# Highlights of hadron physics@ BESIII

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(on behalf of BESIII)

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# Hadrons

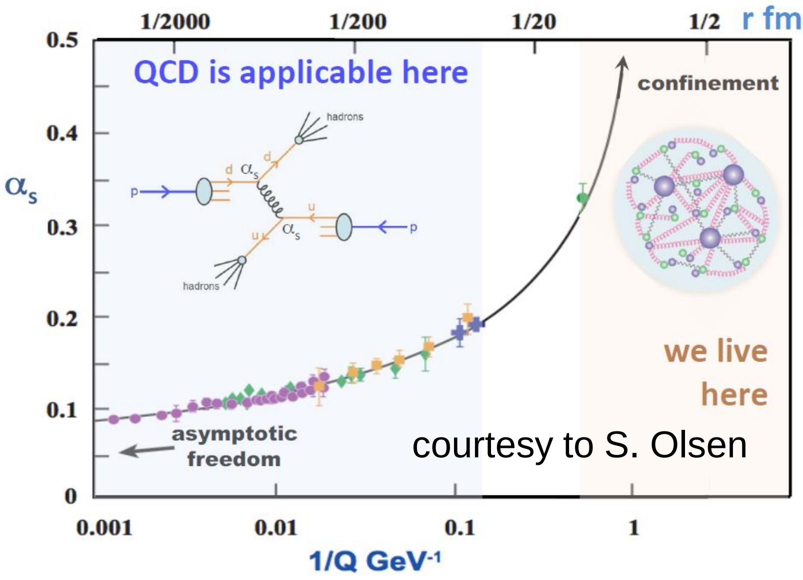
- **Dominant part of visible matter in the universe**
- **To fully understand the strong interaction**
  - **Understanding the rich and complex features of its bound states, hadrons**

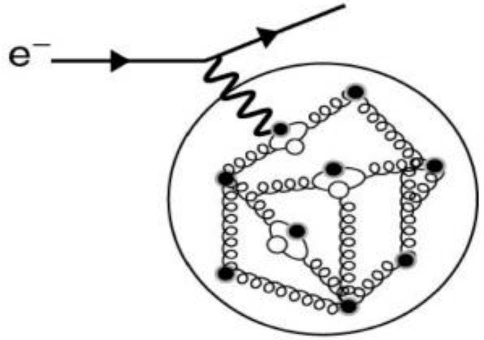
➢How are hadrons formed from quarks and gluons?

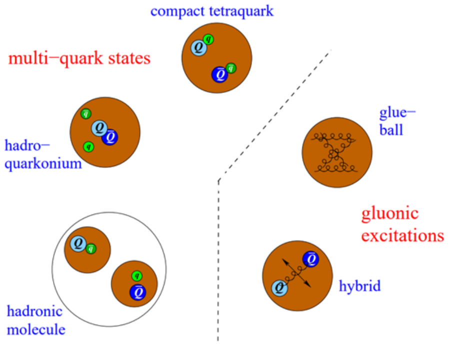
➢What is the origin of confinement?

➢How is the mass of hadron generated in QCD?

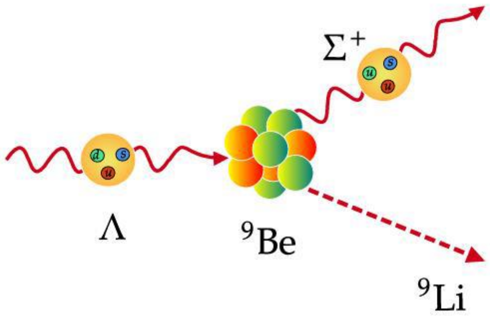
➢What is the dynamics of effective DoF in hadrons?






Phys.Rept. 873 (2020) 1



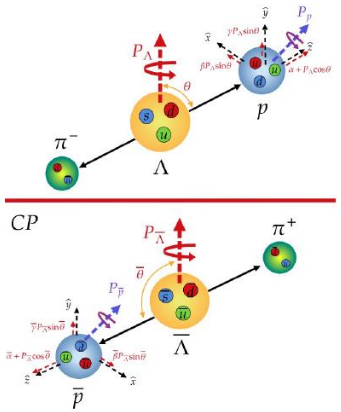

**Structure**

**Spectroscopy**

**Interactions**

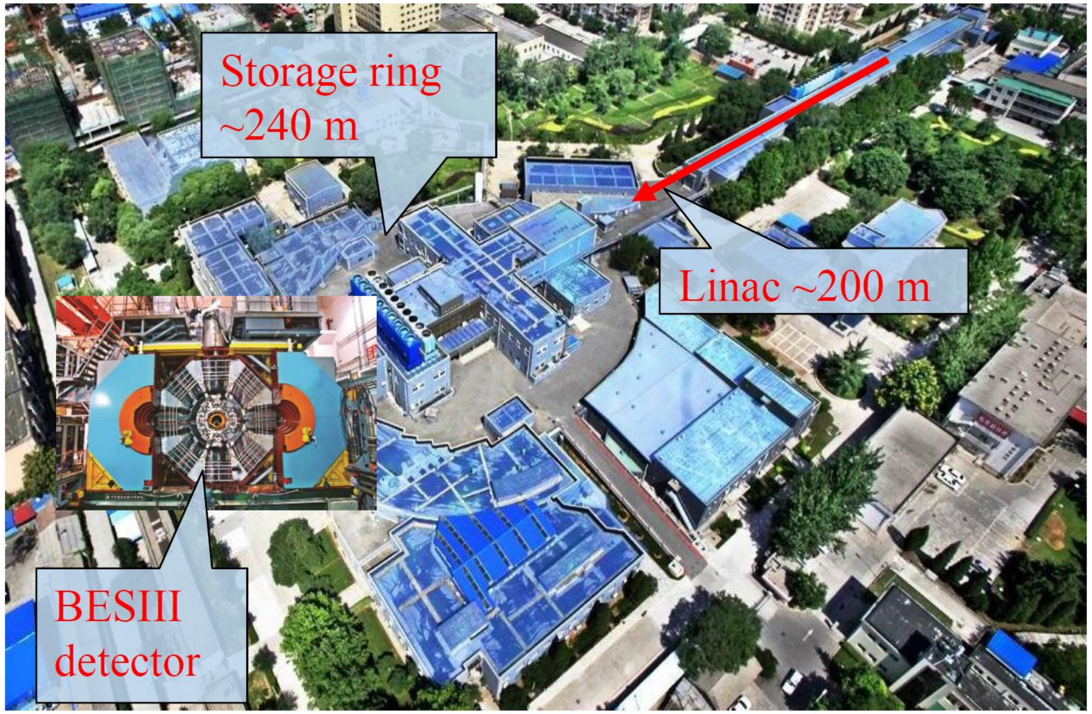
**Hadron physics**

**Precision tests & rare phenomena**



# BESIII@BECPII

**Beijing Electron Positron Collider(BEPCII)**



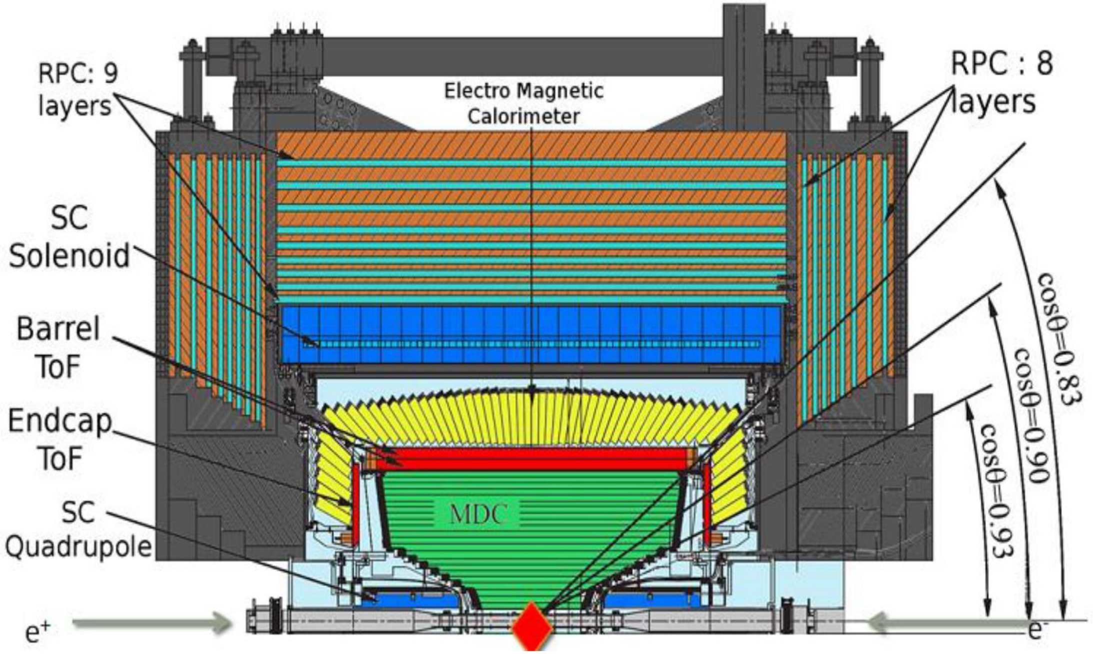

Double-ring, symmetry, multi-bunch $e^+ e^-$ collider

$E_{cm}$= 1.84 to 4.95 GeV

Energy spread: $\Delta E \approx 5 \times 10^{-4}$

Peak luminosity in continuously operation @$E_{cm}$= 3.77 GeV: $1.1 \times 10^{33}$ $cm^{-2}s^{-1}$

**Beijing Spectrometer(BESIII)**




**Main Drift Chamber**
Small cell, 43 layer
$\sigma_{xy}$=130 $\mu$m
dE/dx~6%
$\sigma_p/p$= 0.5% at 1 GeV

**Time Of Flight**
Plastic scintillator
$\sigma_T$(barrel): 65 ps
$\sigma_T$(endcap): 110 ps
(update to 60 ps with MRPC)

**Electromagnetic Calorimeter**
CsI(Tl): L=28 cm
Barrel $\sigma_E$=2.5%
Endcap $\sigma_E$=5.0%

**Muon Counter**
RPC
Barrel: 9 layers
Endcap: 8 layers
$\sigma_{spatial}$: 1.48 cm

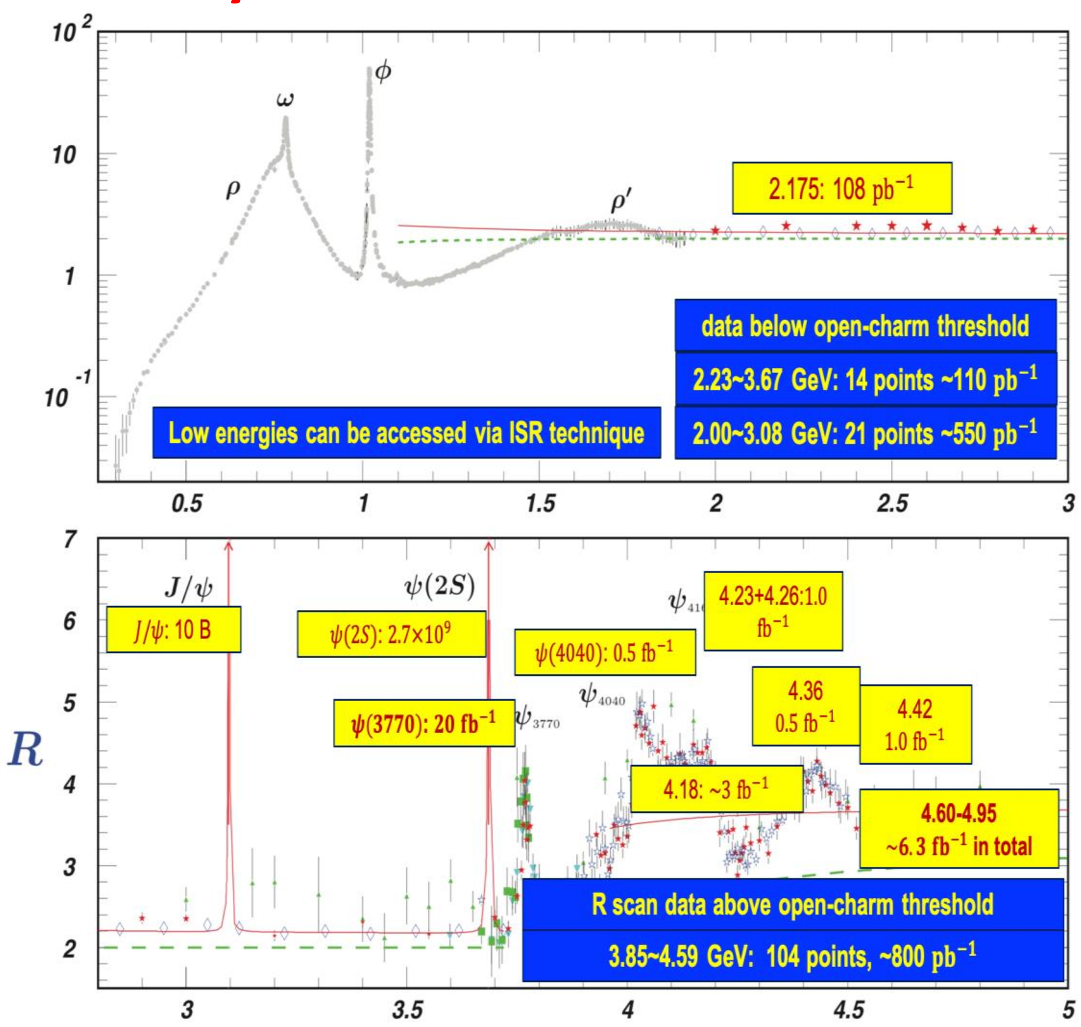
**BESIII collaboration: ~600members from 17countries，89 institutions**

# World' s largest $\tau - \mathrm{charm}$ data sets in $e^+e^-$ annihilation

**Totally about 50 fb$^{-1}$ from 2.0-4.95 GeV**

Data sets collected so far include

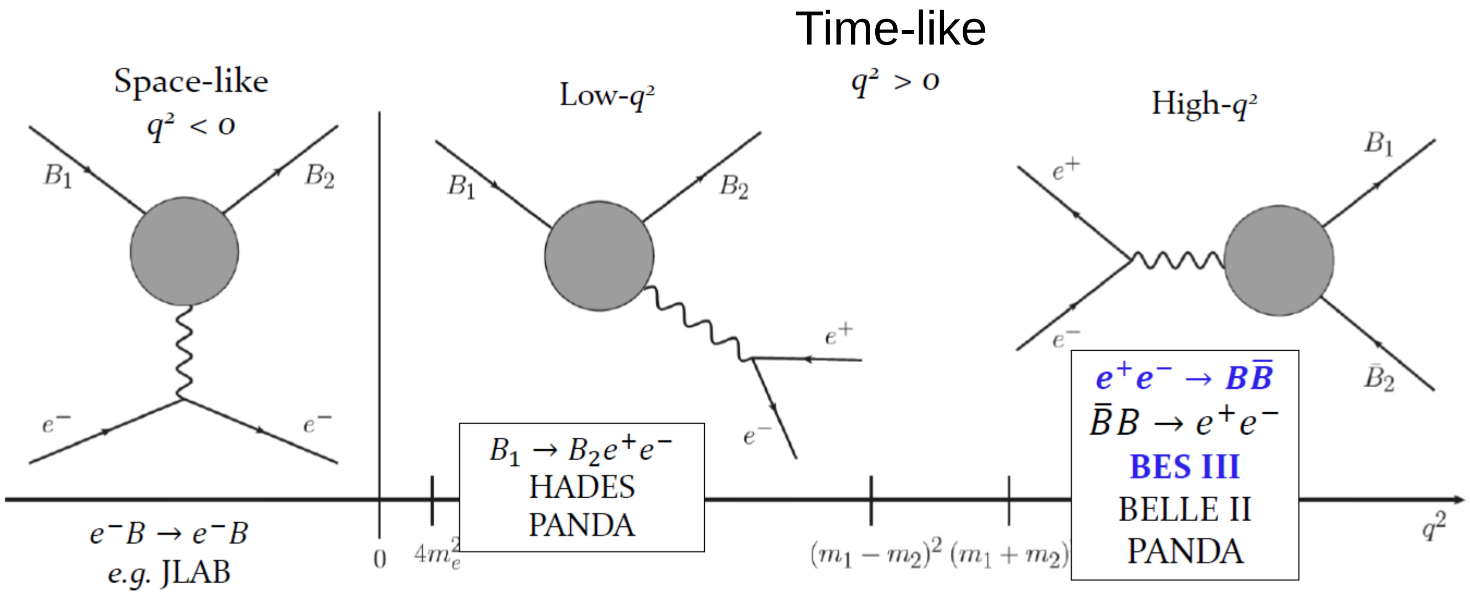
- **$10 \times 10^9$ J/ψ events**
- **$2.7 \times 10^9$ ψ(2S) events**
- **20 fb$^{-1}$ ψ(3770)**
- Scan data [1.84, 3.08] GeV; [3.735, 4.600]GeV, 143 energy points, ~2.0 fb$^{-1}$
- Large data sets for XYZ study ~22 fb$^{-1}$
- Entangled hadron pair-productions near thresholds




## Rich physics program:

Spectroscopy & decays of light hadrons and charmonium, charm physics, precision measurements of QCD parameters, tests of fundamental symmetry, ……

Electromagnetic Form Factors (EMFFs)




# Hadron structure with BESIII

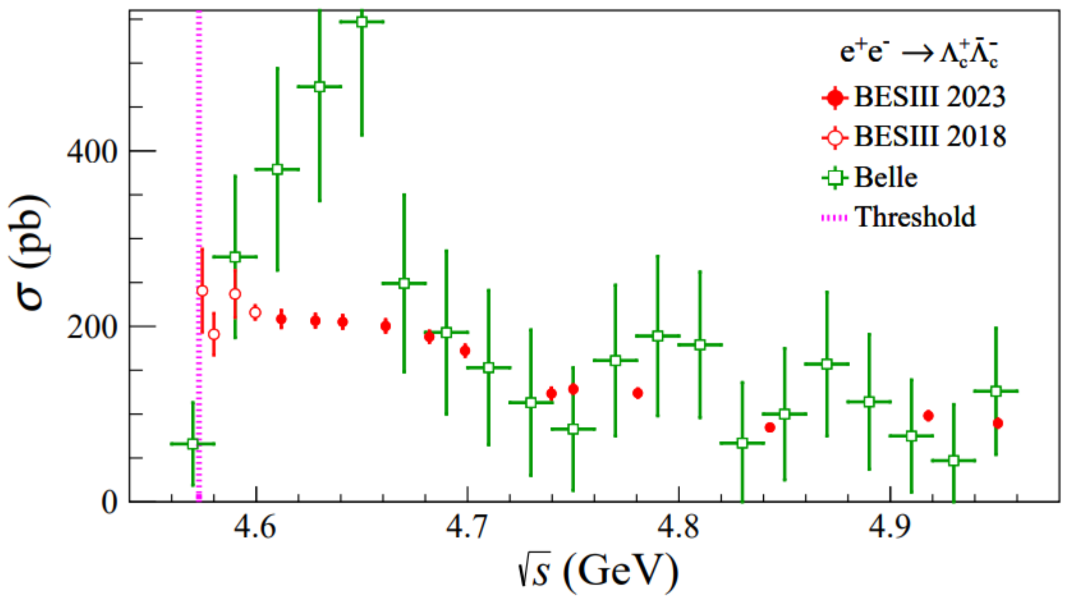
# $e^+e^- \rightarrow \Lambda_c^+\overline{\Lambda_c^-}$

BESIII PRL 131, 191901 (2023)

Energy scans from 4.61 to 4.95 GeV

- Sharp rise in cross section near threshold
- Disagreement with Belle data near 4.6 GeV

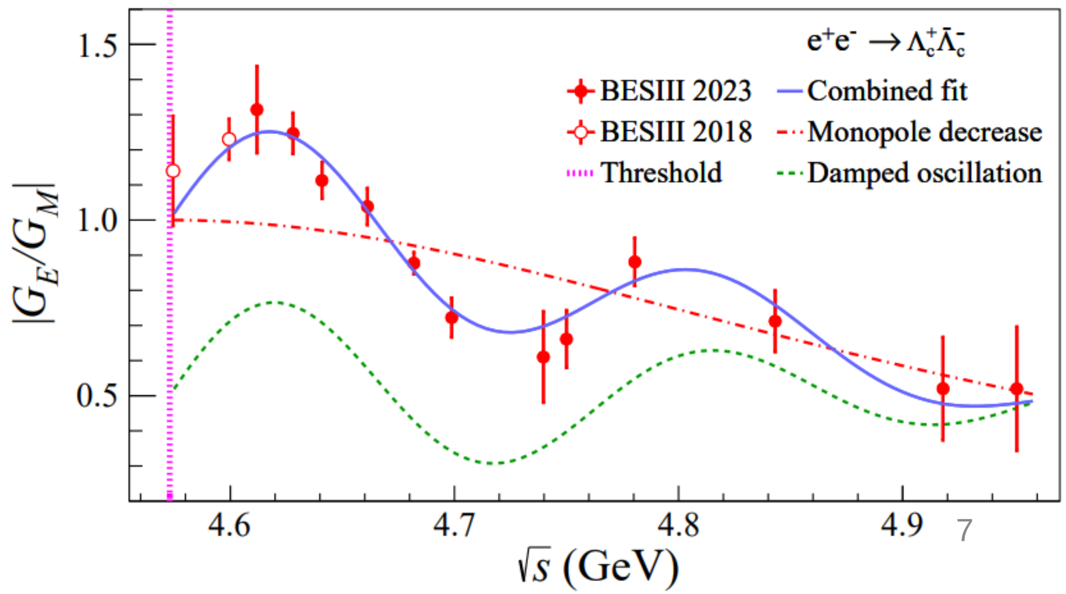
- In contrast to the case for the proton and neutron, No discernible oscillations of the effective form factors $G_{eff}$




With the polar-angle distribution of $\Lambda_c^+$

- $|G_E|$ and $|G_M|$ are extracted
- Energy dependence of $R = |\frac{G_E}{G_M}|$:

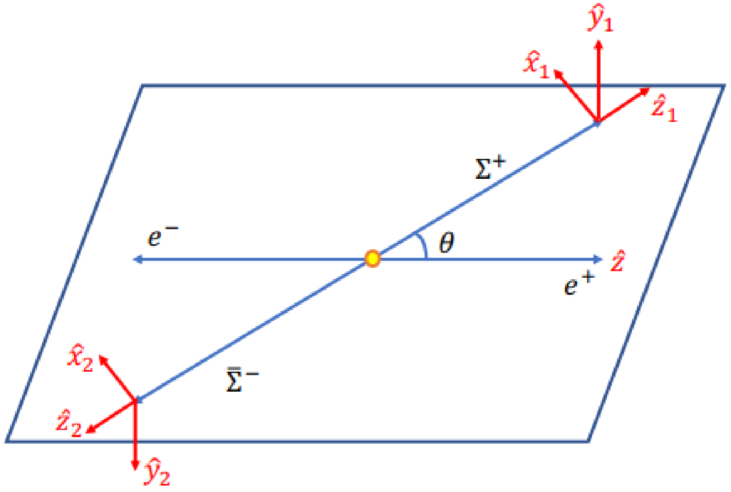
→Damped oscillations with frequency ~3.5 times larger than for the proton



# Complete decomposition of $\Sigma^+$ EMFFs

- Using a fully differential angular description of the final state particles $e^+e^- \rightarrow \Sigma^+(\rightarrow p\pi^0)\bar{\Sigma}^-(\rightarrow \bar{p}\pi^0)$, the relative magnitude and phase of $\Sigma^+$ EMFFs can be extracted:

$$\mathcal{W}(\xi) \propto \mathcal{F}_0(\xi) + \alpha\mathcal{F}_5(\xi) \quad \text{Unpolarized part}$$
$$+ \alpha_1\alpha_2(\mathcal{F}_1(\xi) + \sqrt{1-\alpha^2}\cos(\Delta\Phi)\mathcal{F}_2(\xi) + \alpha\mathcal{F}_6(\xi)) \quad \text{Correlated part}$$
$$+ \sqrt{1-\alpha^2}\sin(\Delta\Phi)(-\alpha_1\mathcal{F}_3(\xi) + \alpha_2\mathcal{F}_4(\xi)), \quad \text{Polarized part}$$




$$\mathcal{F}_0(\xi) = 1$$
$$\mathcal{F}_1(\xi) = \sin^2\theta\sin\theta_1\sin\theta_2\cos\phi_1\cos\phi_2 - \cos^2\theta\cos\theta_1\cos\theta_2$$
$$\mathcal{F}_2(\xi) = \sin\theta\cos\theta(\sin\theta_1\cos\theta_2\cos\phi_1 - \cos\theta_1\sin\theta_2\cos\phi_2)$$
$$\mathcal{F}_3(\xi) = \sin\theta\cos\theta\sin\theta_1\sin\phi_1$$
$$\mathcal{F}_4(\xi) = \sin\theta\cos\theta\sin\theta_2\sin\phi_2$$
$$\mathcal{F}_5(\xi) = \cos^2\theta$$
$$\mathcal{F}_6(\xi) = \sin^2\theta\sin\theta_1\sin\theta_2\sin\phi_1\sin\phi_2 - \cos\theta_1\cos\theta_2.$$

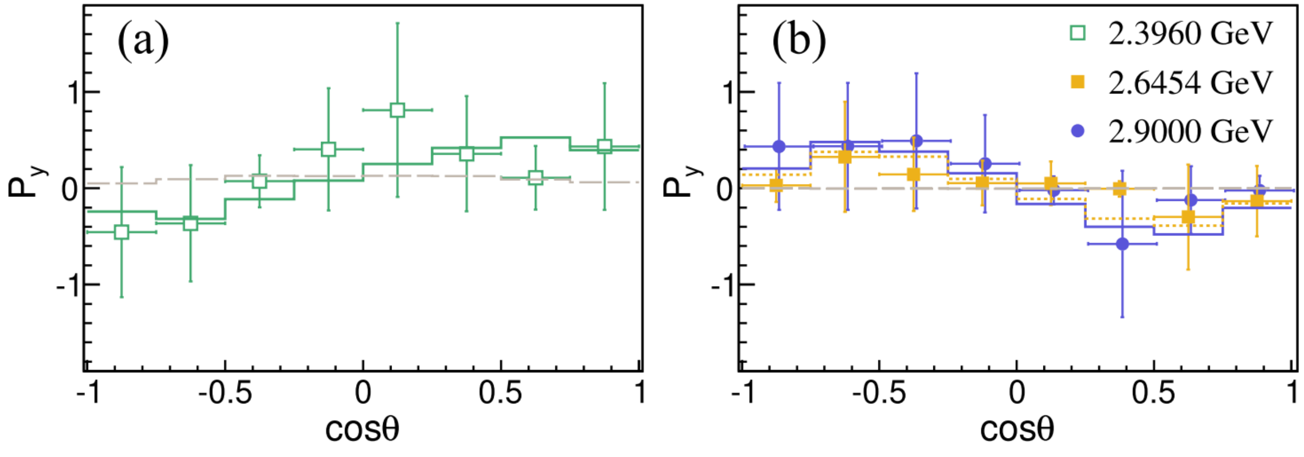
- A nonzero relative phase leads to polarization $P_y$ of the out going baryons:

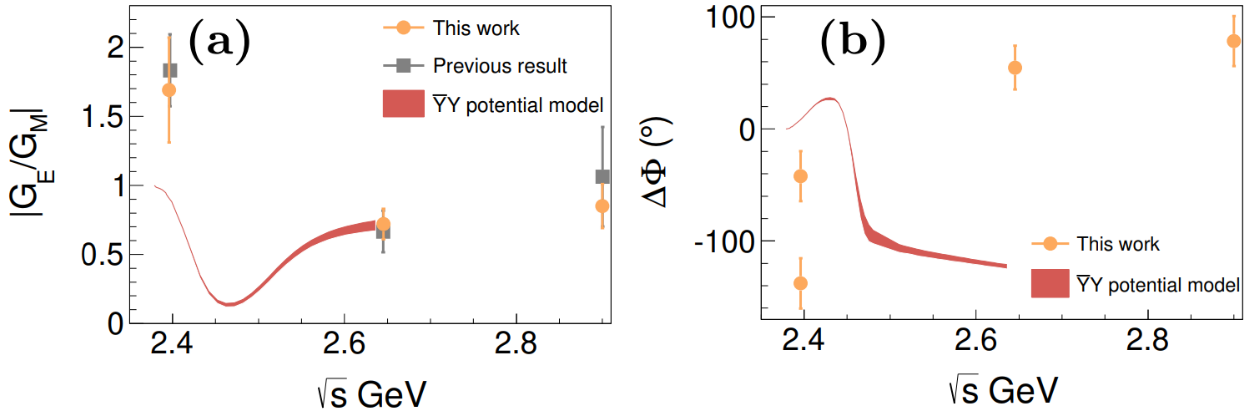
$$P_y = \frac{\sqrt{1-\alpha^2}\sin\theta\cos\theta}{1+\alpha\cos^2\theta}\sin(\Delta\Phi)$$

# Complete decomposition of $\Sigma^+$ EMFFs

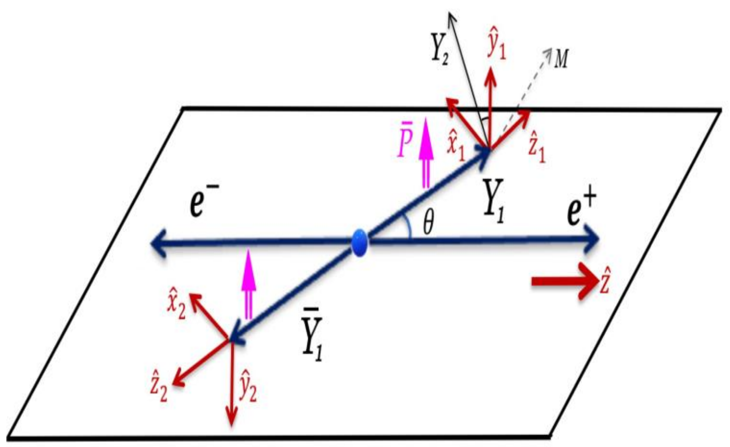
BESIII PRL 132, 081904 (2024)

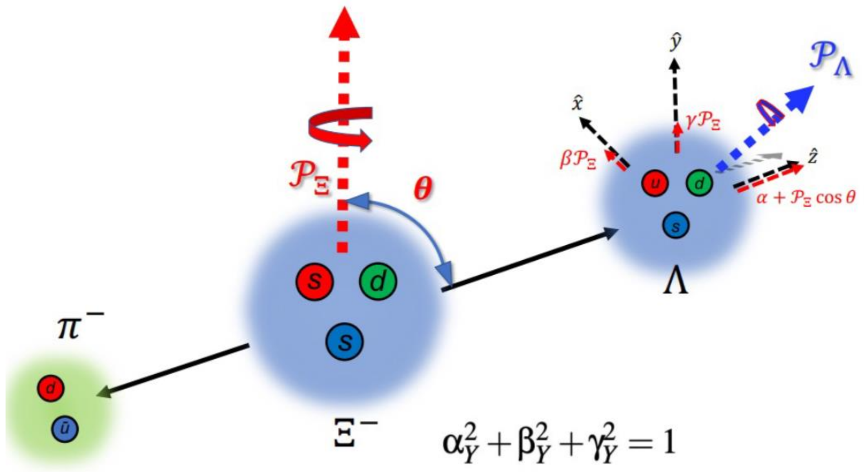
- Polarization is observed at $\sqrt{s}$=2.396, 2.644 and 2.90 GeV with a significance of 2.2$\sigma$, 3.6$\sigma$ and 4.1$\sigma$
- Relative phase is determined for the first time in a wide $q^2$ range
  - $|G_E/G_M|$ and $\Delta\Phi$ line-shape is compared with $\bar{Y}Y$ model [PRD 103, 014028 (2021)], different tendency in $\Delta\Phi$
  - $\Delta\Phi$ evolution is an important input for understanding its asymptotic behavior and the dynamics of baryons




* $\Delta\Phi$ / 180° – $\Delta\Phi$ ambiguity




$$\alpha_Y^2 + \beta_Y^2 + \gamma_Y^2 = 1$$

$$\beta_Y = \sqrt{1-\alpha_Y^2}\sin\phi_Y, \quad \gamma_Y = \sqrt{1-\alpha_Y^2}\cos\phi_Y$$

# Precision test of CP symmetry in hyperon decays

- **Polarized** and **entangled** hyperon pairs
- **Sequential hyperon decays**

separation of strong and weak phases
→ More sensitive CP tests

# Strong and weak CP tests in sequential decays of polarized $\Sigma^0$ hyperons

BESIII PRL 133,101902 (2024)

$$J/\psi, \psi(3686) \to \Sigma^0(\to \Lambda\gamma)\bar{\Sigma}^0(\to \bar{\Lambda}\gamma), \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$$

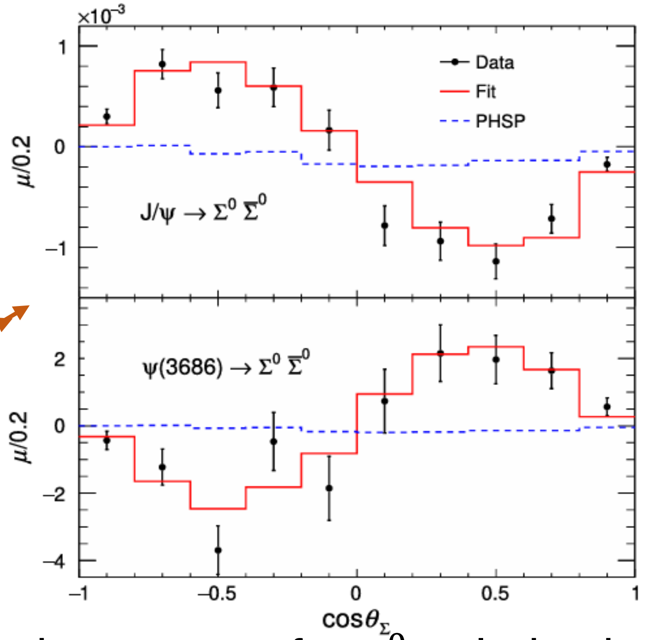
~1.15 million quantum-entangled $\Sigma^0\bar{\Sigma}^0$ pairs reconstructed

EDM of $\Sigma^0 \to \Lambda\gamma$ is related to the neutron EDM via $SU(3)_F$ symmetry
-- a probe to the strong-CPV

S. S. Nair, E. Perotti, and S. Leupold, PLB 788, 535 (2019)

With a 7-dimensional likelihood fit

| Parameter | This Letter | Previous results |
|---|---|---|
| $\alpha_{J/\psi}$ | $-0.4133 \pm 0.0035 \pm 0.0077$ | $-0.449 \pm 0.022$ [52] |
| $\Delta\Phi_{J/\psi}$ (rad) | $-0.0828 \pm 0.0068 \pm 0.0033$ | ... |
| $\alpha_{\psi(3686)}$ | $0.814 \pm 0.028 \pm 0.028$ | $0.71 \pm 0.12$ [52] |
| $\Delta\Phi_{\psi(3686)}$ (rad) | $0.512 \pm 0.085 \pm 0.034$ | ... |
| $\alpha_{\Sigma^0}$ | $-0.0017 \pm 0.0021 \pm 0.0018$ | ... |
| $\bar{\alpha}_{\Sigma^0}$ | $0.0021 \pm 0.0020 \pm 0.0022$ | ... |
| $\alpha_\Lambda$ | $0.730 \pm 0.051 \pm 0.011$ | $0.748 \pm 0.007$ [44] |
| $\bar{\alpha}_\Lambda$ | $-0.776 \pm 0.054 \pm 0.010$ | $-0.757 \pm 0.004$ [44] |
| $A_{CP}^{\Sigma}$ | $(0.4 \pm 2.9 \pm 1.3) \times 10^{-3}$ | ... |
| $A_{CP}^{\Lambda}$ | $(-3.0 \pm 6.9 \pm 1.5) \times 10^{-2}$ | $(-2.5 \pm 4.8) \times 10^{-3}$ [2] |




the moment for $\Sigma^0$ polarizations

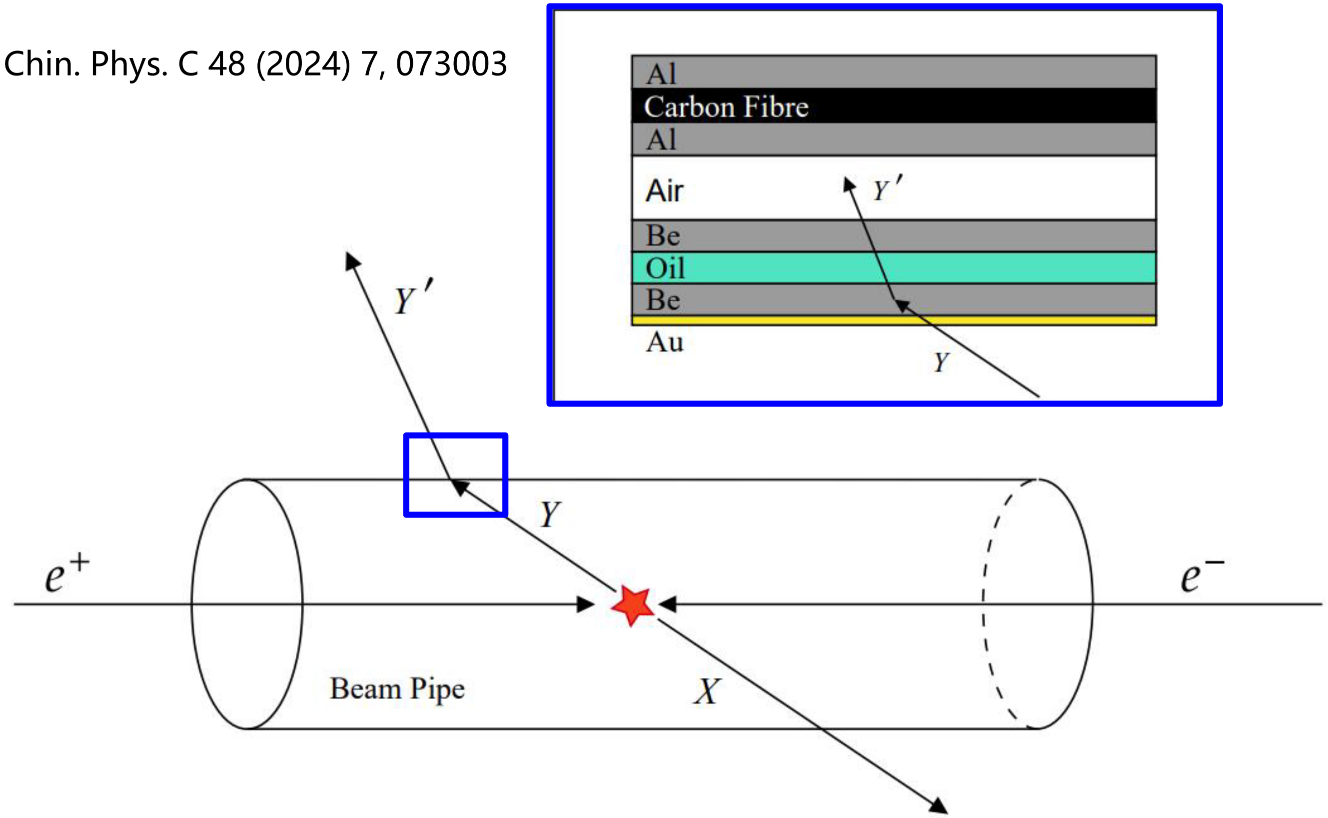
$$\mu^k(\cos\theta_\Sigma) = \frac{1}{N_{total}} \sum_i^{N^k} (\sin\theta_\Lambda^i \sin\varphi_\Lambda^i \cos\theta_p^i + \sin\theta_{\bar{\Lambda}}^i \sin\varphi_{\bar{\Lambda}}^i \cos\theta_{\bar{p}}^i)$$

Opposite directions of the $\Sigma^0$ polarization

The first attempt to measure the P-violating decay parameter of $\Sigma \to \Lambda\gamma$

The first strong-CP test in hyperon decays

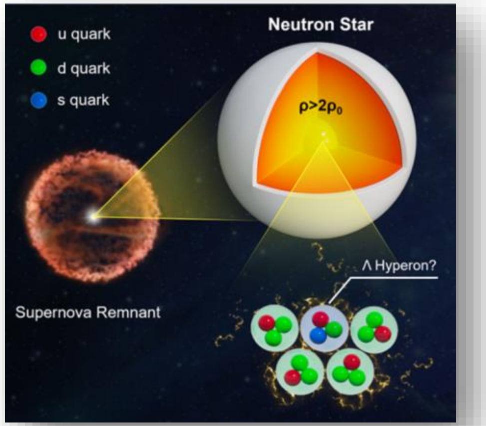
Image from Chin. Phys. C 48 (2024) 7, 073003




BESIII PRL 130, 251902 (2023)
BESIII PRC 109, L052201 (2024)
BESIII PRL 132, 231902 (2024)

# Hadron (YN) interactions with BESIII

- Crucial component to predict hypernuclei properties
- Key to understand the hyperon puzzle of neutron stars



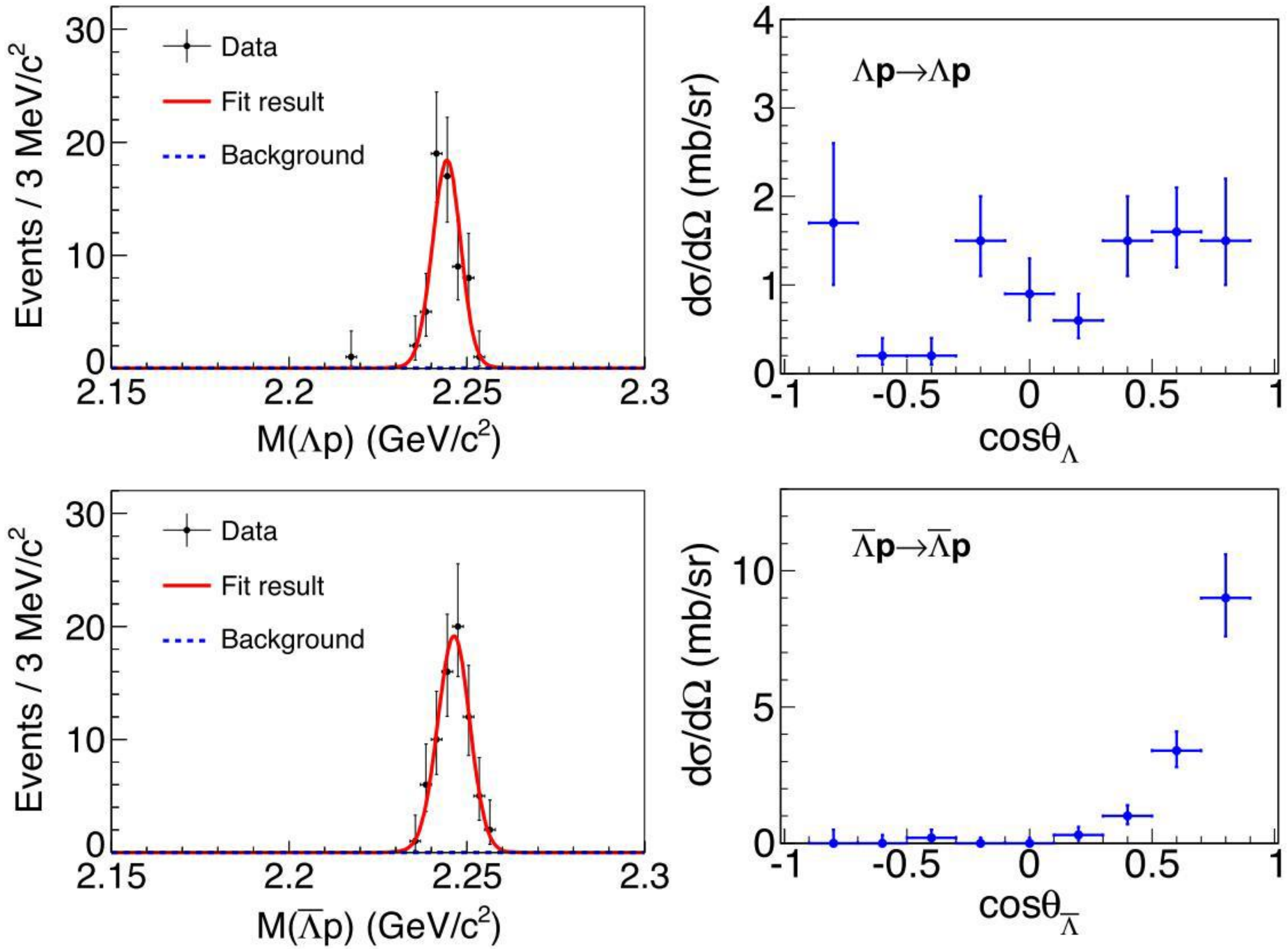
# First study of antihyperon-nucleon scattering

BESIII PRL 132, 231902 (2024)

Beam: $\Lambda/\bar{\Lambda}$ from $J/\psi \to \Lambda\bar{\Lambda}$, using 10B $J/\psi$

$$p_\Lambda = 1.074 \pm 0.017\ \mathrm{GeV}/c^2,\ \left|\cos\theta_{\Lambda(\bar{\Lambda})}\right| < 0.9$$

Target: proton, the hydrogen nuclei in the cooling oil of the beam pipe

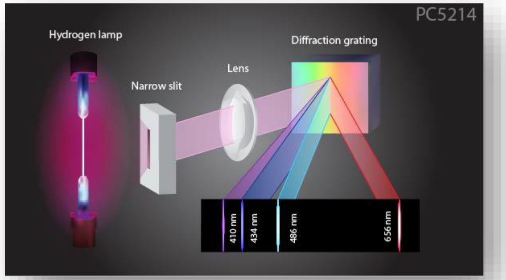



$\sigma(\Lambda p \to \Lambda p)$ = $(12.2 \pm 1.6(\mathrm{stat.}) \pm 1.1(\mathrm{syst.}))$ mb

$\sigma(\bar{\Lambda} p \to \bar{\Lambda} p)$ = $(17.5 \pm 2.1(\mathrm{stat.}) \pm 1.6(\mathrm{syst.}))$ mb

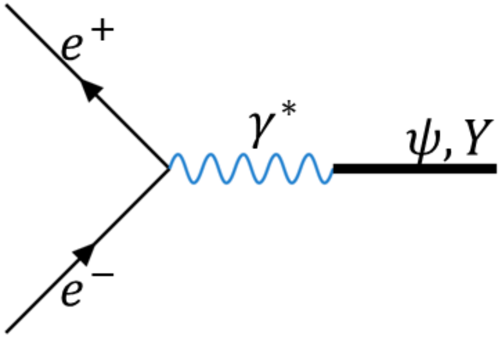
- **Slight tendency of forward scattering for $\Lambda p \to \Lambda p$**
- **Strong forward peak for $\bar{\Lambda} p \to \bar{\Lambda} p$**

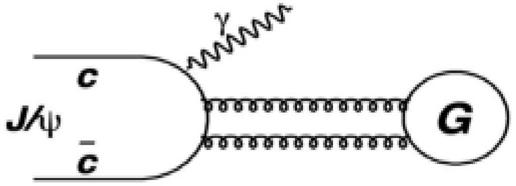
Atomic Spectrum:
Bohr model → QED



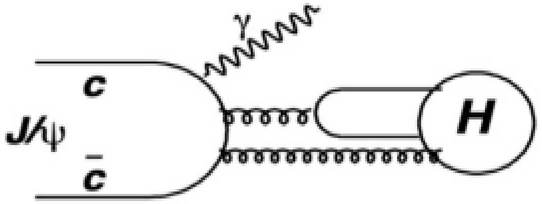

Hadron spectrum:
Quark model → QCD

# Hadron spectroscopy with BESIII




$\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2)$




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

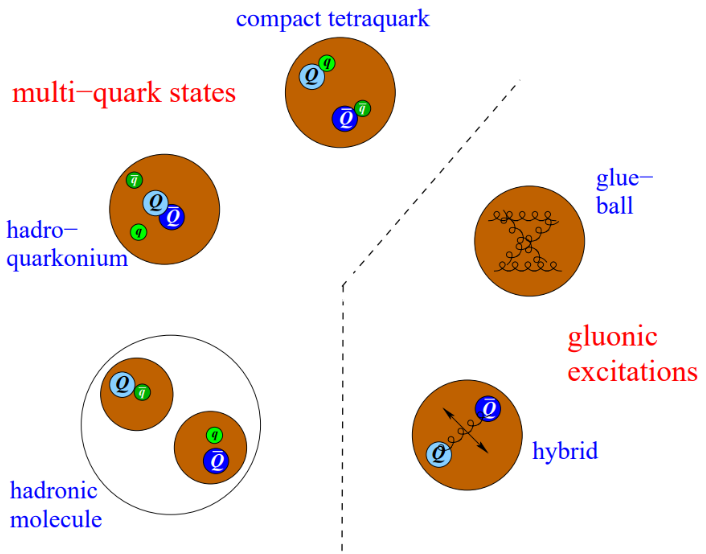
# Hadron spectroscopy

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

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

  - **Evidence for gluonic excitations remains sparse**

**QCD exotics**

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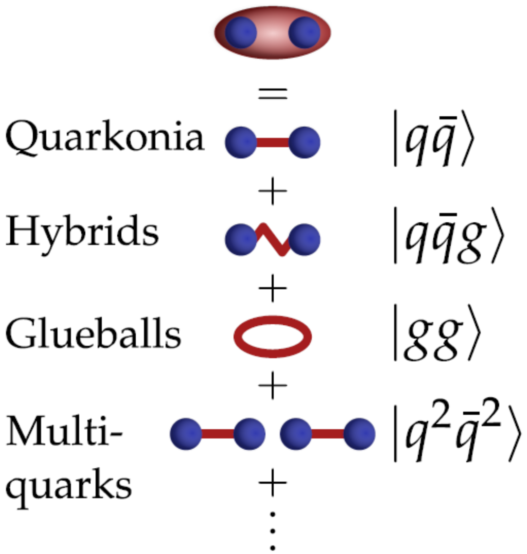



**Physical meson**

A linear superposition of all allowed color-singlet configurations

**Identification of exotics is challenging**

**Manifestly exotic: with forbidden QN**

Flavor exotic: $Z_c, T_{cc}, T_{\psi\psi}$ … …

Spin exotic: $\mathbf{J^{PC} = 0^{--}, even^{+-}, odd^{-+}}$

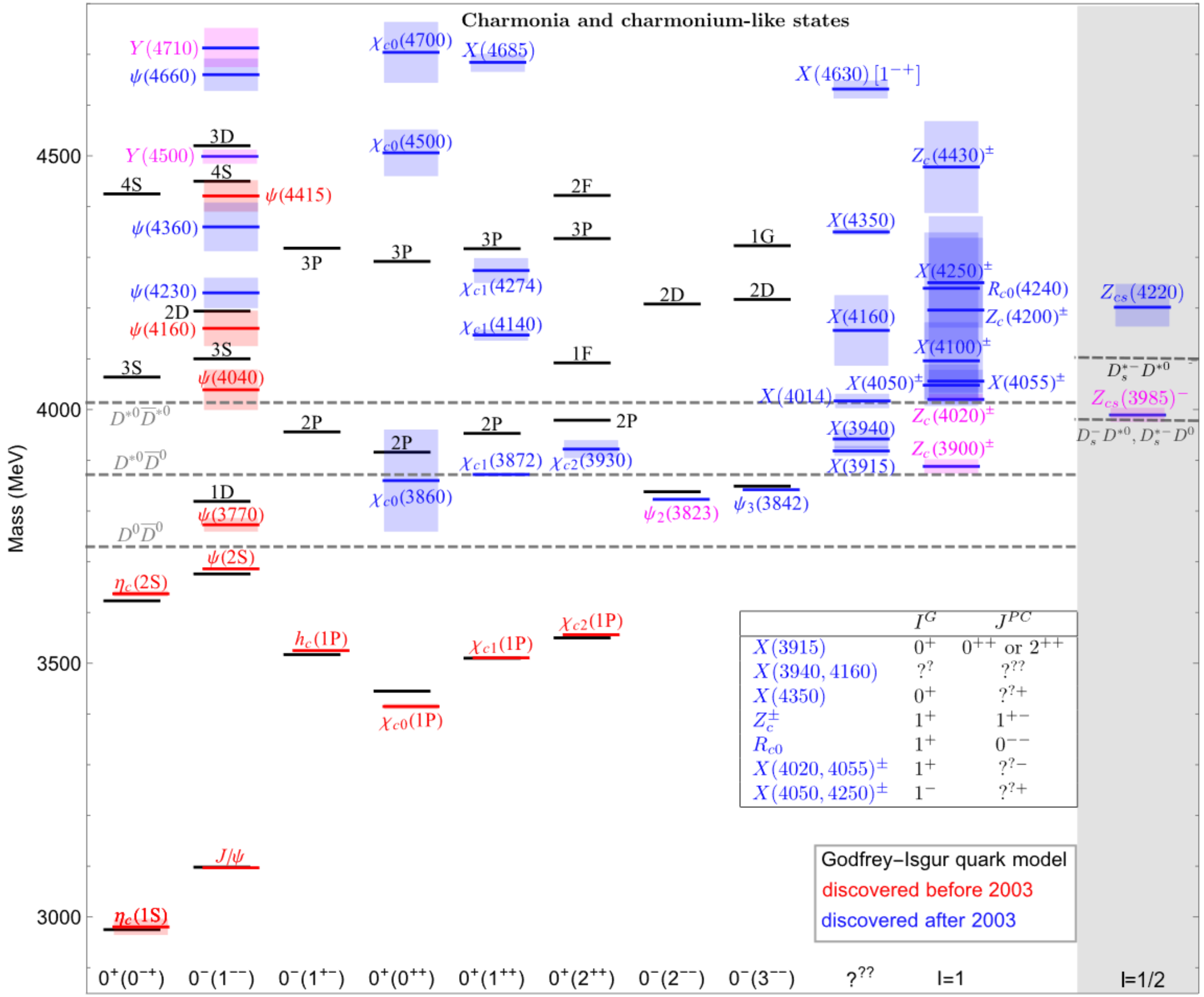
**Crypto exotic: with QN as $\mathbf{q\bar{q}}$**

Supernumerary states - -> **glueball**

Abnormal properties

**+ Kinematic effects**

# Charmonium-like states

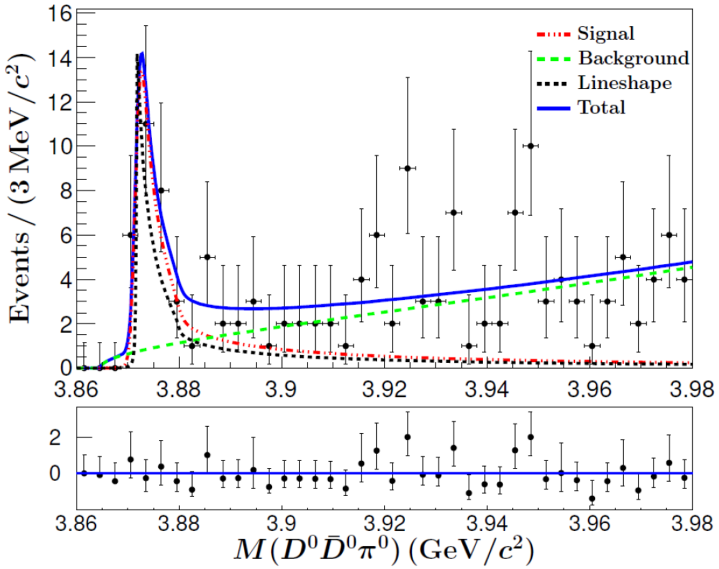


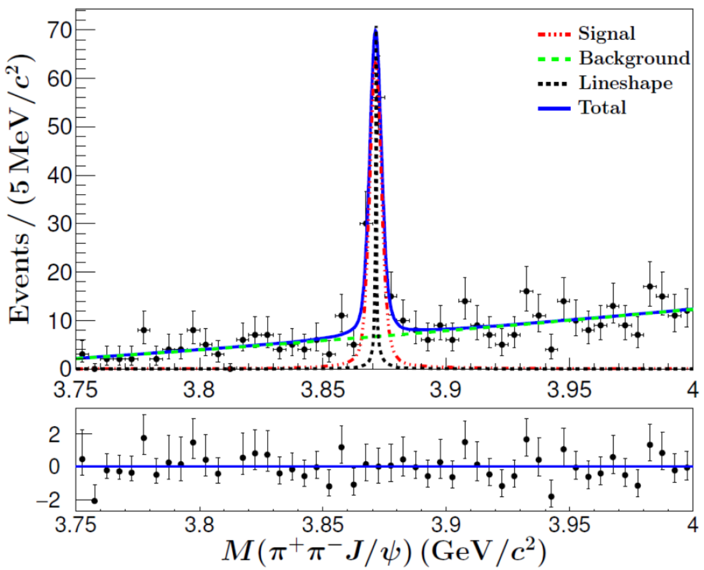

arXiv:2203.08290

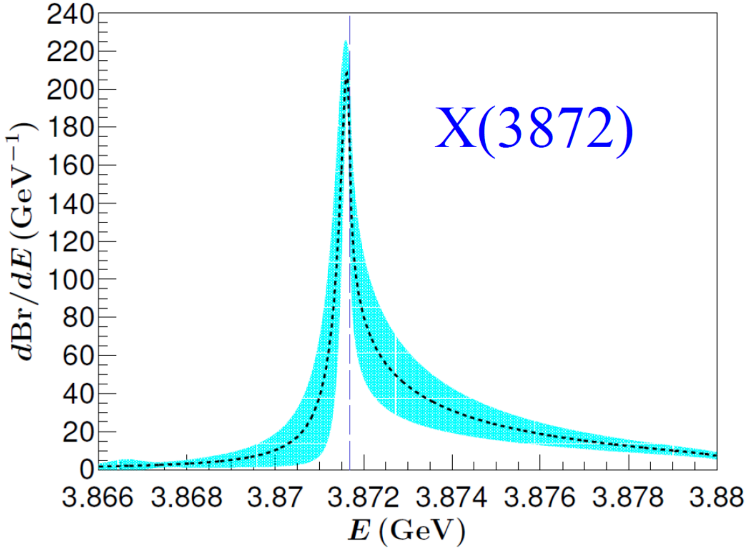
- Conventional $c\bar{c}$ meson fit well with potential model
- Abundance of new states with various probes
  - $b$-hadron decays
  - hadron/heavy-ion collisions
  - $\gamma\gamma$ processes
  - $e^+e^-$ collisions
    - BESIII: dominant for vectors and states produced from vector decays

# New insight on X(3872): line shape @BESIII

$\mathbf{e^+e^- \to \gamma X(3872), X(3872) \to D^0\bar{D}^0\pi^0}$ **and** $\mathbf{\pi^+\pi^- J/\psi}$ BESIII PRL 132, 151903 (2024)




## Pole positions

Two sheets with respect to $D^{*0}\bar{D}^0$ branch cut

- Sheet I: $E - E_X - g\sqrt{-2\mu(E - E_R + i\Gamma/2)}$
- Sheet II: $E - E_X + g\sqrt{-2\mu(E - E_R + i\Gamma/2)}$

$E_{\mathrm{I}} = (7.04 \pm 0.15^{+0.07}_{-0.08}) + (-0.19 \pm 0.08^{+0.14}_{-0.19})i$ MeV

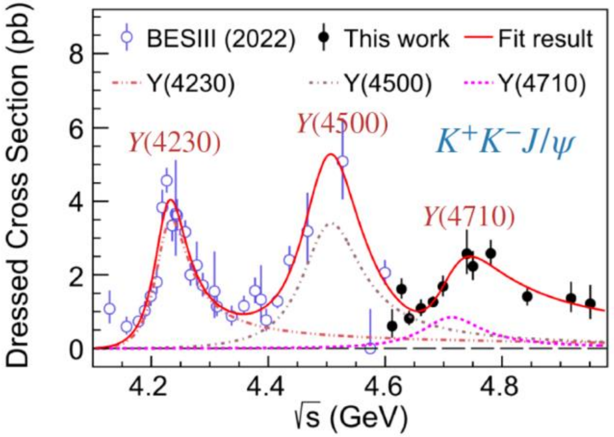
$E_{\mathrm{II}} = \left(0.26 \pm 5.74^{+5.14}_{-38.32}\right) + (-1.71 \pm 0.90^{+0.60}_{-1.96})i$ MeV

| | LHCb | Belle | BESIII |
|---|---|---|---|
| g | $0.108 \pm 0.003^{+0.005}_{-0.006}$ | $0.29^{+2.69}_{-0.15}$ | $0.16 \pm 0.10^{+1.12}_{-0.11}$ |
| $Re[E_I]$ [MeV] | 7.10 | 7.12 | $7.04 \pm 0.15^{+0.07}_{-0.08}$ |
| $Im[E_I]$ [MeV] | -0.13 | -0.12 | $-0.19 \pm 0.08^{+0.14}_{-0.19}$ |
| $Re[k^+]$ [MeV] | $-13.9$ | $-15.3$ | $-12.6 \pm 5.5^{+6.6}_{-6.2}$ |
| $Im[k^+]$ [MeV] | 8.8 | 7.7 | $12.3 \pm 6.8^{+6.0}_{-6.4}$ |
| $a$ (fm) | $-27.1$ | $-31.2$ | $-16.5^{+7.0}_{-27.6}{}^{+5.6}_{-27.7}$ |
| $r_e$ (fm) | -5.3 | $-3.0^{+1.3}_{-1.5}$ | $-4.1^{+0.9}_{-3.3}{}^{+2.8}_{-4.4}$ |
| $\bar{Z}_A$ | 0.15 (0.33) | $0.08^{+0.04}_{-0.03}$ | $0.18^{+0.06}_{-0.17}{}^{+0.19}_{-0.16}$ |

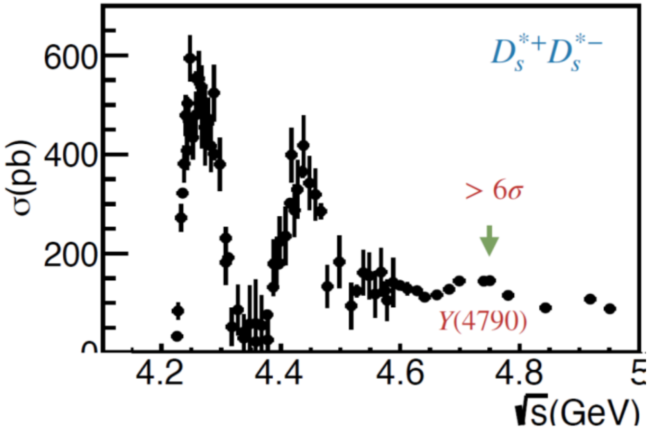
**Weinberg's compositeness: *Z*=1: pure elementary state; *Z*=0: pure bound (composite) state**

# Observations of new vectors: Y(4500), Y(4710) and Y(4790)

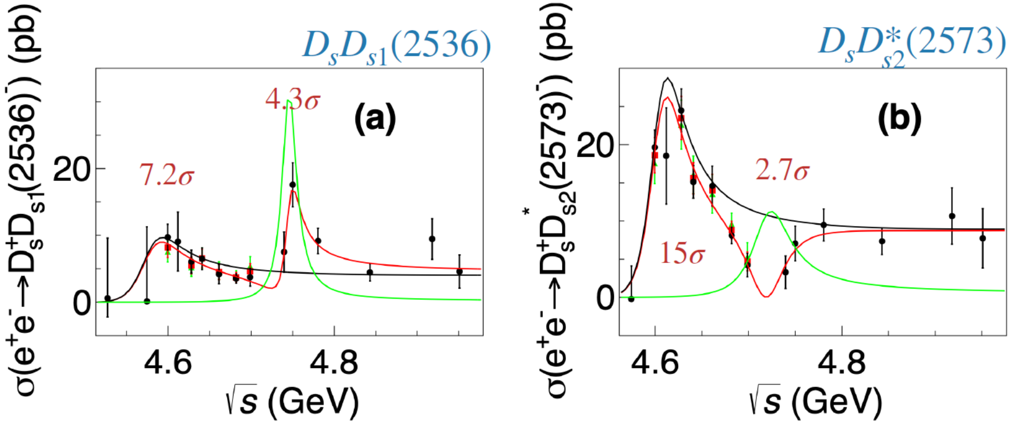
CPC 46, 111002 (2022)
PRL131, 211902 (2023)

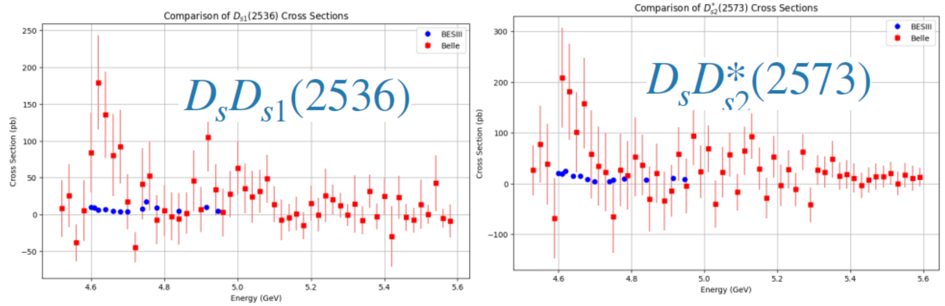



PRL131, 151903 (2023)



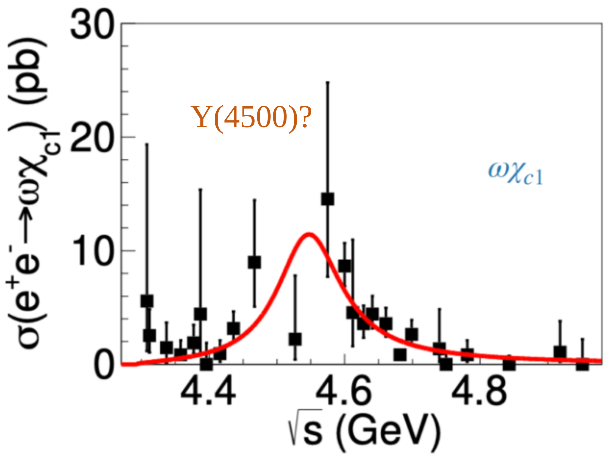

arXiv:2407.07651



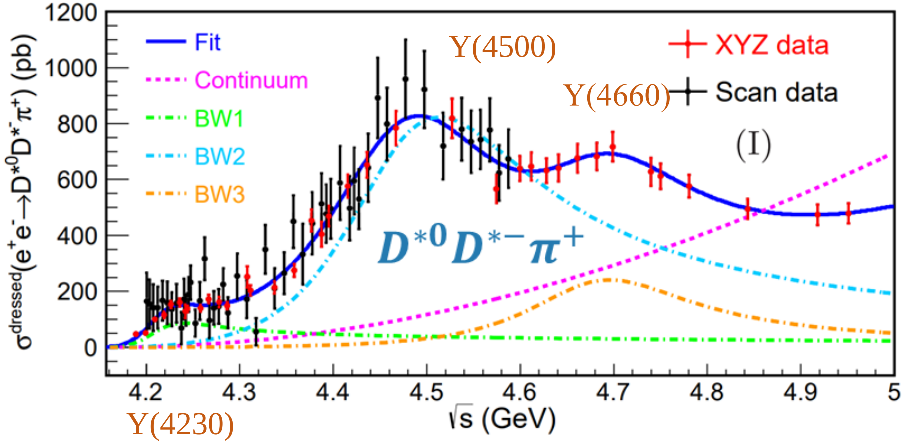




Tension between direct (BESIII) and ISR(Belle) measurements

PRL 132, 161901 (2024)

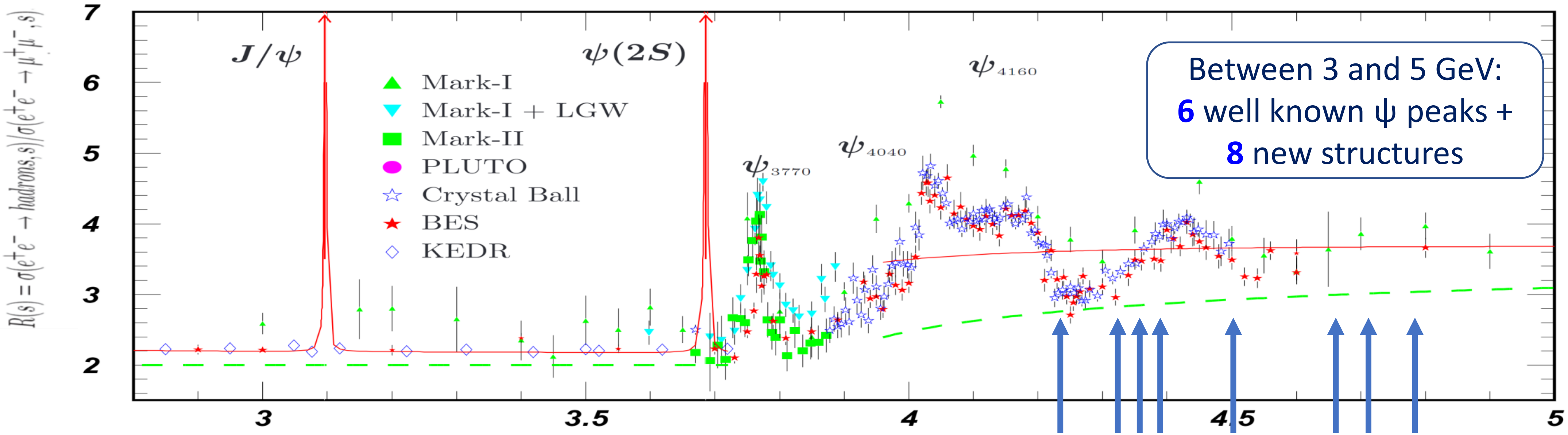



PRL130, 121901 (2023)




$[cs\bar{c}\bar{s}]$ states?

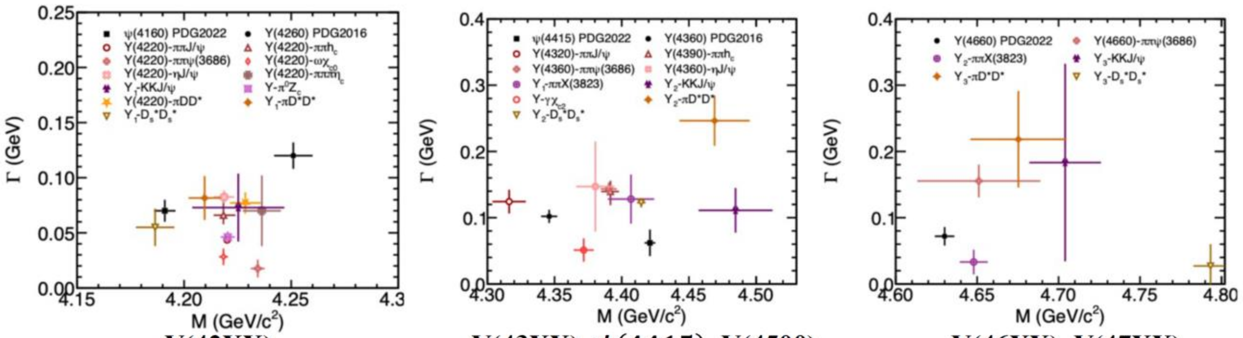
# How many vectors in charmonium energy region?




**Y(4230), Y(4320), Y(4500)   Y(4660), Y(4710),**
**Y(4360), Y(4390)   Y(4790)**

Besides $c\bar{c}$ states, we also expect $gc\bar{c}$ hybrids, and $c\bar{c}q\bar{q}$ tetraquark states. Have they already been observed?

→ **More theoretical/experimental efforts necessary**

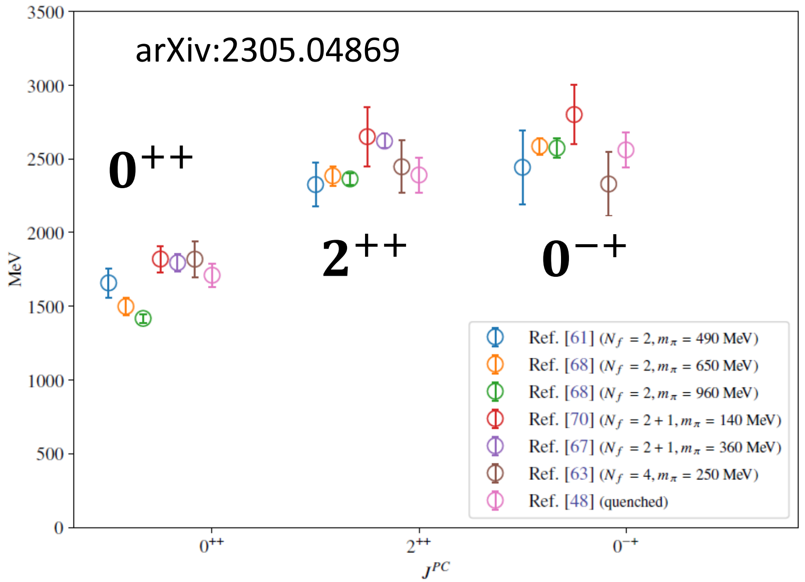



Y(42XX)   Y(43XX), ψ(4415), Y(4500)   Y(46XX), Y(47XX)

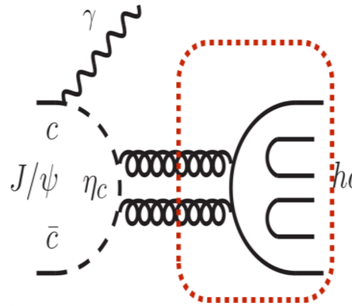
Measurements at BESIII

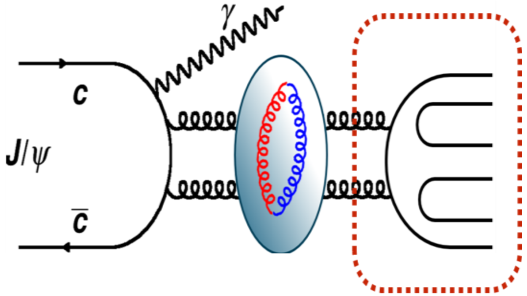
# Glueball hunting for over 40 years

- Glueballs: the most direct prediction of QCD
  - Gluon self-interactions
  - Can massless gluons form massive, exotic matter?
- Theoretical predictions from LQCD and QCD-inspired models mostly consistent
- Supernumerary states that do not fit into $q\bar{q}$ multiplets
- Production: Strongly produced in gluon-rich processes
- Decay: gluon is flavor-blind
  - No rigorous predictions
    - Could be analogy to OZI suppressed decays of charmonium, as they all decay via gluons [PLB 380 189(1996), Commu. Theor. Phys. 24.373(1995)]



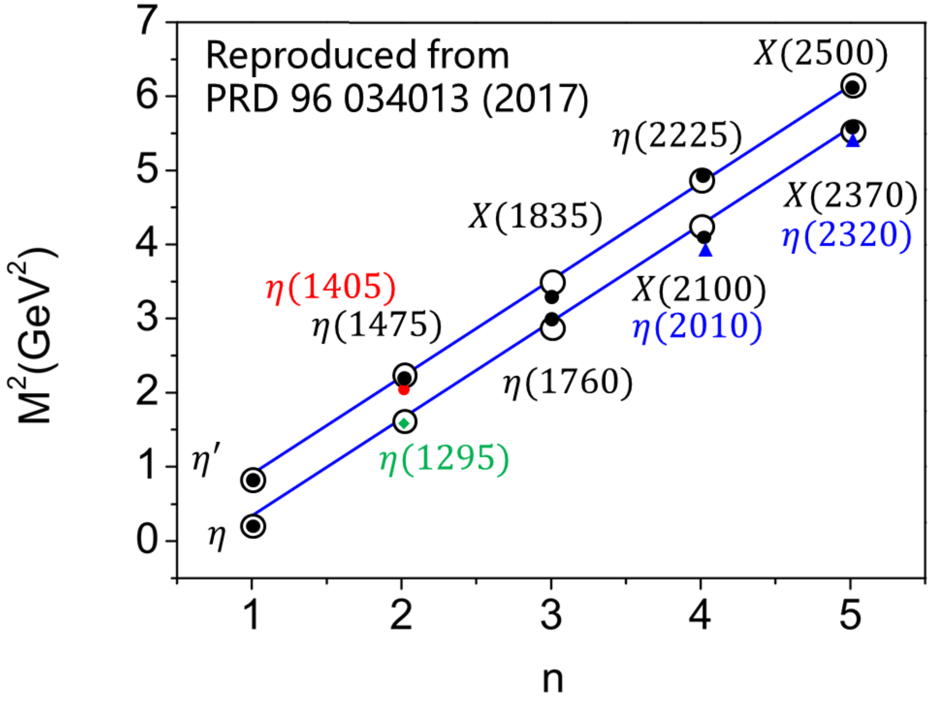

Light Yang-Mills glueballs on lattice (quenched and unquenched results)



# Where is the $0^{-+}$ glueball

- Pseudoscalar sector, a promising window
  - Only $\eta$, $\eta'$ (& radial excitations) from quark model
- Mass
  - LQCD： $0^{-+}$ glueball (2.3~2.6 GeV)
  - The first glueball candidate: $\iota(1440)$ (Split into $\eta(1405)$ and $\eta(1475)$)
    - Mass incompatible with LQCD
  - Little experimental information above 2 GeV
- Production
  - LQCD: $\Gamma(J/\psi \to \gamma G_{0-})/\Gamma_{\mathrm{total}} = 2.31(80) \times 10^{-4}$, at the same level as $0^{-+}$ mesons [PRD.100.054511(2019)]
- **Decays**
  - **Possible guidance: OZI suppressed decays of $\eta_c$**
  - **3 pseudoscalar final state is a good place to look for** ($0^{-+} \to 2P$ is forbidden)




$\eta_c \to 3\,P$ in PDG

**Decays involving hadronic resonances**

| | | |
|---|---|---|
| $\Gamma_1$ | $\eta'(958)\pi\pi$ | ( 1.87±0.26) % |
| $\Gamma_2$ | $\eta'(958)K\overline{K}$ | ( 1.61±0.25) % |

**Decays into stable hadrons**

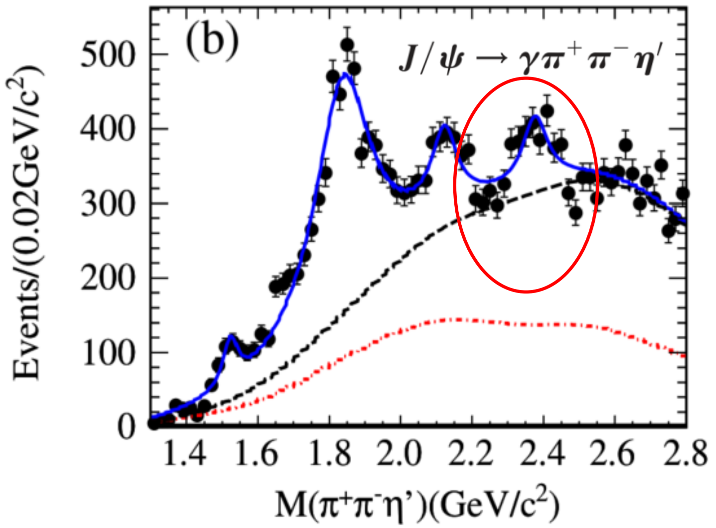
| | | |
|---|---|---|
| $\Gamma_{34}$ | $K\overline{K}\pi$ | ( 7.0 ±0.4 ) % |
| $\Gamma_{35}$ | $K\overline{K}\eta$ | ( 1.32±0.15) % |
| $\Gamma_{36}$ | $\eta\pi^+\pi^-$ | ( 1.7 ±0.5 ) % |

- No dominant decay
- Flavor symmetric

# A glueball-like state $X(2370)$

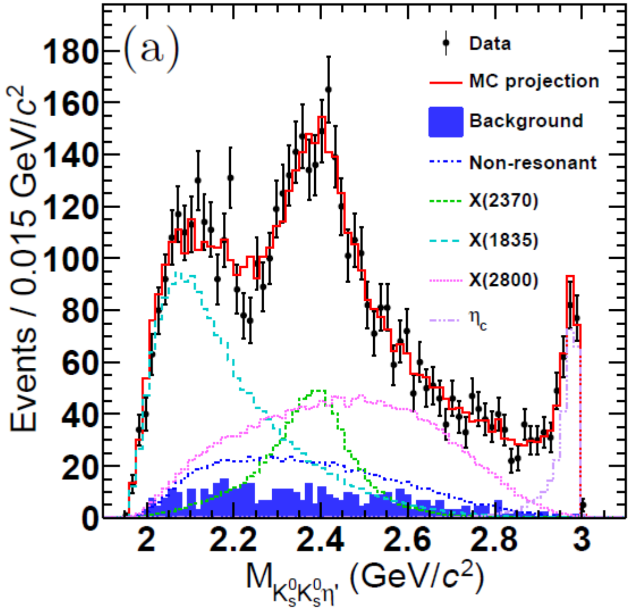
- **Discovered by BESIII in $\mathbf{J/\psi \to \gamma\eta'\pi\pi}$ in 2011**
- Confirmed by BESIII in $\mathbf{J/\psi \to \gamma\eta'\pi\pi, \gamma\eta'KK}$
  - Not seen in $J/\psi \to \gamma\eta'\eta\eta$ [BESIII PRD 103 012009 (2021)], $J/\psi \to \gamma\gamma\phi$ [BESIII arXiv: 2401.00918]. Upper limits of BF are well consistent with predictions of $0^{-+}$glueball
- **Mass consistent with LQCD prediction for $\mathbf{0^{-+}}$ glueball**
- **Spin-parity determined to be $\mathbf{0^{-+}}$** **BESIII PRL 132, 181901(2024)**

$\mathbf{J/\psi \to \gamma\eta'\pi\pi}$




**BESIII PRL 106, 072002(2011), PRL 117, 042002 (2016)**

$\mathbf{J/\psi \to \gamma\eta'K_S^0K_S^0}$



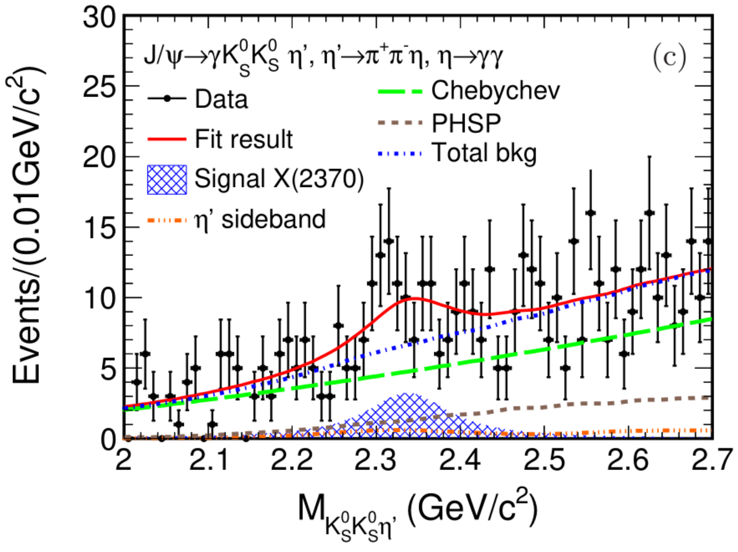

**$J^{PC}$ = $0^{-+}$ with significance >9.8σ**

**M = 2395 ±11$^{+26}_{-94}$ MeV**

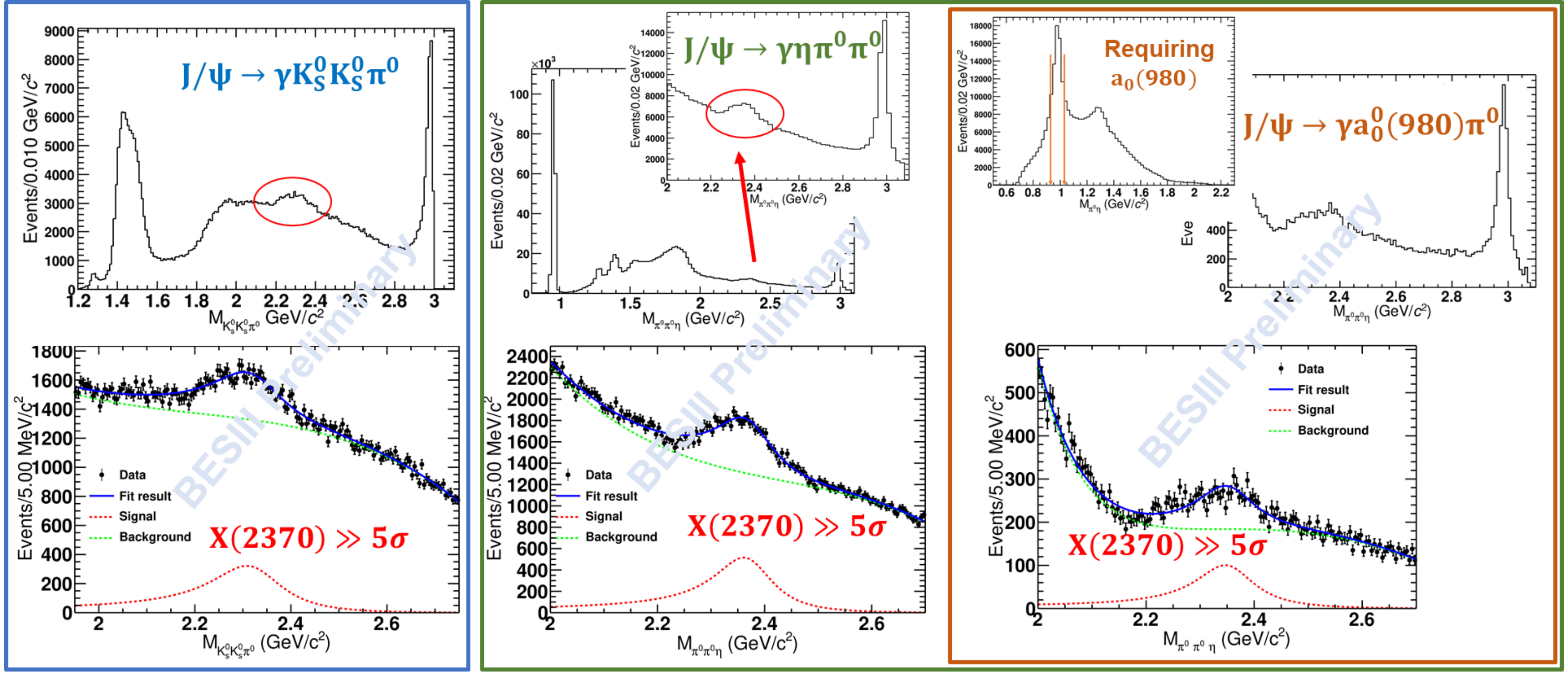
**Γ = 188$^{+18}_{-17}$$^{+124}_{-33}$ MeV**

**B(J/ψ→γX(2370))B(X(2370)→f$_0$(980)η')B(f$_0$(980)→$K^0_sK^0_s$)**
**= 1.31 ± 0.22$^{+2.85}_{-0.84}$ ×10$^{-5}$**

$\mathbf{J/\psi \to \gamma\eta'KK}$




**BESIII EPJC 80 746(2020)**




# New decay modes

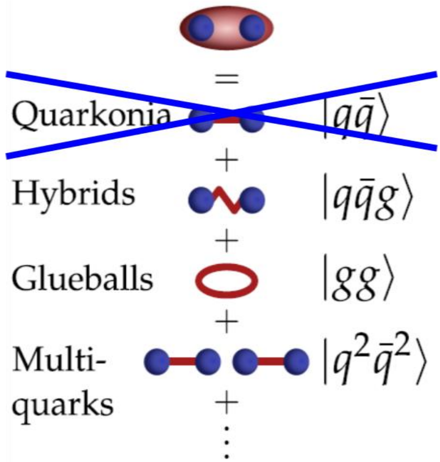
**$\mathrm{X(2370)}$ observed in the gluon-rich $\mathrm{J/\psi}$ radiative decays**

- $\mathrm{J^{PC}}$ determined to be $0^{-+}$
- **Mass and production rate consistent with LQCD**
- **Decay modes** $\mathrm{X(2370)} \rightarrow \eta'\pi\pi, \eta' KK, K^0_S K^0_S \eta, K^0_S K^0_S \pi^0, \eta\pi^0\pi^0, a^0_0(980)\pi^0$ **observed, in analog to $\eta_c$**

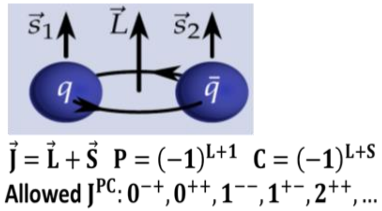
Consistent with $0^{-+}$ glueball

* $\eta(2320) \rightarrow \eta\eta\eta, \eta\pi\pi$ [PL B496 145(2000)] could be the current $\mathrm{X(2370)}$ at BESIII

# Light hadrons with exotic quantum numbers




- Unambiguous signature: exotic quantum numbers forbidden for $q\bar{q}$: $J^{PC} = 0^{--}, \text{even}^{+-}, \text{odd}^{-+}$



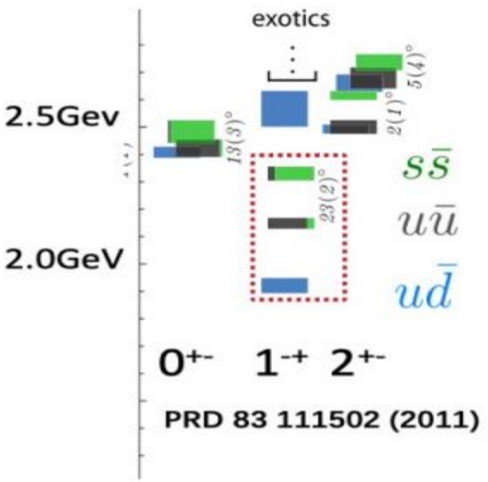

- **Only 3 candidates over 30 yrs:**

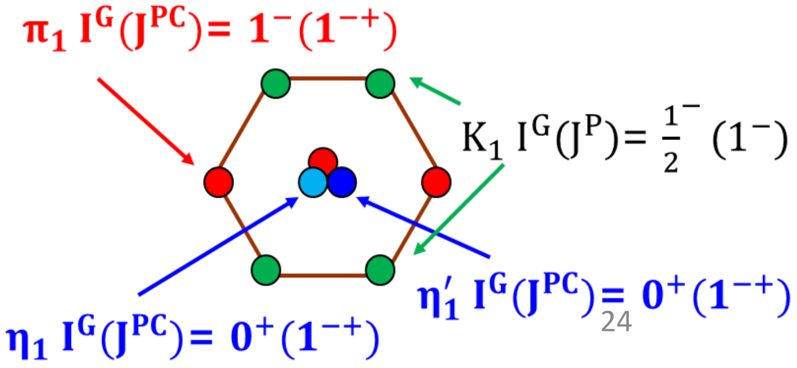
**All $1^{-+}$ isovectors** $\pi_1(1400), \pi_1(1600), \pi_1(2015)$

* $\pi_1(1400)$ and $\pi_1(1600)$ can be explained as one resonance with recent coupled channel analyses

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

**Lattice QCD Predictions:**




PRD 83,014021 (2011)
PRD 83,014006 (2011)
Eur.Phys.J.Plus 135, 945(2020)

# 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 $J/\psi \to \gamma\eta\eta'$ (>19$\sigma$)**

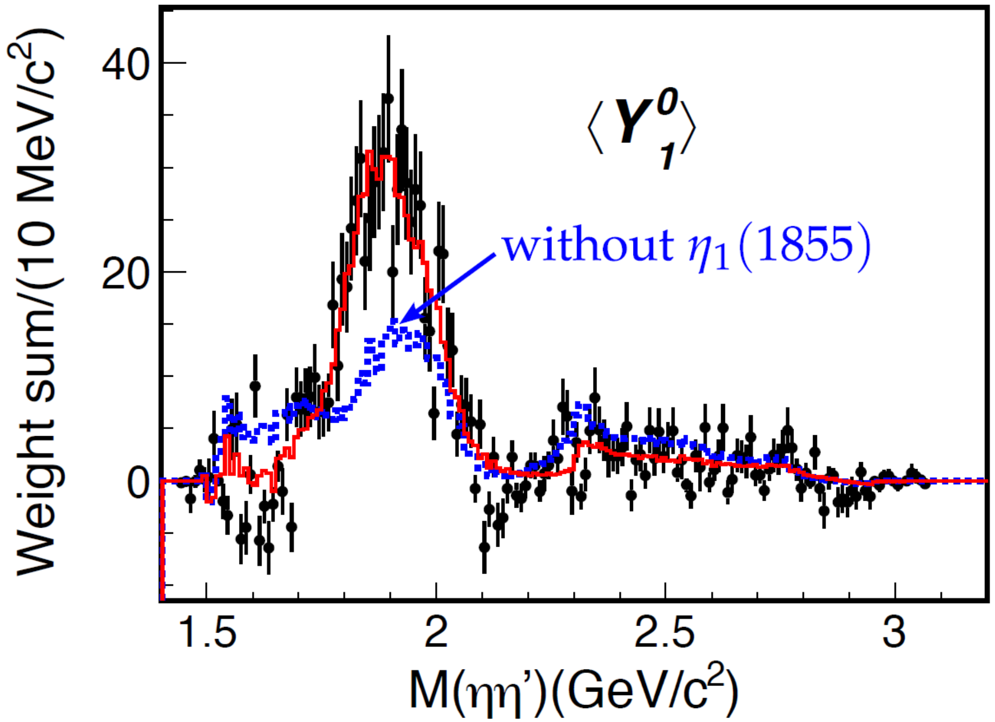
  $M = (1855 \pm 9^{+6}_{-1})$ MeV/c$^2$, $\Gamma = (188 \pm 18^{+3}_{-8})$ MeV/c$^2$

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

  - **Mass consistent with hybrid on LQCD**

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

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

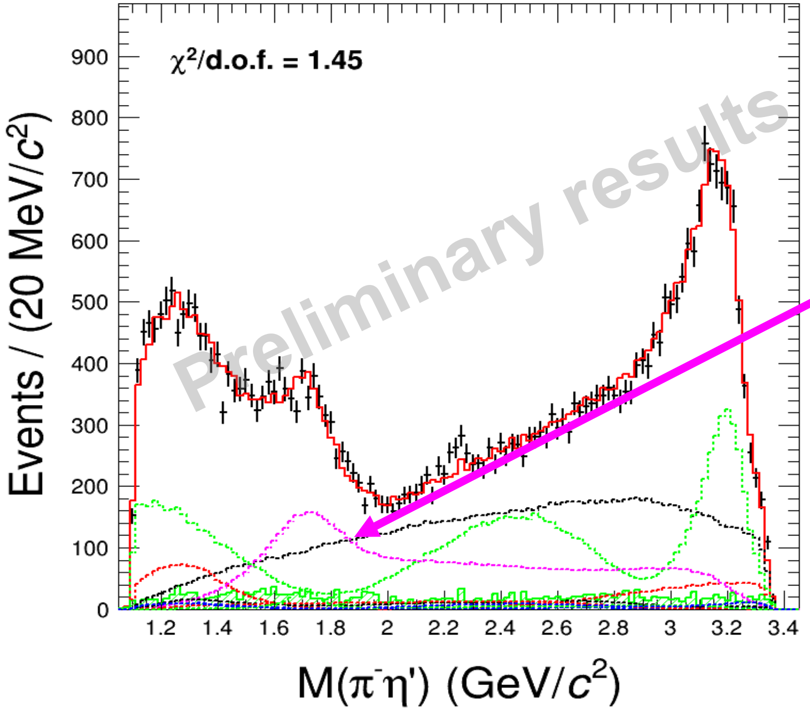



*"Here, the result by the BESIII experiment of a possible observation of an $\eta_1(1855)$ state could be a breakthrough."*

—— *50 years of QCD: Exotic mesons* [EPJ.C 83 (2023) 1125]

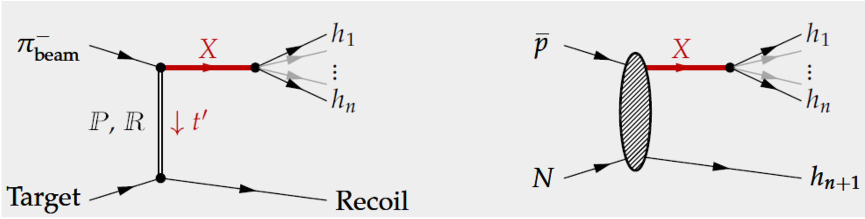
# Observation of $\pi_1(1600)$ in $\chi_{c_1} \to \eta'\pi^+\pi^-$

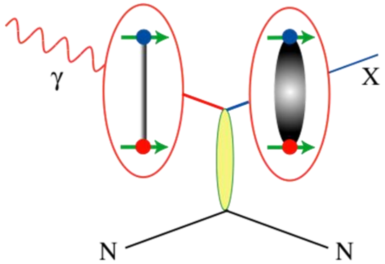
$\mathbf{2.7 \times 10^9}$ $\psi(3686)$@BESIII [preliminary]

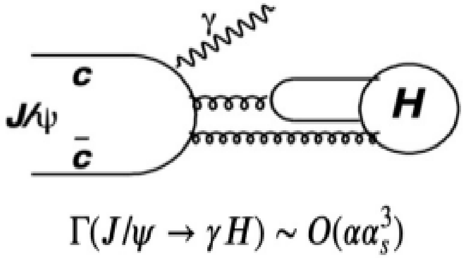



- **Amplitude analysis of $\chi_{c_1} \to \eta'\pi^+\pi^-$ is performed**
- **$\pi_1(1600)$ observed>10$\sigma$**
- **with a significant BW phase motion**
- **$J^{PC}= 1^{-+}$, better than other assignments well over 10$\sigma$**
  - Evidence of $\pi_1 \to \eta'\pi$ at CLEO-c is confirmed [ PR D84 112009 (2011)]

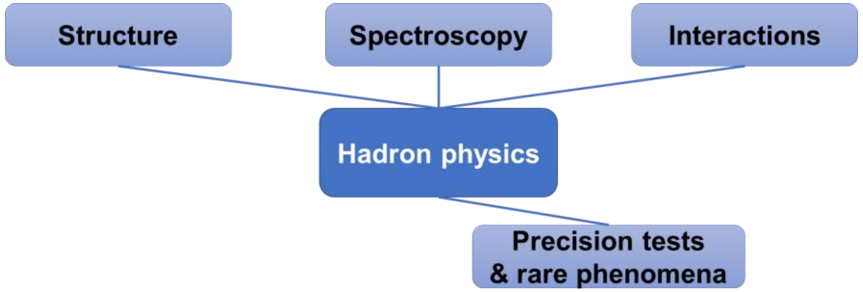
**Observations of $\pi_1$ and $\eta_1$ in charmonium decays provide a new path to study $1^{-+}$**



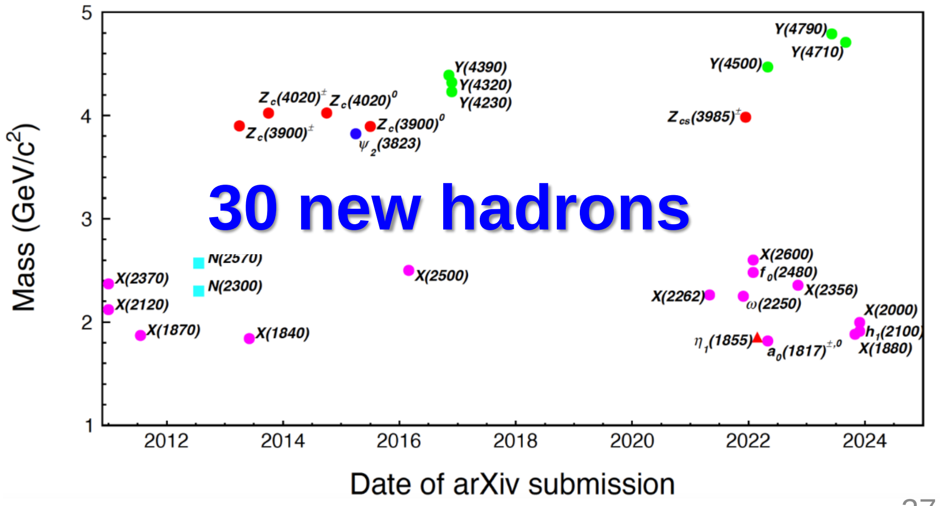



# Summary




- BESIII has a rich and fruitful program of hadron physics

- Great potential to be fully explored
  - $50\ \mathrm{fb}^{-1}$ data on disk, including $10 \times 10^9\ \mathrm{J}/\psi$ and $2.7 \times 10^9\ \psi'$
  - Running until ~2030
  - Upgrade in this summer
    - $\mathcal{L} \times 3$ @$\sqrt{s}$=4.7 GeV
    - $\sqrt{s} \rightarrow 5.6\ GeV$, starting from 2028
    - CGEM inner tracker


*Thank you for your attention*

# Scalar glueball candidate

- **Supernumerary scalars** suggest additional degrees of freedom
  - However, mixing scenarios are controversial
- Measured $\mathrm{B}(\mathrm{J}/\psi \to \gamma f_0(1710))$ is **x10 larger** than $f_0(1500)$

  BESIII [PRD 87 092009, PRD 92 052003, PRD 98 072003]

  - LQCD: $\Gamma(\mathrm{J}/\psi \to \gamma G_{0+})/\Gamma_{\mathrm{total}} = 3.8(9) \times 10^{-3}$ [PRL 110, 091601(2013)]

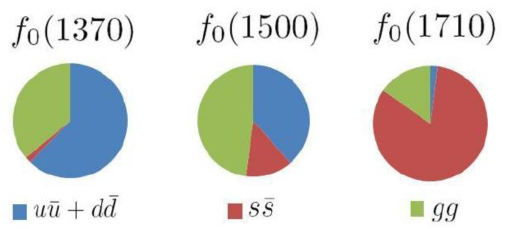
  ➢ **BESIII: $f_0(1710)$ largely overlays with the scalar glueball**

  ➢ **Identification of scalar glueball with coupled-channel analyses based on BESIII data**

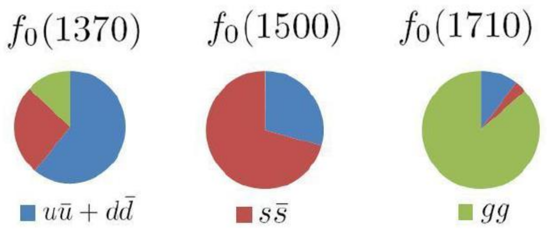
  [PLB 816, 136227 (2021), EPJC 82, 80 (2022), PLB 826, 136906 (2022) ]
- **Further more, suppression of $f_0(1710) \to \eta\eta'$ supports $f_0(1710)$ has a large overlap with glueball**

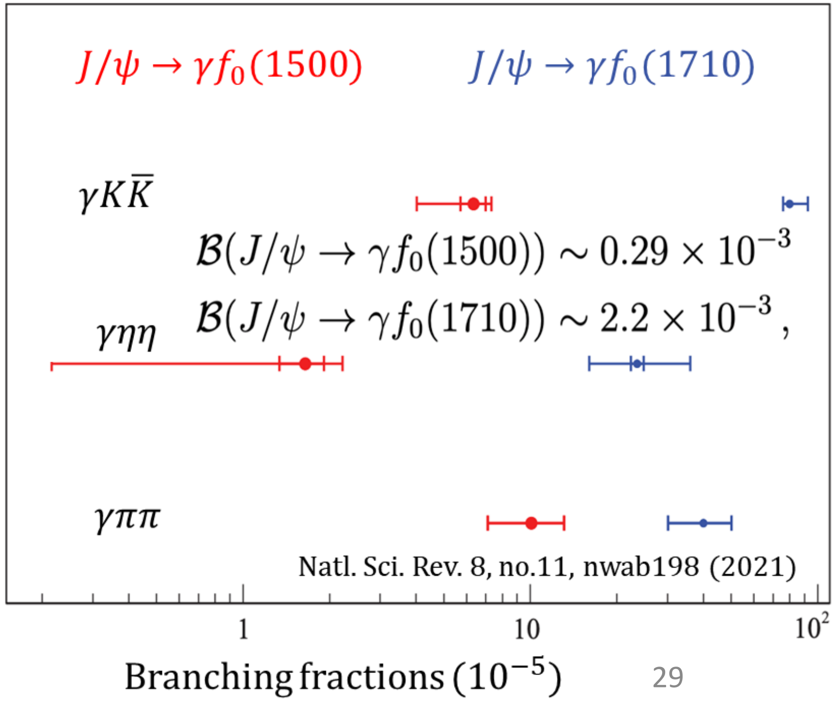
BESIII [PRD 106 072012(2022)]

Close and Kirk, PLB**483** (2000) 345




Cheng *et al*, Phys. Rev. D**74** (2006) 094005



# Indications of tensor glueball

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

*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)

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

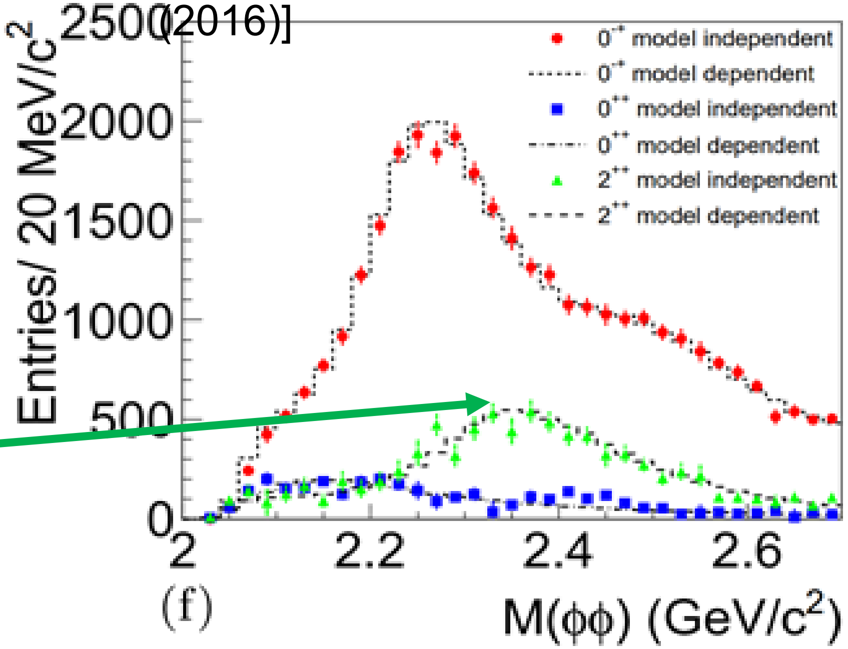
BESIII PRD 98,072003 (2018)

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

BESIII PRD 105,072002 (2022)

still desired to study more decay modes

BESIII $J/\psi \to \gamma\phi\phi$ [PRD 93, 112011 (2016)]



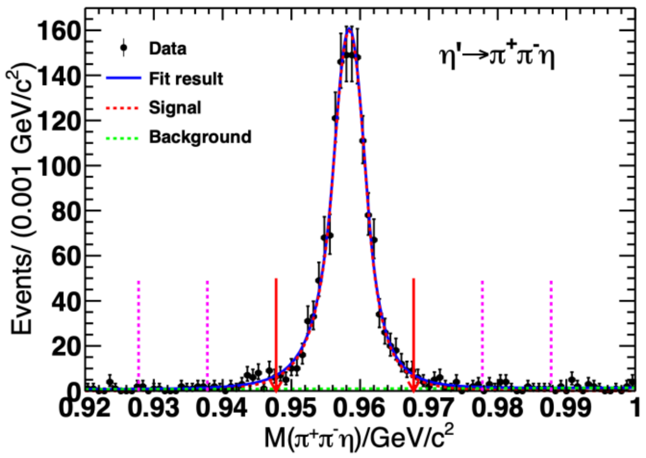

- $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ in πp reactions are all observed in $\mathbf{J/\psi \to \gamma\phi\phi}$ with a **strong production of $f_2(2340)$**
- Consistent with **double-Pomeron exchange** from WA102@CERN

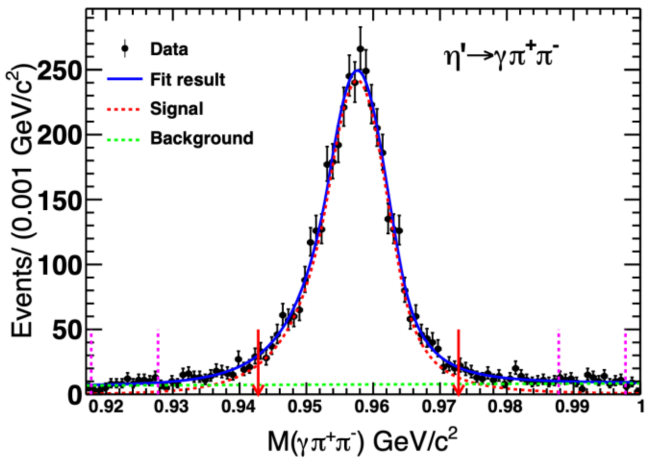
More complicated due to the large number of tensor states

# Spin-parity Determination of $X(2370)$ in $J/\psi \to \gamma\eta' K_S^0 K_S^0$

- $\eta'$ reconstructed with $\eta\pi^+\pi^-$ and $\gamma\pi^+\pi^-$
- $K_S^0$ reconstructed with $\pi^+\pi^-$
- **Almost background free**
  - Negligible mis-combination for $K_S^0$ ( <0.1%)
  - No background from $J/\psi \to \pi^0\eta' K_S^0 K_S^0$ or $\eta' K_S^0 K_S^0$
    - Forbidden by exchange symmetry and CP conservation
  - No peaking background
  - Little Non- $\eta'$ backgrounds estimated from $\eta'$ sidebands
    - **1.8% for $\eta' \to \eta\pi^+\pi^-$, 6.8% for $\eta' \to \gamma\pi^+\pi^-$**

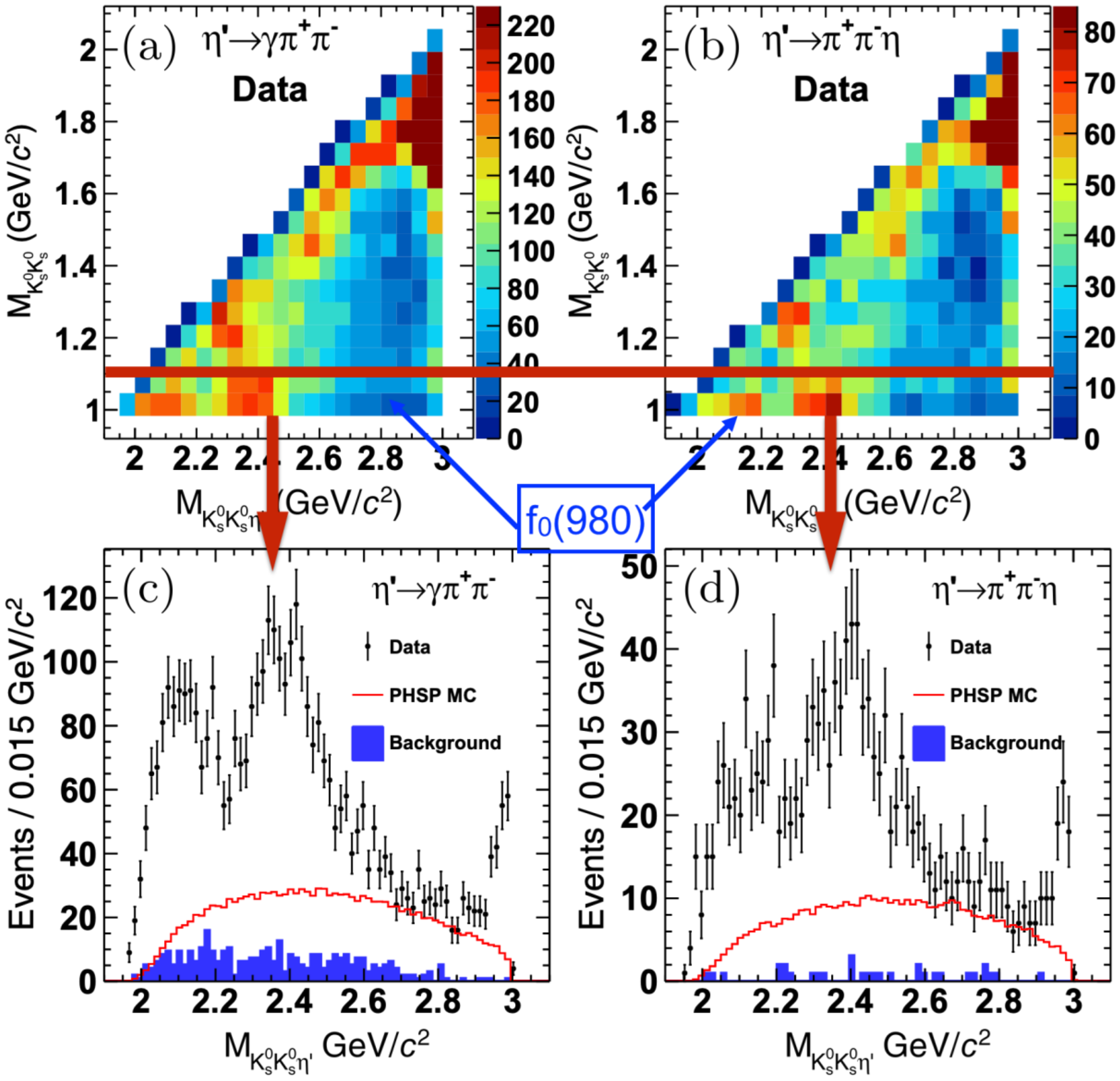
BESIII PRL 132 181901(2024)



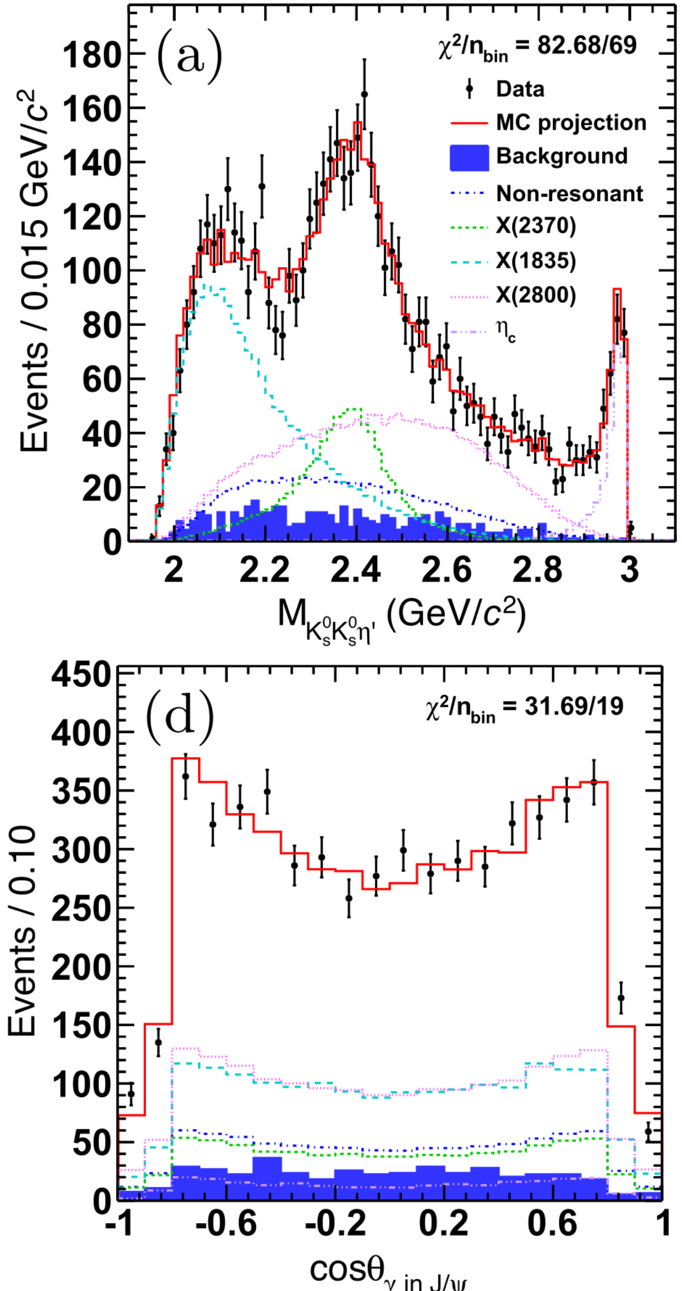
# Spin-parity Determination of $X(2370)$ in $J/\psi \rightarrow \gamma\eta' K_S^0 K_S^0$

BESIII PRL 132 181901(2024)




- A clear connection between the $f_0(980)$ and $X(2370)/\eta_c$
  - $f_0(980)$ selection with $M(K_S^0 K_S^0) < 1.1\mathrm{GeV}/c^2$
  - Clear signals of the $X(2370)$ and $\eta_c$
- Amplitude analysis
  - Quasi two-body decay amplitudes in the sequential decay processes $J/\psi \rightarrow \gamma X, X \rightarrow Y\eta', Y \rightarrow K_S^0 K_S^0$ and $J/\psi \rightarrow \gamma X, X \rightarrow Z K_S^0, Z \rightarrow K_S^0 \eta'$ are constructed using the covariant tensor formalism[Eur. Phys. J. A 16, 537]

# Spin-parity Determination of $X(2370)$ in $\mathrm{J}/\psi \to \gamma\eta' K_S^0 K_S^0$




BESIII PRL 132 181901(2024)

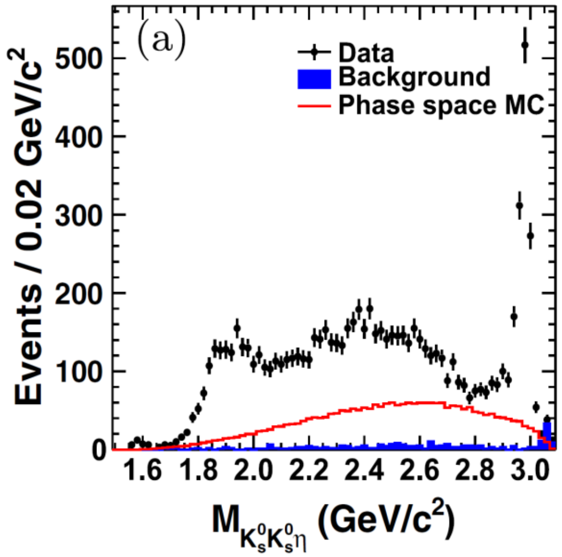
## Nominal fit solution

| state | $J^{PC}$ | Decay mode | Mass $(MeV/c^2)$ | Width $(MeV/c^2)$ | Significance |
|---|---|---|---|---|---|
| X(2370) | $0^{-+}$ | $f_0(980)\eta'$ | $2395^{+11}_{-11}$ | $188^{+18}_{-17}$ | $14.9\sigma$ |
| X(1835) | $0^{-+}$ | $f_0(980)\eta'$ | 1844 | 192 | $22.0\sigma$ |
| X(2800) | $0^{-+}$ | $f_0(980)\eta'$ | $2799^{+52}_{-48}$ | $660^{+180}_{-116}$ | $16.4\sigma$ |
| $\eta_c$ | $0^{-+}$ | $f_0(980)\eta'$ | 2983.9 | 32.0 | $> 20.0\sigma$ |
| PHSP | $0^{-+}$ | $\eta'(K_S^0K_S^0)_{S-wave}$ | − − − | − − − | $9.0\sigma$ |
| | | $\eta'(K_S^0K_S^0)_{D-wave}$ | − − − | − − − | $16.3\sigma$ |

- **$X(2370)'s\ J^{PC} = 0^{-+}$ with 9.8 $\sigma$**
- Product branching fraction:

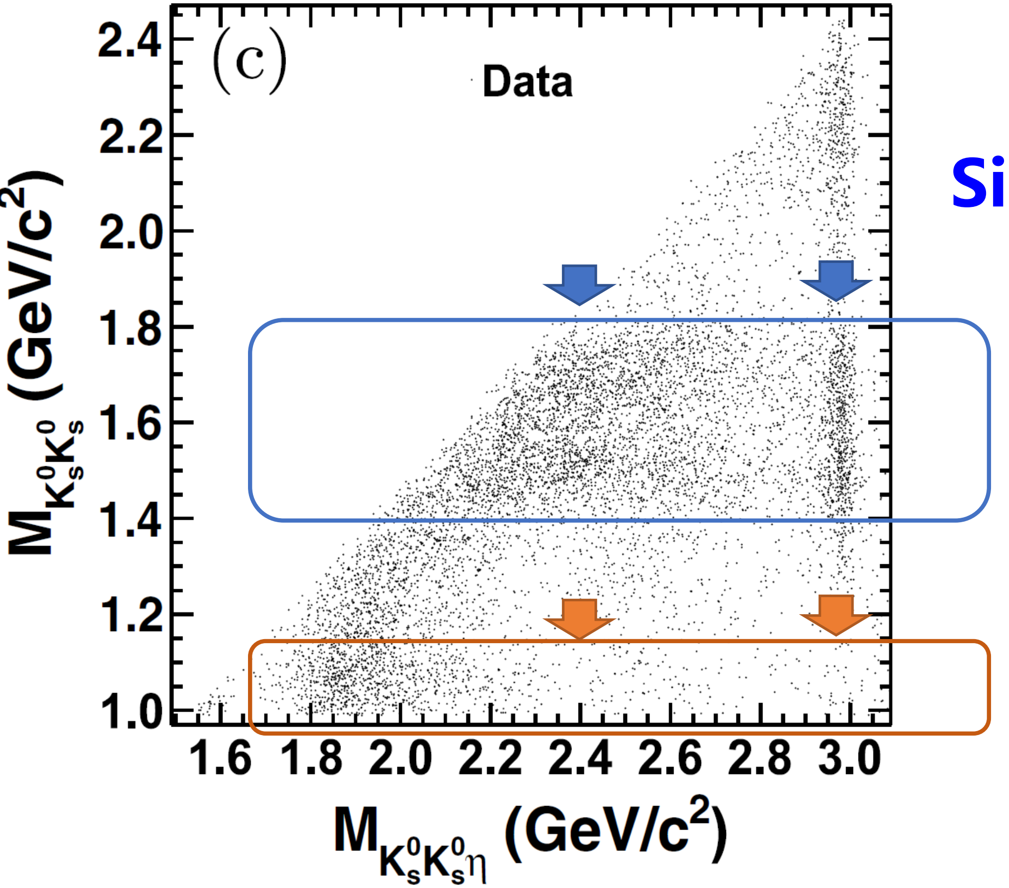
$$B(\mathrm{J}/\psi \to \gamma X(2370)B\left(X(2370) \to \eta' K_S^0 K_S^0\right)B\left(f_0(980) \to K_S^0 K_S^0\right)$$
$$= \left(1.31 \pm 0.22^{+2.85}_{-0.84}\right) \times 10^{-5}$$

# $\mathbf{X(2370)}$ seen in $J/\psi \to \gamma K_S^0 K_S^0 \eta$




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

BESIII PRL 115 091803(2015)




**Similar decay patterns of the $X(2370)$ and $\eta_c$**

**clear $X(2370)$ AND $\eta_c$ signals**

**no $X(2370)$ OR $\eta_c$ signal**

# Scalar glueball candidate: **decay properties**

Flavor-blindness of glueball decays

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

*with chiral suppression

PRL 95 172001， PRL 98 149103

Expectation:

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

Measured:

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

New inputs from $J/\psi\to\gamma\eta\eta'$

[BESIII PRL 129 192002(2022) , PRD 106 072012(2022)]

- Significant $f_0(1500)$

$$\frac{B(f_0(1500)\to\eta\eta')}{B(f_0(1500)\to\pi\pi)}=(1.66^{+0.42}_{-0.40})\times10^{-1}$$

consistent with PDG

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

$$\frac{B(f_0(1710)\to\eta\eta')}{B(f_0(1710)\to\pi\pi)}<2.87\times10^{-3}\ @90\%\ \mathrm{C.L.}$$

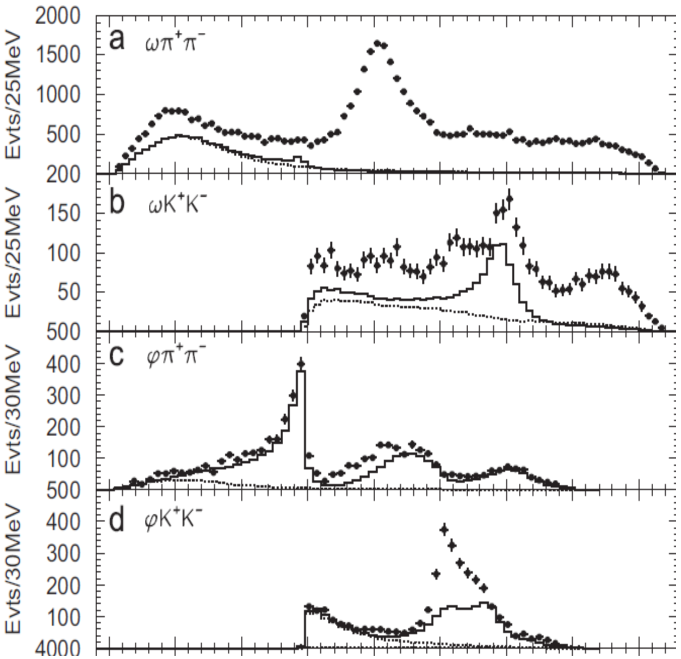
➢ Supports to the hypothesis that $f_0(1710)$ overlaps with the ground state scalar glueball
  - Scalar glueball expected to be suppressed $B(G\to\eta\eta')/B(G\to\pi\pi)<0.04$

[PR D 92, 121902; PR D 92, 114035]

**Bottom line: Predictions on mixing scheme and decay property of glueball are model-dependent**

# More scalars

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

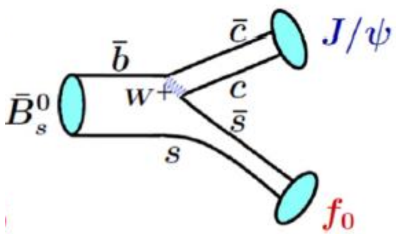



$\omega K^+K^-$ ➜ Peak around 1700 MeV/$c^2$ (OZI rule: $n\bar{n}$ structure)

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

$\phi K^+K^-$ ➜ No peak around 1700 MeV/$c^2$

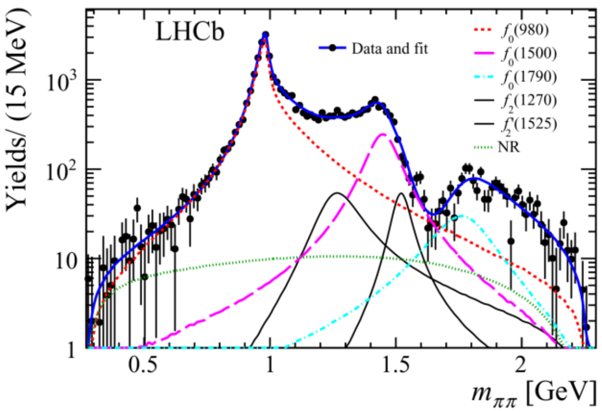
## $f_0(1800)$

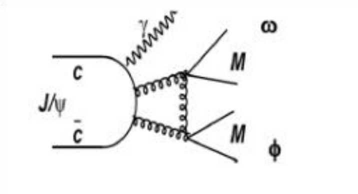



selective for $s\bar{s}$

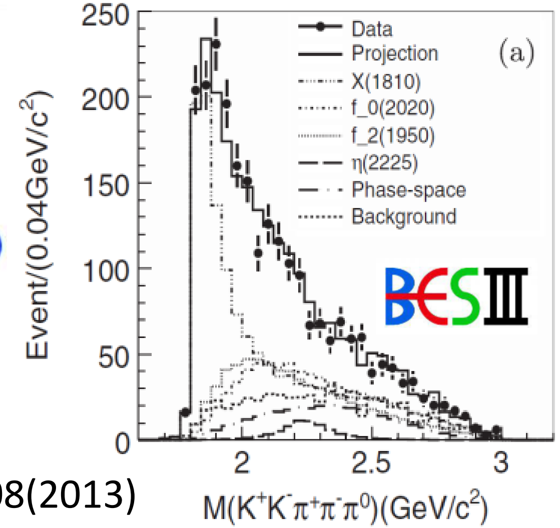
$B_s \to J/\psi f_0$

PLB 797 (2019) 134789




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



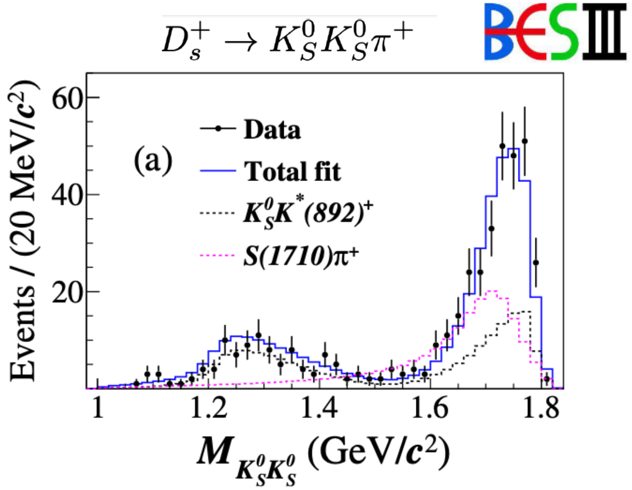

PRD 87, 032008(2013)

## $a_0(1817)$

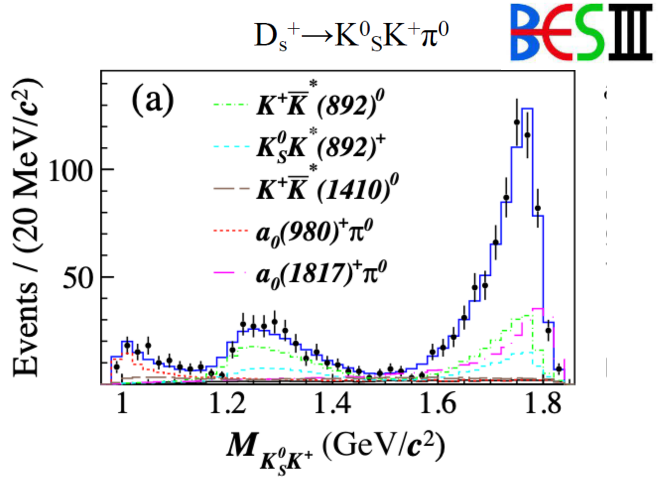
Isovector partner of $f_0(1800)$?

[Shulei 's talk]

PRD105, L051103 (2022)




PRL129, 182001 (2022)



| Parameters | $\Lambda\bar{\Lambda}$ | $\Sigma^+\bar{\Sigma}^-$ | $\Xi^-\bar{\Xi}^+$ | $\Xi^0\bar{\Xi}^0$ |
|---|---|---|---|---|
| | PRL 129, 131801(2022) | PRL 125,052004(2020) | Nature 606,64(2022) | Phys.Rev.D 108 (2023) 3, L031106 |
| $\alpha_{\Xi^-/\Xi^0}$ | - | - | $-0.376 \pm 0.007 \pm 0.003$ | $-0.3750 \pm 0.0034 \pm 0.0016$ |
| $\alpha_{\bar{\Xi}^+/\bar{\Xi}^0}$ | - | - | $0.371 \pm 0.007 \pm 0.002$ | $0.3790 \pm 0.0034 \pm 0.0021$ |
| $\phi_{\Xi^-/\Xi^0}$ | - | - | $0.011 \pm 0.019 \pm 0.009$ | $0.0051 \pm 0.0096 \pm 0.0018$ |
| $\phi_{\bar{\Xi}^+/\bar{\Xi}^0}$ | - | - | $-0.021 \pm 0.019 \pm 0.007$ | $-0.0053 \pm 0.0097 \pm 0.0019$ |
| $A_{CP}(\Xi^-/\Xi^0)$ | - | - | $0.006 \pm 0.013 \pm 0.006$ | $-0.0054 \pm 0.0065 \pm 0.0031$ |
| $\Delta\phi_{CP}(\Xi^-/\Xi^0)$ | - | - | $-0.005 \pm 0.014 \pm 0.003$ | $-0.0001 \pm 0.0069 \pm 0.0009$ |
| $\alpha_{\Lambda/\Sigma^+}$ | $0.7519 \pm 0.0036 \pm 0.0024$ | $-0.998 \pm 0.037 \pm 0.009$ | $0.757 \pm 0.011 \pm 0.008$ | $0.7551 \pm 0.0052 \pm 0.0023$ |
| $\alpha_{\bar{\Lambda}/\bar{\Sigma}^-}$ | $-0.7559 \pm 0.0036 \pm 0.0030$ | $0.990 \pm 0.037 \pm 0.011$ | $-0.763 \pm 0.011 \pm 0.007$ | $-0.7448 \pm 0.0052 \pm 0.0023$ |
| $A_{CP}(\Lambda/\Sigma^+)$ | $-0.0025 \pm 0.0046 \pm 0.0012$ | $-0.004 \pm 0.037 \pm 0.010$ | $-0.004 \pm 0.012 \pm 0.009$ | $0.0069 \pm 0.0058 \pm 0.0018$ |

**BESIII best measurements:** $A_{CP}^{\Lambda} = -0.0025 \pm 0.0046 \pm 0.0012$
**Systematic uncertainties are well controlled!**

- Excellent performance of BESIII detectors.
- Data-driven method to study data-MC inconsistency.