Light QCD exotics at BESIII

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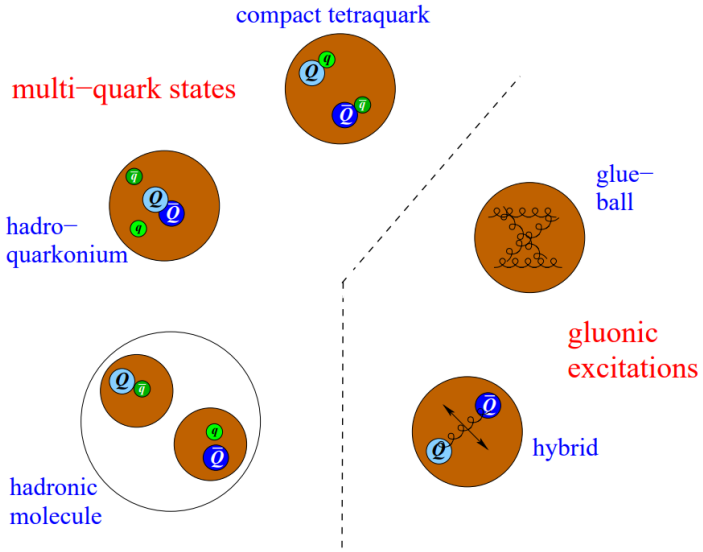
Hadron spectroscopy

- **How does QCD give rise to hadrons?**
  - **Quark model seems to work really well. Why?**
- **Key things to search for: additional degree of freedom**
  - Strong evidences for multi-quark in heavy quark sector

https://qwg.ph.nat.tum.de/exoticshub/

  - **Evidence for gluonic excitations remains sparse**



Phys.Rept. 873 (2020) 1

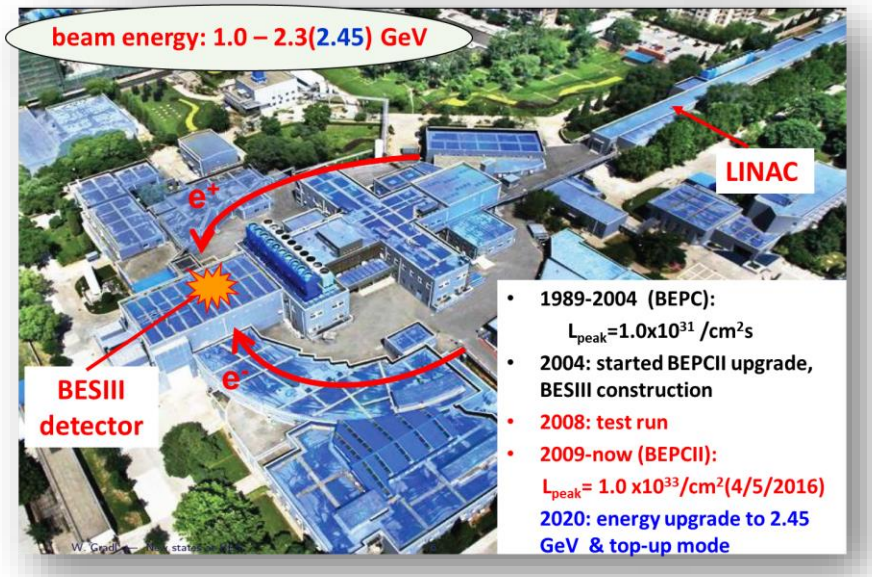
- **Role of gluons:**
  - Gluons mediate the strong force
  - **Hadron constituent: Mass? Quantum numbers? …**
  - Gluons' unique self-interacting property

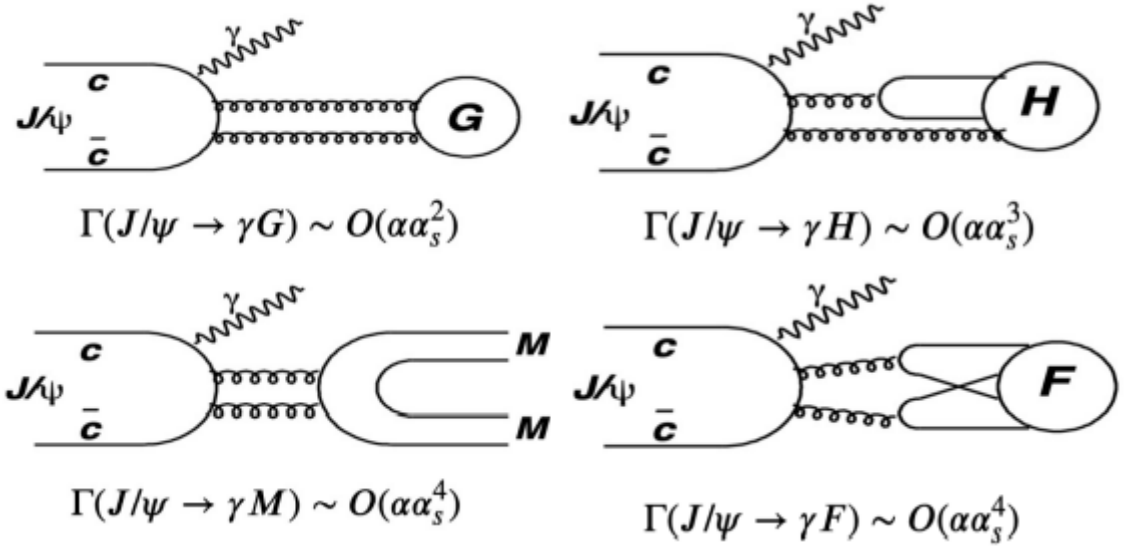
    → New form of matter: glueballs, hybrids
  - **Gluonic Excitations provide measurements of the QCD potential**

Light QCD exotics

Critical to confinement and mass dynamical generation

Beijing Electron Positron Collider (BEPCII)





Charmonium decays provide an ideal lab for light QCD exotics

- **Clean high statistics data samples**
  - **High cross sections of $e^+e^- \to J/\psi,\ \psi'$**
  - **Low background**
- **Well defined initial and final states**
  - **Kinematic constraints**
  - **$I(J^{PC})$ filter**
- **"Gluon-rich" process**

- Glueballs
- Spin-exotic states
- Threshold structures & multi-quark states

Glueballs

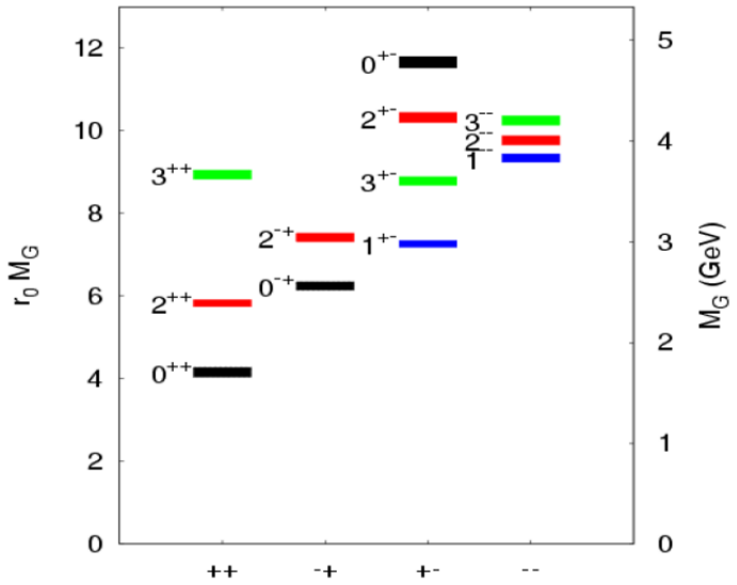
- **Low-lying glueballs with ordinary J^{PC}**

→ mixing with $q\bar{q}$ mesons

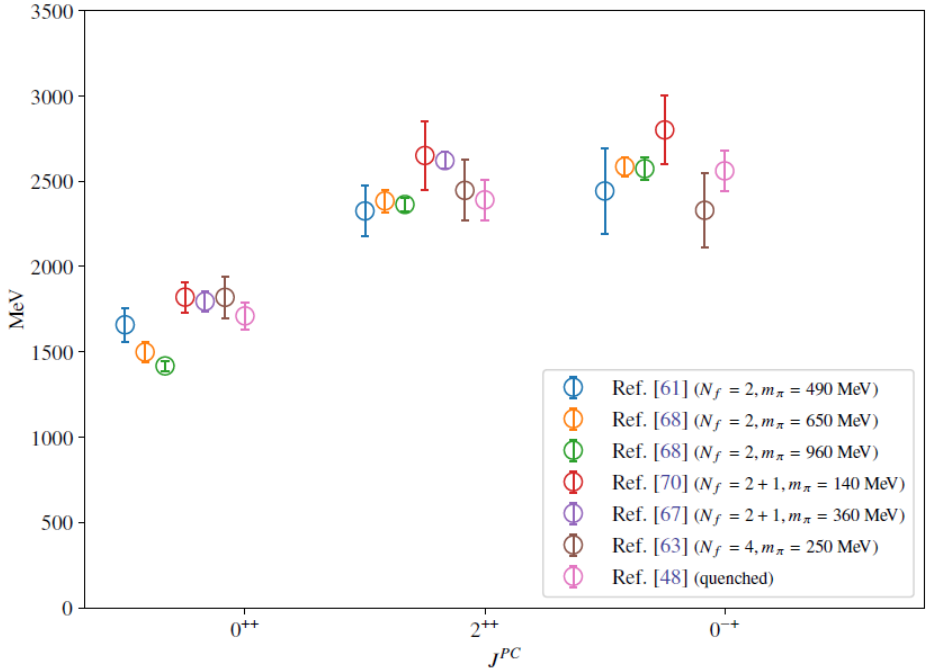
  - ~~**Observe a new peak**~~
  - Challenge: reveal the exotic admixture

- **Model-dependent predictions**
  - mass, width, partial width
- **Non-$q\bar{q}$ nature difficult to be established**
  - Supernumerary states
  - Unusual pattern of production and decay

'Cryptoexotic'



Glueballs from Lattice simulations in the pure gauge theory without quarks



What we have learned before

-- from MarkIII, BES, Crystal barrel, OBELIX, WA102, GAMS, E852, …

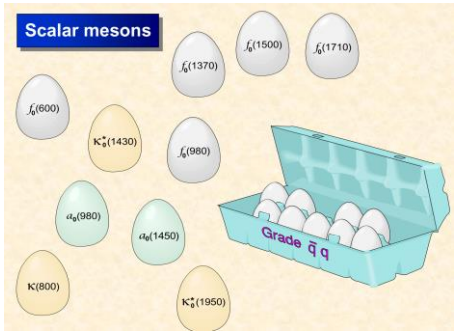
e^+e^- annihilation
$p\bar{p}$ annihilation
central exclusive production
charge-exchange reactions

Scalar: 1 nonet in quark model, f_0 & f_0'

Exp: overpopulation

LQCD : ground state 0^+ glueball ~1.7 GeV;

$$\Gamma(J/\psi \to \gamma G_{0+})/\Gamma_{total} = 3.8(9) \times 10^{-3}$$



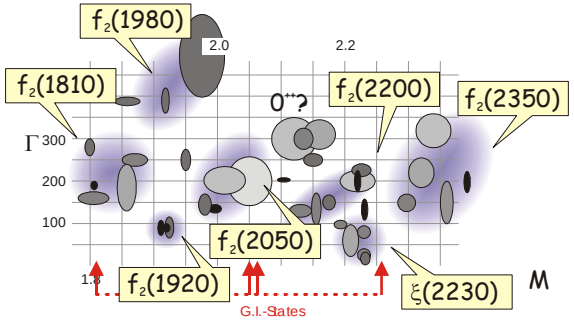
$f_0(1370)$, $f_0(1500)$, $f_0(1710)$

Tensor: 2 nonets($^3P_2$,$^3F_2$), complicated

Exp: large uncertainty

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

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

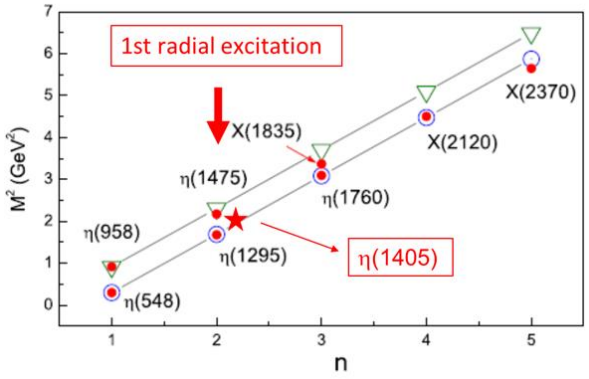


Pseudoscalar: η & η' , "simple"

Exp: lacking of info. above 2 GeV; puzzles $\eta(1295)$? $\eta(1405/1475)$?

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

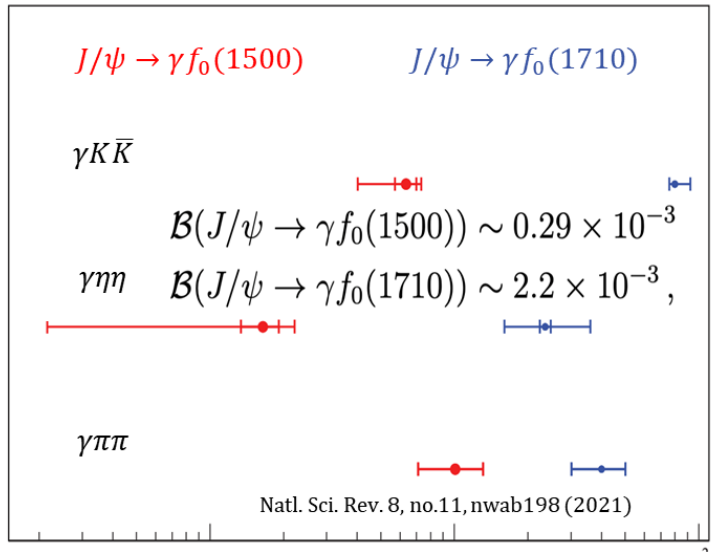
$$\Gamma(J/\psi \to \gamma G_{0-})/\Gamma_{total} = 2.31(80) \times 10^{-4}$$

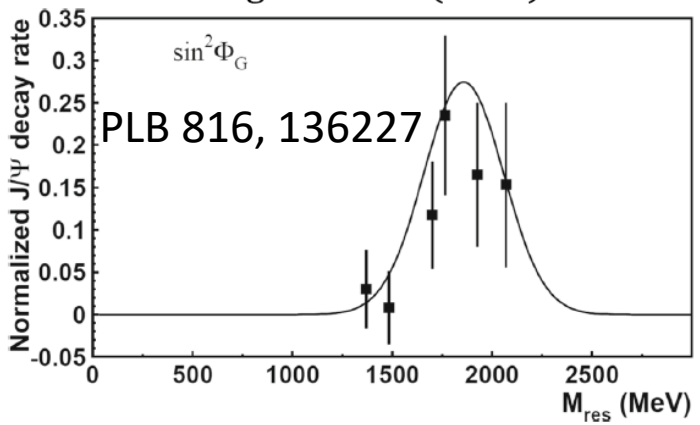


Scalar glueball candidate

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

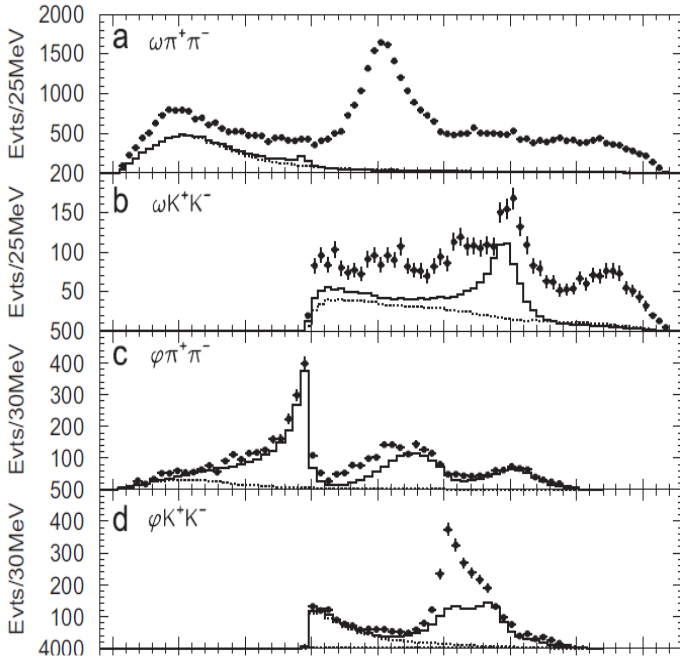
- **Scalar glueball is expected to have a large production in $\mathbf{J/\psi}$ radiative decays**:
  - LQCD: $\Gamma(\mathrm{J/\psi} \to \gamma \mathrm{G_{0+}})/\Gamma_{total} = 3.8(9) \times 10^{-3}$
  - Observed $\mathrm{B}(\mathrm{J/\psi} \to \gamma \mathrm{f_0}(1710))$ is x10 larger than $\mathrm{f_0}(1500)$
  - ➢ **BESIII: $\mathbf{f_0(1710)}$ largely overlapped with scalar glueball**
  - ➢ **Identification of scalar glueball with coupled-channel analyses based on BESIII data** [PLB 816, 136227 (2021), EPJC 82, 80 (2022), EPJC 83,1125(2023)]
- **Further more, suppression of $\boldsymbol{f_0(1710) \to \eta\eta'}$ supports $\boldsymbol{f_0(1710)}$ has a large overlap with glueball** [PRD 106 072012(2022)]





More scalars

$f_0(1710)/f_0(1790)$?



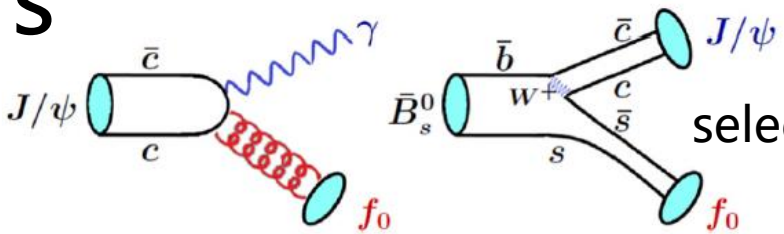
ωK^+K^- ➜ Peak around 1700 MeV/c^2
(OZI rule: $n\bar{n}$ structure)

$\phi\pi^+\pi^-$ ➜ Enhancement at 1790 MeV/c^2

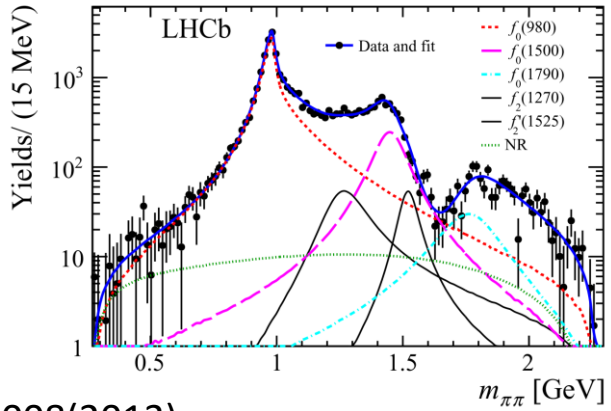
ϕK^+K^- ➜ No peak around 1700 MeV/c^2

$f_0(1800)$

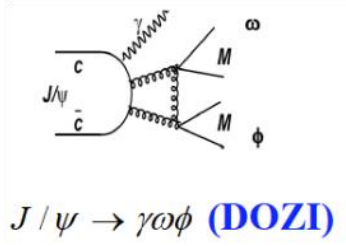
$B_s \to J/\psi f_0$ PLB 797 (2019) 134789



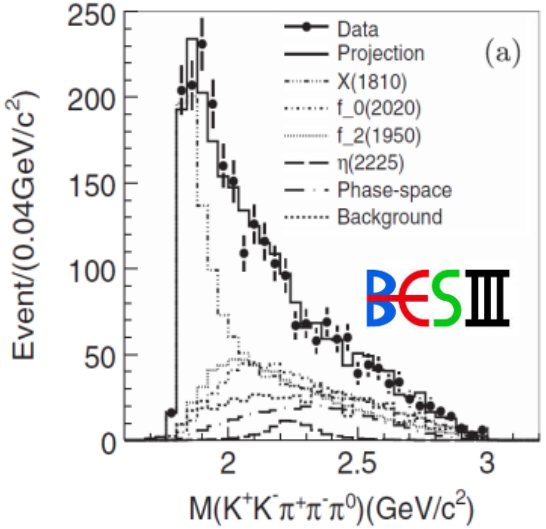
selective for $s\bar{s}$



PRD 87, 032008(2013)



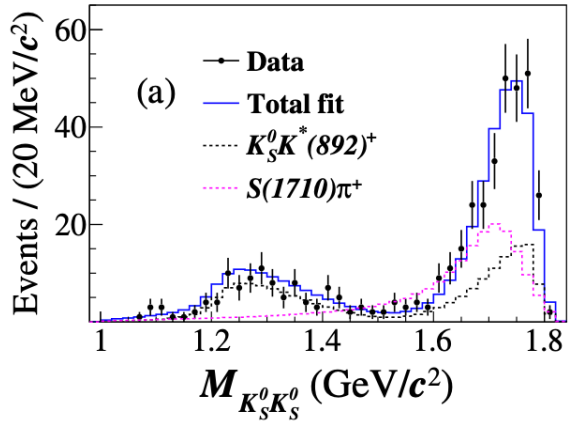
$J/\psi \to \gamma\omega\phi$ **(DOZI)**



$a_0(1817)$

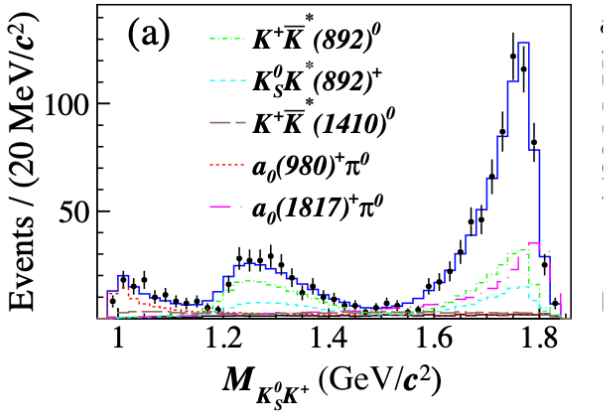
PRD105, L051103 (2022)

$D_s^+ \to K_S^0 K_S^0 \pi^+$ BESIII



PRL129, 182001 (2022)

$D_s^+ \to K^0_S K^+ \pi^0$ BESIII



Trace of tensor glueball

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

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

Experimental results

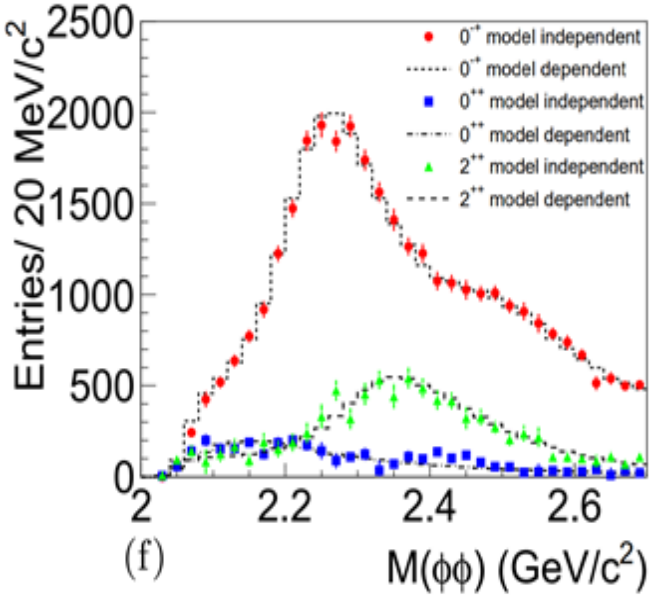
$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = \left(3.8^{+0.62+2.37}_{-0.65-2.07}\right) \times 10^{-5}}$$
BESIII PRD 87,092009 (2013)

$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = \left(1.91 \pm 0.14^{+0.72}_{-0.73}\right) \times 10^{-4}}$$
BESIII PRD 93, 112011 (2016)

$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma K_s K_s) = \left(5.54^{+0.34+3.82}_{-0.40-1.49}\right) \times 10^{-5}}$$
BESIII PRD 98,072003 (2018)

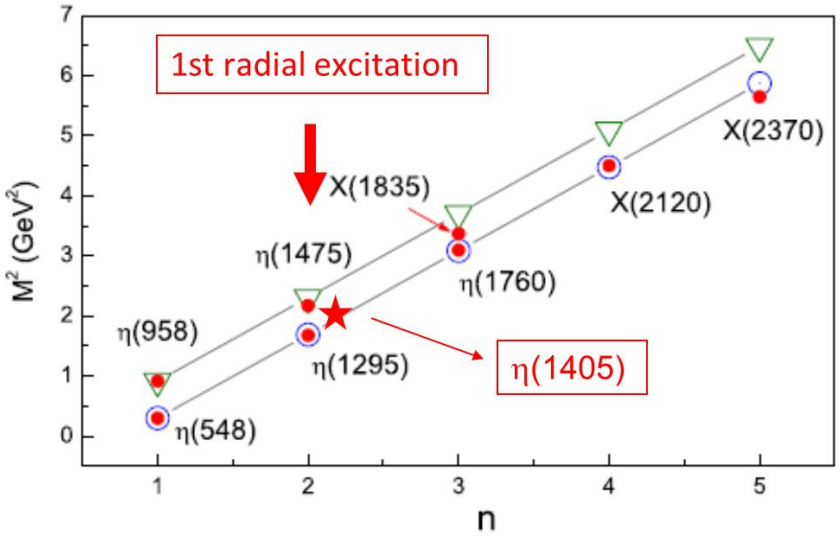
$$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta'\eta') = \left(8.67 \pm 0.70^{+0.16}_{-1.67}\right) \times 10^{-6}}$$
BESIII PRD 105,072002 (2022)

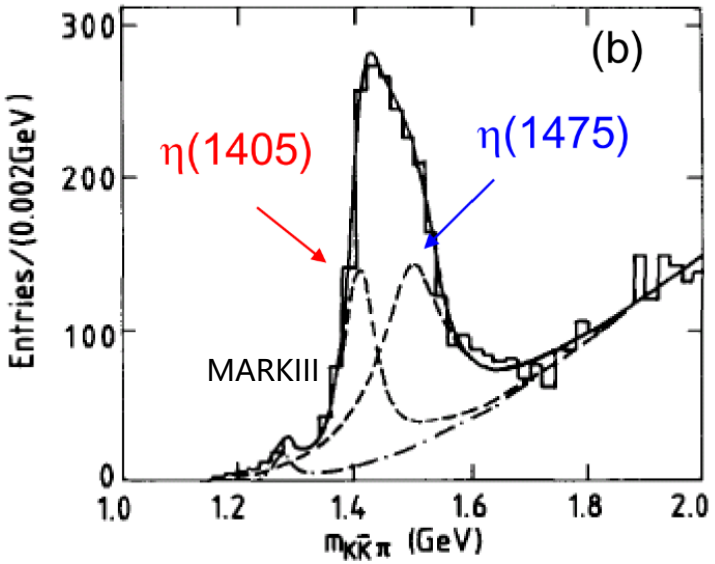
BESIII $J/\psi \to \gamma\phi\phi$ with 1.3B J/ψ



$f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ stated in π^-p reactions are observed with a strong production of $f_2(2340)$
Consist with CEP from WA102@CERN

Where is the 0^{-+} glueball





- LQCD: 0^{-+}(2.3~2.6 GeV)
- What' s the nature of the outnumbered $\eta(1405)$?

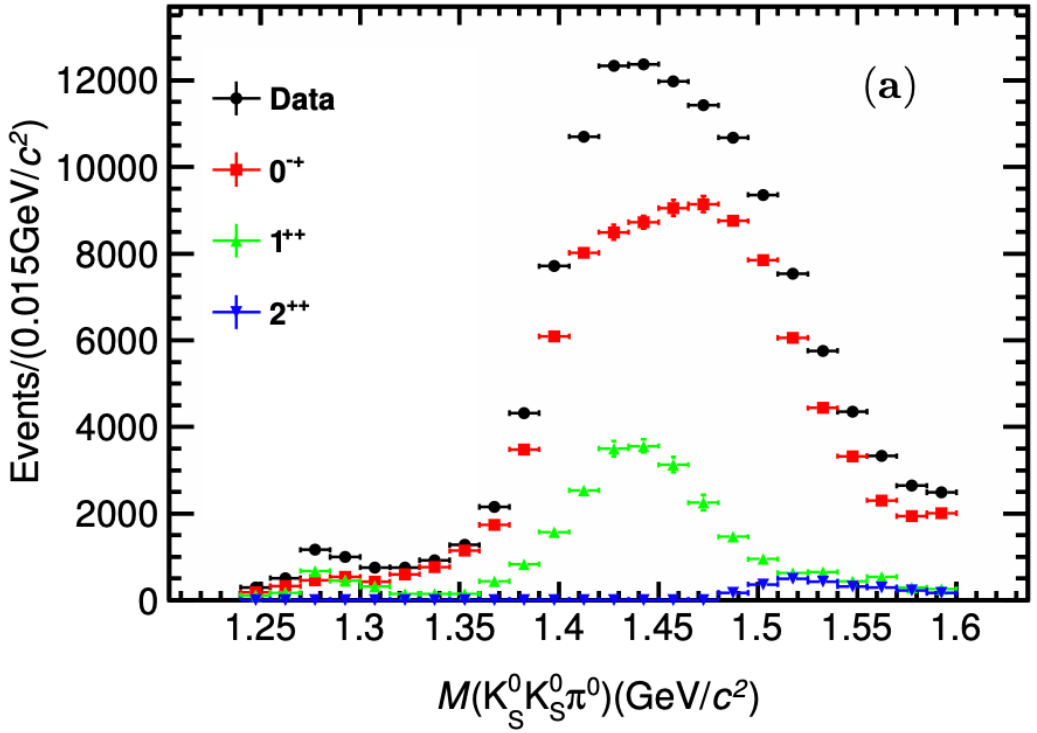
Long standing E-ι puzzle

$$M = 1416 \pm 8^{+7}_{-5}; \Gamma = 91^{+67}_{-31-38}{}^{+15}\ \mathrm{MeV}/c^2$$

$$M = 1490^{+14+3}_{-8-6}; \Gamma = 54^{+37+13}_{-21-24}\ \mathrm{MeV}/c^2$$

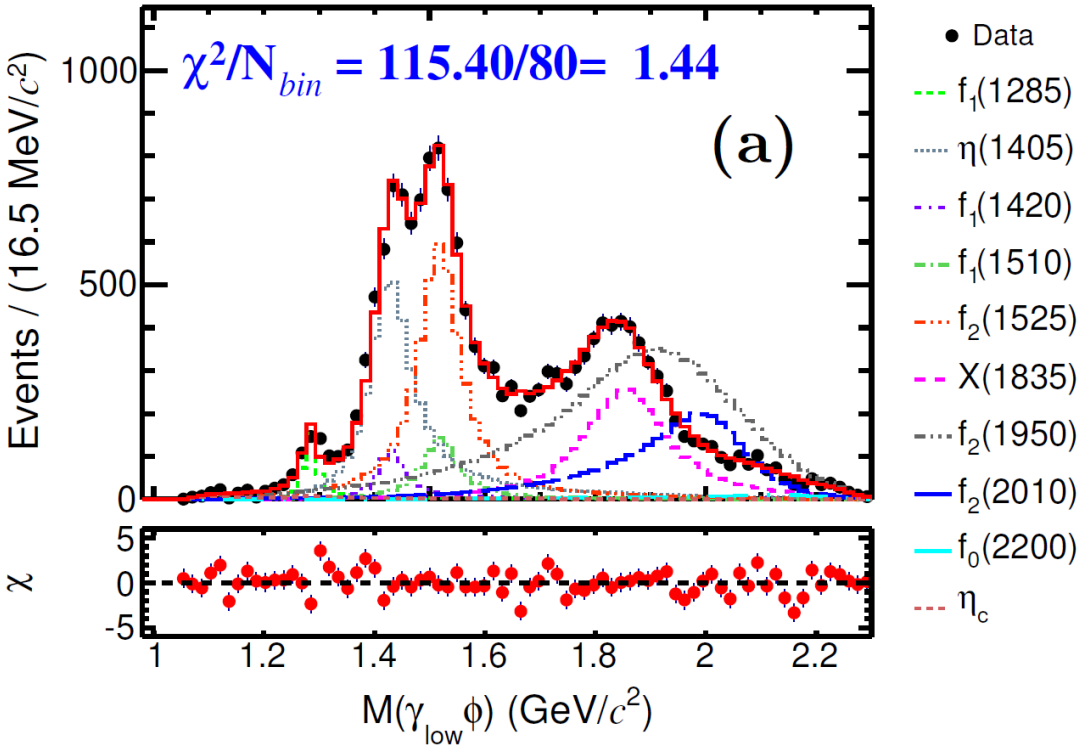
Shed new lights on the $\eta(1405)/\eta(1475)$ puzzle

$J/\psi \to \gamma K_S K_S \pi^0$ **BESIII JHEP 03 121(2023)**



- Two BWs around 1.4 GeV is needed
- $\eta(1405)/\eta(1475)$ poles in coupled-channel analysis
  - PRD 107, L091505 (2023) ; PRD 109, 014021 (2024)

$J/\psi \to \gamma\gamma\phi$ **arXiv: 2401.00918**



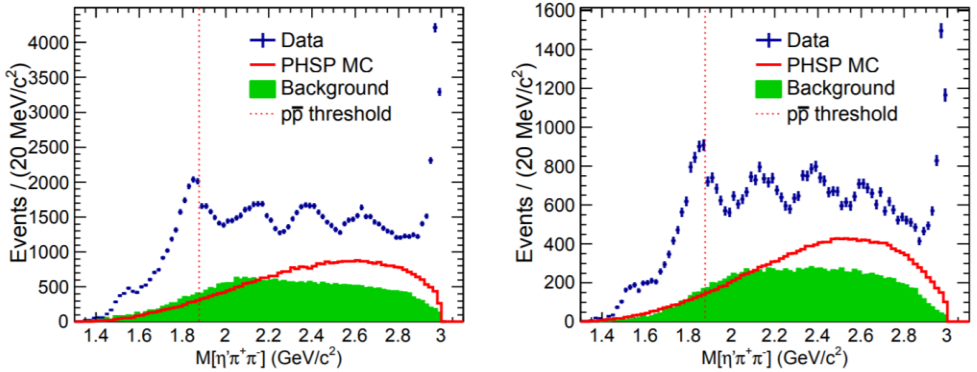
- $\eta(1405)$ is observed, while $\eta(1475)$ can not be excluded
- $X(1835) \to \gamma\phi$, $\eta_c \to \gamma\phi$ are observed

X(2370)

- **Observed in $J/\psi \to \gamma\eta'\pi\pi$ and $J/\psi \to \gamma\eta' KK$**
  - **Upper limits in $J/\psi \to \gamma\eta'\eta\eta$ and $J/\psi \to \gamma\gamma\phi$ (not inconsistent with glueball)**
- **Mass consistent with LQCD prediction for 0^{-+} glueball**

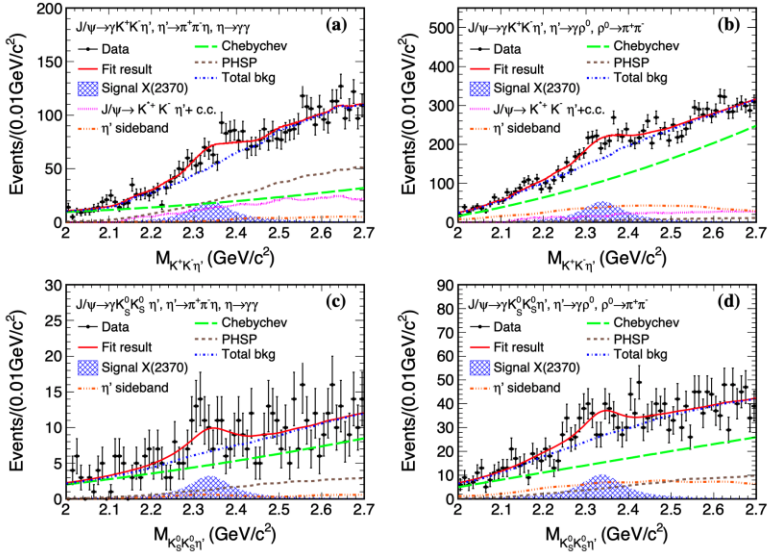
- **Spin-parity determined to be 0^{-+}**

$J/\psi \to \gamma\eta'\pi\pi$ PRL 106, 072002, PRL 117, 042002

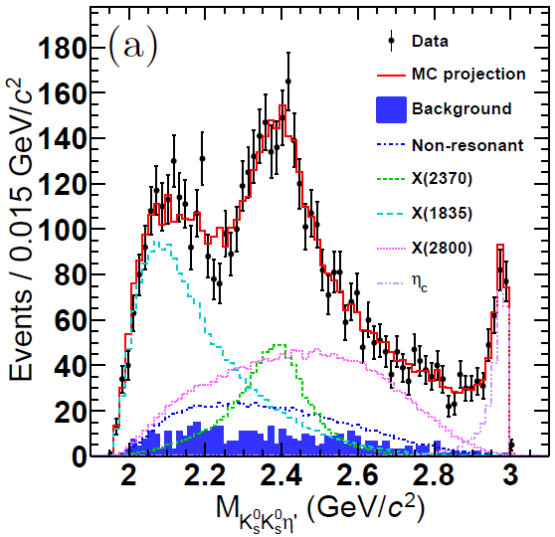


$J/\psi \to \gamma\eta' KK$

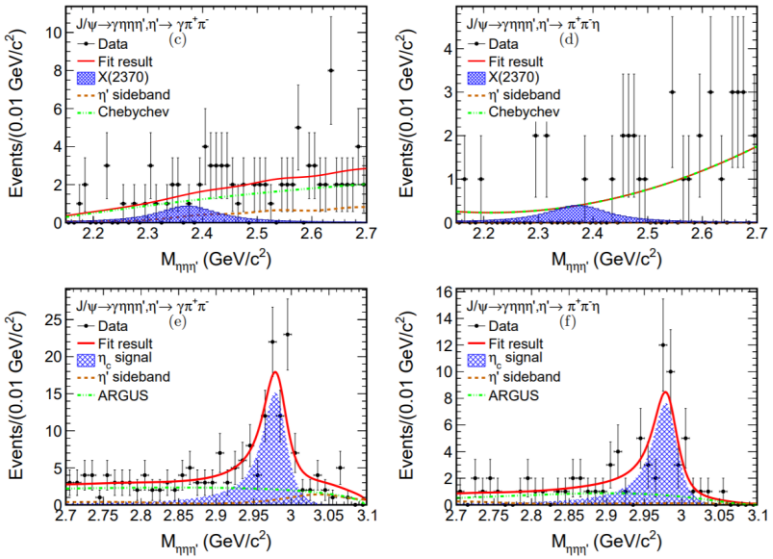
EPJC 80 746(2020)



arXiv:2312.05324



$J/\psi \to \gamma\eta'\eta\eta$ PRD 103 012009 (2021)



Landscape of glueballs has been updated with BESIII' s inputs

Scalar: 1 nonet in quark model, f_0 & f_0'

Exp: overpopulation

LQCD : ground state 0^+ glueball ~1.7 GeV;

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Pseudoscalar: η & η' , "simple"

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

$$\Gamma(J/\psi \to \gamma G_{0-})/\Gamma_{total} = 2.31(80) \times 10^{-4}$$

✓**Large production rate of $f_0(1710)$ in J/ψ radiative decays**

✓**Large production rate of $f_2(2340)$ in J/ψ radiative decays**

✓**Non-observation of $\eta(1295)$**

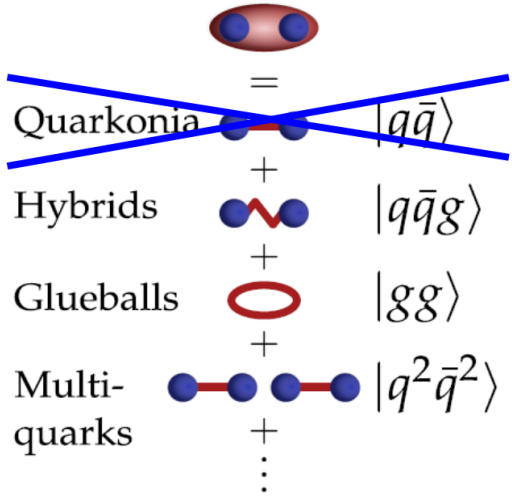
✓**$\eta(1405/1475)$ one state?➔ manifestations of TS**

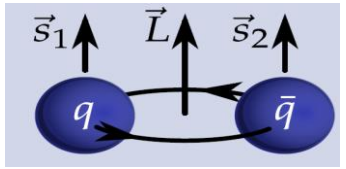
✓**$X(2370)$ → various decay modes**

- Glueballs
- Spin-exotic states
- Threshold structures & multi-quark states

Light hadrons with exotic quantum numbers

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

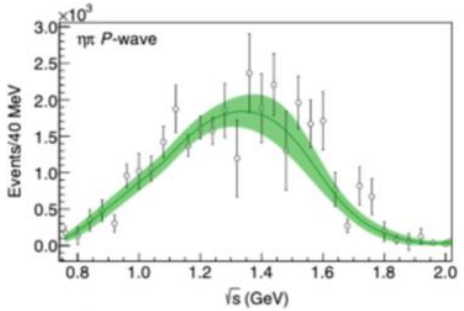


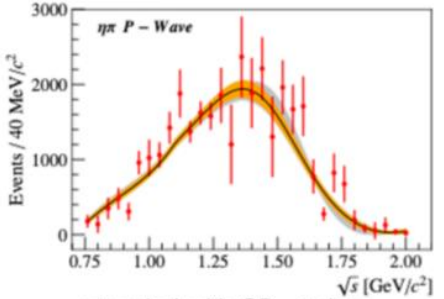


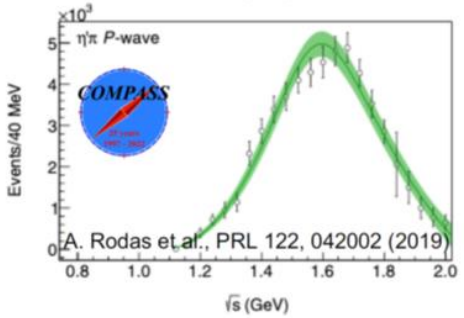
$\vec{J} = \vec{L} + \vec{S}$ $P = (-1)^{L+1}$ $C = (-1)^{L+S}$

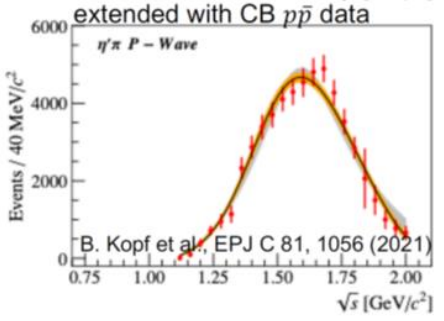
Allowed J^{PC}: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$

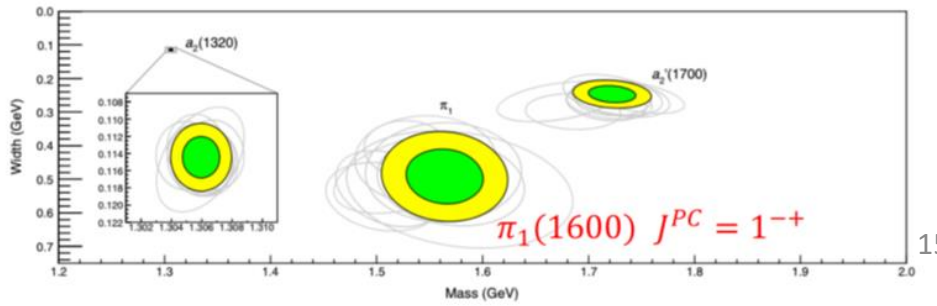
- **Only 3 candidates so far: All 1^{-+} isovectors**
  - $\pi_1(1400)$: seen in $\eta\pi$
  - $\pi_1(1600)$: seen in $\rho\pi$, $\eta'\pi$, $b_1\pi$, $f_1\pi$
  - $\pi_1(2015)$ (needs confirmation): seen in $b_1\pi$, and $f_1\pi$
- $\pi_1(1400)$ & $\pi_1(1600)$ can be explained as one pole, according to recent analyses



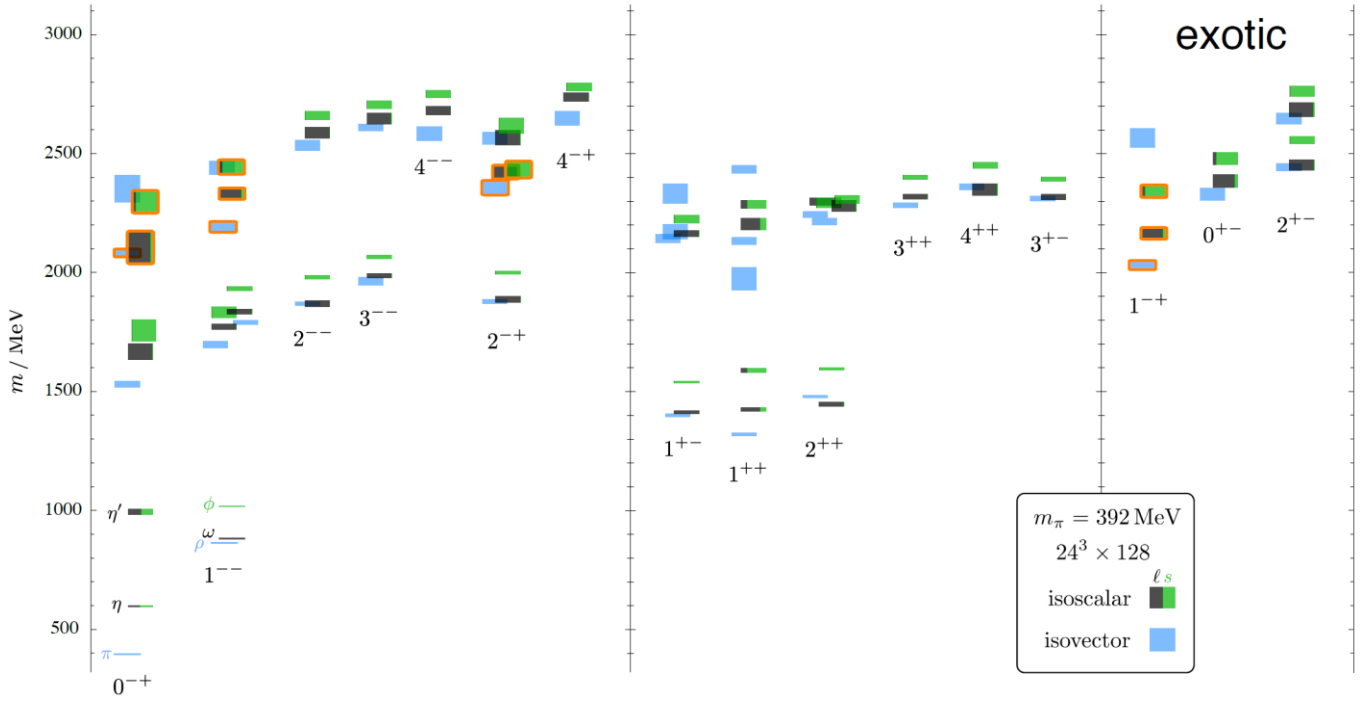






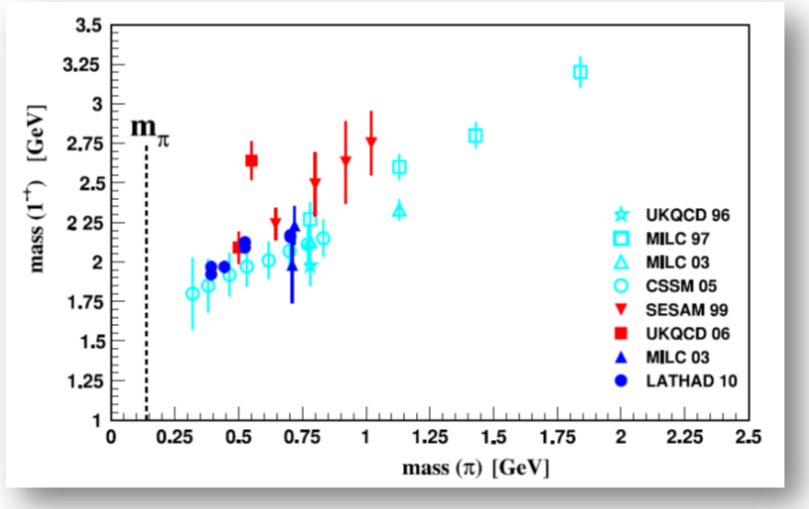


Hybrid from LQCD

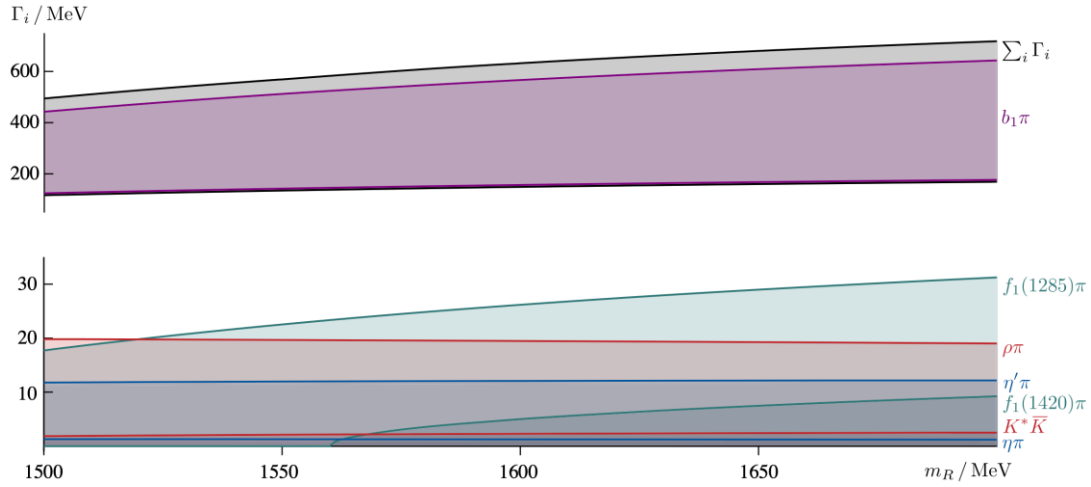


PRD 88 094505(2013)

Lightest spin-exotic state: $\mathbf{1^{-+}}$



Mass of $\mathbf{1^{-+}}$ hybrid

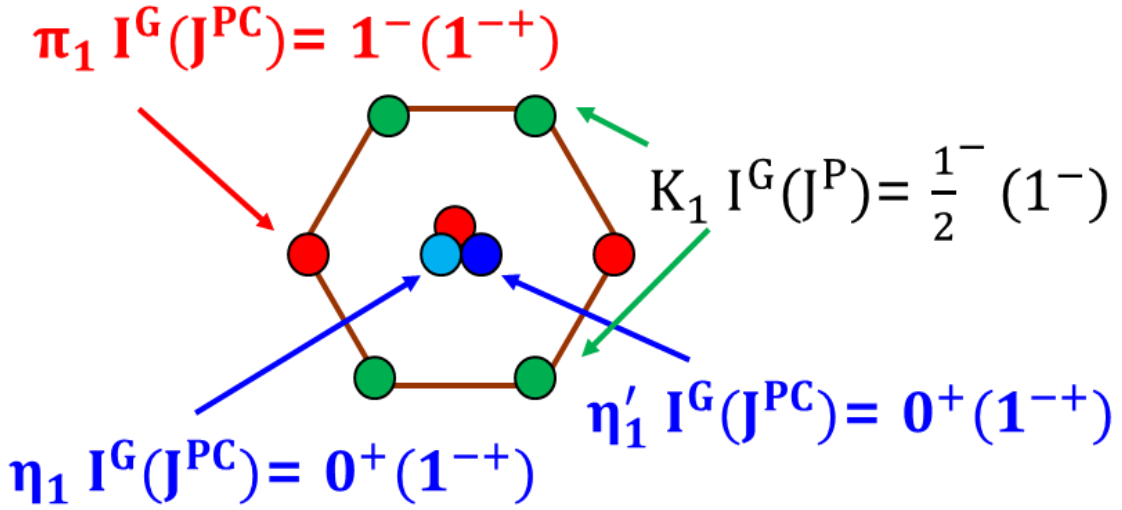


PRD 103, 054502(2021)

Decay width of $\mathbf{1^{-+}}$ hybrid π_1

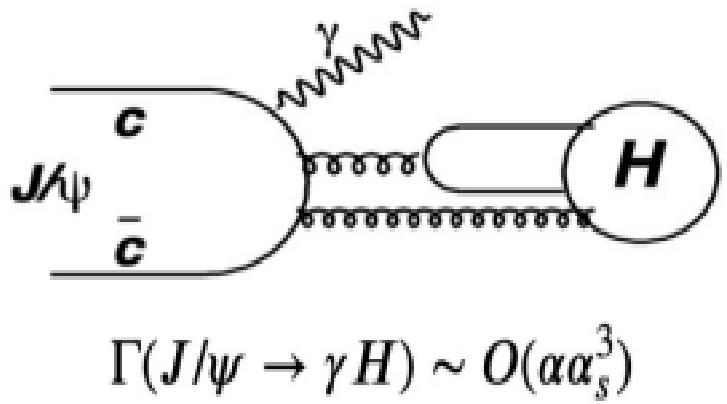
1^{-+} Hybrids

- **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 An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$

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

- **An isoscalar 1^{-+} , $\eta_1(1855)$, has been observed in $J/\psi \to \gamma\eta\eta'$ (>19σ)**

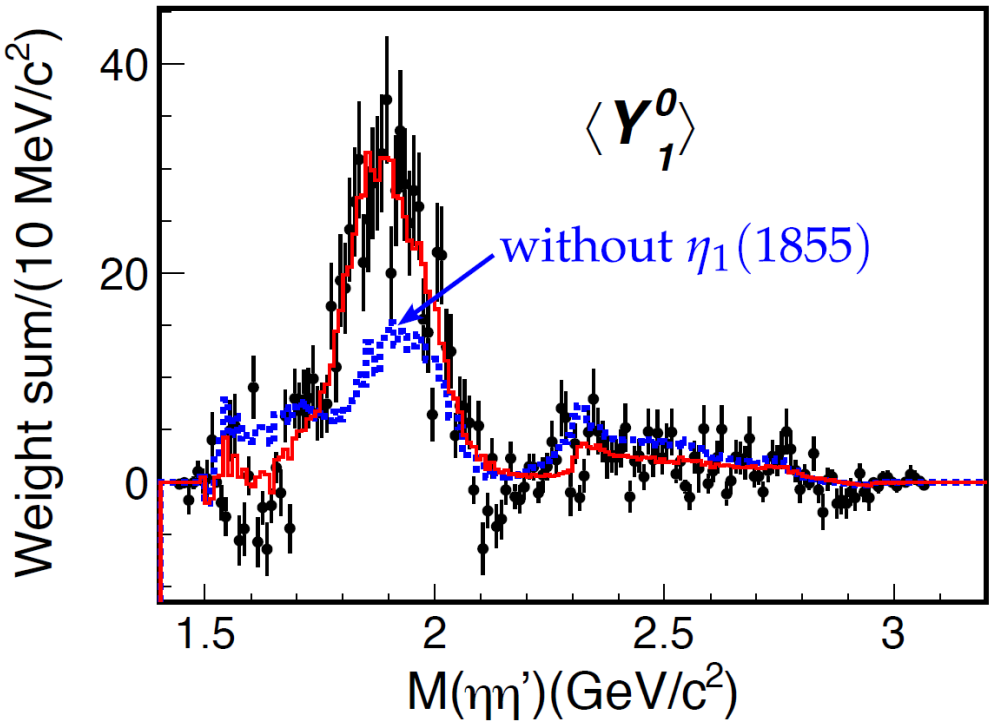
  $M = (1855 \pm 9^{+6}_{-1})\ \mathrm{MeV/c^2}, \Gamma = (188 \pm 18^{+3}_{-8})\ \mathrm{MeV/c^2}$

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

  - **Mass consistent with hybrid on LQCD**

- **Inspired many interpretations:**
  Hybrid/$K\bar{K}_1$ Molecule/Tetraquark?

- **LQCD:** $B(J/\psi \to \gamma\eta_1(\mathrm{hybrid})) \sim O(10^{-5})$ [PRD 107 054511]



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

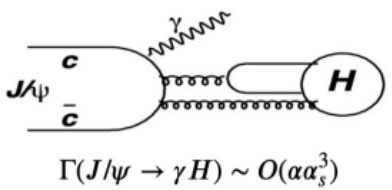
"Here, the result by the BESIII experiment of a possible observation of an $\eta_1(1855)$ state could be a breakthrough."

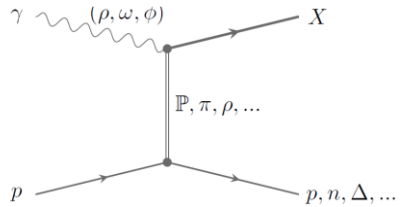
—— *50 years of QCD: Exotic mesons*

Prospects of spin-exotics at BESIII

Uniqueness, enrichment and complementary

- **High statistics gluon-rich environment: 10 B J/ψ, 2.7 B ψ', a lot of χ_{cJ}**
- Snowmass2021: RF7 Summary, 4 whitepapers
  - **Significant impact to GlueX @JLab**



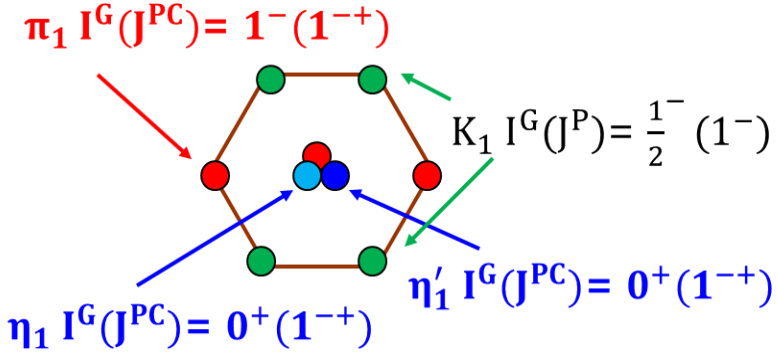


Isoscalar: $\eta_1(1855)$

- **Decay properties**
  - $J/\psi \to \gamma + \pi a_1, \eta f_1, K_1\bar{K}$, ……
- **Production properties**
  - $J/\psi \to \omega\eta\eta'$, $\phi\eta\eta'$, ……
  - $\chi_{c1} \to \eta + \eta\eta'$, ……
- **Where is $\eta_1^{(\prime)}$**
  - **Other partners: 2^{+-} , ……**
  - **Analog in $\bar{c}c$**

Isovector: $\pi_1(1600)$

- $J/\psi \to \rho\eta'\pi$, ……
- $\chi_{c1} \to \pi + \pi b_1, \pi f_1$, $\pi\eta'$, ……
  - LQCD predicted major decay modes: πb_1 , πf_1



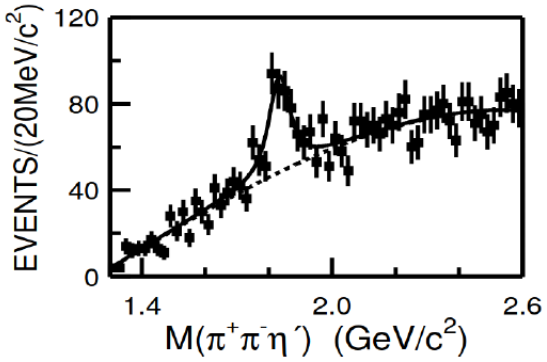
- Glueballs
- Spin-exotic states
- Threshold structures & multi-quark states

Power of statistics

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

58 M J/ψ

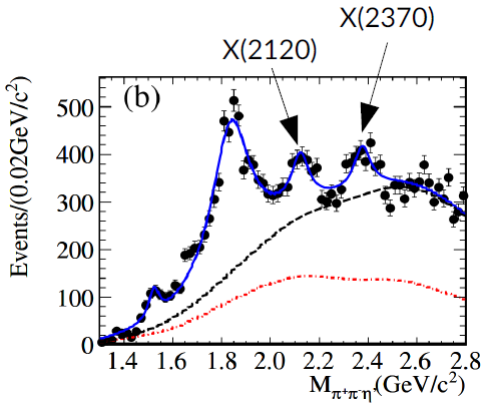
PRL 95 262001(2005)



Observation of X(1835)

225M J/ψ

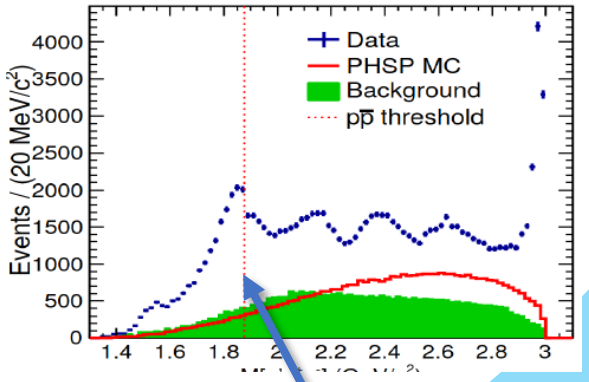
PRL 106 072002(2011)



Observation of X(2120), X(2370)

1.3B J/ψ

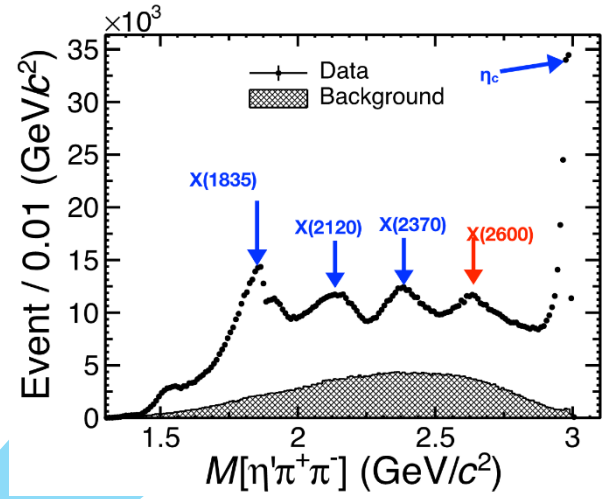
PRL 117 042002(2016)



Observation of anomalous line shape

10B J/ψ

PRL 129, 042001 (2022)

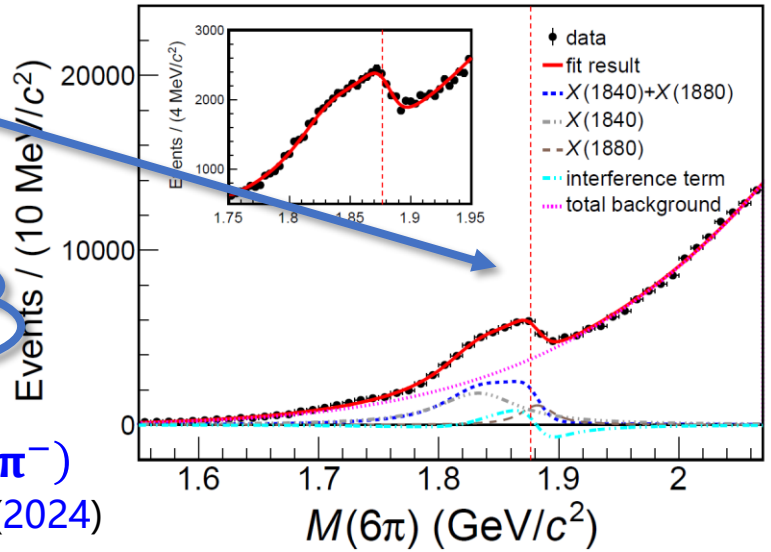


Observation of X(2600)

Indicating a ppbar bound state

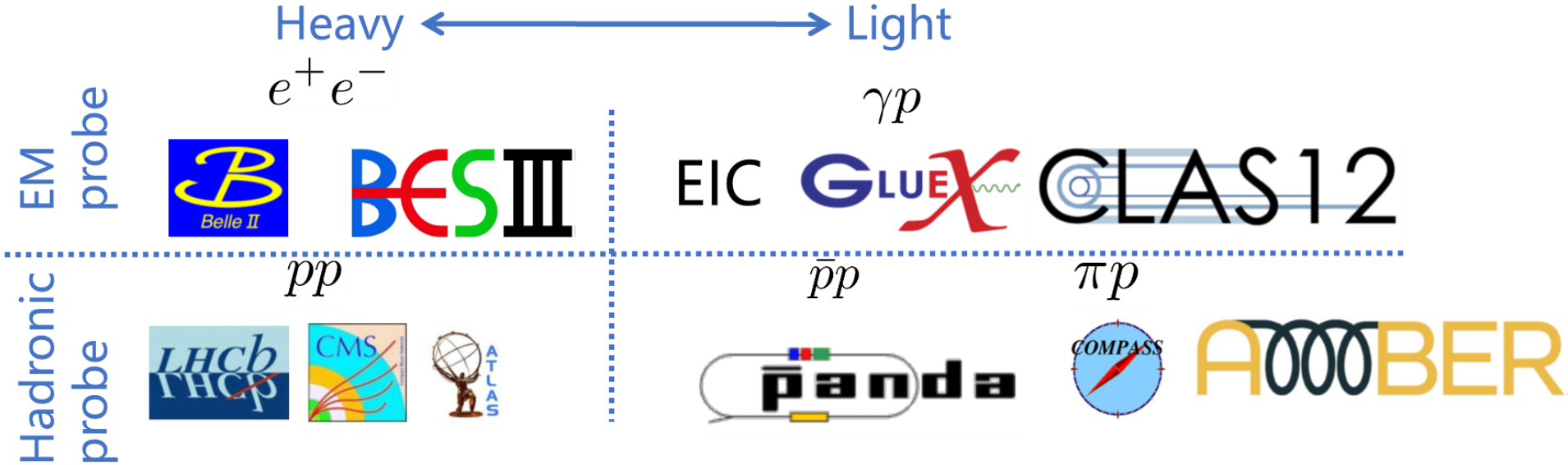
$J/\psi \to \gamma 3(\pi^+\pi^-)$

PRL 132,151904 (2024)



Synergies in new era of precision spectroscopy

- Discoveries of new states → spectral properties and patterns
  - Various probes from both heavy and light sectors



- Close collaboration of experiment-theory are needed

Thank you for your attention