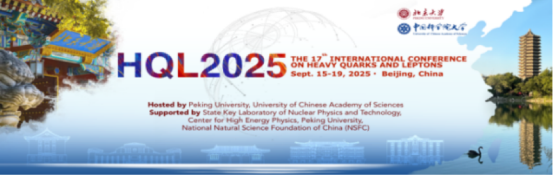


Recent spectroscopy results at BESIII

Yateng Zhang

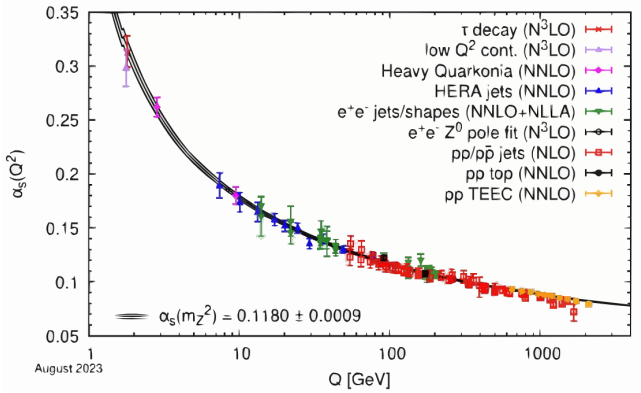
(On behalf of the BESIII Collaboration)
Zhengzhou University

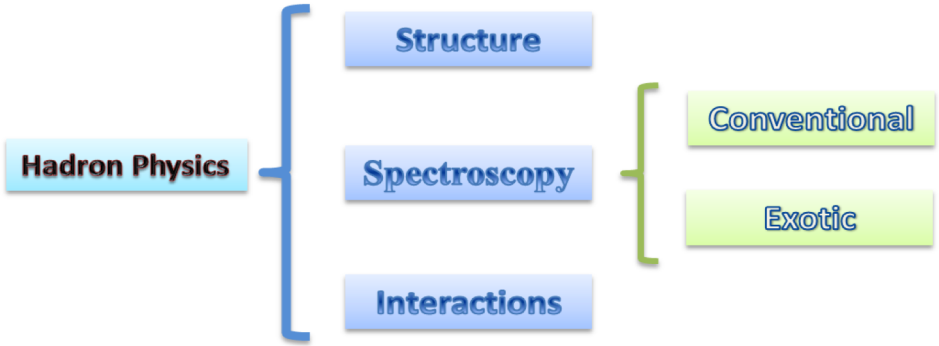
17th International Conference on Heavy Quarks and Leptons (HQL 2025)

Introduction

Hadron Physics, a cornerstone of our understanding of the strong interaction of quarks and gluons as described by QCD, which is primarily responsible for holding the nuclei of atoms together. Nuclei: Dominant part of visible matter in the universe.

- How are hadrons formed from quarks?
- What is the origin of confinement?
- How is the mass generated in QCD?

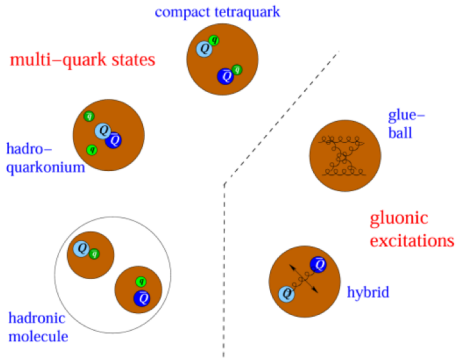




- ✓ $\alpha_s \sim 1$, Occurring in the non-perturbative regime of QCD, perturbative techniques fail.
- ✓ Challenges for both theoretical analyses and experimental investigations.
- ✓ Alternative theoretical tools often model dependent or very computational expensive
- ✓ Highly populated spectrum: many overlapping, interfering, mixing or distorted states

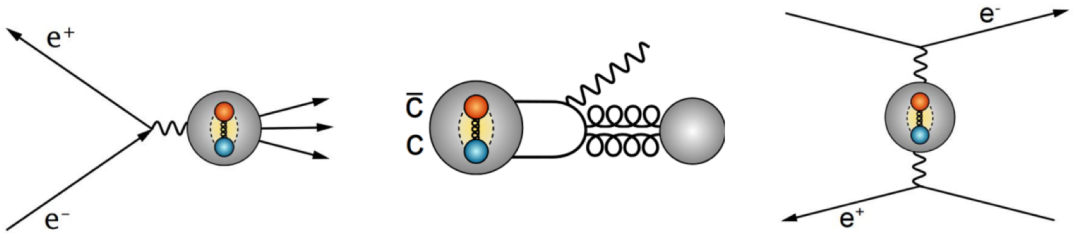
Introduction

- **Quark mode:**
  - ✓ **Mesons**
  - ✓ Baryons
- **New forms of hadrons**

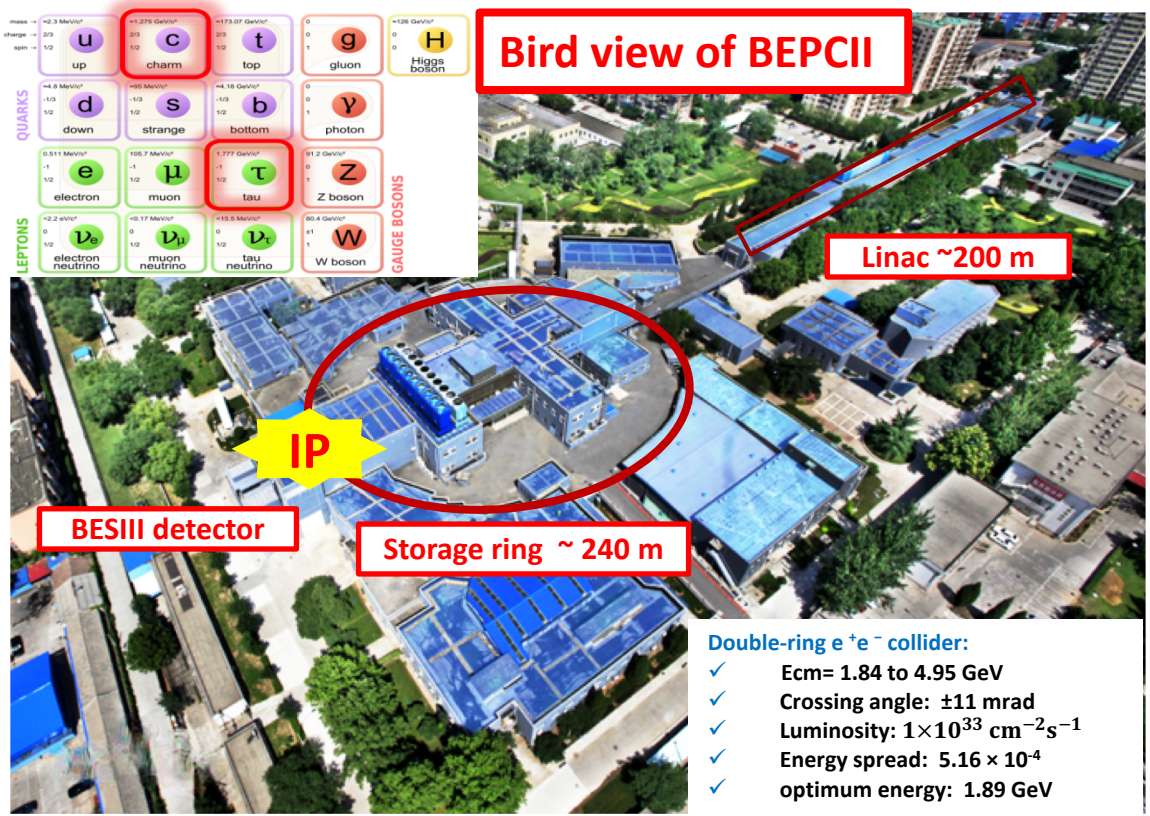


Physics report 873 (2020) 1-154

- **Multi-ways to produce conventional and exotic mesons:**
  - ✓ Direct production of vector states
  - ✓ Charmonium decays
  - ✓ Two-photon scattering

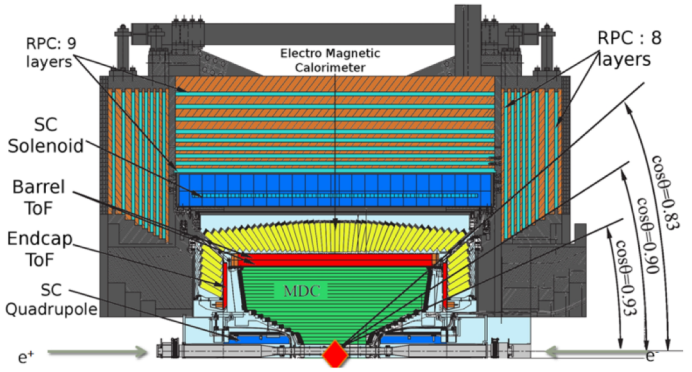


BEPCII&BESIII



Double-ring e $^+$e $^-$ collider:

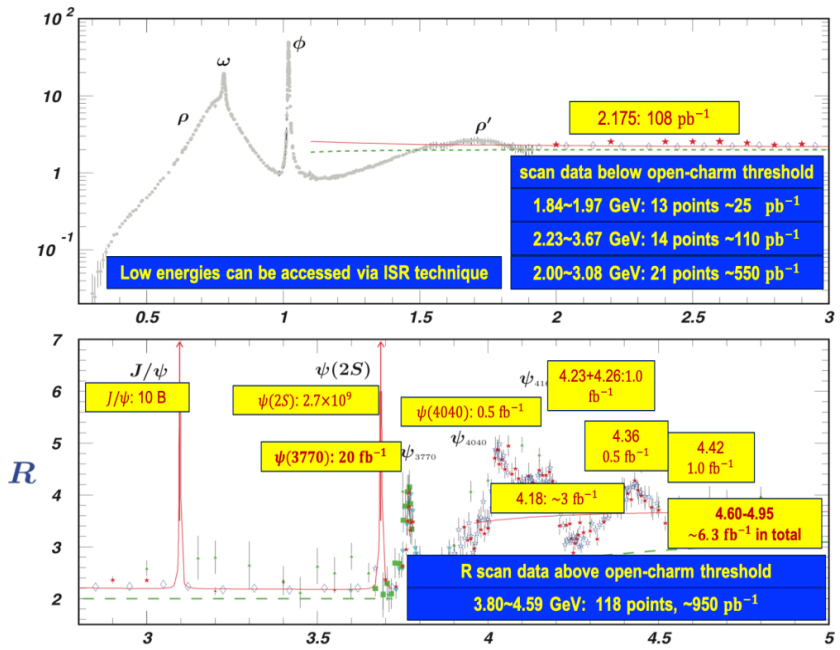
- ✓ **Ecm= 1.84 to 4.95 GeV**
- ✓ **Crossing angle: ±11 mrad**
- ✓ **Luminosity: 1×10^{33} cm^{-2}s^{-1}**
- ✓ **Energy spread: 5.16 × 10^{-4}**
- ✓ **optimum energy: 1.89 GeV**



BESIII

- ✓ Cover 93% of full solid angle
- ✓ 1.0 T supercondacting solenoid
- ✓ Momentum resolution: 0.5% at 1 GeV/c
- ✓ Energy resolution: 2.5%(5%) at 1 GeV/c in the barrel (end cap)
- ✓ Time resolution: 68(60) ps in the barrel (end cap)

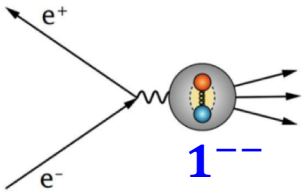
BESIII Data Samples



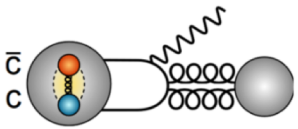
Data sets collected so far include:

- 10×10^9 J/ψ events
- 2.7×10^9 $\psi(3686)$ 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

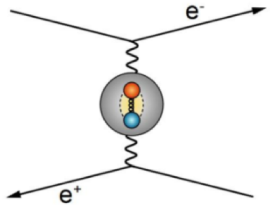
Direct production of vector states



Charmonium decays

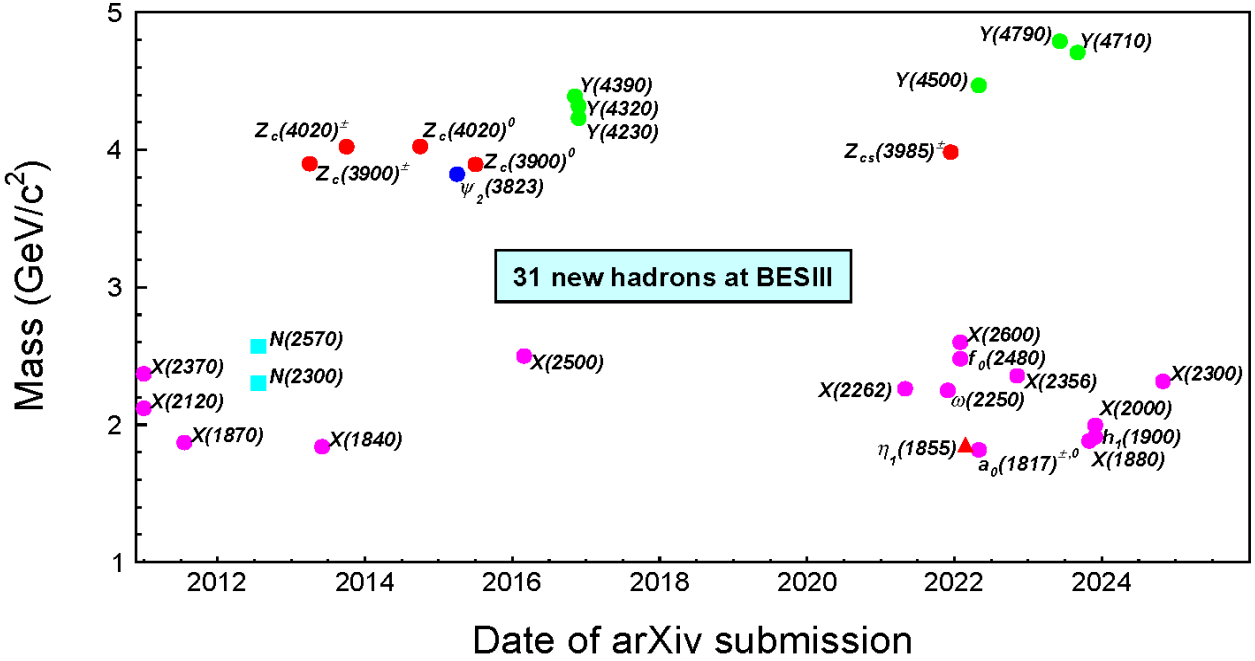


Two-photon scattering



Excellent platform to explore the hadron spectroscopy!

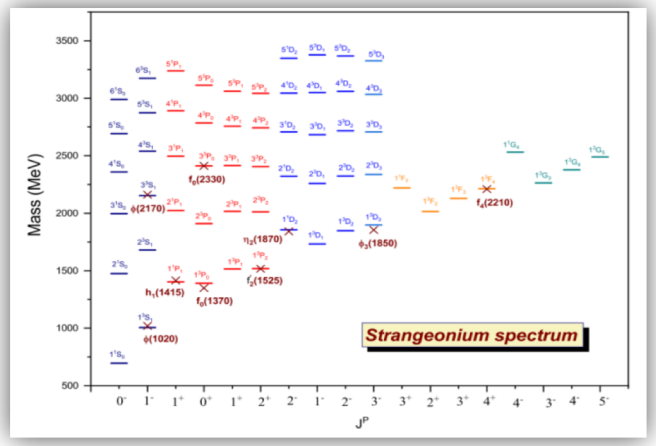
The BESIII Experiment

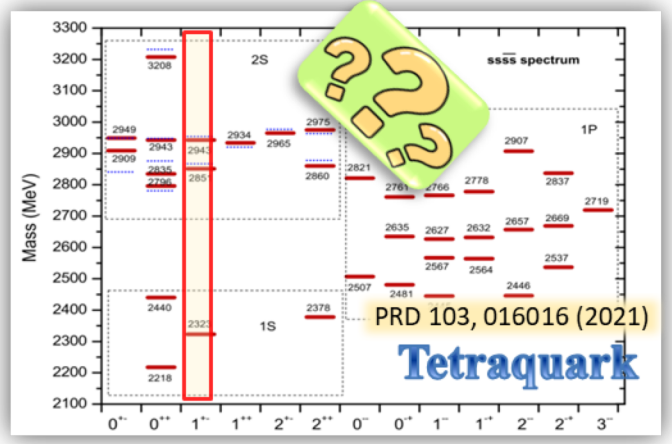


Physics topics span a wide range of topics:

- Light quark spectroscopy;
- Charmonium spectroscopy;
- Spectroscopy of exotic, “XYZ” states; etc.

Strangeonium Spectrum





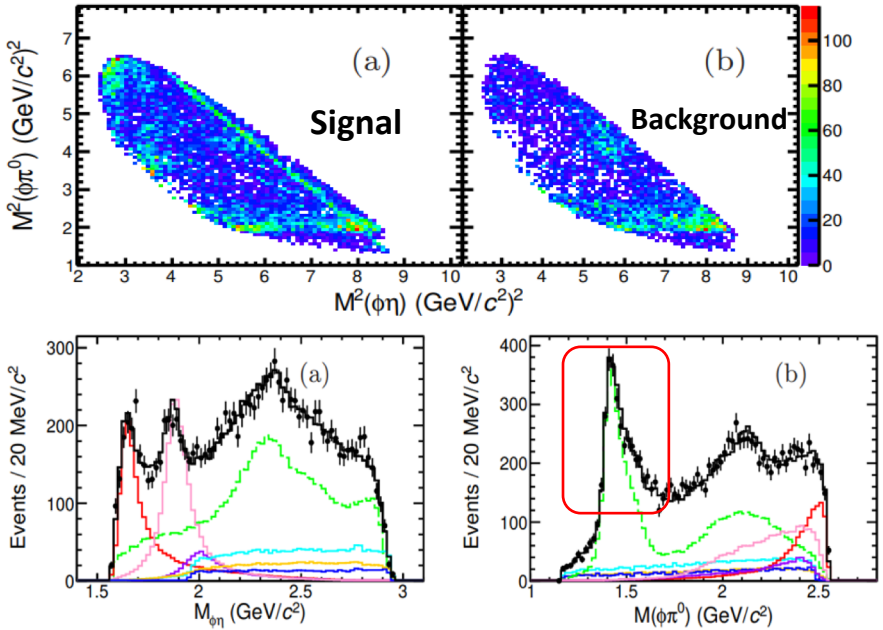
- Experimental study scare, and few strangeonium states confirmed
- Vector sate, only $\boldsymbol{\phi(1020)}$ and $\boldsymbol{\phi(1680)}$; axial-vector state, only $\boldsymbol{h_1(1380)}$ ($\boldsymbol{h_1(1415)}$ PDG) observed
- More excitations, e.g., $h_1(2P)$ and $h_1(3P)$, still **missing** in experiment
- Fully-strange tetraquarks in **same mass region and same final states** predicted in theory
- **Method: Charmonium decay** and **Energy scan**

Recent Analyses:

- ✓ PWA of $J/\psi \to \phi\pi^0\eta$
- ✓ PWA of $\psi(3686) \to \phi\eta\eta'$
- ✓ $e^+e^- \to K_S K_L \pi^0 / K^+K^-\pi^0$

Study of the decay $J/\psi \to \phi\pi^0\eta$

Phys. Rev. D 110, 112014 (2024)



$h_1(1900)$

- Amplitude analysis of $J/\psi \to \phi\pi^0\eta$ is performed with 10 billion J/ψ events.
- Two new resonances in $M(\phi\eta)$ observed for the first time.

- **$h_1(1900)$ $J^{PC} = 1^{+-}$**

$$M = 1908 \pm 6\ ^{+8}_{-4}\ \text{MeV}/c^2$$
$$\Gamma = 175 \pm 13\ ^{+7}_{-16}\ \text{MeV}$$

- **$X(2000)$ $J^{PC} = 1^{--}$**

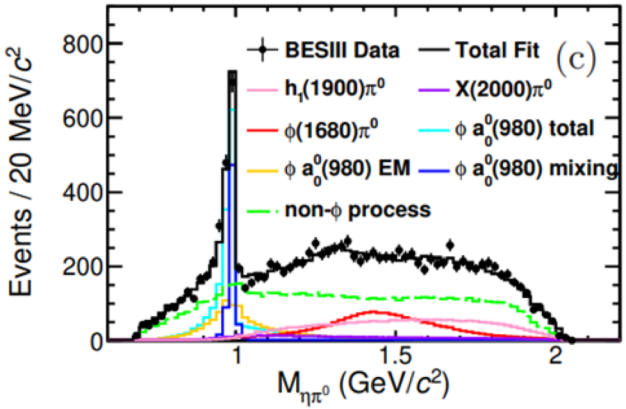
$$M = 1992 \pm 12\ ^{+15}_{-6}\ \text{MeV}/c^2$$
$$\Gamma = 132 \pm 22\ ^{+17}_{-4}\ \text{MeV}$$

$h_1(1900)$ consistent with **$h_1(2P)$** theoretical prediction

No structure around 1.4 GeV in $\phi\pi^0$ invariant spectrum observed!

Study of the decay J/ψ → ϕπ^{0}η

Phys. Rev. D 110, 112014 (2024)



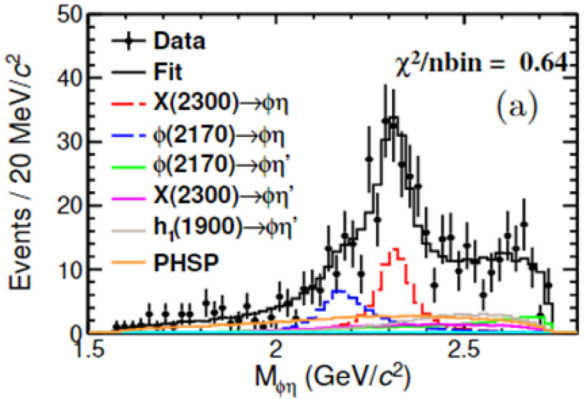
- The $f_0(980) - a_0(980)^0$ mixing signal in J/$\psi \rightarrow \phi f_0\,(980) \rightarrow \phi a_0\,(980)^0$ and the corresponding electromagnetic decay J/$\psi \rightarrow \phi a_0(980)^0$measured with improved precision.
- The mixing intensity of $f_0(980) - a_0(980)^0$ (ξ_{fa}) is calculated to be **$(0.86 \pm 0.04 \pm 0.25)$%.**

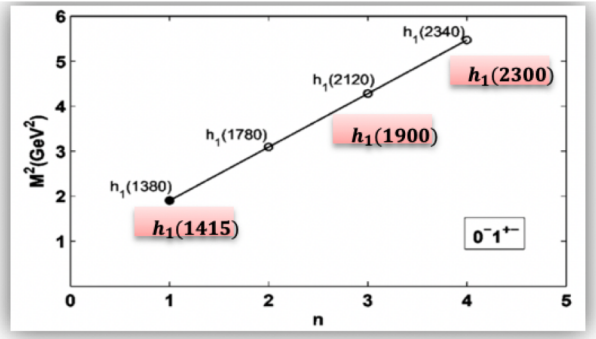
Process	M (MeV/c^2)	Γ (MeV)	fit fraction(%)	$\mathcal{B}$ (10^{-6})	Sig. (σ)
$\phi(1680)\pi^0$	$1663 \pm 5^{+16}_{-4}$	$159 \pm 15^{+11}_{-11}$	14.64 ± 0.56	$6.66 \pm 0.26^{+1.1}_{-1.0}$	32.3
$X(2000)\pi^0$	$1992 \pm 12^{+15}_{-6}$	$132 \pm 22^{+17}_{-4}$	4.05 ± 0.44	$1.70 \pm 0.19^{+0.48}_{-0.13}$	13.2
$h_1(1900)\pi^0$	$1908 \pm 6^{+8}_{-4}$	$175 \pm 13^{+7}_{-16}$	20.76 ± 0.84	$8.44 \pm 0.35^{+1.4}_{-1.2}$	30.1
$\phi a_0(980)_{\rm EM}$	–	–	9.75 ± 0.58	$3.24 \pm 0.20^{+0.52}_{-0.22}$	19.9
$\phi a_0(980)_{\rm mix}$	–	–	7.33 ± 0.35	$2.74 \pm 0.13^{+0.15}_{-0.16}$	31.6

Study of the decay $\psi(3686) \to \phi\eta\eta'$

PRL 134, 191901 (2025)

$h_1(2300)$





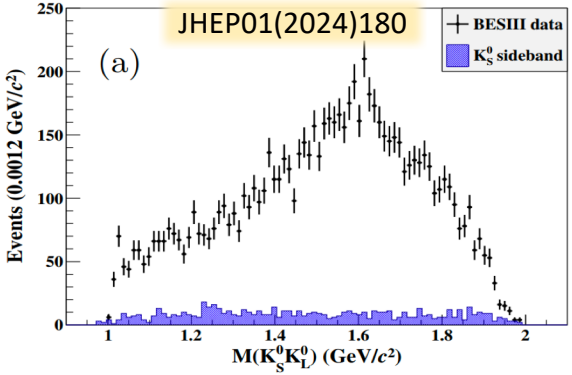
Resonance	M (MeV/c^2)	Γ (MeV)
$h_1(3P)$	2435 [4]	269 [4]
$h_1(3P)$	2449 [8]	N/A
$h_1(3P)$	2100 [12, 13]	N/A
$h_1(3P)$	2490 [9]	N/A
$h_1(3P)$	2398 [10]	N/A
$h_1(3P)$	2495.51±1.46 [11]	N/A
$h_1(4P)$	2340 [12, 13]	N/A
$T_{(ss\bar{s}\bar{s})1^{+-}}$	2323 [26]	N/A
$T_{(ss\bar{s}\bar{s})1^{+-}}$	1960 [27]	N/A
$T_{(ss\bar{s}\bar{s})1^{+-}}$	2000^{+100}_{-90} [28]	N/A
This work	$2316 \pm 9 \pm 30$	$89 \pm 15 \pm 26$

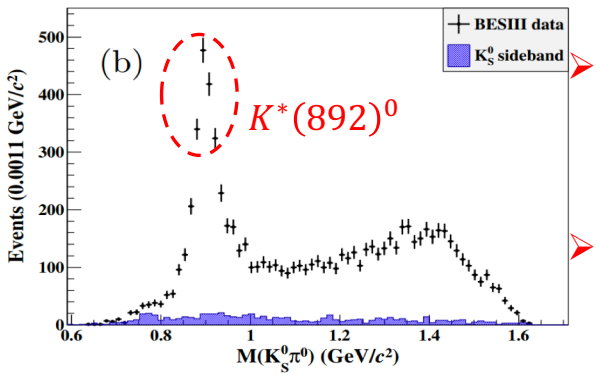
- Amplitude analysis of $\psi(3686) \to \phi\eta\eta'$ is performed with 2.7 billion psi(3686) events.
- New resonances in M($\phi\eta$) observed for the first time.
- **$h_1(2300)$** $\mathbf{J^{PC} = 1^{+-}}$

$$M = 2316 \pm 9 \pm 30 \text{MeV/c}^2$$
$$\Gamma = 89 \pm 15 \pm 26 \text{ MeV}$$

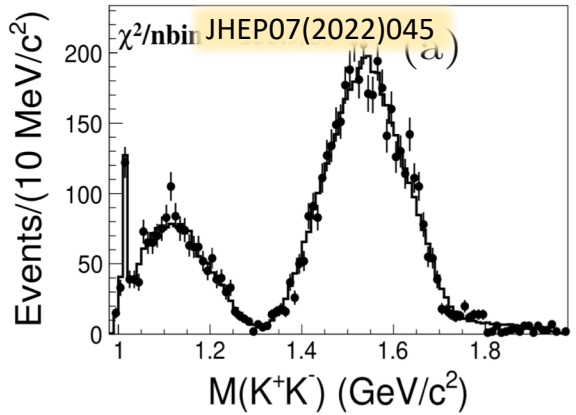
- Systematic discrepancy in the mass of $h_1(3P)$ in theory
- For the $T(ss\bar{s}\bar{s})$ hypothesis, need more theoretical calculations!

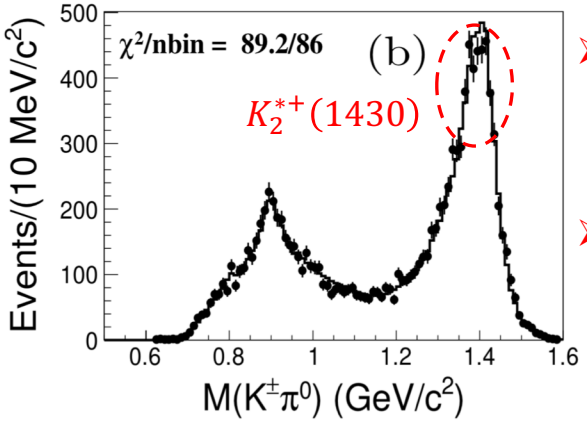
Measurement of the $e^+e^- \to K_S^0 K_L^0\pi^0$ and $e^+e^- \to K^+K^-\pi^0$ cross sections





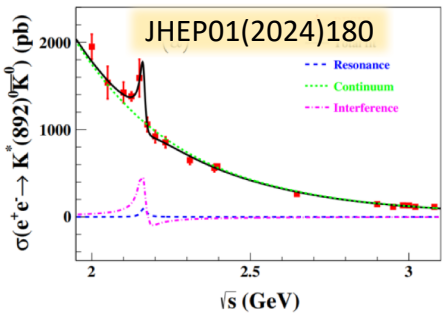
- Measurement of cross section of $e^+e^- \to K_S^0 K_L^0\pi^0$ from $\sqrt{s}$ = 2.000 to 3.080 GeV is performed
- Dominant component: $K^*(892)^0\overline{K^0}$

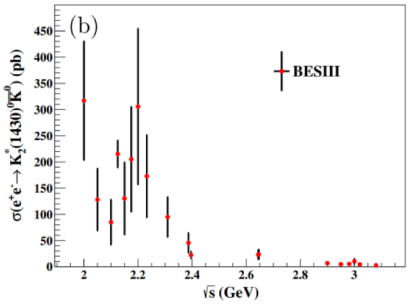




- Amplitude analysis of $e^+e^- \to K^+K^-\pi^0$ from $\sqrt{s}$ = 2.000 to 3.080 GeV is performed
- Dominant component: $K_2^{*+}(1430)K^-$

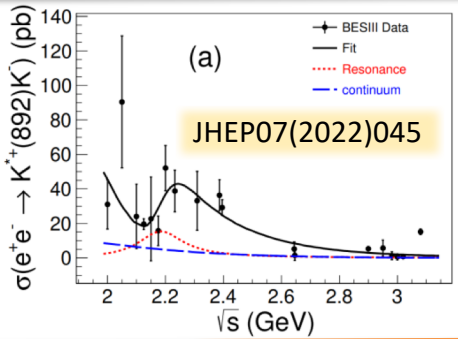
Measurement of the $e^+e^- \to K^0_S K^0_L \pi^0$ and $e^+e^- \to K^+ K^- \pi^0$ cross sections

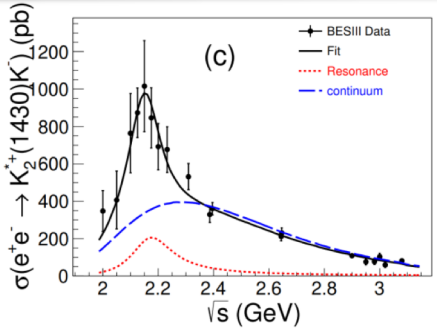




- Amplitude analysis of $e^+e^- \to K^0_S K^0_L \pi^0$ from $\sqrt{s}$ = 2.000 to 3.080 GeV is performed.
- Dominant component: $K^*(892)^0\bar{K}^0$, $K_2^*(1430)^0\bar{K}^0$
- Resonance in $K^*(892)^0\bar{K}^0$: **3.2σ**

$M = 2164.7 \pm 9.1 \pm 3.1 \mathrm{MeV/c^2}$
$\Gamma = 32.4 \pm 21.0 \pm 1.8$ MeV





- Amplitude analysis of $e^+e^- \to K^+ K^- \pi^0$ from $\sqrt{s}$ = 2.000 to 3.080 GeV is performed
- Dominant component: $K^{*+}(892)K^-$, $K_2^{*+}(1430)K^-$
- Resonance in $K_2^{*+}(1430)K^-$: **7.1σ**

$M = 2190 \pm 19 \pm 37 \mathrm{MeV/c^2}$
$\Gamma = 191 \pm 28 \pm 60$ MeV

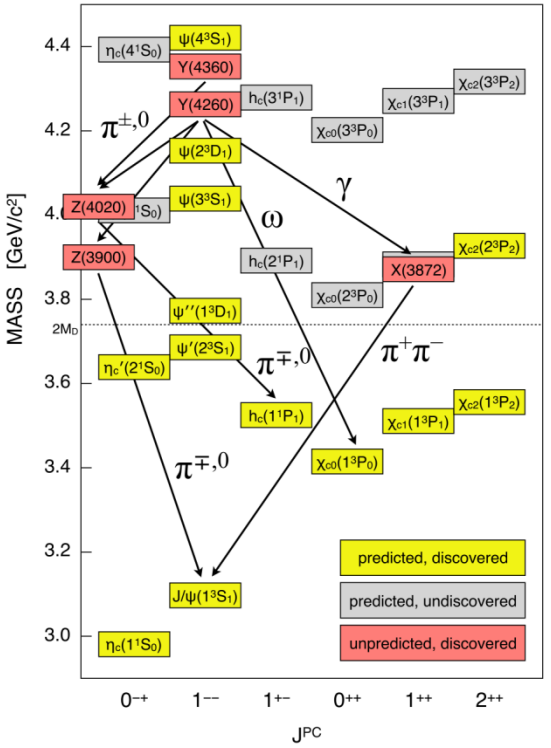
$$R = \frac{B(K^0\bar{K}^{0\prime})}{B(K^{\pm}\bar{K}^{\mp\prime})}: \quad \sim 30 \text{ for } K^*(892)K, \quad \sim 0.25 \text{ for } K_2^*(1430)K$$

No significant $\phi(2170)$ in $K^*(892)^0\bar{K}^0$, but in $K_2^{*+}(1430)K^-$!

Charmonium Spectroscopy

e^+e^- mainly annihilate into a virtual photon, with quantum numbers $J^{PC} = 1^{--}$ Direct → production of 1^{--} vector meson states

- Y states (charmonium(-like) states) numerous and not well understood
- Y(4220), Y(4390) observed in previously at BESIII
- Hybrid? Tetraquark? Excited charmonia? etc. precise measurements needed
- Strong coupling from (supposed) vector charmonium states to would indicate exotic internal structure

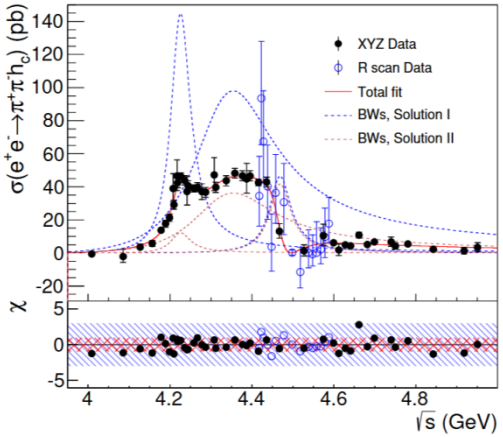


Recent Analyses:

- ✓ $e^+e^- \to \pi^+\pi^- h_c$
- ✓ PWA of $e^+e^- \to \pi^+\pi^- J/\psi$
- ✓ $e^+e^- \to K^+K^-\psi(2S)/e^+e^- \to K_S K_S \psi(2S)$
- ✓ Prompt Inclusive production of J/ψ and $\psi(2S)$

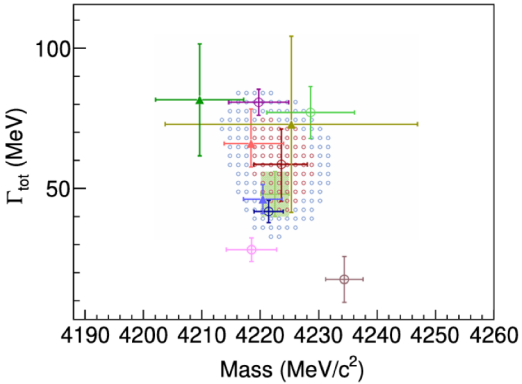
Observation of Three Resonant Structures in the Cross Section of $e^+e^- \to \pi^+\pi^- h_c$

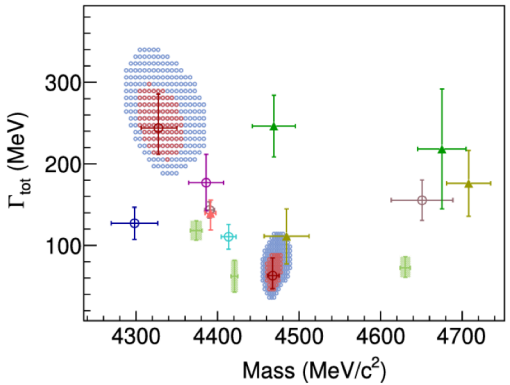
PRL. 135, 071901(2025)

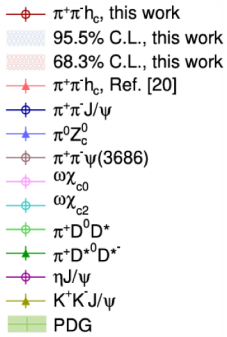


- ✓ Cross sections of $e^+e^- \to \pi^+\pi^- h_c$ at 59 points with center-of-mass energy ranging from 4.009 to 4.950 GeV
- ✓ **Three resonant structures** observed
- ✓ Resonant parameters from three coherent Breit-Wigner functions

$$R_1\colon\ M = 4223.6^{+3.6+2.6}_{-3.7-2.9}\ \text{GeV},\ \Gamma = 58.5^{+10.8+6.7}_{-11.4-6.5}\ \text{GeV}$$
$$R_2\colon\ M = 4327.4^{+20.1+10.7}_{-18.8-9.3}\ \text{GeV},\ \Gamma = 244.1^{+34.0+24.2}_{-27.1-18.3}\ \text{GeV}$$
$$R_3\colon\ M = 4467.4^{+7.2+3.2}_{-5.4-2.7}\ \text{GeV},\ \Gamma = 62.8^{+19.2+9.9}_{-14.4-7.0}\ \text{GeV}$$

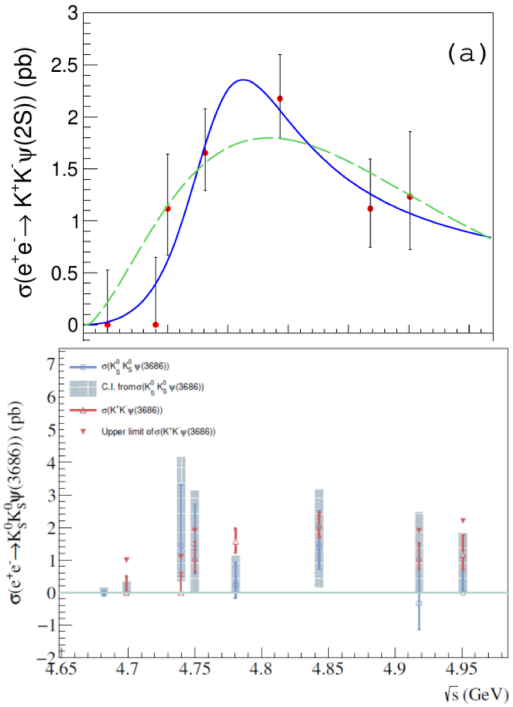






Measurement of the $e^+e^- \to KK\psi(2S)$ Cross Section and Search $Z_{cs}$for in the $Z_{cs} \to K\psi(2S)$ Decay

arXiv:2407.20009

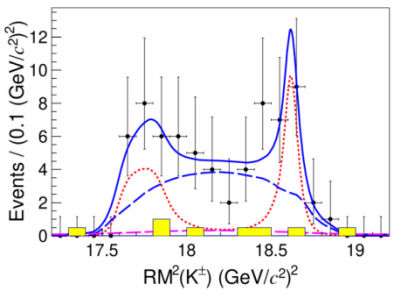


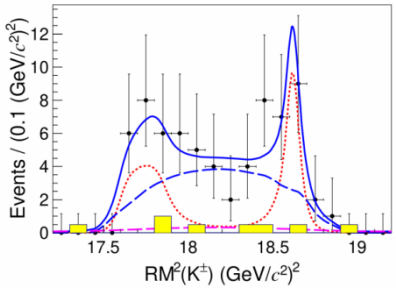
arXiv:2411.15752

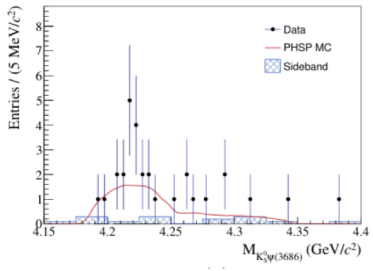
- ✓ Cross section measurenments of processes $e^+e^- \to K^+K^-\psi(2S)$ and $e^+e^- \to K^0_S K^0_S \psi(2S)$ from 4.68 -4.95 GeV
- ✓ deviation of about **2σ** with respect to the ratio of their phase spaces

$$M = 4787.7 \pm 17.7\ \text{MeV}, \Gamma = 110.3 \pm 33.9\ \text{MeV}$$

- ✓ Cross sections of neutral and charged channels are consistent with the prediction based on isospin symmetry.



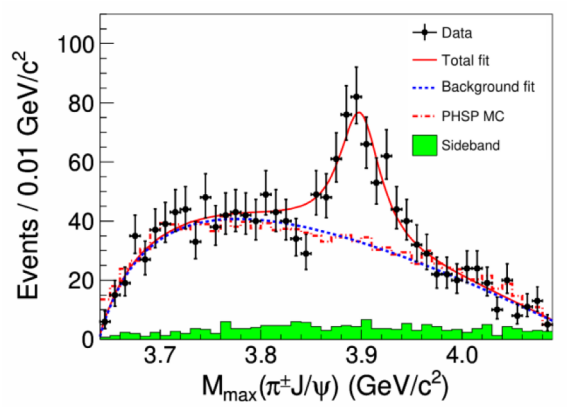




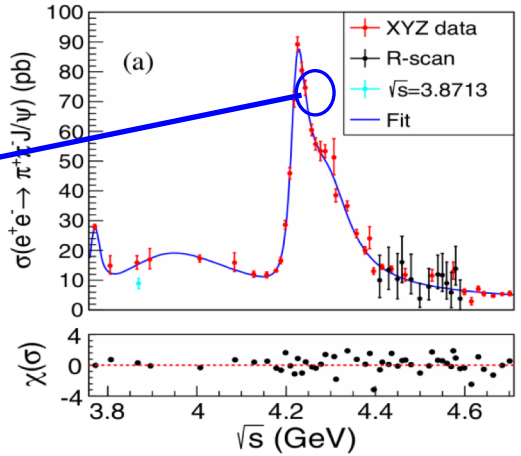
- ✓ Simultaneous fit to the $RM^2(K^+)$ and $RM^2(K^-)$ spectra: one $Z_{cs}^{\pm}$ resonance around **4.208 GeV (1.2σ),** another around **4.315 GeV (1.1σ)**
- ✓ A mass of 4.208 GeV is in the vicinity of the Zcs(4220) reported by LHCb
- ✓ $K^0_S\psi(3686)$ spectrum consistent with three-body phase space. The significance of a contribution beyond three-body phase space is only **0.8σ**

Partial wave analysis of $e^+e^- \to \pi^+\pi^- J/\psi$ and cross section measurement of $e^+e^- \to \pi^\mp Z_c(3900)^\pm$ from 4.1271 to 4.3583 GeV

PRL 110, 252001 (2013)



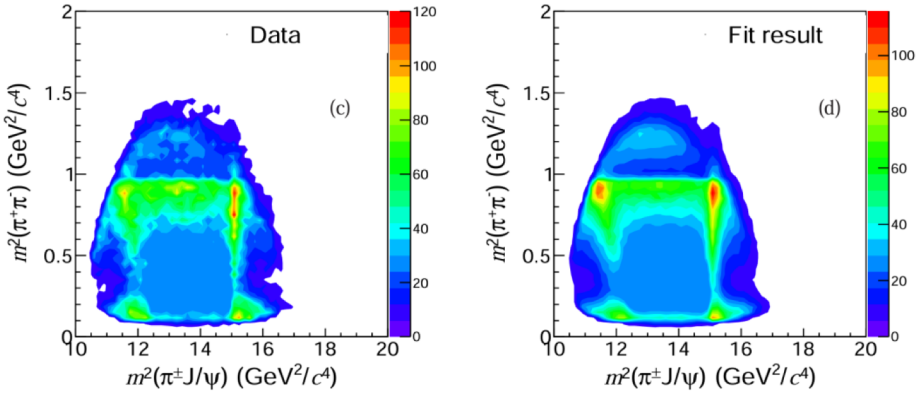
PRD 106, 072001(2022)



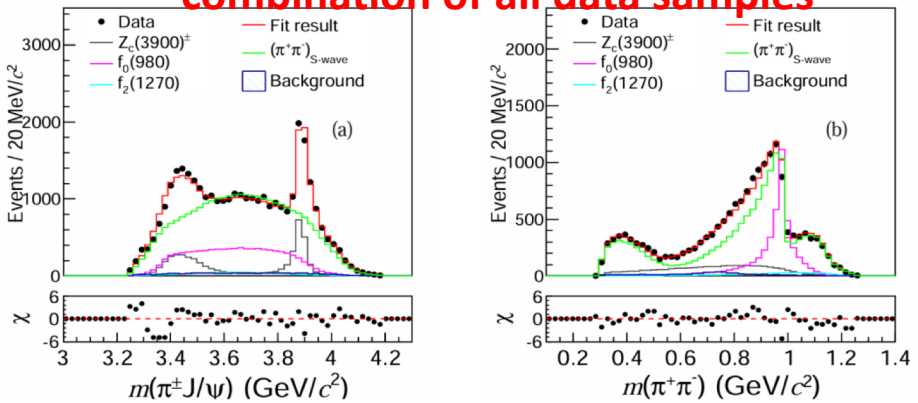
- $Z_c(3900)$ observed simultaneously by BESIII at $\sqrt{s} = 4.26$ GeV and Belle in $\pi^\pm J/\psi$
- If molecular/tetraquark state, strong correlation between Zc and Y system

- Promising to study relationship between and Y states, as well as resonances and Y states to understand internal structure of $Z_c(3900)$ and $\pi^+\pi^- J/\psi$

Partial wave analysis of $e^+e^- \to \pi^+\pi^- J/\psi$ and cross section measurement of $e^+e^- \to \pi^\mp Z_c(3900)^\pm$ from 4.1271 to 4.3583 GeV



combination of all data samples



PWA of $e^+e^- \to \pi^+\pi^- J/\psi$ for datasets between 4.127 - 4.358 GeV

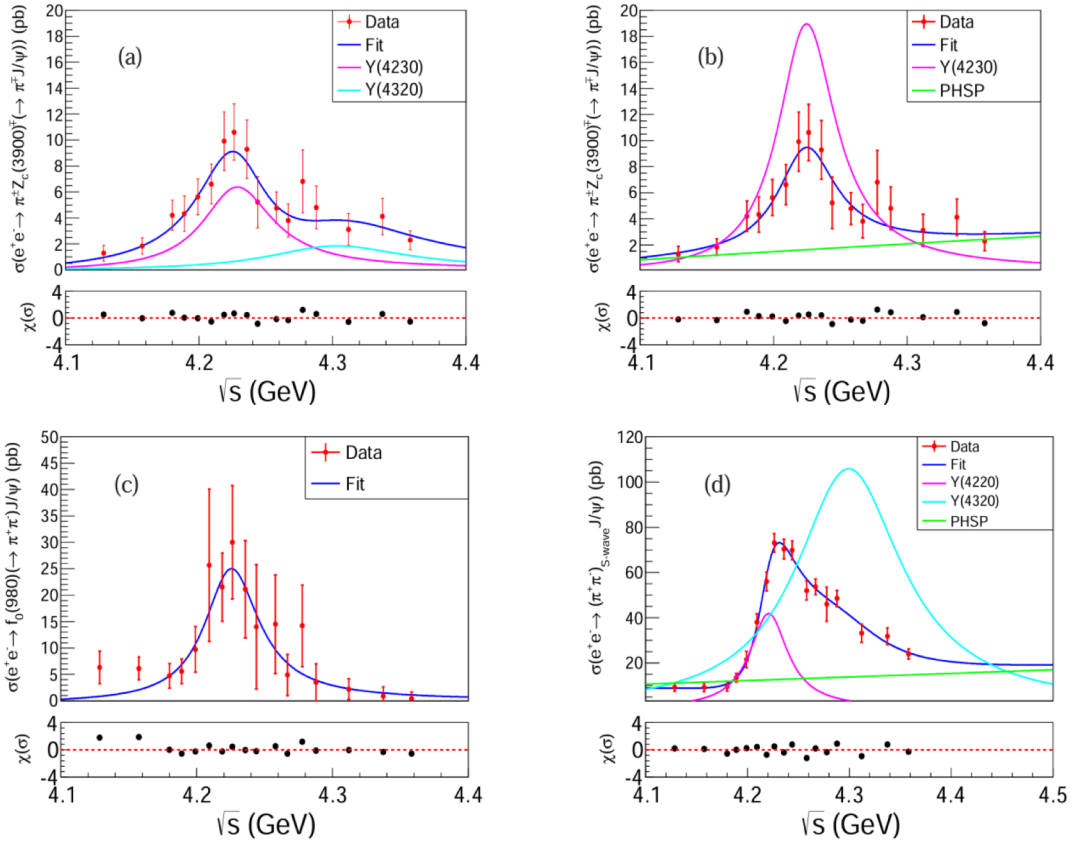
arXiv: 2505.13222

✓ **$Z_c(3900)$ Paramater fit** **from Breit-Wigner**

- Initial BES measurements:
  $M = 3988.0 \pm 3.6 \pm 4.9$ MeV
  $\Gamma = 46 \pm 10 \pm 20$ MeV PRL 110, 252001 (2013)
- Current PDG average:
  $M = 3987.1 \pm 2.6$ MeV
  $\Gamma = 28.4 \pm 2.6$ MeV

Sample	M (MeV/c^2)	Γ (MeV)
$4.1567 - 4.1989$	3883.5 ± 1.6	38.6 ± 3.6
$4.2091 - 4.2357$	3884.0 ± 1.0	37.8 ± 1.6
$4.2438 - 4.2776$	3884.9 ± 1.8	34.2 ± 3.3
$4.2866 - 4.3583$	3890.0 ± 2.3	36.1 ± 4.2
Average	$3884.6 \pm 0.7 \pm 3.3$	$37.2 \pm 1.3 \pm 6.6$

Partial wave analysis of $e^+e^- \to \pi^+\pi^- J/\psi$ and cross section measurement of $e^+e^- \to \pi^\mp Z_c(3900)^\pm$ from 4.1271 to 4.3583 GeV



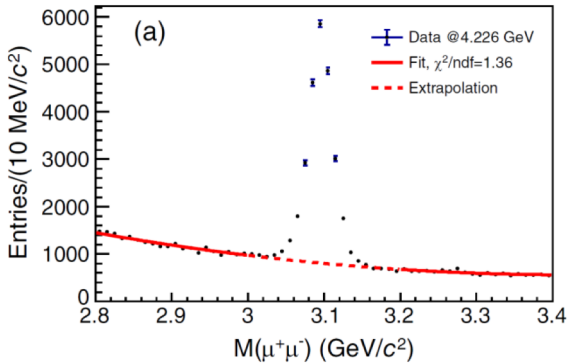
arXiv: 2505.13222

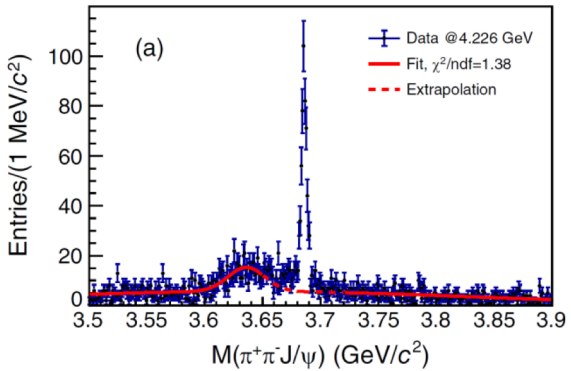
- ✓ Cross section measurements of sub processes $e^+e^- \to \pi^\pm Z_C(3900)^\pm$, $f_0(980)J/\psi$, $(\pi^+\pi^-)_{S-wave}J/\psi$
- ✓ Observation of Y(4220) in sub process cross sections
- ✓ $M = 4225.8 \pm 4.2 \pm 3.1$ MeV
  $\Gamma = 55.3 \pm 9.5 \pm 11.1$ MeV
- ✓ Significance of Y(4220) in $\sigma(e^+e^- \to (\pi^+\pi^-)_{S-wave}J/\psi)$ ~ 12.2σ

Inclusive cross sections of prompt J/ψ and $\psi(3686)$

PRD 111, 052007 (2025)

- Double charmonium production cross sections from factories larger than expected hidden states/processes?
- Can investigate by studying prompt and production below threshold at BESIII

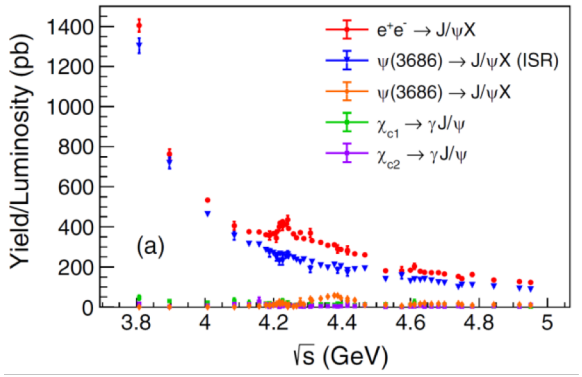


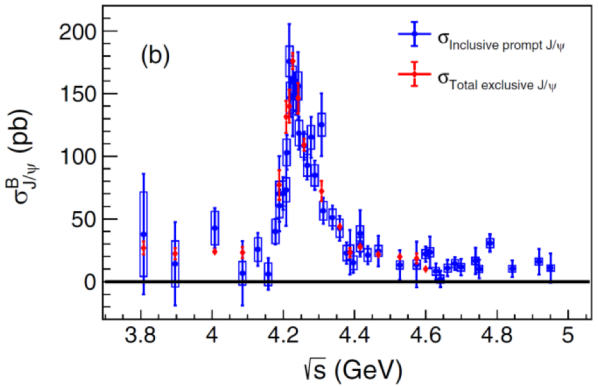


- ✓ Reconstruct J/$\psi \to \mu^+\mu^-$
- ✓ Subtract ISR production/conventional charmonium decays (e.g.ψ(2S)→ $\pi^+\pi^- J/\psi$)

- ✓ Reconstruct $\psi(2S) \to \pi^+\pi^- J/\psi$ with $J/\psi \to l^+l^-(l = e, \mu)$
- ✓ ISR production also substructed

Inclusive cross sections of prompt J/ψ and $\psi(3686)$

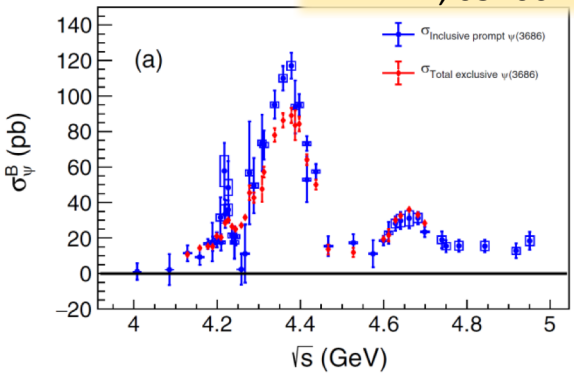


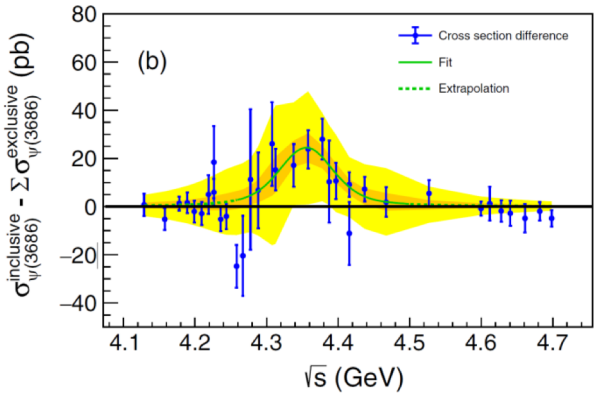


J/ψ: Inclusive and the sum of exclusive processes consistent well.

$\psi(3686)$: Contribution of unknown decay channels of the $\psi(4360) \to \psi(3686)X$ ~23% discrepancy!

PRD 111, 052007 (2025)



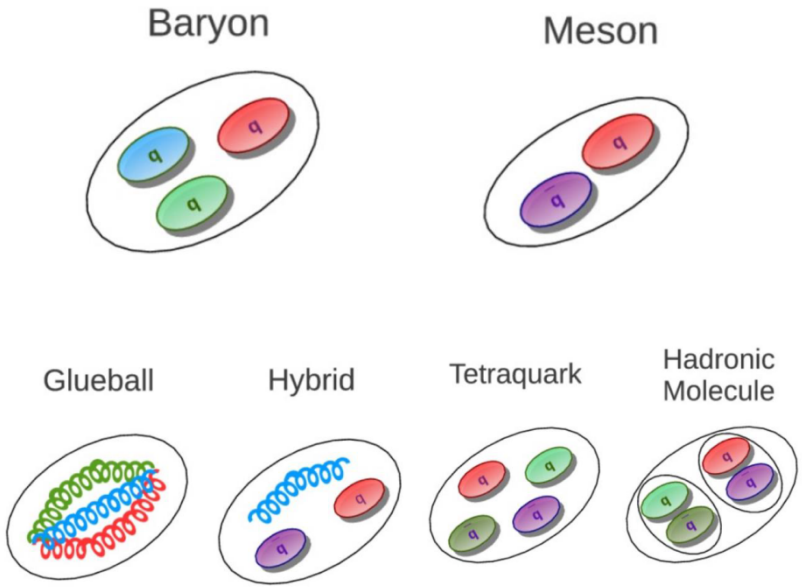


QCD Exotics

- Non-exotic hadrons: mesons ($q\bar{q}$), baryons (**qqq**)
- QCD allows for exotic hadrons:
  - Multi-quark states

    strong evidence in heavy quark sector

    https://qwg.ph.nat.tum.de/exoticshub/
  - Hybrids
  - Glueballs
  - Molecule
  - ect.

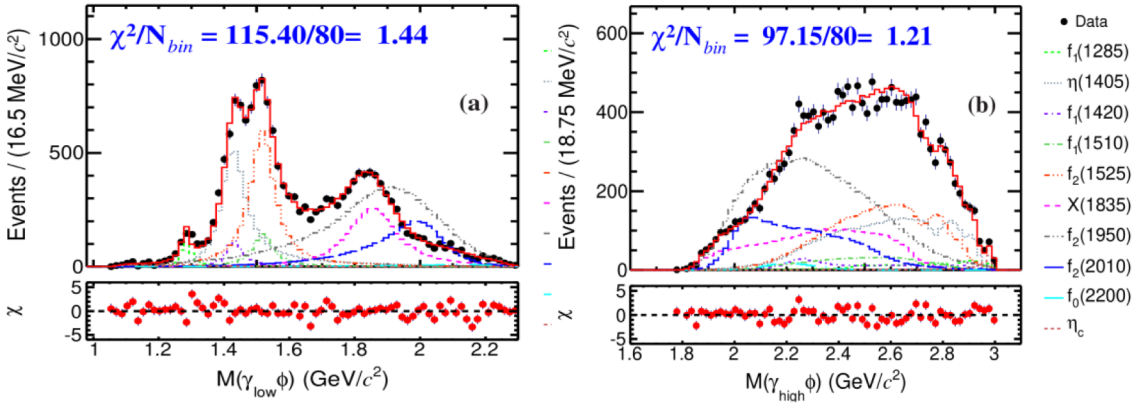


Recent Analyses:

- ✓ $J/\psi \to \gamma\gamma\phi$
- ✓ $J/\psi \to \gamma 3(\pi^+\pi^-)$
- ✓ $J/\psi \to \gamma K_S^0 K_S^0 \eta'$

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

PRD111, 052011 (2025)

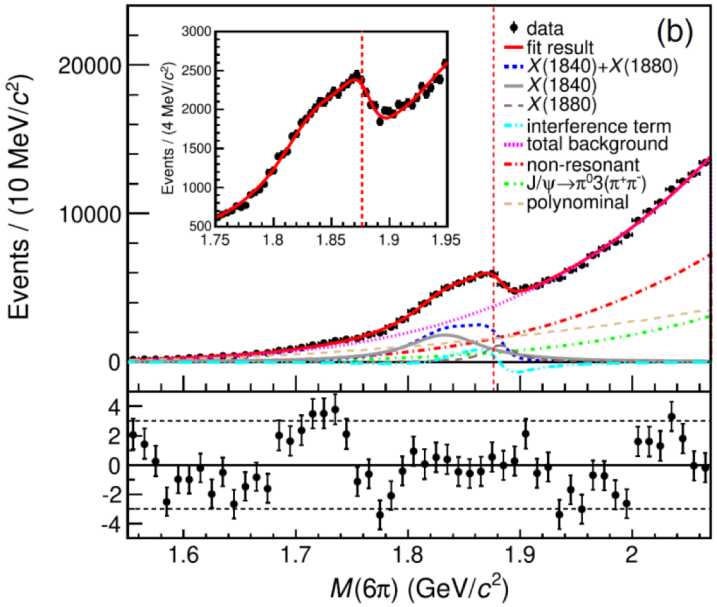


- PWA of $J/\psi \to \gamma\gamma\phi$ is performed with 10 billion J/ψ events.
- 1^{++}: $f_1(1285), f_1(1420), f_1(1510)$
  0^{-+}: $\eta(1405), X(1835), \eta_c$
  2^{++}: $f_2(1525), f_2(1950), f_2(2010)$
  0^{++}: $f_0(2200)$

- $X(1835) \to \gamma\phi$ suggests its assignment of η' excitation.
- $\eta(1405)$ is observed, while $\eta(1475)$ can not be excluded.
- $\eta_c \to \gamma\phi$ are observed. The first radiative decay mode of η_c.

Observation of the Anomalous Shape of X(1840) in $J/\psi \to \gamma 3(\pi^+\pi^-)$ Indicating a Second Resonance Near $p\bar{p}$ Threshold

PRL 132, 151901 (2024)



- The analysis of $J/\psi \to \gamma 3(\pi^+\pi^-)$ near $p\bar{p}$ Threshold is performed with 10 billion J/ψ events.
- Two Resonance near $p\bar{p}$ threshold observed.
- **$X(1840)$**

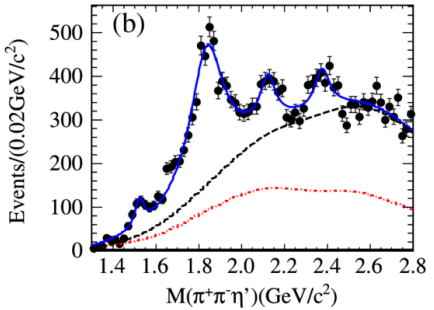
$$M = 1832.5 \pm 3.1 \pm 2.5\ \mathrm{MeV/c^2}$$
$$\Gamma = 80.7 \pm 5.2 \pm 7.7\ \mathrm{MeV}$$

- **$X(1880)$**

$$M = 1882.1 \pm 1.7 \pm 0.7\ \mathrm{MeV/c^2}$$
$$\Gamma = 30.7 \pm 5.5 \pm 2.4\ \mathrm{MeV}$$

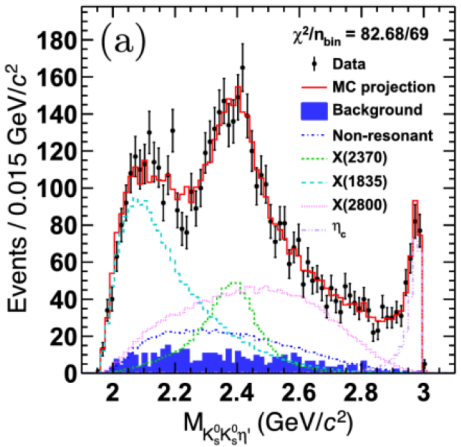
Determination of Spin-Parity Quantum Numbers of $X(2370)$ as 0^{-+} from $J/\psi \to \gamma K_S^0 K_S^0 \eta'$

- 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 $J/\psi \to \gamma\eta'\eta\eta$ [PRD 103, 012009 (2021)], $J/\psi \to \gamma\gamma\phi$ [PRD111, 052011 (2025)]. Upper limits of BF are well consistent with predictions of 0^{-+} glueball

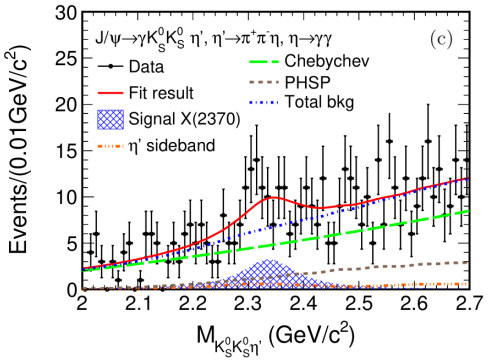


PRL 106, 072002 (2011)
PRL 117, 042002 (2016)

PRL 132, 181901 (2024)



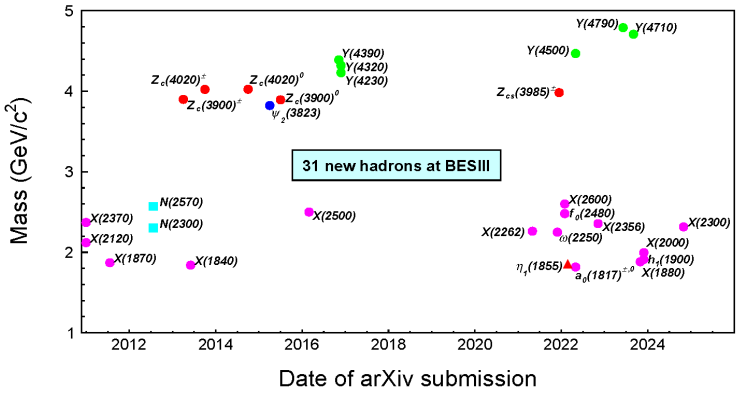
- ✓ PWA of $J/\psi \to \gamma K_S^0 K_S^0 \eta'$
- ✓ Spin-parity determined to be 0^{-+}
- ✓ Mass consistent with LQCD prediction for 0^{-+} glueball



EPJC 80, 746 (2020)

Summary

- BESIII has a rich and fruitful program of spectroscopy physics.
- Especially J/ψ and ψ(3686) decays provide an excellent laboratory to study spectroscopy .
- Recently many indications for new states
  - ✓ $h_1(1900)$: $J/\psi \to \phi\pi^0\eta$
  - ✓ $X(2000)$: $J/\psi \to \phi\pi^0\eta$
  - ✓ $h_1(2300)$: $\psi(3686) \to \phi\eta\eta'$
  - ✓ $Y(4220),Y(4320),Y(4420)$: $e^+e^- \to \pi^+\pi^- h_c$
  - ✓ $X(1840)$: $J/\psi \to \gamma 3(\pi^+\pi^-)$
  - ✓ $X(1880)$: $J/\psi \to \gamma 3(\pi^+\pi^-)$
  - ✓ $X(2370)(0^{-+})$: $J/\psi \to \gamma K_S^0 K_S^0 \eta'$
  - ✓ ……



New exciting results ongoing:

- high statistics datasets in wide energy range already collected
- other approaches to be explored

Thanks !