Highlights of Light Exotics at BESIII

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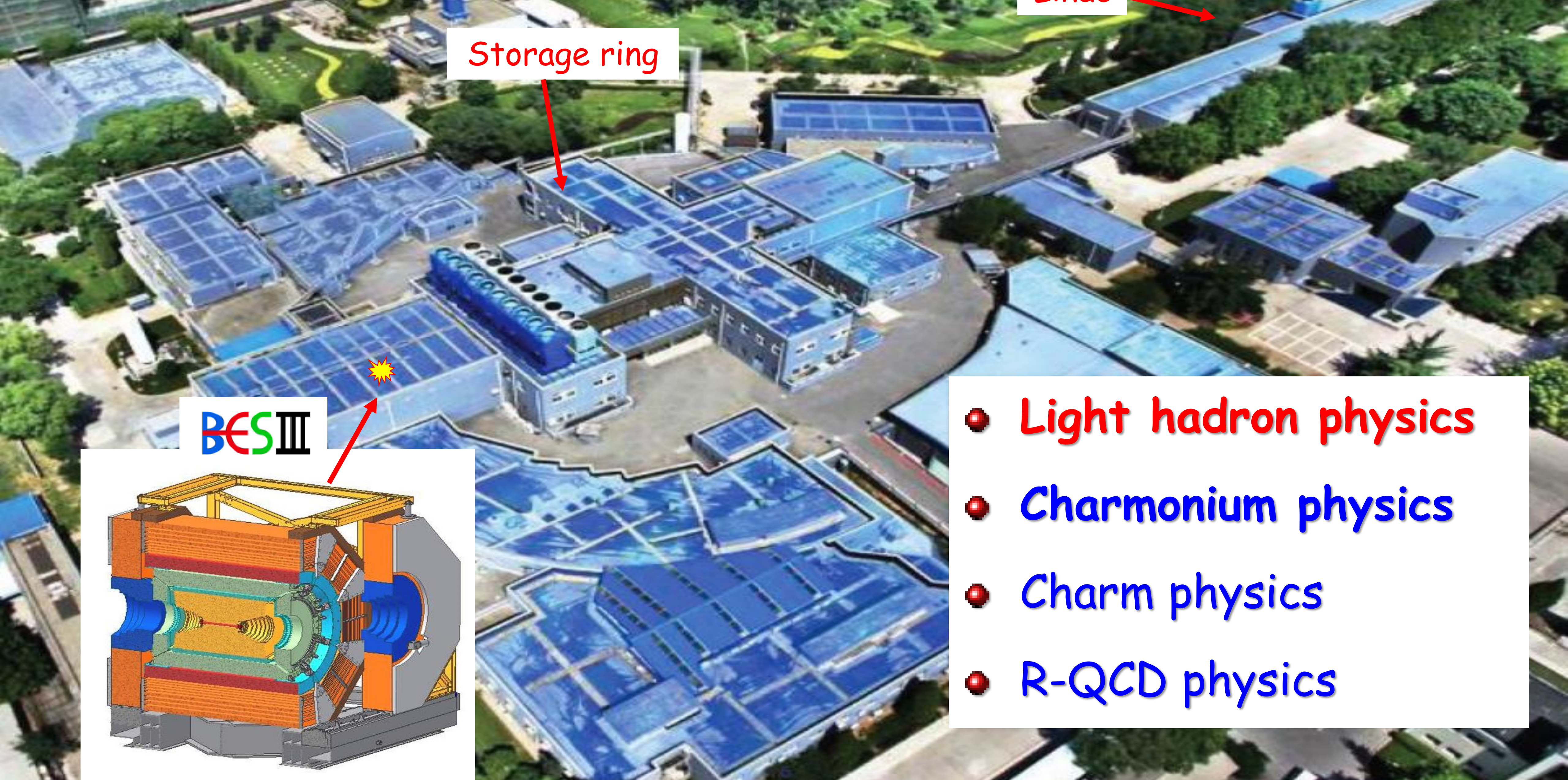
第九届强子谱和强子结构研讨会
2026年8月17-21日

Outline

- BEPCII/BESIII
- Progresses on Light exotics
- Summary & Future prospects

BEPCII/BESIII: τ-charm factory



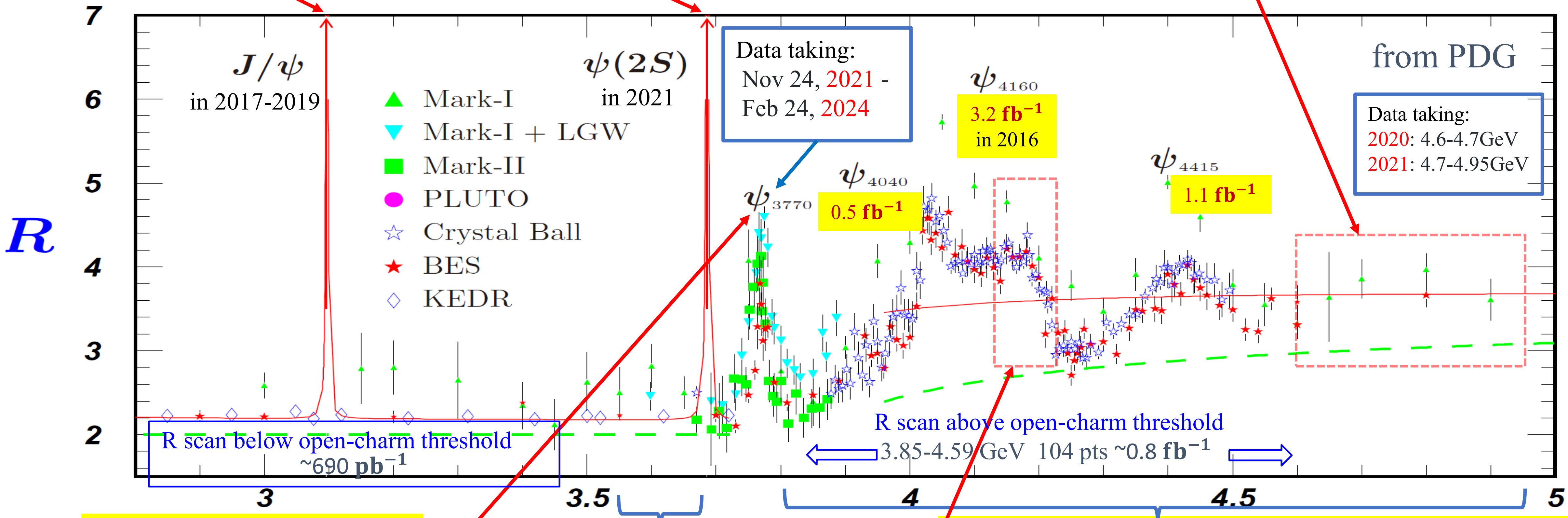
- Light hadron physics
- Charmonium physics
- Charm physics
- R-QCD physics

World largest data sample directly collected in the τ-charm region

10B: J/Ψ

2.7B: Ψ(2S)

6.4 $\mathbf{fb^{-1}}$: ~1.0M $\Lambda_c^+\bar{\Lambda}_c^-$ pairs produced @4.5995-4.9509 GeV



20.3 $\mathbf{fb^{-1}}$ @3.773 GeV

Tau mass scan

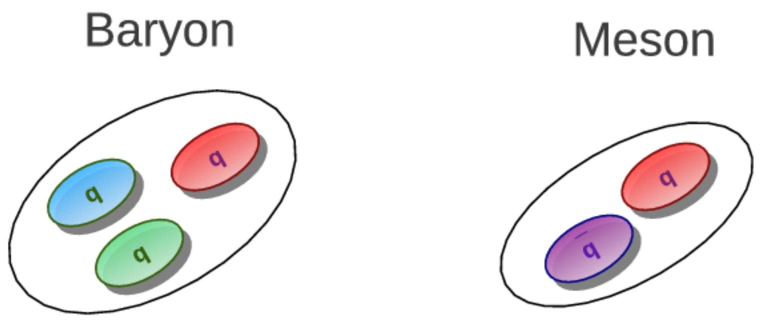
3.8-4.96 GeV: ~22.5 $\mathbf{fb^{-1}}$, XYZ, $D_s^+D_s^-$, $\Lambda_c^+\bar{\Lambda}_c^-$ …

7.33 $\mathbf{fb^{-1}}$: ~6.5M $D_s^+D_s^-$ pairs produced @4.128-4.226 GeV

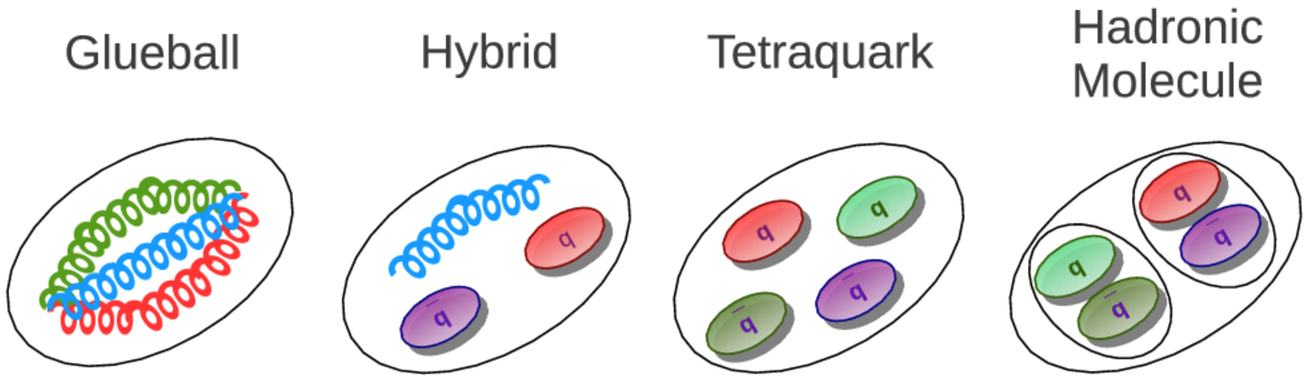
BESIII: ~50 $\mathrm{fb^{-1}}$ from 1.84 – 4.95 GeV

Ordinary vs exotic matter

- Conventional hadrons

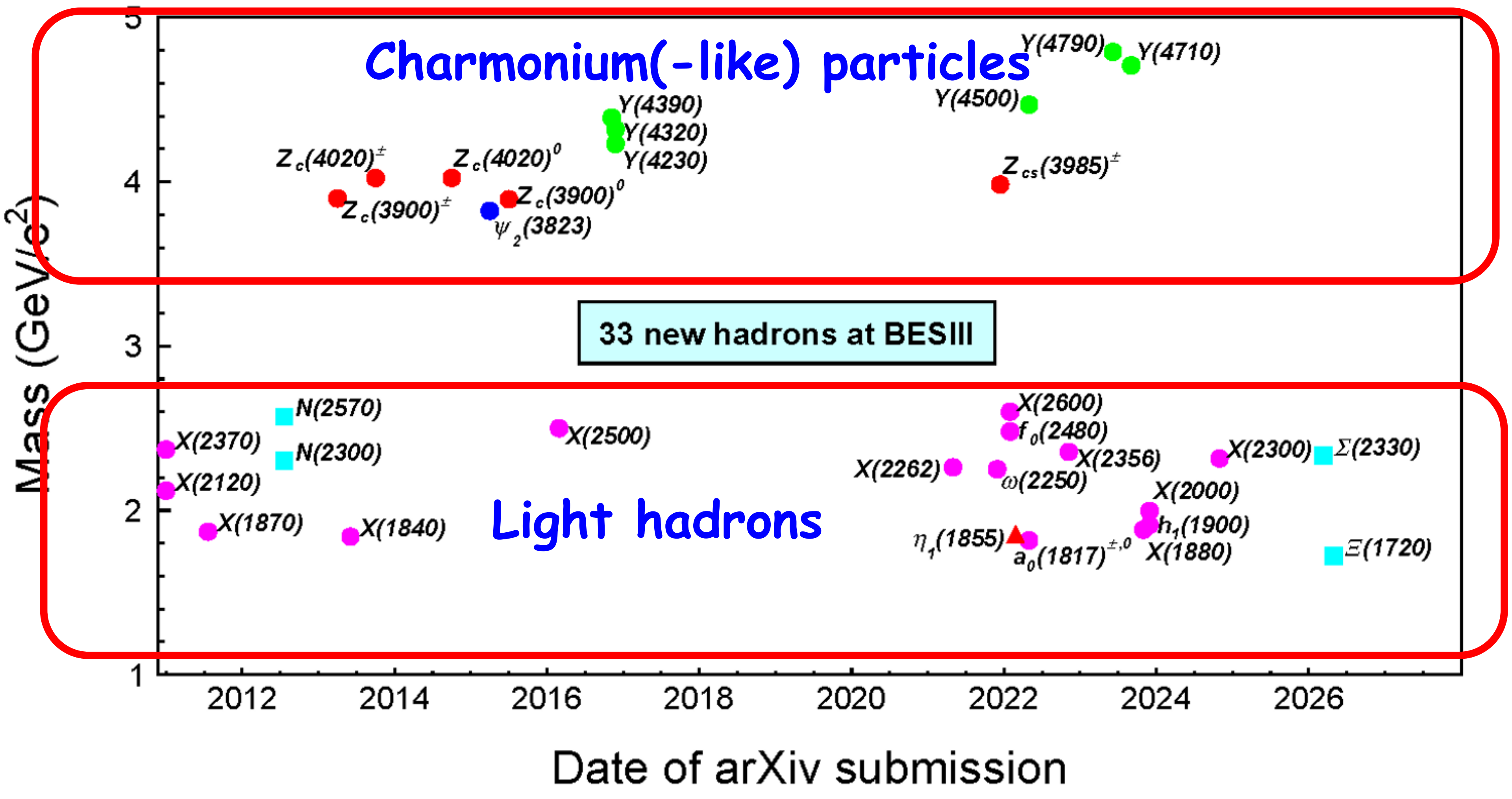


- QCD allows for "exotics"

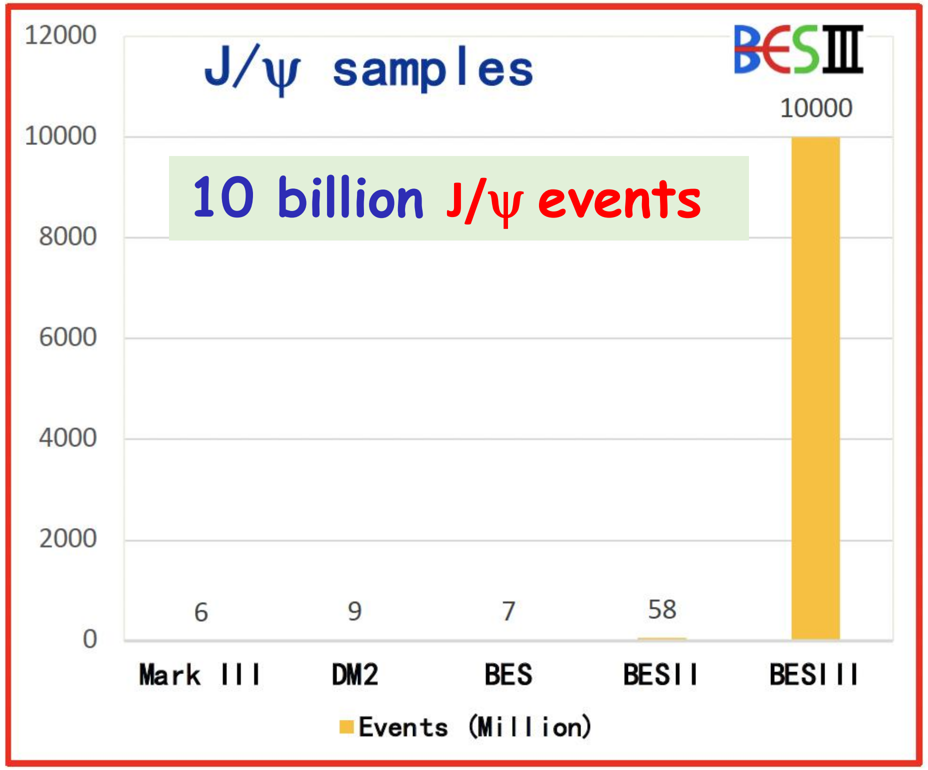


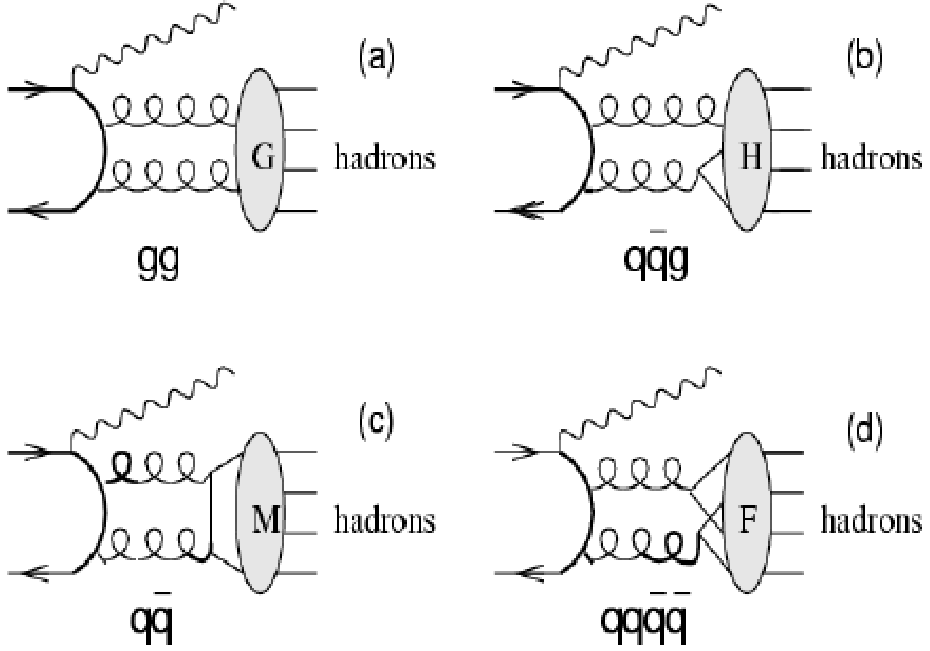
- Searching for those states provides test of QCD

New resonant structures at BESIII



J/ψ : an ideal lab for light exotics



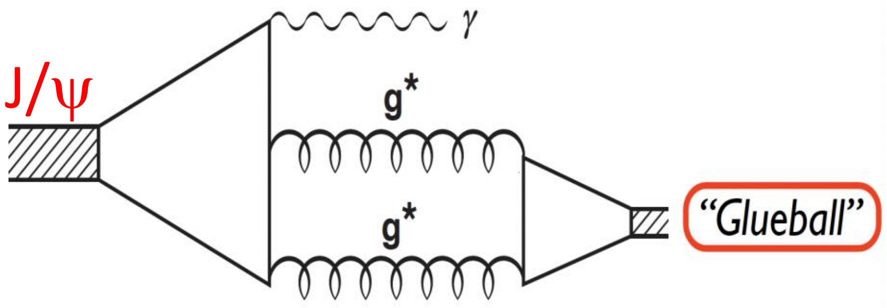


- Especially radiative J/ψ decays: gluon rich production
- Production rates for exotic hadrons is expected to be compatible to the ones for conventional hadrons.

Glueball searches

Two big issues

- What is the production mechanism to utilize?
- What is the mixing with quark model mesons?



Production rate could be calculable in LQCD, but the manifestation of a "glueball" can be tricky!

Chanowitz, Phys.Rev.Lett. 95(2005)172001

Systematic studies needed

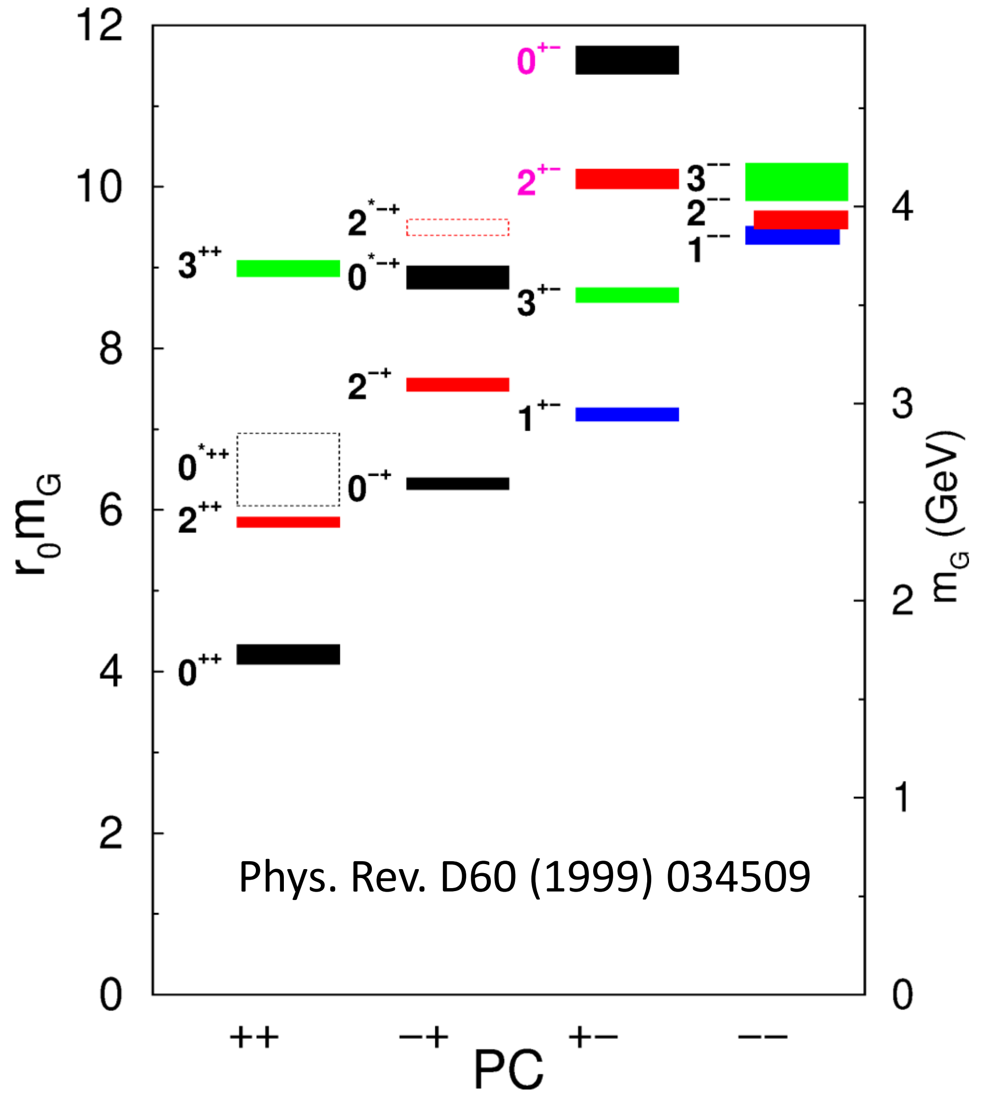
- Outnumbering of conventional QM states
- Abnormal properties ? eg., small production rate in two photon process

Pseudoscalar glueball searches

Where is the 0^{-+} glueball?

- LQCD： 0^{-+}(2.3~2.6 GeV)

The small number of expected pseudoscalars in the quark model provide a clean and promising environment for the search of glueballs



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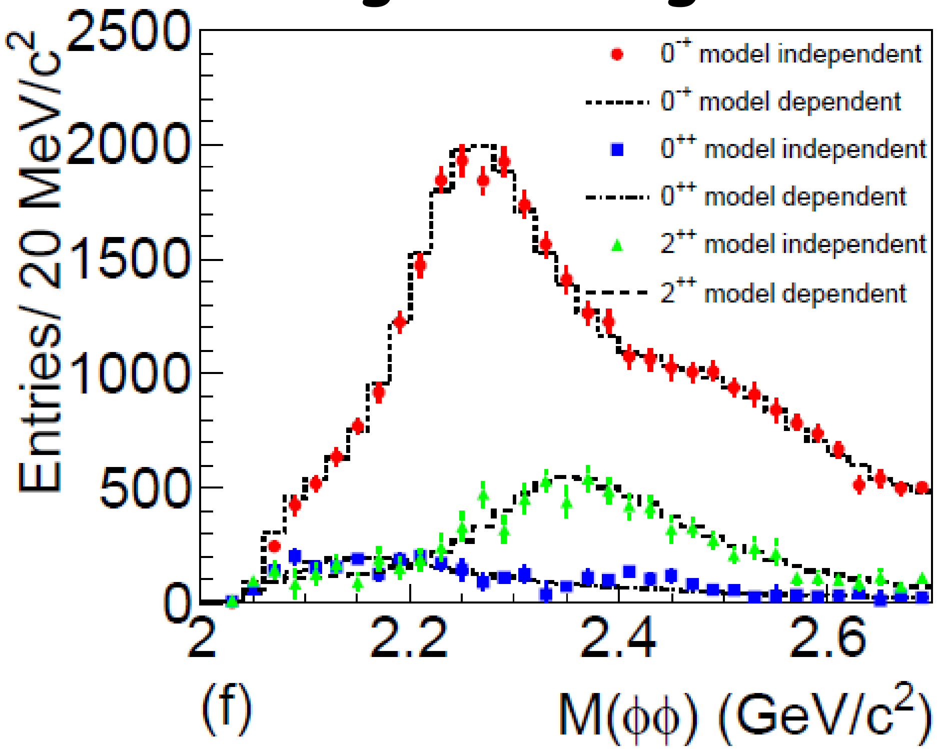
Pseudoscalars above 2 GeV

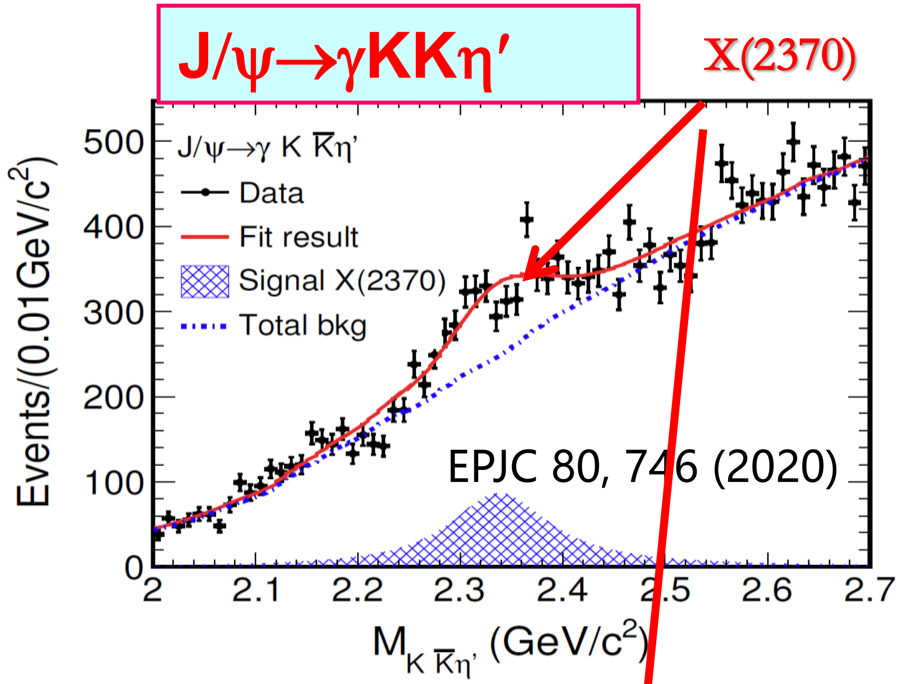
Very little was known for pseudoscalars above 2 GeV. Experimental results are essential for mapping out the pseudoscalar excitations and searching for 0^{-+} glueball.

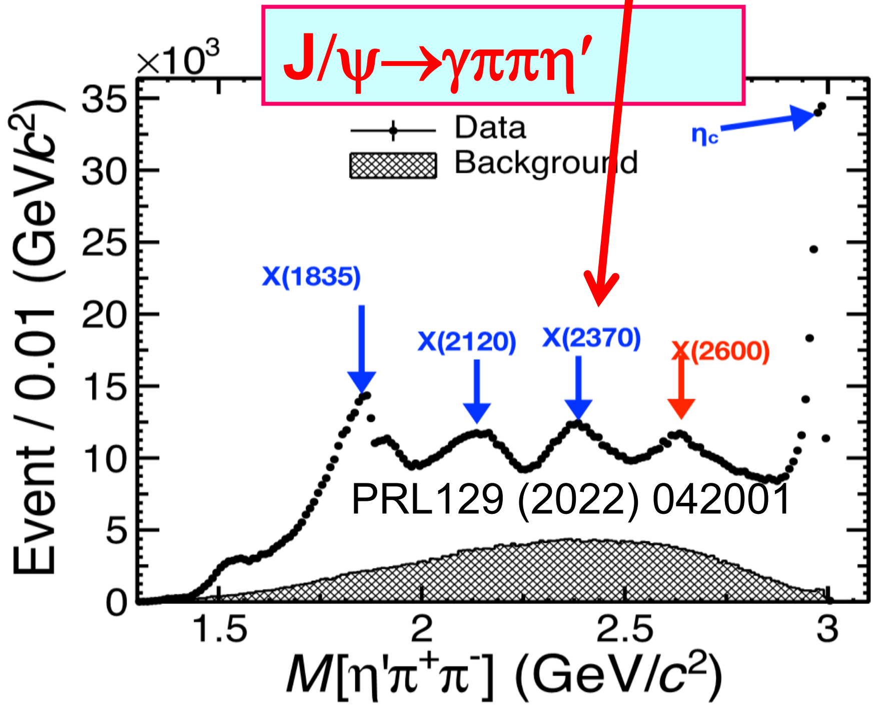


Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	B.F.($\times 10^{-4}$)	Sig.
$\eta(2225)$	2216^{+4+18}_{-5-11}	185^{+12+44}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28.1σ
$\eta(2100)$	2050^{+30+77}_{-24-26}	$250^{+36+187}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	21.5σ
$X(2500)$	2470^{+15+63}_{-19-23}	230^{+64+53}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2102	211	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24.2σ
$f_2(2010)$	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	$(1.91 \pm 0.07^{+0.72}_{-0.69})$	10.7σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ

Phys. Rev. D97, 051101 (2018)

- Dominant contribution from pseudoscalars: η(2225), η(2100) and X(2500)
- Three tensors $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$





X(2370): new glueball candidate ?

An updated review of the new hadron states

We collect as many theoretical predictions on the pseudoscalar glueball mass as we can, and summarize them in Fig. 71. The average value of the mass predictions obtained after the year 1990 is

$$M_{|gg;0-+\rangle} \sim 2360 \text{ MeV} . \qquad (125)$$

Accordingly, the resonance $X(2370)$ first observed in 2010 [880] becomes a possible candidate for the low-lying pseudoscalar glueball, whose mass and width were measured to be [884]:

$$X(2370): M = 2341.6 \pm 6.5 \pm 5.7 \text{ MeV}, \quad \Gamma = 117 \pm 10 \pm 8 \text{ MeV}. \qquad (126)$$

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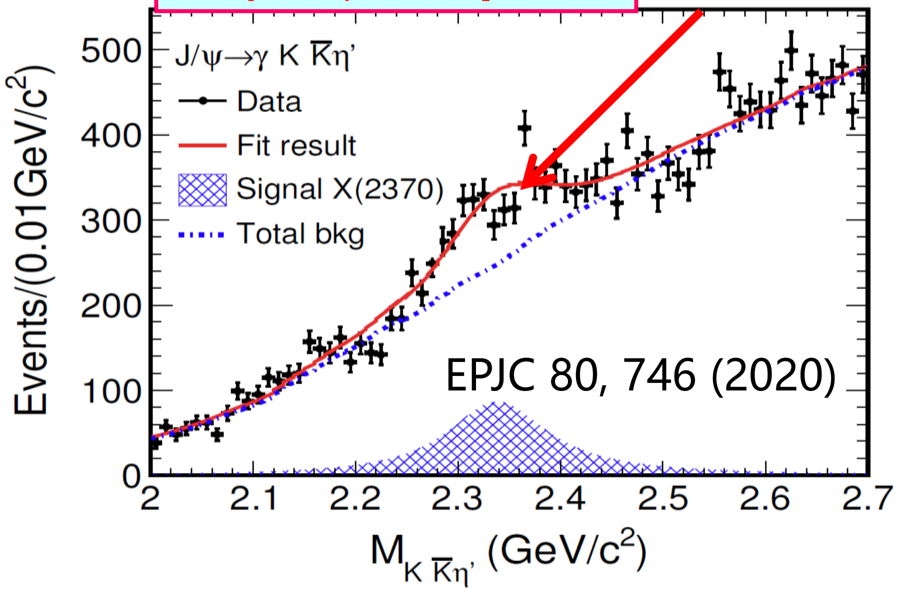
Pseudoscalars above 2 GeV: X(2370)

new glueball candidates ?

J/ψ→γKKη′

X(2370)



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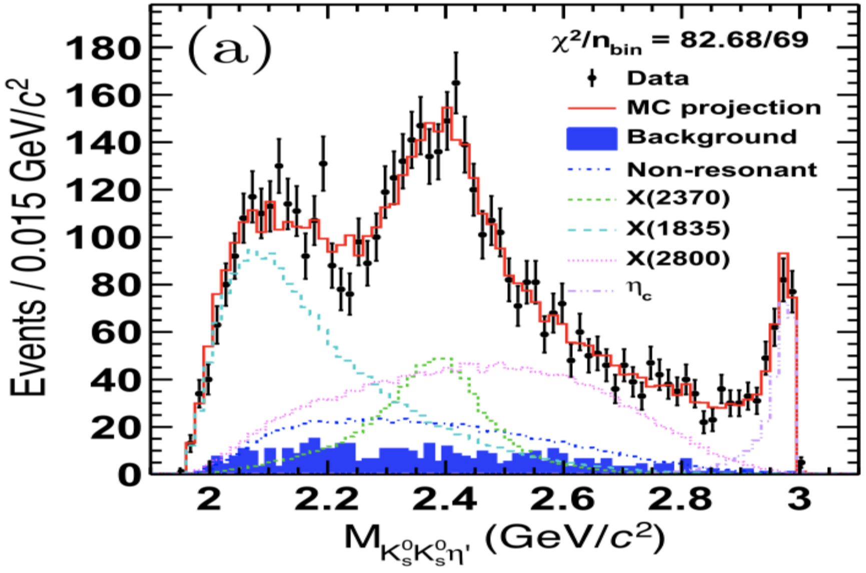
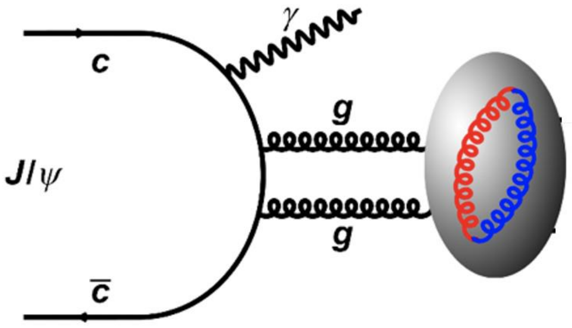




BESIII实验发现胶球存在的迹象

Physics \ General Physics Editors' notes

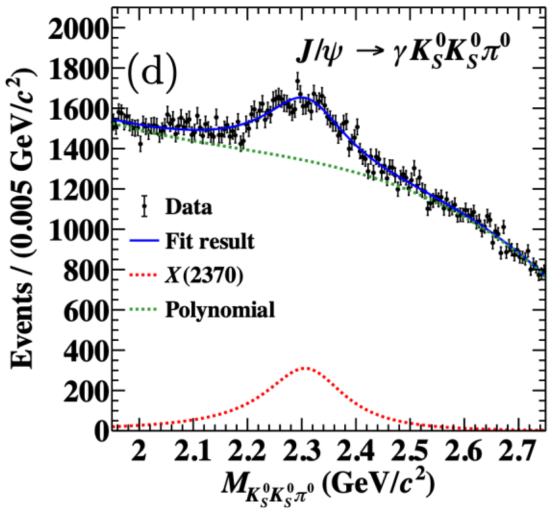
Physics \ Quantum Physics

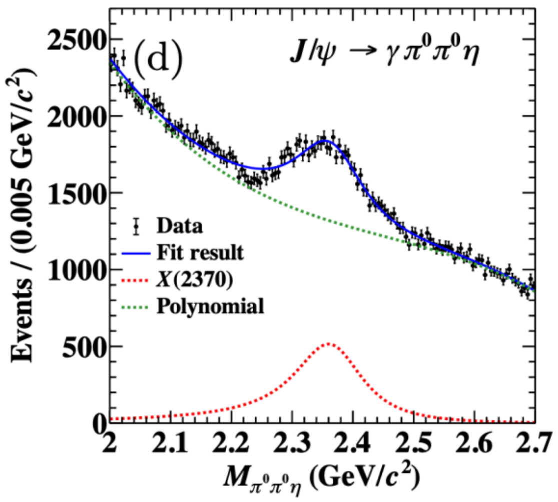
Possible evidence of glueballs found during Beijing Spectrometer III experiments

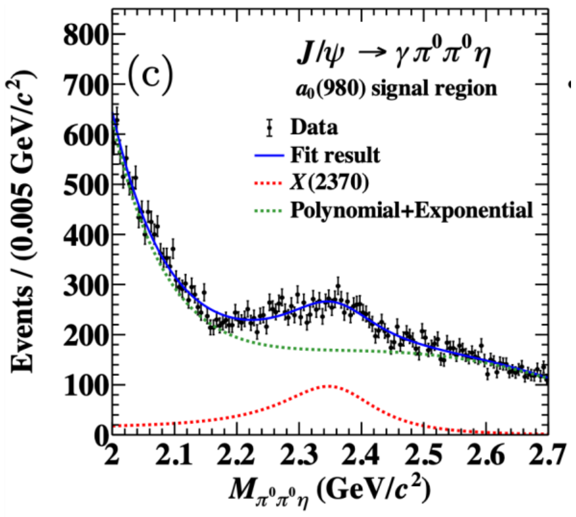
by Bob Yirka , Phys.org

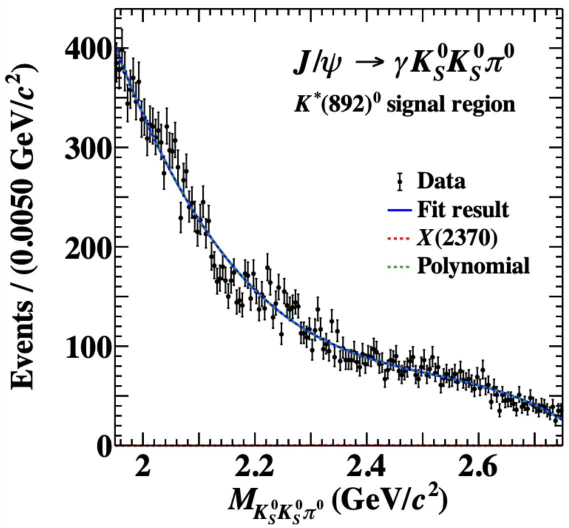
REPORT

Observation of the X(2370) in $K_S^0K_S^0\pi^0$ and $\pi^0\pi^0\eta$









$X(2370) \to K_S^0K_S^0\pi^0 (> 14\sigma)$

$X(2370) \to \pi^0\pi^0\eta (> 20\sigma)$

$X(2370) \to \pi^0 a_0(980) (> 9\sigma)$

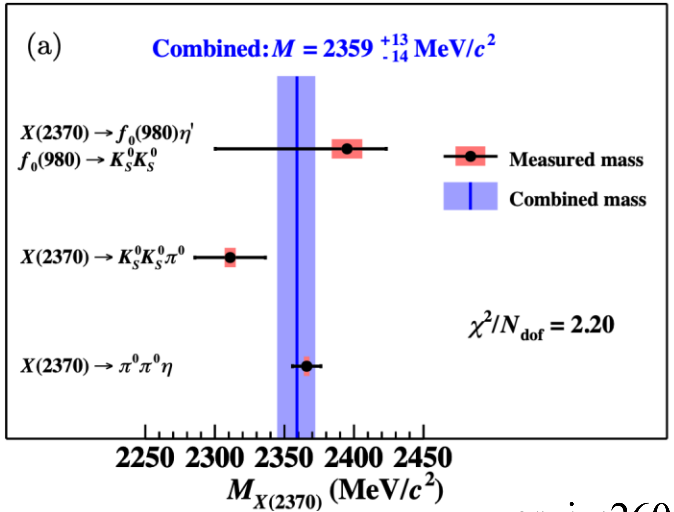
$X(2370) \to K^*(892)\overline{K^0}$

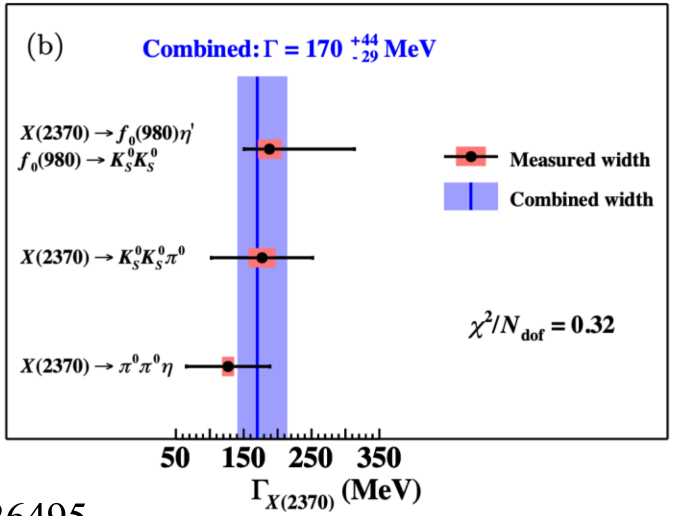
arxiv:2607.20366

arxiv:2605.26495

- **Decay modes of X(2370)→ $\pi\pi\eta'$, $K\overline{K}\eta'$, $K\overline{K}\pi$, $\pi\pi\eta$, $K\overline{K}\eta$, $a(980)\pi$ observed**
- **No evidence of the decay of $X(2370) \to K^*(892)\overline{K^0}$) significance is only 0.1σ)**
- **Such high decay pattern similarity between the X(2370) and η_c strongly supports the glueball interpretation of the X(2370)**
-

Mass, Width, High Production Rate and Narrow Partial Decay Width





arxiv:2605.26495

arxiv:2607.20366

Decay channel	$\mathcal{B}$ $(\times 10^{-4})$
$J/\psi \to \gamma X(2370) \to \gamma K\bar{K}\pi$	$3.25 \pm 0.25^{+0.73}_{-0.75}$
$J/\psi \to \gamma X(2370) \to \gamma\pi\pi\eta$	$3.2 \pm 0.1^{+0.9}_{-1.0}$
$J/\psi \to \gamma X(2370) \to \gamma\pi\pi\eta'$	$1.94 \pm 0.04^{+0.33}_{-0.88}$
$J/\psi \to \gamma X(2370) \to \gamma K\bar{K}\eta'$	$0.39 \pm 0.05 \pm 0.10$

$K\overline{K}\eta'$: $f_0(980)\eta'$ …

$\pi\pi\eta'$: $f_0(980)\eta'$, $f_0(500)\eta'$ …

$\pi\pi\eta$: $a_0(980)\pi^0$, $f_0(500)\eta$, $f_0(1500)\eta$, $f_0(1710)\eta$ …

$K\overline{K}\pi$: $K_0^*(1430)\overline{K}$, $K_0^*(800)\overline{K}$, $a_0(980)\pi^0$ …

Combined results (consistent with lightest 0^{-+} glueball predictions)

- **Mass:** $M_{X(2370)} = 2359^{+13}_{-14} MeV/c^2$
- **Width:** $\Gamma_{X(2370)} = 170^{+44}_{-29} MeV$
- **Based on BR measurements in 4 channels + accounting for missing decay modes:**
  - **Reasonable to have the high production rate**: $B(J/\psi \to \gamma X(2370)) > 1 \times 10^{-3}$
  - **Narrow partial decay width: S-wave two-body decay with 1~10% →partial width ~ a few MeV**

Lightest 0^{-+} Glueball as Dominant Constituent of X(2370)

- Properties of the X(2370)
  - High production rate in J/ψ radiative decays
  - Decay pattern similarities to η_c
  - Flavor-singlet state
  - Narrow partial decay widths
  - Strong suppressions of $\gamma\omega$,$\gamma\phi$ decays

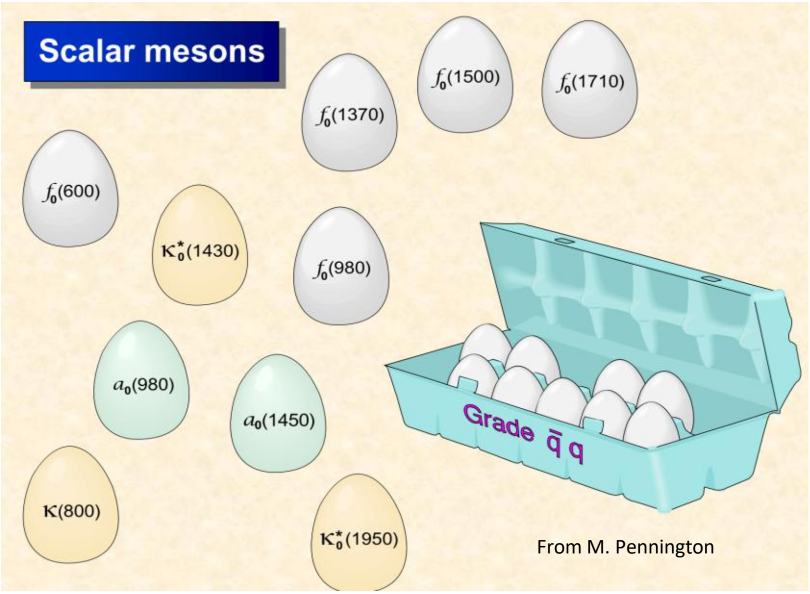
The combination of these signatures enable us to identify the X(2370) is a glueball

- These properties are fully consistent with the expected signatures of glueball
  - Other interpretations can hardly explain all of them simultaneously
- The lightest 0^{-+} glueball is needed for a natural and complete explanation of the X(2370) properties

Scalar glueball searches

- Why light scalar mesons are interesting?
  - There have been hot debates on **the existence of σ and κ**
  - **σ, κ and f_0(980) are also possible mutiquark states. They are all near threshold.**
  - Lattice QCD predicts the **0^{++} scalar glueball mass ~ 1.6 GeV. f_0(1500)** and **f_0(1710)** are good candidates.

Overpopulated!



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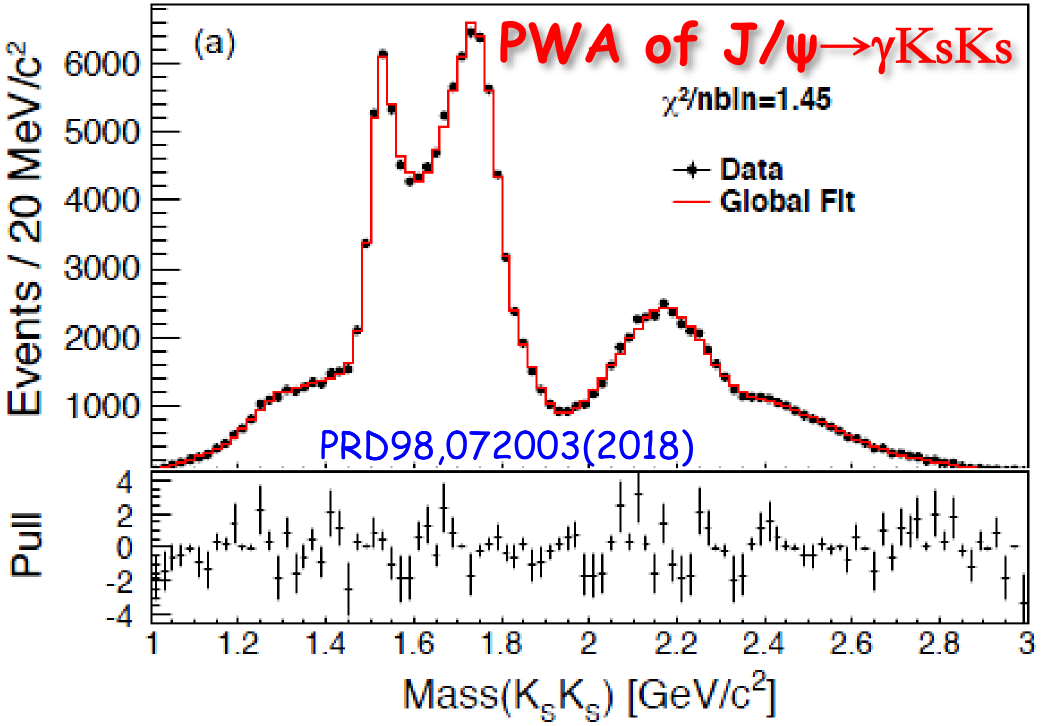
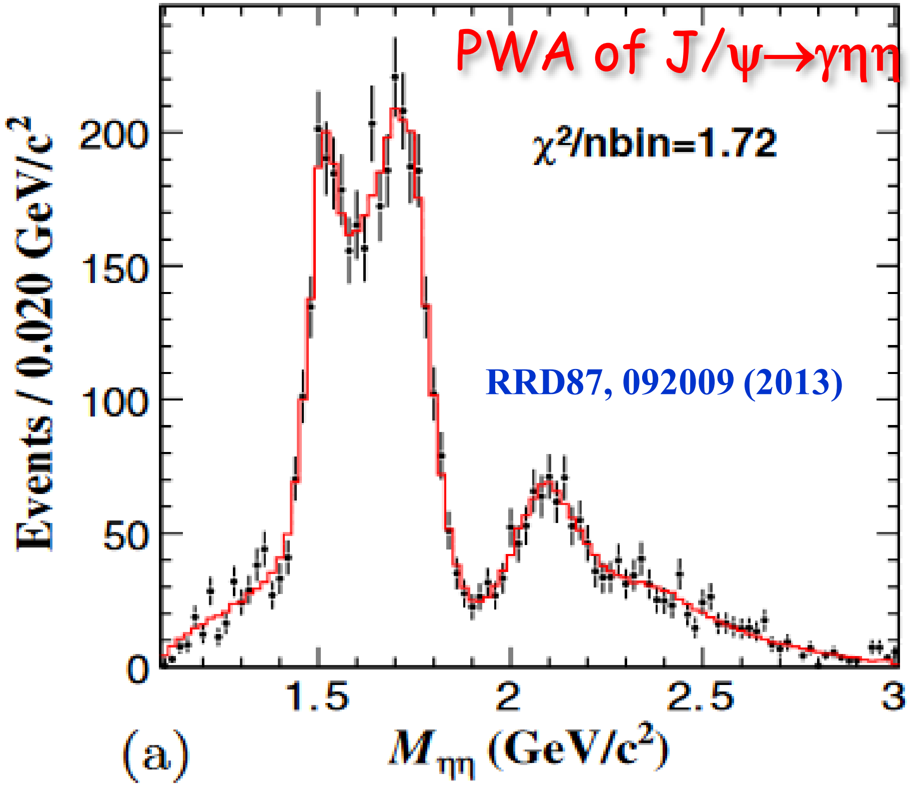
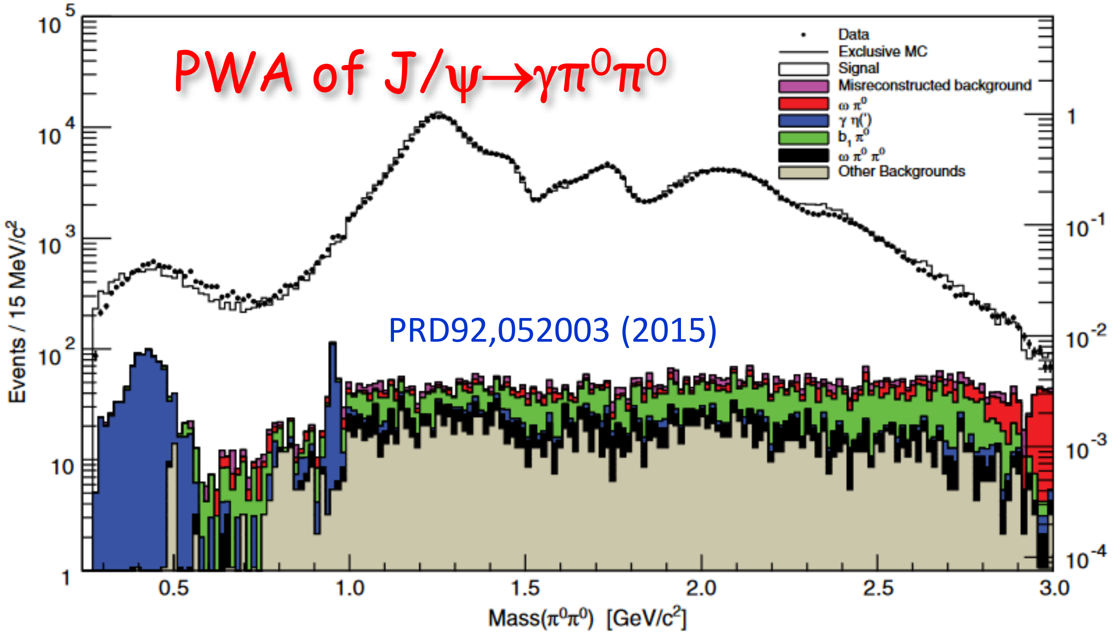






- $f_0(1710)$ and $f_0(1500)$ are dominant
- $f_2'(1525)$ also seen
- Broad bump above 2 GeV, contributions from scalar and tensor

Scalar glueball candidate: $f_0(1710)$

$$\Gamma(J/\psi \to \gamma G_{0^+}) = \frac{4}{27}\alpha \frac{|p|}{M^2_{J/\psi}} |E_1(0)|^2 = 0.35(8) keV$$
$$\Gamma/\Gamma_{tot} = 0.33(7)/93.2 = 3.8(9) \times 10^{-3}$$

CLQCD, Phys. Rev. Lett. 110, 021601 (2013)

Experimental results

- $B(J/\psi \to \gamma f_0(1710) \to \gamma K\bar{K}) = (8.5^{+1.2}_{-0.9}) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi) = (4.0\pm1.0) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\omega\omega) = (3.1\pm1.0) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta) = (2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$

$\Rightarrow$ $B(J/\psi \to \gamma f_0(1710)) > 1.7 \times 10^{-3}$

Flavor-blindness of glueball decays

$$\frac{1}{P.S.}\Gamma(G \to \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta') = 3:4:1:0:1$$

*with chiral suppression
PRL 98 149103

$$\Gamma(G \to \pi\pi)/\Gamma(G \to K\bar{K}) \approx \frac{f_\pi^4}{f_K^4} \approx 0.48$$

$$\frac{1}{P.S.}\Gamma(G \to \pi\pi : K\bar{K} : \eta\eta) \approx \underline{1.3 : 3.16} : 1$$

$f_0(1710)$ largely overlapped with scalar glueball

Tensor glueball searches

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

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

6 Glueballs and light hybrid mesons

Rept.Prog.Phys. 86 (2023) 2, 026201

BESIII results

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = (3.8^{+0.62}_{-0.65}{}^{+2.37}_{-2.07}) \times 10^{-5}$$
Phys.Rev. D87, 092009 (2013)

$$Br(J/\psi \to f_2(2340) \to \gamma\phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73}) \times 10^{-4}$$
Phys.Rev. D93, 112011 (2016)

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma K_S K_S) = (5.54^{+0.34}_{-0.40}{}^{+3.82}_{-1.49}) \times 10^{-5}$$
Phys.Rev. D98, 072003 (2018)

$f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ are observed with a strong production of $f_2(2340)$; consist with central production and pp-bar annihilations

It is desirable to search for more decay modes!

Landscape of light glueball has updated

Scalar: Overpopulation

- LQCD : ground state 0^+ glueball ~1.7 GeV, first excitation ~2.1 GeV

✓ **Strong production of $f_0(1710)/f_0(2100)$ in $J/\psi \rightarrow \gamma\, \eta\eta/KK/\pi\pi$**, the pattern consists with LQCD's prediction

Tensor: large uncertainty

- LQCD: 2^{++}(2.3~2.4 GeV)

✓ **Strong production of $f_2(2340)$ in $J/\psi \rightarrow \gamma\eta\eta/KK/\pi\pi/\phi\phi$**; consists with LQCD's prediction

Pseudoscalar: very little known above 2 GeV, puzzles in low mass region

- LQCD: 0^{-+}(2.3~2.6 GeV)

✓ **Trajectory**:
- **$f_1(1285)$, no $\eta(1295)$**
- **$\eta(1405)$ /$\eta(1475)$ can be one resonance**

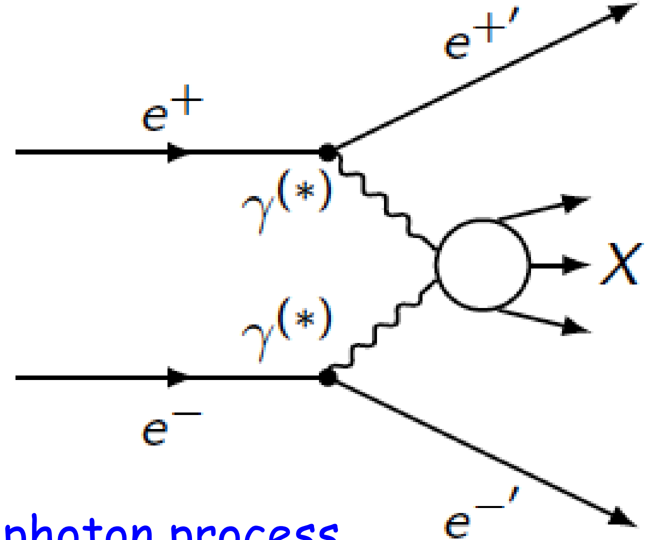
□ **Above 2 GeV: X(2370)**

Prospects: 10B J/ψ and 2.7B ψ(2S) provide great opportunities

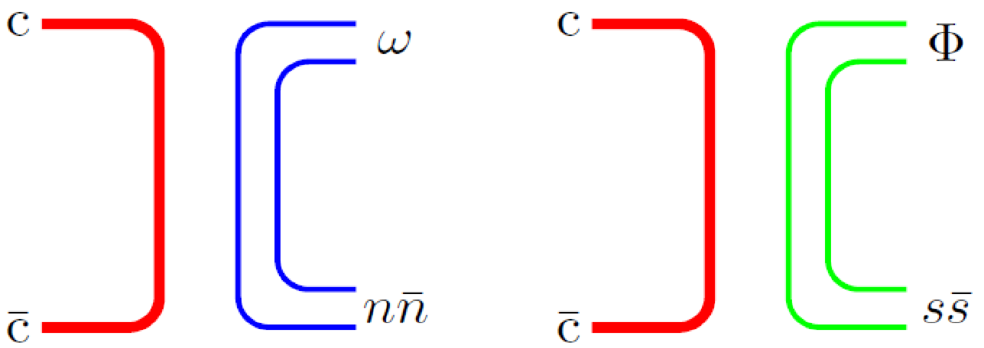
	0^+	2^+	0^-
J/ψ→γPP			
J/ψ→γVV			
J/ψ→γPPP			
J/ψ→γPPPP			

- 0^+, 2^+ : coupled channel analysis
  - J/ψ→γPP
  - J/ψ→ω/φ + X
- 0^- : trajectory >2 GeV, X(2370)
  - J/ψ→γPPP
  - J/ψ→γγ V
- 1^{-+}
  - J/ψ→$\gamma\eta_1^{(\prime)}$
  - $\chi_{c1} \to \eta\eta_1^{(\prime)}, \pi\pi_1$

Anti filter:



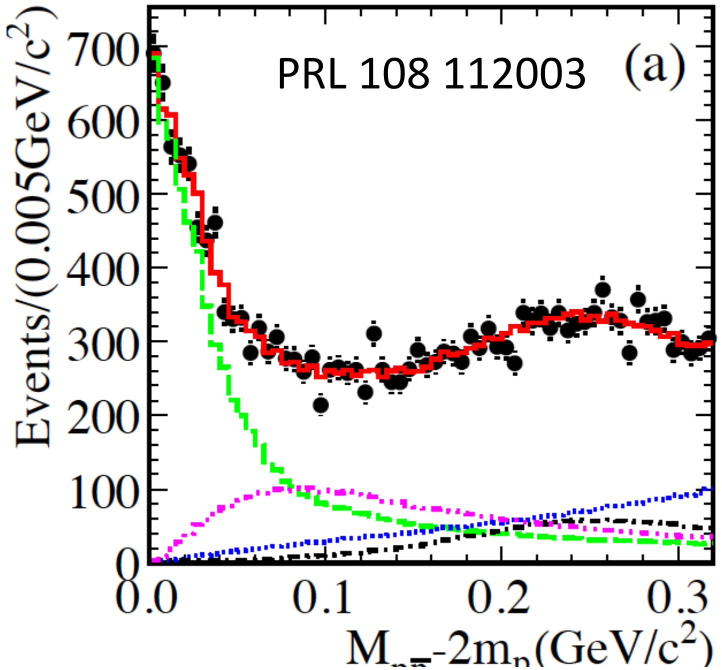
Two photon process

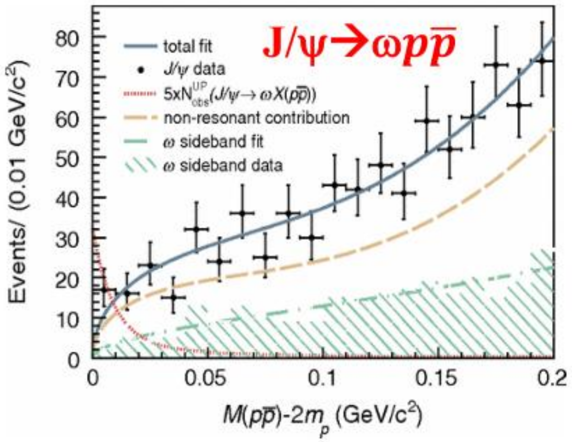


Flavor Filters: J/ψ→ω/ϕ + X

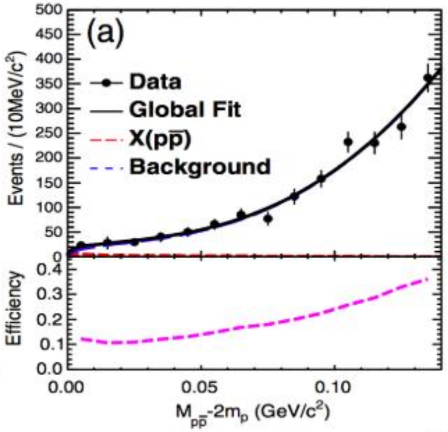
$p\bar{p}$ threshold enhancement $X(p\bar{p})$: Baryonium state?

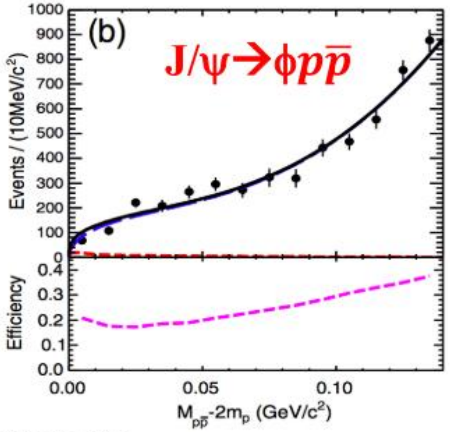
- First observed in $J/\psi \to \gamma p\bar{p}$ at BESII, confirmed by BESIII and CLEO-c
- PWA of $J/\psi \to \gamma p\bar{p}$: $J^{PC} = 0^{-+}$
  - The fit with a BW and S-wave FSI (I=0) factor can well describe $p\bar{p}$ mass threshold structure
- Non-observation in hadronic decays: not from pure FSI



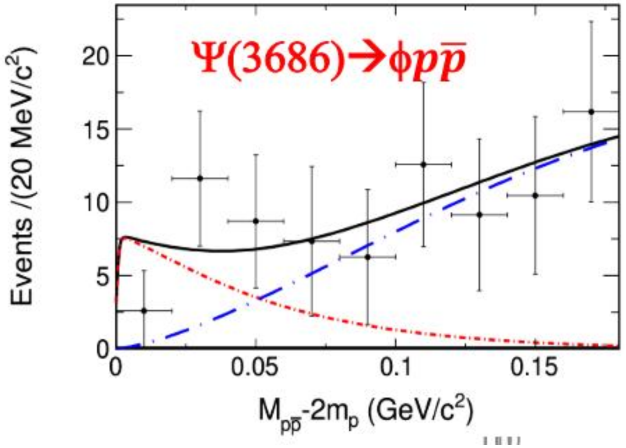


PRD87,112014(2013)



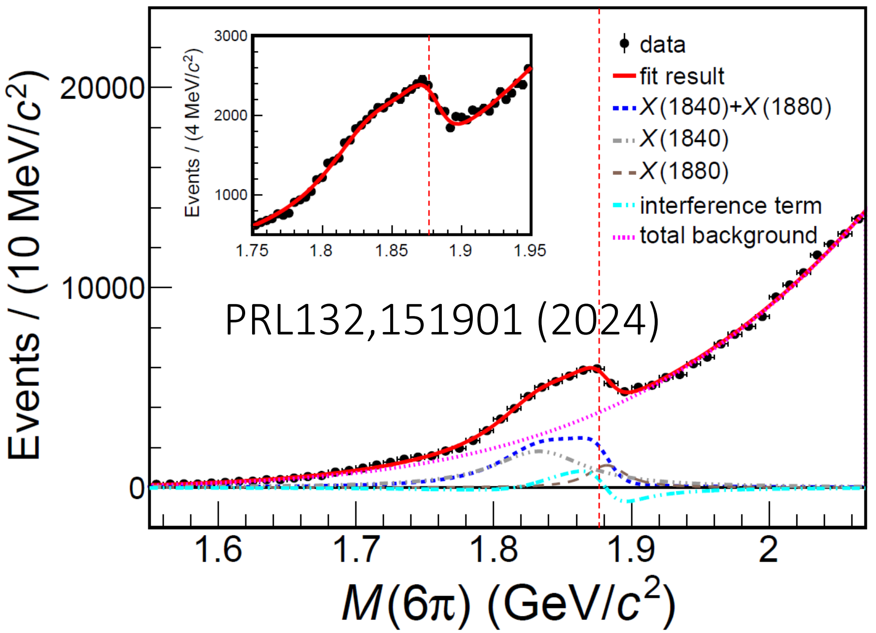


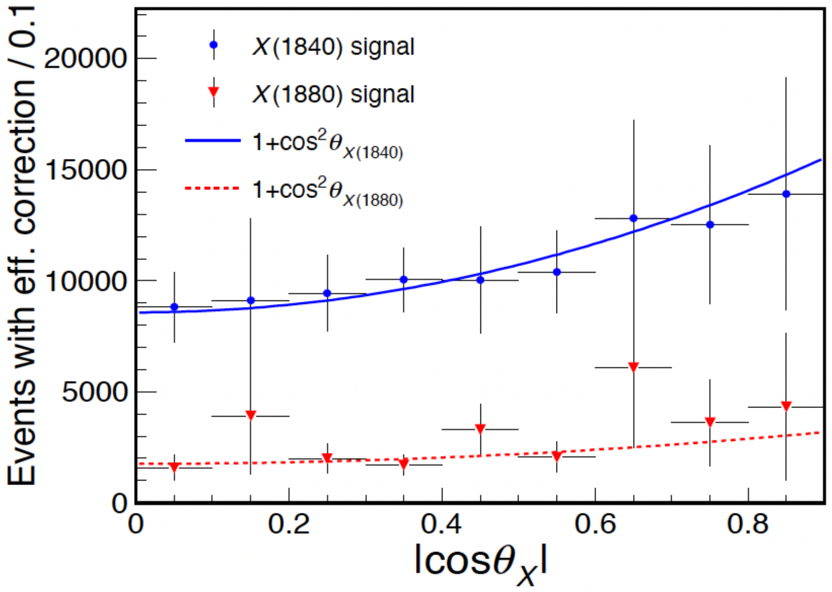
PRD93,052010(2016)

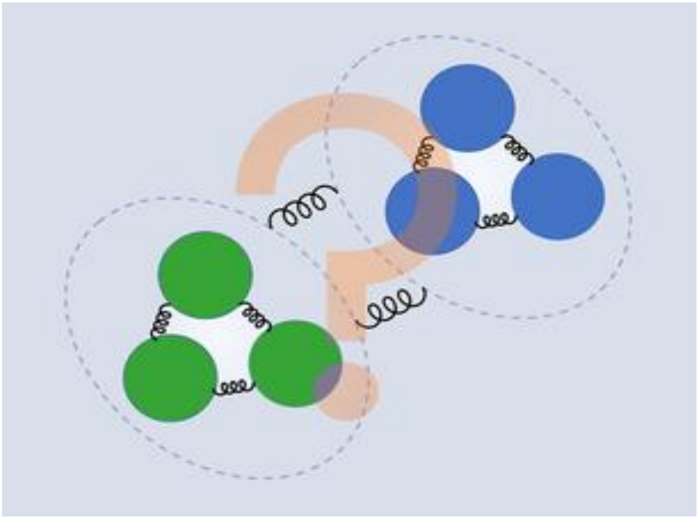


PR D99 112010(2019)

Observation of NN-bar threshold structure X(1880)







Resonanc e	M(MeV/c^2)	Γ(MeV/c^2)
X(1880)	1882.1±1.7±0.7	30.7±5.5±2.4
X(1830)	1832.5±3.1±2.5	80.7±5.2±7.7

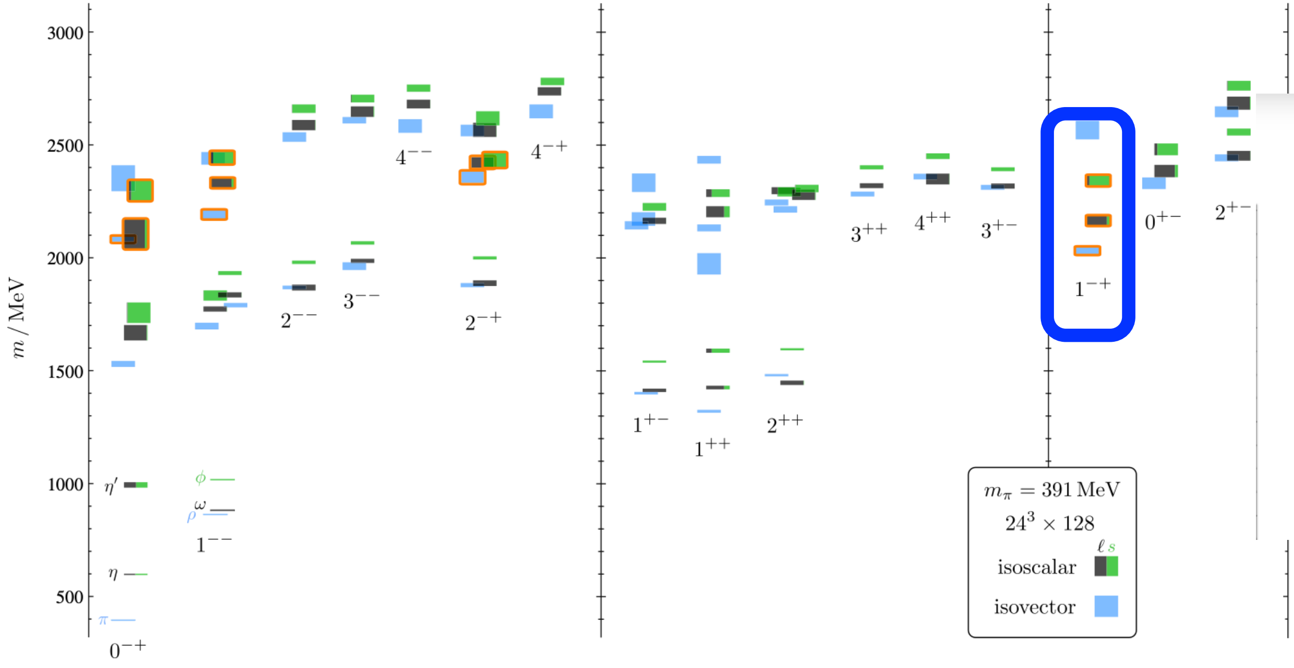
Featured in Physics:
"Evidence of a new subatomic particle"

Narrow state around NN-bar threshold !

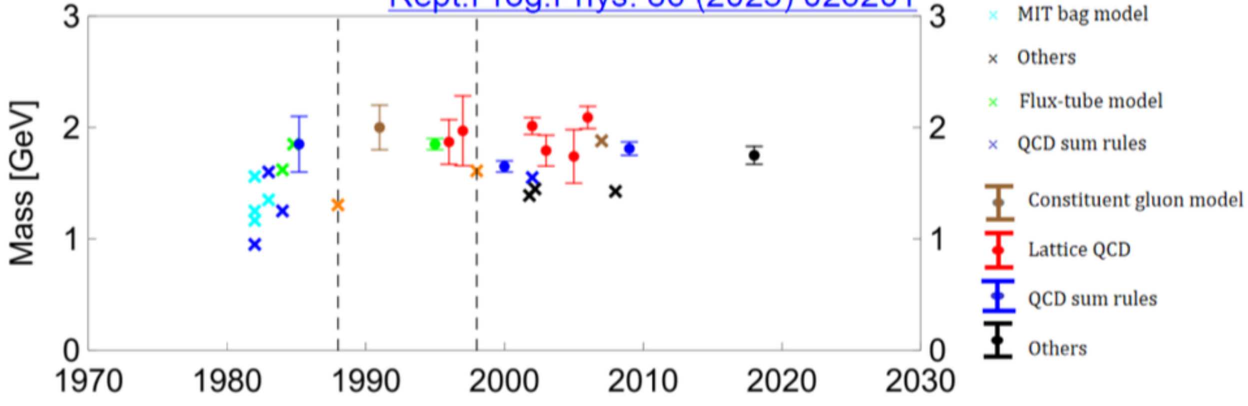
Consistent with pseudoscalars

PRL132,151901(2024)

Exotic 1^{-+} state



Rept.Prog.Phys. 86 (2023) 026201

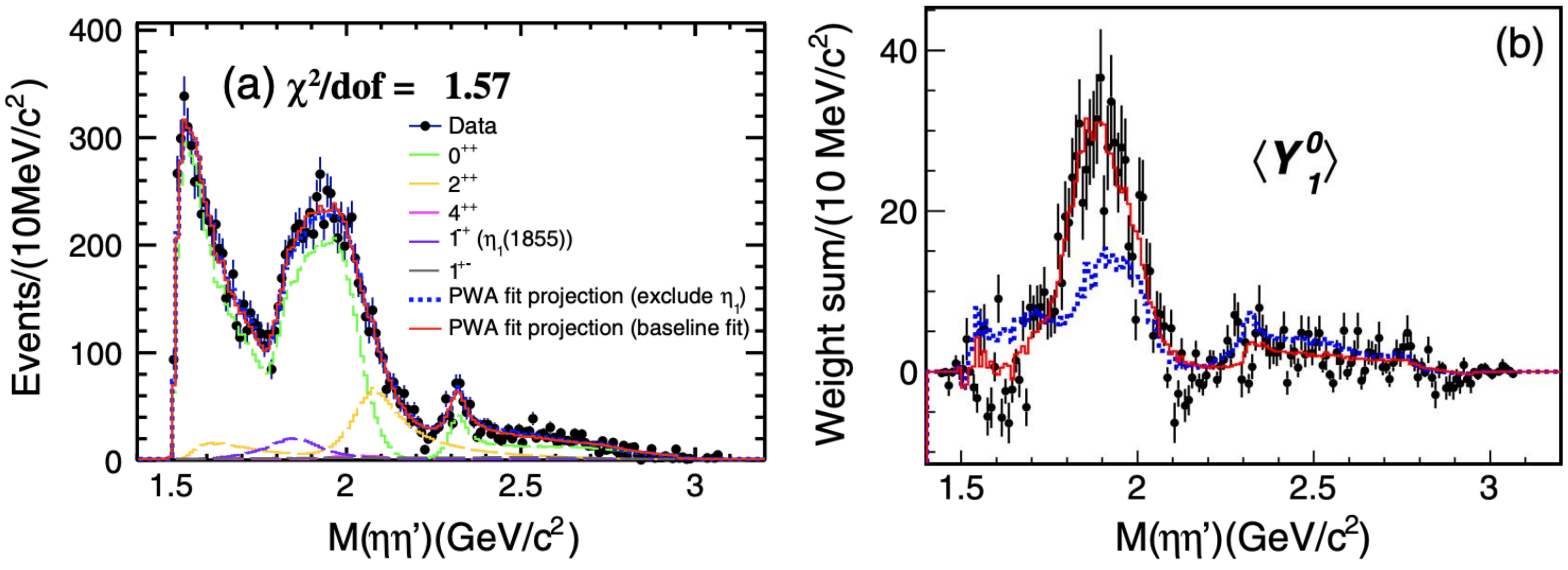


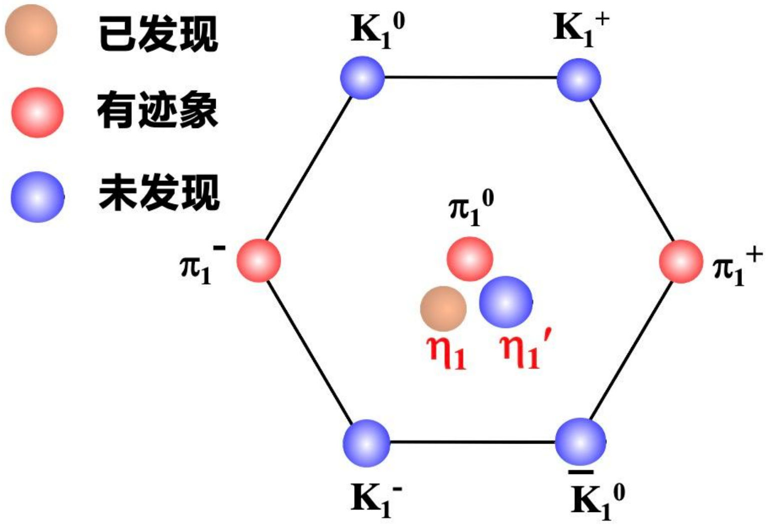
Mass of 1^{-+} hybrid

PRD 88 094505(2013)

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

Observation of $\eta_1(1855)$ with exotic 1^{-+} in $J/\psi\to\gamma\eta\eta'$





PRL129, 192002(2022)

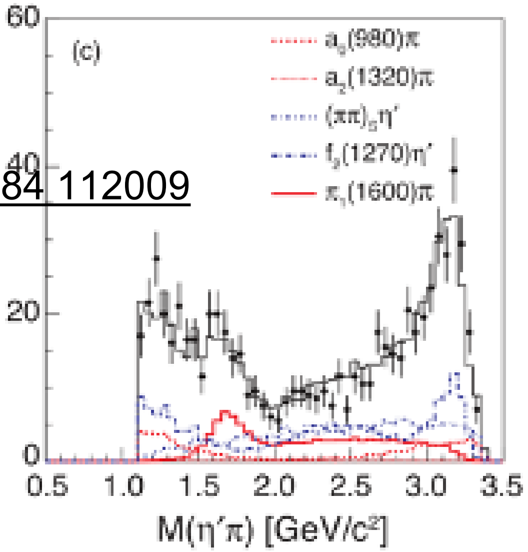
Isoscalar state with $J^{PC}=1^{-+}$

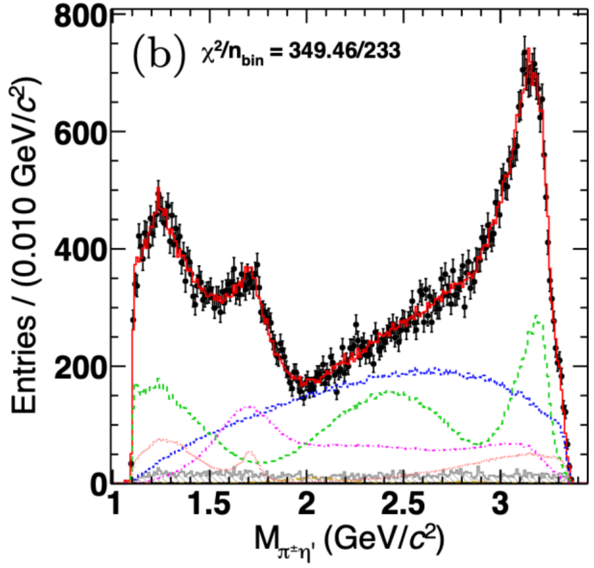
$$M = 1855 \pm 9^{+6}_{-1}\ \mathrm{MeV}/c^2$$
$$\Gamma = 188 \pm 18^{+3}_{-8}\ \mathrm{MeV}$$

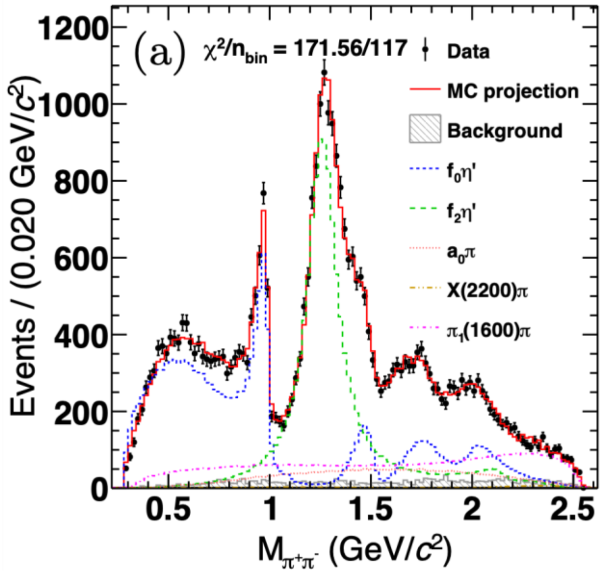
Critical to establish the 1^{-+} hybrid nonet !

Observation of Exotic 1^{-+} Isovector state $\pi_1(1600)$

PRD 84 112009







- CLEO-c results: evidence of an exotic P-wave $\eta'\pi$ amplitude with4σ 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 >21σ
  - The significance of phase motion is also greater than 11σ
  - Difference mass shape descriptions achieve the consistent pole position:

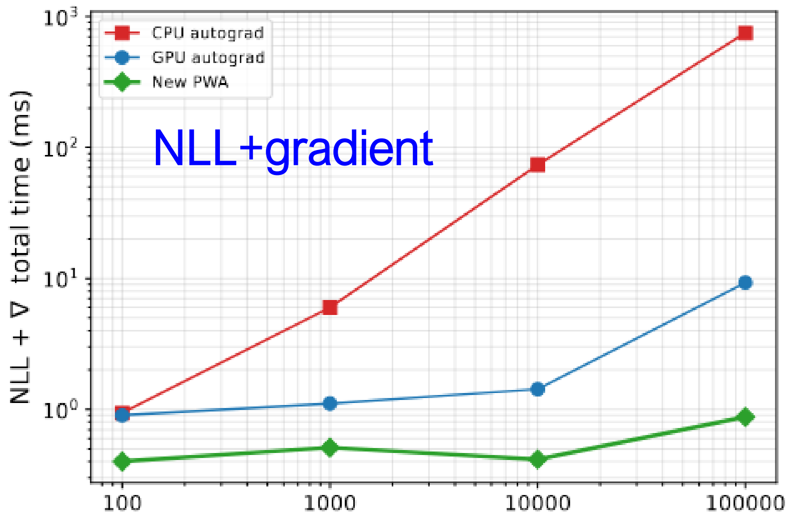
arxiv:2604.12524,submitted to PRL

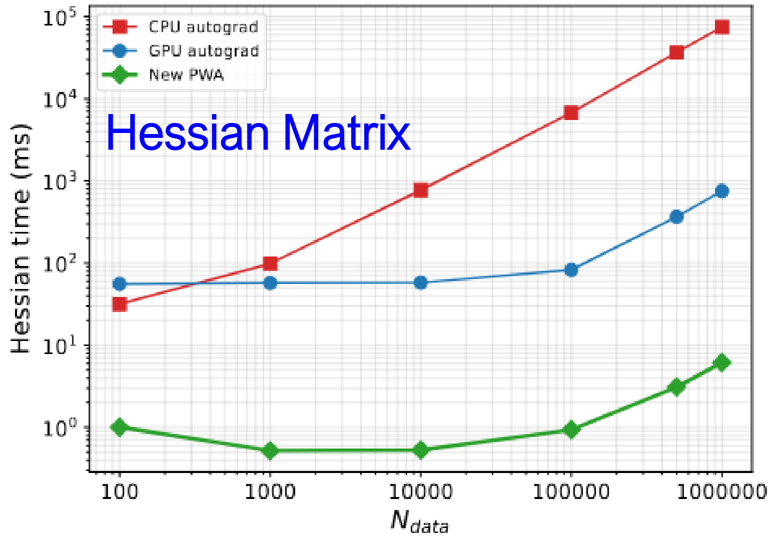
$$(1690 \pm 16^{+36}_{-44}) - i(217 \pm 5^{+7}_{-19})\ \mathbf{MeV}$$

$$B[\chi_{c1} \to \pi_1(1600)^\pm\pi^\mp] \times B[\pi_1(1600)^\pm \to \pi^\pm\eta'] = (4.30 \pm 0.14^{+1.04}_{-1.03}) \times 10^{-4}$$

A Covariant Tensor Partial Wave Analysis Framework (CTPWA)

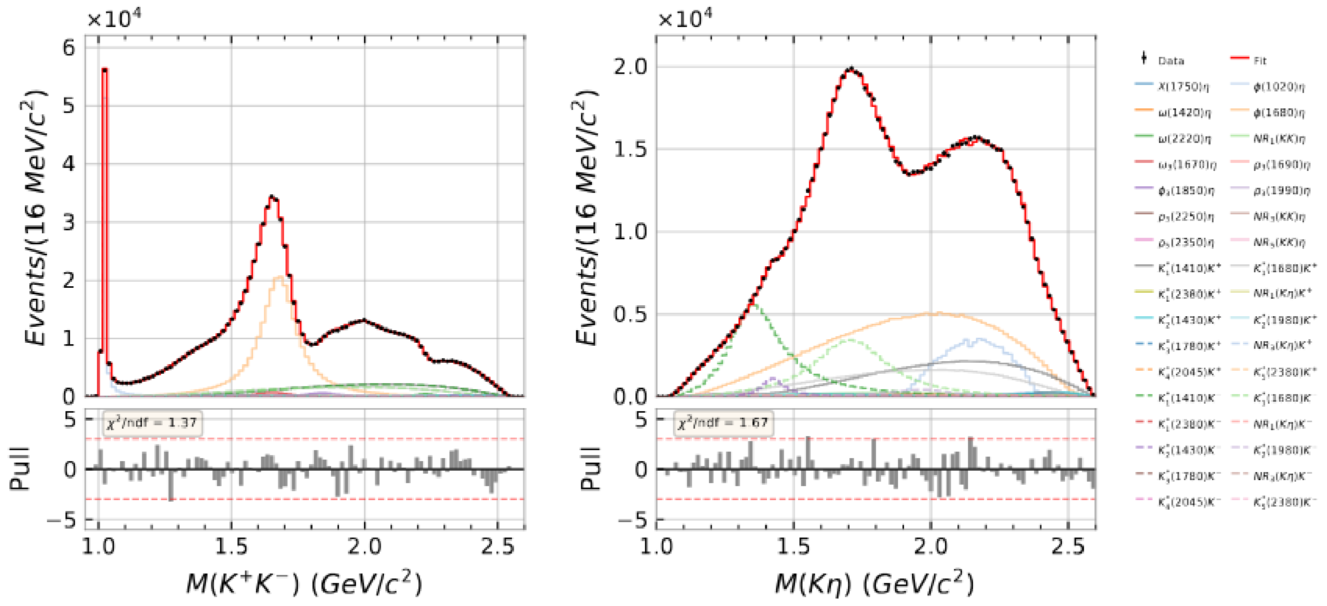
H.J. Jing,.. J.J. WU et al., JHEP 06, 039 (2023), PRD 110, 016014 (2024)





Nsig=1000000, Nphsp=5000000,Nstate = 16

Stage	Fixed resonances params	Free resonances params
$\mathcal{A}_{L,S}$ precomputation	$\sim$94 s	$\sim$94 s
NLL + gradient per iteration	$\sim$15 ms	$\sim$100 ms
Full Hessian	$\sim$0.35 s	$\sim$1.6 s
Device memory	$\sim$20 GB	$\sim$32 GB
Complete fit	$\sim$7.0 s	$\sim$100 s



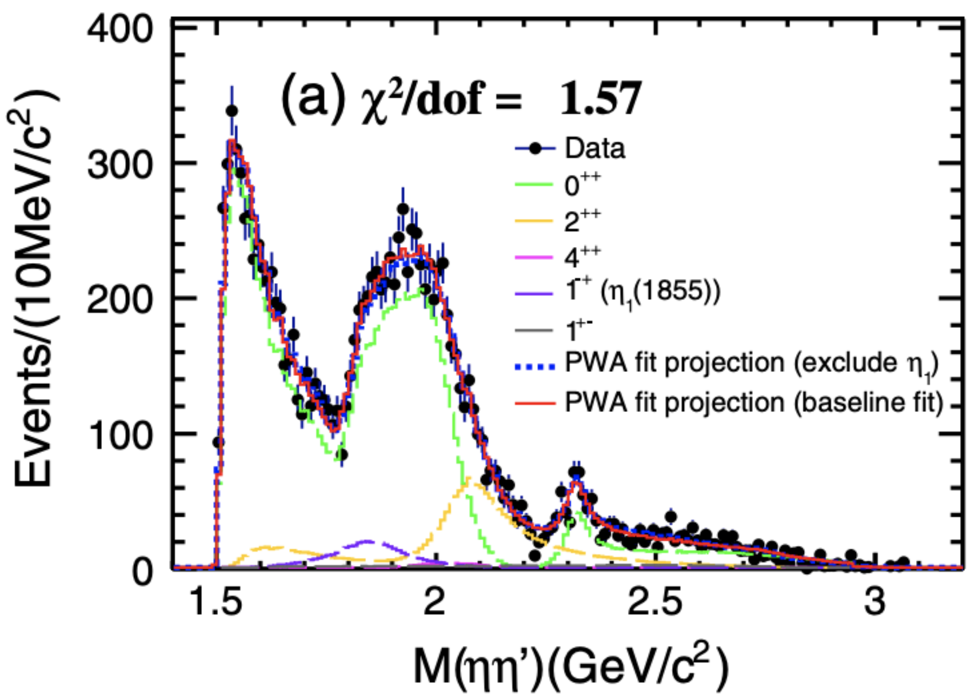
~100 times faster than the conventional PWA !

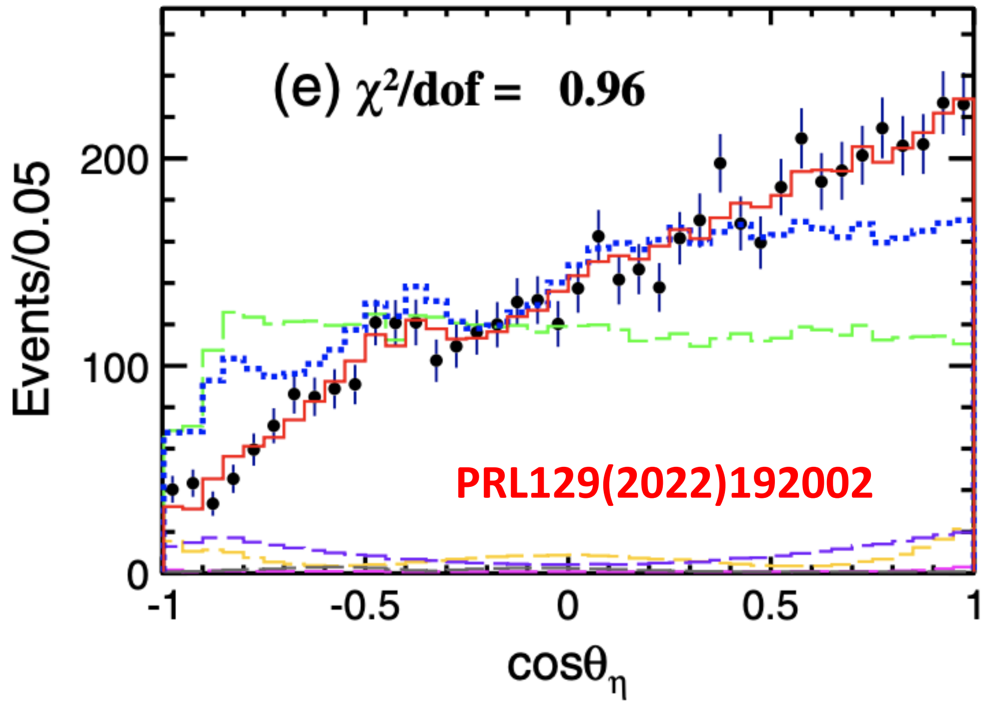
Summary & Future prospects

- BEPCII/BESIII: the world's largest sample produced in e+e- annihilations
- Significant progresses on light exotics
  - Glueballs, baryonium and hybrids
- BEPCII/BESIII upgraded in 2024
  - Luminosity 3 times higher
  - Extend E_{cm} up to 5.6 GeV
  - Continue to run for >5 years
- More exciting results are expected in the near future !

Many thanks!

Observation of $\eta_1(1855)$ with exotic 1^{-+} in $J/\psi\to\gamma\eta\eta'$





Isoscalar state with exotic quantum numbers

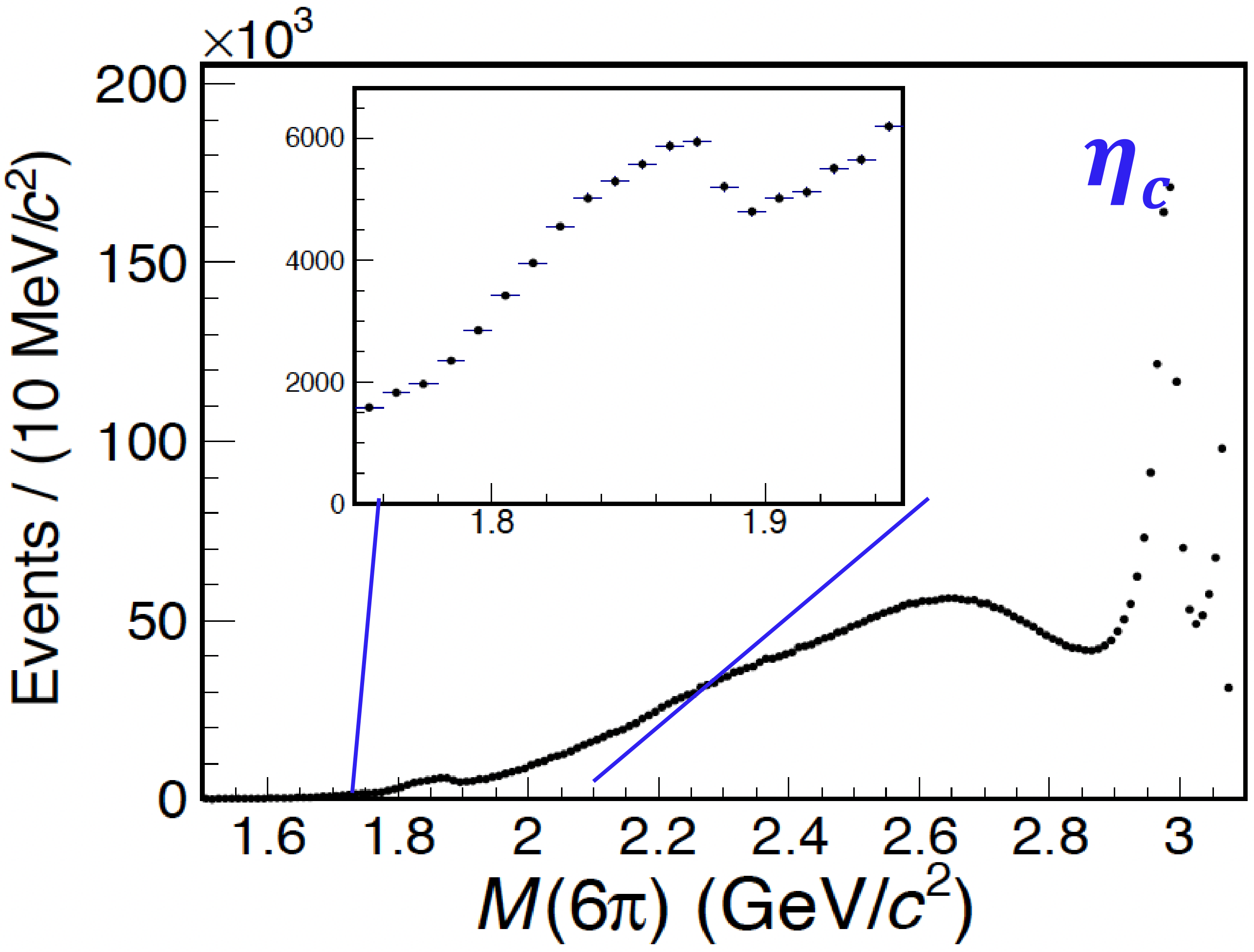
$J^{PC}=1^{-+}$

Critical to establish the 1^{-+} spectroscopy !

$M = 1855 \pm 9^{+6}_{-1}$ MeV/c^2

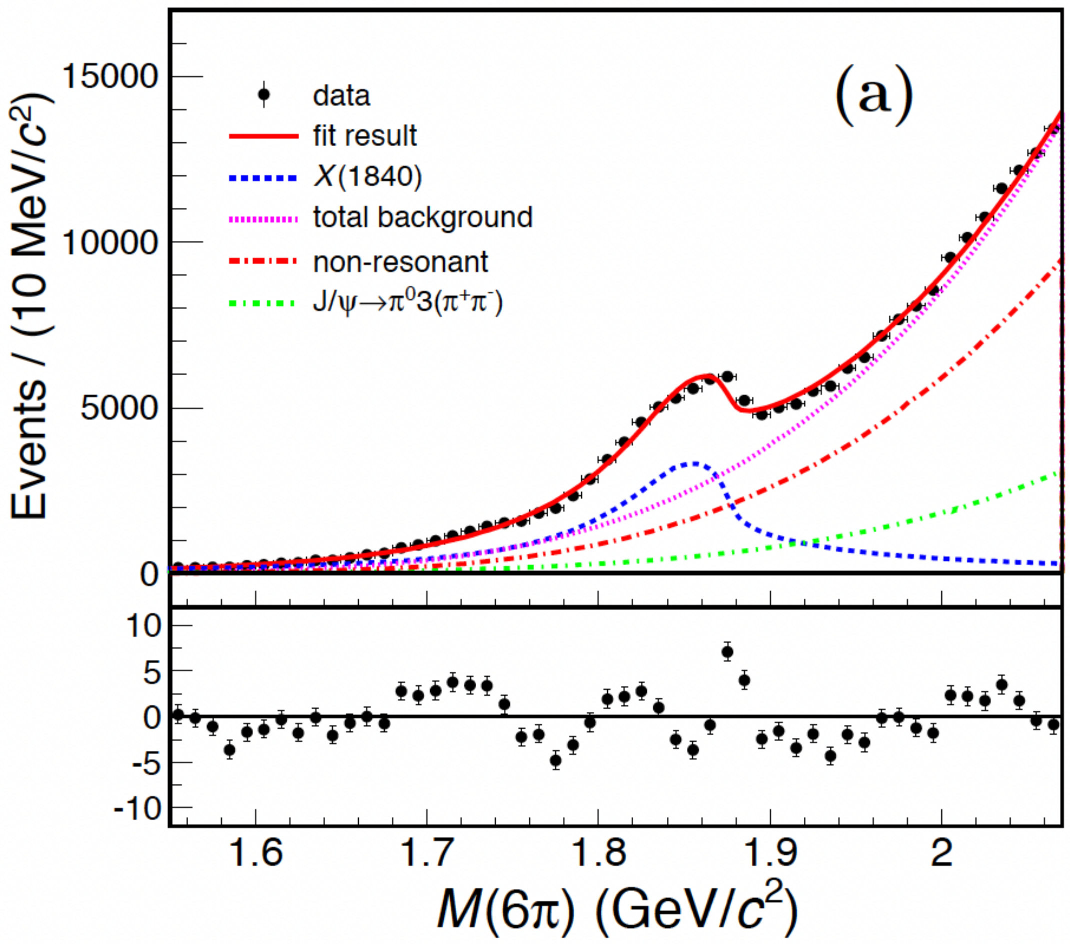
$\Gamma = 188 \pm 18^{+3}_{-8}$ MeV

Anomalous line-shape of $3(\pi^+\pi^-)$ in $J/\psi\to\gamma\,3(\pi^+\pi^-)$



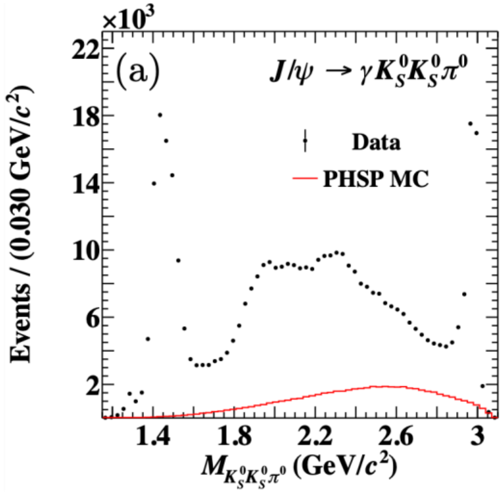
PRL132,151901(2024)

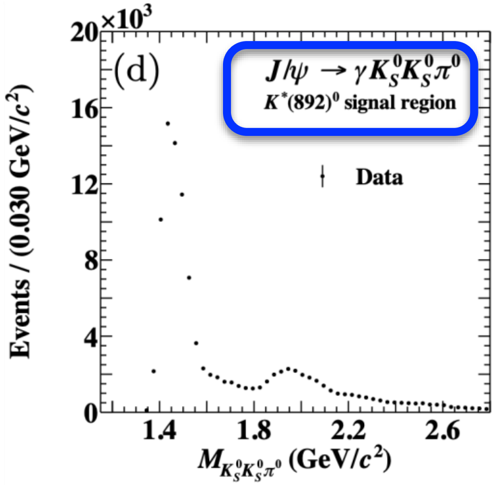
Flatte function

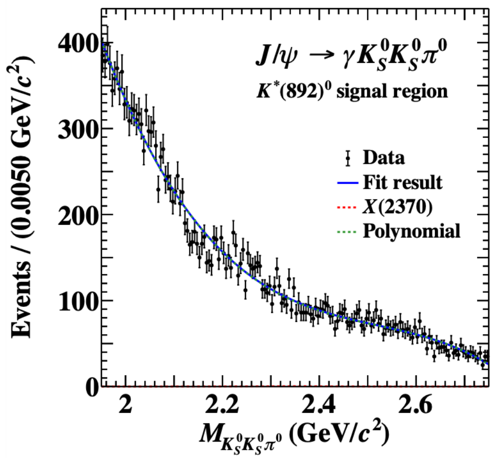


Flatte function can not describe data well!

Flavor-singlet property measurement for the X(2370)



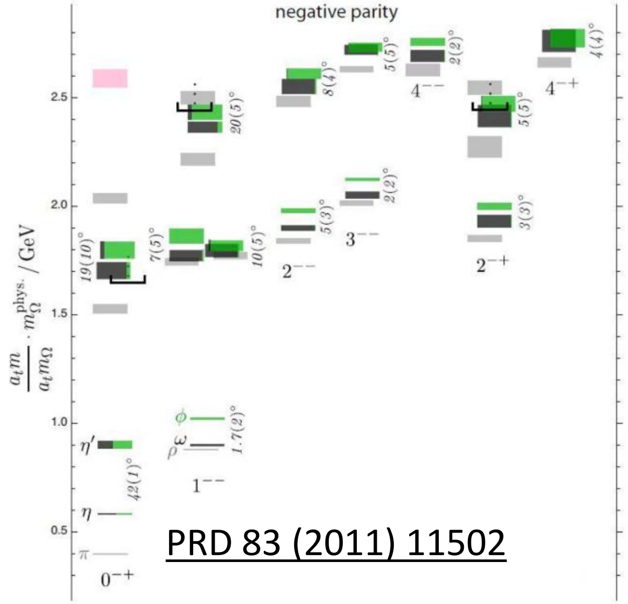




- **No evidence of the decay of $X(2370) \to K^*(892)\overline{K^0}$ (significance is only 0.1σ)**
  - **Branching fraction ratio in $K_S^0 K_S^0 \pi^0$ mode:** $R = \frac{B[X(2370)\to K^*(892)^0\overline{K}^0]+c.c.\to K_S^0 K_S^0 \pi^0}{X(2370)\to K_S^0 K_S^0 \pi^0} < 0.081@90\%C.L.$
  - **Branching fraction ratio w.r.t. total X(2370) production:** $B[X(2370) \to K^*(892)\overline{K}] < 1.6\%@90\%C.L.$
- **Suppression of $X(2370) \to K^*(892)\overline{K^0}$ mode indicates the X(2370) to be a flavor-singlet state**
  - **First flavor-singlet hadron state observed above 1GeV**

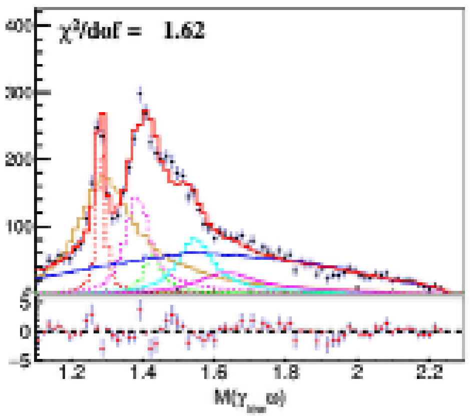
arxiv:2607.20366

Suppression of $q\bar{q}$ contents

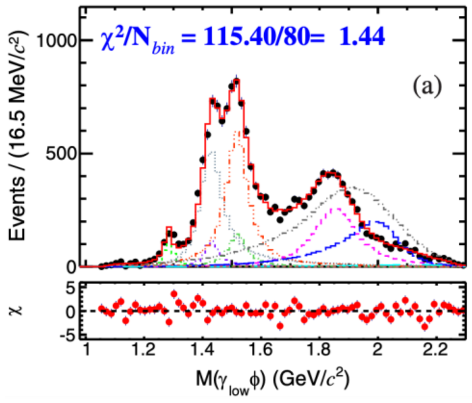


PRD 83 (2011) 11502

$J/\psi \to \gamma\gamma\omega$



$J/\psi \to \gamma\gamma\phi$



PRD 111(2025) 052011

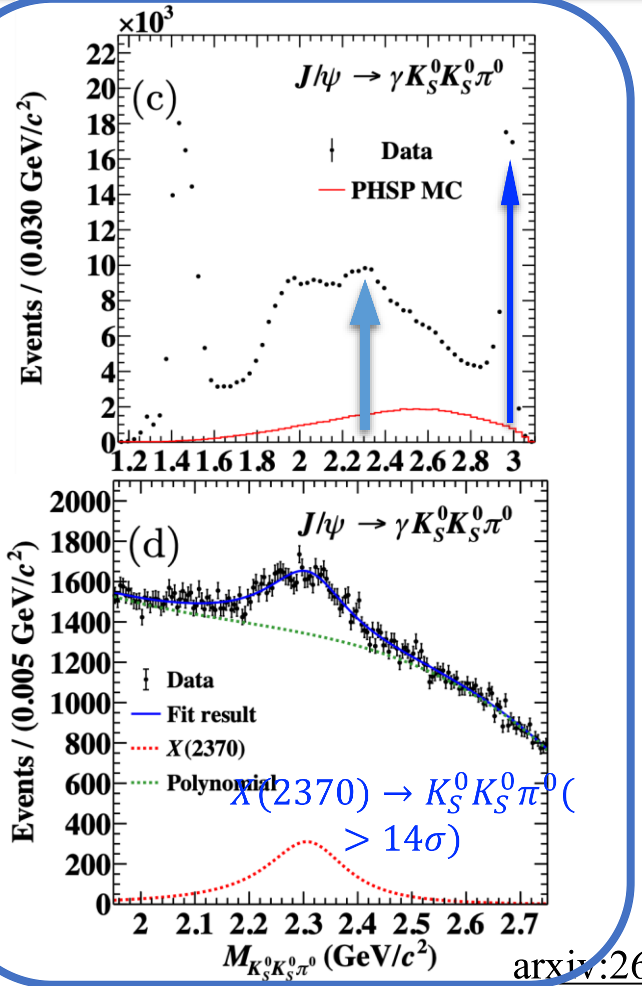
Resonance R	$J/\psi \to \gamma R \to \gamma\gamma\omega$ ($\times 10^{-6}$) [29]	$J/\psi \to \gamma R \to \gamma\gamma\phi$ ($\times 10^{-6}$) [30]
$\eta(1405)$	$3.54 \pm 0.20^{+0.65}_{-0.24}$	$3.57 \pm 0.18^{+0.59}_{-0.61}$
$X(1835)$	< 0.11	$3.37 \pm 0.19^{+0.78}_{-1.10}$
$X(2370)$	< 0.04	< 0.11

$$B(J/\psi \to \gamma X(2370)) > 1 \times 10^{-3}$$

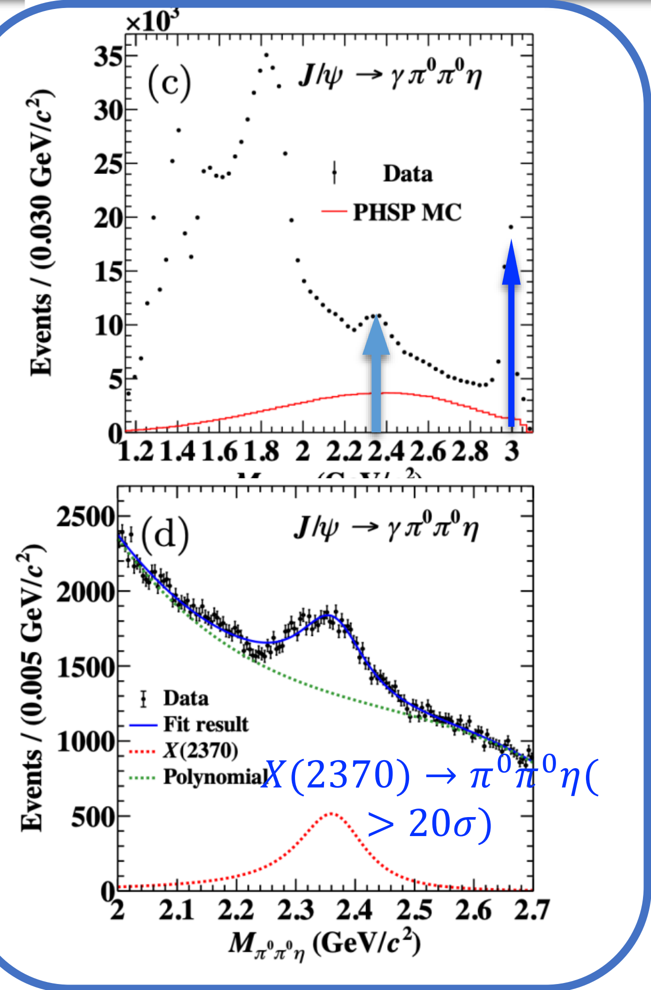
- **LQCD prediction: no flavor singlet formed via $s\bar{s}/u\bar{u}+d\bar{d}$ mixing** above 1GeV (supported by PDG data)
- **Study in $J/\psi \to \gamma\gamma\omega$ and $J/\psi \to \gamma\gamma\phi$**
  - **Strong suppression of $X(2370) \to \gamma\omega, \gamma\phi$: disfavor $s\bar{s}/u\bar{u}+d\bar{d}$ content**
  - **Significantly lower than the decay rates of $\eta(1405)$ and X(1835): disfavor η/η' excitation**
- **Narrow partial decay widths ~a few MeV: disfavor $q\bar{q}$, multi-quark or hybrid states (typical OZI decay width ~100MeV)**
- **Flavor-singlet property $B[X(2370) \to K^*(892)\bar{K}] < 1.6\%$(decay width <2MeV): disfavor η/η' excitation (expected 15-200MeV)**

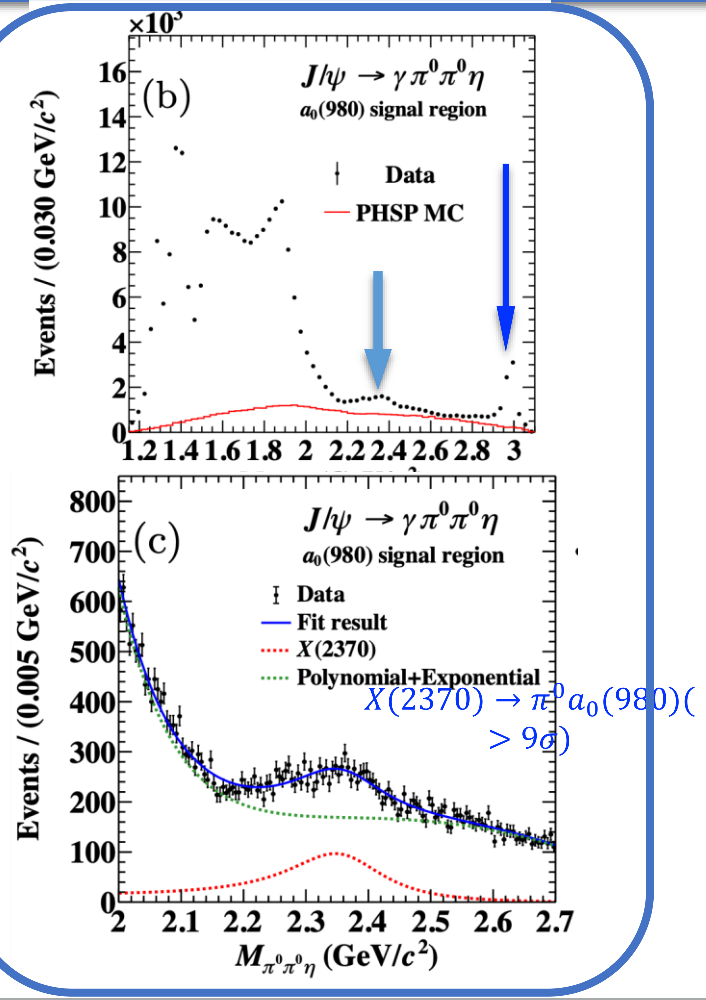
$s\bar{s}/u\bar{u}+d\bar{d}$ **content should be strongly suppressed in X(2370)**

Observation of the X(2370) in $K_S^0K_S^0\pi^0$ and $\pi^0\pi^0\eta$



arxiv:2605.26495





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