Highlights of BESIII Light Hadron Spectroscopy

(For BESIII Collaboration)

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Outline

- **Introduction**
- **Selected Results from LHS**
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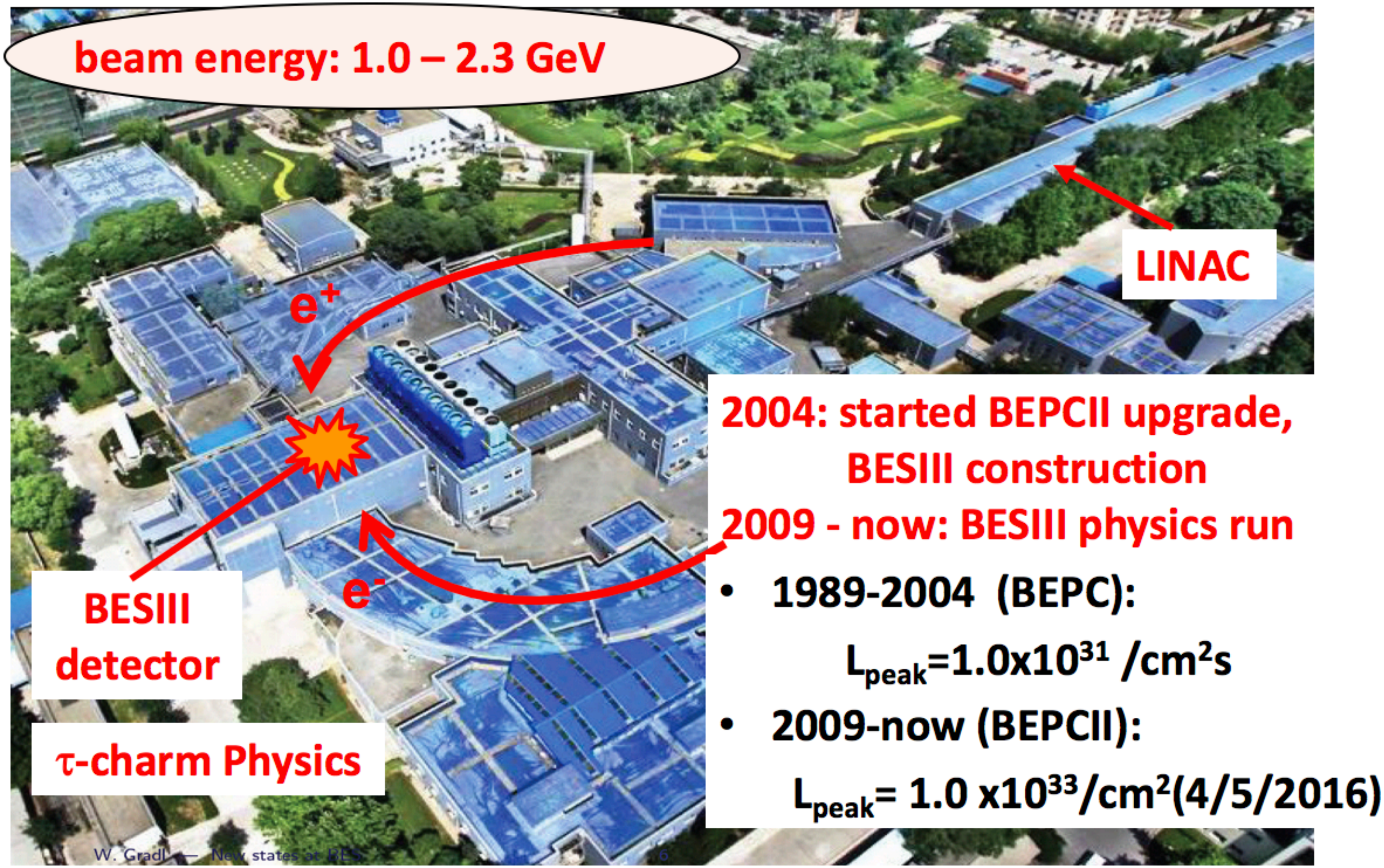
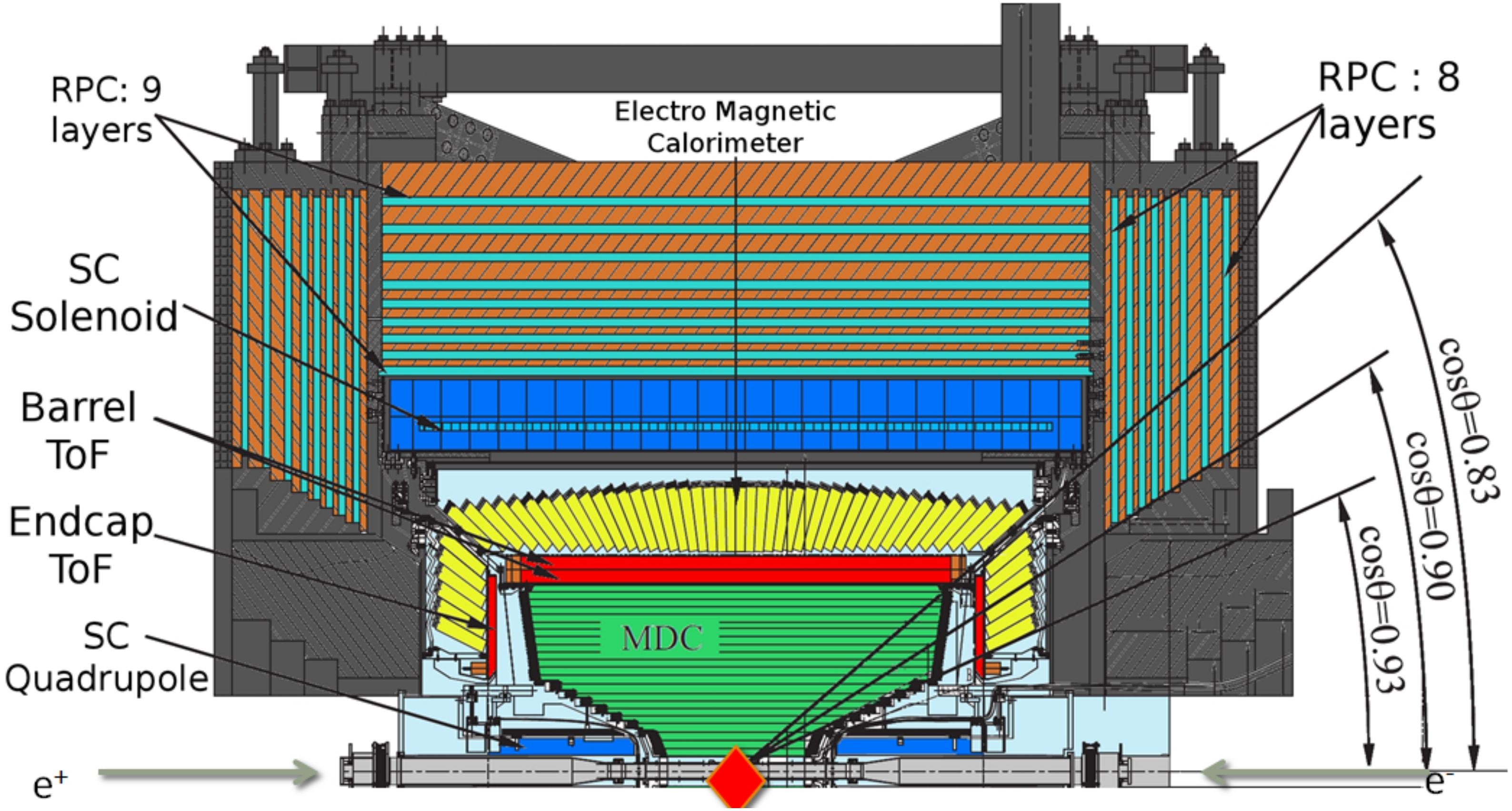
    - X($p\bar{p}$) and X(1835)
    - Mixing of $a_0(980)$-$f_0(980)$
    - Search for Glueball
    - Search for Hybrid
    - Strangeonium spectrum
  - **Light meson decays**
    - $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$
    - $\eta' \to \gamma\pi^+\pi^-$
    - Br($\eta' \to X$) Measurement
  - **Baryon spectroscopy**
    - *Search for N^*, Λ^*, Σ^** **and Ξ^***
- **Summary and Outlook**

Beijing Electron Positron Collider (BEPC)



BESIII detector



- **Main Drift Chamber**

σ_P/P = 0.5% @ 1 GeV

$\sigma_{dE/dx}$ = ~5%

- **Time of Flight**

σ_T = 70 ps (barrel)

110 ps (ETOF endcap)

60 ps (MRPC update)

- **Electromagnetic Calorimeter**

$\sigma_E/\sqrt{E}$ = 2.4% @ 1 GeV

- **Super Conducting Solenoid**

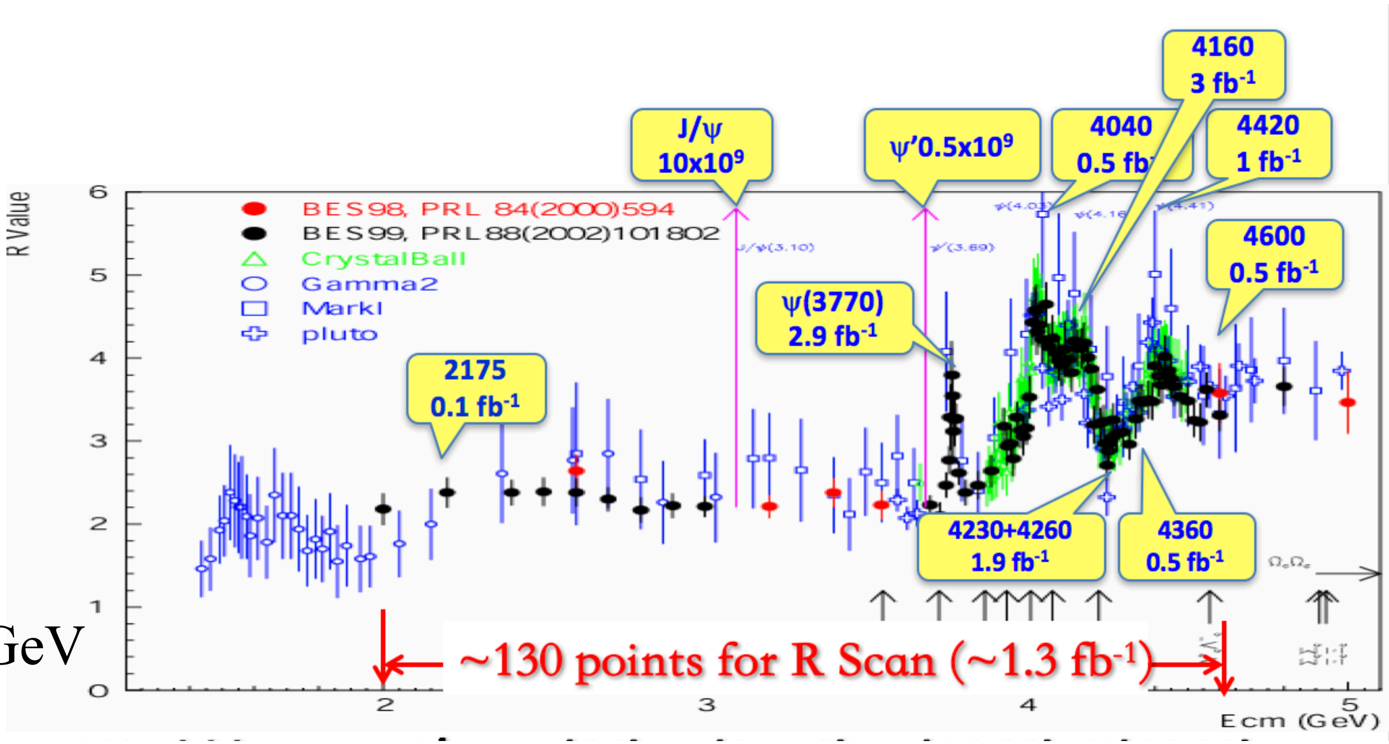
1.0 T (2009)

0.9 T (2012)

BESIII Data Sample

J/ψ and ψ(3686)

- ■ 2009
  - ~106M ψ(3686)
  - ~225M J/ψ
- ■ 2012
  - ~352M ψ(3686)
  - ~1.09B J/ψ
- ■ 2015
  - ~0.1 fb^{-1} at 2.125 GeV
- ■ 2018-2019
  - ~4.6B J/ψ
  - ~4.1B J/ψ



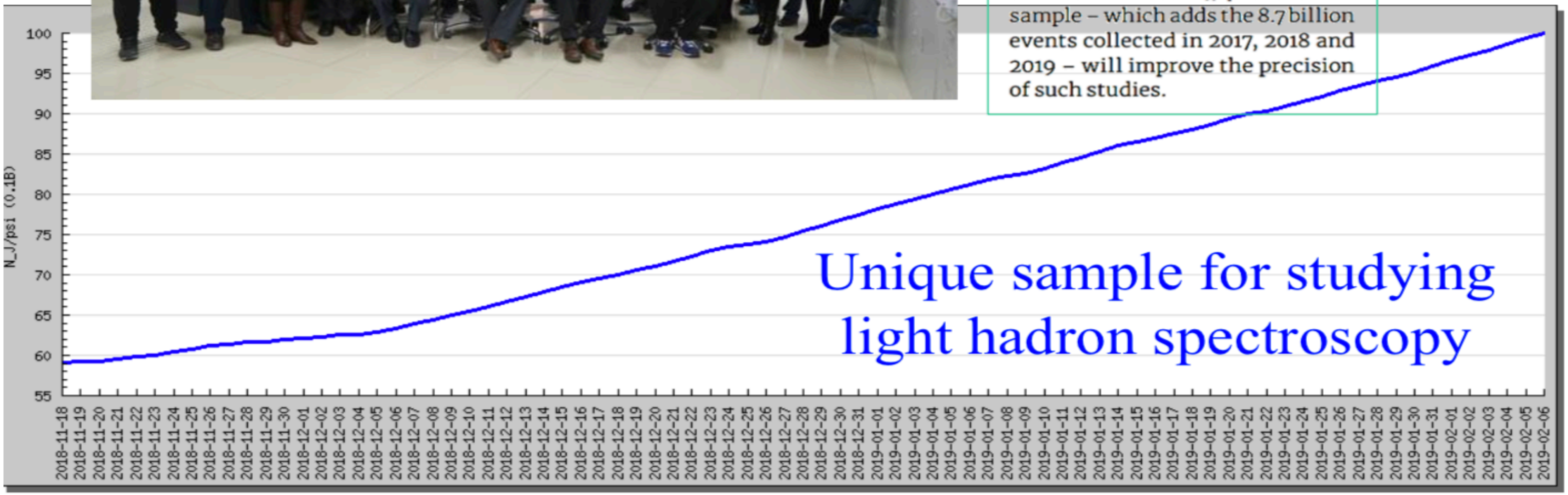
World largest J/ψ, ψ(3686), ψ(3770), …produced directly from e^+e^- collision

— ideal factory to study hadron spectroscopy

10 Billion J/ψ events by Feb. 2019

BESIII amasses record J/ψ dataset
On 11 February, the BESIII experiment at the Beijing Electron Positron Collider in China finished accumulating a sample of 10 billion J/ψ events – the world's largest dataset produced directly from electron–positron annihilations. Decays of the J/ψ particle offer a clean laboratory for studying exotic hadrons composed of light quarks and gluons, including those composed of pure gluons. With 1.3 billion J/ψ events collected in 2009 and 2012, BESIII has reported many such studies. The record J/ψ-event data sample – which adds the 8.7 billion events collected in 2017, 2018 and 2019 – will improve the precision of such studies.

CERN courier



实现了BESIII J/ψ 数据目标！

Selected Results from LHS

- **Meson spectroscopy**
  - X($p\bar{p}$) and X(1835)
  - Mixing of $a_0(980)$-$f_0(980)$
  - Search for Glueball
  - Search for Hybrid
  - Strangeonium spectrum
- **Light meson decays**
  - $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$
  - $\eta' \to \gamma\pi^+\pi^-$
  - Br($\eta' \to X$) measurements
- **Baryon spectroscopy**
  - *Search for N^*,Λ^* ,Σ^** **and Ξ^***

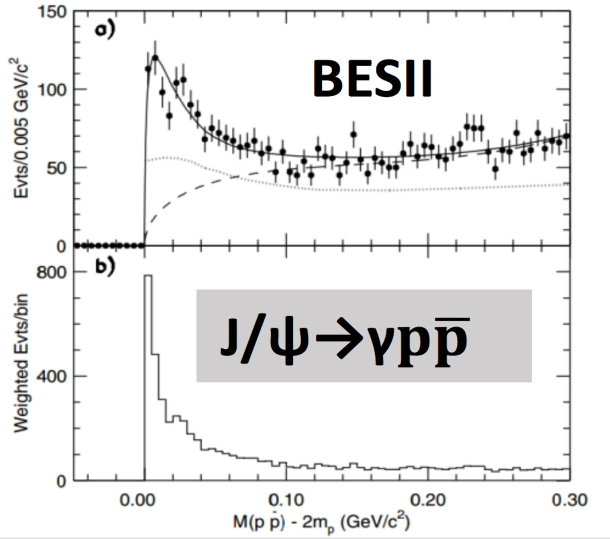
X($p\overline{p}$) and X(1835)

$p\bar{p}$ threshold enhancement X($p\bar{p}$)

- Observed at BESII in $J/\psi \to \gamma p\bar{p}$

$$M = 1859^{+3}_{-10}{}^{+5}_{-25}\ MeV/c^2,$$
$$\Gamma < 30\ MeV/c^2\ (90\%\ CL)$$

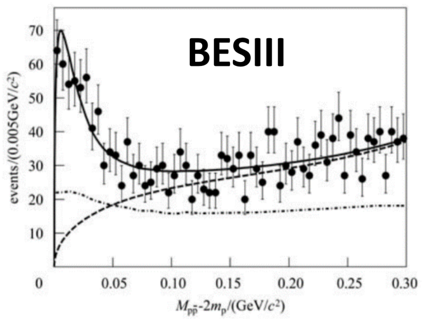
Phys. Rev. Lett. 91, 022001 (2003)



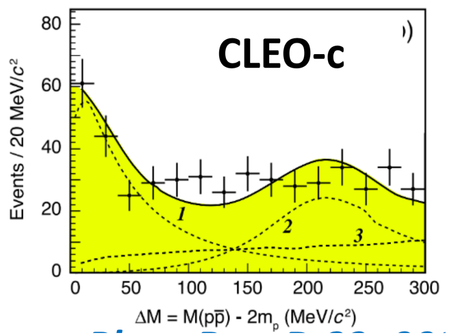
- Confirmed by CLEO-c and BESIII in $\psi(3686) \to \pi^+\pi^-\ J/\psi, J/\psi \to \gamma p\bar{p}$

$$M = 1861^{+6}_{-13}{}^{+7}_{-26}\ MeV/c^2,$$
$$\Gamma < 38\ MeV/c^2\ (90\%\ CL)$$

- Agree with BESII



Chin. Phys. C 34, 421 (2010)



Phys. Rev. D 82, 092002 (2010)

- Many possibilities:

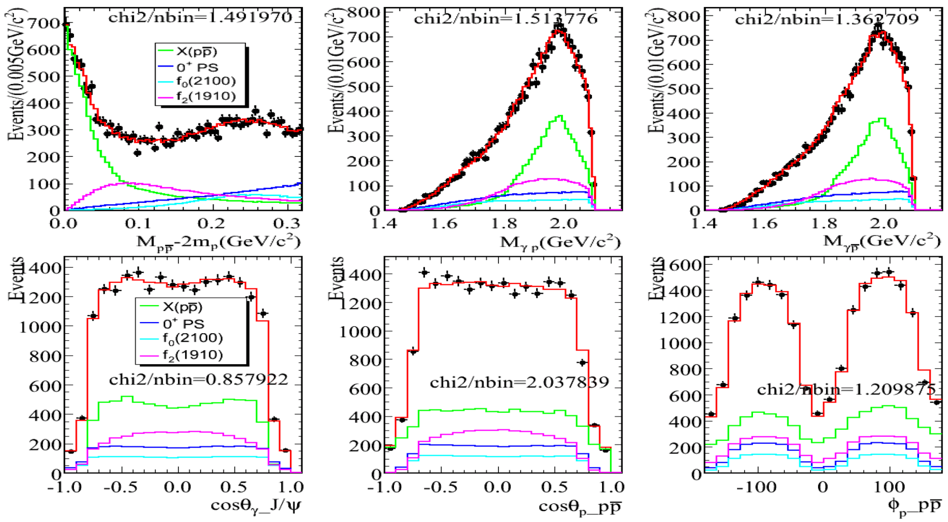
ordinary meson/$p\bar{p}$ bound state/ multiquark/glueball/final state interaction (FSI)

PWA of $J/\psi \to \gamma p\bar{p}$

Phys. Rev. Lett. 108, 112003 (2012)

- Confirmed in $J/\psi \to \gamma p\bar{p}$
- J^{pc} determined by PWA
  - $J^{pc} = 0^{-+}$
  - $M = 1832^{+19}_{-5}\ {}^{+18}_{-17} \pm 19\ MeV/c^2$
  - $\Gamma = 13 \pm 39^{+10}_{-13} \pm 4\ MeV/c^2$
  - $B(J/\psi \to \gamma X)\cdot B(X \to p\bar{p}) = 9.0^{+0.4}_{-1.1}\ {}^{+1.5}_{-5.0} \pm 2.3 \times 10^{-5}$.

$f_0(2100)$ and $f_2(1910)$ fixed to PDG.
Significance of X(pp) >>30σ



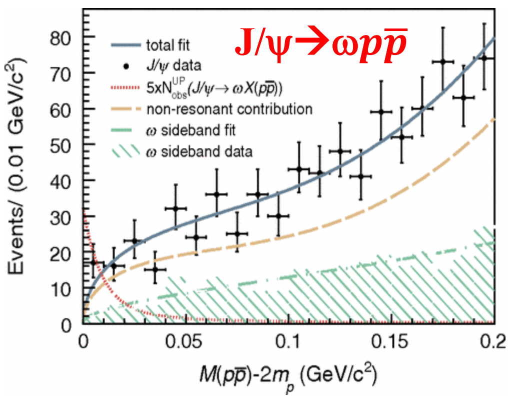
- A signal model of BW and S-wave FSI factor can well describe $p\bar{p}$ mass threshold structure
- The fit quality is much better than that without FSI effect.

Searching for X($p\bar{p}$) in other hadronic decays

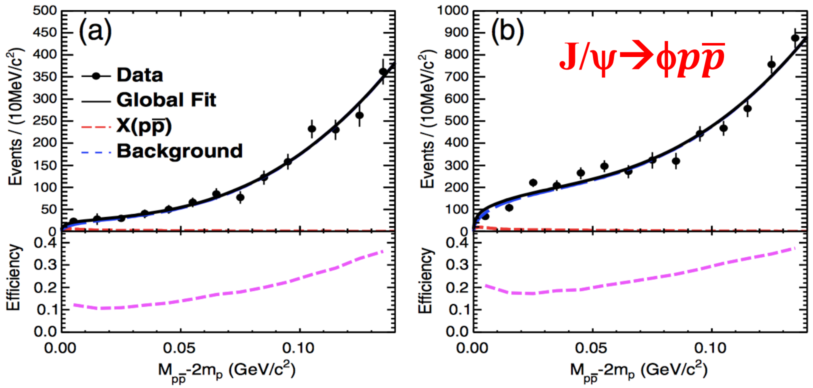
■ No significant narrow threshold enhancement observed ：

- **J/ψ→ω$p\bar{p}$**: $B(J/\psi \to \omega X(p\bar{p}) \to \omega p\bar{p}) < 3.7 \times 10^{-6}$ (95% CL), > 10x suppressed
- **J/ψ→ϕ$p\bar{p}$**: $B(J/\psi \to \phi X(p\bar{p}) \to \phi p\bar{p}) < 2.0 \times 10^{-7}$ (90% CL), > 100x suppressed
- **Ψ(3686)→ϕ$p\bar{p}$** : $B(\psi(3686) \to \phi X(p\bar{p}) \to \phi p\bar{p}) < 1.82 \times 10^{-7}$ (90% CL)

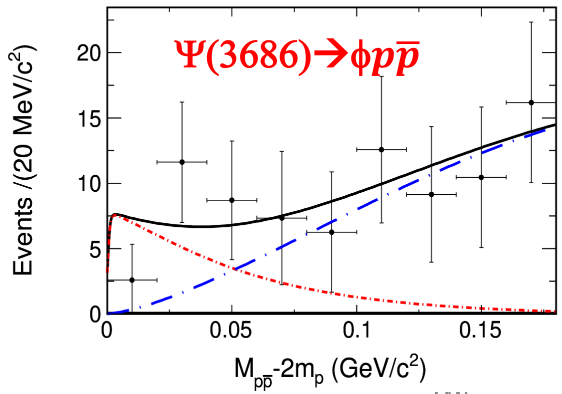
■ Seems not from pure FSI effect



Phys. Rev. D 87, 112014 (2013)



Phys. Rev. D 93, 052010 (2016)

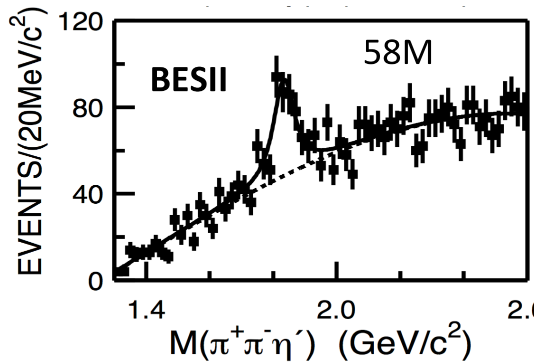


arXiv:1902.09756,accepted by PRD

X(1835) in $J/\psi \rightarrow \gamma\pi^+\pi^-\eta'$ ($\eta' \rightarrow \gamma\rho/\eta\pi\pi$)

Phys. Rev. Lett. 95, 262001 (2005)

- Observed at BESII

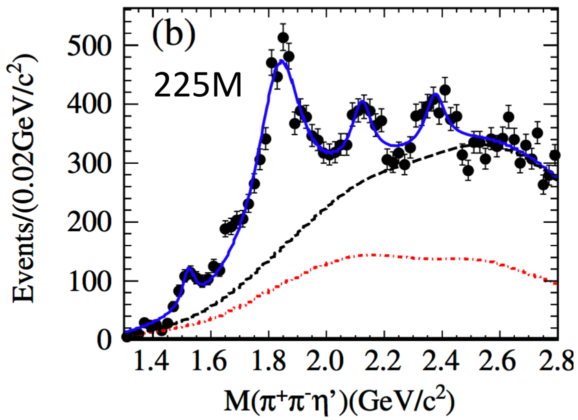


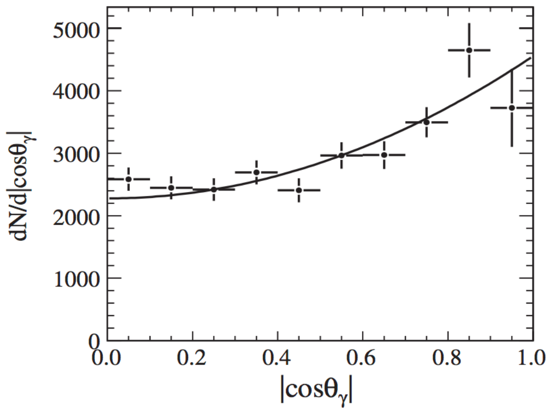
- Confirmed by BESIII in $J/\psi \rightarrow \gamma\eta'\pi^+\pi^-$ with two η' decays
  - $M = 1836.5^{+19}_{-5} \pm 3.0^{+5.6}_{-2.1}\ MeV/c^2$
  - $\Gamma = 190 \pm 9^{+38}_{-36}\ MeV/c^2$
  - Angular distribution is consistent with 0^-
  - η' excited state? Glueball state? same as pp enhancement?

Phys. Rev. Lett. 106, 072002 (2011)

- Observed two additional structures > 2 GeV/c^2

Resonance	M(MeV/c^2)	Γ(MeV/c^2)	N_{event}	
$f_1(1510)$	1522.7 ± 5.0	48 ± 11	230 ± 37	> 5.7σ
$X(1835)$	1836.5 ± 3.0	190.1 ± 9.0	4265 ± 131	> 20σ
$X(2120)$	2122.4 ± 6.7	83 ± 16	647 ± 103	>7.2σ
$X(2370)$	2376.3 ± 8.7	83 ± 17	565 ± 105	>6.4σ





Observation and spin-parity determination of X(1835) in $J/\psi \to \gamma K_S^0 K_S^0 \eta$

- Clear structure on mass spectrum of $K_S^0 K_S^0 \eta$ around 1.85 GeV/c^2
- Strongly correlated to $f_0(980)$
  - PWA in M $(K_s K_s) < 1.1$ GeV

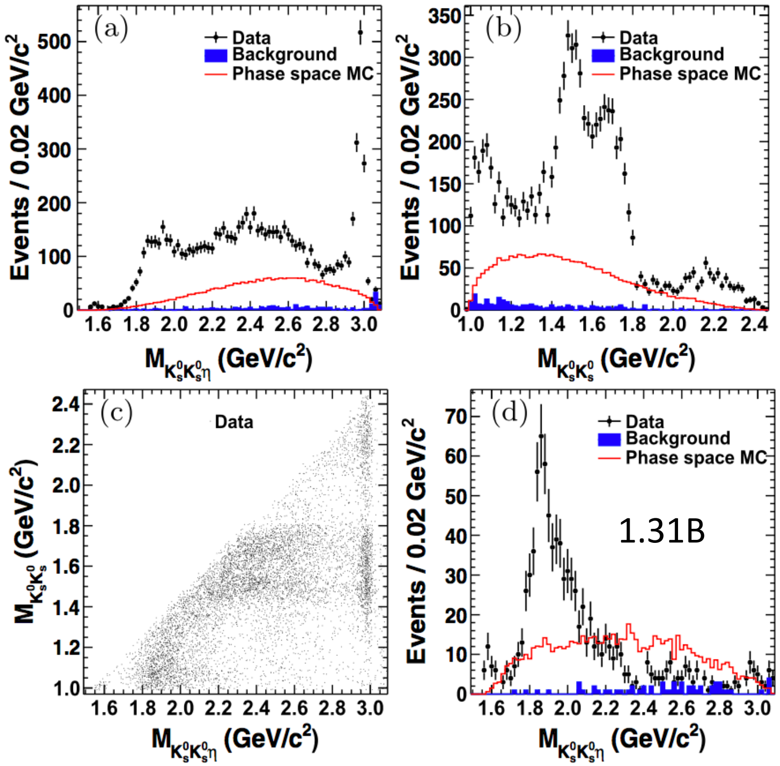
Phys. Rev. Lett. 115, 091803 (2015)

X(1835)

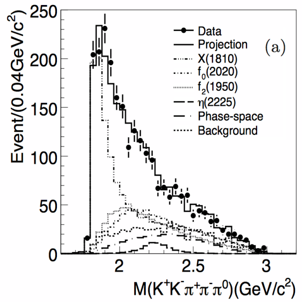
- J^{pc} determined to be 0^{-+}
- $X(1835) \to \eta K_S^0 K_S^0$ (> 12.9 σ), dominated by $f_0(980)$ production
- $M = 1844 \pm 9^{+16}_{-25}\ MeV/c^2$
- $\Gamma = 192^{+20+62}_{-17-43}\ MeV/c^2$
- $B(J/\psi \to \gamma X(1835)) \cdot B(X(1835) \to \eta K_S^0 K_S^0) = (3.31^{+0.33+1.96}_{-0.30-1.29}) \times 10^{-5}$
- Consistent with X(1835) parameters obtained from $J/\psi \to \gamma \eta' \pi^+ \pi^-$

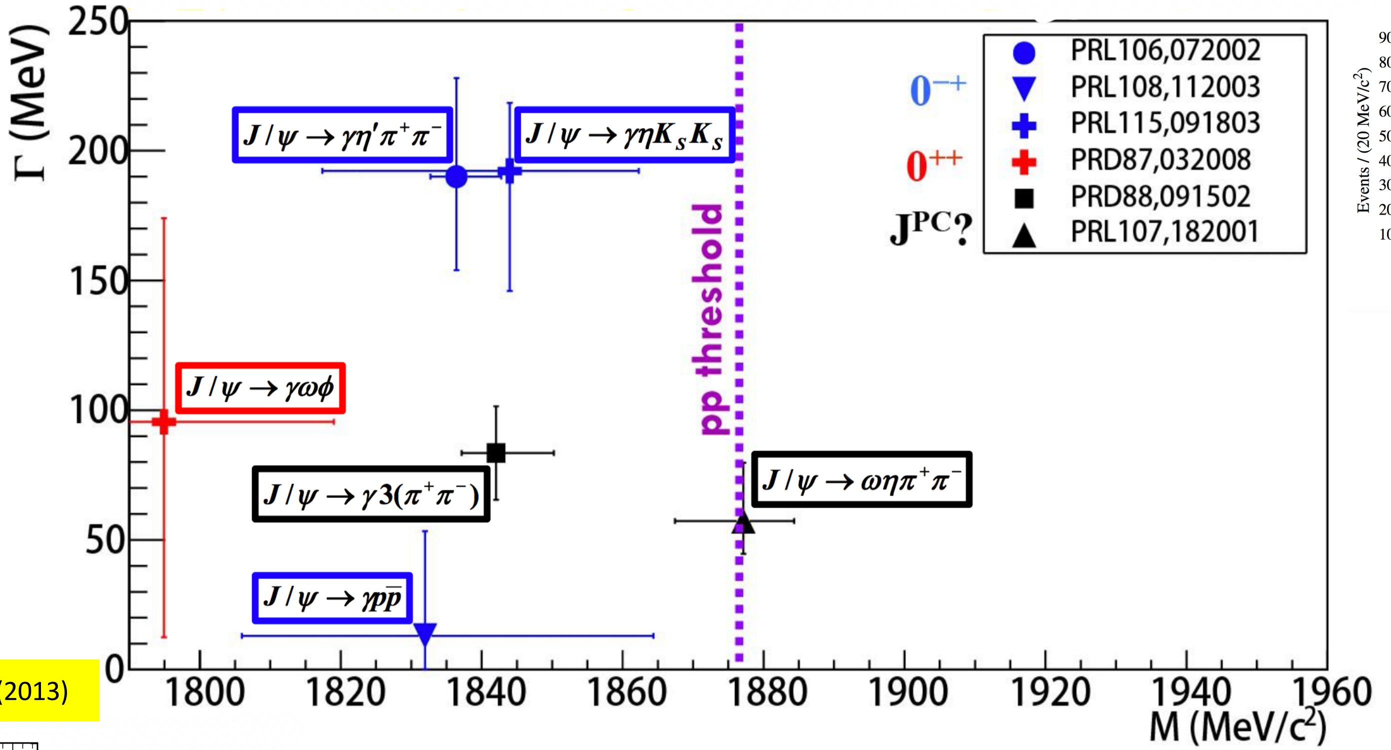
X(1560)

- $J^{pc} = 0^{-+}$; $X(1560) \to \eta K_S^0 K_S^0$ (> 8.9 σ)
- $M = 1565 \pm 8^{+0}_{-63}\ MeV/c^2$
- $\Gamma = 45^{+14+21}_{-13-28}\ MeV/c^2$
- Consistent with $\eta(1405)/\eta(1475)$ within 2.0 σ

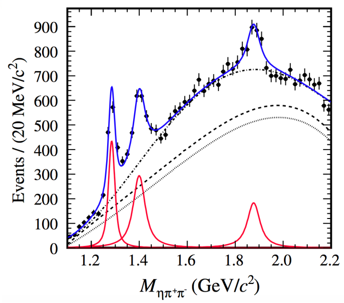


Phys. Rev. D 87, 032008 (2012)

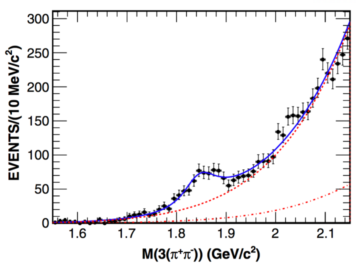




Phys. Rev. Lett. 107, 182001 (2011)



Phys. Rev. D 88, 091502 (2013)

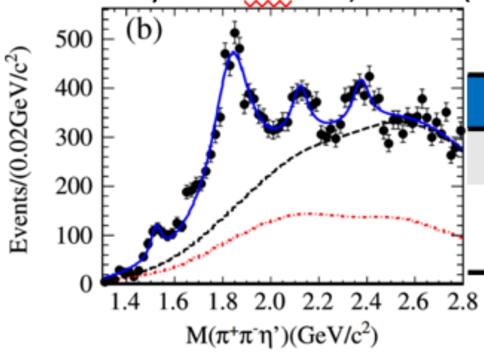


- **Any relations?**
- **What is the role of the $p\bar{p}$ threshold (and other thresholds)?**
- **Patterns in the production and decay modes**

Anomalous line shape of $\eta'\pi^+\pi^-$ near the $\mathrm{p}\bar{p}$ mass threshold: connection between X(1835) and X($p\bar{p}$)

X(1835) observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$

Phys. Rev. Lett. 106, 072002 (2011)



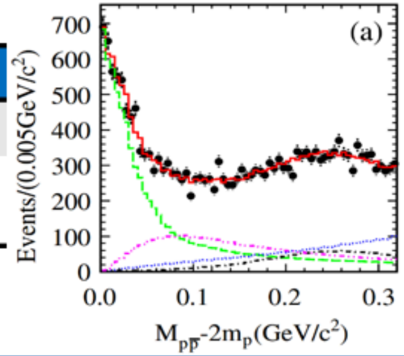
X(1835) $J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2

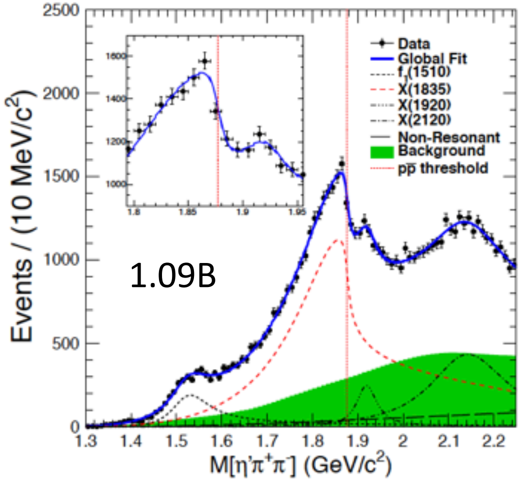
X($\mathrm{p}\bar{\mathrm{p}}$) observed in $J/\psi \to \gamma \mathrm{p}\bar{\mathrm{p}}$

PRL 108, 112003 (2012)

PRL 115, 091803 (2015)

X($\mathrm{p}\bar{\mathrm{p}}$) $J^{PC}=0^{-+}$
$M = 1832^{+19}_{-5}{}^{+18}_{-17} \pm 19$ MeV/c^2
$\Gamma = 13 \pm 19$ MeV/c^2 (< 76 MeV/c^2 @ 90% C.L.)



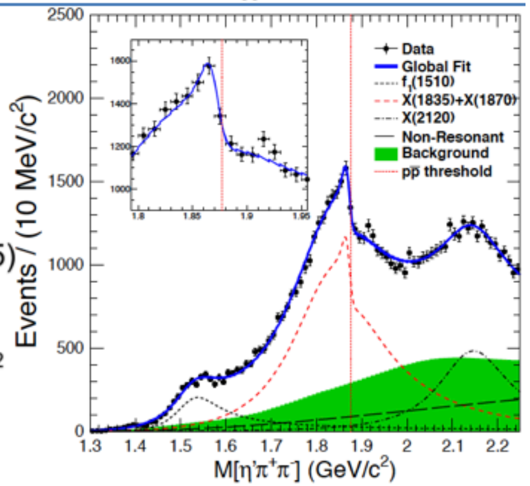


Connection is emerging

PRL 117, 042002 (2016)

Model 1:
Flatte lineshape with strong coupling to pp̄ and one additional, narrow Breit-Wigner at ~1920 MeV/c²

Model 2:
Coherent sum of X(1835) Breit-Wigner and one additional, narrow Breit-Wigner at ~1870 MeV/c²



- **Suggest the existence of a state, either a broad one with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass thresh.**
- **Support the existence of a $p\bar{p}$ molecule-like state or bound state**

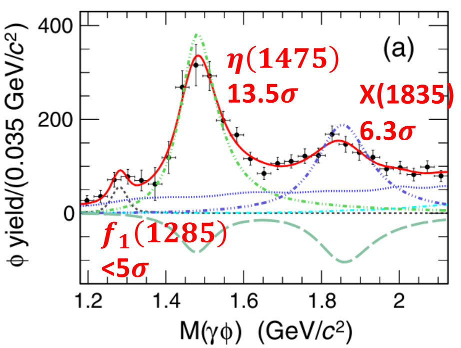
Search for X(1835)'s other decay modes

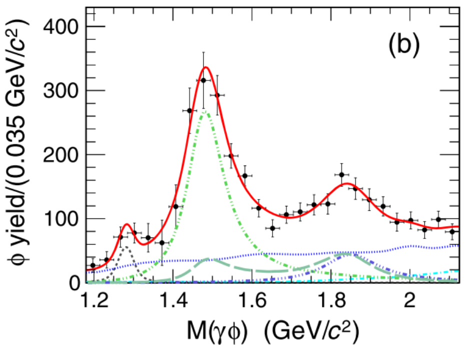
$J/\psi \to \gamma\gamma\phi$

Phys. Rev. D **97**, 051101(R) (2018)

■ Observation of $\eta(1475), \mathrm{X}(1835) \to \gamma\phi$

■ Angular distributions favor 0^{-+}



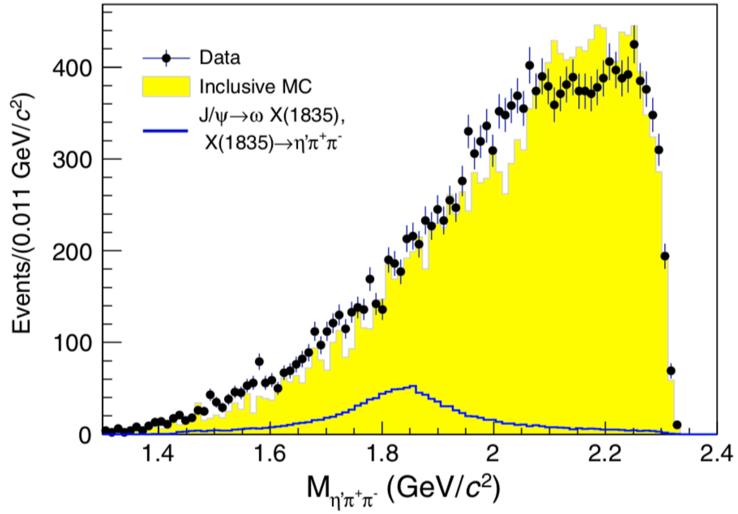


$J/\psi \to \omega\pi^+\pi^-\eta'$

Phys. Rev. D **99**, 071101(R) (2019)

■ No obvious signal of X(1835) is found

■ B.R. ($J/\psi \to \omega X(1835) \to \omega\pi^+\pi^-\eta$) $< 6.2 \times 10^{-5}$ @ 90% C.L.

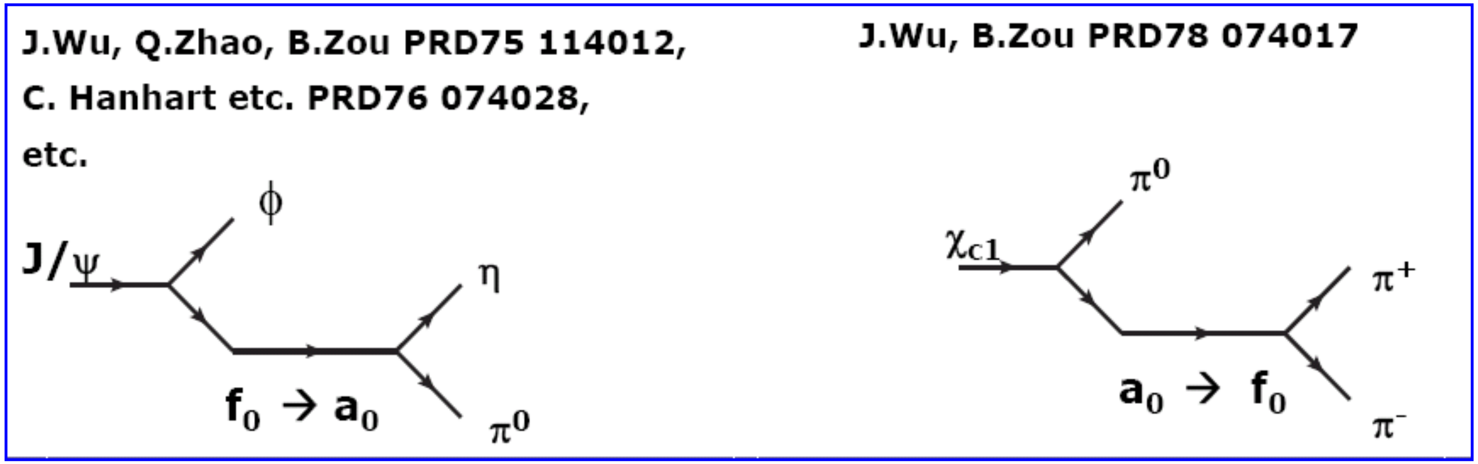


■ X(1835) contains a sizable $s\bar{s}$ component

Mixing of $a_0(980)$-$f_0(980)$

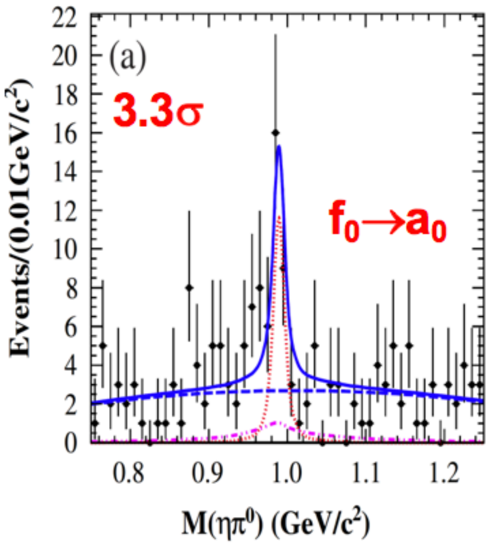
$a_0(980)$ and $f_0(980)$

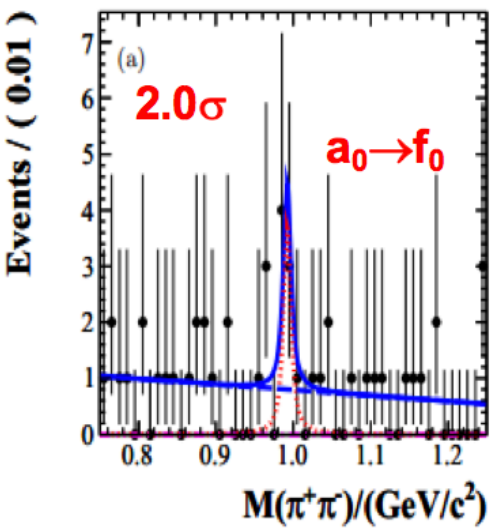
- $a_0(980)$ and $f_0(980)$ are theoretically explained as ordinary mesons, tetraquarks, molecules or hybrids.
- Mixing intensity provides important information in understanding the nature of $a_0(980)$ and $f_0(980)$.
- Narrow peak (8 MeV) at around 980 MeV can be expected:
  - in $\eta\pi$ invariant mass spectra of $J/\psi \to \phi f_0 \to \phi a_0 \to \phi\eta\pi$
  - or in $\pi^+\pi^-$ invariant mass spectra of $\chi_{c1} \to a_0\pi^0 \to f_0\pi^0 \to \pi^+\pi^-\pi^0$

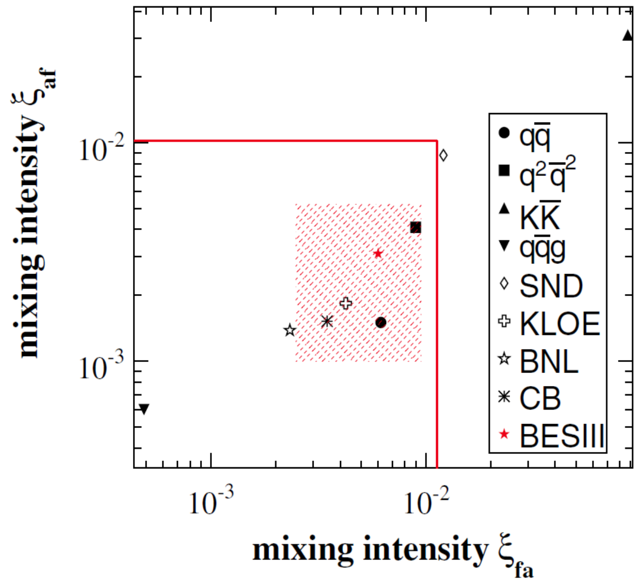


Evidence of $a_0(980) - f_0(980)$ mixing

PRD 83, 032003 (2011)







$$\xi_{fa} = \frac{Br(J/\psi \to \phi f_0(980) \to \phi a_0^0(980) \to \phi\eta\pi^0)}{Br(J/\psi \to \phi f_0(980) \to \phi\pi\pi)\ [20]}$$
$$= (0.60 \pm 0.20(stat.) \pm 0.12(sys.) \pm 0.28(para.)\%,$$

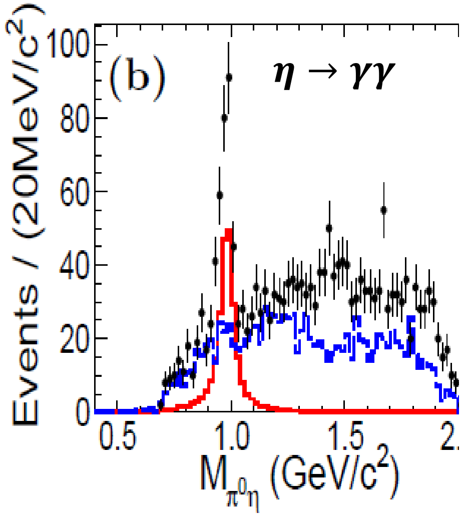
$$\xi_{af} = \frac{Br(\psi' \to \gamma\chi_{c1} \to \gamma\pi^0 a_0^0(980) \to \gamma\pi^0 f_0(980) \to \gamma\pi^0\pi^+\pi^-)}{Br(\psi' \to \gamma\chi_{c1} \to \gamma\pi^0 a_0^0(980) \to \gamma\pi^0\pi^0\eta)\ [17]}$$
$$= (0.31 \pm 0.16(stat.) \pm 0.14(sys.) \pm 0.03(para.))\%.$$

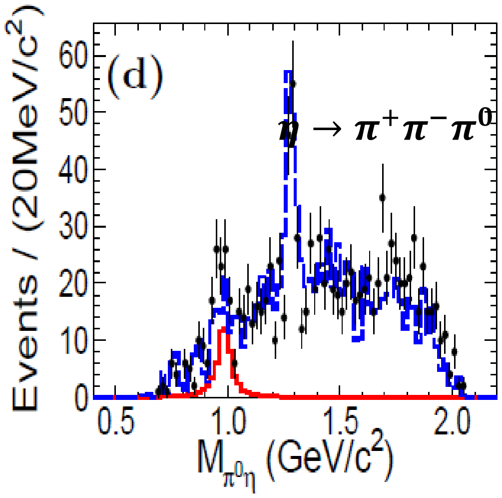
Observation of $a_0(980)$ -$f_0(980)$ mixing at BESIII

Phys. Rev. Lett. 121, 022001(2018)

- Using 1.3×10^9 J/ψ, $f_0 \to a_0$ is observed in the isospin violating decay:

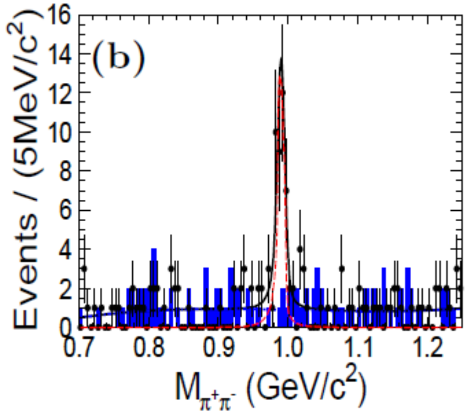
$J/\psi \to \phi a_0^0(980) \to \phi\eta\pi^0$ (7.4 σ)





- Using 4.48×10^8 ψ', $a_0 \to f_0$ is observed in the isospin violating decay:

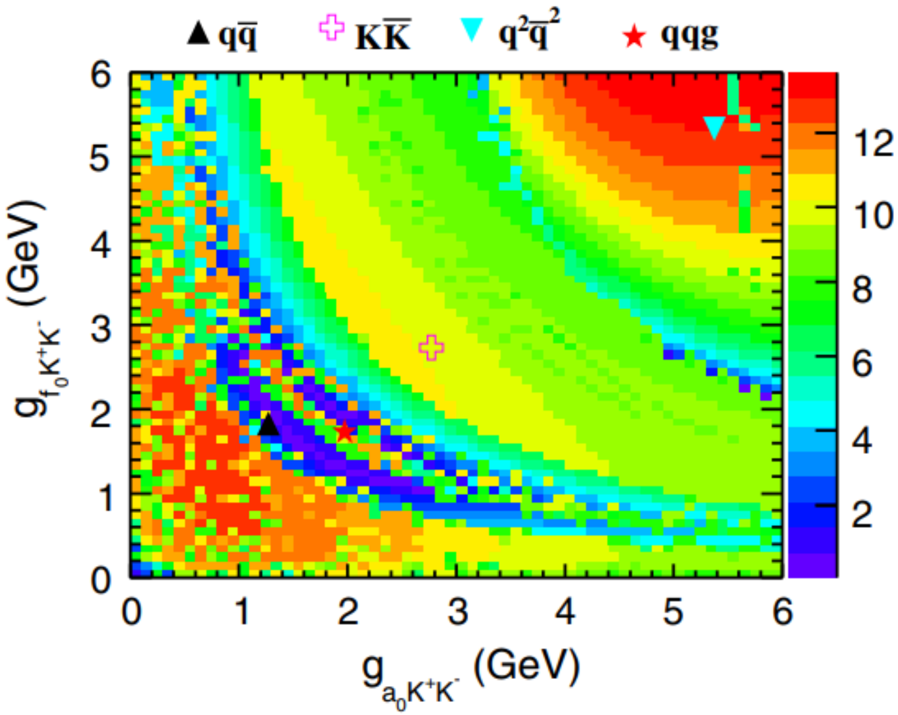
$\chi_{c1} \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0$ (5.5 σ)



Observation of $a_0(980)$-$f_0(980)$ mixing

Phys. Rev. Lett. 121, 022001(2018)

- The statistical significance of the mixing signal scanned in the 2D space of $g_{f_0 \to K^+K^-}$ and $g_{a_0 \to K^+K^-}$
- The region with higher significance indicate the larger probability
- The markers indicate predictions from various theoretical models (without uncertainties of model)

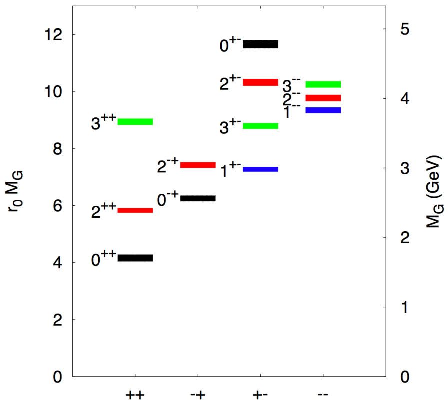


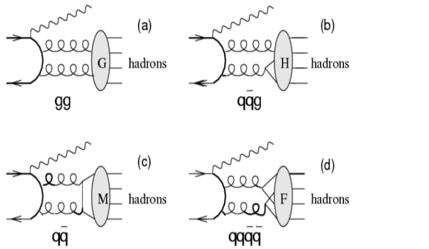
Search for Glueball

Search for Glueball

- Formed by gluon-gluon interaction
  - Allowed by QCD
  - Lattice QCD prediction
    - 0^{++}ground state: 1.5~1.7GeV/c²
    - 2^{++}ground state: 2.3~2.4 GeV/c²
    - 0^{-+}ground state: 2.3~2.6 GeV/c²

Phys. Rev. D 73, 014516 (2006)





$\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2), \Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3),$

$\Gamma(J/\psi \to \gamma M) \sim O(\alpha\alpha_s^4), \Gamma(J/\psi \to \gamma F) \sim O(\alpha\alpha_s^4)$

- Challenges
  - Ground glueballs have ordinary quantum number
  - Mixing with qqbar mesons
  - No clear criterion
- Systematic exp. studies are required:
  - Over-population
    - Mapout the resonances
  - Production patterns
    - $\mathbf{J/\psi \to \gamma\ /\omega/\phi + X}$
    - Other experiments
  - Decay patterns
    - "flavor blind", "chiral suppression", …

- J/ψ radiative decays: gluon rich
- An ideal place to search for glueballs

Glueball program @BESIII in a nutshell

	0^+	2^+	0^-
$J/\psi \to \gamma PP$			
$J/\psi \to \gamma VV$			
$J/\psi \to \gamma PPP$			

- 0^+, 2^+ : Coupled channel analyses
  - $J/\psi \to \gamma PP$
  - $J/\psi \to \omega/\phi + X$
- 0^- : trajectory, X(2370)
  - $J/\psi \to \gamma PPP$
  - $J/\psi \to \gamma\gamma V$

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

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

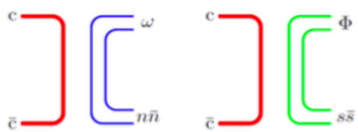
$J/\psi \to \gamma\, \eta'\pi\pi$ $/\eta' KK/\eta\pi\pi/KK\pi/\eta KK/\pi\pi\pi$

- PWA published
- Published, PWA undone
- Ongoing

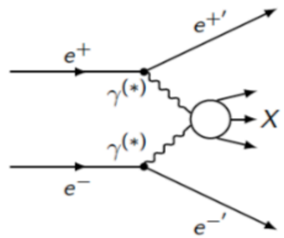
Flavor Filters:

$J/\psi \to \gamma X \to \gamma\gamma V$

$J/\psi \to \omega/\phi + X$

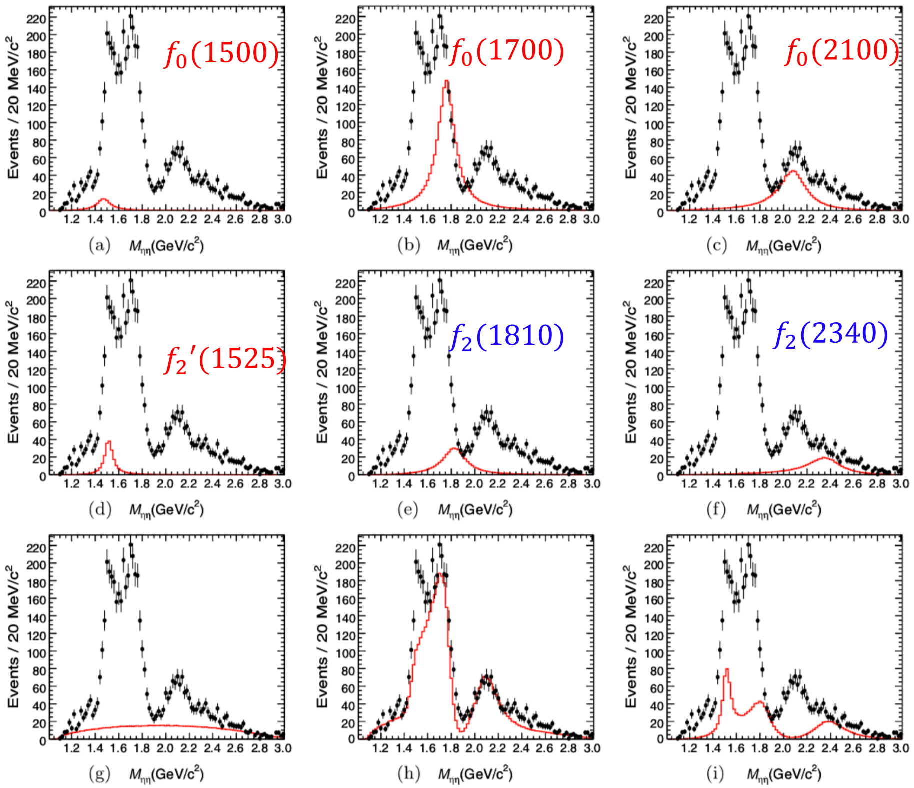


Anti filter:



PWA of $J/\psi \rightarrow \gamma\eta\eta$

Phys. Rev. D 87, 092009 (2013)

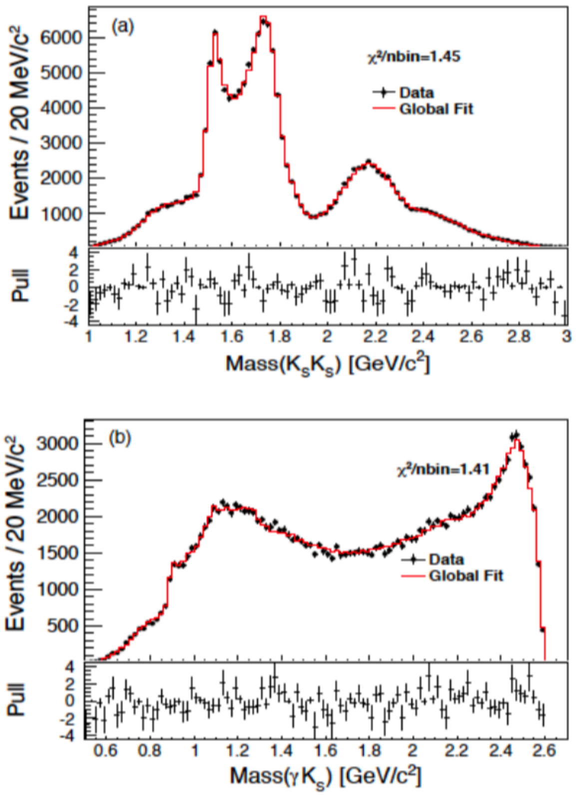


- Use 225×10^6 J/ψ events
- Br. of $f_0(1700)$ and $f_0(2100)$ are $\sim$ 10 X larger than than of $f_0(1500)$
- Possible large overlap with LQCD predictions of 0^+Glueball (PRL 110 021601)
- Strong production of $f_2(2340)$

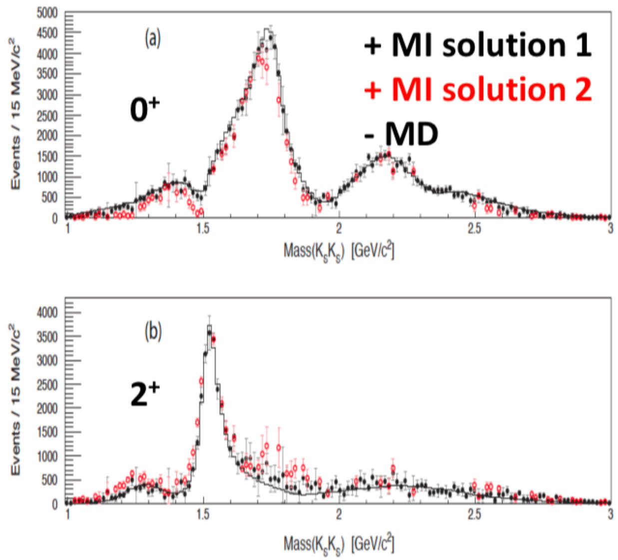
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(J/\psi \rightarrow \gamma X \rightarrow \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	8.2σ
$f_0(1710)$	$1759 \pm 6^{+14}_{-25}$	$172 \pm 10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0σ
$f_0(2100)$	$2081 \pm 13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9σ
$f_2'(1525)$	$1513 \pm 5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	6.4σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6σ

Amplitude analysis of J/ψ → γKsKs

PRD 98, 072003 (2018)



- MD analysis is well consistent with mass-independent(MI) analysis.

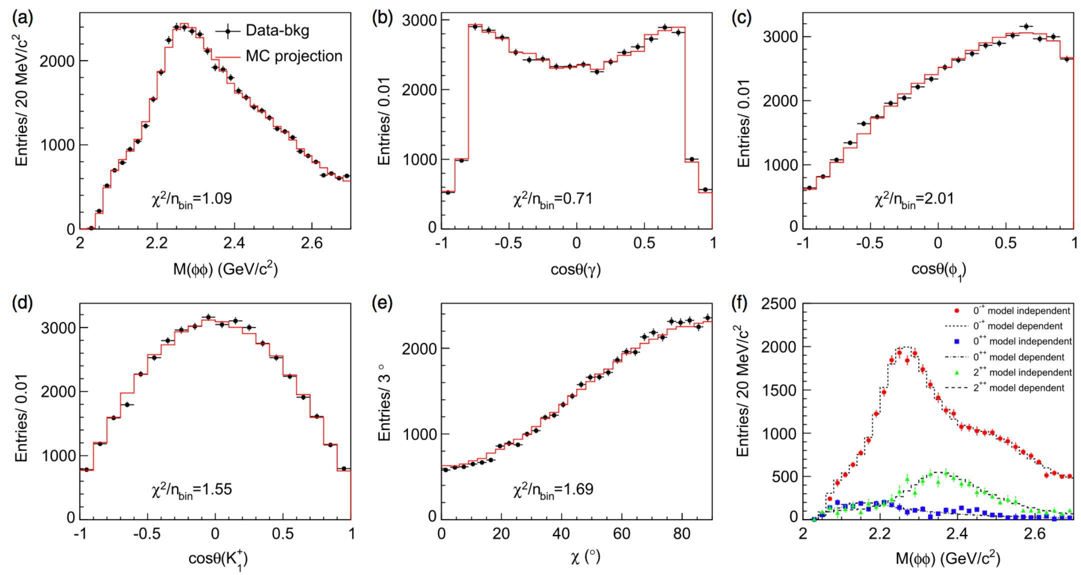


- Dominate scalars: $f_0(1710)$, $f_0(2200)$
- Dominate tensors: $f'_2(1525)$, $f_2(2340)$

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

Phys. Rev. D 93, 112011 (2016)

- Besides $\eta(2225)$, little known on the pseduoscalar above 2 GeV
- New ressults help to map out the psedoscalar excitations and search for 0^{-+} glueball



- Dominant contribution from pseudoscalars
  - $\eta(2225)$ is confirmed
  - $\eta(2100)$ and X(2500) are significant
- Three tensor states
  - $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ are observed
  - Strong production of $f_2(2340)$
- Well consistent with the results from

  Model Independent PWA

Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. ($\times 10^{-4}$)	Sig.
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28σ
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	22σ
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2101	224	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24σ
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$	9.5σ
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$	6.4σ
$f_2(2340)$	2339	319	$(1.91 \pm 0.14^{+0.72}_{-0.73})$	11σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ

Scalar glueball candidate (0^{++})

$\boxed{J/\psi \to \gamma X \to \gamma\pi\pi}$ BES, PLB(2006)441

$Br(J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi) = (4.01 \pm 1.0) \times 10^{-4}$

$Br(J/\psi \to \gamma f_0(1500) \to \gamma\pi\pi) = (1.01 \pm 0.34) \times 10^{-5}$

$Br(J/\psi \to \gamma f_0(1370) \to \gamma\pi\pi) = ----$

$\boxed{J/\psi \to \gamma X \to \gamma\eta\eta}$ BESIII, PRD87(2013)092009

$Br(J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta) = \left(2.35^{+1.27}_{-0.77}\right) \times 10^{-4}$

$Br(J/\psi \to \gamma f_0(1500) \to \gamma\eta\eta) = \left(1.65^{+0.57}_{-1.50}\right) \times 10^{-5}$

$Br(J/\psi \to \gamma f_0(1370) \to \gamma\eta\eta) = ----$

$\boxed{J/\psi \to \gamma X \to \gamma K_s K_s}$ BESIII, PRD 98, 072003 (2018)

$Br(J/\psi \to \gamma f_0(1710) \to \gamma K_s K_s) = \left(2.00^{+0.03+0.31}_{-0.02-0.10}\right) \times 10^{-4}$

$Br(J/\psi \to \gamma f_0(1500) \to \gamma K_s K_s) = \left(1.59^{+0.16+0.18}_{-0.16-0.59}\right) \times 10^{-5}$

$Br(J/\psi \to \gamma f_0(1370) \to \gamma K_s K_s) = \left(1.07^{+0.08+0.36}_{-0.07-0.34}\right) \times 10^{-5}$

Scalar glueball candidate (0^{++})

Lattice QCD:

$$\Gamma(J/\psi \to \gamma G_{0^+}) = \frac{4}{27}\alpha\frac{|p|}{M_{J/\psi}^2}|E_1(0)|^2 = 0.35(8)keV$$

$$\Gamma/\Gamma\_tot = 0.33(7)/93.2 = 3.8(9)\times 10^{-3}$$

L.Gui, et al. (CLQCD Collaboration), PRL 110, 021601 (2013))

Experimental results from J/ψ radiative decays to scalars

$$J/\psi \to \gamma f_0(1500 \to \gamma\pi\pi) \quad = \quad (1.01 \pm 0.32)\times 10^{-4}$$

$$Br(f_0(1500) \to \pi\pi) = (34.9 \pm 2.3)\% \quad \Rightarrow Br(J/\psi \to \gamma f_0(1500)) = 2.9 \times 10^{-4}$$

$$J/\psi \to \gamma f_0(1710) \to \gamma K\bar{K} \qquad \left(1.0^{+0.11}_{-0.09}\right)\times 10^{-3}$$

$$J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi \qquad (3.8 \pm 0.5)\times 10^{-4}$$

$$J/\psi \to \gamma f_0(1710) \to \gamma\omega\omega \qquad (3.1 \pm 1.0)\times 10^{-4}$$

$$J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta \qquad \left(2.4^{+1.2}_{-0.7}\right)\times 10^{-4}$$

$$\Rightarrow Br(J/\psi \to \gamma f_0(1710) > 1.9 \times 10^{-3}$$

Using $Br(f_0(1710)\to K\underline{K})=0.36$ $\Rightarrow$ $Br(J/\psi\to\gamma f_0(1710))= 2.4\times10^{-3}$

$Br(f_0(1710)\to \pi\pi)= 0.15$ $\Rightarrow$ $Br(J/\psi\to\gamma f_0(1710))= 2.7\times10^{-3}$

$f_0(1710)$ ：the candidate of the scalar glueball？

Tensor glueball candidate (2^{++})

Lattice QCD: $\Gamma(J/\psi \to \gamma G_{2^+}) = \frac{4}{27}\alpha \frac{|p|}{M_{J/\psi}^2}\left[|E_1(0)|^2 + |M_2(0)|^2 + |E_3(0)|^2\right]$

Y.B. Yang ,et al .(CLQCD Collaboration)
Phys. Rev. Lett. 111, 091601 (2013))

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

$\boxed{J/\psi \to \gamma X \to \gamma\eta\eta}$ BESIII, PRD87(2013)092009

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = \left(5.60^{+0.62+2.37}_{-0.65-2.07}\right)\times 10^{-5}$$

$\boxed{J/\psi \to \gamma X \to \gamma\varphi\varphi}$ BESIII, PRD93(2016)112011

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

$\boxed{J/\psi \to \gamma X \to \gamma K_s K_s}$ BESIII，PRD 98, 072003 (2018)

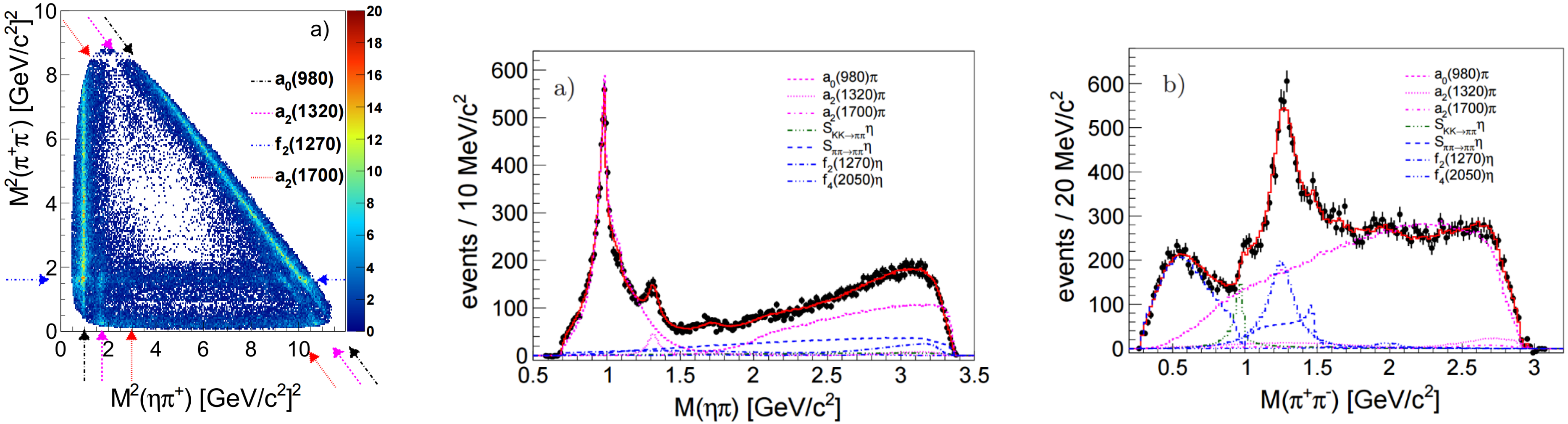
$$Br(J/\psi \to \gamma f_2(2340) \to \gamma K_s K_s) = \left(5.54^{+0.34+3.82}_{-0.40-1.49}\right)\times 10^{-5}$$

$f_2(2340)$ ：the candidate for the tensor glueball？

Amplitude Analysis of $\chi_{c1} \to \eta\pi^+\pi^-$

- World largest χ_{c1} sample (～35K)
  - 448M $\psi(3686) \to \gamma\, \chi_{c1} \to \gamma\, \eta\pi^+\pi^-$
  - Search for exotic meson with 1^{-+} in $\eta\pi, \eta'\pi$ and $\pi\pi$ final states

Phys. Rev. D 95, 032002 (2017)



- Observed $\chi_{c1} \to a_2(1700)\pi$ for the first time ($> 17\sigma$)
- First measurement of $g'_{\eta'\pi} \neq 0$ using $a_0(980) \to \eta\pi$ line shape.
- Determined upper limits for $\pi_1(1^{-+})$ in 1.4-2.0 GeV/c^2 region

Strangeonium Spectrum

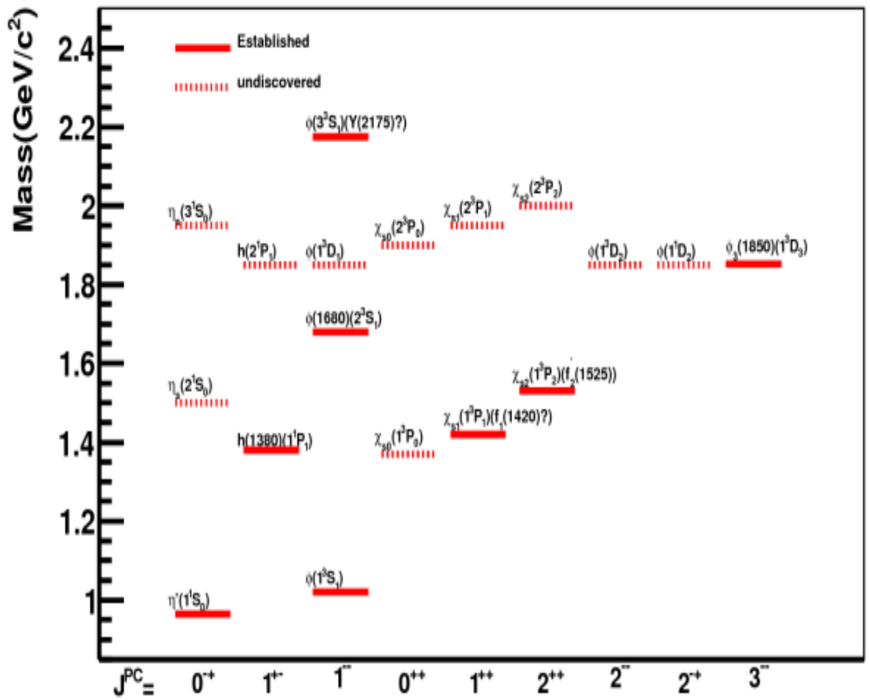
Strangeonium spectrum

PHYS. REV.D 68, 054014 (2003)

- Like charmonium and bottomonium, a similar pattern for the strangeonium is expected

- Much less well understood, most of them have not been observed yet

- Similarity of Y(2175) and Y(4260) production(ISR) and decay



Only 7 of them have been identified !

- Narrow Z_S states in Y(2175n → πZS → ππϕ, with Z_S mass close to KK* and K*K* thresholds

Eur. Phys. J. C 72, 2008 (2012)

Search for Zs at 2.125 GeV

Phys. Rev. D99. 011101 (2019)

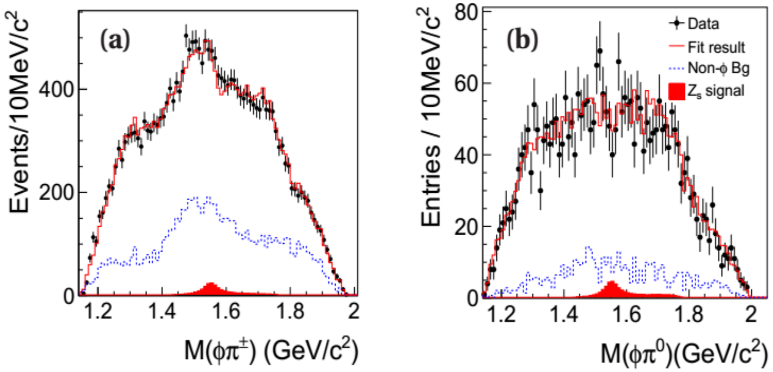
- Data: 108.49 ± 0.75 pb^{-1} collected at 2.125 GeV

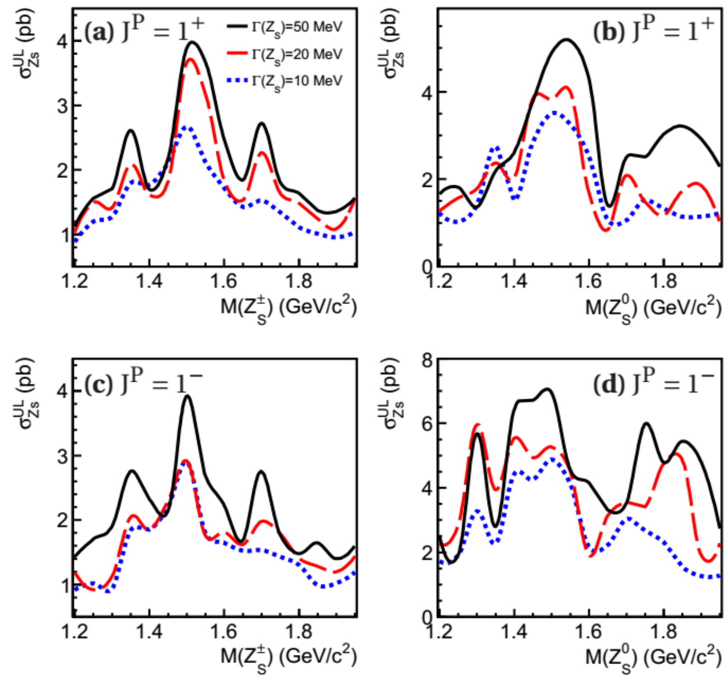
- No clear Z_S signal is observed in the $\phi\pi$ mass spectrums around 1.5 GeV/c^2.

- The cross-sections of $e^+e^-\to\phi\pi^+\pi^-$ and $e^+e^-\to\phi\pi^0\pi^0$ at 2.125 GeV/c^2 are measured

- Determined upper limits on the cross-section for Z_S production (90% C.L.)

$e^+e^- \to \phi\pi^+\pi^-$ $\qquad$ $e^+e^- \to \phi\pi^0\pi^0$





Observation of $h_1(1380)$ in $\psi(3686)\to\gamma\chi_{cJ}\to\gamma\phi h_1(1380)$

Phys. Rev. D 91, 112008 (2015)

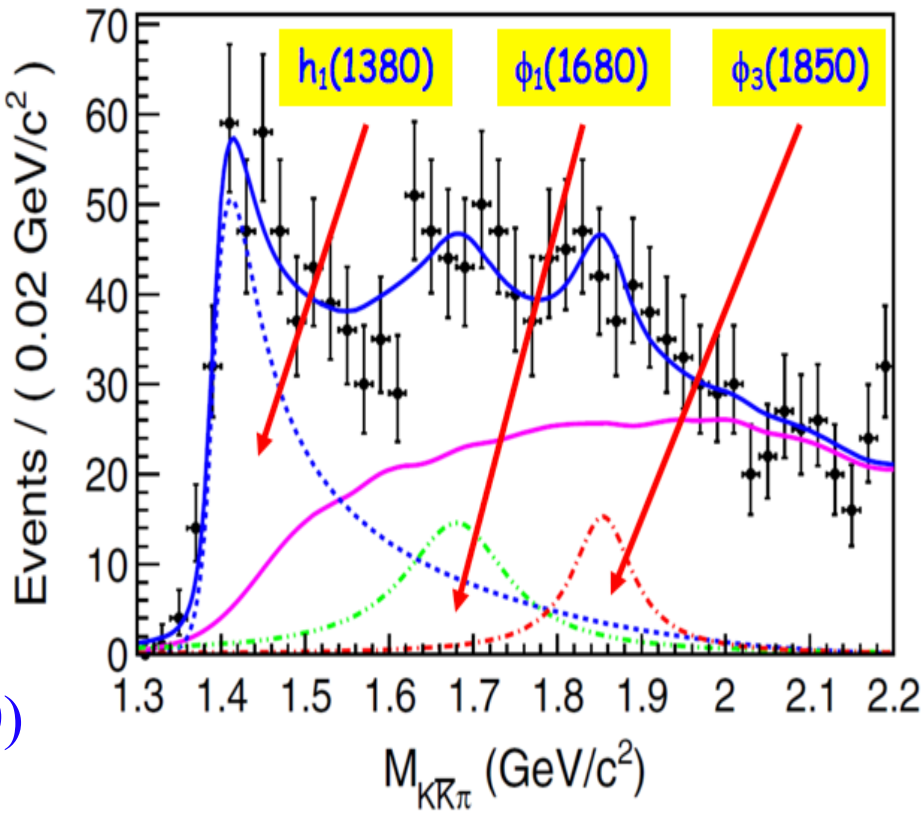
■ With 106M $\psi(3686)$, Study $\psi(3686)\to\gamma\chi_{cJ}$ (J=1,2), and $\chi_{cJ}\to\phi h_1(1380)$

■ First direct observation of $h_1(1380)\to K^*(892)\bar{K}$

● $M = 1412 \pm 4 \pm 8 MeV/c^2$
● $\Gamma = 84 \pm 12 \pm 40 MeV/c^2$

■ Eveidences for the decays

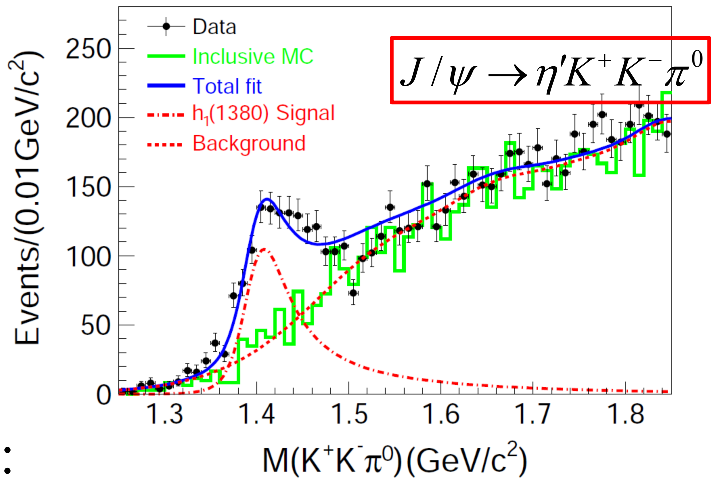
$\chi_{cJ} \to \varphi\ \varphi(1680)$ and $\chi_{cJ} \to \varphi\ \varphi(1850)$



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

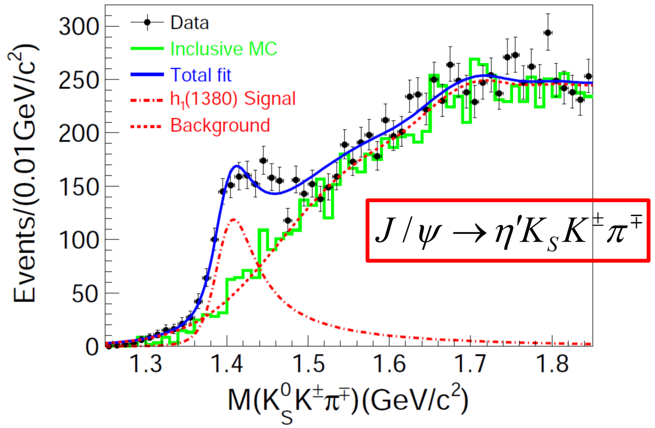
Phys. Rev. D 98, 072005 (2018)

- Simultaneous fit to the $M(K^*(892)\bar{K})$ in $K^+K^-\pi^0$ and $K_S^0K^\pm\pi^\mp$ modes.



- Observation of $h_1(1380)$ in $J/\psi \to \eta' h_1(1380)$ **(>10σ)**

$$M=(1423.2 \pm 2.1 \pm 7.3)MeV/c^2$$
$$\Gamma=(90.3 \pm 9.8 \pm 17.5)MeV/c^2$$



- The quark contents of $h_1(1380)$ is predominantly $s\bar{s}$:
  - Mixing angle between $h_1(1170)$ and $h_1(1380)$:$35.9^\circ \pm 2.6^\circ$

- Isospin symmetry violation

$$\frac{\mathcal{B}(h_1(1380) \to K^{*+}(892)K^- + c.c.)}{\mathcal{B}(h_1(1380) \to K^{*0}(892)K^0 + c.c.)} = 2.35 \pm 0.44$$

2019 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update.

PDG

LIGHT UNFLAVORED MESONS
($S = C = B = 0$)
For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ ($\eta, \eta', h, h', \omega, \phi, f, f'$): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

INSPIRE search

$h_1(1415)$ $\quad I^G(J^{PC}) = 0^-(1^{+-})$

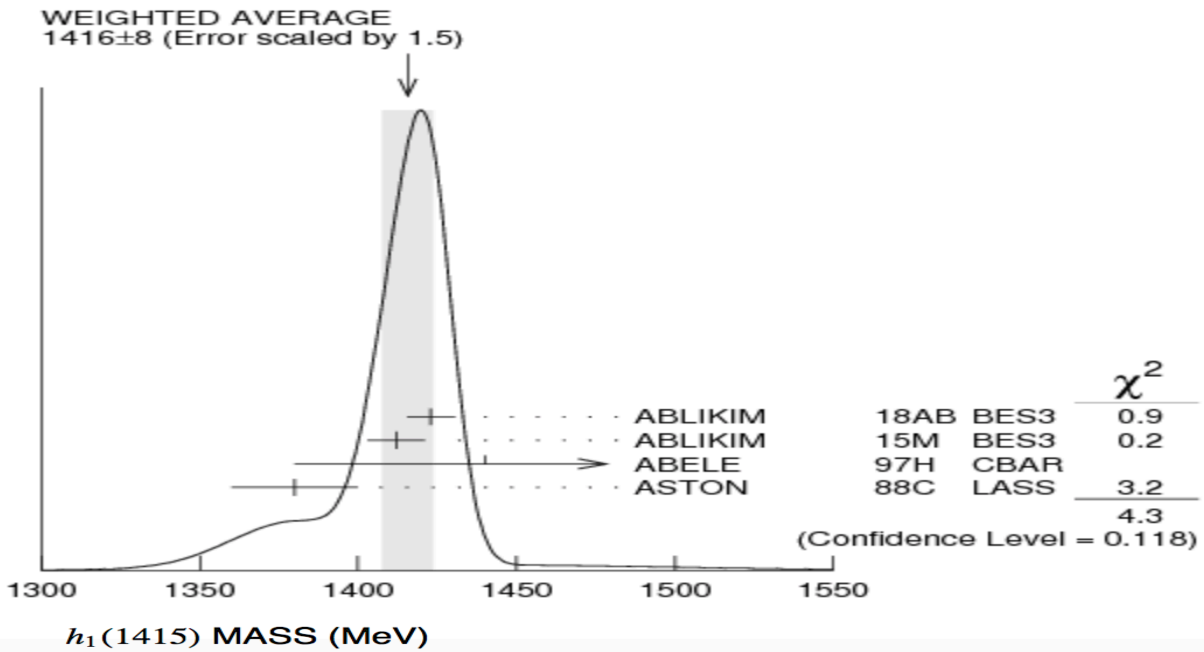
was $h_1(1380)$

$h_1(1415)$ MASS

INSPIRE search

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1416 ± 8	**OUR AVERAGE** Error includes scale factor of 1.5.				
1423 ±2.1 ±7.3	2.2k	[1] ABLIKIM	2018AB	BES3	$J/\psi \to \eta' h_1 \to \eta' K^* \bar{K}$
1412 ±4 ±8		[1] ABLIKIM	2015M	BES3	$\psi(2S) \to \gamma\chi_{c1,2} \to \gamma\phi(h_1 \to K^* \bar{K})$
1440 ±60		ABELE	1997H	CBAR	$\bar{p}p \to K^0_L K^0_S \pi^0\pi^0$
1380 ±20		ASTON	1988C	LASS	11 $K^- p \to K^0_S K^\pm \pi^\mp \Lambda$

[1] Final states $K^+ K^- \pi^0$ and $K^0_S K^\pm \pi^\mp$.

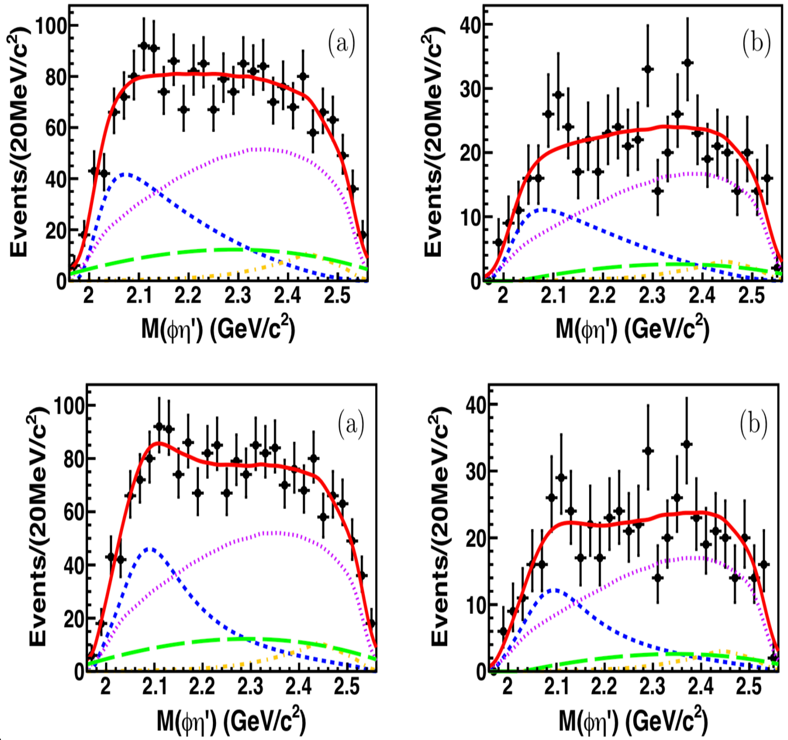


Observation and study of the decay J/ψ→φηη′

- Evidence for a structure denoted as X in the φη′ mass spectra
- $J^p=1^-$ $(4.4\ \sigma)$
  - Mass: (2002.1 ± 27.5 ± 21.4) MeV/c2
  - Width:(129 ± 17 ± 9) MeV
  - B(J/ψ → ηX) × B(X → φη′) =(9.8 ± 1.2 ± 1.7) × 10^{-5}
  - The mass is 5σ away from Y (2175)
- $J^p=1^+$$(3.8\ \sigma)$
  - Mass: (2062.8±13.1±7.2) MeV/c2
  - Width:(177 ± 36 ± 35) MeV
  - B(J/ψ → ηX) × B(X → φη′) (9.6 ± 1.4 ± 2.0) × 10^{-5}
- Two assumptions cannot clearly be distinguished due to the limited statistics.

Phys. Rev. D **99**, 112008 (2019)

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



$J^p=1^-$

$J^p=1^+$

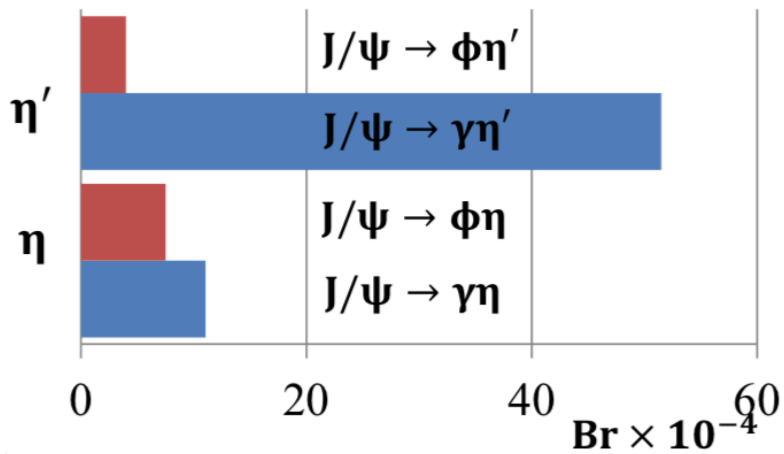
Light Meson Decay

η and η´ decays

η′ →2γ	chiral anomaly
η′ →π+π-π^0	quark masses, π+π- scattering
η′ →γπ+π-	box anomaly
η′ →γπ+π-	form factor
η′ →ππ	CP violation
η′ → μ+μ-π^0 ,e+e-π^0	C violation
η′ → μ e	LF violation

- Rich physics
  - Test ChPT predictions
  - Form factors
  - Test fundamental symmetries
  - Probe new physics beyond the SM

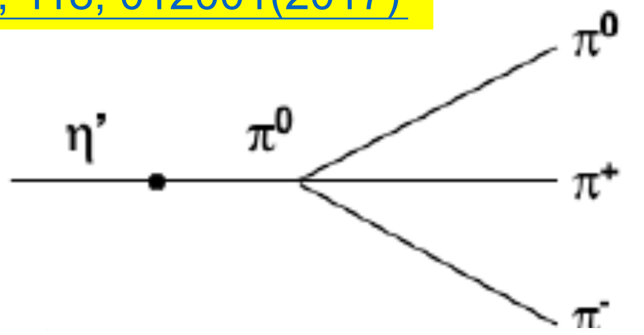
- High Production (1.3 B J/ψ)
  - 7.2×10^6 η'
  - 2.4×10^6 η



Amplitude Analysis of $\eta' \to \pi^{+(0)}\pi^{-(0)}\pi^0$

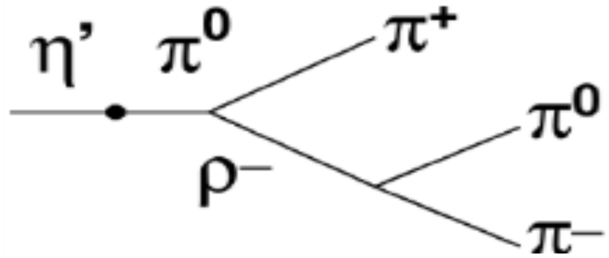
PRL, 118, 012001(2017)

- $\eta' \to \pi\,\pi\,\pi$ are isospin-violating processes, dominated by strong interaction



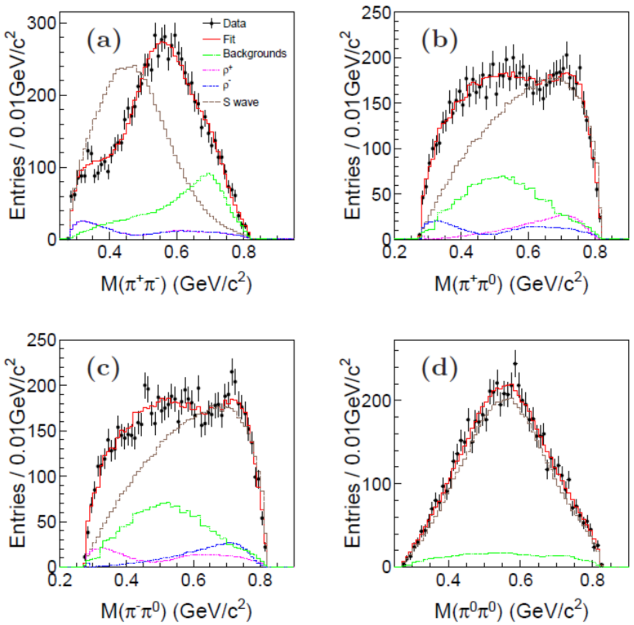
- Light quark mass difference can be extracted

$$r = \frac{\Gamma_{\eta' \to \pi^+\pi^-\pi^0}}{\Gamma_{\eta' \to \eta\pi^+\pi^-}} \approx (16.8)\frac{3}{16}\left(\frac{m_d - m_u}{m_s}\right)^2$$



- Using ChPT, large P-wave contribution of $\boldsymbol{\eta' \to \rho^{\pm}\pi^{\mp}}$ is predicted

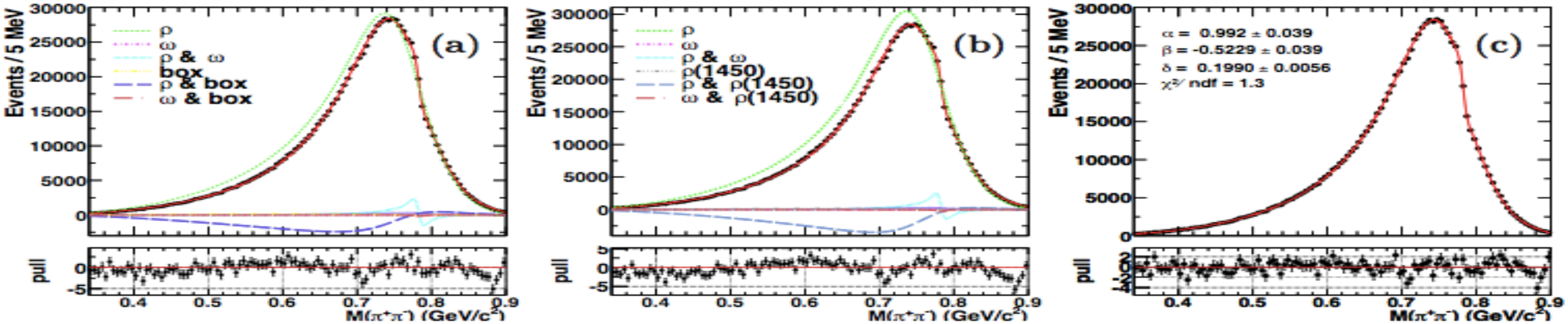
Decay Mode	$\mathcal{B}$ $(\times 10^{-4})$
$\pi^+\pi^-\pi^0$	$35.91 \pm 0.54 \pm 1.74$
$\pi^0\pi^0\pi^0$	$35.22 \pm 0.82 \pm 2.60$
$\rho^+\pi^-$	$3.72 \pm 0.30 \pm 0.63 \pm 0.92$
$\rho^-\pi^+$	$3.72 \pm 0.30 \pm 0.63 \pm 0.92$
$(\pi^+\pi^-\pi^0)_S$	$37.63 \pm 0.77 \pm 2.22 \pm 4.48$



Study of $\eta' \to \gamma\pi^+\pi^-$ decay dynamics

PRL120,242003(2018)

- The second most probable decay mode of the η’ meson
- In VMD model, the process is dominated by $\eta' \to \gamma\rho$**(770)**
- A peak shift of ~ 20 MeV/c2 for the ρ(770) meson
- This discrepancy could be attributed to the box anomaly in ChPT



fit with ρ(770)-ω-box anomaly **fit with ρ(770)-ω-r(1450)** $P(s_{\pi\pi}) = 1 + a\, s_{\pi\pi} + b\, O(s^2_{\pi\pi}) + d\, BW_w$

- Besides the $\boldsymbol{\rho}$(770), the $\boldsymbol{\omega}$ contribution is needed
- ρ(770)-ω cannot describe data well
- Extra contribution (maybe r(1450) or box-anomaly) is also necessary

Precision Measurement of the Branching Fractions of η’ Decays

PhysRevLett.122.142002 (2019)

- Gamma conversion: $J/\psi \rightarrow \gamma\eta', \gamma \rightarrow e^+ e^-$

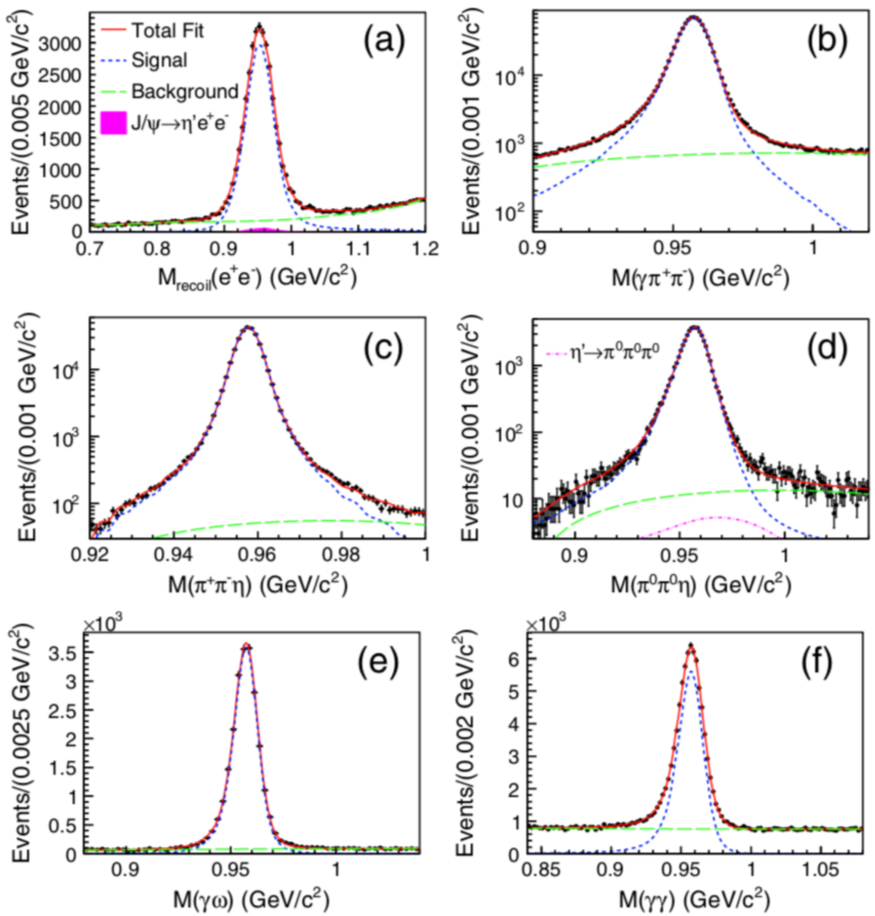
$\Gamma(\eta'(958) \rightarrow \pi^+\pi^-\eta)/\Gamma_{total}$

Value	EVTS	Document ID	TECN	Comment
0.429 ± 0.007	OUR FIT			
*** We do not use the following data for averages, fits, limits, etc ***				
0.424 ±0.011 ±0.004	1.2k	[1] PEDLAR 2009	CLEO	$J/\psi \rightarrow \gamma\eta'$

[1] Not independent of other η' branching fractions and ratios in PEDLAR 2009 .

- Independent measurements of five dominant decay channels with higher precision

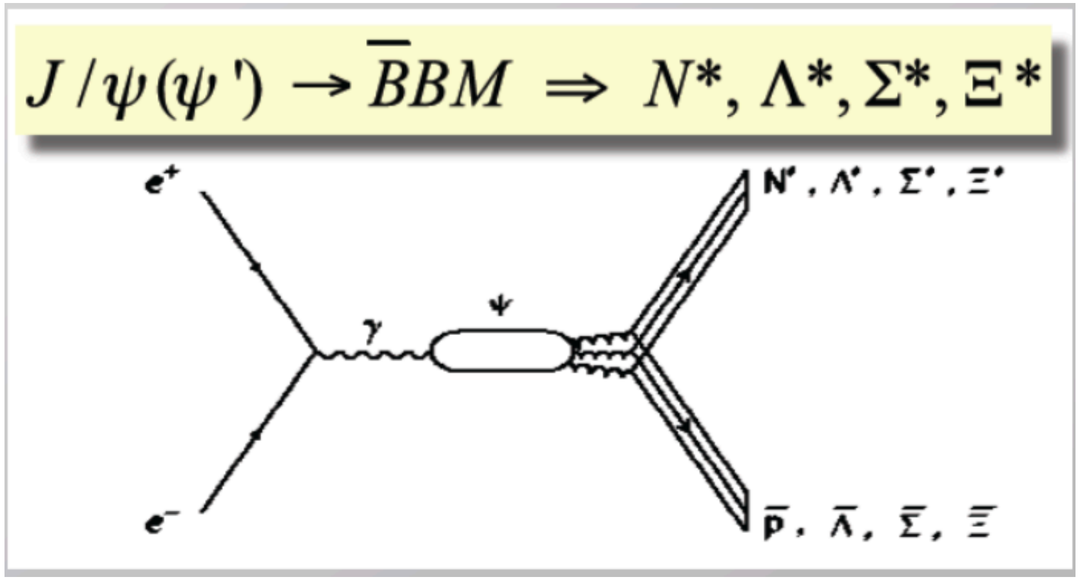
Decay mode	$\mathcal{B}(\eta' \rightarrow X)(\%)$ This measurement	PDG [7]
$\eta' \rightarrow \gamma\pi^+\pi^-$	$29.90 \pm 0.03 \pm 0.55$	28.9 ± 0.5
$\eta' \rightarrow \eta\pi^+\pi^-$	$41.24 \pm 0.08 \pm 1.24$	42.6 ± 0.7
$\eta' \rightarrow \eta\pi^0\pi^0$	$21.36 \pm 0.10 \pm 0.92$	22.8 ± 0.8
$\eta' \rightarrow \gamma\omega$	$2.489 \pm 0.018 \pm 0.074$	2.62 ± 0.13
$\eta' \rightarrow \gamma\gamma$	$2.331 \pm 0.012 \pm 0.035$	2.22 ± 0.08



Baryon spectroscopy

Search for excited baryons

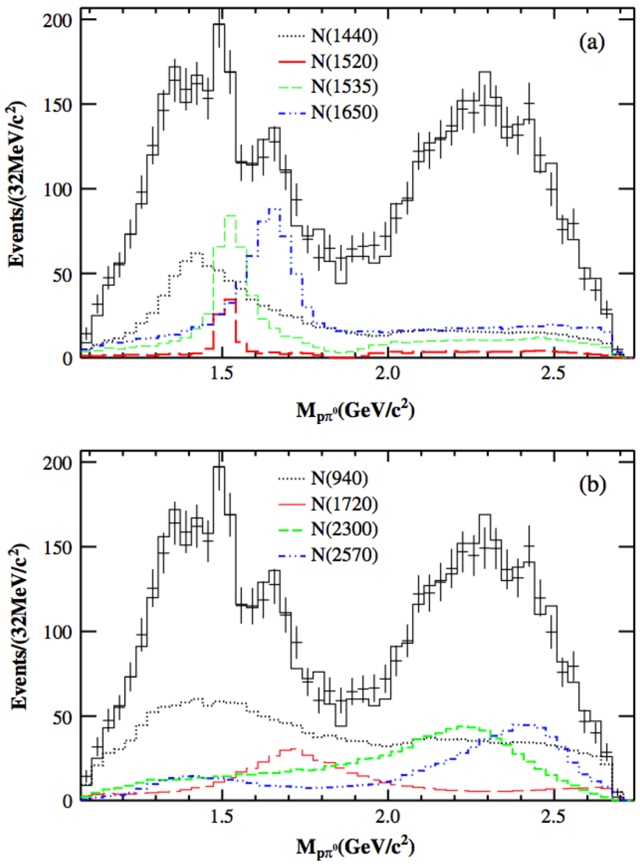
- NRQM is successful in interpreting of the excited baryons
- Predicted more excited stated (“missing resonance problem”)
- J/ψ (ψ')decays offers an window to search for the missing resonance
- Isospin filter for $J/\psi \to N\bar{N}\pi$ and $J/\psi \to N\bar{N}\pi\pi$, $N\pi$ and $NN\pi$ systems are limited to be pure isospin $\frac{1}{2}$



N* in PWA of $\psi(2S) \rightarrow p\bar{p}\,\pi^0$

PRL 110, 022001 (2013)

106 M $\psi(2S)$



Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	ΔS	ΔN_{dof}	Sig.
$N(1440)$	1390^{+11+21}_{-21-30}	$340^{+46+70}_{-40-156}$	72.5	4	11.5σ
$N(1520)$	1510^{+3+11}_{-7-9}	115^{+20+0}_{-15-40}	19.8	6	5.0σ
$N(1535)$	1535^{+9+15}_{-8-22}	120^{+20+0}_{-20-42}	49.4	4	9.3σ
$N(1650)$	1650^{+5+11}_{-5-30}	150^{+21+14}_{-22-50}	82.1	4	12.2σ
$N(1720)$	1700^{+30+32}_{-28-35}	$450^{+109+149}_{-94-44}$	55.6	6	9.6σ
N(2300)	$\mathbf{2300^{+40+109}_{-30-0}}$	$\mathbf{340^{+30+110}_{-30-58}}$	**120.7**	**4**	$\mathbf{15.0\sigma}$
N(2570)	$\mathbf{2570^{+19+34}_{-10-10}}$	$\mathbf{250^{+14+69}_{-24-21}}$	**78.9**	**6**	$\mathbf{11.7\sigma}$

- 7 N* intermediate resonances are observed
- Two new baryonic excited states are observed
    - N(2300) (½+)
    - N(2570)(5/2-)
- No clear evidence for N(1885) or N(2065) has been found

N* in PWA of $\psi(2S) \rightarrow p\bar{p}\,\eta$

PRD 88, 032010(2013)

106 M $\psi(2S)$

- **Intermediate state**

  $N(1535) \rightarrow p\eta$ dominant

- **No evidence for a $p\bar{p}$ resonance**

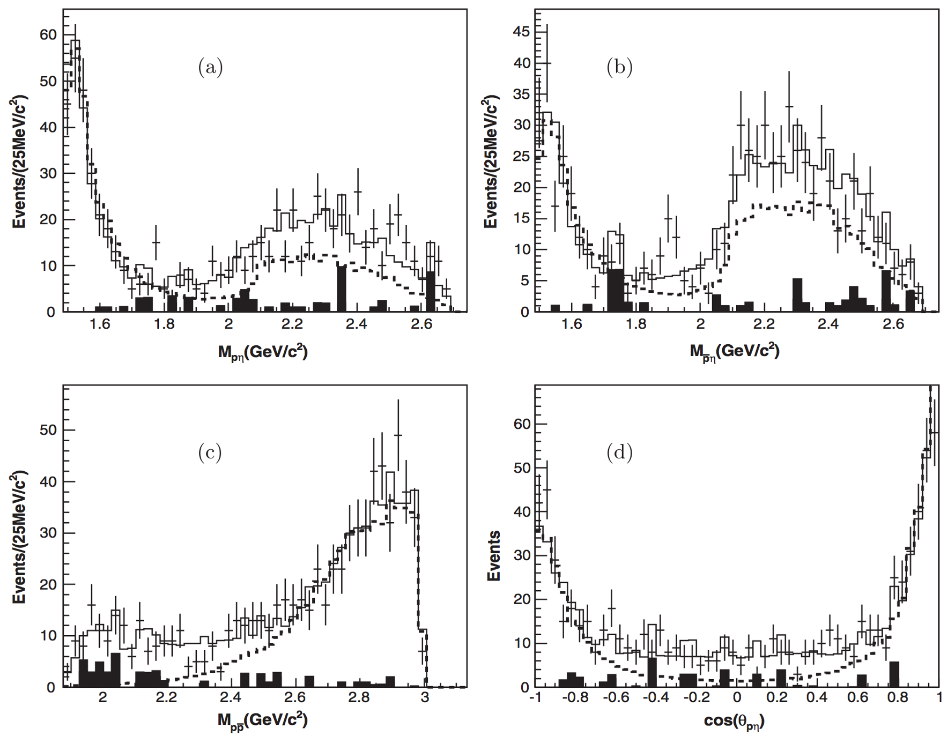
Mass and width of N(1535)

- $M = 1524 \pm 5^{+10}_{-4}$ MeV$/c^2$
- $\Gamma = 130^{+27+57}_{-24-10}$ MeV$/c^2$

PDG value:

- $M = 1525$ to 1545 MeV$/c^2$
- $\Gamma = 125$ to 175 MeV$/c^2$

$$B(\psi(2S)\to N(1535)\bar{p})\times B(N(1535)\to p\eta)$$
$$=\frac{N_{\rm obs}}{\varepsilon\cdot N_{\psi(2S)}\cdot B(\eta\to\gamma\gamma)}=(5.2\pm0.3^{+3.2}_{-1.2})\times10^{-5},$$

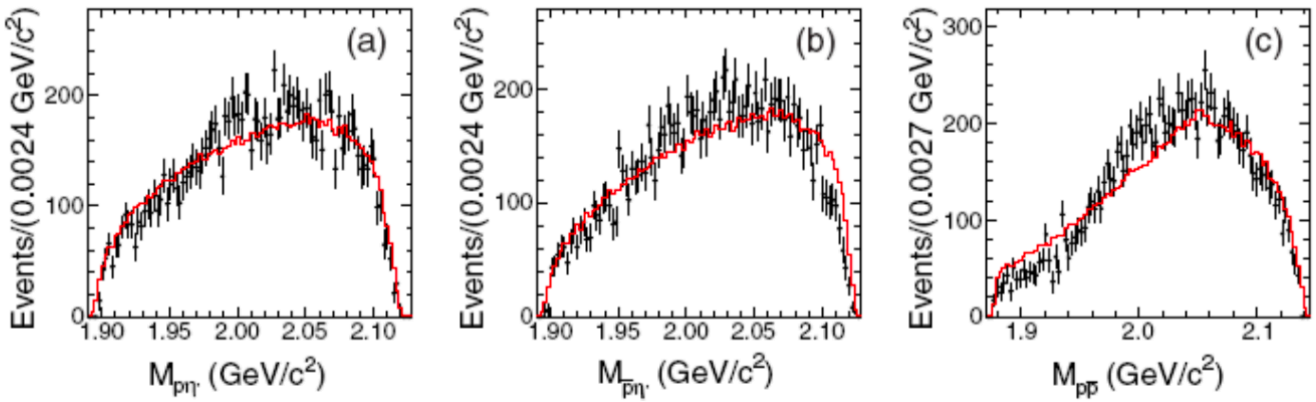


$$B(\psi(2S)\to p\bar{p}\eta) = (6.4 \pm 0.2 \pm 0.6)\times 10^{-5}.$$

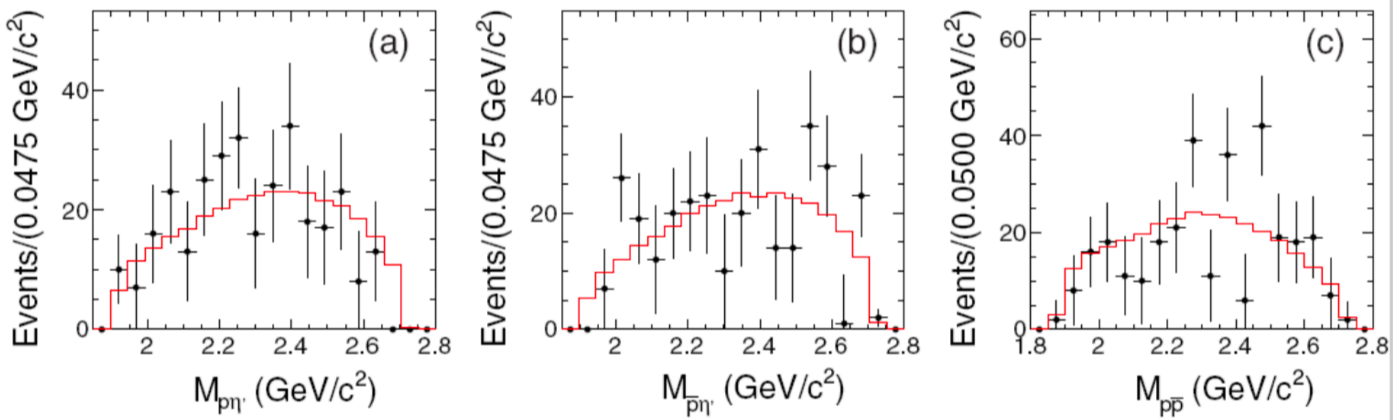
N* in J/ ψ (ψ(2S)) $\rightarrow p\bar{p}\,\eta'$

Phys. Rev. D 99, 032006 (2019)

1.31B J/ψ



106 M ψ(2S)

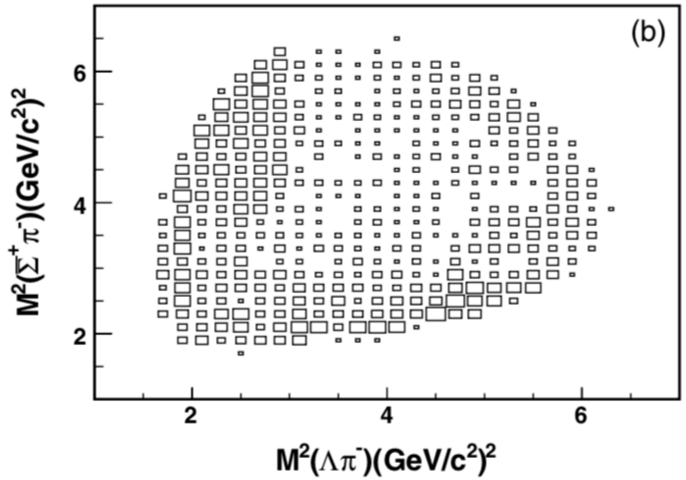


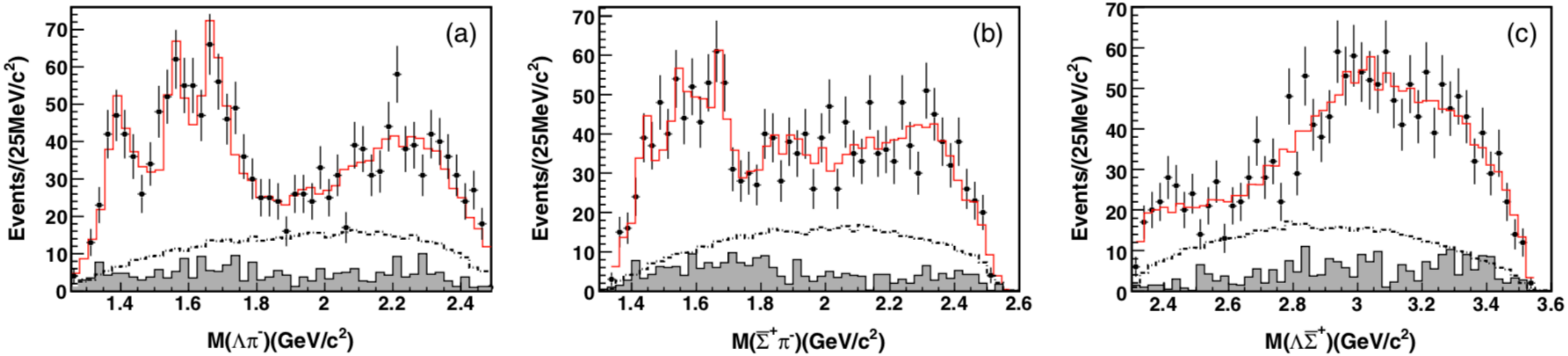
No evident structures were observed

Λ^* and Σ^* in $\psi(2S) \to \Lambda\Sigma\pi$

Phys. Rev. D 88, 112007 (2013)

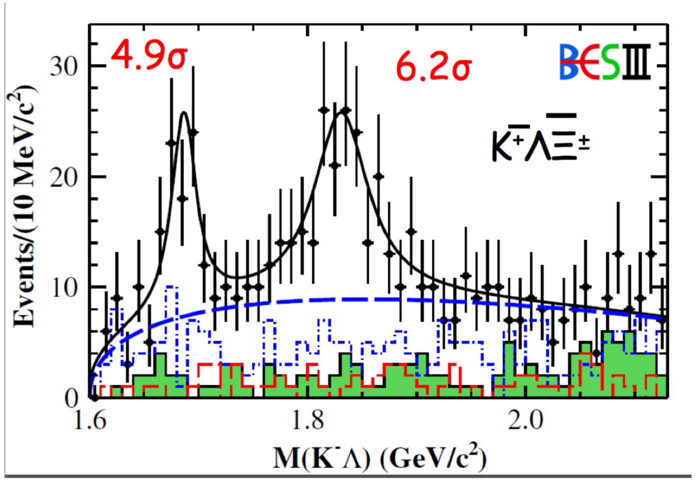
- 106 M $\psi(2S)$
- **Clear structures were observed**





Observation Ξ^* of $\psi(2S) \to (\gamma)K^-\Lambda\bar{\Xi}^+$+c.c.

PRD 91, 092006 (2015)



450 M $\psi(2S)$

- $\Xi(1690)^-$ and $\Xi(1820)^-$ observed in M(K**Λ**)
- Mass and width consistent with PDG
- First observation in Charmonium decay

	$\Xi(1690)^-$	$\Xi(1820)^-$
M(MeV/c^2)	$1687.7 \pm 3.8 \pm 1.0$	$1826.7 \pm 5.5 \pm 1.6$
Γ(MeV)	$27.1 \pm 10.0 \pm 2.7$	$54.4 \pm 15.7 \pm 4.2$
Event yields	74.4 ± 21.2	136.2 ± 33.4
Significance(σ)	4.9	6.2
Efficiency(%)	32.8	26.1
$\mathcal{B}(10^{-6})$	$5.21 \pm 1.48 \pm 0.57$	$12.03 \pm 2.94 \pm 1.22$
$M_{\rm PDG}$(MeV/c^2)	1690 ± 10	1823 ± 5
$\Gamma_{\rm PDG}$(MeV)	< 30	24^{+15}_{-10}

Decay	Branching fraction
$\psi(3686) \to K^-\Lambda\bar{\Xi}^+$	$(3.86 \pm 0.27 \pm 0.32) \times 10^{-5}$
$\psi(3686) \to \Xi(1690)^-\bar{\Xi}^+$, $\Xi(1690)^- \to K^-\Lambda$	$(5.21 \pm 1.48 \pm 0.57) \times 10^{-6}$
$\psi(3686) \to \Xi(1820)^-\bar{\Xi}^+$, $\Xi(1820)^- \to K^-\Lambda$	$(12.03 \pm 2.94 \pm 1.22) \times 10^{-6}$
$\psi(3686) \to K^-\Sigma^0\bar{\Xi}^+$	$(3.67 \pm 0.33 \pm 0.28) \times 10^{-5}$
$\psi(3686) \to \gamma\chi_{c0}$, $\chi_{c0} \to K^-\Lambda\bar{\Xi}^+$	$(1.90 \pm 0.30 \pm 0.16) \times 10^{-5}$
$\psi(3686) \to \gamma\chi_{c1}$, $\chi_{c1} \to K^-\Lambda\bar{\Xi}^+$	$(1.32 \pm 0.20 \pm 0.12) \times 10^{-5}$
$\psi(3686) \to \gamma\chi_{c2}$, $\chi_{c2} \to K^-\Lambda\bar{\Xi}^+$	$(1.68 \pm 0.26 \pm 0.15) \times 10^{-5}$
$\chi_{c0} \to K^-\Lambda\bar{\Xi}^+$	$(1.96 \pm 0.31 \pm 0.16) \times 10^{-4}$
$\chi_{c1} \to K^-\Lambda\bar{\Xi}^+$	$(1.43 \pm 0.22 \pm 0.12) \times 10^{-4}$
$\chi_{c2} \to K^-\Lambda\bar{\Xi}^+$	$(1.93 \pm 0.30 \pm 0.15) \times 10^{-4}$

Summary and Outlook

■ Highlights from BESIII LHS

- Connection between X($p\bar{p}$) and X(1835) to upport a $p\bar{p}$ molecule-like state or bound state
- First observation of $a_0(980)$-$f_0(980)$ Mixing
- Scale Glueball: strong production of $f_0(1710)$ in $J/\psi \to \gamma\eta\eta/\gamma KK/\gamma\pi\pi$, consists with LQCD’ s prediction;
- Tensor Glueball: strong production of $f_2(2340)$ in $J/\psi \to \gamma\eta\eta/\gamma KK/\gamma\phi\phi$; consists with LQCD’ s prediction ?
- No obvious Zs was found and h1(1380) changed to h1(1415)
- Precision measurement of light meson (η’) decays
- *Several* $N*$,$\Lambda*$,$\Sigma*$ and $\Xi*$ were observed

■ Collected 10 billion J/ψ events

- ■ Allows us to study light hadrons with the unprecedented statistics
- ■ More interesting results are expected

Thanks for your attention!