Light QCD exotics at BESIII

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(On behalf of the BESIII Collaboration)

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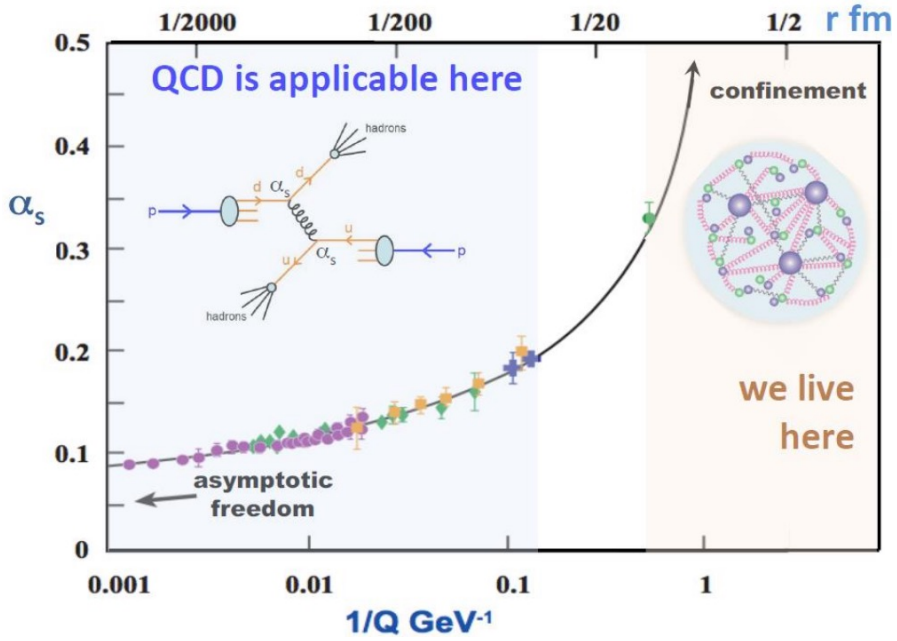
Light QCD Exotics

■ Quantum Chromodynamics （QCD）

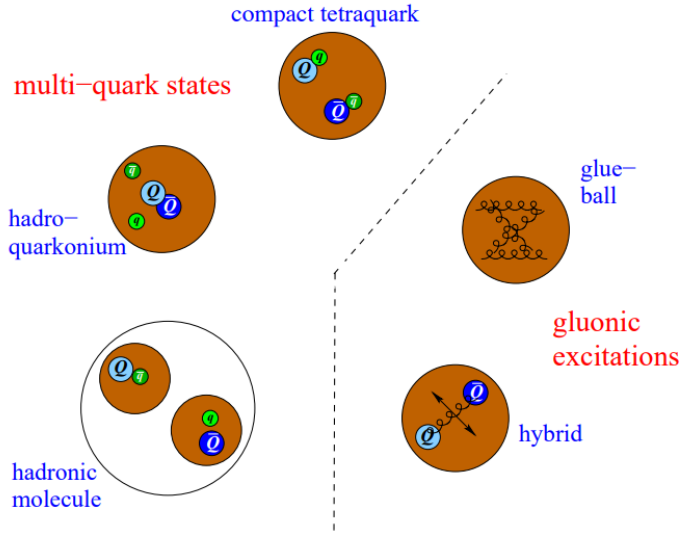
- **High energy region :** nature of asymptotic freedom has been confirmed experimentally
- **Low energy region :** non-perturbation effects are dominant and the solution cannot be solved analytically (color confinement)



■ Hadron spectroscopy

- **Study the effective degrees of freedom in non-perturbative regime of QCD.**

Light QCD Exotics



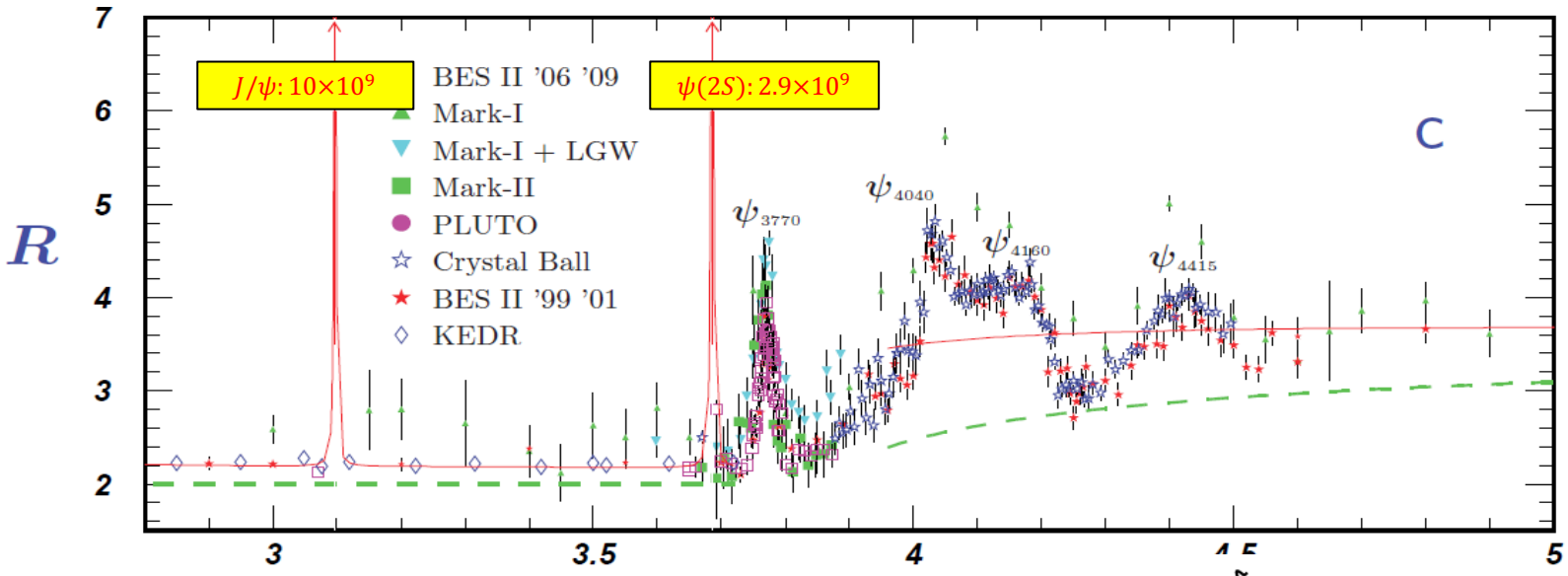
Phys.Rept. 873 (2020) 1

■ Hadron spectroscopy

- Well-known classes of hadrons: meson($\mathbf{q\bar{q}}$), baryon($\mathbf{qqq}$)
- QCD allows the existence of exotic hadrons
  - **multi-quark states ; hybrids; glueballs**
  - Strong evidences for multi-quark in heavy quark sector

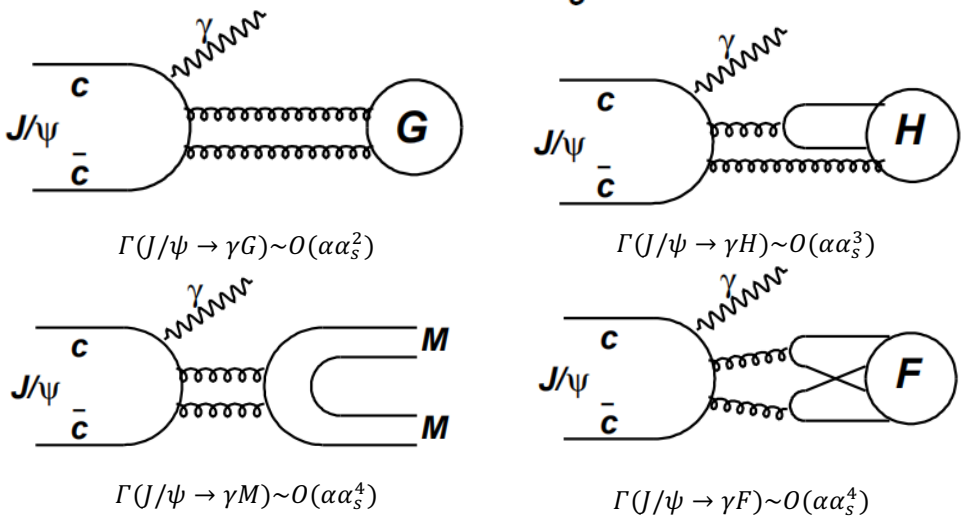
    A new "particle zoo": https://qwg.ph.nat.tum.de/exoticshub/
  - **Evidence for gluonic excitations remains sparse**

World's Largest τ –charm Data Sets in e^+e^- Annihilation



Ideal place for light QCD exotics

- **Charmonium decays ⇨ "Gluon-rich" process**
- **Clean high statistics data sample**
- **Kinematic constraints**
- **I(J^{pc}) filter**

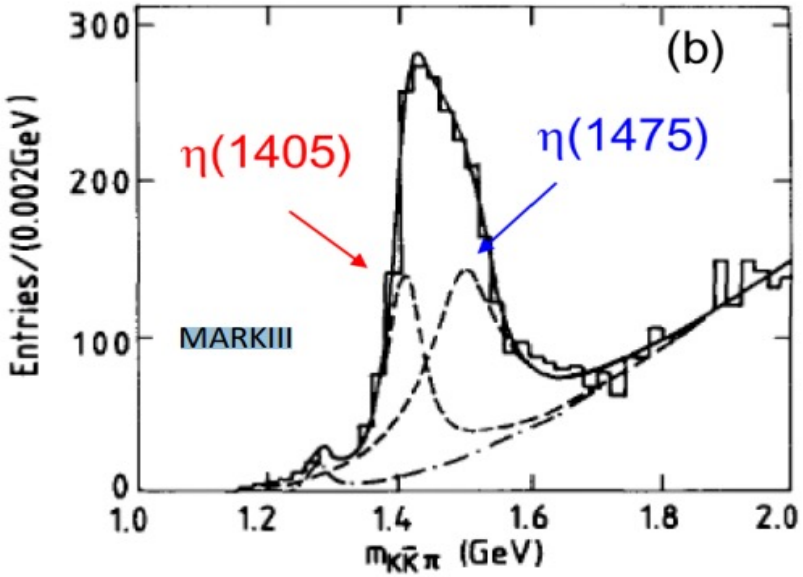


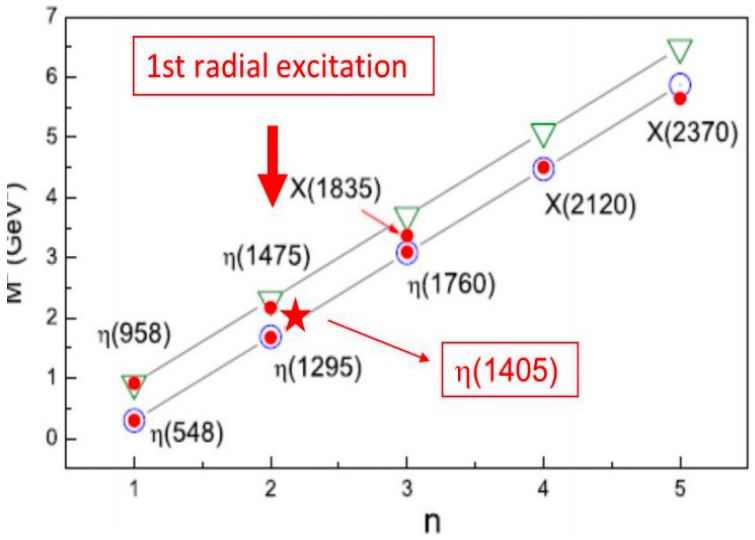
Glueballs and hybrids are expected to have a larger yield compared to mesons.

Long Standing E – ι Puzzle

- MarkIII experiments found that $\eta(1405) \to a_0(980)\pi$ and $\eta(1475) \to K^*K$, confirmed by Crystal Barrel and Obelix.

  - Quark model predicts: only one pseudoscalar meson near 1.4 GeV.
  - Theoretical interpretations :
    - $\eta(1475)$ ⇨ the first radial excitation of η' ;
    - $\eta(1405)$ ⇨ the glueball candidate
  - LQCD predicts: 0^{-+} glueball (2.3~2.6 GeV)

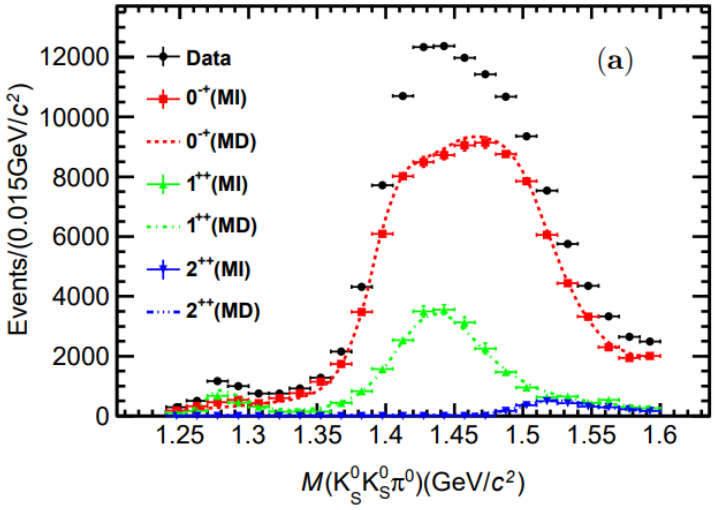


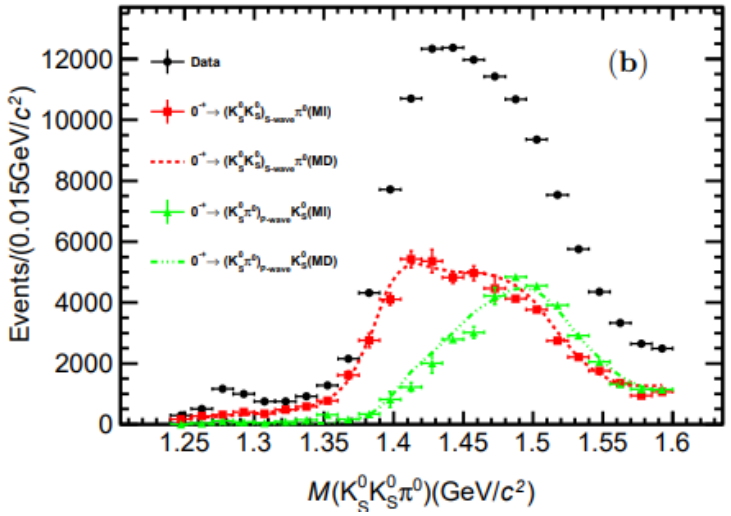


What's the nature of the outnumbered $\eta(1405)$?

Partial Wave Analysis of $J/\psi \to \gamma K_S^0 K_S^0 \pi^0$

JHEP03(2023)121





■ **Mass Dependent PWA : Isobar model**

- Two pseudoscalar states needed: $\eta(1405)/\eta(1475)$.
- $f_1(1285)$, $f_1(1420)$, $f_2(1525)$ are observed

■ **Mass Independent PWA : Disentangle J^{PC} in each bin**

- Two 0^{-+} around 1.4 GeV/c^2 in $(K_S^0 K_S^0)_{s-wave}\pi^0$ and $(K_S^0\pi^0)_{p-wave}K_S^0$ partial waves
- Consistency between MI and MD results

Resonance	M(MeV/c^2)	Γ(MeV)
$\eta(1405)$	$1391.7 \pm 0.7^{+11.3}_{-0.3}$	$60.8 \pm 1.2^{+5.5}_{-12.0}$
$\eta(1475)$	$1507.6 \pm 1.6^{+15.5}_{-32.2}$	$115.8 \pm 2.4^{+14.8}_{-10.9}$
$f_1(1285)$	$1280.2 \pm 0.6^{+1.2}_{-1.5}$	$28.2 \pm 1.1^{+5.5}_{-2.9}$
$f_1(1420)$	$1433.5 \pm 1.1^{+27.9}_{-0.7}$	$95.9 \pm 2.3^{+13.6}_{-10.9}$
$f_2(1525)$	$1515.4 \pm 2.5^{+3.2}_{-7.6}$	$64.0 \pm 4.3^{+2.0}_{-6.1}$

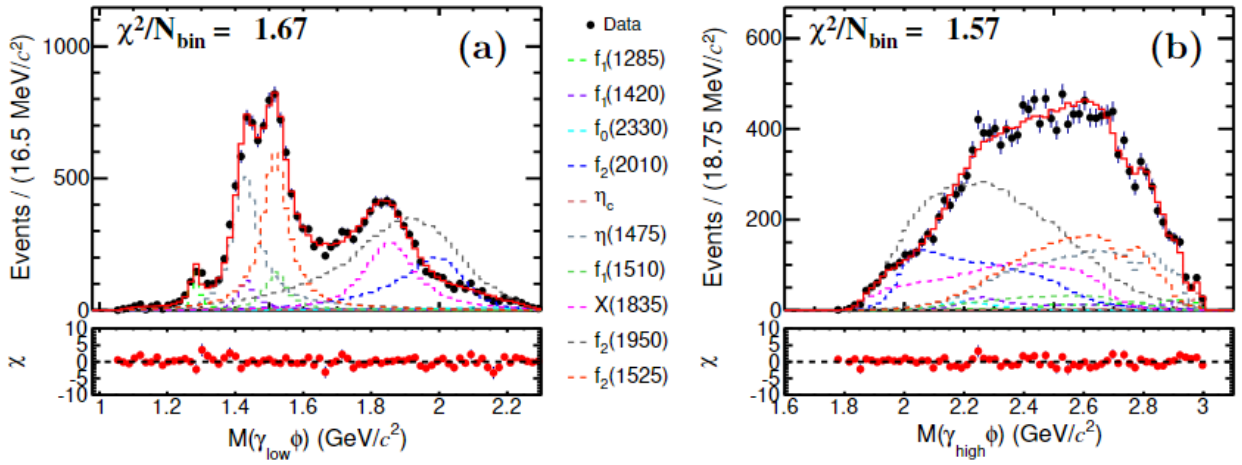
■ **Theorists attempt to explain $\eta(1405)/\eta(1475)$ using one pole**

- further study is needed

Phys.Rev.D 107 (2023) 9, L091505

Partial Wave Analysis of $J/\psi \to \gamma\gamma\phi$

arXiv: 2401.00918



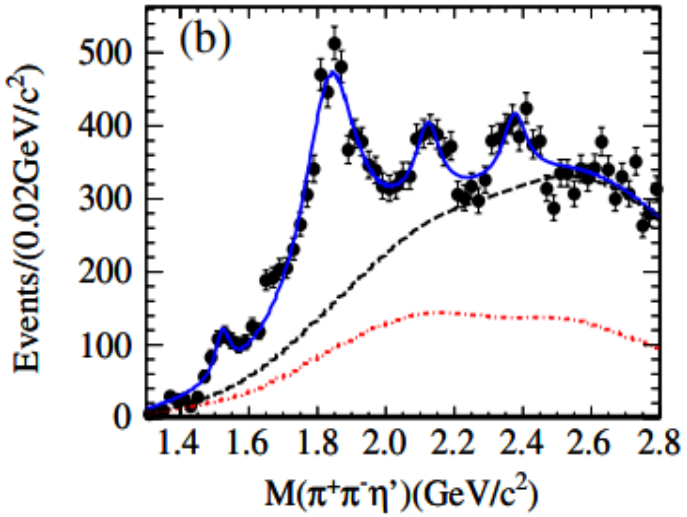
Resonance	M (MeV/c^2)	Γ (MeV)	$\mathcal{B}(\times 10^{-6})$	Significance
$f_1(1285)$	1281.9	22.7	$0.29\pm0.03^{+0.11}_{-0.09}$	17.3σ
$f_1(1420)$	1426.3	54.5	$0.55\pm0.07^{+0.18}_{-0.17}$	9.0σ
$\eta(1405)$	$1422.0 \pm 2.1^{+5.9}_{-7.8}$	$86.3 \pm 2.7^{+6.6}_{-17.4}$	$3.57\pm0.18^{+0.59}_{-0.61}$	18.9σ
$f_1(1510)$	1518.0	73.0	$0.78\pm0.09^{+0.34}_{-0.30}$	5.3σ
$f_2(1525)$	1517.4	86.0	$2.76\pm0.18^{+0.90}_{-0.61}$	16.4σ
$X(1835)$	$1849.3 \pm 3.0^{+7.6}_{-10.0}$	$179.6 \pm 8.7^{+22.5}_{-27.9}$	$3.37\pm0.19^{+0.78}_{-1.10}$	15.3σ
$f_2(1950)$	1936.0	464.0	$9.96\pm0.60^{+3.44}_{-2.13}$	13.1σ
$f_2(2010)$	2011.0	202.0	$4.63\pm0.43^{+1.42}_{-1.46}$	11.3σ
$f_0(2200)$	2187.0	207.0	$0.20\pm0.04^{+0.05}_{-0.07}$	6.3σ
η_c	2983.9	32.0	$0.21\pm0.03^{+0.05}_{-0.07}$	12.9σ

- **Flavor filter reactions ⇨ $\eta(1405)$ and *X(1835)* decaying into $\gamma\phi$: contain a sizable $s\bar{s}$**
- **Just one $\eta(1405)$ state and a $f_1(1420)$ are needed around 1.4 GeV/c^2**
- **$\eta_c \to \gamma\phi$ is observed for the first time**
- **The upper limit for $\eta(1295)$, $\eta(1475)$, $\eta_1(1855)$ and X(2370) are also reported**

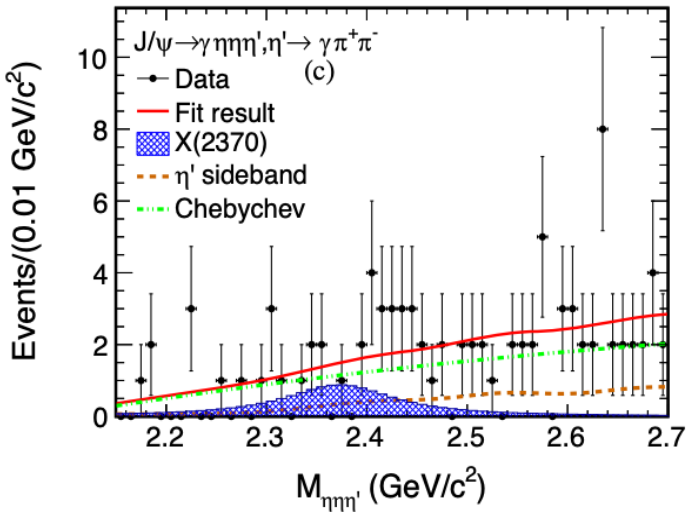
Study of X(2370)

- The $X(2370)$ is first observed in the process of $J/\psi \to \gamma\pi^+\pi^-\eta'$.
- The X(2370) is also observed in $J/\psi \to \gamma K\bar{K}\eta'$; $B(J/\psi \to \gamma X(2370) \to \gamma K\bar{K}\eta')$= $(1.79 \pm 0.23 \pm 0.65)\times 10^{-5}$
- No X(2370) signal in $J/\psi \to \gamma\eta\eta\eta'$, $B(J/\psi \to \gamma X(2370) \to \gamma\eta\eta\eta') < 9.2\times 10^{-6}$ at 90% C.L.
- ◆ No contradiction to the calculation for X(2370) as 0^{-+} glueball [2.3-2.6 GeV/c^2]

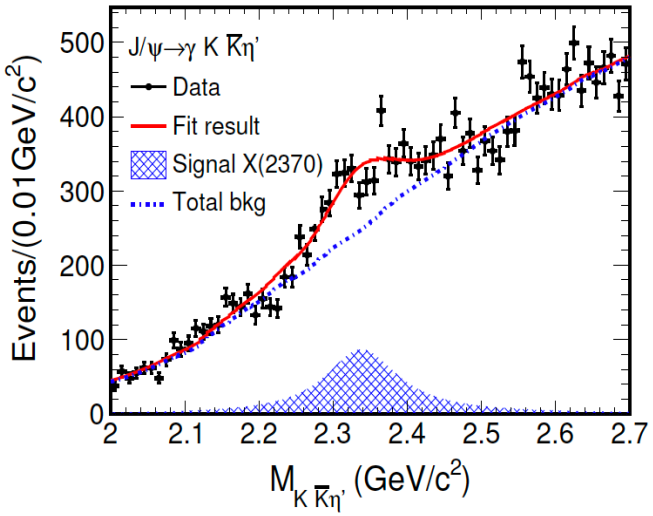
PRL 106, 072002 (2011)



Eur. Phys. J. C (2020) 80 ,746



Phys. Rev. D 103, 012009

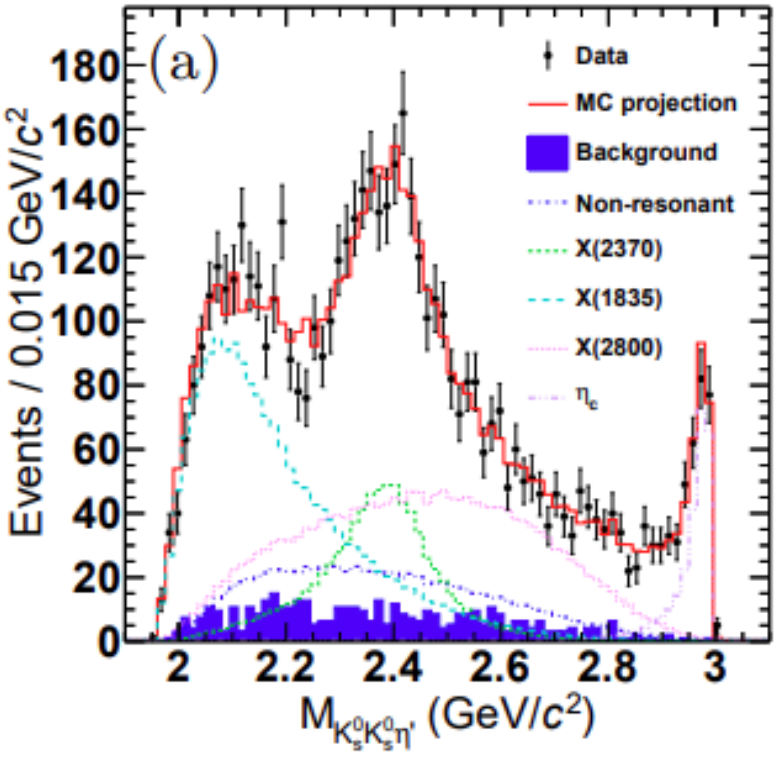


Study of X(2370)

arXiv:2312.05324

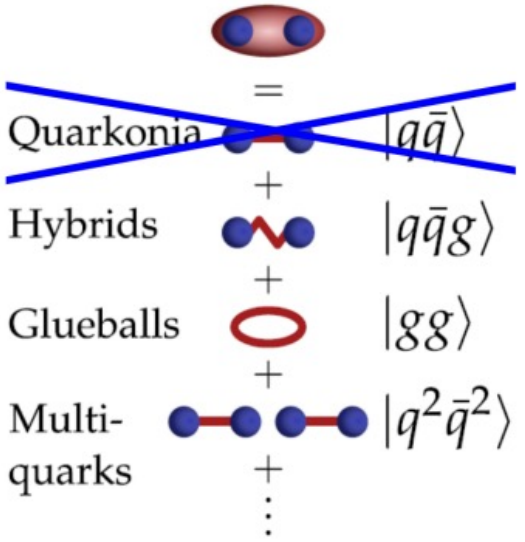
- **Partial wave analysis of $J/\psi \to \gamma K_S^0 K_S^0 \eta'$**
  - Simultaneous fit to $\eta' \to \eta\pi\pi$ and $\eta' \to \gamma\pi\pi$ mass spectra
  - Using a subsample by requiring $M_{K_S^0 K_S^0} < 1.1\ GeV/c^2$

- **The spin-parity is determined to be 0^{-+}**



Light hadrons with exotic quantum numbers

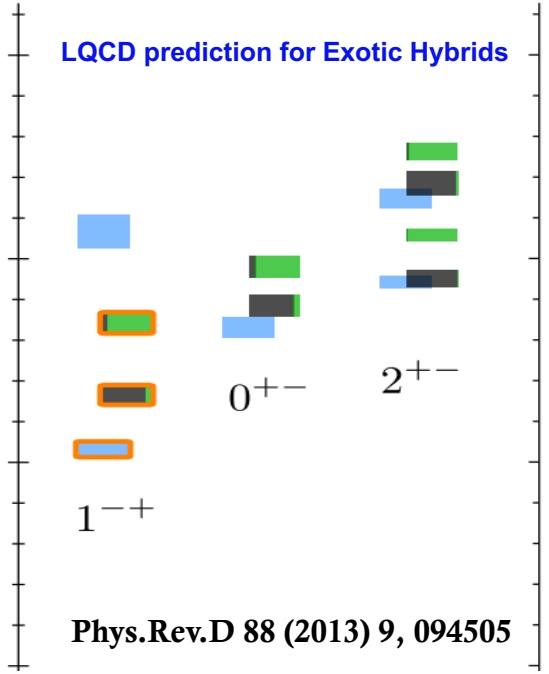
- **Unambiguous signature for exotics**
  - ✓ Light Flavor-exotic hard to establish
  - ✓ Efforts concentrate on Spin-exotic
    - Forbidden for $(q\bar{q})$: $0^{--}, even^{+-}, odd^{-+}$



- **Lightest spin-exotic:** 1^{-+}
  - $1.7\sim2.1 GeV/c^2$

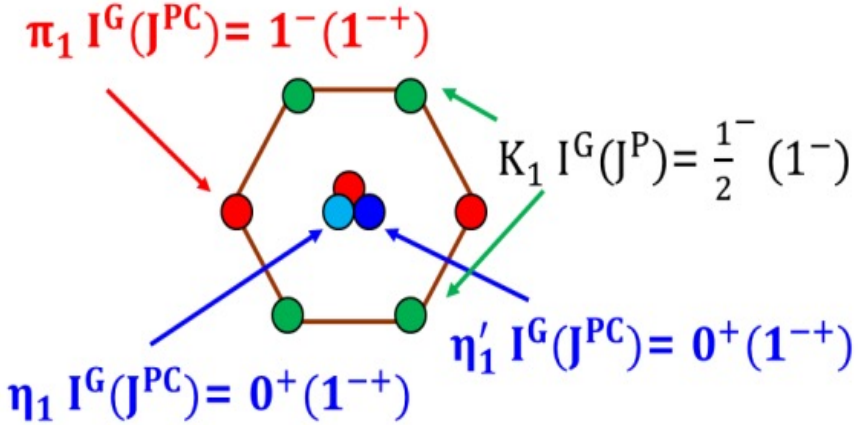
- **Only 3 spin exotic candidate so far : All 1^{-+} isovectors**
  - $\pi_1(1400), \pi_1(1600), \pi_1(2015)$

$\pi_1(1400), \pi_1(1600)$ can be explained as one pole



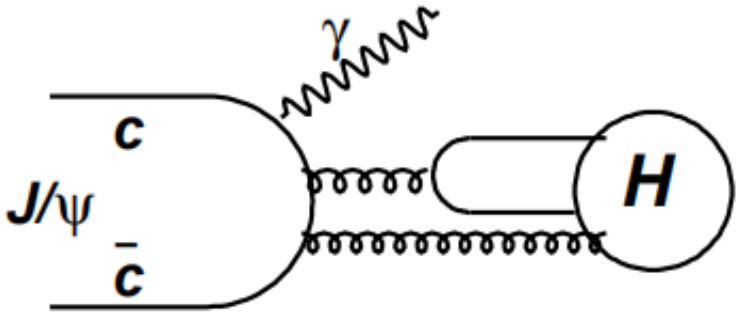
1^{-+} Hybrids

- **Isoscalar 1^{-+} is critical to establish the hybrid nonet**
  - **Can be produced in the gluon-rich charmonium decays**
  - **Can decay to $\eta\eta'$ in P-wave**



[PRD 83,014021 (2011), PRD 83,014006 (2011), EP.J.P 135, 945(2020)]

Search for $\eta_1(1^{-+})$ in $J/\psi \to \gamma\eta\eta'$



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

Observation of Exotic Isoscalar State $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$

- An isoscalar 1^{-+} state, $\eta_1(1855)$, has been observed with statistical significance larger than 19σ

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

$$B(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$$

  - Mass is consistent with hybrid on LQCD

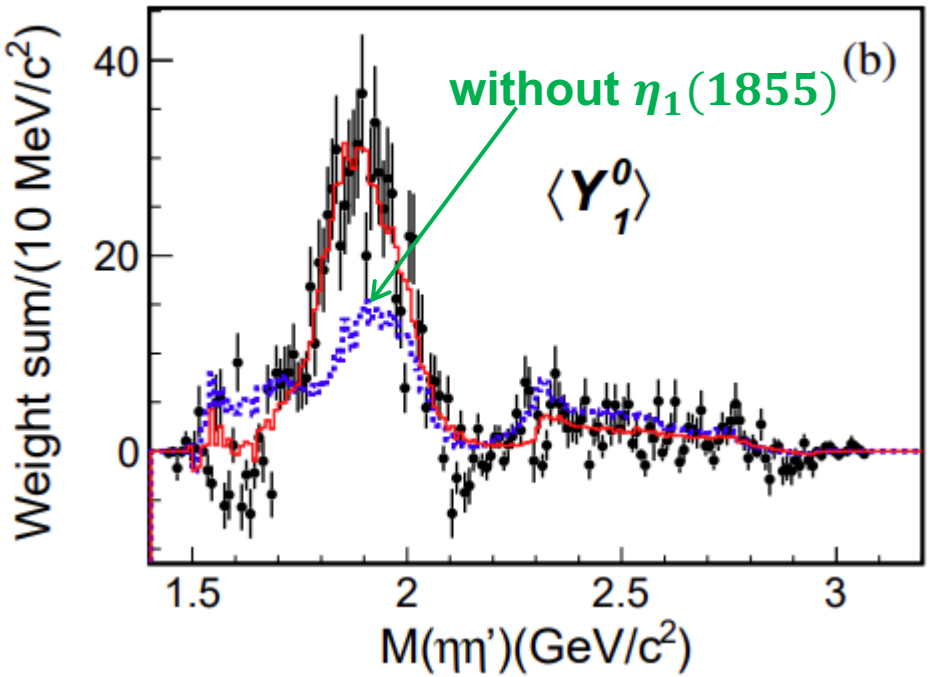
- Inspired many interpretations:
  - Hybrid? Molecule? Tetraquark?

- Further more, suppression of $f_0(1710) \to \eta\eta'$ supports it has a large overlap with glueball

$$\frac{Br(f_0(1500) \to \eta\eta')}{Br(f_0(1500) \to \pi\pi)} = (1.66^{+0.42}_{-0.40}) \times 10^{-1}$$

$$\frac{Br(f_0(1710) \to \eta\eta')}{Br(f_0(1710) \to \pi\pi)} < 2.7 \times 10^{-3} @ 90\% C.L$$

PRL 129, 192002 (2022) ; PRL 130, 159901 (2023) (erratum)
PRD 106,072012 (2022) ; PRD 107,079901 (2023) (erratum)

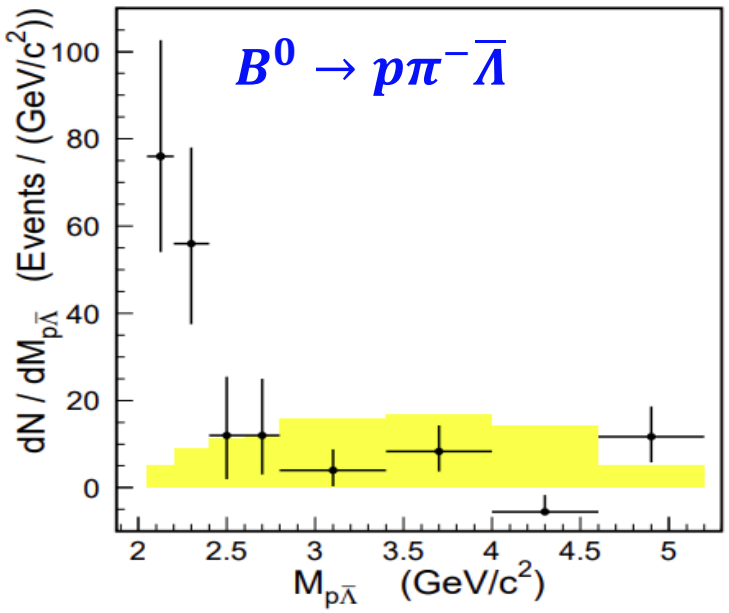


Opens a new direction to completing the picture of spin-exotics

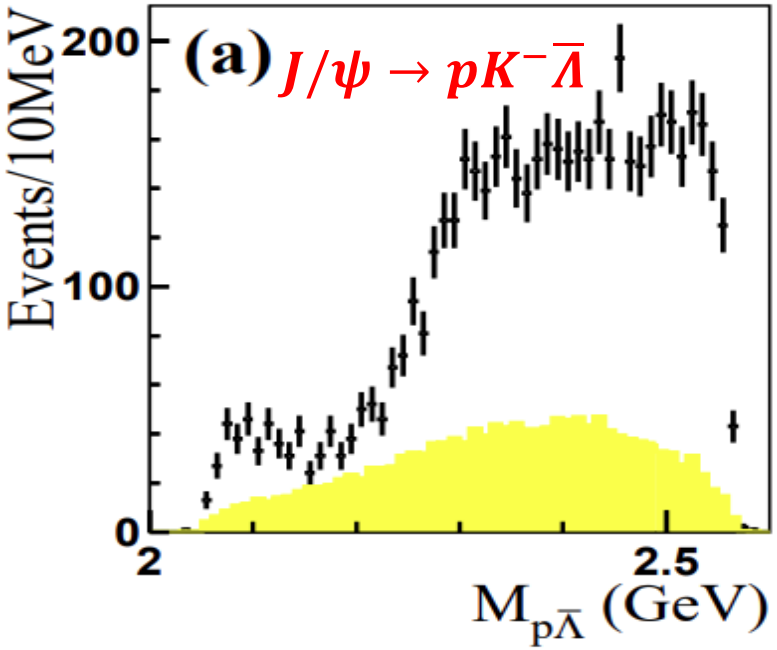
Observation of the Narrow Structure Near the $p\bar{\Lambda}$ Threshold

- Similar evidence of a structure of $p\bar{\Lambda}$ in several decays of B mesons and charmonium states

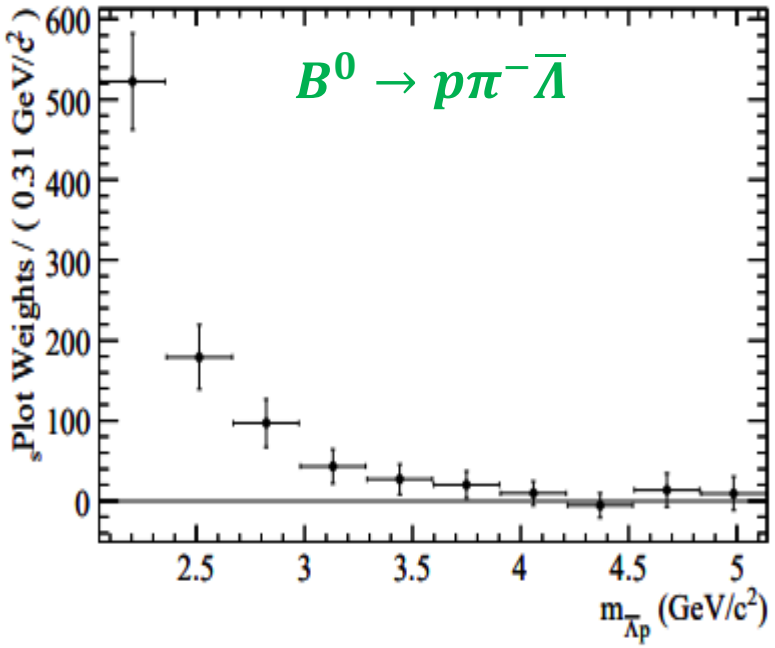
BELLE PRL90,201802 (2003)



BES, PRL93,112002 (2004)



BaBar, PRD79,112009 (2009)

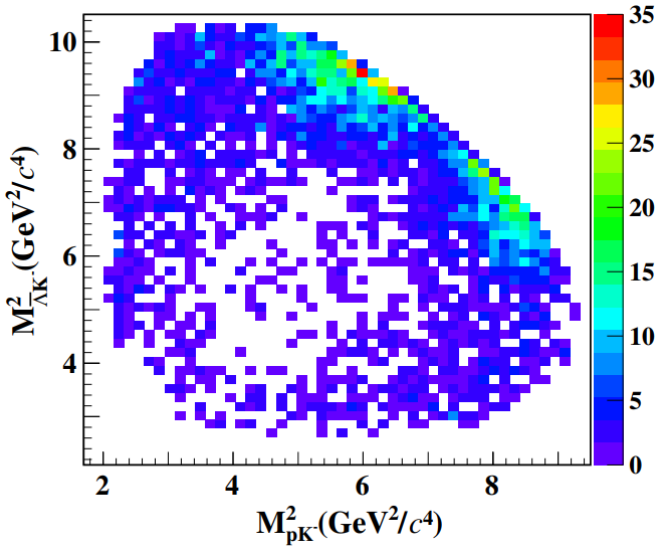


Different scenarios investigated: baryonium state [PRD74,014029], baryon-antibaryon SU(3) nonets [PLB626,95], final state interaction [IJMPA22,5401], ...

Observation of the Narrow Structure Near the $p\bar{\Lambda}$ Threshold

➢ $e^+e^- \to pK^-\bar{\Lambda}$: Amplitude analysis for spin parity determination

PRL 131, 151901 (2023)

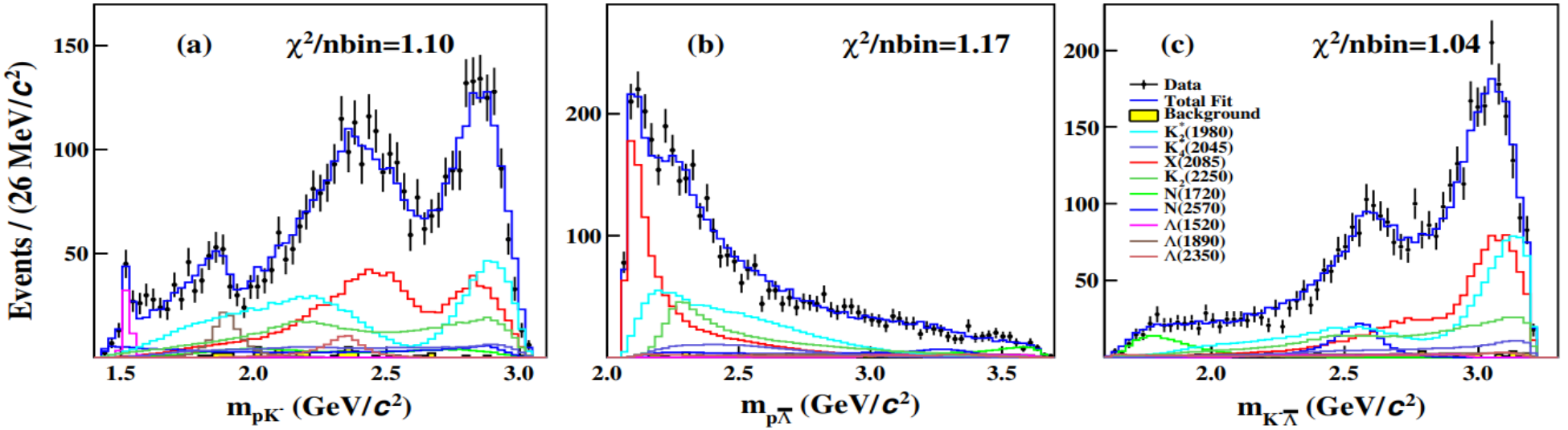


- Anomalous enhancement near the $p\bar{\Lambda}$ mass threshold observed in $e^+e^- \to pK^-\bar{\Lambda}$
- X(2085) observed with statistical significance >20σ

  $M = (2086 \pm 4 \pm 6)\text{MeV}$; $\Gamma = (56 \pm 5 \pm 16)\text{MeV}$; $J^P = 1^+$
- No matching with the prediction by potential model+ narrow width,

  ⇨ exotic properties of X(2085)!!!
- Same structure as in PRL93,112002 ?

8.35f



Summary and outlook

BESIII experiment is an excellent laboratory to study light hadron physics and search for light QCD exotic states

Exciting results from new J/ψ data are presented

- **pesudoscalar state : $\eta(1405)$, X(2370)**
- **isoscalar 1^{-+} spin exotics state: $\eta_1(1855)$**
- **$p\bar{\Lambda}$ threshold structure: X(2085)**

BESIII is taking data since 2008. It will continue to run ~2030

- **BEPCII-U: 3x upgrade on luminosity; Ecms expanded to 5.6 GeV (summer 2024)**

More interesting results are expected!!!

Thank you for your attention

Discussions about $f_0(1500)$ & $f_0(1710)$

- **Production properties:**
  - $\Gamma(J/\psi \to \gamma f_0(1710))$ is compatible with LQCD predictions for a scalar glueball
  - Observed $\Gamma(J/\psi \to \gamma f_0(1710))$ is x10 larger than $f_0(1500)$
  - PWA fit result

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	$M_{\rm PDG}$ (MeV/c^2)	$\Gamma_{\rm PDG}$ (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	3.05±0.07	$\gg 30\sigma$
	$f_0(1810)$	1795	95	1795	95	0.07±0.01	7.6σ
	$f_0(2020)$	1935±5	266±9	1992	442	1.67±0.07	11.0σ
	$f_0(2100)$	2109±11	253±21	2086	284	0.33±0.03	5.2σ
	$f_0(2330)$	2327±4	44±5	2314	144	0.07±0.01	8.5σ
	$f_2(1565)$	1542	122	1542	122	0.20±0.03	6.2σ
	$f_2(1810)$	1815	197	1815	197	0.37±0.03	7.0σ
	$f_2(2010)$	2022±6	212±8	2011	202	1.36±0.10	8.8σ
	$f_2(2340)$	2345	322	2345	322	0.25±0.04	6.5σ
	$f_4(2050)$	2018	234	2018	234	0.11±0.02	5.6σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	1416	90	0.14±0.01	10.3σ
	$h_1(1595)$	1584	384	1584	384	0.41±0.04	9.7σ
	$\phi(2170)$	2160	125	2160	125	0.24±0.03	5.6σ
$J/\psi \to \eta X \to \gamma\eta\eta'$	$h_1(1595)$	1584	384	1584	384	0.50±0.03	11.0σ
	$\rho(1700)$	1720	250	1720	250	0.22±0.03	8.8σ

- The decay of scalar glueball to the $\eta\eta'$ final state are suppressed due to gauge duality

$$\frac{Br(G \to \eta\eta')}{Br(G \to \pi\pi)} < 0.04$$

- **Significant $f_0(1500)$**

$$\frac{Br(f_0(1500) \to \eta\eta')}{Br(f_0(1500) \to \pi\pi)} = (1.66^{+0.42}_{-0.40}) \times 10^{-1}$$

- **Absence of $f_0(1710)$**

$$\frac{Br(f_0(1710) \to \eta\eta')}{Br(f_0(1710) \to \pi\pi)} < 2.87 \times 10^{-3} @\ 90\% C.L$$

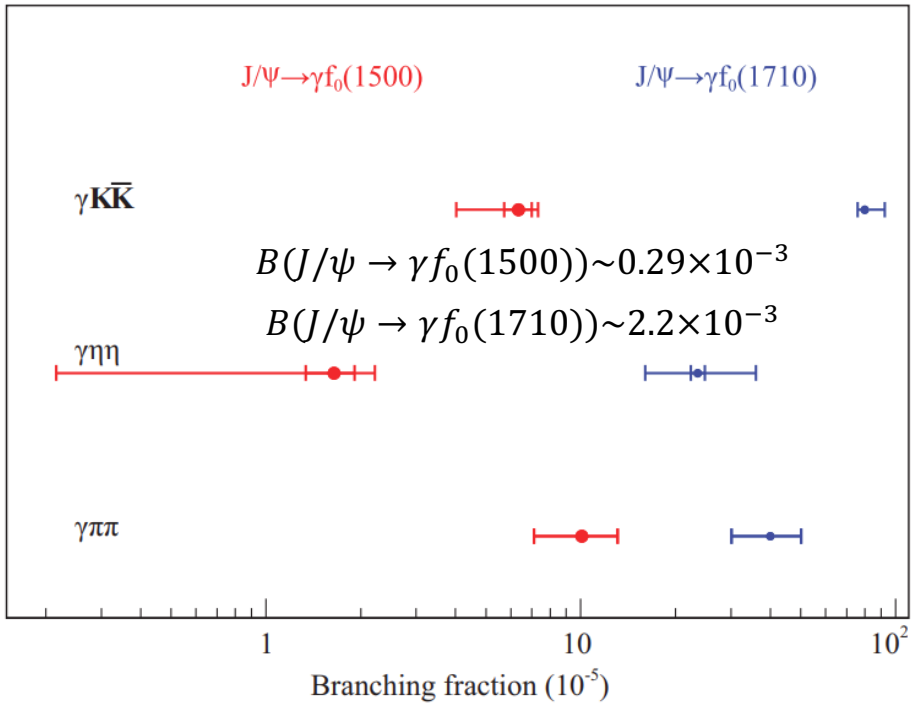
- Supports to the hypothesis: $f_0(1710)$ has overlaps with the ground state scalar glueball

Scalar Glueball

- **Scalar glueball is expected to have a large production in J/ψ radiative decays**

  - LQCD: $\Gamma(J/\psi \to \gamma G_{0^+})/\Gamma_{total} = 3.8(9)\times10^{-3}$
  - Observed $B(J/\psi \to \gamma f_0(1710))$ is x10 larger than $f_0(1500)$
  - BESIII: $f_0(1710)$largely overlapped with scalar glueball

Natl. Sci. Rev. 8, no.11, nwab198 (2021)



BESIII PRD 87 092009 (2013)
BESIII PRD 92 052003 (2015)
BESIII PRD 98 072003 (2018)

phenomenology studies of coupled channel analysis with BESIII results:
PLB 816, 136227 (2021), EPJC 82, 80 (2022)

Tensor glueball candidate

$$\Gamma(J/\psi \to \gamma G_{2^+}) = 1.01(22)keV$$
$$\Gamma(J/\psi \to \gamma G_{2^+})/\Gamma_{total} = 1.1\times10^{-2}$$

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

Experimental results

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = (3.8^{+0.62+2.37}_{-0.65-2.07})\times10^{-5}$$

BESIII PRD 87,092009 (2013)

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73})\times10^{-4}$$

BESIII PRD 93, 112011 (2016)

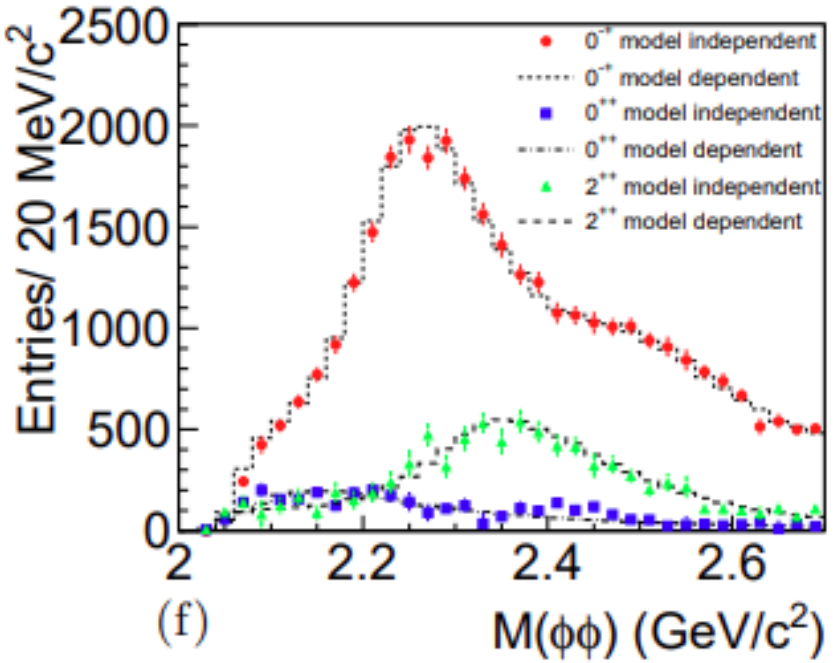
$$Br(J/\psi \to \gamma f_2(2340) \to \gamma K_S^0 K_S^0) = (5.54^{+0.34+3.82}_{-0.40-1.49})\times10^{-5}$$

BESIII PRD 98,072003 (2018)

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta'\eta') = (8.67 \pm 0.70^{+0.16}_{-1.67})\times10^{-6}$$

BESIII PRD 105,072002 (2022)

BESIII $J/\psi \to \gamma\phi\phi$ with 1.3B J/ψ



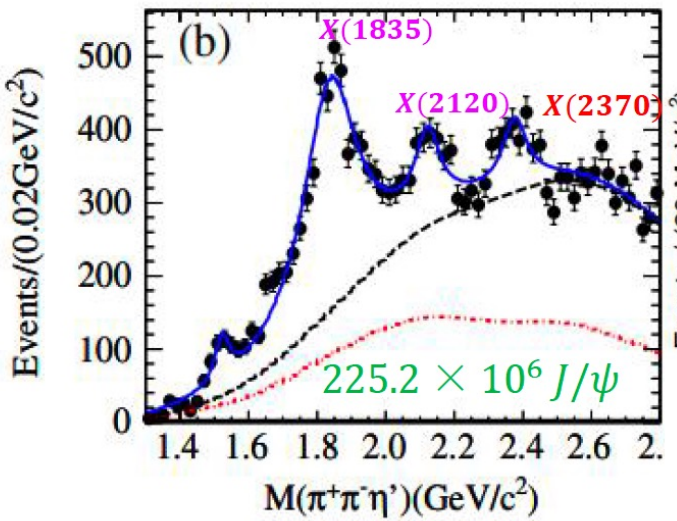
$f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ stated in $\pi^- p$ reactions are observed with a strong production of $f_2(2340)$Consist with central exclusion production in WA102

It is desirable to search for more decay modes

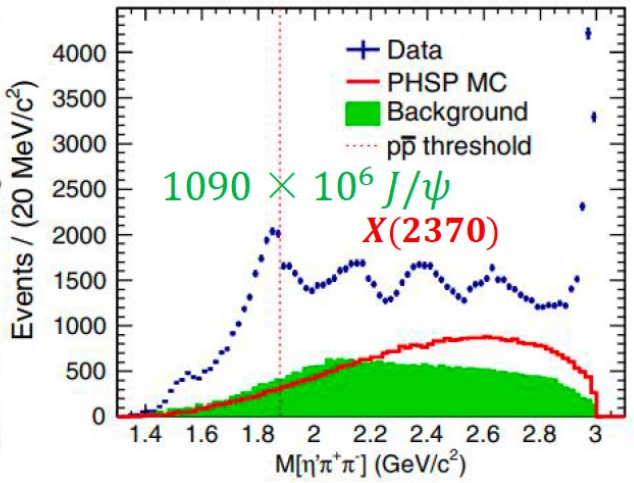
Pseudoscalar glueball searches

Study of $J/\psi \to \gamma\pi^+\pi^-\eta'$

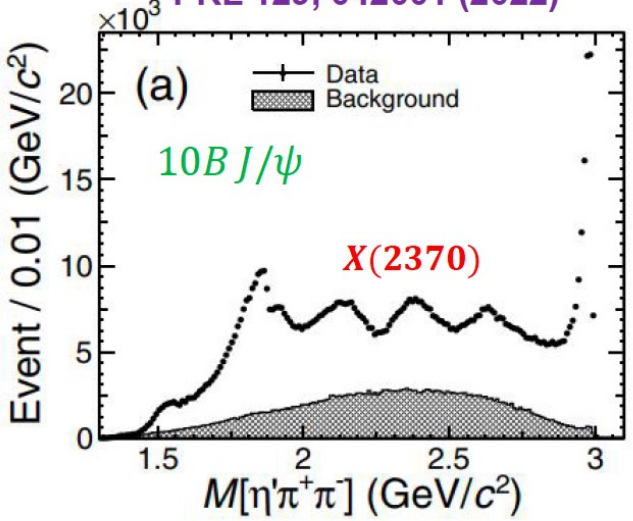
PRL 106, 072002 (2011)



PRL 117, 042002 (2016)



PRL 129, 042001 (2022)



- **The $X(2370)$ is first observed in the process of $J/\psi \to \gamma\pi^+\pi^-\eta'$, comfirmed with higher statistic**
- **Based on chiral effective Lagrangian with mass of X(2370), the predicted branching ratio of pseudoscalar glueball is : $B(G \to \eta\eta\eta') : B(G \to KK\eta') : B(G \to \pi\pi\eta') = 0.00082,\ 0.011,\ 0.09$** [Phys. Rev. D 87, 054036 (2013)]