Exotic states at BESIII and Belle experiments

Chang-Zheng Yuan

(yuancz@ihep.ac.cn)

IHEP, Beijing

International School of Nuclear Physics
44th Course
From quarks and gluons to hadrons and nuclei
Erice-Sicily
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BEPC storage ring and BES detector

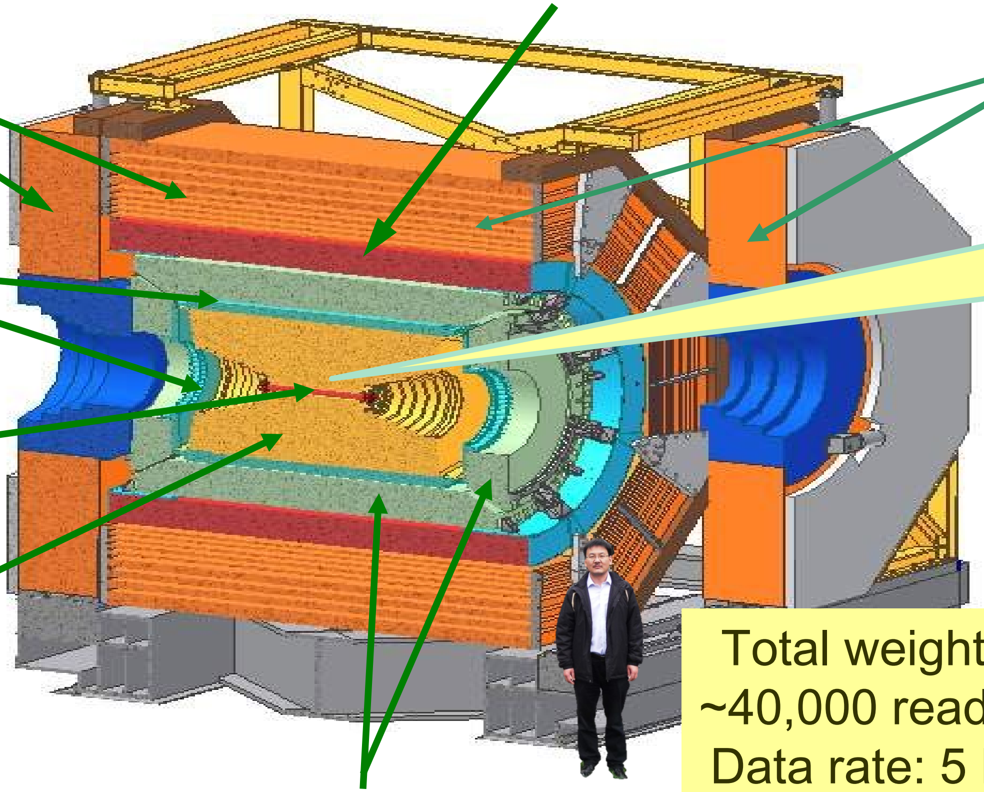
Ground breaking: 1984
CM energy : 2 - 5 GeV
Major upgrade: 2004
Energy upgrade: 2024

1989-2005 (BEPC): L_{peak}=1.0x10^{31} /cm^2s
2008-now (BEPCII): L_{peak}=1.0x10^{33}/cm^2s (Apr. 5, 2016)

World unique e^+e^- accelerator in τ-charm energy region

IHEP, Beijing

BESIII detector



SC magnet, 1 T

Magnet yoke

RPC

CGEM-IT is being built & placed here

BTOF, 70 ps

ETOF, 60 ps

Be beam pipe

MDC, 120 μm
0.5% at 1 GeV/c

Total weight 750 tonnes,
~40,000 readout channels,
Data rate: 5 kHz, 50 Mb/s

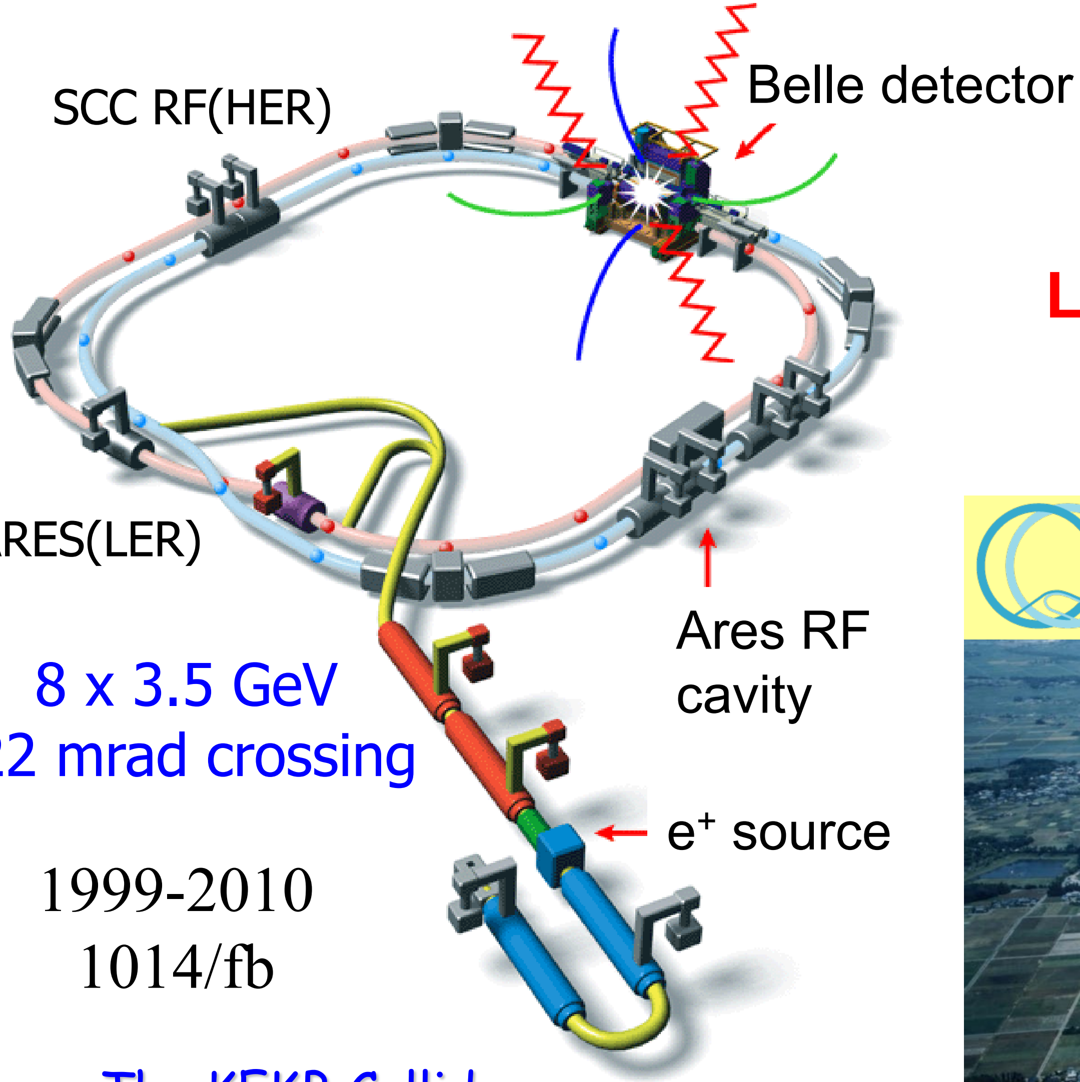
CsI(Tl) calorimeter, 2.5% @ 1 GeV

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

BESIII Collaboration

17 countries，86 institutions, ~600 members

The Belle experiment



8 x 3.5 GeV
22 mrad crossing

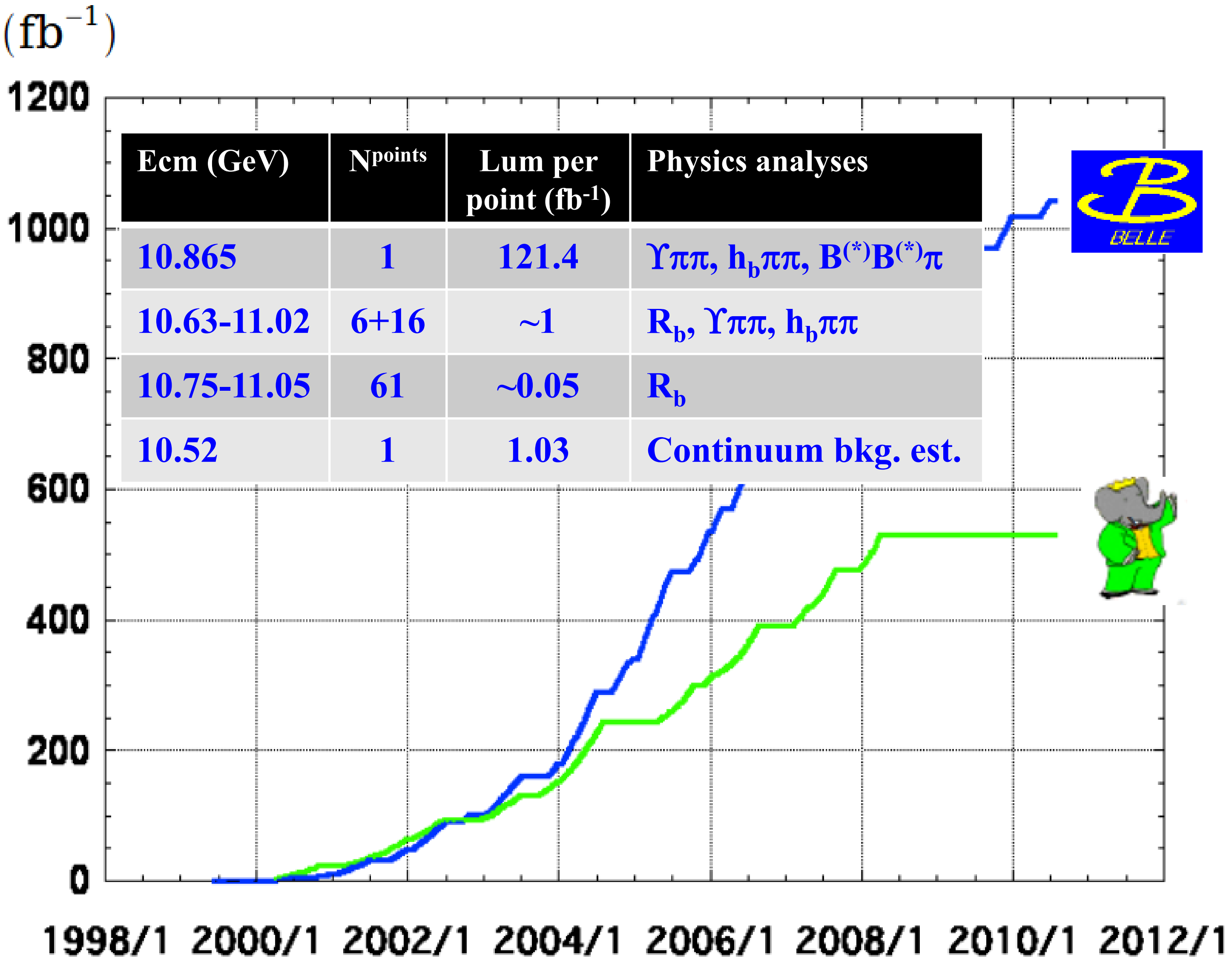
1999-2010
1014/fb

The KEKB Collider

World record:

$L = 2.1 \times 10^{34}/cm^2/sec$

Integrated luminosity of B factories



Ecm (GeV)	N_{points}	Lum per point (fb^{-1})	Physics analyses
10.865	1	121.4	$\Upsilon\pi\pi$, $h_b\pi\pi$, $B^{(*)}B^{(*)}\pi$
10.63-11.02	6+16	~1	R_b, $\Upsilon\pi\pi$, $h_b\pi\pi$
10.75-11.05	61	~0.05	R_b
10.52	1	1.03	Continuum bkg. est.

> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

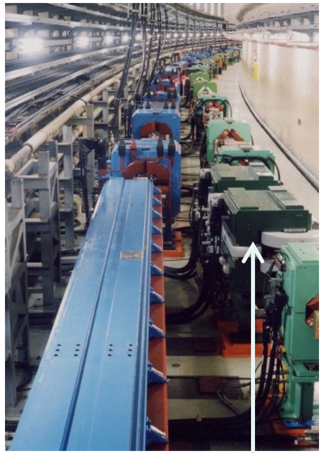
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

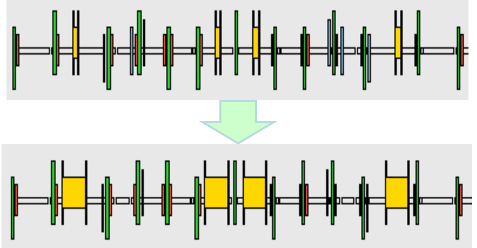
~ 54 fb^{-1}

From KEKB to SuperKEKB

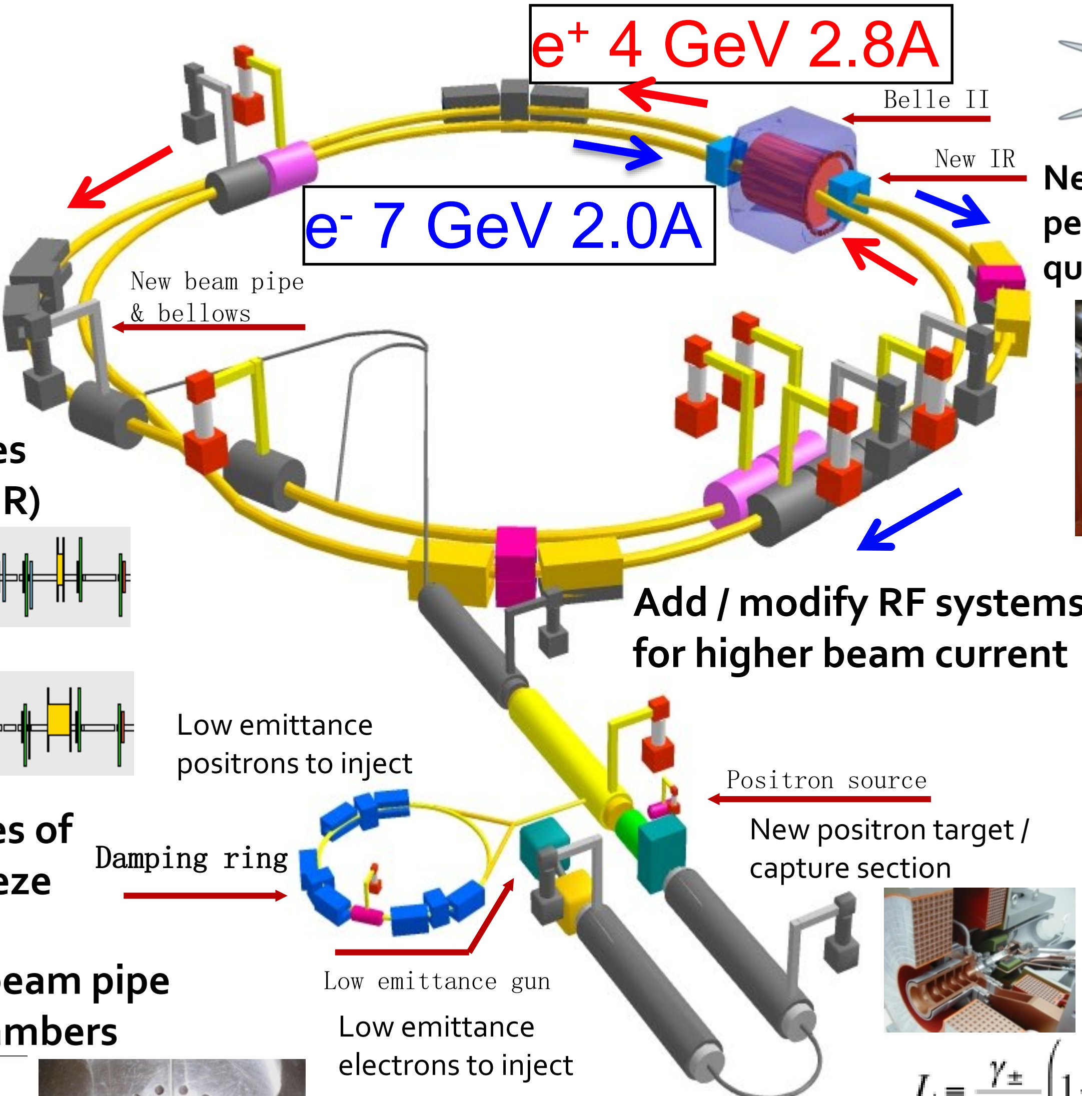
Grey is recycled, colored is new

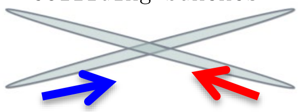


Replace short dipoles with longer ones (LER)

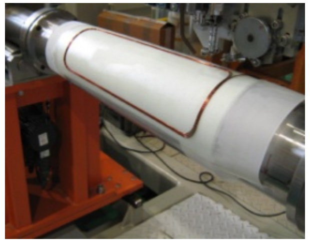


Redesign the lattices of HER & LER to squeeze the emittance





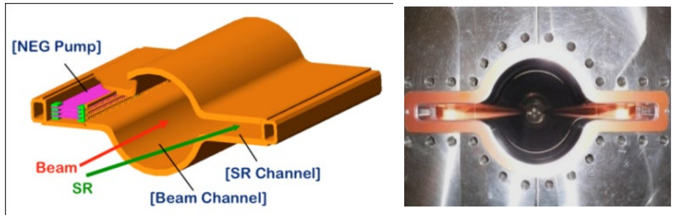
New superconducting / permanent final focusing quads near the IP



Add / modify RF systems for higher beam current

New positron target / capture section

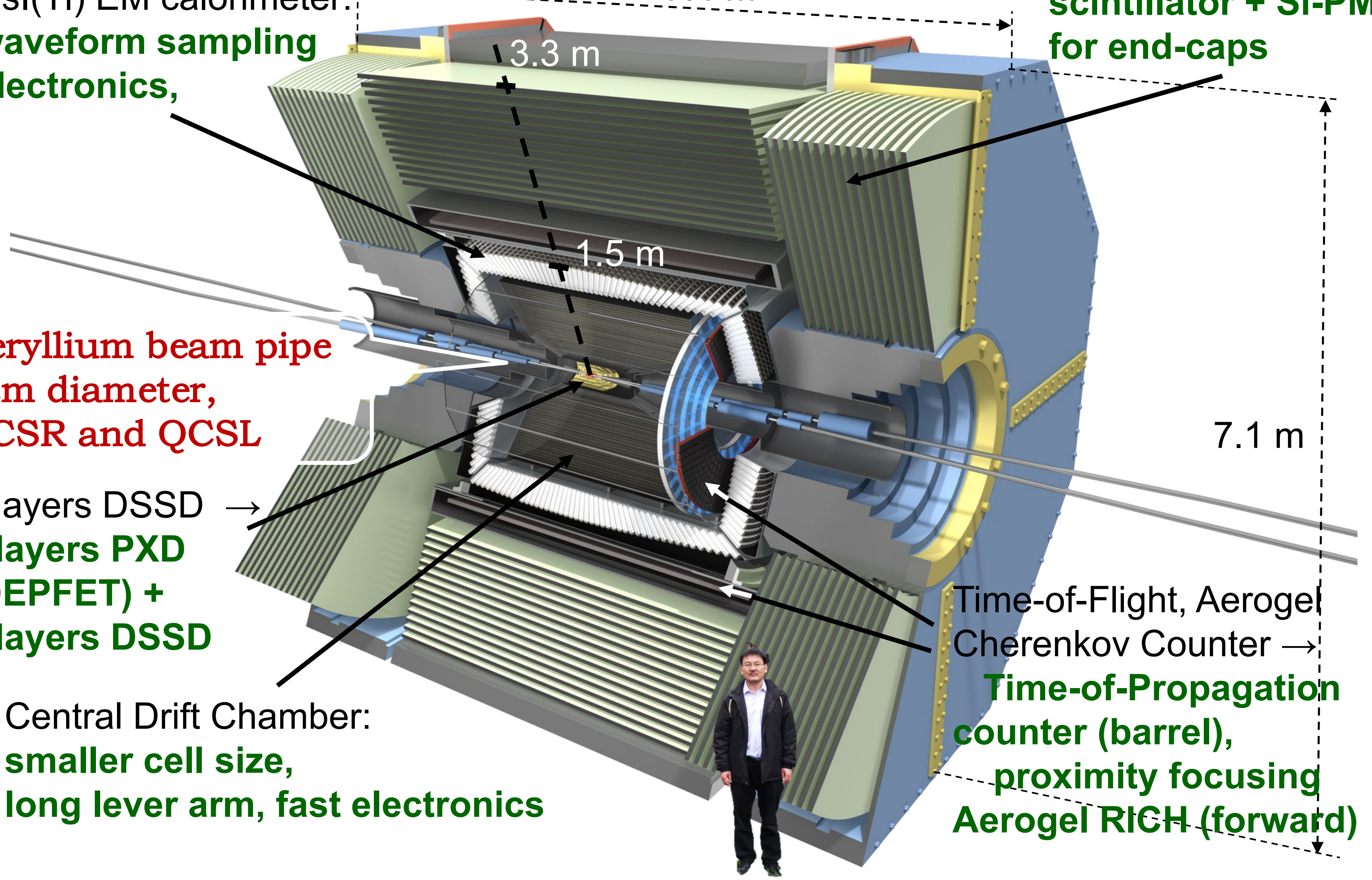
TiN-coated beam pipe with antechambers



$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

Target: $L = 6.5\times10^{35}/cm^2/s$

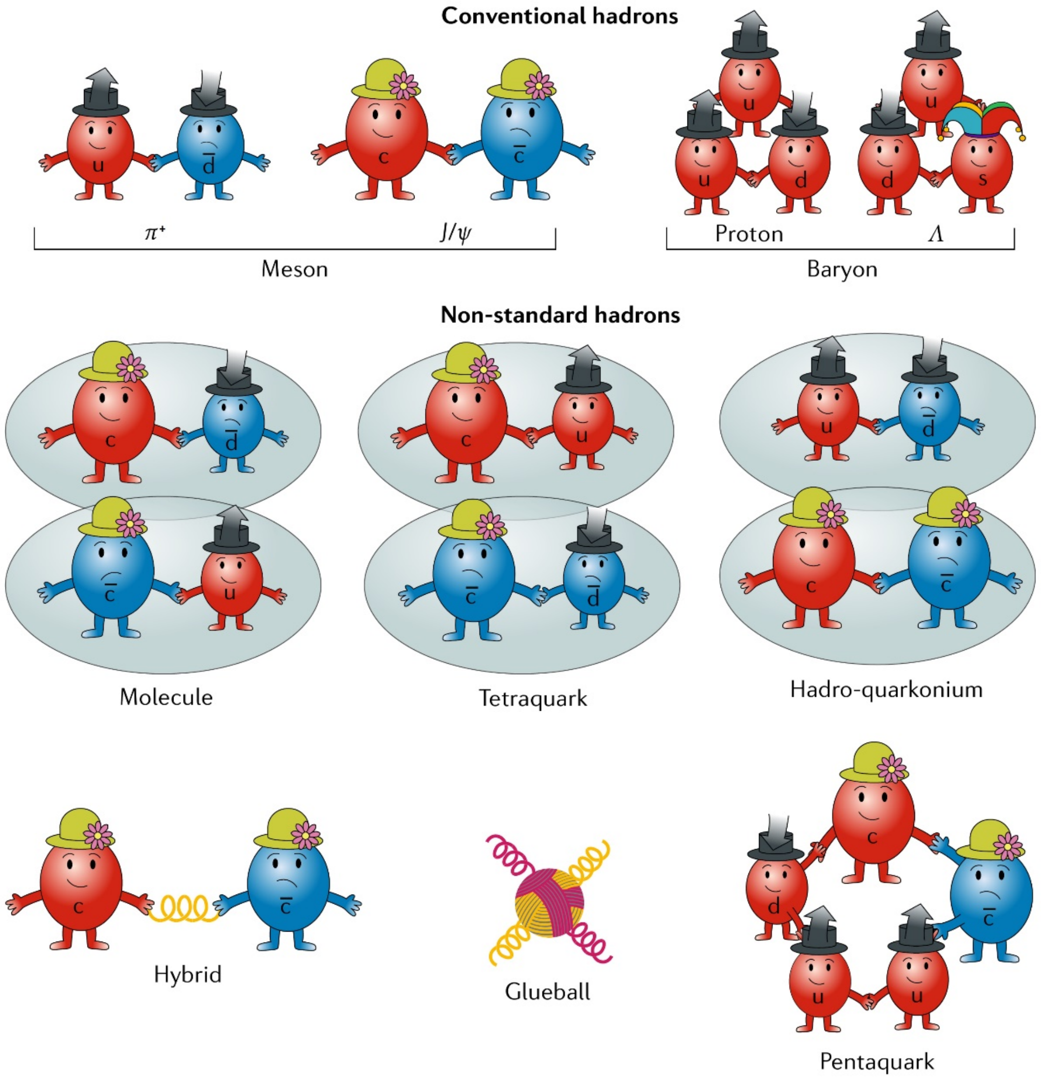
Belle II detector upgrade

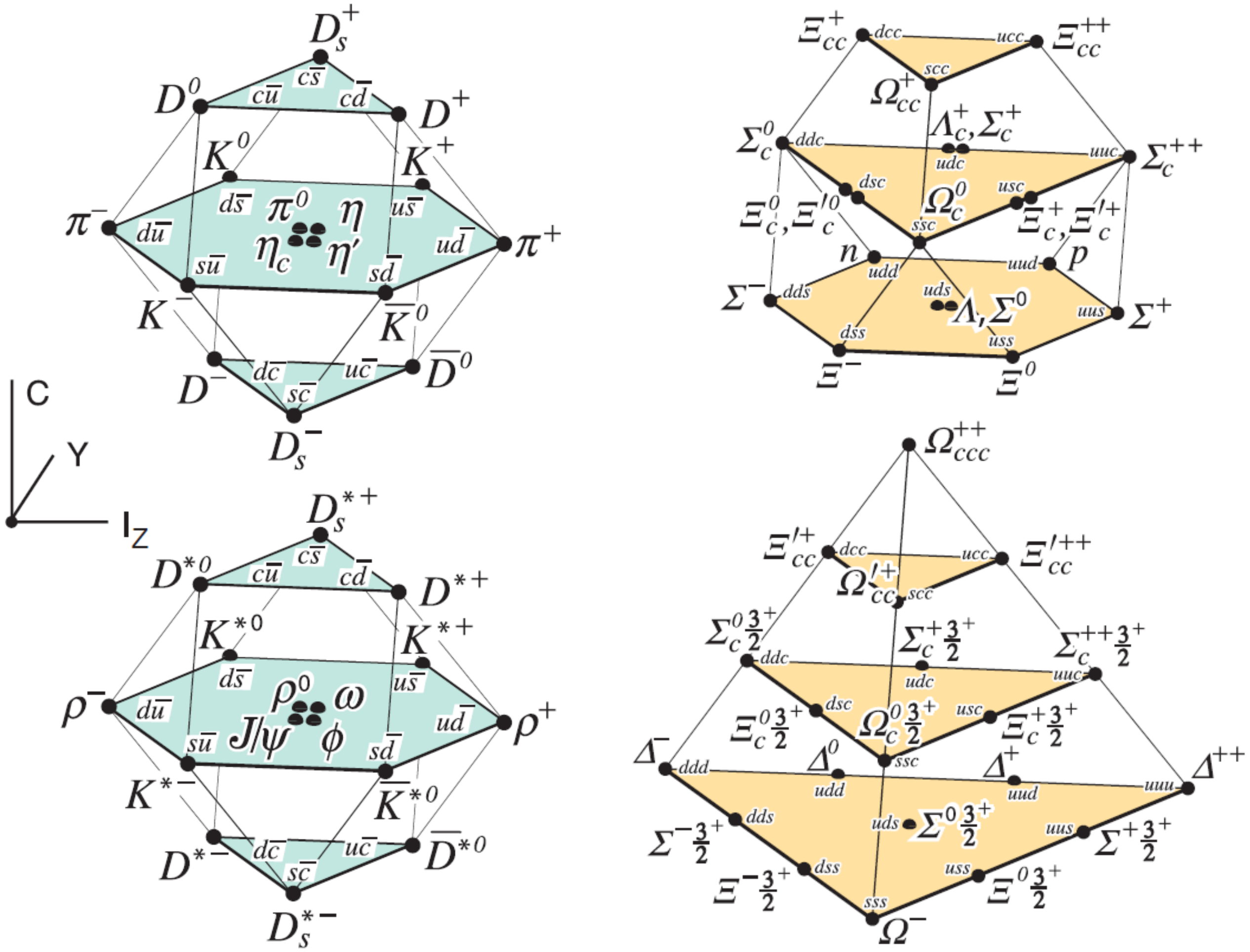


Belle II Collaboration

27 countries，132 institutions,
1167 members

Hadrons: conventional & exotic

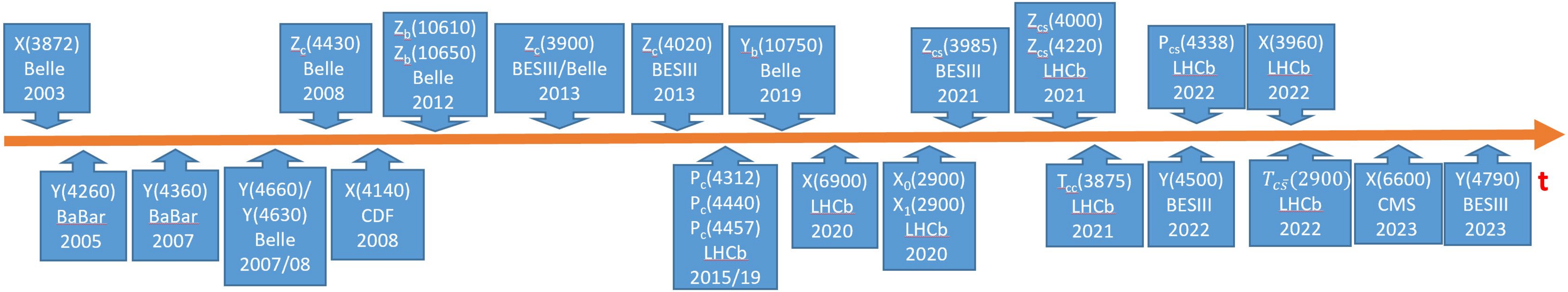




SU(4) multiplets of mesons & baryons

CZY & S. L. Olsen, *Nature Reviews Physics* **1**, 480 (2019)

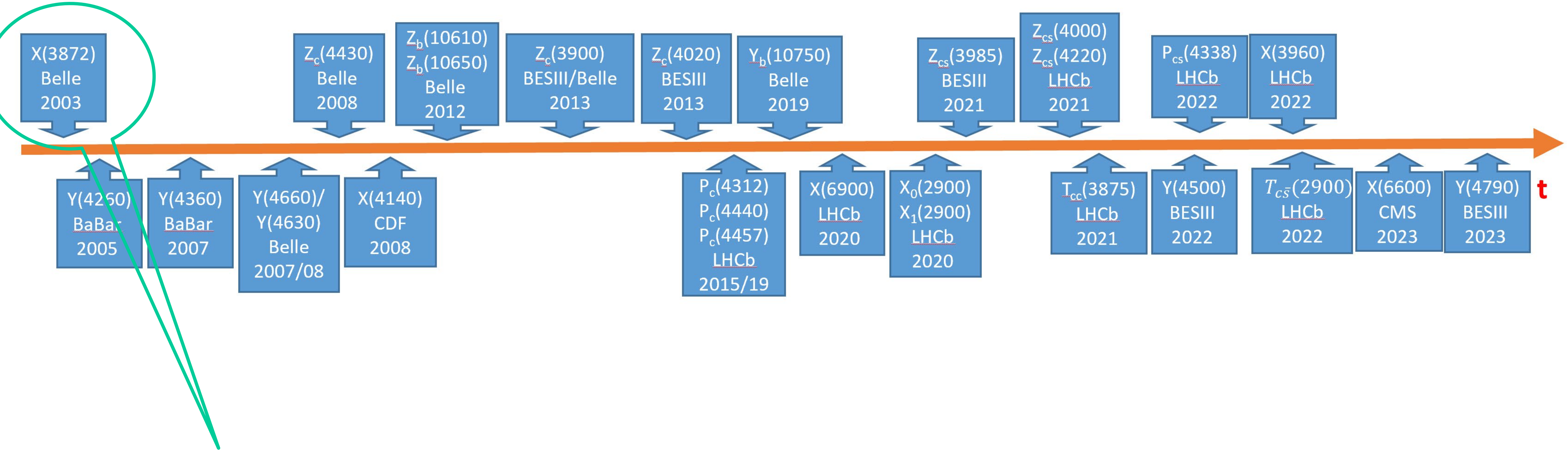
- Lots of states with heavy quarks (c, b) and exotic properties were observed since the discovery of the X(3872) in 2003!
- They are candidates of hadronic molecules, hybrids, and multiquark states.



Z_Q: I=1 & a $Q\bar{Q}$ pair
P_Q: I=1/2 & a $Q\bar{Q}$ pair
Y: $J^{PC}=1^{--}$
$T_{QQ'}$: tetraquark state
X: other states

New spectrum emerges although more effort is needed to understand the nature of them.

This workshop: Alexey Nefediev, Gernot Eichmann, Joshua Hoffer, Sinead Ryan, Alessandro Pilloni, Adam Szczepaniak, Wyatt Smith, Sasa Prelovsek, …

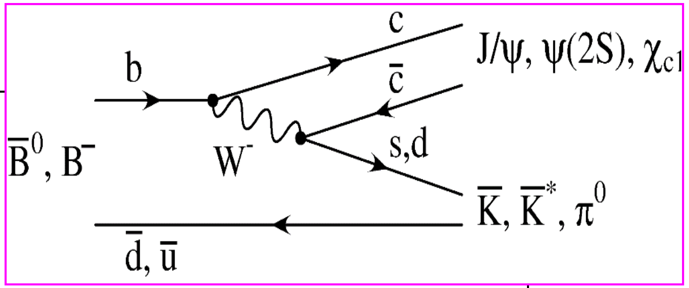


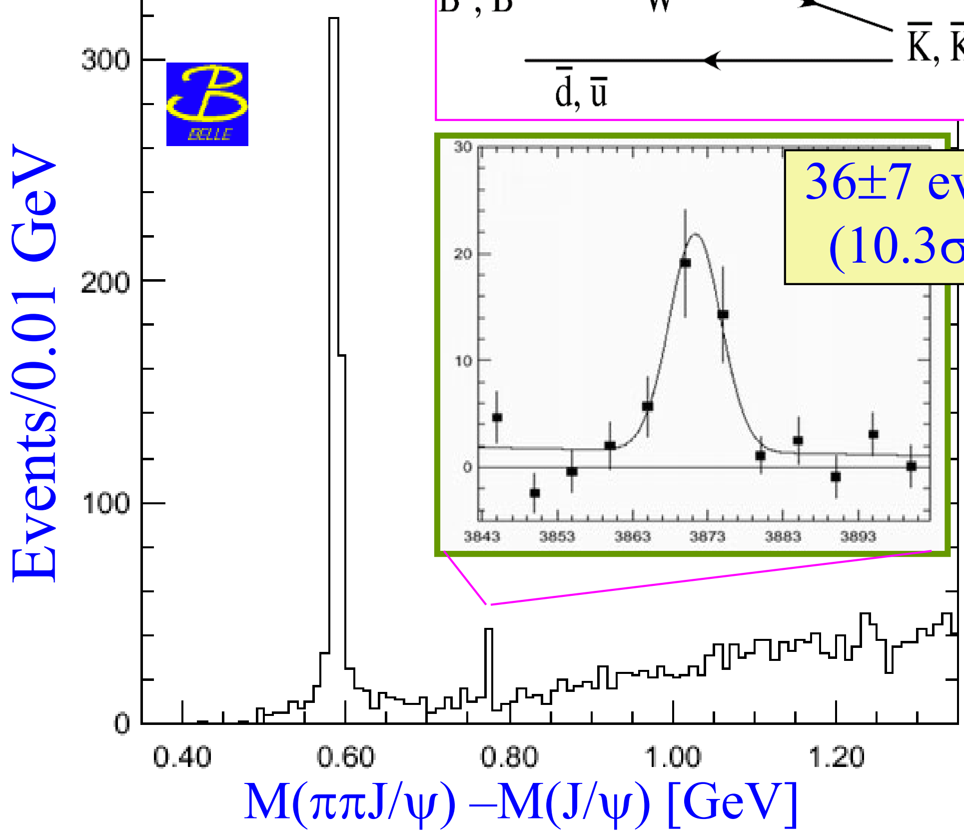
Lots of information on its quantum numbers, mass, width, production and decay properties,

and many new measurements are available

Discovery of the X(3872) [$\chi_{c1}(3872)$ in PDG2023]

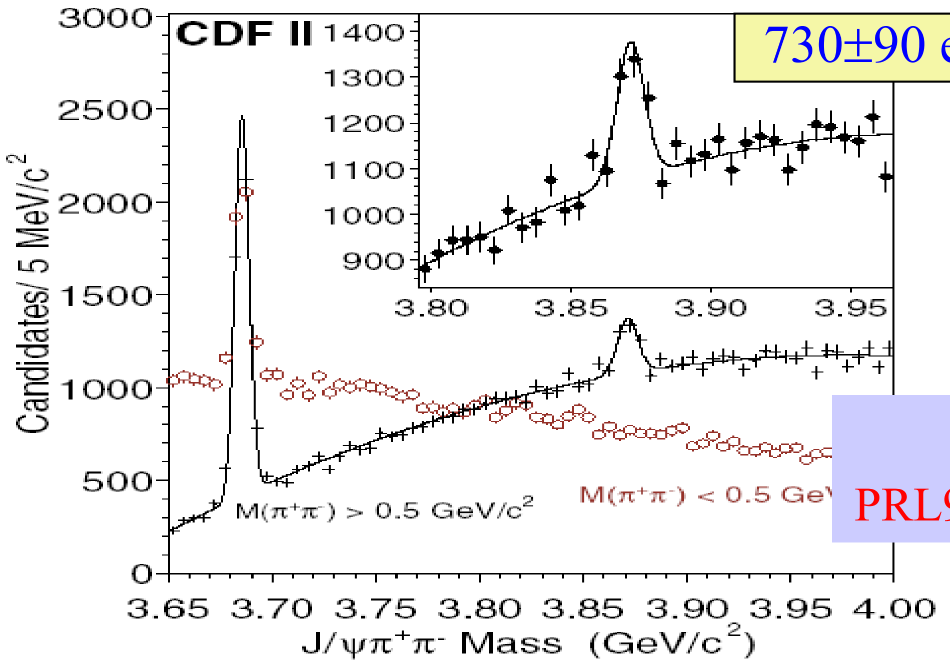
Belle, 20030908, PRL91, 262001



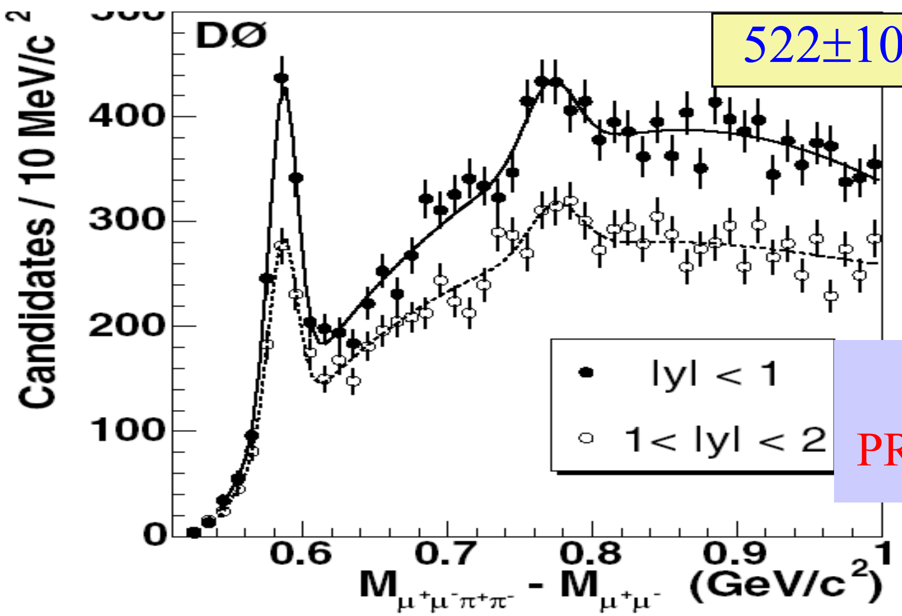


$M = 3872.0 \pm 0.6 \pm 0.5$ MeV, $\Gamma < 2.7$ MeV

$$\frac{B(B^\pm \to XK^\pm \to \pi^+\pi^- J/\psi K^\pm)}{B(B^\pm \to \psi' K^\pm \to \pi^+\pi^- J/\psi K^\pm)} = (6.3 \pm 1.2 \pm 0.7)\%$$



CDF, 2004
PRL93, 072001



D0, 2004
PRL93, 162002

Mass of the X(3872)

VALUE (MeV)		*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3871.65 ± 0.06	**OUR AVERAGE**					
$3871.64 \pm 0.06 \pm 0.01$		19.8k	[1] AAIJ	2020S	LHCB	$B^+ \to J/\psi\pi^+\pi^- K^+$
$3871.9 \pm 0.7 \pm 0.2$		20	ABLIKIM	2014	BES3	$e^+ e^- \to J/\psi\pi^+\pi^-\gamma$
$3871.95 \pm 0.48 \pm 0.12$		0.6k	AAIJ	2012H	LHCB	$p\, p \to J/\psi\pi^+\pi^- X$
$3871.85 \pm 0.27 \pm 0.19$		170	[2] CHOI	2011	BELL	$B \to K\pi^+\pi^- J/\psi$
$3873\ ^{+1.8}_{-1.6} \pm 1.3$		27	[3] DEL-AMO-SANCH..	2010B	BABR	$B \to \omega J/\psi K$
$3871.61 \pm 0.16 \pm 0.19$		6k	[4, 3] AALTONEN	2009AU	CDF2	$p\, \overline{p} \to J/\psi\pi^+\pi^- X$
$3871.4 \pm 0.6 \pm 0.1$		93.4	AUBERT	2008Y	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$
$3868.7 \pm 1.5 \pm 0.4$		9.4	AUBERT	2008Y	BABR	$B^0 \to K^0_S\, J/\psi\pi^+\pi^-$
$3871.8 \pm 3.1 \pm 3.0$		522	[5, 3] ABAZOV	2004F	D0	$p\, \overline{p} \to J/\psi\pi^+\pi^- X$

$M_{D0} + M_{D^{*}0} = 3871.69 \pm 0.11$ MeV

$E_b = -0.04 \pm 0.12$ MeV

E_b(deuteron) $= -2.2$ MeV

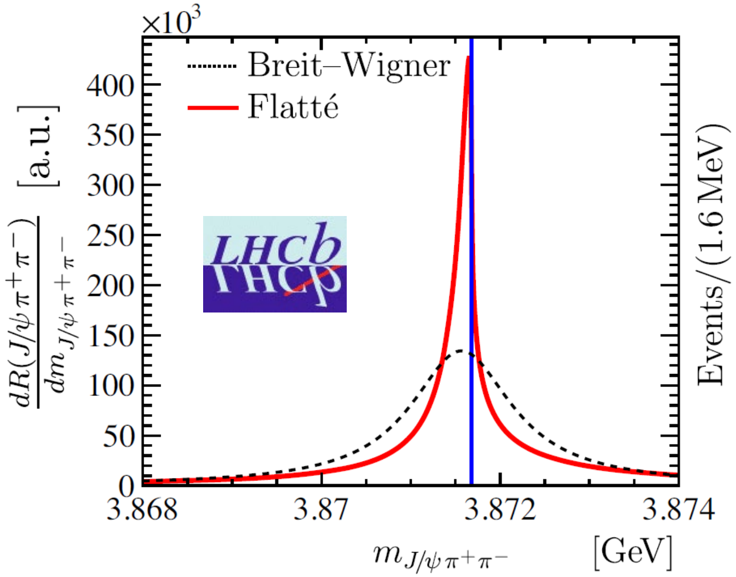
$$r_X = (8\mu|E_b|)^{-1/2} > 5\ \text{fm}$$

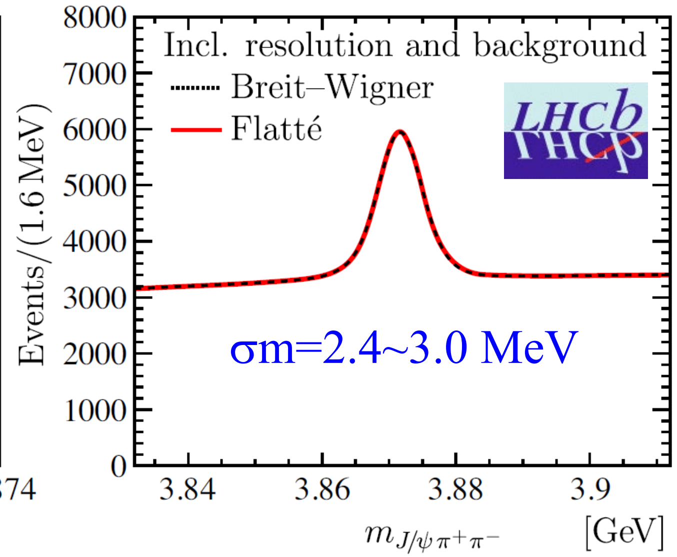
LHCb, PRD102, 092005 (2020)

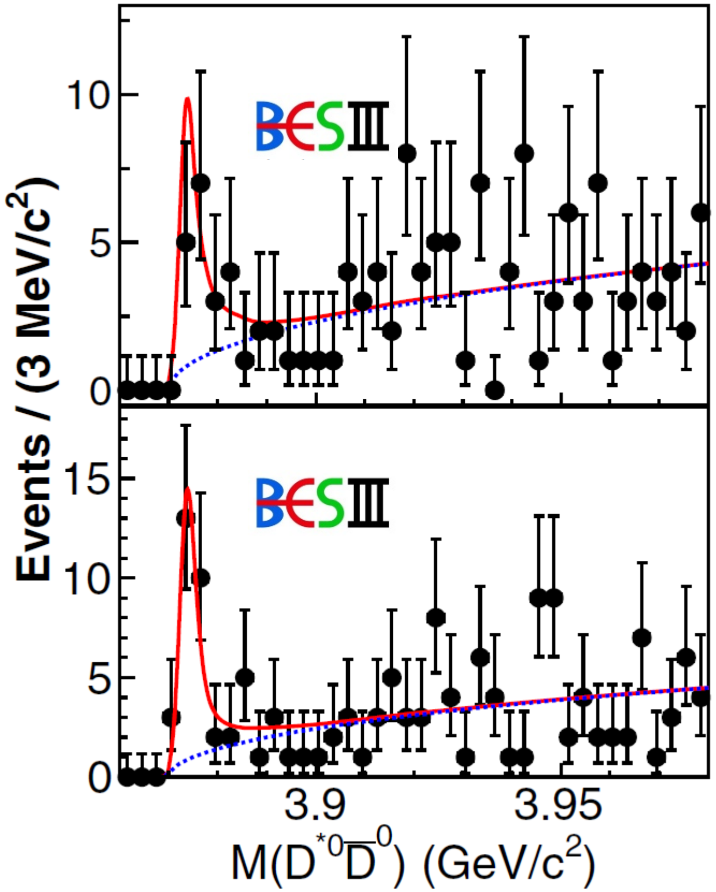
Width of the X(3872)

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.19 ± 0.21			**OUR AVERAGE** Error includes scale factor of 1.1.			
1.39 ±0.24 ±0.10		15.6k	[1] AAIJ	2020AD	LHCB	$p\,p \to J/\psi\pi^+\pi^- X$
$0.96\ ^{+0.19}_{-0.18}$ ±0.21		4.2k	[2] AAIJ	2020S	LHCB	$B^+ \to J/\psi\pi^+\pi^- K^+$

BW width!







BESIII may supply crucial information on *g & line shape.*

Mass resolution σm < 1 MeV!

PRL124, 242001 (2020)

Flatté parametrization:

$$D(E) = E - E_f + \frac{i}{2}[g(k_1 + k_2) + \Gamma_\rho(E) + \Gamma_\omega(E) + \Gamma_0]$$

Depends strongly on *g*, coupling to $\bar{D}^0 D^{*0}$!

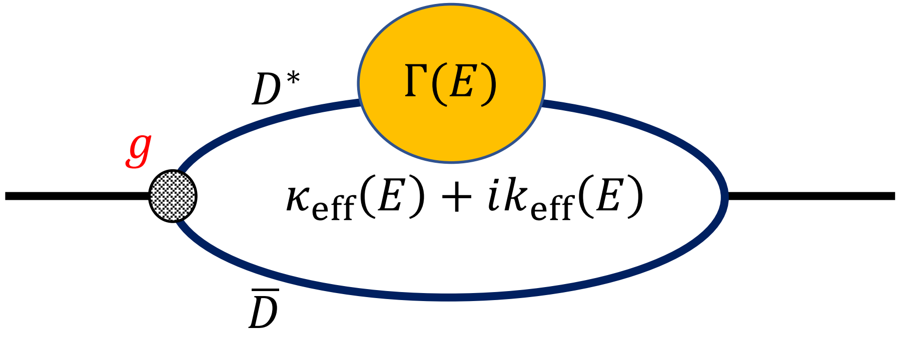
$$\text{FWHM} = 0.22^{+0.06+0.25}_{-0.08-0.17}\ \text{MeV}$$

A coupled channel analysis of the X(3872) line shape at BESIII

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

$$\frac{d\mathrm{Br}(D^0\bar{D}^0\pi^0)}{dE} = \boldsymbol{B}\frac{1}{2\pi}\times\frac{g * k_{\mathrm{eff}}(E)}{|D(E)|^2}\times\mathrm{Br}(D^{*0}\to D^0\pi^0)$$

$$\frac{d\mathrm{Br}(\pi^+\pi^- J/\psi)}{dE} = \boldsymbol{B}\frac{1}{2\pi}\times\frac{\Gamma_{\pi^+\pi^- J/\psi}}{|D(E)|^2}$$



$$D(E) = E - E_X + \frac{1}{2}g * \left(\boldsymbol{\kappa_{\mathrm{eff}}(E) + ik_{\mathrm{eff}}(E) + \kappa^c_{\mathrm{eff}}(E) + ik^c_{\mathrm{eff}}(E)}\right) + \frac{i}{2}\boldsymbol{\Gamma_0}$$

$$k_{\mathrm{eff}}(E) = \sqrt{\mu_p}\sqrt{\sqrt{(E-E_R)^2+\Gamma^2/4}+E-E_R}$$

$$\kappa_{\mathrm{eff}}(E) = -\sqrt{\mu_p}\sqrt{\sqrt{(E-E_R)^2+\Gamma^2/4}-E+E_R} + \sqrt{\mu_p}\sqrt{\sqrt{(E_X-E_R)^2+\Gamma_X^2/4}-E_X+E_R}$$

$$\Gamma_0 = \Gamma_{\pi^+\pi^- J/\psi} + \Gamma_{known} + \Gamma_{unknown}$$

$$E_X = M_X - (m_{D^0} + m_{\bar{D}^0} + m_{\pi^0})$$

∗superscript c: charged $D^{*+}D^-$

∗Due to the limited statistics, $\boldsymbol{\Gamma_{unknown}/\Gamma_{\pi^+\pi^- J/\psi}}$ is fixed

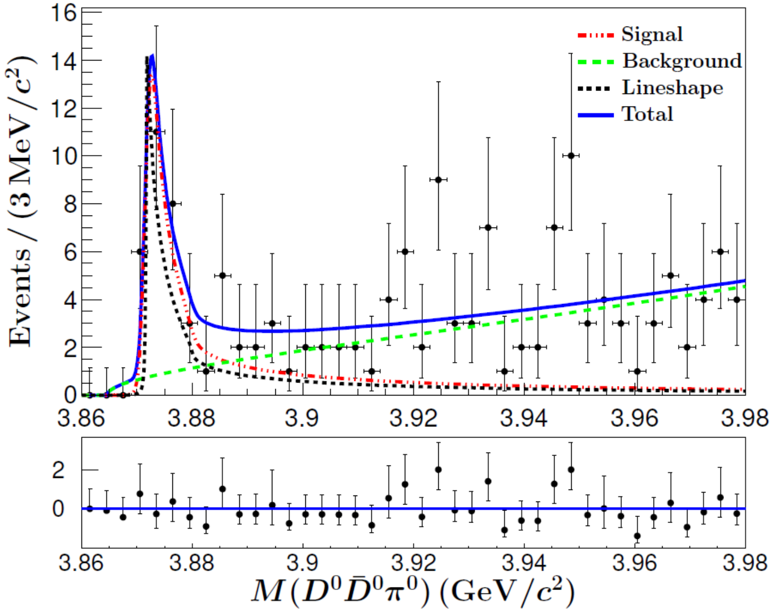
[Chunhua Li, Chang-Zheng Yuan, PRD 100, 094003 (2019)]

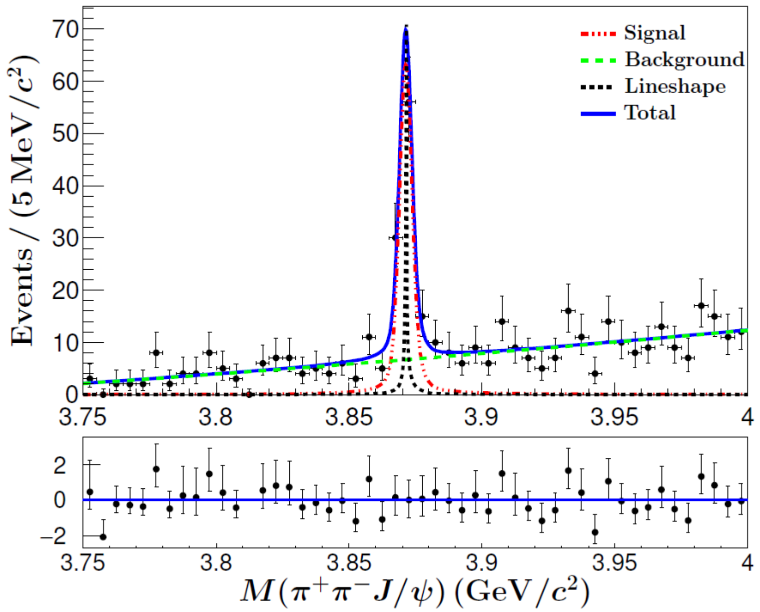
Key features:

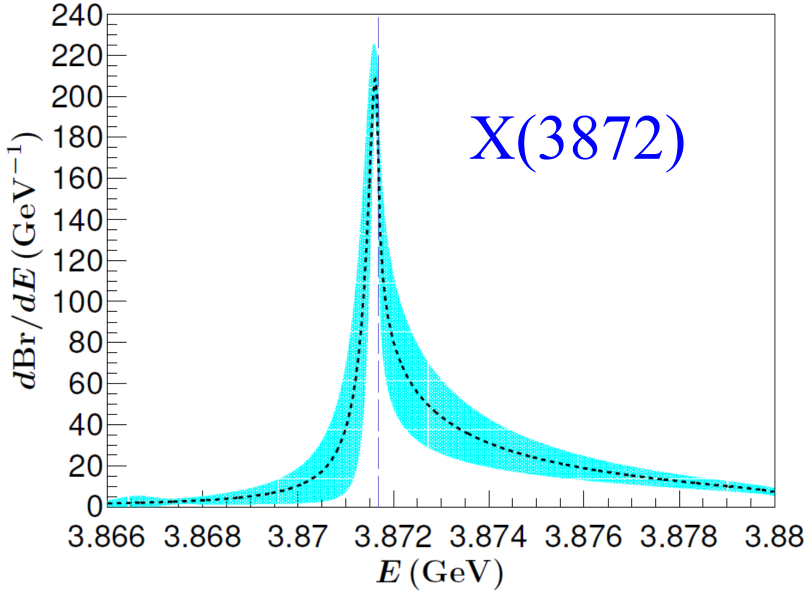
- Model independent
- Including the $D^*\bar{D}$ self energy terms
- Including the width of D^*
- Including the coupled channel effect
- Fit parameters: $\boldsymbol{g}$, $\boldsymbol{\Gamma_{\pi^+\pi^- J/\psi}}$, $\boldsymbol{M_X}$

BESIII *2309.01502*

X(3872) line shape @ BESIII







Pole positions

Two sheets with respect to $D^{*0}\bar{D}^0$ branch cut

- Sheet I: $E - E_X - g\sqrt{-2\mu(E - E_R + i\Gamma/2)}$
- Sheet II: $E - E_X + g\sqrt{-2\mu(E - E_R + i\Gamma/2)}$

$E_{\mathrm{I}} = (7.04 \pm 0.15^{+0.07}_{-0.08}) + (-0.19 \pm 0.08^{+0.14}_{-0.19})i$ MeV

$E_{\mathrm{II}} = \left(0.26 \pm 5.74^{+5.14}_{-38.32}\right) + (-1.71 \pm 0.90^{+0.60}_{-1.96})i$ MeV

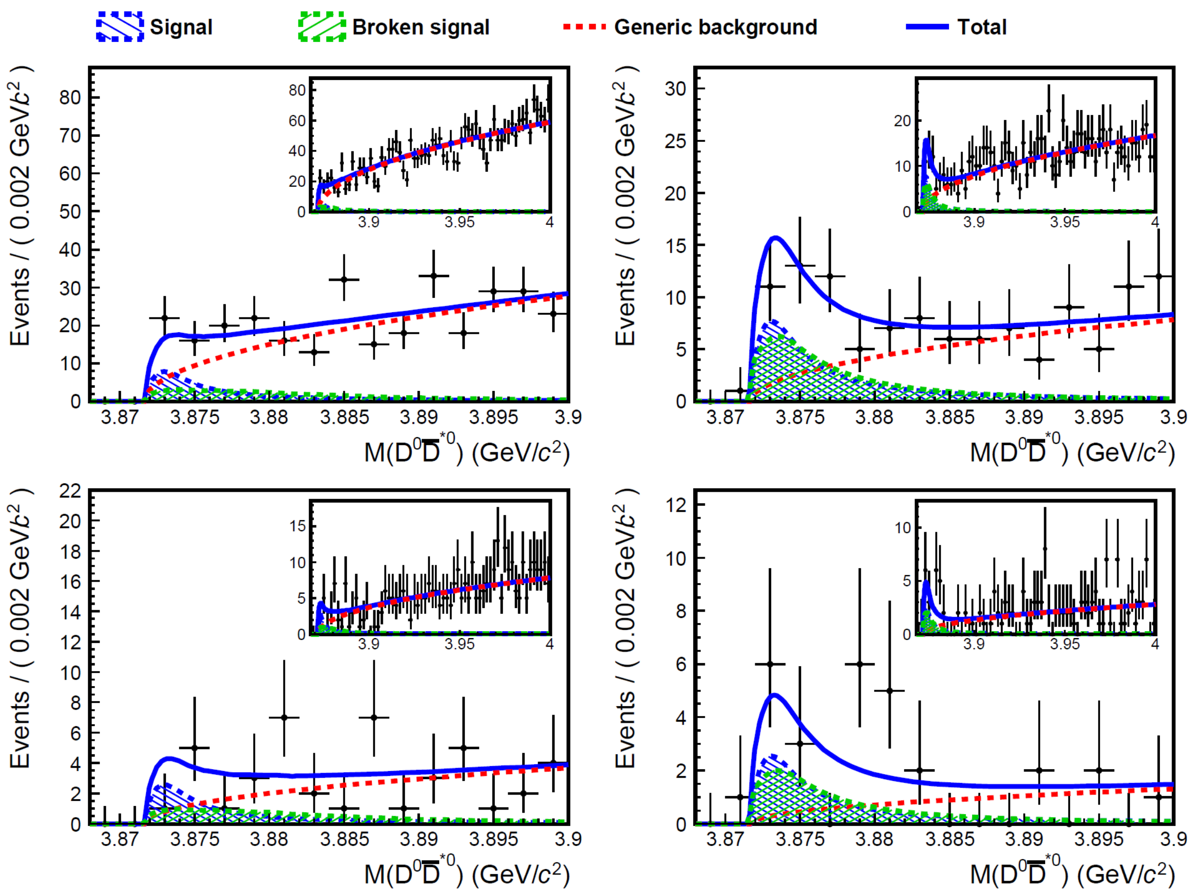
Parameters	BESIII	LHCb
g	$0.16 \pm 0.10^{+1.12}_{-0.11}$	$0.108 \pm 0.003^{+0.005}_{-0.006}$
$Re[E_I]$ [MeV]	$7.04 \pm 0.15^{+0.07}_{-0.08}$	7.10
$Im[E_I]$ [MeV]	$-0.19 \pm 0.08^{+0.14}_{-0.19}$	-0.13
$\Gamma(\pi^+\pi^- J/\psi)/\Gamma(D^0\bar{D}^{*0})$	$0.05 \pm 0.01^{+0.01}_{-0.02}$	0.11 ± 0.03
FWHM (MeV)	$0.44^{+0.13}_{-0.35}{}^{+0.38}_{-0.25}$	$0.22^{+0.06}_{-0.08}{}^{+0.25}_{-0.17}$
Z	0.18	0.15

Weinberg's compositeness: $Z = 1$: pure elementary state; $Z = 0$: pure bound (composite) state.

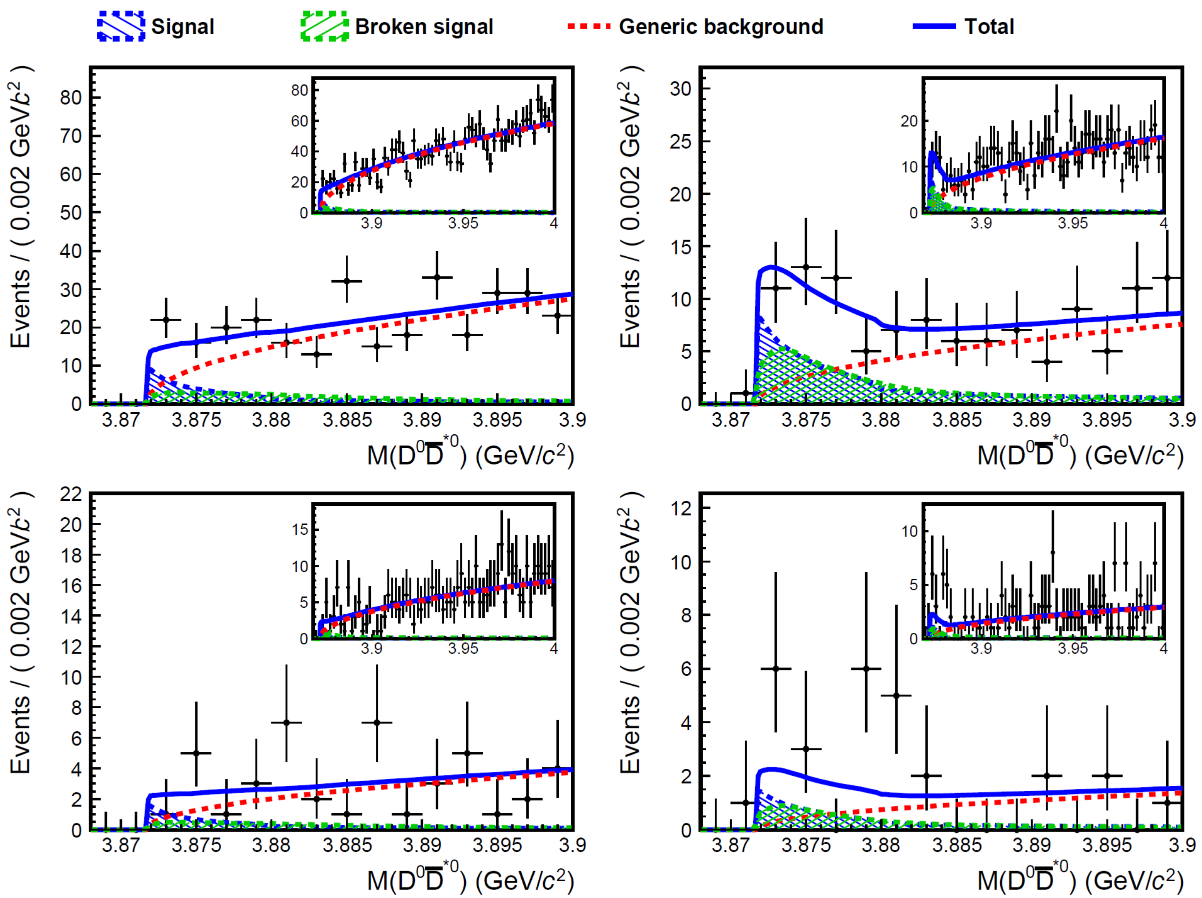
PRD107, 112011 (2023)

X(3872) line shape @ Belle

BW parametrization



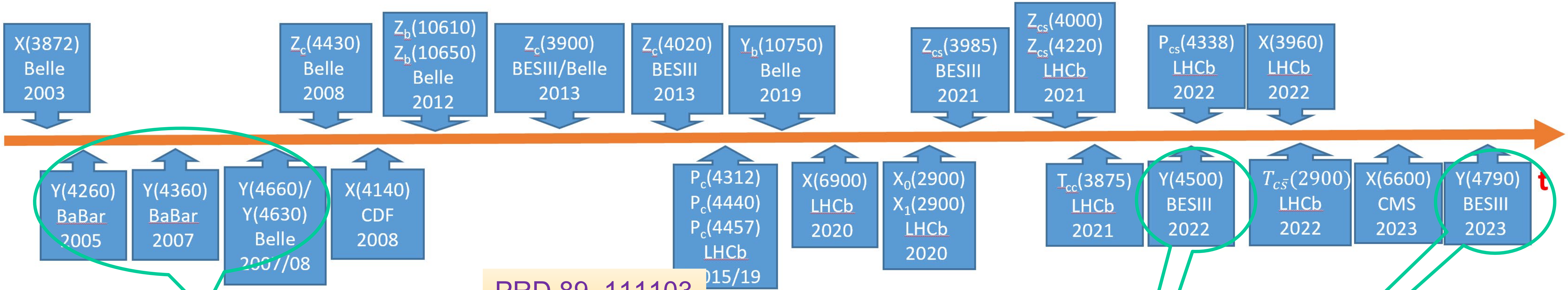
Flatté parametrization

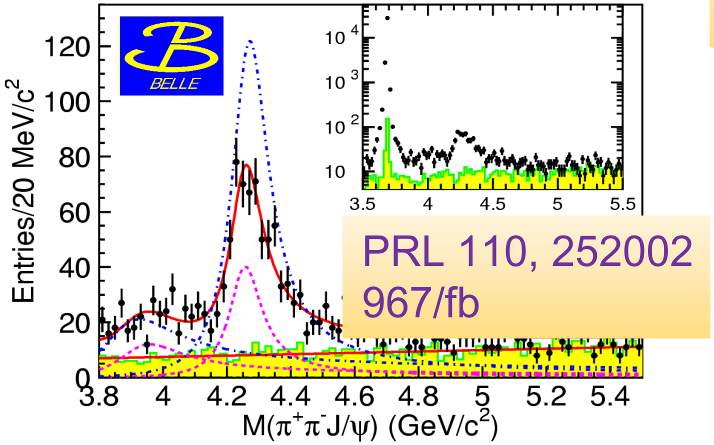


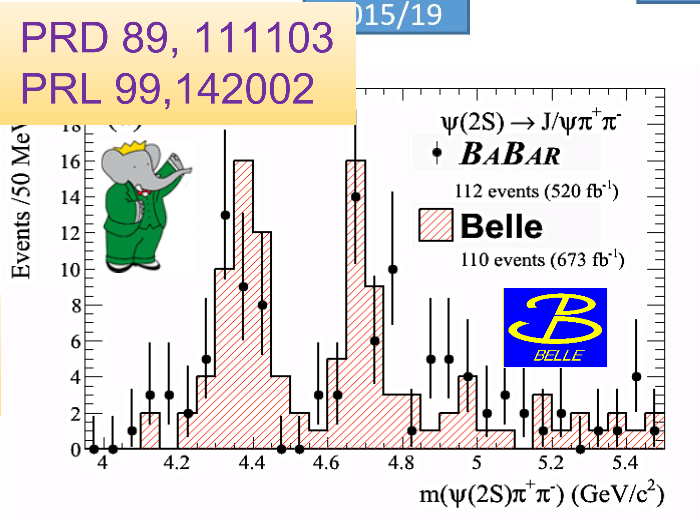
$$m_{\mathrm{BW}} = 3873.71^{+0.56}_{-0.50}(\mathrm{stat}) \pm 0.13(\mathrm{syst})\ \mathrm{MeV}/c^2,$$

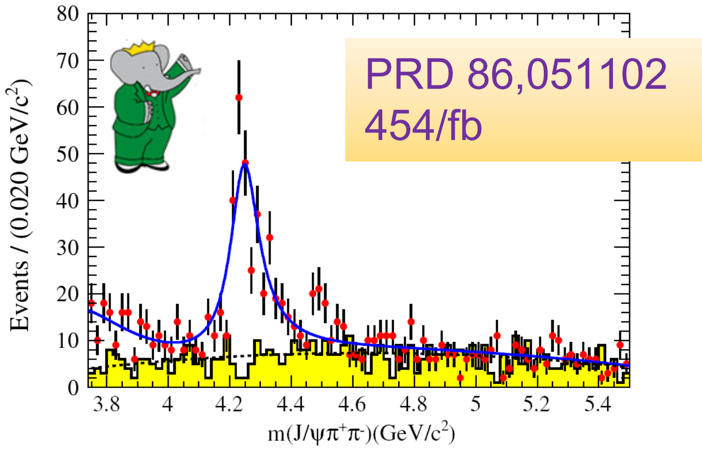
$$\Gamma_{\mathrm{BW}} = 5.2^{+2.2}_{-1.5}(\mathrm{stat}) \pm 0.4(\mathrm{syst})\ \mathrm{MeV}.$$

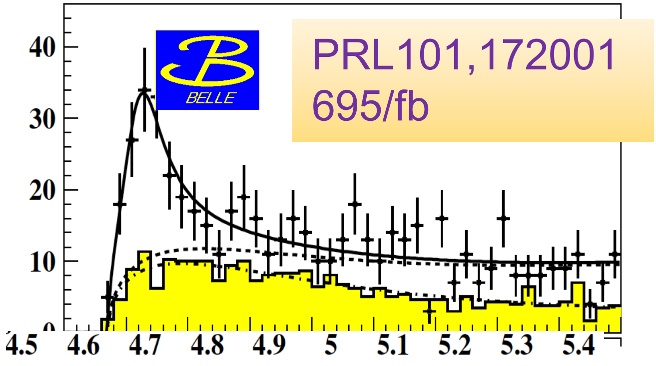
- Fit $D^0\overline{D}^{*0}$ mode only, not a coupled-channel analysis
- BW is favored over Flatté parametrization
- coupled-channel analysis highly recommended







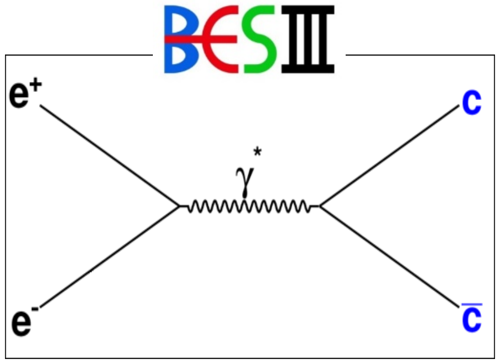


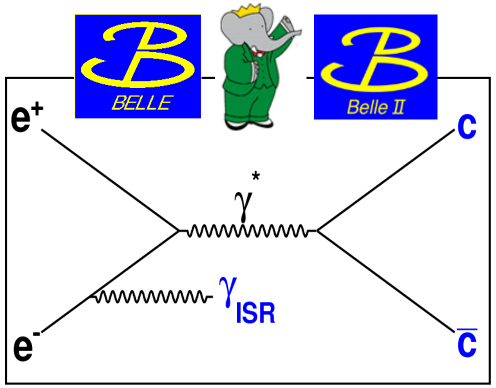


$M(\Lambda_c^+\Lambda_c^-)$

The Y states discovered via initial states radiation (ISR) in e^+e^- annihilation have $J^{PC}=1^{--}$.

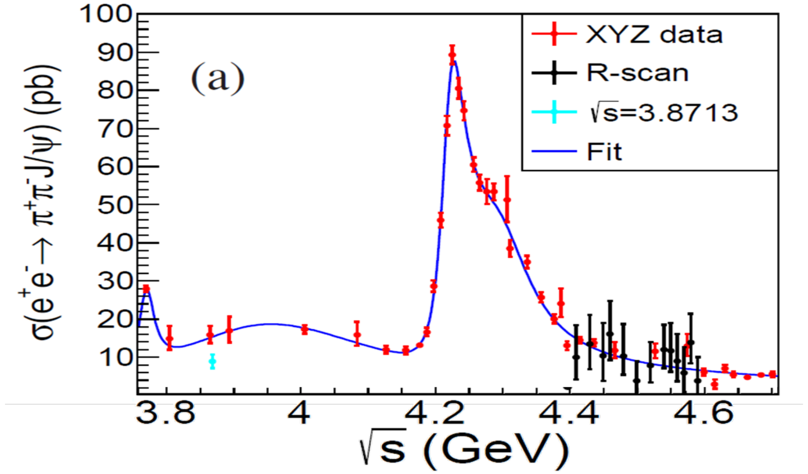
Direct e^+e^- annihilation experiment BESIII can measure them in higher precision.



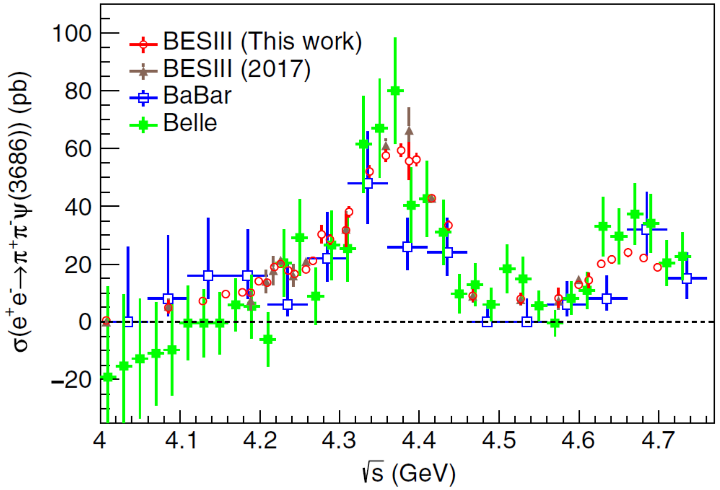


Y(4260) is now Y(4230) [ψ(4230) in PDG2023]

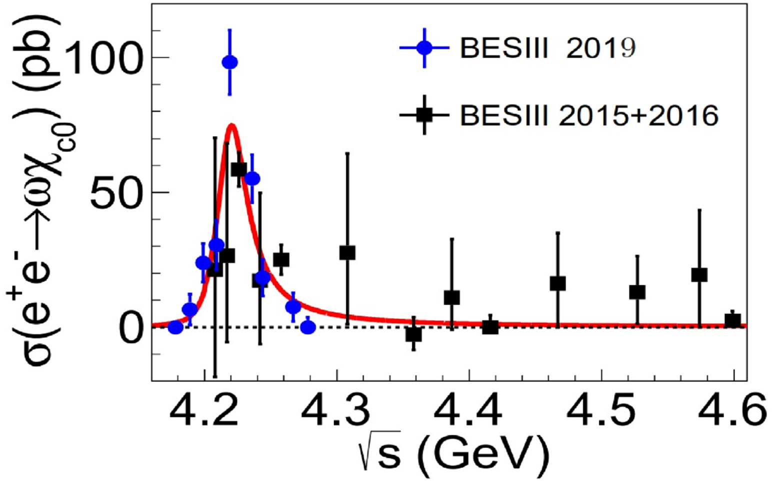
PRD106, 072001 (2022)



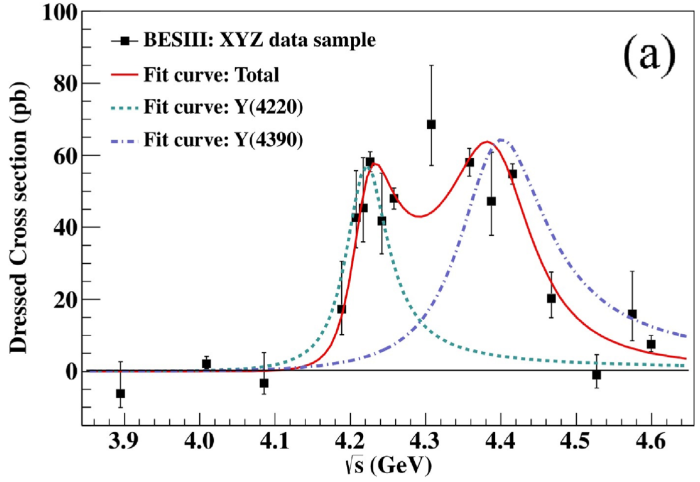
PRD104, 052102 (2021)



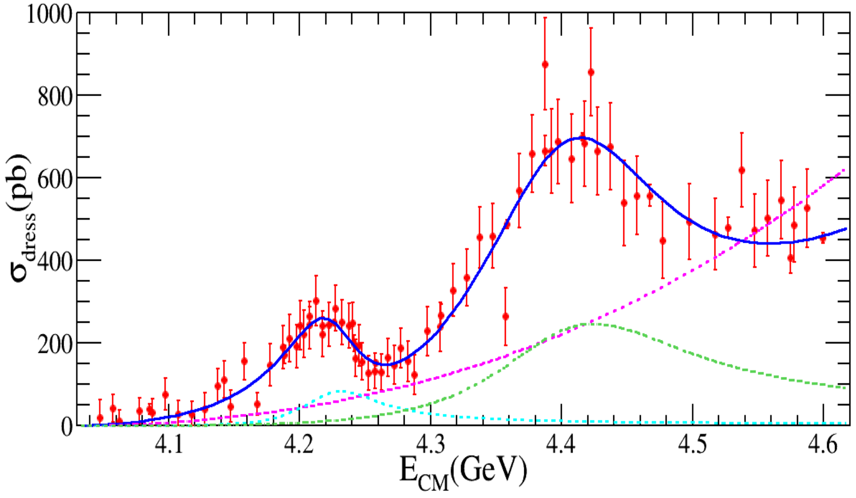
PRD99, 091103 (2019)



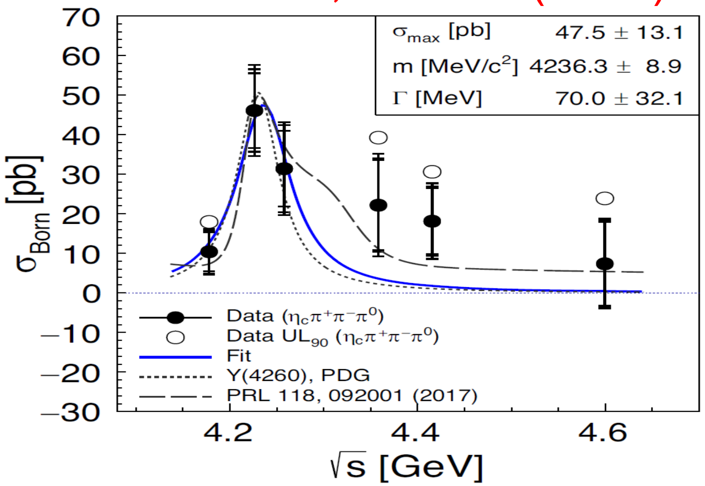
PRL118, 092002 (2017)



PRL122, 102002 (2019)



PRD 103, 032006 (2021)



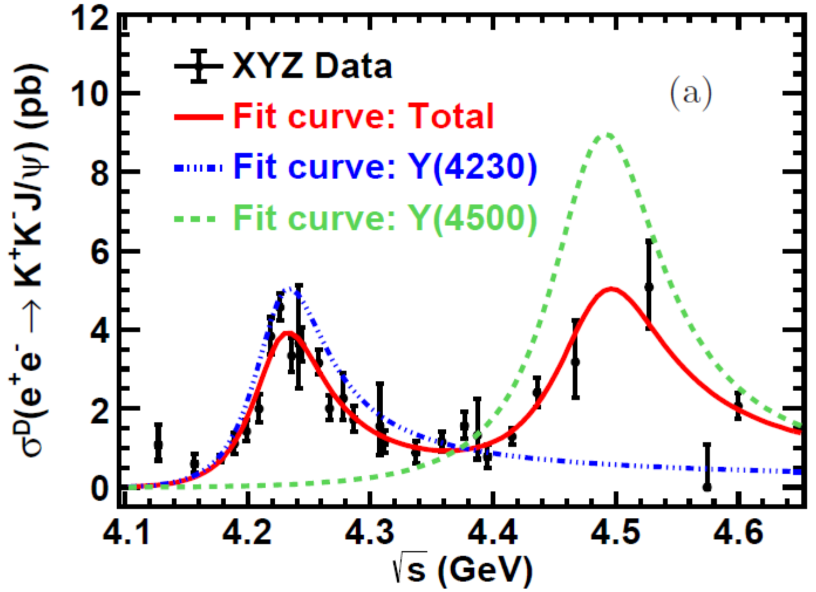
Y(4230) appears in $\omega\chi_{c0}$, $\pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi'$, $\pi^+\pi^- h_c$, $D^0 D^{*-}\pi^+$, $\eta_c\pi^+\pi^-\pi^0$, $K^+K^- J/\psi$, $D^{*0}D^{*-}\pi^+$,

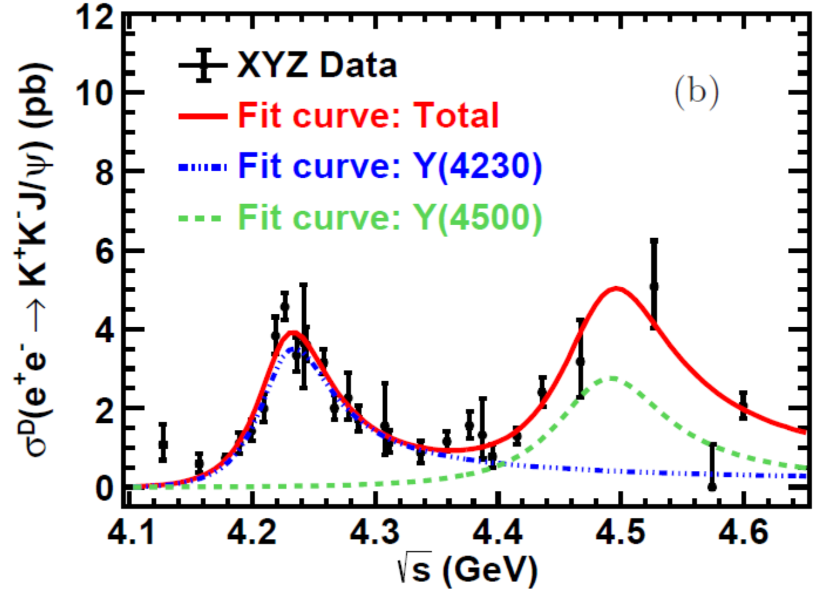
Mass~4220 MeV, width~ 50 MeV!

A new decay mode Y(4230)→K⁺K⁻J/ψ and a new Y(4500) state

CPC46, 111002 (2022)

15.6 fb^{-1}, Ecm=4.12-4.60 GeV





✓ First observation of Y(4230) → K^+K^-J/ψ (29σ)

$$0.02 < \frac{\mathcal{B}(Y(4230) \to K^+K^-J/\psi)}{\mathcal{B}(Y(4230) \to \pi^+\pi^-J/\psi)} < 0.26$$

✓ Significance of the Y(4500) > 8σ

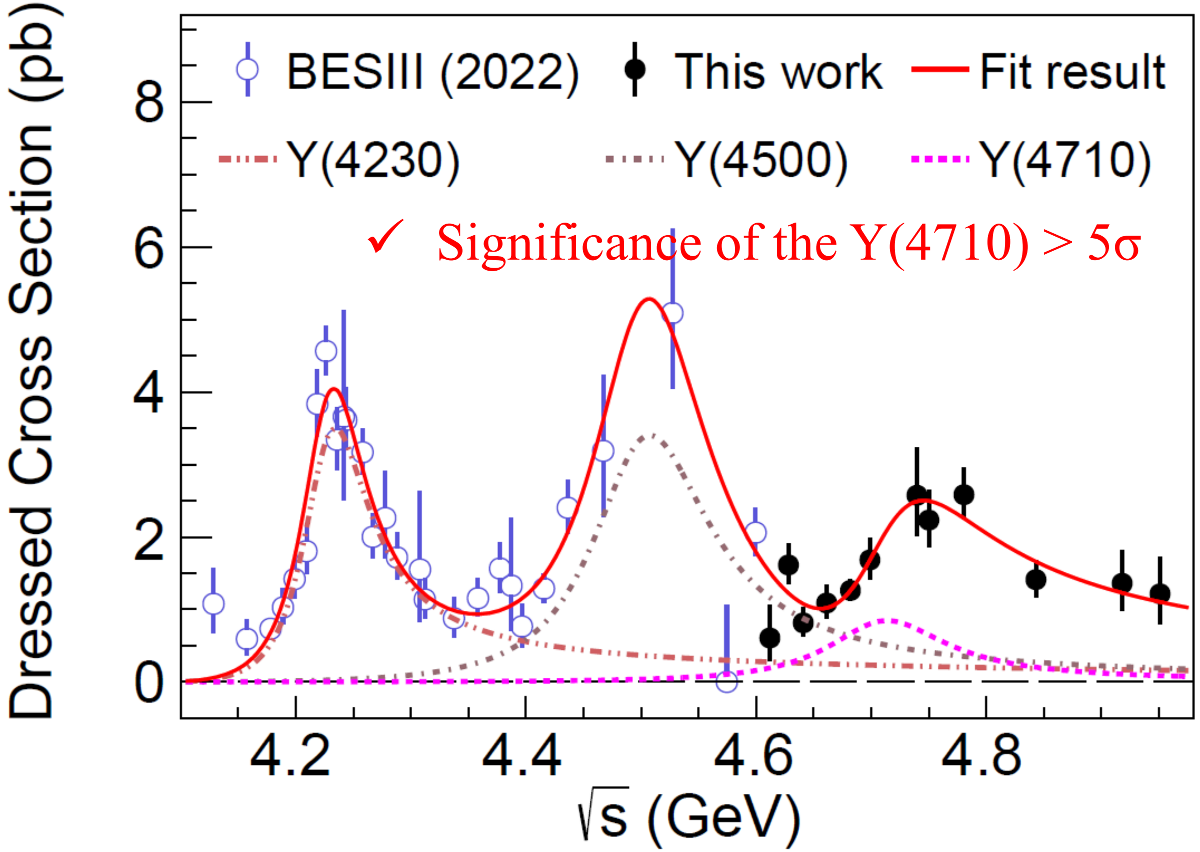
- A 5S-4D mixing state (J. Z. Wang et al., PRD 99, 114003 (2019))
- A heavy-antiheavy hadronic molecule (X. K. Dong et al., Prog. Phys. 41, 65 (2021))
- A $(cs\bar{c}\bar{s})$ state on LQCD (T. W. Chiu et al., PRD 73, 094510 (2006))

	Parameters	Solution I	Solution II
$Y(4230)$	M(MeV)	$4225.3 \pm 2.3 \pm 21.5$	
	Γ_{tot}(MeV)	$72.9 \pm 6.1 \pm 30.8$	
	$\Gamma_{ee}\mathcal{B}$(eV)	$0.42 \pm 0.04 \pm 0.15$	$0.29 \pm 0.02 \pm 0.10$
$Y(4500)$	M(MeV)	$4484.7 \pm 13.3 \pm 24.1$	
	Γ_{tot}(MeV)	$111.1 \pm 30.1 \pm 15.2$	
	$\Gamma_{ee}\mathcal{B}$(eV)	$1.35 \pm 0.14 \pm 0.06$	$0.41 \pm 0.08 \pm 0.13$
phase angle	φ(rad)	$1.72 \pm 0.09 \pm 0.52$	$5.49 \pm 0.35 \pm 0.58$

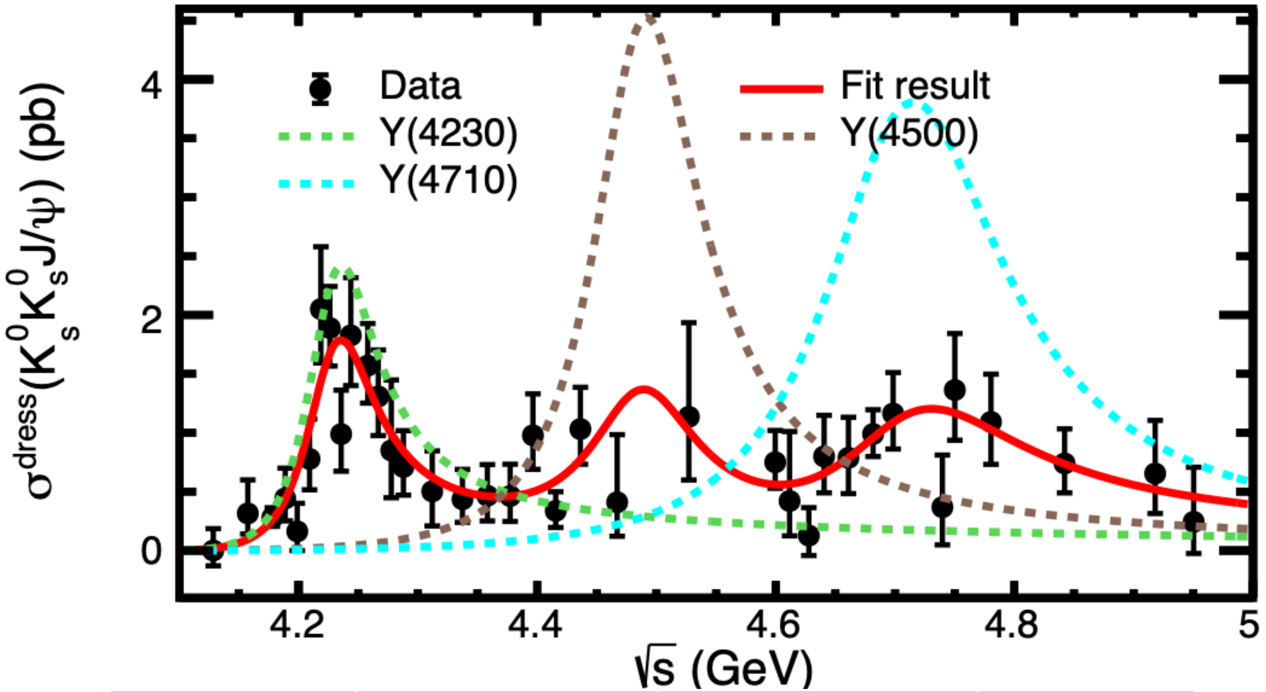
An even higher mass vector state Y(4710) in KKJ/ψ

2308.15362 $e^+e^- \to K^+K^-J/\psi$ 5.85 fb^{-1}, Ecm=4.61-4.95 GeV

PRD107, 092005 (2023) $e^+e^- \to K_S K_S J/\psi$



resonance	mass (MeV)	width (MeV)	note
Y(4230)	4226±2	70±4	Stat. only
Y(4500)	4499±8	124±20	Stat. only
Y(4710)	$4708^{+17}_{-15}\pm21$	$126^{+27}_{-23}\pm30$	>5σ

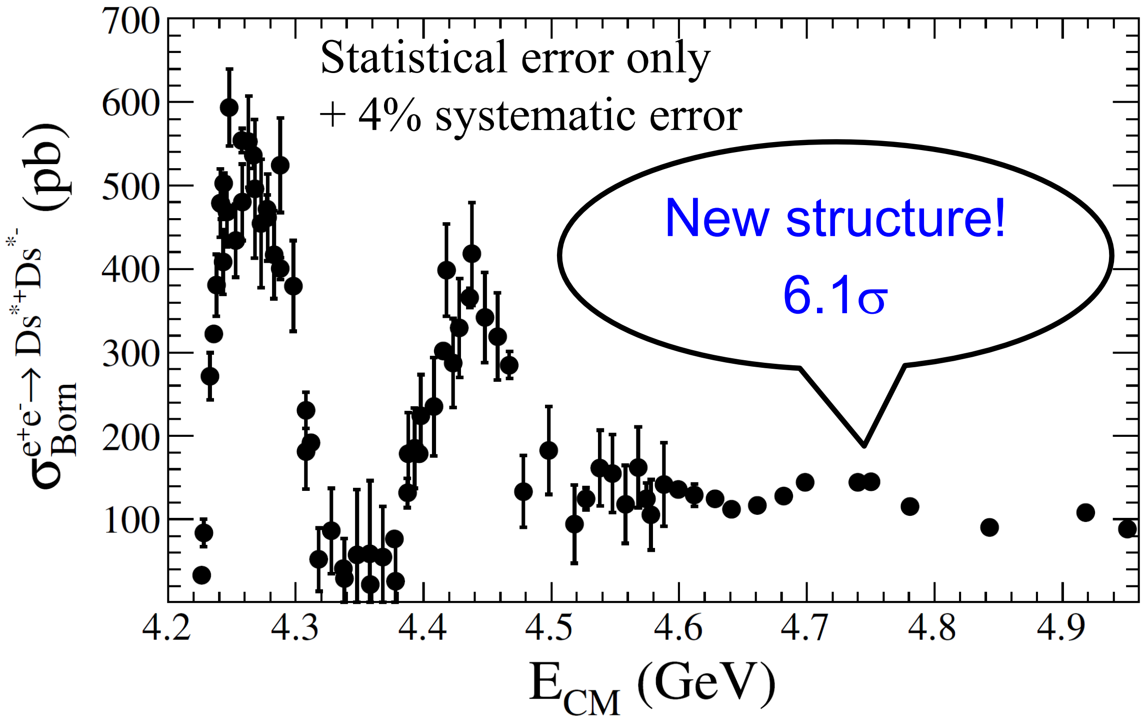


resonance	mass (MeV)	width (MeV)	note
Y(4230)	4227±7±22	72±16±33	
Y(4500)	Fixed	Fixed	1.4σ
Y(4710)	4704±52±70	183±114±96	4.0σ

5S vector charmonium states?

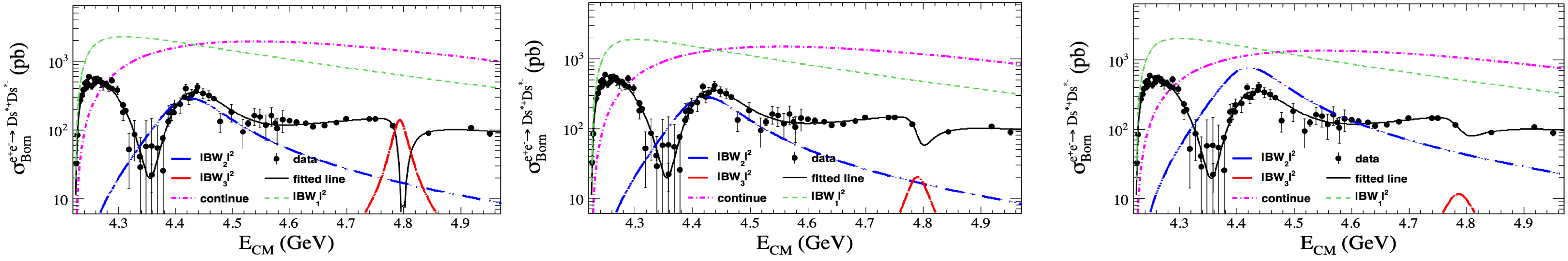
A new vector charmoniumlike state Y(4790) in $e^+e^- \to D_s^{*+} D_s^{*-}$?

arXiv: 2305.10789, PRL (in press)



- The peak position depends on the parametrization of the background amplitudes.
- Data at around 4.8 GeV are needed to understand the line shape.
- Could it be the Y(4710) in KKJ/ψ?

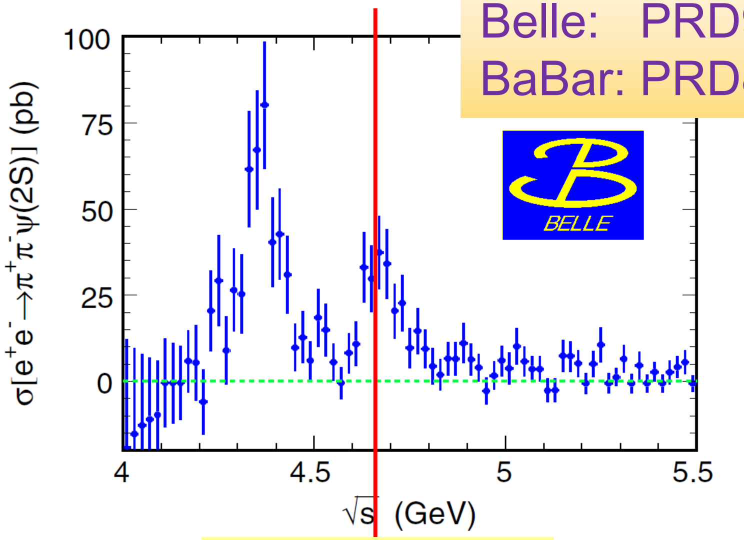
	Result 1	Result 2	Result 3
M_1 (MeV/c^2)	4186.5±9.0	4193.8±7.5	4195.3±7.5
Γ_1 (MeV)	55±17	61.2±9.0	61.8±9.0
M_2 (MeV/c^2)	4414.5±3.2	4412.8±3.2	4411.0±3.2
Γ_2 (MeV)	122.6±7.0	120.3±7.0	120.0±7.0
M_3 (MeV/c^2)	4793.3±7.5	4789.8±9.0	4786±10
Γ_3 (MeV)	27.1±7.0	41±39	60±35

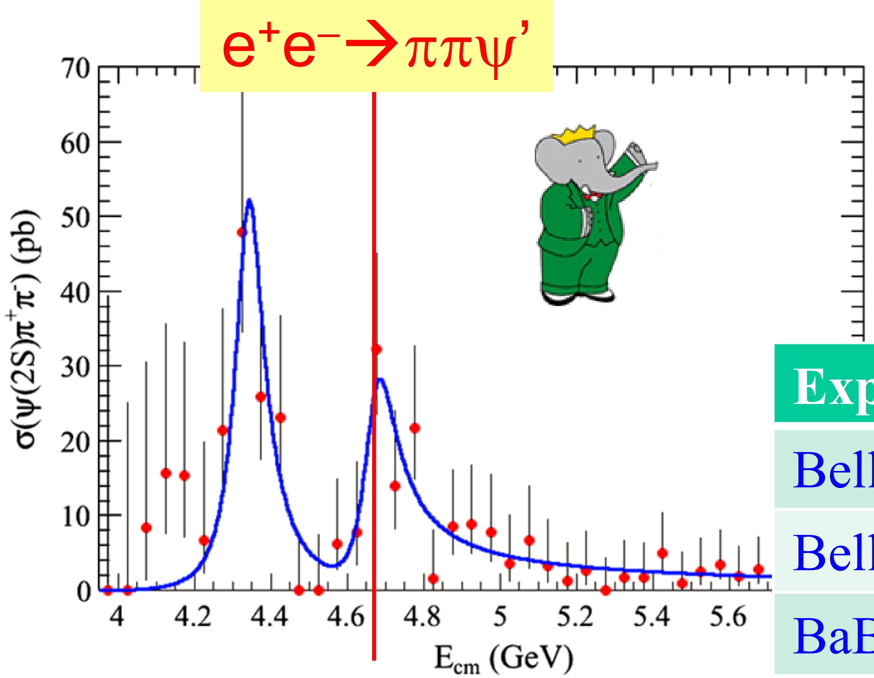


Y(4630)=Y(4660)? Are there other decay modes?

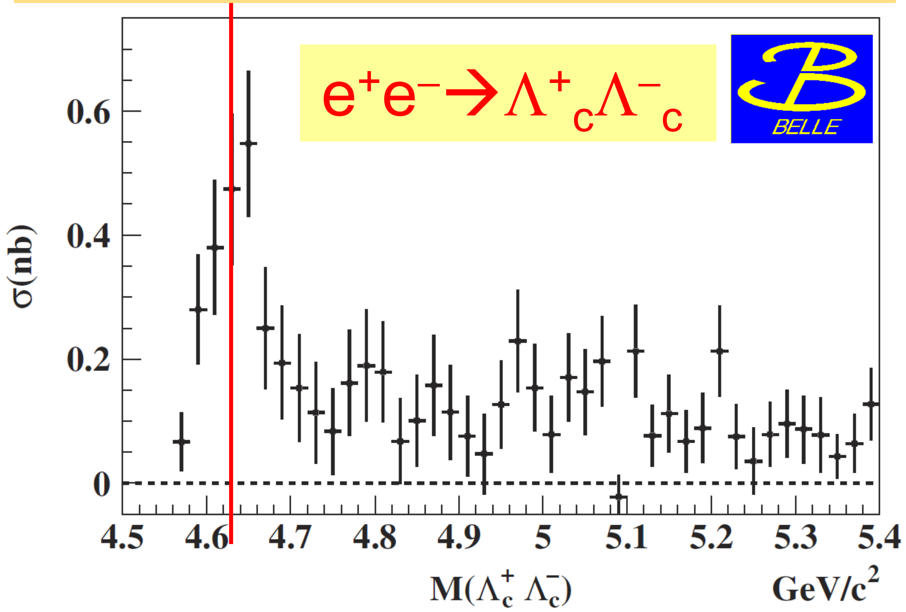
Belle: PRD91, 112007 (2015), 980/fb
BaBar: PRD89, 111103 (2014), 520/fb

Y(4660) discovered by Belle in 2007
Y(4630) discovered by Belle in 2008





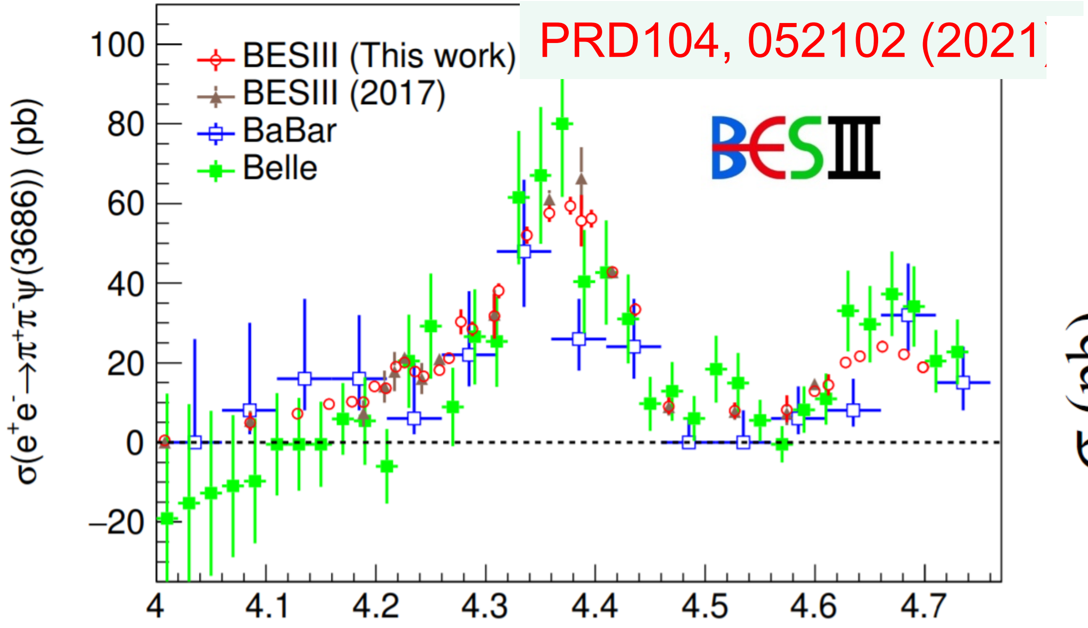
Belle: PRL101, 172001 (2008), 695/fb

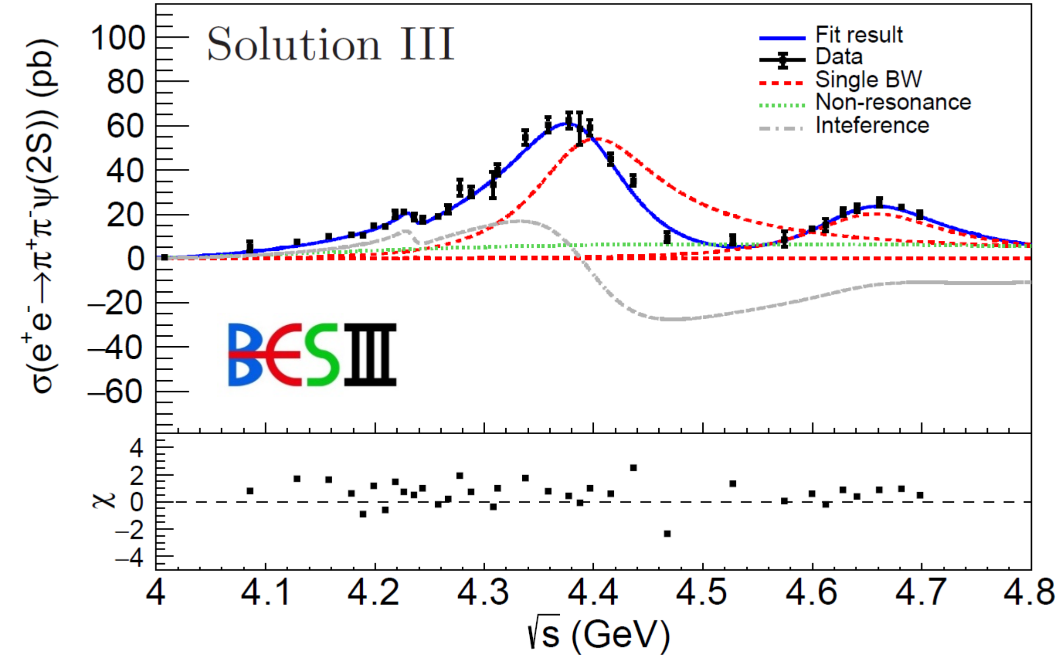


Experiment	Mass (MeV)	Width (MeV)
Belle, $\Lambda^+_c\Lambda^-_c$	$4634^{+8}_{-7}{}^{+5}_{-8}$	$92^{+40}_{-24}{}^{+10}_{-21}$
Belle, $\pi\pi\psi'$	$4652 \pm 10 \pm 8$	$68 \pm 11 \pm 1$
BaBar, $\pi\pi\psi'$	$4669 \pm 21 \pm 3$	$104 \pm 48 \pm 10$

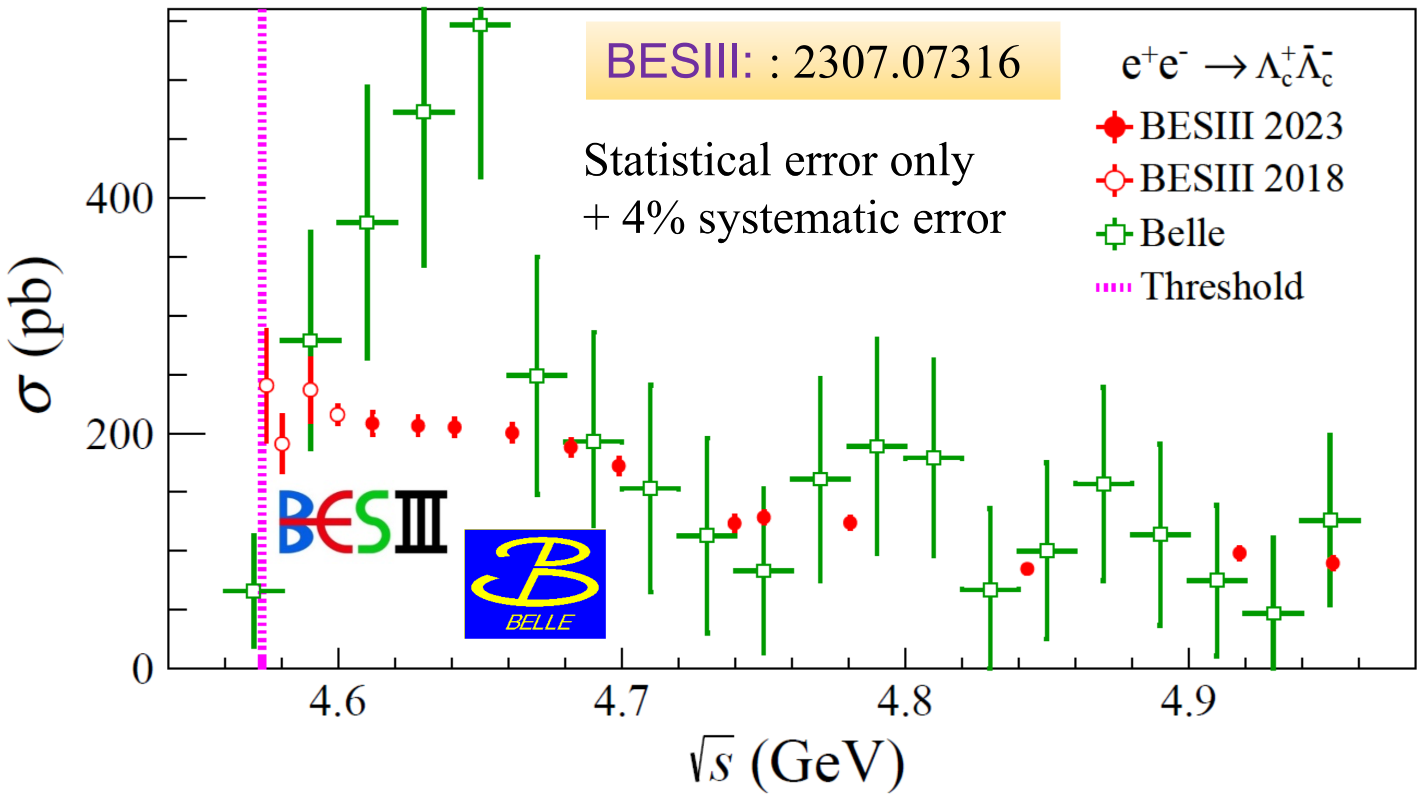
Recent measurements

$e^+e^- \rightarrow \pi^+\pi^-\psi'$





$e^+e^- \rightarrow \Lambda^+_c\Lambda^-_c$



BESIII data confirmed Belle & BaBar measurements with much improved precision!

BESIII data did not confirm the Y(4630) in $e^+e^- \rightarrow \Lambda^+_c\Lambda^-_c$!

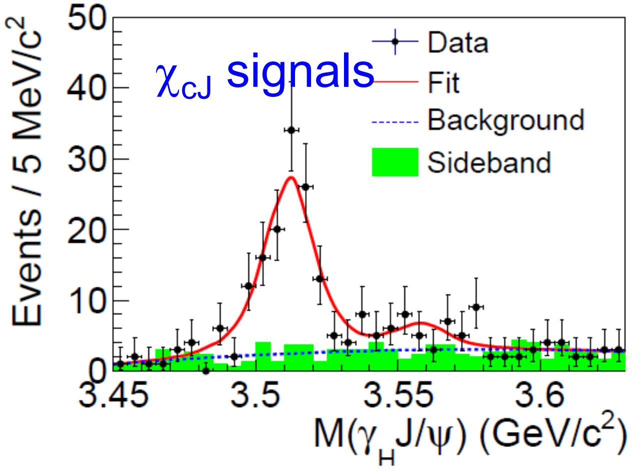
$e^+e^- \to \pi^+\pi^-\psi_2(3823)$

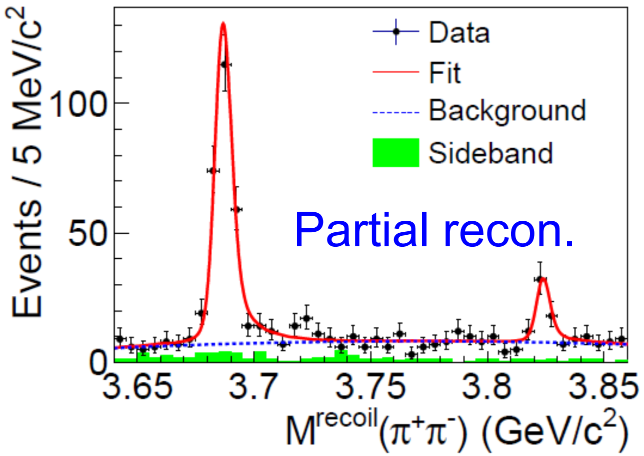
Recent measurements

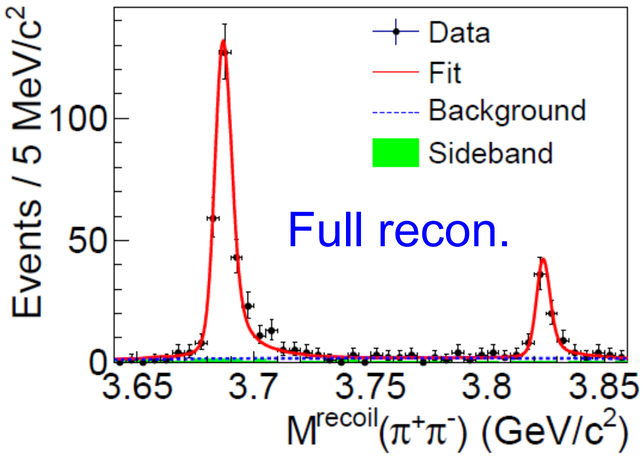
$\psi_2(3823) \to \gamma\chi_{c1} \to \gamma\gamma J/\psi$

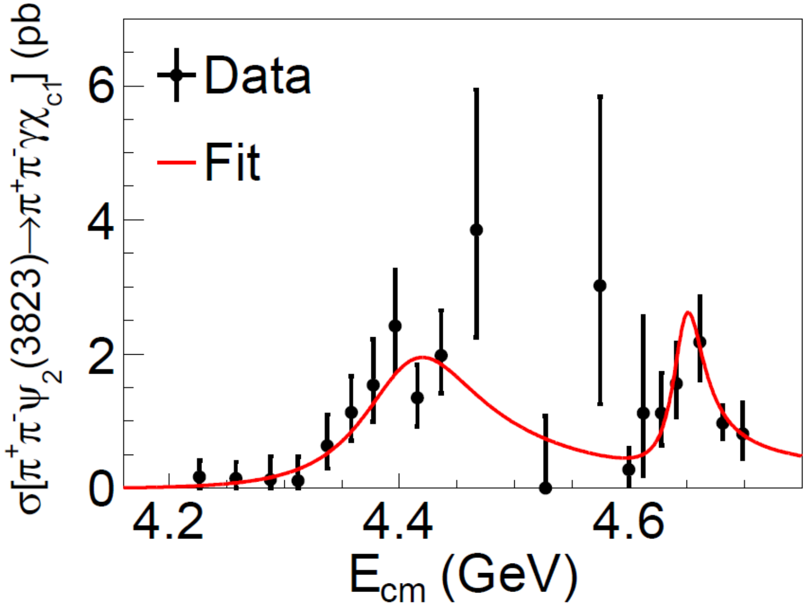
11.3 fb^{-1}, Ecm=4.23-4.70 GeV

PRL129, 102003 (2022)









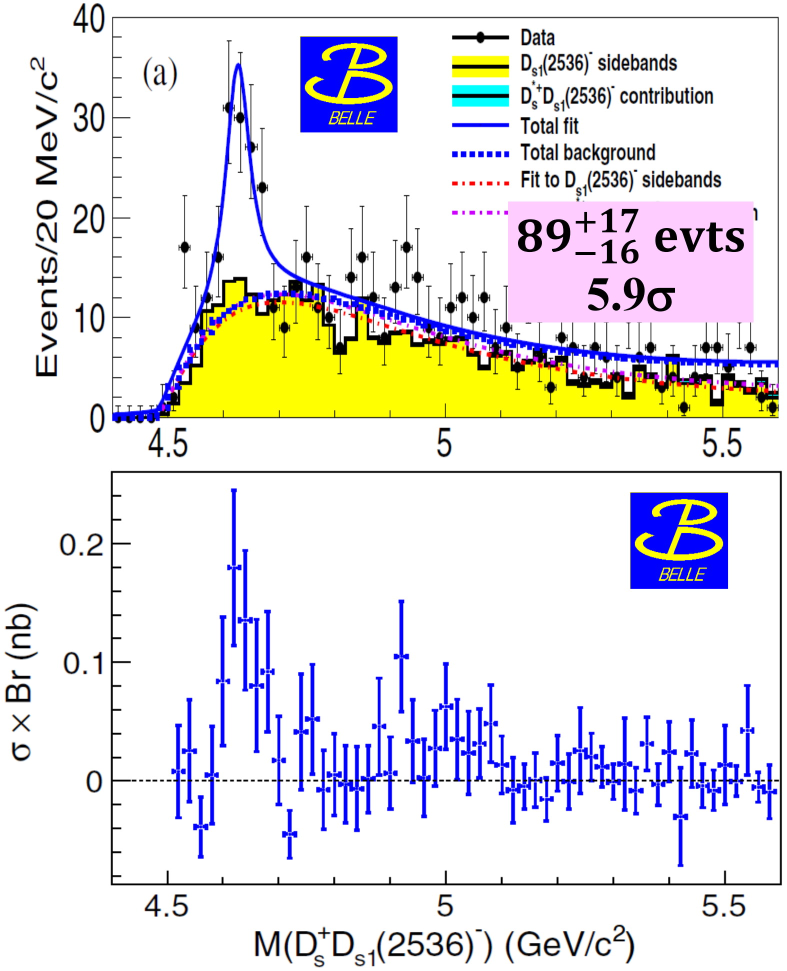
Parameters	Solution I	Solution II
$M[R_1]$	$4406.9 \pm 17.2 \pm 4.5$	
$\Gamma_{\rm tot}[R_1]$	$128.1 \pm 37.2 \pm 2.3$	
$\Gamma_{e^+e^-}\mathcal{B}_1^{R_1}\mathcal{B}_2$	$0.36 \pm 0.10 \pm 0.03$	$0.30 \pm 0.09 \pm 0.03$
$M[R_2]$	$4647.9 \pm 8.6 \pm 0.8$	
$\Gamma_{\rm tot}[R_2]$	$33.1 \pm 18.6 \pm 4.1$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

New decay mode of the Y(4360) & Y(4660)! $\psi_2(3823)$ is a D-wave charmonium!

Y(4660) decays into open charm final states?

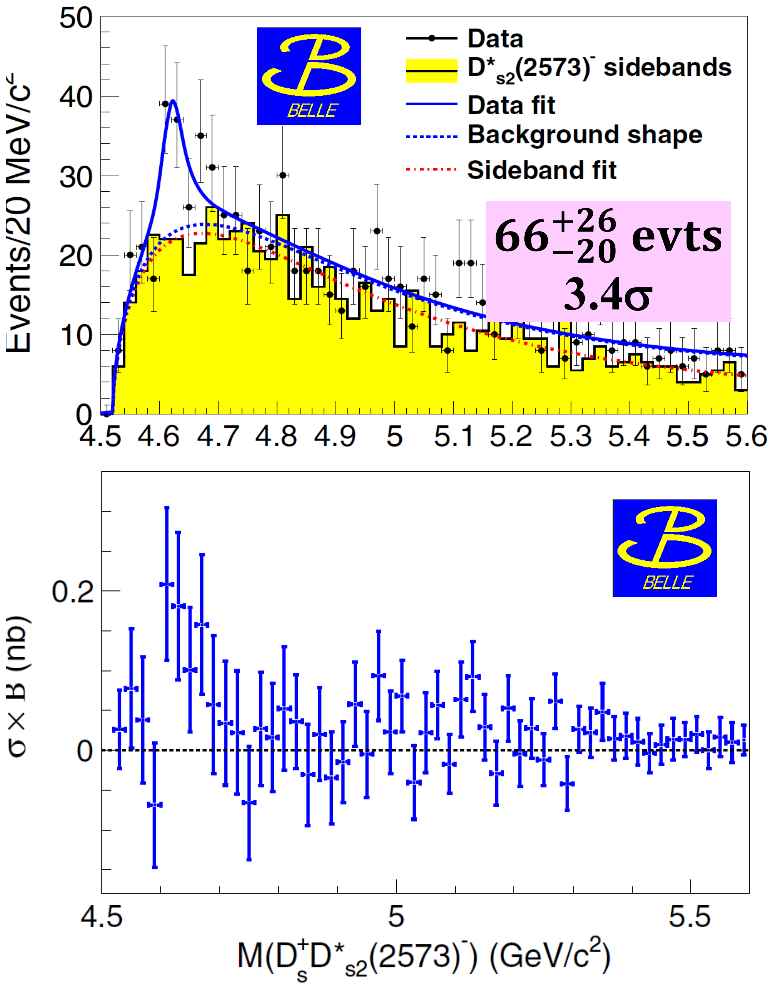
PRD 100, 111103 (2019)

$e^+e^- \to D_s^+ D_{s1}(2536)^- + c.c.$



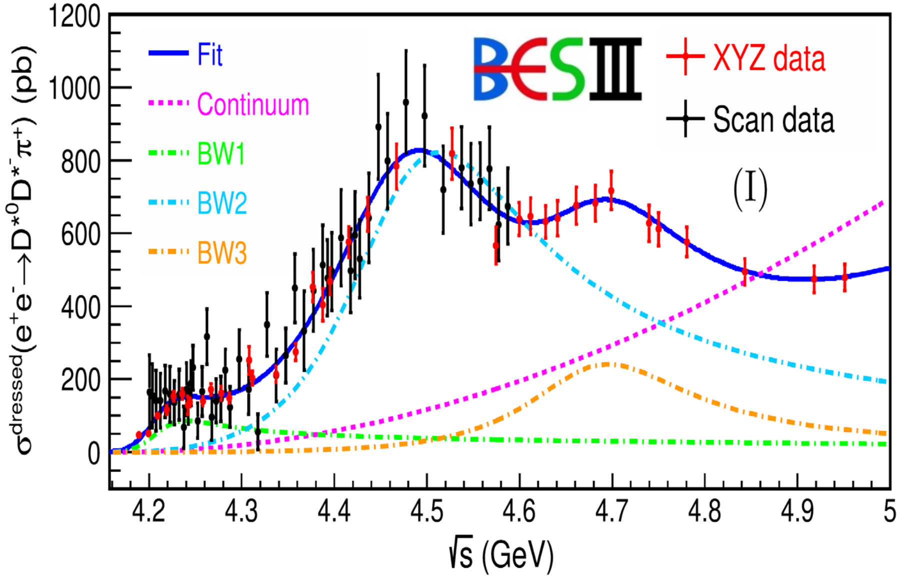
PRD 101, 091101 (2020)

$e^+e^- \to D_s^+ D_{s2}^*(2573)^- + c.c.$



PRL130, 121901 (2023)

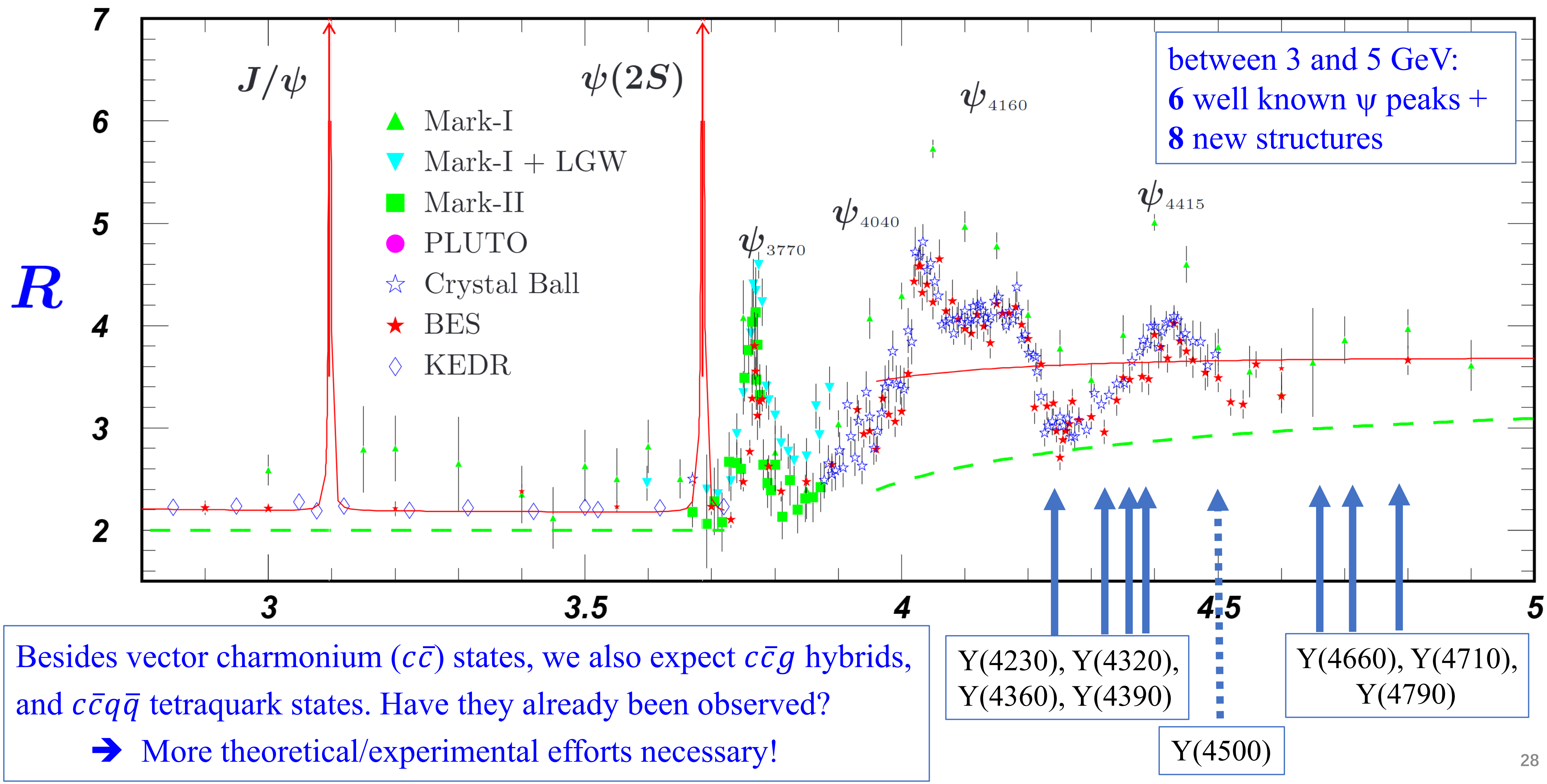
$e^+e^- \to D^{*0}D^{*-}\pi^+$



resonance	mass (MeV)	width (MeV)
BW1	4210±5±6	82±18±9
BW2	4469±26±4	246±37±9
BW3	4675±30±4	218±73±9

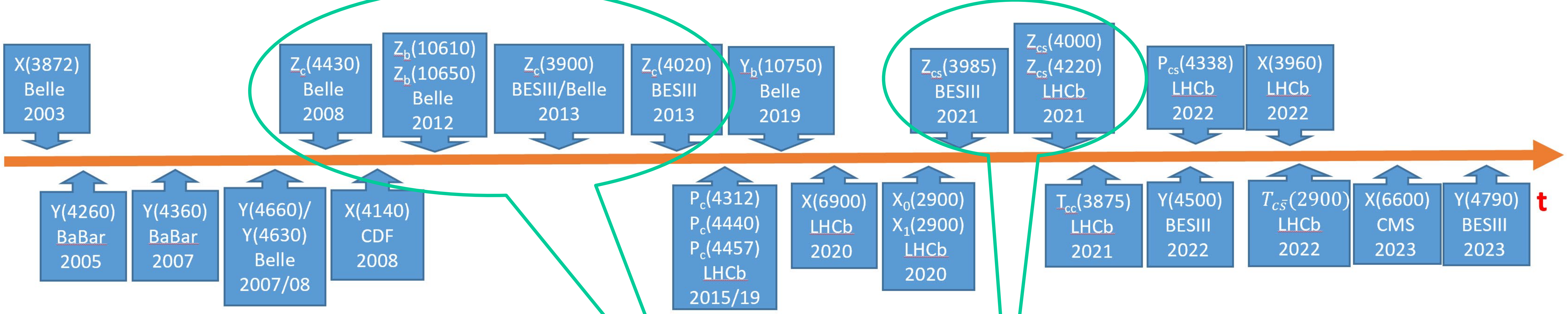
BESIII has data from threshold to 4.95 GeV, improved measurements on D_sD_{sJ} are expected!

How many vectors in charmonium energy region?

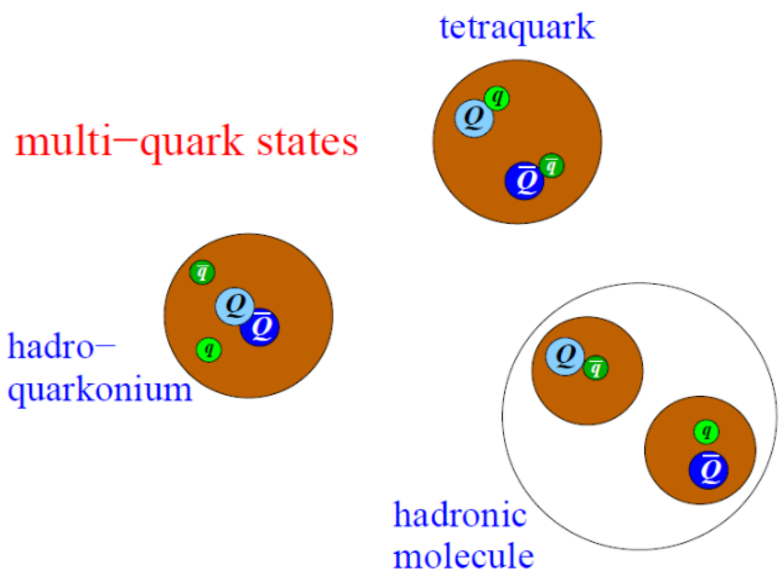


Besides vector charmonium ($c\bar{c}$) states, we also expect $c\bar{c}g$ hybrids, and $c\bar{c}q\bar{q}$ tetraquark states. Have they already been observed?

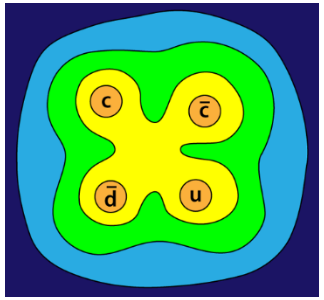
➔ More theoretical/experimental efforts necessary!



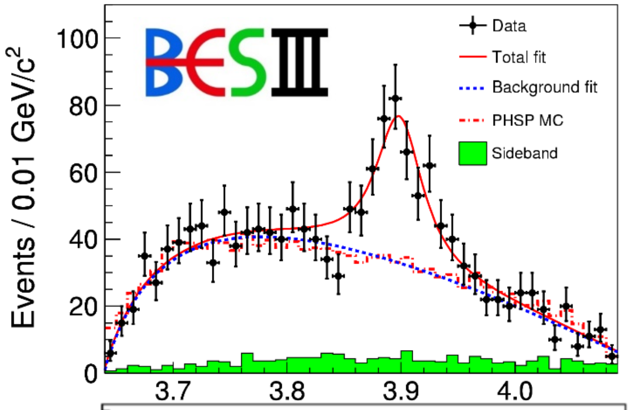
Charged quarkoniumlike states must have at least 4 quarks!

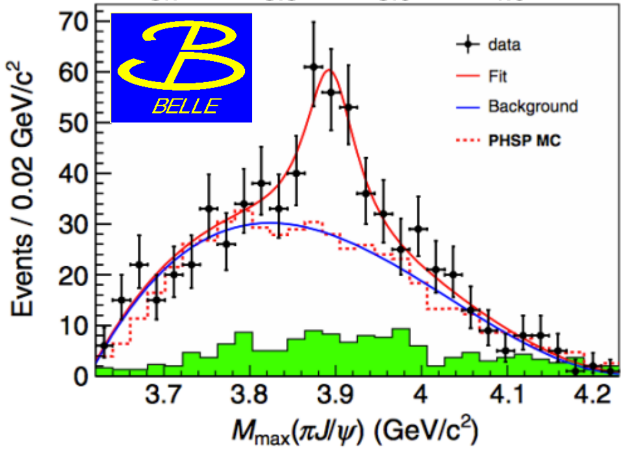


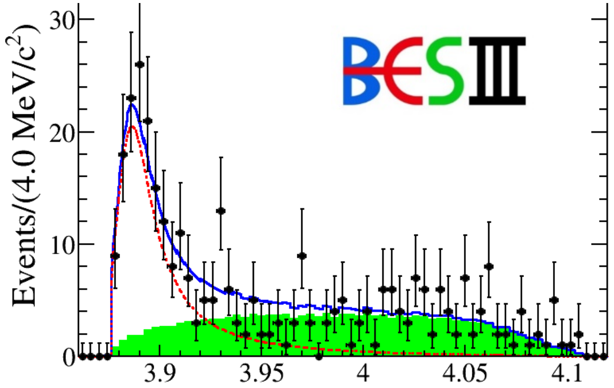
The Z_c states with u,d-quark



$Z_c(3900)$, 2013

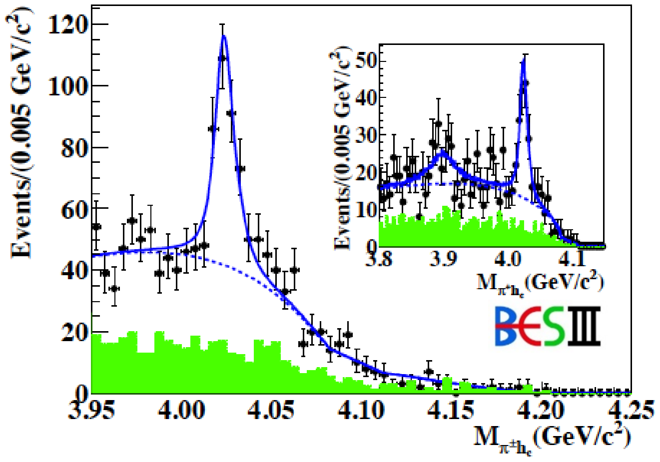


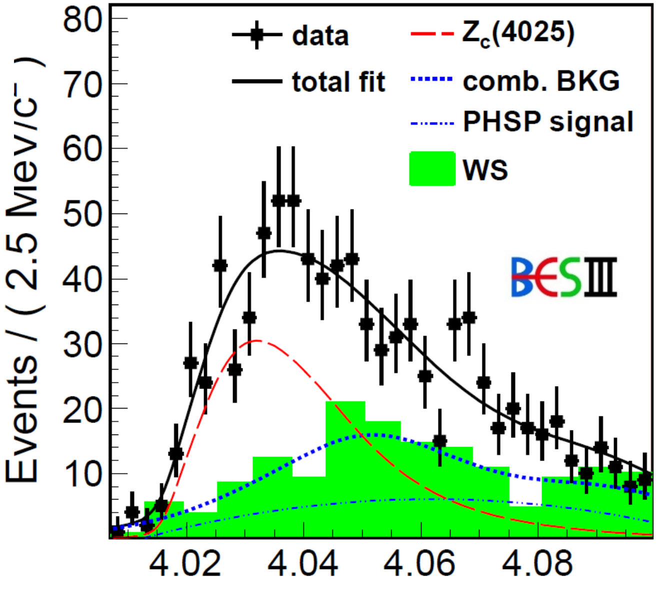




$M(D^0D^{*-})$ (GeV/c^2)

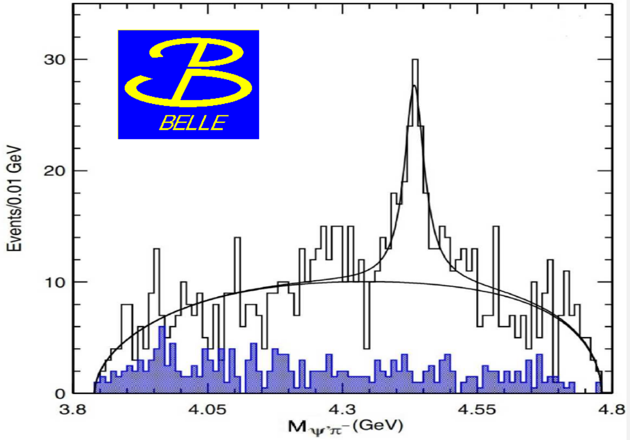
$Z_c(4020)$, 2013

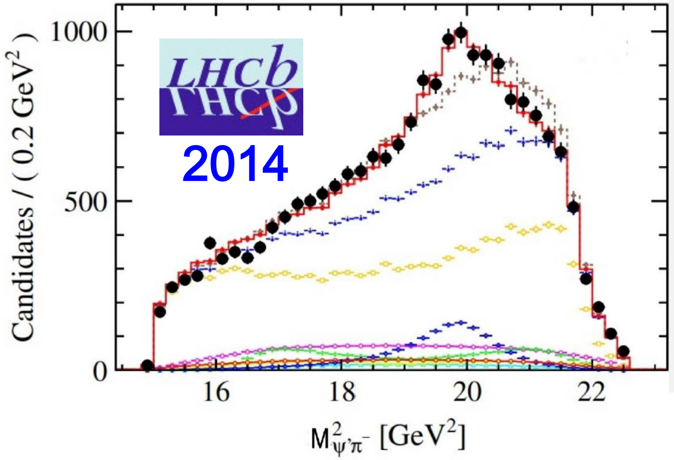




$M(D^{*0}D^{*-})$ (GeV/c^2)

$Z_c(4430)$, 2008



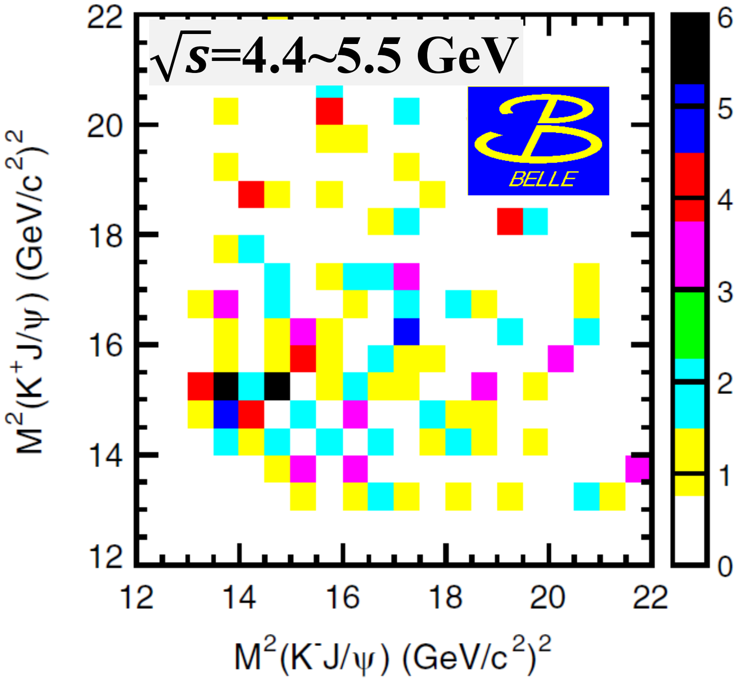


All are observed in π+charmonium (J/ψ, h_c, $\psi(2S)$) final states, candidate $\bar{c}\,c\,\bar{d}\,u$ tetraquark states

➔ Existence of states with d→s?

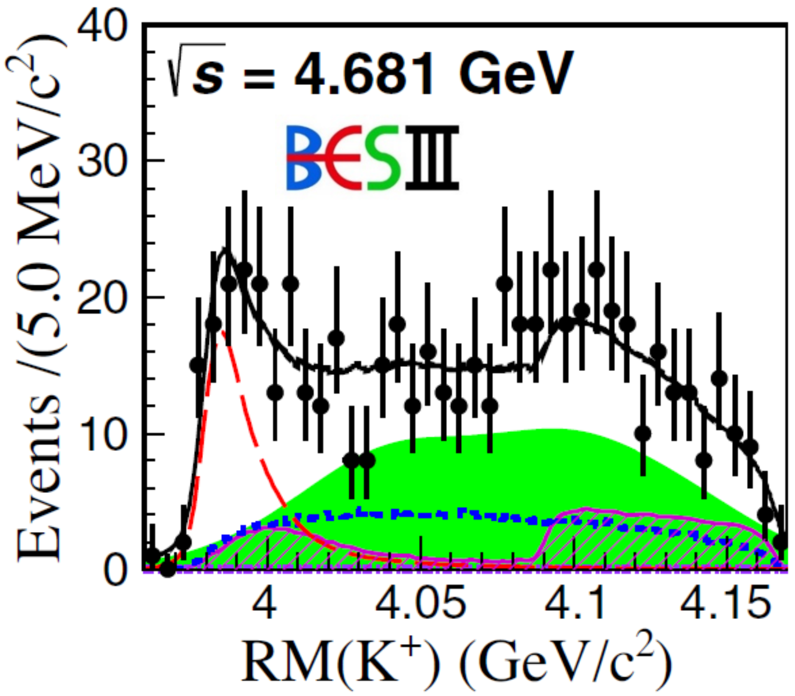
➔ Search for states decay into $K^{\pm}J/\psi$, $\bar{D}^*D_s + \bar{D}D^*_s$!

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



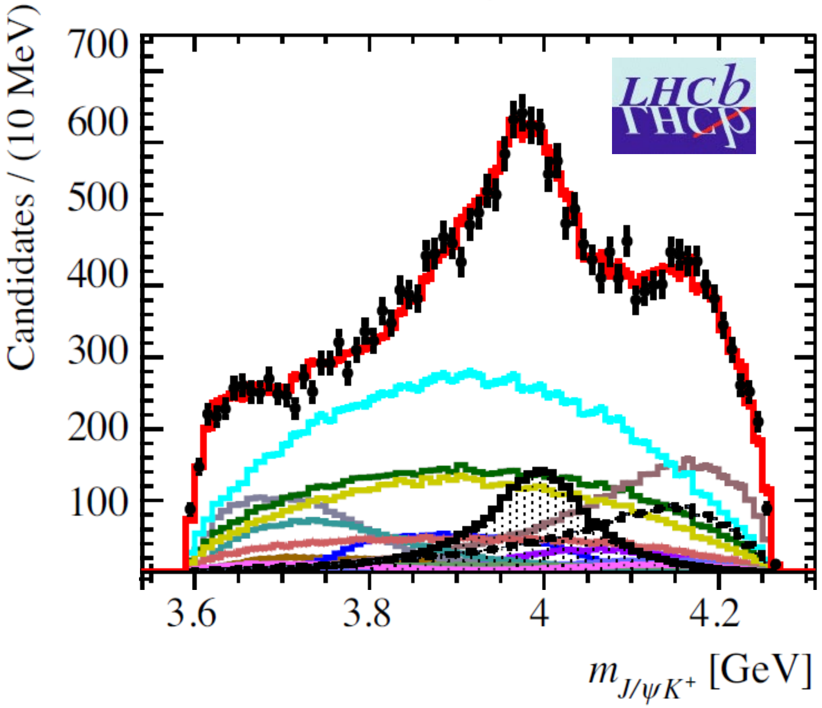
PRD 89, 072015 (2014)

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



PRL 126, 102001 (2021)

$B^+ \to J/\psi\phi K^+$



PRL 127, 082001 (2021)

No significant signal in $K^{\pm}J/\psi$ decay mode!

(statistics low!)

$Z_{cs}(3985)$ in $\bar{D}^*D_s + \bar{D}D^*_s$ mode!

$Z_{cs}(4000)$ and $Z_{cs}(4220)$ in $K^{\pm}J/\psi$ decay mode!

State	Signif.	JP	Mass (MeV)	Width (MeV)
$Z_{cs}(3985)$	5.3σ	??	$3982.5^{+1.8}_{-2.6} \pm 2.1$	$12.8^{+5.3}_{-4.4} \pm 3.0$
$Z_{cs}(4000)$	15σ	1+	$4003 \pm 6^{+4}_{-14}$	131±15±26
$Z_{cs}(4220)$	5.9σ	1+	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$

Widths very different, not the same state!

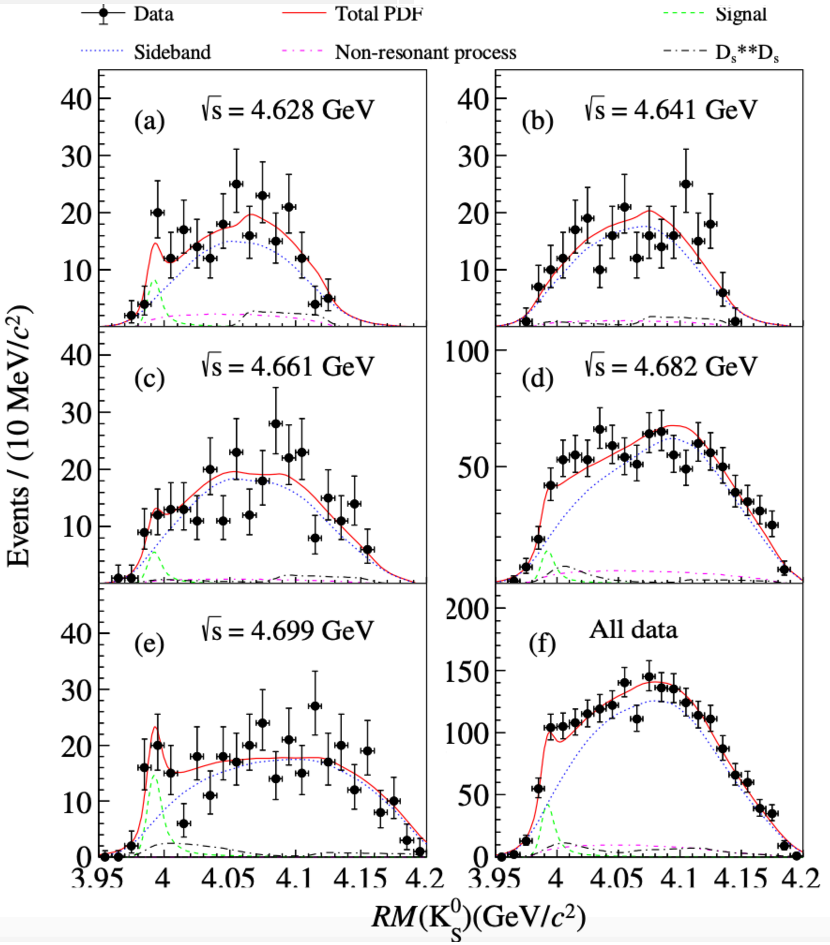
Do their isospin partners exist? May BESIII see Z_{cs} in $e^+e^- \rightarrow K^+K^-J/\psi$?

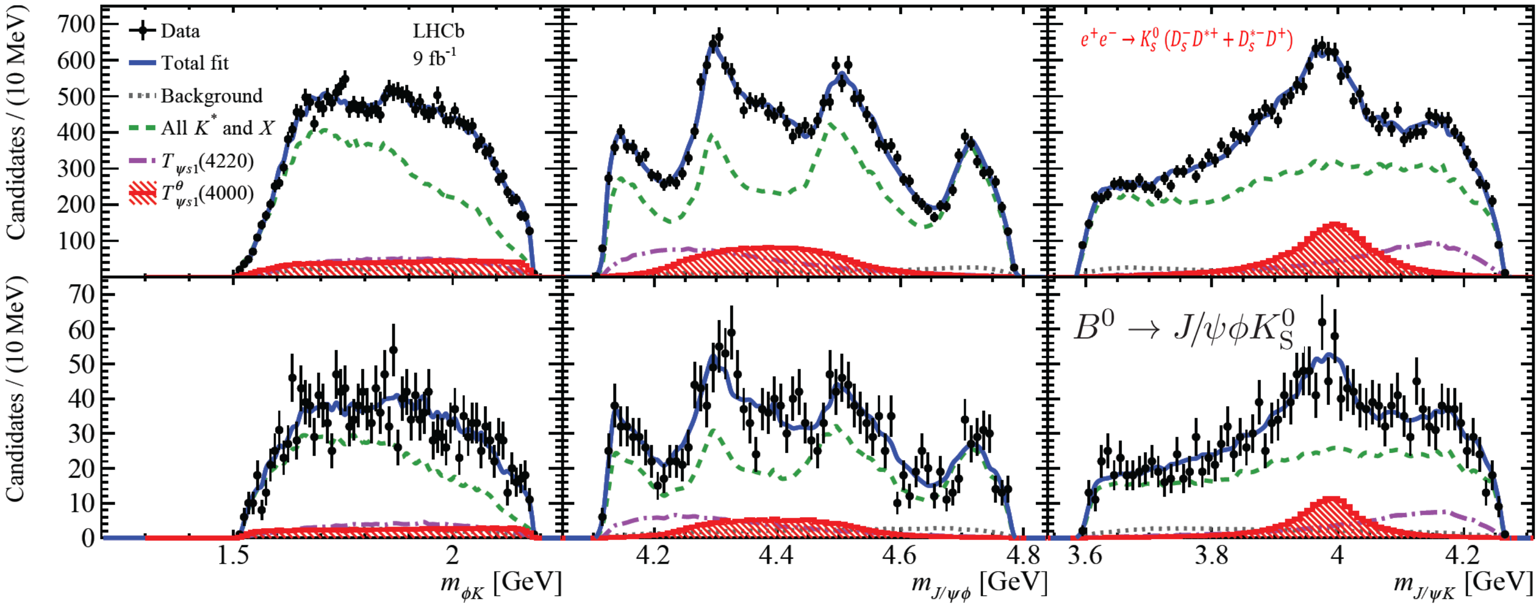
Evidence for the neutral $Z_{cs}(3985)$ & $Z_{cs}(4000)$

PRL129, 112003 (2022) $e^+e^- \to K_S^0\,(D_s^- D^{*+} + D_s^{*-} D^+)$

$B^0 \to J/\psi \phi K_S^0$

arXiv:2301.04899v2





Significance >4.0σ after including systematic uncertainties

Significance 5.4σ with isospin symmetry imposed

State	Mass (MeV/c^2)	Width (MeV)	Significance
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$	5.3σ
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$	4.6σ

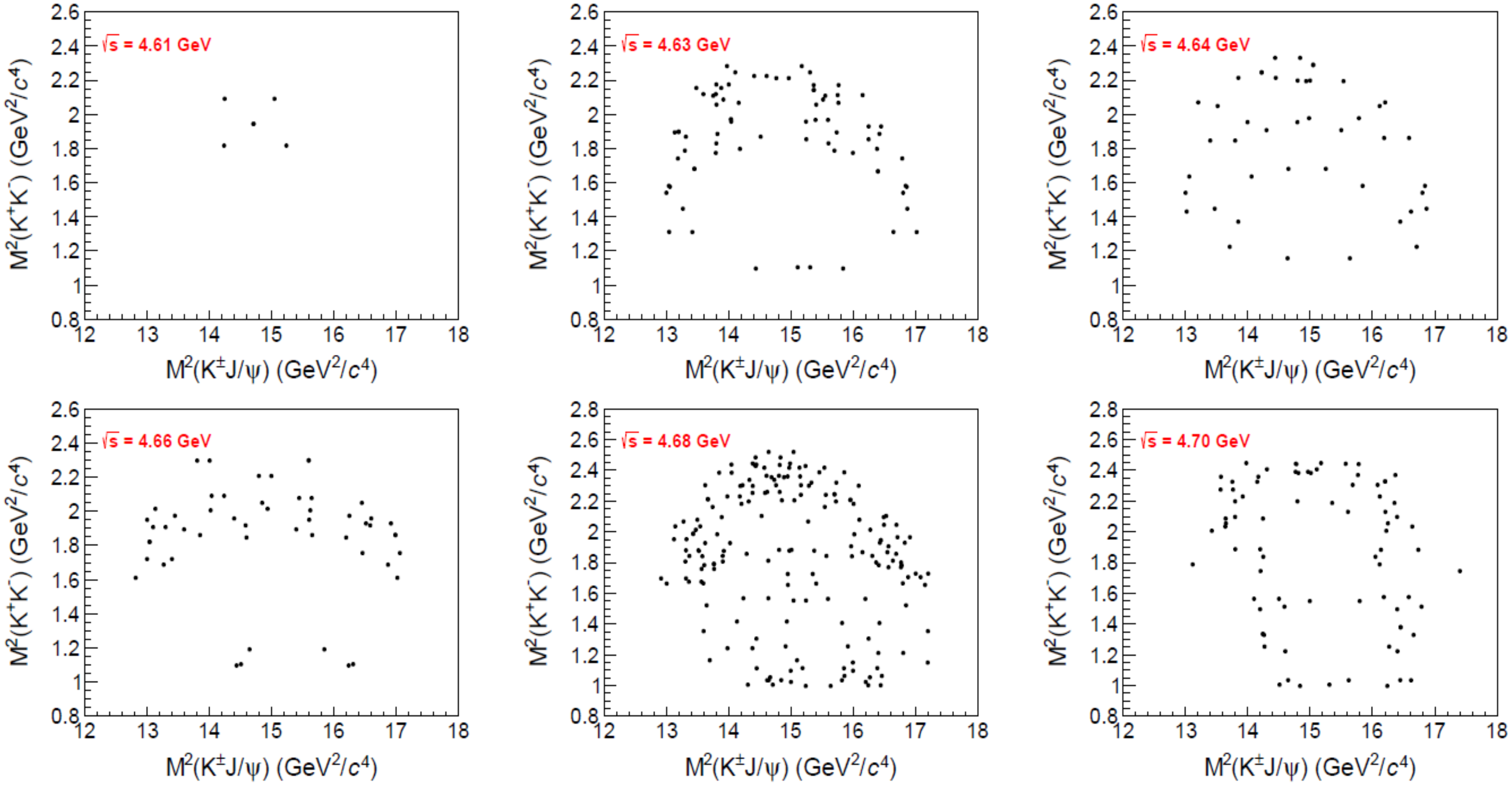
Mass (MeV)	Width (MeV)	Fit fraction (%)	ΔM (MeV)
$3991\,^{+12}_{-10}\,^{+9}_{-17}$	$105\,^{+29}_{-25}\,^{+17}_{-23}$	$7.9 \pm 2.5\,^{+3.0}_{-2.8}$	$-12\,^{+11}_{-10}\,^{+6}_{-4}$

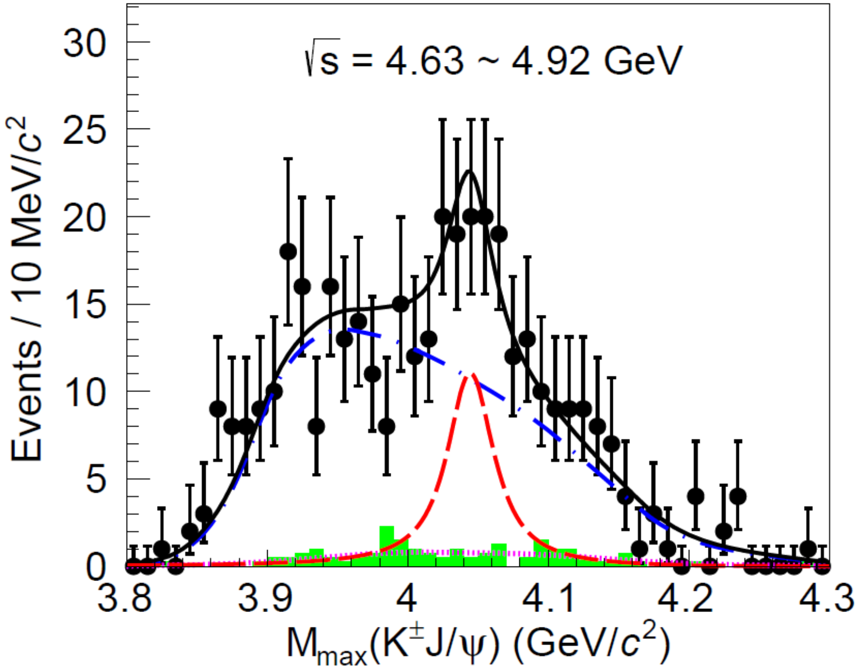
➢ Minimal quark content $c\bar{c}s\bar{d}$? Mass and width consistent with charged Z_{cs} → isospin partner

No Z_{cs} in BESIII $e^+e^- \rightarrow K^+K^-J/\psi$ data!

arXiv: 2308.15362

No significant structures in $K^{\pm}J/\psi$ decay mode!





M=4044±6 MeV

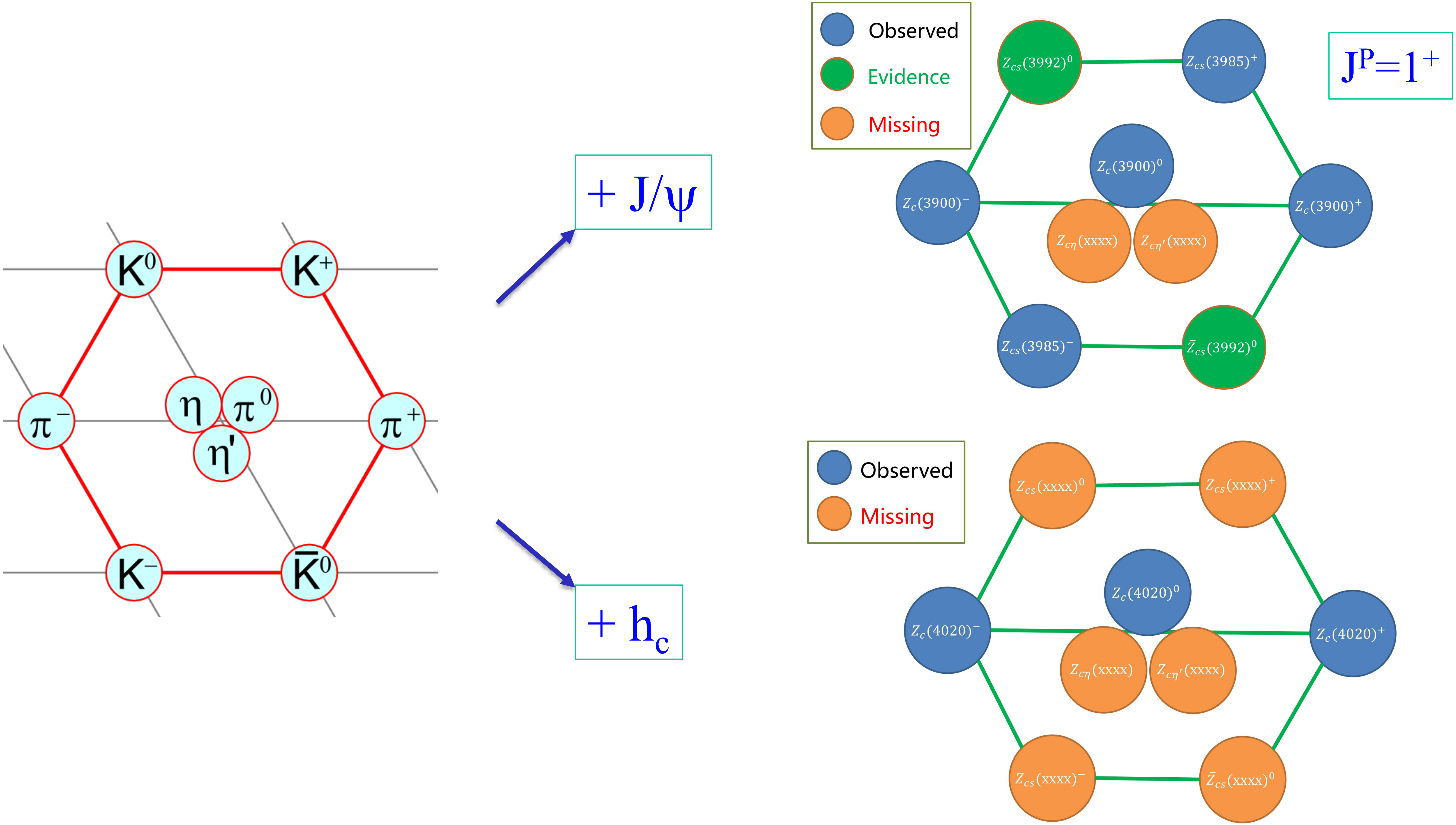
Γ = 36±16 MeV

Significance: 2.3σ

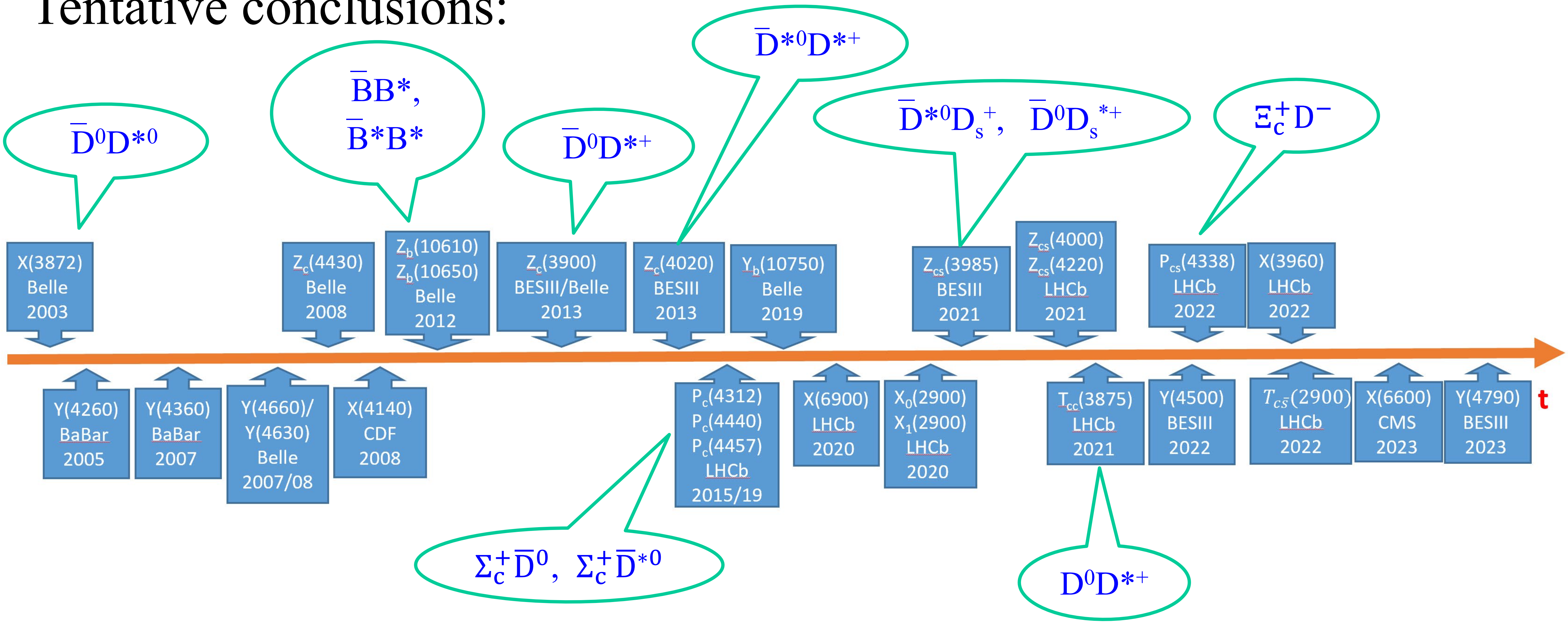
$$\frac{B(Z_c(3900) \rightarrow (D^*\bar{D})^{\pm})}{B(Z_c(3900) \rightarrow J/\psi\pi^{\pm})} = 6.2 \pm 2.9$$

PRL 119, 072001 (2017)

$$\frac{\mathcal{B}(Z_{cs}(3985)^+ \rightarrow K^+J/\psi)}{\mathcal{B}(Z_{cs}(3985)^+ \rightarrow (\bar{D}^0D_s^{*+} + \bar{D}^{*0}D_s^+))} < 0.03 \text{ @ 90\% C.L.}$$

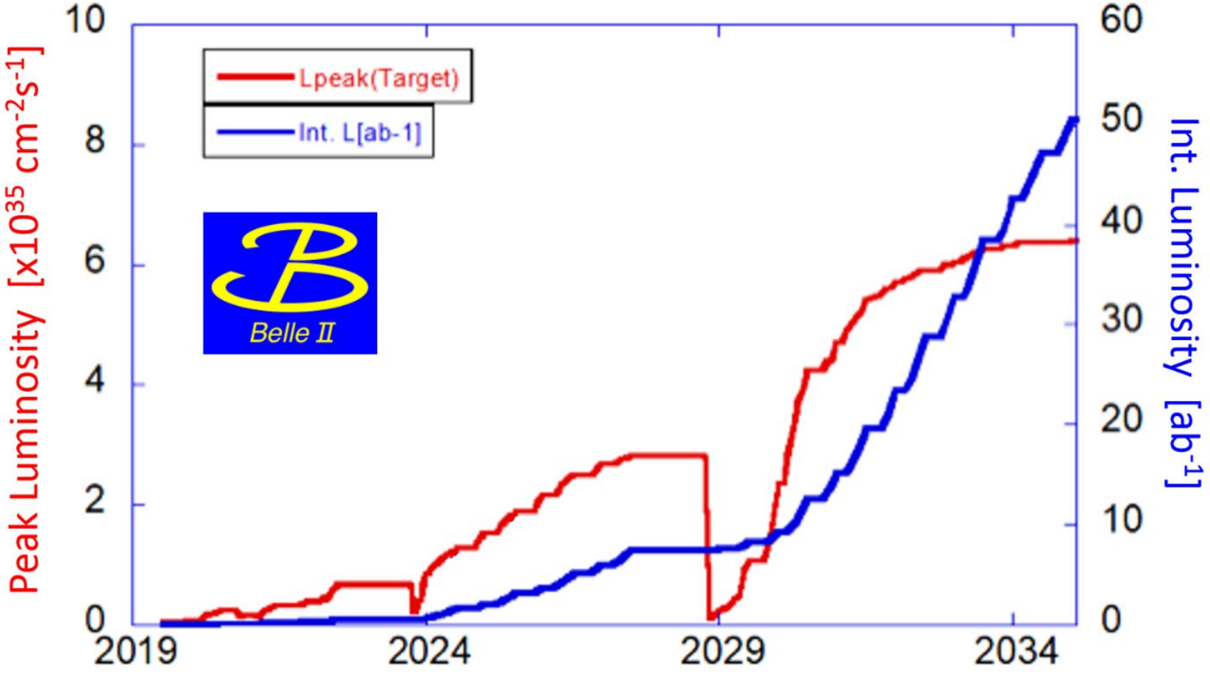

K0
K+
π−
η
π0
η'
π+
K−
K̄0
+ J/ψ
+ hc
Observed
Evidence
Missing
Zcs(3992)0
Zcs(3985)+
JP=1+
Zc(3900)0
Zc(3900)−
Zc(3900)+
Zcη(xxxx)
Zcη'(xxxx)
Zcs(3985)−
Z̄cs(3992)0
Observed
Missing
Zcs(xxxx)0
Zcs(xxxx)+
Zc(4020)0
Zc(4020)−
Zc(4020)+
Zcη(xxxx)
Zcη'(xxxx)
Zcs(xxxx)−
Z̄cs(xxxx)0

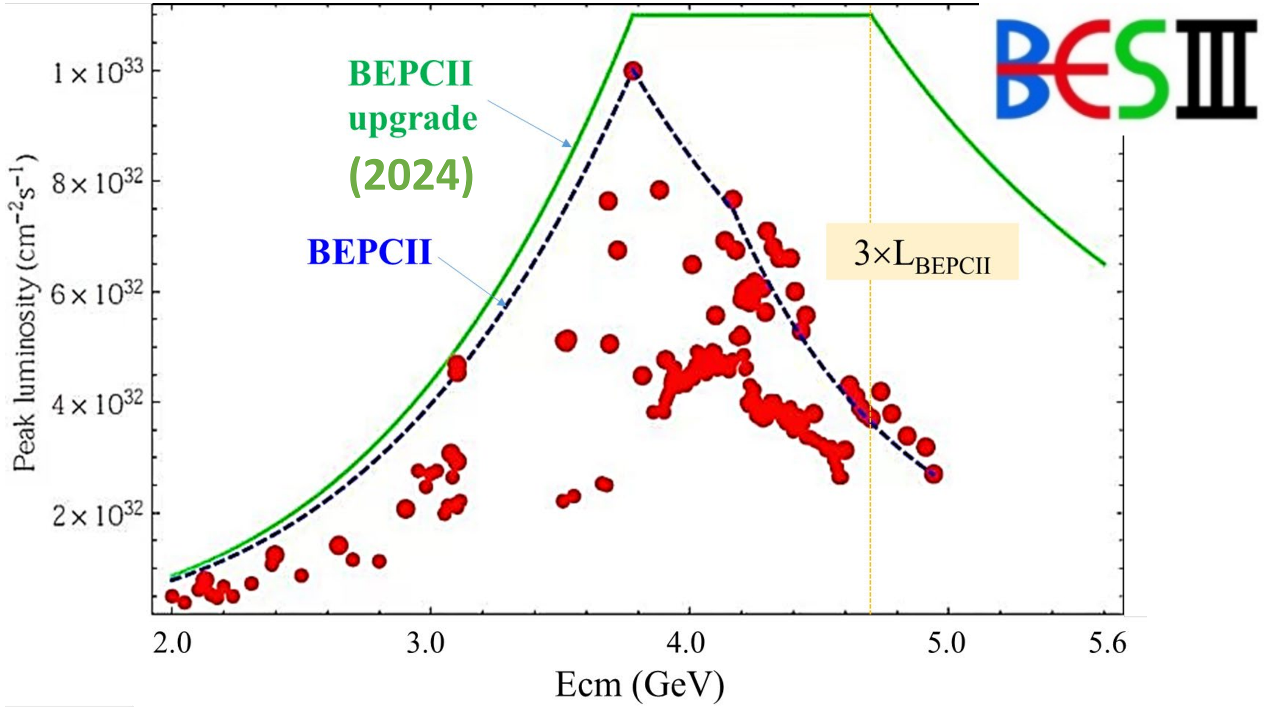
Tentative conclusions:



1. We did observe hadronic molecules close to the thresholds
2. There must be dynamics beyond molecule to explain many other states far from thresholds of narrow hadrons

More data are coming ……





ATLAS EXPERIMENT

CMS

LHC: L = 2-3x10^{34} cm^{-2}.s^{-1}
~80 interactions per bunch crossing

HL-LHC, Phase II Upgrade : L = 7.5x10^{34} cm^{-2}.s^{-1}
~200 interactions per bunch crossing

2019 **2020** 2021 2022 2023 2024 **2025** 2026 2027 2028 2029 **2030** 2031 2032 2033 2034 2035 2036 2036 2037

LHC: LS2 | Run 3 | LS3 | Run 4 | LS4 | Run 5

LHCb

Upgrade I : L = 2x10^{33} cm^{-2}.s^{-1}
~5 interactions per bunch crossing
~50 fb^{-1} (Run 3 and 4)

Upgrade II : L = 1.5x10^{34} cm^{-2}.s^{-1}
~50 interactions per bunch crossing
~300 fb^{-1} (Run 5….)

Summary

- Lots of progress in the experimental study of hadron spectroscopy.
- Spectroscopy of hadronic molecules to be further investigated.
- States formed by other dynamics may have been discovered.
- More results to come (Belle II, BESIII, LHCb, …), and lots of opportunities and challenges ahead.
- Theoretical efforts needed to understand the hadron spectroscopy and the strong interaction.

Thank you very much!

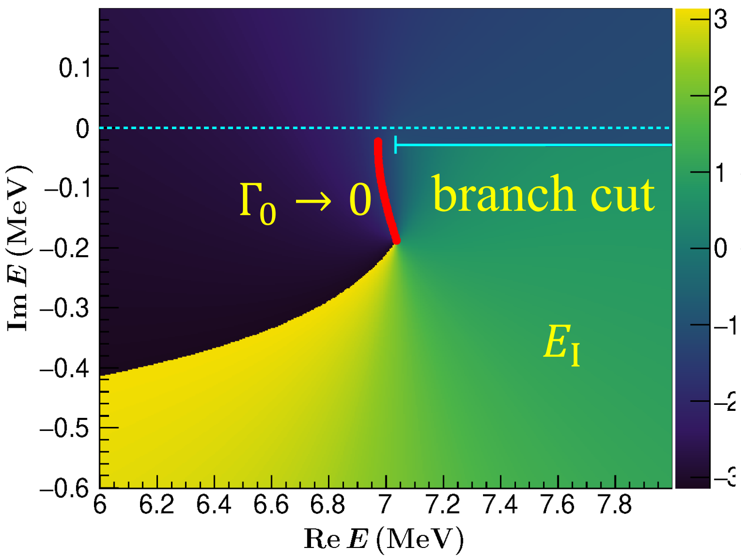
Backup slides

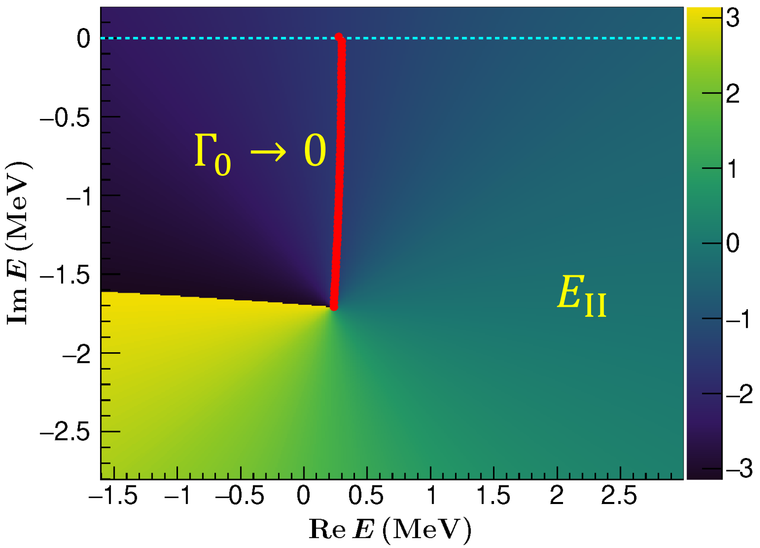
2309.01502

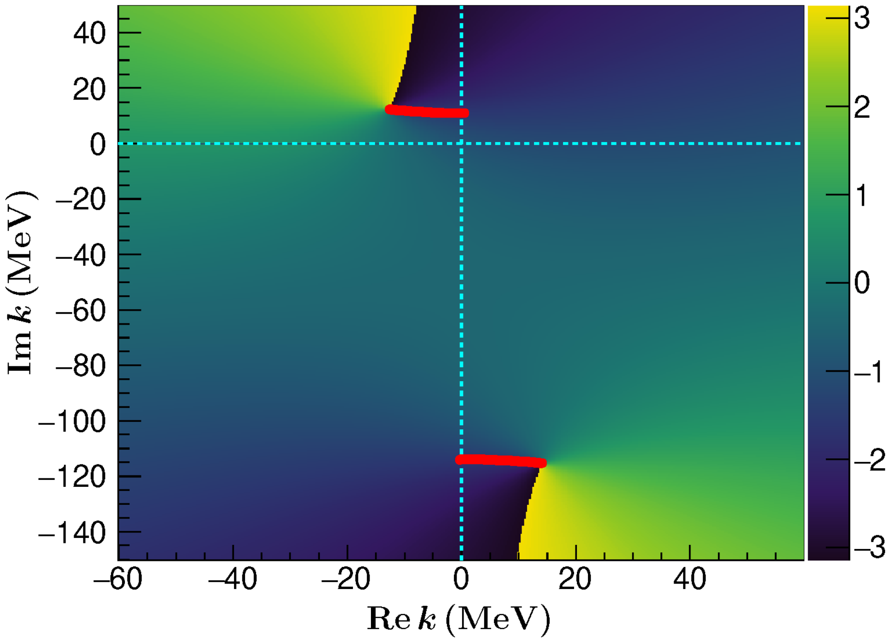
X(3872) pole search & effective range expansion

- Two sheets with respect to $D^{*0}\bar{D}^0$ branch cut
  - Sheet I: $E - E_X - g\sqrt{-2\mu(E - E_R + i\Gamma/2)}$
  - Sheet II: $E - E_X + g\sqrt{-2\mu(E - E_R + i\Gamma/2)}$
- $E_{\rm I} = (7.04 \pm 0.15^{+0.07}_{-0.08}) + (-0.19 \pm 0.08^{+0.14}_{-0.19})i$ MeV
- $E_{\rm II} = \left(0.26 \pm 5.74^{+5.14}_{-38.32}\right) + (-1.71 \pm 0.90^{+0.60}_{-1.96})i$ MeV

- Near threshold, scattering amplitude can be expanded as the power series of the momentum $k = \sqrt{2\mu(E - E_R)}$
- S-Wave $f^{-1}(E) \sim \frac{1}{a} + \frac{r_e}{2}k^2 - ik + \mathcal{O}(k^4)$
- In the limit of $\Gamma_0 \to 0$ and stable D^*
  - scattering length $a = (-16.5^{+7.0}_{-27.6}{}^{+5.6}_{-27.7})$ fm
  - effective range: $r_e = (-4.1^{+0.9}_{-3.3}{}^{+2.8}_{-4.4})$ fm







BESIII 2309.01502

The effective range expansion

[S. Weinberg, Phys. Rev. 137, B672 (1965)]

$$a = -\frac{2(1-Z)}{(2-Z)}\frac{1}{\gamma} + \mathcal{O}(\beta^{-1})$$
$$r_e = -\frac{Z}{1-Z}\frac{1}{\gamma} + \mathcal{O}(\beta^{-1})$$

Z: field renormalization constant

- $Z = 0$: pure bound (composite) state
- $Z = 1$: pure elementary state

$\beta^{-1} \approx \frac{1}{m_\pi} \approx$ 1.4 fm, for both deuteron and the $X(3872)$

$\gamma = \sqrt{2\mu E_b}$

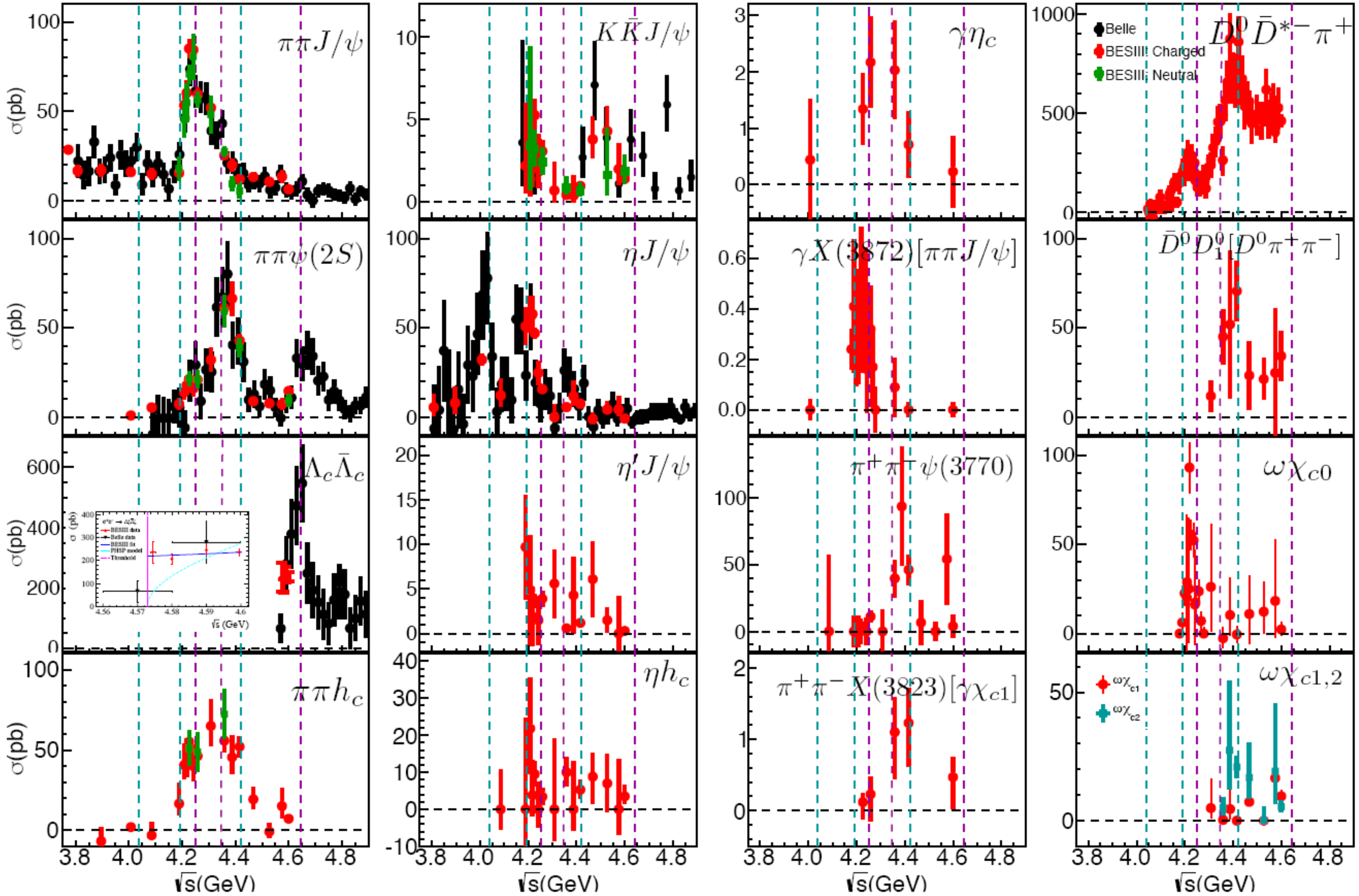
Parameters	$X(3872)$	deuteron
Nearby threshold	$D^{*0}\bar{D}^0$	pn
a	$-16.5^{+\,7.0\,+\,5.6}_{-27.6\,-27.7}$ fm	-5.41 fm
r_e	$-4.1^{+0.9\,+2.8}_{-3.3\,-4.4}$ fm	1.75 fm
Range correction	negligible	important for r_e
Z	≈ 0.18	-

➡ Different sign, may suggest an elementary $c\bar{c}$ core [A. Esposito PRD 105, L031503]

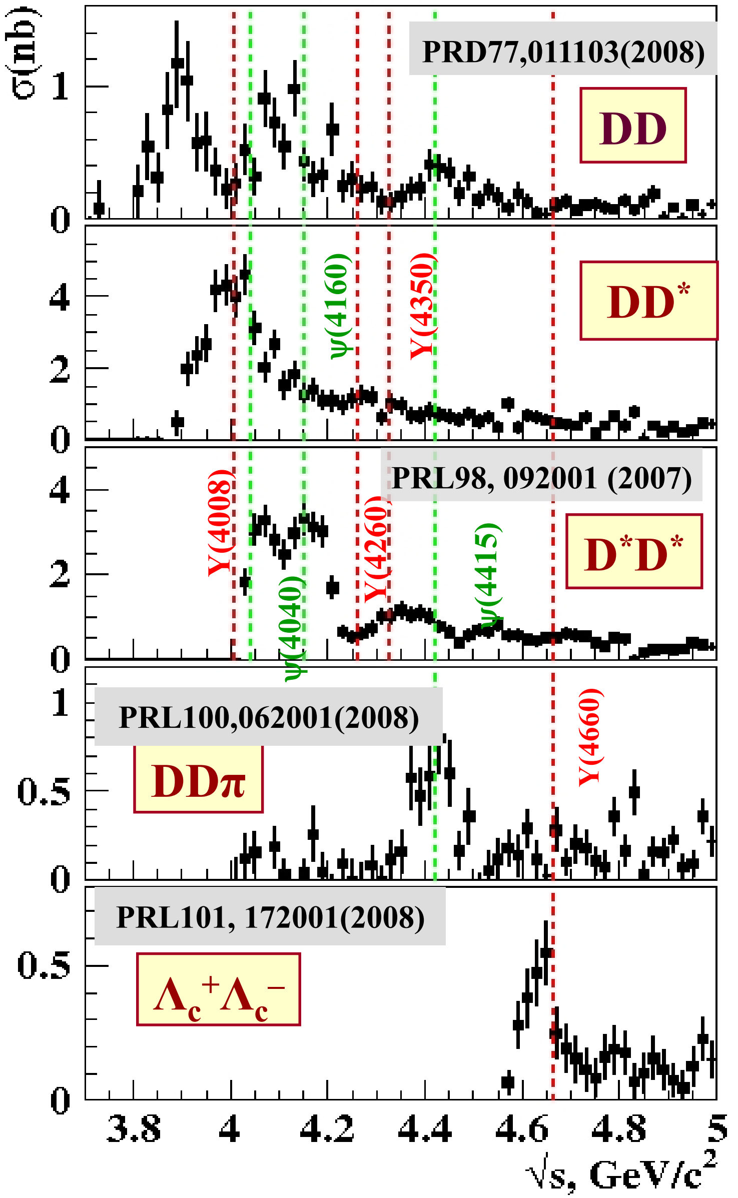
➡ Close to 0 but can not be solved model-independently due to the range correction

Effective Range Expansion ➔ scattering length a and effective range r_e

After we have measured all the e^+e^- annihilation cross sections, what do we do to get the resonant parameters of the vector charmonium(-like) states?



From Yuping Guo, talk @ Hadron2019, Guilin



From Galina Pakhlova

Inclusive fit: coupled channels

EICHTEN, GOTTFRIED, KINOSHITA, LANE, AND YAN PRD 21 203 (1980)

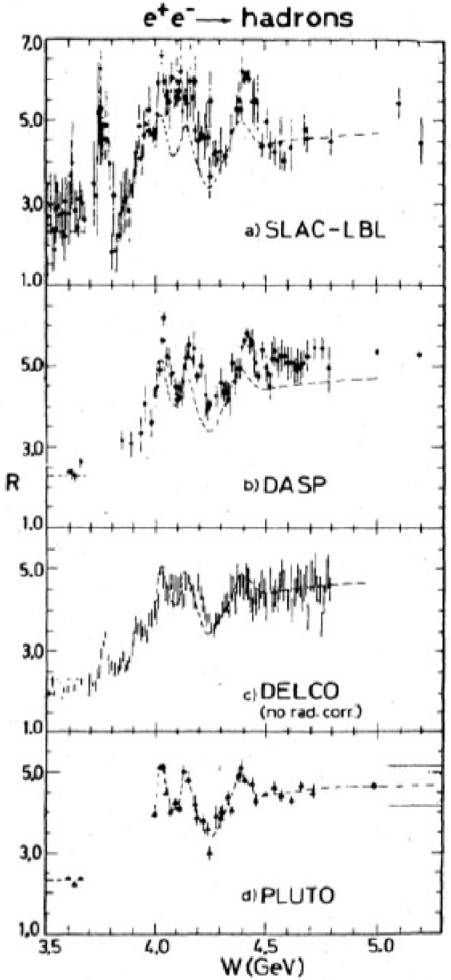


FIG. 15. Results of R (including $e^+e^- \to \tau^+\tau^-$) from four experiments: (a) SLAC-LBL (Ref. 44), (b) DASP (Ref. 46), (c) DELCO (Ref. 45), (d) PLUTO (Ref. 47). The curves represent a hand-drawn line through the PLUTO data. The band in Fig. 15(d) indicates the systematic errors of the PLUTO measurement. The plots shown were compiled by G. Feldman.

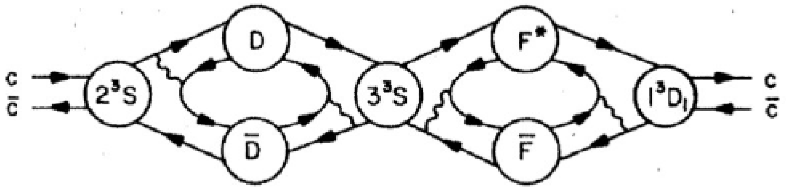


FIG. 8. The propagation of a $c\bar{c}$ pair in the presence of open and closed decay channels as described in the Green's function $\mathcal{G}$.

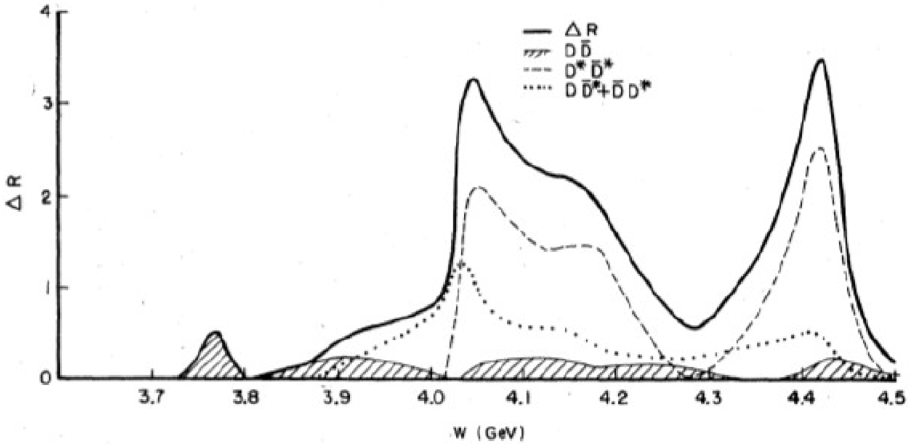


FIG. 13. The charm contribution to R in the region $3.7 < W < 4.5$ GeV as computed in the coupled-channel model. Contributions from $F_1\bar{F}_2$ channels are included but not indicated separately since they are too small; they are shown in Fig. 12.

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K-matrix fit by T. V. Uglov et al.

i runs over $D^{(*)}\bar{D}^{(*)}$ channels,
α runs over ψ's

g is real, so there will be no multiple solutions!

$$S = 1 + 2iA,$$

$$A = K(1 - iK)^{-1},$$

$$AA^\dagger = \frac{1}{2i}(A - A^\dagger).$$

Ensures unitarity

$$(P^{-1}(s))_{\alpha\beta} = (M_\alpha^2 - s)\delta_{\alpha\beta} - i\sum_m G_{m\alpha}G_{m\beta}$$

$$K_{ij} = \sum_\alpha G_{i\alpha}(s)\frac{1}{M_\alpha^2 - s}G_{j\alpha}(s),$$

$$\Gamma_{e\alpha} \equiv \Gamma(\psi_\alpha \to e^+e^-) = \frac{\alpha g_{e\alpha}^2}{3M_\alpha^3}.$$

Electron width

$$G_{i\alpha}^2(s) = g_{i\alpha}^2\frac{k_i^{2l_i+1}}{\sqrt{s}}\theta(s - s_i)$$

Coupling constant

$$\Gamma_{i\alpha} \equiv \Gamma(\psi_\alpha \to [D^{(*)}\bar{D}^{(*)}]_i) = \frac{g_{i\alpha}^2}{M_\alpha^2}[p_i(M_\alpha)]^{2l_i+1}$$

Partial decay width

$$A_{ij} = \sum_{\alpha\beta} G_{i\alpha}(s)P_{\alpha\beta}(s)G_{j\beta}(s)$$

$$\sigma_i(s) = \frac{4\pi\alpha}{s^{5/2}}[p_i(s)]^{2l_i+1}\left|\sum_{\alpha,\beta} g_{e\alpha}P_{\alpha\beta}(s)g_{i\beta}\right|^2$$

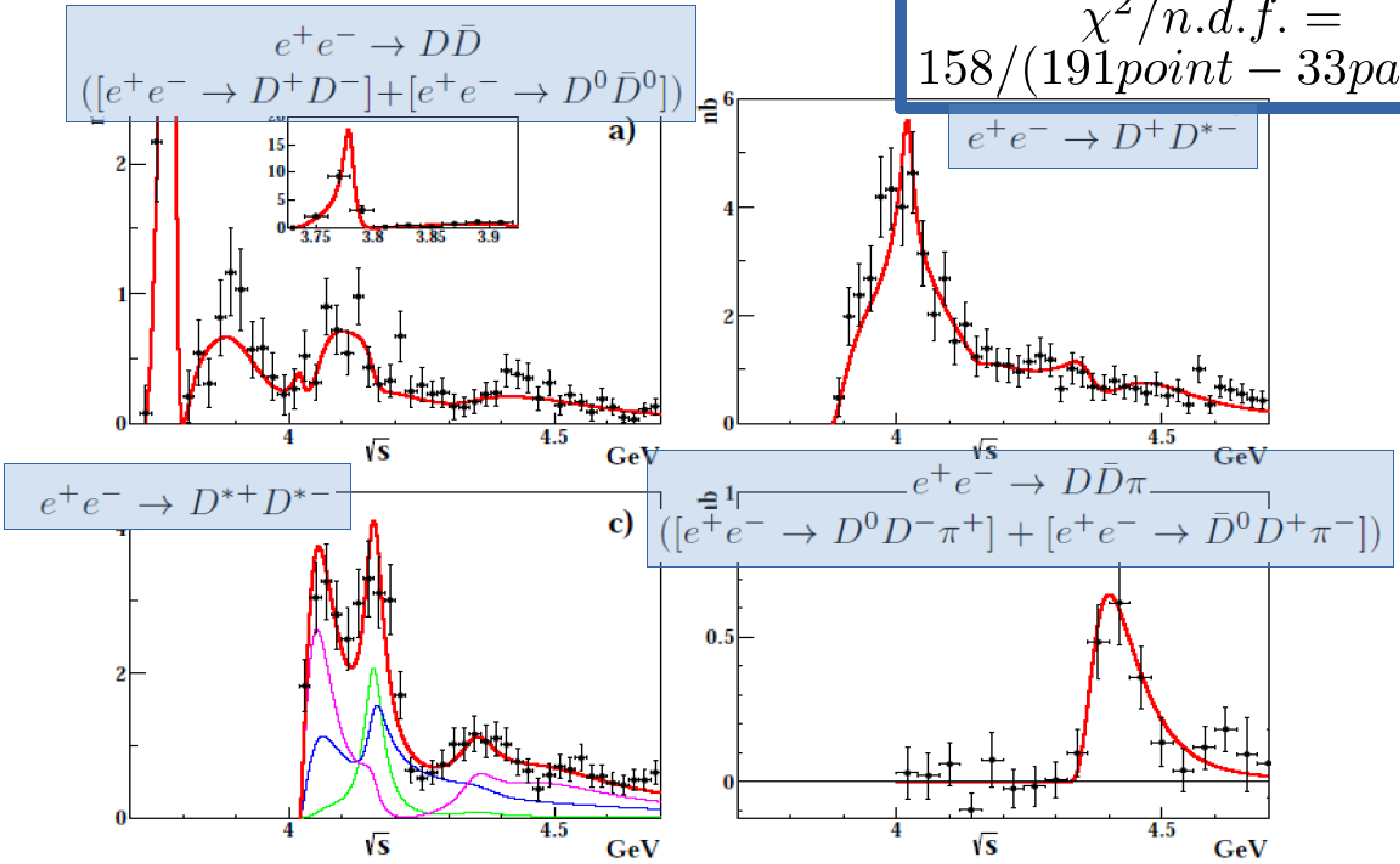
Cross-section

T. V. Uglov et al., JETP letters 105, 1 (2017)

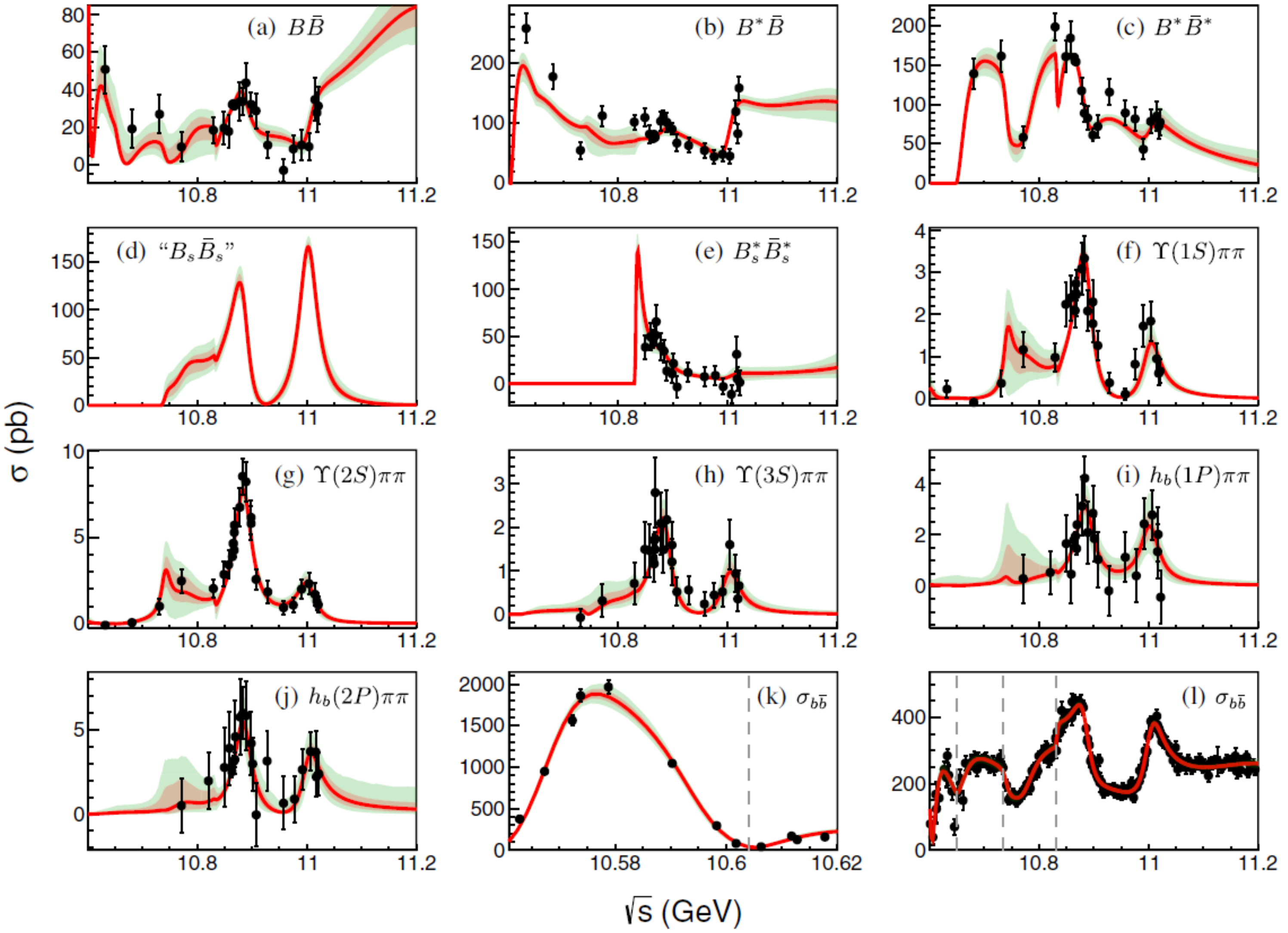
cross sections in a coupled-channel approach 8/19

Results

$$\chi^2/n.d.f. = 158/(191point - 33par)$$



K-matrix fit by N. Hüsken, R. E. Mitchell and E. S. Swanson



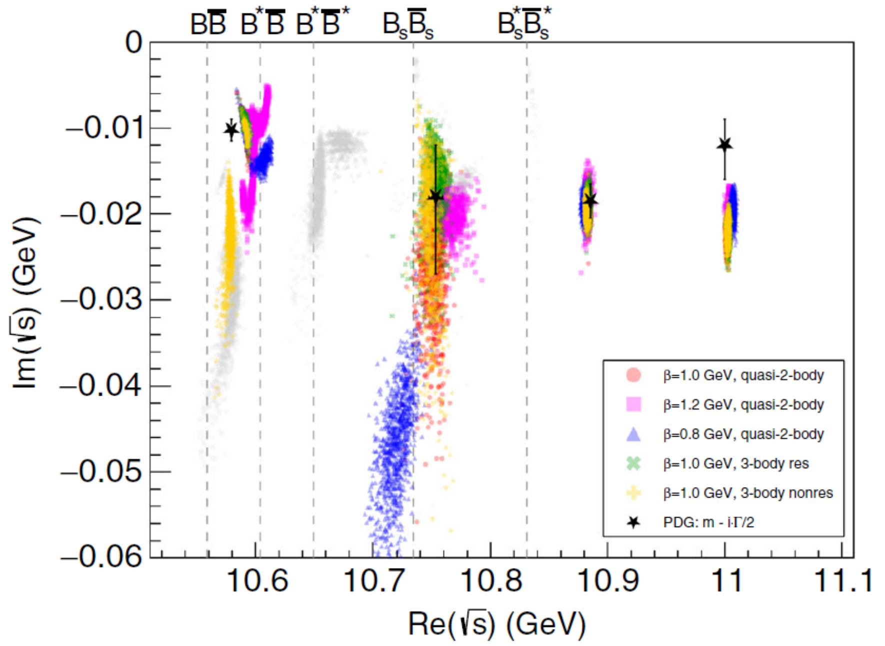


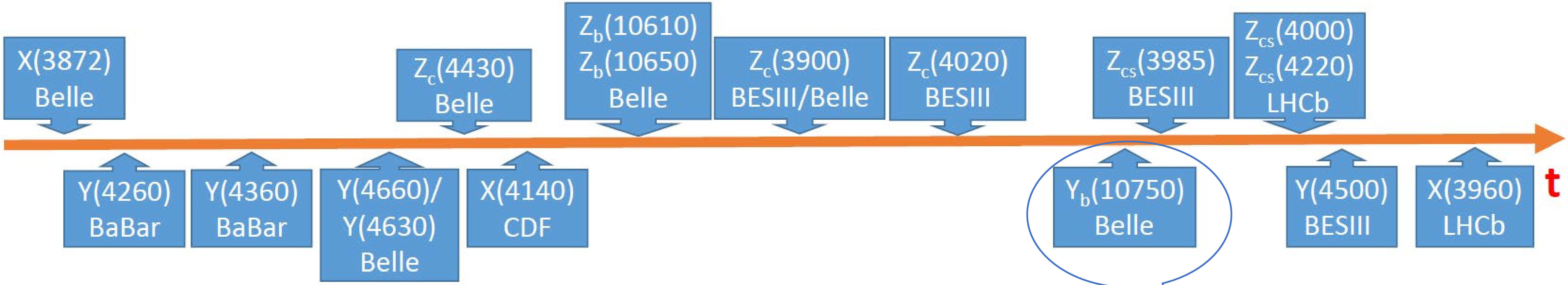
FIG. 3. Bootstrap pole positions for five different models indicated by different colors and markers. Gray points with the same marker indicate ghost poles with sizable residues in that model. The black stars represent the RPP estimate using a Breit-Wigner parametrization.

PRD 106, 094013 (2022)

Fit not very good, many model assumptions.
More precise data are necessary, better model for multi-body final states is needed.

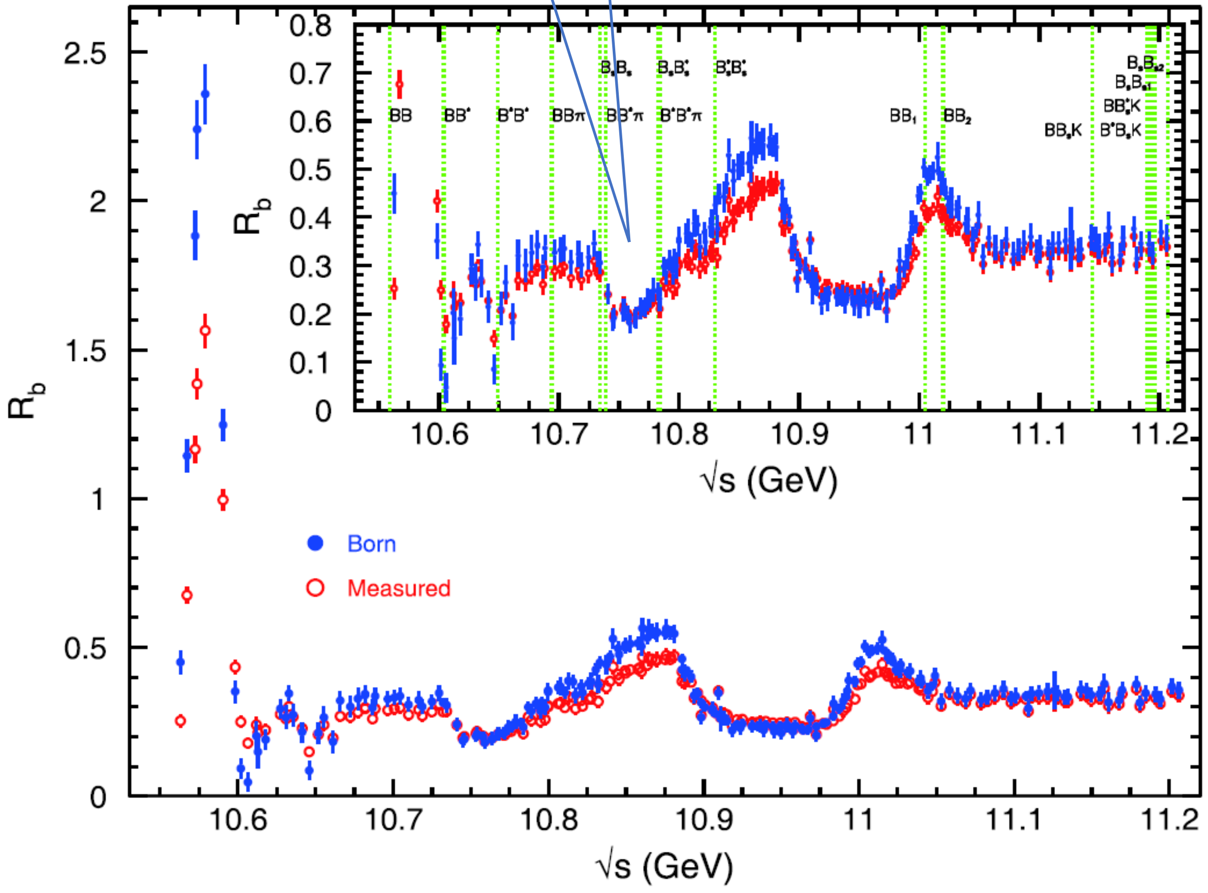
Recent review articles, books, web pages

- H.-X. Chen et al., The hidden-charm pentaquark and tetraquark states, Phys. Rept. 639 (2016) 1
- A. Hosaka et al., Exotic hadrons with heavy flavors: X, Y, Z, and related states, PTEP 2016 (2016) 062C01
- J.-M. Richard, Exotic hadrons: review and perspectives, Few Body Syst. 57 (2016) 1185
- R. F. Lebed, R. E. Mitchell, E. Swanson, Heavy-quark QCD exotica, PPNP 93 (2017) 143
- A. Esposito, A. Pilloni, A. D. Polosa, Multiquark resonances, Phys. Rept. 668 (2017) 1
- A. Ali, J. S. Lange, S. Stone, Exotics: Heavy pentaquarks and tetraquarks, PPNP 97 (2017) 123
- F. K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, Hadronic molecules, RMP 90 (2018) 015004
- S. L. Olsen, T. Skwarnicki, Nonstandard heavy mesons and baryons: Experimental evidence, RMP 90 (2018) 015003
- Y.-R. Liu et al., Pentaquark and tetraquark states, PPNP107 (2019) 237
- N. Brambilla et al., The XYZ states: experimental and theoretical status and perspectives, Phys. Rept. 873 (2020) 1
- Y. Yamaguchi et al., Heavy hadronic molecules with pion exchange and quark core couplings: a guide for practitioners, JPG 47 (2020) 053001
- F. K. Guo, X.-H. Liu, S. Sakai, Threshold cusps and triangle singularities in hadronic reactions, PPNP 112 (2020) 103757
- G. Yang, J. Ping, J. Segovia, Tetra- and penta-quark structures in the constituent quark model, Symmetry 12 (2020) 1869
- C. Z. Yuan, Charmonium and charmoniumlike states at the BESIII experiment, Natl. Sci. Rev. 8 (2021) nwab182
- H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, S.-L. Zhu, An updated review of the new hadron states, RPP 86 (2023) 026201
- L. Meng, B. Wang, G.-J. Wang, S.-L. Zhu, Chiral perturbation theory for heavy hadrons and chiral effective field theory for heavy hadronic molecules, Phys. Rept. 1019 (2023) 1
- A. Ali, L. Maiani, A. D. Polosa, Multiquark Hadrons, Cambridge University Press (2019)
- QWG: https://qwg.ph.nat.tum.de/exoticshub/



Are there similar vector states in the bottomonium sector (Y_b)?

- ➢ BaBar & Belle data mainly on ϒ(4S) peak
- ➢ Limited energy scan data above ϒ(4S)
  - ✓ BaBar: 136 energy points, 4 fb^{-1}
  - ✓ Belle: 78 energy points, 22 fb^{-1}
- ➢ Belle II started to contribute
  - ✓ 4 energy points, 19 fb^{-1}



X. K. Dong et al., CPC 44, 083001 (2020)

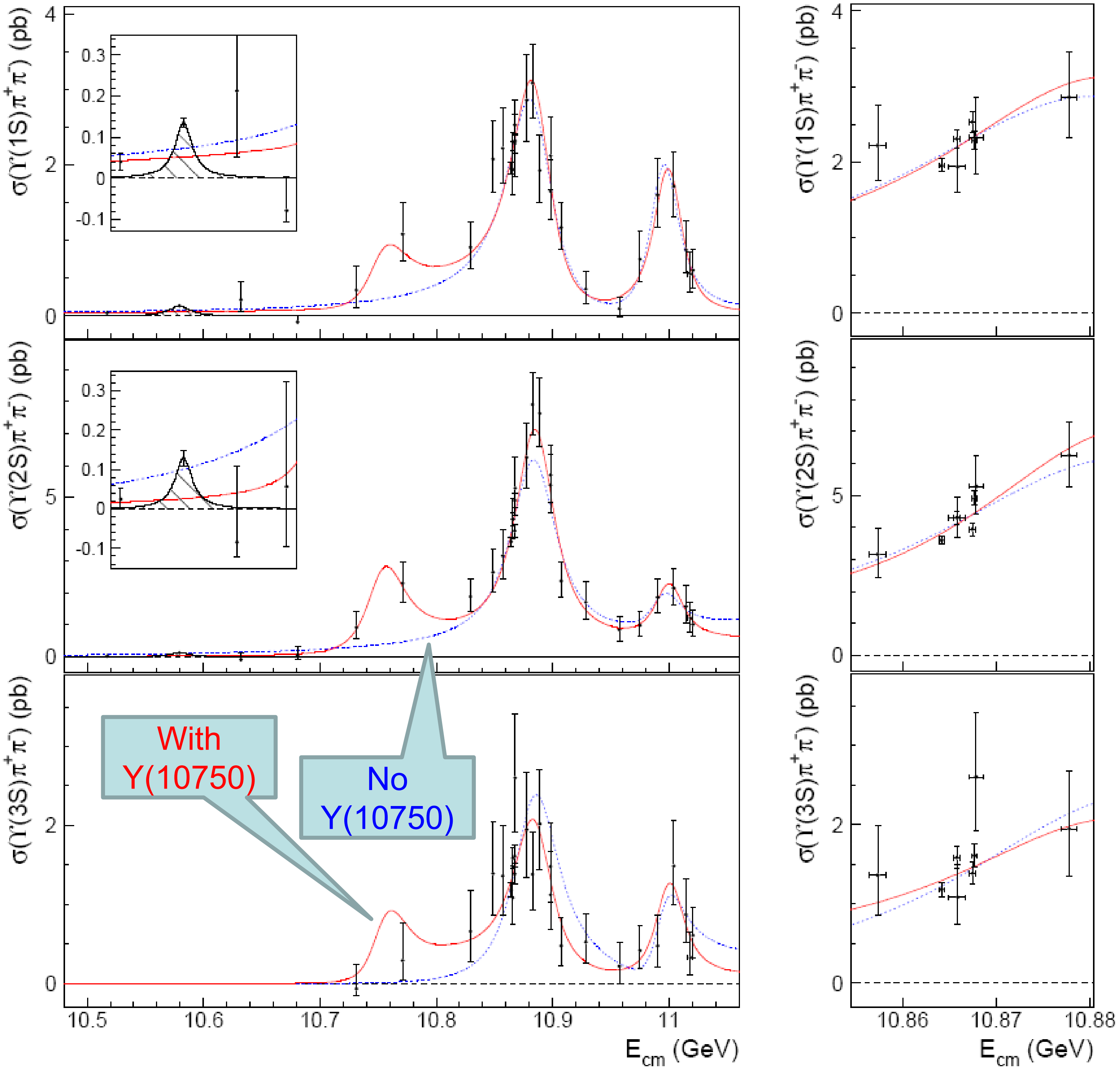
Y(10750) in $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)$

Significance of the Y(10750):

- 5.1σ in Υ(2S)
- 5.2σ in all modes

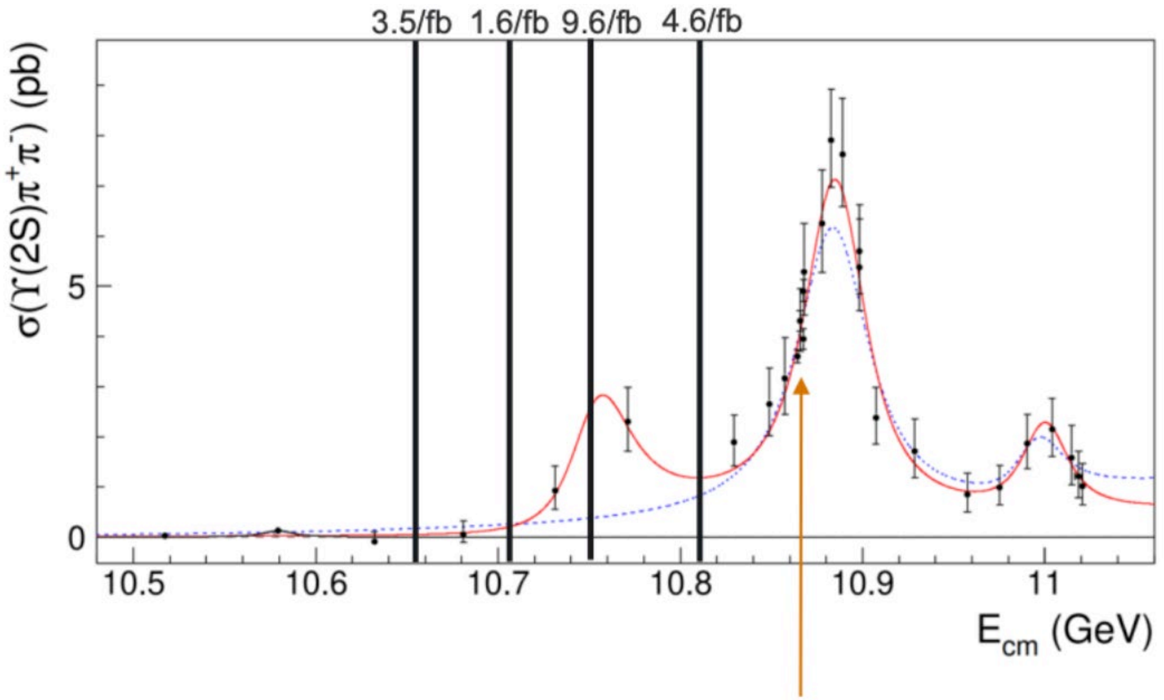
With all kinds of systematic effects considered!

arXiv:1905.05521, JHEP10(2019)220

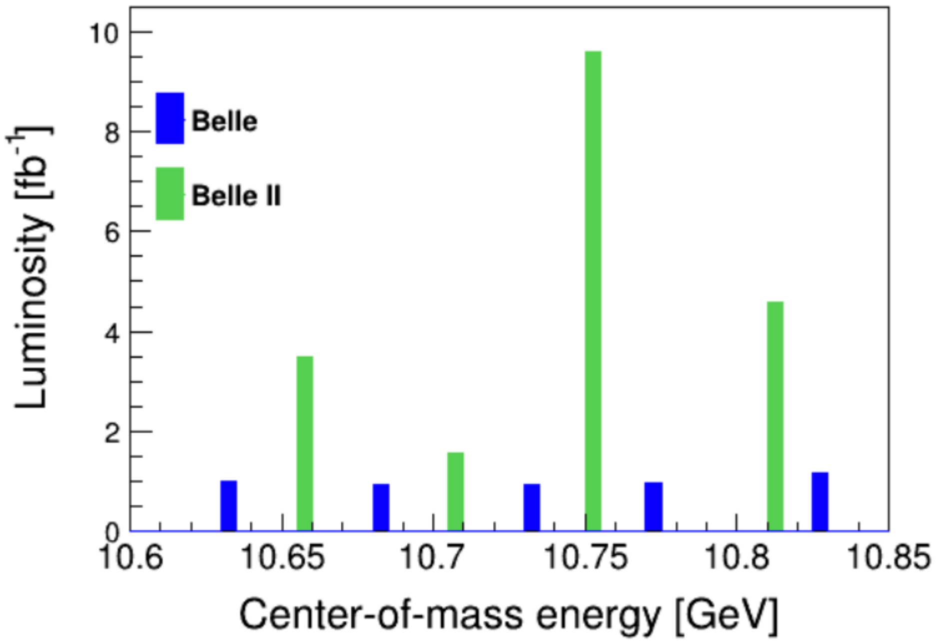


Unique scan data near $\sqrt{s} = 10.75$GeV

- In November 2021, Belle II collected 19 fb^{-1} of unique data at energies above the $\Upsilon(4S)$: four energy scan points around 10.75 GeV
- Physics goal: understand the nature of the $Y(10750)$.

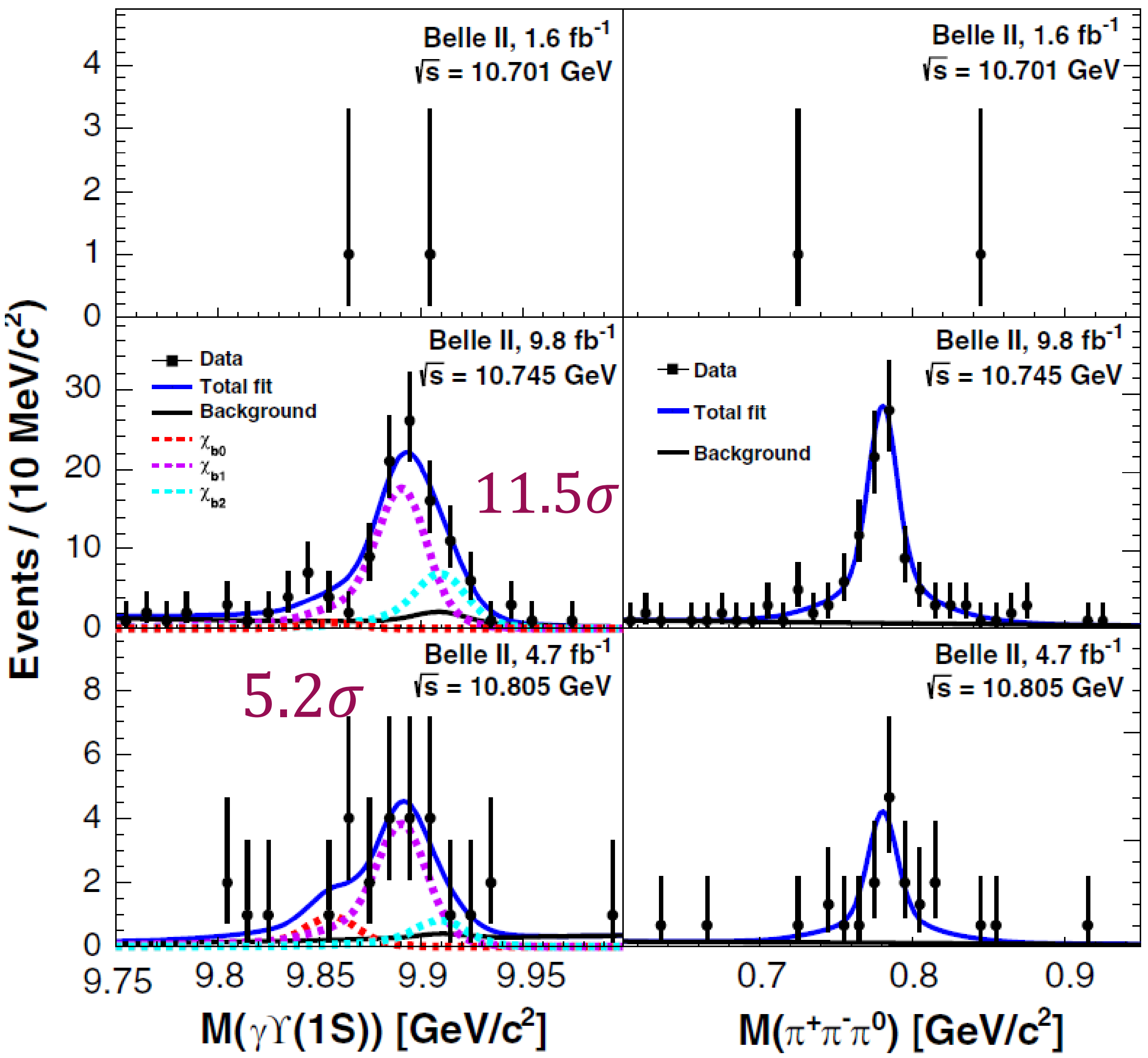


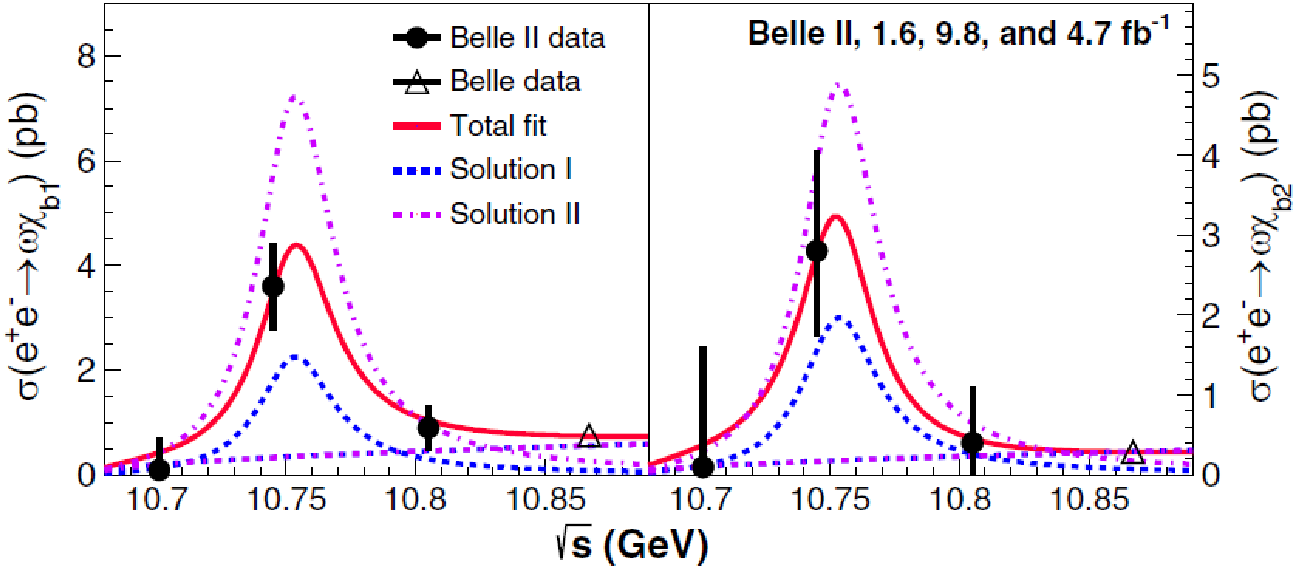
All points ~1/fb except these (~20+/fb)



Y(10750) in $e^+e^- \to \omega\chi_{bJ}(1P)$

PRL130, 091902 (2023)



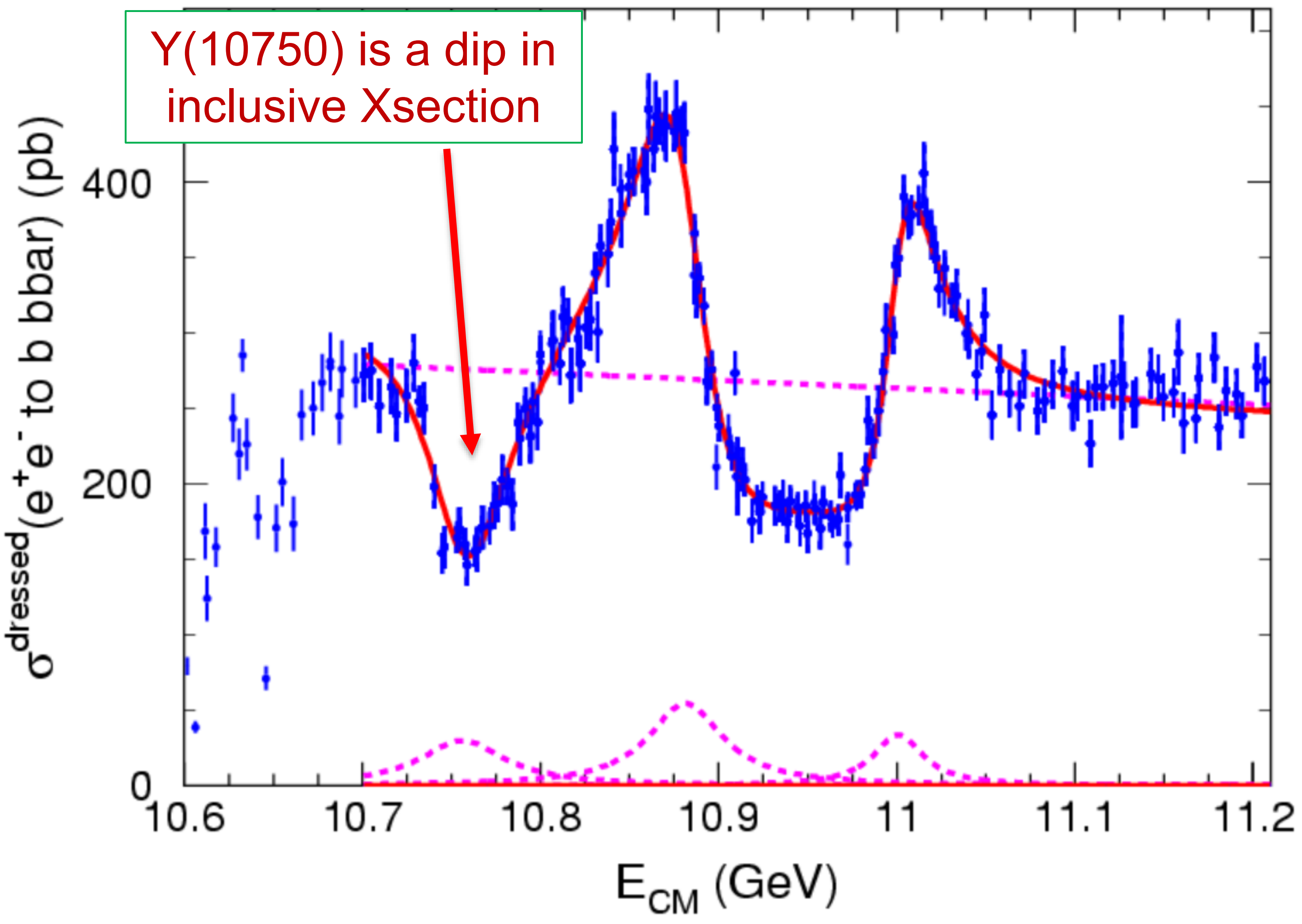


$\Gamma_{ee}\mathcal{B}_f$	Solution I	Solution II
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b1})$	$(0.63 \pm 0.39 \pm 0.20)$ eV	$(2.01 \pm 0.38 \pm 0.76)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b2})$	$(0.53 \pm 0.46 \pm 0.15)$ eV	$(1.32 \pm 0.44 \pm 0.55)$ eV

- $\frac{\Gamma_{ee}\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b1})}{\Gamma_{ee}\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b2})} \sim 1.0$ agrees with the expectation for HQET[3]
- $\frac{\Gamma_{ee}\mathcal{B}(\omega\chi_{b1/2})}{\Gamma_{ee}\mathcal{B}(\pi^+\pi^-\Upsilon(2S))^{[2]}} \sim 1.5$ for $\Upsilon(10753)$ and ~ 0.1 for $\Upsilon(10870)$

[1]PRL 113, 142001(2014); [2]. JHEP 10, 220(2019); [3]. arXiv:hep-ph/9908366;

The Y(10750) in inclusive hadronic cross sections



Coherent sum of a continuum amplitude ($\propto 1/\sqrt{s}$) and 3 BW functions (constant width).

Free parameters:

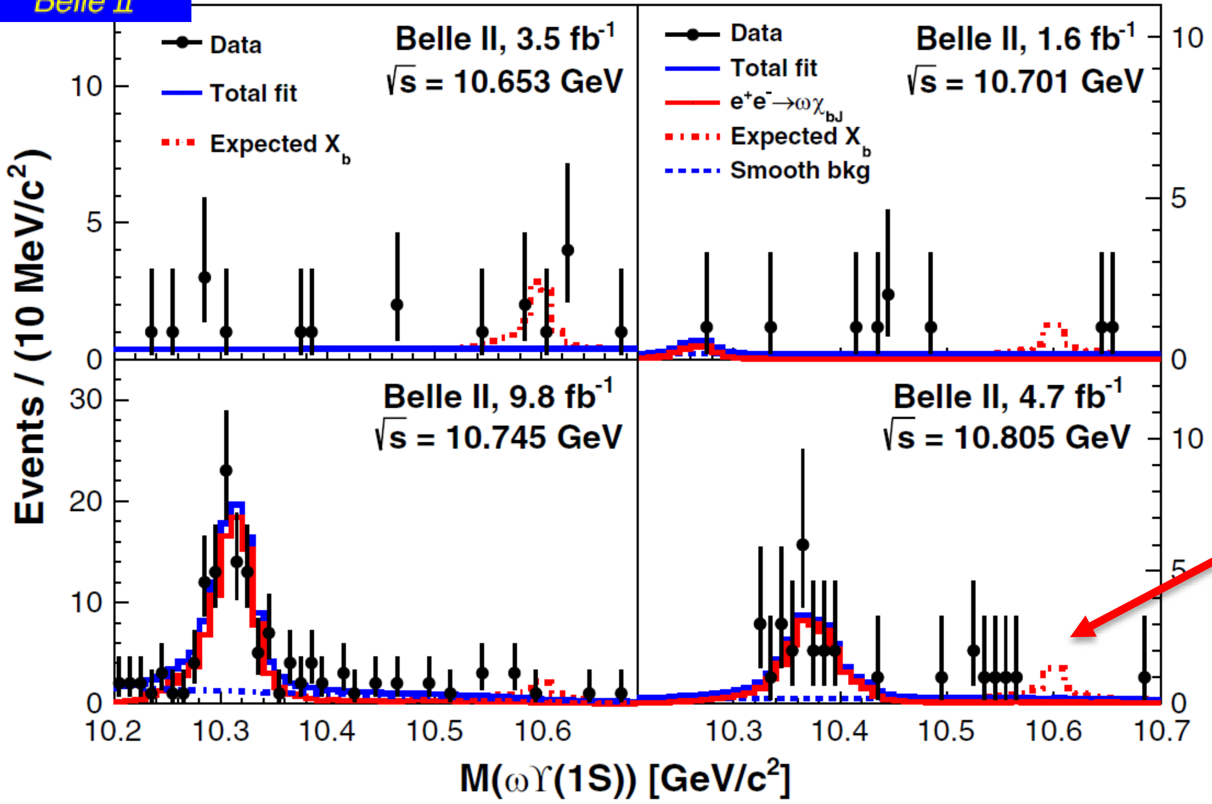
- Mass M
- width Γ
- leptonic partial width Γ_{ee}
- relative phase ϕ

Belle II will supply more information about this structure!

X. K. Dong et al., CPC 44, 083001 (2020)

No X_b observed in $e^+e^- \to \gamma X_b \to \gamma\omega\Upsilon(1S)$

PRL130, 091902 (2023)



- No significant X_b signal is observed.
- The peaks are the reflections of $e^+e^- \to \omega\chi_{\mathrm{bJ}}$

From simulated events with $M(X_\mathrm{b})$ =10.6 GeV

The yield is fixed at the upper limit on 90% C.L.

Upper limits of	$\sqrt{s}$ (GeV)	10.653	10.701	10.745	10.805
$\sigma_\mathrm{B}(e^+e^- \to \gamma X_b)\cdot$ $\mathcal{B}(X_b \to \omega\Upsilon(1S))$ (pb) at 90% C.L.	$M(X_\mathrm{b}) = 10.60$ GeV	0.45	0.33	0.10	0.14
	$M(X_\mathrm{b}) = 10.45$ GeV	0.14	0.25	0.06	0.08
	$M(X_\mathrm{b}) = 10.65$ GeV	0.54	0.84	0.14	0.36