Highlights of hadron physics@ BESIII

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(on behalf of BESIII)

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Hadrons

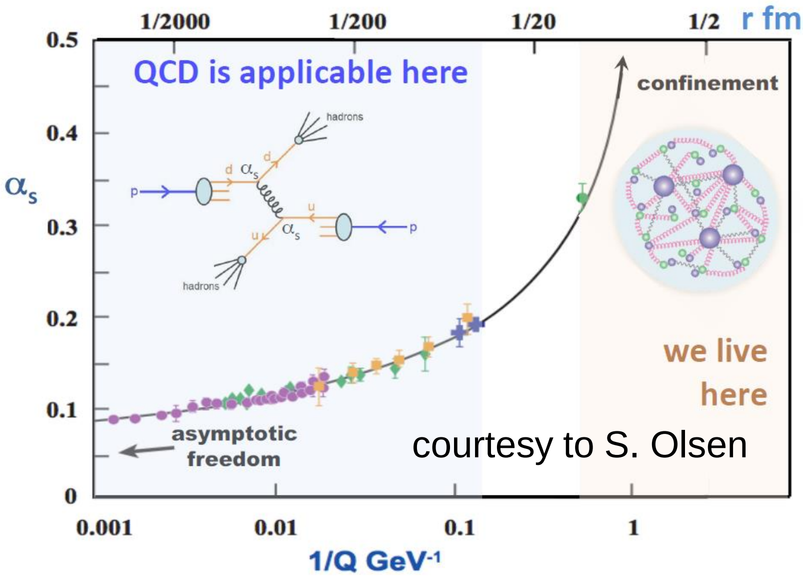
- **Dominant part of visible matter in the universe**
- **To fully understand the strong interaction**
  - **Understanding the rich and complex features of its bound states, hadrons**

➢ How are hadrons formed from quarks and gluons?

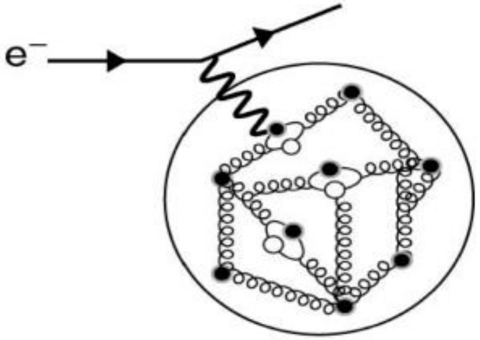
➢ What is the origin of confinement?

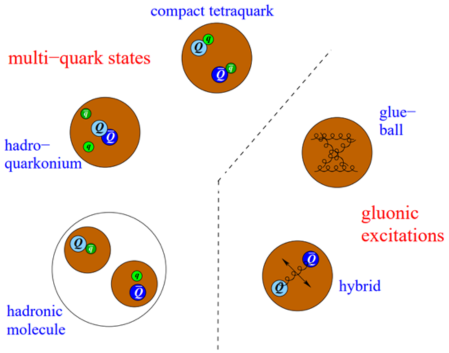
➢ How is the mass of hadron generated in QCD?

➢ What is the dynamics of effective DoF in hadrons?

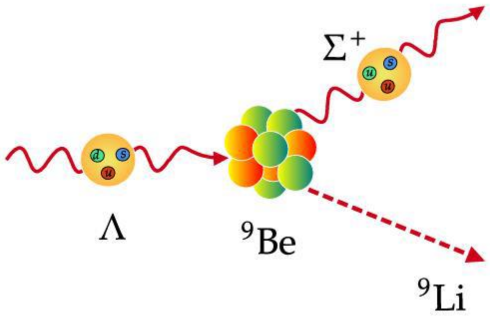


courtesy to S. Olsen





Phys.Rept. 873 (2020) 1



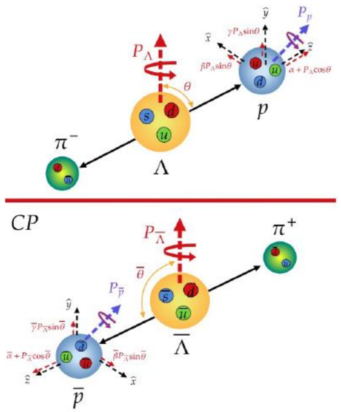
Structure

Spectroscopy

Interactions

Hadron physics

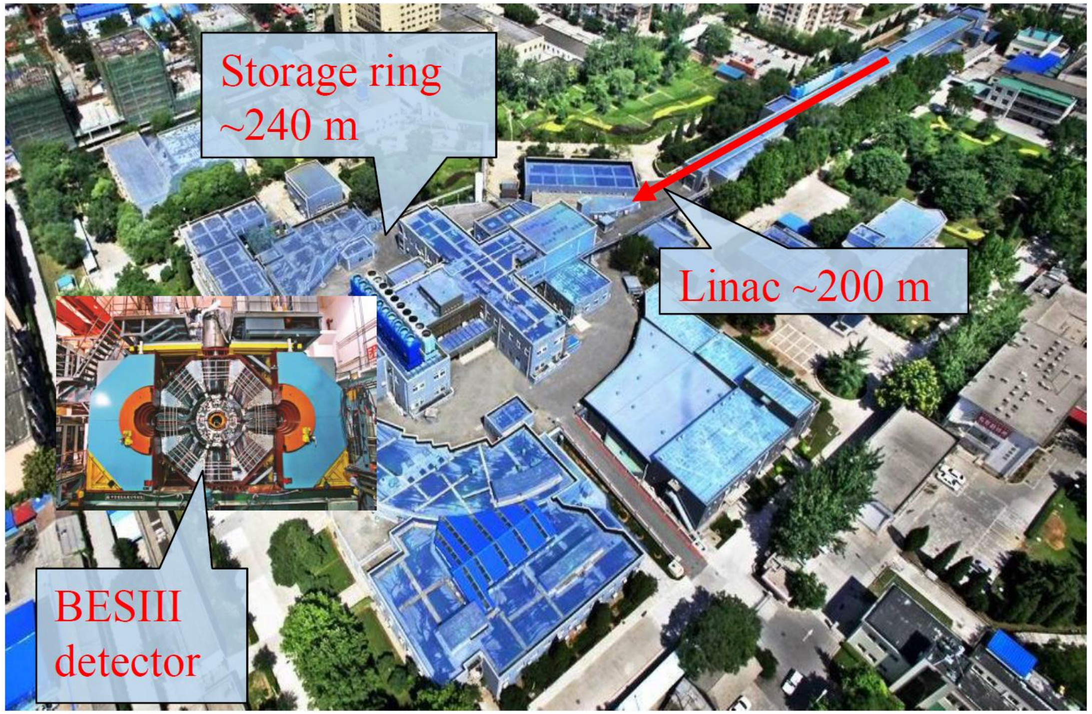
Precision tests & rare phenomena



*See Shuangshi's talk

BESIII@BECPII

Beijing Electron Positron Collider(BEPCII)



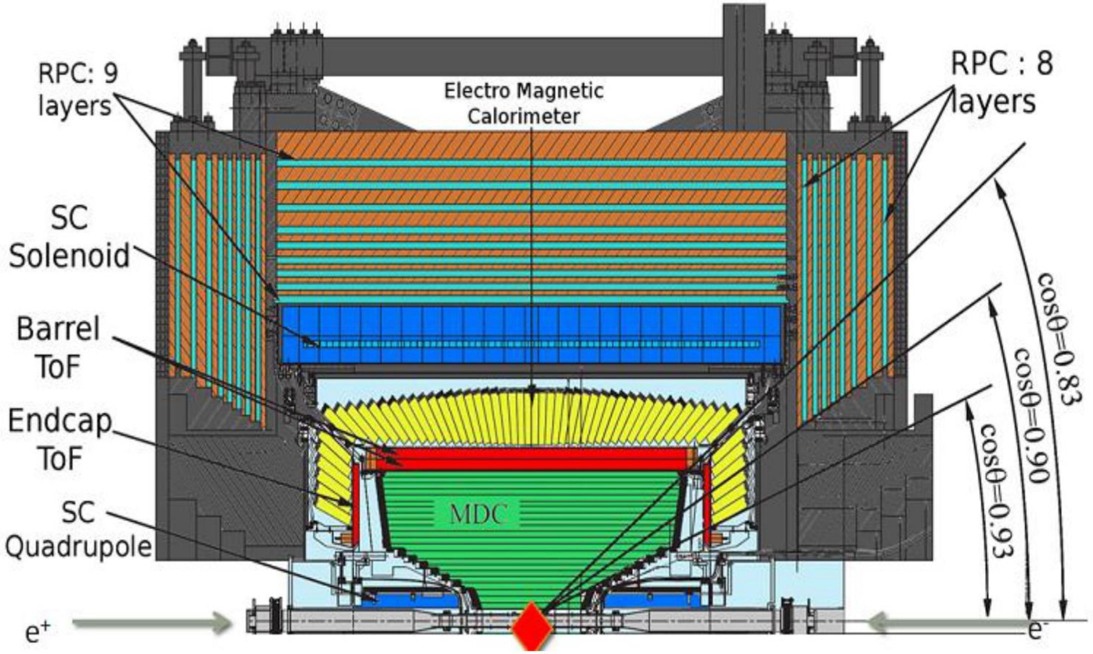
Double-ring, symmetry, multi-bunch $e^+ e^-$ collider

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: 1.1×10^{33} $cm^{-2}s^{-1}$

Beijing Spectrometer(BESIII)



Main Drift Chamber	Time Of Flight	Electromagnetic Calorimeter	Muon Counter
Small cell, 43 layer	Plastic scintillator	CsI(Tl): L=28 cm	RPC
σ_{xy}=130 μm	σ_T(barrel): 65 ps	Barrel σ_E=2.5%	Barrel: 9 layers
dE/dx~6%	σ_T(endcap): 110 ps	Endcap σ_E=5.0%	Endcap: 8 layers
σ_p/p= 0.5% at 1 GeV	(update to 60 ps with MRPC)		$\sigma_{spatial}$: 1.48 cm

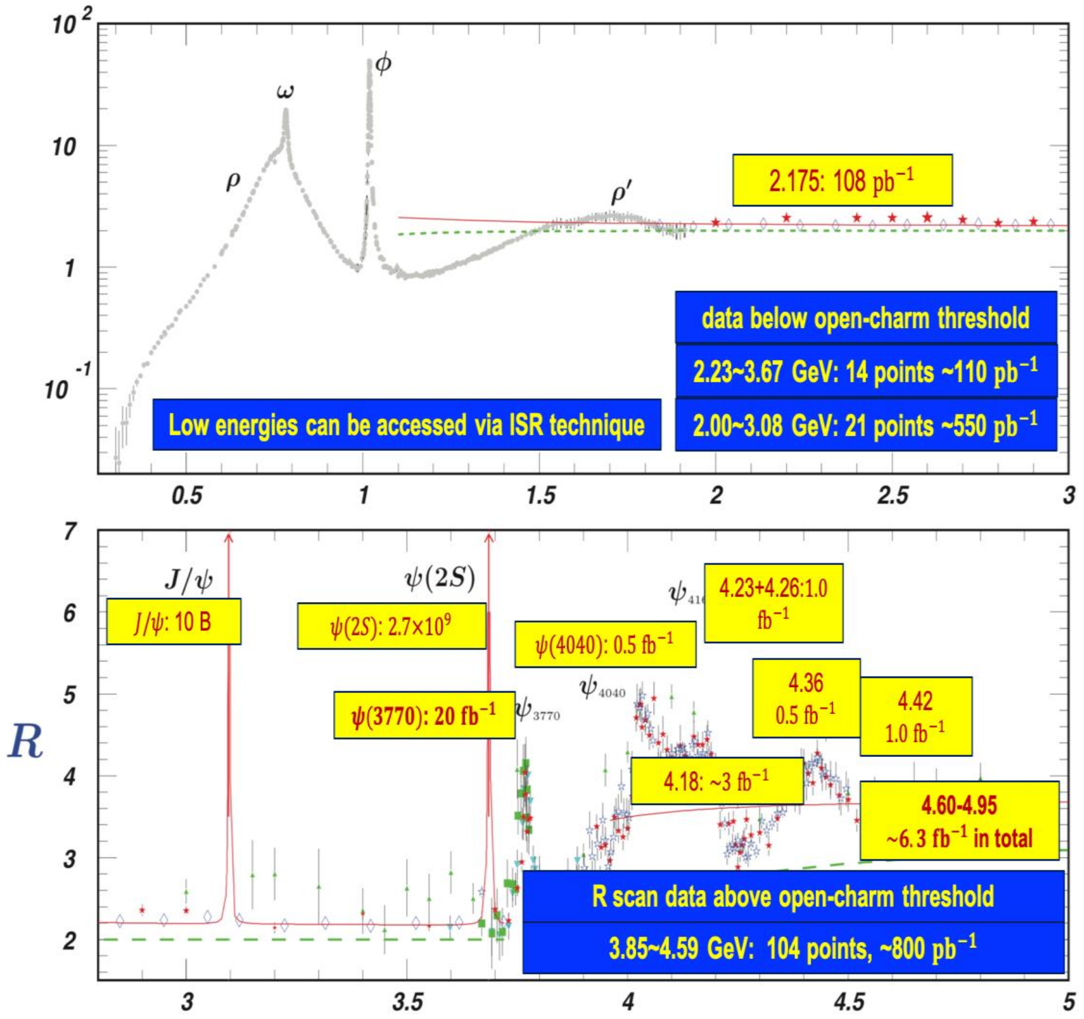
BESIII collaboration: ~600members from 17countries，89 institutions

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

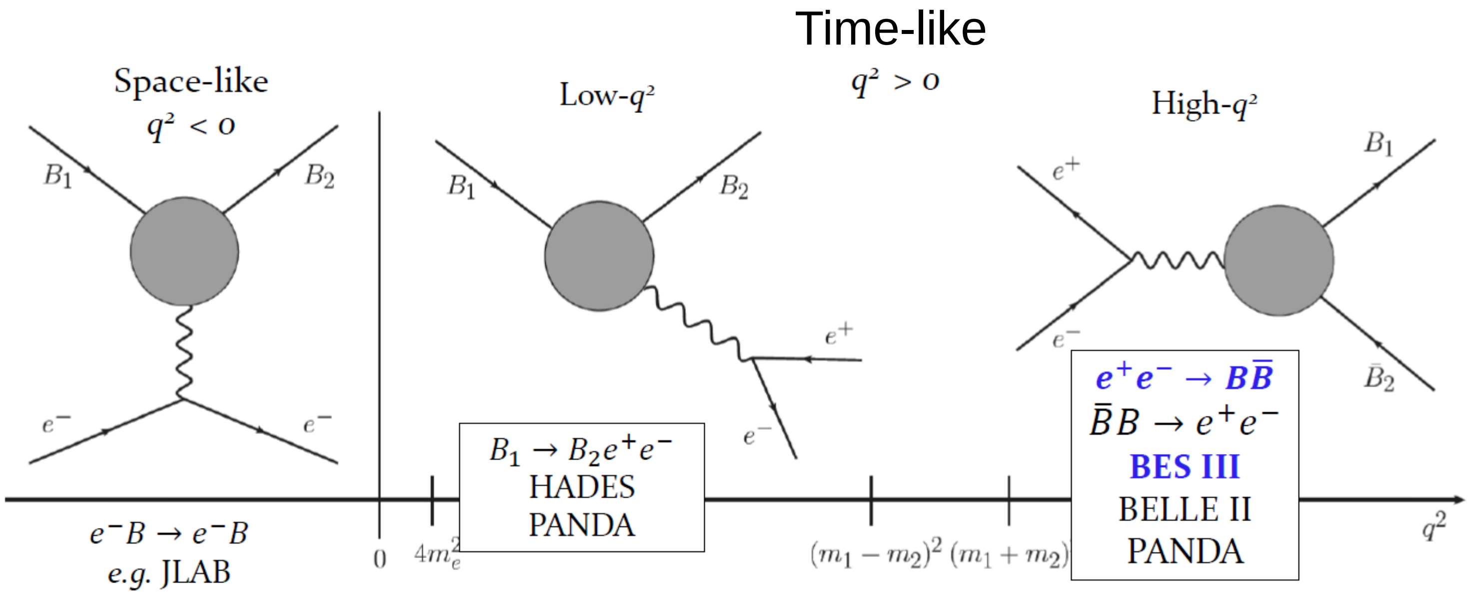
- **10×10^9 J/ψ events**
- **2.7×10^9 $\psi(2S)$ events**
- **20 fb^{-1} $\psi(3770)$**
- Scan data [1.84, 3.08] GeV; [3.735, 4.600]GeV, 143 energy points, ~2.0 fb^{-1}
- Large data sets for XYZ study ~22 fb^{-1}
- Entangled hadron pair-productions near thresholds



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

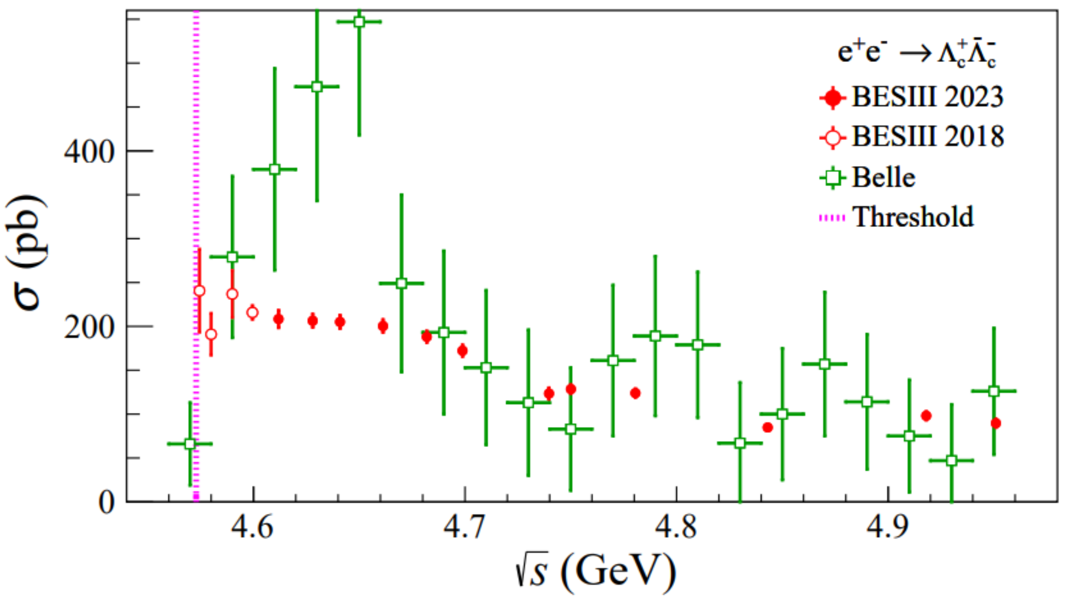
$e^+e^- \to \Lambda_c^+\overline{\Lambda_c}^-$

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

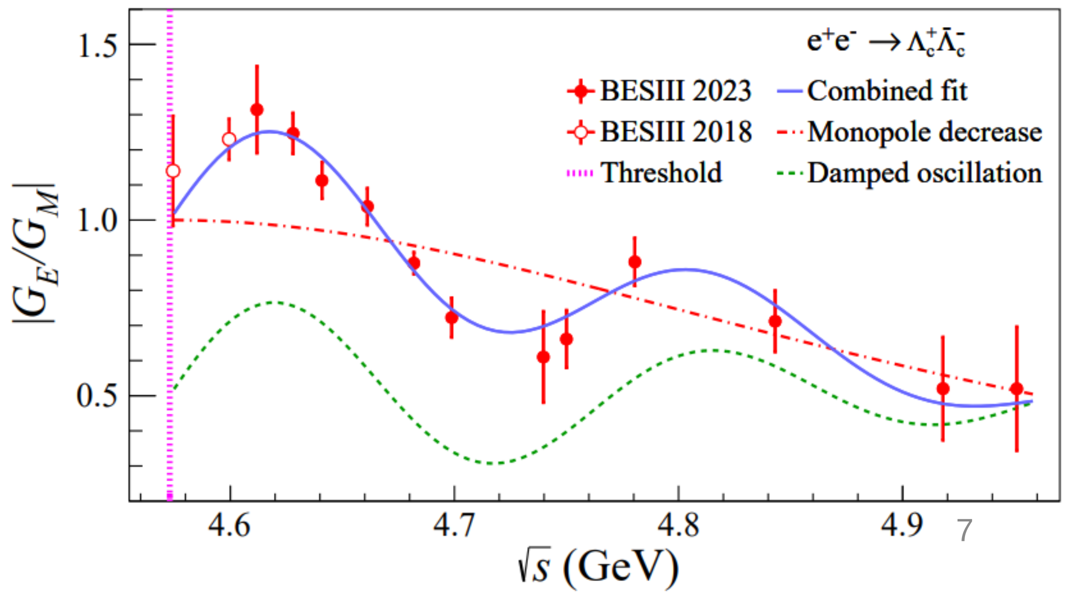
- No discernible oscillations of the effective form factors G_{eff}



With the polar-angle distribution of Λ_c^+

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

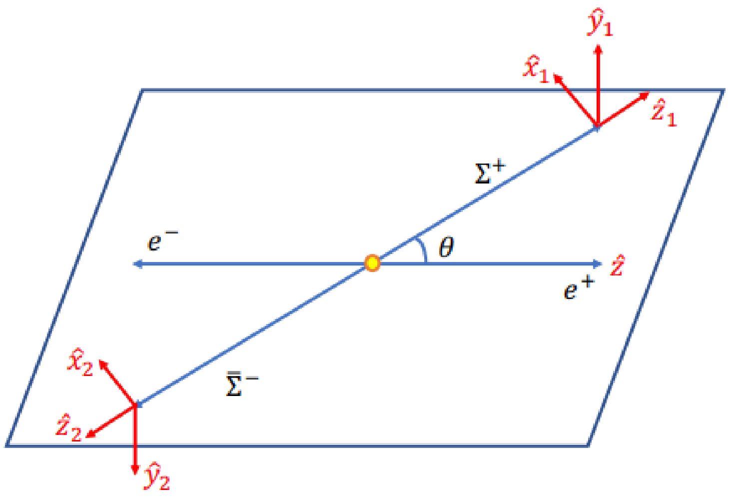
→Damped oscillations with frequency ~3.5 times larger than for the proton



Complete decomposition of Σ^+ 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 Σ^+ EMFFs can be extracted:

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



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

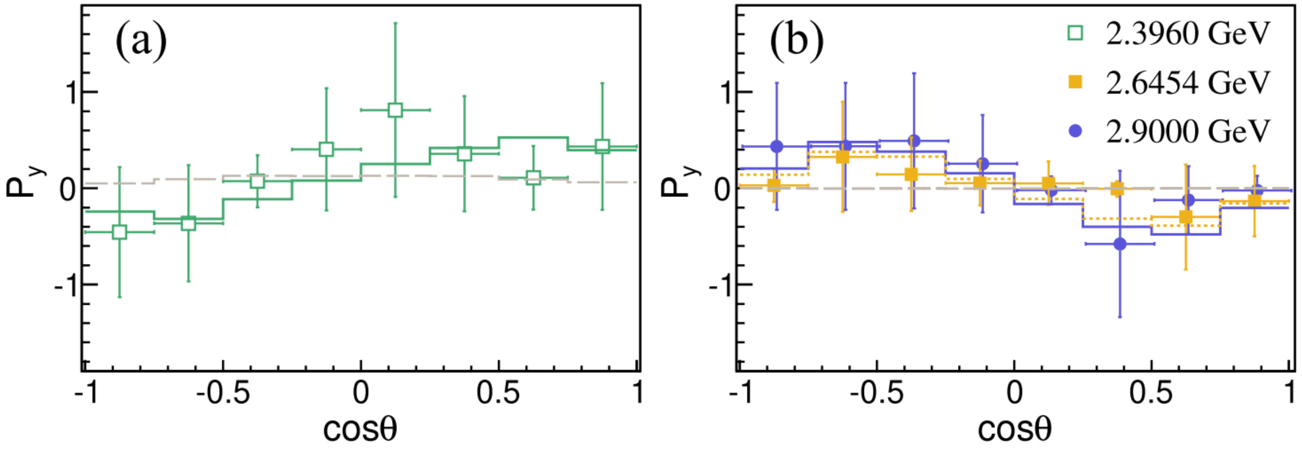
- A nonzero relative phase leads to polarization P_y of the out going baryons:

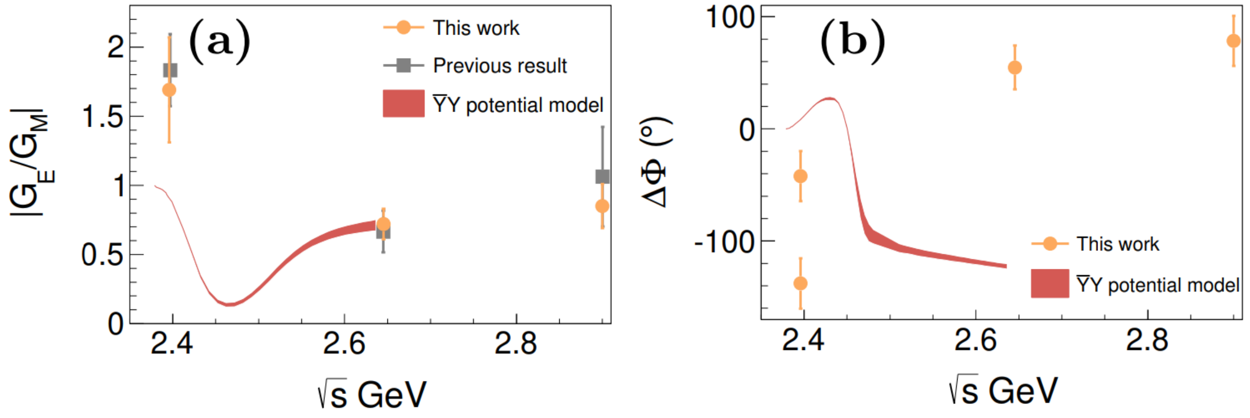
$$P_y = \frac{\sqrt{1-\alpha^2}\sin\theta\cos\theta}{1+\alpha\cos^2\theta}\sin(\Delta\Phi)$$

Complete decomposition of Σ^+ EMFFs

BESIII PRL 132, 081904 (2024)

- Polarization is observed at $\sqrt{s}$=2.396, 2.644 and 2.90 GeV with a significance of 2.2σ, 3.6σ and 4.1σ
- 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

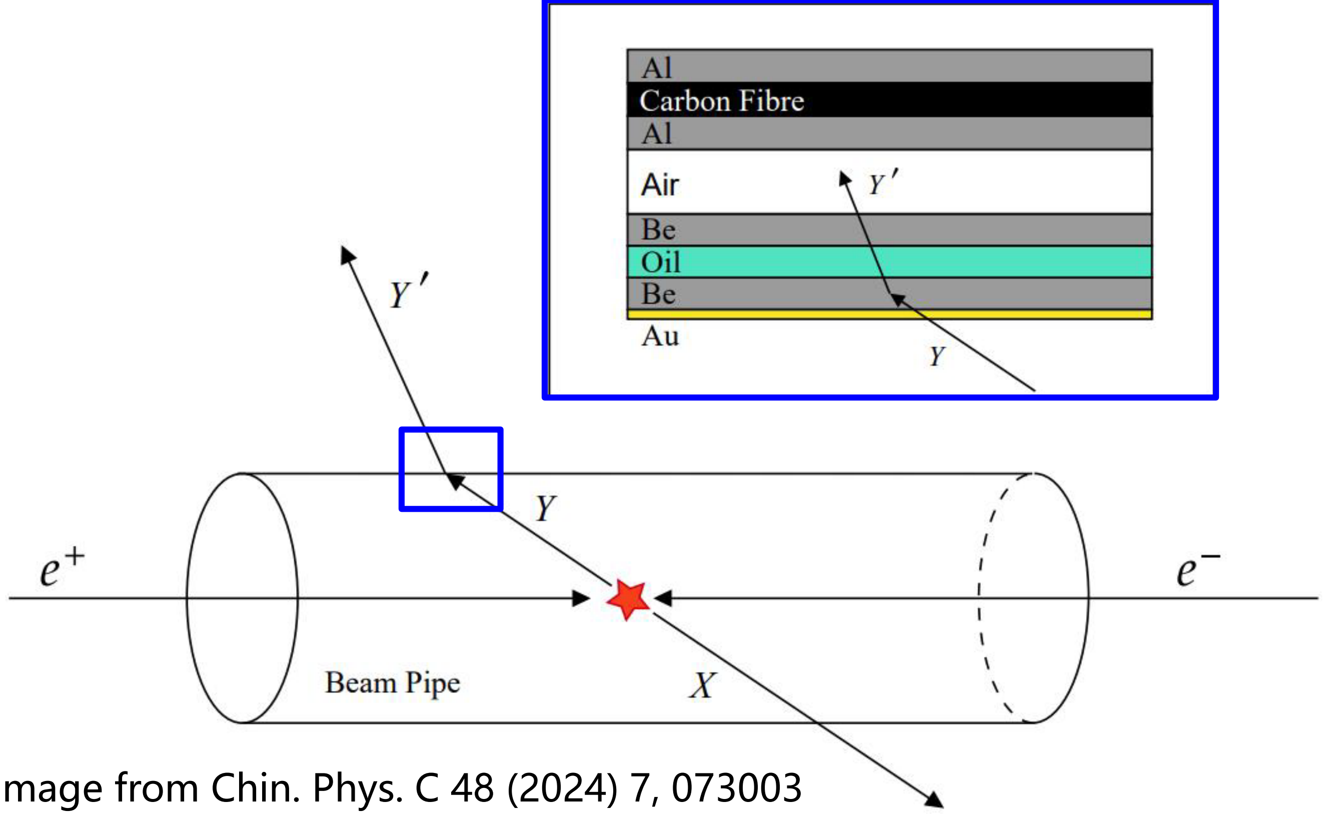


Image from Chin. Phys. C 48 (2024) 7, 073003

Hadron (YN) interactions with BESIII

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

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

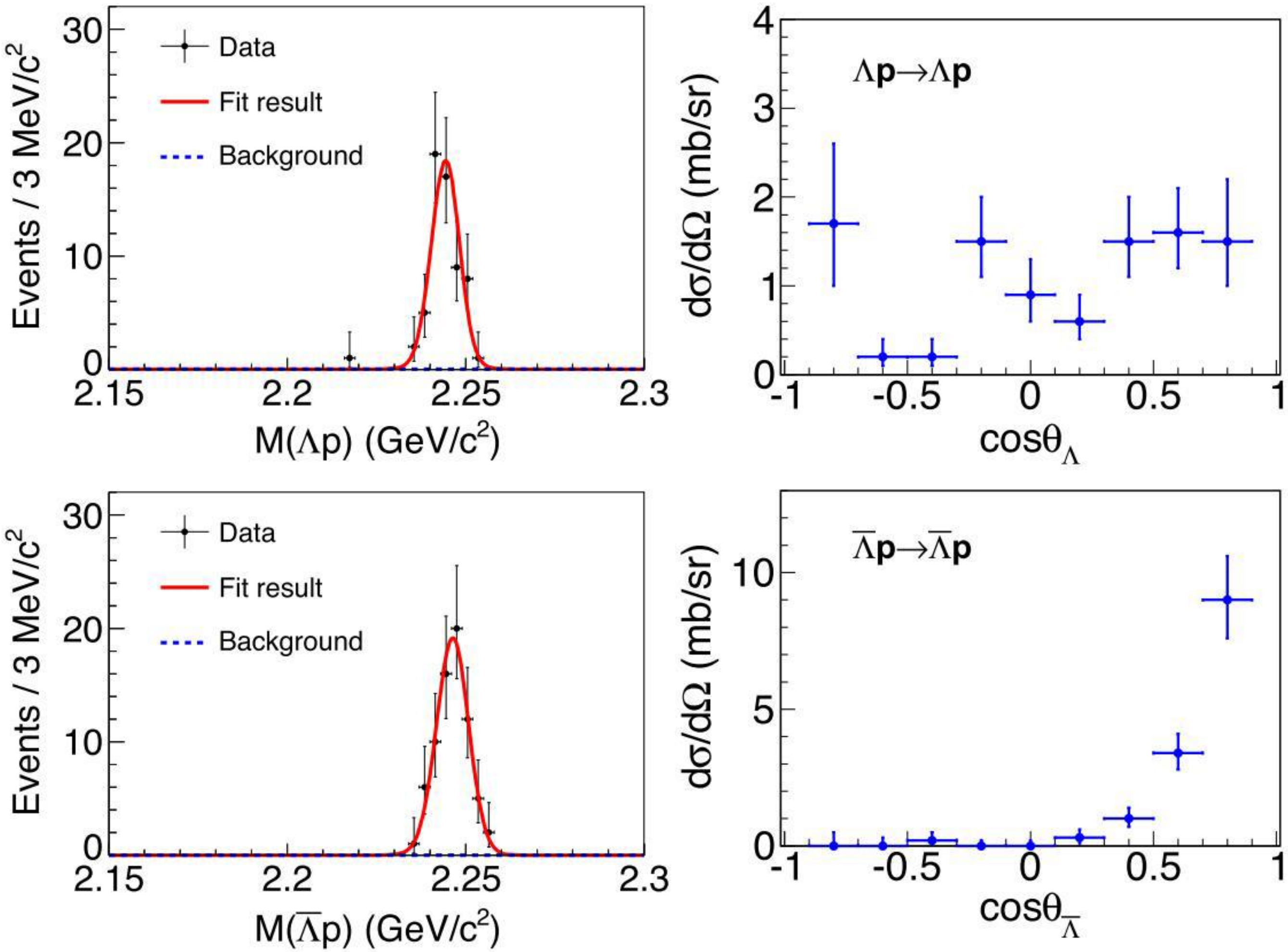
First study of antihyperon-nucleon scattering

BESIII PRL 132, 231902 (2024)

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

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

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



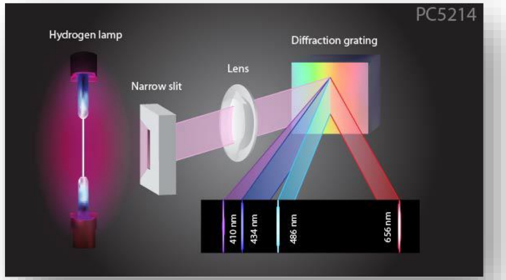
$\sigma(\Lambda p \to \Lambda p) = (12.2 \pm 1.6(\mathrm{stat.}) \pm 1.1(\mathrm{syst.}))$ mb

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

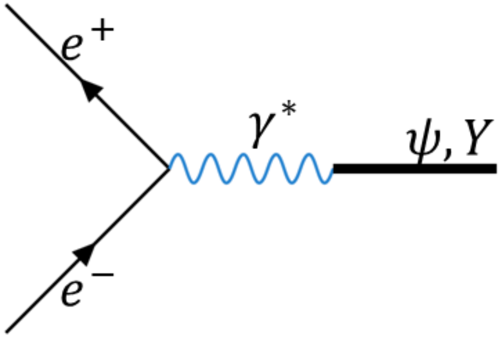
Bohr model → QED

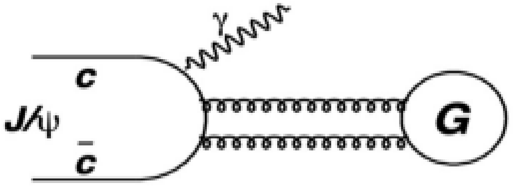


Hadron spectrum:

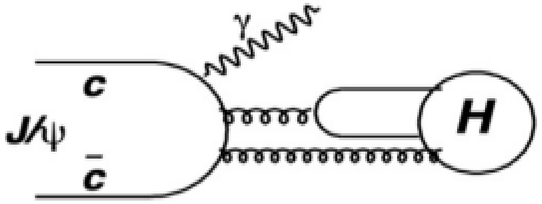
Quark model → QCD

Hadron spectroscopy with BESIII





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



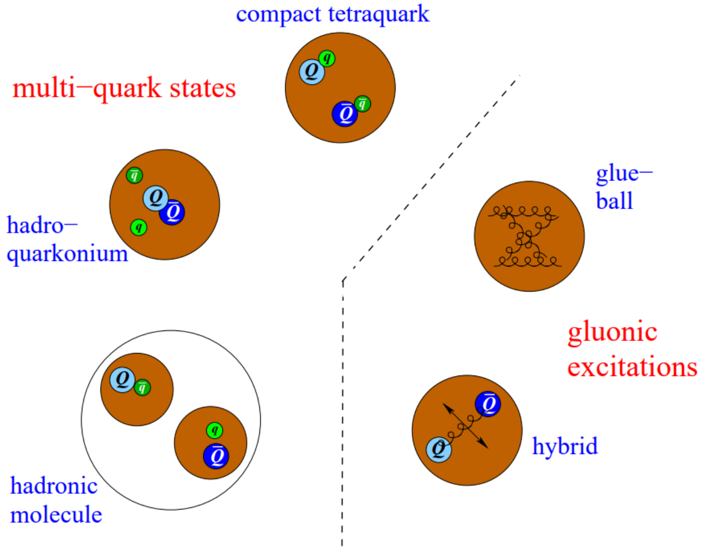
$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$

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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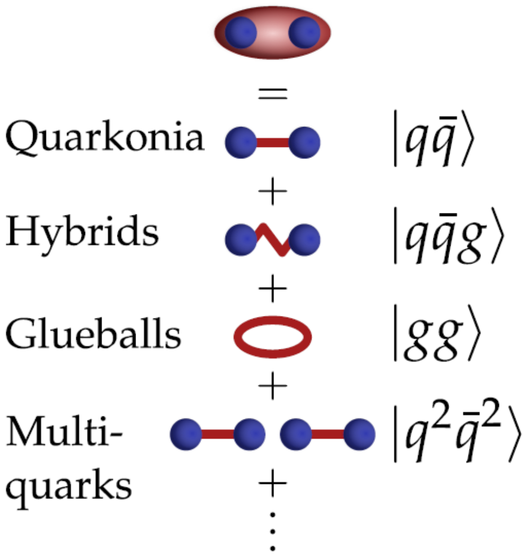


Physical meson

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

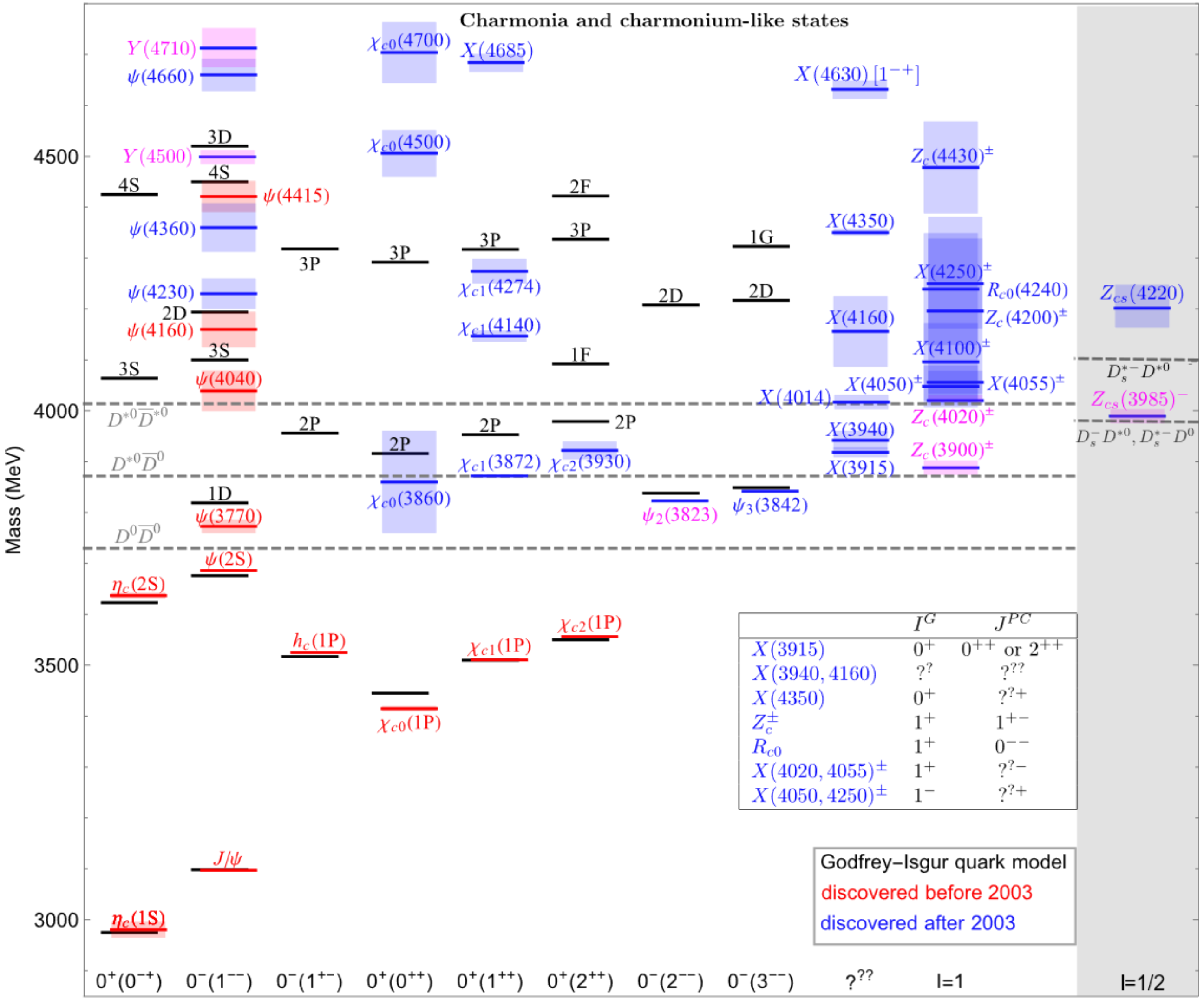
Crypto exotic: with QN as $q\bar{q}$

Supernumerary states - -> **glueball**

Abnormal properties

+ Kinematic effects

Charmonium-like states

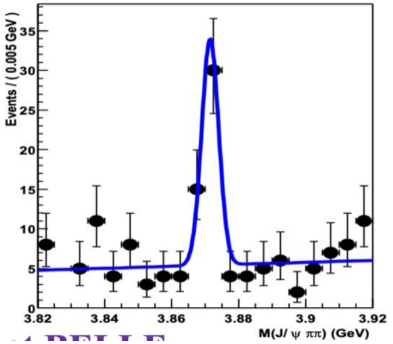


arXiv:2203.08290

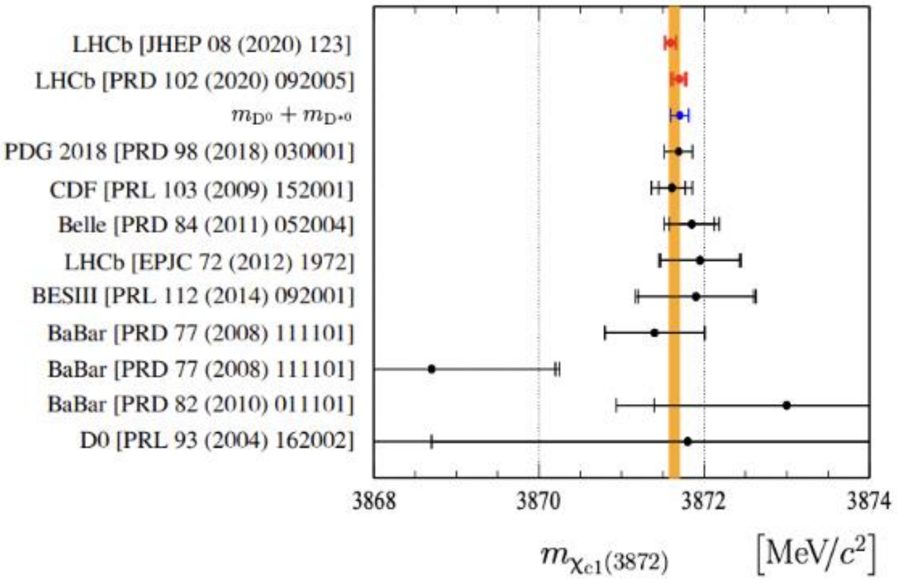
- Conventional $c\bar{c}$ meson fit well with potential model
- Abundance of new states with various probes
  - b-hadron decays
  - hadron/heavy-ion collisions
  - $\gamma\gamma$ processes
  - e^+e^- collisions
    - BESIII: dominant for vectors and states produced from vector decays

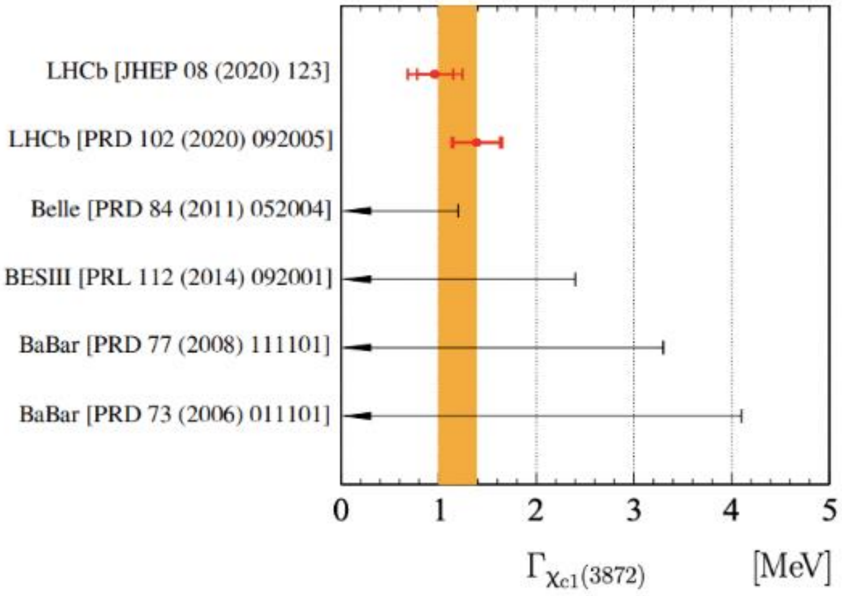
X(3872)

Discovery at Belle



PRL **91**, 262001 (2003)





Many experiments contribute to it

- Spin assignment: $\mathbf{J^{PC} = 1^{++}}$
- Mass is consistent with **m(D⁰) + m(D*⁰)**
- Width is **surprisingly narrow**
- **Prompt production:** X(3872)-$\psi(2S)$ yield ratio from p-p with increasing multiplicities toward p-Pb and Pb-Pb collisions
- **Decay properties:** $\rightarrow \omega J/\psi, \rho J/\psi; \rightarrow \gamma J/\psi, \gamma\psi(2S)$

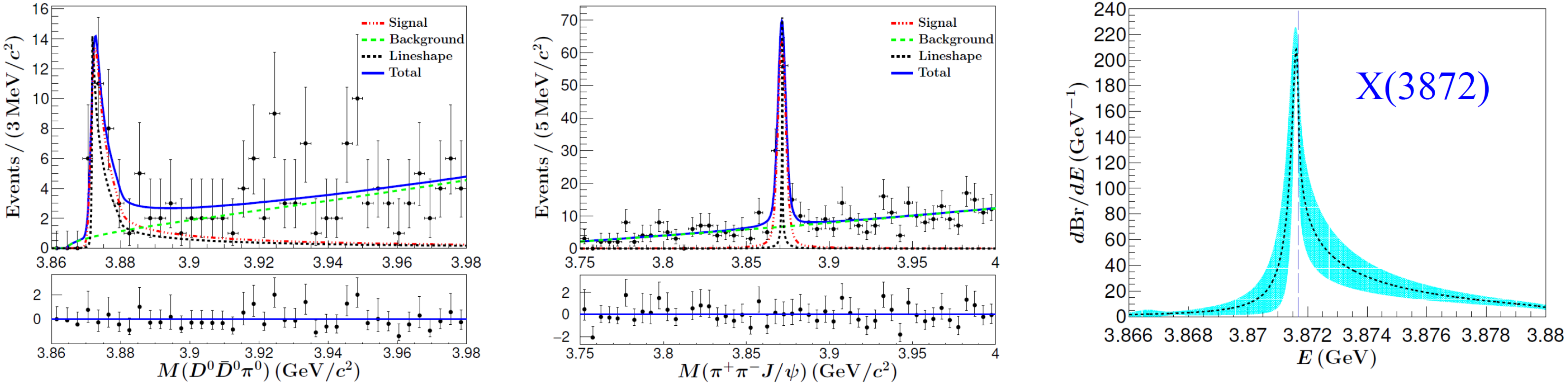
Its nature is still under debate!

→ conventional $\chi_{c1}(2^3P_1)$, DD* molecular state, tetraquark, hybrid, vector glueball, or mixed?

[BESIII PRL 124, 242001 (2020)]

X(3872) line shape @BESIII

$e^+e^- \to \gamma X(3872), X(3872) \to D^0\bar{D}^0\pi^0$ and $\pi^+\pi^- J/\psi$ 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: $E - E_X + g\sqrt{-2\mu(E - E_R + i\Gamma/2)}$

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

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

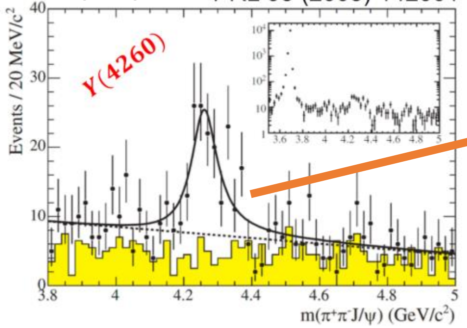
	LHCb	Belle	BESIII
g	$0.108 \pm 0.003^{+0.005}_{-0.006}$	$0.29^{+2.69}_{-0.15}$	$0.16 \pm 0.10^{+1.12}_{-0.11}$
$Re[E_I]$ [MeV]	7.10	7.12	$7.04 \pm 0.15^{+0.07}_{-0.08}$
$Im[E_I]$ [MeV]	-0.13	-0.12	$-0.19 \pm 0.08^{+0.14}_{-0.19}$
$Re[k^+]$ [MeV]	-13.9	-15.3	$-12.6 \pm 5.5^{+6.6}_{-6.2}$
$Im[k^+]$ [MeV]	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)	$0.08^{+0.04}_{-0.03}$	$0.18^{+0.06}_{-0.17}{}^{+0.19}_{-0.16}$

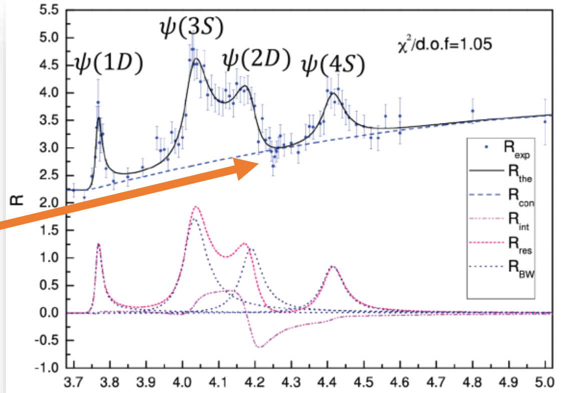
Weinberg's compositeness: *Z*=1: pure elementary state; *Z*=0: pure bound (composite) state

Vector states: Y(4260) → Y(4230)

- Y(4260) firstly seen by BaBar
  - Inconsistent with simple $c\bar{c}$ scenario
  - Candidates for exotics:
    - Hybrid /molecule /Tetraquark ?

BaBar PRL 95 (2005) 142001

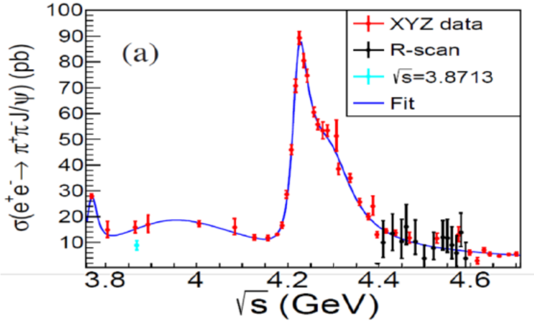




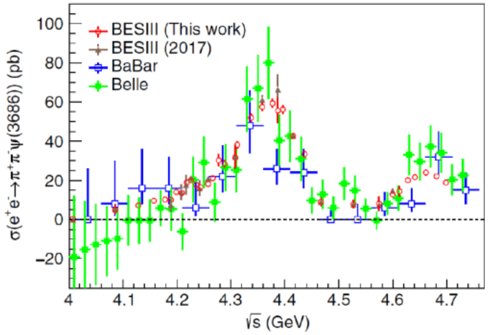
PLB 660:315-319 (2008)

Y(4230) appears in $\pi\pi J/\psi, \omega\chi_{c0}, \pi\pi h_c, \eta_c 3\pi, KKJ/\psi, D^0 D^{*-}\pi^+, D^{*0} D^{*-}\pi^+$

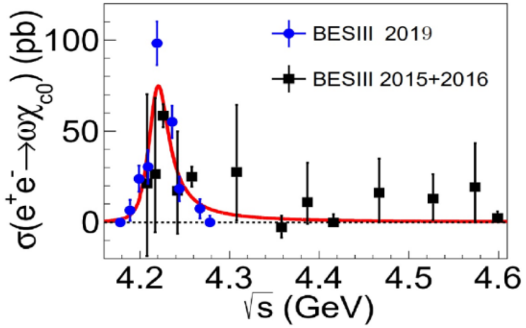
PRD106, 072001 (2022)



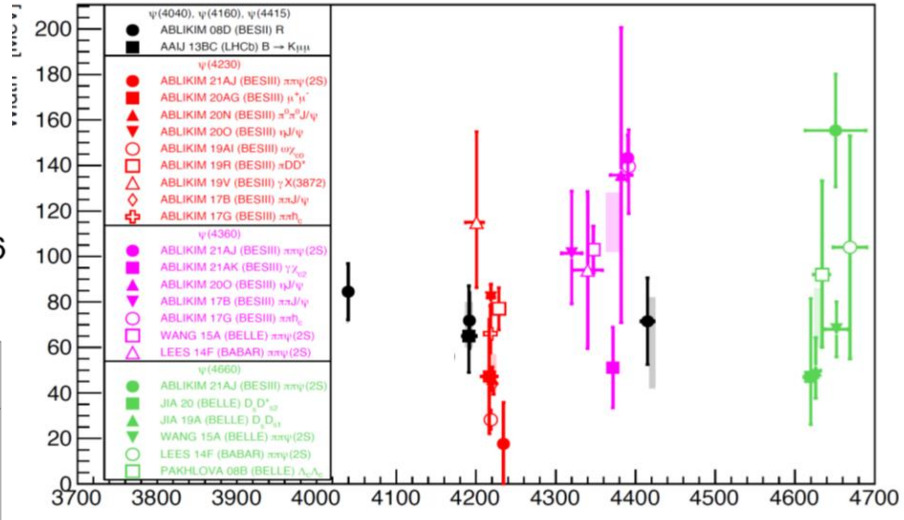
PRD104, 052102 (2021)



PRD99, 091103 (2019)

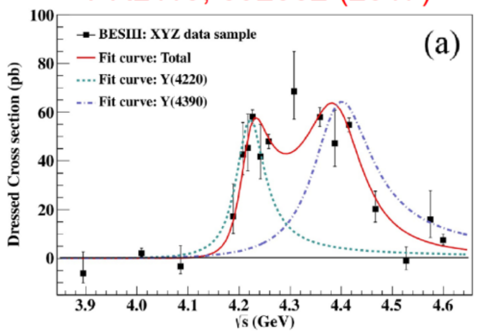


PDG 2022 ψ States

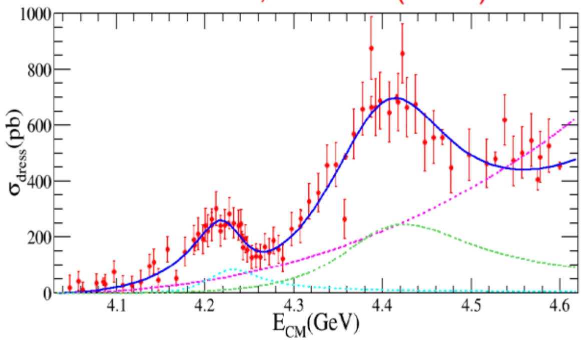


Plot from R. Mitchell

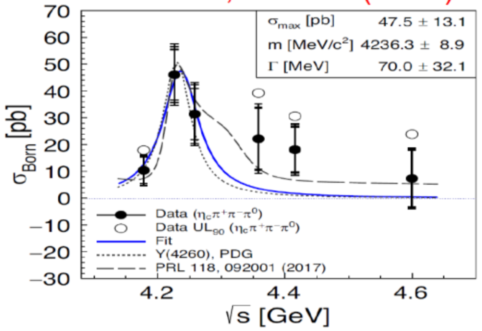
PRL118, 092002 (2017)



PRL122, 102002 (2019)



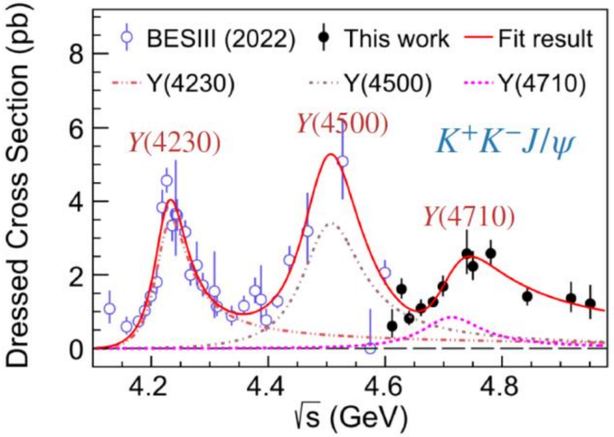
PRD 103, 032006 (2021)



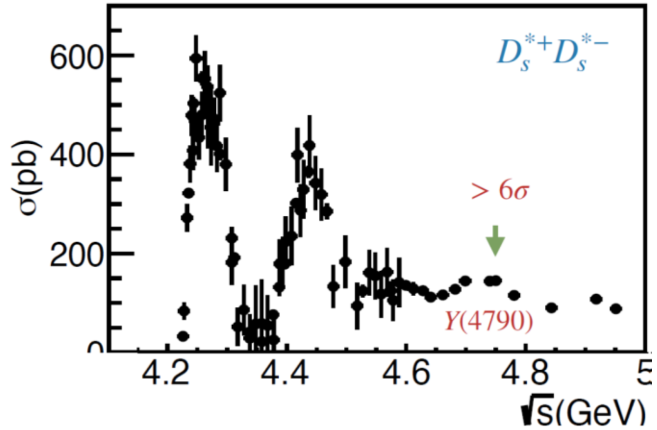
Mass~4220 MeV, width~ 50 MeV

Observations of Y(4500), Y(4710) and Y(4790)

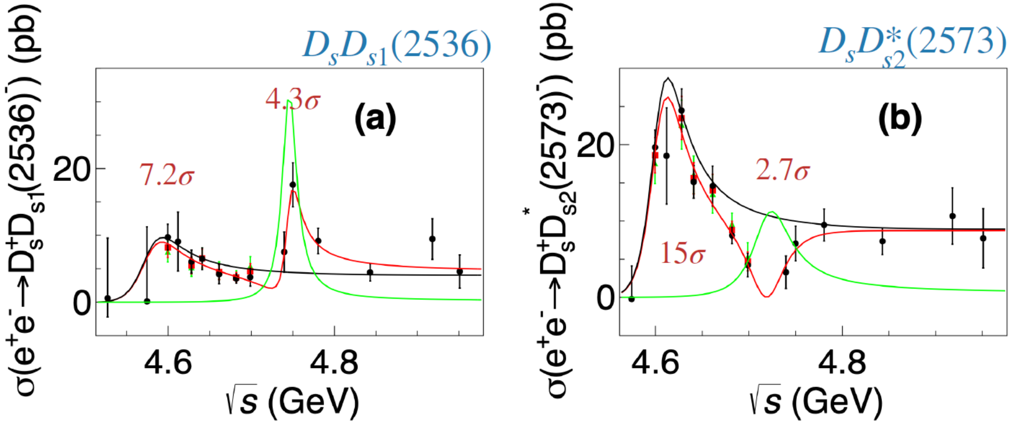
CPC 46, 111002 (2022)
PRL131, 211902 (2023)

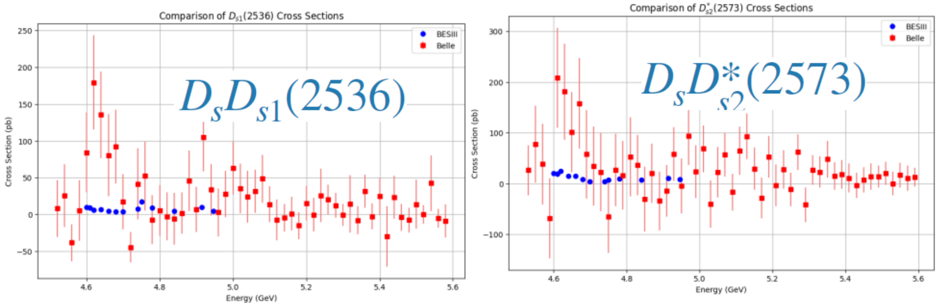


PRL131, 151903 (2023)



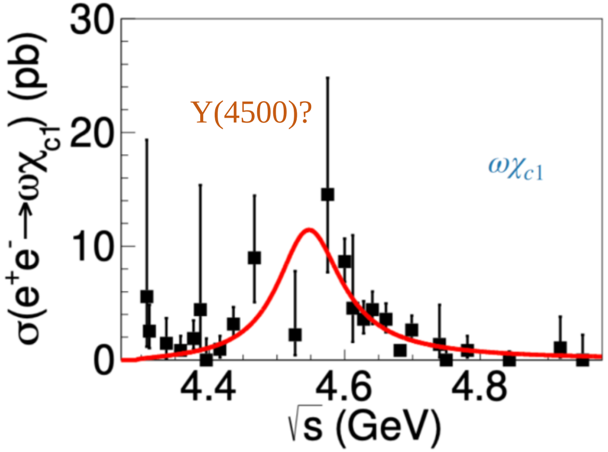
arXiv:2407.07651



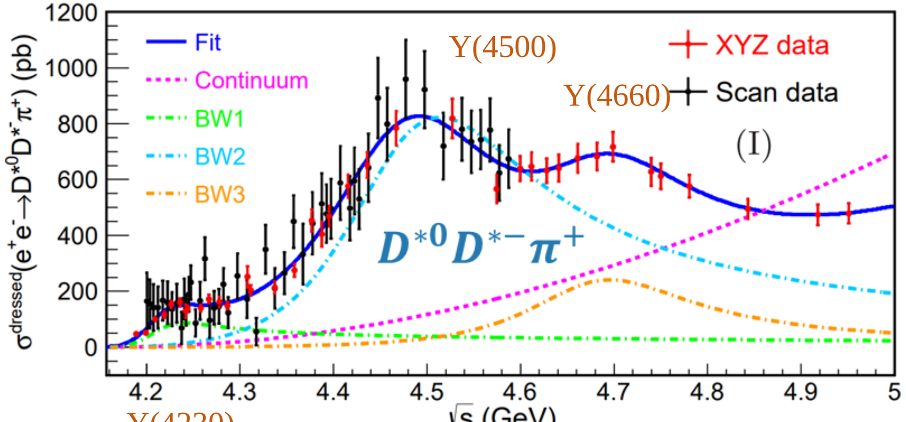


Tension between direct (BESIII) and ISR(Belle) measurements

PRL 132, 161901 (2024)

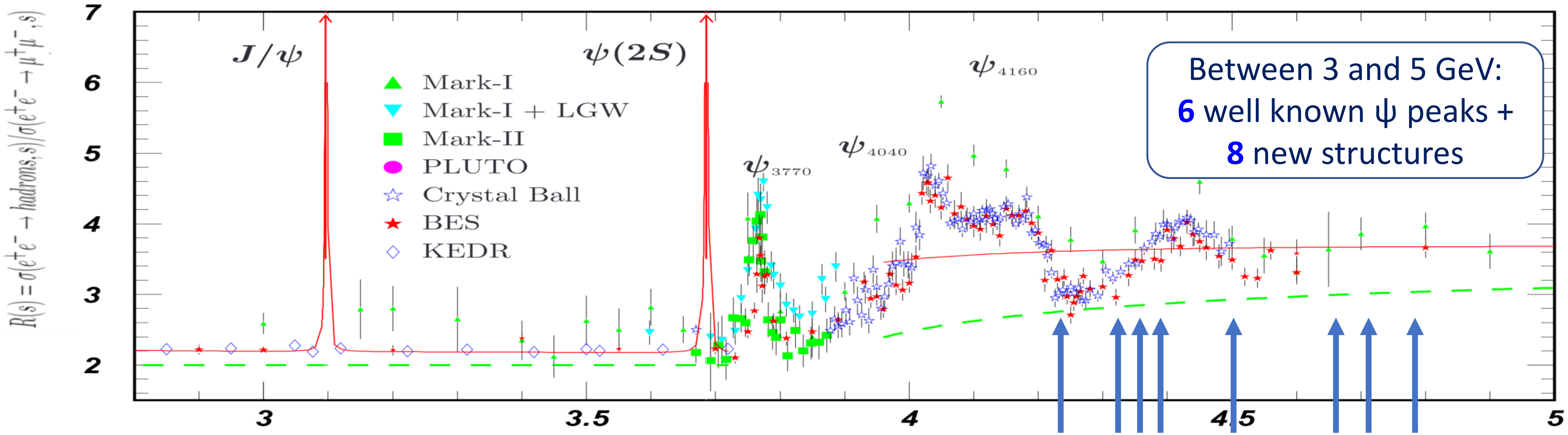


PRL130, 121901 (2023)



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

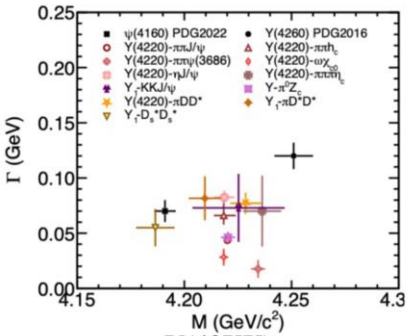
How many vectors in charmonium energy region?



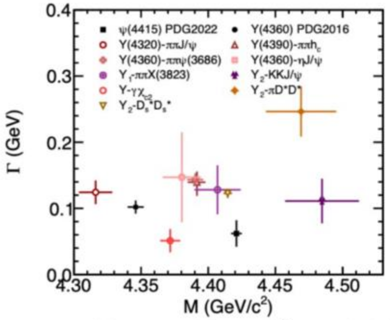
Y(4230), Y(4320), Y(4500) Y(4660), Y(4710),
Y(4360), Y(4390) Y(4790)

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?

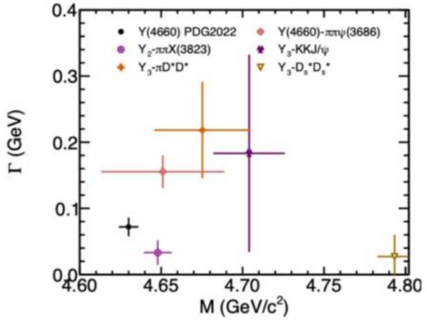
→ **More theoretical/experimental efforts necessary**



Y(42XX)



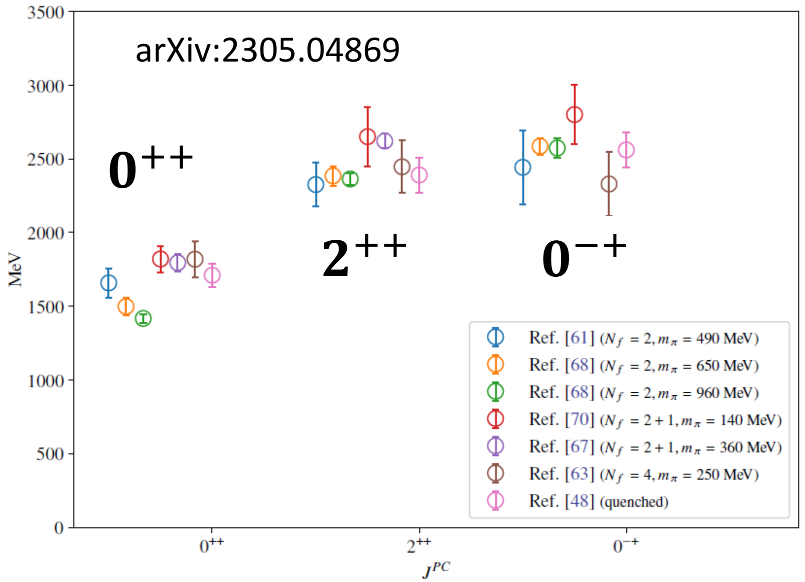
Y(43XX), ψ(4415), Y(4500)



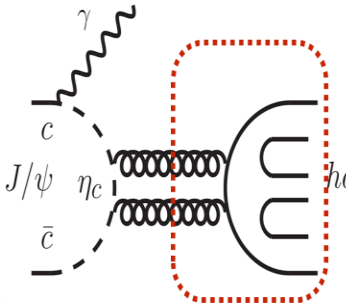
Y(46XX), Y(47XX)

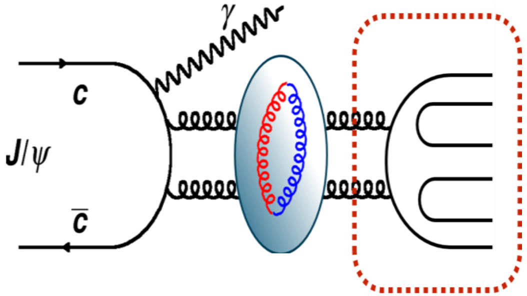
Glueball hunting for over 40 years

- 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)





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

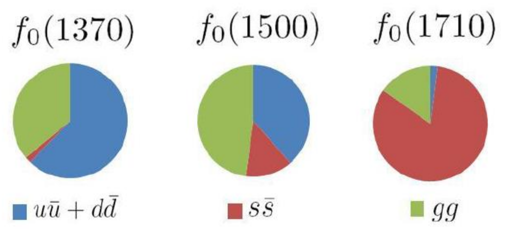
  ➢**BESIII: $f_0(1710)$ largely overlays with the scalar glueball**

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

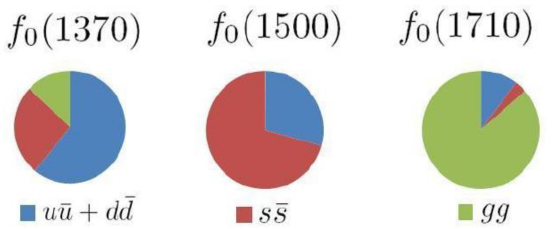
  [PLB 816, 136227 (2021), EPJC 82, 80 (2022), PLB 826, 136906 (2022)]
- **Further more, suppression of $f_0(1710) \to \eta\eta'$ supports $f_0(1710)$ has a large overlap with glueball**

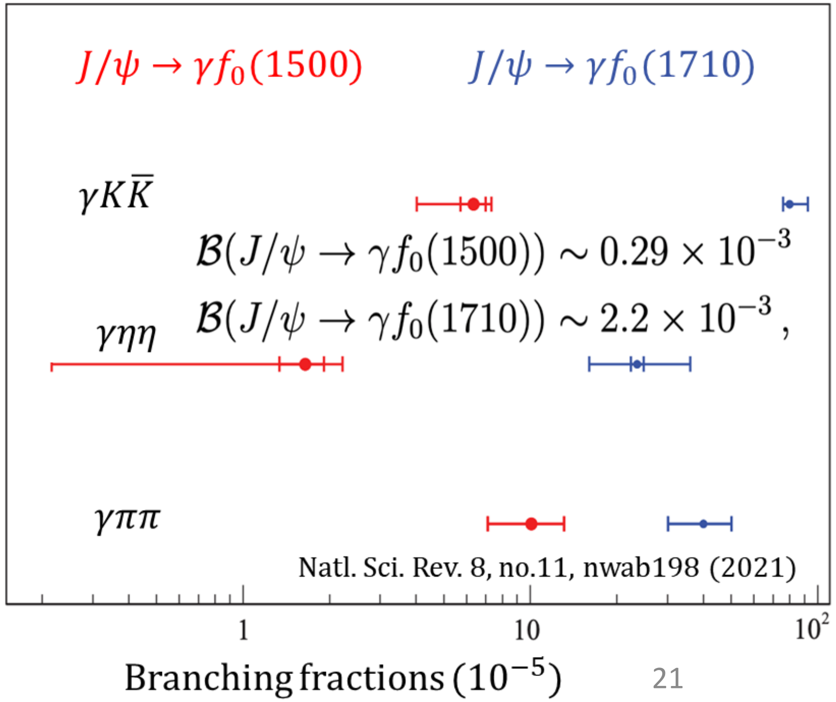
BESIII [PRD 106 072012(2022)]

Close and Kirk, PLB483 (2000) 345



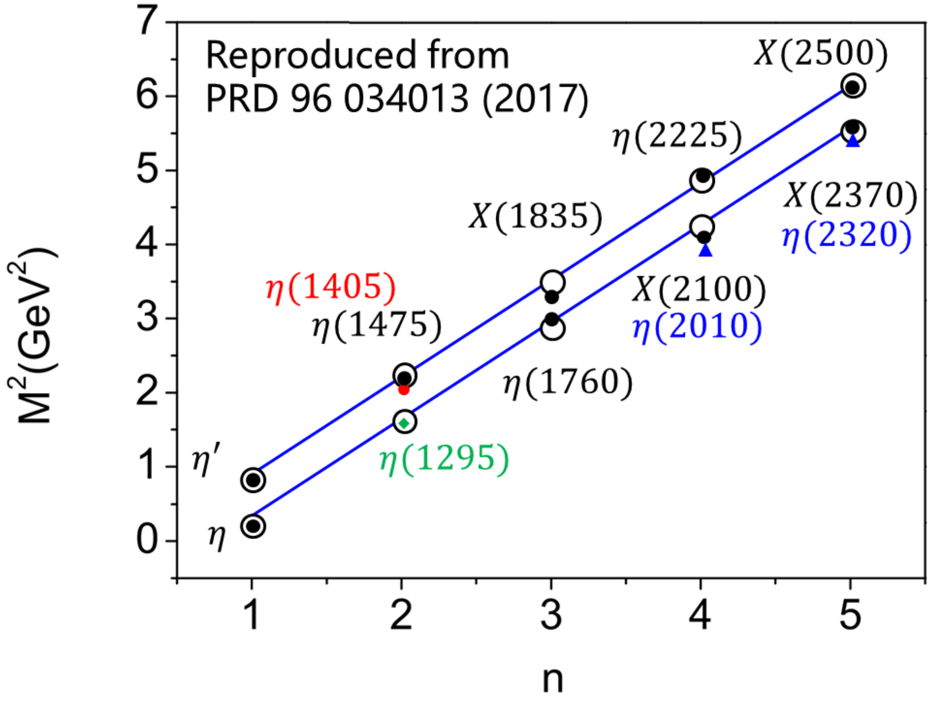
Cheng et al, Phys. Rev. D74 (2006) 094005





Where is the 0^{-+} glueball

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



$\eta_c \to 3$ P in PDG

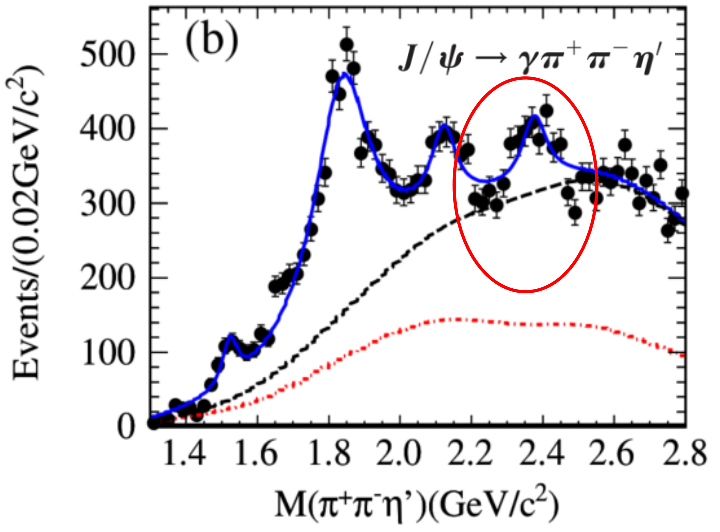
	Decays involving hadronic resonances	
Γ_1	$\eta'(958)\pi\pi$	(1.87±0.26) %
Γ_2	$\eta'(958)K\overline{K}$	(1.61±0.25) %
	Decays into stable hadrons	
Γ_{34}	$K\overline{K}\pi$	(7.0 ±0.4) %
Γ_{35}	$K\overline{K}\eta$	(1.32±0.15) %
Γ_{36}	$\eta\pi^+\pi^-$	(1.7 ±0.5) %

- No dominant decay
- Flavor symmetric

A glueball-like state $X(2370)$

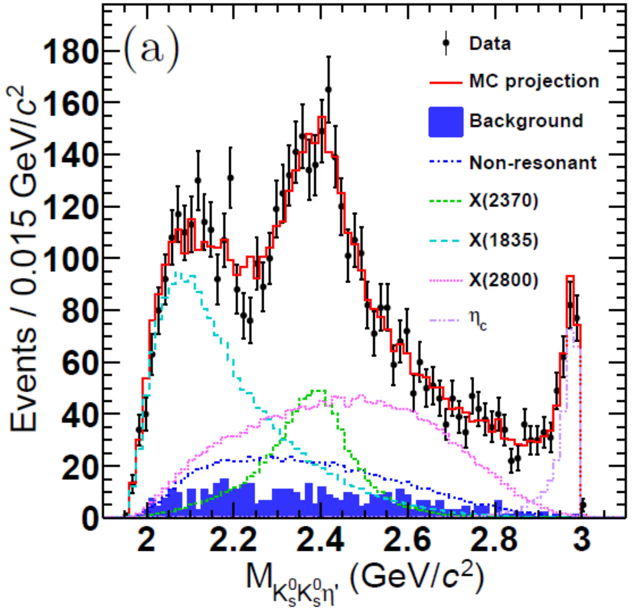
- **Discovered by BESIII in $J/\psi \to \gamma\eta'\pi\pi$ in 2011**
- Confirmed by BESIII in $J/\psi \to \gamma\eta'\pi\pi, \gamma\eta' KK$
  - Not seen in $J/\psi \to \gamma\eta'\eta\eta$ [BESIII PRD 103 012009 (2021)], $J/\psi \to \gamma\gamma\phi$ [BESIII arXiv: 2401.00918]. Upper limits of BF are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

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



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

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



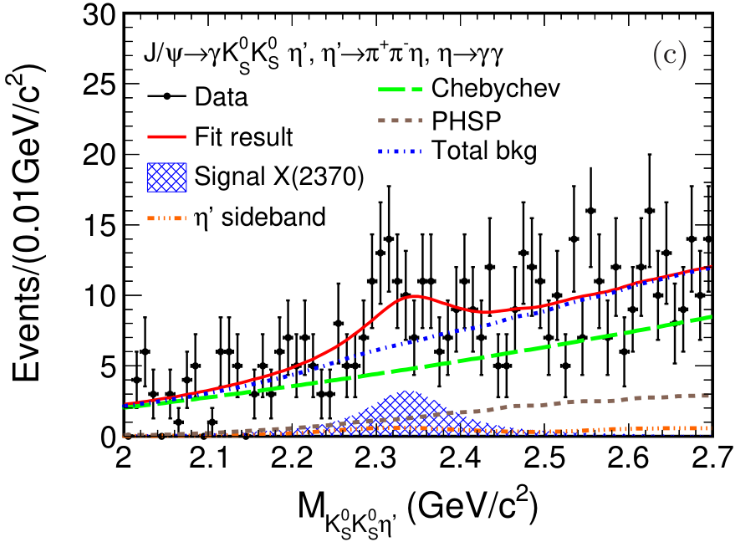
$J^{PC} = 0^{-+}$ with significance >9.8σ

$M = 2395 \pm 11^{+26}_{-94}$ MeV

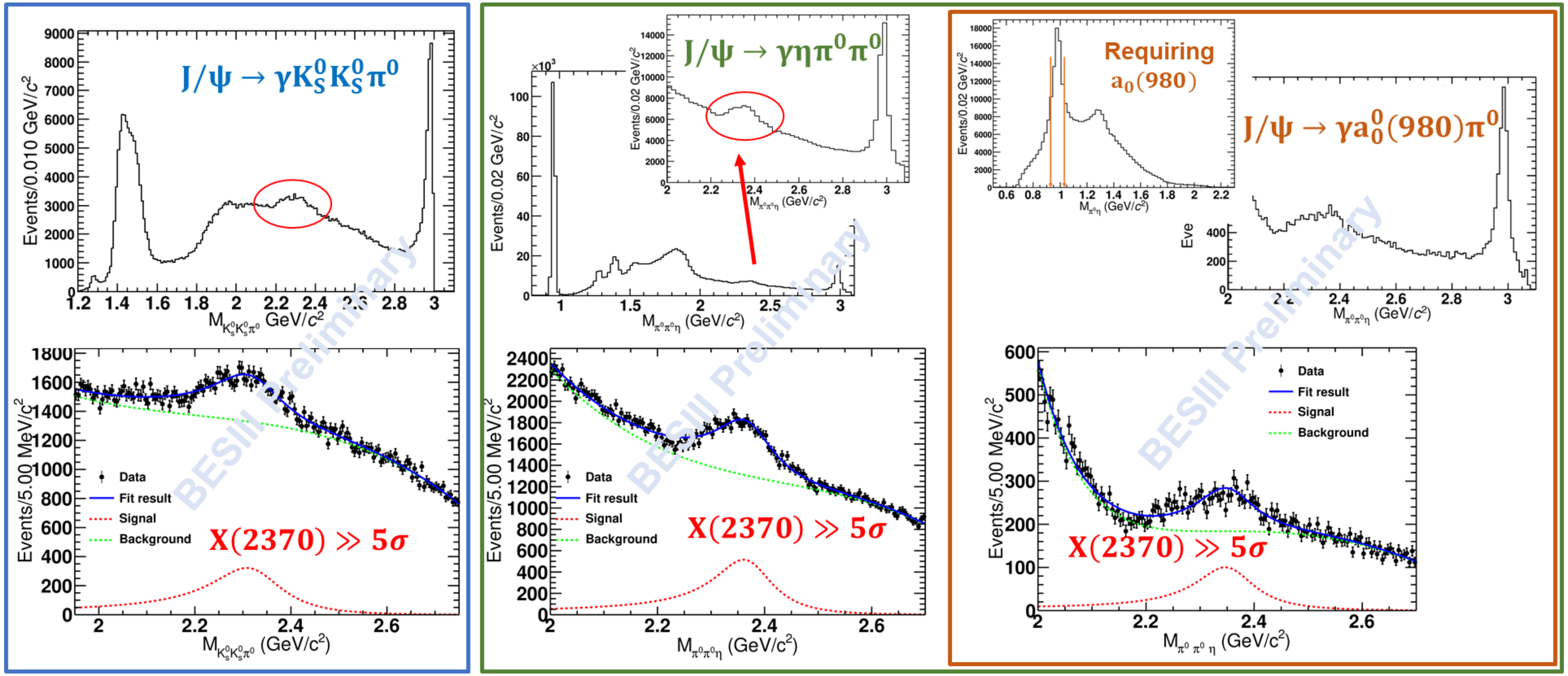
$\Gamma = 188^{+18}_{-17}{}^{+124}_{-33}$ MeV

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

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



BESIII EPJC 80 746(2020)



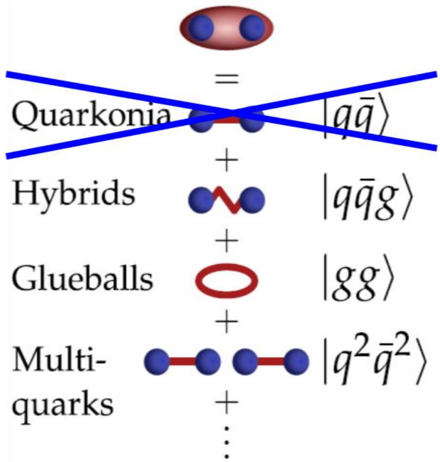
New decay modes

$X(2370)$ observed in the gluon-rich J/ψ radiative decays

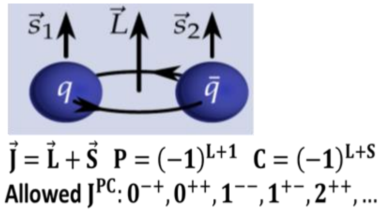
- **J^{PC} determined to be 0^{-+}**
- **Mass and production rate consistent with LQCD**
- **Decay modes $X(2370) \to$ $\eta'\pi\pi, \eta' KK, K^0_S K^0_S \eta, K^0_S K^0_S \pi^0, \eta\pi^0\pi^0, a^0_0(980)\pi^0$ observed, in analog to η_c**

Consistent with 0^{-+} glueball

Light hadrons with exotic quantum numbers



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

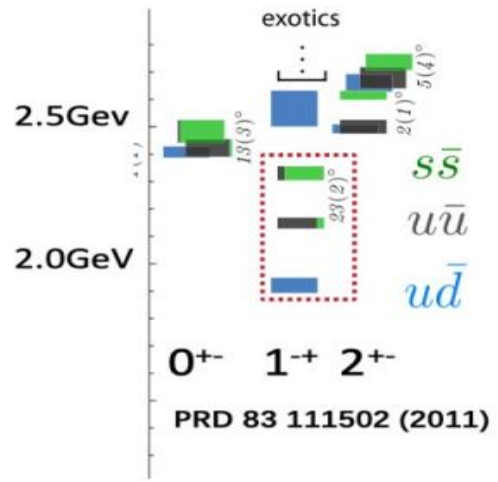


- **Only 3 candidates over 30 yrs:**

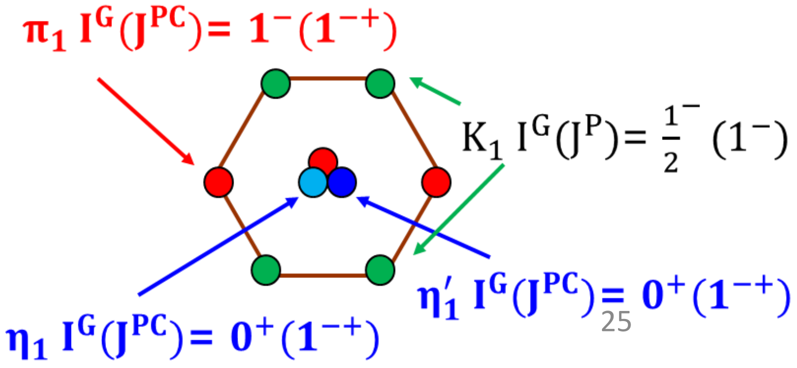
All 1^{-+} isovectors $\pi_1(1400), \pi_1(1600), \pi_1(2015)$

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

Lattice QCD Predictions:



- **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**



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

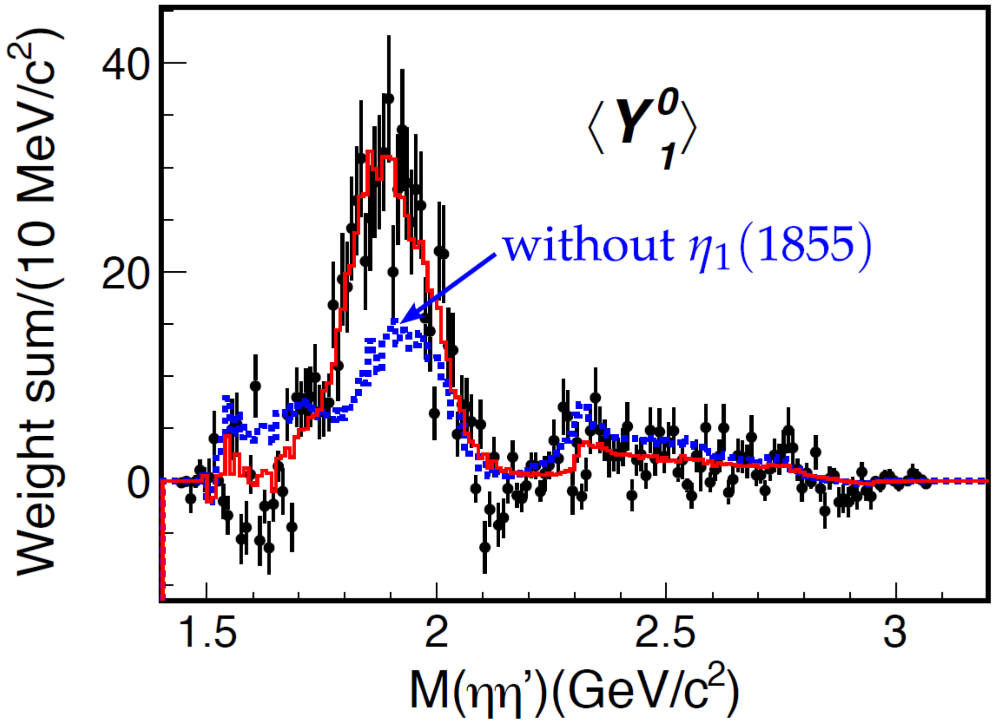
  $M = (1855 \pm 9^{+6}_{-1})\ \mathrm{MeV}/c^2$, $\Gamma = (188 \pm 18^{+3}_{-8})\ \mathrm{MeV}/c^2$

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

  - **Mass consistent with hybrid on LQCD**

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

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

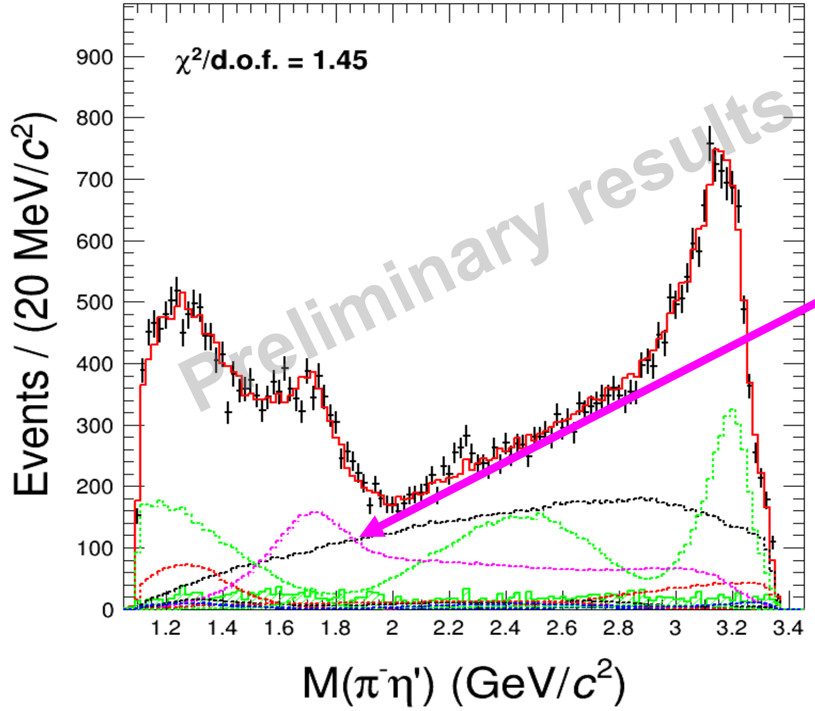


"Here, the result by the BESIII experiment of a possible observation of an $\eta_1(1855)$ state could be a breakthrough."

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

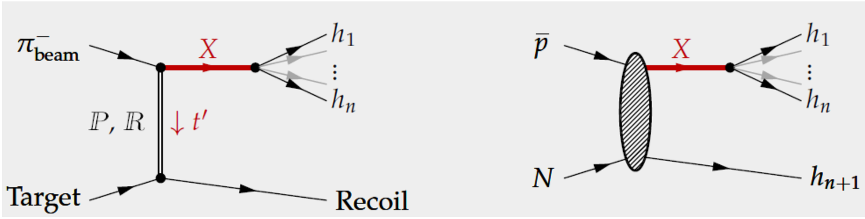
Observation of $\pi_1(1600)$ in $\chi_{c1} \to \eta'\pi^+\pi^-$

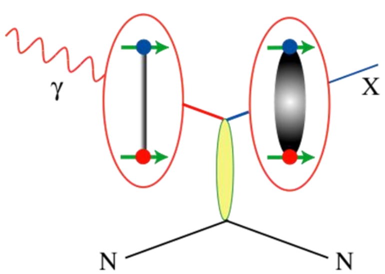
2.7×10^9 $\psi(3686)$@BESIII [preliminary]

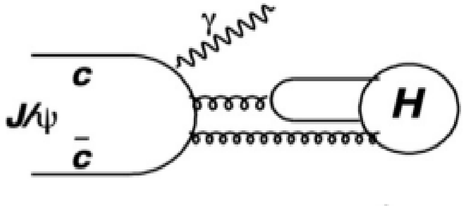


- **Amplitude analysis of $\chi_{c1} \to \eta'\pi^+\pi^-$ is performed**
- **$\pi_1(1600)$ observed>10σ**
- **with a significant BW phase motion**
- **$J^{PC} = 1^{-+}$, better than other assignments well over 10σ**
  - Evidence of $\pi_1 \to \eta'\pi$ at CLEO-c is confirmed [PR D84 112009 (2011)]

Observations of π_1 and η_1 in charmonium decays provide a new path to study 1^{-+}

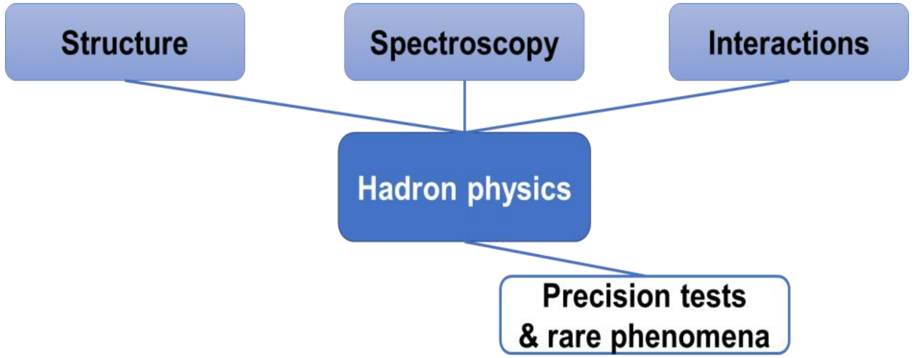




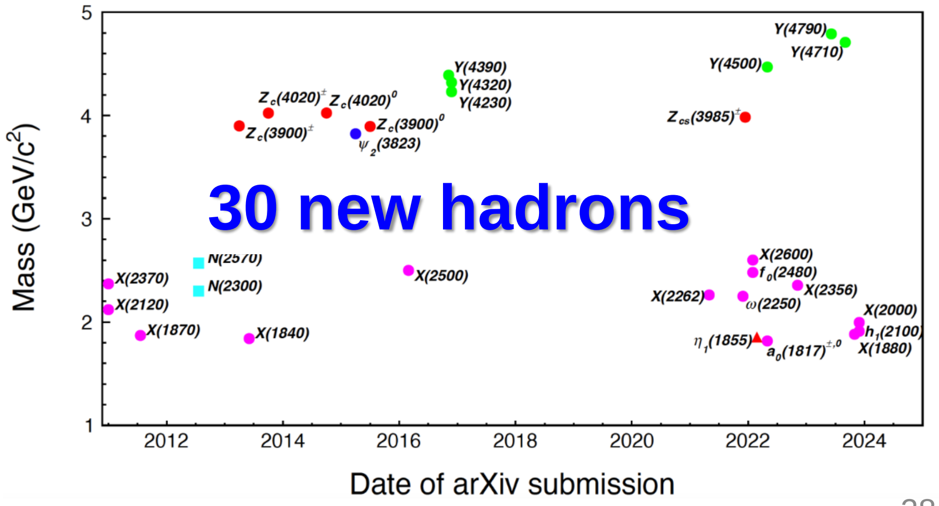


$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$

Summary



- BESIII has a rich program of hadron physics
- Lots of progress
- Great potential to be fully explored
  - $50\ \mathrm{fb}^{-1}$ data on disk, including $10 \times 10^9\ J/\psi$ 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

Indications of tensor glueball

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

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

Experimental results

$$\mathbf{Br(J/\psi \rightarrow \gamma f_2(2340) \rightarrow \gamma\eta\eta) = \left(3.8^{+0.62+2.37}_{-0.65-2.07}\right) \times 10^{-5}}$$

BESIII PRD 87,092009 (2013)

$$\mathbf{Br(J/\psi \rightarrow \gamma f_2(2340) \rightarrow \gamma\phi\phi) = \left(1.91 \pm 0.14^{+0.72}_{-0.73}\right) \times 10^{-4}}$$

BESIII PRD 93, 112011 (2016)

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

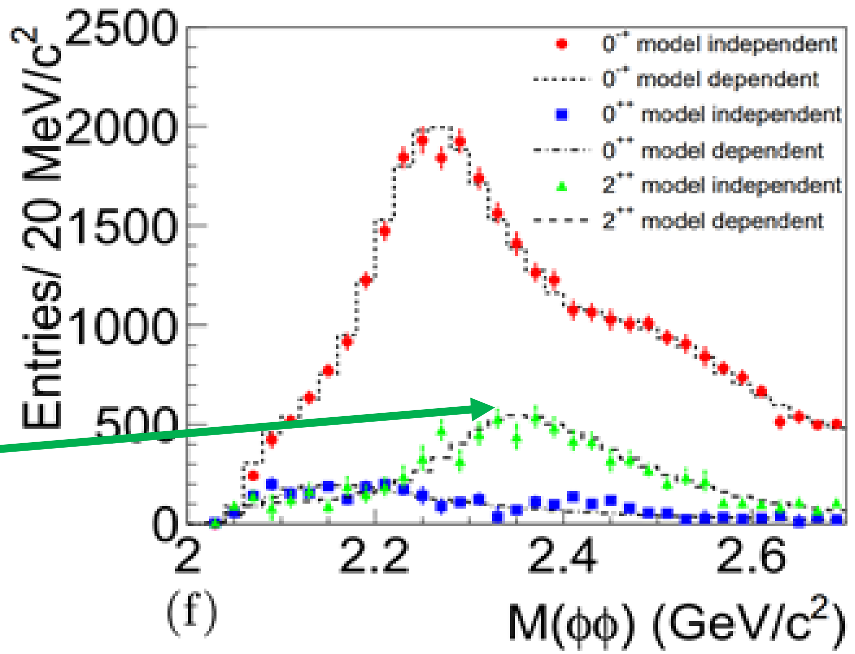
BESIII PRD 98,072003 (2018)

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

BESIII PRD 105,072002 (2022)

still desired to study more decay modes

BESIII J/ψ → γϕϕ [PRD 93, 112011 (2016)]



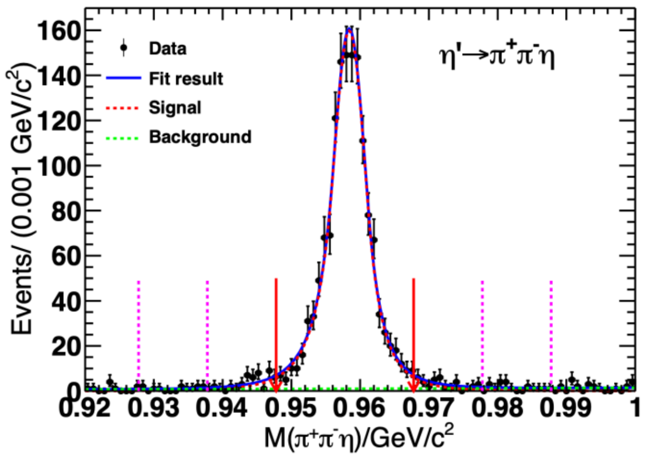
- $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ in πp reactions are all observed in $\mathbf{J/\psi \rightarrow \gamma\phi\phi}$ with a **strong production of $f_2(2340)$**
- Consistent with **double-Pomeron exchange** from WA102@CERN

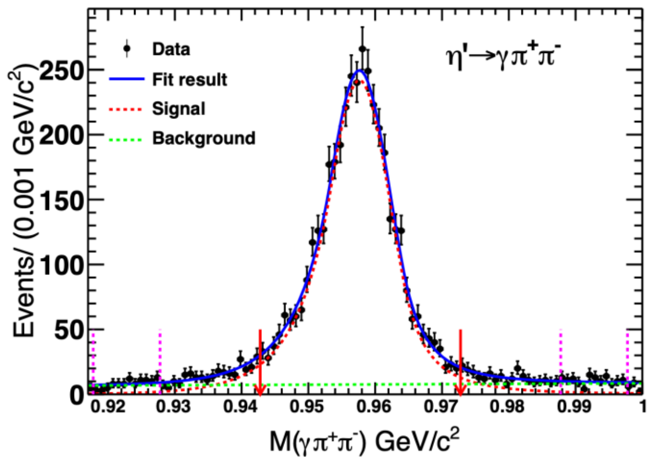
More complicated due to the large number of tensor states

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

BESIII PRL 132 181901(2024)

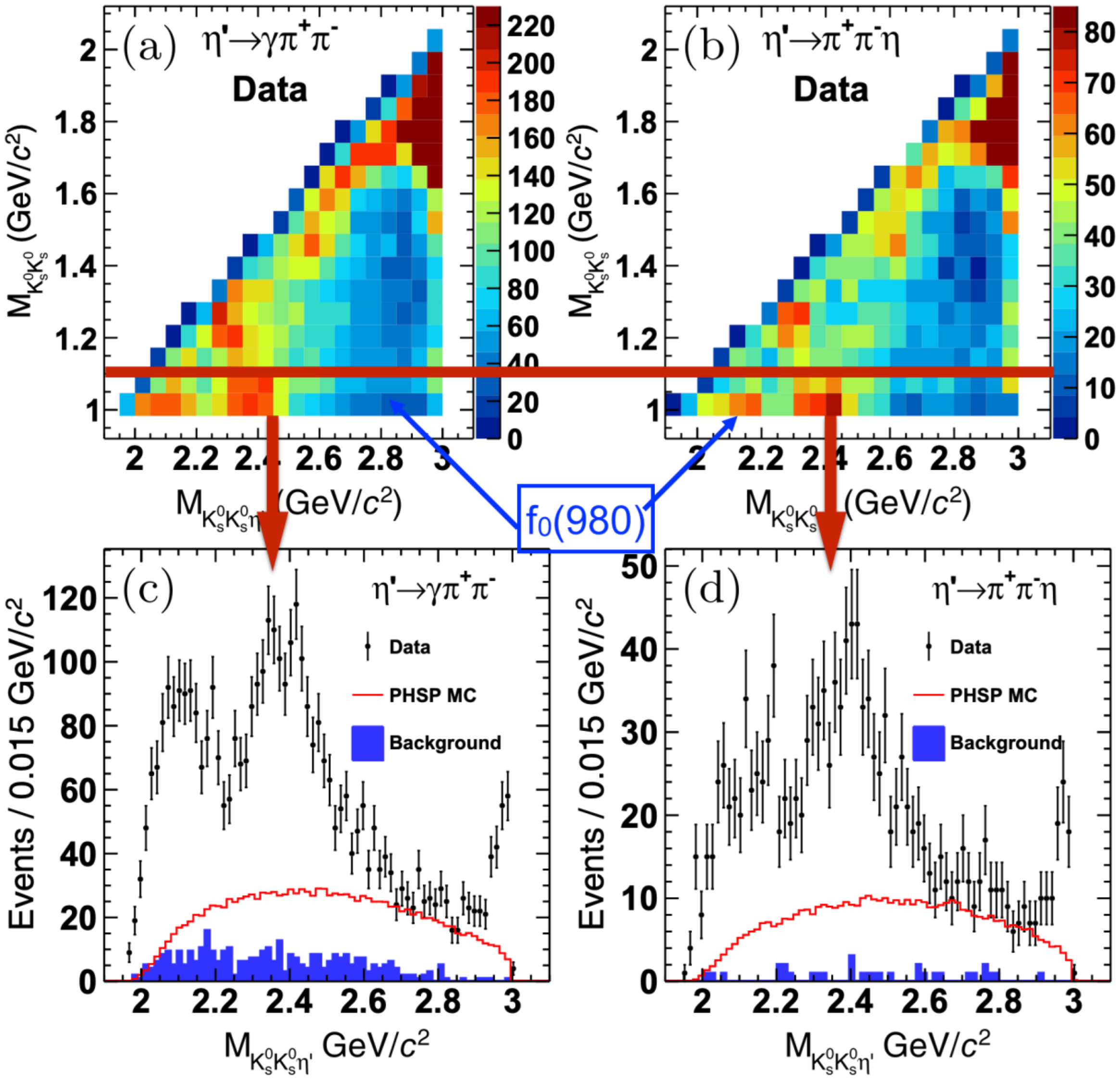
- η' reconstructed with $\eta\pi^+\pi^-$ and $\gamma\pi^+\pi^-$
- K_S^0 reconstructed with $\pi^+\pi^-$
- **Almost background free**
  - Negligible mis-combination for K_S^0 (<0.1%)
  - No background from $J/\psi \rightarrow \pi^0\eta' K_S^0 K_S^0$ or $\eta' K_S^0 K_S^0$
    - Forbidden by exchange symmetry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





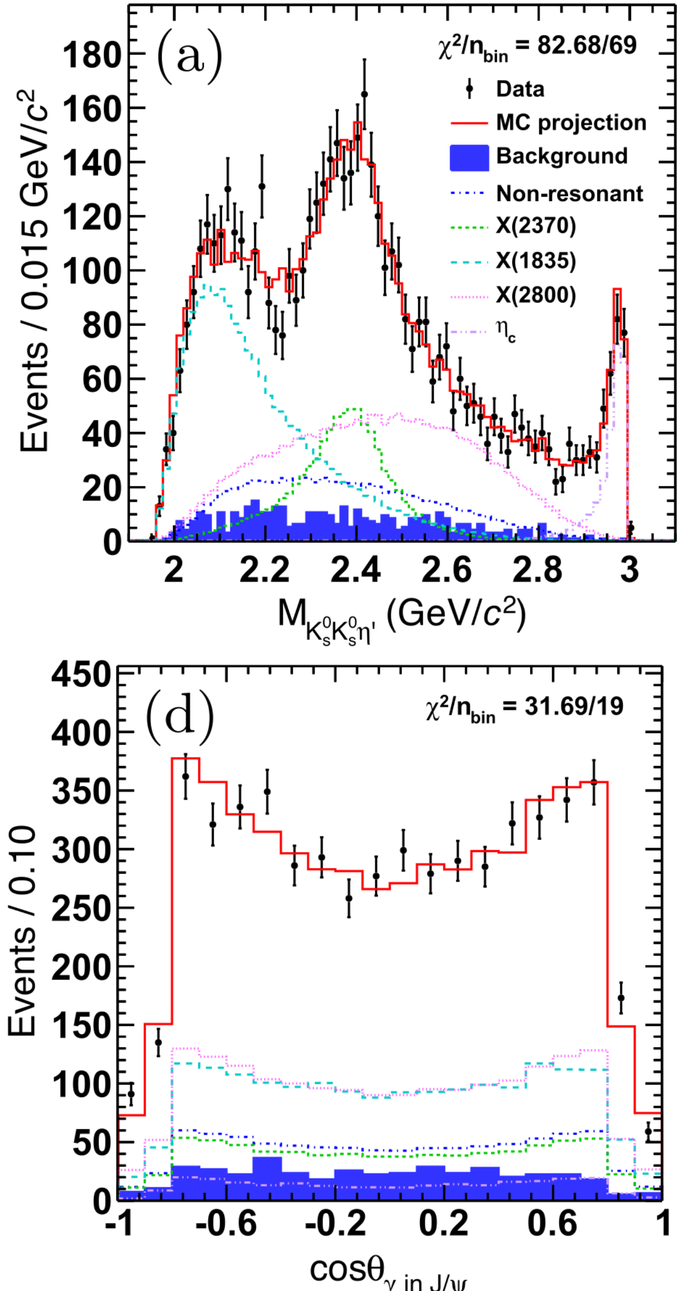
Spin-parity Determination of $X(2370)$ in $J/\psi \to \gamma\eta' K_S^0 K_S^0$

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 η_c
- Amplitude analysis
  - Quasi two-body decay amplitudes in the sequential decay processes $J/\psi \to \gamma X, X \to Y\eta', Y \to K_S^0 K_S^0$ and $J/\psi \to \gamma X, X \to Z K_S^0, Z \to K_S^0 \eta'$ are constructed using the covariant tensor formalism[Eur. Phys. J. A 16, 537]

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



BESIII PRL 132 181901(2024)

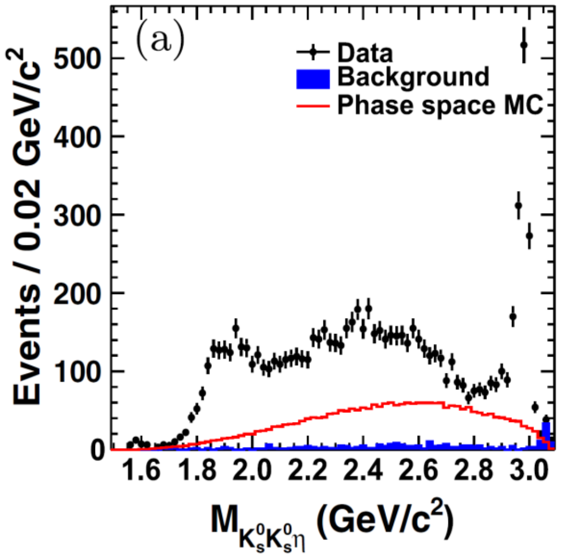
Nominal fit solution

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}	14.9σ
X(1835)	0^{-+}	$f_0(980)\eta'$	1844	192	22.0σ
X(2800)	0^{-+}	$f_0(980)\eta'$	2799^{+52}_{-48}	660^{+180}_{-116}	16.4σ
η_c	0^{-+}	$f_0(980)\eta'$	2983.9	32.0	$> 20.0\sigma$
PHSP	0^{-+}	$\eta'(K_S^0K_S^0)_{S-wave}$	− − −	− − −	9.0σ
		$\eta'(K_S^0K_S^0)_{D-wave}$	− − −	− − −	16.3σ

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

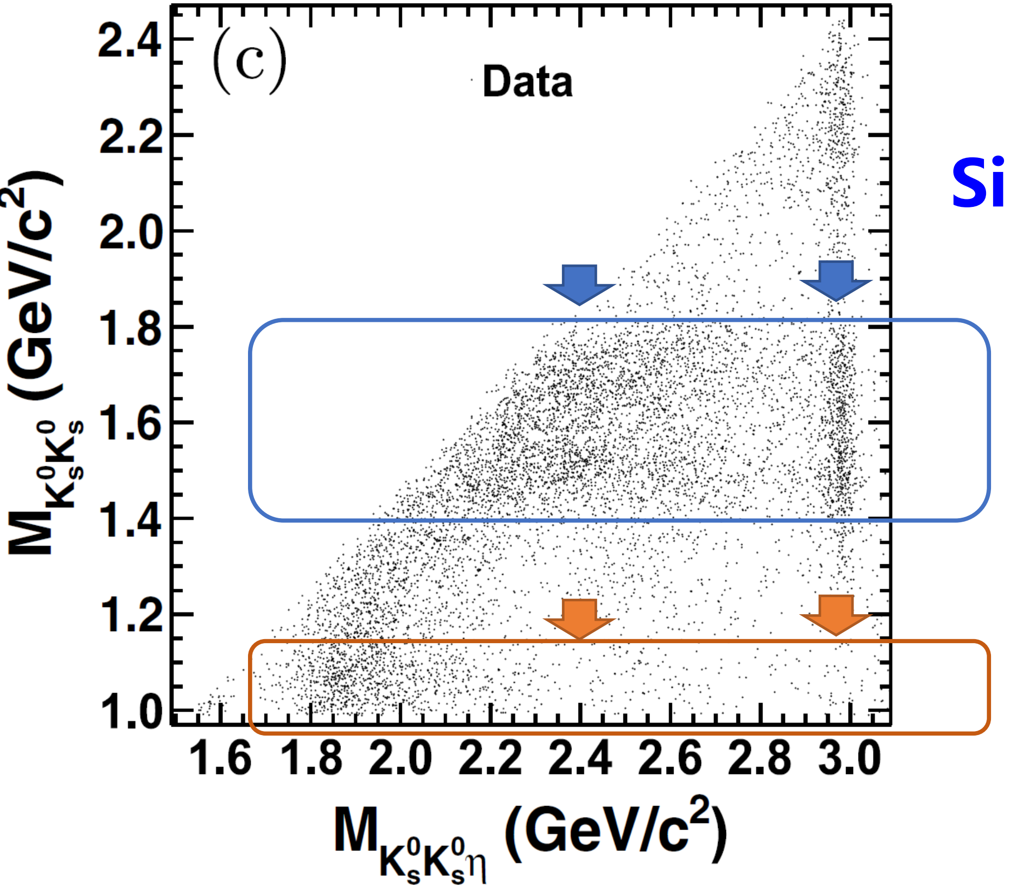
$$B(J/\psi \to \gamma X(2370)B\left(X(2370) \to \eta' K_S^0 K_S^0\right)B\left(f_0(980) \to K_S^0 K_S^0\right)$$
$$= \left(1.31 \pm 0.22^{+2.85}_{-0.84}\right) \times 10^{-5}$$

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



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

BESIII PRL 115 091803(2015)

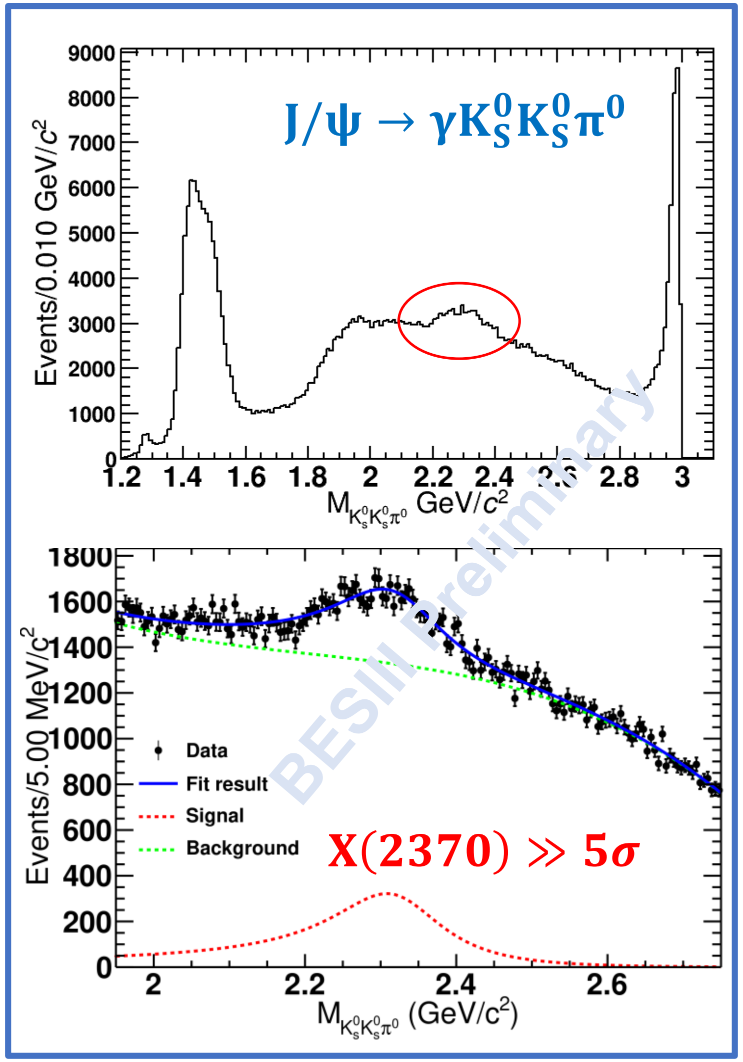


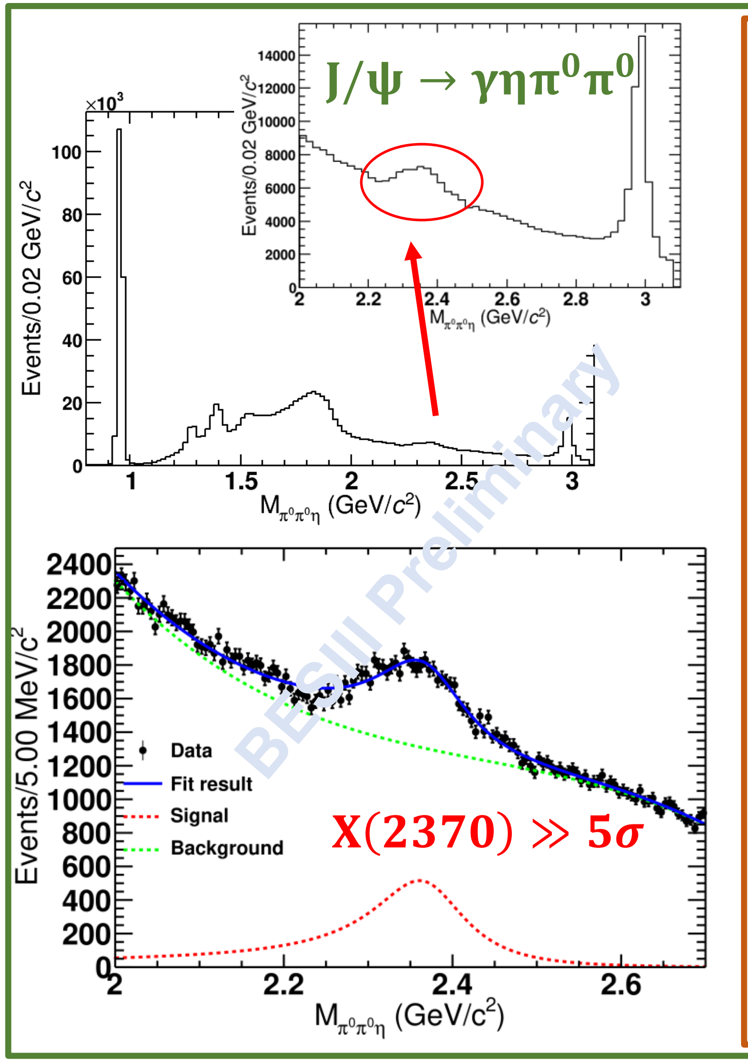
Similar decay patterns of the $X(2370)$ and η_c

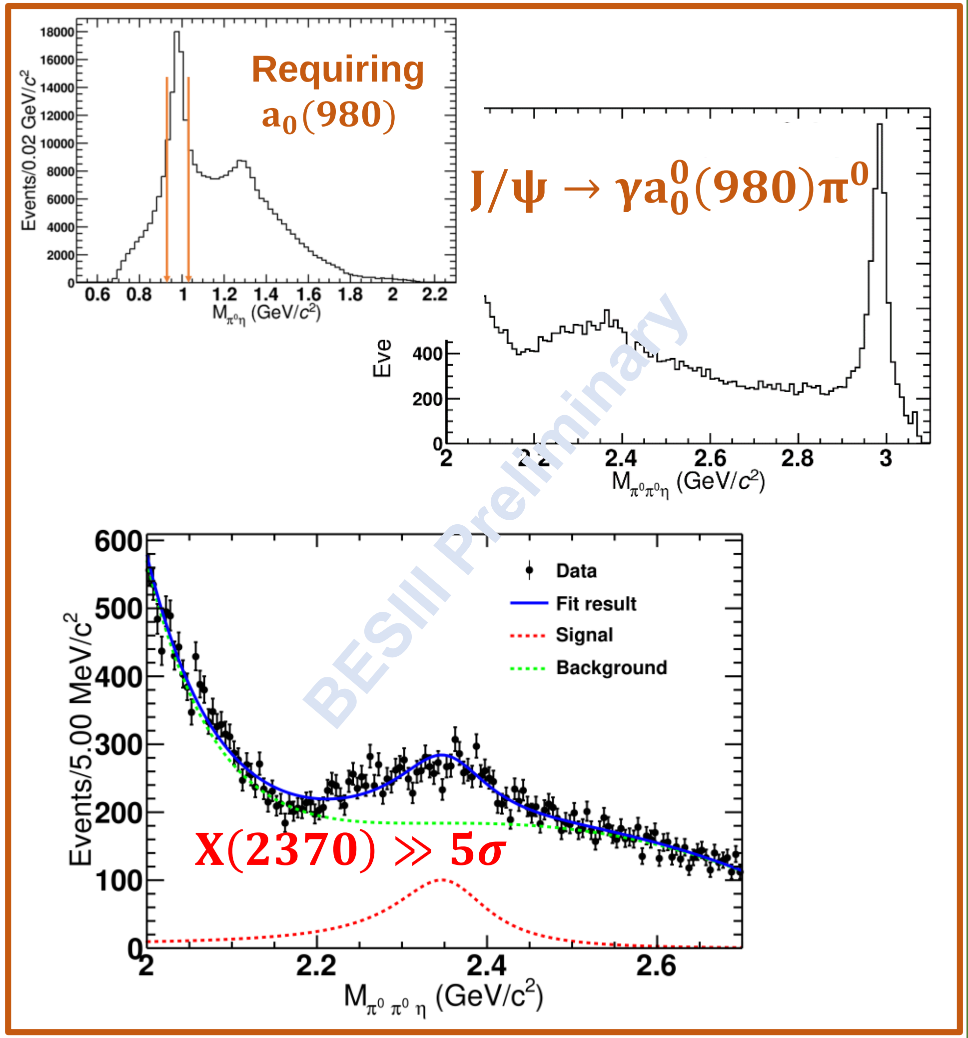
clear $X(2370)$ AND η_c signals

no $X(2370)$ OR η_c signal

Observation of new decay modes of X(2370)







- $X(2370) \to K_S^0 K_S^0 \pi^0$, * $\eta\pi^0\pi^0$, $a_0^0(980)\pi^0$ firstly observed, all accompanied with η_c

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

What we have learned before

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

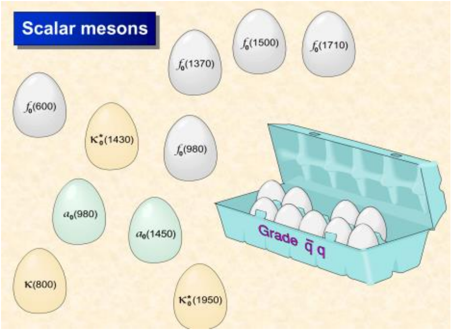
e^+e^- annihilation
$p\bar{p}$ annihilation
central exclusive production
charge-exchange reactions

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

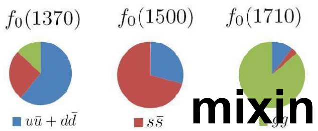
Exp: **overpopulation**

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

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

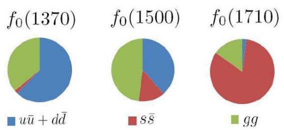


Cheng *et al*, Phys. Rev. D**74** (2006) 094005



mixing schemes

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

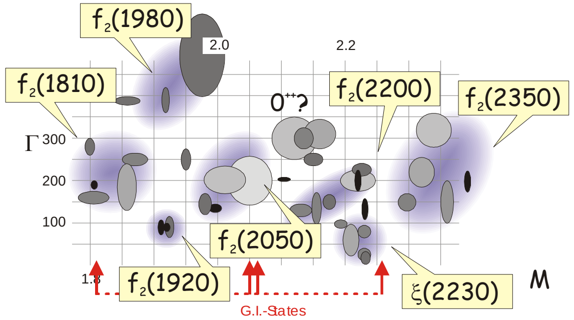


Tensor: 2 nonets($^3P_2$,$^3F_2$), complicated

Exp: **large uncertainty**

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

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

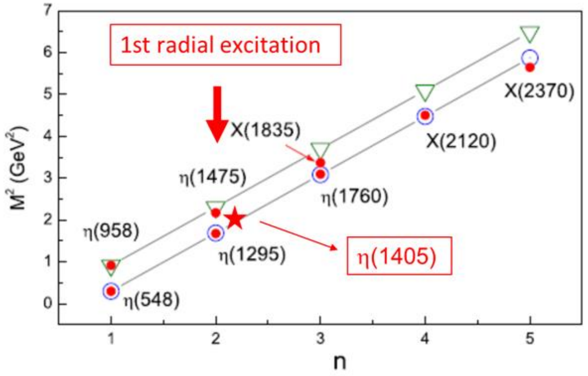


Pseudoscalar: η & η′ , "simple"

Exp: **lacking of info. above 2 GeV**; puzzles η(1295)? η(1405/1475)?

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

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



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;

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

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)

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

- ✓ **$f_0(1710)$ is largely overlapped with the scalar glueball, according to its production and decay properties**
- ✓ **Large production rate of $f_2(2340)$ in J/ψ radiative decays**
- ✓ **Non-observation of $\eta(1295)$**
- ✓ **Insights of $\eta(1405/1475)$**
- ✓ **$X(2370)$: a good candidate with analogy decay pattern as η_c**

Scalar glueball candidate: **decay properties**

Flavor-blindness of glueball decays

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

*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 $f_0(1500)$

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

consistent with PDG

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

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

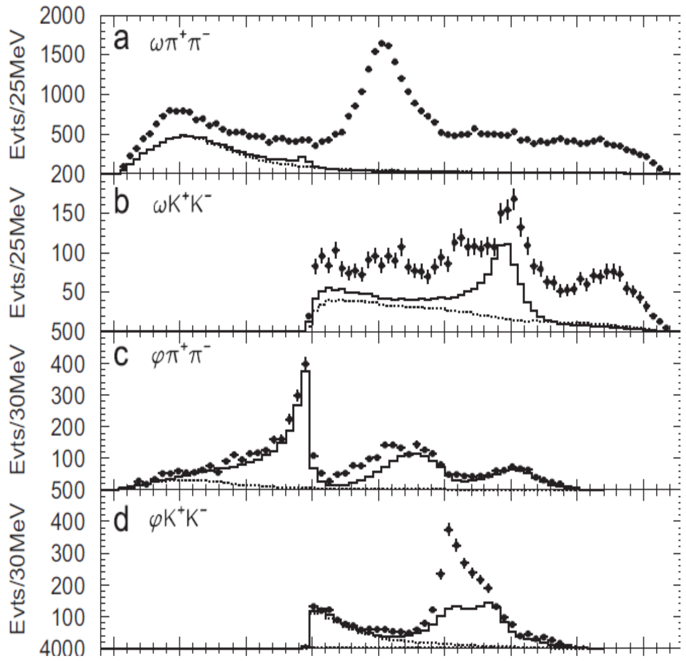
➢ Supports to the hypothesis that $f_0(1710)$ overlaps with the ground state scalar glueball
  - Scalar glueball expected to be suppressed $B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$

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

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

More scalars

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

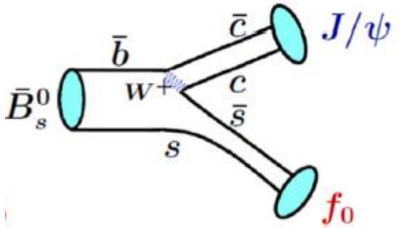


ωK^+K^- ➜ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

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

ϕK^+K^- ➜ No peak around 1700 MeV/c^2

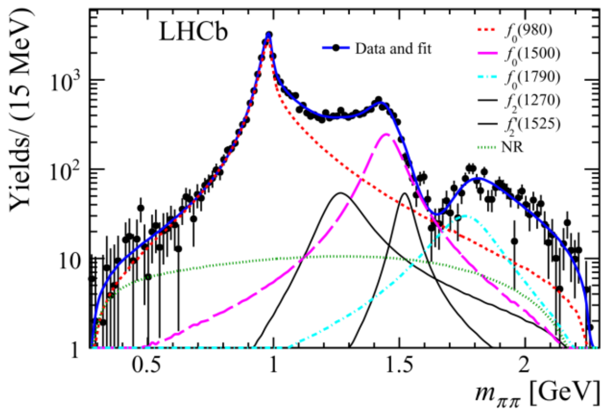
$f_0(1800)$

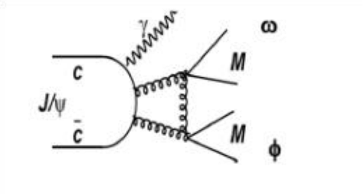


selective for $s\bar{s}$

$B_s \to J/\psi f_0$

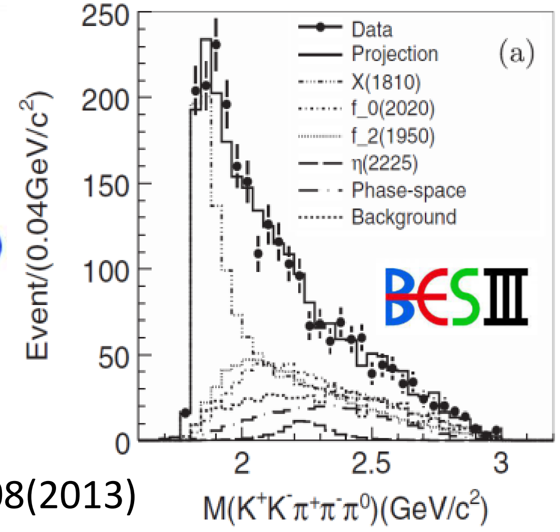
PLB 797 (2019) 134789





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

PRD 87, 032008(2013)

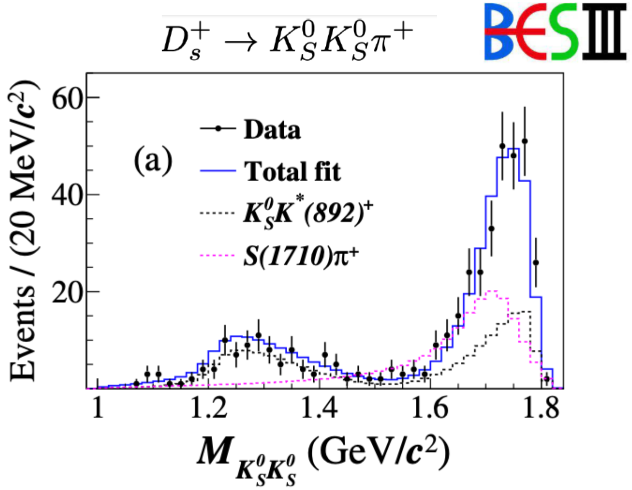


$a_0(1817)$

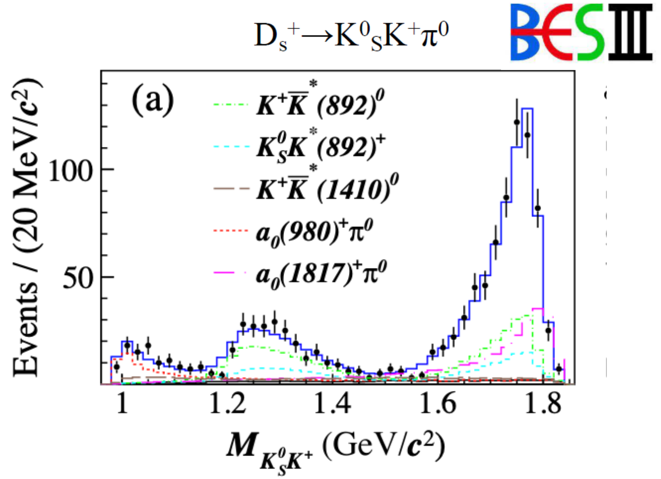
Isovector partner of $f_0(1800)$?

[Shulei 's talk]

PRD105, L051103 (2022)



PRL129, 182001 (2022)



Two photon couplings

$\gamma\gamma \to K_S K_S$

Belle PTEP 2013 (2013) 12, 123C01

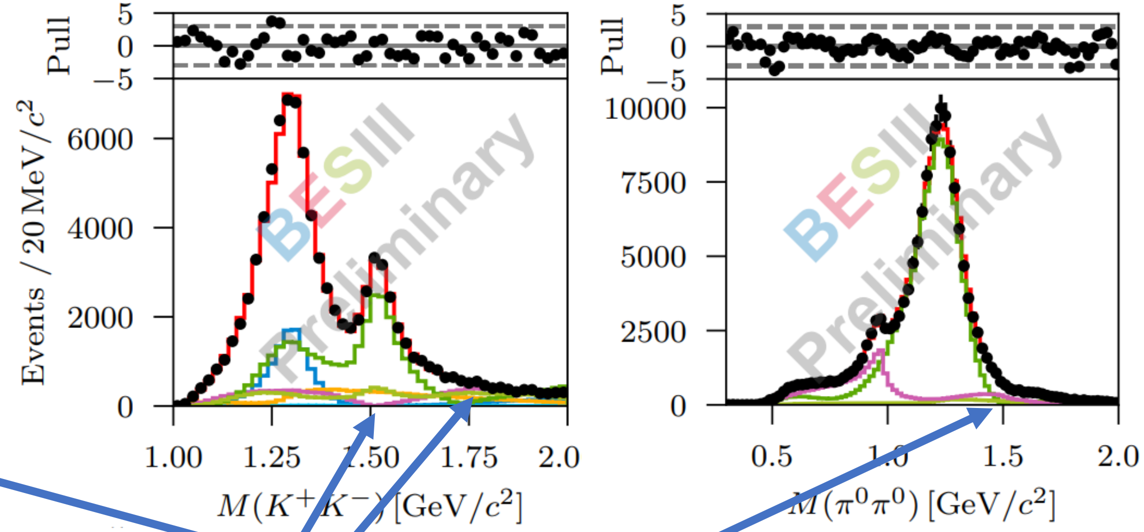
Parameter	$f_0(1710)$ fit			
	fit-H	fit-L	H,L combined	PDG
χ^2/ndf	694.2/585	701.6/585	–	–
Mass(f_J) (MeV/c^2)	1750^{+5+29}_{-6-18}	1749^{+5+31}_{-6-42}	1750^{+6+29}_{-7-18}	1720 ± 6
$\Gamma_{tot}(f_J)$ (MeV)	138^{+12+96}_{-11-50}	145^{+11+31}_{-10-54}	139^{+11+96}_{-12-50}	135 ± 6
$\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})_{f_J}$ (eV)	12^{+3+227}_{-2-8}	21^{+6+38}_{-4-26}	12^{+3+227}_{-2-8}	unknown

$\gamma\gamma \to \pi^0\pi^0$

Belle PRD 78 (2008) 052004

Parameter	Nominal	$r_{02}=0$	No $f_0(Y)$	Unit
Mass$(f_0(980))$	982.2 ± 1.0	980.2 ± 1.0	$983.7^{+1.5}_{-1.0}$	MeV/c^2
$\Gamma_{\gamma\gamma}(f_0(980))$	$285.5^{+17.2}_{-17.1}$	$297.0^{+14.2}_{-13.7}$	$370.5^{+20.2}_{-18.7}$	eV
$g_{f_0(980)\pi\pi}$	1.82 ± 0.03	1.79 ± 0.03	1.89 ± 0.03	GeV
Mass$(f_0(Y))$	1469.7 ± 4.7	1466.8 ± 0.6	–	MeV/c^2
$\Gamma(f_0(Y))$	$89.7^{+8.1}_{-6.6}$	$422.4^{+18.4}_{-19.8}$	–	MeV
$\Gamma_{\gamma\gamma}\mathcal{B}(f_0(Y)\to\pi^0\pi^0)$	$11.2^{+5.0}_{-4.0}$	$6780.2^{+626.5}_{-574.7}$	0 (fixed)	eV

BESIII preliminary



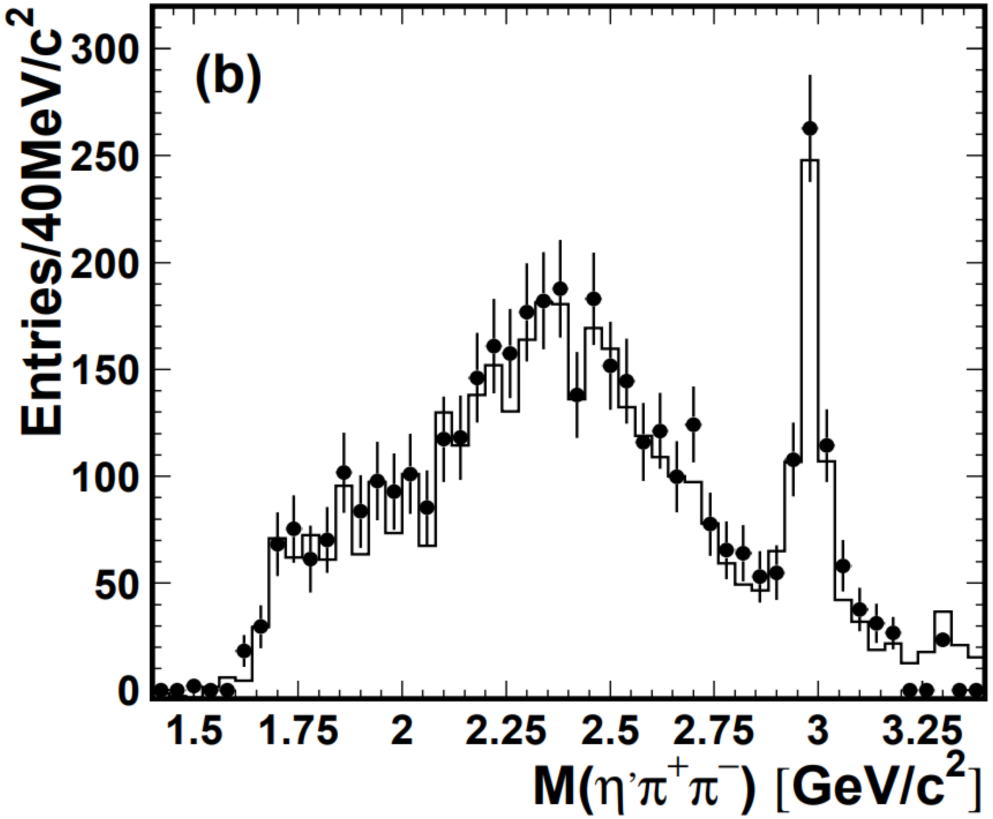
$f_0(1710)$? $f_0(1800)$?

$f_0(1500)$?

Proper assignment requires **more sophisticated model**

- $\gamma\gamma \rightarrow \eta'\pi^+\pi^-$

Belle PRD 86 052002(2012)



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

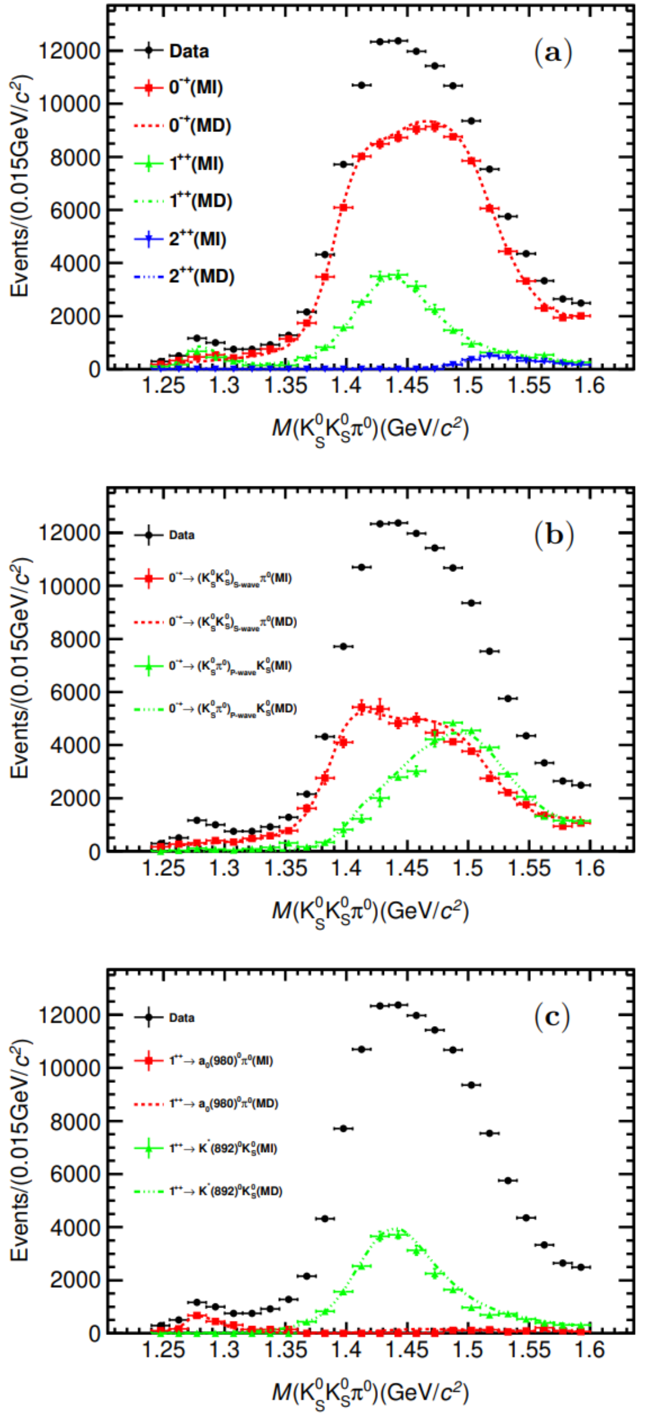
$$J/\psi \rightarrow \gamma K_S K_S \pi^0$$

BESIII JHEP 03 121(2023)

- **M**ass **I**ndependent PWA in bins of $M(K_S K_S \pi^0)$ to detangle J^{PC} components
  - **Valuable inputs to develop models**
- **M**ass **D**ependent PWA with BW to extract resonances
- **Consistency between MI and MD results**

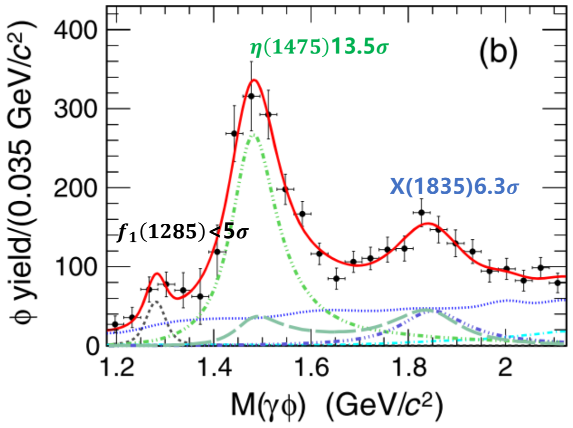
- **Dominated by 0^{-+}**
  - **Two BWs around 1.4 GeV is needed**

- $\eta(1405)/\eta(1475)$ poles in coupled-channel analysis
  - PRD 107, L091505 (2023) ; PRD 109, 014021 (2024)



J/ψ → γγϕ, a $s\bar{s}$ flavor filter

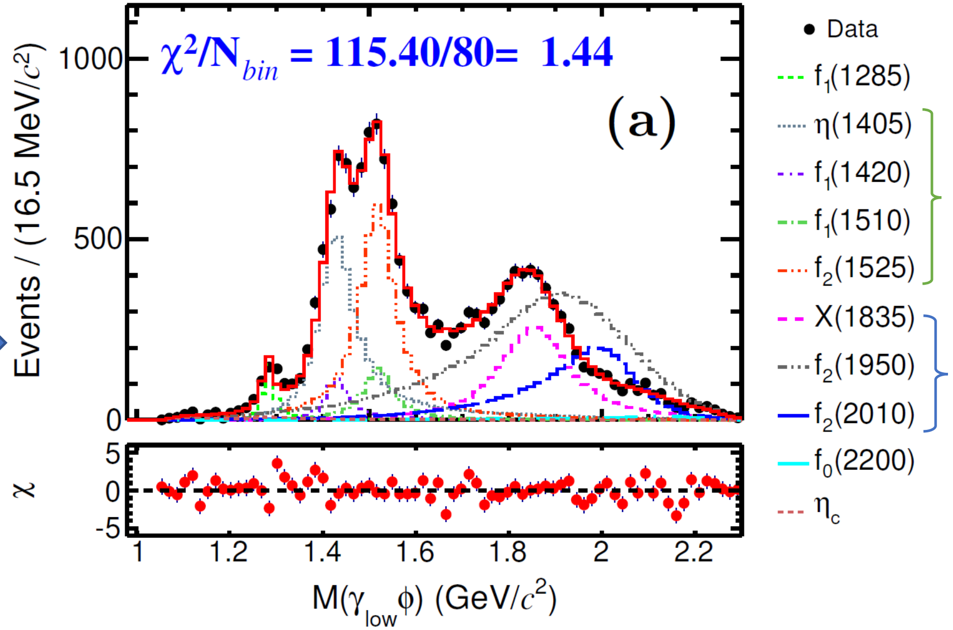
PR D97 051101 (2018)



←Fit to mass spectrum

Amplitude analysis with advanced techniques for background subtraction

arXiv: 2401.00918



From the amplitude analysis,

- η(1405) is observed, while η(1475) can not be excluded
- **X(1835) → γϕ suggests its assignment of η' excitation**
- **η_c → γϕ are observed. The very first radiative decay mode of η_c**
- **Observation of $f_2(1950)$ and $f_0(2200) \to \gamma\phi$ unfavored their glueball interpretations**[PRD 108, 014023, arXiv: 2404.01564]
- **No evidence of X(2370)/$\eta_1(1855)$, well consistent with the predictions for glueball/hybrid** [PRD 107, 114020, NPA 1037, 122683]

Amplitude analysis

Amplitude analysis is a key tool of hadron spectroscopy to disentangle contributions from individual resonances and to extract the resonance's spin-parity, mass, width and decay properties

$$Prob(\xi:\alpha) = \frac{\omega(\xi,\alpha)\epsilon(\xi)}{\int d\xi\,\omega(\xi,\alpha)\epsilon(\xi)}$$

$$\ln L = \sum_{n=1}^{N_{data}} \ln(Prob(\xi,\alpha))$$

ξ (the four-momenta of the final-state particles),

$\omega(\xi,\alpha) = \frac{d\sigma}{d\Phi} = |\sum_i A_i|^2$ differential cross section,

$\epsilon(\xi)$ efficiency

Perform an un-binned log-likelihood fit (fit the data event-wise to high-dimensional distributions using complex weights) to make our model for ω agree with the experimental distribution by varying the α

For J/ψ radiative decays [Eur. Phys. J. A 16, 537]

$$A = \psi_\mu(m_1)e^*_\nu(m_2)A^{\mu\nu} = \psi_\mu(m_1)e^*_\nu(m_2)\sum_i \Lambda_i U_i^{\mu\nu}$$

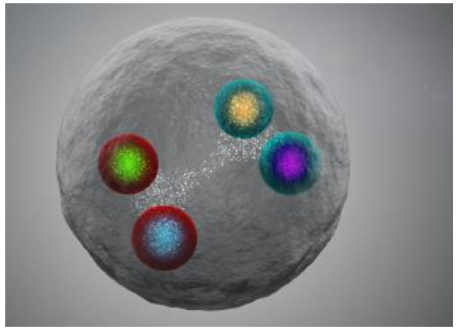
e.g. $J/\psi \rightarrow \gamma 0^{-+}, 0^{-+} \rightarrow f_0\eta, f_0\pi\pi$

$$\langle\gamma 0^{-+}|(f_0\eta)1\rangle = S_{\mu\nu}B_1(Q_{\psi\gamma X})f^{(f_0)}_{(12)}$$

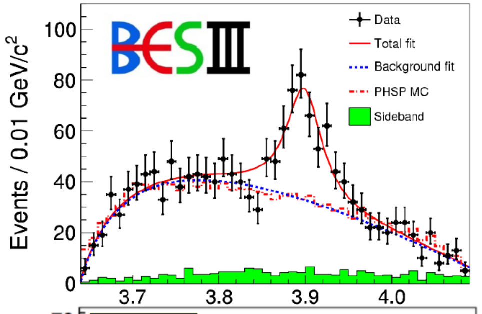
$$S_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta}p^\alpha_\psi q^\beta$$

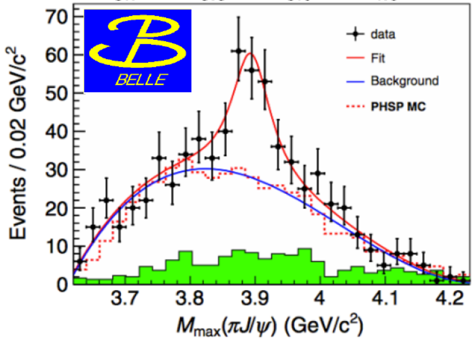
$B_1(Q_{\psi\gamma X})$ is Blatt-Weisskopf centrifugal barrier for $J/\psi \rightarrow \gamma X$

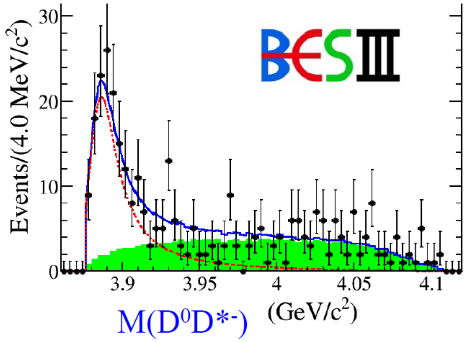
Z_c states



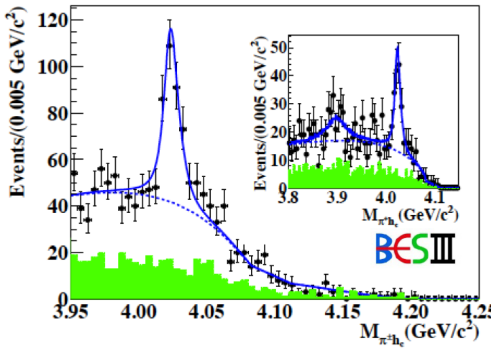
$Z_c(3900)$, 2013

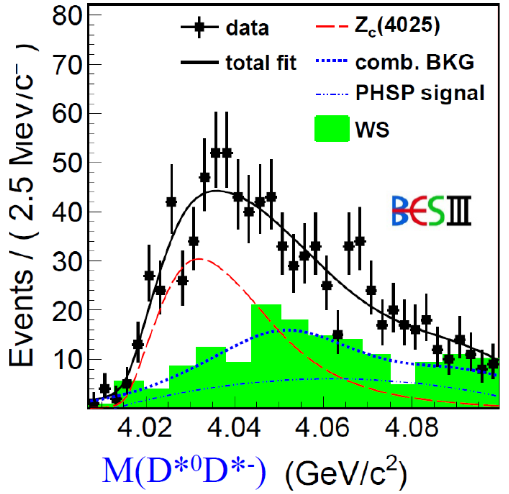




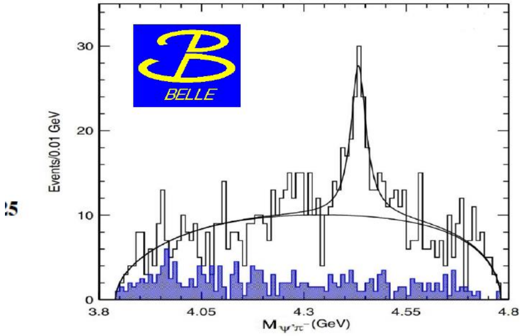


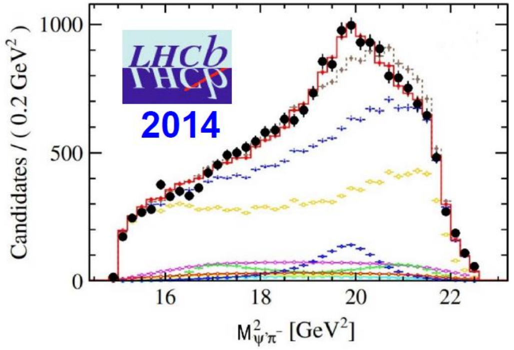
$Z_c(4020)$, 2013





$Z_c(4430)$, 2008





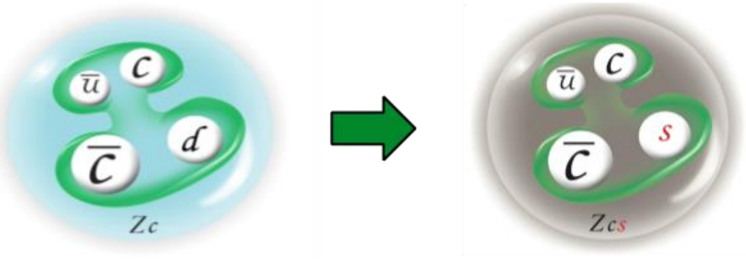
$I = 1\ Z_c(4020)$ near $D^*\overline{D^*}$ threshold

$I = 1\ Z_c(3900)$ near $D\overline{D^*}$ threshold

All are observed in π+charmonium

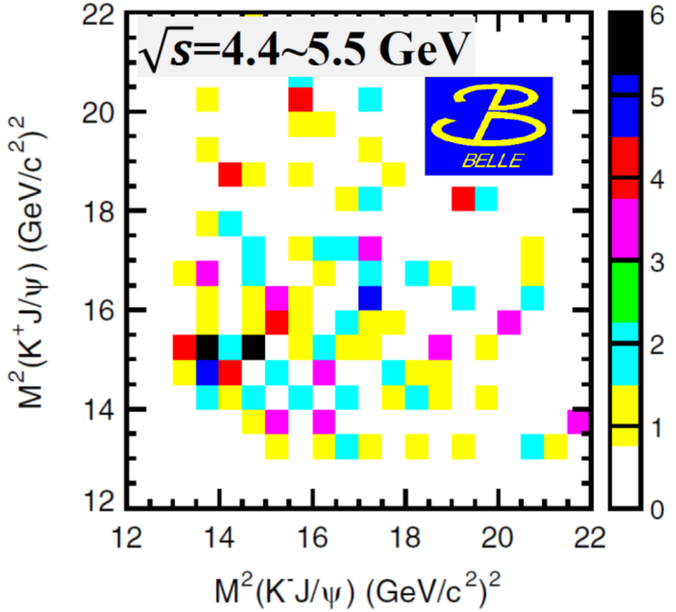
$c\bar{c}u\bar{d}$

Existence of states with d→s?



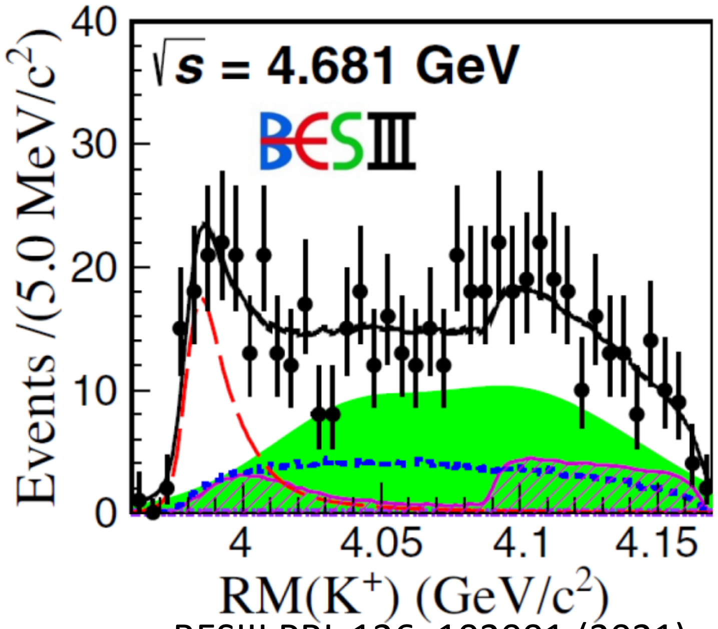
Search for states decay into $KJ/\psi, D_s^*\overline{D}, D_s\overline{D^*}$

$e^+e^- \to K^+K^-J/\psi$



Belle PRD 89, 072015 (2014)

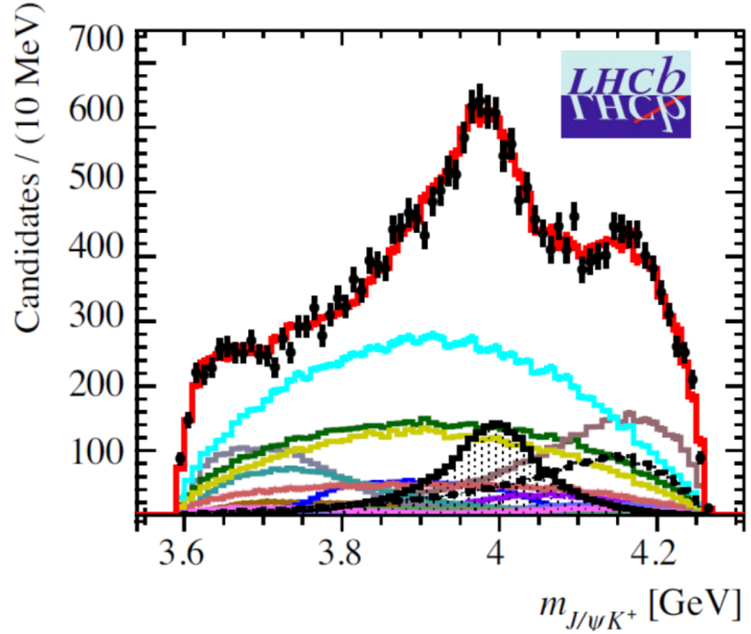
$e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$



BESIII PRL 126, 102001 (2021)

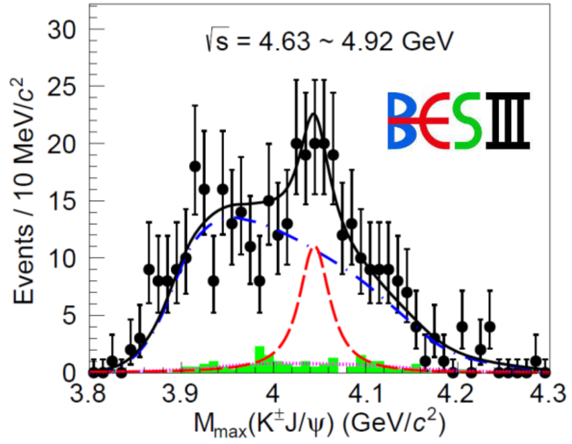
$Z_{cs}(3985)$ in $\bar{D}^*D_s + \bar{D}D^*_s$ mode!

$B^+ \to J/\psi\phi K^+$



LHCb PRL 127, 082001 (2021)

$Z_{cs}(4000)$ and $Z_{cs}(4220)$ in $K^\pm J/\psi$ decay mode!



No significant signal in $K^\pm J/\psi$ decay mode!

M=4044±6 MeV
Γ = 36±16 MeV
Significance: 2.3σ

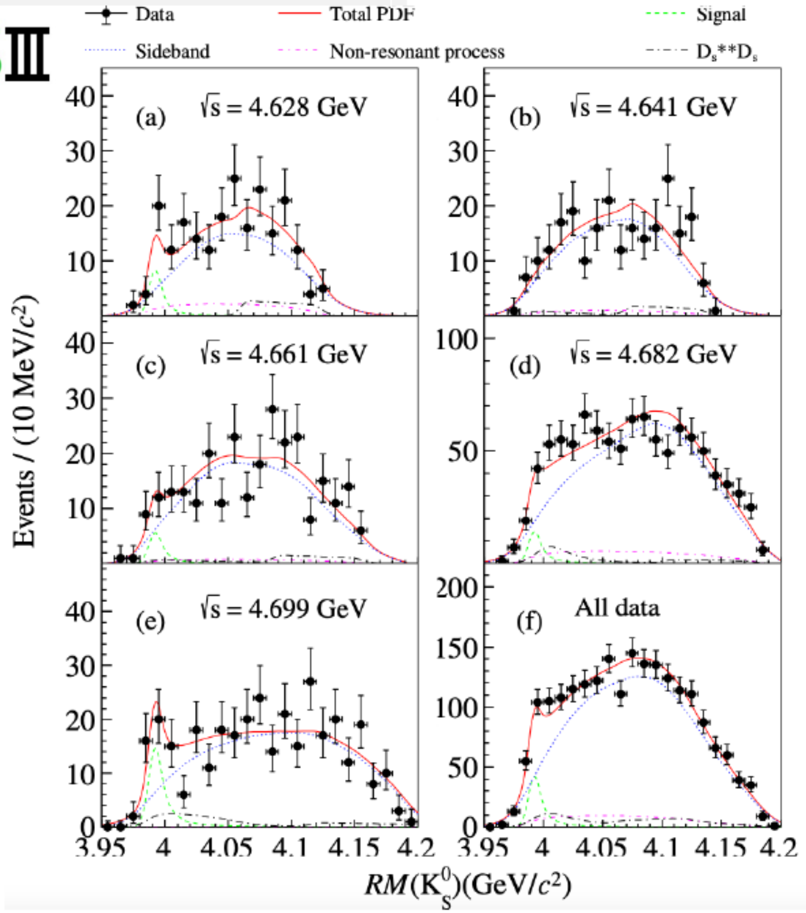
BESIII PRL131, 211902 (2023)

State	Signif.	JP	Mass (MeV)	Width (MeV)
$Z_{cs}(3985)$	5.3σ	??	$3982.5^{+1.8}_{-2.6} \pm 2.1$	$12.8^{+5.3}_{-4.4} \pm 3.0$
$Z_{cs}(4000)$	15σ	1+	$4003 \pm 6^{+4}_{-14}$	131±15±26
$Z_{cs}(4220)$	5.9σ	1+	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$

Same state? ($Z_{cs}(3985)$ and $Z_{cs}(4000)$)

Evidence for the neutral $Z_{cs}(3985), Z_{cs}(4000)$

PRL129, 112003 (2022) $e^+e^- \to K_S^0\,(D_s^- D^{*+} + D_s^{*-} D^+)$

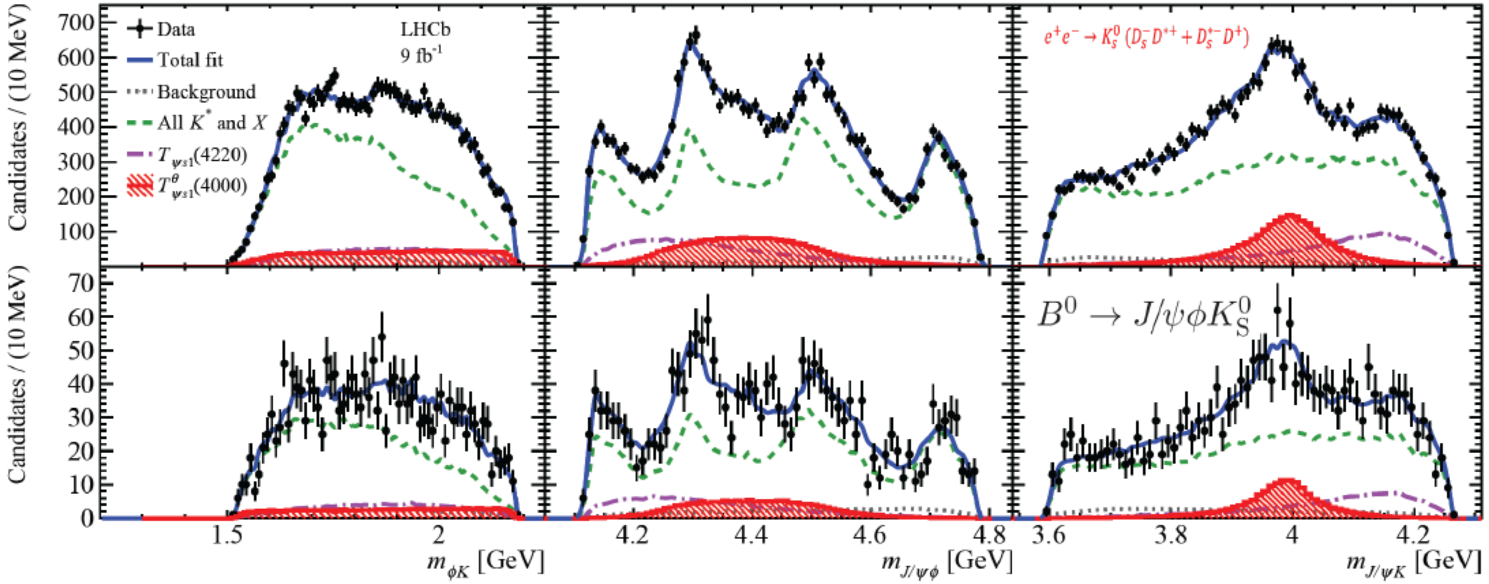


State	Mass (MeV/c^2)	Width (MeV)	Significance
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$	5.3σ
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$	4.6σ

$\mathrm{I} = \frac{1}{2}\ \mathrm{Z_{cs}}(3985)$

$B^0 \to J/\psi \phi K_S^0$

arXiv:2301.04899v2



Significance >4.0σ after including systematic uncertainties

Significance 5.4σ with isospin symmetry imposed

Mass (MeV)	Width (MeV)	Fit fraction (%)	ΔM (MeV)
$3991\,^{+12}_{-10}\,^{+9}_{-17}$	$105\,^{+29}_{-25}\,^{+17}_{-23}$	$7.9 \pm 2.5\,^{+3.0}_{-2.8}$	$-12\,^{+11}_{-10}\,^{+6}_{-4}$

Time-like EMFFs: theoretic review

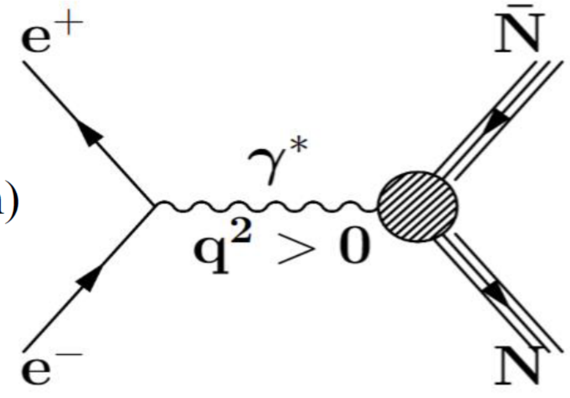
1961, first paper by N. Cabibbo and R. Gatto *Phys.Rev.* 124 (1961) 1577-1595

- The production cross section of $e^+e^- \to B\bar{B}$ (1/2 baryon) is given:

$$\frac{d\sigma_{B\bar{B}}}{d\cos\theta} = \frac{\pi\alpha^2 C\beta}{2q^2}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}|G_E|^2\sin^2\theta\right], \tau = \frac{q^2}{4m_B^2}$$

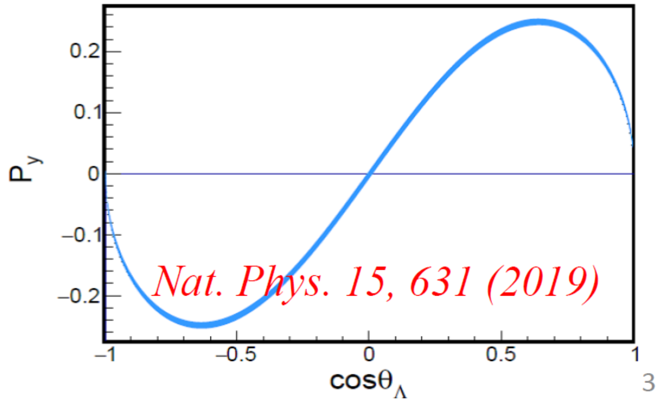
Integrated version: $\sigma_{B\bar{B}} = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M|^2 + \frac{1}{2\tau}|G_E|^2\right]$ (Born cross section)

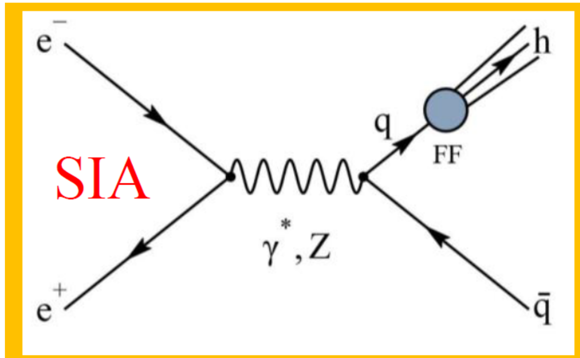
$$\xrightarrow{|G_E|=|G_M|} \sigma_{B\bar{B}} = \frac{2\pi\alpha^2 C\beta}{q^2}|G_{\rm eff}|^2$$



- The complex feature of TLFF leads to transversely polarized baryon even the beams are unpolarized. *Nuov Cim A* **109**, 241–256 (1996)

$$P_y = -\frac{\sin 2\theta\, {\rm Im}[G_E G_M^*]/\sqrt{\tau}}{\frac{|G_E|^2\sin^2\theta}{\tau} + |G_M|^2(1+\cos^2\theta)}$$





e+e-: $\sigma = \sum_q \sigma(e^+e^- \to q\bar{q}) \otimes FF$

- No PDFs necessary
- Calculations know at NNLO
- Flavor structure not directly accessible

Two types of fragmentation functions can be studied at BEPCII/BESIII

- Unpolarized fragmentation function
  - Unique Q<10 GeV data
  - More results from charged π/K and heavy flavor

Normalized differential cross section

$$\frac{1}{\sigma_{\mathrm{had}}}\frac{d\sigma_{\pi^0}}{dp_{\pi^0}} = \frac{N_{\pi^0}}{N_{\mathrm{had}}}\frac{1}{\Delta p_{\pi^0}}$$

π^0/K_S, PRL 130 231901(2023)
η, arXiv:2401.17873

- Collins fragmentation function
  - Essential input in the 3D imaging era of the nucleon structure study
  - More results from $K\pi + X$ and $KK + X$

$\pi\pi$, PRL 116, 042001 (2016)