郑州大学
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Experimental Study of Strangeonium Spectrum at BESIII

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2025年轻强子专题研讨会

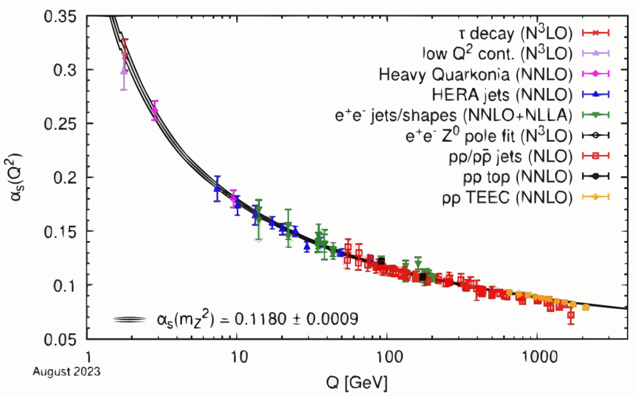
2025年5月8日-12日 安阳

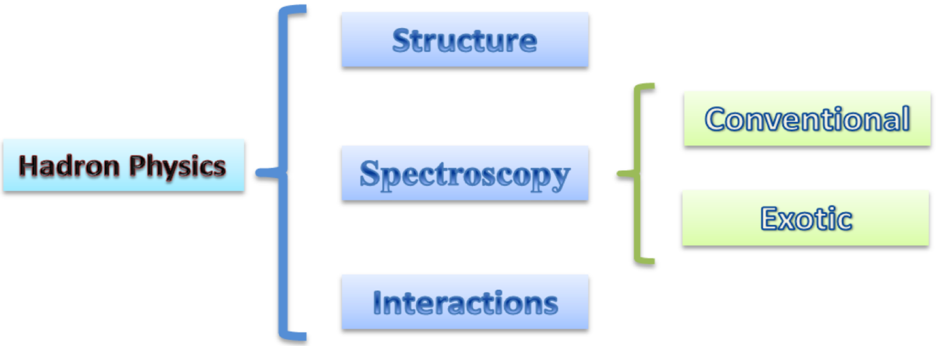
BESIII

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?



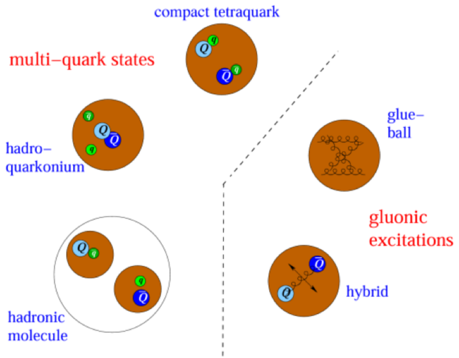


Light Meson

- ✓ $\alpha_s \sim 1$, 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

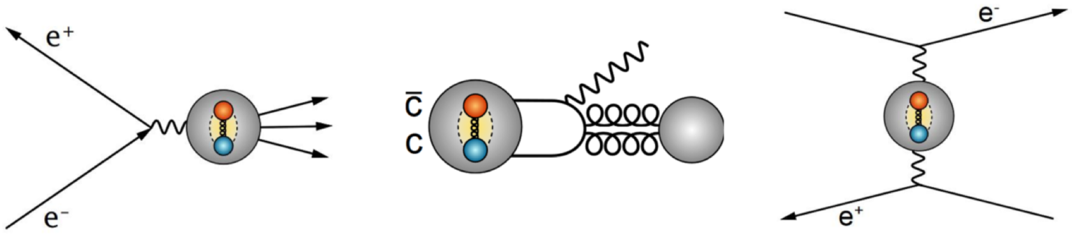
Introduction

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



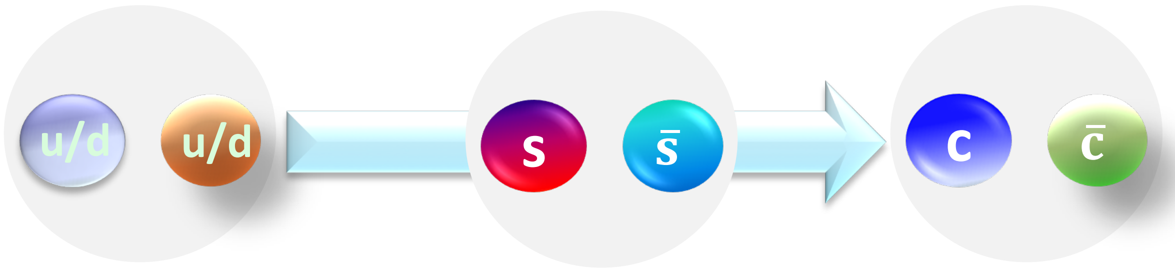
Physics report 873 (2020) 1-154

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



Introduction

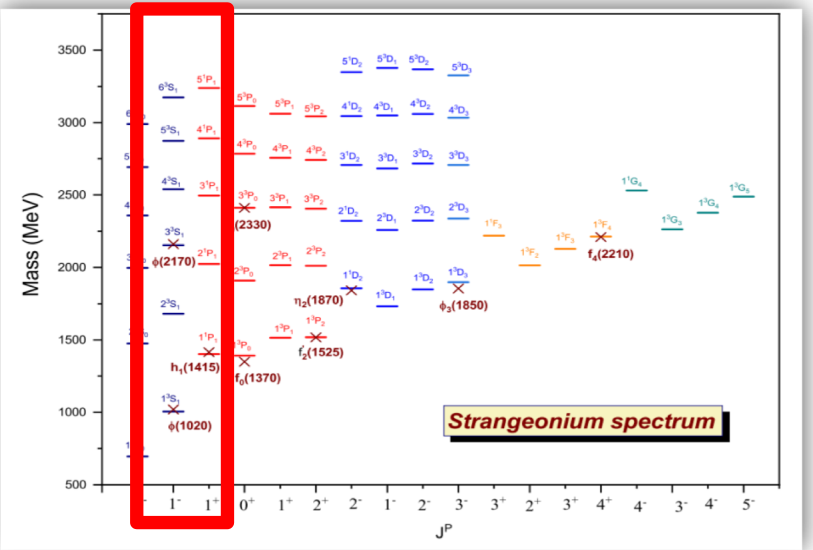
Hadron Spectroscopy: Precision SM tests & rare phenomena

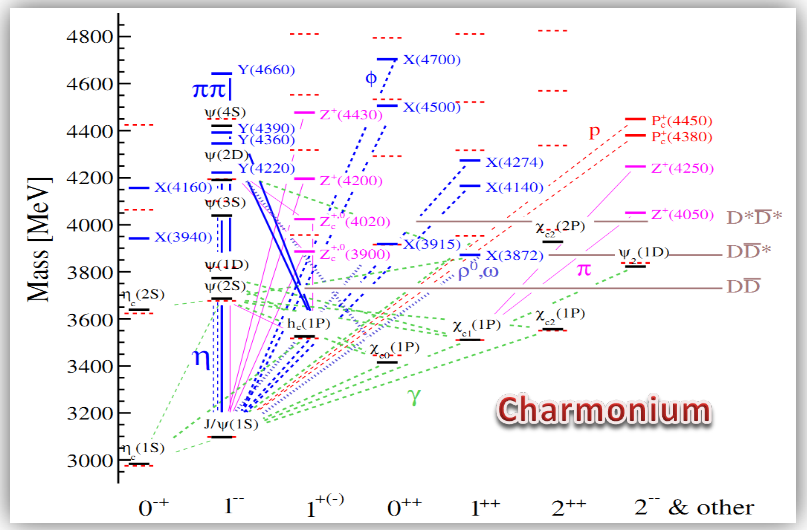


- Nonrel. potential model
- Conventional cc meson fit well with potential model below Open charm

The study of strangeonium is of particular interest since they are a bridge between the light u, d quarks and the heavy c, b quarks

Introduction

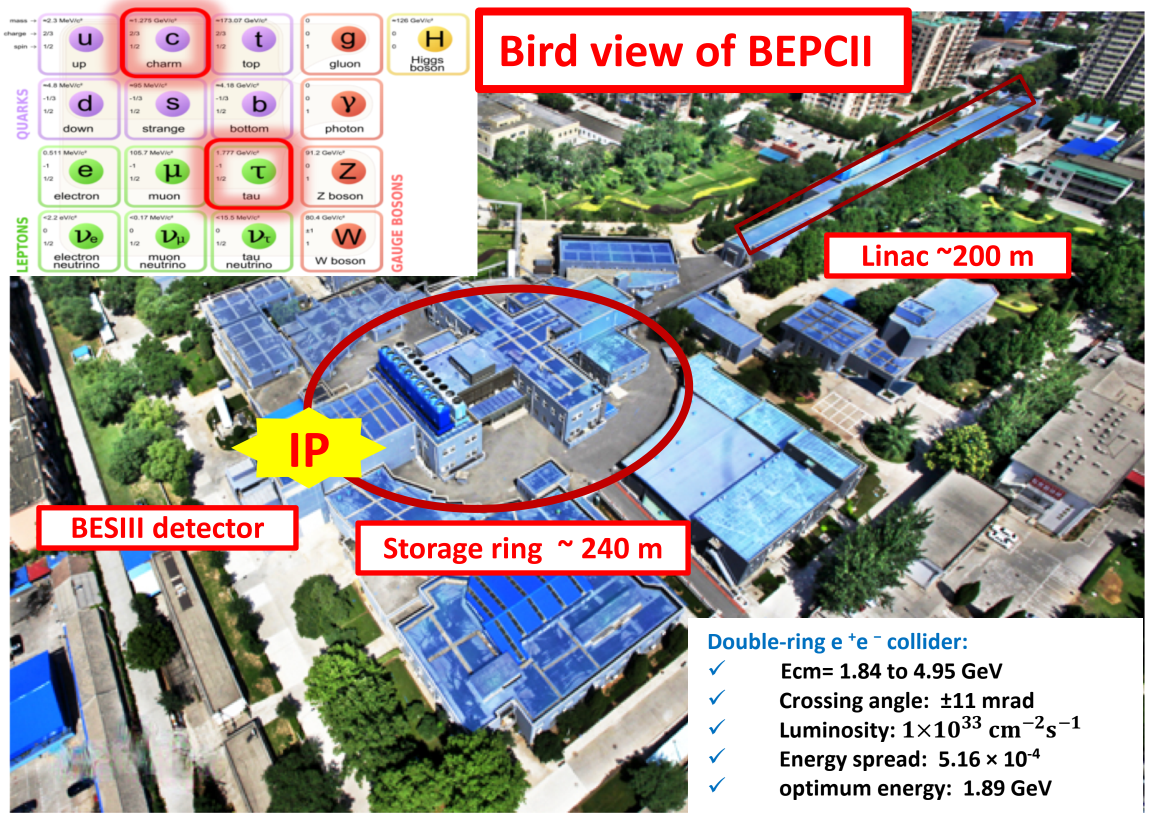




- ➢ Contribution to hadron spectroscopy
- ➢ Analogy to heavy flavour vector meson, exotic hadron

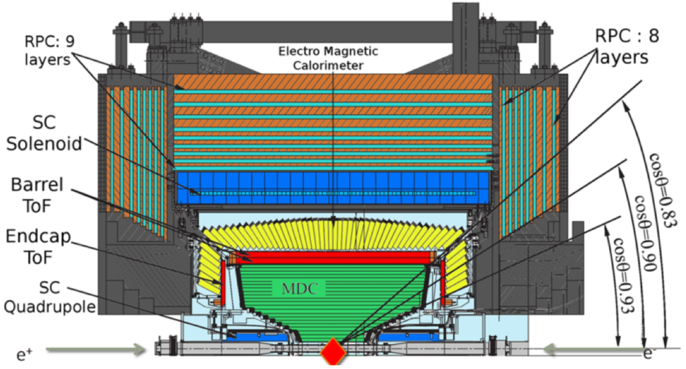
- ➢ Compared with $c\bar{c}$ and $b\bar{b}$, $s\bar{s}$ is a terra incognita
- ➢ Only a small fraction of the predicted strangeonium is confirmed

BEPCII&BESIII



Double-ring e^+e^- collider:

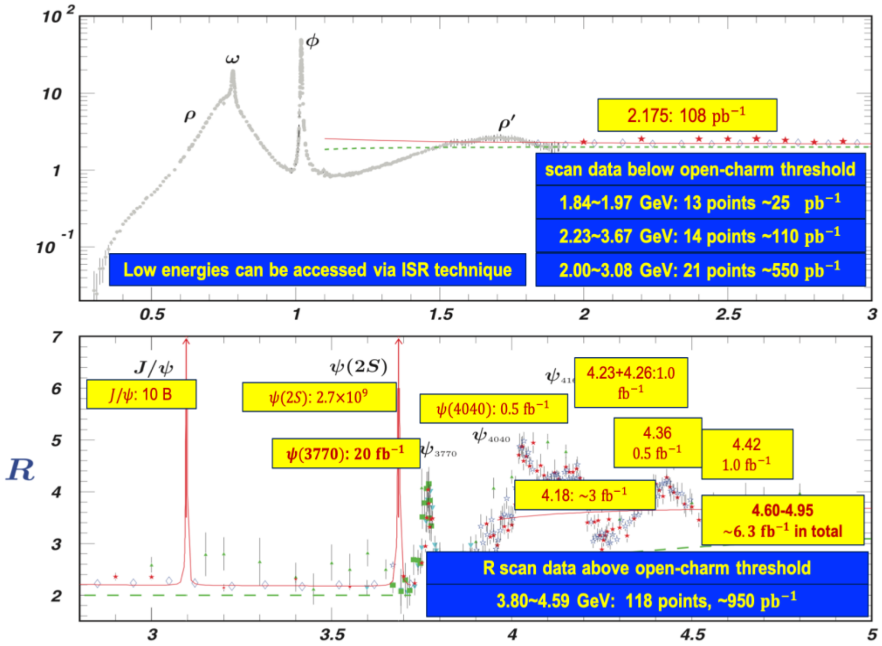
- ✓ Ecm= 1.84 to 4.95 GeV
- ✓ Crossing angle: ±11 mrad
- ✓ Luminosity: $1\times10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- ✓ Energy spread: 5.16×10^{-4}
- ✓ optimum energy: 1.89 GeV



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

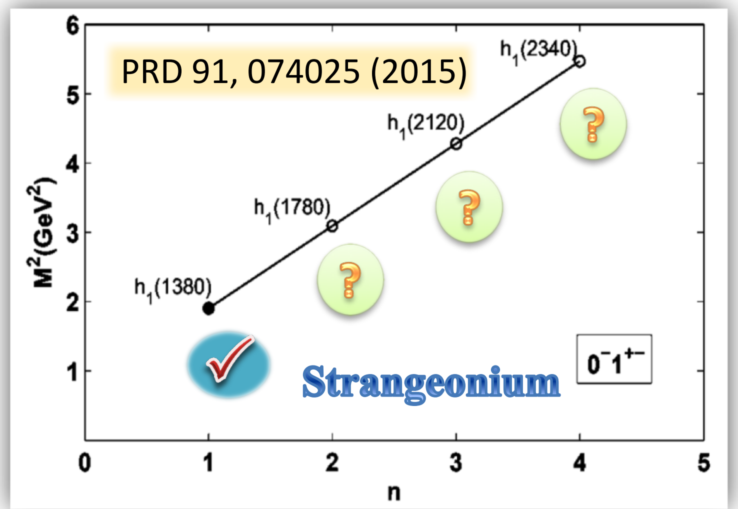


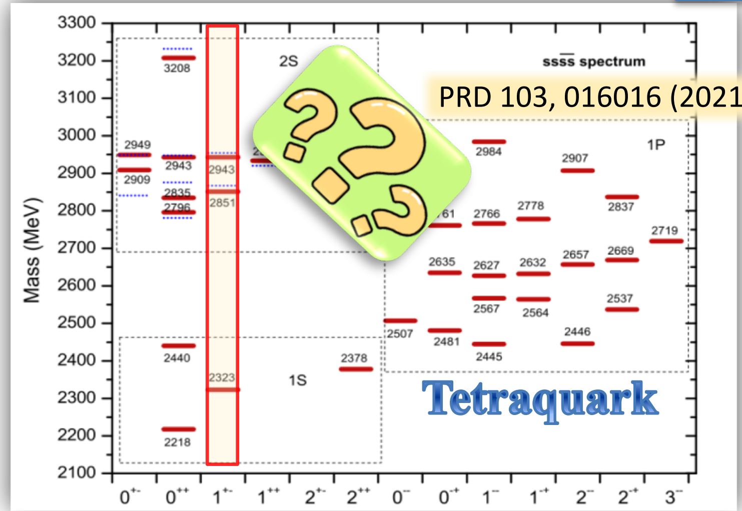
Data sets collected so far include:

- 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

Axial-Vector Strangeonium

1^{+-}





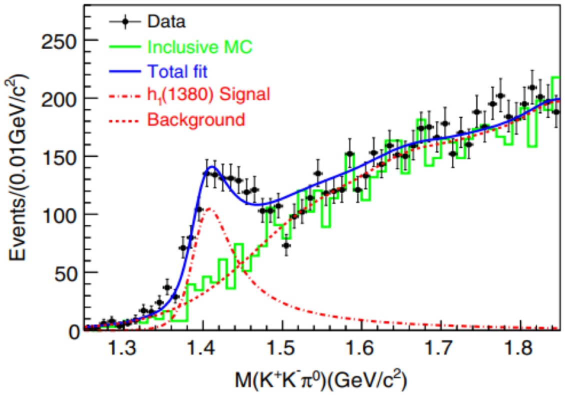
- ➤ Only the lightest axial-vector state $h_1(1380)$ ($h_1(1415)$ PDG) observed
- ➤ More excitations, e.g., $h_1(2P)$ and $h_1(3P)$, still **missing** in experiment
- ➤ Fully-strange tetraquarks in **same mass region and same final states** predicted in theory

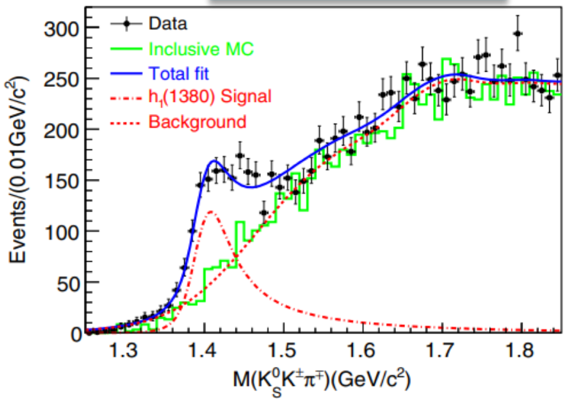
Observation of $h_1(1380)$ in the $J/\psi \to \eta' KK\pi$ decay

PRD98, 072005 (2018)

$h_1(1380)$

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





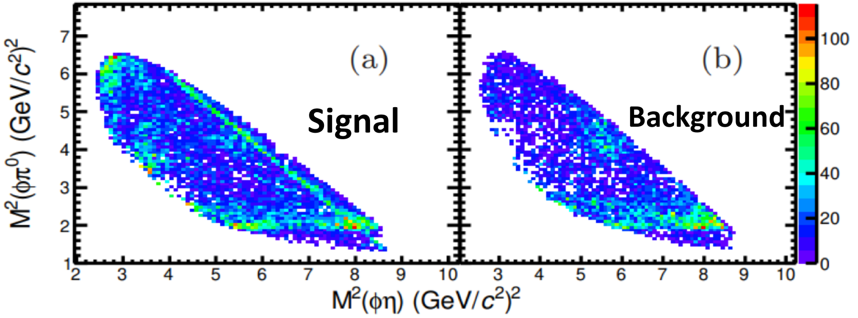
- Measurement of $J/\psi \to \eta' KK\pi$ performed with 1.3 billion J/ψ events
- $h_1(1380)$ observed in $M(KK\pi)$ with >10σ statistical significance

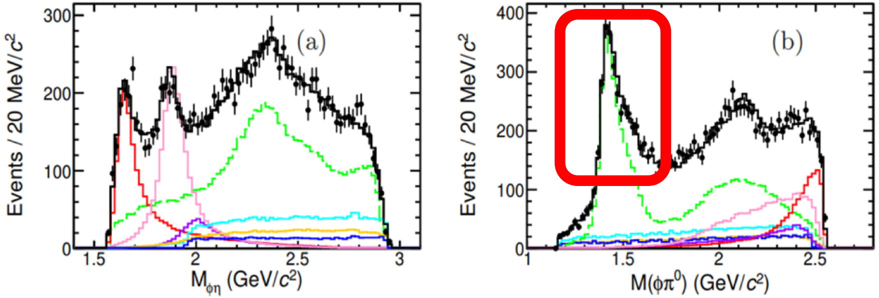
$$M = 1423.2 \pm 2.1 \pm 7.3\ \mathrm{MeV}/c^2$$
$$\Gamma = 90.3 \pm 9.8 \pm 17.5\ \mathrm{MeV}$$

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.

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

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

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

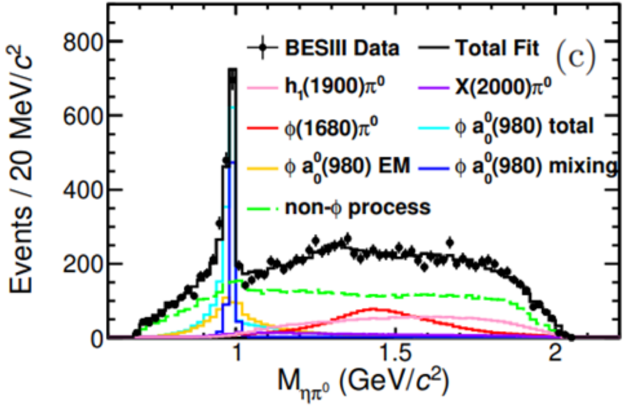
$$M = 1992 \pm 12\ ^{+15}_{-6}\ \mathrm{MeV}/c^2$$
$$\Gamma = 132 \pm 22\ ^{+17}_{-4}\ \mathrm{MeV}$$

$h_1(1900)$ 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 → $\phi\pi^0\eta$

Phys. Rev. D 110, 112014 (2024)



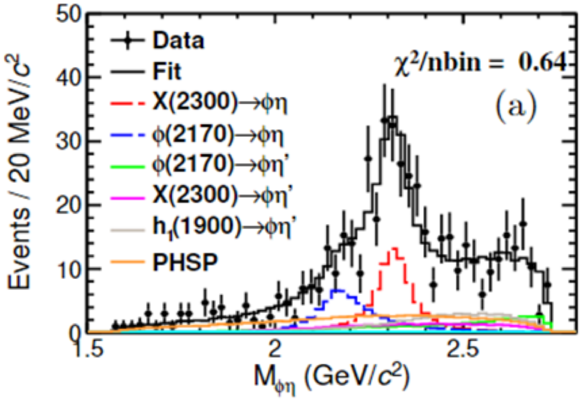
- The $f_0(980) - a_0(980)^0$ mixing signal in J/$\psi \to \phi f_0\,(980) \to \phi a_0\,(980)^0$ and the corresponding electromagnetic decay J/$\psi \to \phi a_0(980)^0$measured with improved precision.
- The mixing intensity of $f_0(980) - a_0(980)^0$ (ξ_{fa}) is calculated to be **(0.86 ± 0.04 ± 0.25)%.**

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
$\phi a_0(980)_{\mathrm{EM}}$	–	–	9.75 ± 0.58	$3.24 \pm 0.20^{+0.52}_{-0.22}$	19.9
$\phi a_0(980)_{\mathrm{mix}}$	–	–	7.33 ± 0.35	$2.74 \pm 0.13^{+0.15}_{-0.16}$	31.6

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

arXiv: 2410.05736, accepted by PRL

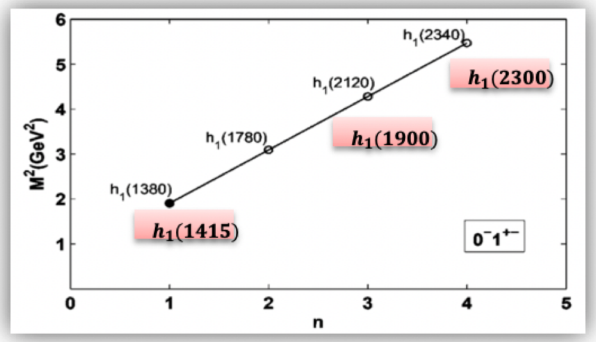
$h_1(2300)$



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 ± 9 ± 30	89 ± 15 ± 26

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

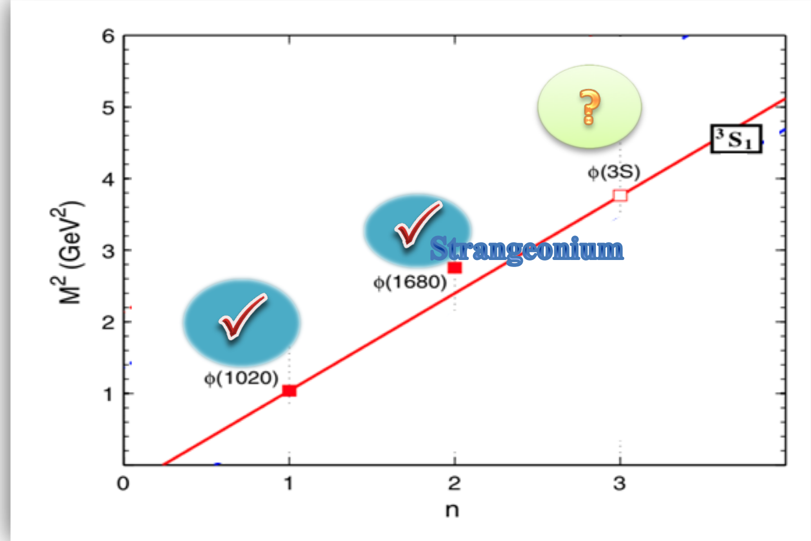
$$M = 2316 \pm 9 \pm 30 \mathrm{MeV}/c^2$$
$$\Gamma = 89 \pm 15 \pm 26 \text{ MeV}$$



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

Vector Strangeonium

1^{--}



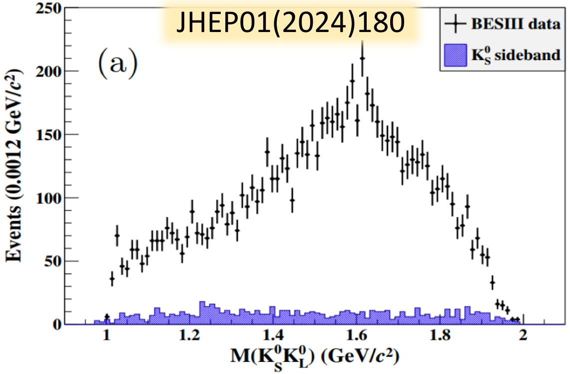
$\phi(2170)$ $\quad I^G(J^{PC}) = 0^-(1^{--})$

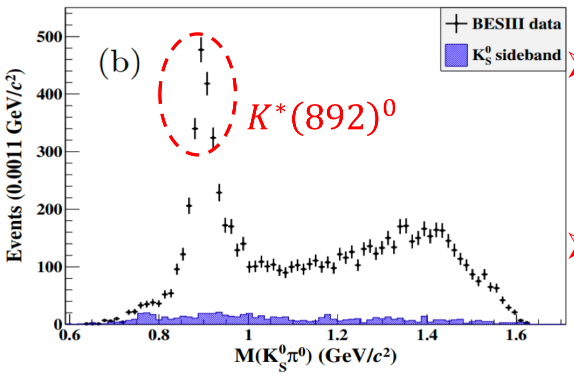
ϕ(2170) MASS

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 $e^+e^- \to K^+K^-\pi\pi\gamma$

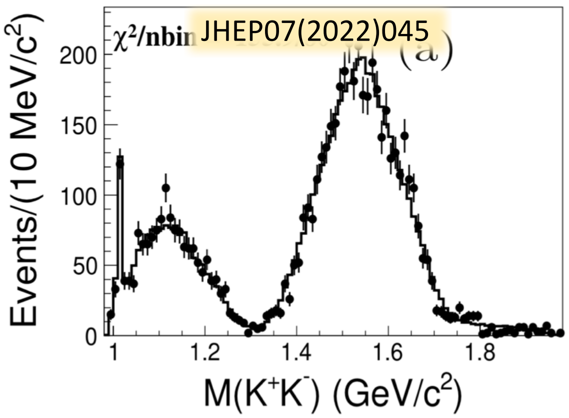
- More excitations, e.g., $\phi(3S)$, still **missing** in experiment
- $\phi(2170)$, containing strange quarkonium, is controversial

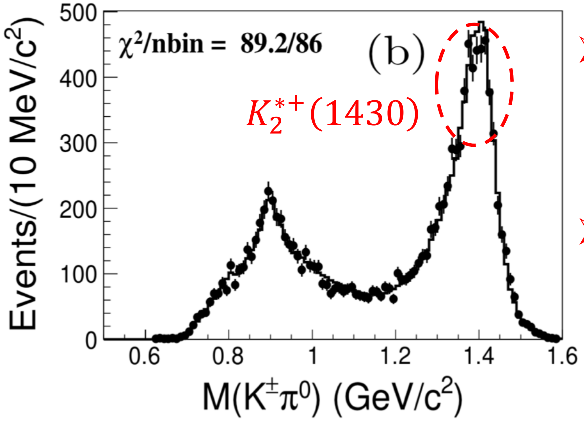
Measurement of the $e^+e^- \to K_S^0 K_L^0\pi^0$ and $e^+e^- \to K^+ K^-\pi^0$ cross sections





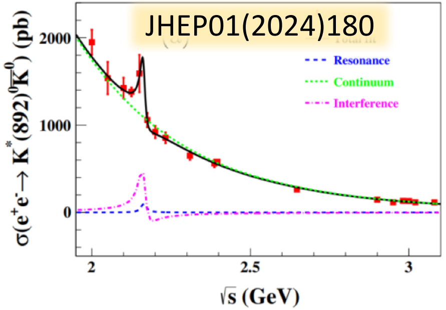
- Measurement of cross section of $e^+e^- \to K_S^0 K_L^0\pi^0$ from $\sqrt{s}$ = 2.000 to 3.080 GeV is performed
- Dominant component: $K^*(892)^0\overline{K^0}$

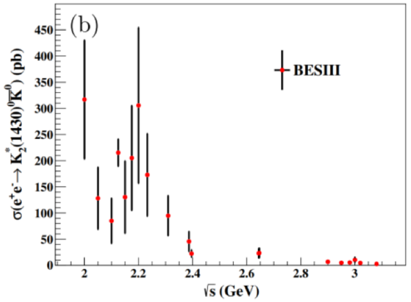




- Amplitude analysis of $e^+e^- \to K^+ K^-\pi^0$ from $\sqrt{s}$ = 2.000 to 3.080 GeV is performed
- Dominant component: $K_2^{*+}(1430)K^-$

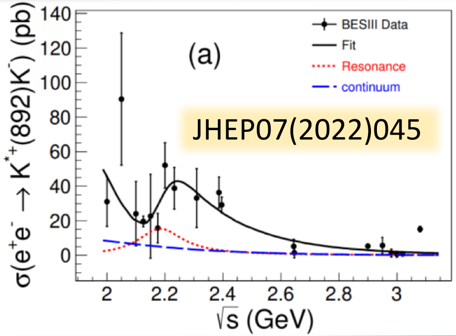
Measurement of the $e^+e^- \to K_S^0 K_L^0 \pi^0$ and $e^+e^- \to K^+ K^- \pi^0$ cross sections

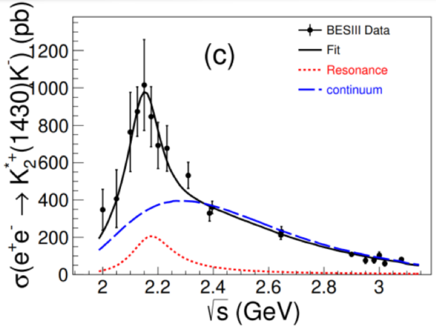




- Amplitude analysis of $e^+e^- \to K_S^0 K_L^0 \pi^0$ from $\sqrt{s}$ = 2.000 to 3.080 GeV is performed.
- Dominant component: $K^*(892)^0\bar{K}^0$, $K_2^*(1430)^0\bar{K}^0$
- Resonance in $K^*(892)^0\bar{K}^0$: **3.2σ**

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

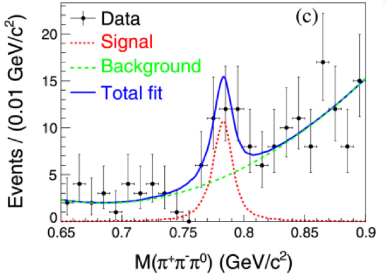
$$R = \frac{B(K^0\bar{K}^{0\prime})}{B(K^\pm\bar{K}^{\mp\prime})}: \quad \sim 30 \text{ for } K^*(892)K, \quad \sim 0.25 \text{ for } K_2^*(1430)K$$

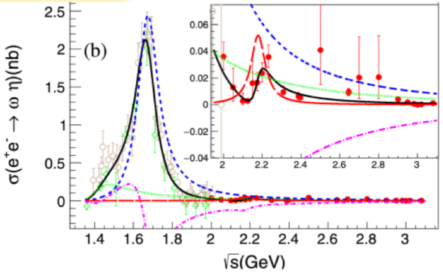
?

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

Measurement of the $e^+e^- \to \omega\eta$ and $e^+e^- \to \omega\eta'$ cross sections

Phys. Lett. B 813, 136059 (2021)



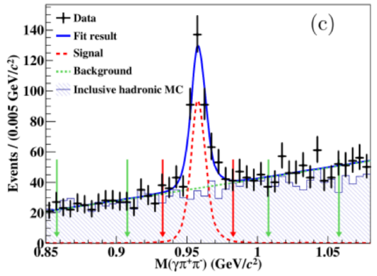


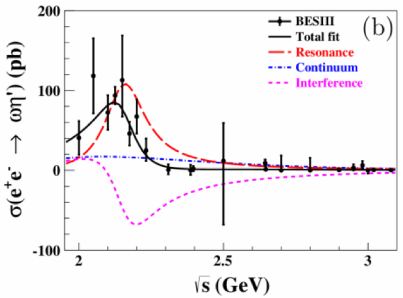
- Measurement of cross section of $e^+e^- \to \omega\eta$ from $\sqrt{s}$ = 2.000 to 3.080 GeV is performed
- Resonance : **6.2σ**

$M = 2176 \pm 24 \pm 3$ MeV/c^2

$\Gamma = 89 \pm 50 \pm 5$ MeV

JHEP07(2024)093





- Measurement of cross section of $e^+e^- \to \omega\eta'$ from $\sqrt{s}$ = 2.000 to 3.080 GeV is performed
- Resonance : **9.6σ**

$M = 2153 \pm 30 \pm 31$ MeV/c^2

$\Gamma = 167 \pm 77 \pm 7$ MeV

$$R = \frac{B_R^{\omega\eta'}}{B_R^{\omega\eta}}:$$

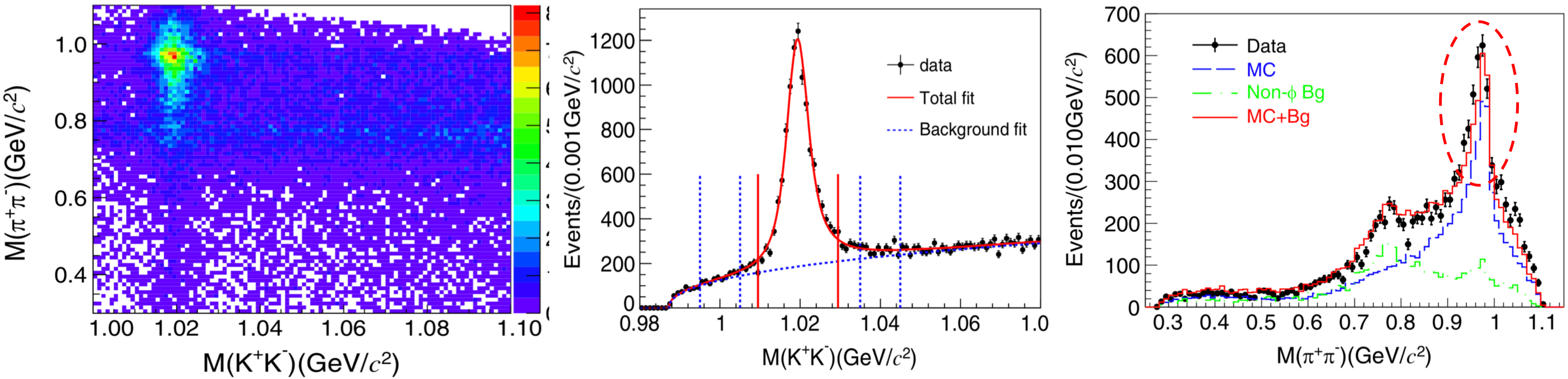
$13.30 \pm 6.06 \pm 3.61, 2.39 \pm 1.63 \pm 1.01$

$4.58 \pm 2.21 \pm 1.34, 6.95 \pm 4.60 \pm 2.83$

Discrepancy with the ratio predicted by lattice QCD， 0.32

Measurement of $e^+e^- \to \phi\pi^+\pi^-$ cross sections

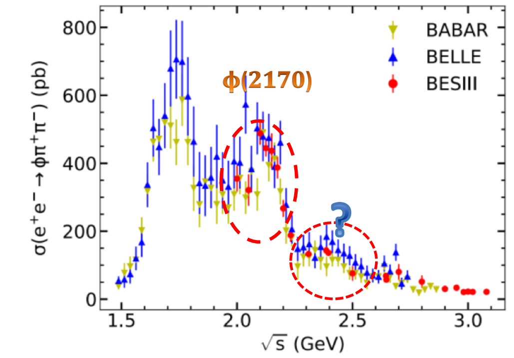
PRD 108, 032011 (2023)

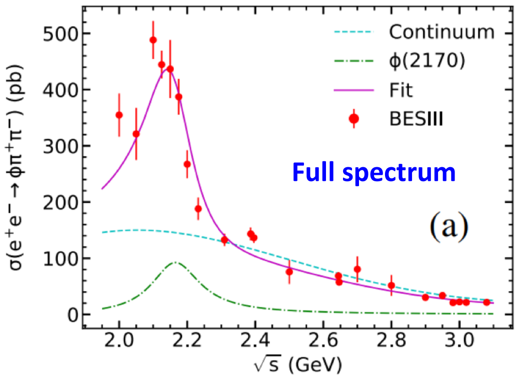


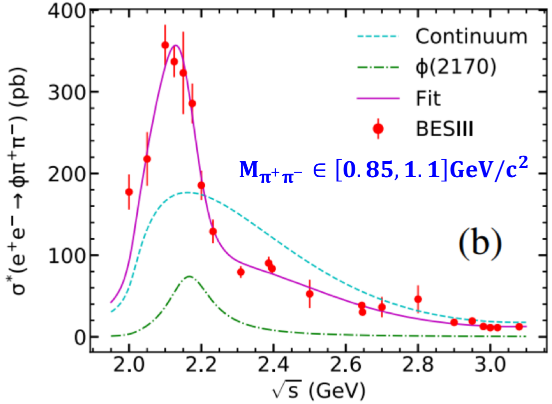
Dominant component: $\phi f_0(980)$

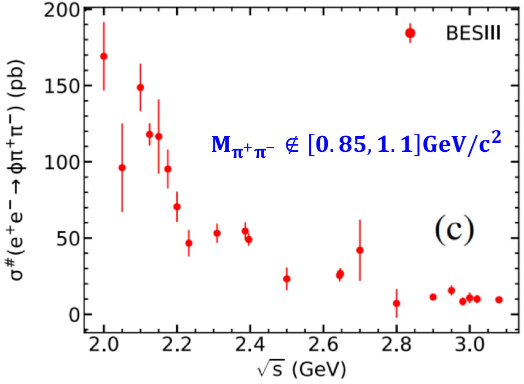
Measurement of $e^+e^- \to \phi\pi^+\pi^-$ cross sections

PRD 108, 032011 (2023)









- Resonances at 2.1 and 2.4 GeV
- Fits to the cross sections of $e^+e^- \to \phi\pi^+\pi^-$ within **full $M(\pi^+\pi^-)$** range (**σ**)and within **$M_{\pi^+\pi^-} \in [0.85, 1.1]$** (**$\sigma^*$**) GeV/c^2

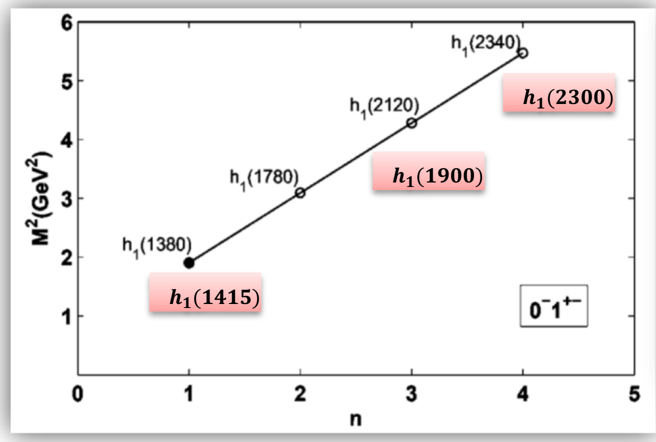
Parameter	σ	σ^*
$M_r(\phi(2170))$	2171 ± 12	2178 ± 20
$\Gamma_r(\phi(2170))$	115 ± 28	140 ± 36
ϕ_P^D	1.01 ± 0.14	1.13 ± 0.06
ϕ_P^C	-1.87 ± 0.16	-1.71 ± 0.12
χ^2/ndf	$28/15$	$23/15$

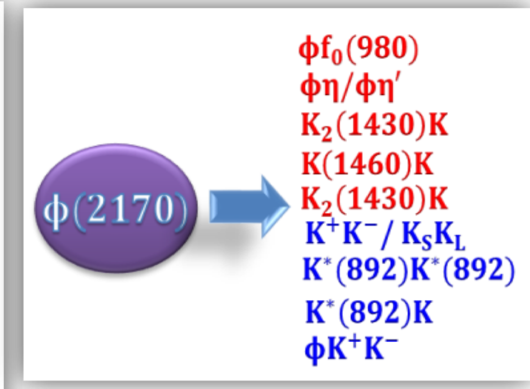
- **No significant $\phi(2170)$** observed in the cross section line shape of $e^+e^- \to \phi\pi^+\pi^-$ with **$M_{\pi^+\pi^-} \notin [0.85, 1.1]$**GeV/c^2

Summary

- BESIII has a rich and fruitful program of hadron physics
- New resonances $h_1(1900)$ and $h_1(2300)$ are observed for the first time.

- ✓ How to arrangement and understand those axel vector states?
- ✓ Where vector state $\phi(3S)$?
- ✓ $\phi(2170)$ nature is still controversial





Efforts from theoretical and experimental sides are desirable!

Thanks !