta'$	$>> 10\sigma$
$a_0(980)$	0^{++}	$\pi^{\pm}\eta'$	$> 10\sigma$
$f_2(1270)$	2^{++}	$\pi^+\pi^-$	$>> 10\sigma$
$a_2(1320)$	2^{++}	$\pi^{\pm}\eta'$	$> 5\sigma$
$f_2(1950)$	2^{++}	$\pi^+\pi^-$	$> 10\sigma$
$f_0(2200)$	0^{++}	$\pi^+\pi^-$	$> 10\sigma$
$a_0(1710)$	0^{++}	$\pi^{\pm}\eta'$	$> 10\sigma$
$f_2(PHSP)$	2^{++}	$\pi^+\pi^-$	$> 5\sigma$

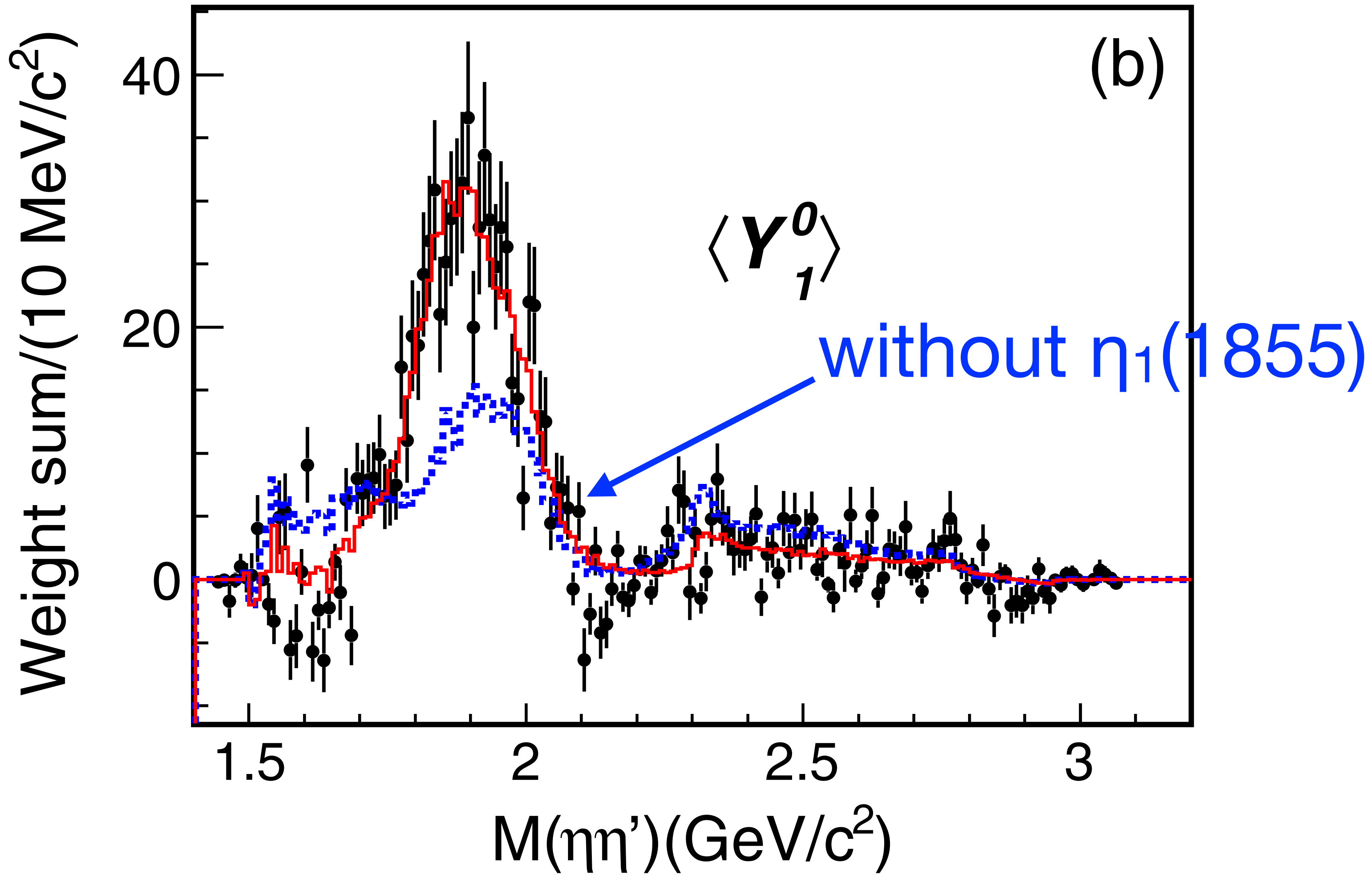
- CLEO-c results: evidence of an exotic P-wave $\eta'\pi$ amplitude with 4σ and but no significant phase motion
- PWA in $\psi' \to \gamma\chi_{c1}(\chi_{c1} \to \pi^+\pi^-\eta')$ with higher ψ' data sample @ BESIII:
  - **First observation of Exotic 1^{-+} Isovector state $\pi(1600)$ with a significance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

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

Isoscalar 1^{-+} is critical to establish the hybrid nonet: partners for the Isovector 1^{-+} candidates $\pi(1600)$



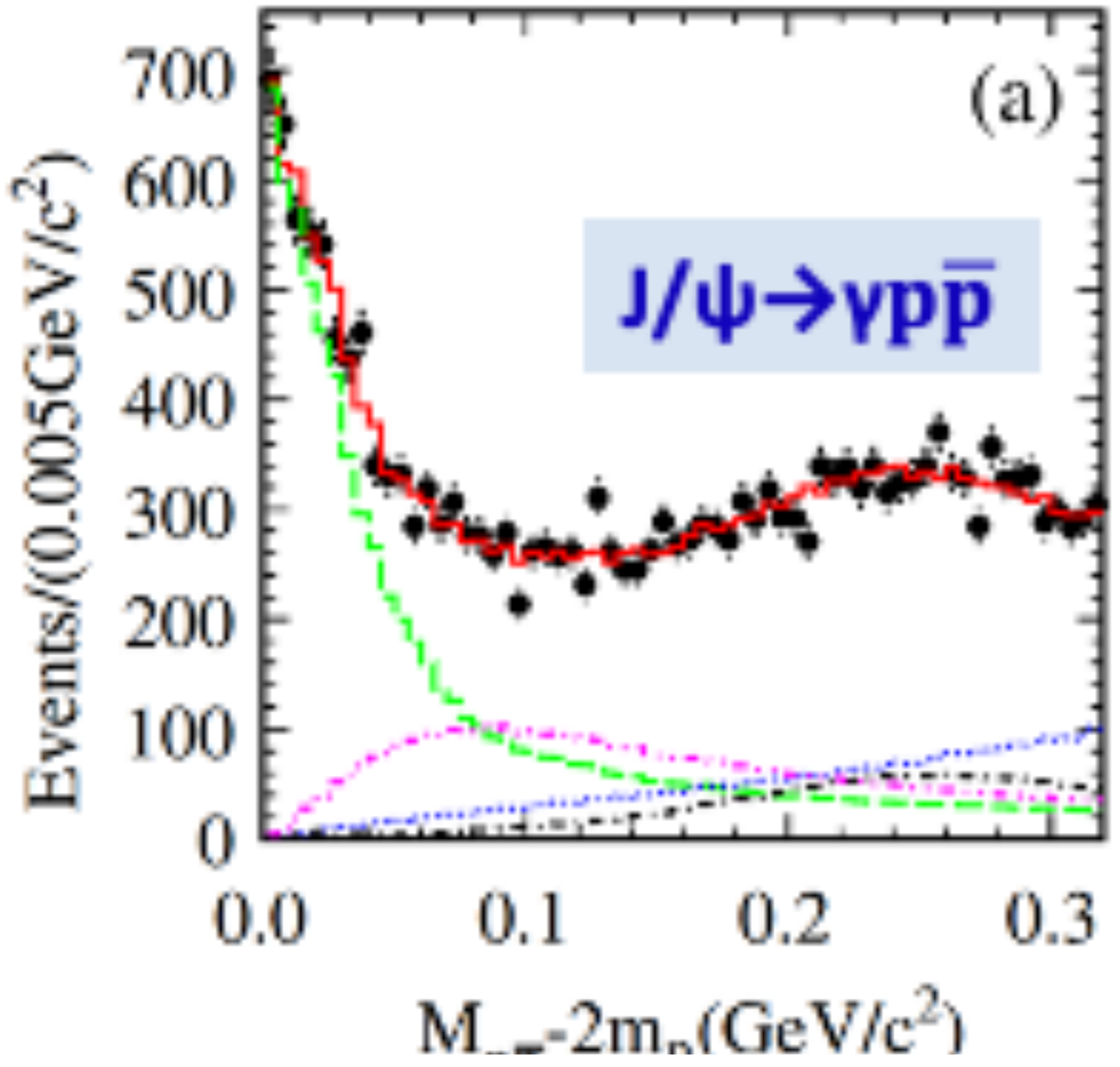




PRL 129 192002(2022), PRD 106 072012(2022)

- **$J/\psi \to \gamma\eta\eta'$ 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)**
  - M= 1855±9+6-1MeV, Γ=188±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)

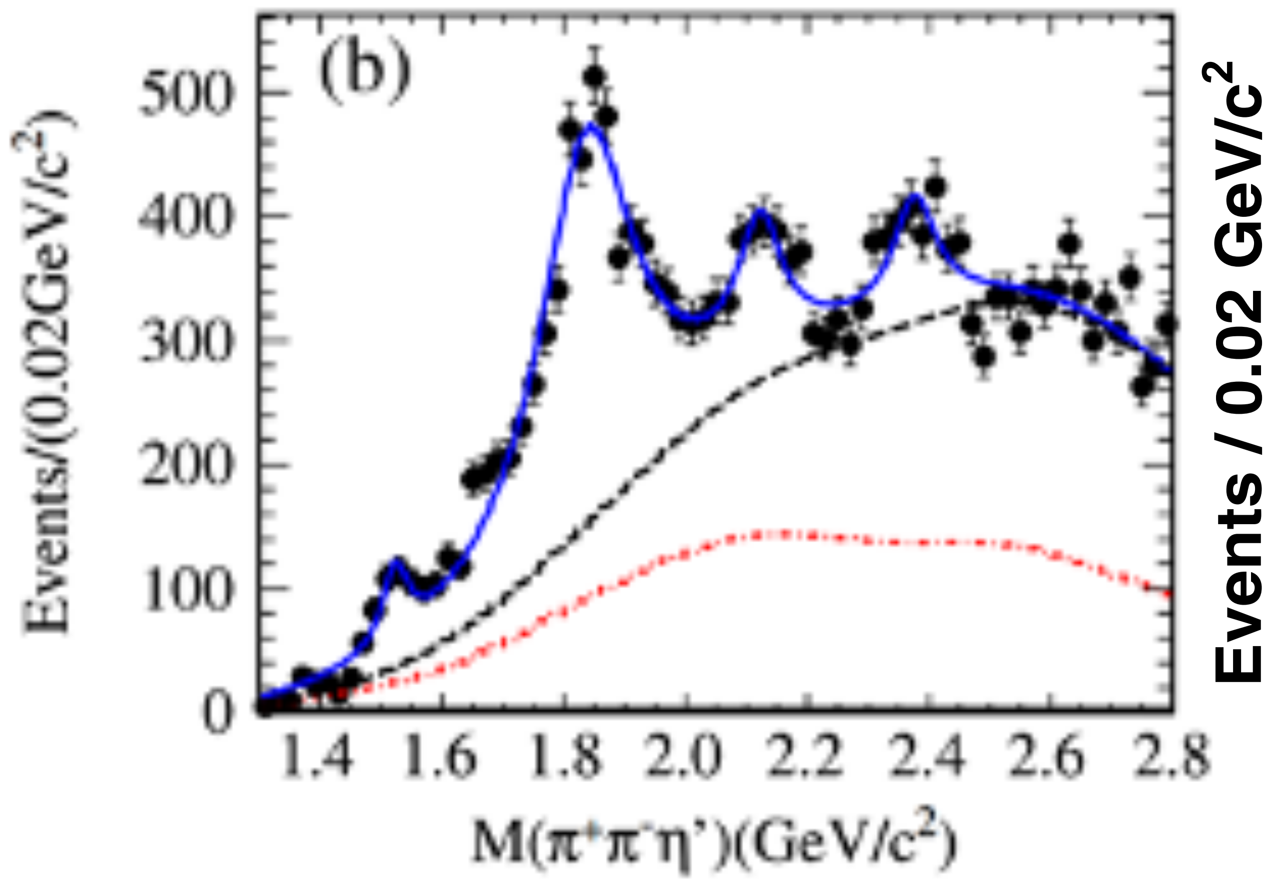
Observation of X($p\bar{p}$) and X(1835)



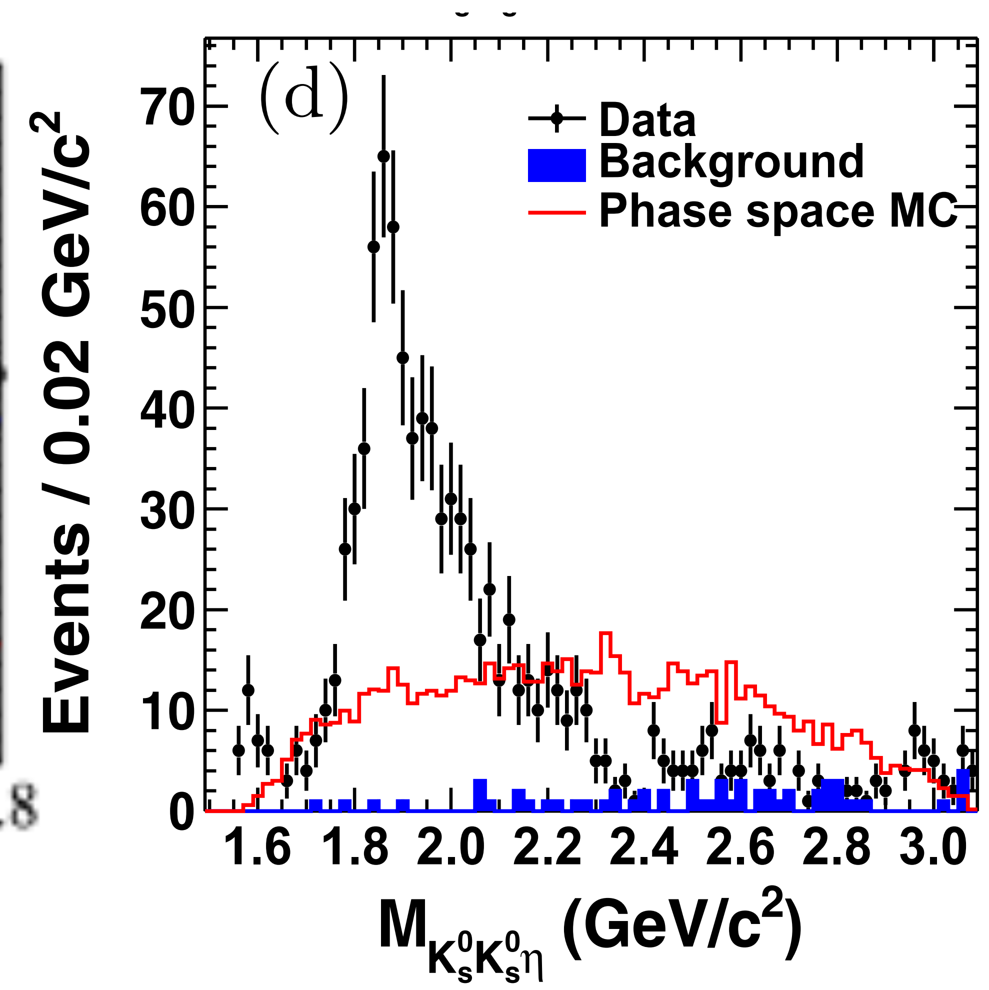
PRL 108 (2012)112003

- $p\bar{p}$ 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



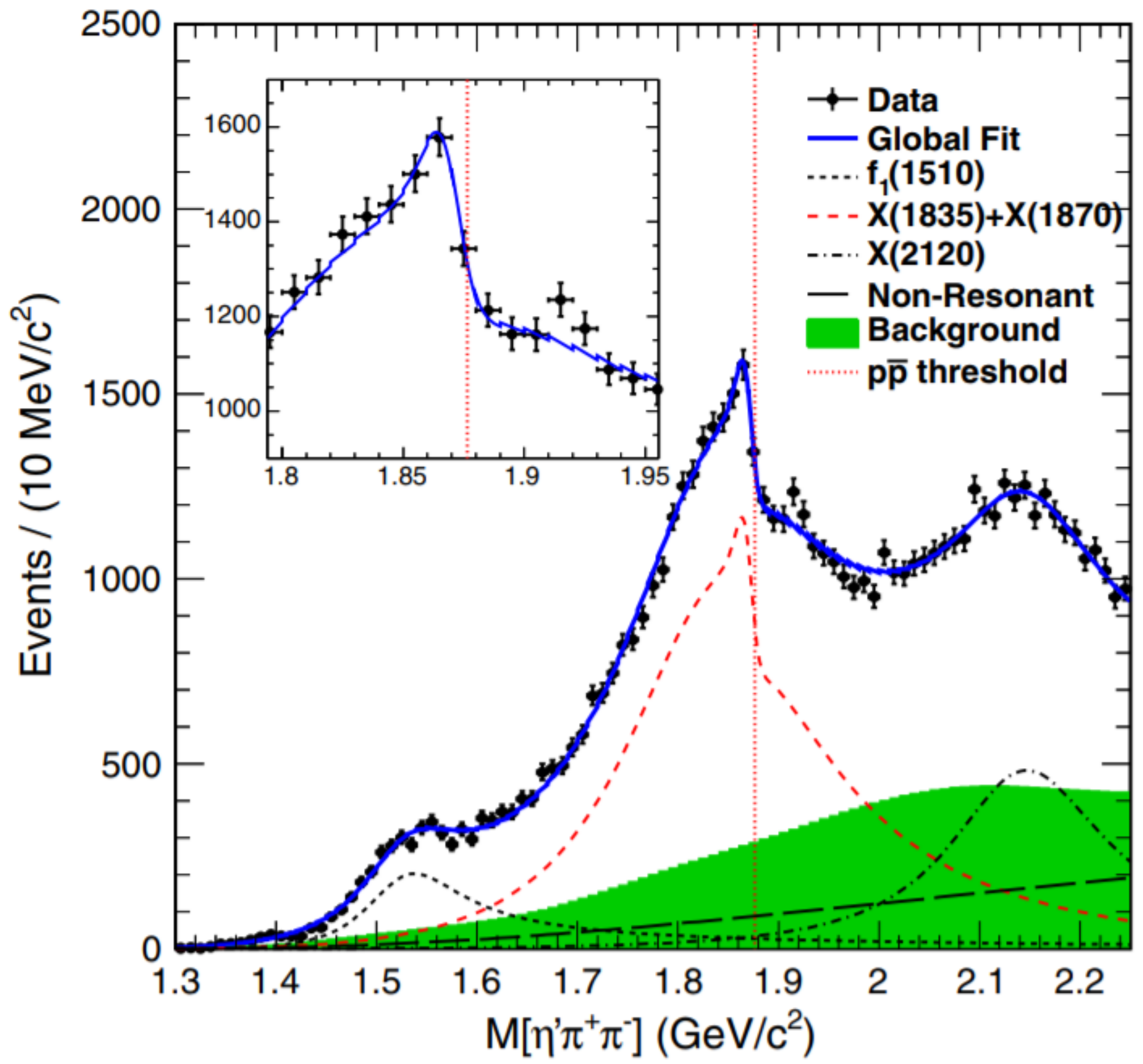
PRL 115 091803

- 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 $J/\psi \to K_sK_s\eta$

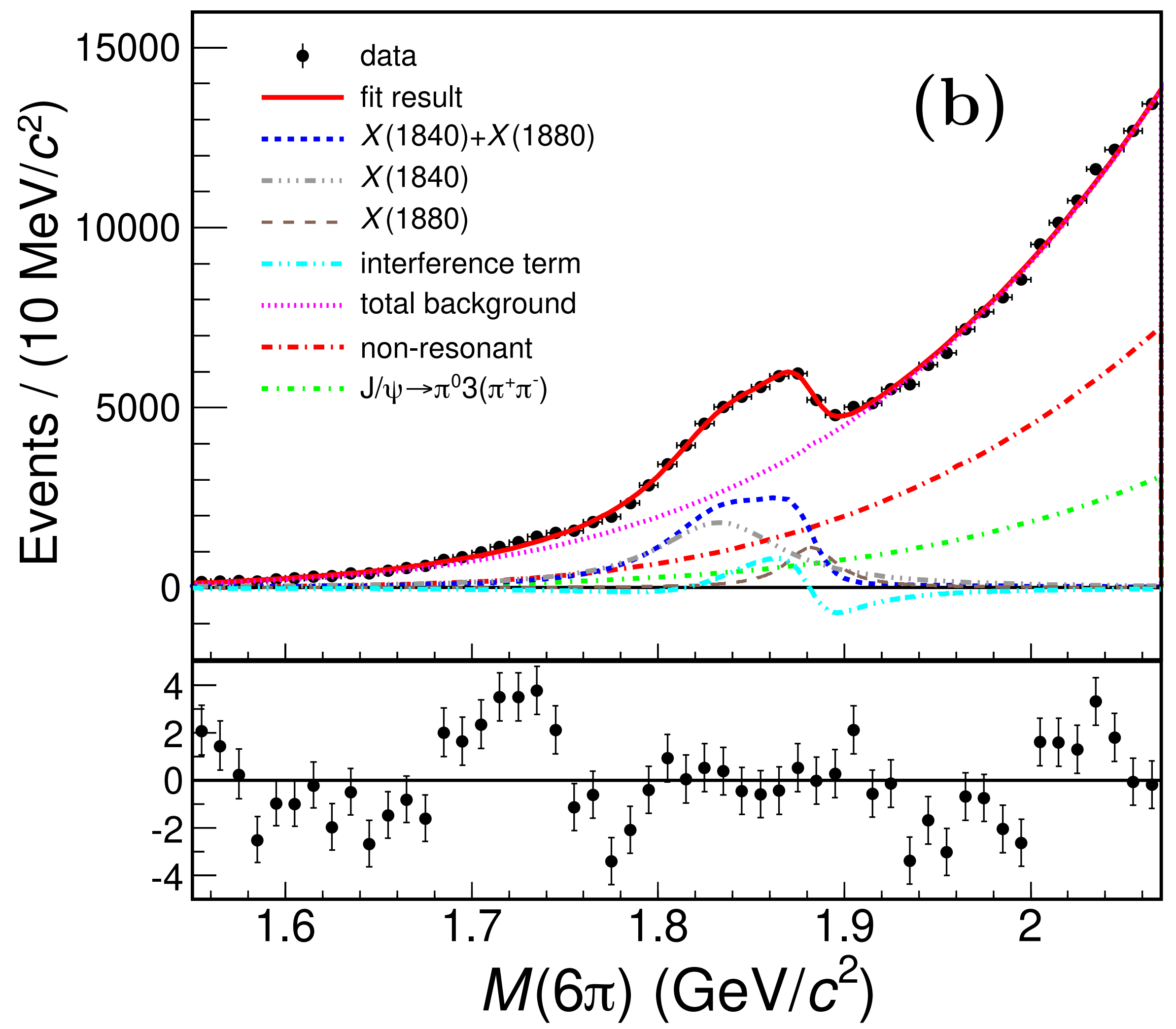
  M= $1844\pm9^{+16}_{-25}$ MeV/c^2

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

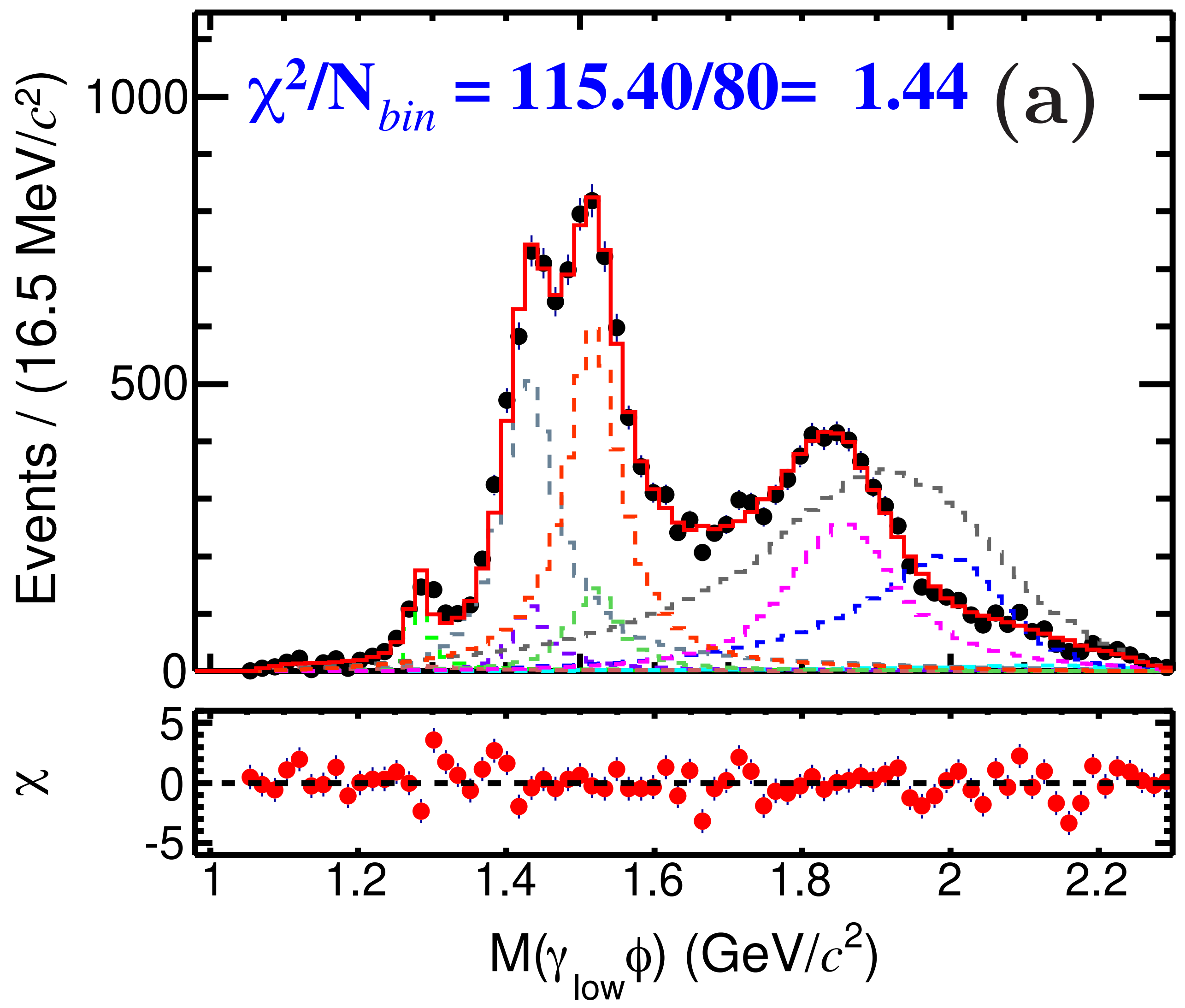
Direct link between the X($p\bar{p}$) and X(1835)



PRL 117, 042002



PRL 132 (2024) 151901

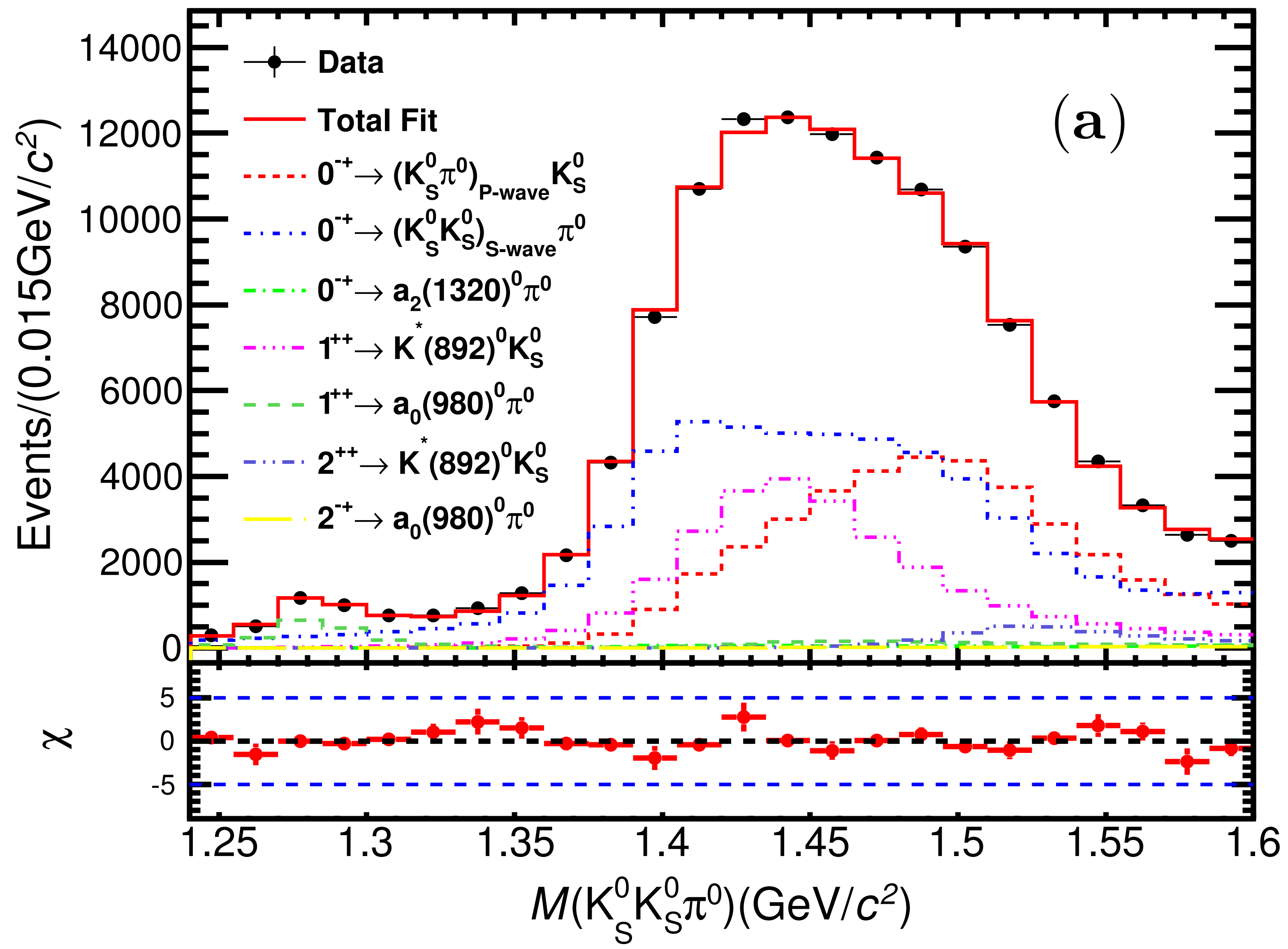


arxiv:2401.00918

- **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**

η(1405) - η(1475)

- The first 0^{-+} glueball candidate η(1405): mass incompatible with LQCD prediction
- 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



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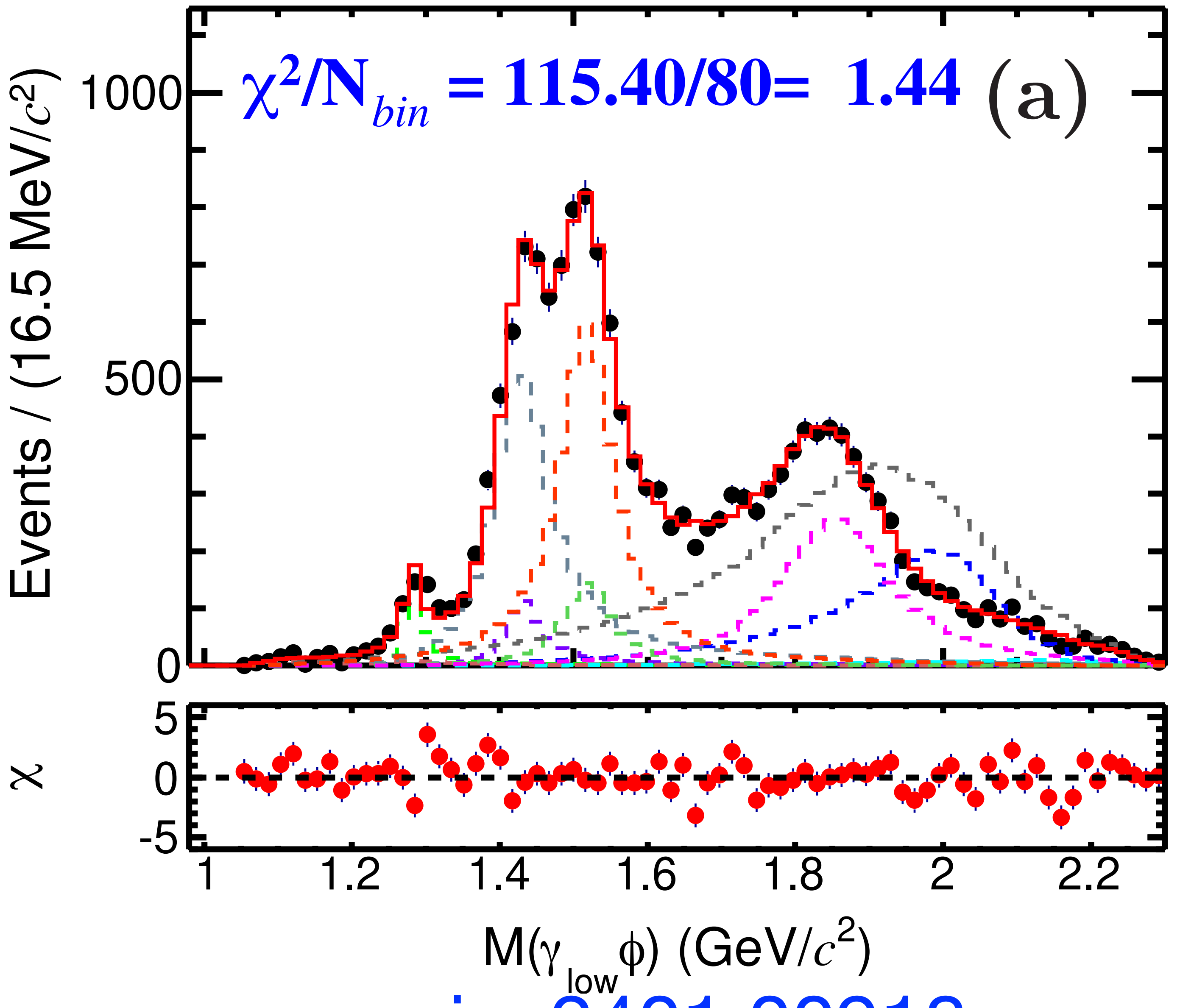


arxiv: 2401.00918

$J/\psi \to \gamma K_s K_s \pi^0$:

$M(\eta(1405)) = 1391.7 \pm 0.7\ ^{+11.3}_{-0.3}$ MeV

$\Gamma(\eta(1405)) = 60.8 \pm 1.2\ ^{+5.5}_{-12.0}$ MeV

$M(\eta(1475)) = 1507.6 \pm 1.6\ ^{+15.5}_{-32.2}$ MeV

$\Gamma(\eta(1475)) = 115.8 \pm 2.4\ ^{+14.8}_{-11.0}$ MeV

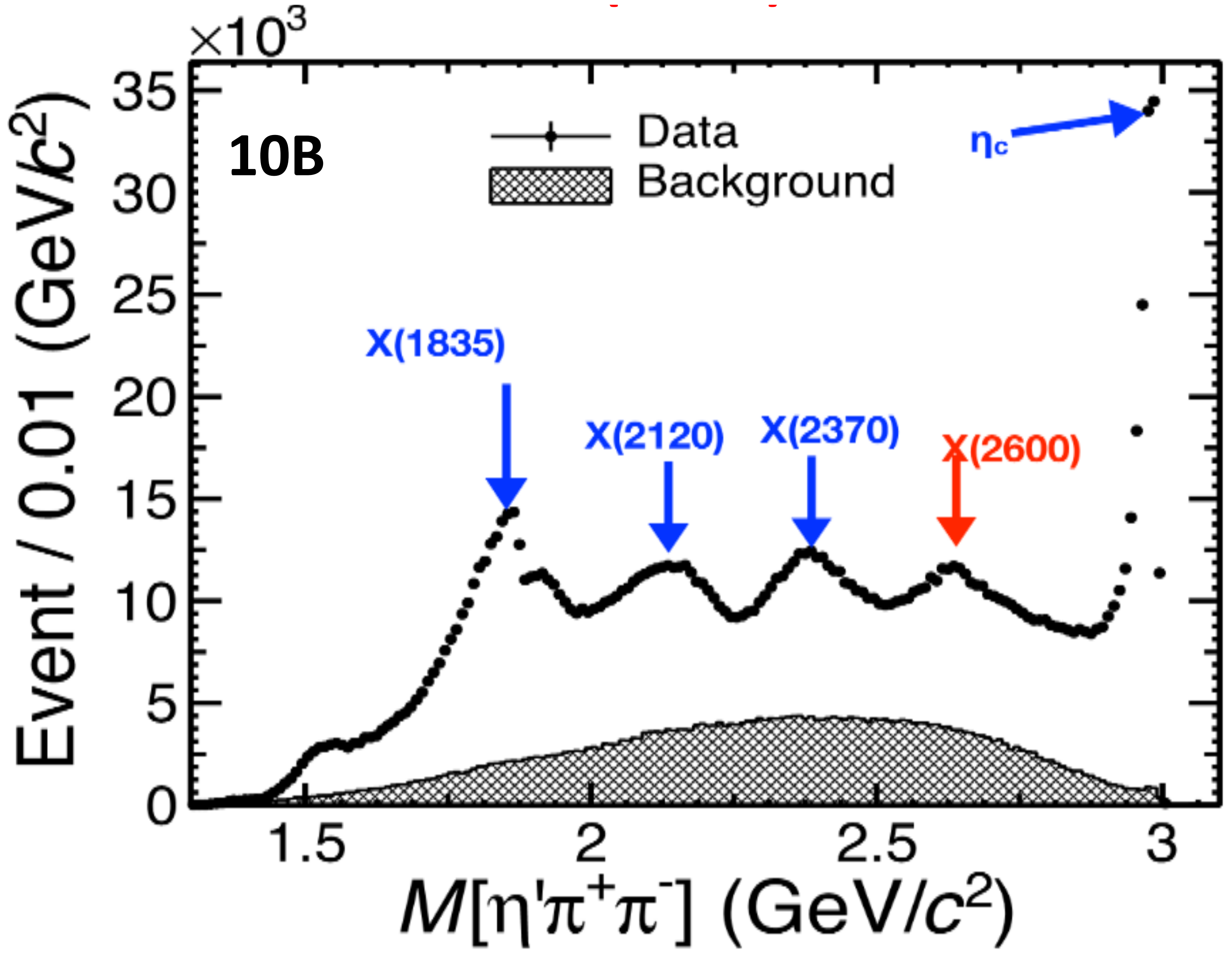
$J/\psi \to \gamma\gamma\Phi$:

$M(\eta(1405)) = 1422.0 \pm 2.1\ ^{+5.9}_{-7.8}$ MeV

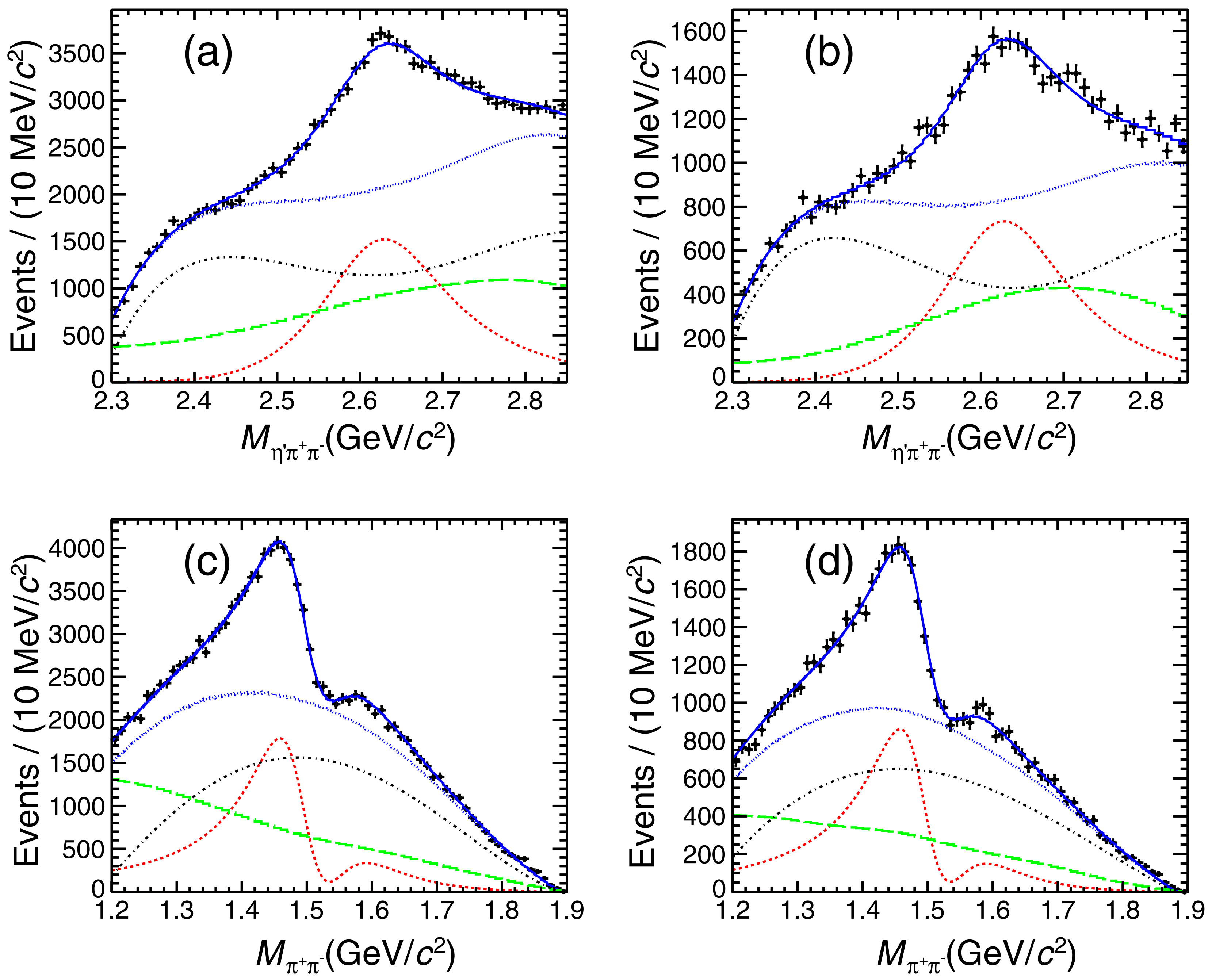
$\Gamma(\eta(1405)) = 86.3 \pm 2.7\ ^{+6.6}_{-12.0}$ MeV

—> what's the source of η(1405)?

Observation of X(2600) in $J/\psi \to \gamma\pi\pi\eta'$



PRL 129, (2022) 042001



◈ **Besides of X(1835), X(2120), X(2370), η_c, observation of X(2600) with >20σ in $J/\psi \to \gamma\pi\pi\eta'$**

✦ Two decays modes: $X(2600) \to f_0(1500)/X(1540)\eta', f_0(1500)/X(1540) \to \pi^+\pi^-$

✦ Explanation: η **radial excitation or exotic hadron?**

Summary

- A set of interesting and important results from the light hadron spectra achieved:
  - **Discovery of a glueball-like particle: X(2370)**
  - Strong correlation between the X(1835) and mppb 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 is ongoing, looking forward to new results in the near future.