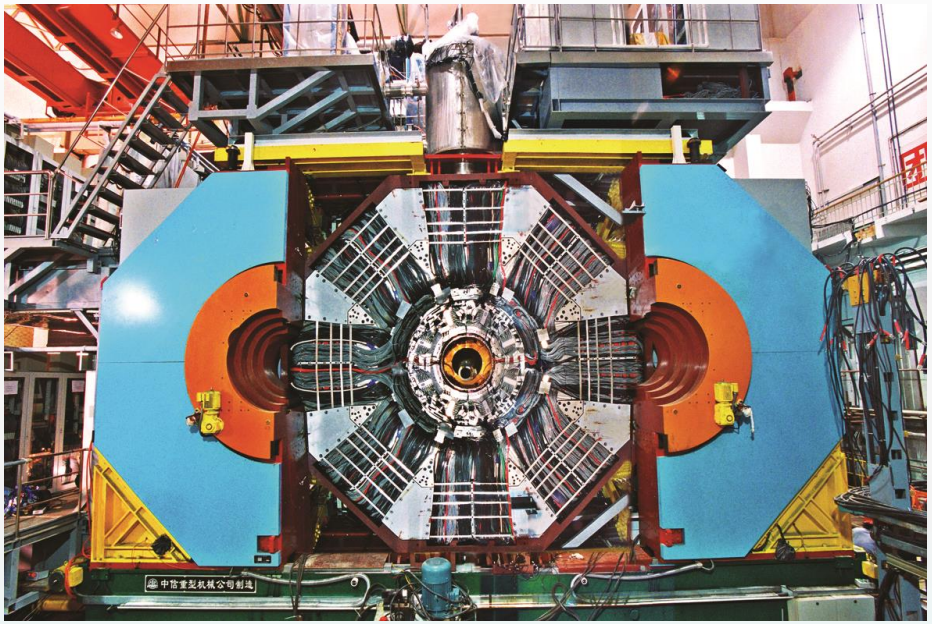
Light hadron spectroscopy at BESIII



Yingchun Zhu

(on behalf of BESIII Collaboration)

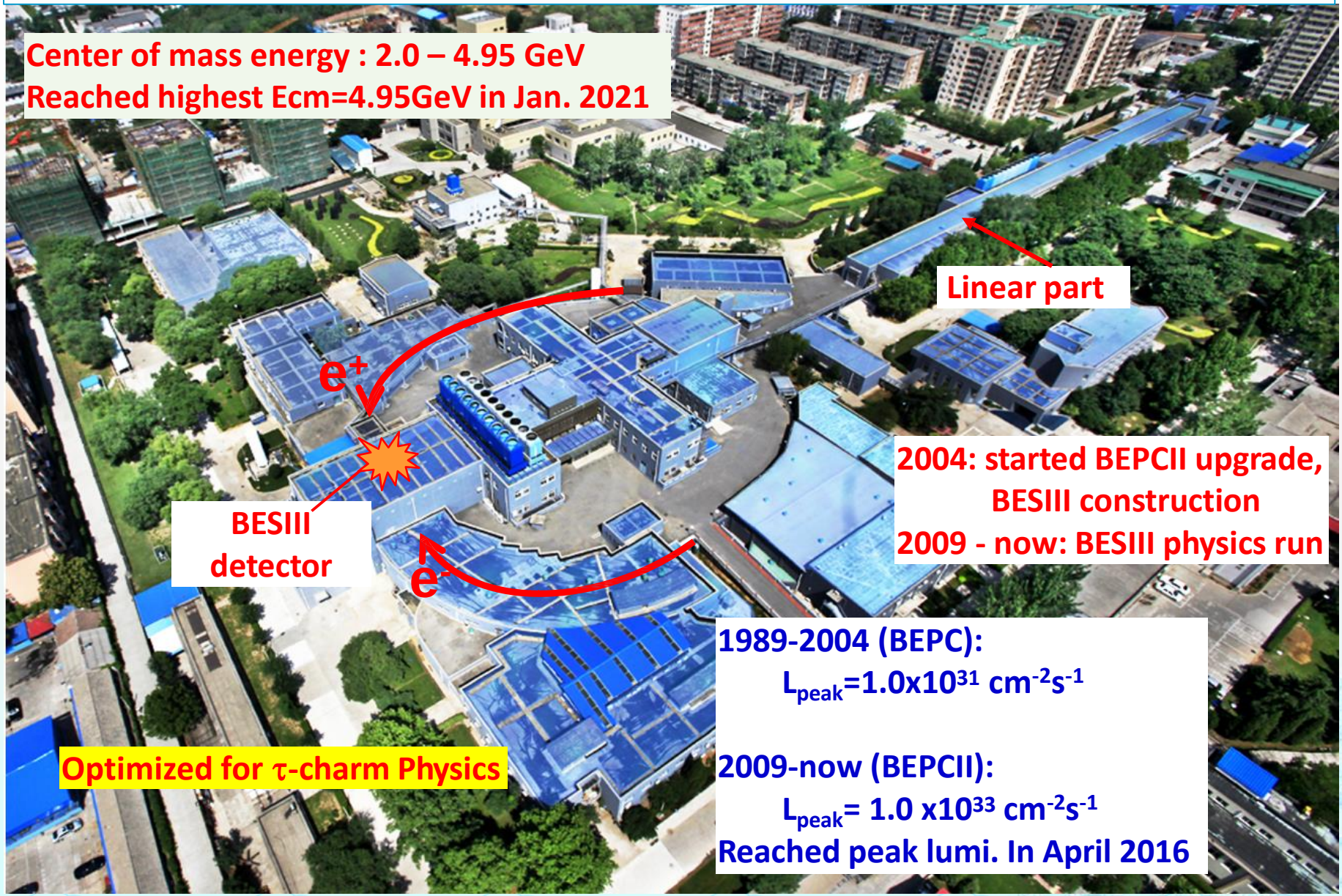
University of Science and Technology of China

Exotic Hadron Spectroscopy 2023, Durham UK, April 19-21

OUTLINE

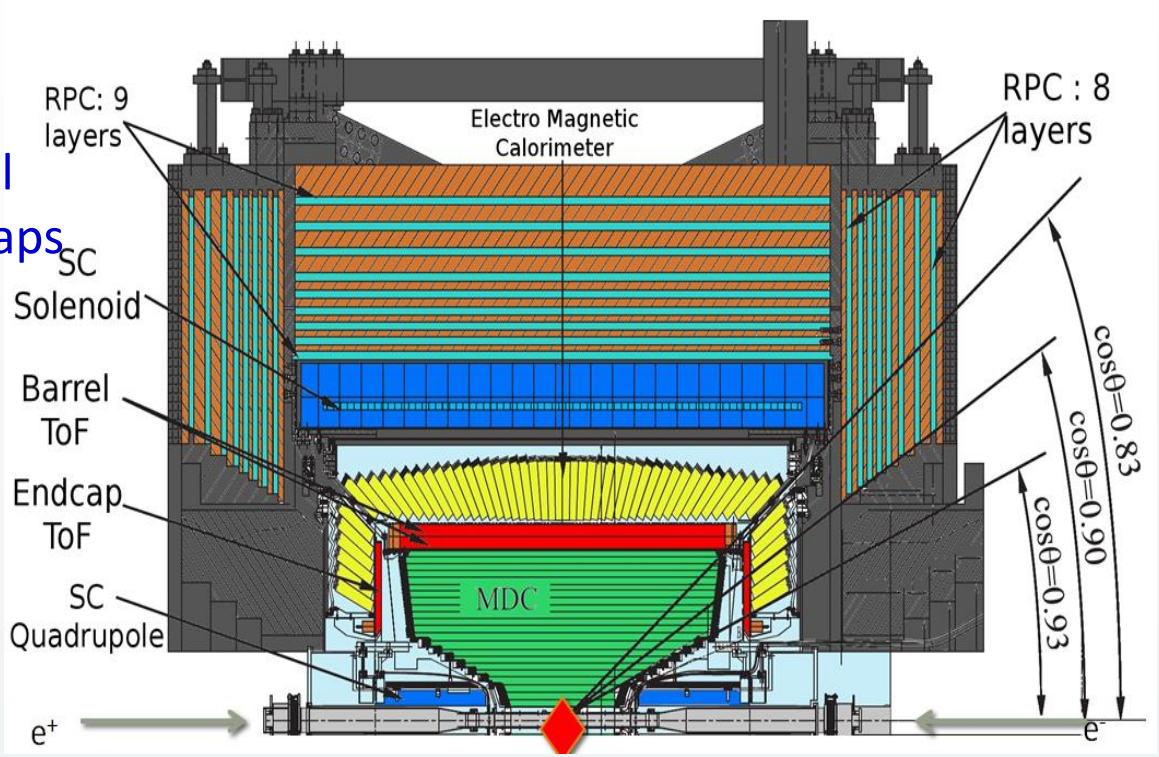
- Introduction on BESIII@BPCII
- Light hadrons
- Selected results at BESIII
- Summary

BESIII @ Beijing Electron Positron Collider (BEPC) – charm facility



BESIII at BEPCII

- EMC: CsI crystals
  $\Delta E/E=2.5\%$@1GeV –barrel
  $\Delta E/E=5.0\%$@1GeV –endcaps
- TOF
  σ_T =68ps for barrel
  σ_T =110(60)ps for endcap
- MDC: spatial reso. 115μm
  $\sigma_p/p=0.5\%$@1GeV
  dE/dx reso.=6%
- Magnet: 1T super conducting
- Muon ID: 9 layer RPC
- Trigger: Tracks & showers



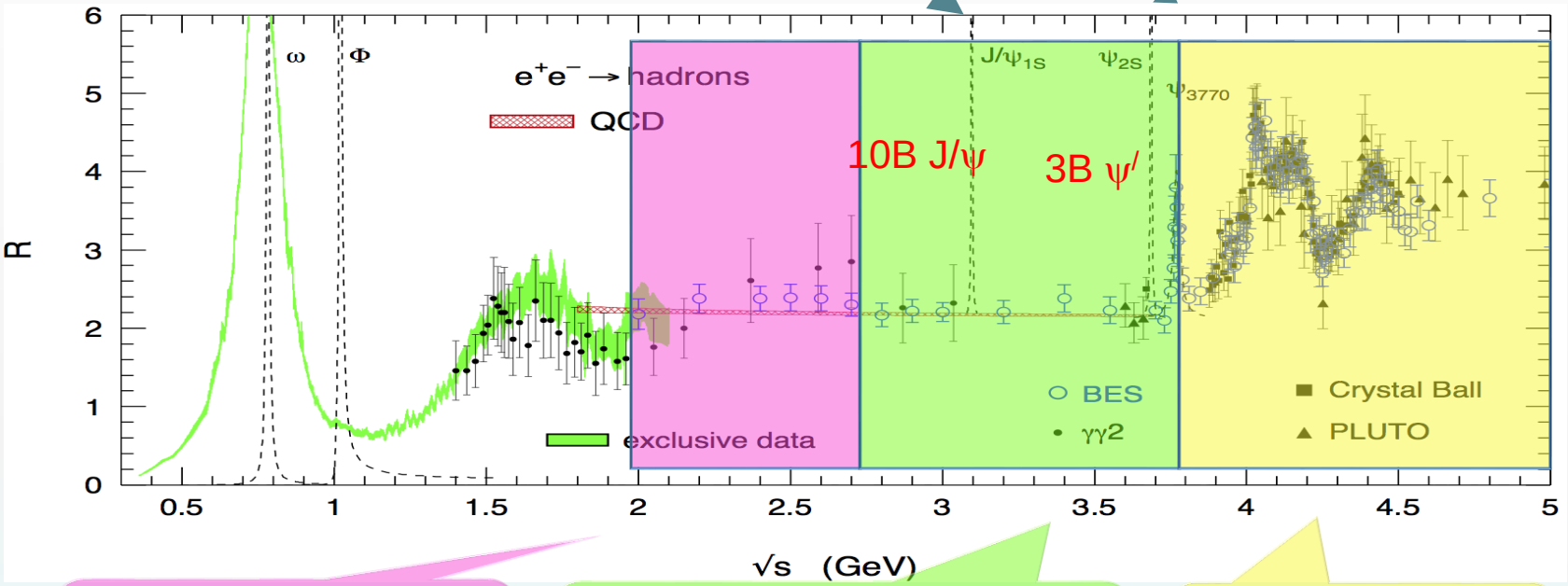
Total weight 730ton, ~40,000 readout channels
Data rate: 5kHz, 50Mb/s

Has been in full operation since 2008,
all subdetectors are in very good status!

Rich Physics at τ-charm Energy Region

$\sigma(e^+e^- \to J/\psi) = 3400nb$

$\sigma(e^+e^- \to \psi(3686)) = 600nb$



- Hadron form factors
- R values and QCD

- **Light hadron spectroscopy**
- Gluonic and exotic states
- Physics with t lepton

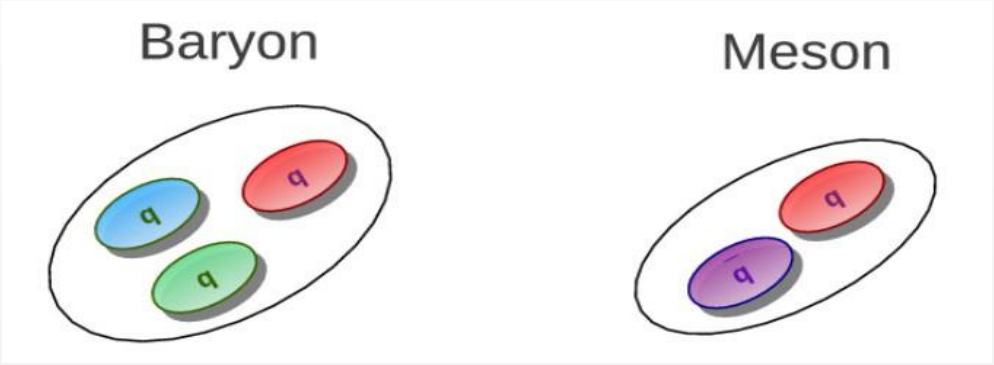
- XYZ particles
- Charm mesons
- Charm baryons

world's largest data samples directly collected , ~40fb^{-1} data in E_{cm} = 2~4.95GeV

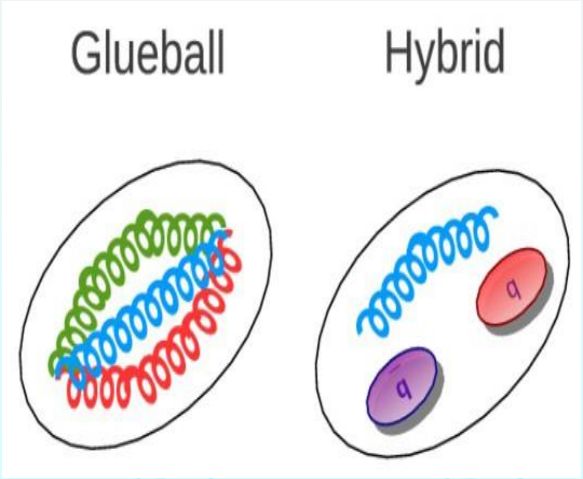
light hadrons

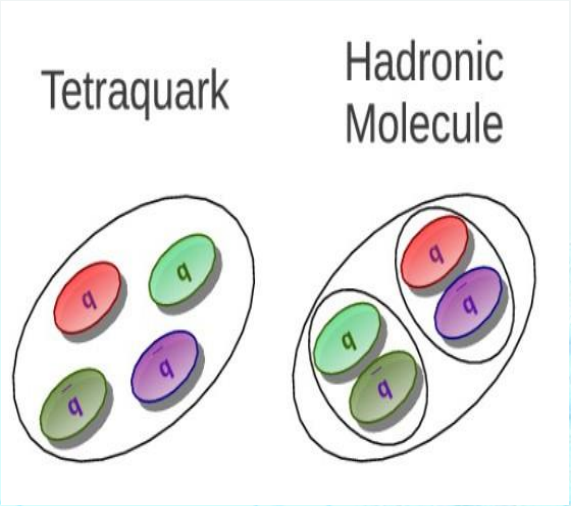
Establish the spectrum and study the exotic hadrons properties

- Conventional hadron in quark model



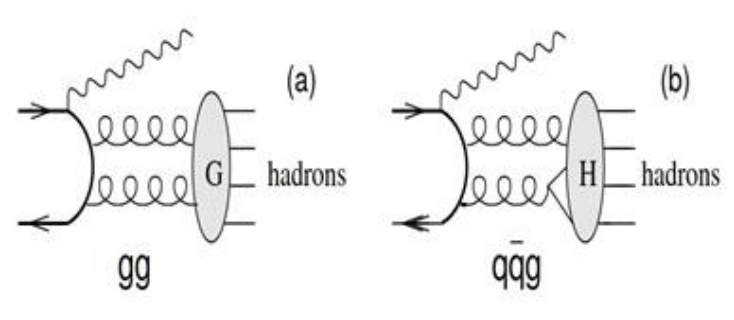
- QCD allows for hadrons beyond quark model

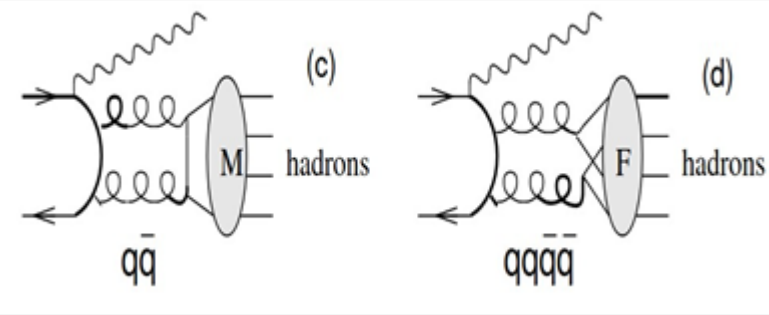




Searches for glueballs and new exotics

- Charmonium decays provide an ideal laboratory for light hadron studies (clean, high statistics and gluon-rich environment)

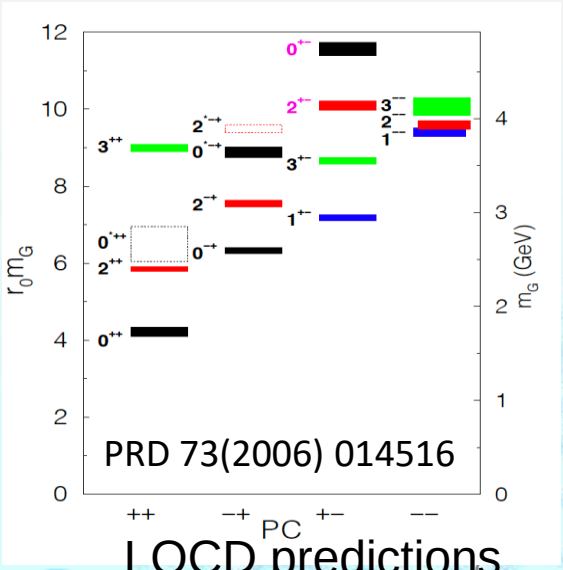




$\Gamma(J/\psi\to\gamma G)\sim o(\alpha\alpha_s^2)$, $\Gamma(J/\psi\to\gamma H)\sim o(\alpha\alpha_s^3)$, $\Gamma(J/\psi\to\gamma M)\sim o(\alpha\alpha_s^4)$, $\Gamma(J/\psi\to\gamma F)\sim o(\alpha\alpha_s^4)$

- Glueball searches

--Evidence of gluon self interaction
--Provide critical information on the gluon field
--quantitative understanding of confinement



LQCD predictions

Searches for glueballs and new exotics

- Charmonium decays provide an ideal laboratory for light hadron studies (clean, high statistics and gluon-rich environment)

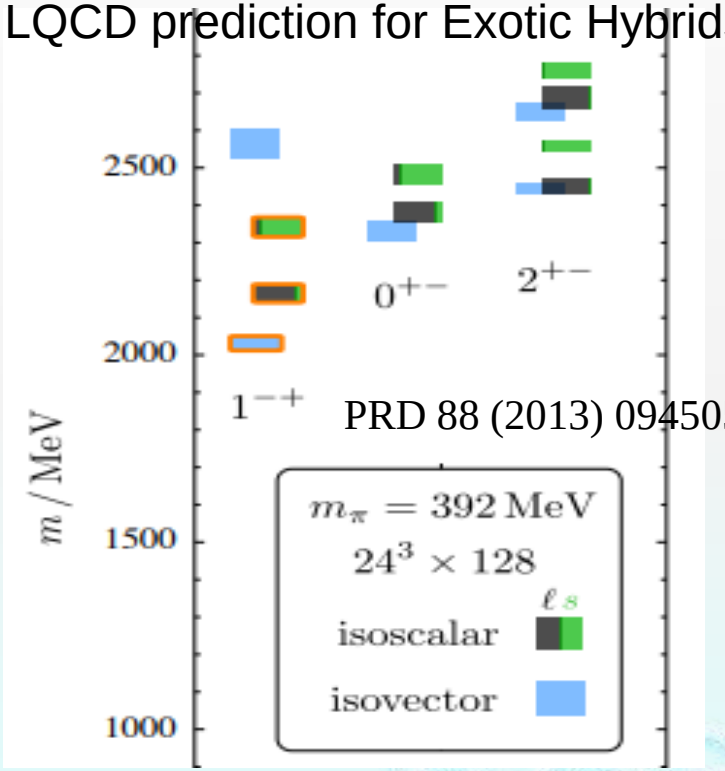
  - Exotic hybrids

    --J^{PC} = 0^{+-}, 1^{-+}, 2^{+-} (forbidden in the conventional QCD)

    -- 1^{-+} nonet of hybrid mesons is predicted to be the lightest (1.8-2.1GeV mass region)

    -- Only isovector candidate observed $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2015)$

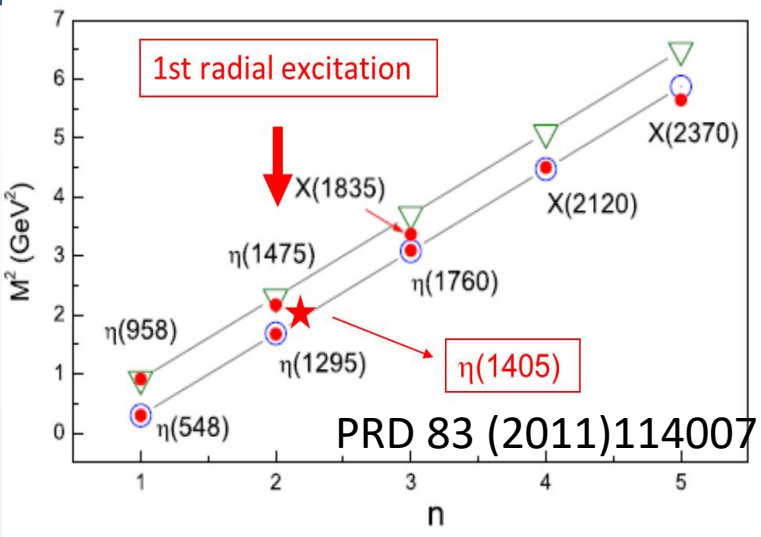
LQCD prediction for Exotic Hybrids

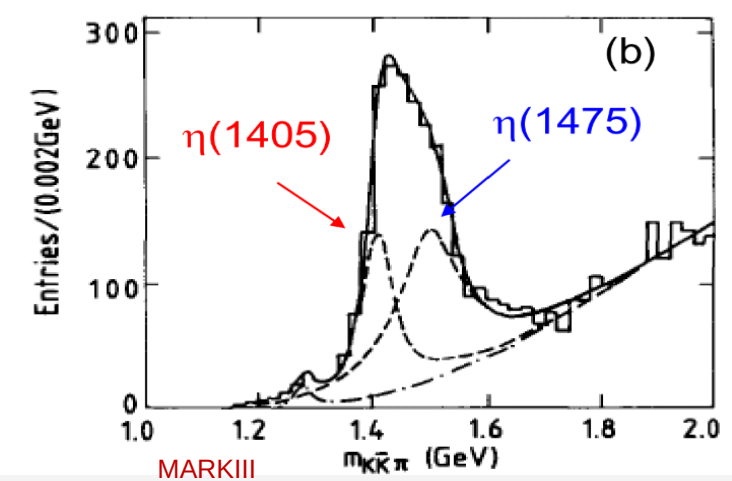


PRD 88 (2013) 094505

Finding an isoscalar 1^{-+} hybrid state is critical to establish the hybrid multiplet.

Pseudoscalar glueball searches: η(1405/1475)

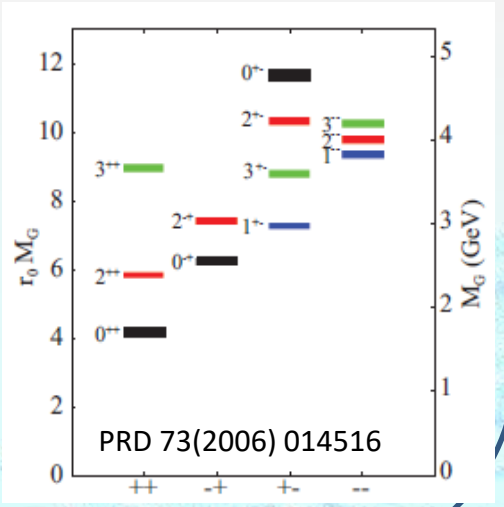




- A structure was first observed by MARKIII.
- One or two pseudoscalar mesons exist in ~1.4GeV?

$$\eta(1405) \rightarrow a_0\pi$$
$$\eta(1475) \rightarrow K^*\overline{K}$$

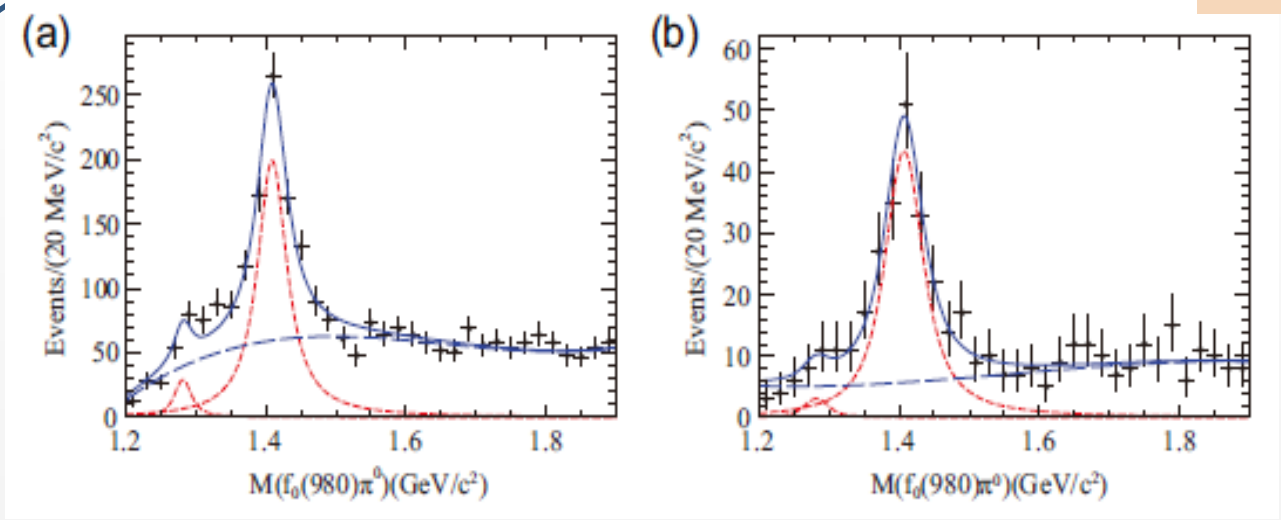
Long puzzle!



- Where is the 0^{-+} glueball?
  - LQCD: 0^{-+}(2.3~2.6 GeV); • Nature of $\eta(1405)$?

Pseudoscalar glueball searches:

$\eta(1405/1475)$
$J/\psi \to \gamma\pi^+\pi^-\pi^0, \gamma 3\pi^0$



225M J/ψ events,

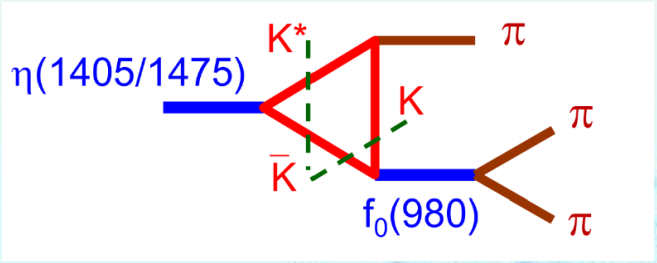
PRL 108 (2012) 182001

- Isospin-violating decay $\eta(1405) \to f_0(980)\pi^0$ observed for the first time. stat. significance >10σ
- Anomalously large isospin violation:

$$\frac{Br(\eta(1405) \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\eta(1405) \to a_0^0(980)\pi^0 \to \eta\pi^0\pi^0)} = (17.9 \pm 4.2)\%$$

$$\frac{Br(\chi_{cJ} \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\chi_{cJ} \to a_0^0(980)\pi^0 \to \eta\pi^0\pi^0)} < 1\%\ (90\%\ CL)$$

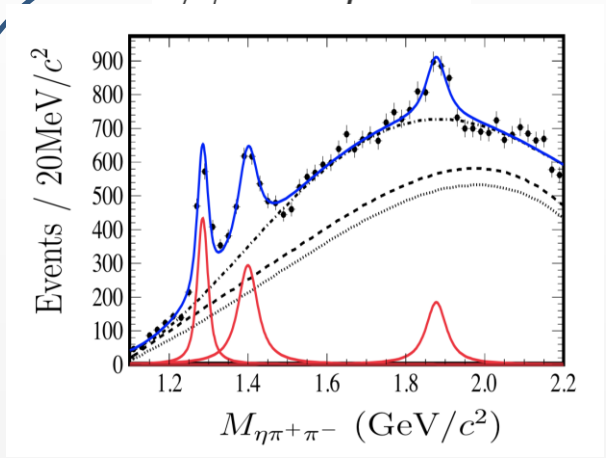
PRD83 (2011) 032003



J.J.Wu et al, PRL 108 (2012) 081803

Pseudoscalar glueball searches: η(1405/1475) J/ψ hadronic decays

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



PRL 107 (2011) 182001

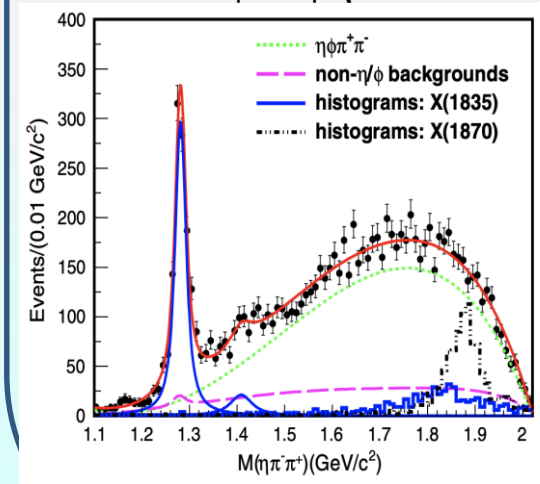
Mass, witdth and B(J/ψ →ω X) × B(X → $a_0^{\pm}(980)\pi$) × B($a_0^{\pm}(980)$ → $\eta\pi^{\pm}$)

Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}$ (10^{-4})
$f_1(1285)$	$1285.1 \pm 1.0^{+1.6}_{-0.3}$	$22.0 \pm 3.1^{+2.0}_{-1.5}$	$1.25 \pm 0.10^{+0.19}_{-0.20}$
$\eta(1405)$	$1399.8 \pm 2.2^{+2.8}_{-0.1}$	$52.8 \pm 7.6^{+0.1}_{-7.6}$	$1.89 \pm 0.21^{+0.21}_{-0.23}$
$X(1870)$	$1877.3 \pm 6.3^{+3.4}_{-7.4}$	$57 \pm 12^{+19}_{-4}$	$1.50 \pm 0.26^{+0.72}_{-0.36}$

(>10σ)

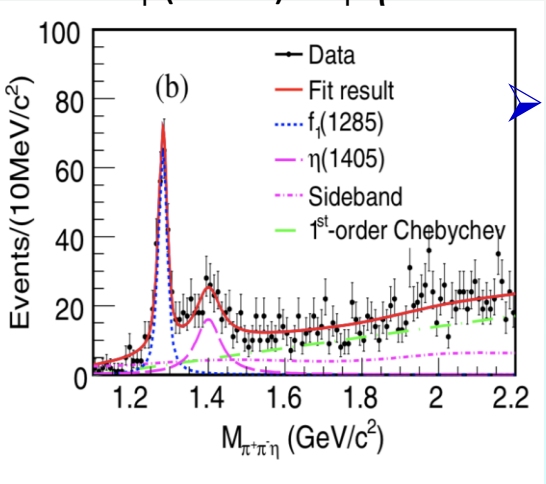
- Observed in J/ψ hadronic decays

J/ψ→φηππ



PRD97 (2015) 052017

ψ(3686)→φηππ



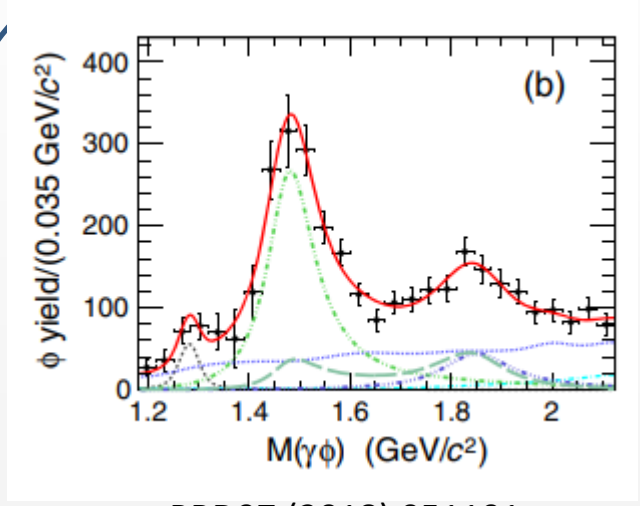
PRD100 (2019)092003

- No significant structure at~1.4GeV for J/ψ→φηππ , 3.6σ
- Larger significance (9.7σ) in ψ'→φηππ

Br(ψ'→φη(1405),η(1405)→ππη) = $(8.46 \pm 1.37_{stat} \pm 0.92_{syst}) \times 10^{-6}$

More of quark contents u and d!

Pseudoscalar glueball searches: $\eta(1405/1475)$ $J/\psi \to \gamma\gamma\phi$

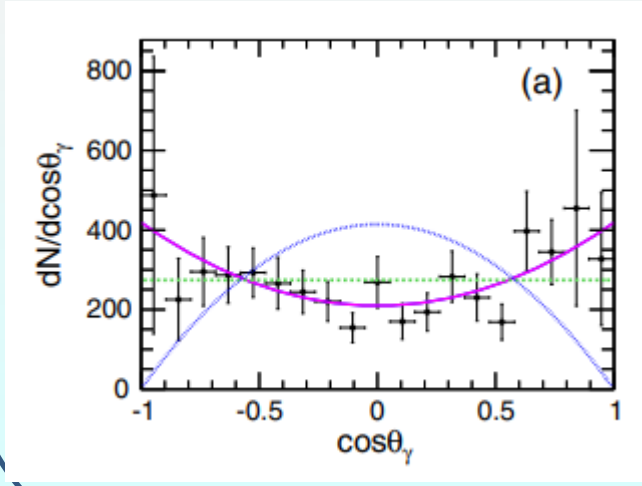


PRD97 (2018) 051101

Resonance	m_R (MeV/c^2)	Γ (MeV)	B (10^{-6})
$\eta(1475)$	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$	$10.36 \pm 1.51 \pm 1.54$
$X(1835)$	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$	$8.09 \pm 1.99 \pm 1.36$

- Observed in $J/\psi \to \gamma\gamma\phi$ using 1.3B J/ψ events
- Favor 0^{-+}
- Contain a sizeble $s\bar{s}$ component

  Not match to the expectation for 0^{-+} glueball!

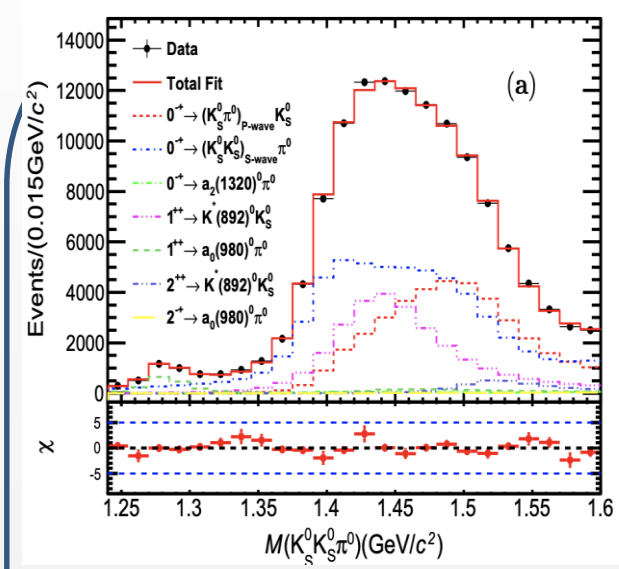


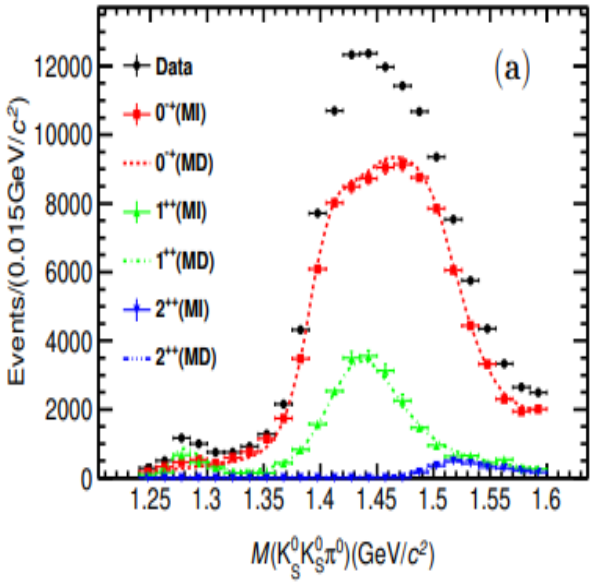
- $\dfrac{\Gamma(\eta(1475) \to \gamma\rho)}{\Gamma(\eta(1475) \to \gamma\phi)} = (11.1 \pm 3.5) : 1$

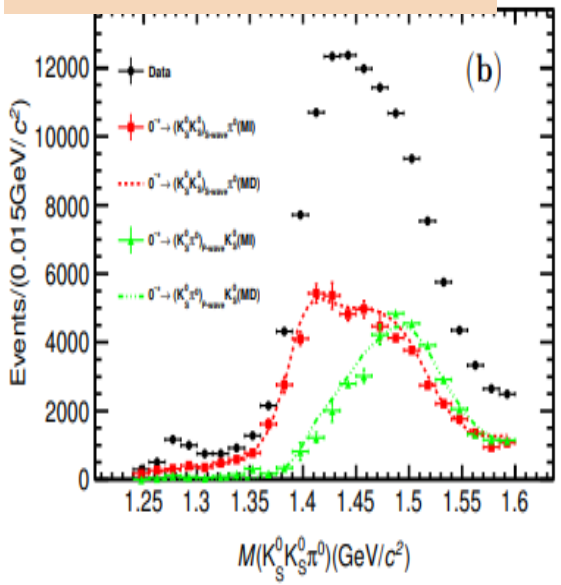
  Larger than the theory prediction 3.8:1

PWA of $J/\psi \to \gamma\gamma\phi$ ongoing using 10B J/ψ events

Pseudoscalar glueball searches: $\eta(1405/1475)$ $J/\psi \to \gamma K_S^0 K_S^0 \pi^0$







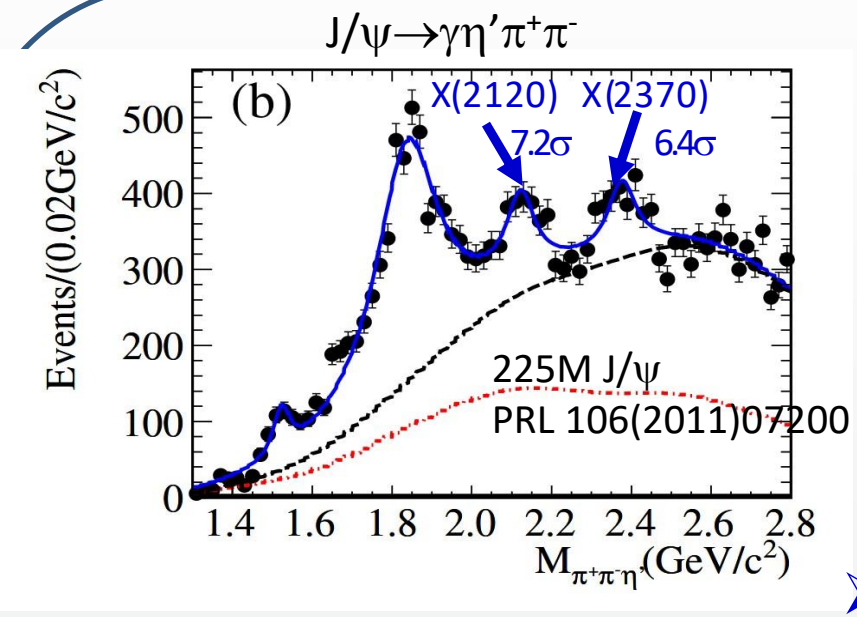
10B J/ψ; JHEP03 (2023) 121

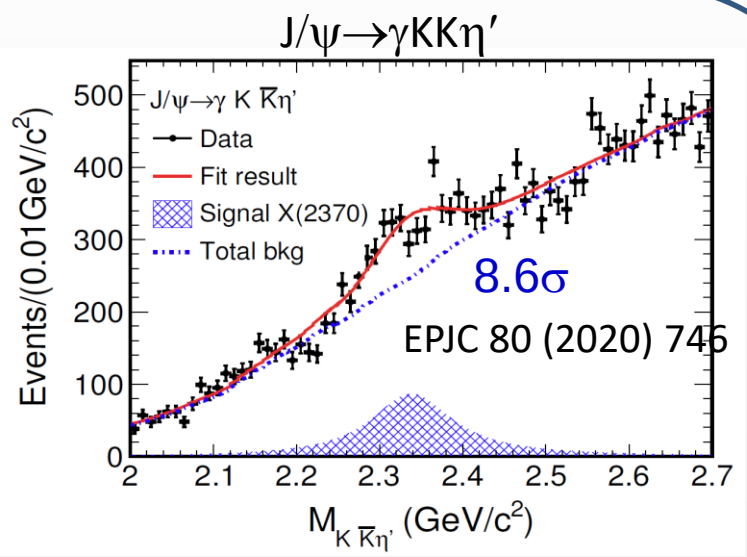
- Two pseudoscalar states needed, both decay into $(K_S^0 K_S^0)_{s-wave}\pi^0$ and $(K_S^0\pi^0)_{p-wave}K_S^0$

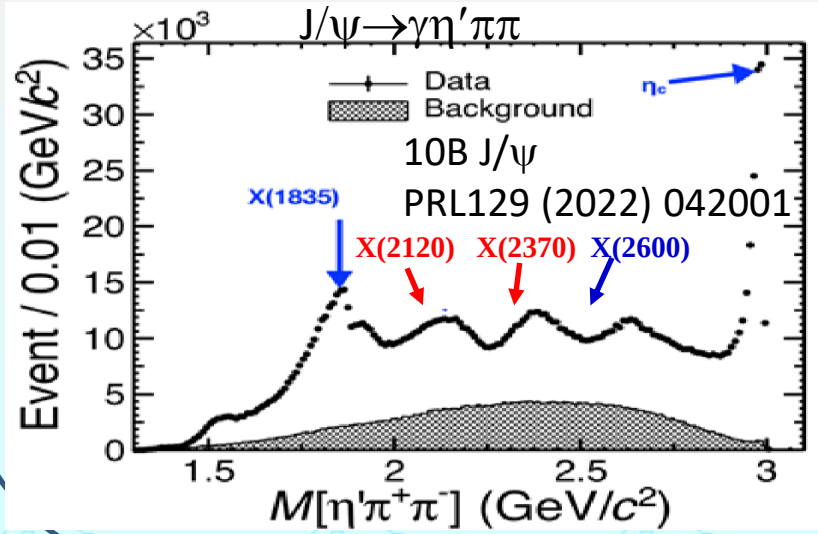
Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV})$
$\eta(1405)$	$1391.7 \pm 0.7^{+11.3}_{-0.3}$	$60.8 \pm 1.2^{+5.5}_{-12.0}$
$\eta(1475)$	$1507.6 \pm 1.6^{+15.5}_{-32.2}$	$115.8 \pm 2.4^{+14.8}_{-10.9}$

- $f_1(1285)$, $f_1(1420)$ and $f_2(1525)$ observed for the first time in this process

Pseudoscalar glueball searches: X(2370)?



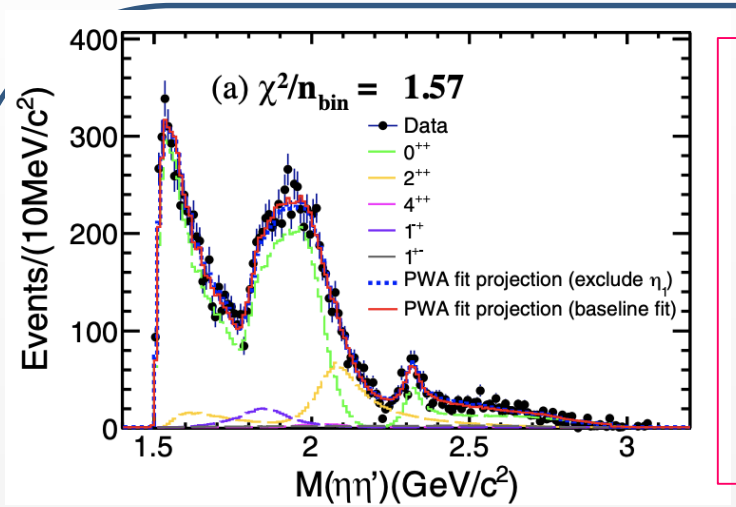




- Two structures first observed in $\eta'\pi\pi$ using 225M J/ψ events, confirmed by analysis using 10B J/ψ events
- $K\bar{K}\eta'$:
  - X(2370) observed with signif. 8.6σ;
  - no evidence signal for X(2120)

X(2370) could be 0^{-+} glueball candidate

New results about $f_0(1500)$ and $f_0(1710)$



PRD 106, 072012 (2022)

- Amplitude analysis of $J/\psi \to \gamma\eta\eta'$
- Since glueball decays to the ηη' final state are suppressed due to gauge duality, the ηη' final state is a crucial probe for distinguishing glueballs from conventional mesons

$$\frac{\mathcal{B}(f_0(1500) \to \eta\eta')}{\mathcal{B}(f_0(1500) \to \pi\pi)} = (8.96^{+2.95}_{-2.87}) \times 10^{-2}$$

→ consistent with PDG

$$\frac{\mathcal{B}(f_0(1710) \to \eta\eta')}{\mathcal{B}(f_0(1710) \to \pi\pi)} < 1.61 \times 10^{-3}$$ @90%CL.

Such suppressed decay rate supports the $f_0(1710)$ has a large overlap with the ground state scalar glueball

Resonance	M (MeV/c^2)	Γ (MeV)	M_{PDG} (MeV/c^2)	Γ_{PDG} (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$f_0(1500)$	1506	112	1506	112	$1.81 \pm 0.11^{+0.19}_{-0.13}$	$\gg 30\sigma$
$f_0(1810)$	1795	95	1795	95	$0.11 \pm 0.01^{+0.04}_{-0.03}$	11.1σ
$f_0(2020)$	$2010 \pm 6^{+6}_{-4}$	$203 \pm 9^{+13}_{-11}$	1992	442	$2.28 \pm 0.12^{+0.29}_{-0.20}$	24.6σ
$f_0(2330)$	$2312 \pm 7^{+7}_{-3}$	$65 \pm 10^{+3}_{-12}$	2314	144	$0.10 \pm 0.02^{+0.01}_{-0.02}$	13.2σ
$\eta_1(1855)$	$1855 \pm 9^{+6}_{-1}$	$188 \pm 18^{+3}_{-8}$	-	-	$0.27 \pm 0.04^{+0.02}_{-0.04}$	21.4σ

Tensors glueball candidate $f_2(2340)$

LQCD prediction:

$$\Gamma(J/\psi \to \gamma G_{2^+}) = 1.01(22) keV$$

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

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

Experimental results:

$$Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = (3.8^{+0.62\,+2.37}_{-0.65\,-2.07}) \times 10^{-5}$$

Phys.Rev. D87, 092009 (2013)

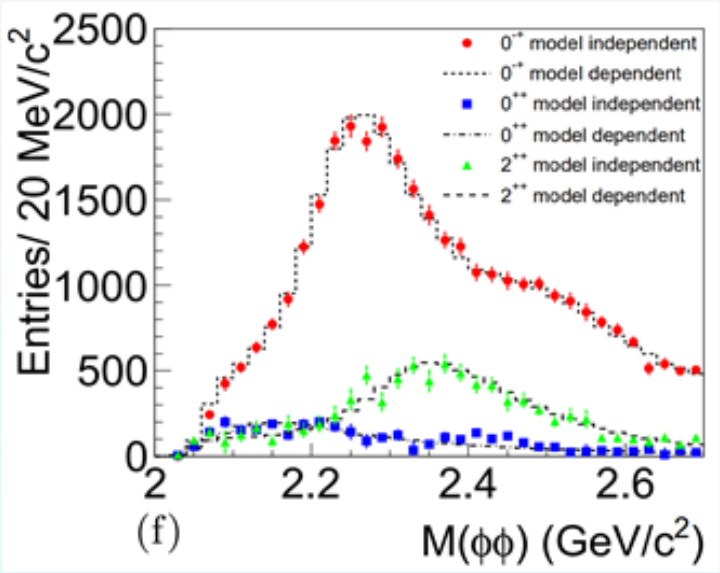
$$Br(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73}) \times 10^{-4}$$

Phys.Rev. D93, 112011 (2016)

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

Phys.Rev. D98, 072003 (2018)

PWA of $J/\psi \to \gamma\phi\phi$,1.3B J/ψ



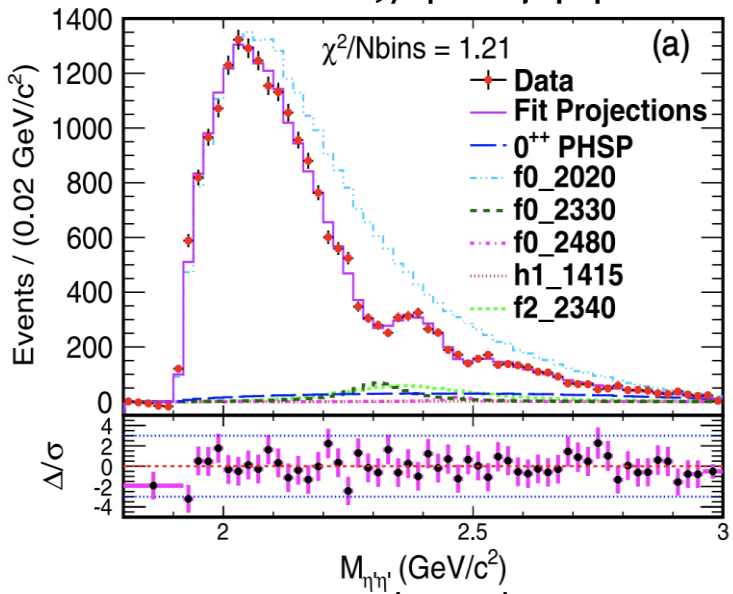
- $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ observed
- $Br(J/\psi \to \gamma f_2(2340), f_2(2340) \to \phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.73}) \times 10^{-4}$

-$f_2(2340)$ be a tensor glueball candidate

-Searches for additional decay modes are necessary.

Salars and Tensors in $J/\psi \to \gamma\eta'\eta'$

PWA of $J/\psi \to \gamma\eta'\eta'$



PRD 105 (2022) 072002

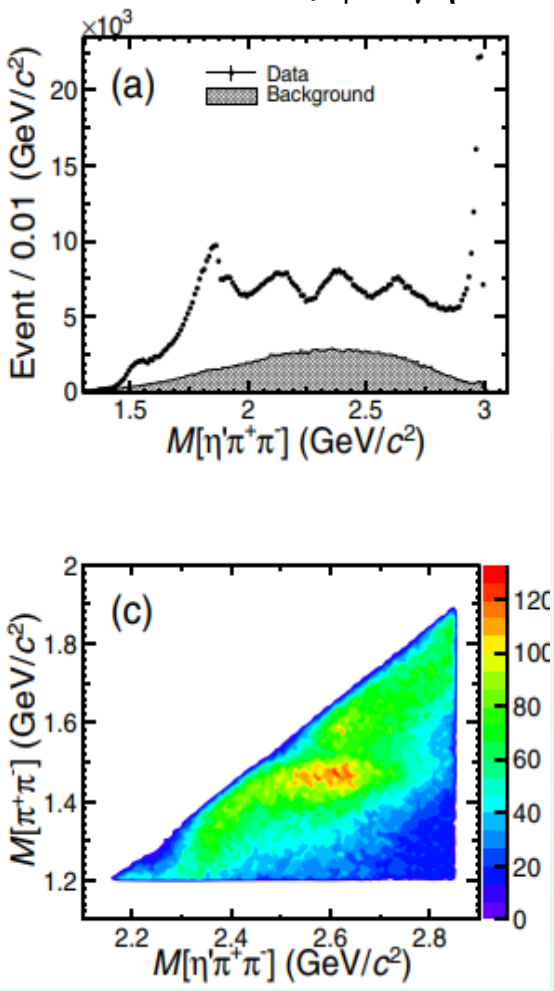
- Dominant contributions are from the $f_0(2020)$, $f_0(2330)$, $f_2(2340)$
- $f_0(2020)$, the same as $f_0(2100)$ in $J/\psi \to \gamma\eta\eta$ and $f_0(2200)$ in $J/\psi \to \gamma K_S K_S \pi^0$

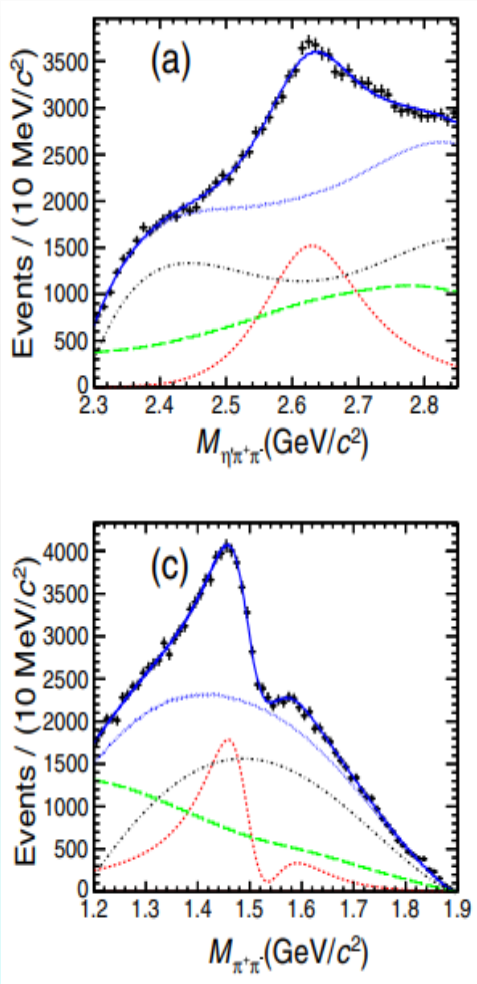
  A large overlap with 0^{++} glueball; Mass lower than the 1st excitation of 0^{++} glueball
- $f_2(2340)$ observed in $\eta'\eta'$ mode for the first time, Stat. significance 16.1σ
- new scalar $f_0(2480)$

Resonance	M(MeV/c^2)	Γ(MeV)	B.F.
$f_0(2020)$	$1982 \pm 3^{+54}_{-0}$	$436 \pm 4^{+46}_{-49}$	$(2.63 \pm 0.06^{+0.31}_{-0.46}) \times 10^{-4}$
$f_0(2330)$	$2312 \pm 2^{+10}_{-0}$	$134 \pm 5^{+30}_{-9}$	$(6.09 \pm 0.64^{+4.00}_{-1.68}) \times 10^{-6}$
$f_0(2480)$	$2470 \pm 4^{+4}_{-6}$	$75 \pm 9^{+11}_{-8}$	$(8.18 \pm 1.77^{+3.73}_{-2.23}) \times 10^{-7}$
$h_1(1415)$	$1384 \pm 6^{+9}_{-0}$	$66 \pm 10^{+12}_{-10}$	$(4.69 \pm 0.80^{+0.74}_{-1.82}) \times 10^{-7}$
$f_2(2340)$	$2346 \pm 8^{+22}_{-6}$	$332 \pm 14^{+26}_{-12}$	$(8.67 \pm 0.70^{+0.61}_{-1.67}) \times 10^{-6}$
0^{++} PHSP	...	...	$(1.17 \pm 0.23^{+4.09}_{-0.70}) \times 10^{-5}$

A new exotic X(2600) in $J/\psi\to\gamma\eta'\pi^+\pi^-$

$J/\psi\to\gamma\eta'\pi^+\pi^-$ 10B J/ψ events



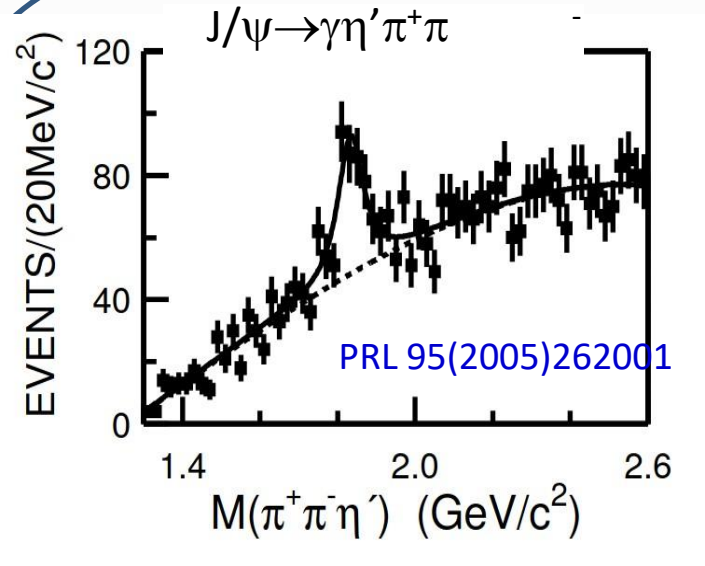


PRL 129(2022)042001

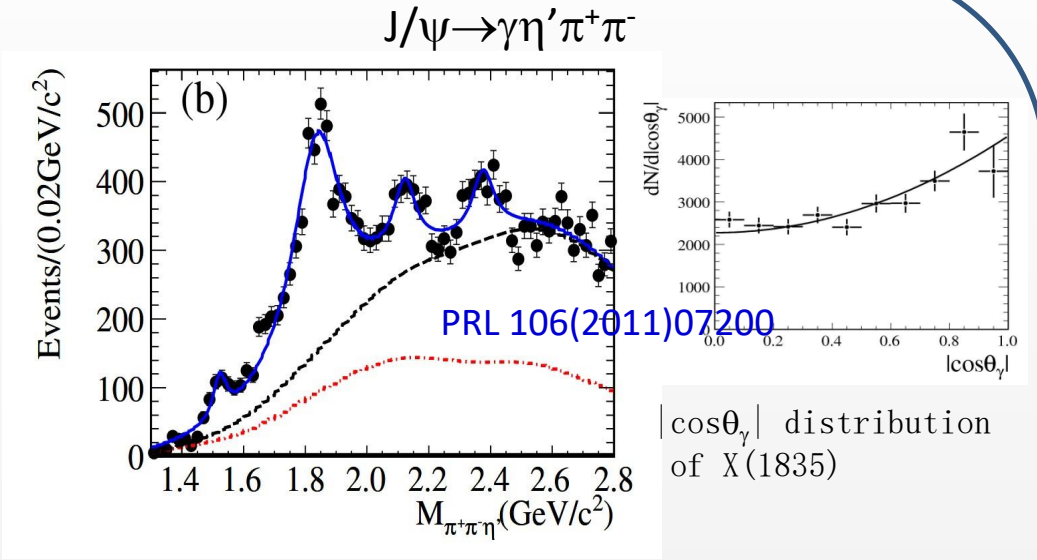
- A new state X(2600)
  -- stat. signif. >20σ
  -- connection with a structure ~1.5GeV in $\pi\pi$ mass spectrum
- $M = 2618.3 \pm 2.1^{+16.3}_{-1.4}$MeV
  $\Gamma = 195 \pm 5^{+26}_{-17}$MeV
- 0^{-+} or 2^{-+} is favored for X(2600)

an η radial excitation?
or an exotic hadron?
J^{PC} ?

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



58M J/ψ events (BESII)



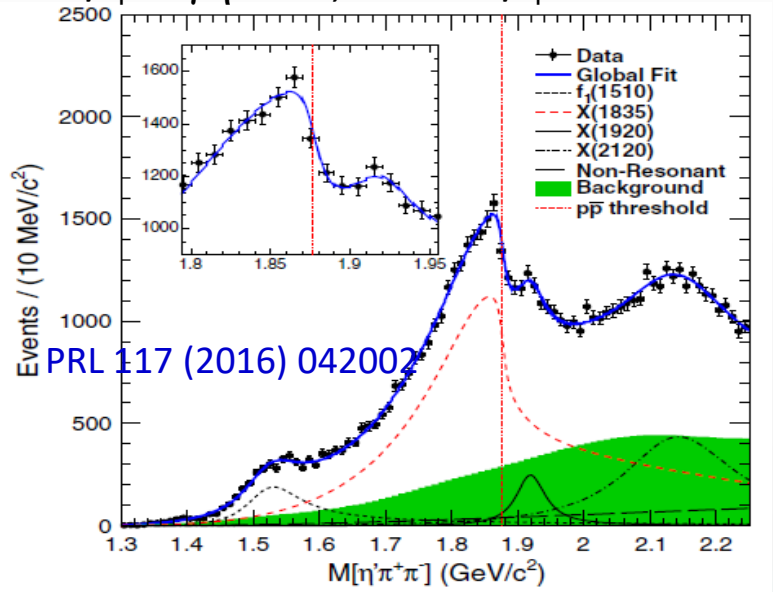
225M J/ψ events (BESIII)

- First observed exotic X(1835)
  - significance 7.7σ,
  - M=1833.7±6.1±2.7 MeV/c^2
    Γ=67.7±20.3±7.7 MeV/c^2
  - prime candidate for the source of $p\bar{p}$ mass threshold in $J/\psi\to\gamma p\bar{p}$

- X(1835) confirmed
  - significance >20σ
  - $M = 1836.5 \pm 3.0^{+5.6}_{-2.1}$ MeV/c^2
    $\Gamma = 190 \pm 9^{+38}_{-36}$ MeV/c^2
  - angular distribution consists with 0^-

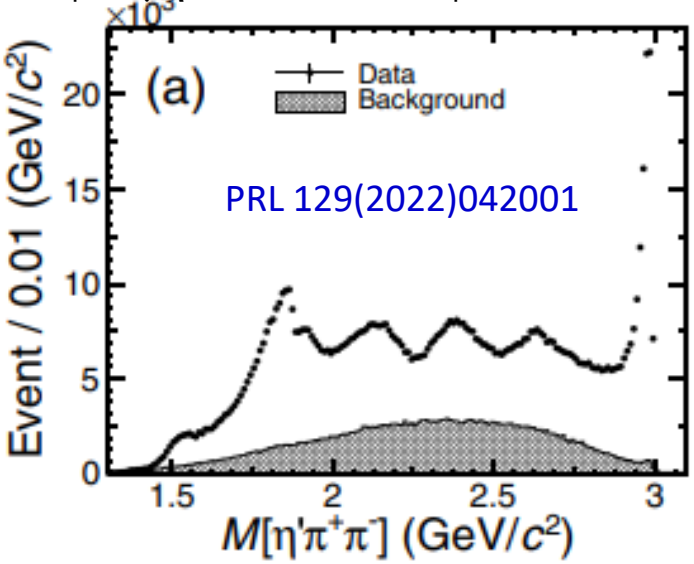
Exotic X(1835) in $J/\psi \to \gamma\eta'\pi^+\pi^-$

$J/\psi \to \gamma\eta'\pi^+\pi^-$, 1.09 B J/ψ events



PRL 117 (2016) 042002

$J/\psi \to \gamma\eta'\pi^+\pi^-$, 10 B J/ψ events

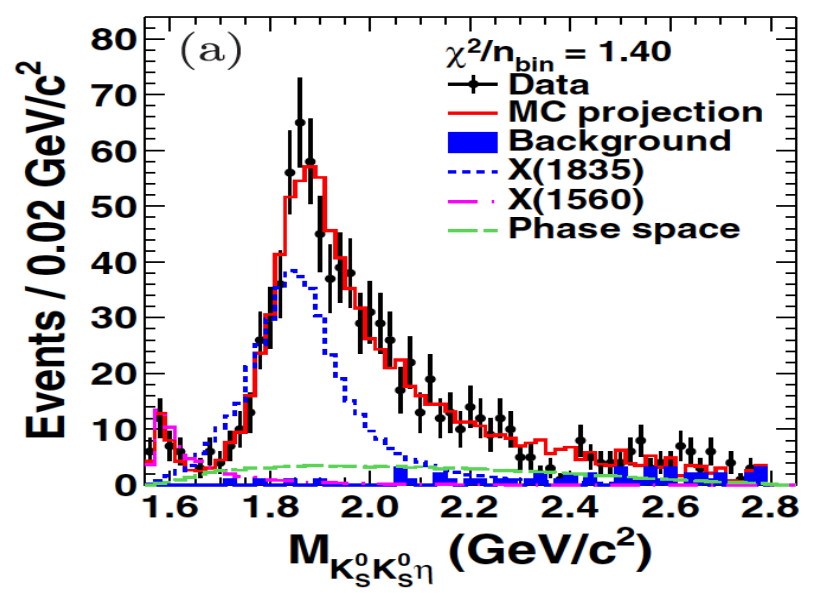


PRL 129(2022)042001

- a significant distoration near $P\bar{P}$ mass threshold
- two models used to describe the anomalous line shape :
  flatte formula or the coherent sum of two resonant amplitudes.
  Both support the existence of a $p\bar{p}$ molecule-like state or bound state

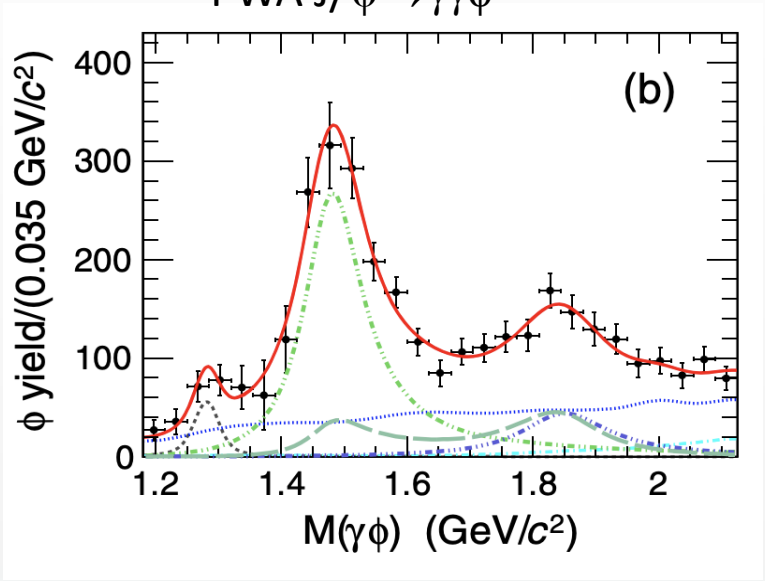
Exotic X(1835) in $J/\psi \to \gamma K_S^0 K_S^0 \eta$ and $\gamma\gamma\phi$

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



PRL 115, 091803(2015)

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



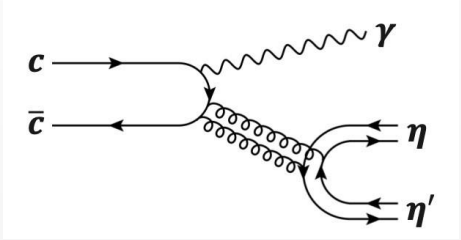
PRD97, 051101(2018)

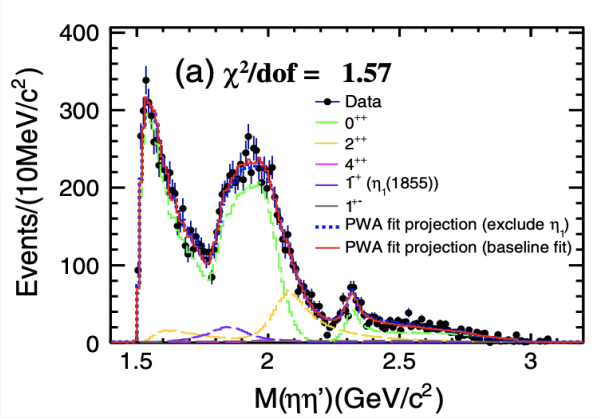
- Observed in KsKsη invariant mass spectrum
  $J^{PC} = 0^{-+}$ determined by performing PWA, using 1.3B J/ψ events
- Observed in $\gamma\phi$ invariant mass spectrum
  $J^{PC} = 0^{-+}$ favored by performing angle distribution fit, using 1.3B J/ψ events

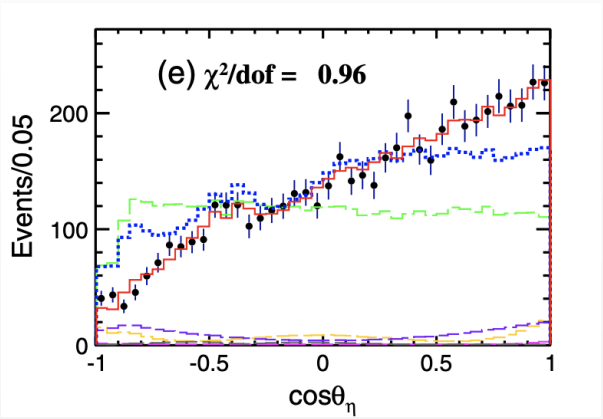
Contains a sizeable $s\bar{s}$ component!

Observation of $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$

PWA of $J/\psi \to \gamma\eta\eta'$ ($\eta' \to \gamma\pi^+\pi^-/\eta\pi^+\pi^-$) using 10B J/ψ events







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

- Isoscalar state $\eta_1(1855)$ with exotic quantum numbers $J^{PC} = 1^{-+}$
  a stat. significance >19σ
- Mass is consistent with LQCD calculation for the 1^{-+} hybrid (1.7–2.1GeV)

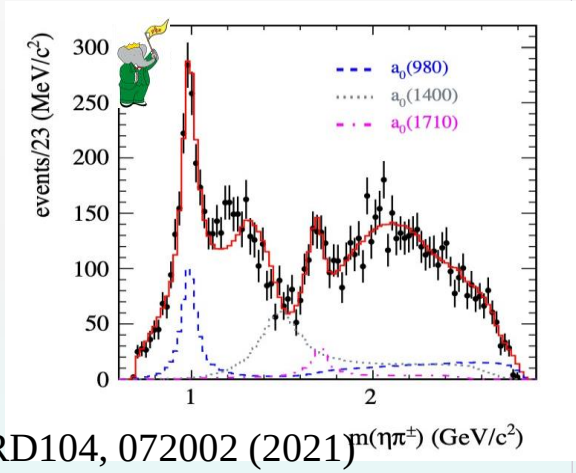
$$M = (1855 \pm 9^{+6}_{-1})MeV$$
$$\Gamma = (188 \pm 18^{+3}_{-8})MeV$$
$$\mathcal{B}(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$$

- Critical to establish the 1^{-+} hybrid nonet !

Light hadrons in open-charm decays

Ground state	Radial excited states	Next radial excitation	higher radial excitation
$f_0(500)$, $f_0(980)$:0^{++}, I=0 $a_0(980)$: 0^{++}, I=1	$f_0(1370)$, $f_0(1500)$ $a_0(1450)$	$f_0(1710)$, $f_0(1770)$ **$a_0(1710)$?**	X(1812) $a_0(1817)$?

BaBar $\eta_c \to \eta\pi^+\pi^-$



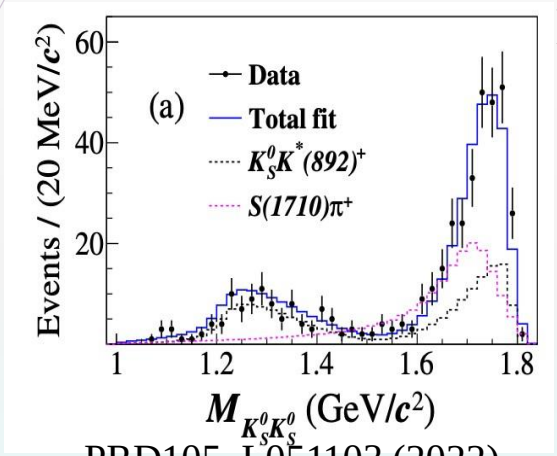
PRD104, 072002 (2021)

$a_0(1710)^{\pm}$:

M=1704±5$_{stat}$±2$_{syst}$ MeV/c^2

Γ=110±15$_{stat}$±11$_{syst}$ MeV/c^2

BESIII $D_s^+ \to K_S^0 K_S^0 \pi^+$



PRD105, L051103 (2022)

- $\mathcal{B}(D_s^+ \to S(980)\pi^+) < 1.8 \times 10^{-4}$ @ 90% CL

suppression attributed to the destructive interference between $a_0(980)$ and $f_0(980)$

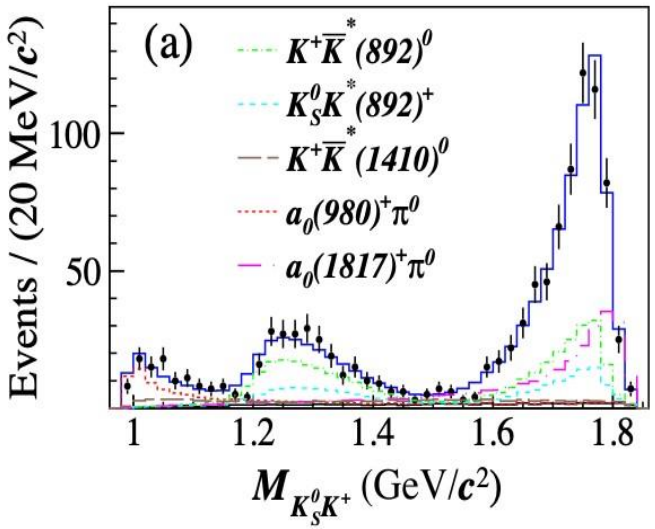
- $\mathcal{B}(D_s^+ \to S(1710)\pi^+) = (0.31 \pm 0.03 \pm 0.01)\%$

- one order of magnitude larger than expectation.

- implies the existence of $a_0(1710)$

Light hadrons in open-charm decays

Ground state	Radial excited states	Next radial excitation	higher radial excitation
$f_0(500)$, $f_0(980)$:0^{++}, I=0 $a_0(980)$: 0^{++}, I=1	$f_0(1370)$, $f_0(1500)$ $a_0(1450)$	$f_0(1710)$, $f_0(1770)$ $a_0(1710)$?	X(1812) **$a_0(1817)$?**



PRL129, 182001 (2022

Amplitude analysis of $D_s^+ \to K_S^0 K^+ \pi^0$ based on 6.32fb^{-1} data between 4.178 and 4.226GeV

➢ Observed $a_0(1817)$ for the first time

$M = (1.817 \pm 0.008_{stat} \pm 0.020_{syst})$ GeV/c^2

$\Gamma = (0.097 \pm 0.022_{stat} \pm 0.015_{syst})$ GeV/c^2

-- the mass is ~100MeV greater than the predicted value for $a_0(1710)$

-- $a_0(1817)$ could be the isovector partner of the X(1812)

➢ A more sophisticated study of this a_0-like state is necessary

Summary

- Rich physics in light hadrons
- Charmonium data provides a unique opportunity to map the light hadron spectroscopy and search for glueball and exotic states

  - $\eta(1405)/\eta(1475)$ puzzle:
    - a sizeble $s\bar{s}$ component
    - not match to the expectation for 0^{-+} glueball
    - two separated states in $J/\psi \to \gamma K_S^0 K_S^0 \pi^0$

  - X(1835),X(2120),X(2370) and X(2600) observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$
    - 0^{-+} glueball candidate X(2370)

  - $f_2(2340)$ observed in $\eta'\eta'$ mode for the first time in $J/\psi \to \gamma\eta'\eta'$
    - a tensor glueball candidate

Summary

- first observation of exotic 1^{-+} state $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$
- new results on $f_0(1500)$ and $f_0(1710)$ in $J/\psi \to \gamma\eta\eta'$
  - $f_0(1710)$ has a large overlap with the ground state scalar glueball

➢ Light hadrons $a_0(1710)$ and $a_0(1817)$ observed in open-charm decays

➢ More surprise at BESIII are expected

I am sorry for not being able to cover all the important results.

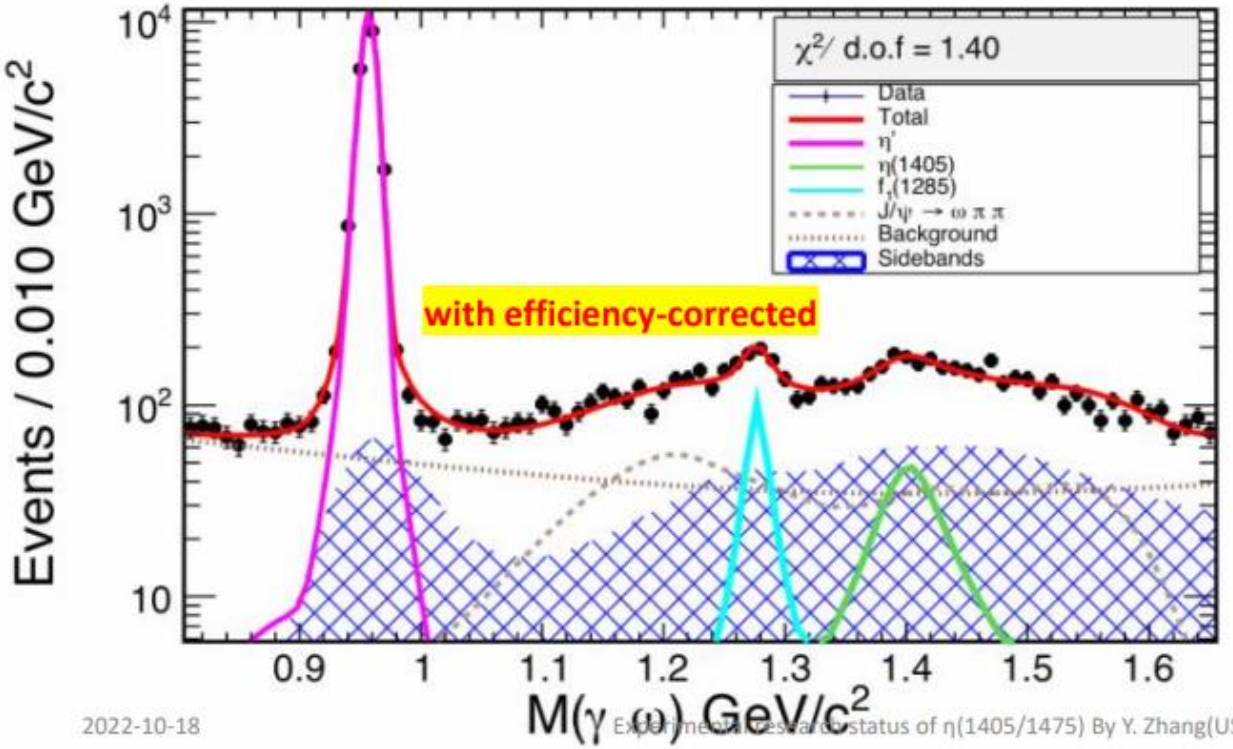
Thanks for your attention!

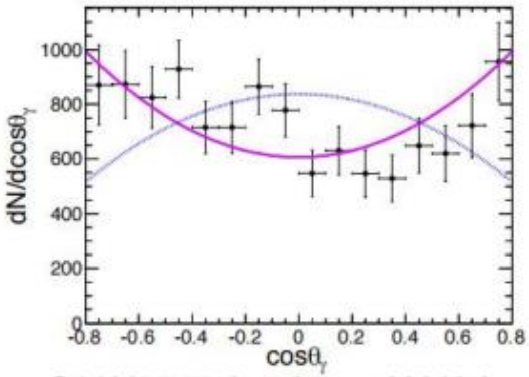
J^{PC}	0^{++}	0^{+-}	0^{-+}	0^{--}	1^{++}	1^{+-}	1^{-+}	1^{--}	2^{++}	2^{+-}	2^{-+}	2^{--}	3^{++}	3^{+-}	3^{-+}	3^{--}
$q\bar{q}$	✓	×	✓	×	✓	✓	×	✓	✓	×	✓	✓	✓	✓	×	✓
$q\bar{q}q\bar{q}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$q\bar{q}g$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
gg	✓	×	✓	×	✓	×	✓	×	✓	×	✓	×	✓	×	✓	×

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

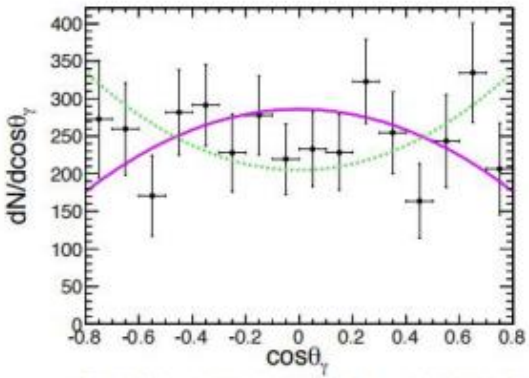
BESIII preliminary result
From X.S Kang, G.F Xu's report

$f_1(1285)$	1276.6±2.1	17.2±6.4
$\eta(1405)$	1400.8±5.2	55.1±15.9





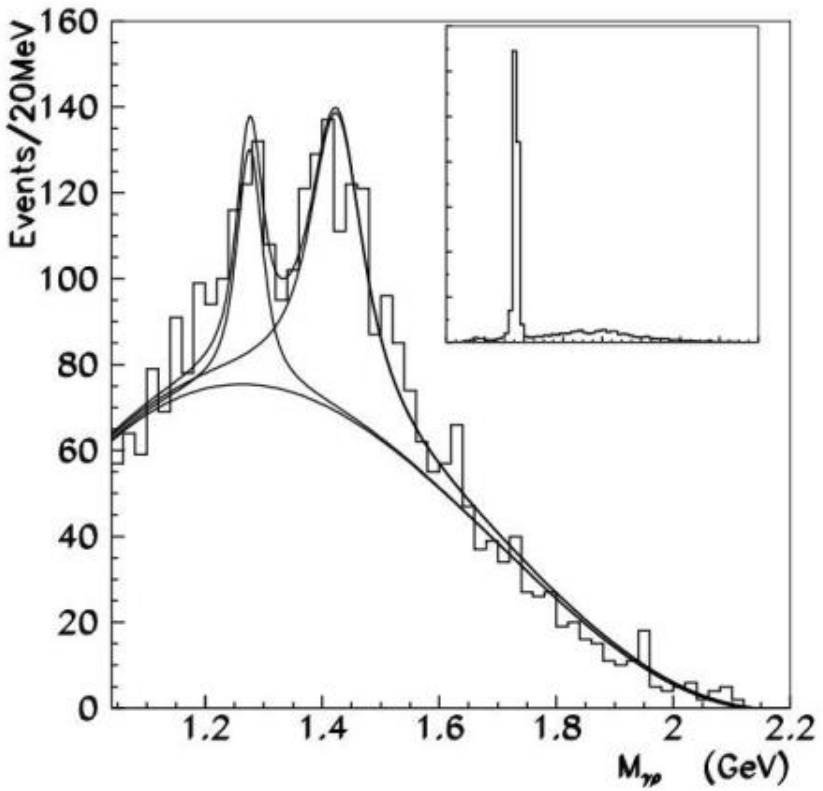
@1400MeV 0^-: -lnL = -93048.9
1^+: -lnL = -92753.4
Favors 0^- [η(1405)]



@1300MeV 0^-: -lnL = -27171.6
1^+: -lnL = -27183.4
Nearly equal goodness

$J/\psi \to \gamma\gamma\rho$ (BESII)

Phys.Lett.B 594 (2004) 47-53



$J/\psi \to \gamma X(X \to \gamma\rho)$ results.

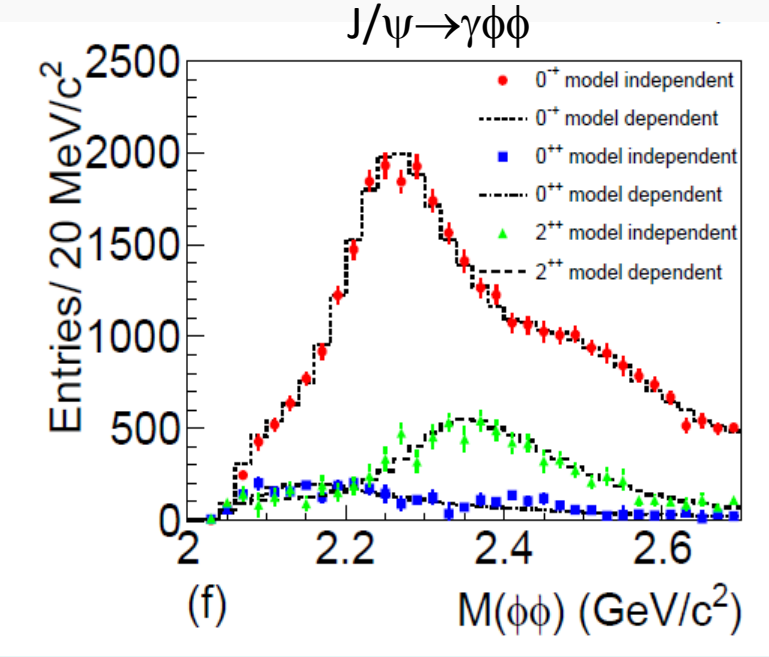
Mass (MeV/c^2)	Width (MeV/c^2)	$B(J/\psi \to \gamma X \to \gamma\gamma\rho)$ ($\times 10^{-4}$)	Events	Signi-ficanc
$1276.1 \pm 8.1 \pm 8.0$	$40.0 \pm 8.6 \pm 9.3$	$0.38 \pm 0.09 \pm 0.06$	203 ± 49	6.3σ
$1424 \pm 10 \pm 11$	$101.0 \pm 8.8 \pm 8.8$	$1.07 \pm 0.17 \pm 0.11$	547 ± 86	9.3σ

Comparison with other experiments

Decay Mode	Mass (MeV/c^2)	Width (MeV/c^2)	$B(J/\psi \to \gamma X) * B(X \to \gamma V)$ ($\times 10^{-4}$)	Experi-ment
$f_1(1285)$	1281.9 ± 0.6	24.0 ± 1.2	0.34 ± 0.09	PDG [1]
$\to \gamma\rho^0$	1271 ± 7	31 ± 14	$0.25 \pm 0.07 \pm 0.03$	MarkIII [7]
	$1276.1 \pm 8.1 \pm 8.0$	$40.0 \pm 8.6 \pm 9.3$	$0.38 \pm 0.09 \pm 0.06$	BESII
$\eta(1440)$	1400-1470	50-80	$0.64 \pm 0.12 \pm 0.07$	PDG [1]
$\to \gamma\rho^0$	1432 ± 8	90 ± 26	$0.64 \pm 0.12 \pm 0.07$	MarkIII [7]
	$1424 \pm 10 \pm 11$	$101.0 \pm 8.8 \pm 8.8$	$1.07 \pm 0.17 \pm 0.11$	BESII
$\eta(1440)$			< 0.82 (95% C.L)	BESII
$\to \gamma\phi$				

Pseudoscalar states above 2GeV

Aside from η(2225), the structure in pseudoscalar sector above 2GeV are poorly understood.

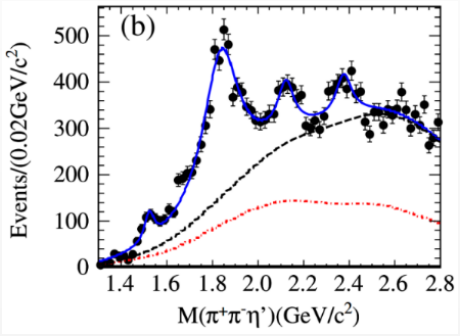


1.3B J/ψ, PRD93 (2016) 112011

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

- Dominant contribution from 0^{-+}: η(2225), η(2100) and X(2500)
- Three 2^{++}: $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$

Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold



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

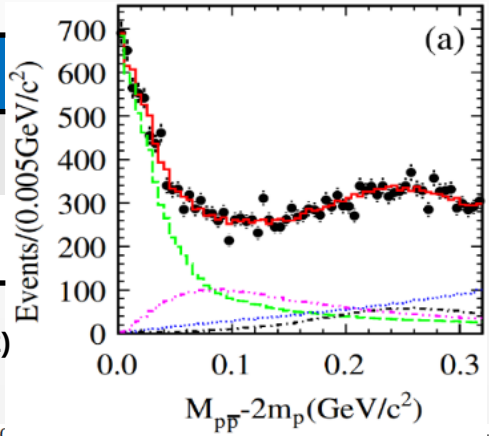
X(1835) $J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2

PRL 106, 072002 (2011)

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

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

PRL 108, 112003 (2012)

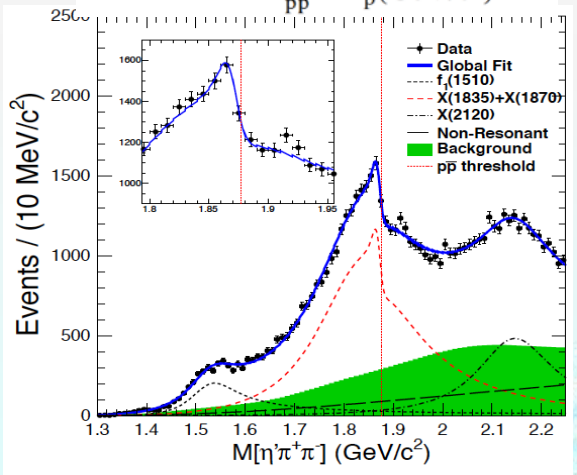


connection between X(1835) and X($p\bar{p}$)

The anomalous line shape :

-- Suggest the existence of a state, either a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold

-- Support the existence of a $p\bar{p}$ molecule-like state or bound state



PRL 117, 042002 (2016)

Landscape of light glueball has updated

Scalar: Overpopulation

- LQCD : ground state 0^+ glueball ~1.7 GeV, first excitation ~2.1 GeV

✓ **Strong production of $f_0(1710)/f_0(2100)$ in $J/\psi \to \gamma\eta\eta/KK/\pi\pi$** , the pattern consists with LQCD' s prediction

Tensor: large uncertainty

- LQCD: 2^{++}(2.3~2.4 GeV)

✓ **Strong production of $f_2(2340)$ in $J/\psi \to \gamma\eta\eta/KK/\pi\pi/\phi\phi$** ; consists with LQCD' s prediction

Pseudoscalar: very little known above 2 GeV, puzzles in low mass region

- LQCD: 0^{-+}(2.3~2.6 GeV)

✓ **Trajectory:**

- **$f_1(1285)$, no $\eta(1295)$**
- **$\eta(1405)$ /$\eta(1475)$ can be two resonances?**

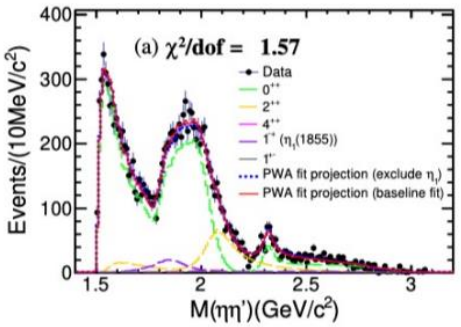
□ **Above 2 GeV: X(2370)?**

Discussions about $f_0(1500)$ & $f_0(1710)$ $J/\psi \to \gamma\eta\eta'$

- Significant $f_0(1500)$

$$\frac{B(f_0(1500) \to \eta\eta')}{B(f_0(1500) \to \pi\pi)} = (1.66^{+0.42}_{-0.40}) \times 10^{-1}$$

consistent with PDG



- **Absence of $f_0(1710)$**

$$\frac{B(f_0(1710) \to \eta\eta')}{B(f_0(1710) \to \pi\pi)} < 2.87 \times 10^{-3} \ @90\%\ \text{C. L.}$$

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	M_{PDG} (MeV/c^2)	Γ_{PDG} (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg 30\sigma$
	$f_0(1810)$	1795	95	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	1992	442	$2.28\pm0.12^{+0.29}_{-0.20}$	24.6σ
	$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	2314	144	$0.10\pm0.02^{+0.01}_{-0.02}$	13.2σ
	$\eta_1(1855)$	$1855\pm9^{+6}_{-1}$	$188\pm18^{+3}_{-8}$	-	-	$0.27\pm0.04^{+0.02}_{-0.04}$	21.4σ
	$f_2(1565)$	1542	122	1542	122	$0.32\pm0.05^{+0.12}_{-0.02}$	8.7σ
	$f_2(2010)$	$2062\pm6^{+10}_{-7}$	$165\pm17^{+10}_{-5}$	2011	202	$0.71\pm0.06^{+0.10}_{-0.06}$	13.4σ
	$f_4(2050)$	2018	237	2018	237	$0.06\pm0.01^{+0.03}_{-0.01}$	4.6σ
	0^{++} PHSP	-	-	-	-	$1.44\pm0.15^{+0.10}_{-0.20}$	15.7σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	1416	90	$0.08\pm0.01^{+0.01}_{-0.02}$	10.2σ
	$h_1(1595)$	1584	384	1584	384	$0.16\pm0.02^{+0.03}_{-0.01}$	9.9σ

➢ Supports to the hypothesis that $f_0(1710)$ overlaps with the ground state scalar glueball

- Scalar glueball expected to be suppressed

$B(G \to \eta\eta')/B(G \to \pi\pi) < 0.04$

Prospects for 1^{-+} hybrids

- **Together with $\pi_1(1600)$**

  Opens a new direction to completing the picture of the hybrid multiplets

- **LQCD: B($J/\psi \to \gamma\eta_1$(hybrid)~O(10^{-5}) [2207.04694]**

  $\eta\eta'$ is not a dominate mode→ Search for more

- **Interpretations: Hybrid/$K\bar{K}_1$Molecule/Tetraquark?**

Isoscalar: $\eta_1(1855)$

- Decay properties

  $J/\psi \to \gamma\eta f_1$, K_1Kbar, ……
- Production properties

  $J/\psi \to \omega\eta\eta'$, $\phi\eta\eta'$, ……
- Where is $\eta_1^{(\prime)}$ and other partners?
- Analogs in the heavy sector ?

Isovector: $\pi_1(1600)$

- $J/\psi \to \rho\eta'\pi$, ……
- $\chi_{c1} \to \pi\pi b_1, \pi\pi f_1, \pi\pi\eta'$, ……
- LQCD predicted major decay modes: πb_1, πf_1

➢ Data with unprecedented statistical accuracy from BESIII provides great opportunities to study QCD exotics. Will continue to run until ~2030

➢ To explore the high statistics data sets, synergies between experiment and theory are essential