Light hadron spectroscopy at BESIII

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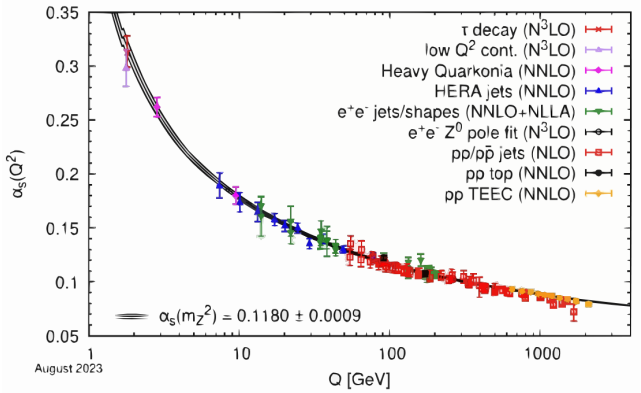
(On behalf of the BESIII Collaboration)

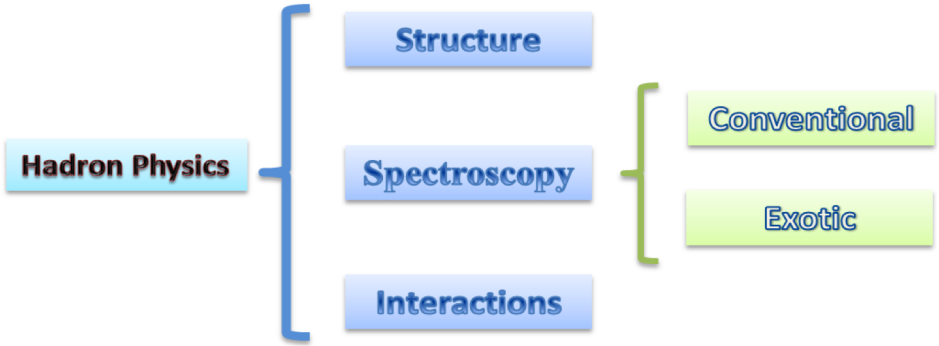
第五届强子与重味物理理论与实验联合研讨会

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?

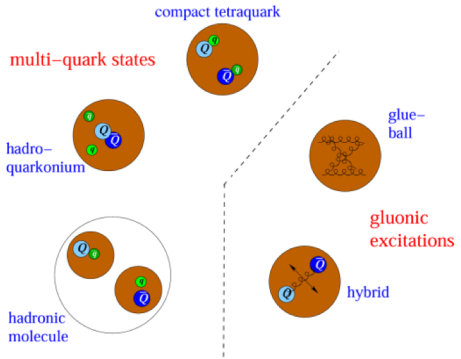




- ✓ $\alpha_s \sim 1$, Occurring in the non-perturbative regime of QCD, perturbative techniques fail.
- ✓ Challenges for both theoretical analyses and experimental investigations.
- ✓ Alternative theoretical tools often model dependent or very computational expensive
- ✓ Highly populated spectrum: many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

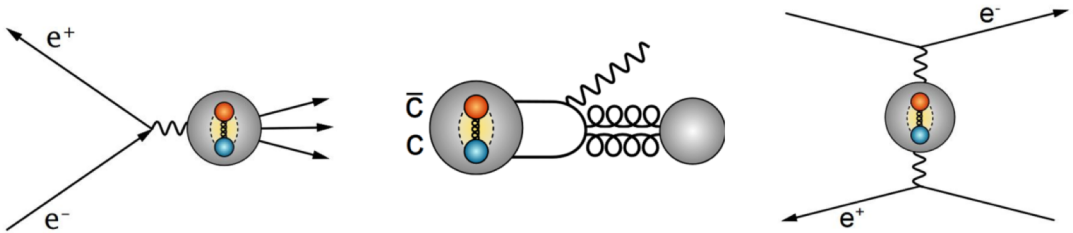
Introduction

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

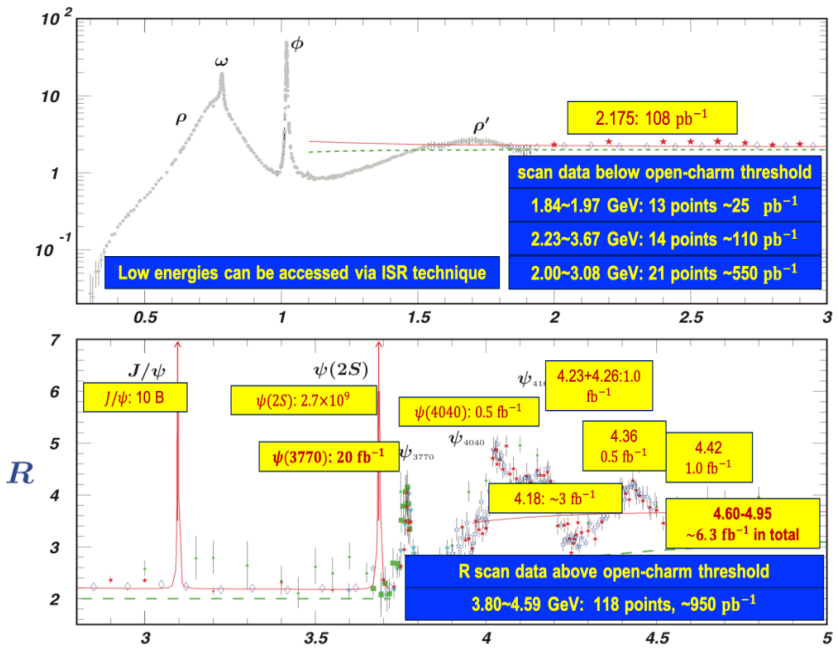


Physics report 873 (2020) 1-154

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



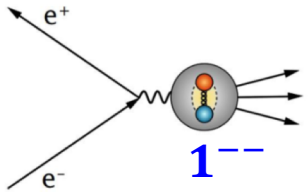
BESIII Data Samples



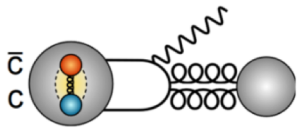
Data sets collected so far include:

- 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

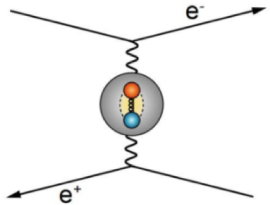
Direct production of vector states



Charmonium decays

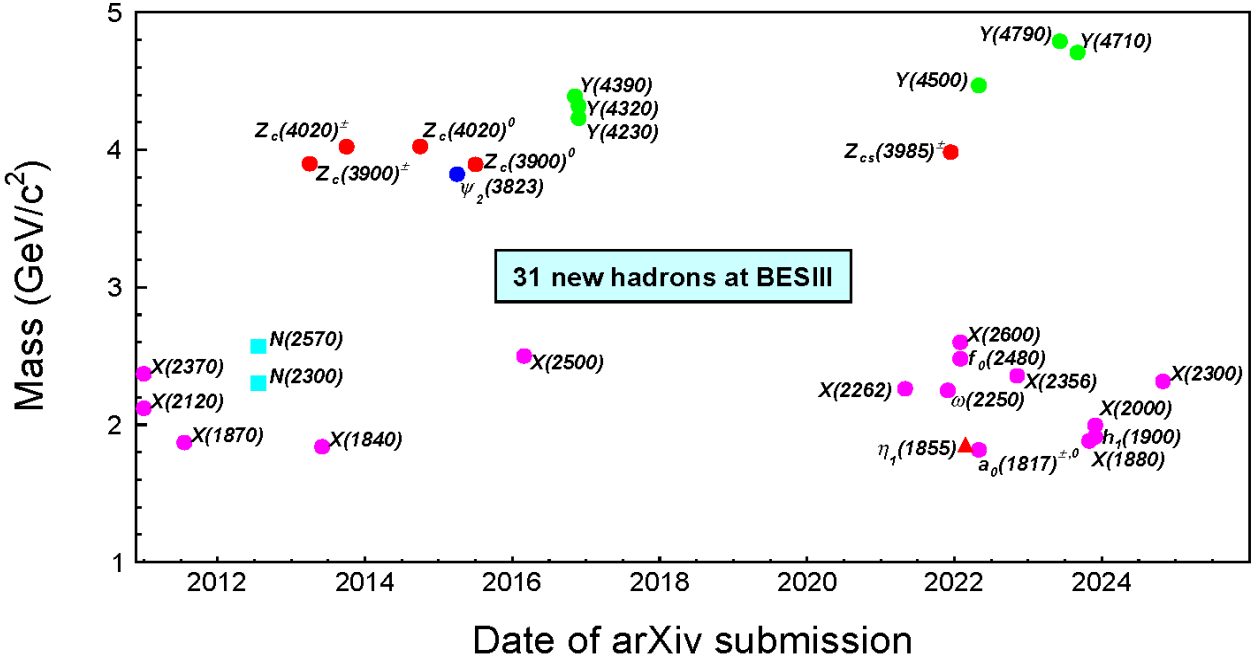


Two-photon scattering



Excellent platform to explore the hadron spectroscopy!

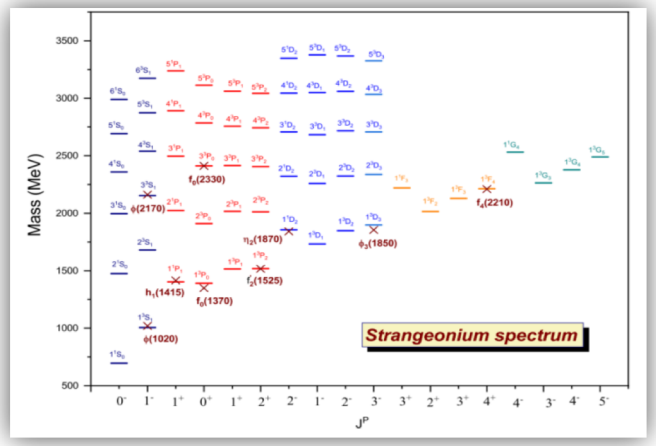
The BESIII Experiment

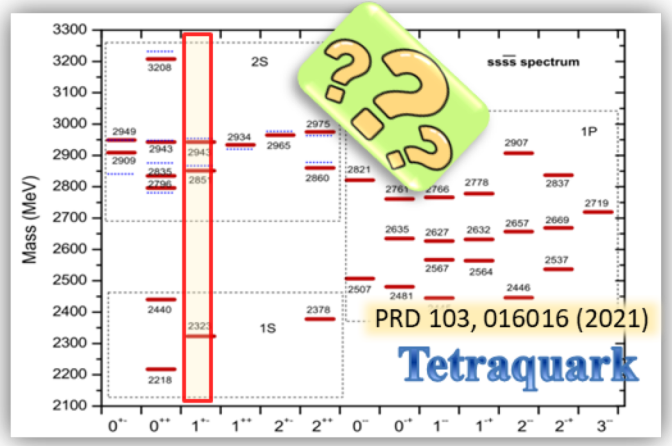


Physics topics span a wide range of topics:

- 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:

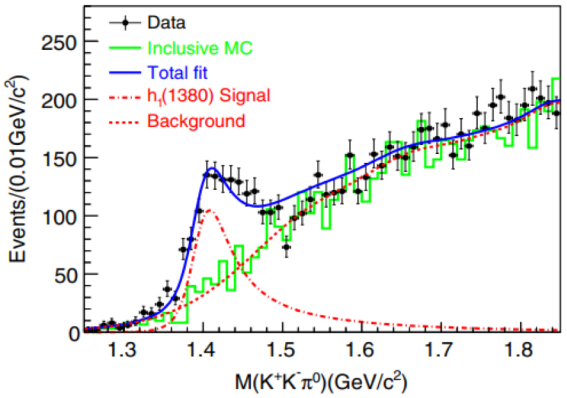
- ✓ Study of $J/\psi \to \eta' K K \pi$
- ✓ PWA of $J/\psi \to \phi \pi^0 \eta$
- ✓ PWA of $\psi(3686) \to \phi \eta \eta'$
- ✓ $e^+e^- \to K_S K_L \pi^0 / K^+ K^- \pi^0$

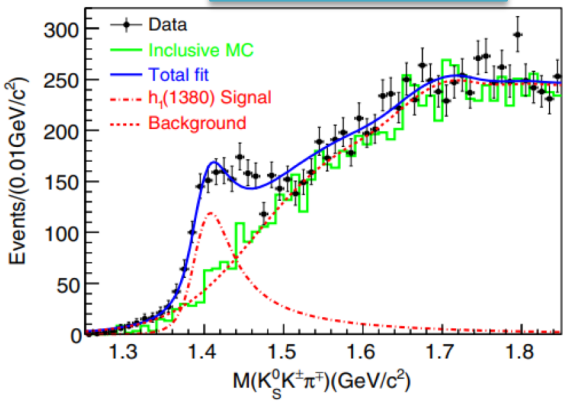
Observation of $h_1(1380)$ in the $J/\psi \to \eta' KK\pi$ decay

- $h_1(1380)$ ($h_1(1415)$ PDG) observed about 35 years ago by fixed target
- Nature of $h_1(1380)$ still not fully understood

PRD98, 072005 (2018)

$h_1(1380)$





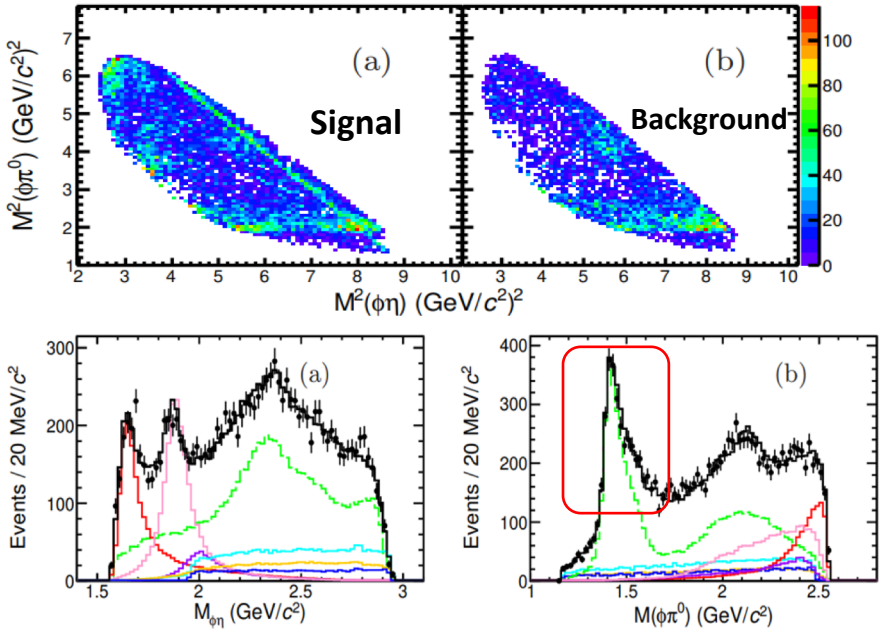
- Measurement of $J/\psi \to \eta' KK\pi$ performed with 1.3 billion J/ψ events
- $h_1(1380)$ observed in $M(KK\pi)$ with >10σ statistical significance

$$M = 1423.2 \pm 2.1 \pm 7.3\ \mathrm{MeV/c^2}$$
$$\Gamma = 90.3 \pm 9.8 \pm 17.5\ \mathrm{MeV}$$

Mass (MeV/c²) (1^1P_1)	Model
1470	Relativized quark model
(1457±11) or (1490±5)	Non relativistic quark model
1495.18±8.82	$h_1(1170)$-$h_1(1380)$ mixing
1511	Constituent quark model

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.

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

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

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

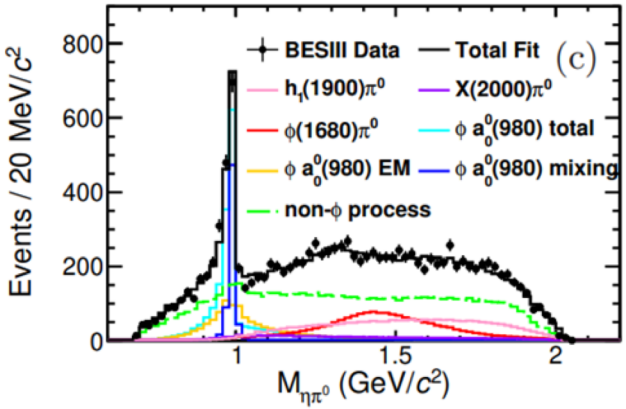
$$M = 1992 \pm 12\ ^{+15}_{-6}\ \text{MeV}/c^2$$
$$\Gamma = 132 \pm 22\ ^{+17}_{-4}\ \text{MeV}$$

$h_1(1900)$ 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)



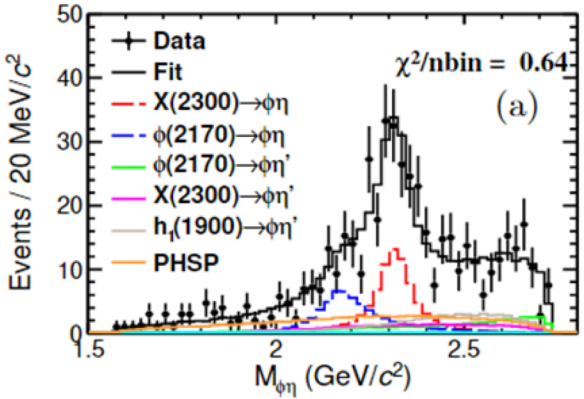
- The $f_0(980) - a_0(980)^0$ mixing signal in J/$\psi \rightarrow \phi f_0\,(980) \rightarrow \phi a_0\,(980)^0$ and the corresponding electromagnetic decay J/$\psi \rightarrow \phi a_0(980)^0$measured with improved precision.
- The mixing intensity of $f_0(980) - a_0(980)^0$ (ξ_{fa}) is calculated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

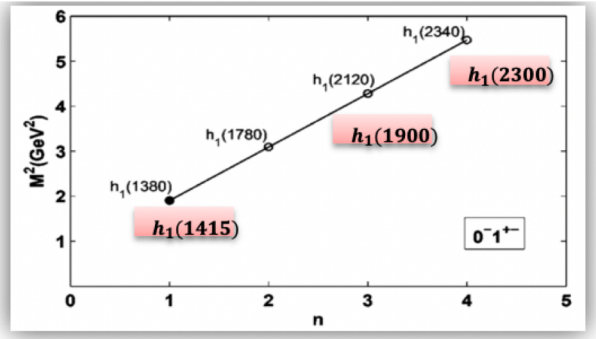
Process	M (MeV/c^2)	Γ (MeV)	fit fraction(%)	$\mathcal{B}$ (10^{-6})	Sig. (σ)
$\phi(1680)\pi^0$	$1663 \pm 5^{+16}_{-4}$	$159 \pm 15^{+11}_{-11}$	14.64 ± 0.56	$6.66 \pm 0.26^{+1.1}_{-1.0}$	32.3
$X(2000)\pi^0$	$1992 \pm 12^{+15}_{-6}$	$132 \pm 22^{+17}_{-4}$	4.05 ± 0.44	$1.70 \pm 0.19^{+0.48}_{-0.13}$	13.2
$h_1(1900)\pi^0$	$1908 \pm 6^{+8}_{-4}$	$175 \pm 13^{+7}_{-16}$	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)

$h_1(2300)$





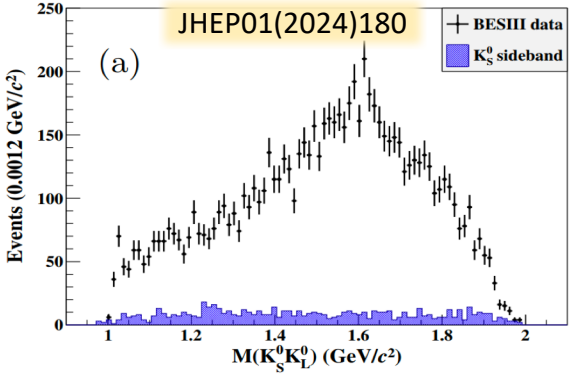
Resonance	M (MeV/c^2)	Γ (MeV)
$h_1(3P)$	2435 [4]	269 [4]
$h_1(3P)$	2449 [8]	N/A
$h_1(3P)$	2100 [12, 13]	N/A
$h_1(3P)$	2490 [9]	N/A
$h_1(3P)$	2398 [10]	N/A
$h_1(3P)$	2495.51±1.46 [11]	N/A
$h_1(4P)$	2340 [12, 13]	N/A
$T_{(ss\bar{s}\bar{s})1^{+-}}$	2323 [26]	N/A
$T_{(ss\bar{s}\bar{s})1^{+-}}$	1960 [27]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

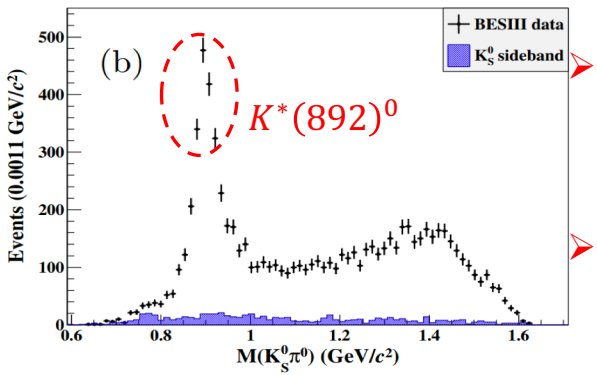
- Amplitude analysis of $\psi(3686) \to \phi\eta\eta'$ is performed with 2.7 billion psi(3686) events.
- New resonances in M($\phi\eta$) observed for the first time.
- **$h_1(2300)$** $\mathbf{J^{PC} = 1^{+-}}$

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

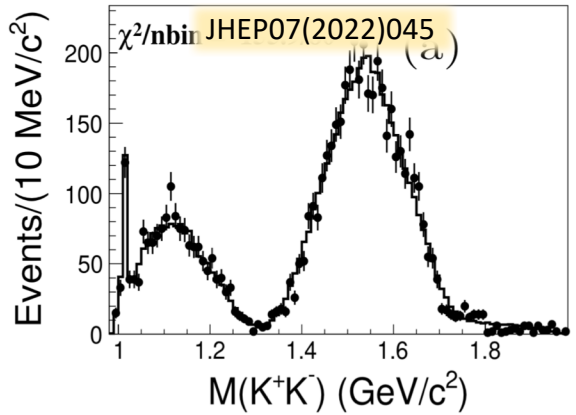
- Systematic discrepancy in the mass of $h_1(3P)$ in theory
- For the $T(ss\bar{s}\bar{s})$ hypothesis, need more theoretical calculations!

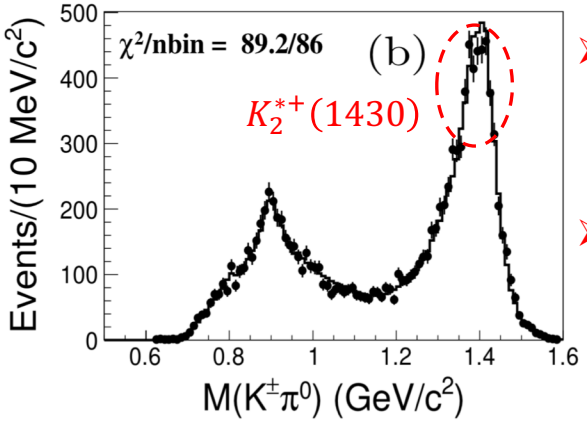
Measurement of the $e^+e^- \to K_S^0 K_L^0\pi^0$ and $e^+e^- \to K^+K^-\pi^0$ cross sections





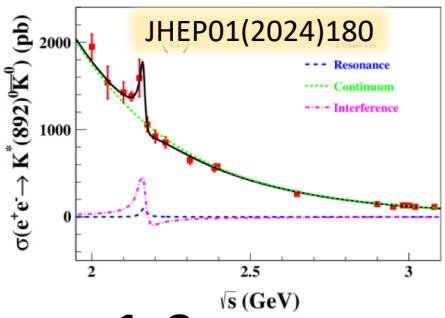
- Measurement of cross section of $e^+e^- \to K_S^0 K_L^0\pi^0$ from $\sqrt{s}$ = 2.000 to 3.080 GeV is performed
- Dominant component: $K^*(892)^0\overline{K^0}$

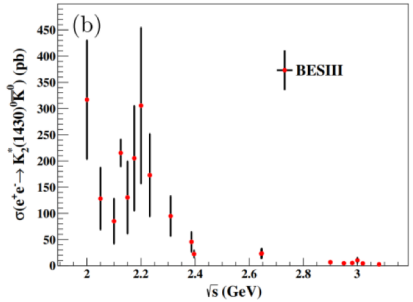




- Amplitude analysis of $e^+e^- \to K^+K^-\pi^0$ from $\sqrt{s}$ = 2.000 to 3.080 GeV is performed
- Dominant component: $K_2^{*+}(1430)K^-$

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





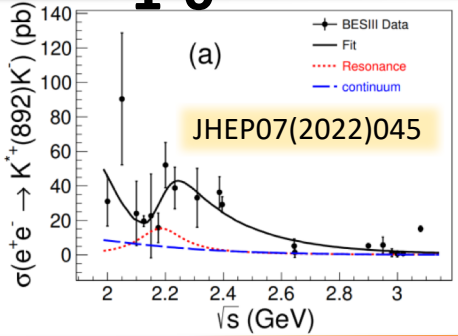
1-0-

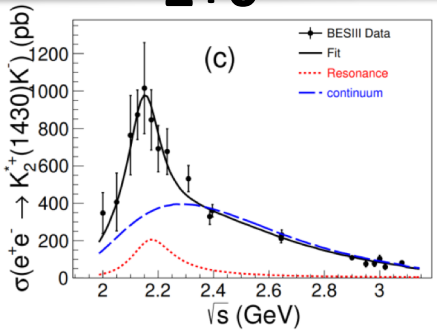
2+0-

- 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

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

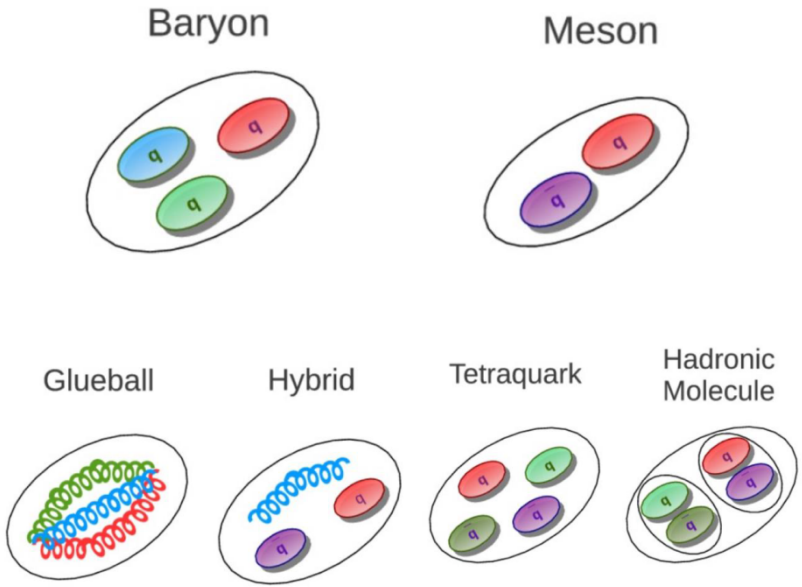
No significant $\phi(2170)$ in $K^*(892)^0\bar{K}^0$, but in $K_2^{*+}(1430)K^-$!

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.

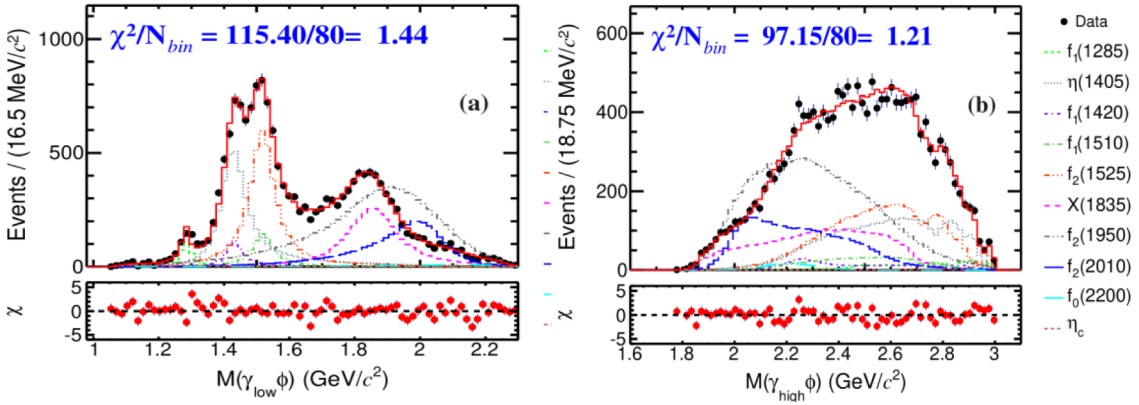


Recent Analyses:

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

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

PRD111, 052011 (2025)

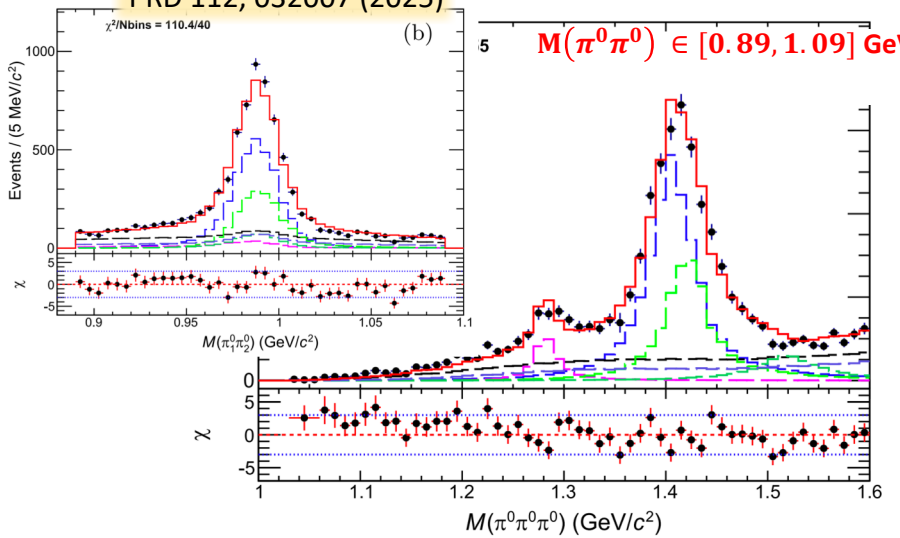


- PWA of $J/\psi \to \gamma\gamma\phi$ is performed with 10 billion J/ψ events.
- 1^{++}: $f_1(1285), f_1(1420), f_1(1510)$
  0^{-+}: $\eta(1405), X(1835), \eta_c$
  2^{++}: $f_2(1525), f_2(1950), f_2(2010)$
  0^{++}: $f_0(2200)$

- ✓ $X(1835) \to \gamma\phi$ 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.

Study of $f_1(1420)$ and $\eta(1405)$ in the decay $J/\psi \to \gamma\pi^0\pi^0\pi^0$

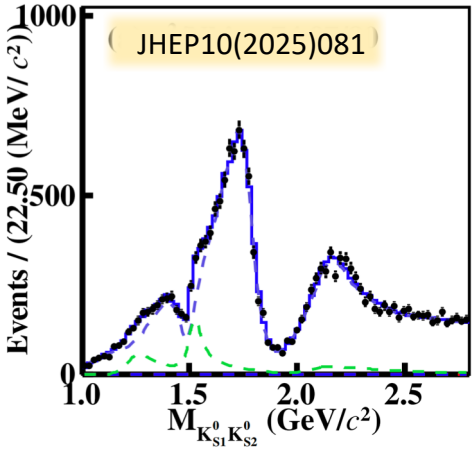
PRD 112, 032007 (2025)

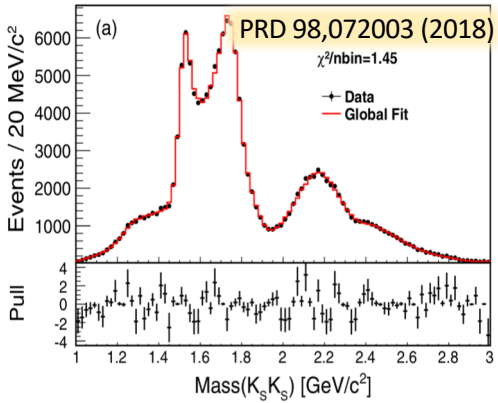


- Amplitude analysis of $J/\psi \to \gamma\pi^0\pi^0\pi^0$ is performed with 10 billion J/ψ events, within $M(\pi^0\pi^0) \in [0.89, 1.09]$ GeV.
- $\pi^0\pi^0$ system: contributions from $f_0(980)$ and 0++ PHSP
  $\pi^0\pi^0$ π^0 system:
  1^{++}: $f_1(1285), f_1(1420), f_1(1510)$
  0^{-+}: $\eta(1405)$

- ✓ Three axial vectors observed in the $3\pi^0$ for the first time
- ✓ Difficult to resolve the η(1405) and η(1475) structures

Amplitude analysis of $\psi(3686) \to \gamma K_S^0 K_S^0$

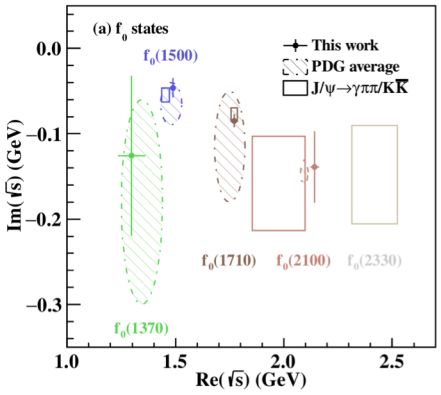


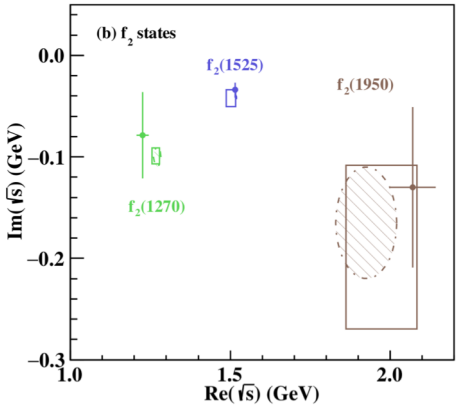


- Amplitude analysis of $\psi(3686) \to \gamma K_S^0 K_S^0$ is performed with 2.7 billion $\psi(3686)$ events, within $M(K_S^0 K_S^0) < 2.8$ GeV.
- $K_S^0 K_S^0$ system

  0^{++}: $f_0(1370), f_0(1500), f_0(1710), f_0(2100)$

  2^{++}: $f_2(1270), f_2(1525), f_2(1950)$

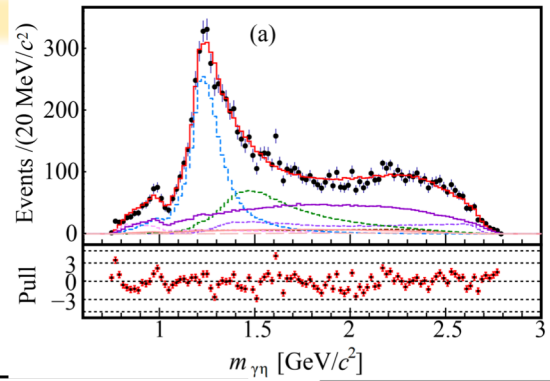


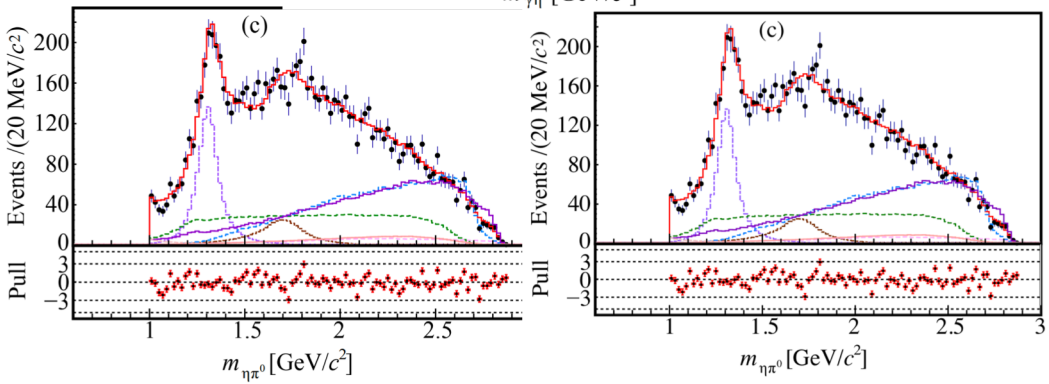


✓ All resonances consistent with the well-known states in PDG

Amplitude Analysis of the Isospin-Violating Decay $J/\psi \to \gamma\eta\pi^0$

arXiv:2603.23081



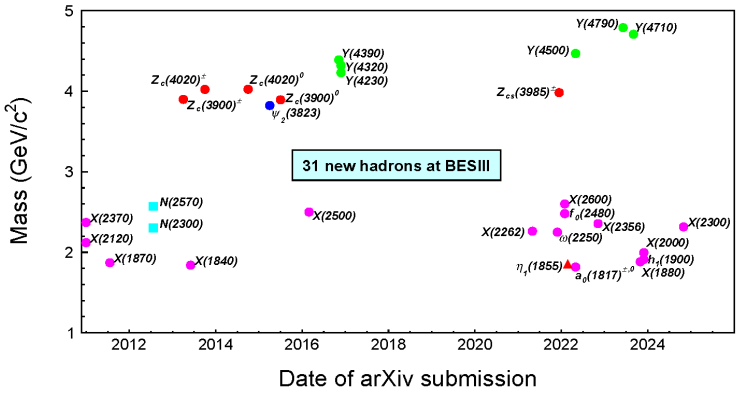


- Amplitude analysis of $J/\psi \to \gamma\eta\pi^0$ is performed with 10 billion J/ψ events,
- $\eta\pi^0$ system: $a_0(980), a_2(1320), a_2(1700)$
- $\gamma\eta$ system $\rho(770), \rho(1450), b_1(1235)$
- $\gamma\pi^0$ system: $h_1(1170), h_1(1595)$

- ✓ The branching fraction for $J/\psi \to \gamma a_0(980)$ consistent with theoretical predication.
- ✓ The partial decay width of $b_1(1235) \to \gamma\eta$ agrees with the VMD model prediction

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
  - ✓ $h_1(1415)$: $J/\psi \to \eta' K K \pi$
  - ✓ $h_1(1900)$: $J/\psi \to \phi\pi^0\eta$
  - ✓ $X(2000)$: $J/\psi \to \phi\pi^0\eta$
  - ✓ $h_1(2300)$: $\psi(3686) \to \phi\eta\eta'$
  - ✓ $X(1835)/\eta(1405)$: $J/\psi \to \gamma\gamma\phi$
  - ✓ $\eta(1405)$: $J/\psi \to \gamma 3\pi^0$
  - ✓ ……



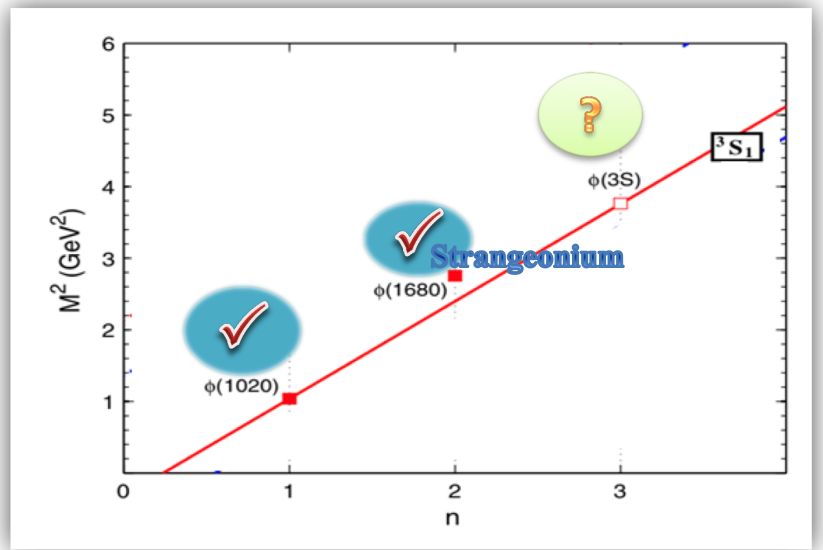
New exciting results ongoing:

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

Thanks !

Vector Strangeonium

1^{--}



$\phi(2170)$ $I^G(J^{PC}) = 0^-(1^{--})$

$\phi(2170)$ MASS

VALUE (MeV)			*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2159	**±17**	**OUR AVERAGE**		Error includes scale factor of 1.4. See the ideogram below.			
2176	±24	± 3		[1] ABLIKIM	21A	BES3	$e^+e^- \to \omega\eta$
2177.5	± 4.8	±19.5		[2] ABLIKIM	20M	BES3	$e^+e^- \to \eta'\phi$
2126.5	±16.8	±12.4		[3] ABLIKIM	20S	BES3	$e^+e^- \to K^+K^-\pi^0\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •							
2135	± 8	± 9	95	ABLIKIM	19I	BES3	$e^+e^- \to \eta\phi f_0(980)$
2239.2	± 7.1	±11.3		[4] ABLIKIM	19L	BES3	$e^+e^- \to K^+K^-$
2200	± 6	± 5	471	ABLIKIM	15H	BES3	$J/\psi \to \eta\phi\pi^+\pi^-$
2180	± 8	± 8		[5,6] LEES	12F	BABR	10.6 $e^+e^- \to \phi\pi^+\pi^-\gamma$
2079	±13	$^{+79}_{-28}$	4.8k	[7] SHEN	09	BELL	10.6 $e^+e^- \to K^+K^-\pi^+\pi^-\gamma$
2186	±10	± 6	52	ABLIKIM	08F	BES	$J/\psi \to \eta\phi f_0(980)$
2125	±22	±10	483	AUBERT	08S	BABR	10.6 $e^+e^- \to \phi\eta\gamma$
2192	±14		116	[8] AUBERT	07AK	BABR	10.6 $e^+e^- \to K^+K^-\pi^+\pi^-\gamma$
2169	±20		149	[8] AUBERT	07AK	BABR	10.6 $e^+e^- \to K^+K^-\pi^0\pi^0\gamma$
2175	±10	±15	201	[6,9] AUBERT,BE	06D	BABR	10.6 $e^+e^- \to K^+K^-\pi\pi\gamma$

- More excitations, e.g., $\phi(3S)$, still **missing** in experiment
- $\phi(2170)$, containing strange quarkonium, is controversial