New experimental results on exotic XYZ states

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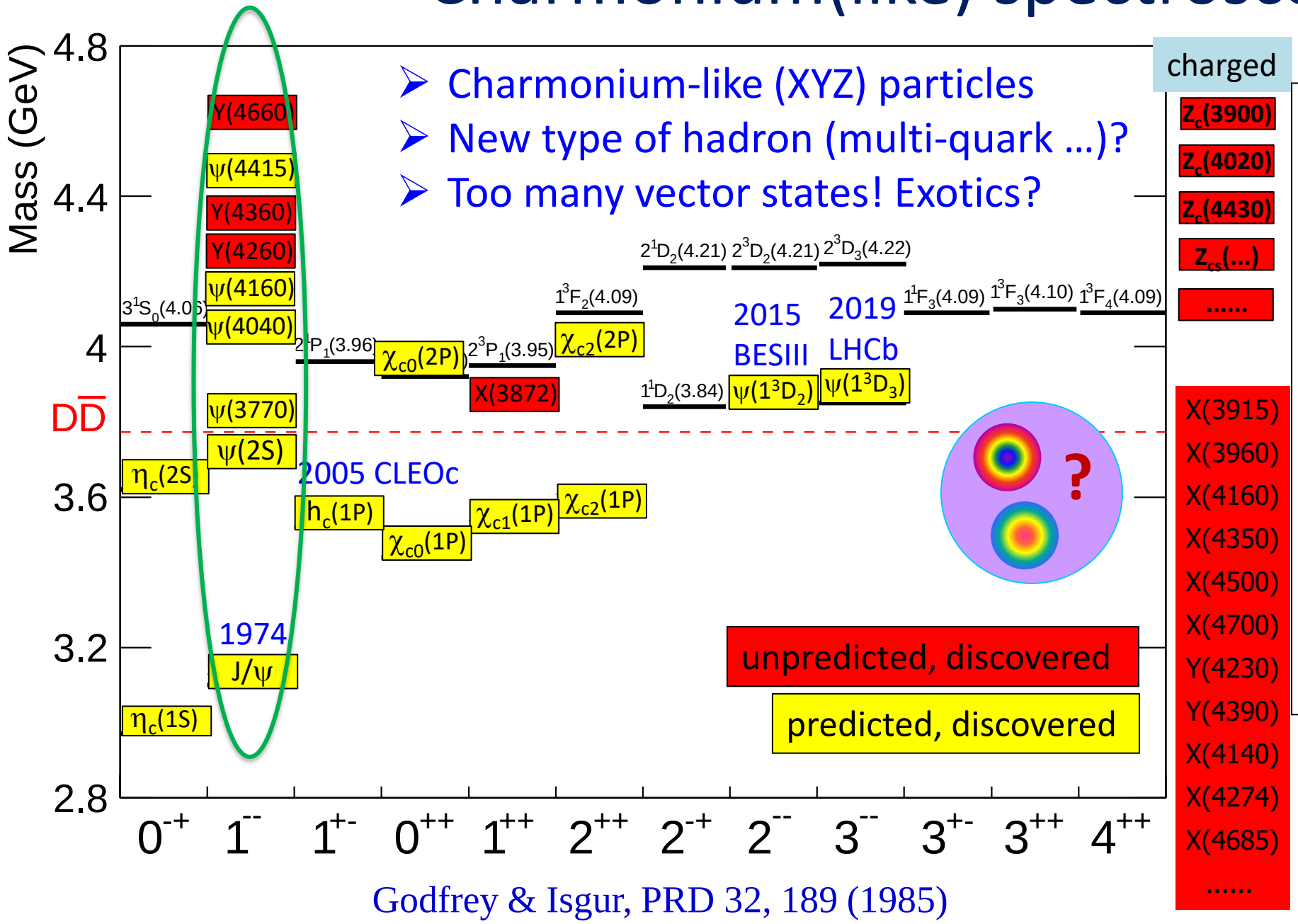
Charmonium(like) spectroscopy



- Charmonium-like (XYZ) particles
- New type of hadron (multi-quark …)?
- Too many vector states! Exotics?

charged

- $Z_c(3900)$
- $Z_c(4020)$
- $Z_c(4430)$
- $Z_{cs}(...)$
- .....

- X(3915)
- X(3960)
- X(4160)
- X(4350)
- X(4500)
- X(4700)
- Y(4230)
- Y(4390)
- X(4140)
- X(4274)
- X(4685)
- .....

Godfrey & Isgur, PRD 32, 189 (1985)

Limit my talk to

- charmoniumlike XYZ states
- States with information available from two or more experiments
- X(3872)
- Y(4660)
- Z_{cs}(xxxx)

More in a recent review:

N. Brambilla et al.,

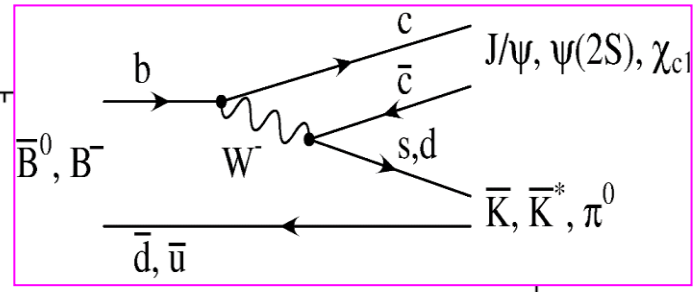
Phys. Rept. 873 (2020) 1-154.

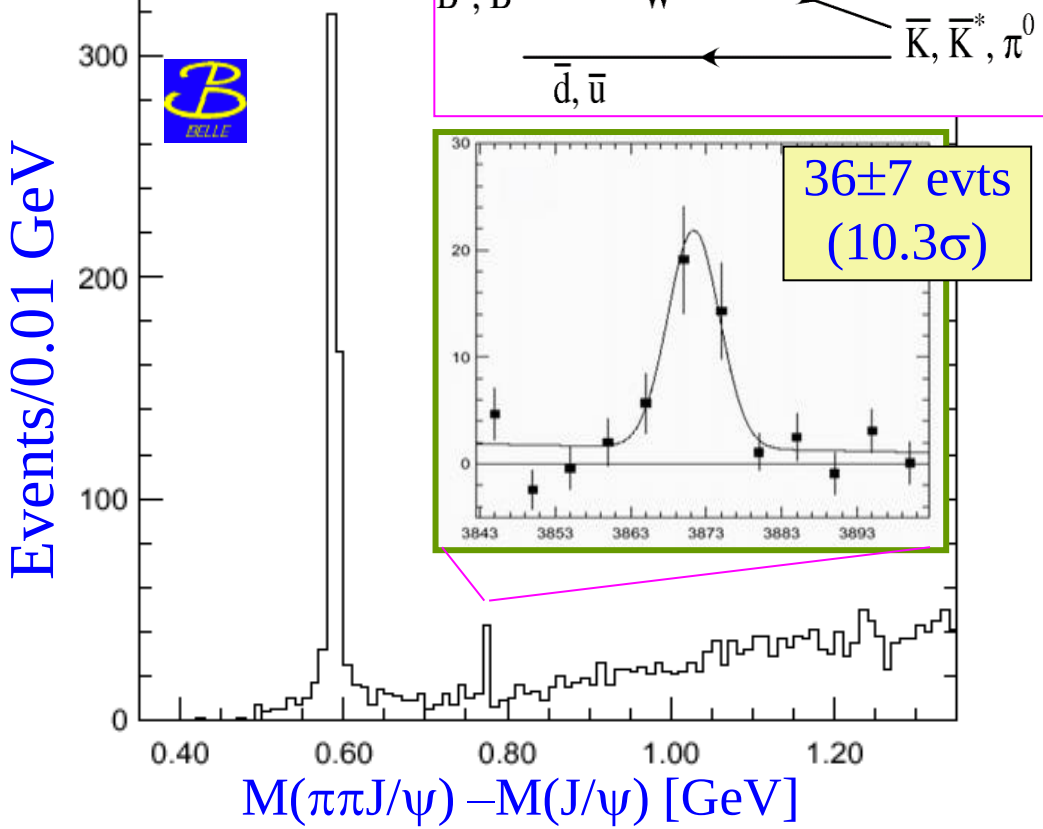
The X(3872):

how many efforts must we make before we understand a particle?

Discovery of the X(3872)

Belle, 2003
PRL91, 262001

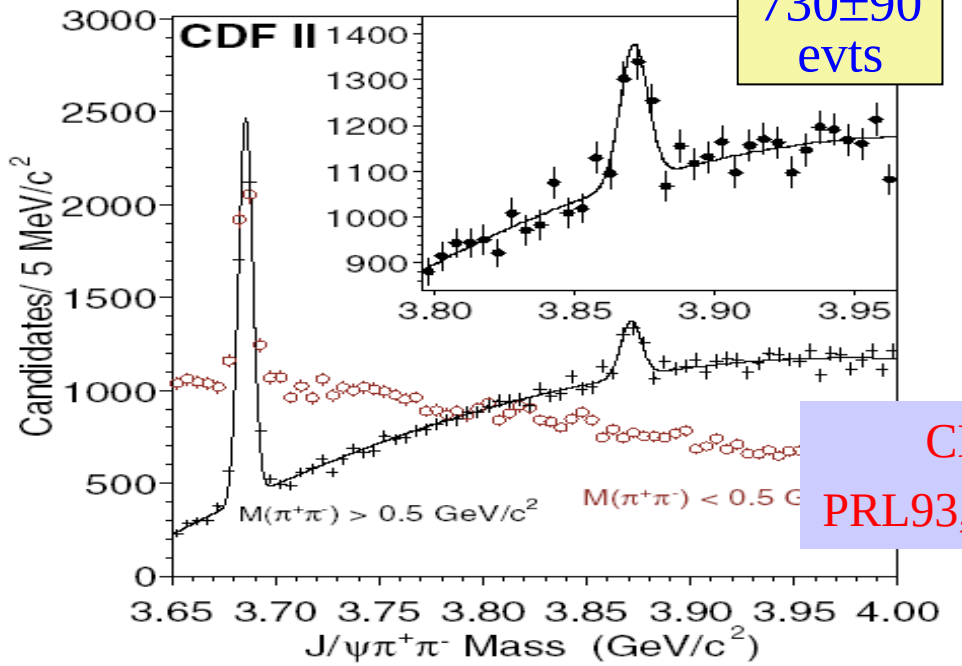




$M = 3872.0 \pm 0.6 \pm 0.5$ MeV, $\Gamma < 2.7$ MeV

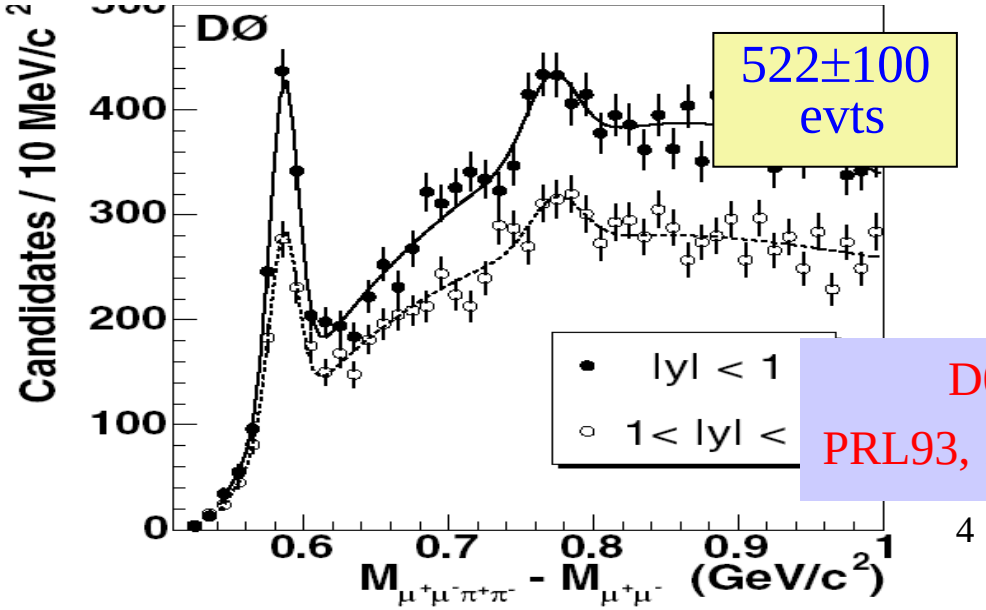
$$\frac{B(B^{\pm} \to XK^{\pm} \to \pi^+\pi^- J/\psi K^{\pm})}{B(B^{\pm} \to \psi' K^{\pm} \to \pi^+\pi^- J/\psi K^{\pm})} = (6.3 \pm 1.2 \pm 0.7)\%$$

730±90 evts



CDF 2004
PRL93, 072001

522±100 evts



D0, 2004
PRL93, 162002

Mass of the X(3872)

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

$M_{D0} + M_{D*0}$= 3871.69 ± 0.11 MeV

E_b = – 0.04 ± 0.12 MeV

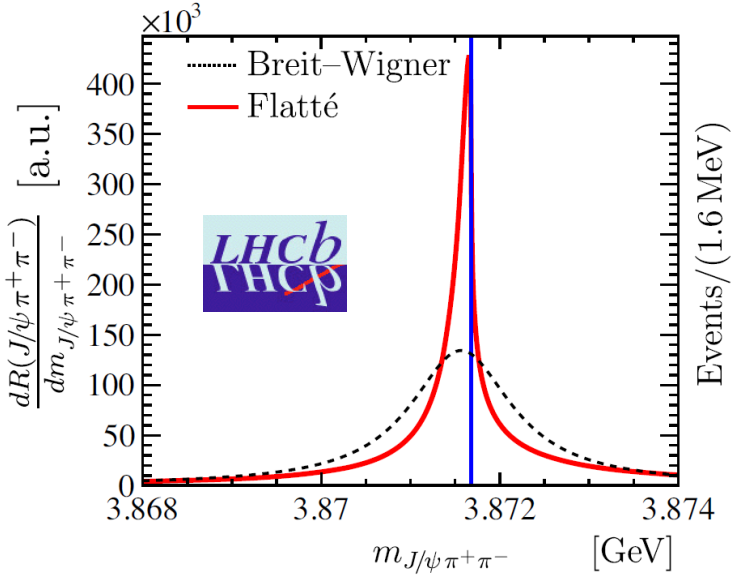
E_b(deuteron) = – 2.2 MeV

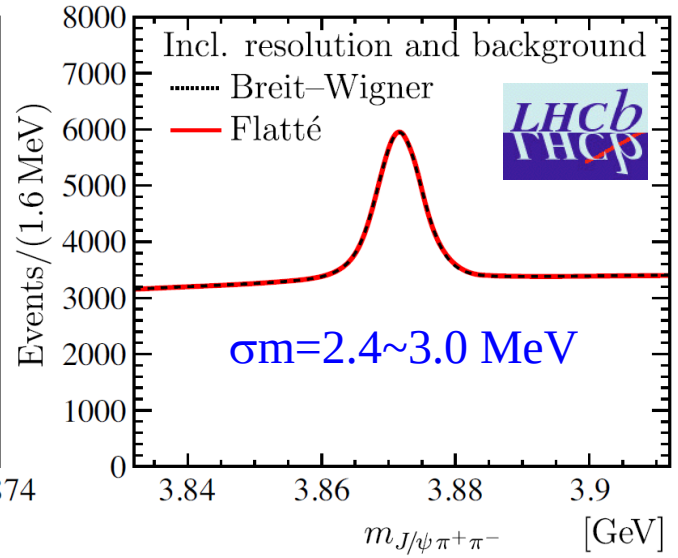
$$r_X = (8\mu|E_b|)^{-1/2} > 5 \text{ fm}$$

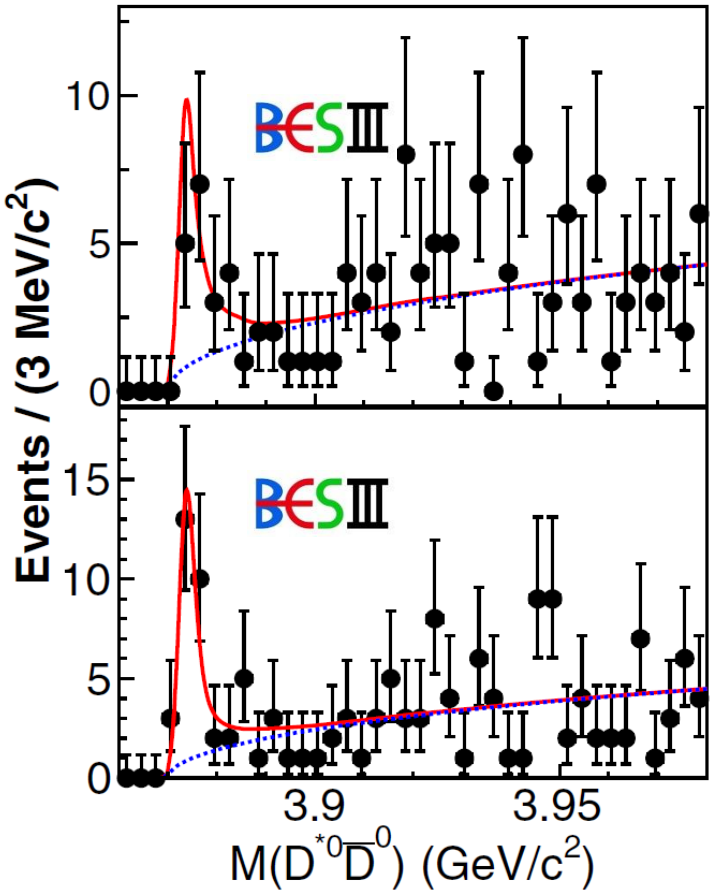
Width of the X(3872)

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

PRL124, 242001 (2020)

Flatté parametrization:

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

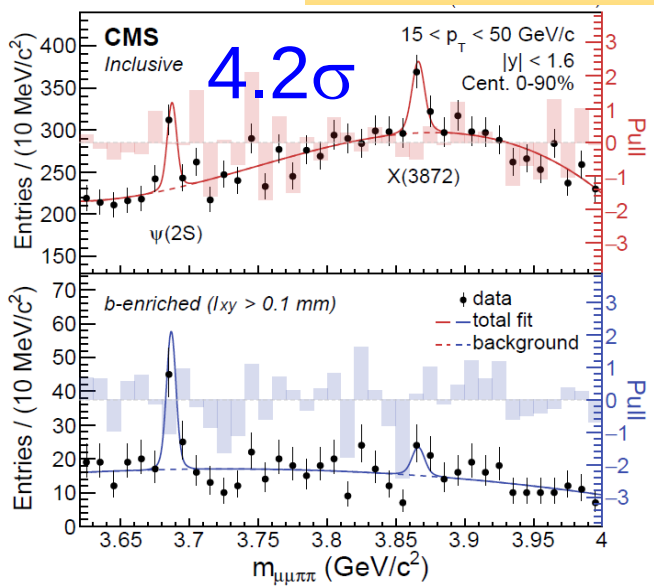
Depends strongly on *g*, coupling to $\bar{D}^0 D^{*0}$!

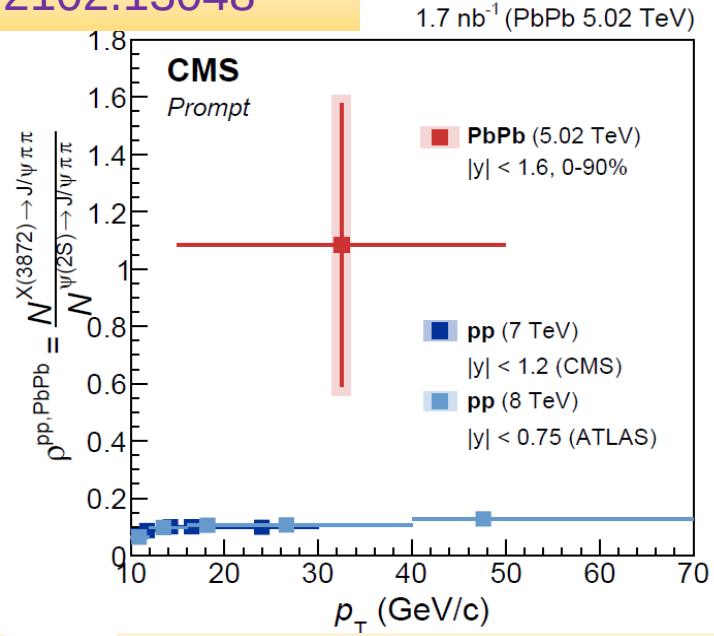
$$\text{FWHM} = 0.22^{+0.06+0.25}_{-0.08-0.17}\ \text{MeV}$$

Production of the X(3872)

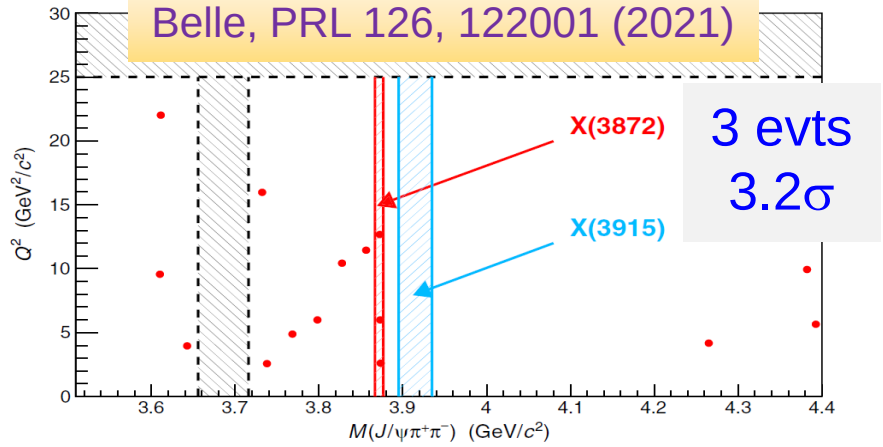
Production	experiments
B decays	BaBar, Belle, CMS, LHCb
B_s decays	CMS, LHCb
Λ_b decays	LHCb
$p\bar{p}$ collision	CDF, D0
pp collision	ATLAS, CMS, LHCb
PbPb collision	CMS
$e^+e^- \rightarrow \gamma X(3872)$	BESIII
$\gamma\gamma^* \rightarrow X(3872)$	Belle

CMS, arXiv: 2102.13048



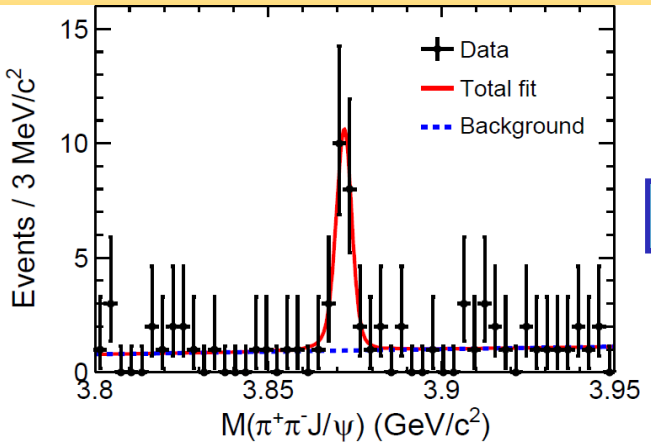


Belle, PRL 126, 122001 (2021)



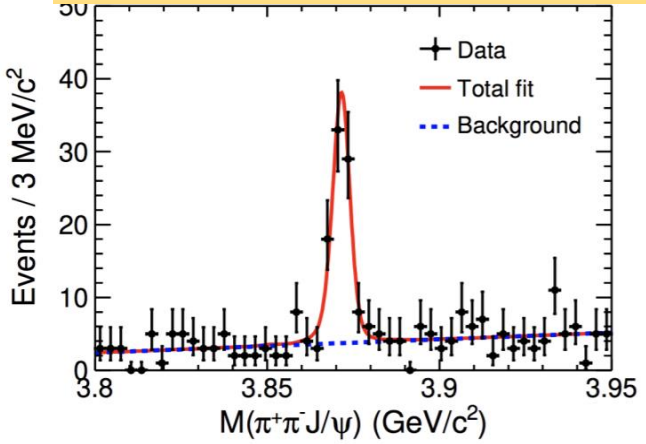
$\widetilde{\Gamma}_{\gamma\gamma}B(X \rightarrow \pi^+\pi^- J/\psi) = (5.5^{+4.1}_{-3.8} \pm 0.7)$ eV

BESIII, PRL 112, 092001 (2014)



4.0 fb^{-1}, 20±5 evts

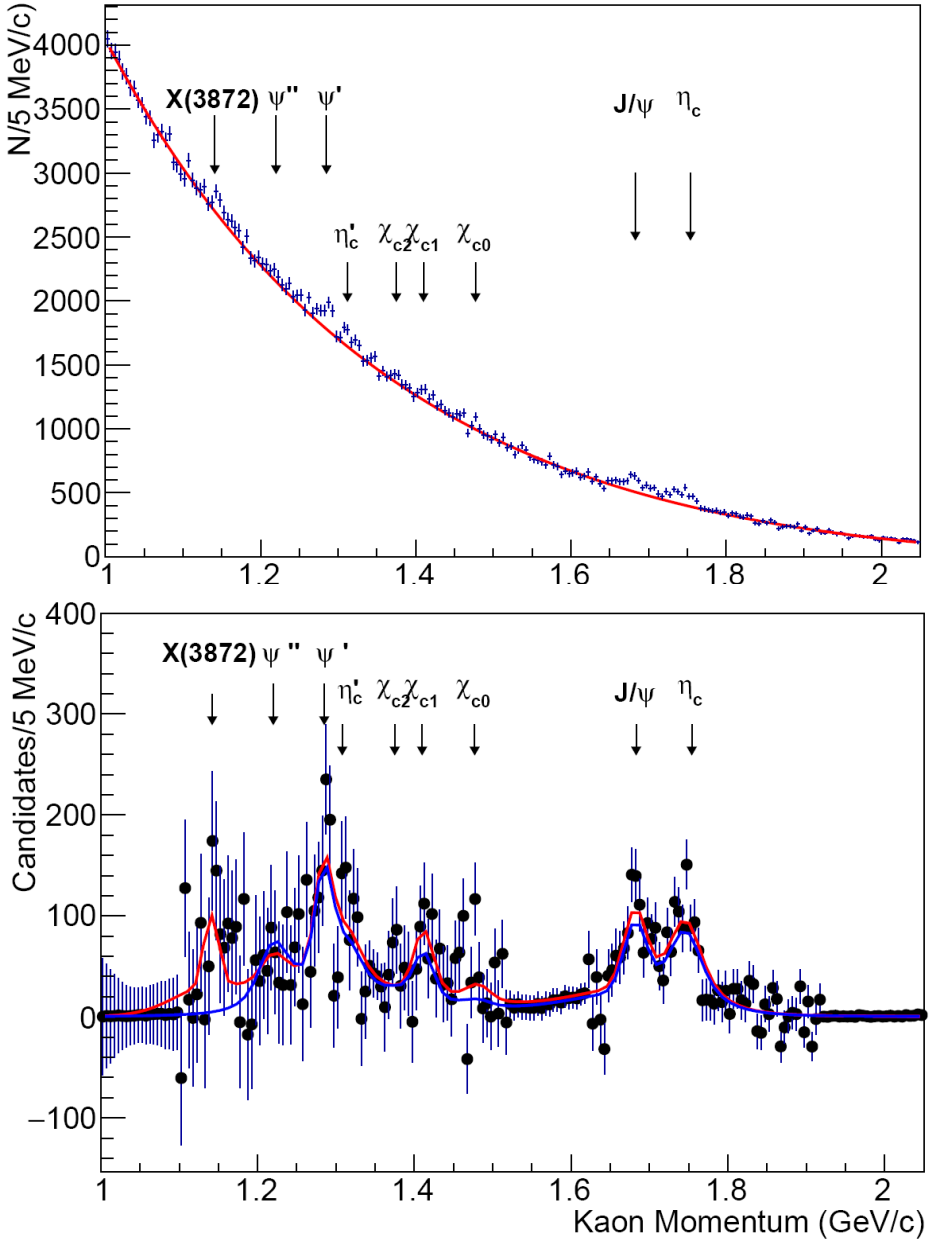
PRL122, 232002 (2019)



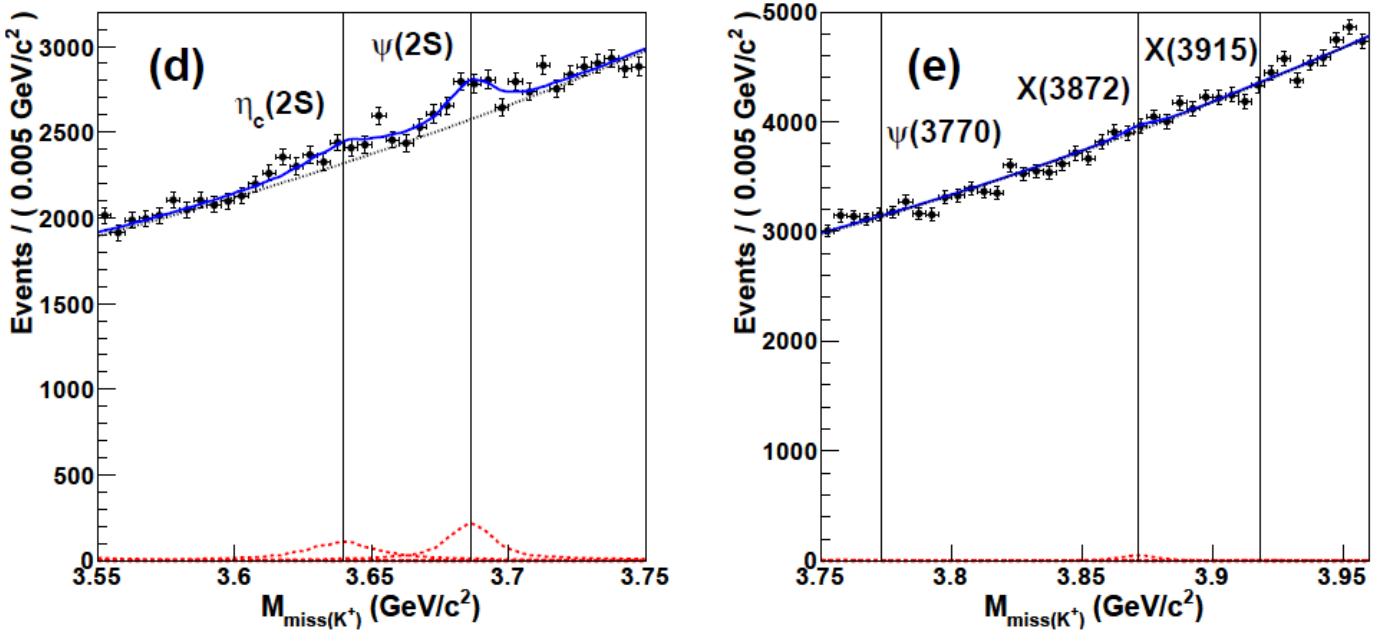
11.6 fb^{-1}, 79±9 evts

Production of the X(3872) in $B^+ \to K^+ X$

PRL 124, 152001 (2020)



PRD 97, 012005 (2018)

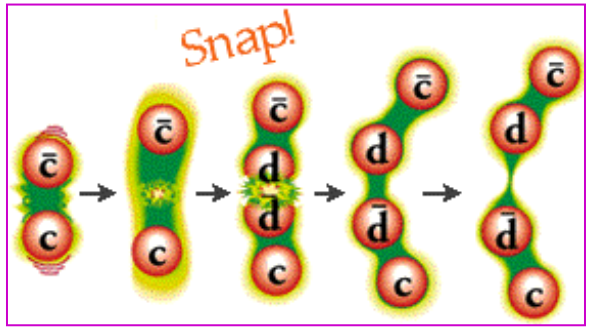


	N^{signal}	Signif.	$B(B^+ \to K^+ X)$
BaBar	992±285	3.0σ	$(2.1\pm0.6\pm0.3)\times10^{-4}$
Belle	260±230	1.1σ	$(1.2\pm1.1\pm0.1)\times10^{-4}$

These allow a determination of the X(3872) decay BFs with the product BFs and the BRs.

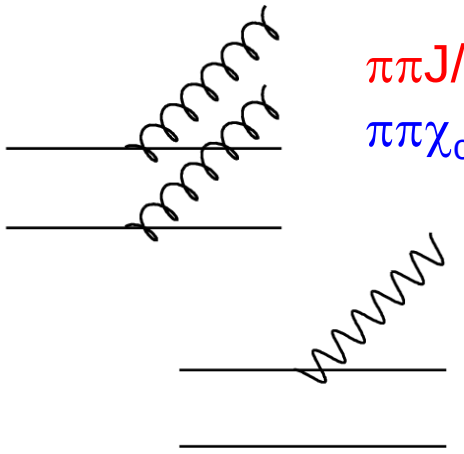
Decay of the X(3872)

- Open charm



$\bar{D}^0D^{*0}$? Threshold?
$\bar{D}^0D^0\pi^0$ (non $\bar{D}^0D^{*0}$)
$\bar{D}^0D^0\gamma$ (non $\bar{D}^0D^{*0}$)
$D^+D^-\gamma$

- Transitions
  - Hadronic transitions
  - Radiative transitions



$\pi\pi J/\psi$, $\pi\pi\pi J/\psi$, $\pi\chi_{cJ}$,
$\pi\pi\chi_{cJ}$, $\pi\pi\eta_c$, …

$\gamma J/\psi$, $\gamma\psi(2S)$

- Hadronic decays
- Radiative decays

New measurements
from BESIII & Belle.

Global fit to X(3872) decays

Chunhua Li and CZY, PRD 100, 094003 (2019)

Index (i)	Parameters	Values	Experiments
	$X(3872) \to \pi^+\pi^- J/\psi$	($\times 10^{-6}$)	
1	$B^+ \to X(3872)K^+$	$8.61 \pm 0.82 \pm 0.52$	Belle [14]
2		$8.4 \pm 1.5 \pm 0.7$	BaBar [15]
3	$B^0 \to X(3872)K^0$	$4.3 \pm 1.2 \pm 0.4$	Belle [14]
4		$3.5 \pm 1.9 \pm 0.4$	BaBar [15]
	$X(3872) \to \gamma J/\psi$	($\times 10^{-6}$)	
5	$B^+ \to X(3872)K^+$	$1.78^{+0.48}_{-0.44} \pm 0.12$	Belle [22]
6		$2.8 \pm 0.8 \pm 0.1$	BaBar [23]
7	$B^0 \to X(3872)K^0$	$1.24^{+0.76}_{-0.61} \pm 0.11$	Belle [22]
8		$2.6 \pm 1.8 \pm 0.2$	BaBar [23]
	$X(3872) \to \gamma\psi(3686)$	($\times 10^{-6}$)	
9	$B^+ \to X(3872)K^+$	$0.83^{+1.98}_{-1.83} \pm 0.44$	Belle [22]
10		$9.5 \pm 2.7 \pm 0.6$	BaBar [23]
11	$B^0 \to X(3872)K^0$	$1.12^{+3.57}_{-2.90} \pm 0.57$	Belle [22]
12		$11.4 \pm 5.5 \pm 1.0$	BaBar [23]
	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	($\times 10^{-4}$)	
13	$B^+ \to X(3872)K^+$	$0.77 \pm 0.16 \pm 0.10$	Belle [16]
14		$1.67 \pm 0.36 \pm 0.47$	BaBar [17]
15	$B^0 \to X(3872)K^0$	$0.97 \pm 0.46 \pm 0.13$	Belle [16]
16		$2.22 \pm 1.05 \pm 0.42$	BaBar [17]
	$X(3872) \to \omega J/\psi$	($\times 10^{-6}$)	
17	$B^+ \to X(3872)K^+$	$6 \pm 2 \pm 1$	BaBar [18]
18	$B^0 \to X(3872)K^0$	$6 \pm 3 \pm 1$	BaBar [18]
	Ratios		
19	$\frac{\mathcal{B}(X(3872)\to\gamma J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	0.79 ± 0.28	BESIII [19]
20	$\frac{\mathcal{B}(X(3872)\to D^{*0}D^0+c.c.)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	14.81 ± 3.80	BESIII [19]
21	$\frac{\mathcal{B}(X(3872)\to\omega J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$1.6^{+0.4}_{-0.3} \pm 0.2$	BESIII [20]
22	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$0.88^{+0.33}_{-0.27} \pm 0.10$	BESIII [21]
23	$\frac{\mathcal{B}(X(3872)\to\gamma\psi(3686))}{\mathcal{B}(X(3872)\to\gamma J/\psi)}$	$2.46 \pm 0.64 \pm 0.29$	LHCb [24]
	$B^+ \to X(3872)K^+$	($\times 10^{-4}$)	
24		$2.1 \pm 0.6 \pm 0.3$	BaBar [27]
25		$1.2 \pm 1.1 \pm 0.1$	Belle [26]

$$\chi^2(x) = \sum_{i=1}^{25} \frac{(x_i - x)^2}{\sigma_i^2}$$

Parameter index	Decay mode	Branching fraction
1	$X(3872) \to \pi^+\pi^- J/\psi$	$(4.1^{+1.9}_{-1.1})\%$
2	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	$(52.4^{+25.3}_{-14.3})\%$
3	$X(3872) \to \gamma J/\psi$	$(1.1^{+0.6}_{-0.3})\%$
4	$X(3872) \to \gamma\psi(3686)$	$(2.4^{+1.3}_{-0.8})\%$
5	$X(3872) \to \pi^0\chi_{c1}$	$(3.6^{+2.2}_{-1.6})\%$
6	$X(3872) \to \omega J/\psi$	$(4.4^{+2.3}_{-1.3})\%$
7	$B^+ \to X(3872)K^+$	$(1.9 \pm 0.6) \times 10^{-4}$
8	$B^0 \to X(3872)K^0$	$(1.1^{+0.5}_{-0.4}) \times 10^{-4}$
	$X(3872) \to$ unknown	$(31.9^{+18.1}_{-31.5})\%$

Parameter index	1	2	3	4	5	6	7	8
1	1	0.87	0.84	0.75	0.64	0.79	-0.95	-0.87
2		1	0.79	0.71	0.56	0.74	-0.90	-0.77
3			1	0.78	0.54	0.73	-0.88	-0.78
4				1	0.49	0.65	-0.79	-0.69
5					1	0.51	-0.61	-0.56
6						1	-0.82	-0.72
7							1	0.84

Chunhua Li and CZY, PRD 100, 094003 (2019)

X(3872) decay BFs

A global fit to BaBar/Belle/LHCb/BESIII data (χ^2/ndf=25/17):

- $B(X(3872) \to \pi^+\pi^- J/\psi) = (4.1^{+1.9}_{-1.1})\%$
- $B(X(3872) \to \omega J/\psi) = (4.4^{+2.3}_{-1.3})\%$
- $B(X(3872) \to \gamma J/\psi) = (1.1^{+0.6}_{-0.3})\%$
- $B(X(3872) \to D^{*0}\bar{D}^0 + c.c.) = (52^{+25}_{-14})\%$
- $B(X(3872) \to \pi^0\chi_{c1}) = (3.6^{+2.2}_{-1.6})\%$
- $\underline{B(X(3872) \to unknown) = (32^{+18}_{-32})\%}$

$\sigma(e^+e^- \to \gamma X(3872), X \to \pi^+\pi^- J/\psi)$=(0.29±0.11) pb @ 4.226 GeV

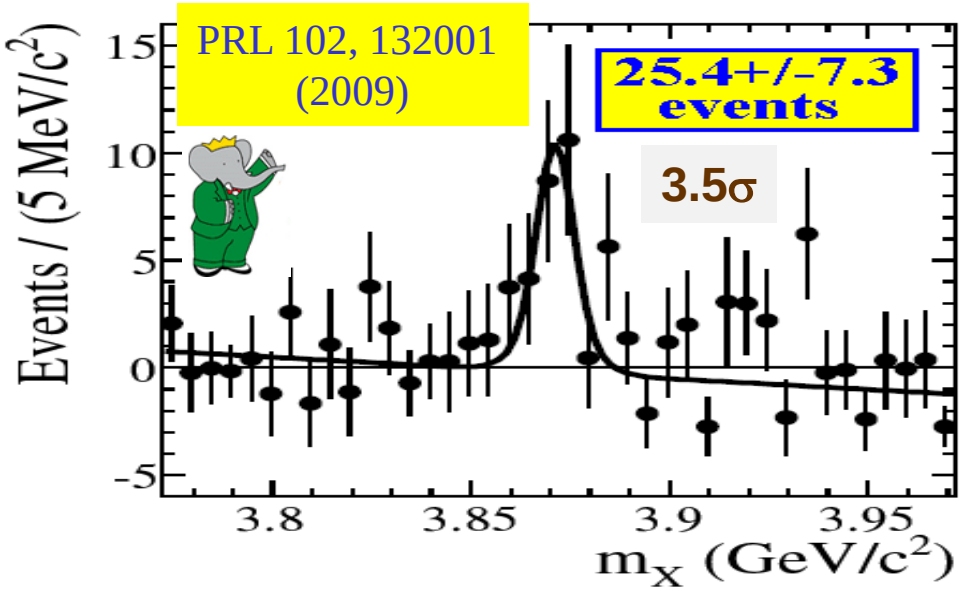
BESIII

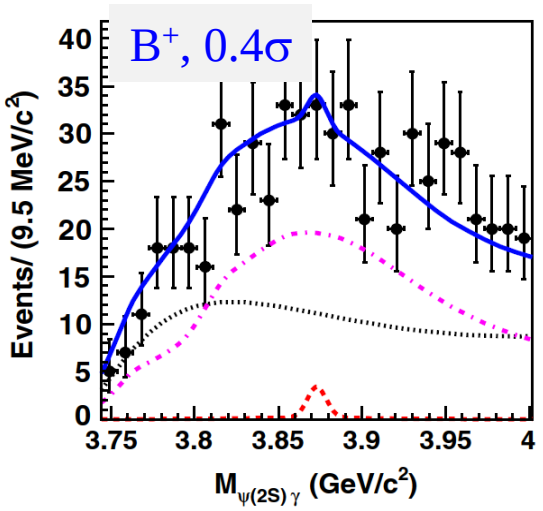
$\sigma(e^+e^- \to \gamma X(3872)) = (5.5^{+2.8}_{-3.6})$ pb @ 4.226 GeV

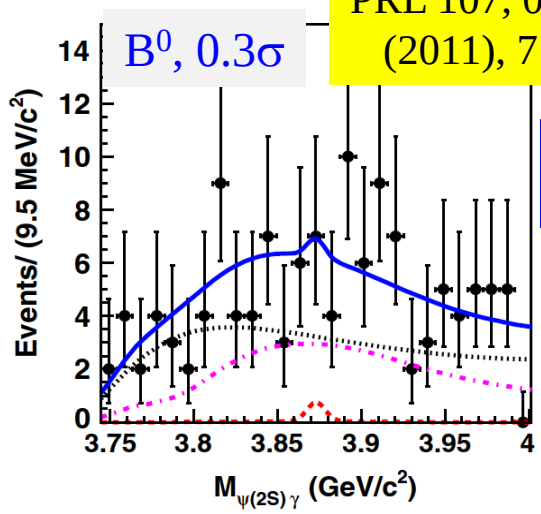
$\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ = (85.1±5.1) pb @ 4.226 GeV

X(3872) → γψ(2S) puzzle

PRL 102, 132001 (2009)

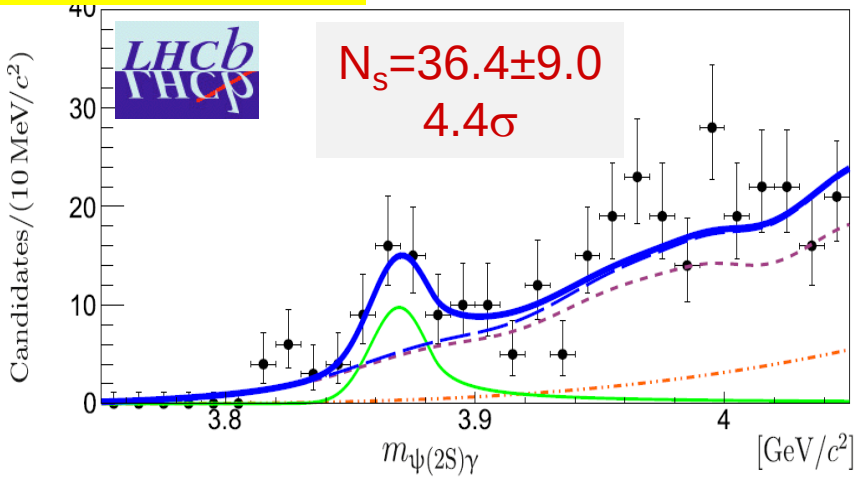




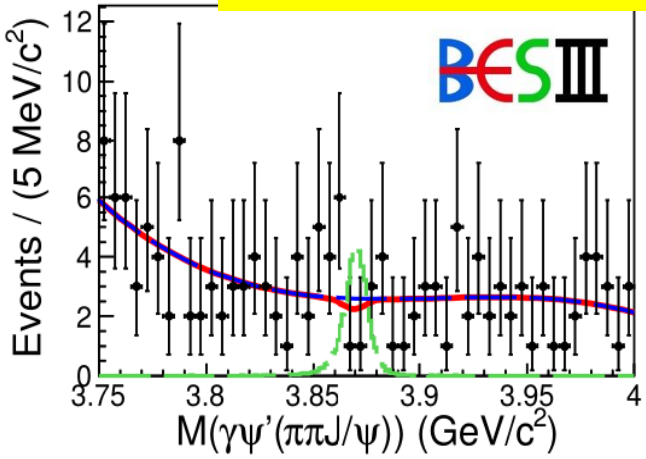


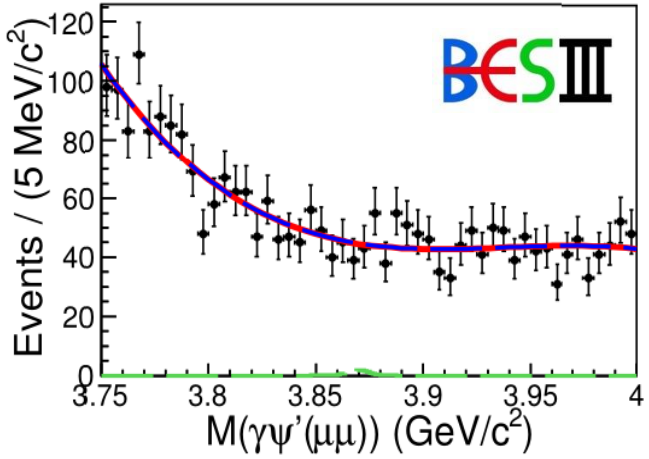
PRL 107, 091803 (2011), 711/fb

NPB 886 (2014) 665, 3/fb



PRL124, 242001 (2020)





It is still not clear if X(3872)→γψ(2S) exists or not!

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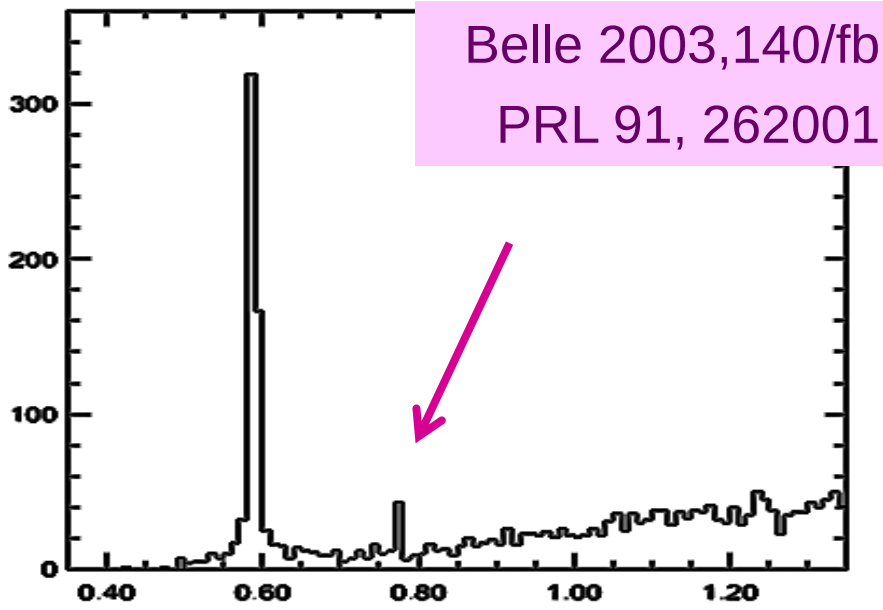
What is the X(3872)?

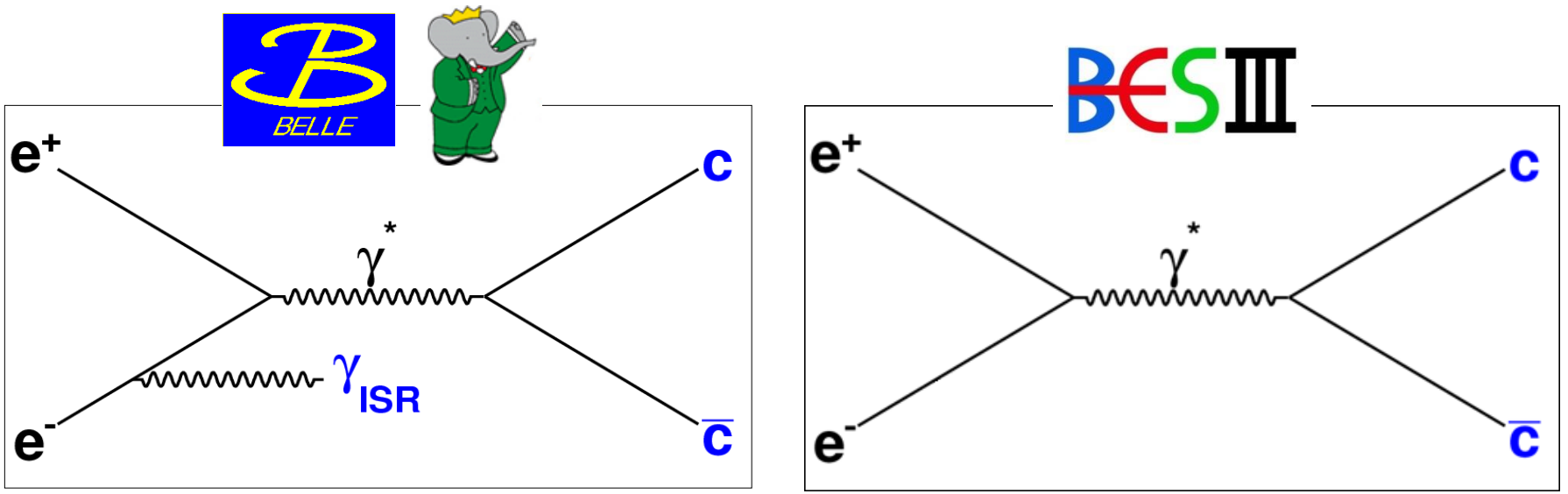
- Mass: Very close to $\bar{D}^0D^{*0}$ threshold
- Width: Very narrow!
- $I^G(J^{PC})=0^+(1^{++})$ [➔ $\chi_{c1}(3872)$ by PDG]
- Production
  - in $\bar{p}p$/pp/PbPb collision, multiplicity dependence
  - In B, B_s, Λ_b decays
  - e^+e^-→γ+X(3872), $\gamma\gamma^*$→X(3872)
- Decay BFs: open charm ~1/2, charmonium~O(%)
  - ~1/3 decays missing
  - $\gamma\psi(2S)$ needs confirmation
- Nature (very likely exotic, theoretical efforts needed)
  - Loosely $\bar{D}^0D^{*0}$ bound state (like deuteron)?
  - Mixture of excited χ_{c1} and $\bar{D}^0D^{*0}$ bound state?
  - Many other possibilities (if it is not χ'_{c1}, where is χ'_{c1}?)



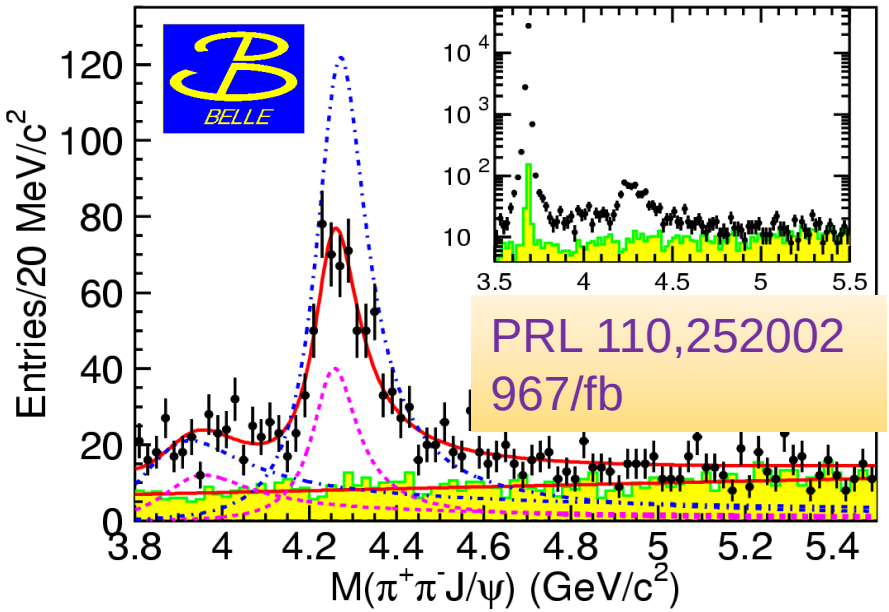
Still mind-boggling (crazy) after all these years!

The Y(4660):

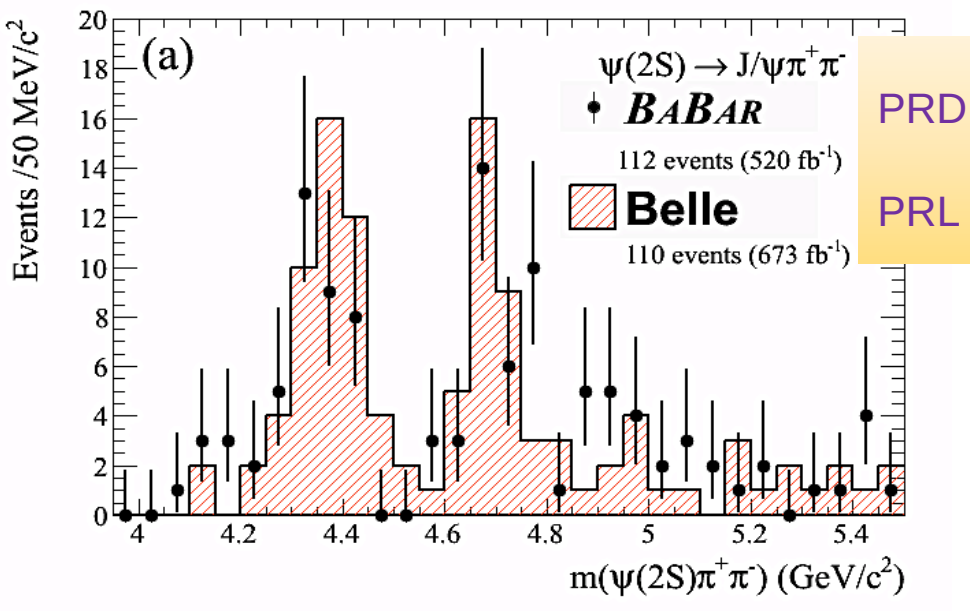
charmonium, $f_0(980)\psi(2S)$, or $\Lambda^+_c\Lambda^-_c$ molecule?



The Y states were discovered via ISR

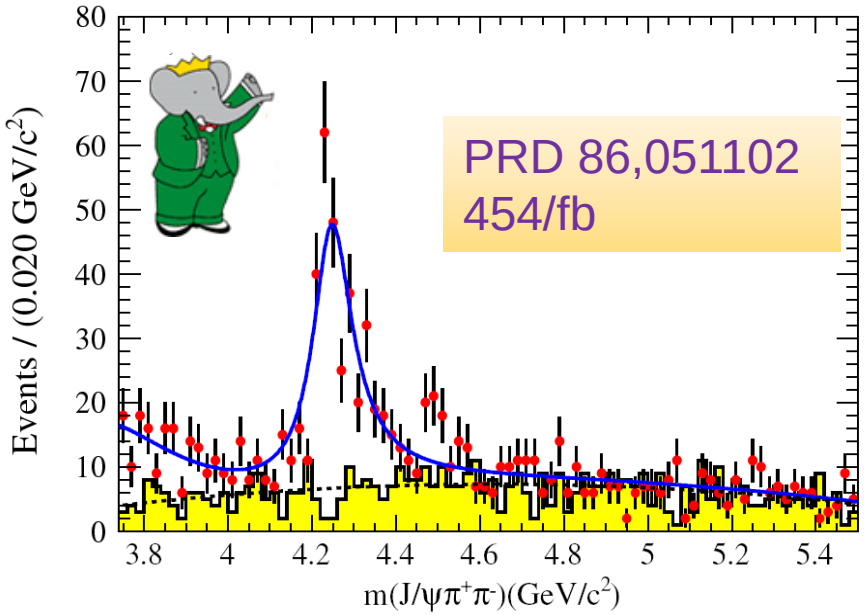


PRL 110,252002
967/fb

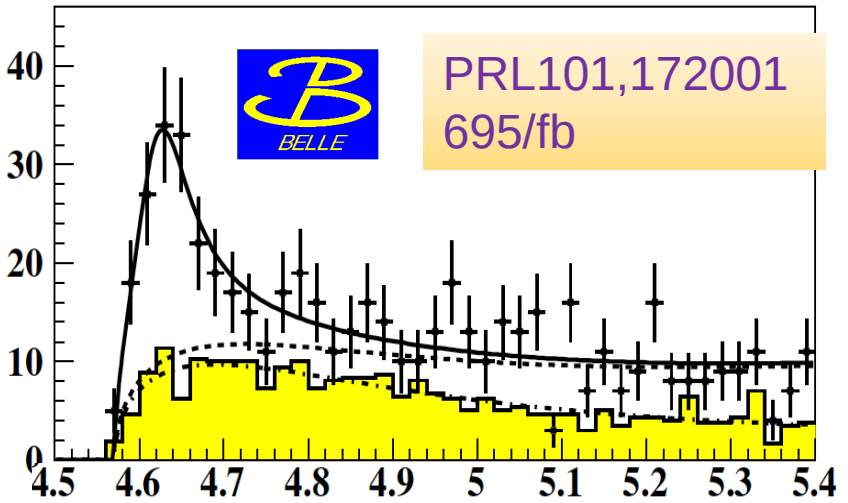


PRD 89, 111103 (2014)

PRL 99,142002 (2007)



PRD 86,051102
454/fb



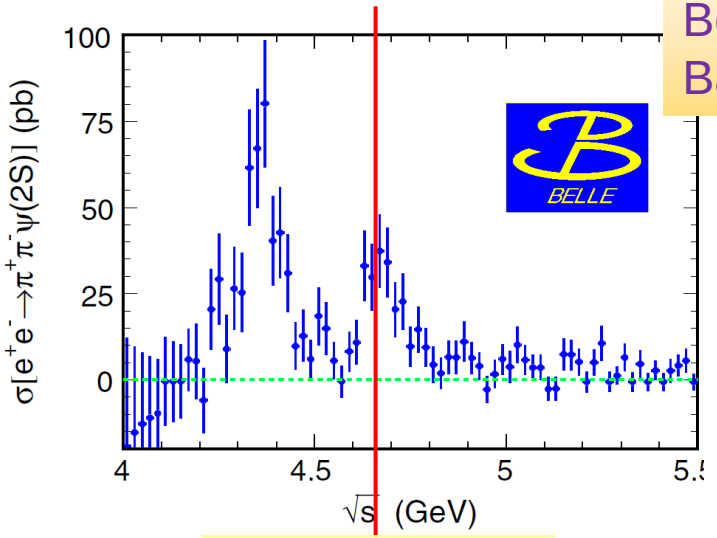
PRL101,172001
695/fb

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

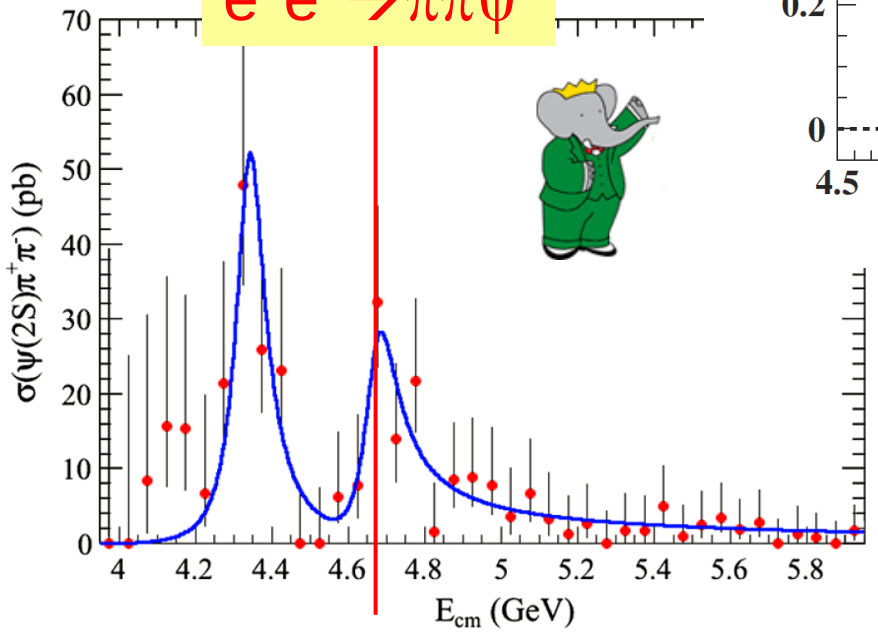
Y(4630)=Y(4660)? Are there other decay modes?

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

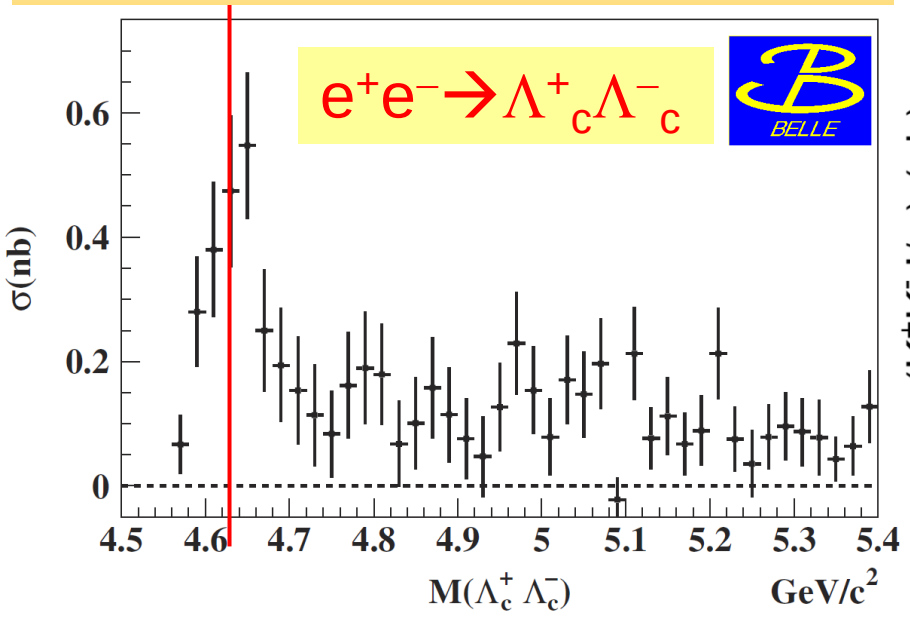


$e^+e^-\to\pi\pi\psi'$



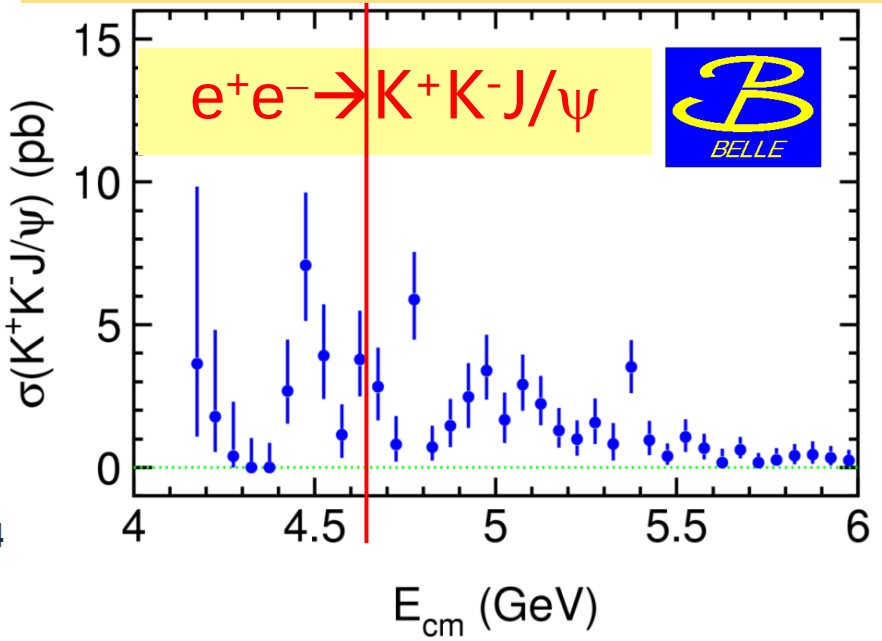
Belle: PRL101, 172001 (2008), 695/fb

$e^+e^-\to\Lambda_c^+\Lambda_c^-$



Belle: PRD89, 072015 (2014), 980/fb

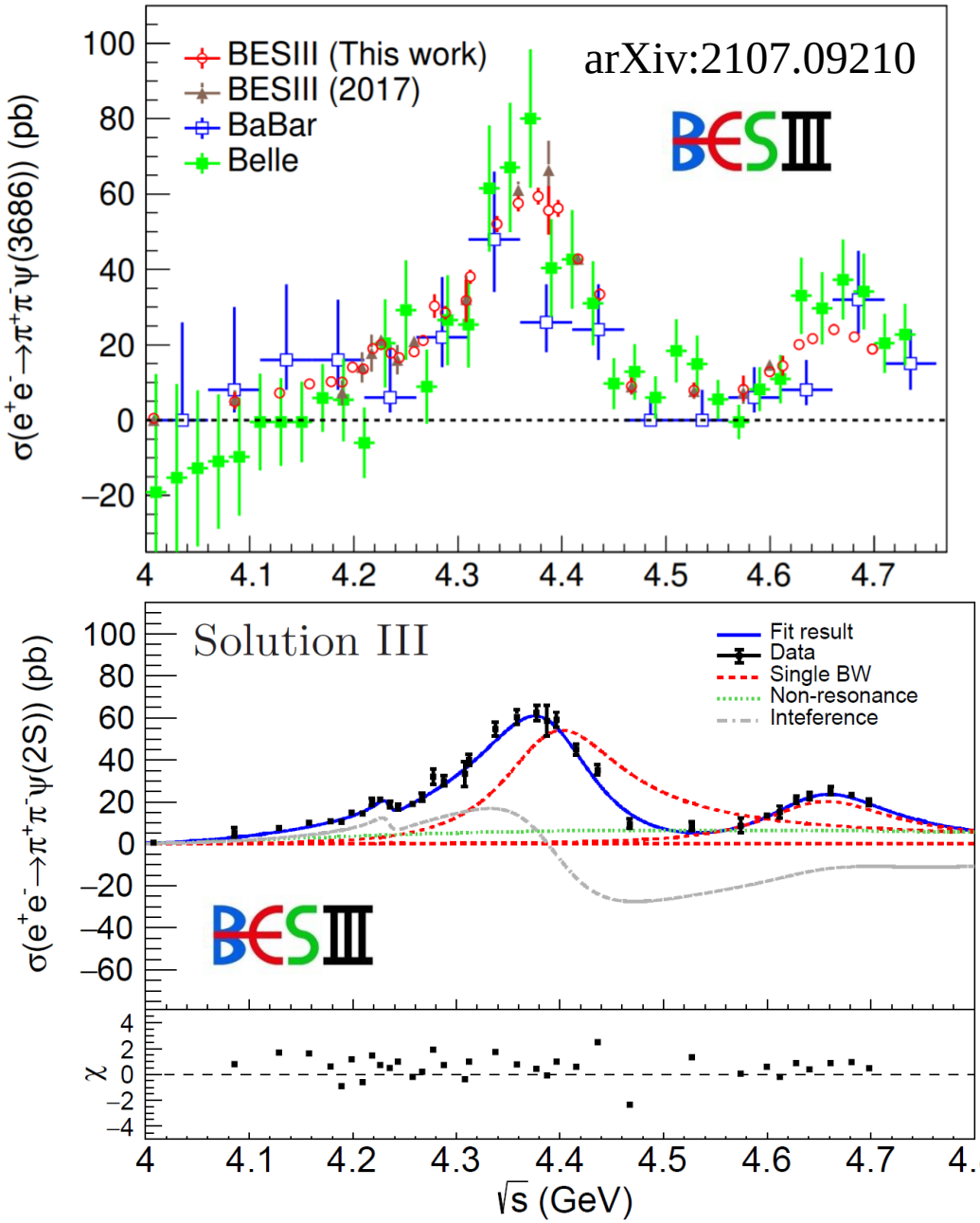
$e^+e^-\to K^+K^-J/\psi$



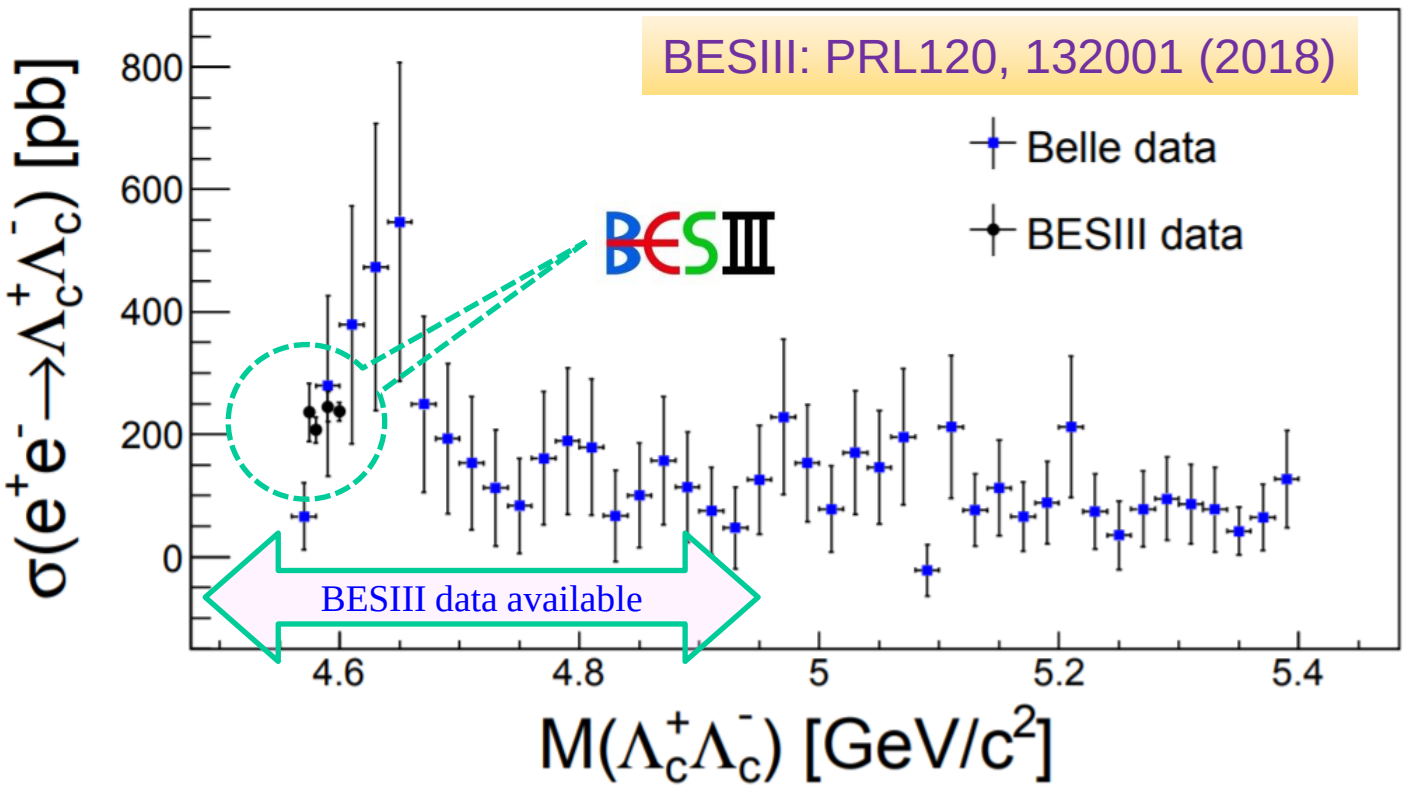
Experiment	Mass (MeV)	Width (MeV)
Belle, $\Lambda_c^+\Lambda_c^-$	$4634^{+8}_{-7}{}^{+5}_{-8}$	$92^{+40}_{-24}{}^{+10}_{-21}$
Belle, $\pi\pi\psi'$	$4652\pm10\pm8$	$68\pm11\pm1$
BaBar, $\pi\pi\psi'$	$4669\pm21\pm3$	$104\pm48\pm10$

Recent measurements

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



$e^+e^- \to \Lambda_c^+\Lambda_c^-$



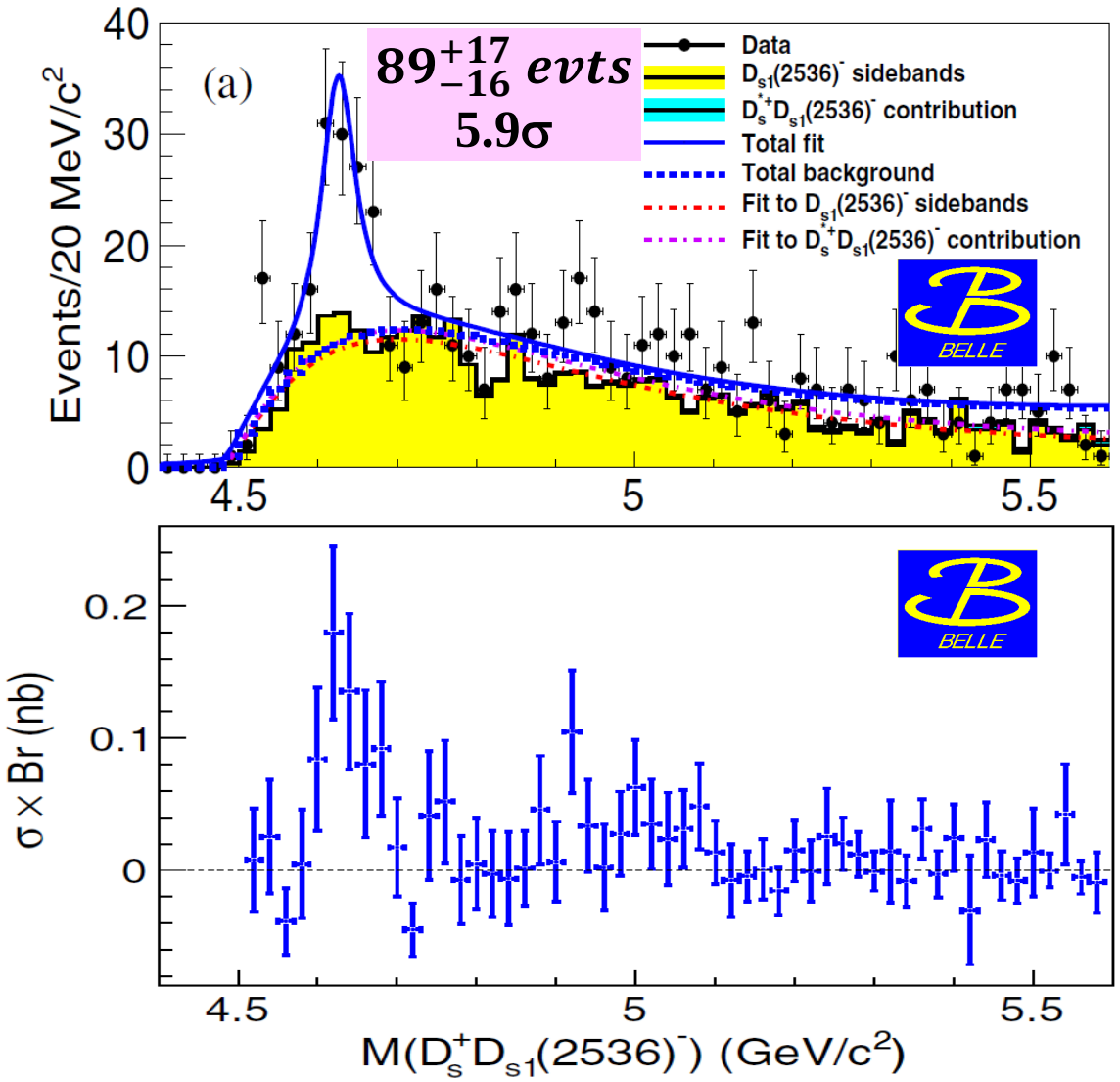
BESIII data confirmed Belle & BaBar measurements with much improved precision!

BESIII has data now covering from threshold to 4.95 GeV, comparable precision as at 4.6 GeV is expected!

Recent measurements

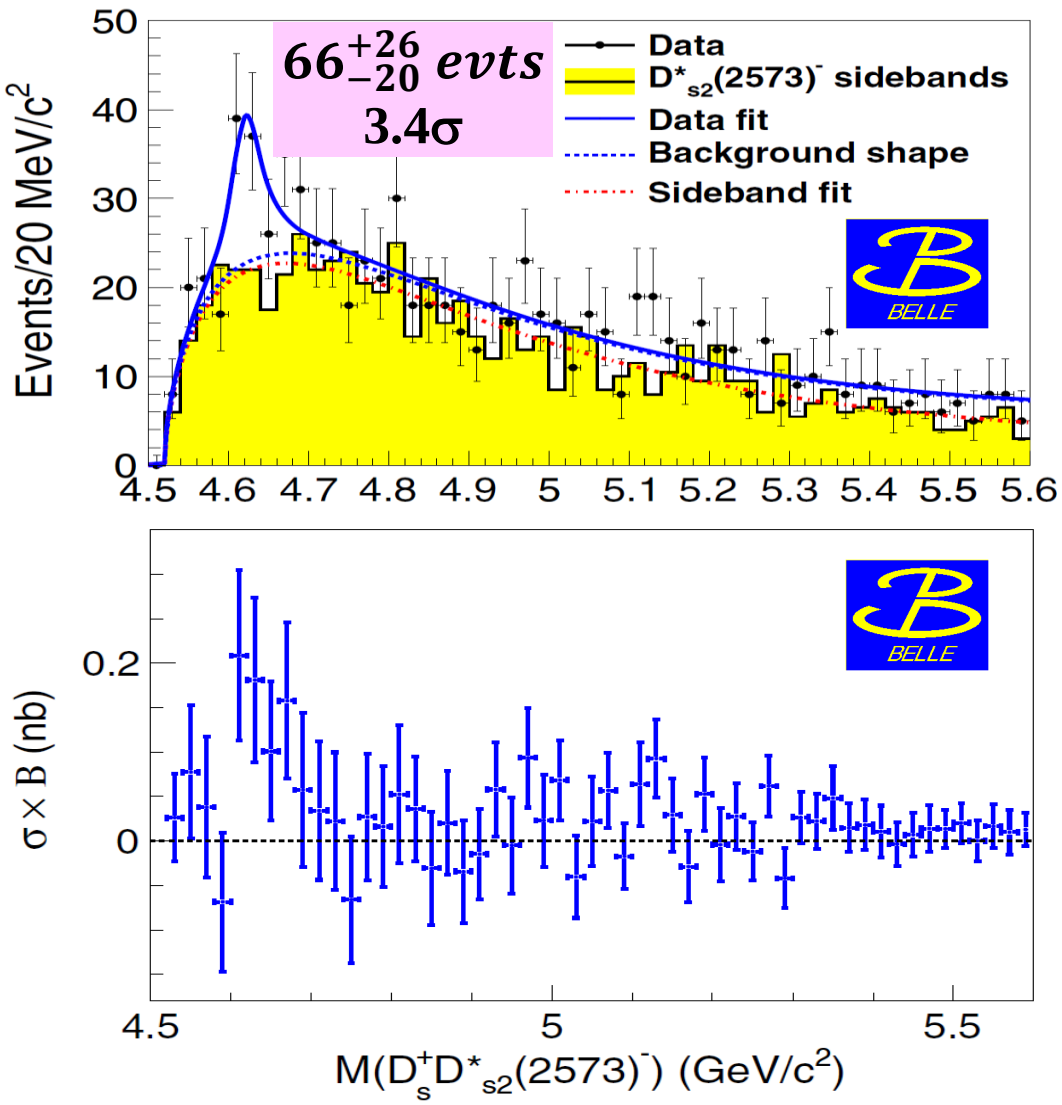
PRD 100, 111103 (2019)

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



PRD 101, 091101 (2020)

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

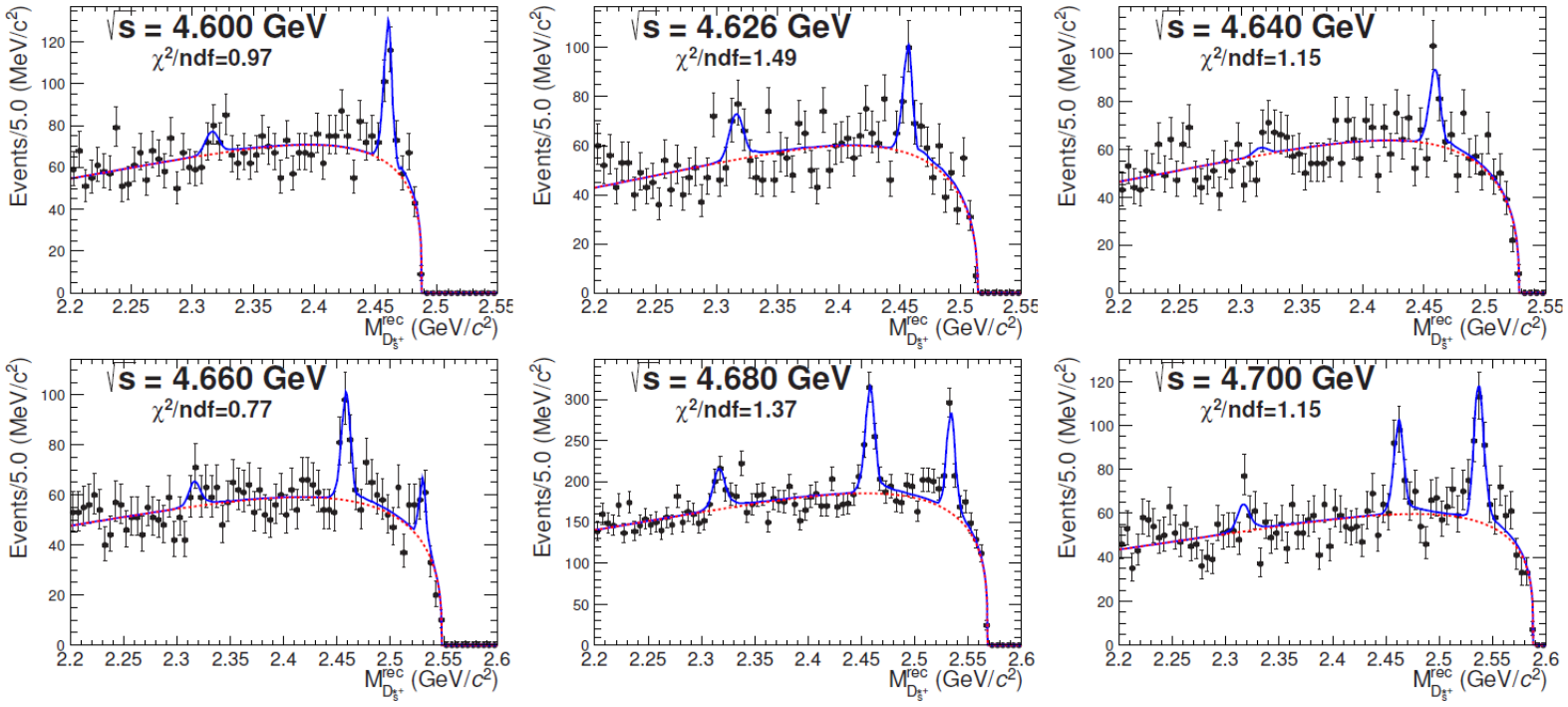


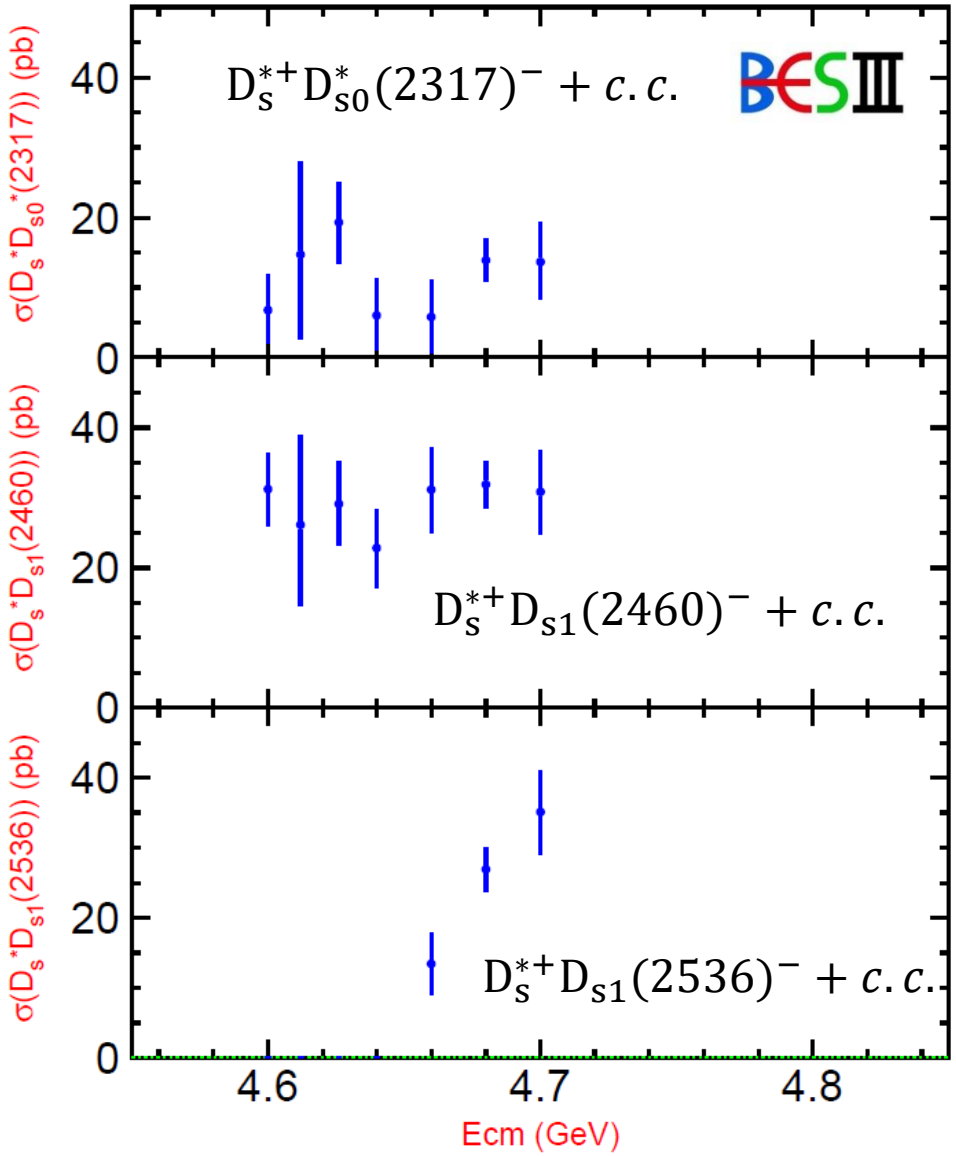
BESIII has data from threshold to 4.95 GeV, improved measurements are expected!

arXiv: 2106.02298
PRD (in press)

Recent measurements

$e^+e^- \to D_s^{*+}D_{s0}^*(2317)^- + c.c.$
$D_s^{*+}D_{s1}(2460)^- + c.c.$
$D_s^{*+}D_{s1}(2536)^- + c.c.$



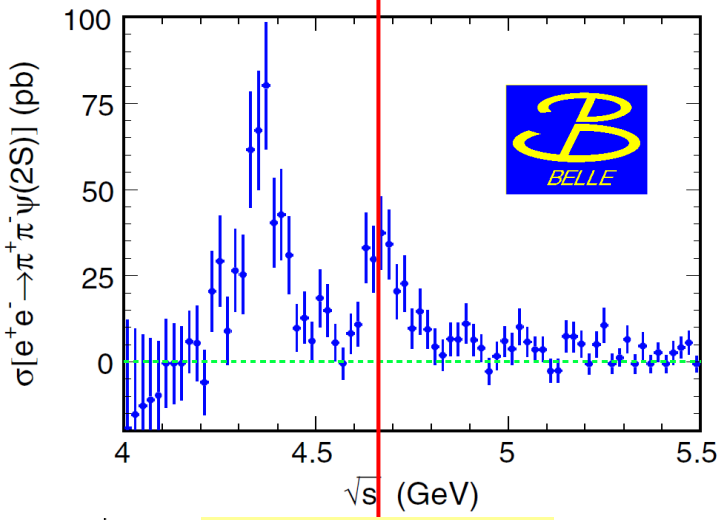


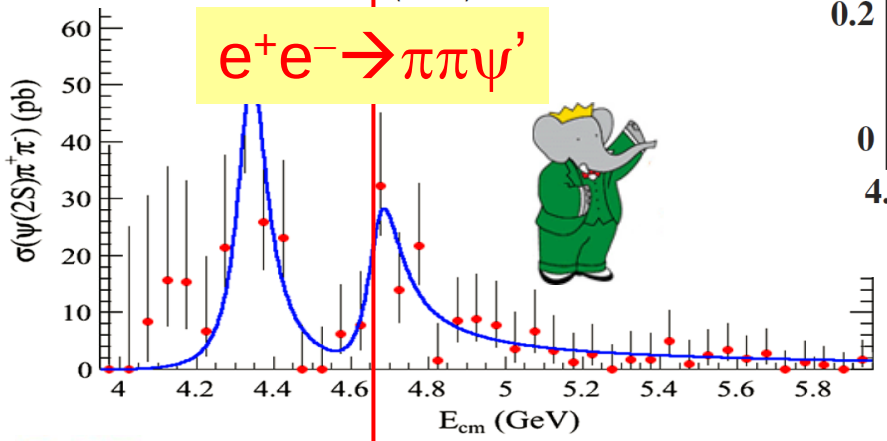
Clear $e^+e^- \to D_s^* D_{sJ}$ production between 4.6 and 4.7 GeV.

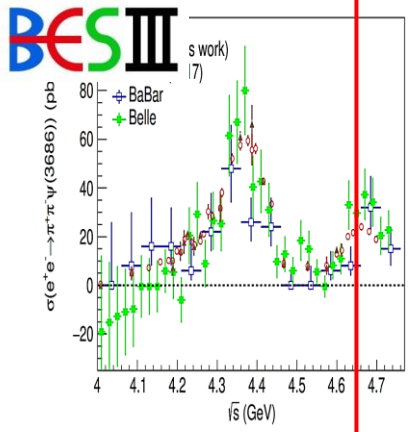
No significant Y(46xx)$\to D_s^* D_{sJ}$ signal

BESIII has data from threshold to 4.95 GeV, improved measurements are expected!

Y(4630)? Y(4660)?

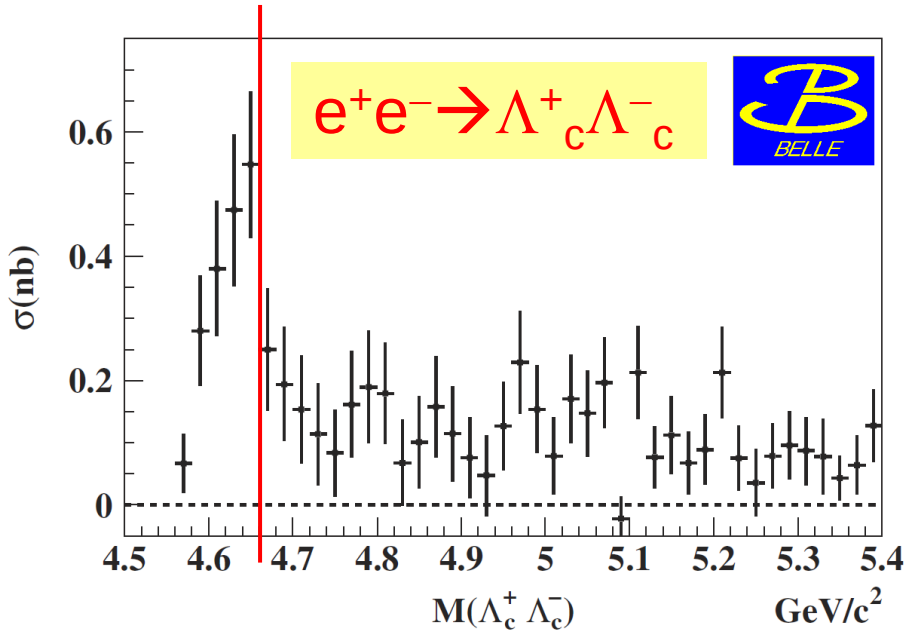


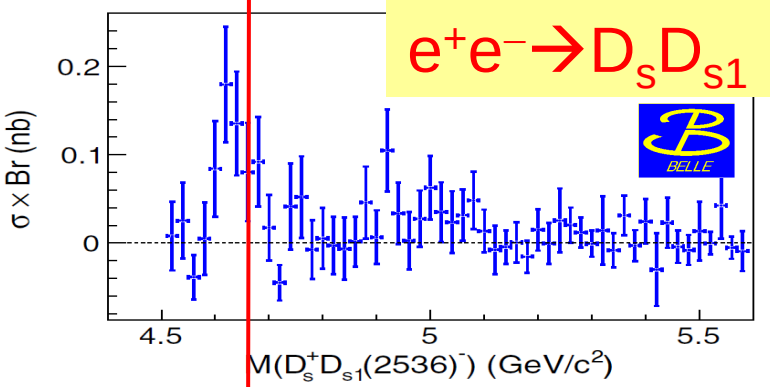


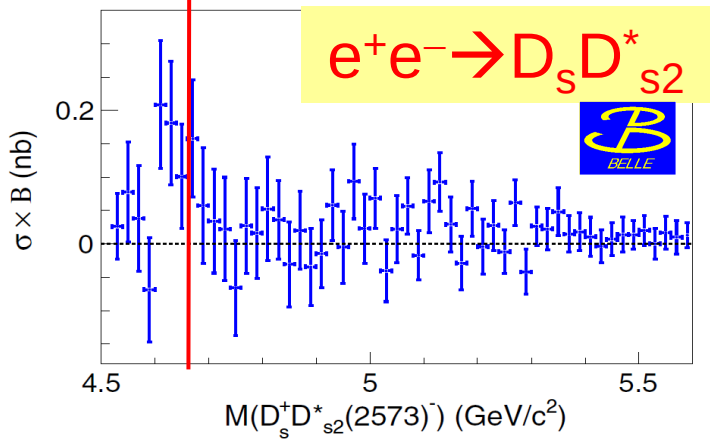


Tension between open charm & charmonium modes.

Parametrization affects the resonance parameters.

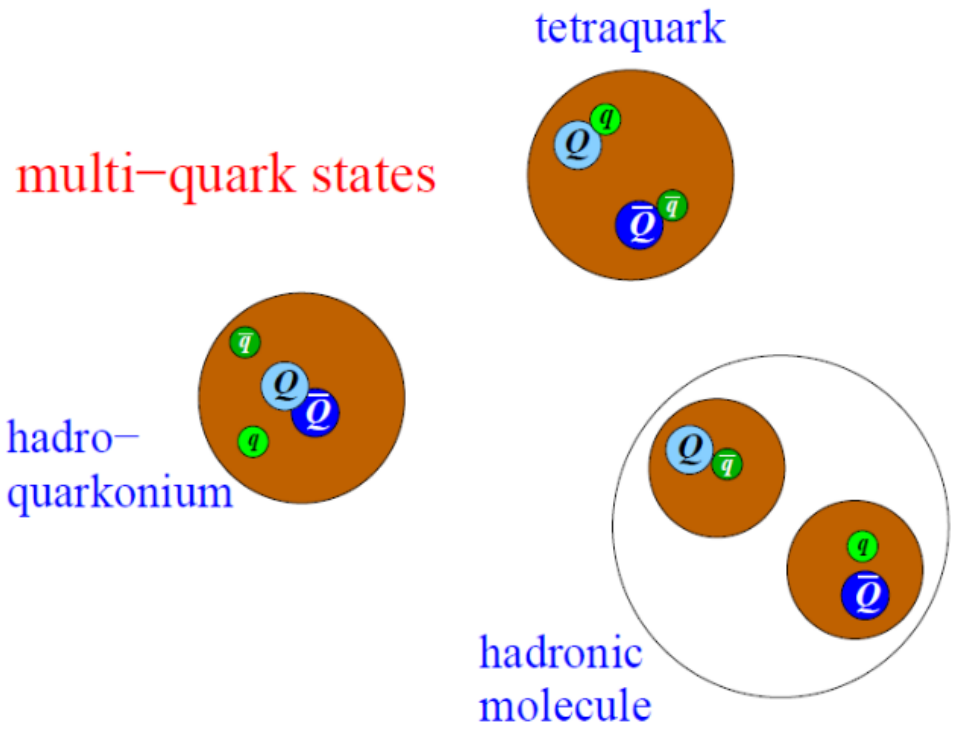




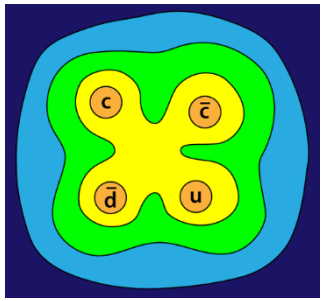


Experiment	Mass (MeV)	Width (MeV)
Belle, $\pi\pi\psi'$	$4652\pm10\pm8$	$68\pm11\pm1$
BaBar, $\pi\pi\psi'$	$4669\pm21\pm3$	$104\pm48\pm10$
BESIII, $\pi\pi\psi'$	$4651\pm38\pm2$	$155\pm25\pm1$
Belle, $\Lambda_c^+\Lambda_c^-$	$4634^{+8}_{-7}{}^{+5}_{-8}$	$92^{+40}_{-24}{}^{+10}_{-21}$
Belle, D_sD_{s1}	$4625.9^{+6.2}_{-6.0}\pm0.4$	$49.8^{+13.9}_{-11.5}\pm4.0$
Belle, $D_sD^*_{s2}$	$4619.8^{+8.9}_{-8.0}\pm2.3$	$47.0^{+31.3}_{-14.8}\pm4.6$

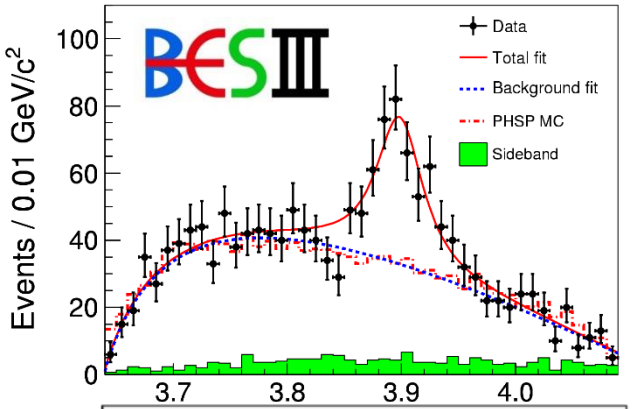
The Z_{cs} states

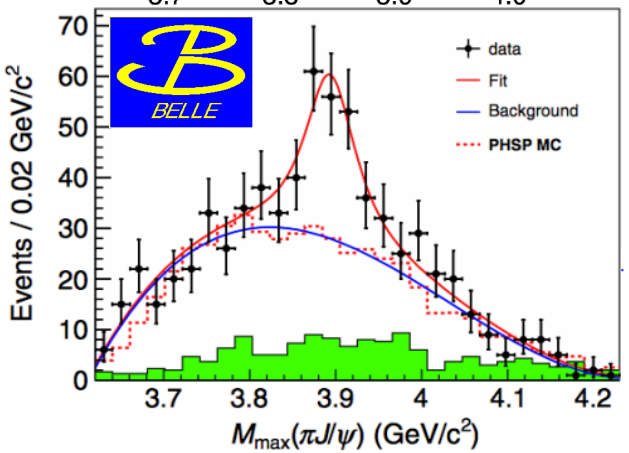


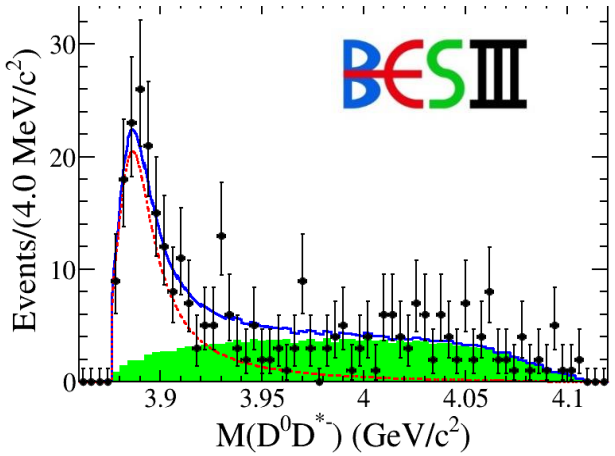
The famous Z_c states



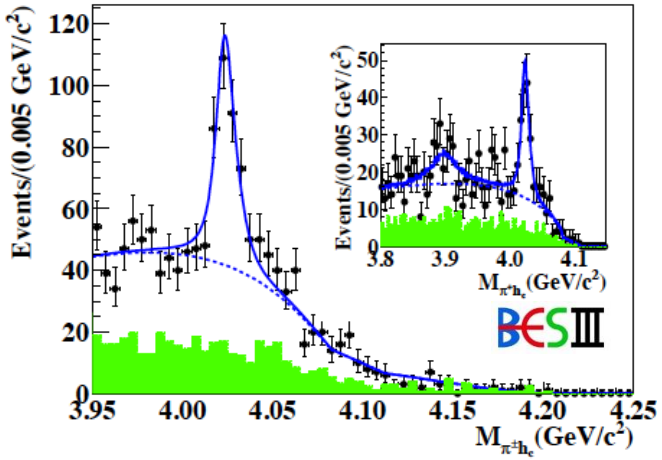
$Z_c(3900)$

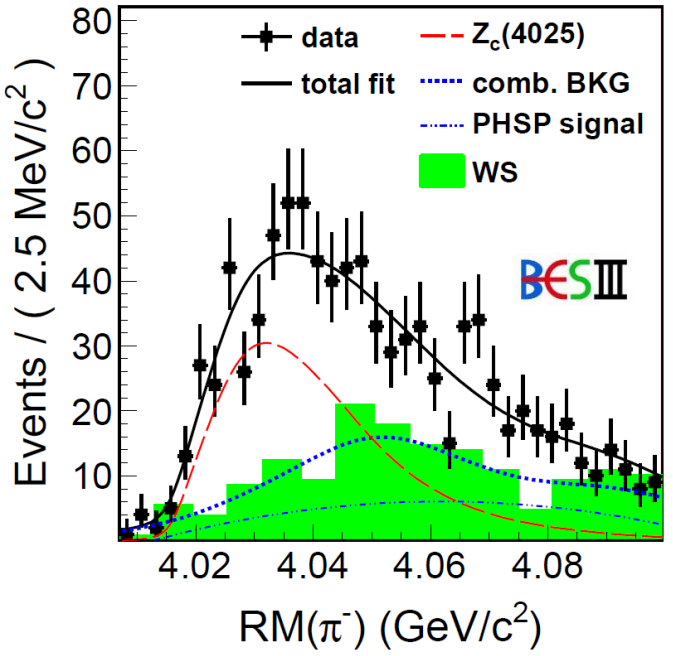




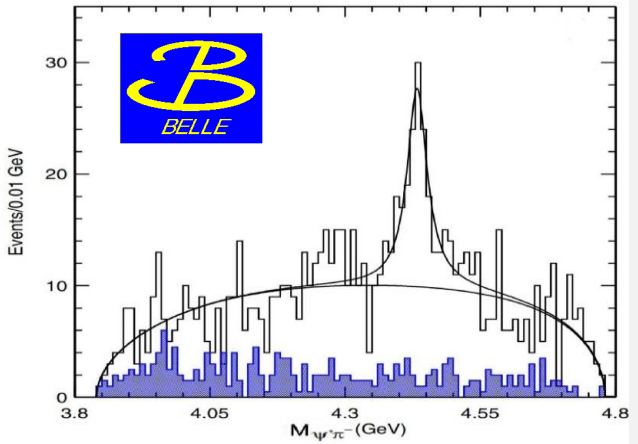


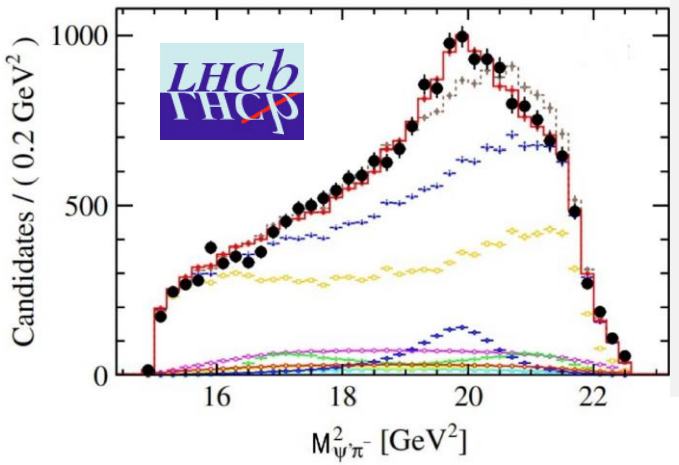
$Z_c(4020)$





$Z_c(4430)$



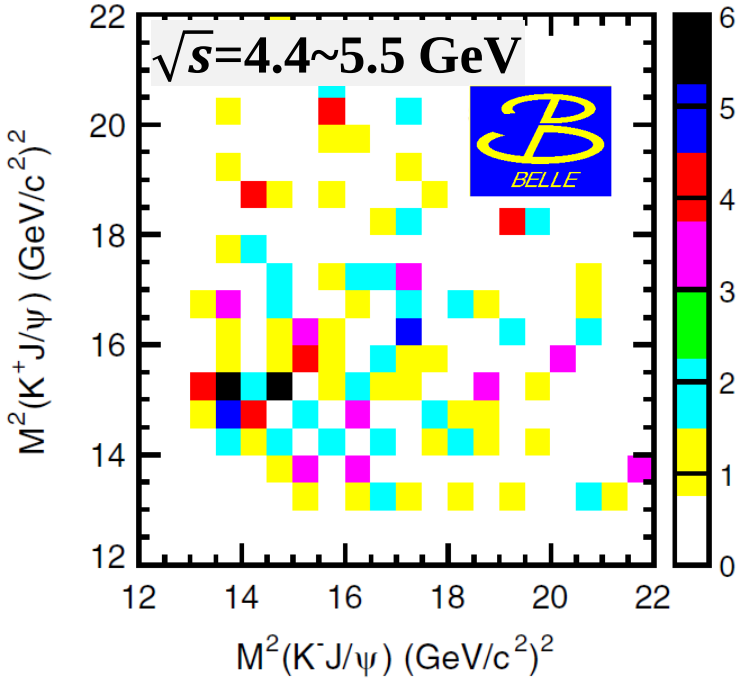


All are observed in π+charmonium (J/ψ, h_c, $\psi(2S)$) final states, candidate $\bar{c}\,c\,\bar{d}\,u$ tetraquark states

➔ Existence of states with d→s?

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

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

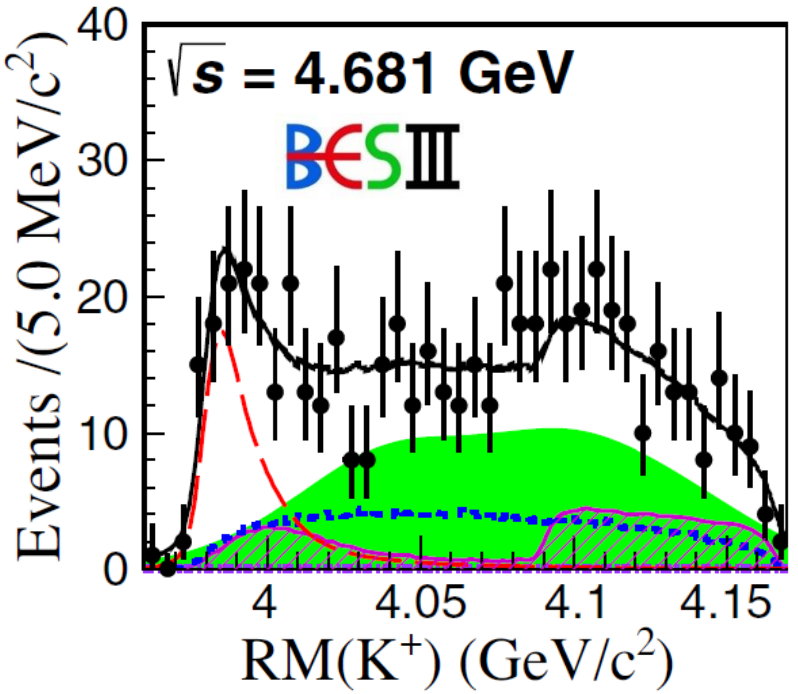


PRD 89, 072015 (2014)

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

(statistics low!)

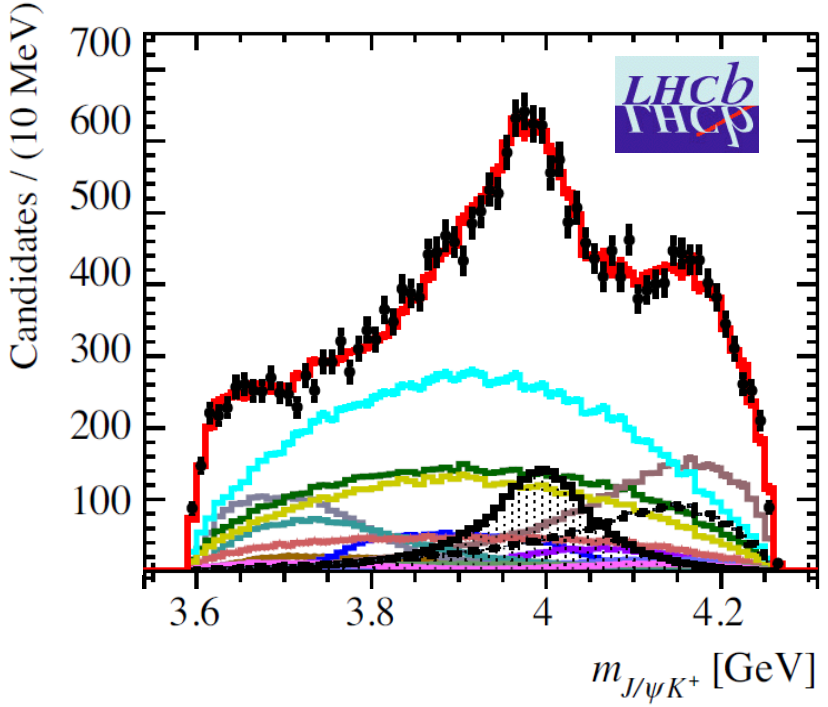
$e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$



PRL 126, 102001 (2021)

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

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



PRL 127, 082001 (2021)

$Z_{cs}(4000)$ 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+	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$
$Z_{cs}(4220)$	5.9σ	1+	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$

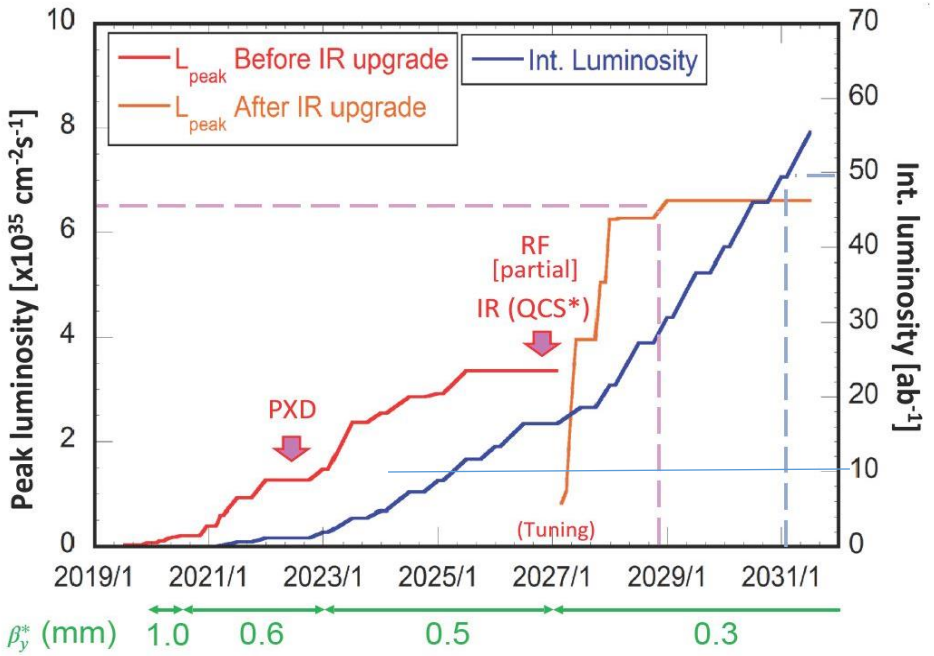
Widths very different, not the same state!

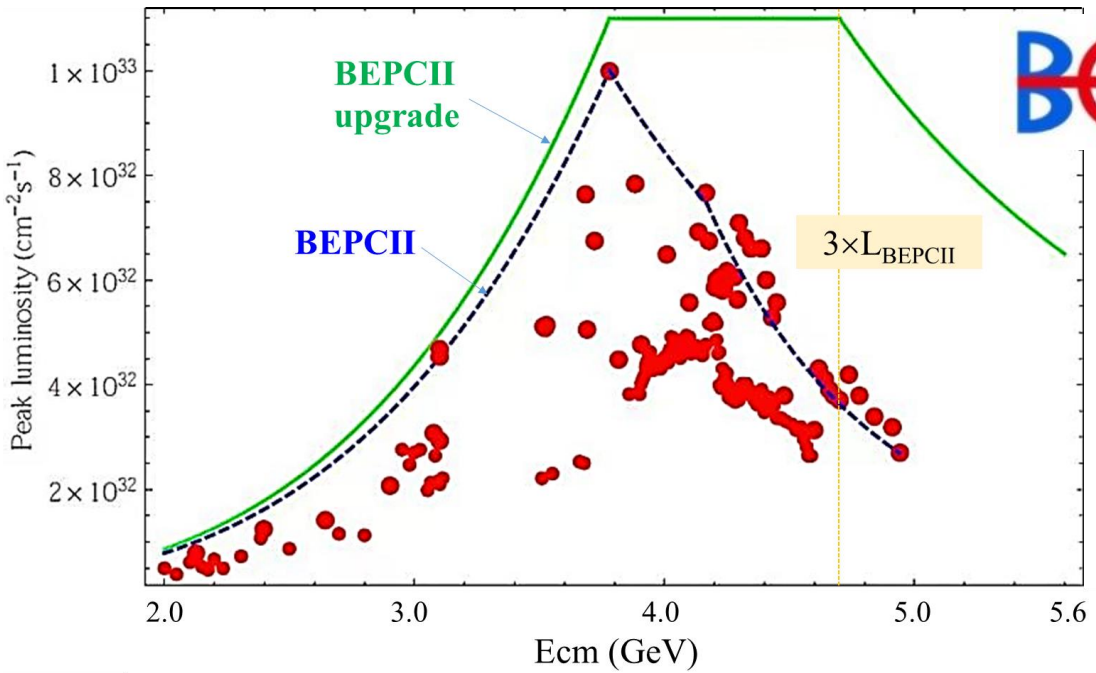
Waiting for BESIII result on $e^+e^- \to K^+K^-J/\psi$ from the same data sample!

Summary

- Lots of progress in the experimental study of the XYZ states.
- X(3872) width to be refined, still ~30% decays to be discovered
- More data available for the Y(4630)/Y(4660) states, still not clear whether they are the same
- Three Z_{cs}(xxxx) discovered, need confirmation
- More results to come, and lots of *Opportunities and Challenges* ahead

The near future





2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	203+
		Run III						Run IV					Run V	
LS2					LS3						LS4			
LHCb 40 MHz UPGRADE I		$L = 2 \times 10^{33}$			LHCb Consolidate: UPGRADE Ib			$L = 2 \times 10^{33}$ 50 fb^{-1}			LHCb UPGRADE II		L=1-2x 10^{34} 300 fb^{-1}	
ATLAS Phase I Upgr		$L = 2 \times 10^{34}$			ATLAS Phase II UPGRADE			HL-LHC $L = 5 \times 10^{34}$					HL-LHC $L = 5 \times 10^{34}$	
CMS Phase I Upgr		300 fb^{-1}			CMS Phase II UPGRADE								3000 fb^{-1}	

Thank you very much! Большое спасибо!