Prospect of hadron spectroscopy at BESIII

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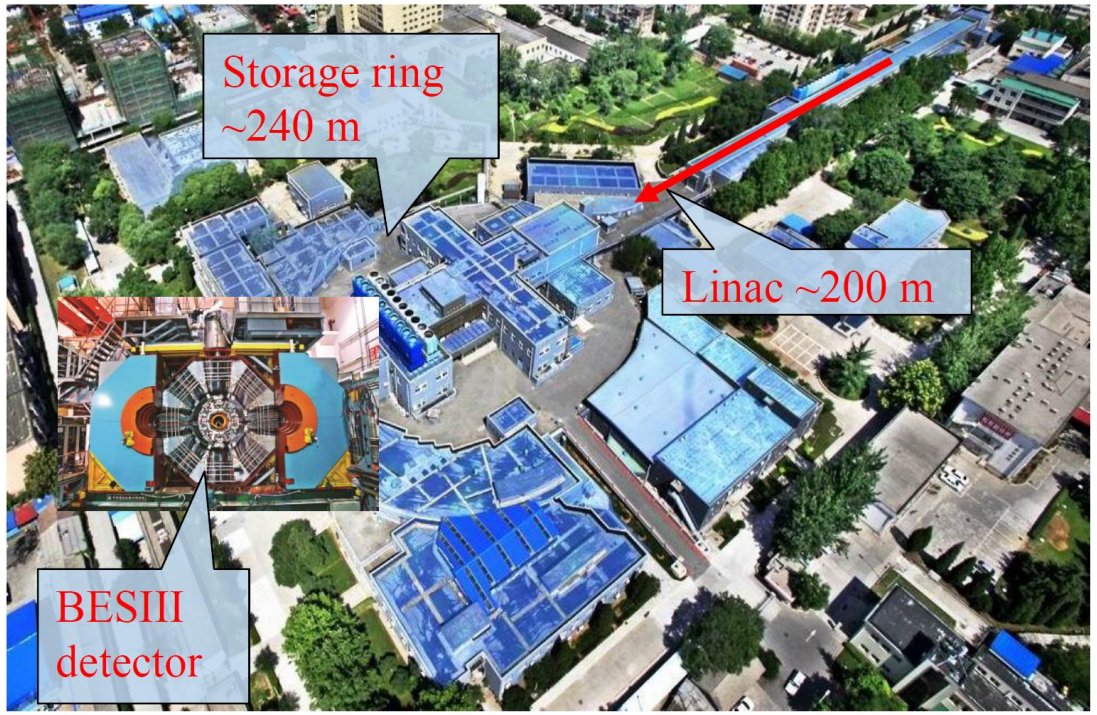
BESIII@BECPII

Beijing Electron Positron Collider(BEPCII)



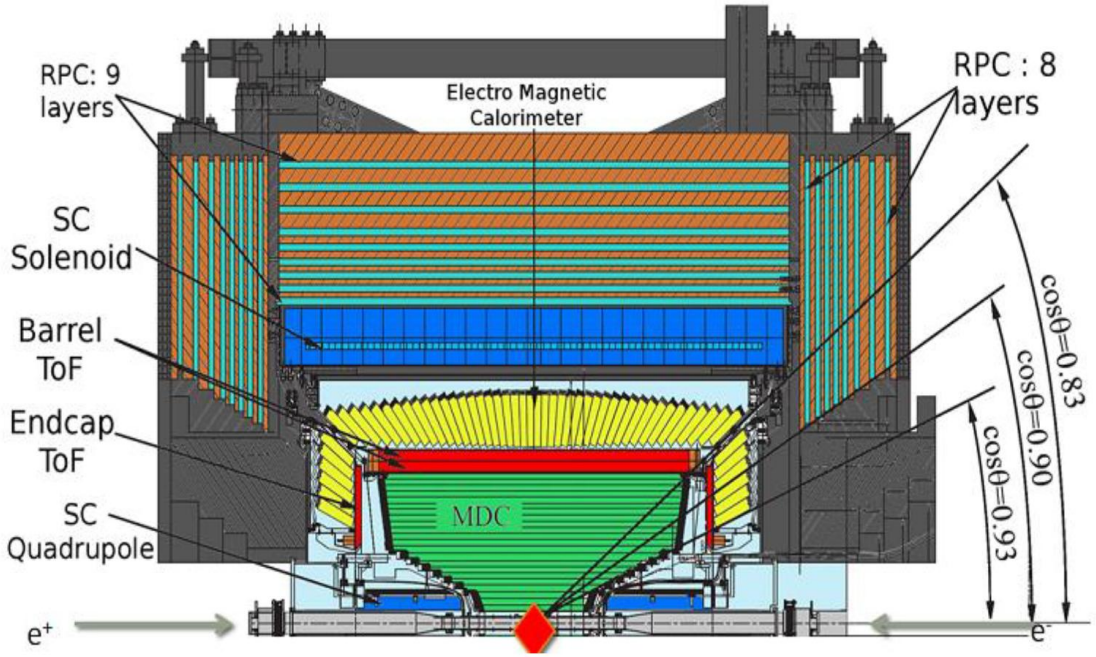
Double-ring, symmetry, multi-bunch e^+ e^- collider

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)



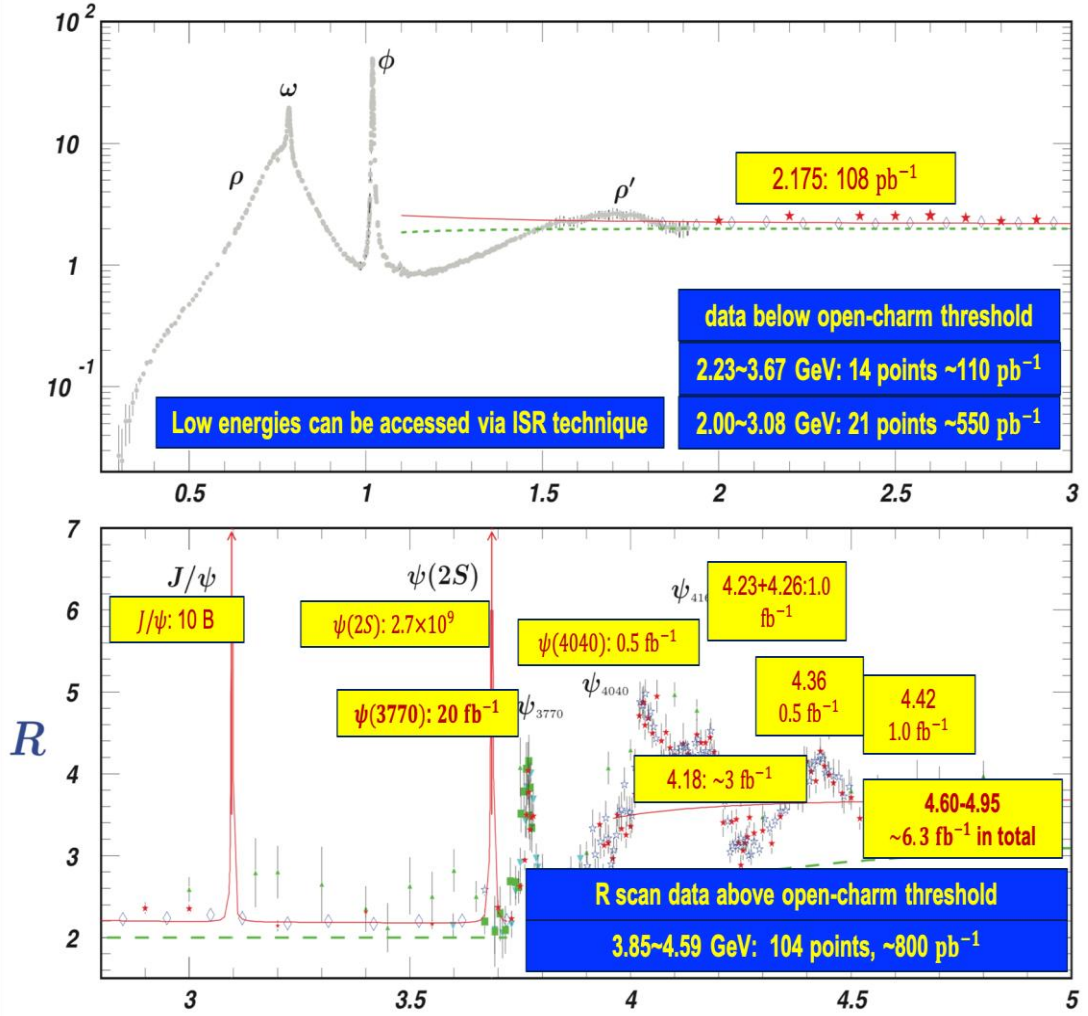
Main Drift Chamber	Time Of Flight	Electromagnetic Calorimeter	Muon Counter
Small cell, 43 layer	Plastic scintillator	CsI(Tl): L=28 cm	RPC
σ_{xy}=130 μm	σ_T(barrel): 65 ps	Barrel σ_E=2.5%	Barrel: 9 layers
dE/dx~6%	σ_T(endcap): 110 ps (update to 60 ps with MRPC)	Endcap σ_E=5.0%	Endcap: 8 layers
σ_p/p=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

World's largest τ – charm data sets in e^+e^- annihilation

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

Data sets collected so far include

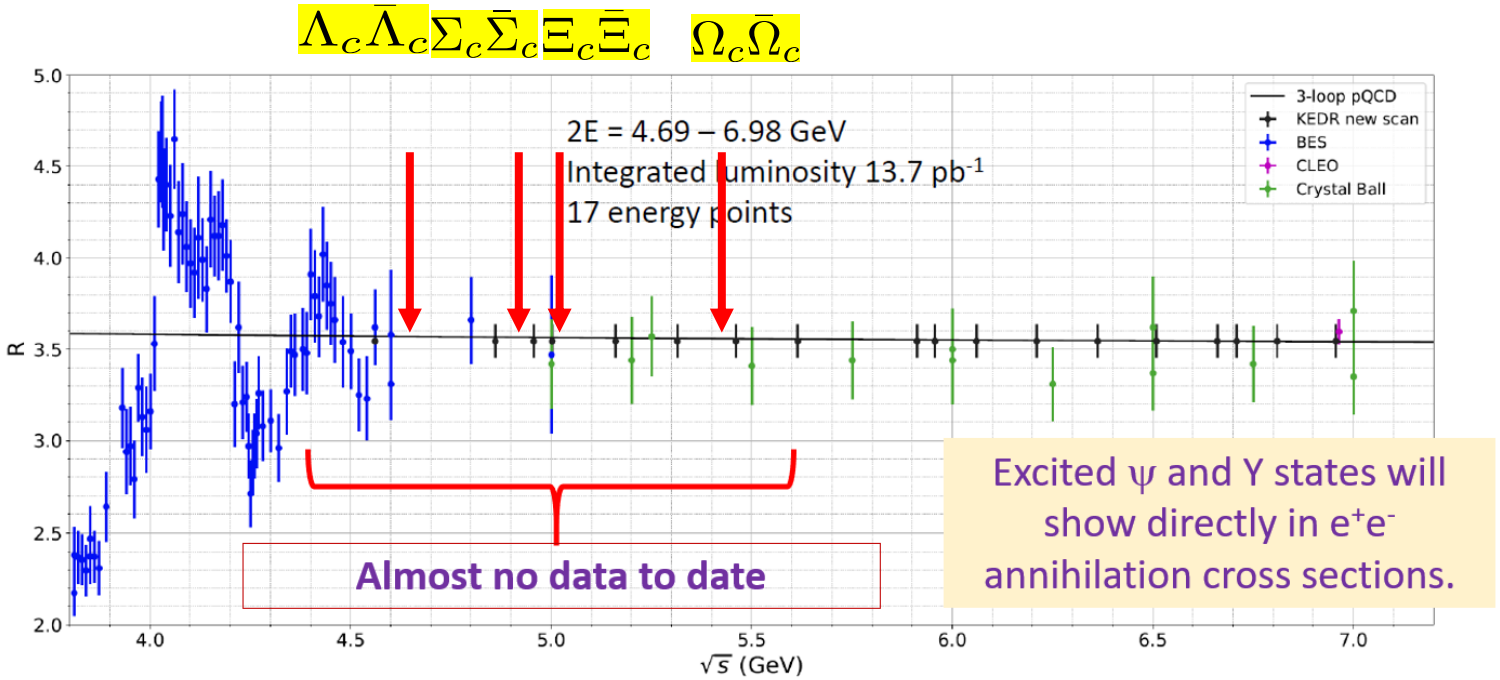
- $\mathbf{10 \times 10^9}$ **J/ψ events**
- $\mathbf{2.7 \times 10^9}$ **ψ(2S) events**
- **20 fb^{-1} ψ(3770)**
- Scan data [1.84, 3.08] GeV; [3.735, 4.600]GeV, 143 energy points, ~2.0 fb^{-1}
- Large data sets for XYZ study ~22 fb^{-1}
- Entangled hadron pair-productions near thresholds



Rich physics program:

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

Overview of BEPCII upgrade project



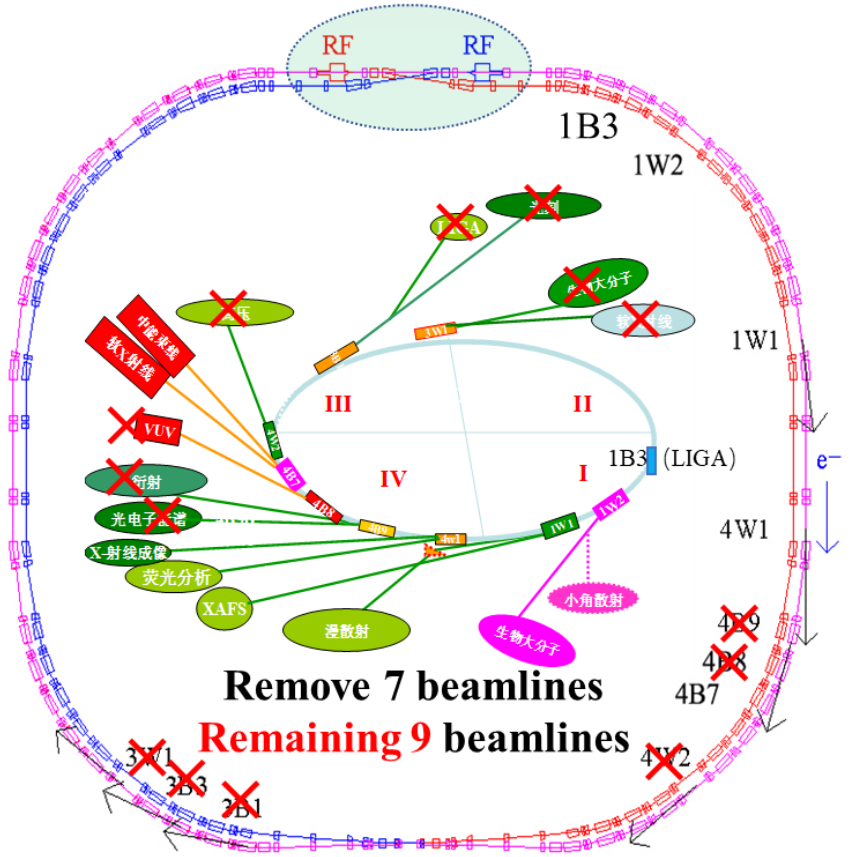
- Direct study of vector states in high-energy regions
- Provide a great opportunity for the study of charmonium-like states
- Cover all the ground-state charmed baryons: production and decays

BEPCII-U: Design Parameters

Key Technologies: Double beam power & Optics upgrade & Higher gradient of magnets

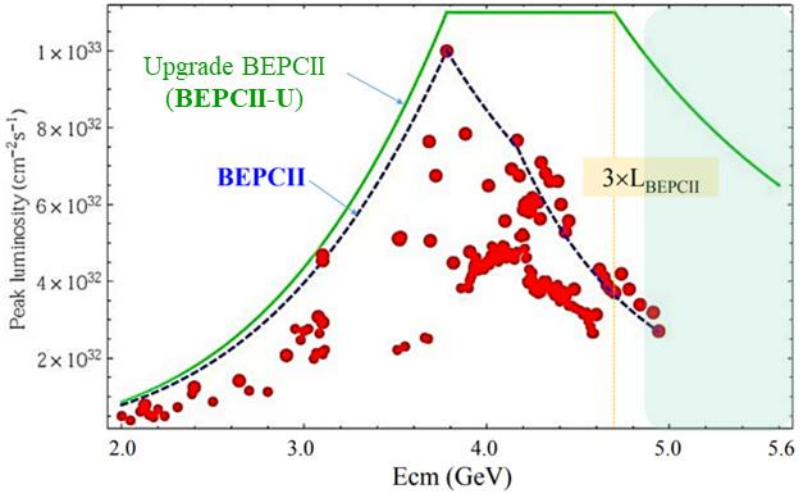
	BEPCII @ 2.35GeV	BEPCII-U @ 2.35GeV	BEPCII-U @ 2.8GeV
L $[10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	**3.5**	**11**	**3.7**
β_y^* [cm]	**1.5**	**1.35**	**3.0**
Beam current [mA]	400	900	450
SR Power [kW]	**110**	**250**	**250**
$\xi_{y,\mathrm{lum}}$	0.029	0.033	0.043
Emittance [nmrad]	**147**	**152**	**200**
Couping [%]	**0.53**	**0.35**	**0.5**
Bucket Height	0.0069	0.011	0.009
$\sigma_{z,0}$ [cm]	1.54	1.07	1.4
σ_z [cm]	**1.69**	**1.22**	**1.6**
RF Voltage [MV]	**1.6**	**3.3**	**3.3**

C.H. Yu @ BESIII 2025 summer Col. meeting



No dedicated SR operation, only parasitic SR experiments, 10 months/year BESIII time.

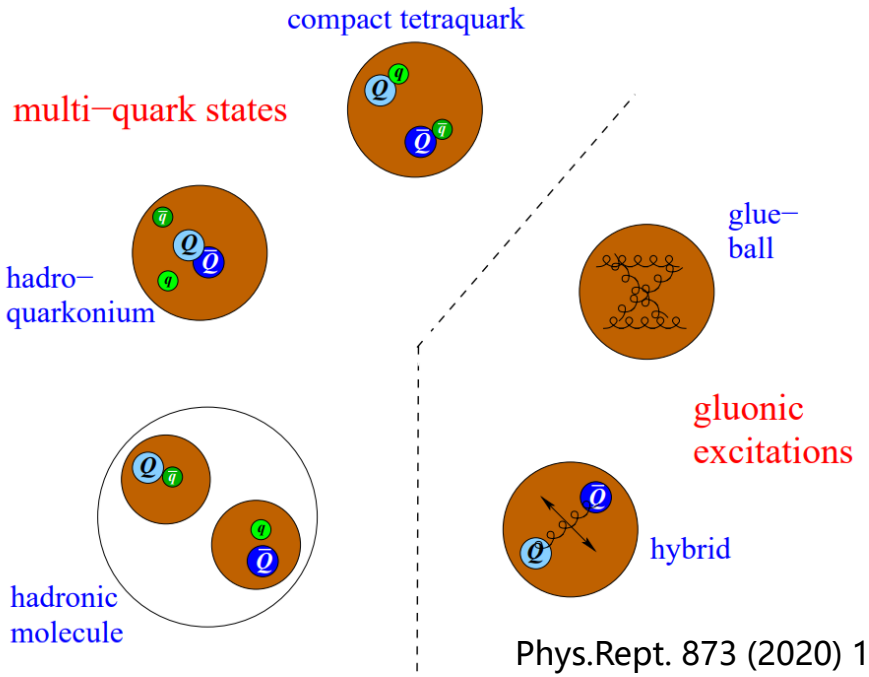
Status of BEPCII-U commissioning



- **Jul. 2024 – Dec. 2024** **Summer shutdown for installation**
- **Jan. 2025 – Jul. 2025** **Commissioning & Data taking @1.843GeV ψ(3686)**
- **Aug. 2025** **Summer shutdown**
- **Sep. 2025 – Jul. 2026** **Data taking @1.843GeV & 2.35GeV (project test)**
- **Aug. 2026 – Sep. 2026** **Summer shutdown & LINAC final upgrade**
- **Oct. 2026 – Sep. 2028** **Data taking within beam energy 2.1-2.5GeV**
- **Sep. 2028 – Jul. 2030** **Data taking within beam energy 2.5-2.8GeV**

Hadron spectroscopy

- How do the rich and complex features of hadrons emerge from QCD?
  - Understanding hadron spectra in terms of the quark and gluon degrees of freedom
- Key things to search for: exotic forms of matter beyond quark model
  - Strong evidences for multi-quark in heavy quark sector *https://qwg.ph.nat.tum.de/exoticshub/*
  - Evidence for gluonic excitations remains sparse



Phys.Rept. 873 (2020) 1

Identification is challenging

Manifestly exotic: with forbidden QN

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

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

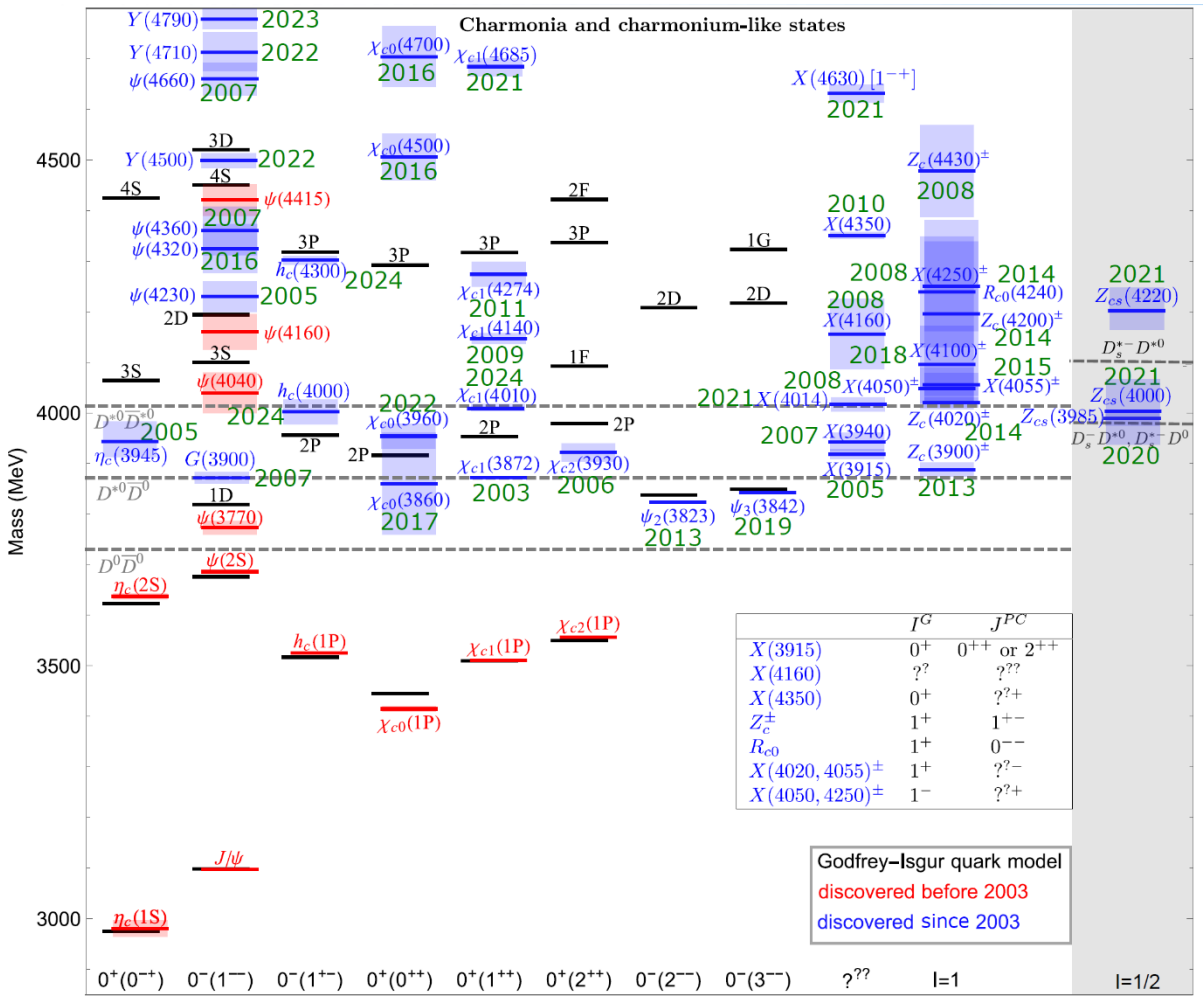
Crypto exotic: with QN as $\mathbf{q\bar{q}}$

Supernumerary states

Abnormal properties

+ Kinematic effects

Heavy QCD exotics



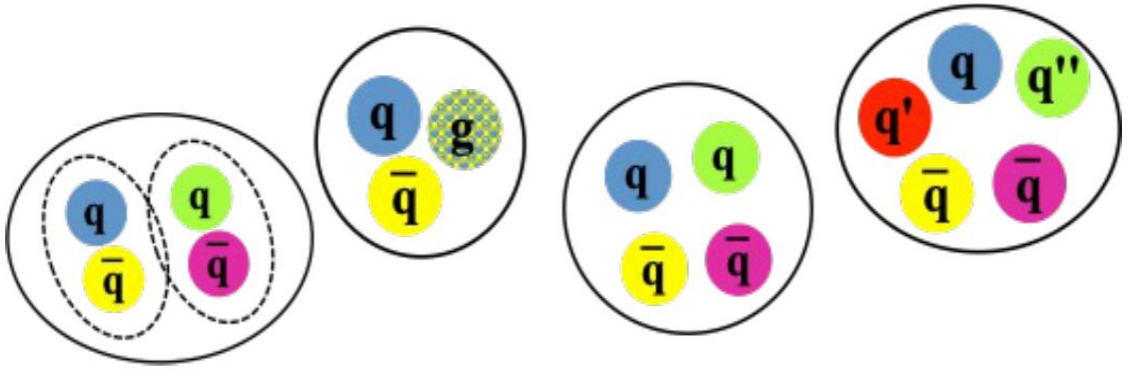
Courtesy to F.K. Guo

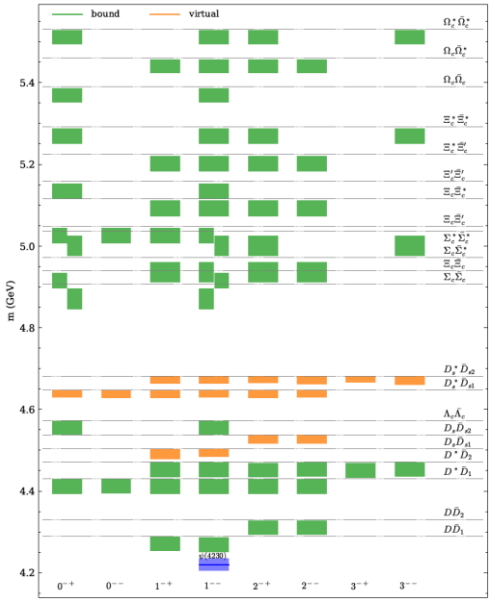
- Conventional $c\bar{c}$ meson fit well with potential model
- Abundance of new states with various probes
  - b-hadron decays
  - hadron/heavy-ion collisions
  - $\gamma\gamma$ processes
  - e^+e^- collisions

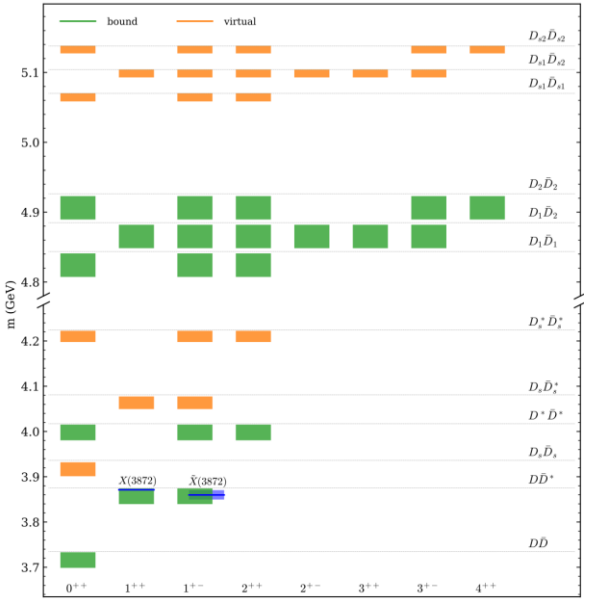
Heavy QCD exotics

With tremendous progress of multiquark candidates, many puzzles remain

- Proximity to open thresholds
- With few exceptions, mostly observed in single production modes
- Binding mechanism(s) unclear



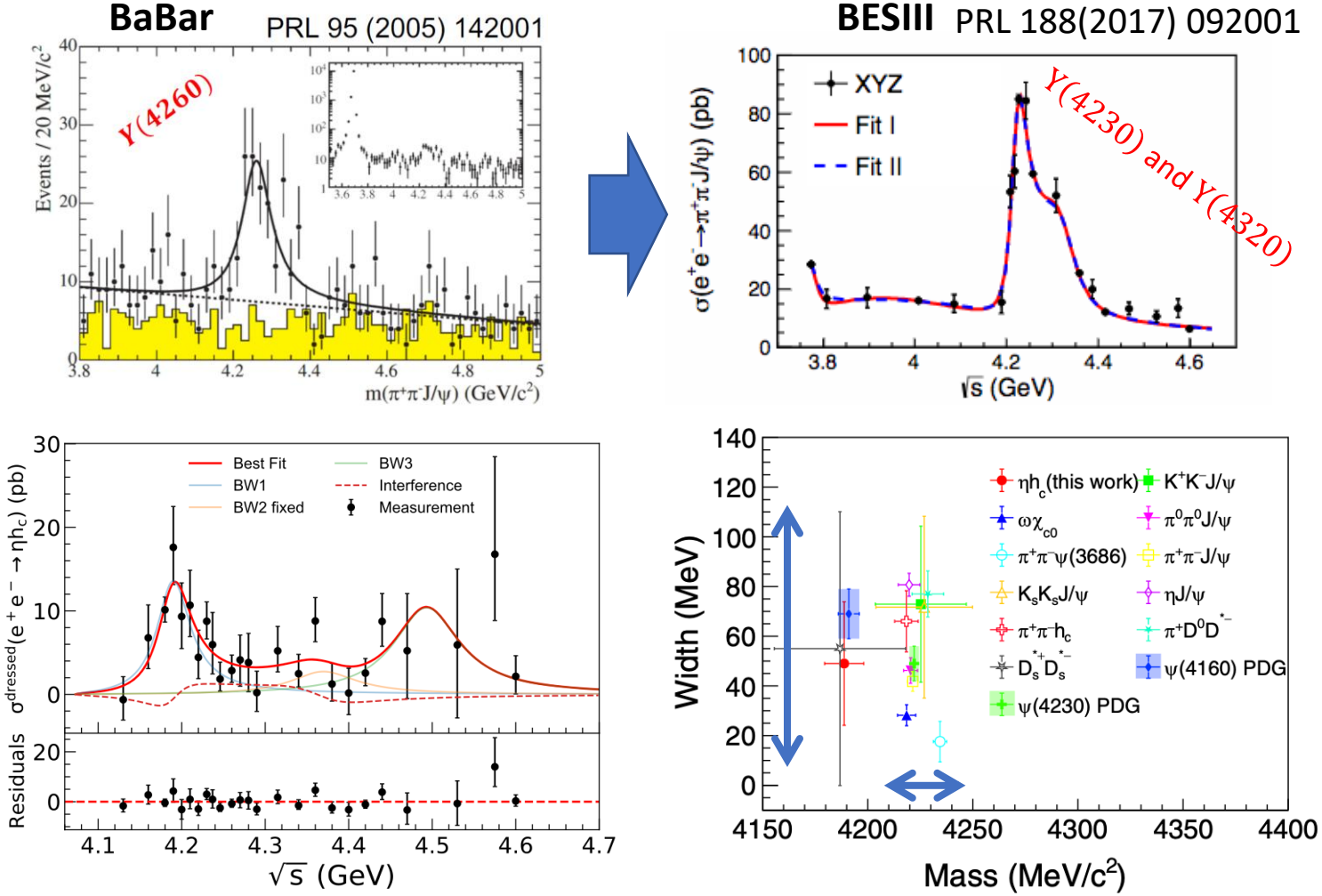




Progr.Phys. 41 (2021) 65

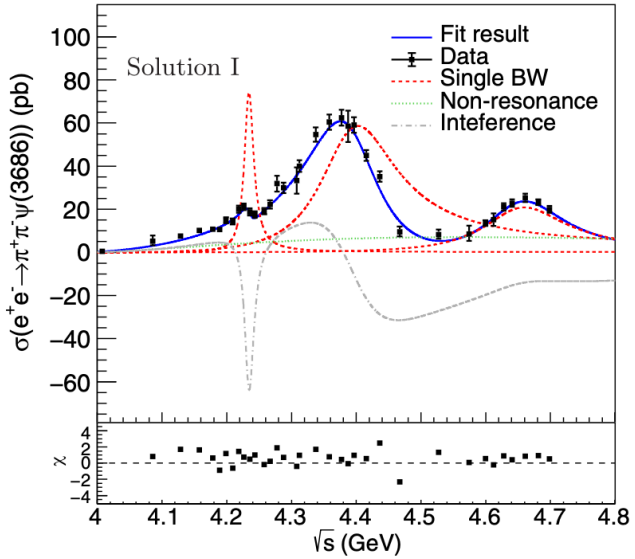
Vector states: Y(4260) → Y(4230)

- Y(4260) firstly seen by BaBar, afterwards split into two states $\mathrm{Y}(4230)$ and $\mathrm{Y}(4320)$ by BESIII
  - Inconsistent with simple $c\bar{c}$ scenario
  - Candidates for exotics:
    - Hybrid ($gc\bar{c}$)?
    - Hadronic molecule ?
    - Tetraquark ?
- Seen in more than ten decay modes at BESIII
  - With consistent mass, not width



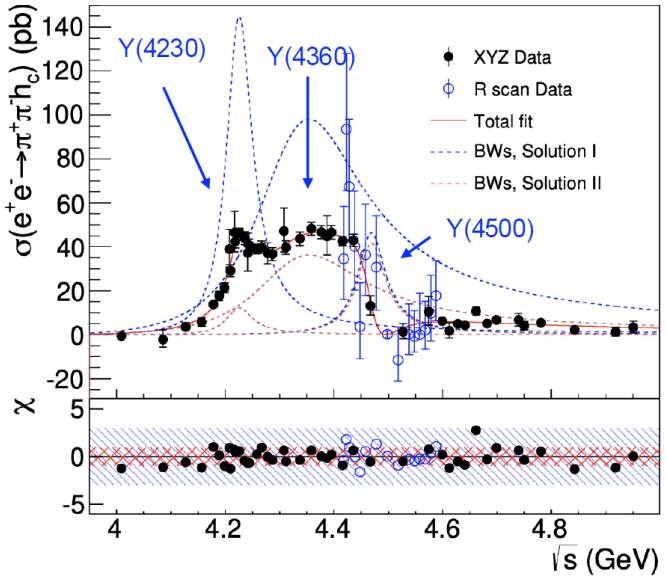
BESIII, Phys.Rev.D 111 (2025) 1, L011101

Vector states: at higher masses



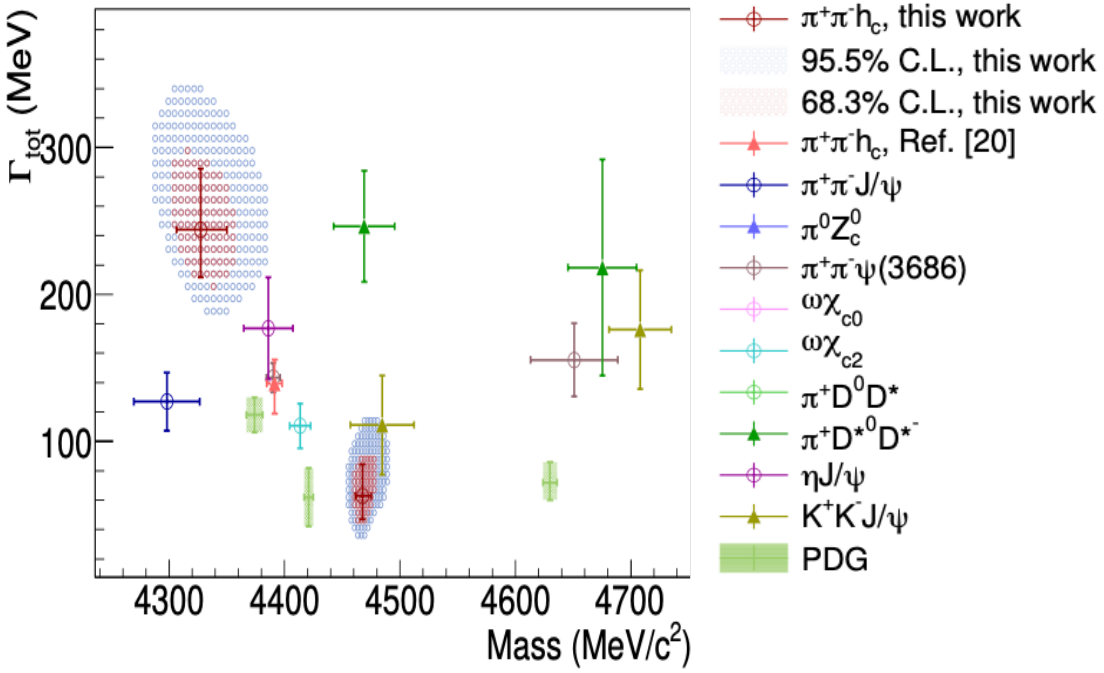
$e^+e^- \to \pi\pi\psi(3686)$

BESIII, PRD 104 (2021), 052012



$e^+e^- \to \pi\pi h_c$

BESIII, arXiv: 2504.04096



Less consistency between exclusive channels

Requires global analysis:
High precision measurements + Sophisticated models

N. Husken, et al., arXiv:2404.03896

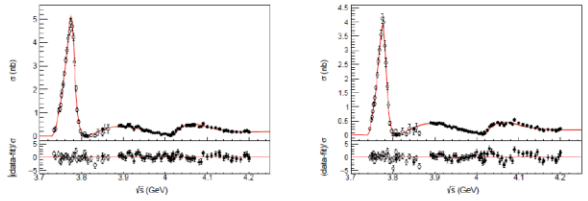


FIG. 2. Fit result for Model 1. Left: $e^+e^- \to D^0\bar{D}^0$. Right: $e^+e^- \to D^+D^-$. Open data points are the Born cross section values based on observed cross sections, as reported in Ref. [18]; closed data points are from Ref. [1].

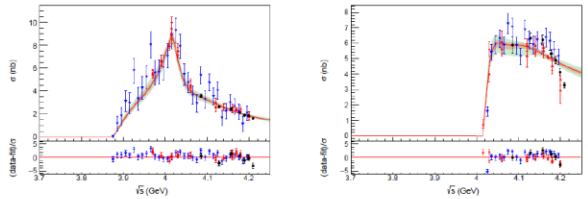


FIG. 3. Fit result for Model 1. Left: $e^+e^- \to D^*\bar{D}$. Right: $e^+e^- \to D^*\bar{D}^*$. The red region indicates the 68% confidence level, while green is the 90% confidence level. Black data points are from BESIII [21], red data is from CLEO-c [23, 24], blue data is from Belle [22].

S. G. Salnikov & A. I. Milstein, arXiv:2404.06160

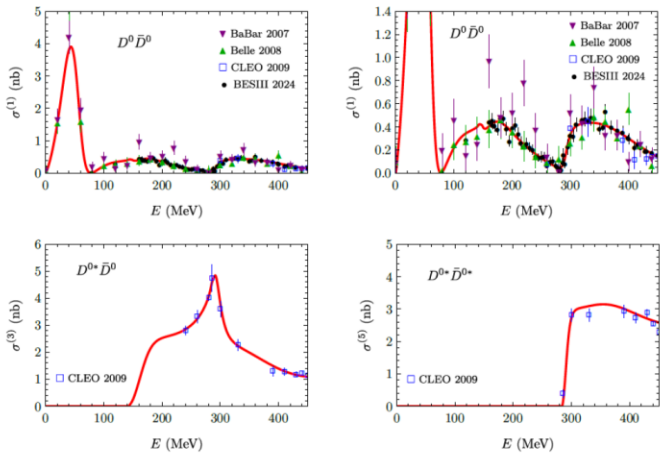


FIG. 1. Energy dependence of the cross sections for the production of neutral particles. Experimental data are taken from Refs. [32, 34–36, 39].

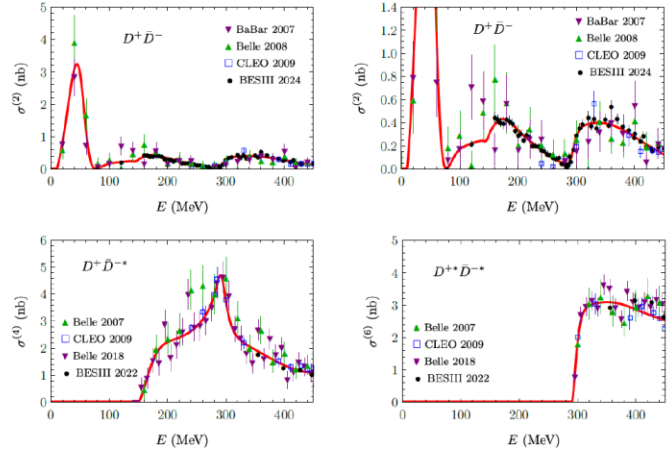
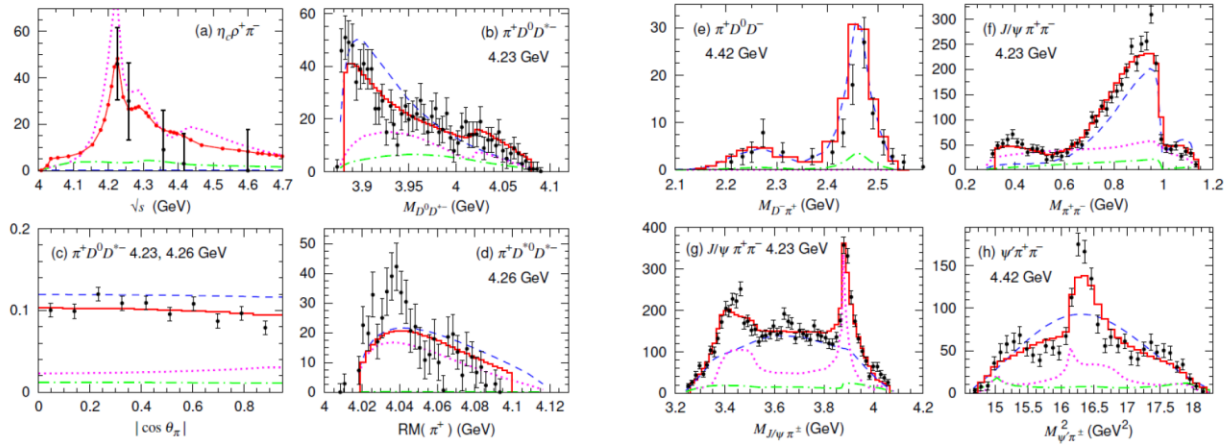
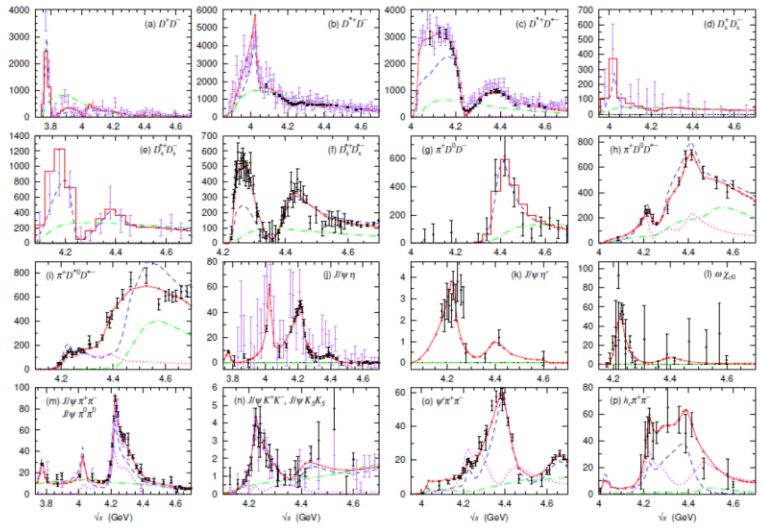


FIG. 2. Energy dependence of the cross sections for production of charged particles. Experimental data are taken from Refs. [32–39].

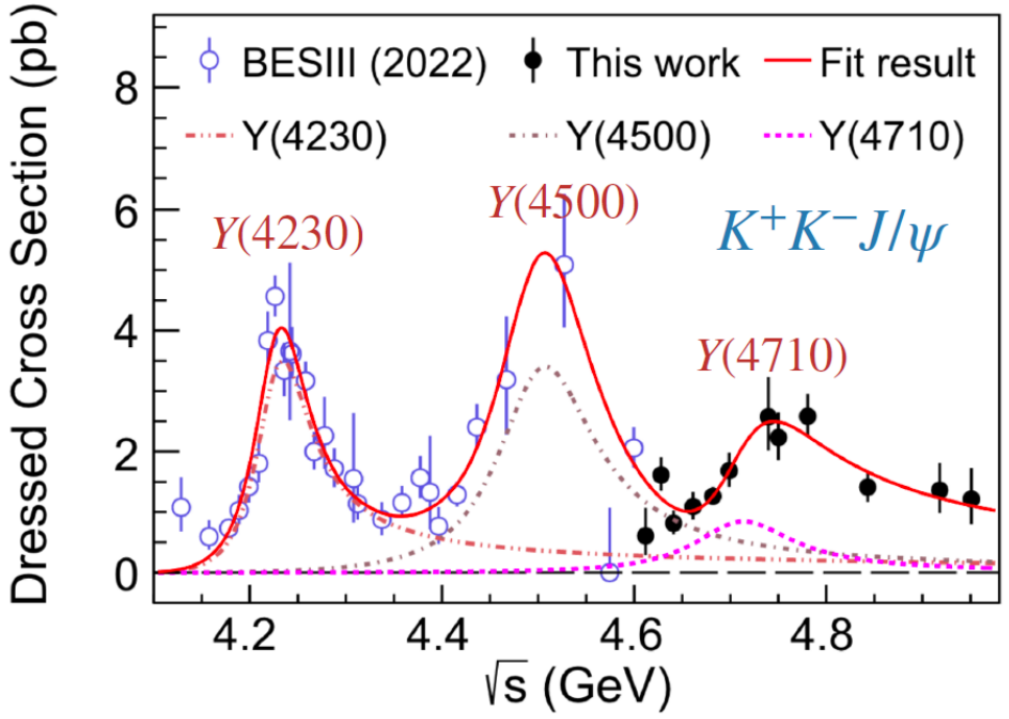
S. X. Nakamura, et al., arXiv:2312.17658



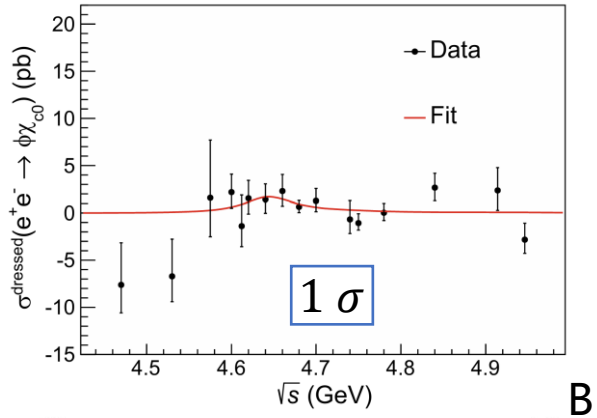


Vectors in $c\bar{c} + s\bar{s}$ final states

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

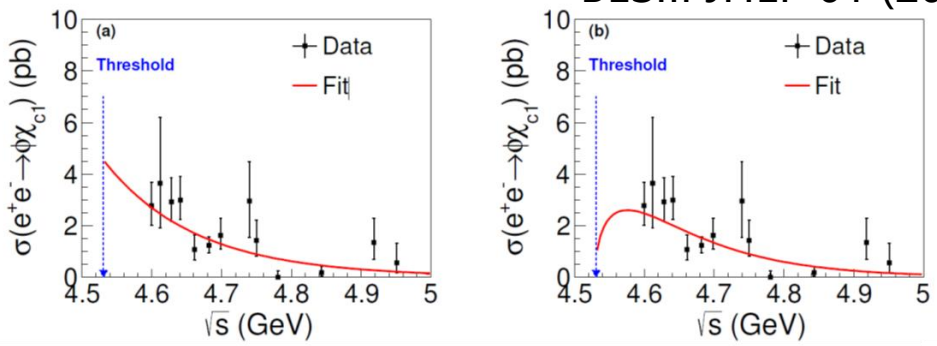


BESIII PRD111, 012016 (2025)

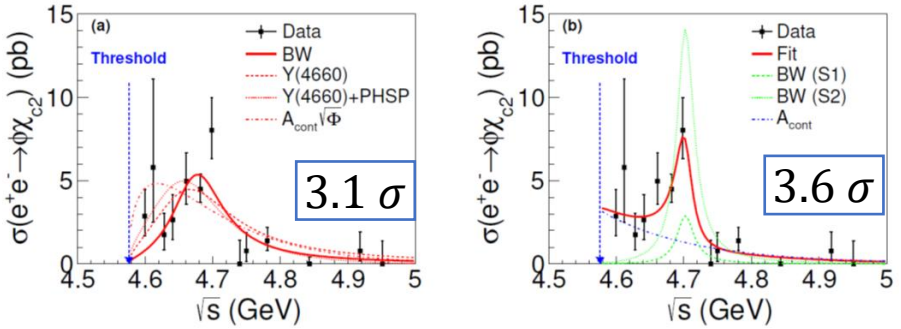


$\phi\chi_{c0}$

BESIII JHEP 01 (2023) 132



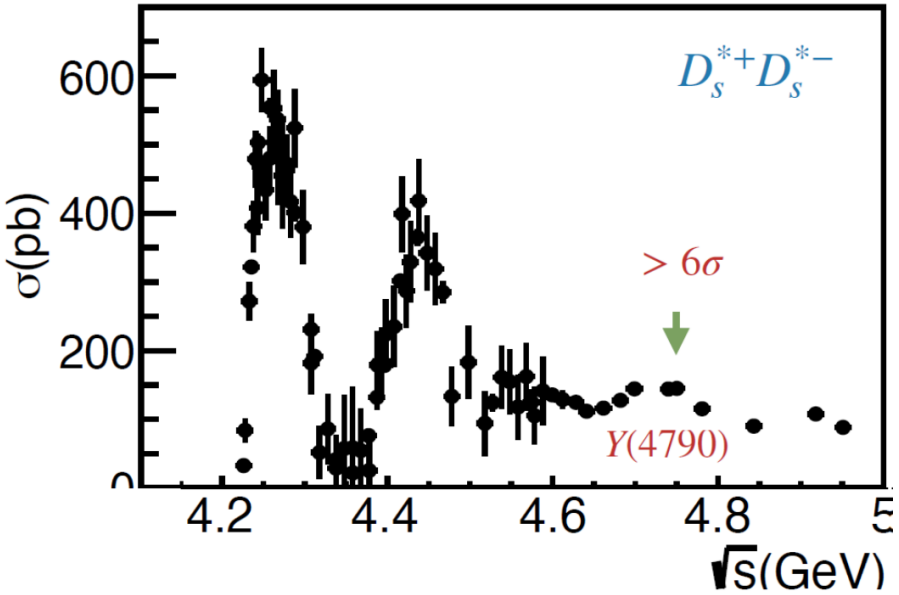
$\phi\chi_{c1}$

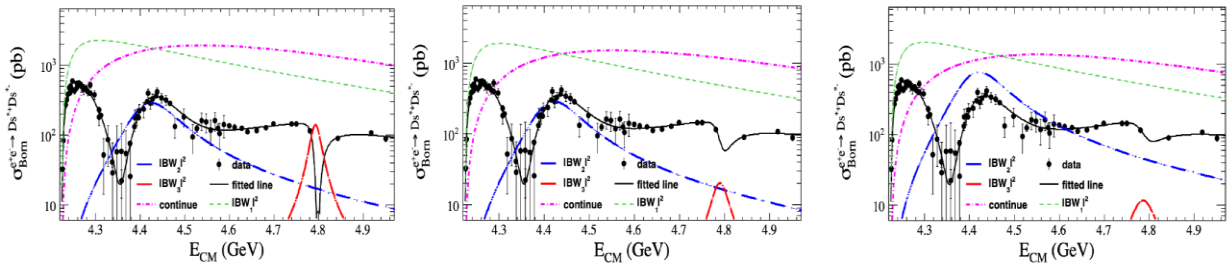


$\phi\chi_{c2}$

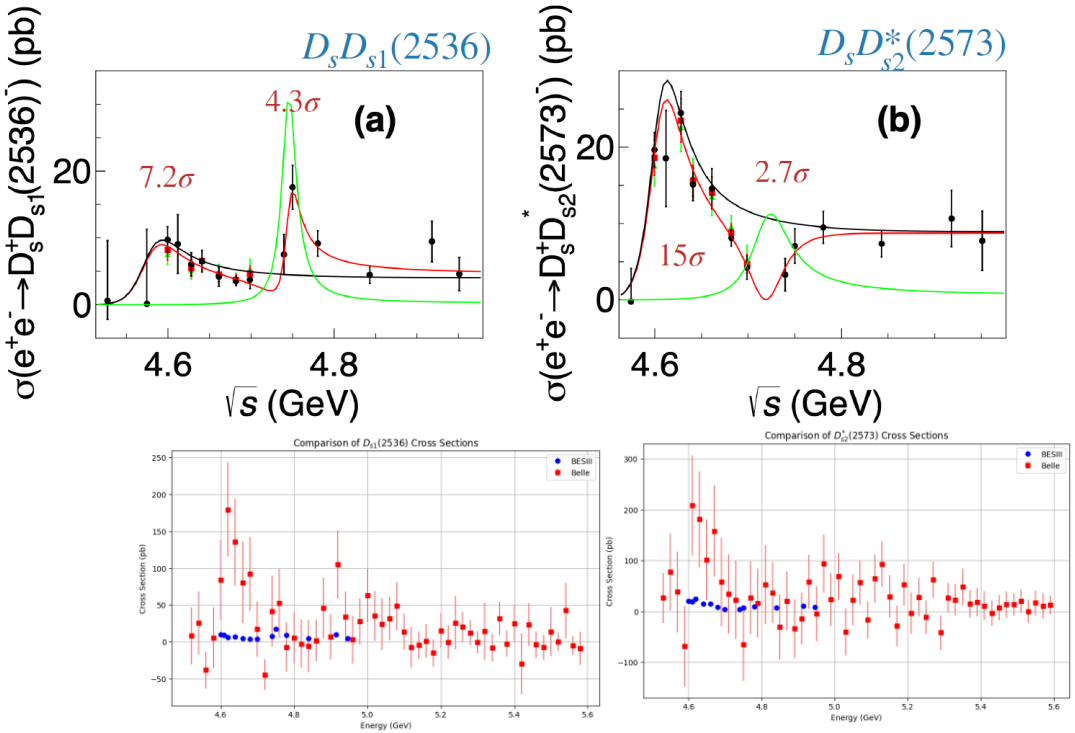
Vectors in $c\bar{c} + s\bar{s}$ final states

BESIII PRL131, 151903 (2023)





BESIII PRL 133 (2024) 171903

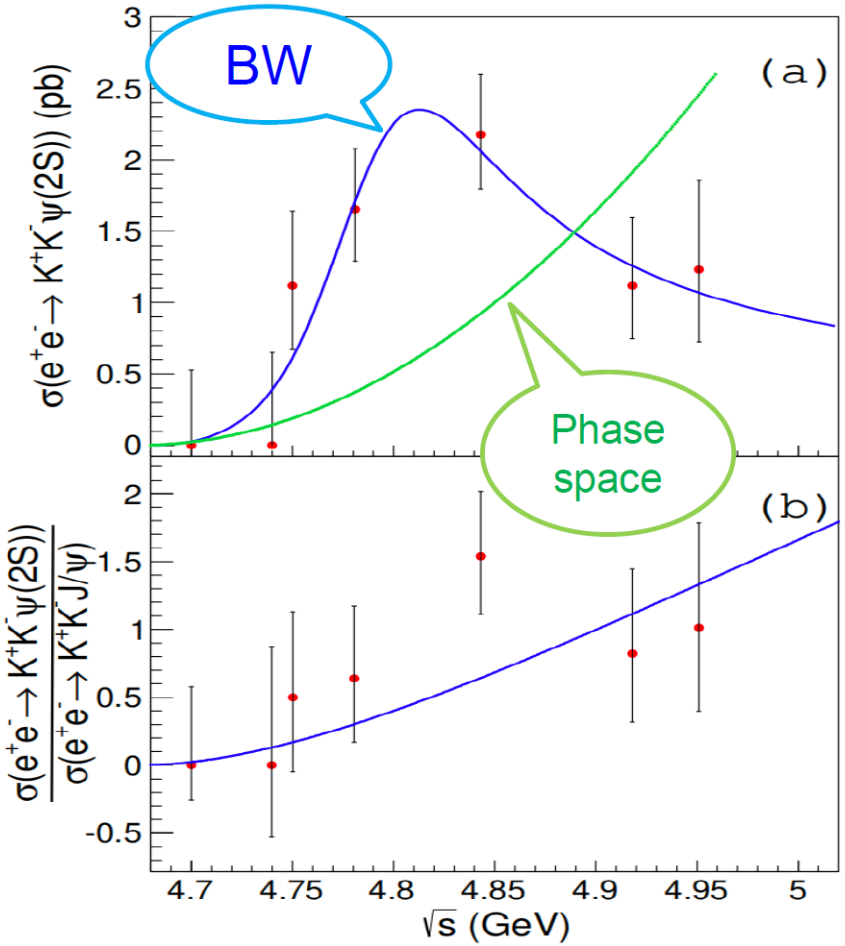


Tension between direct (BESIII) and ISR(Belle) measurements

Vectors in $c\bar{c} + s\bar{s}$ final states: more data needed

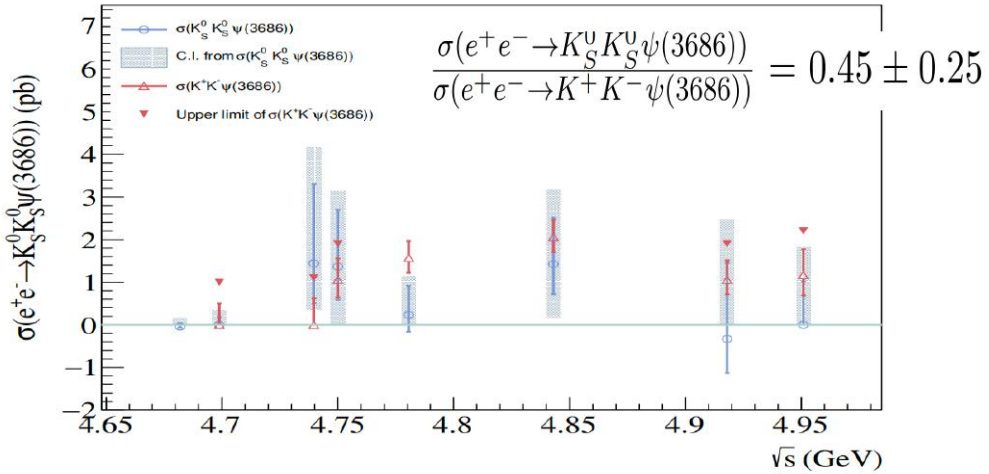
$e^+e^- \to K^+K^-\psi(2S)$

BESIII arXiv: 2407.20009



$e^+e^- \to K_S^0K_S^0\psi(2S)$

BESIII JHEP 02 (2025) 120



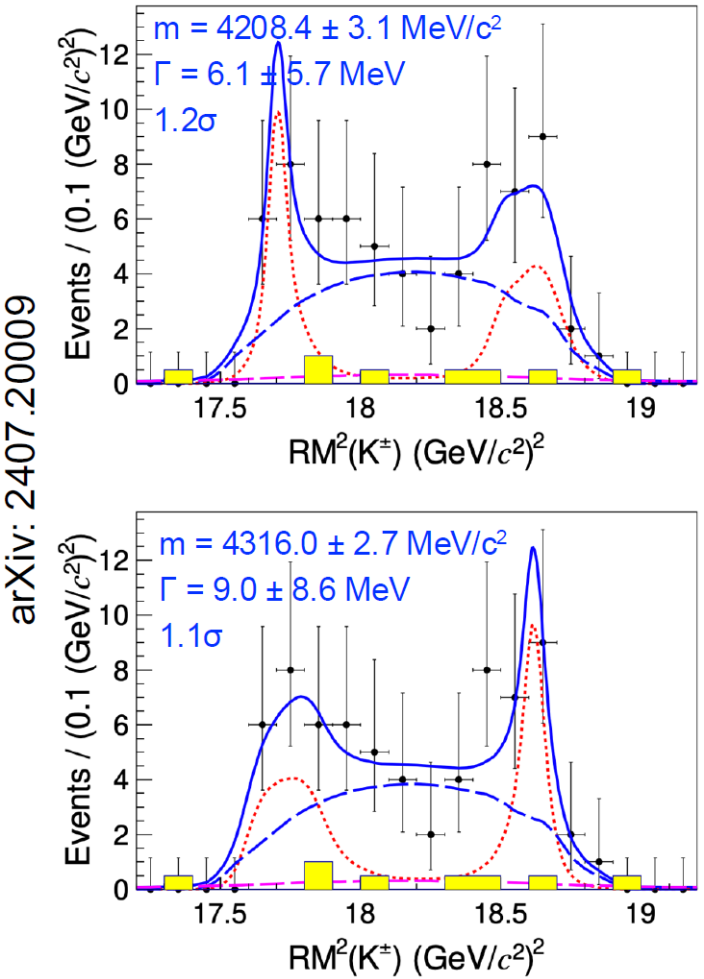
Mass: 4788 ± 18MeV

Width: 110 ± 34 MeV

No significant Y states observed in the line shape

Search for $Z_{cs} \to K\psi(2S)$: more data needed

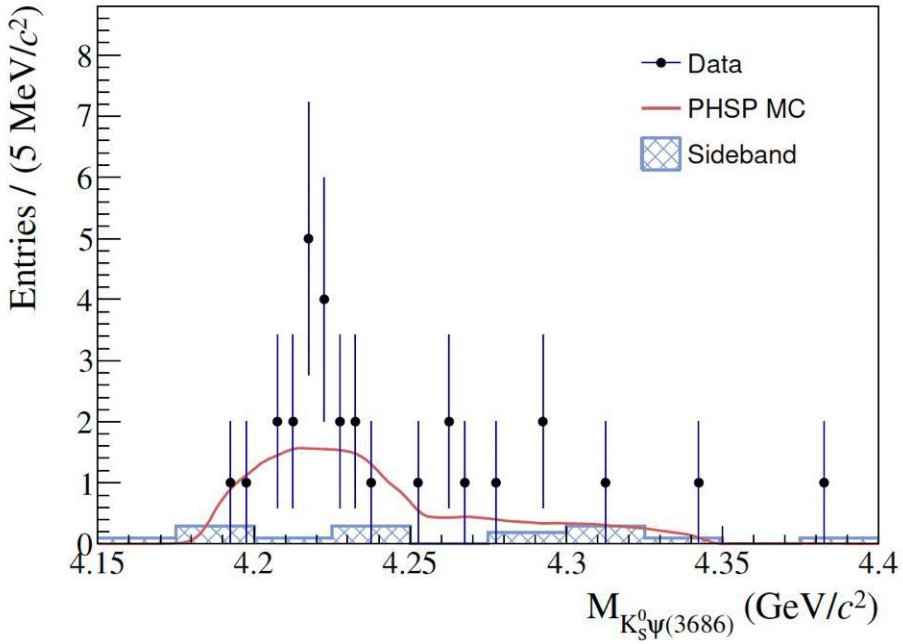
$e^+e^- \to K^+K^-\psi(2S)$



arXiv: 2407.20009

$e^+e^- \to K_S^0K_S^0\psi(2S)$

BESIII JHEP 02 (2025) 120



No significant tetraquark $Z_{cs} \to K\psi(2S)$ signal

Light QCD exotics

Light sector is even harder

- **Light flavor-exotic hard to establish**
- **Assignment of some $SU(3)_{flavor}$ $|q\bar{q}>$ nonets difficult**

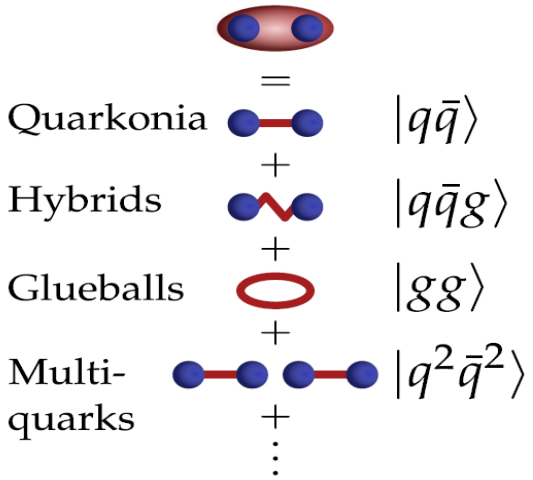
- **Role of gluons:**
  - Gluons mediate the strong force
  - Gluons' unique self-interacting property
    → **New form of matter: glueballs, hybrids**
  - **Gluonic Excitations provide measurements of the QCD potential**

Critical to confinement and mass dynamical generation

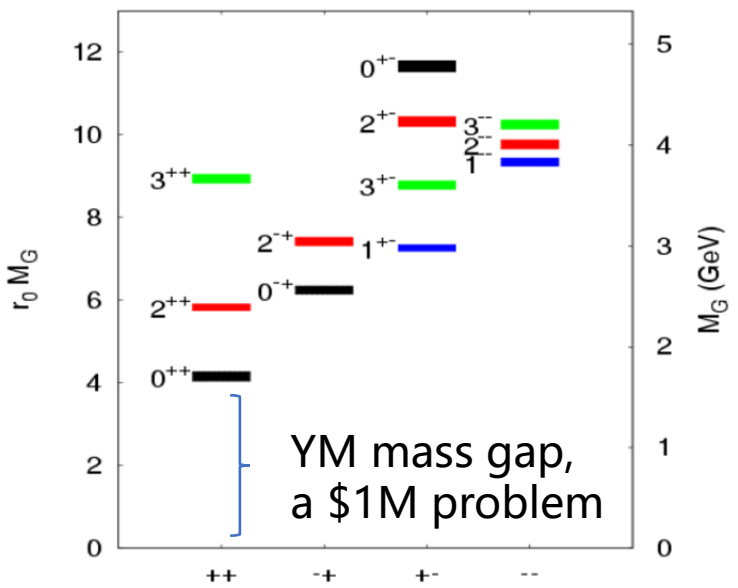
Glueballs

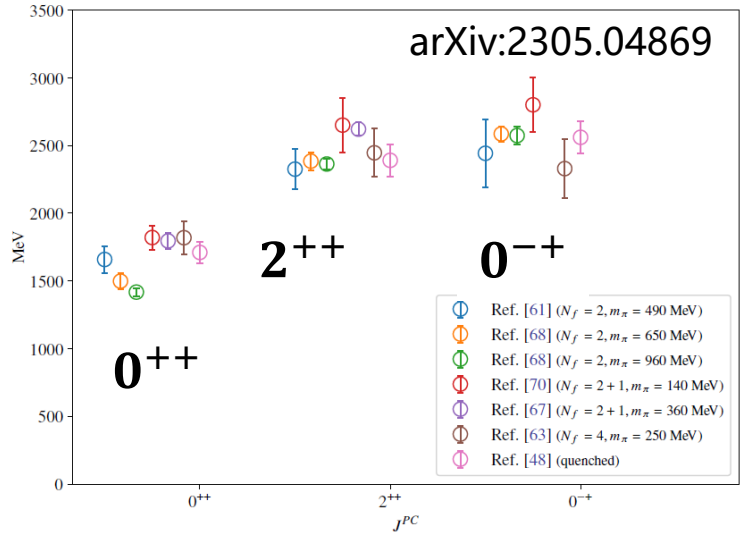
- Glueballs are the most direct prediction of QCD
  - Color singlets emerge as a consequence of the gluon self-interactions
  - Unique particles formed by gauge bosons (force)
- Essential for understanding of confinement and mass dynamical generation
- Theoretical predictions from lattice QCD and QCD-inspired models mostly consistent
  - Light-mass glueballs: $J^{PC} = 0^{++}, 2^{++}, 0^{-+}$

non-$\mathbf{q\bar{q}}$ nature with ordinary quantum numbers is difficult to establish



PRD 73 014516 (2006)



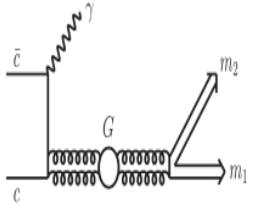


Yang-Mills glueballs on lattice (quenched and unquenched)

Glueball hunting for over 40 years

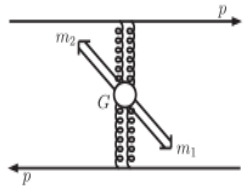
- **Supernumerary states** w.r.t. quark model
  - A priori, mixed with nearby $\mathbf{q\bar{q}}$
  - Assignment of some $q\bar{q}$ multiplets is difficult
- Detailed and accurate information about couplings to production and decay channels is required
- Strongly produced in **gluon-rich processes**
- Decay: **gluon is flavor-blind**
  - $SU(3)_{flavor}$ symmetry expected, but differing quark masses leads exceptions
  - No rigorous predictions on decay patterns
  - 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)]

gluon-rich processes [Phys. Rept. 454 1]



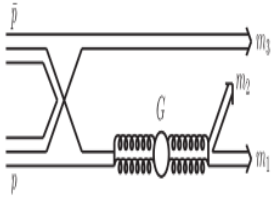
Charmonium decays:

BESIII, MRKIII…



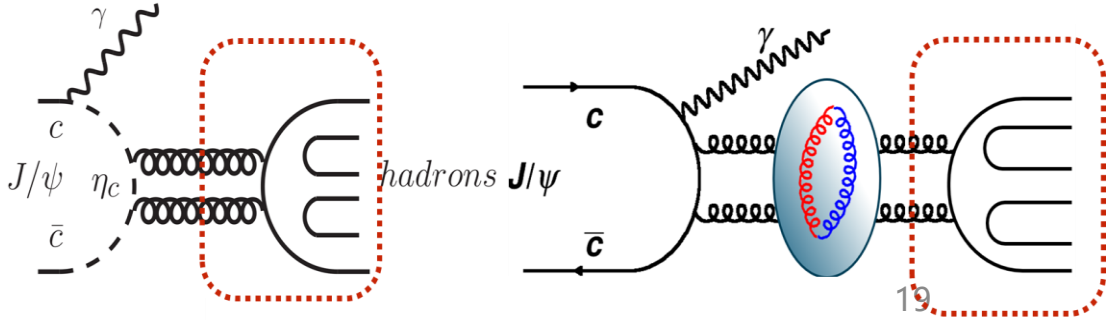
pp double-Pomeron exchange:

WA102, GAMS…



$p\bar{p}$ annihilation:

Crystal barrel, OBELIX…



Story thus far (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)

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

✓**$B(J/\psi \to \gamma f_0(1710))$ is x10 larger than $f_0(1500)$; suppression of $f_0(1710) \to \eta\eta'$**

➔ **Large gluonic component**

BESIII [PRD 87 092009, PRD 92 052003, PRD 98 072003, PRD 106 072012]

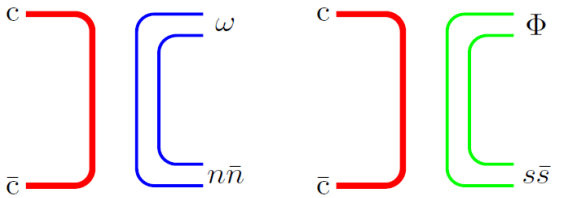
✓**Large production rate of $f_2(2340)$ in J/ψ radiative decays**

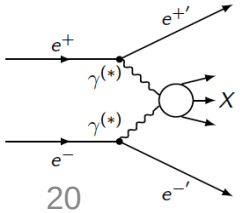
BESIII [PRD 87,092009, PRD 93, 112011, PRD 98,072003, PRD 105,072002]

✓**$X(2370)$: a good candidate with analogy decay pattern as η_c**

BESIII [PRL 106, 072002, PRL 117, 042002, EPJC 80 746, PRL 132, 181901, PoS ICHEP2024 490]

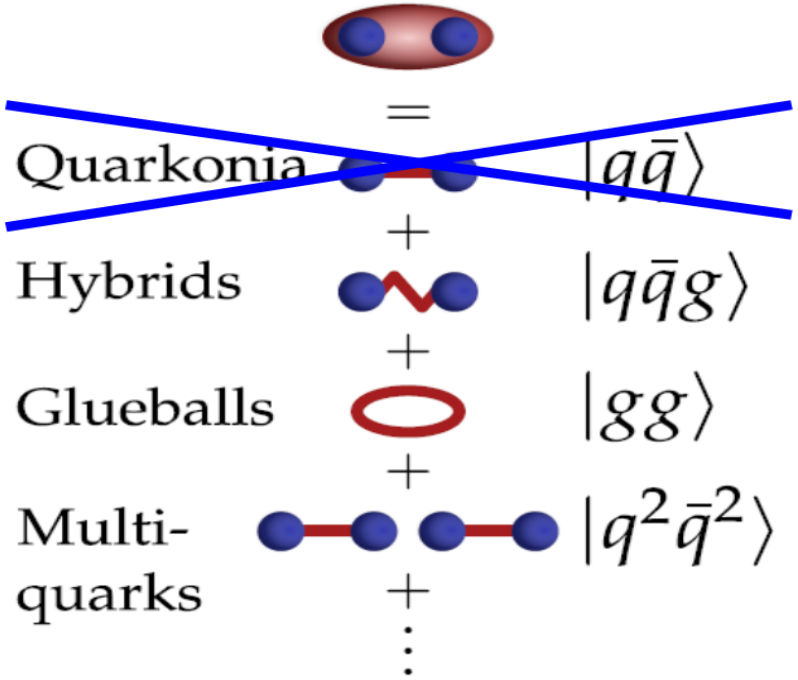
More to be explored:
Production/Decay properties, coupled channel, …





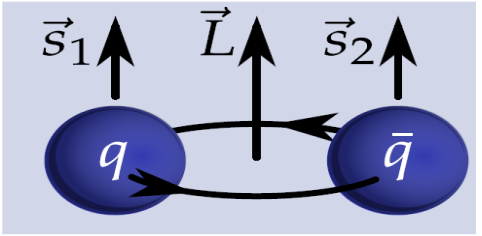
Light hadrons with exotic quantum numbers

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



Experiments:

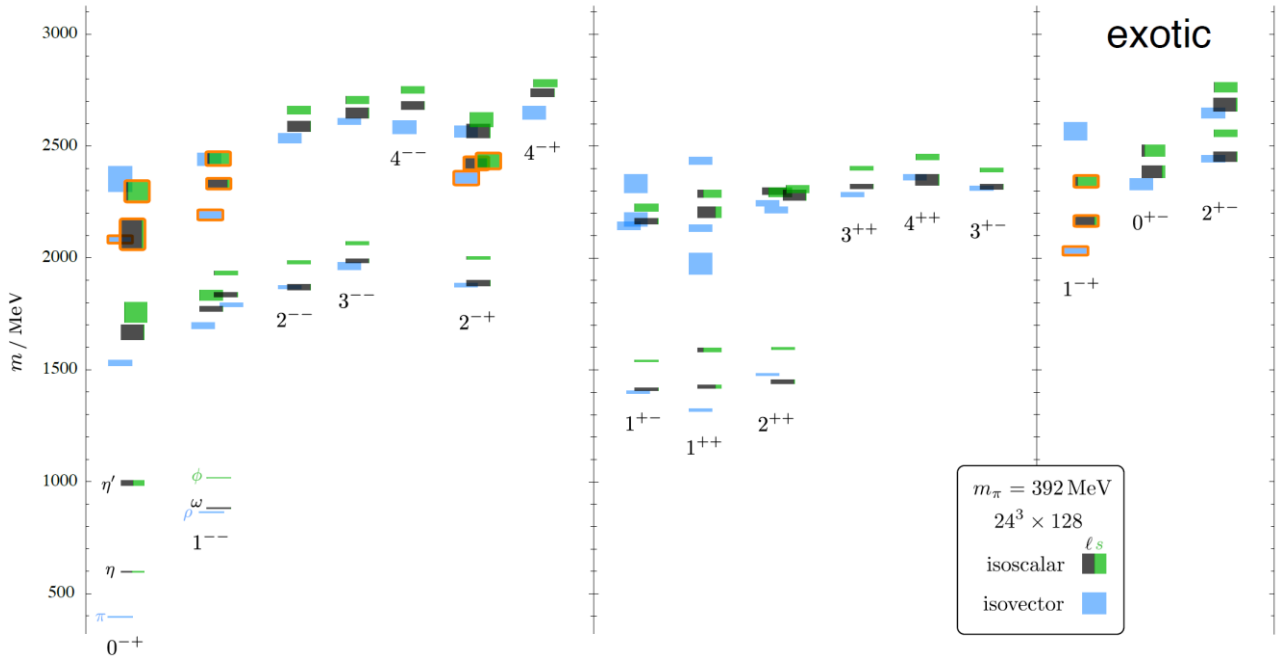
- **Hadroproduction:** GAMS, VES, E852, COMPASS
- **$p\bar{p}$ annihilation:** Crystal Barrel, OBELIX, PANDA(under construction)
- **Photoproduction:** GlueX(2017-), CLAS



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

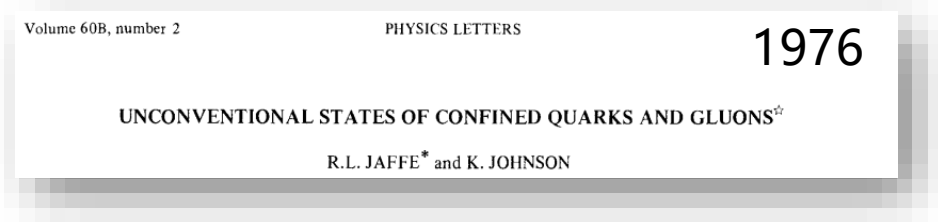
Allowed $\mathbf{J^{PC}}$: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$

Predictions



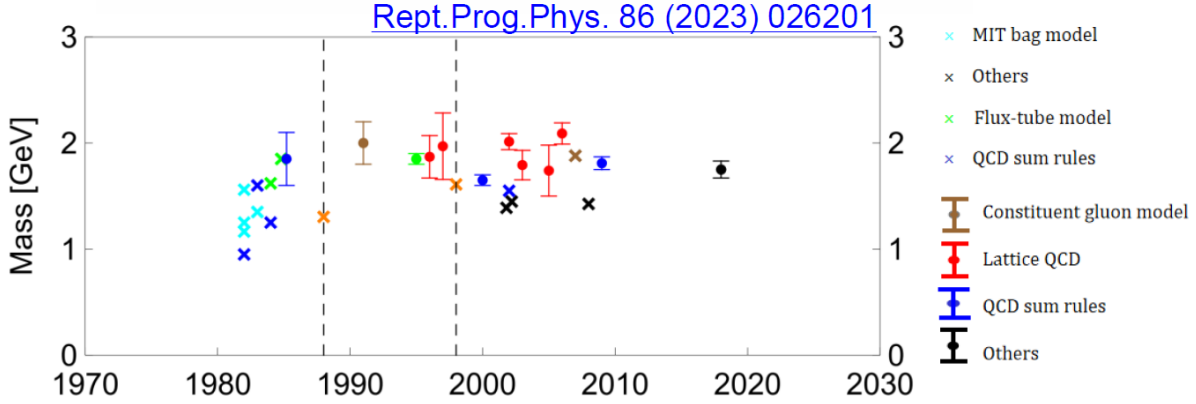
PRD 88 094505(2013)

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

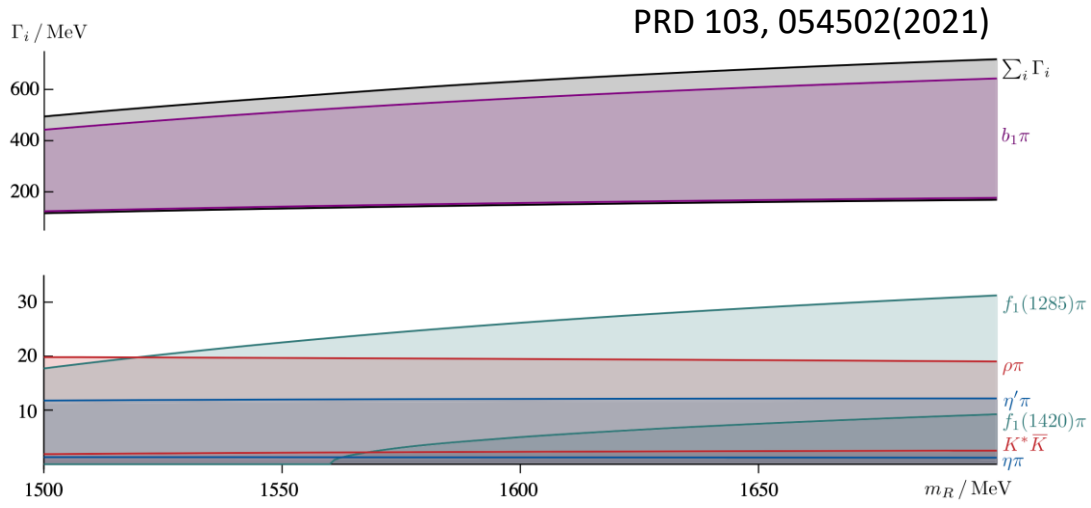

Volume 60B, number 2 PHYSICS LETTERS 1976

UNCONVENTIONAL STATES OF CONFINED QUARKS AND GLUONS☆

R.L. JAFFE* and K. JOHNSON



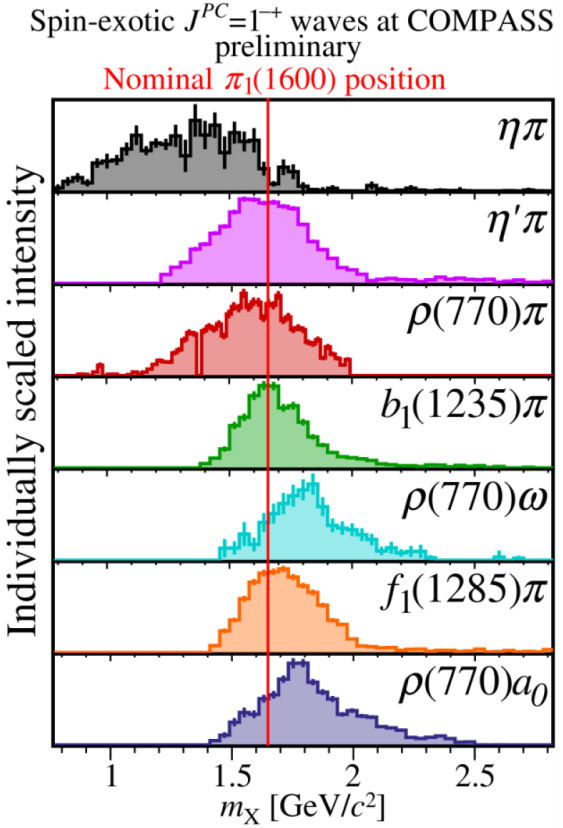
Mass of $\mathbf{1^{-+}}$ hybrid

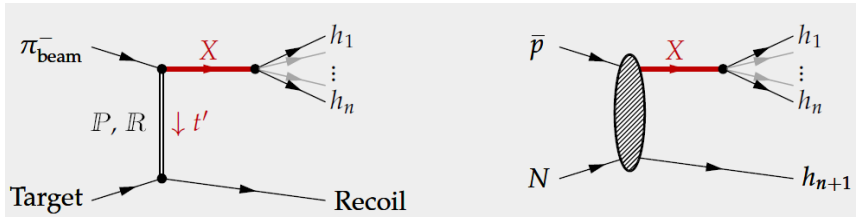


Decay width of $\mathbf{1^{-+}}$ hybrid π_1

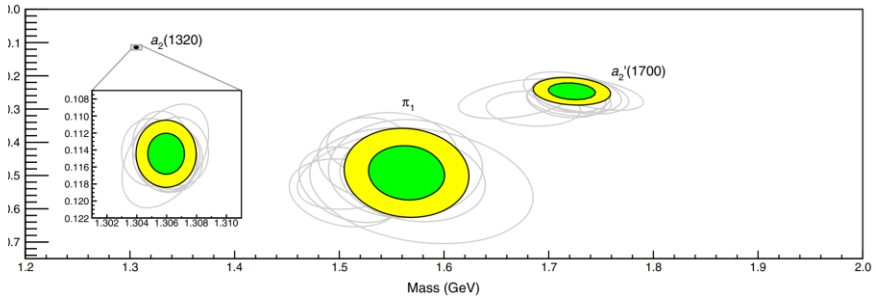
1^{-+} Hybrids

- Candidates over 3 decades
  - $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2015)$ (needs confirmation), all isovetors





Review: PRC 82, 025208 (2010), PPNP 82, 21 (2015), EPJC 83 (2023) 1125

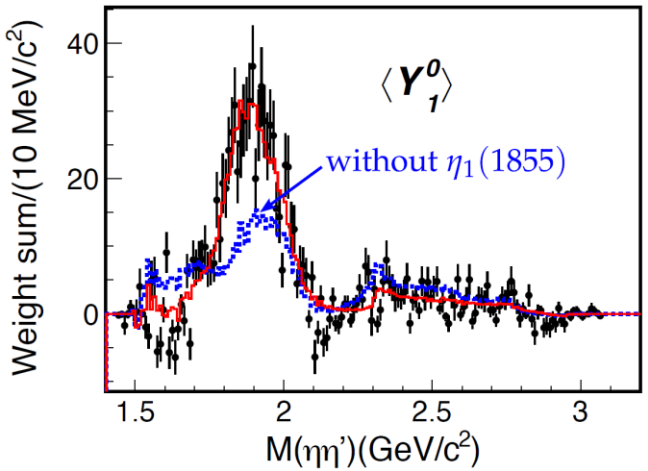


$\pi_1(1400)$ & $\pi_1(1600)$ can be one pole

[PRL 122, 042002 (2019), EPJ C 81, 1056 (2021])

- Observation of an exotic 1^{-+} isoscalar state $\eta_1(1855)$

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



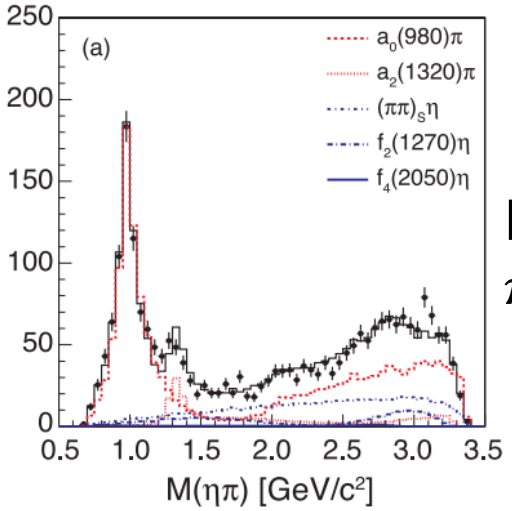
Can be $\pi_1(1600)$' s partner

Opens a new direction to completing the picture of 1^{-+}

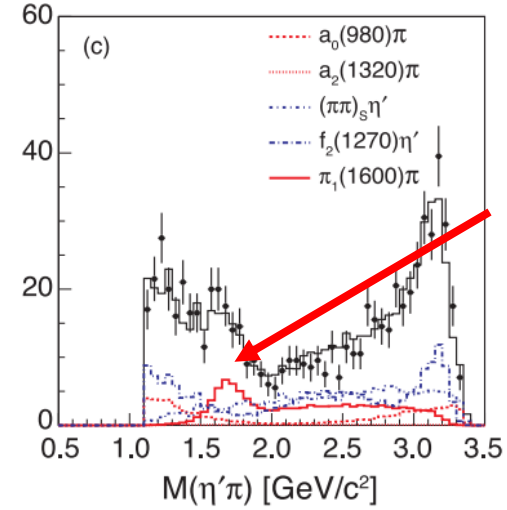
$\chi_{c1} \to \pi^+\pi^-\eta^{(\prime)}$

PR D84 112009 (2011)

$\mathbf{2.6 \times 10^7}$ ψ(3686)@CLEO − c



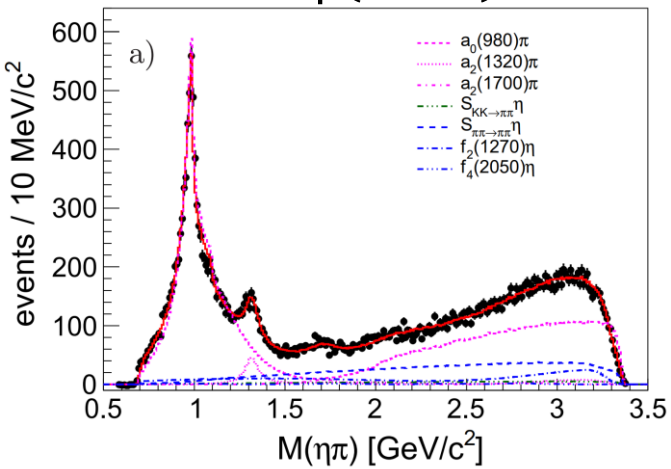
No evidence of $\pi_1 \to \eta\pi$



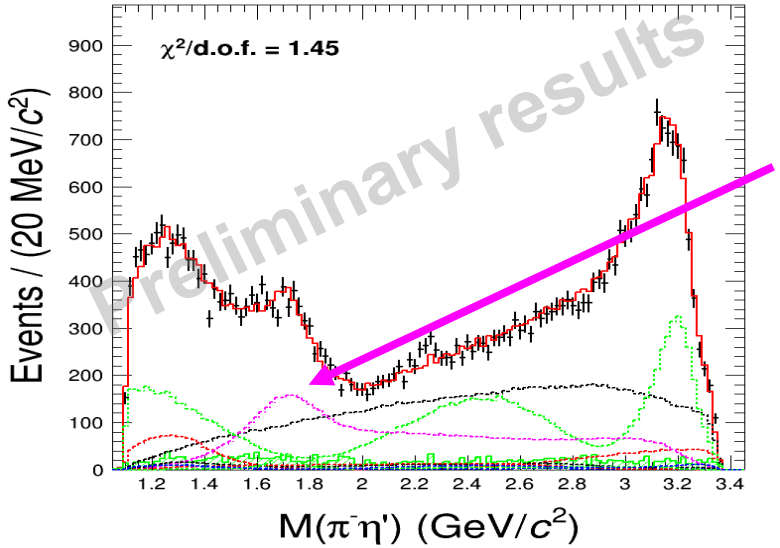
Evidence of $\pi_1 \to \eta'\pi$ (without significant BW phase motion)

PR D95 032002(2017)

44.8×10^7 ψ(3686)@BESIII



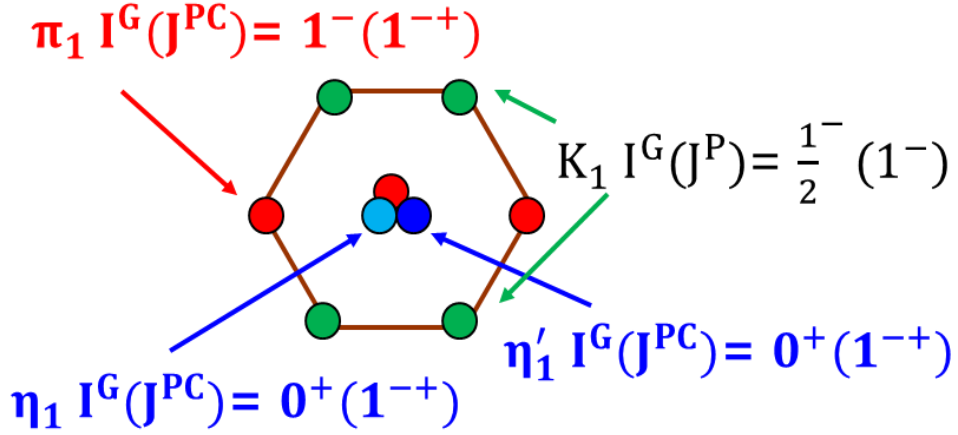
$\mathbf{2.7 \times 10^9}$ ψ(3686)@BESIII [preliminary]



- $\pi_1(1600)$ observed>10σ
- with a significant BW phase motion
- $J^{PC}= 1^{-+}$, better than other assignments well over 10σ

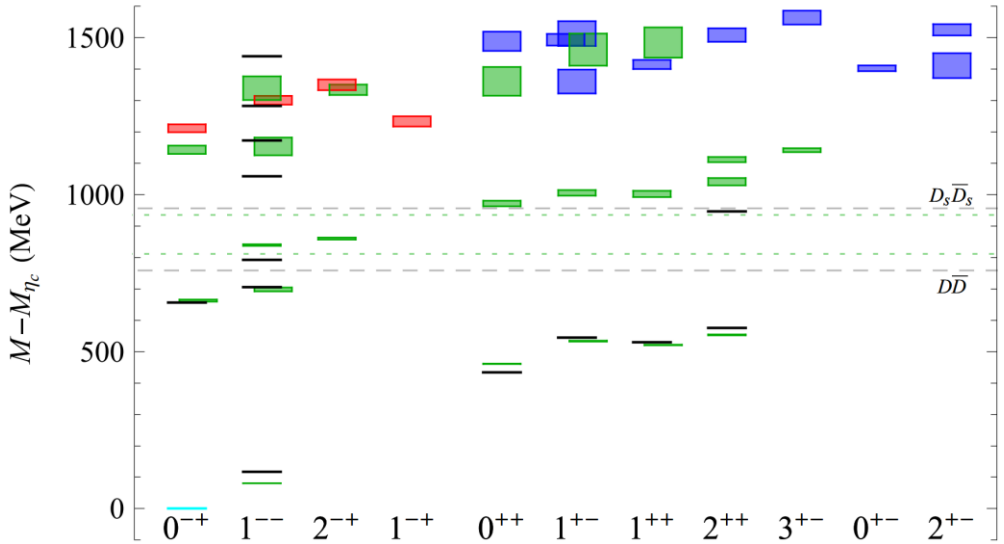
1^{-+} Hybrids

- What are the nature of $\pi_1(1600)$ and $\eta_1(1855)$?
  - Hybrid/$K\bar{K}_1$Molecule/Tetraquark?
    - Decay:$J/\psi \to \gamma + \eta f_1, K_1\bar{K}$
    - Production: $J/\psi \to \omega\eta\eta'$, $\phi\eta\eta'$
- Where is the $\eta_1^{(\prime)}$?
- Does K_1 exist and how to identify it?
- Where are the other $J^{PC} = 0^{--}, \text{even}^{+-}, \text{odd}^{-+}$ states?
- New results from COMPASS, AMBER, BESIII, GlueX and PANDA are eagerly awaited



$\bar{c}cg$ hybrids

LQCD predicts similar supermultiplet as light hybrids



JHEP 07 (2012), 126

- Y(4230)? Other vector?
- Transitions between 1^{--} and $\{0,1,2\}^{-+}$
- Molecule states of 1^{-+} and 1^{--} ?

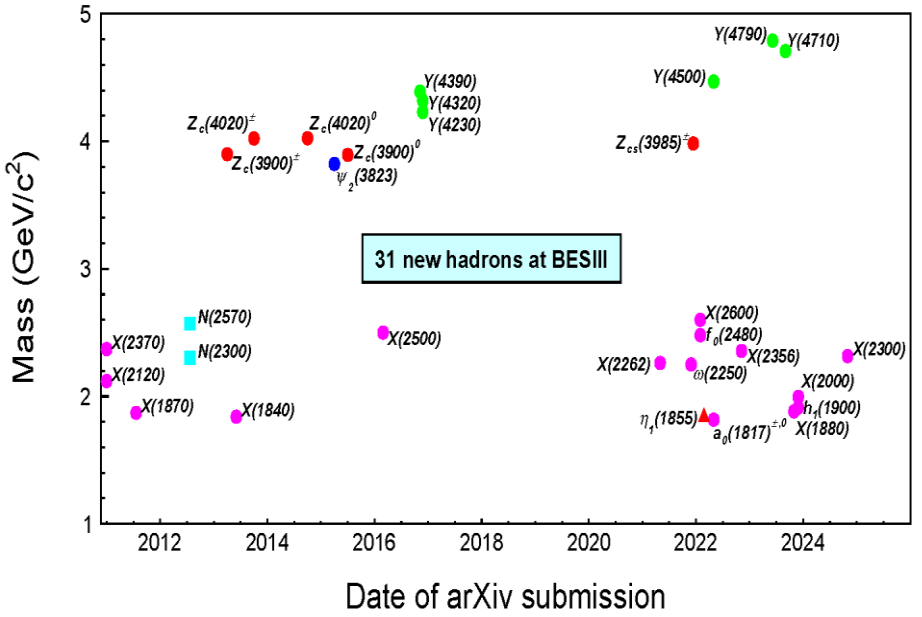
Searched for in

$e^+e^- \to \gamma\eta^{(\prime)}\eta_c,\ \gamma D_s^+ D_{s1}^-$

BESIII PRD 111, 112007 (2025), PRD 112, 032002(2025)

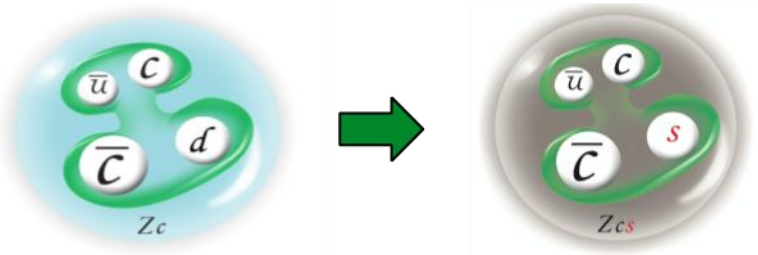
Summary

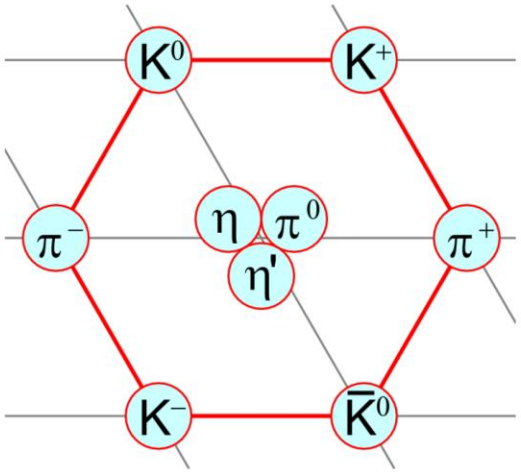
- BESIII has a rich physics program
  - Lots of progress in hadron spectroscopy



- $50\ \mathrm{fb}^{-1}$ data on disk, including 10×10^9 J/ψ and 2.7×10^9 ψ′
- BEPCII-U will provide new opportunities
- Great potential to be fully explored
  - More measurements, more production/decay modes, …
  - Advance analysis techniques: Amplitude analysis, ML, …
  - Close exp-th collaboration

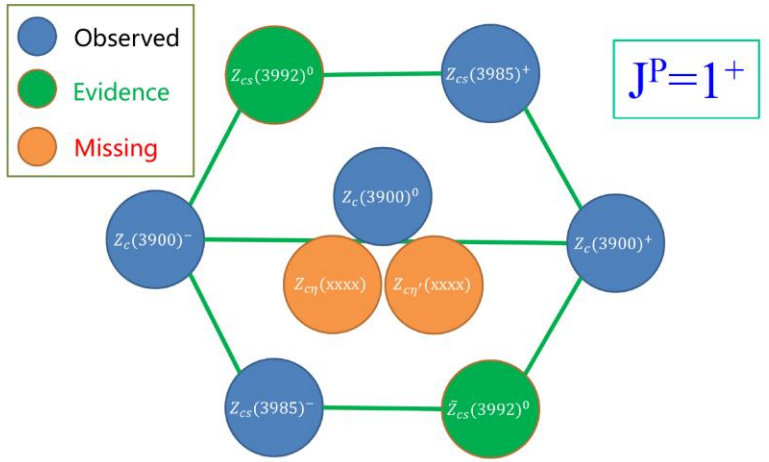
Symmetries governing the multiplets e.g. Z states

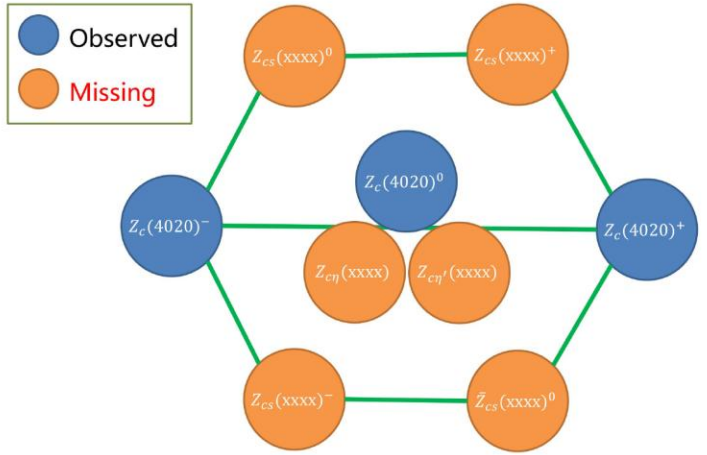




$+ J/\psi$

$+ h_c$





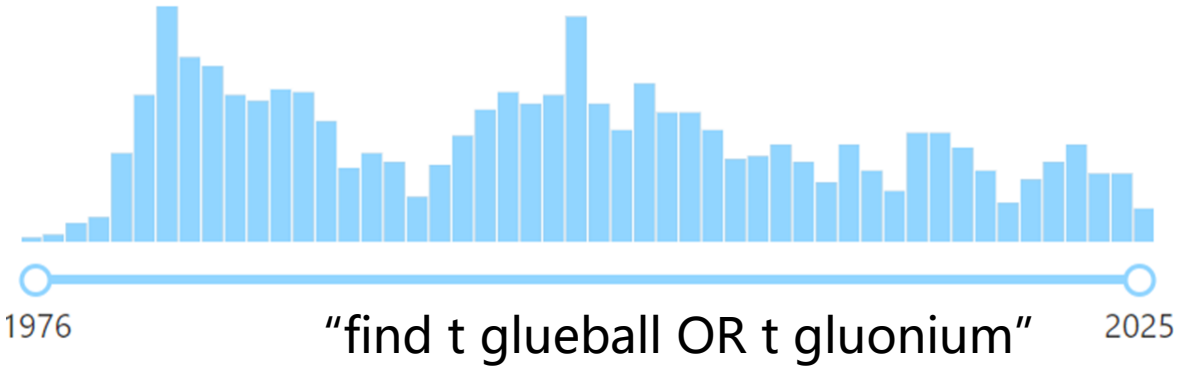
courtesy to C.Z. Yuan

Some glueball candidates in the past

- The first glueball candidate, $\iota(1440)$, observed in J/ψ radiative decays in 1980s
- Scalar candidates $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ (MarkII in1980s, Crystal Barrel in 1990s)
- Narrow tensor glueball candidate $\xi(2230)$ (MarkIII in 1980s/BESI in 1990s)
  - Not confirmed by CLEO, BESII nor BESIII with much higher statistics

And,

- Odderon (odd C-parity) from D0 and TOTEM (2021)



"Update on Glueballs", C. Morningstar, Lattice 2024
"A review on glueball hunting", D. Vadacchino, Lattice 2022
"The Physics of Glueballs" Mathieu, Kochelev, and Vento, 2009
"The Status of Glueballs" Ochs, 2013
"Glueballs as the Ithaca of meson spectroscopy: From simple theory to challenging detection" Llanes-Estrada, 2021
"The Experimental Status of Glueballs" Crede and C. A.Meyer, 2009
...

Scalar glueball candidate

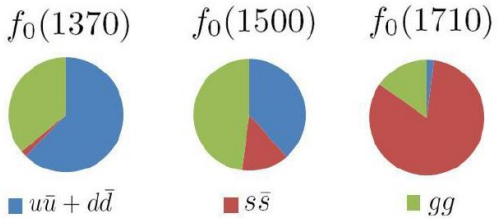
- **Supernumerary scalars** suggest additional degrees of freedom
  - However, mixing scenarios are controversial
- Measured $B(J/\psi \to \gamma f_0(1710))$ is **x10 larger** than $f_0(1500)$

  BESIII [PRD 87 092009, PRD 92 052003, PRD 98 072003]
  - LQCD: $\Gamma(J/\psi \to \gamma G_{0+})/\Gamma_{total} = 3.8(9) \times 10^{-3}$ [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**

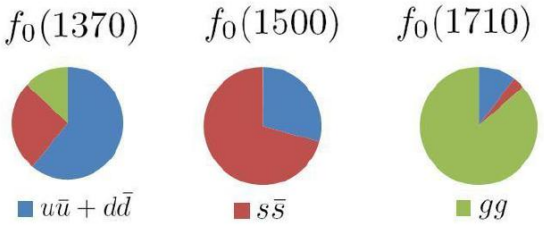
  [PLB 816, 136227 (2021), EPJC 82, 80 (2022), PLB 826, 136906 (2022)]
- **Further more, suppression of $f_0(1710) \to \eta\eta'$ supports $f_0(1710)$ has a large overlap with glueball**

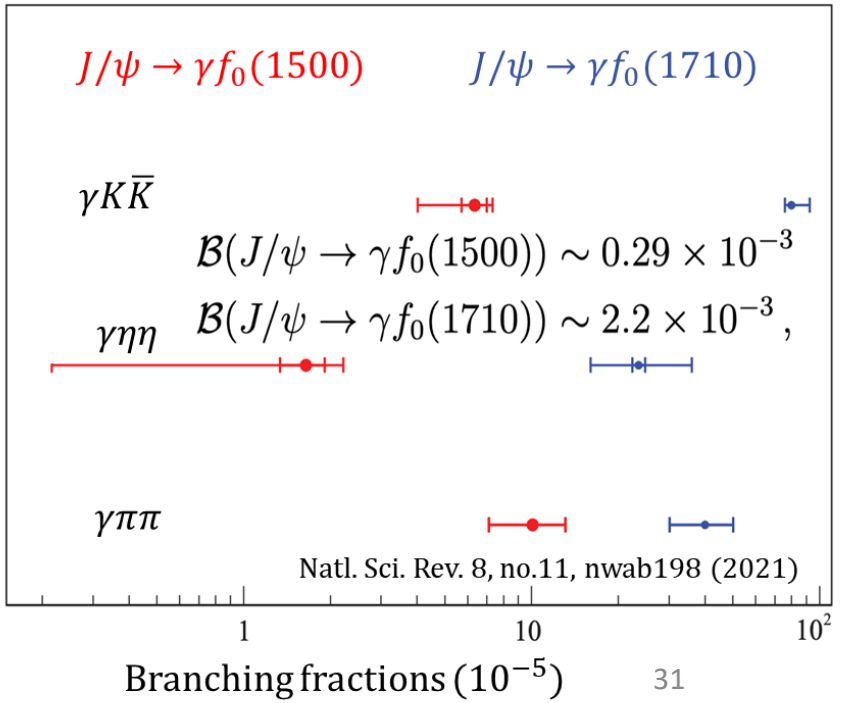
BESIII [PRD 106 072012(2022)]

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



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





Indications of tensor glueball

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

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

Experimental results

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

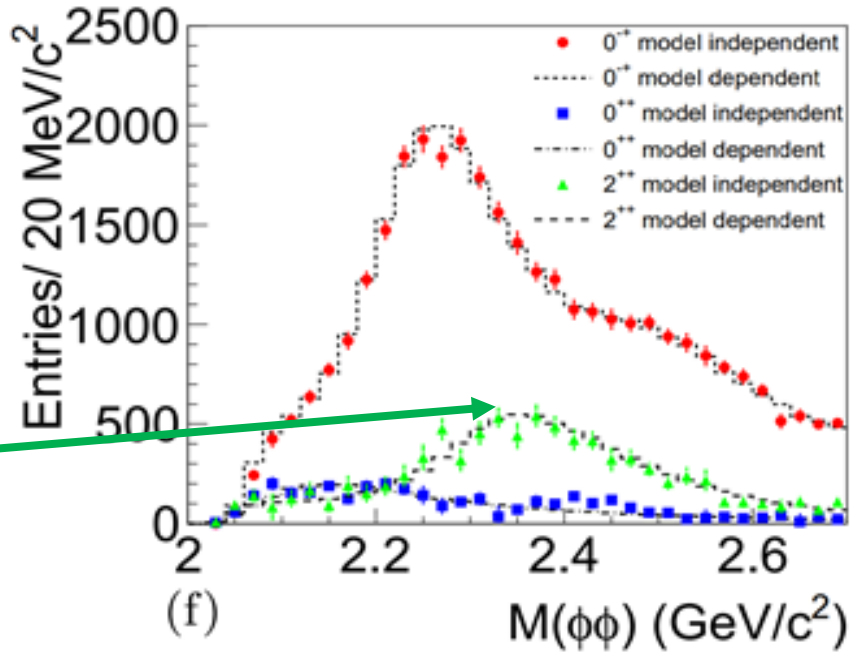
$\mathbf{Br(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = \left(1.91 \pm 0.14^{+0.72}_{-0.73}\right) \times 10^{-4}}$
BESIII PRD 93, 112011 (2016)

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

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

still desired to study more decay modes

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

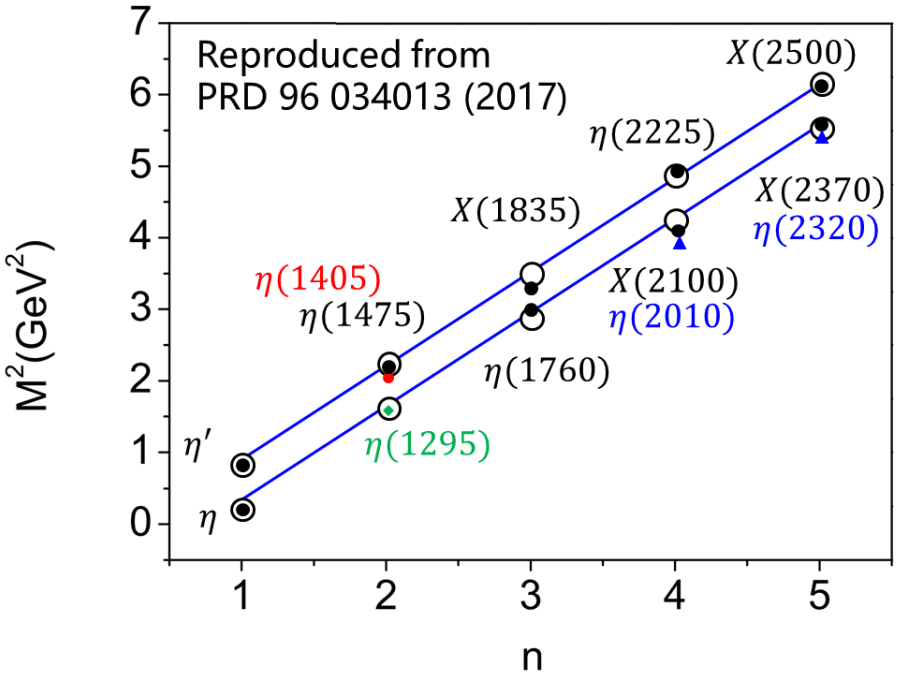


- $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ in πp reactions are all observed in $\mathbf{J/\psi \to \gamma\phi\phi}$ with a **strong production of $f_2(2340)$**
- Consistent with **double-Pomeron exchange** from WA102@CERN

More complicated due to the large number of tensor states

Where is the 0^{-+} glueball

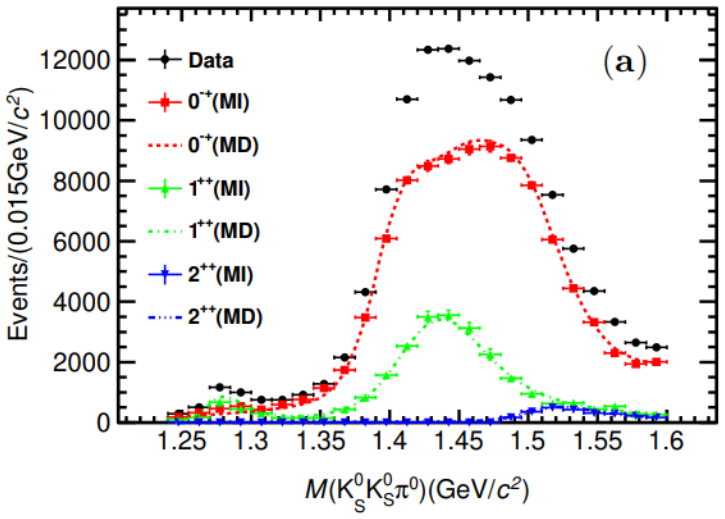
- Pseudoscalar sector, a promising window
  - Only η, η' (& radial excitations) from quark model
- Mass
  - LQCD: 0^{-+} glueball (2.3~2.6 GeV)
  - The first glueball candidate: $\iota(1440)$ (Split into $\eta(1405)$ and $\eta(1475)$)
    - Mass incompatible with LQCD
  - Little experimental information above 2 GeV
- Production
  - LQCD: $\Gamma(J/\psi \to \gamma G_{0^-})/\Gamma_{\text{total}} = 2.31(80) \times 10^{-4}$, 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)



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

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

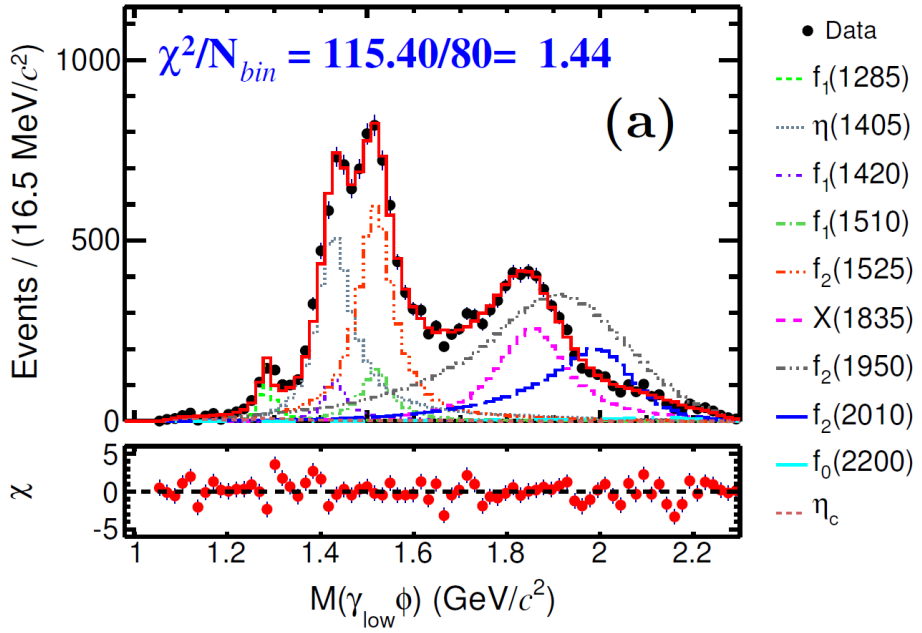
BESIII JHEP 03 121(2023)



- **Dominated by 0^{-+} with non-trivial lineshape**
- **Two BWs around 1.4 GeV needed**
- **Coupled-channel analyses to extract the pole info.**

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

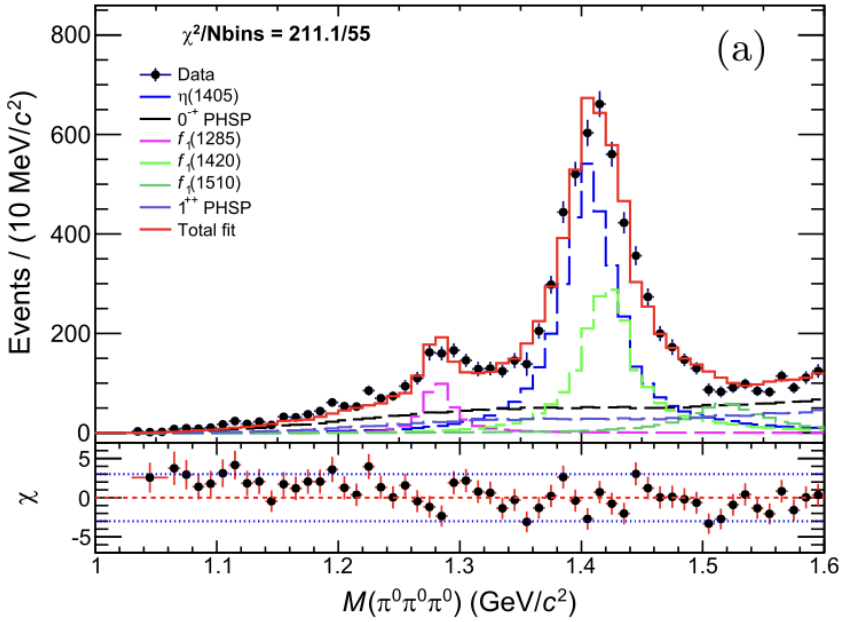
BESIII PRD 111, 052011(2025)



- **$\eta(1405)$ is observed, while $\eta(1475)$ can not be excluded**
- **$X(1835) \to \gamma\phi$ suggests its assignment of η' excitation**
- **No evidence of $X(2370)/\eta_1(1855)$**

$J/\psi \to \gamma\pi^0\pi^0\pi^0$

BESIII PRD 112,032007 (2025)

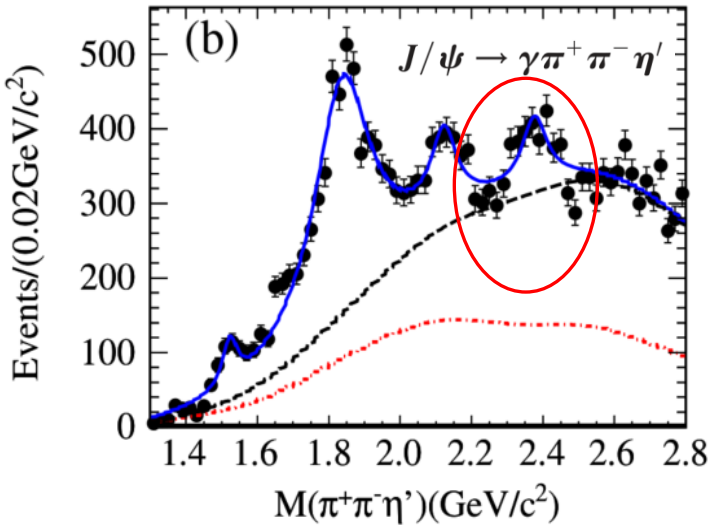


- **$\eta(1405)$ is observed, together with $f_1(1285)$, $f_1(1420)$ and $f_1(1510)$**

A glueball-like state $X(2370)$

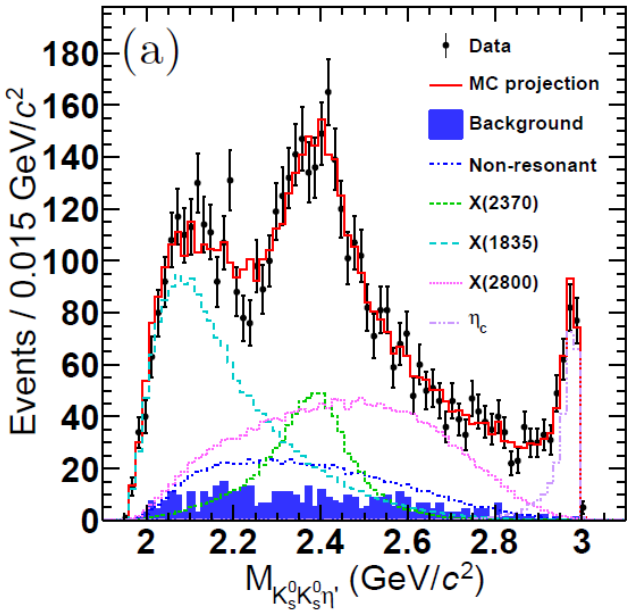
- **Discovered by BESIII in $J/\psi \to \gamma\eta'\pi\pi$ in 2011**
- Confirmed by BESIII in $J/\psi \to \gamma\eta'\pi\pi, \gamma\eta'KK$
  - Not seen in $J/\psi \to \gamma\eta'\eta\eta$ [BESIII PRD 103 012009 (2021)], $J/\psi \to \gamma\gamma\phi$ [BESIII arXiv: 2401.00918]. Upper limits of BF are 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)

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



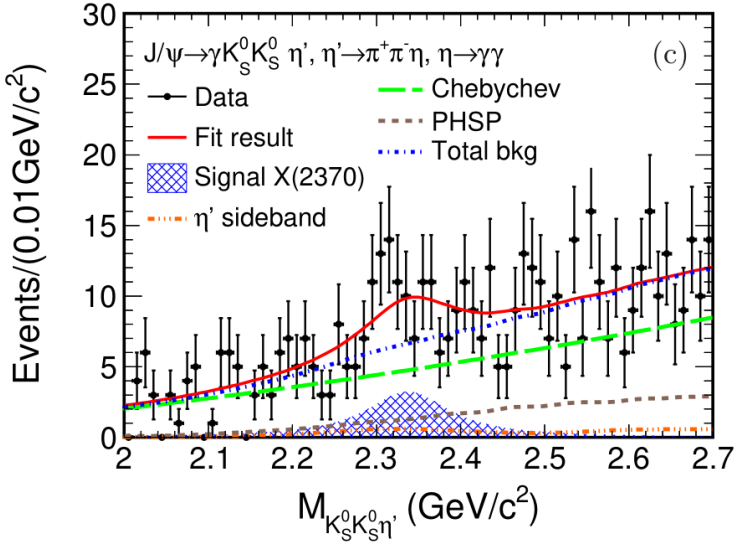
$J^{PC} = 0^{-+}$ with significance >9.8σ

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

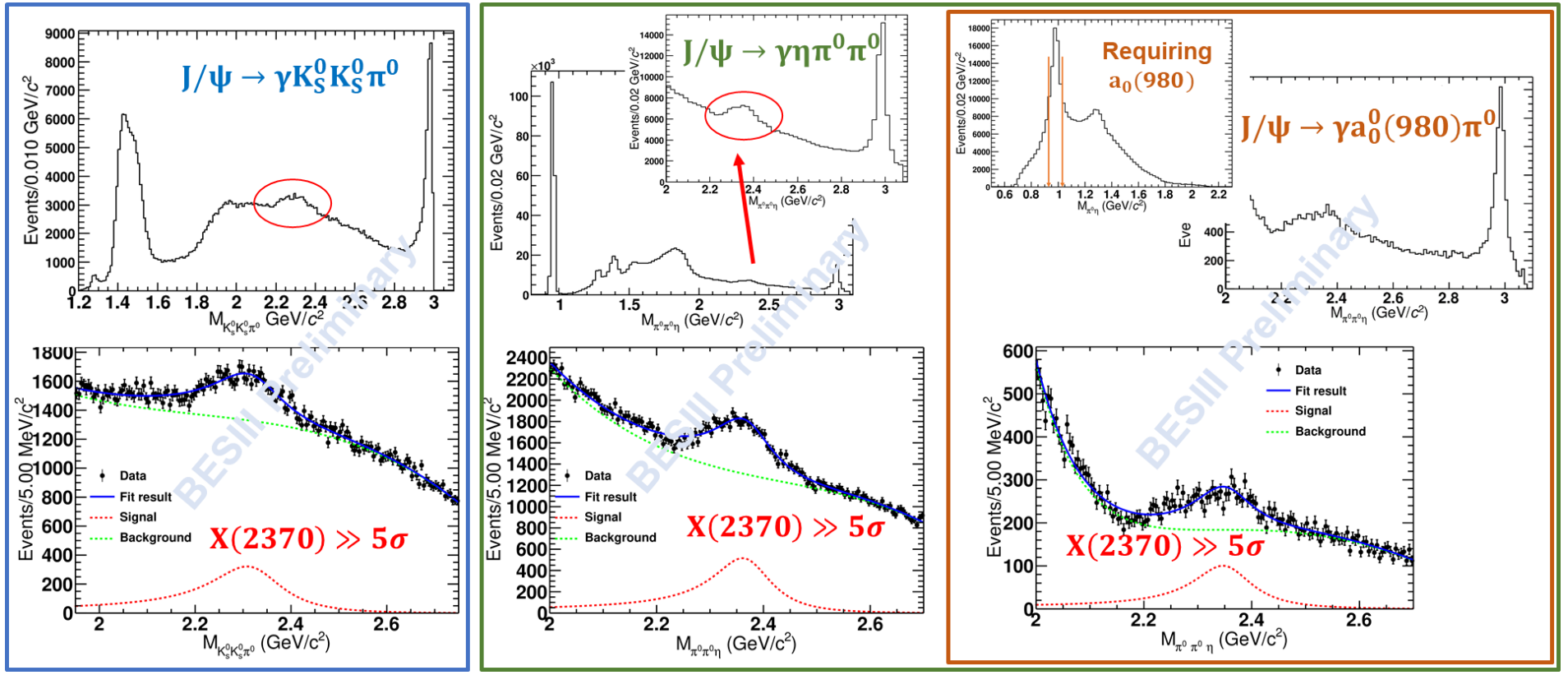
$\Gamma = 188^{+18}_{-17}{}^{+124}_{-33}$ MeV

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

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



BESIII EPJC 80 746(2020)

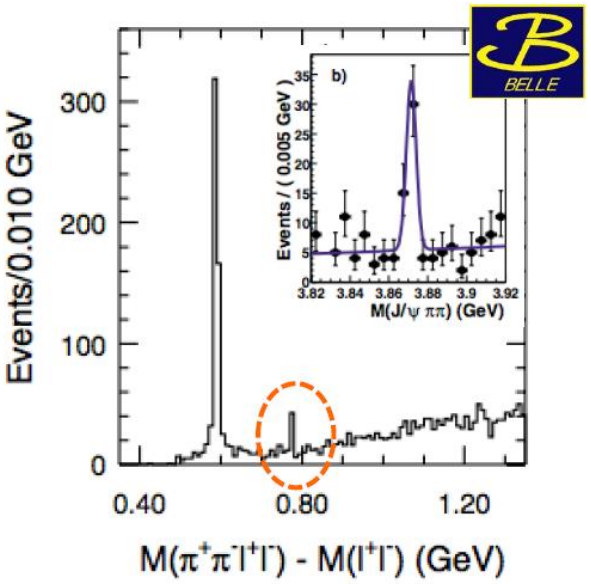


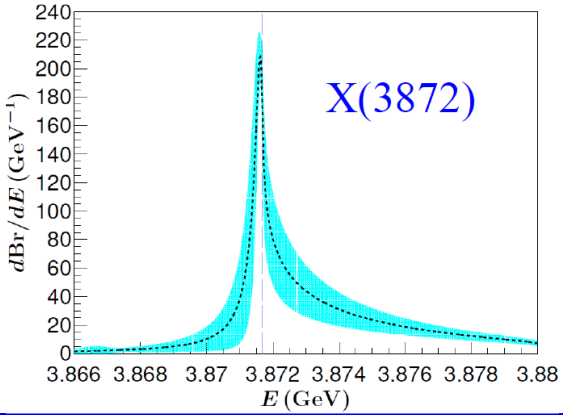
New decay modes

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

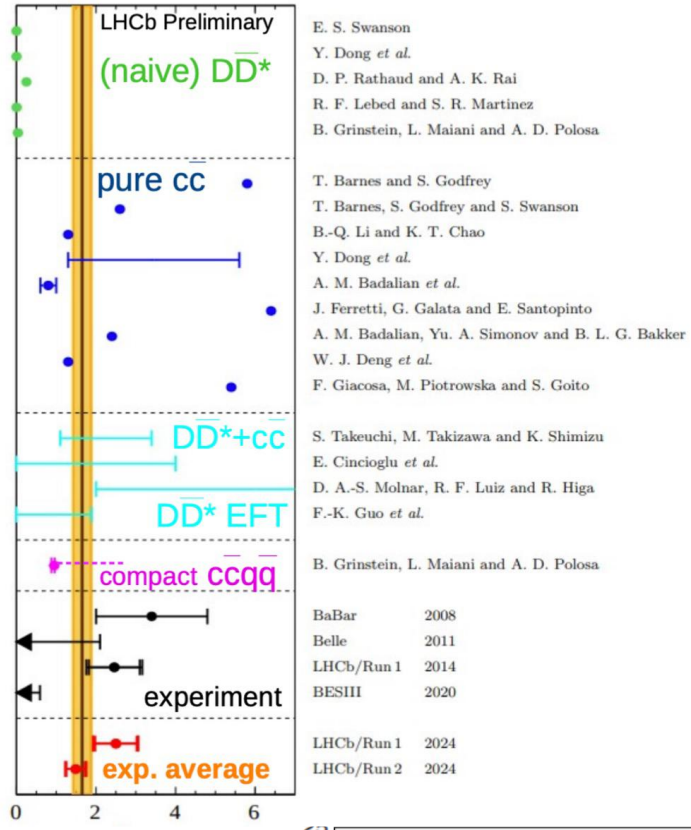
- **J^{PC} determined to be 0^{-+}**
- **Mass and production rate consistent with LQCD**
- **Decay modes $X(2370) \to$**
  $\eta'\pi\pi, \eta' KK, K_S^0 K_S^0 \eta, K_S^0 K_S^0 \pi^0, \eta\pi^0\pi^0, a_0^0(980)\pi^0$ observed, in analog to η_c

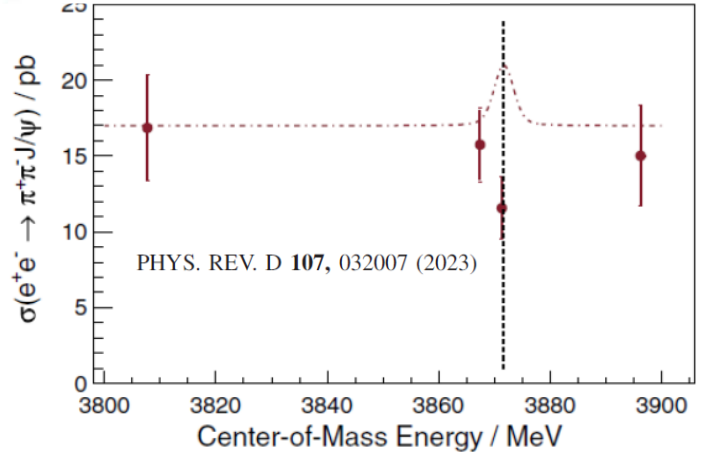
Further details
e.g. 22 yrs "young" X(3872)





	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	$-16.5^{+7.0\ +5.6}_{-27.6\ -27.7}$
r_e (fm)	-5.3	$-3.0^{+1.3}_{-1.5}$	$-4.1^{+0.9\ +2.8}_{-3.3\ -4.4}$
$\bar{Z}_A$	0.15 (0.33)	$0.08^{+0.04}_{-0.03}$	$0.18^{+0.06\ +0.19}_{-0.17\ -0.16}$





- More studies at BESIII, Belle II, LHCb, e.g. $\Gamma_{ee}(X(3872))$ @ BESIII