Hadron Spectroscopy at BESIII

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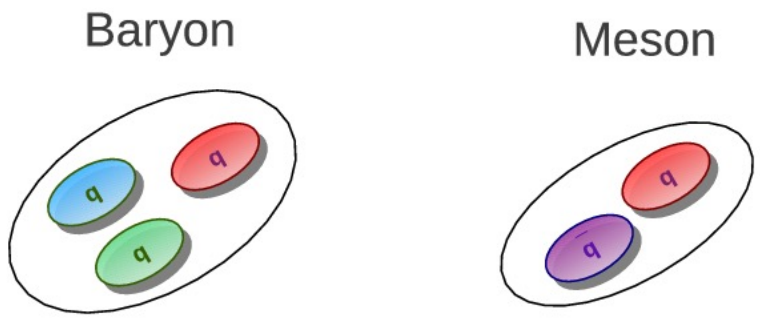
Outline

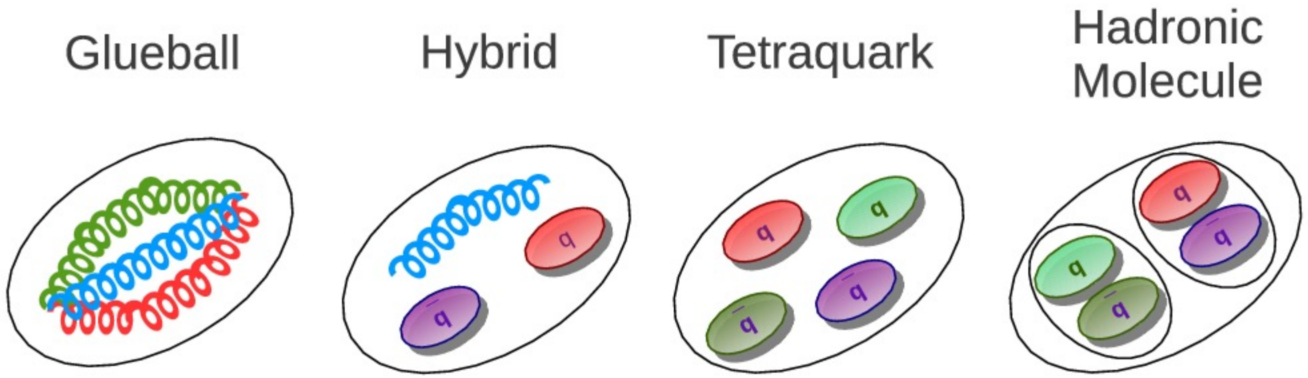
- Status of BEPCII/BESIII
- Highlights of hadron spectroscopy
  - Light exotics
  - XYZ particles
- Future prospects

Ordinary vs exotic matter

- Conventional hadrons

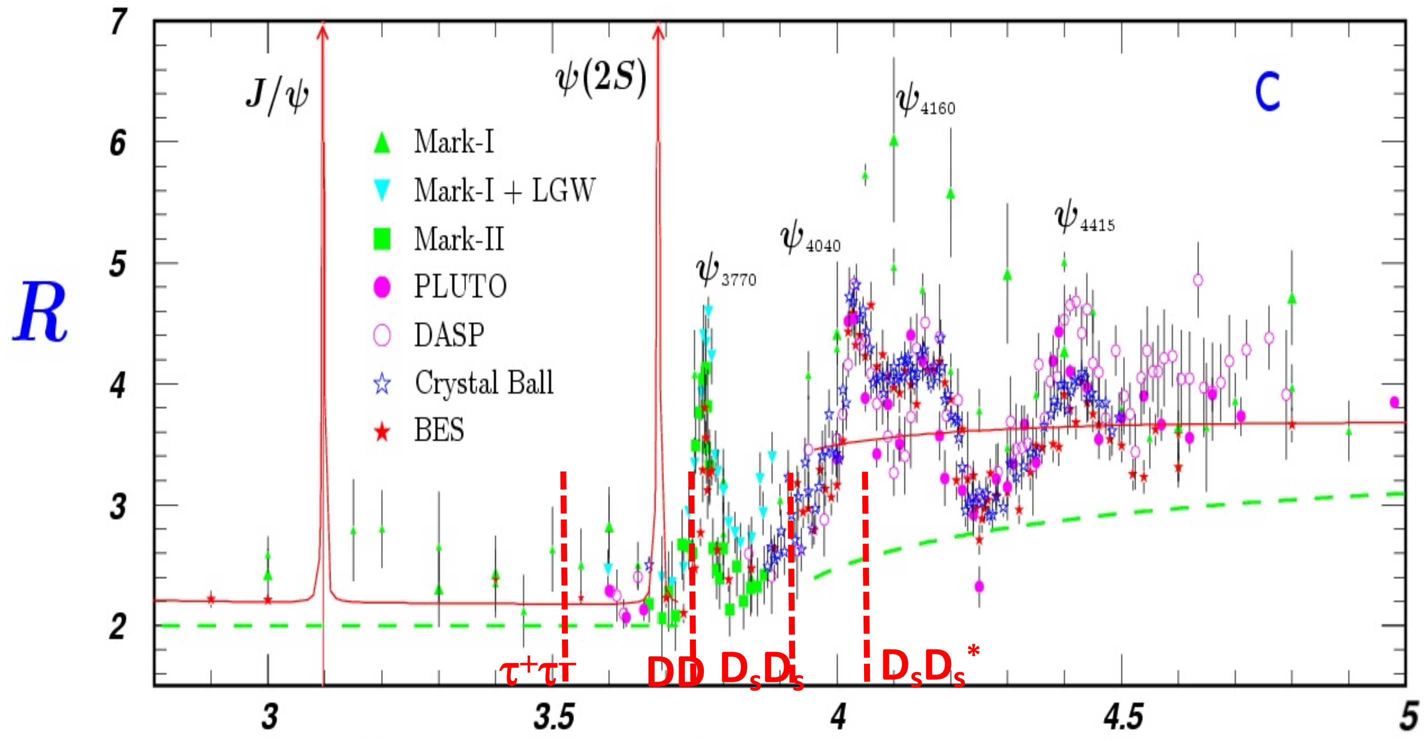


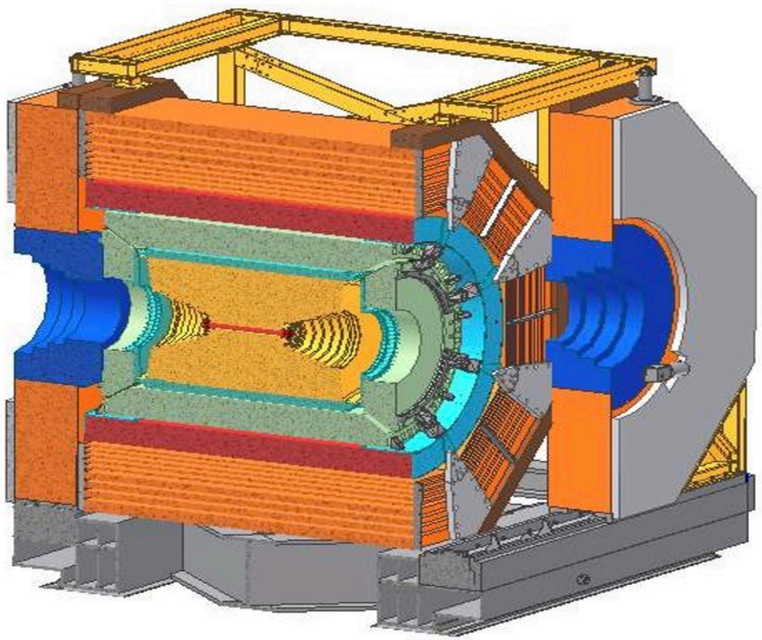
- QCD allows for "exotics"



- Searching for those states provides test of QCD

BEPCII/BESIII : τ-charm factory



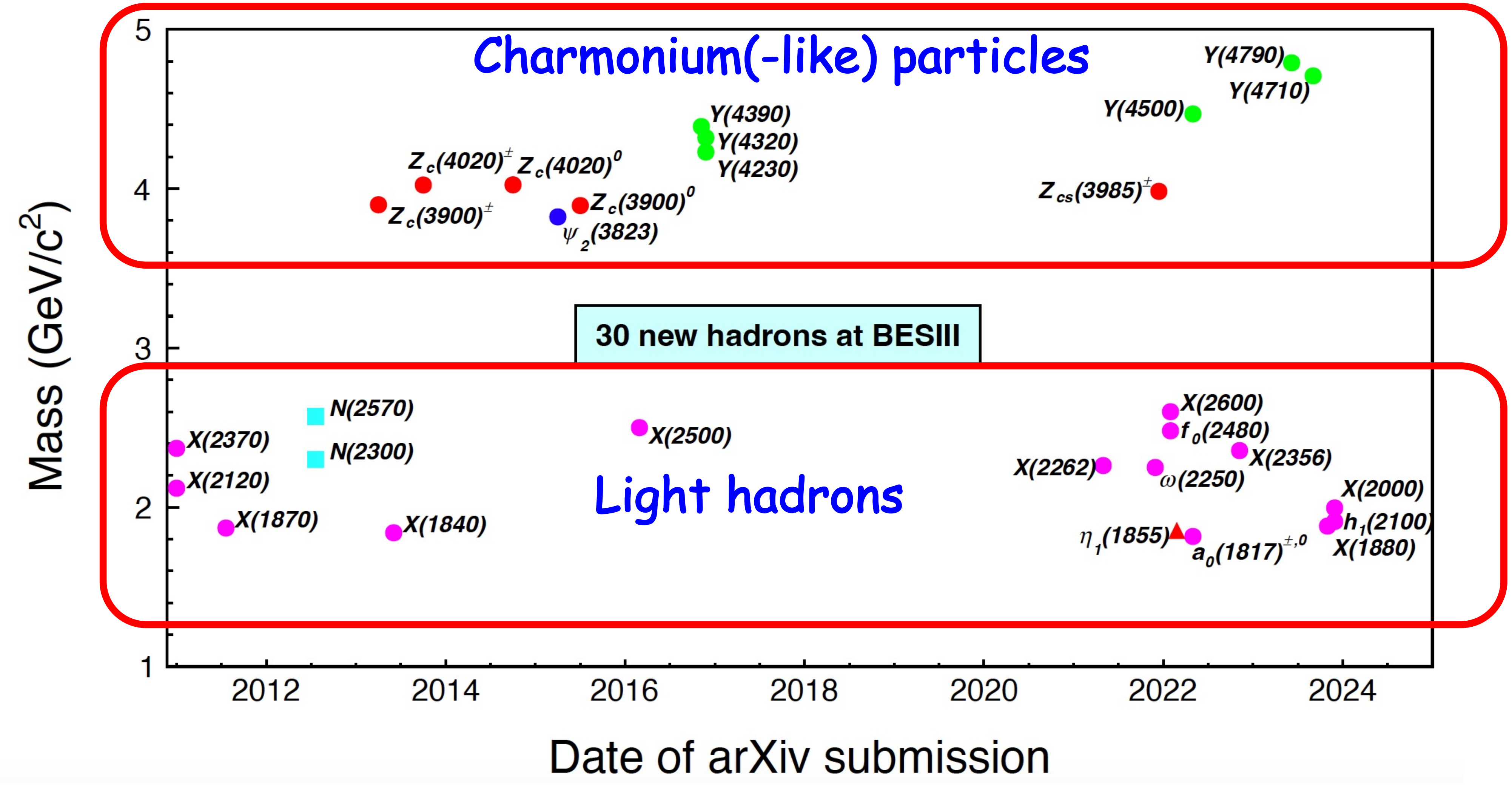


- Charmonium physics
- Light hadron physics
- Charm physics
- R-QCD physics

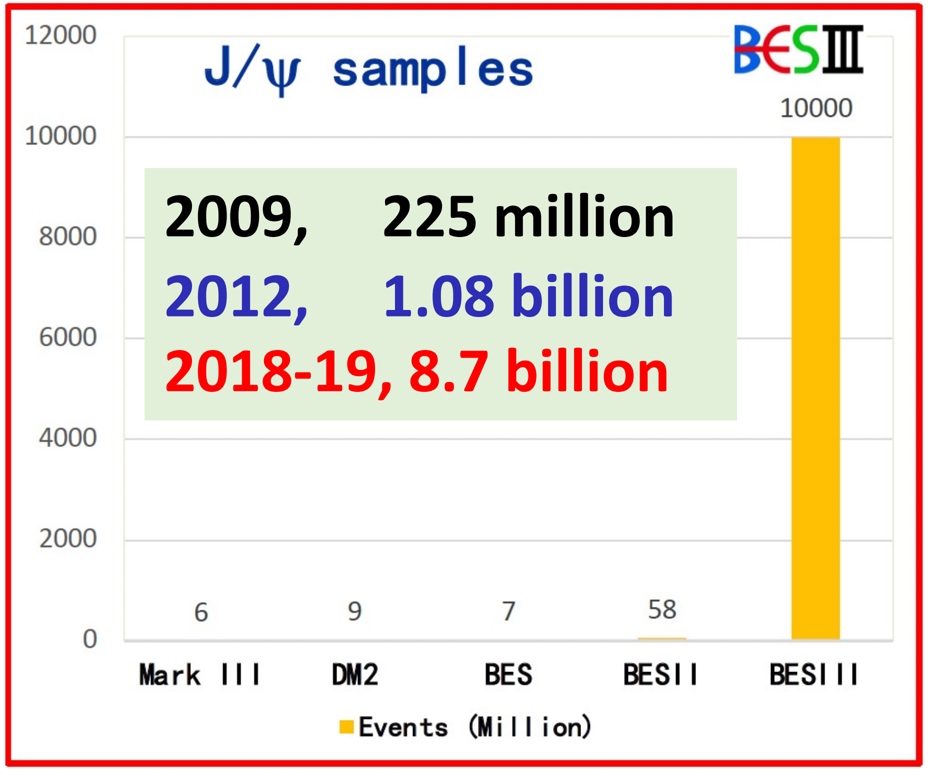
BESIII: ~50 fb^{-1} data in E_{cm} = 2-4.95 GeV

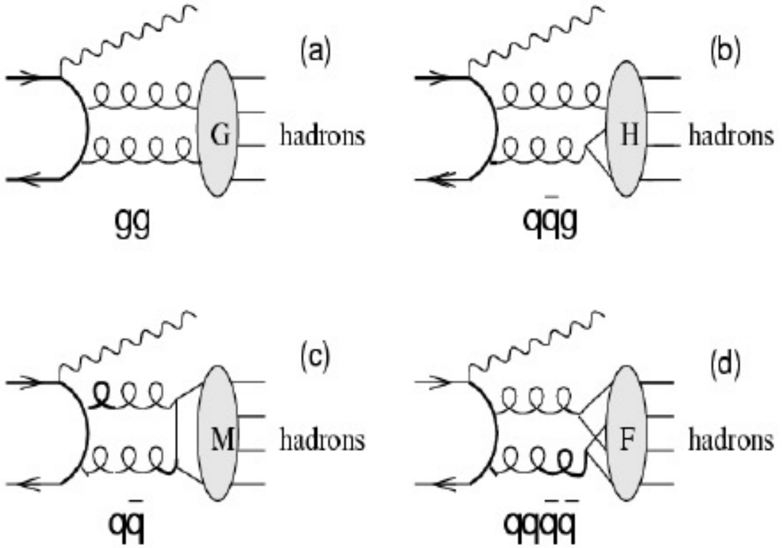
World largest data sample directly collected in the τ-charm region

New resonant structures at BESIII



J/ψ : an ideal lab for light hadron spectroscopy



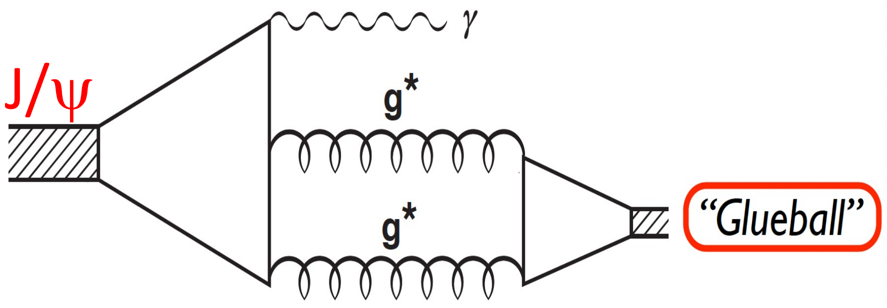


- Especially radiative J/ψ decays : gluon rich production
- Production rates for exotic hadrons is expected to be compatible to the ones for conventional hadrons.

Glueball searches

Two big issues

- What is the production mechanism to utilize?
- What is the mixing with quark model mesons?



Production rate could be calculable in LQCD, but the manifestation of a "glueball" can be tricky!

Chanowitz, Phys.Rev.Lett. 95(2005)172001

Systematic studies needed

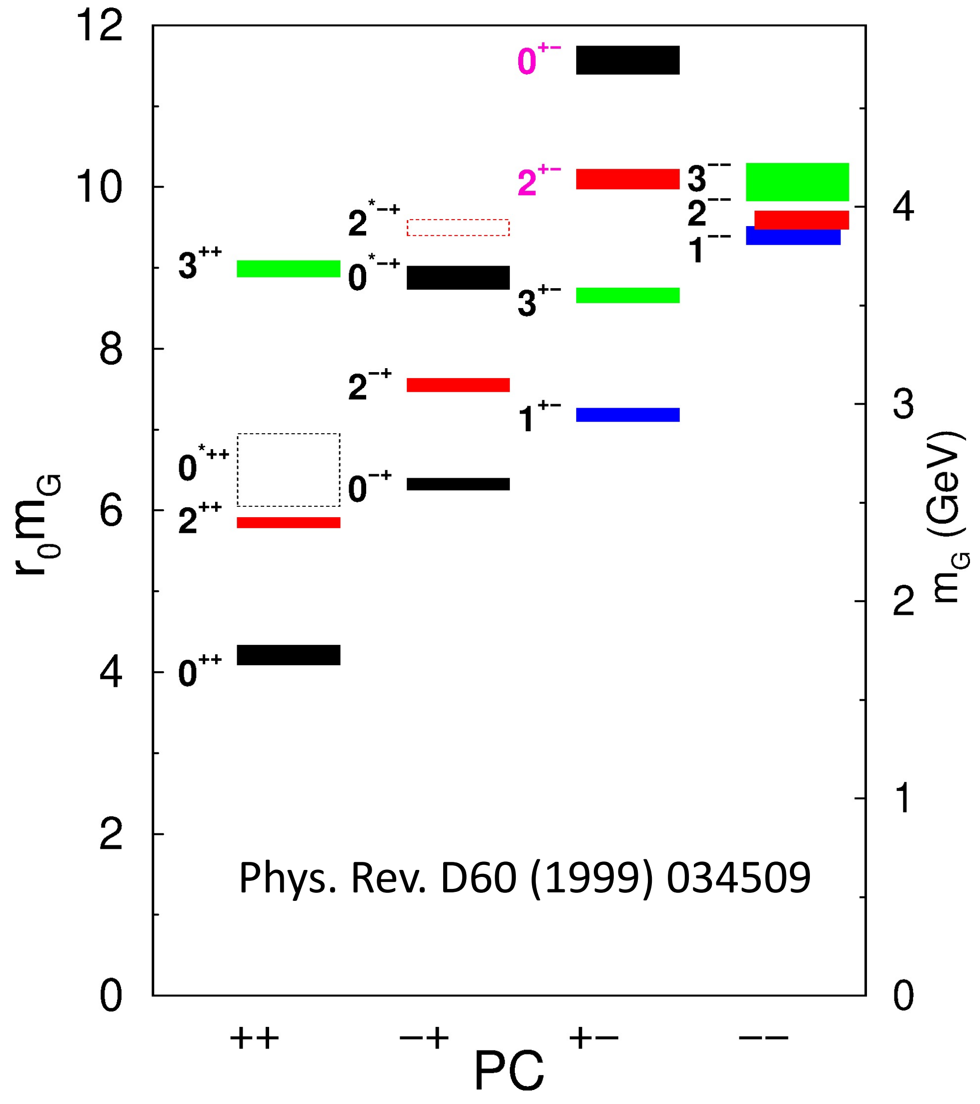
- Outnumbering of conventional QM states
- Abnormal properties ? Eg., small production rate in two photon process

Pseudoscalar glueball searches

Where is the 0^{-+} glueball?

- LQCD：0^{-+}(2.3~2.6 GeV)

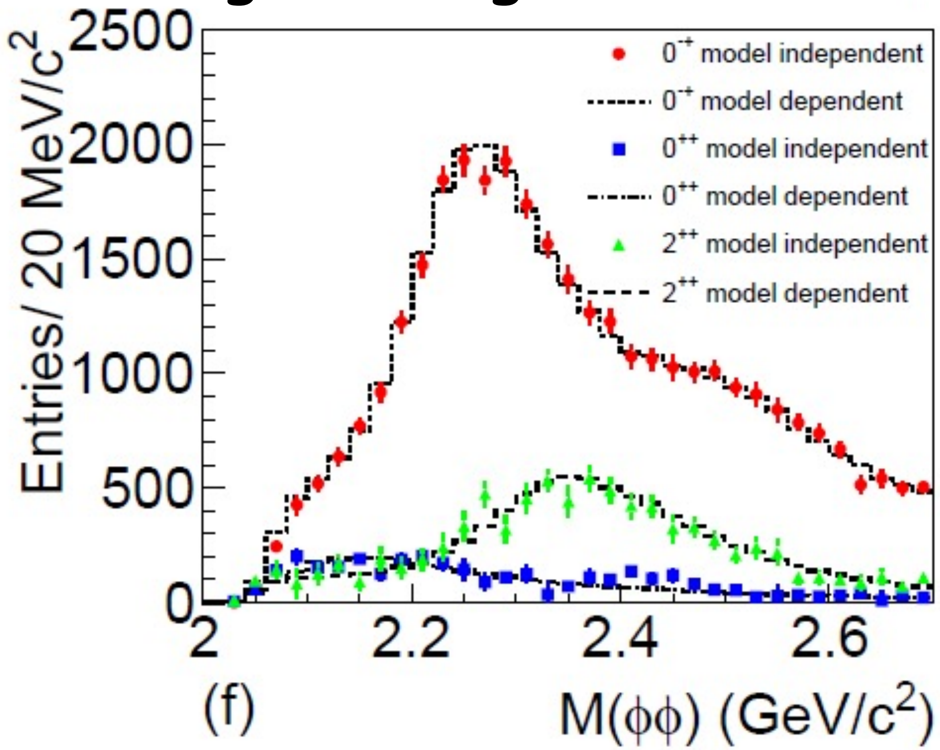
The small number of expected pseudoscalars in the quark model provide a clean and promising environment for the search of glueballs



H.X.Chen, W Chen, X Liu, Y.R. Liu, S.L. Zhu Rept.Prog.Phys. 86 (2023) 2, 026201

Pseudoscalars above 2 GeV

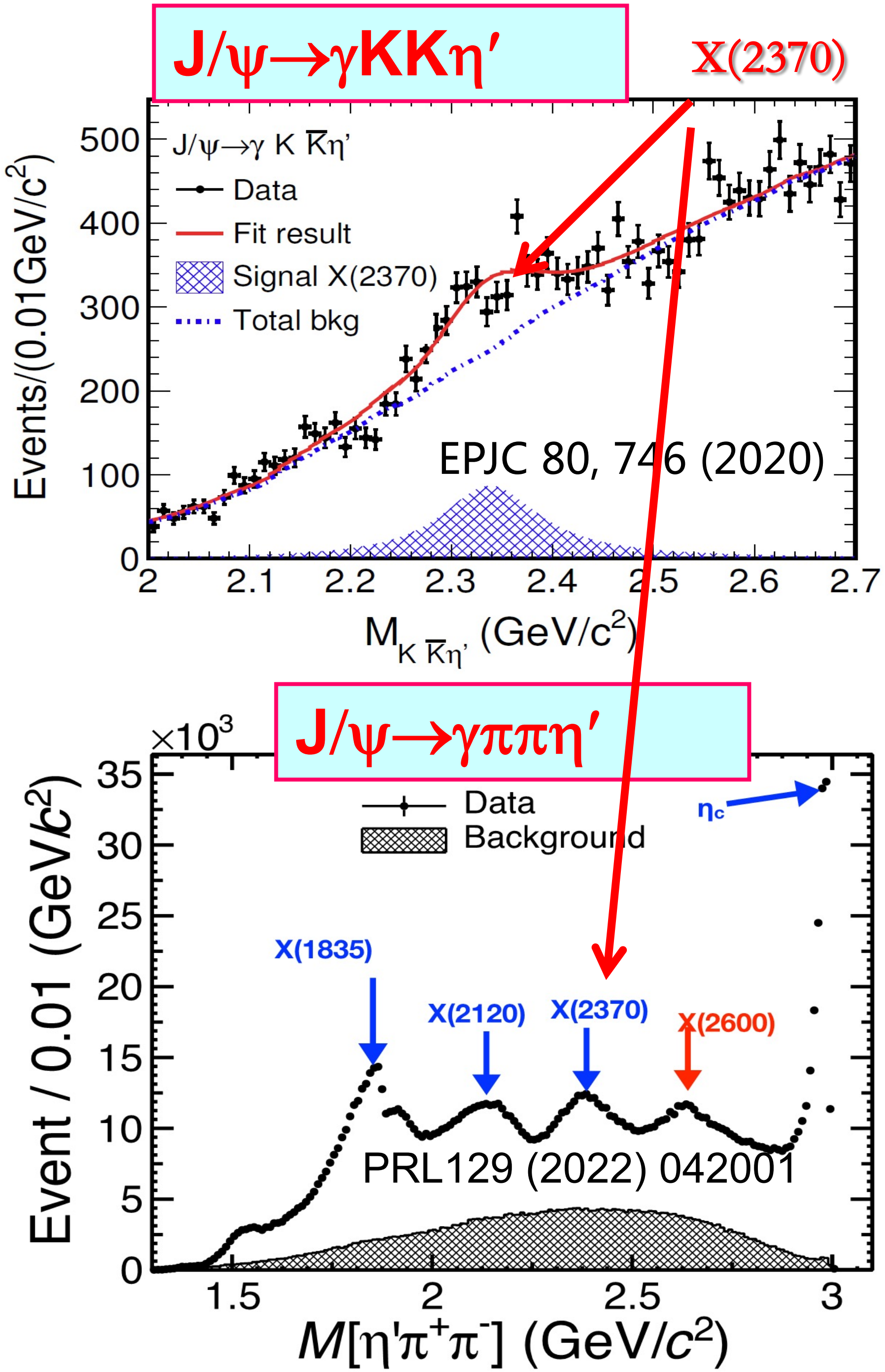
Very little was known for pseudoscalars above 2 GeV. Experimental results are essential for mapping out the pseudoscalar excitations and searching for 0^{-+} glueball



Resonance	M(MeV/c^2)	Γ(MeV/c^2)	B.F.(×10^{-4})	Sig.
$\eta(2225)$	2216^{+4+18}_{-5-11}	185^{+12+44}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28.1σ
$\eta(2100)$	2050^{+30+77}_{-24-26}	$250^{+36+187}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	21.5σ
X(2500)	2470^{+15+63}_{-19-23}	230^{+64+53}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2102	211	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24.2σ
$f_2(2010)$	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	$(1.91 \pm 0.07^{+0.72}_{-0.69})$	10.7σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ

Phys. Rev. D97, 051101 (2018)

- Dominant contribution from pseudoscalars: η(2225), η(2100) and X(2500)
- Three tensors $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$



X(2370): new glueball candidate ?

An updated review of the new hadron states

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We collect as many theoretical predictions on the pseudoscalar glueball mass as we can, and summarize them in Fig. 71. The average value of the mass predictions obtained after the year 1990 is

$$M_{|gg;0^{-+}\rangle} \sim 2360 \text{ MeV}\,. \quad (125)$$

Accordingly, the resonance $X(2370)$ first observed in 2010 [880] becomes a possible candidate for the low-lying pseudoscalar glueball, whose mass and width were measured to be [884]:

$$X(2370): M = 2341.6 \pm 6.5 \pm 5.7 \text{ MeV}\,, \quad \Gamma = 117 \pm 10 \pm 8 \text{ MeV}\,. \quad (126)$$

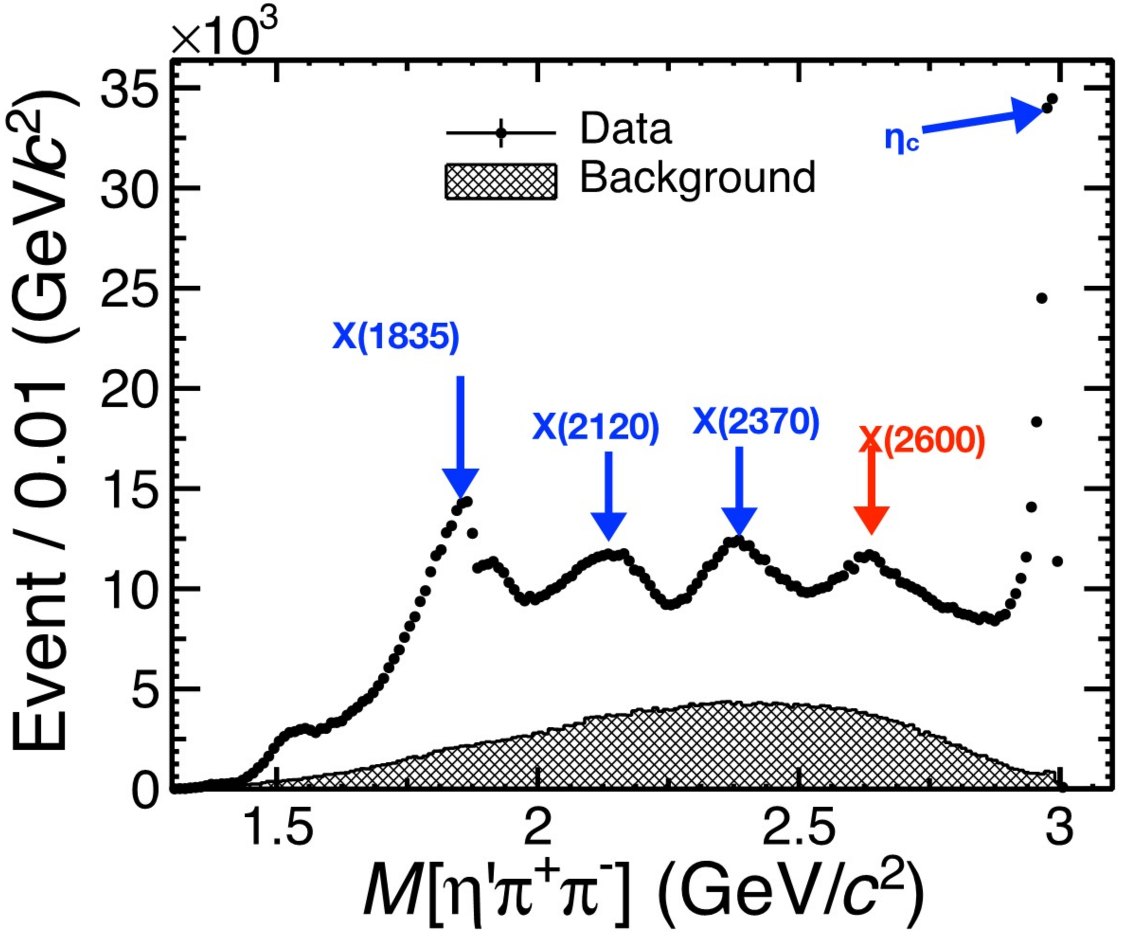
H.X.Chen, W Chen, X Liu, Y.R. Liu, S.L. Zhu Rept.Prog.Phys. 86 (2023) 2, 026201

QCD sum rules

X(2600): new glueball candidate ?

S.Q. Zhang et al, PRD 106 (2022) 7, 074010

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



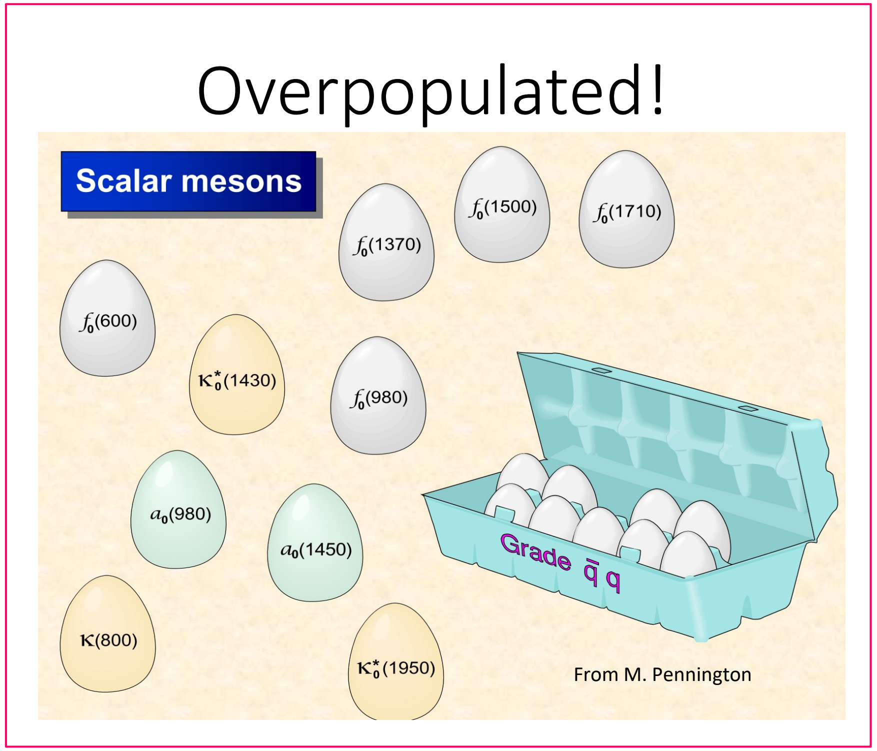
PRL129 (2022) 042001

Motivated by the newly observed resonance $X(2600)$ by BESIII Collaboration, we examine the trigluon glueball interpretation for it in the framework of QCD sum rules. We evaluate the mass spectra of the trigluon glueballs with quantum numbers 0^{-+} and 2^{-+} up to dimension 8 condensate in the operator product expansion. Our numerical results indicate that the mass of the 2^{-+} trigluon glueball is about 2.66 ± 0.06 GeV, which is consistent with the mass of the X(2600) within the uncertainties, while 0^{-+} has a mass of 2.01 ± 0.14 GeV. The possible decay channels of the 2^{-+} state are analyzed, which are crucial in decoding $X(2600)$'s internal structure and are hopefully measurable in BESIII, BEllEII, PANDA, and LHCb experiments.

Cases	Possible decay channels	
0^{-+} two-gluon glueball $\to$	$a_0(980) + \pi$	$\{f_0(500),\ f_0(980)\} + \eta$
0^{-+} trigluon glueball $\to$	$\{f_0(500),\ f_0(980),\ f_0(1370),\ f_0(1500)\} + \eta$	$\eta\eta\eta,\ \eta\eta\eta',\ \{\eta,\ \eta'\} + \pi + \pi$
	$f_0(500) + f_0(980) + \eta$	$\{\omega\omega,\ \rho\rho\} + f_0(500)$
	$f_0(500) + f_0(500) + \{\eta,\ \eta'\}$	$N\bar{N}$
	$\{f_0(500),\ f_0(980)\} + a_0(980) + \pi$	
2^{-+} two-gluon glueball $\to$	$a_2(1320) + \pi$	$f_0(500) + f_1(1285)$
	$f_2(1270) + \eta$	
2^{-+} trigluon glueball $\to$	$\eta_2(1645) + f_0(500)$	$2f_1(1285),\ 2a_1(1260),\ 2h_1(1170)$
	$\{f_2(1270),\ f_2'(1525)\} + \{\eta,\ \eta'\}$	$\rho + \rho + f_0(980)$
	$a_2(1320) + f_0(500) + \pi$	$\{\omega\omega,\ \rho\rho,\ \omega + \phi\} + f_0(500)$
	$\{f_2(1270),\ f_2'(1525)\} + f_0(500) + \eta$	$h_1(1170) + \omega + \eta$
	$\{f_2(1270),\ f_2'(1525)\} + a_0(980) + \pi$	$\{h_1(1170),\ h_1(1415)\} + \rho + \pi$
	$\omega + \phi + \eta,\ \{\pi\pi,\ \omega\omega,\ \rho\rho\} + \{\eta,\ \eta'\}$	$N\bar{N},\ \Lambda\bar{\Lambda},\ \Sigma\bar{\Sigma},\ \Xi\bar{\Xi}$

Scalar glueball searches

- Why light scalar mesons are interesting?
  - There have been hot debates on **the existence of** σ and κ
  - σ, κ and $f_0(980)$ **are also possible mutiquark states.** They are all near threshold.
  - Lattice QCD predicts the 0^{++} **scalar glueball mass** ~ **1.6 GeV.** $f_0(1500)$ and $f_0(1710)$ are good candidates.



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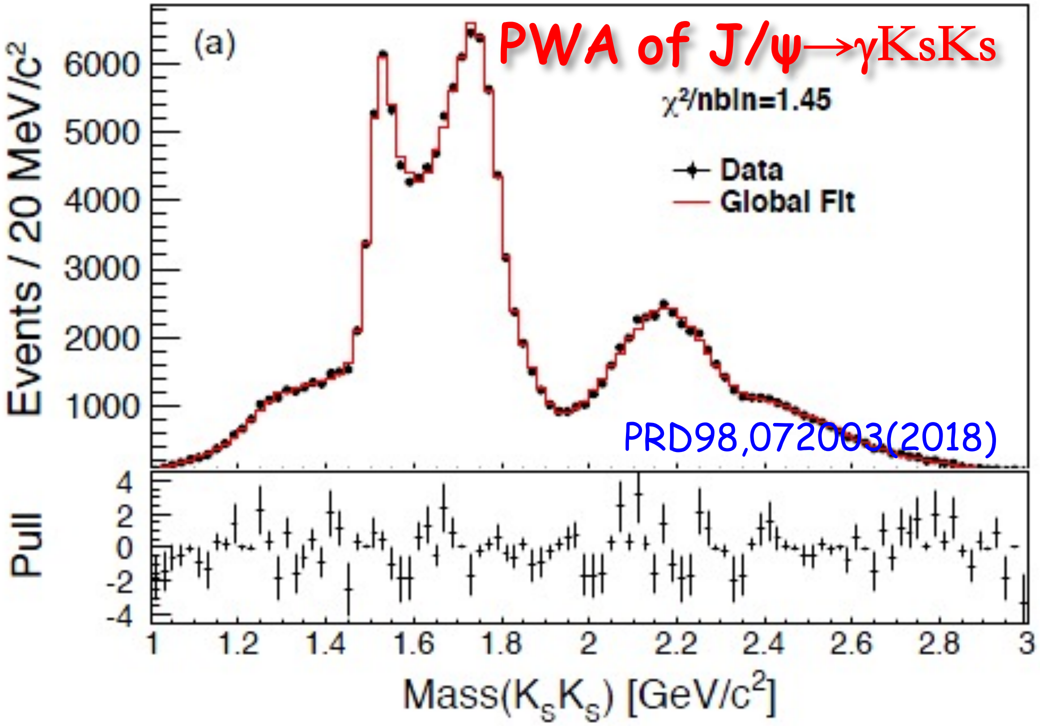

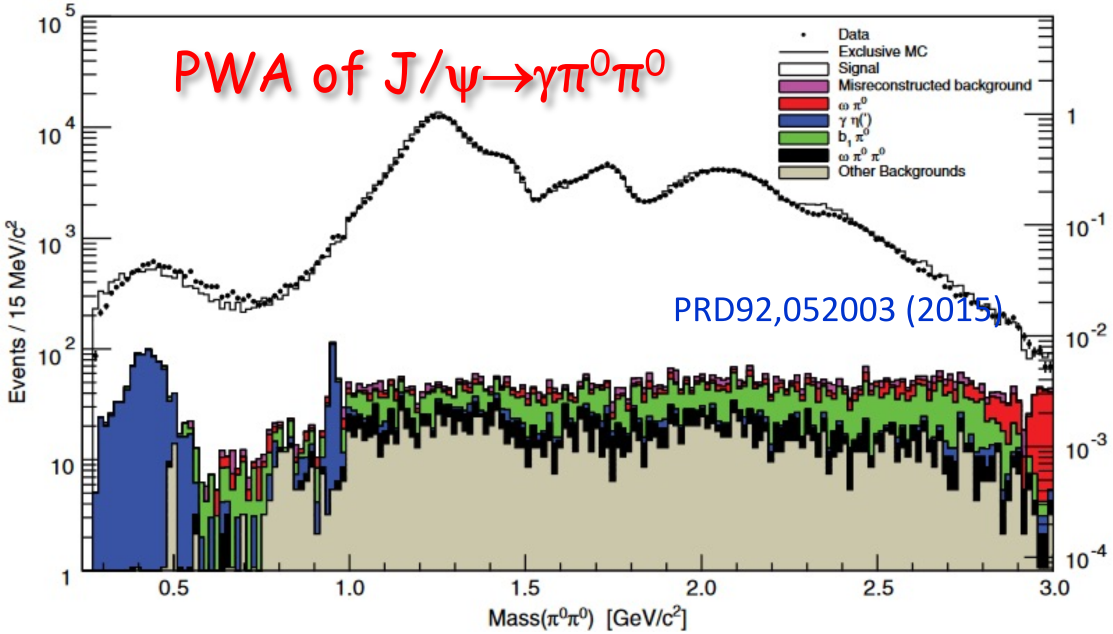

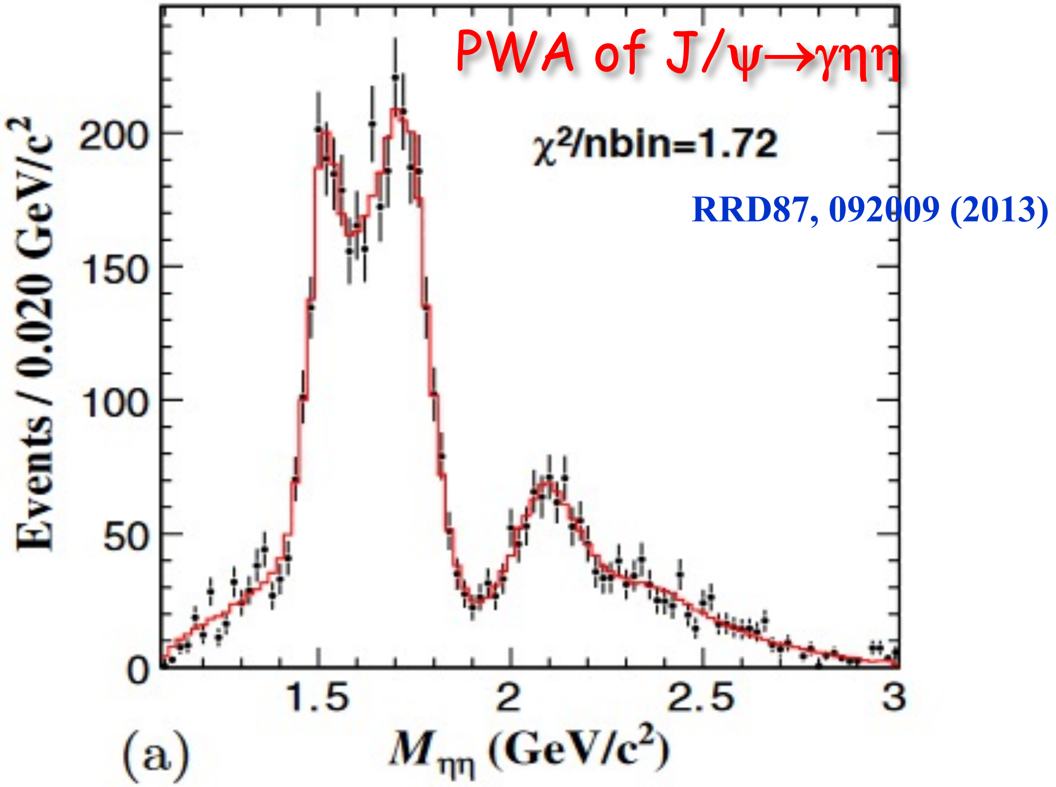

- $f_0(1710)$ and $f_0(1500)$ are dominant
- $f_2'(1525)$ also seen
- Broad bump above 2 GeV, contributions from scalar and tensor

Scalar glueball candidate: $f_0(1710)$

$$\Gamma(J/\psi \to \gamma G_{0^+}) = \frac{4}{27}\alpha \frac{|p|}{M_{J/\psi}^2}|E_1(0)|^2 = 0.35(8) keV$$
$$\Gamma/\Gamma_{tot} = 0.33(7)/93.2 = 3.8(9) \times 10^{-3}$$

CLQCD, Phys. Rev. Lett. 110, 021601 (2013)

Experimental results

- $B(J/\psi \to \gamma f_0(1710) \to \gamma K\bar{K}) = (8.5^{+1.2}_{-0.9}) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi) = (4.0 \pm 1.0) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\omega\omega) = (3.1 \pm 1.0) \times 10^{-4}$
- $B(J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta) = (2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$

$\Rightarrow$ $B(J/\psi \to \gamma f_0(1710)) > 1.7 \times 10^{-3}$

Flavor-blindness of glueball decays

$$\frac{1}{P.S.}\Gamma(G \to \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta') = 3:4:1:0:1$$

*with chiral suppression
PRL 98 149103

$$\Gamma(G \to \pi\pi)/\Gamma(G \to K\bar{K}) \approx \frac{f_\pi^4}{f_K^4} \approx 0.48$$

$$\frac{1}{P.S.}\Gamma(G \to \pi\pi : K\bar{K} : \eta\eta) \approx 1.3 : 3.16 : 1$$

$f_0(1710)$ largely overlapped with scalar glueball

Tensor glueball searches

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

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

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

BESIII results

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

Phys.Rev. D87, 092009 (2013)

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

Phys.Rev. D93, 112011 (2016)

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

Phys.Rev. D98, 072003 (2018)

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Rept.Prog.Phys. 86 (2023) 2, 026201

$f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ are observed with a strong production of $f_2(2340)$; consist with central production and pp-bar annihilations

It is desirable to search for more decay modes!

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)

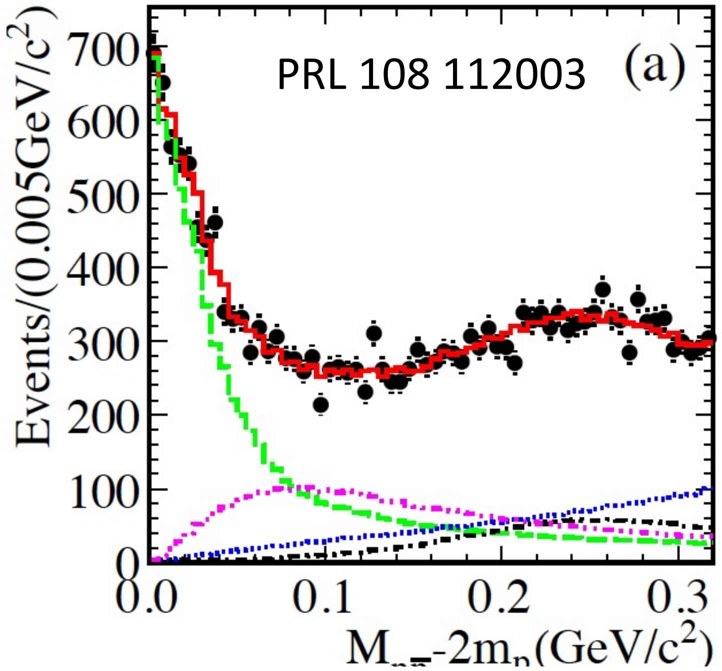
✓ **Trajectory :**

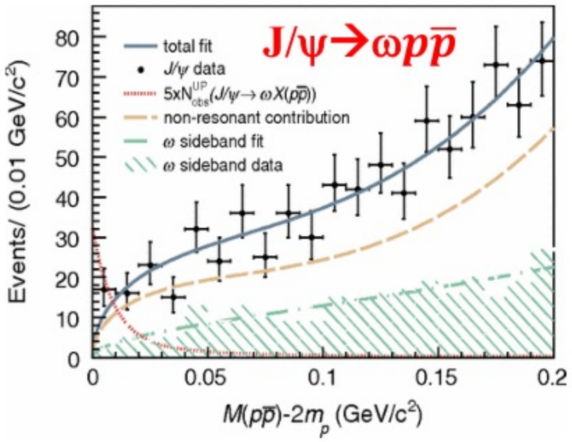
- **$f_1(1285)$, no $\eta(1295)$**
- **$\eta(1405)$ /$\eta(1475)$ can be one resonance**

□ **Above 2 GeV: X(2370)?**

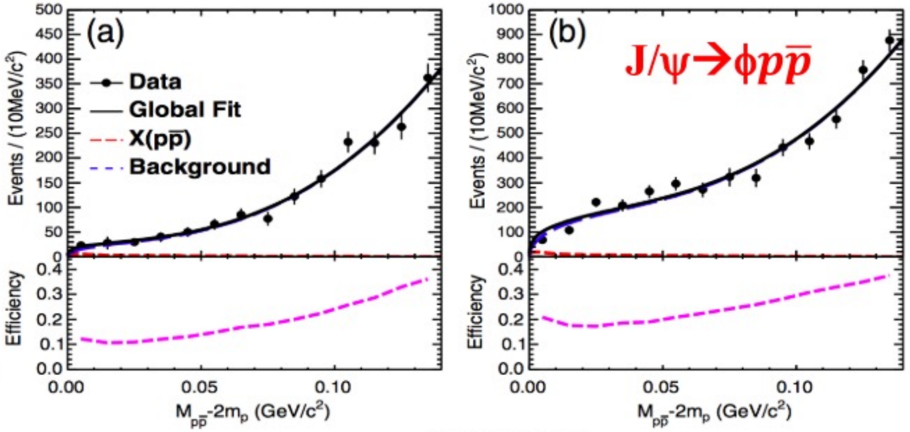
$p\bar{p}$ threshold enhancement $X(p\bar{p})$: Baryonium state?

- First observed in $J/\psi \rightarrow \gamma p\bar{p}$ at BESII, confirmed by BESIII and CLEO-c
- PWA of $J/\psi \rightarrow \gamma p\bar{p}$: $J^{PC} = 0^{-+}$
  - The fit with a BW and S-wave FSI (I=0) factor can well describe $p\bar{p}$ mass threshold structure
- Non-observation in hadronic decays: not from pure FSI

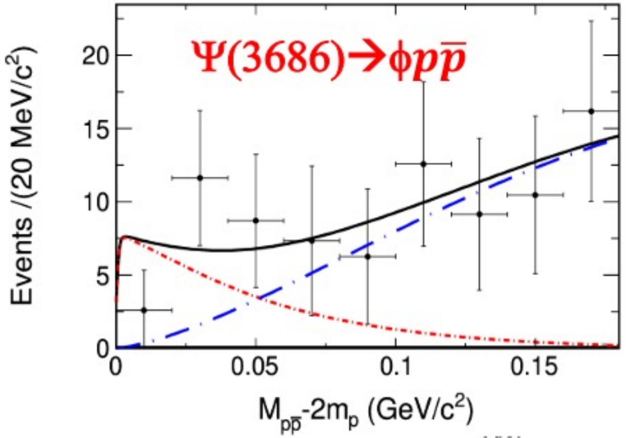




PRD87,112014(2013)

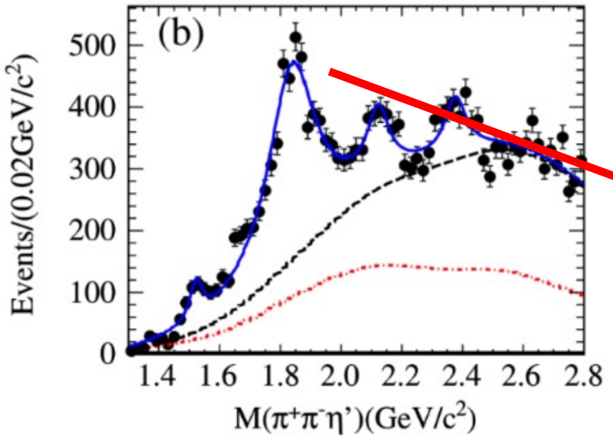


PRD93,052010(2016)



PR D99 112010(2019)

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

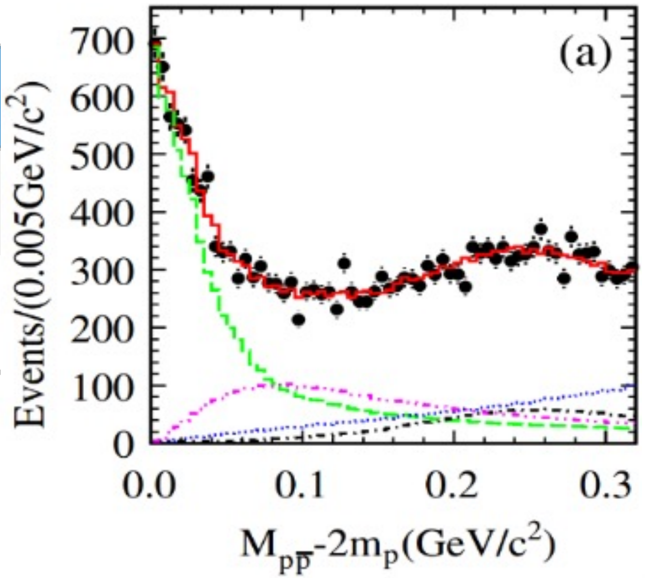


X(1835) observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$
$X(1835)$ $J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20}_{-17}{}^{+62}_{-43}$ MeV/c^2

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)

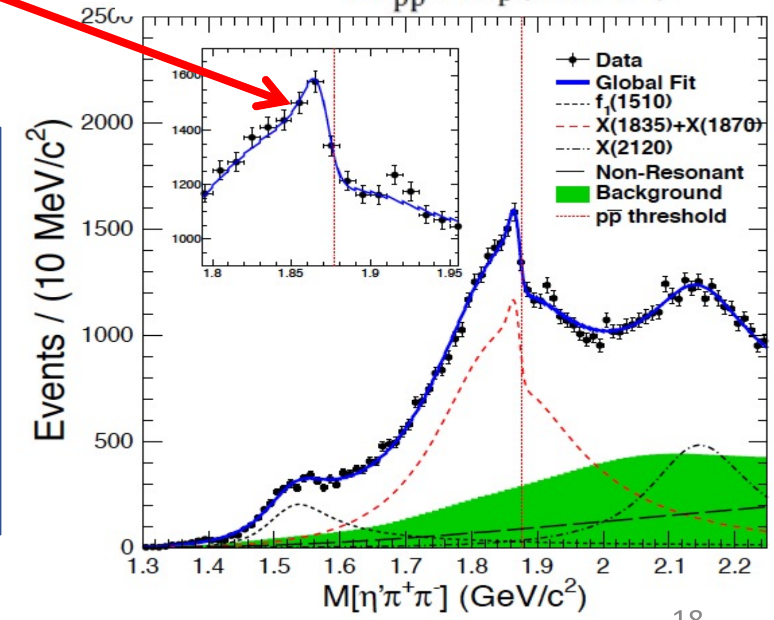


connection between X(1835) and X($p\bar{p}$)

The anomalous line shape :

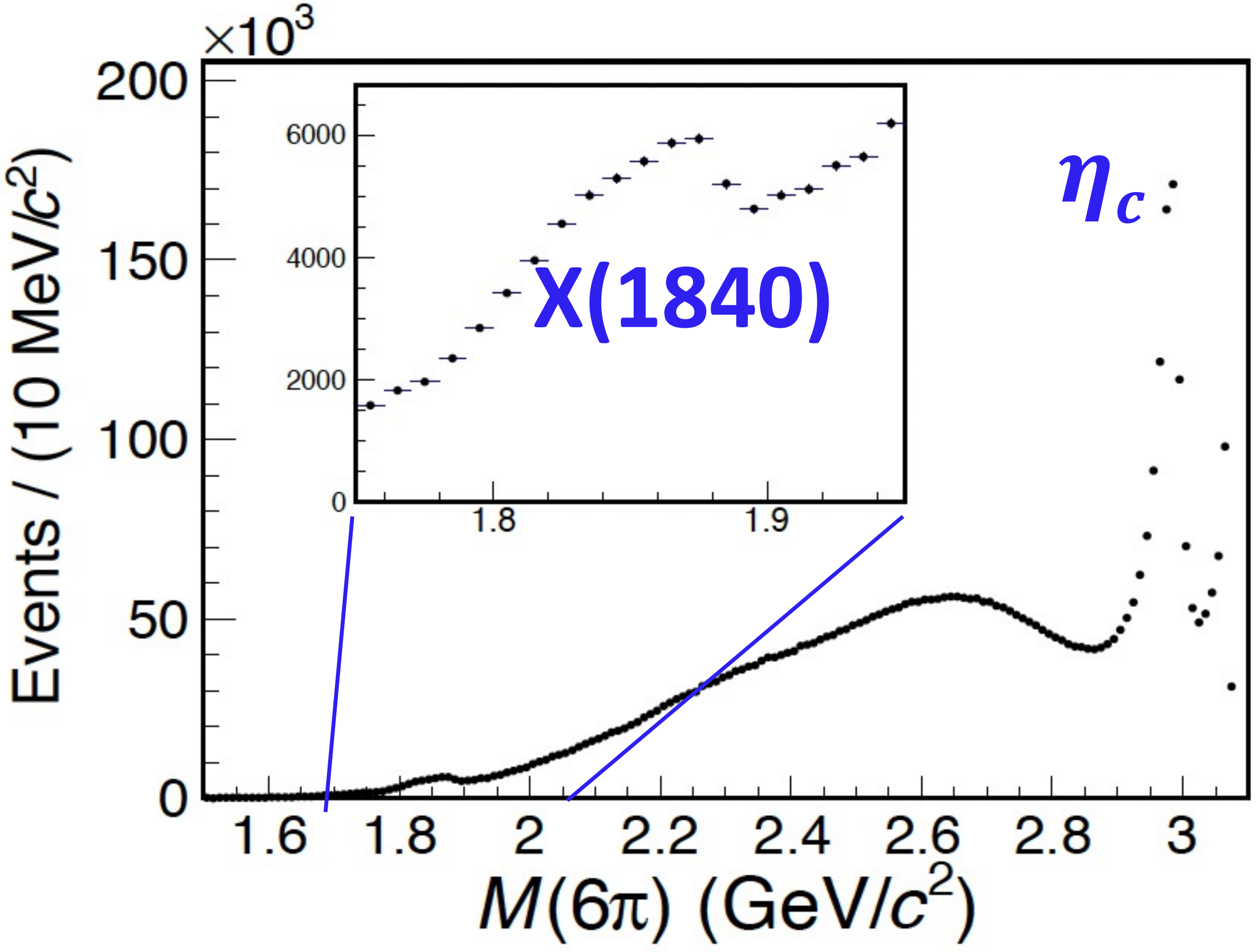
-- Suggest the existence of a state, either a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold

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

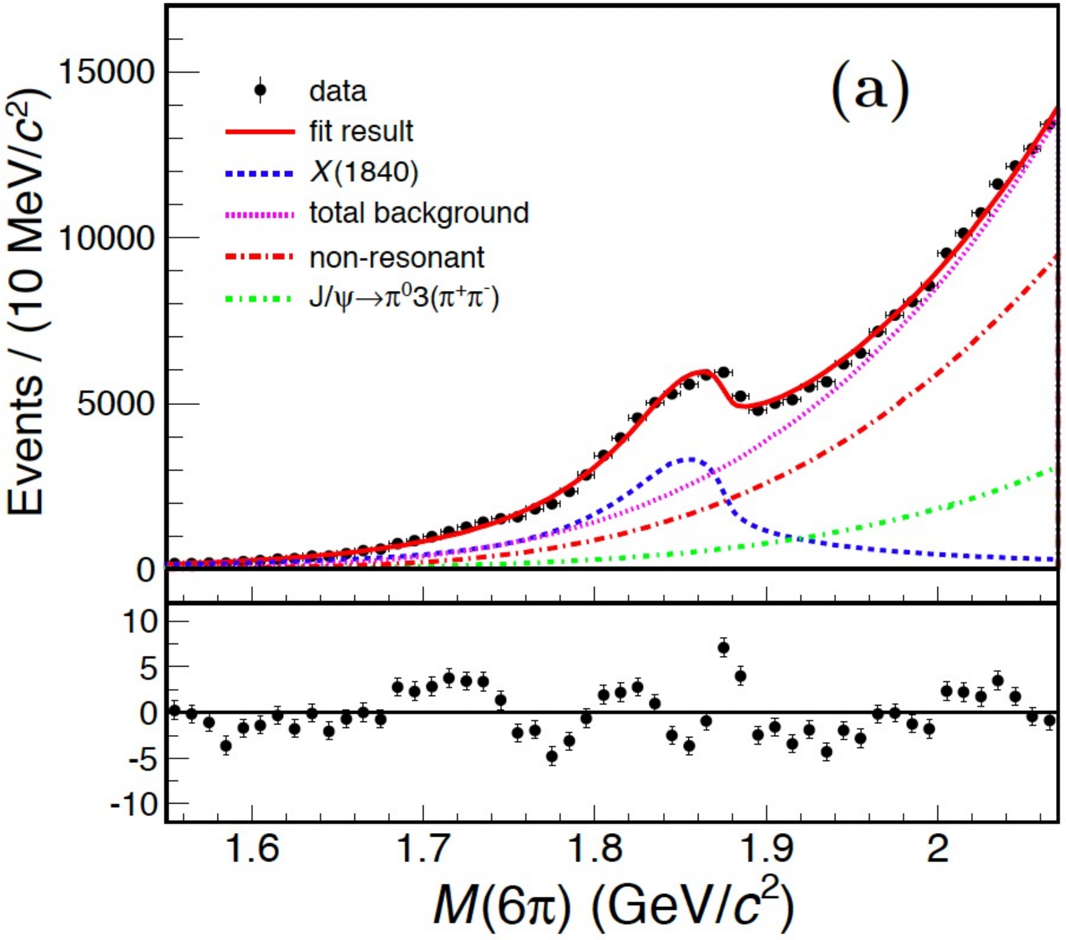


PRL 117, 042002 (2016)

Anomalous line-shape of $3(\pi^+\pi^-)$ in $J/\psi\to\gamma\, 3(\pi^+\pi^-)$

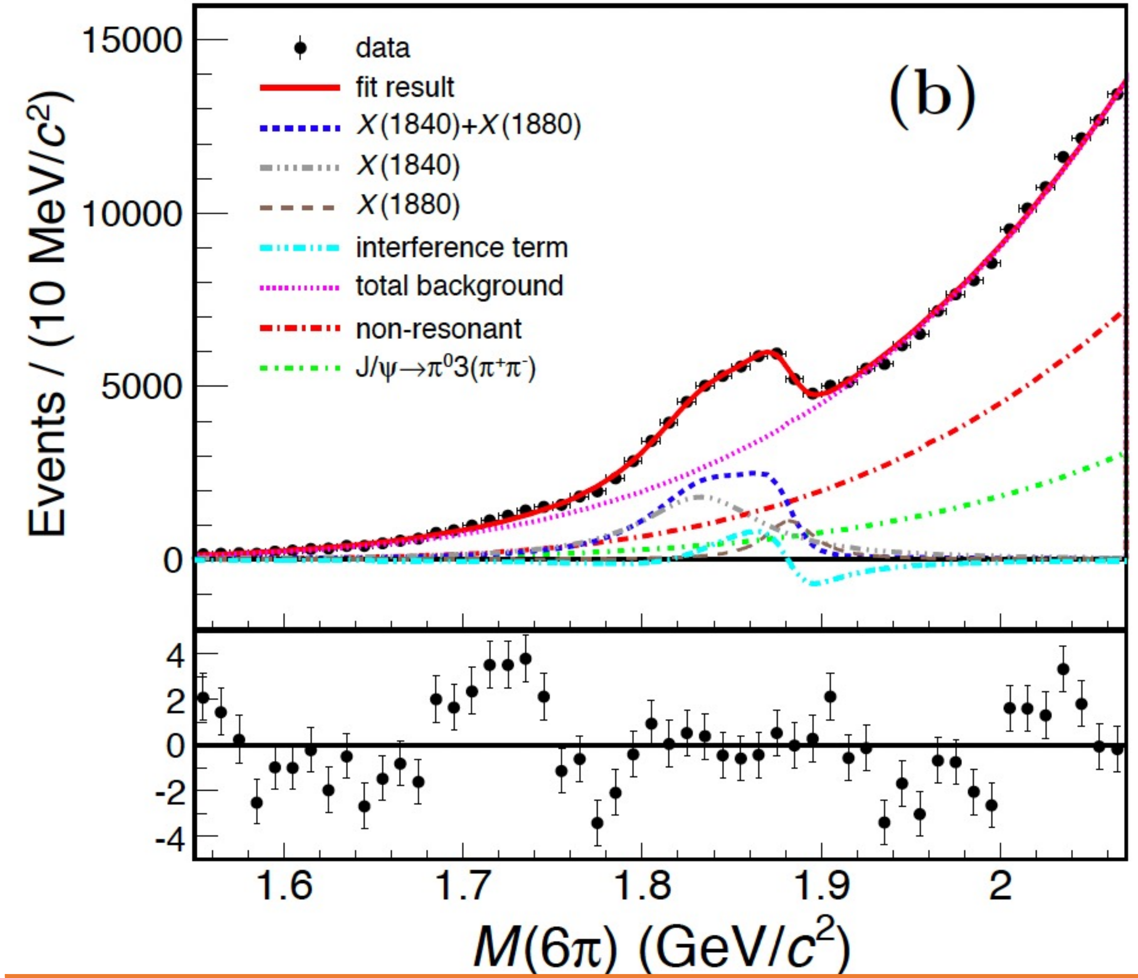


Flatte function



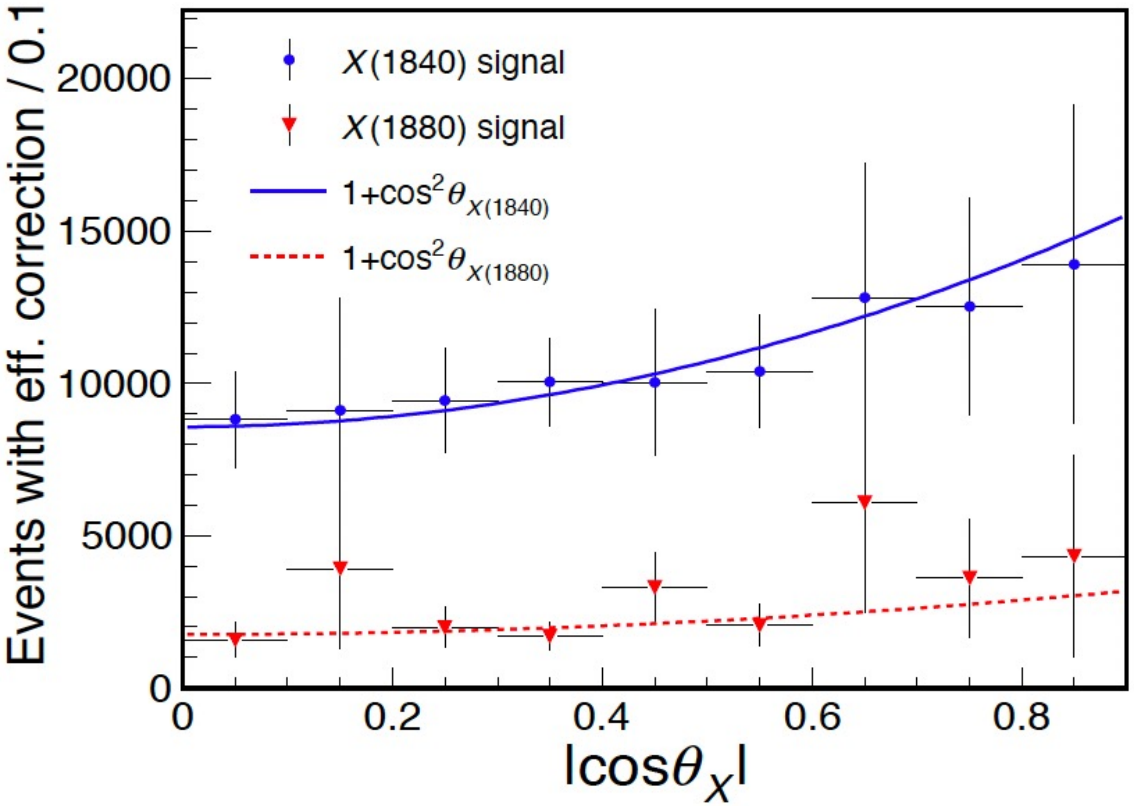
arXiv:2310.17937,submitted PRL

Two BWs



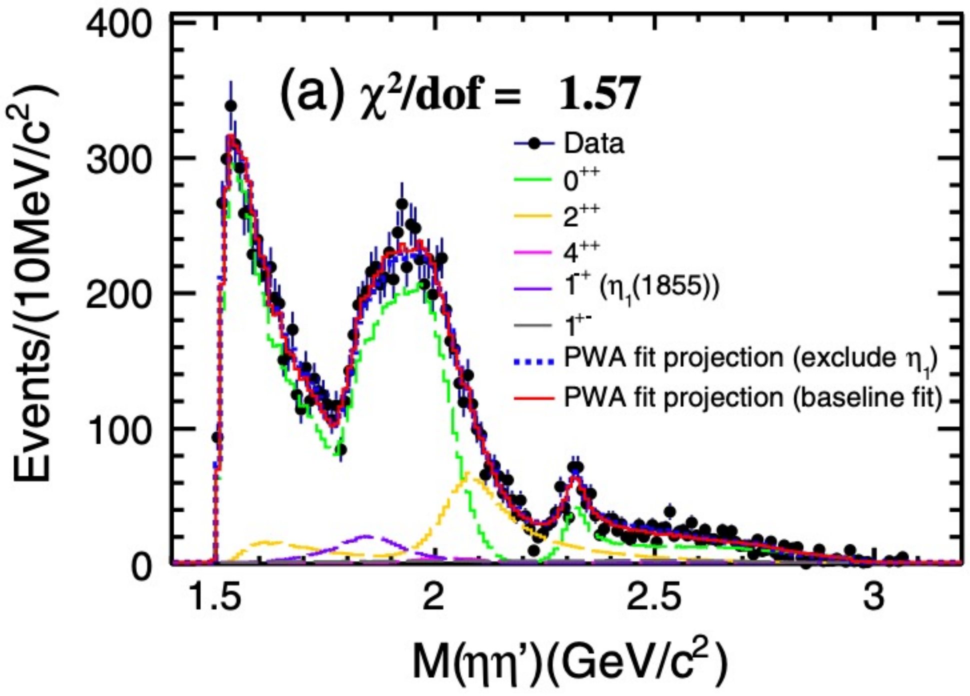
Resonance	M(MeV/c²)	Γ(MeV/c²)
X(1880)	1882.1±1.7±0.7	30.7±5.5±2.4
X(1840)	1832.5±3.1±2.5	80.7±5.2±7.7

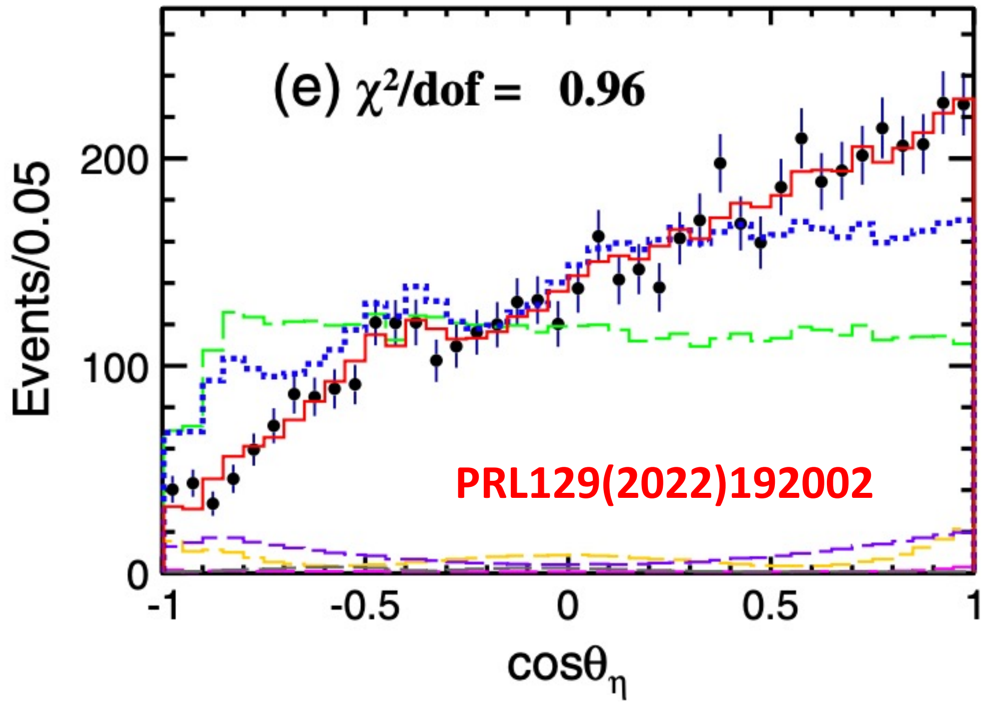
Consistent with pseudoscalars



narrow state below $p\bar{p}$ threshold !

Observation of 1^{-+} $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$





Isoscalar state with exotic quantum numbers $J^{PC}=1^{-+}$

Critical to establish the 1^{-+} spectroscopy !

M = $1855 \pm 9^{+6}_{-1}$ MeV/c^2

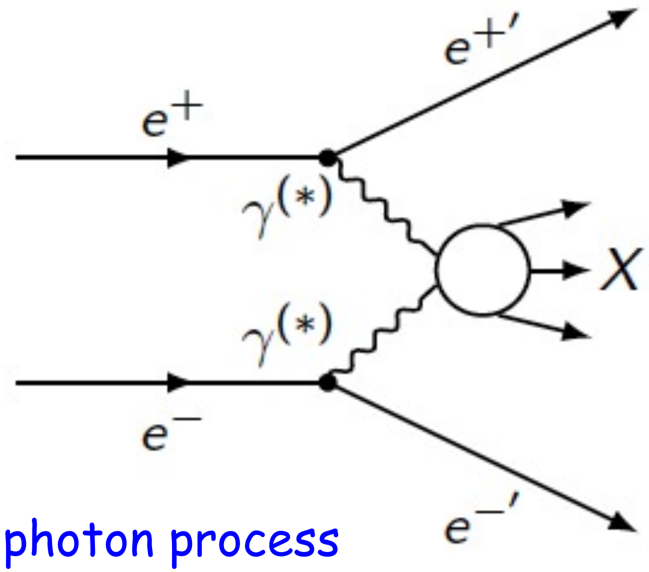
Γ = $188 \pm 18^{+3}_{-8}$ MeV

Prospects: 10B J/ψ and 2.7B ψ(2S) provide great opportunities

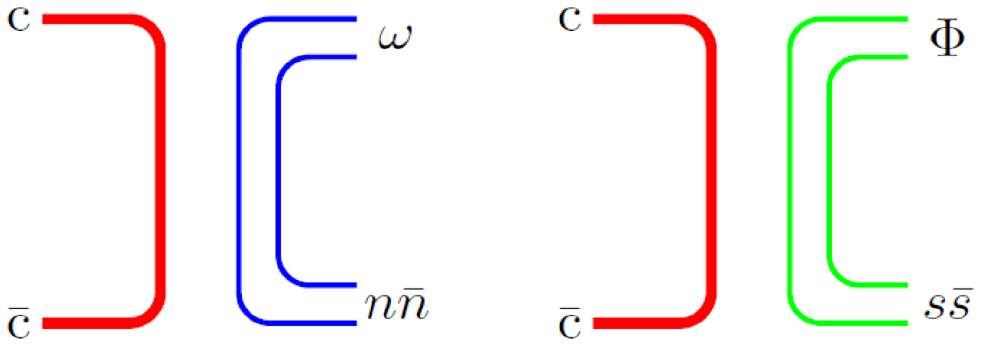
	0^+	2^+	0^-
J/ψ→γPP	■	■	
J/ψ→γVV		■	■
J/ψ→γPPP			■
J/ψ→γPPPP	■	■	■

- 0^+, 2^+ : coupled channel analysis
  - J/ψ→γPP
  - J/ψ→ω/φ + X
- 0^- : trajectory >2 GeV, X(2370)
  - J/ψ→γPPP
  - J/ψ→γγ V
- 1^{-+}
  - J/ψ→$\gamma\eta_1^{(\prime)}$
  - $\chi_{c1} \rightarrow \eta\eta_1^{(\prime)}, \pi\pi_1$

Anti filter:

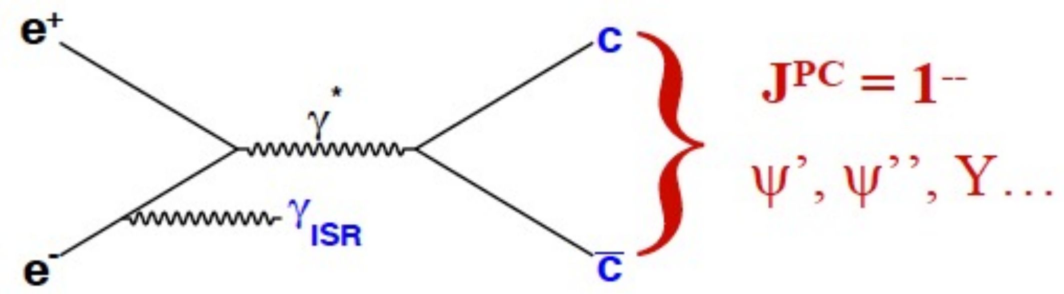


Two photon process

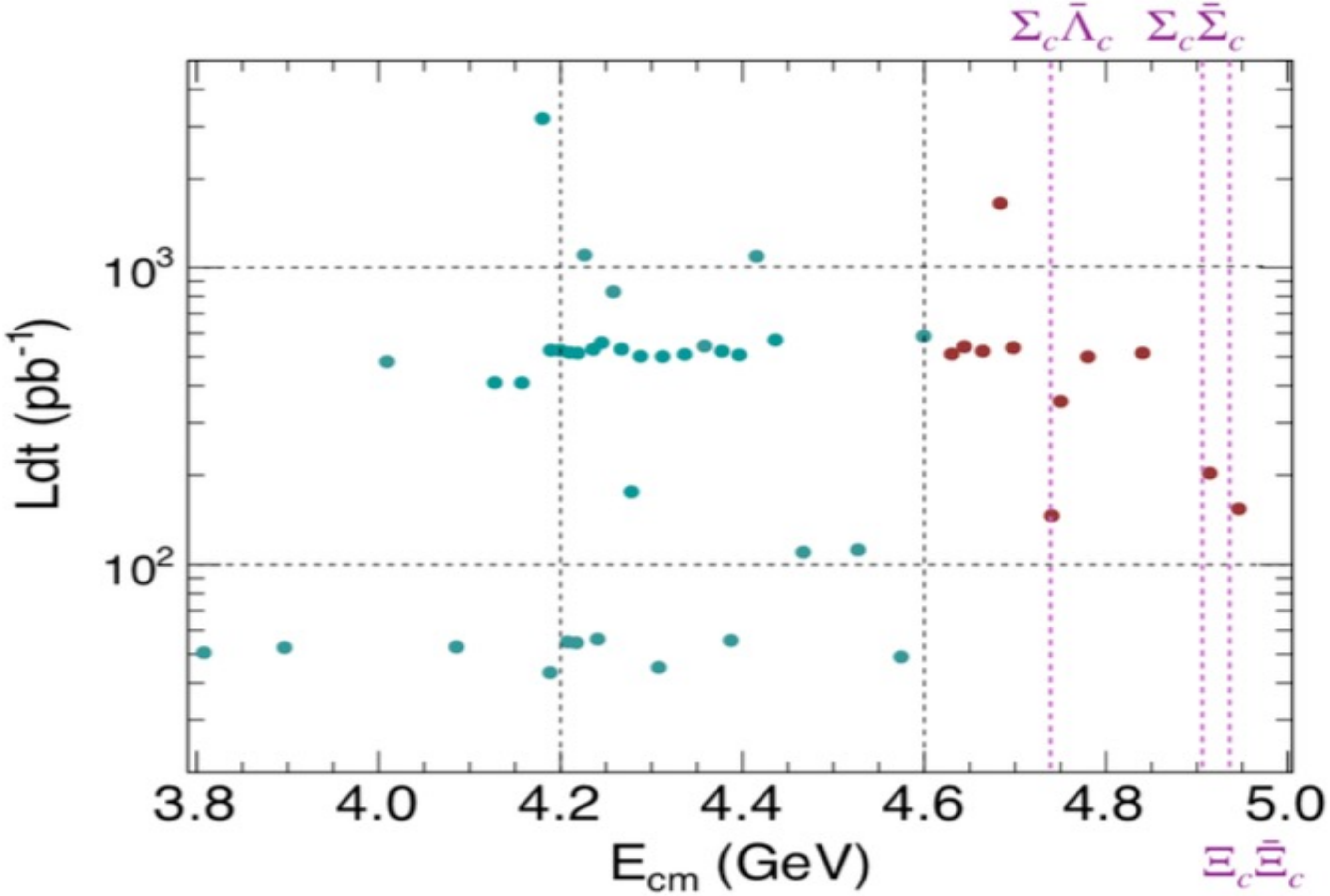


Flavor Filters : J/ψ→ω/ϕ + X

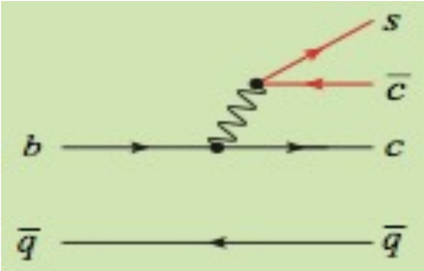
Charmonium(-like) states

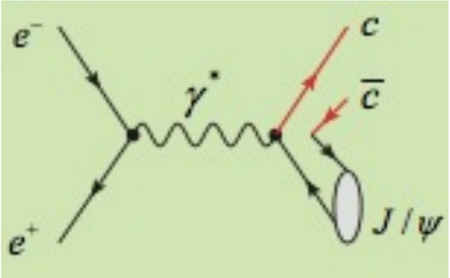


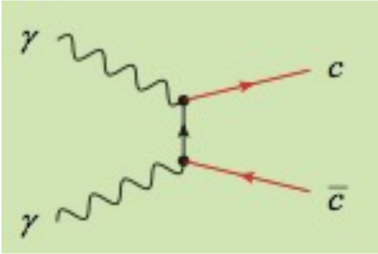
XYZ studies with ~25 fb^{-1} data above 3.8 GeV

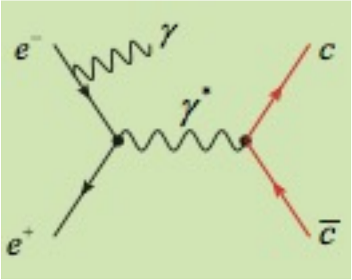


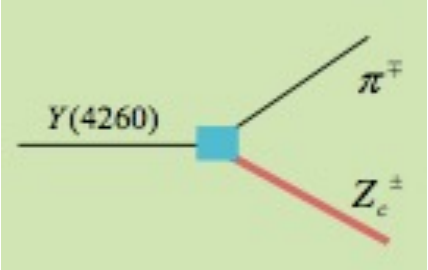
Hints of a new heavy flavor spectrum

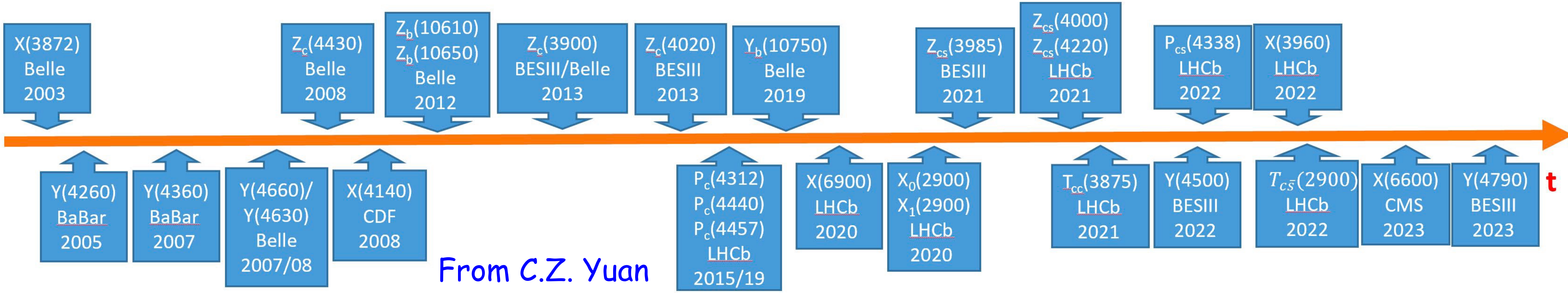








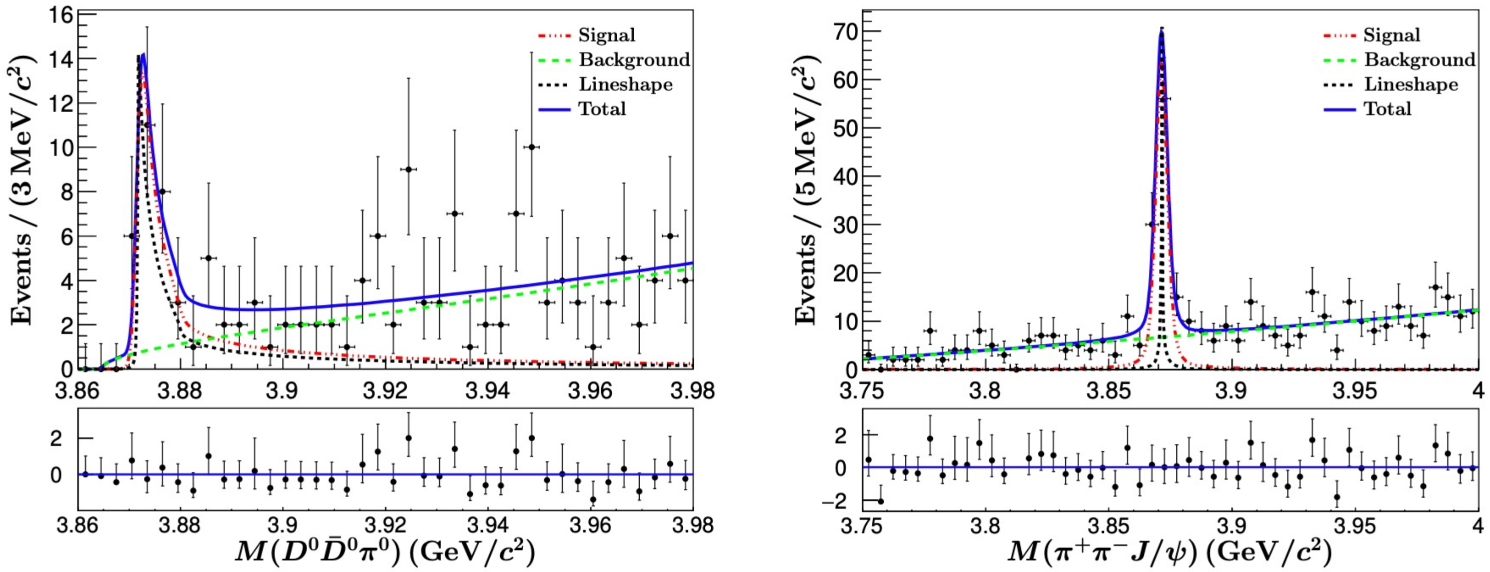


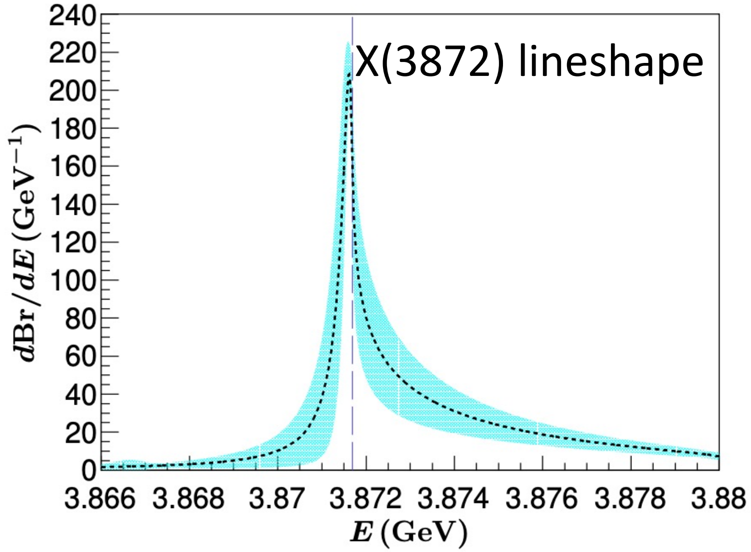


From C.Z. Yuan

Candidates of hadronic molecules, hybrids, and multiquark states !

Couple channel analysis of X(3872) line shape





Parameters	g	Γ_0 (MeV)	M_X (MeV)
Fit results	0.16 ± 0.10	2.67 ± 1.77	3871.63 ± 0.13

$$\frac{\Gamma(X(3872)\to\pi^+\pi^-J/\psi)}{\Gamma(X(3872)\to D^0\bar{D}^{*0})} = 0.05 \pm 0.01^{+0.01}_{-0.02}$$

LHCb: 0.11±0.03

Hanhart, Kalashnikova, Nefediev, PRD 81, 094028 (2010)

$$Z = 0.18$$

LHCb: Z=0.15

A. Esposito et al., Phys. Rev. D 105, L031503 (2022).

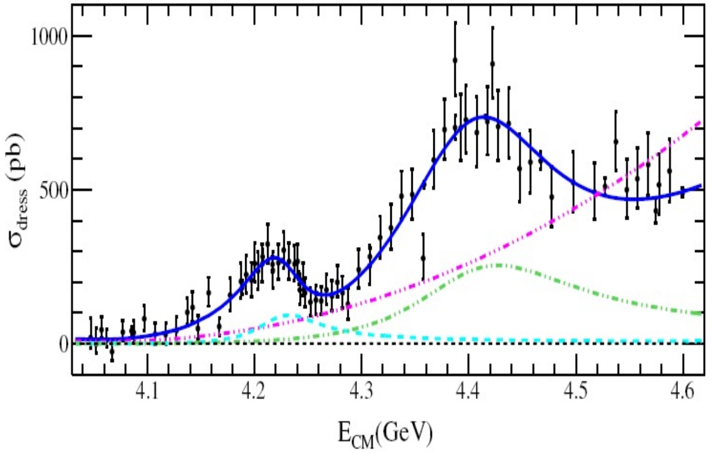
Field renormalization constant : Z=1: pure elementary state;

Z=0: pure bound (composite) state.

Fine Structure of $Y(4260) \to Y(4220) + Y(4320)$?

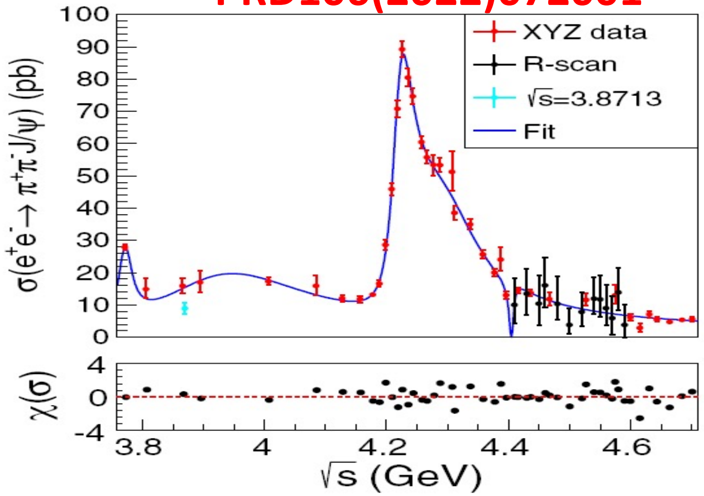
$e^+e^- \to \pi^+ D^0 D^{*-}$ +c.c.

PRL122(2019)102002

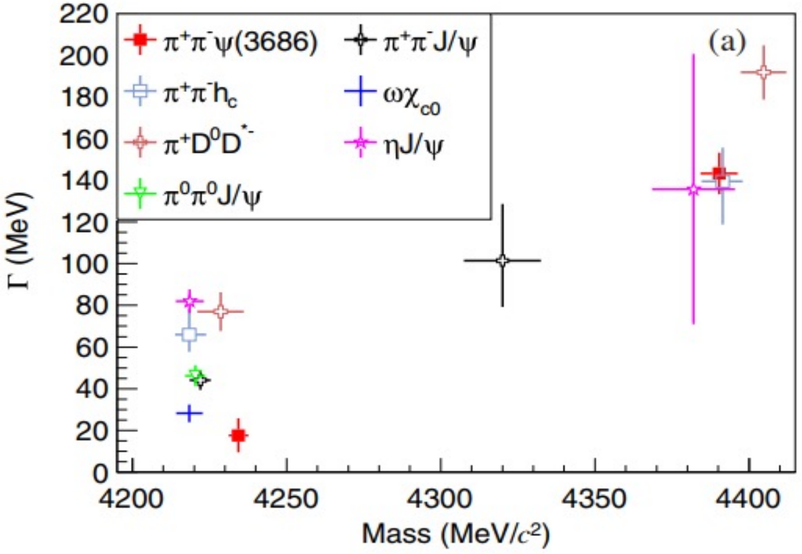


$e^+e^- \to \pi^+\pi^- J/\psi$

PRD106(2022)072001

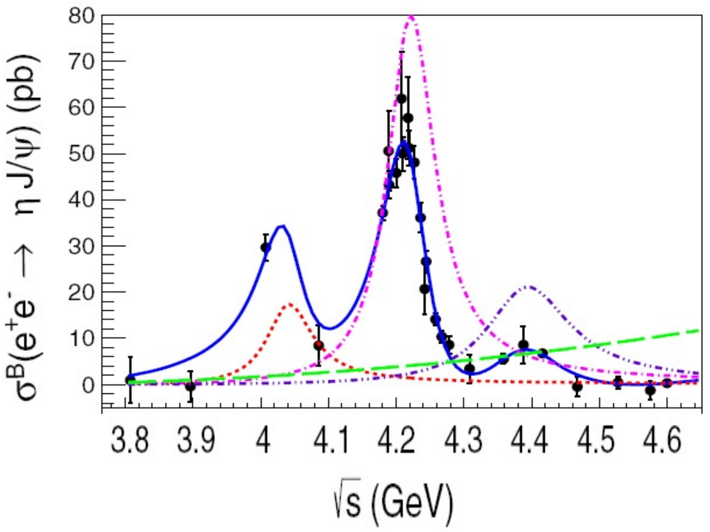


Different masses and widths in various processes



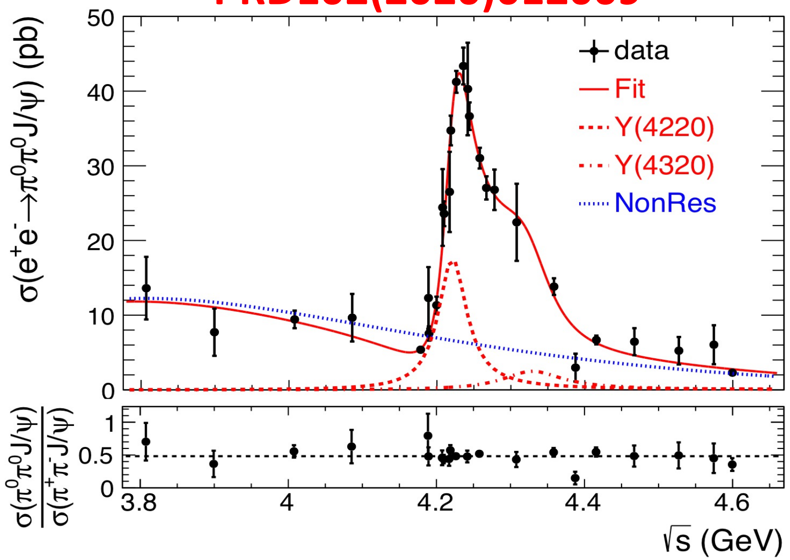
$e^+e^- \to \eta J/\psi$

PRD102(2020)031101(RC)



$e^+e^- \to \pi^0\pi^0 J/\psi$

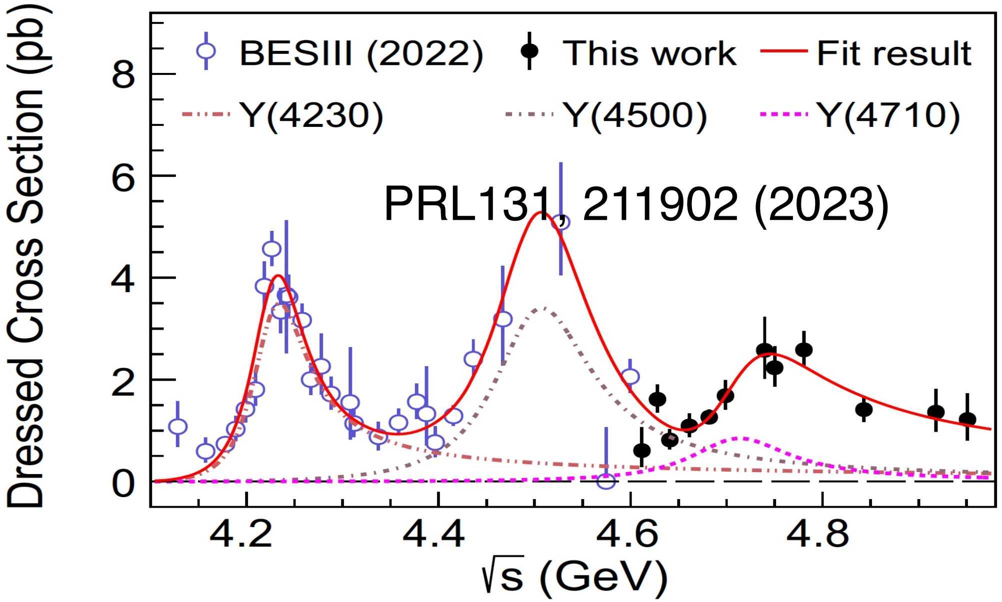
PRD102(2020)012009



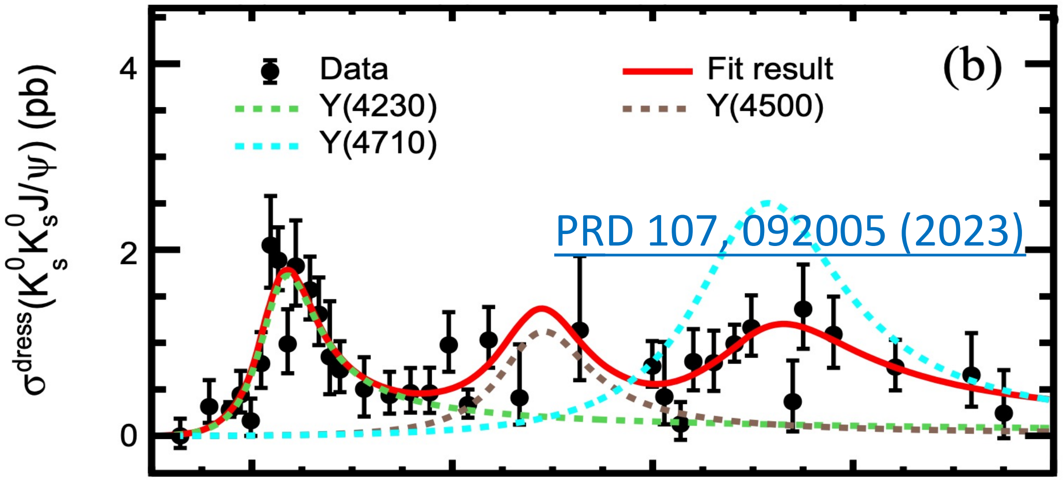
Mass~4220 MeV, width~ 50 MeV!

Observations of Y(4230), Y(4500) and Y(4710)

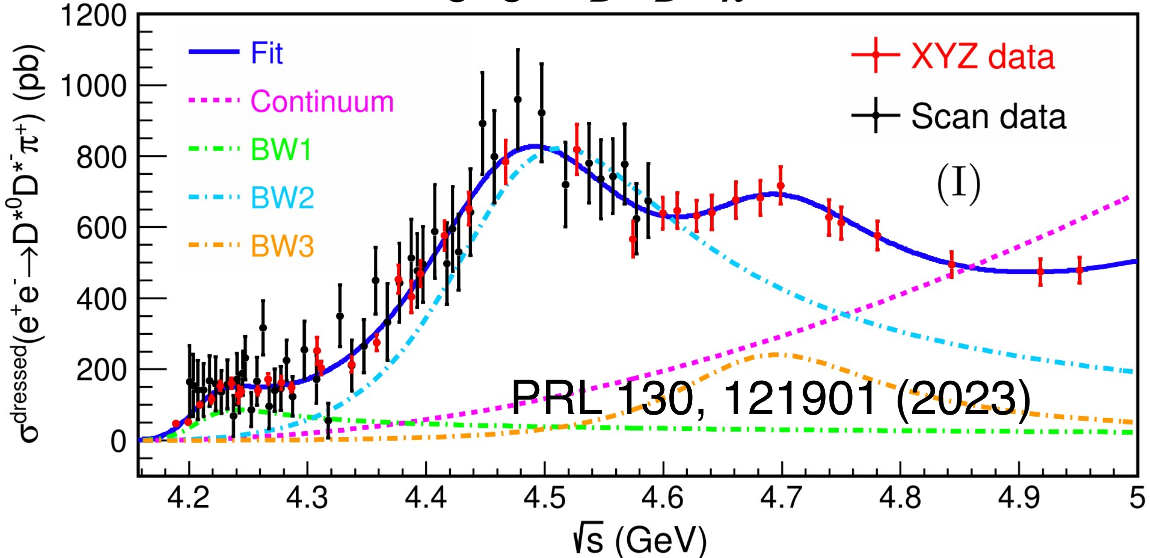
$e^+e^- \to K^+K^-J/\psi$



$e^+e^- \to K_SK_SJ/\psi$



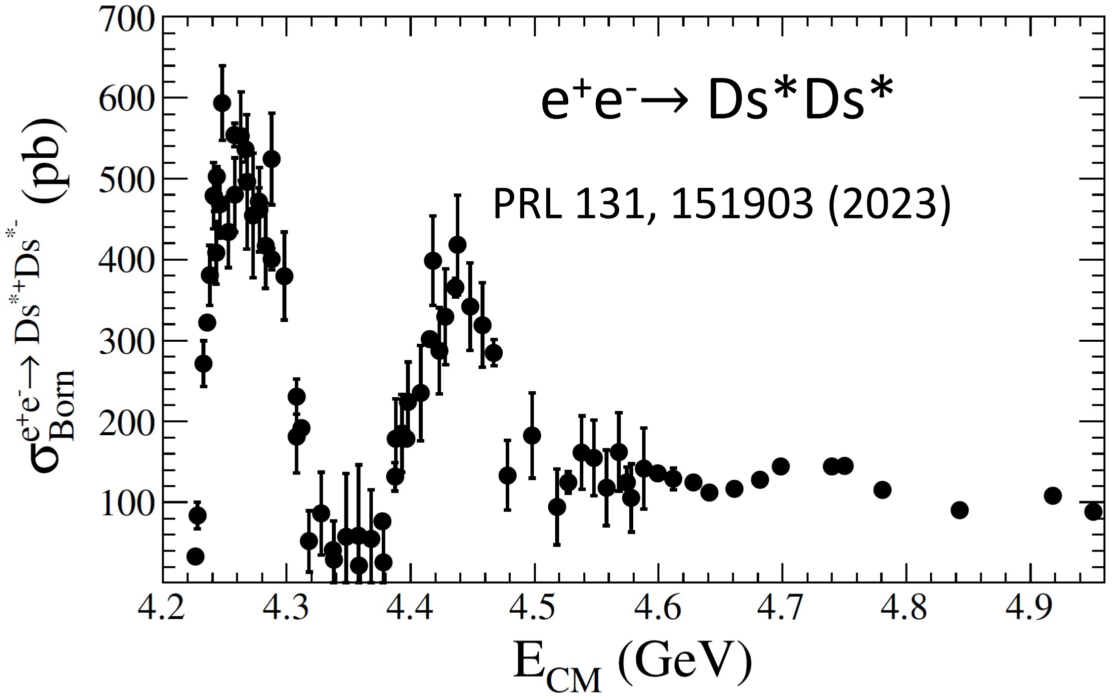
e+e-$\to D^{*0}D^{*-}\pi^+$



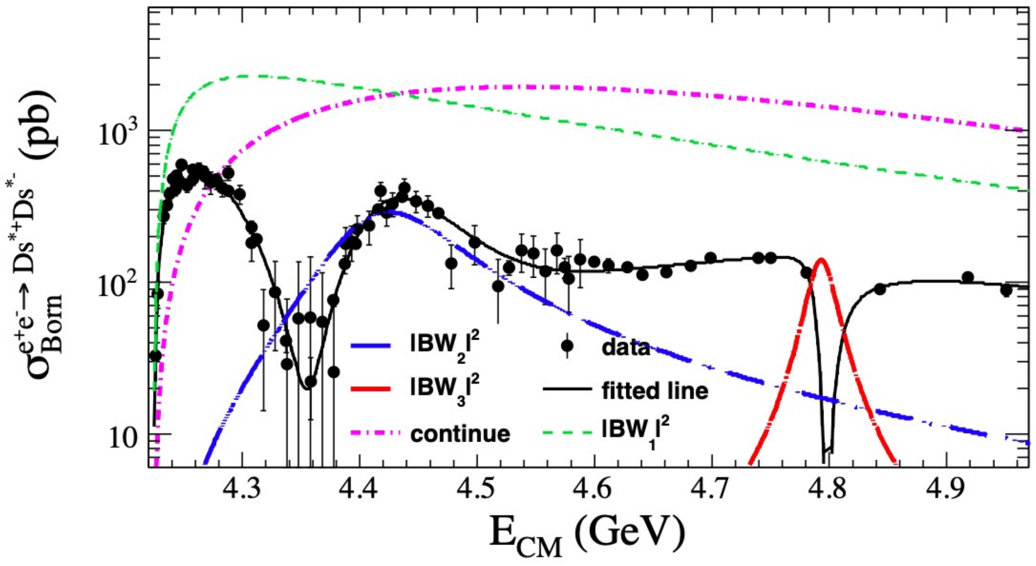
- New decay mode of Y(4230)
- Confirmation of Y(4500)
- Y(4710): one of the heaviest vector charmonium-like state, hybrid, 5S charmonium, 5S-4D/6S-5D mixing?

M~4710 MeV/c^2, Γ~ 180 MeV

Observation of a new charmonium-like state Y(4790)

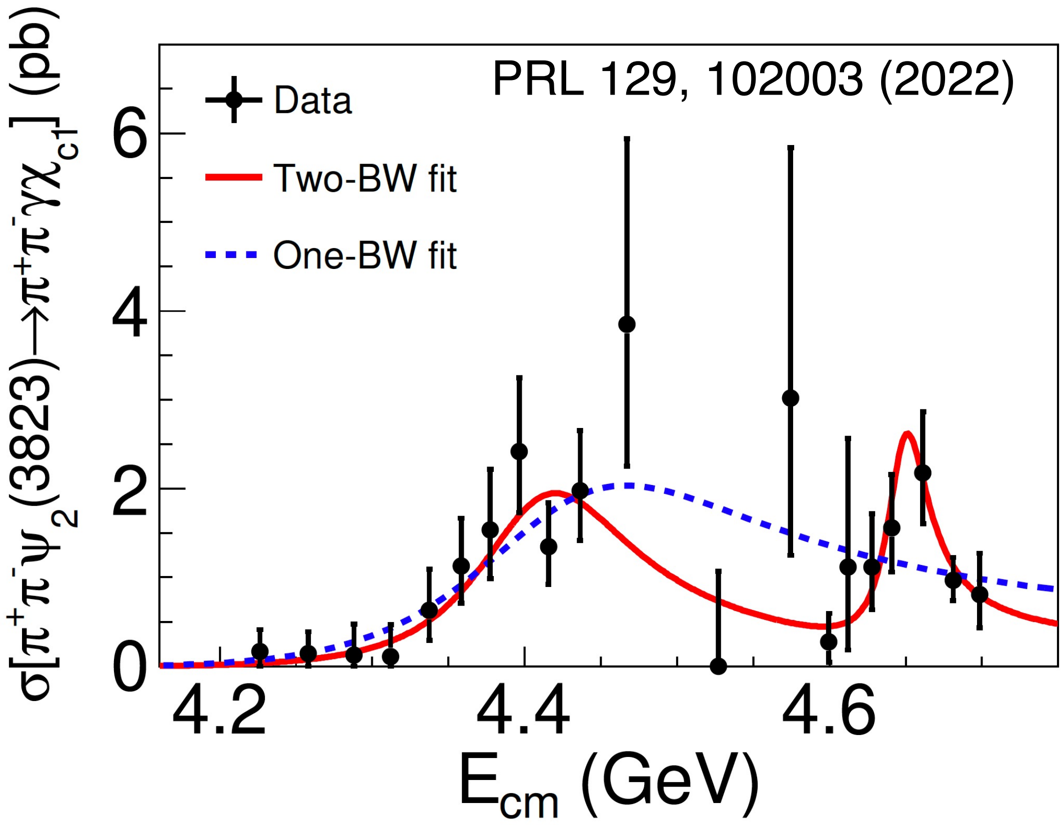


	Result 1	Result 2	Result 3
M_1 (MeV/c^2)	4186.5±9.0	4193.8±7.5	4195.3±7.5
Γ_1 (MeV)	55±17	61.2±9.0	61.8±9.0
M_2 (MeV/c^2)	4414.5±3.2	4412.8±3.2	4411.0±3.2
Γ_2 (MeV)	122.6±7.0	120.3±7.0	120.0±7.0
M_3 (MeV/c^2)	4793.3±7.5	4789.8±9.0	4786±10
Γ_3 (MeV)	27.1±7.0	41±39	60±35



- Y(4160) or Y(4260) [strong coupling to Ds*Ds*?]
- Consistent with $\Psi(4415)$
- Y(4790): necessary to improve fit quality (>6σ)

Observation of Y(4360)/Y(4660)→$\pi^+\pi^-\psi_2(3823)$



Two coherent Y(4360)+Y(4660)

Parameters	Solution I	Solution II
$M[R_1]$	$4406.9 \pm 17.2 \pm 4.5$	
$\Gamma_{\rm tot}[R_1]$	$128.1 \pm 37.2 \pm 2.3$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_1}\mathcal{B}_2$	$0.36 \pm 0.10 \pm 0.03$	$0.30 \pm 0.09 \pm 0.03$
$M[R_2]$	$4647.9 \pm 8.6 \pm 0.8$	
$\Gamma_{\rm tot}[R_2]$	$33.1 \pm 18.6 \pm 4.1$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_2}\mathcal{B}_2$	$0.24 \pm 0.07 \pm 0.02$	$0.06 \pm 0.03 \pm 0.01$
ϕ	$267.1 \pm 16.2 \pm 3.2$	$-324.8 \pm 43.0 \pm 5.7$

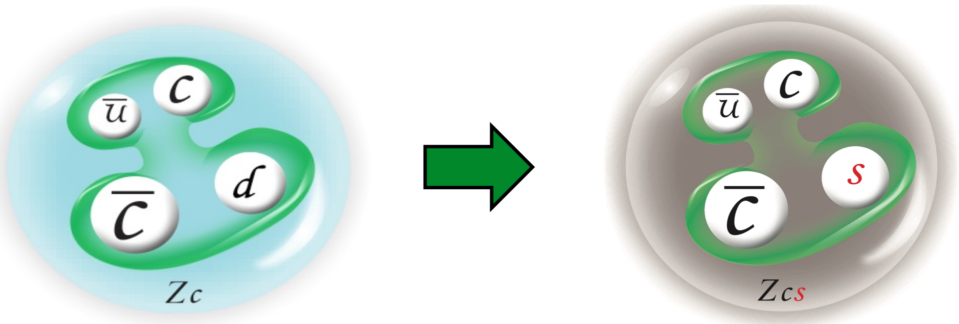
$$\frac{\Gamma[\psi(4660)\to\pi^+\pi^-\psi_2(3823)]}{\Gamma[\psi(4660)\to\pi^+\pi^-\psi(2S)]} \sim 20\%$$

- $f_0(980)\psi(2S)$ molecule ?
- Radial excitation of $\Psi(2S)$?

…

Observation of Z_{cs}(3985): SU(3) partner of Z_c

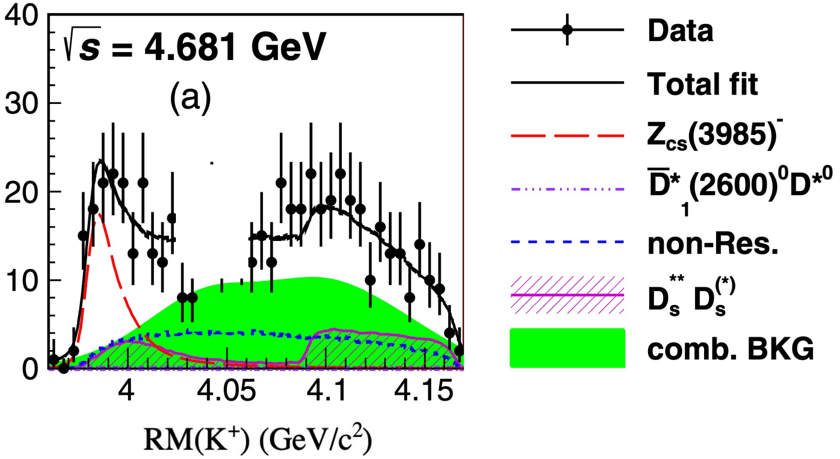
$e^+e^- \to K^+K^-J/\psi$



Given tetraquark state assumption, there should exist SU(3) partner Z_{cs} state with strangeness

$e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

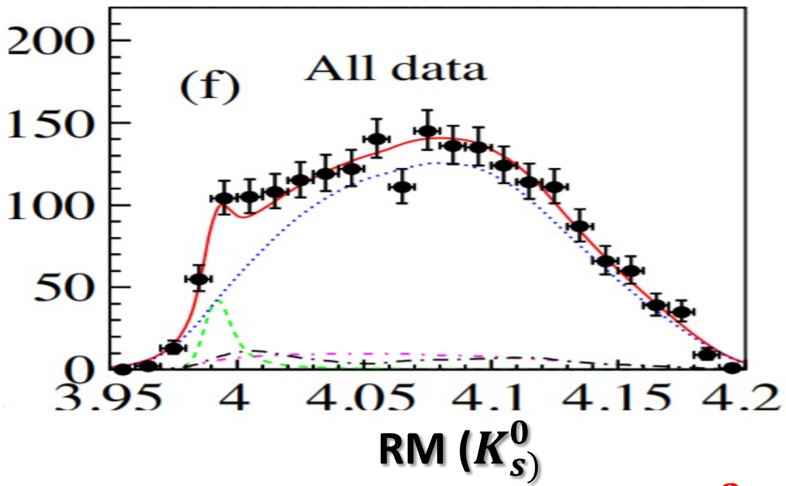
PRL126(2021)102001



- M=$(3985.2^{+2.1}_{-2.0}\pm1.7)$ MeV/c^2
- Γ =$(13.8^{+8.1}_{-5.2}\pm4.9)$ MeV

$e^+e^- \to K_S^0(D_s^+ D^{*-} + D_s^{*+} D^-)$

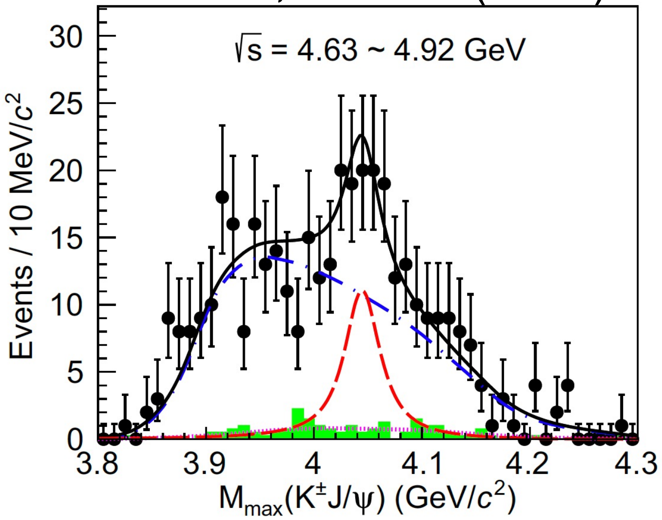
PRL129(2022)112003



- M=$3992.2\pm1.7\pm1.6)$ MeV/c^2
- Γ =$(7.7^{+4.1}_{-3.8}\pm4.3)$ MeV

$e^+e^- \to K^+K^- J/\Psi$

PRL131, 211902 (2023)

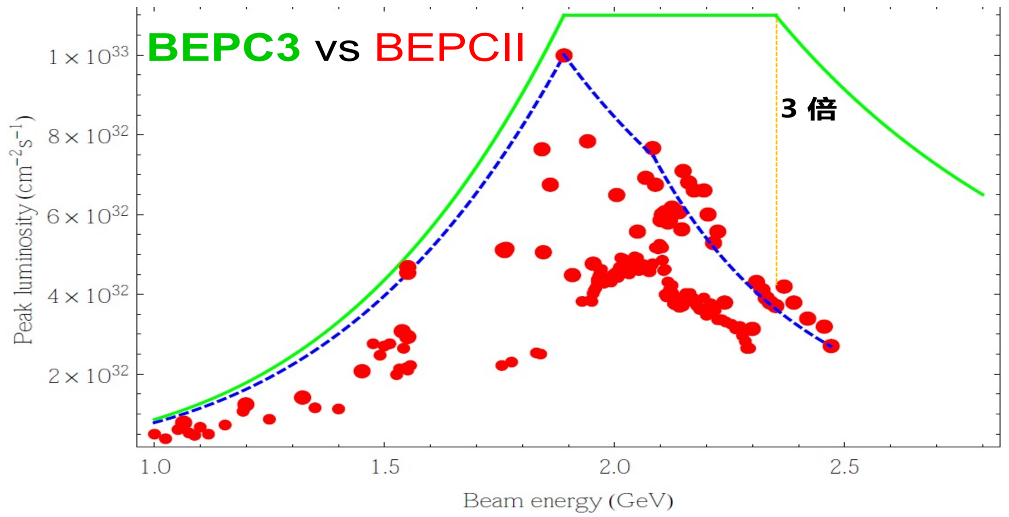


Not significant !

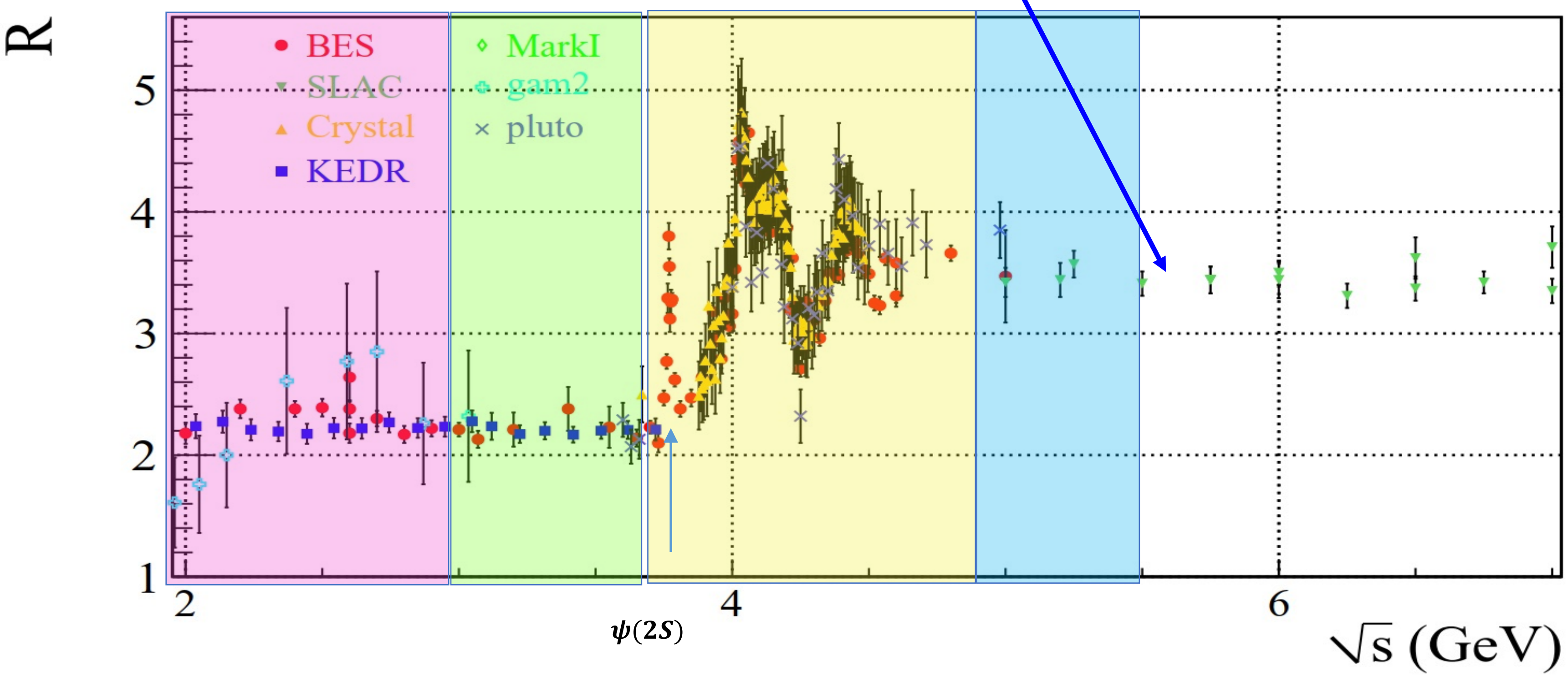
Close mass but very different widths for Zcs(4000) at LHCb !

Plan of BEPCII/BESIII upgrade

- **Optimize E_{cm} at 4.7 GeV with luminosity 3 times higher than the current BEPCII → more effective data taking**



Extend the maximum E_{cm} up to 5.6 GeV → more physics opportunity



Nearly blank at 5-7GeV

Summary

- World largest data samples at BESIII
  - Offers a unique place to investigate light hadron physics
- Recent progresses on hadron spectroscopy are briefly overviewed
  - Provides novel insights into the hadron spectroscopy
- To understand the "new" hadron spectroscopy
  - More theoretical/experimental efforts strongly necessary
  - A great need for a new experiment: STCF !!

Many thanks for your attention !