Light exotic hadron at BESIII

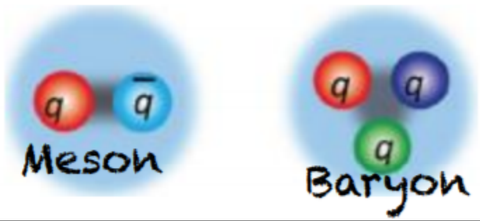
Yanping Huang

Institute of High Energy Physics, CAS

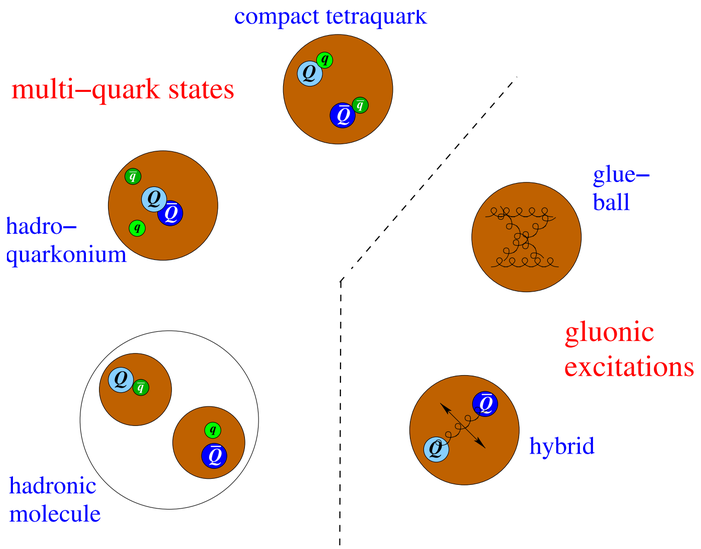
第四届强子和重味物理理论与实验联合研讨会，

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**

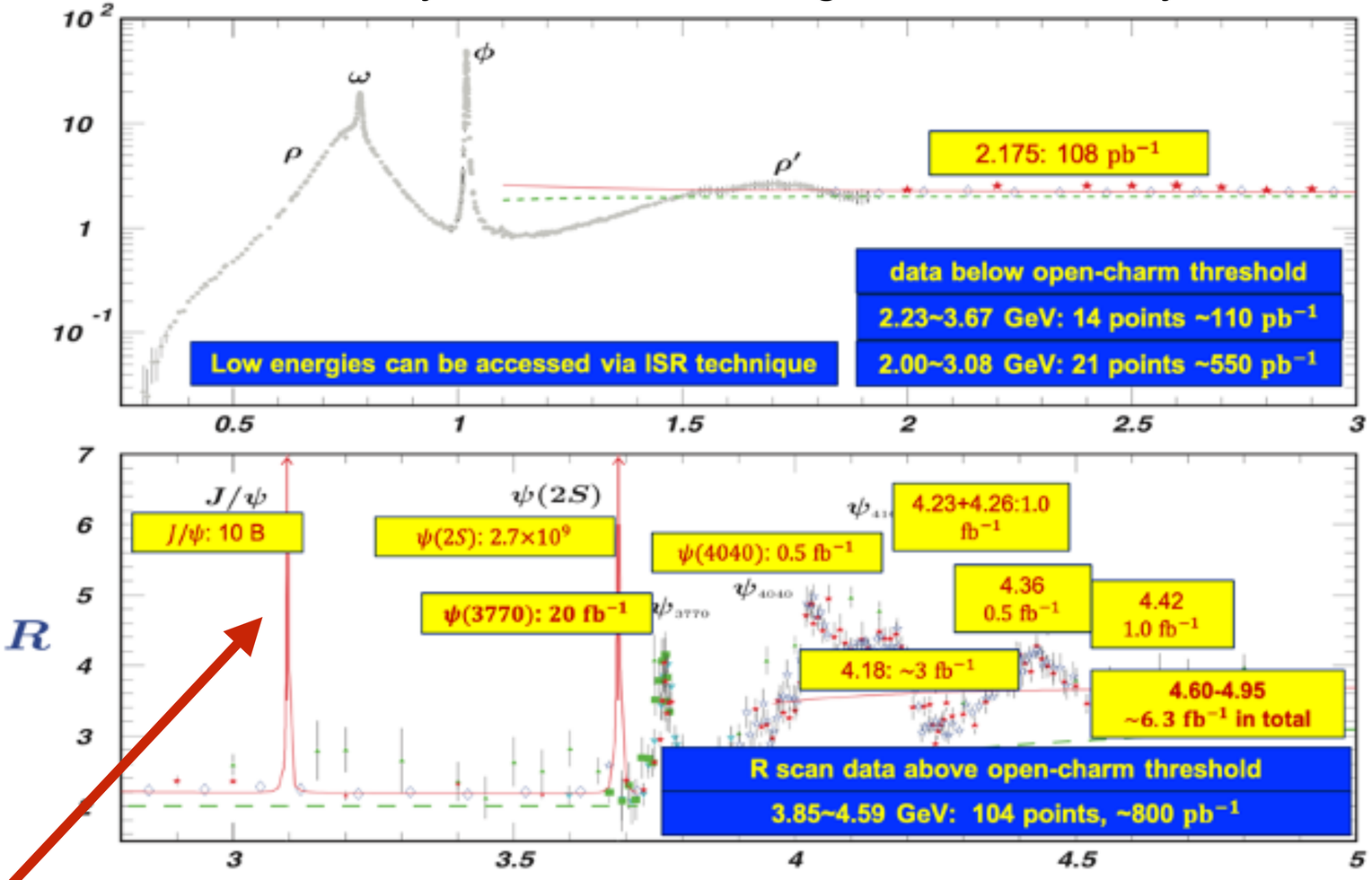
BESIII Data samples

Totally about 50fb^{-1} integrated luminosity

Data sets collected so far include

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

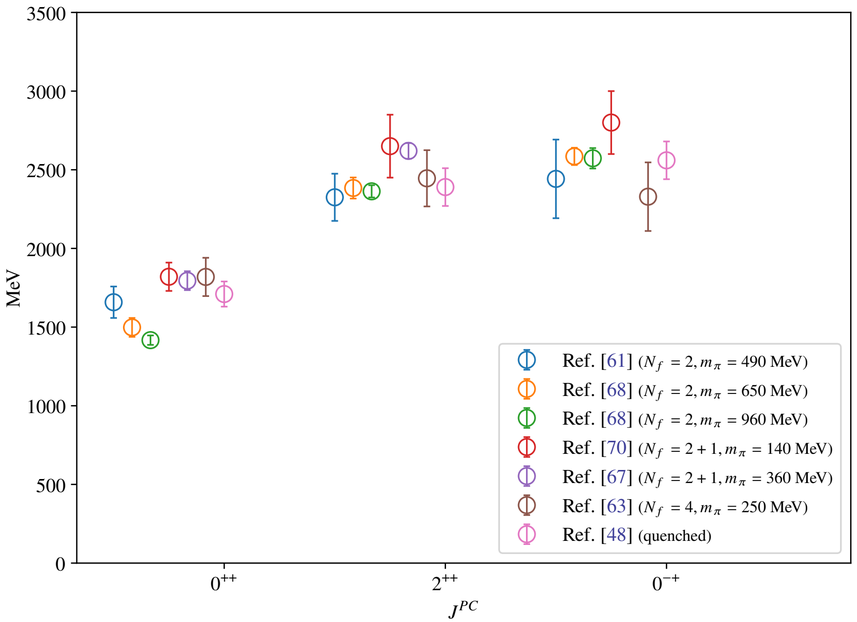


World largest J/ψ data sample : ~10 billion

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



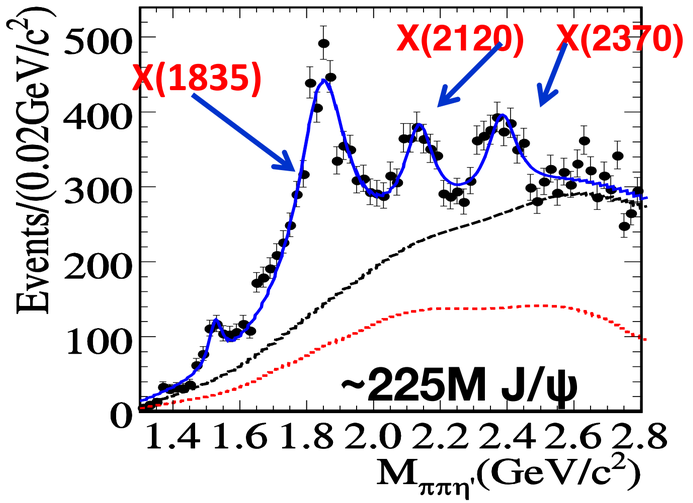
arxiv:2305.04869

X(2370)

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

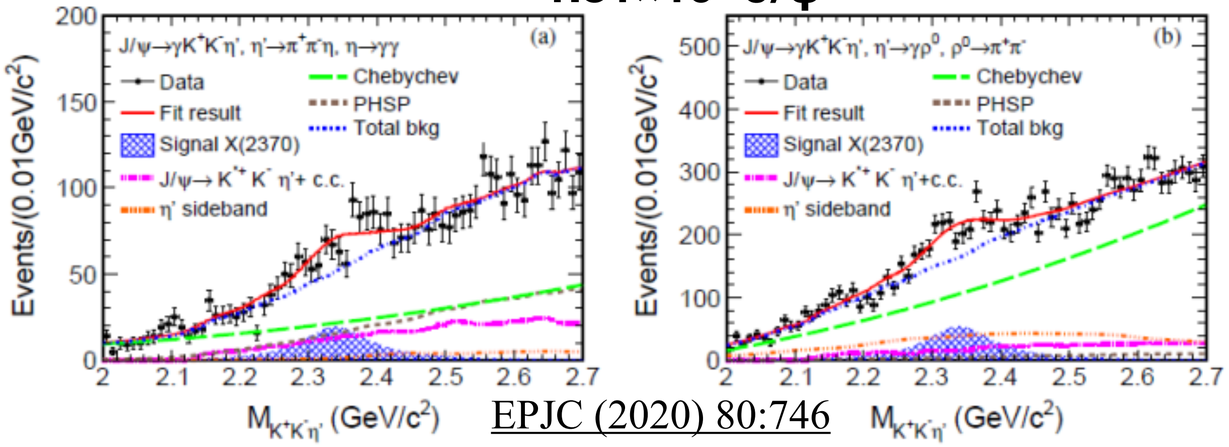
	M(MeV/c²)	Γ(MeV/c²)	Sig.
X(1835)	$1836.5\pm3.0^{+5.6}_{-2.1}$	$190.1\pm9.0^{+38}_{-36}$	>20σ
X(2120)	$2122.4\pm6.7^{+4.7}_{-2.7}$	$83\pm16^{+31}_{-11}$	7.2σ
X(2370)	$2376.3\pm8.7^{+3.2}_{-4.3}$	$83\pm17^{+44}_{-6}$	6.4σ

PRL 106, 072002 (2011)

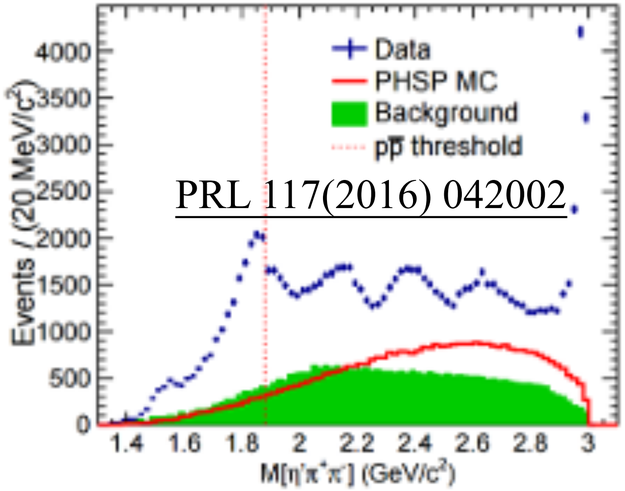


- **Confirmed by BESIII in $J/\psi \to \gamma\pi^+\pi^-\eta'$ and $J/\psi \to \gamma K\bar{K}\eta'$ (new mode)**

1.31×10⁹ J/ψ



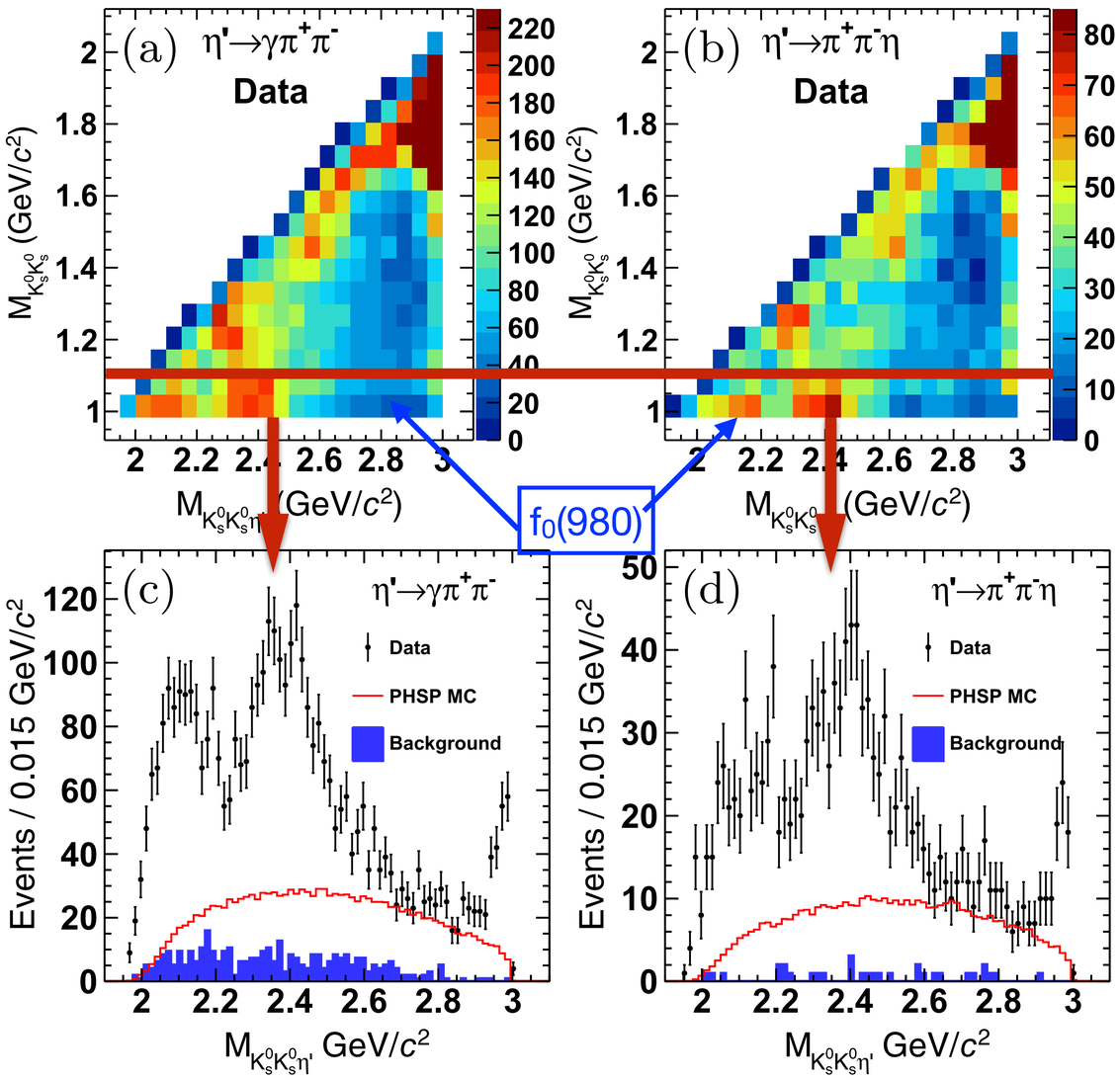
EPJC (2020) 80:746



PRL 117(2016) 042002

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

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



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**

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

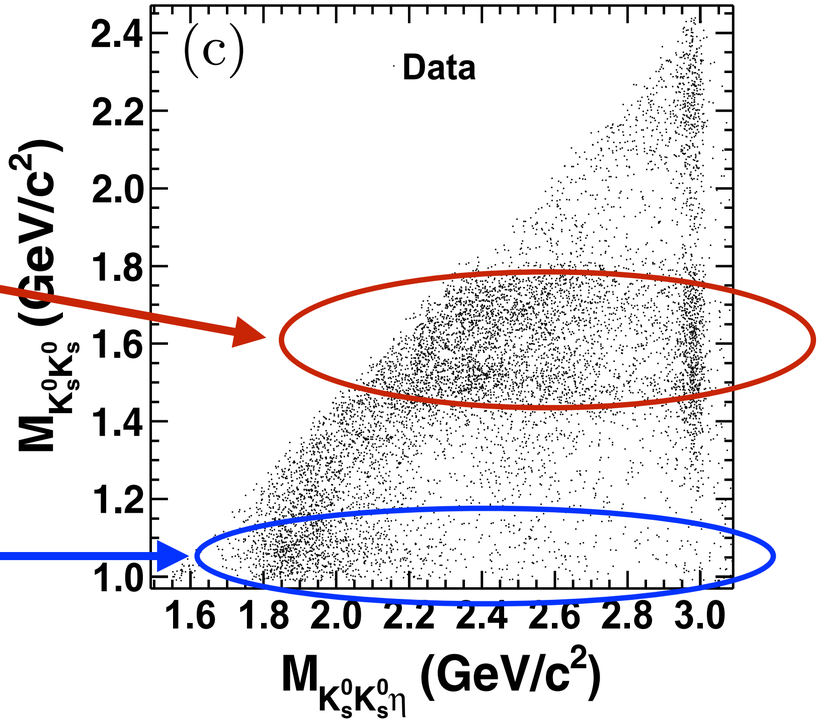
Observation and Spin-Parity Determination of the $X(1835)$ in $J/\psi \to \gamma K^0_S K^0_S \eta$

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

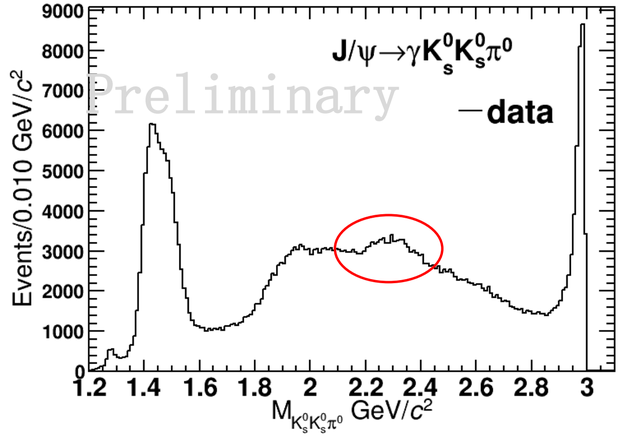
With 1.31×10^9 J/ψ events

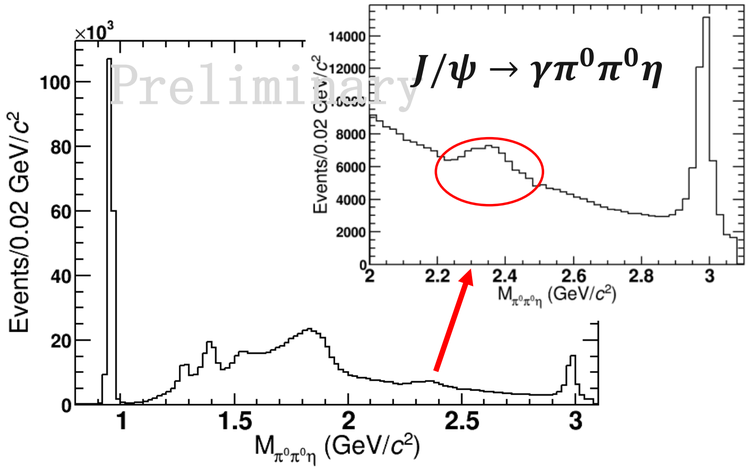


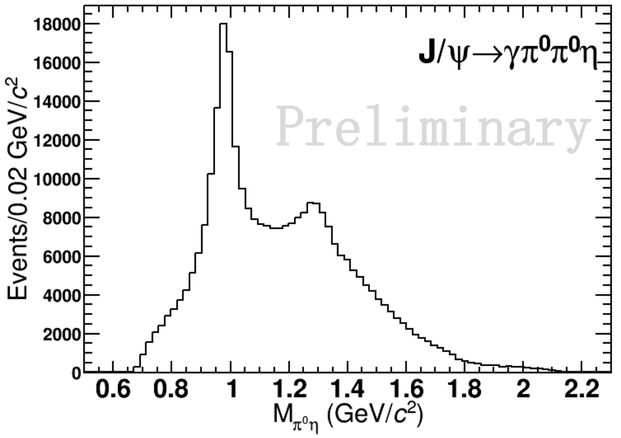
PRL 115 (2015) 091803

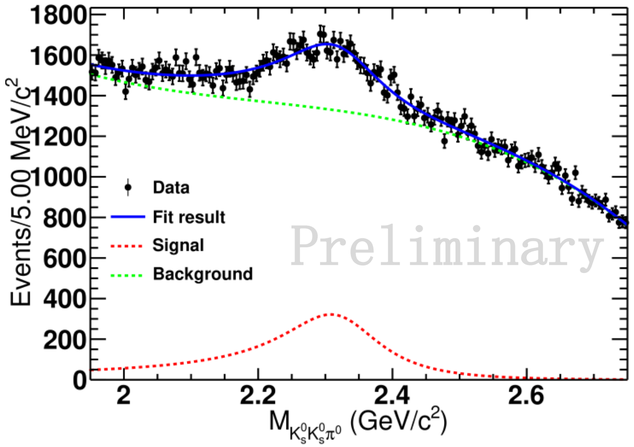
Such high similarity between the X(2370) and η_c decay modes

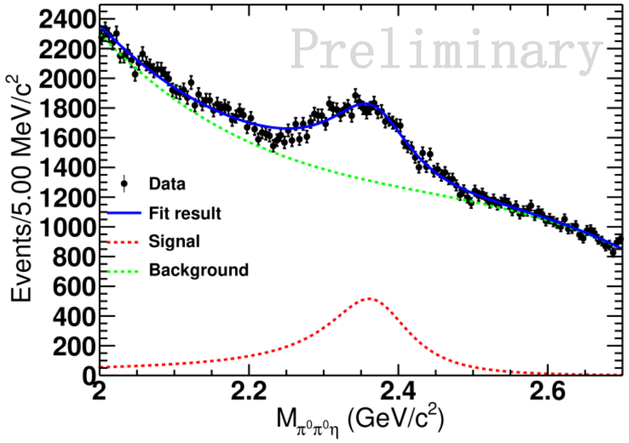
Observation of new decay modes of the X(2370)

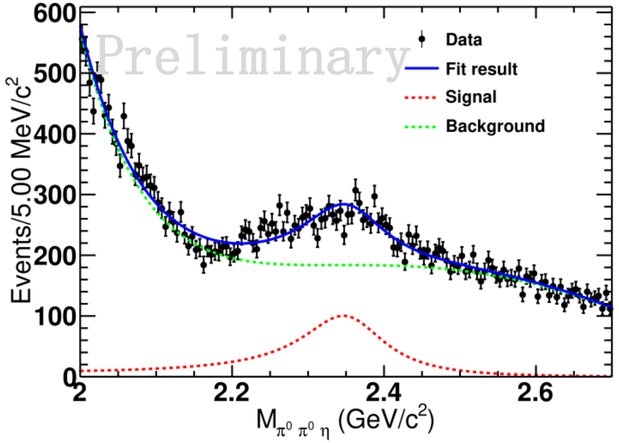












First observation of $X(2370) \to K_s^0 K_s^0 \pi^0$, $X(2370) \to \pi^0\pi^0\eta$ and $X(2370) \to a(980)\eta$ with **significances >> 5σ and accompanied with η_c**

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

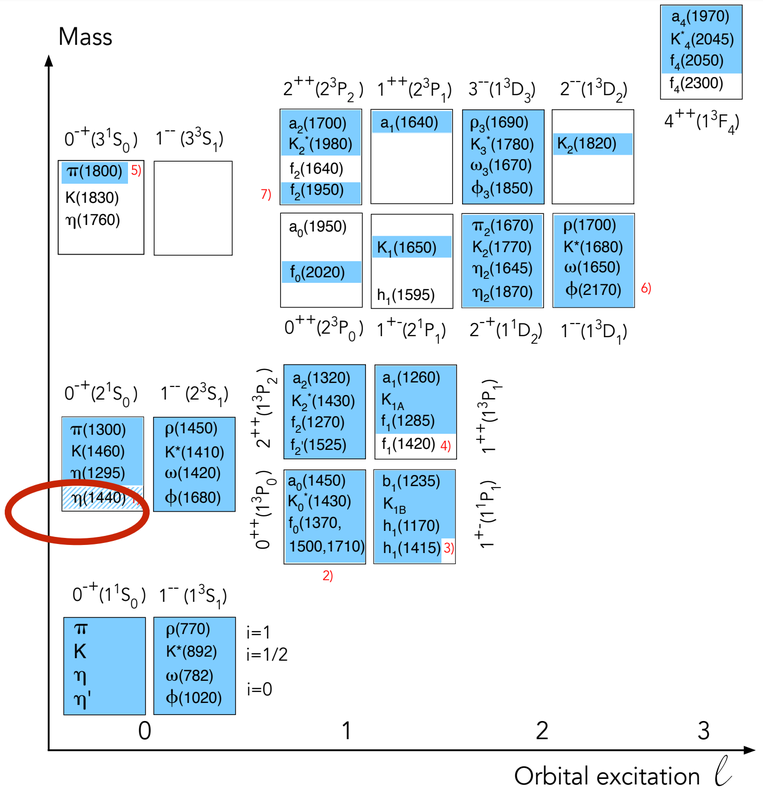
Γ_{34}	$K\overline{K}\pi$	(7.0 ±0.4) %
Γ_{35}	$K\overline{K}\eta$	(1.32±0.15) %
Γ_{36}	$\eta\pi^+\pi^-$	(1.7 ±0.5) %

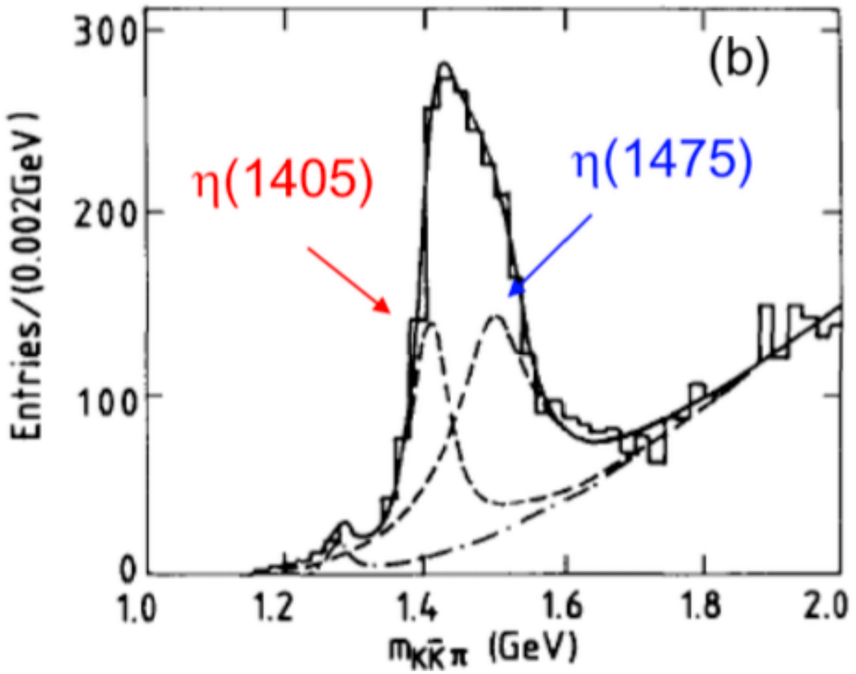
- **The 0^{-+} glueball decays could be the analogy to η_c decays**
  - **Decay modes of X(2370)$\rightarrow\pi\pi\eta'$,$K\bar{K}\eta'$,$K\bar{K}\pi$, $\pi\pi\eta$, $K\bar{K}\eta$, $a(980)\pi$ observed, consistent with 0^{-+} glueball**

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

More details and discussion in Prof. Jin Shan's talk tomorrow

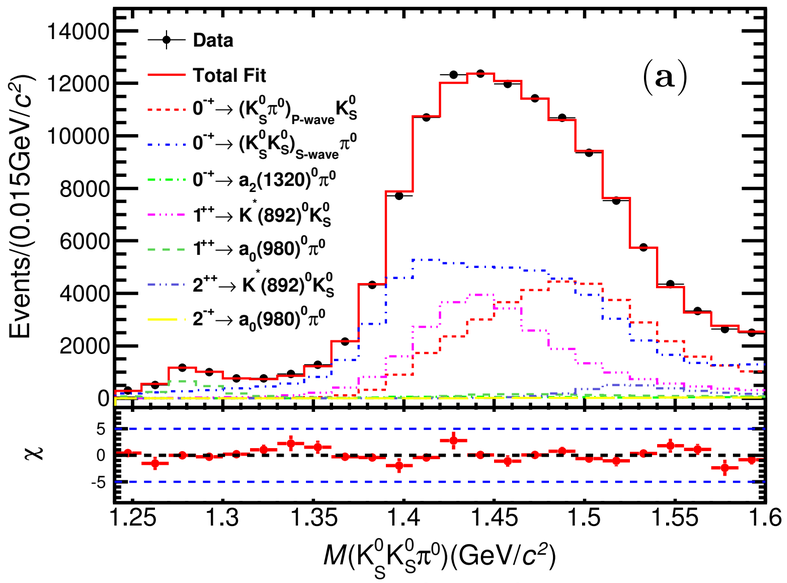
E-ι puzzle





- 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



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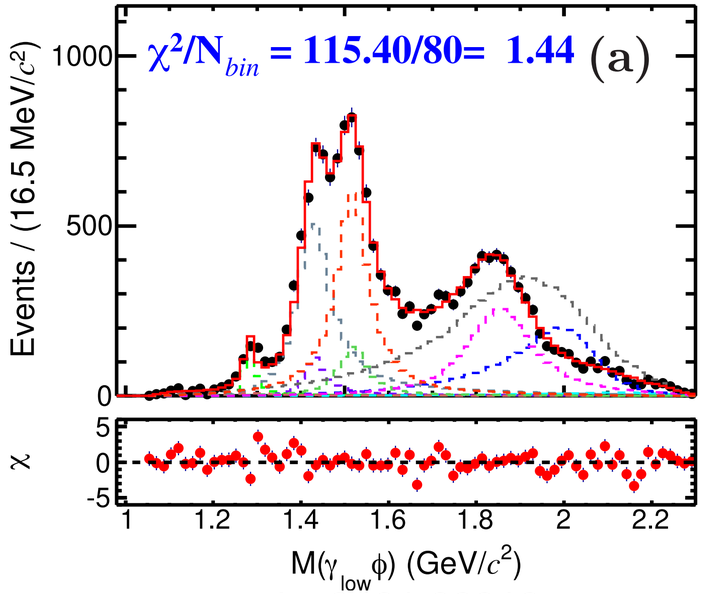
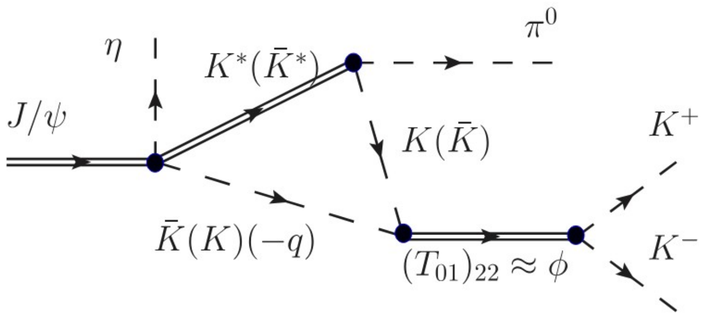


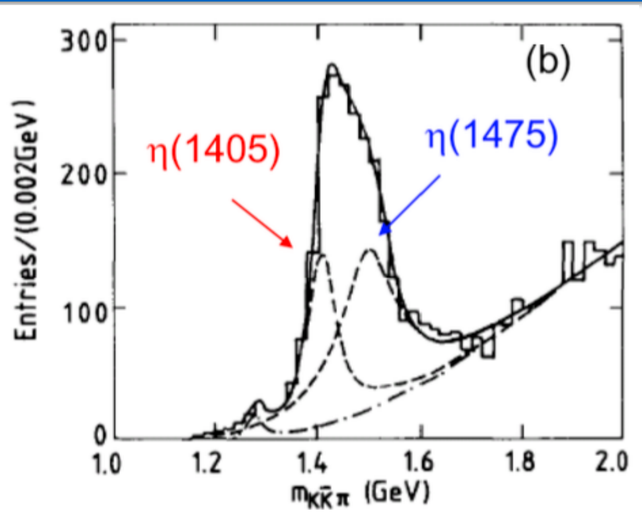
arxiv: 2401.00918

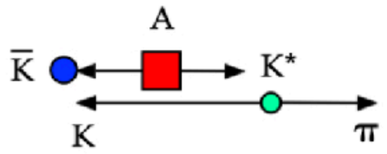


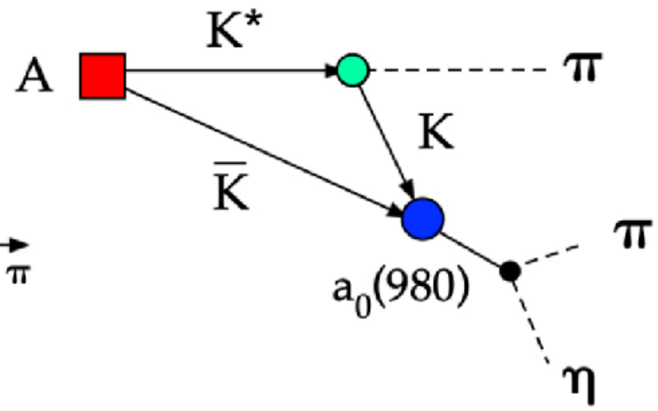
Triangle singularity?

- 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)



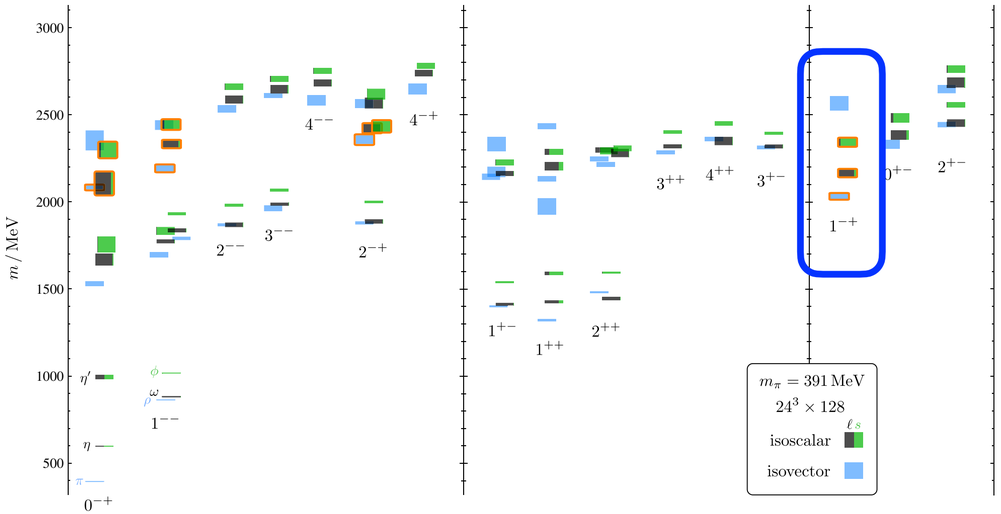




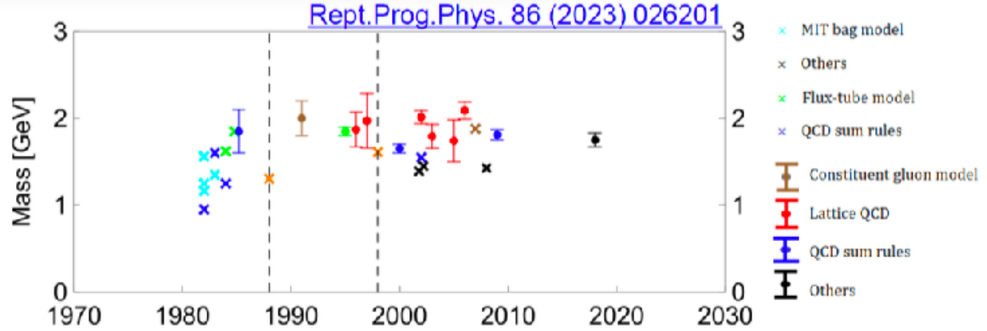
- The broad structure ~1.4GeV: η(1405) and η(1475) / Triangle singularity
  - Probe the quark constitute and triangle singularity effect via ω/ϕ associated production
  - Probe the triangle singularity via the ratio between $a_0(980)$ and $f_0(980)$
    - Need to check the complexity of $\pi^+\pi^-\pi^0$ decay mode
    - Need to expected ratio: measurement and prediction

Exotic 1^{-+} state

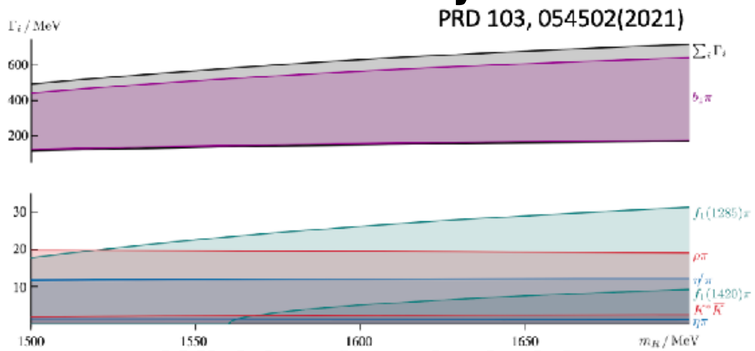
J^{PC}	$q\bar{q}$
0^{++}	yes
0^{+-}	–
0^{-+}	yes
0^{--}	–
1^{++}	yes
1^{+-}	yes
1^{-+}	–
1^{--}	yes
2^{++}	yes
2^{+-}	–
2^{-+}	yes
2^{--}	yes
3^{++}	yes
3^{+-}	yes
3^{-+}	–
3^{--}	yes



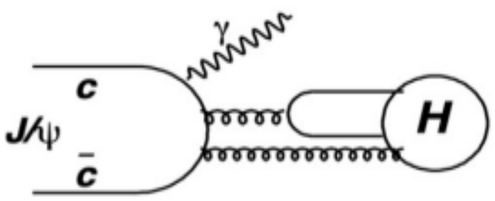
PRD 88 094505(2013)



Mass of 1^{-+} hybrid



Width of 1^{-+} hybrid

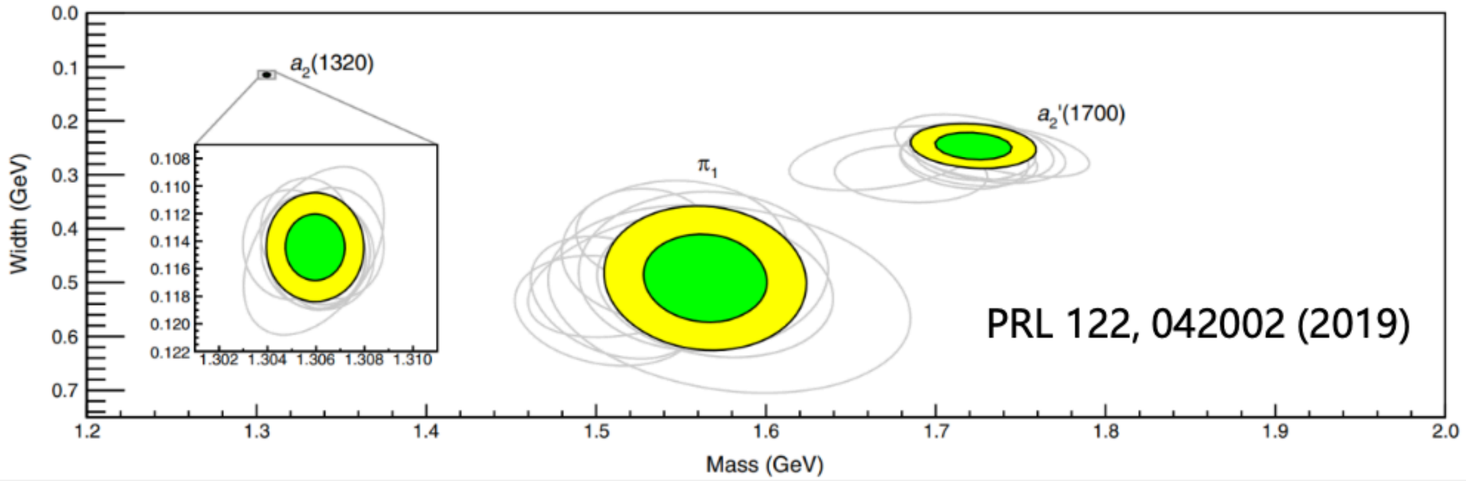


$$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$$

- **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

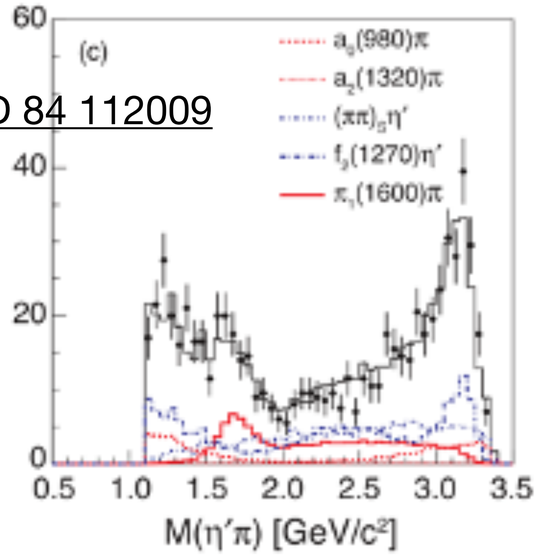
- Over 3 decades, experimental evidence for 3 candidates with 1^{-+} state:
  - All 1^{-+} iso-vectors
  - $\pi_1(1400)$: seen in $\eta\pi$
  - $\pi_1(1600)$: seen in $\rho\pi$, $\eta'\pi$, $b_1\pi$, $f_1\pi$
  - $\pi_1(2015)$: seen in $b_1\pi$ and $f_1\pi$
- Some claims are controversial
- $\pi_1(1400)$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

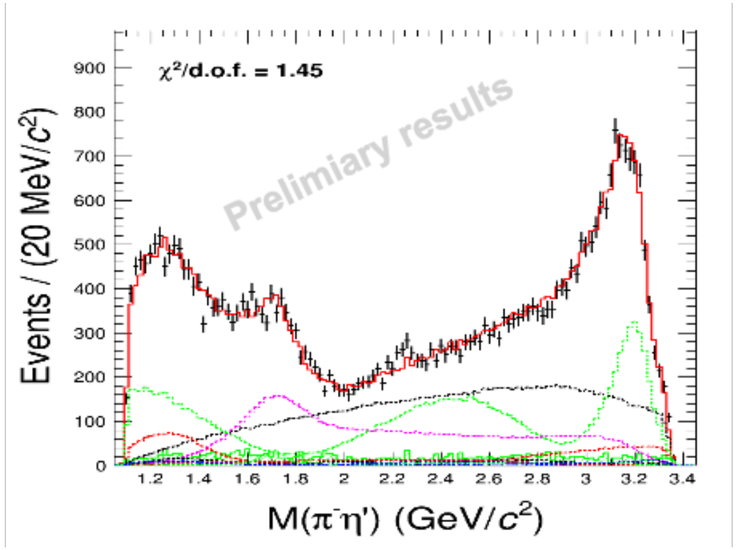


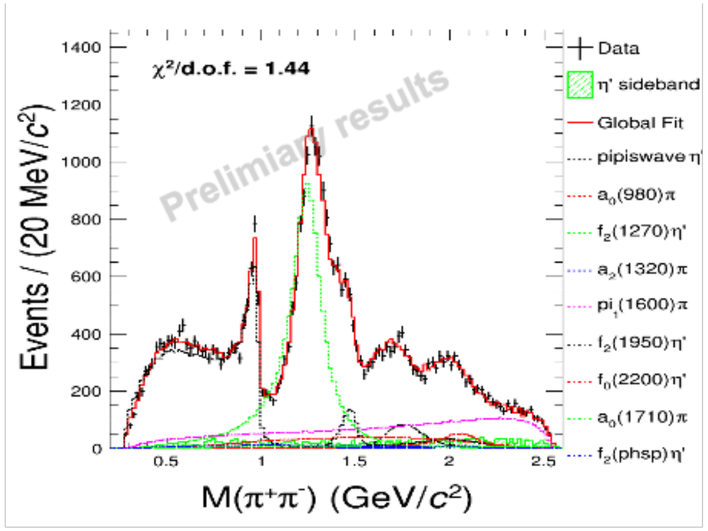
	Decay mode	Reaction	Experiment
$\pi_1(1400)$	$\eta\pi$	$\pi^- p \to \pi^- \eta p$ $\pi^- p \to \pi^0 \eta n$ $\pi^- p \to \pi^- \eta p$ $\pi^- p \to \pi^0 \eta n$ $\bar{p}n \to \pi^- \pi^0 \eta$ $\bar{p}p \to \pi^0 \pi^0 \eta$	GAMS KEK E852 E852 CBAR CBAR
	$\rho\pi$	$\bar{p}p \to 2\pi^+ 2\pi^-$	Obelix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

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

PRD 84 112009



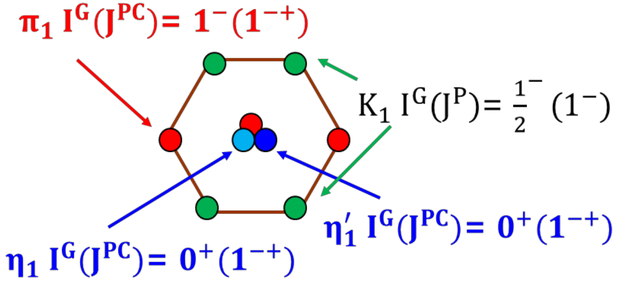


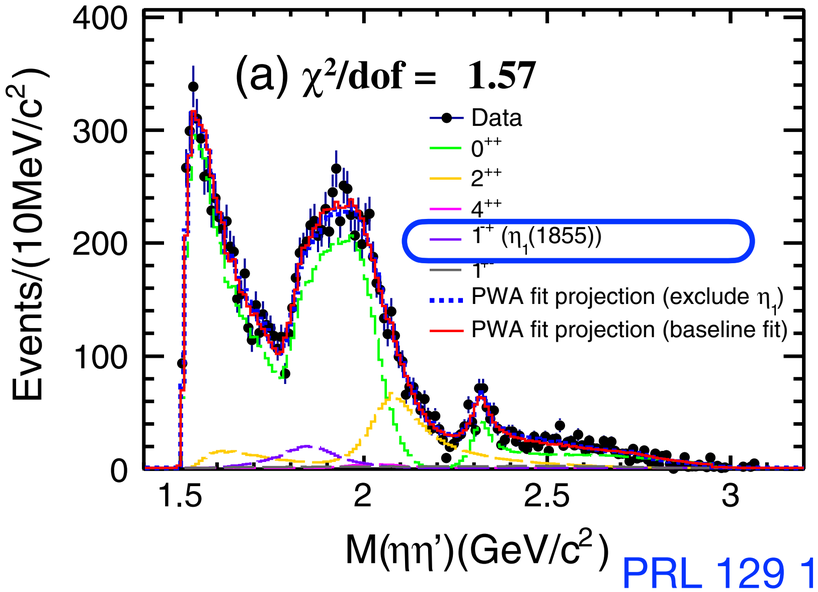


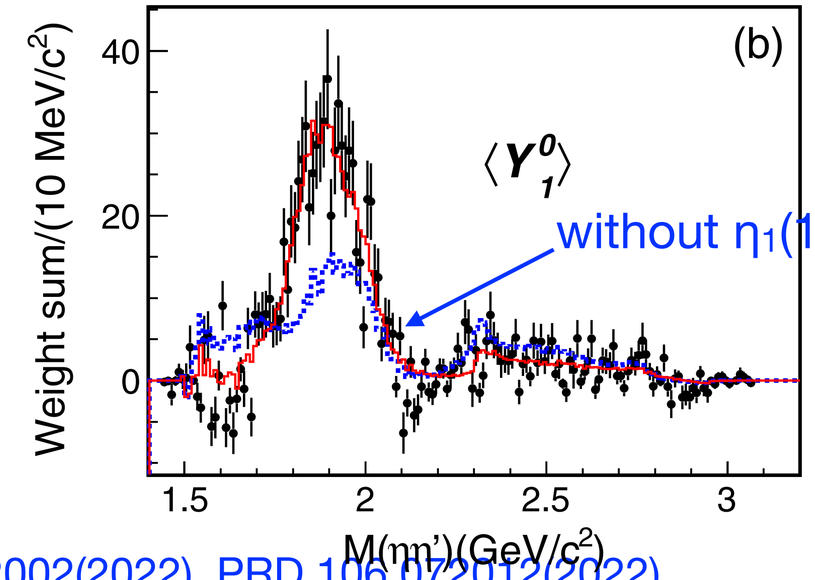
- CLEO-c results: evidence of an exotic P-wave $\eta'\pi$ amplitude with 4σ and but no significant phase motion
- PWA in $\psi' \to \gamma\chi_{c1}(\chi_{c1} \to \pi^+\pi^-\eta')$ with higher ψ' data sample @ BESIII:
  - **First observation of Exotic 1^{-+} Isovector state $\pi(1600)$ with a significance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





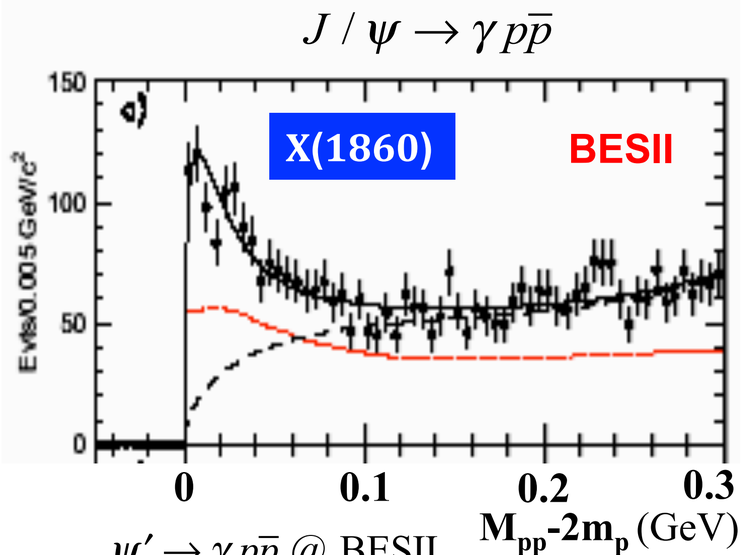


PRL 129 192002(2022), PRD 106 072012(2022)

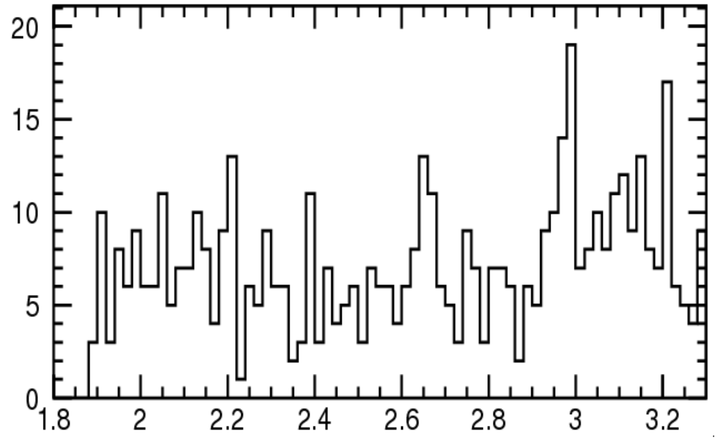
- **$J/\psi\to\gamma\eta\eta'$ is a good channel for $\eta_1(1^{-+})$ search**
- **Observation of an isoscalar 1^{-+} $\eta_1(1855)$ in $J/\psi\to\gamma\eta\eta'$ (>19σ)**
  - PWA: quasi two-body decay amplitudes in the sequential decay processes with covariant tensor formalism
  - $M= 1855\pm9^{+6}_{-1}$MeV, $\Gamma=188\pm18^{+3}_{-8}$ MeV, $B(J/\psi\to\gamma\eta1(1855)\to\gamma\eta\eta')=(2.70\pm0.41^{+0.16}_{-0.35})\times10^{-6}$
- **Mass consistent with hybird on LQCD, and more interpretations** (KK Molecule/Tetraquark)

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

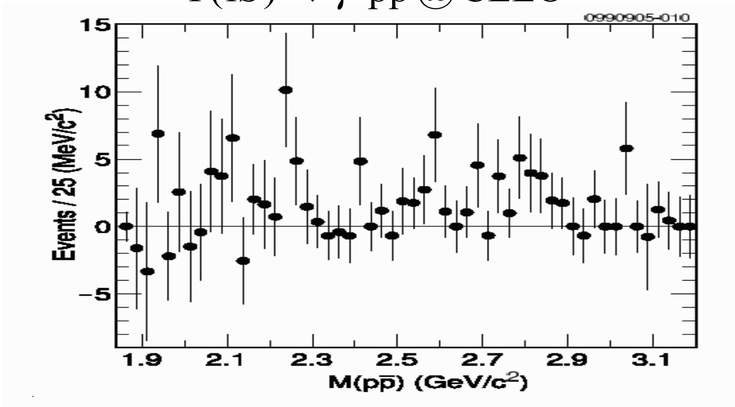
$J/\psi \to \gamma p\bar{p}$



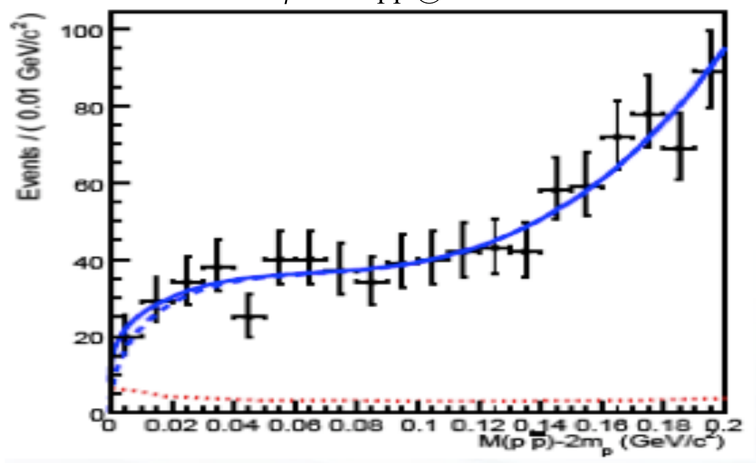
$\psi' \to \gamma p\bar{p}$ @ BESII



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

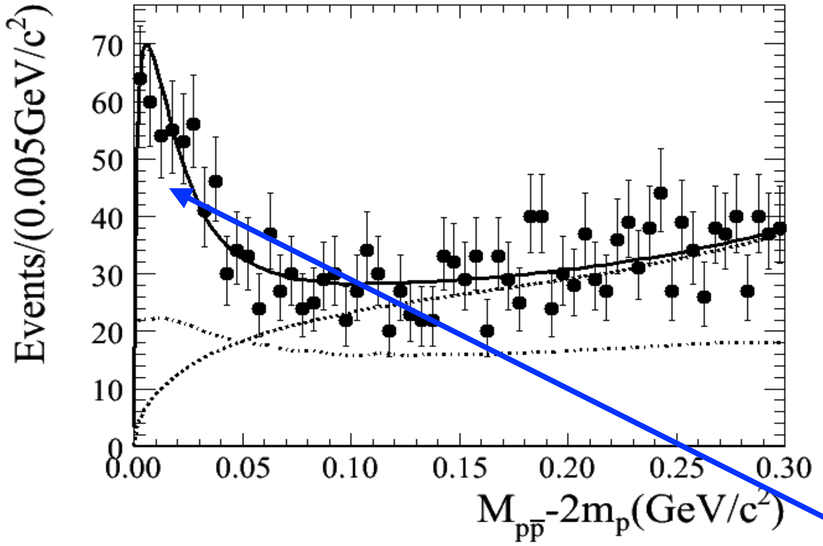


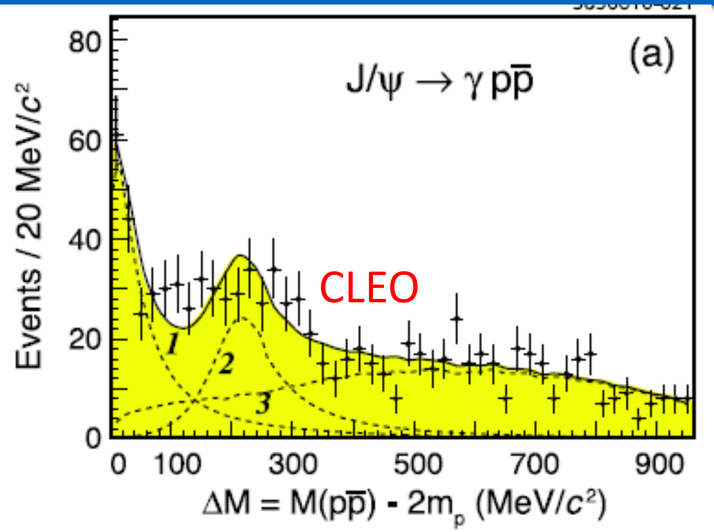
$J/\psi \to \omega\ p\bar{p}$ @ BESII

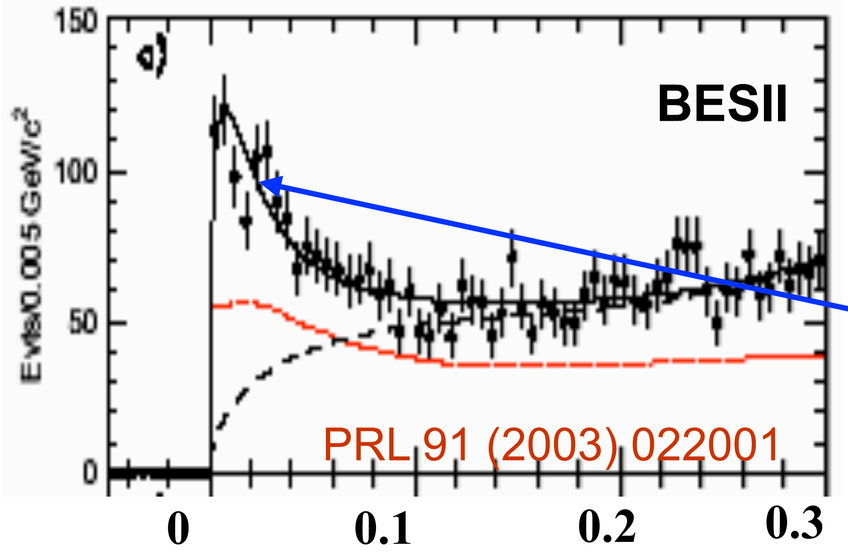


- First observation of ppb mass threshold enhancement
- No similar threshold structure in other channels → It can not be pure FSI effect

Confirmation of M_{ppb} threshold enhancement







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

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

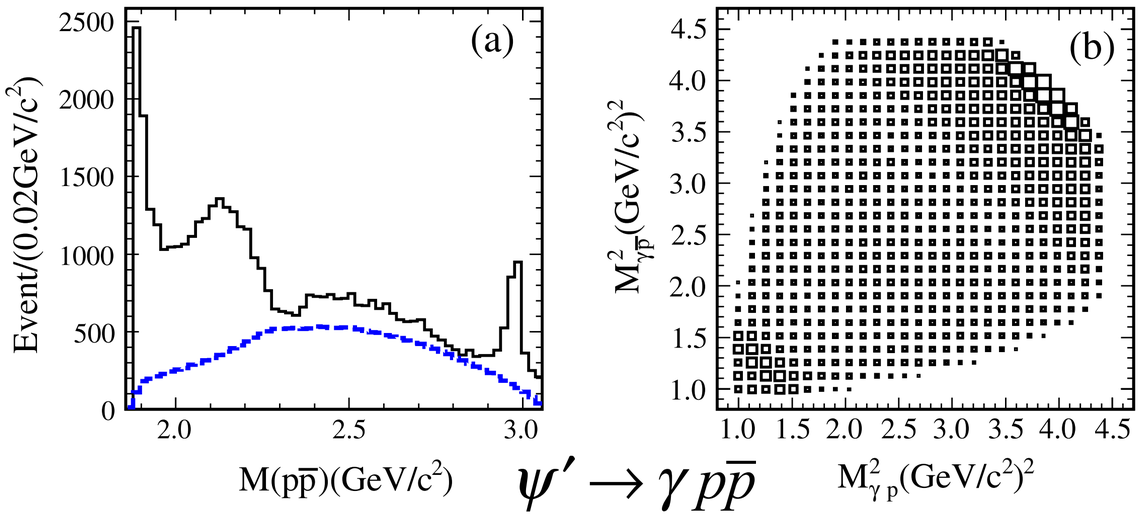
$M = 1861\ ^{+6}_{-13}\ ^{+7}_{-26}\ MeV/c^2$

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

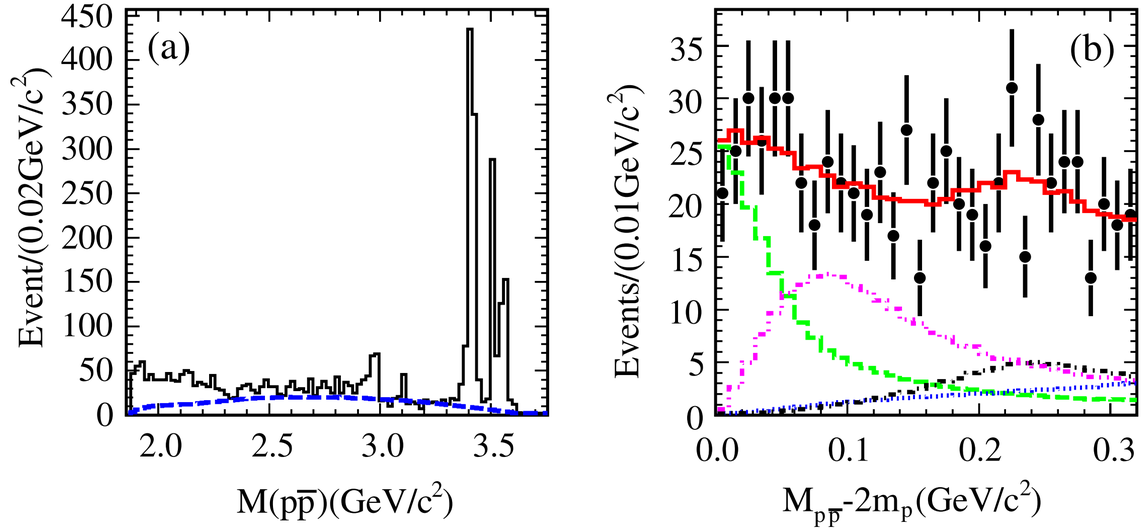
Good agreement on the mass and width measurements which indicated that the confirmation of the M_{ppb} threshold enhancement

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

$M = 1861 \pm 1^{+13}_{-4}$ MeV

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

$B(J/\psi \to \gamma X(1860))B(X(1860) \to pp)$

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

X(pp) significance >6.9σ

Production ratio:

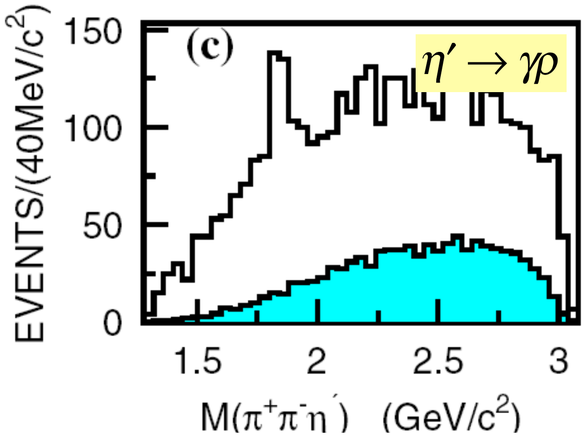
$R = 5.08 \pm 0.56^{+0.64}_{-3.09} \pm 0.12\%$

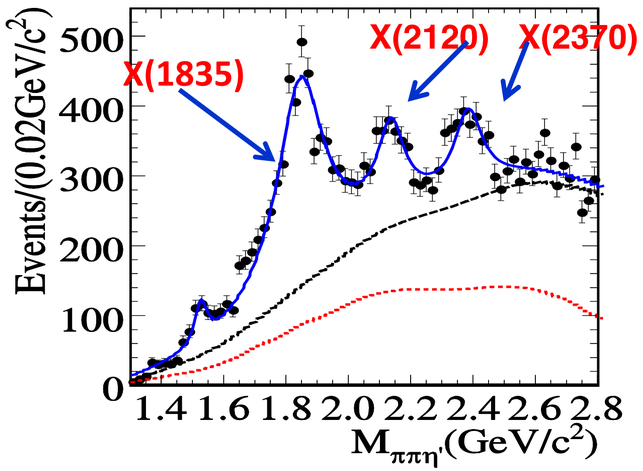
Evident suppression w.r.t. "12%rule"

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

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

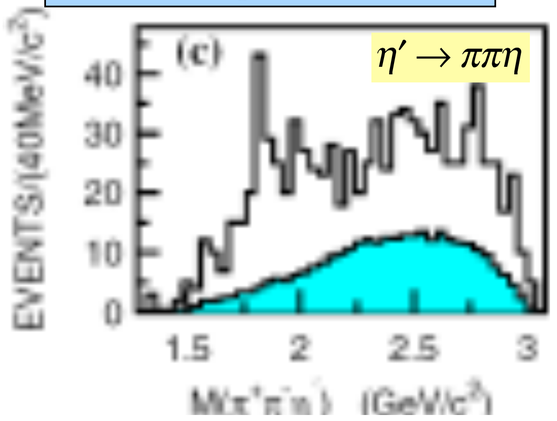
Statistical Significance ~ 6σ

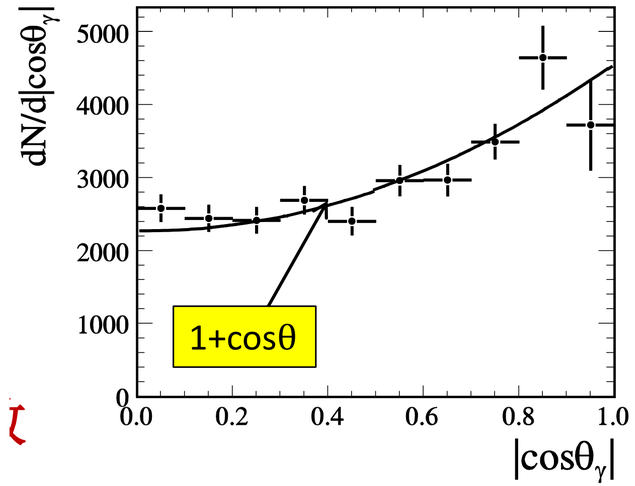




PRL 95,262001(2005)

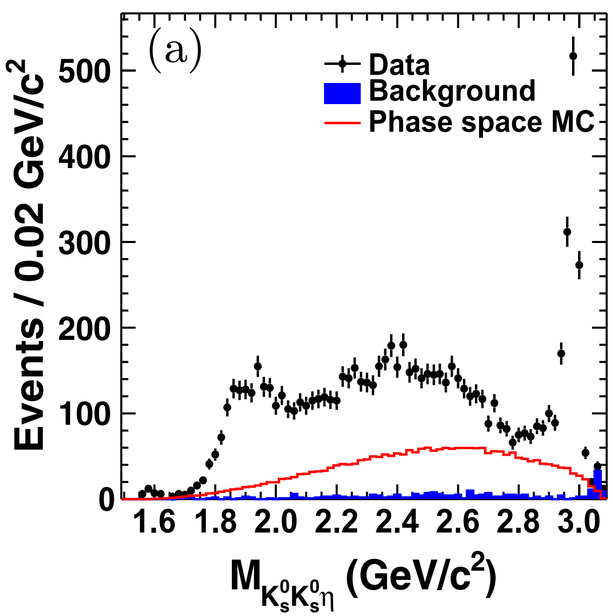
Statistical Significance ~ 5.1σ

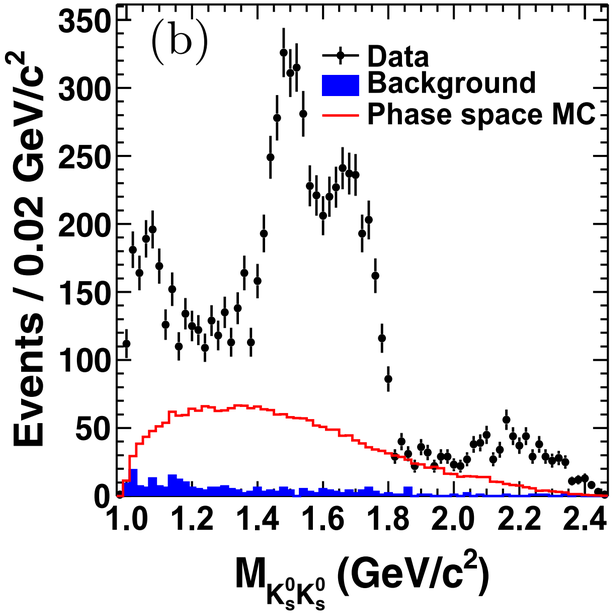


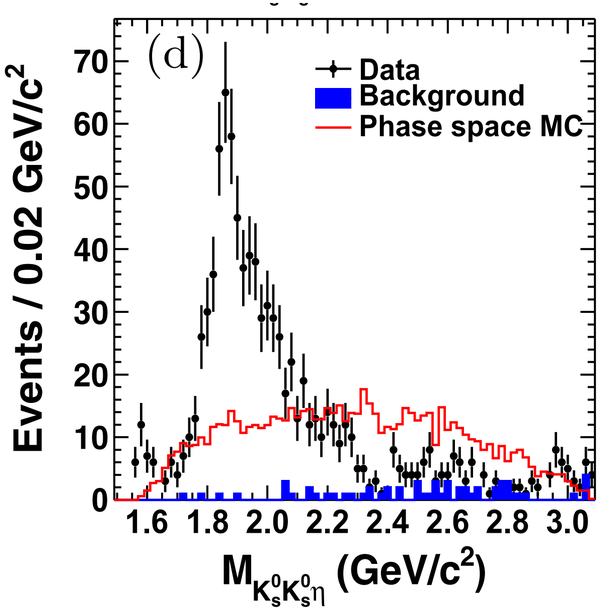


- First observation of the X(1835) @ BESII
- Confirmation of the X(1835) and observation of the two new resonances (X(2120) and X(2370)) @ BESIII

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

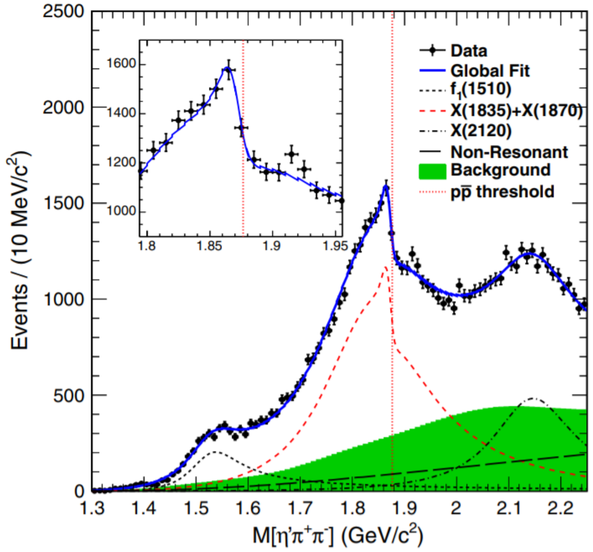




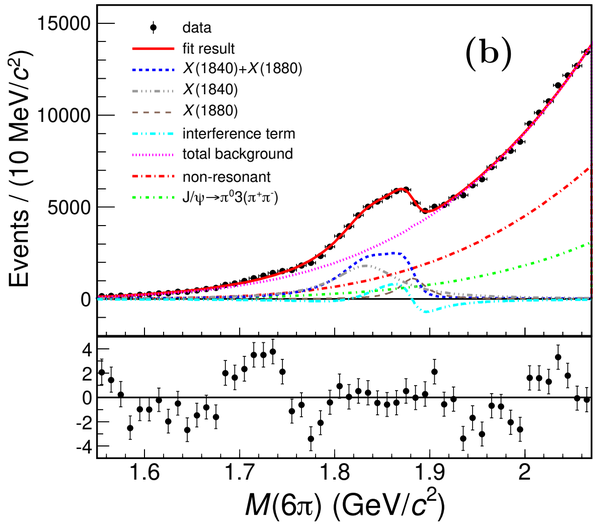


- **$X(1835)\to K_sK_s\eta$ is dominated by the $f_0(980)$ production with the significance >12.9σ.**
- **The spin-parity is determined to be 0^{-+}**
  - $M = 1844\pm9^{+16}_{-25}$ MeV, $\Gamma = 192^{+20}_{-17}{}^{+62}_{-43}$ MeV
  - $B(J/\psi\to\gamma X(1835))B(X(1835)\to f_0(980)\eta) = 3.31^{+0.33}_{-0.30}{}^{+1.96}_{-1.29}\times10^{-5}$

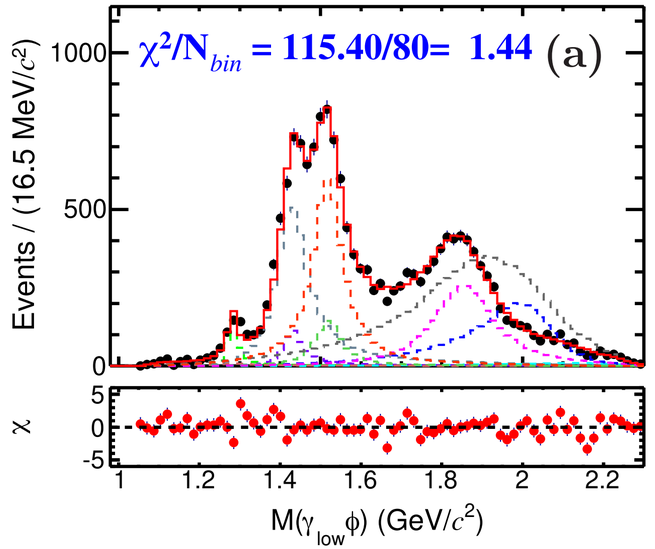
Direct link between the X($p\bar{p}$) and X(1835)



PRL 117, 042002



PRL 132 (2024) 151901



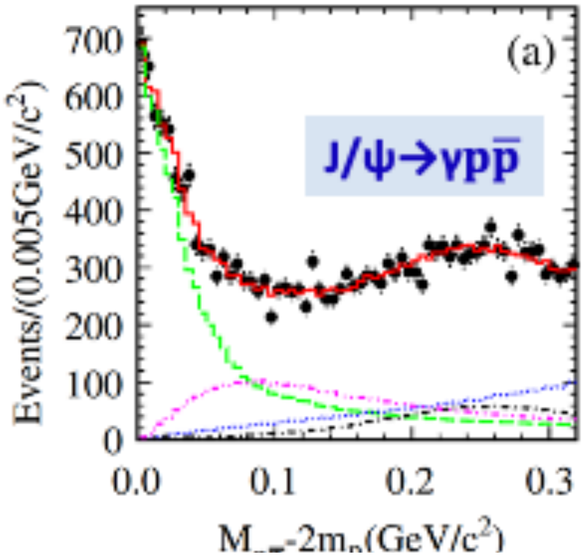
arxiv:2401.00918

- **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.

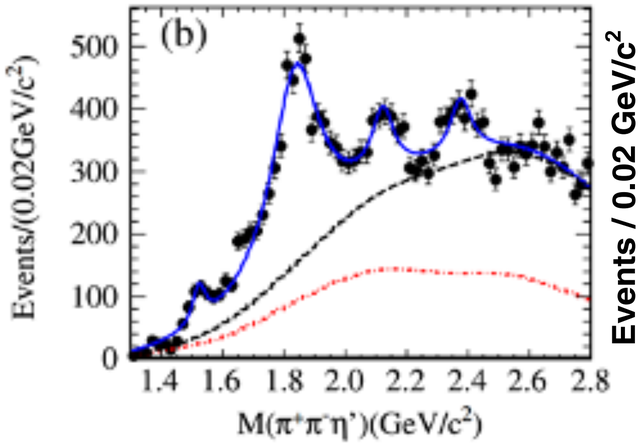
Observation of X($p\bar{p}$) and X(1835)



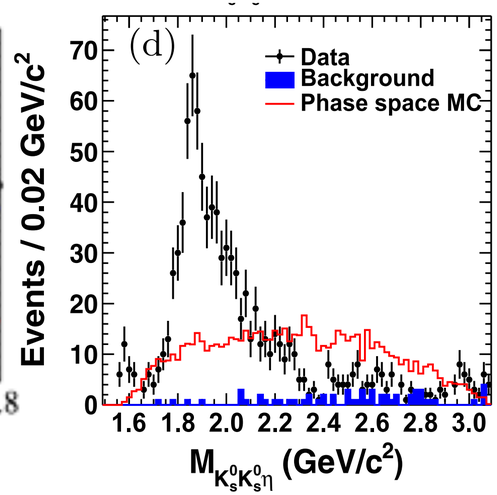
PRL 108 (2012)112003

- $p\bar{p}$ 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/c², Γ=13±19MeV/c² (<76MeV/c²@90% C.L.)



PRL 106 (2011)072002



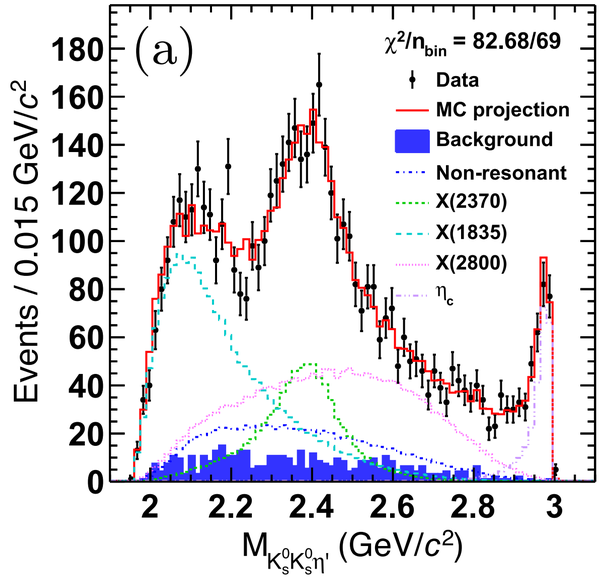
PRL 115 091803

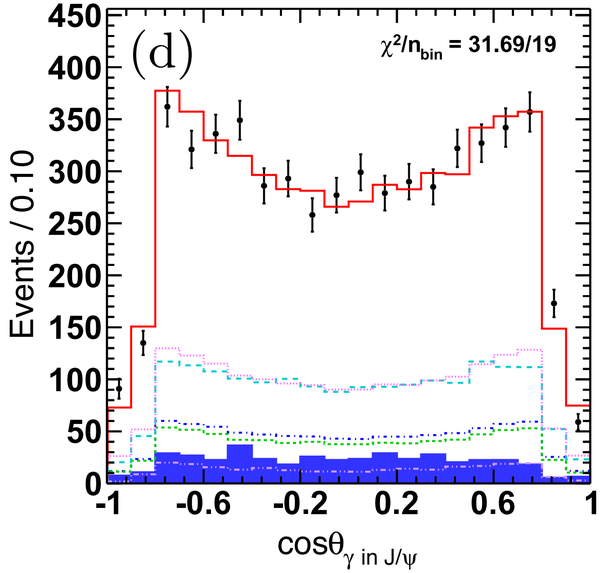
- X(1835) :
  - Discovered by BESII and confirmed by BESIII in $J/\psi \to \gamma\pi\pi\eta'$
  - Determination of Spin-parity to be 0^{-+} in $J/\psi \to \gamma K_s K_s \eta$

M= $1844\pm9^{+16}_{-25}$ MeV/c²

Γ=$192^{+20}_{-17}{}^{+62}_{-43}$ MeV/c²

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
  - 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**

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 ($\pi\pi\eta'$,$K\bar{K}\eta'$,$K\bar{K}\pi$,$\pi\pi\eta$, $K\bar{K}\eta$)

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