New experimental results on light and heavy hadrons

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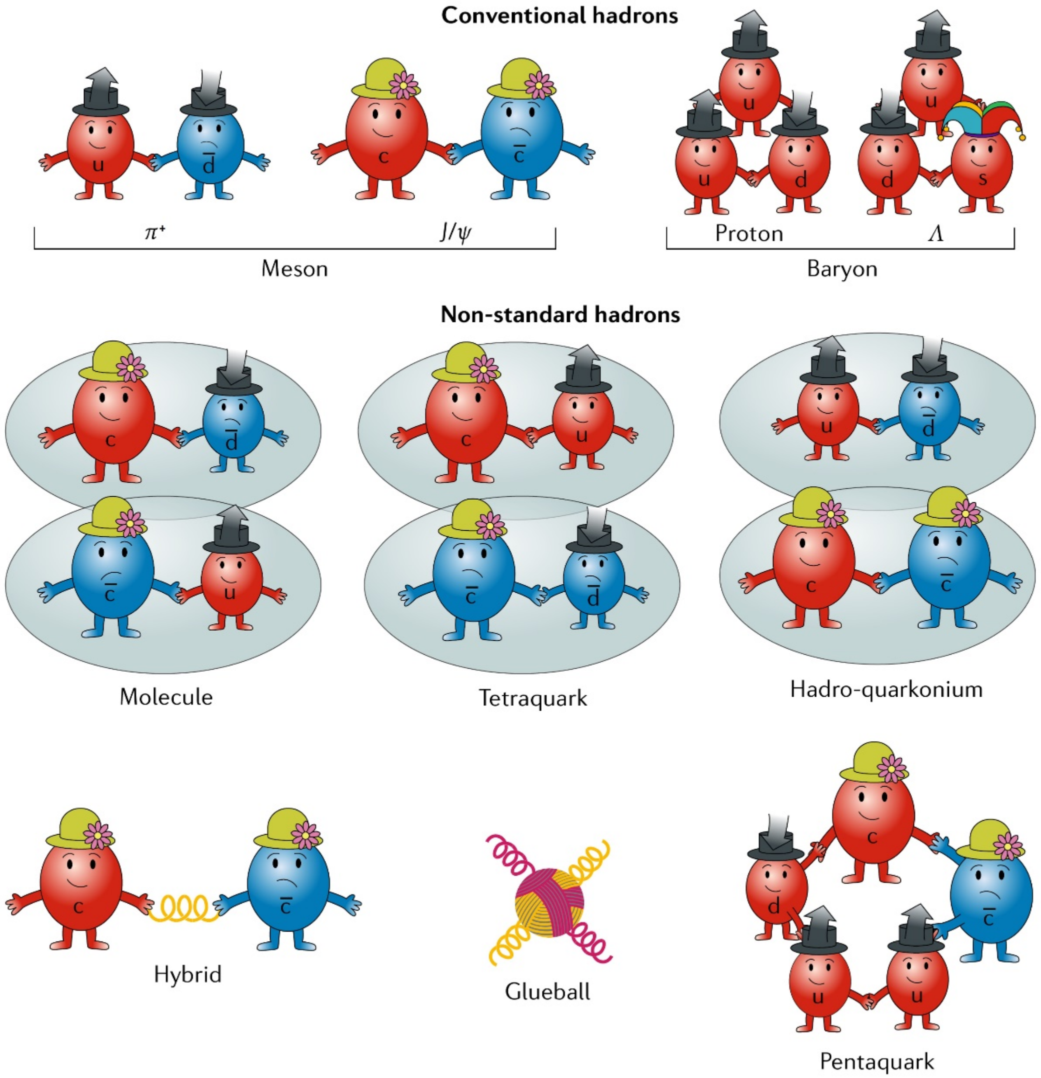
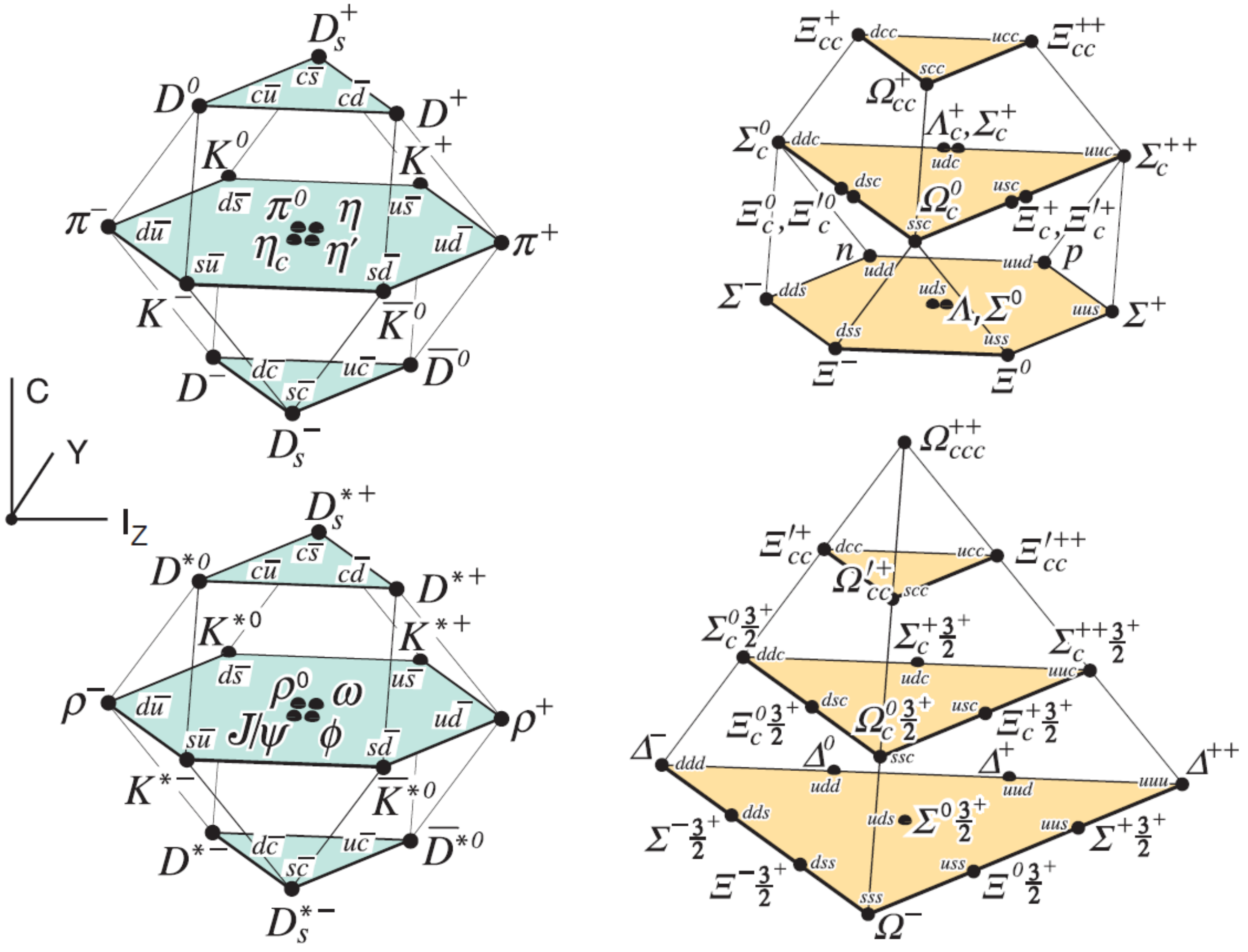
Hadrons: conventional & exotic

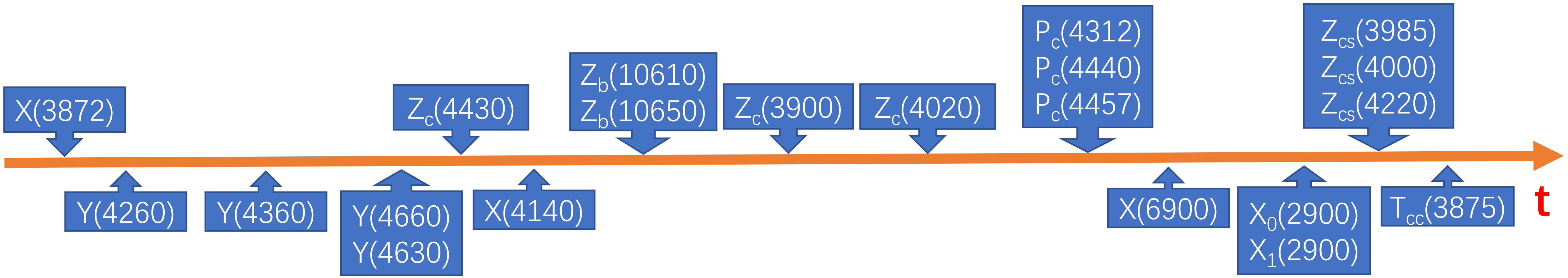




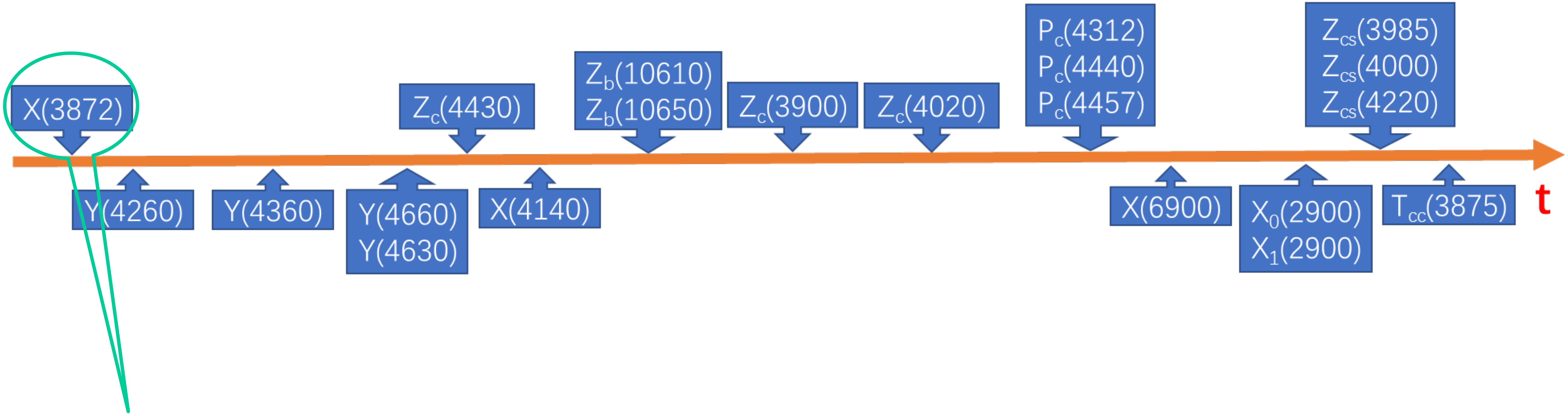
SU(4) multiplets of mesons & baryons

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

Lots of states with heavy quarks observed since the discovery of the X(3872) in 2003!



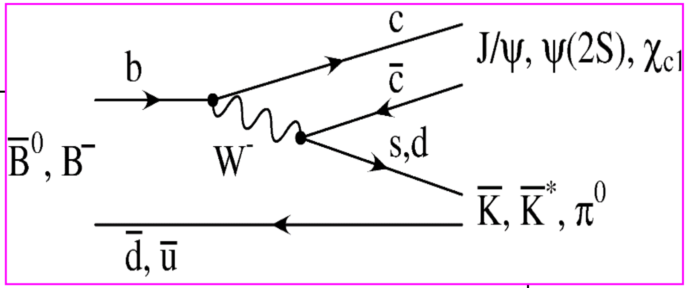
New spectrum emerges although more effort is needed to understand the nature of them.

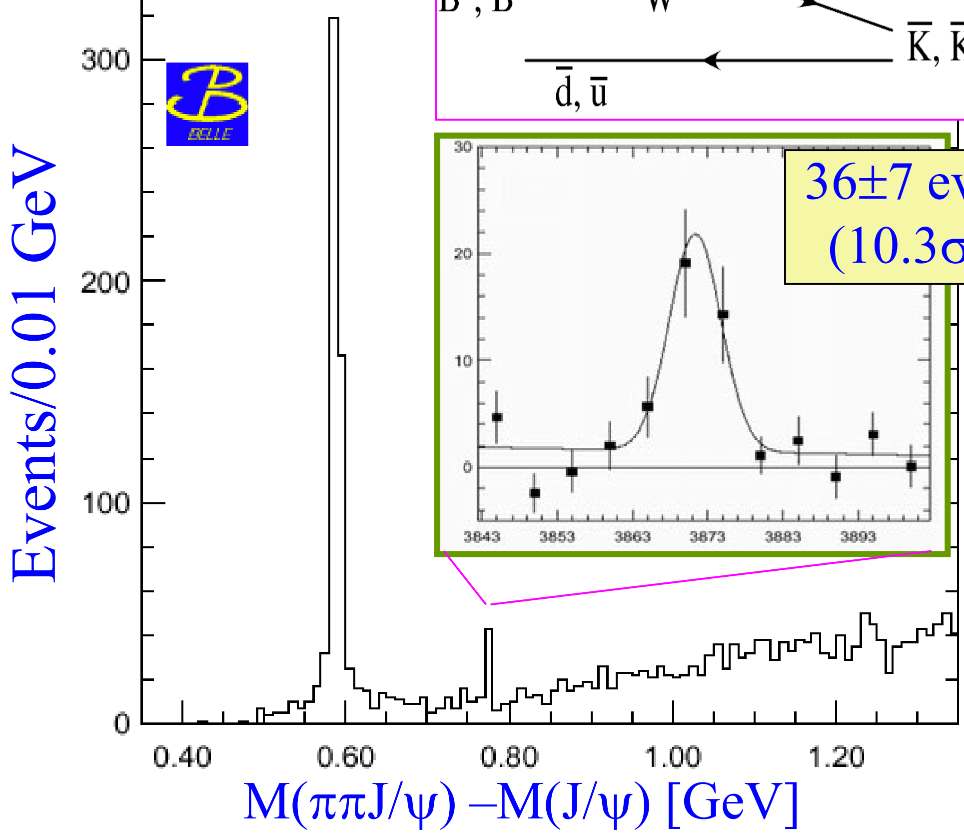


how many efforts must we make before we understand a particle?

Discovery of the X(3872)

Belle, 2003
PRL91, 262001

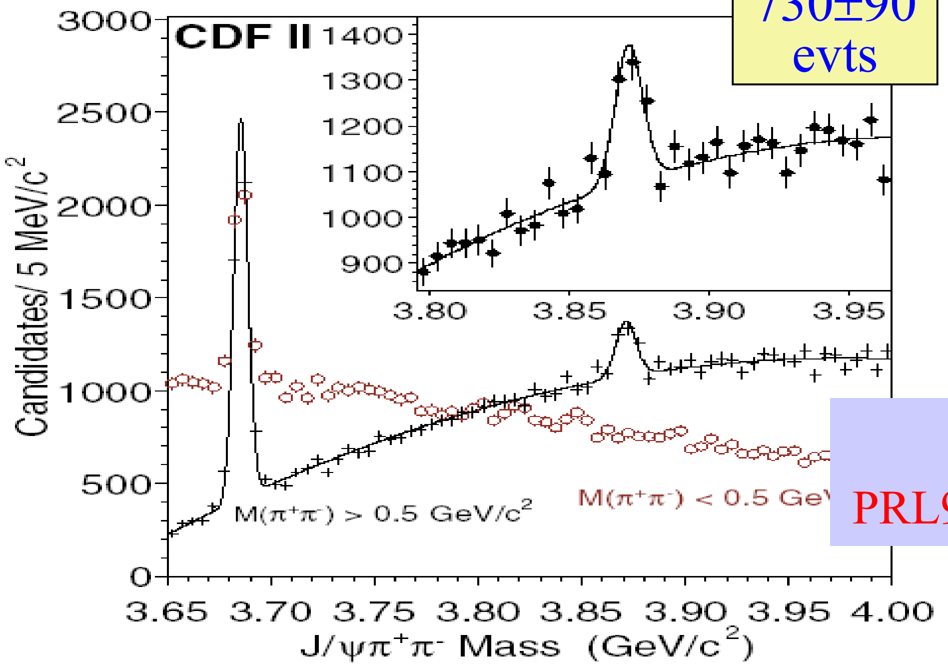




36±7 evts
(10.3σ)

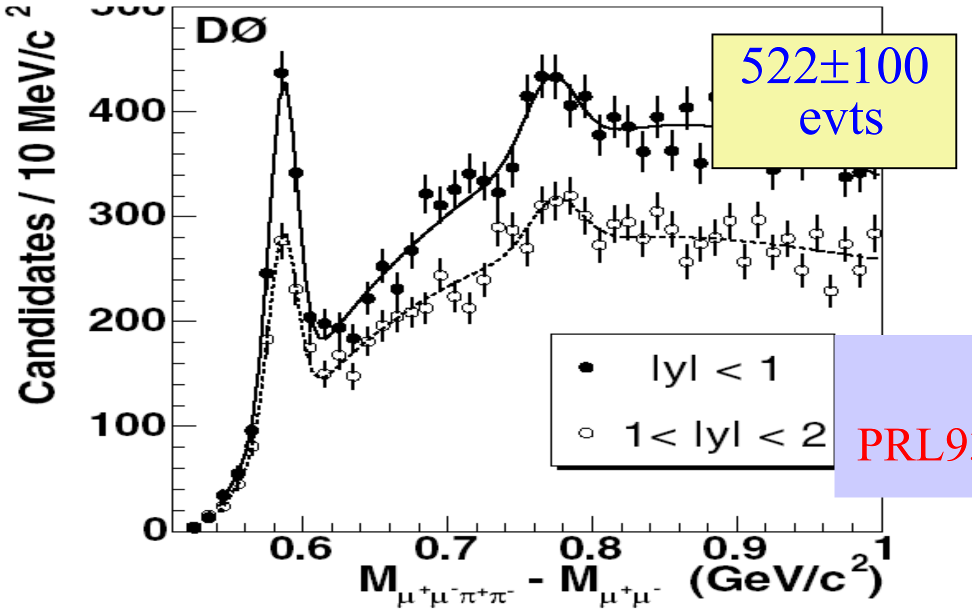
$$M = 3872.0 \pm 0.6 \pm 0.5\ \text{MeV},\ \Gamma < 2.7\ \text{MeV}$$

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



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**					
$3871.64 \pm 0.06 \pm 0.01$	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

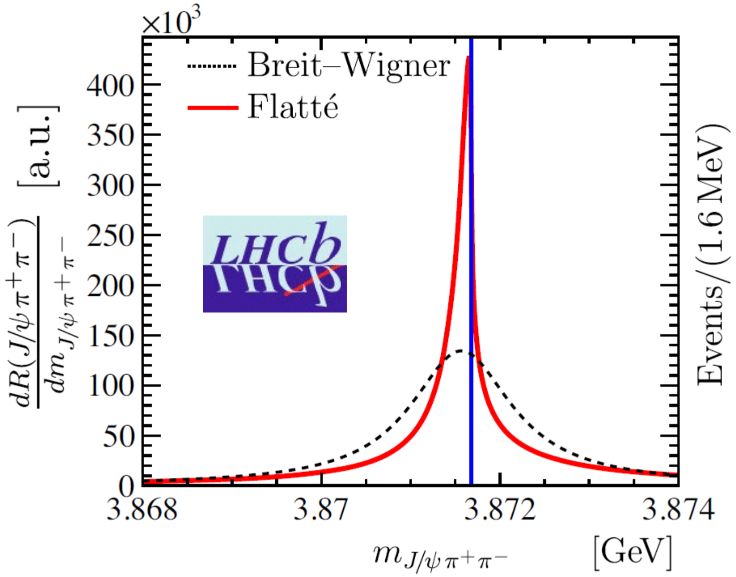
$E_b(\text{deuteron}) = -2.2$ MeV

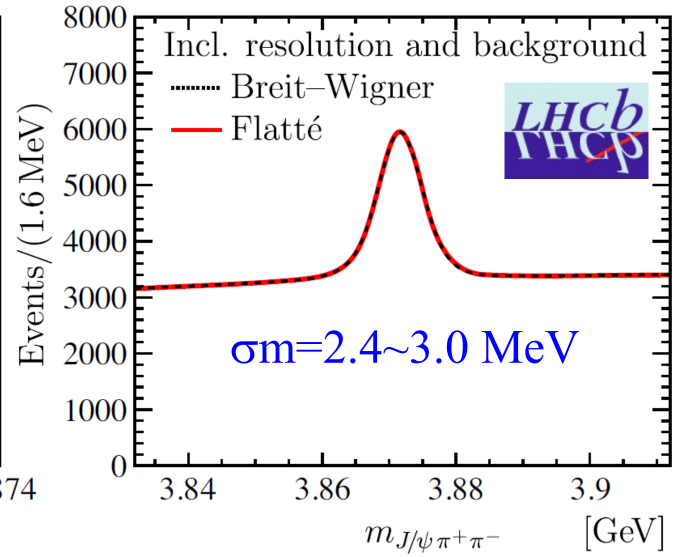
$$r_X = (8\mu|E_b|)^{-1/2} > 5\ \text{fm}$$

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!



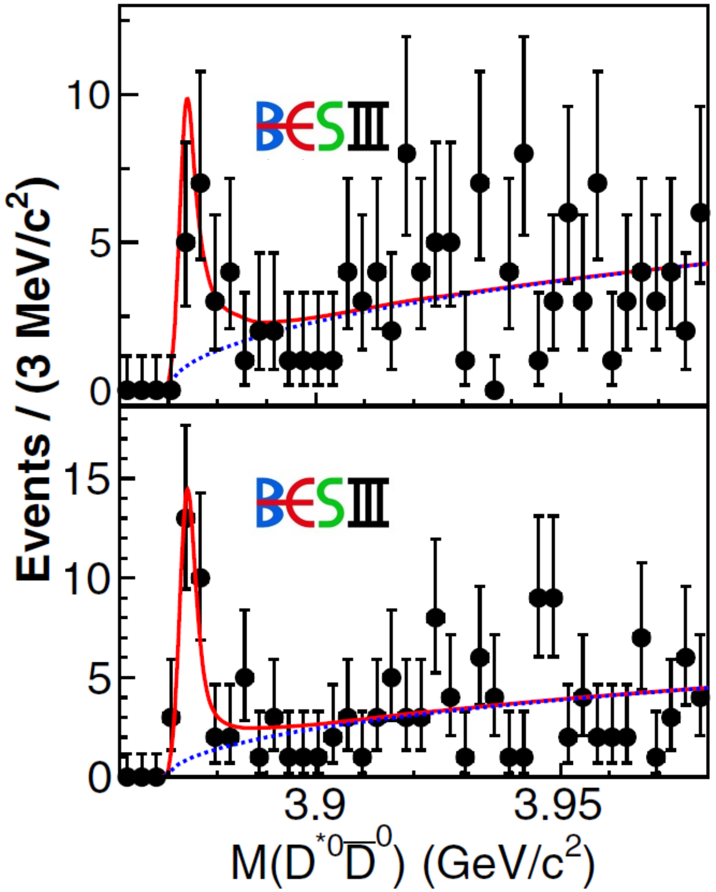


Flatté parametrization:

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

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

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



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

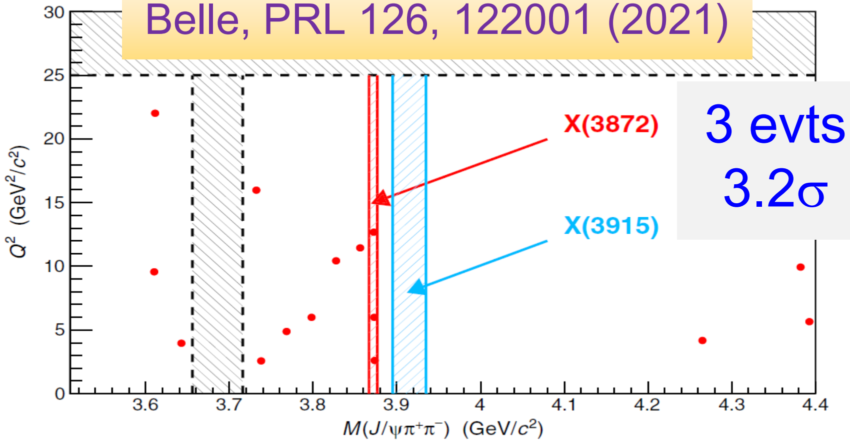
Mass resolution $\sigma m < 1$ MeV!

PRL124, 242001 (2020)

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
$e^+e^- \to \gamma X(3872)$	BESIII
$\gamma\gamma^* \to X(3872)$	Belle

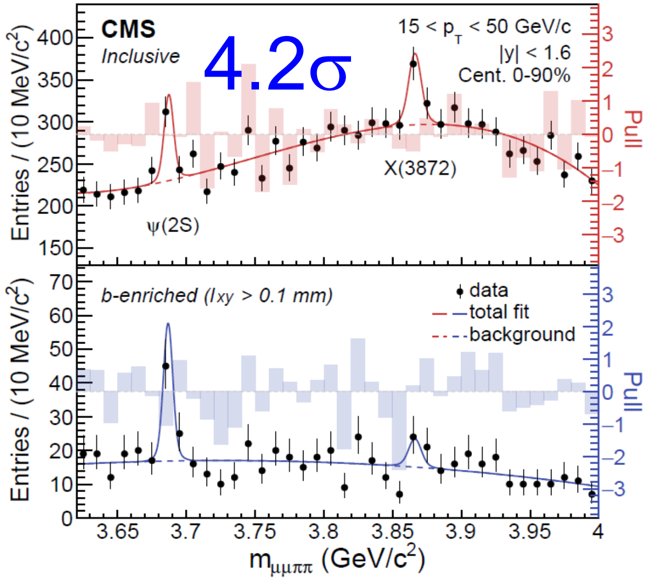
Belle, PRL 126, 122001 (2021)

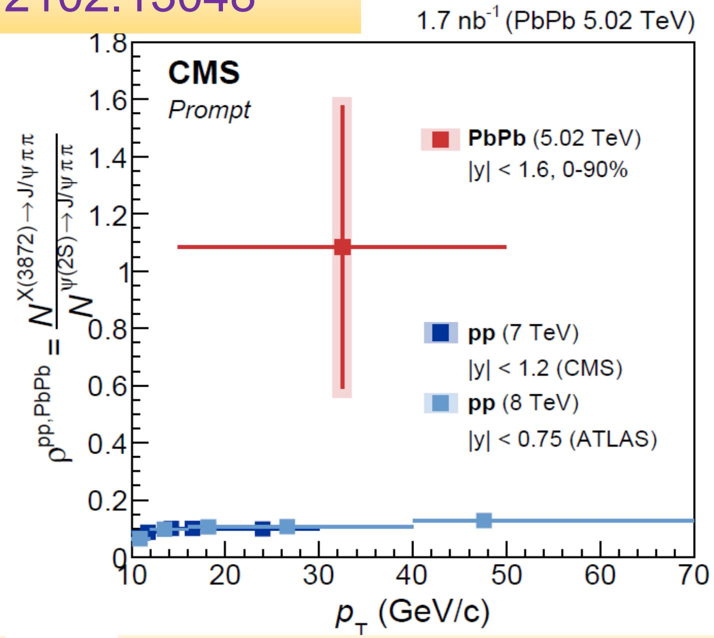


3 evts
3.2σ

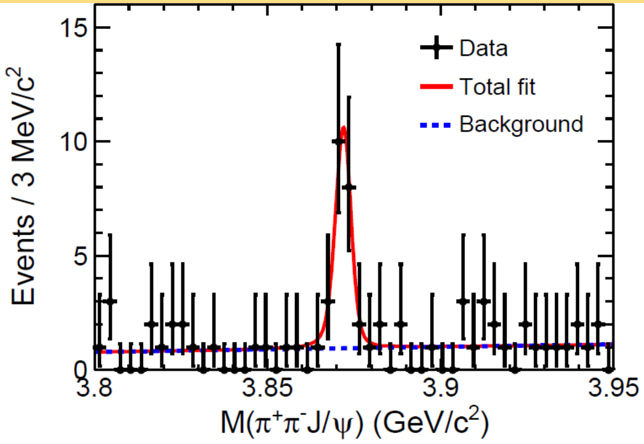
$\widetilde{\Gamma}_{\gamma\gamma}B(X \to \pi^+\pi^-J/\psi)=(5.5^{+4.1}_{-3.8}\pm0.7)$ eV

CMS, arXiv: 2102.13048



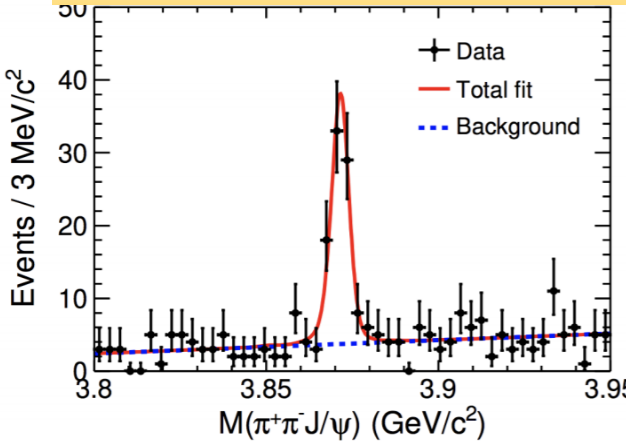


BESIII, PRL 112, 092001 (2014)



4.0 fb^{-1}, 20±5 evts

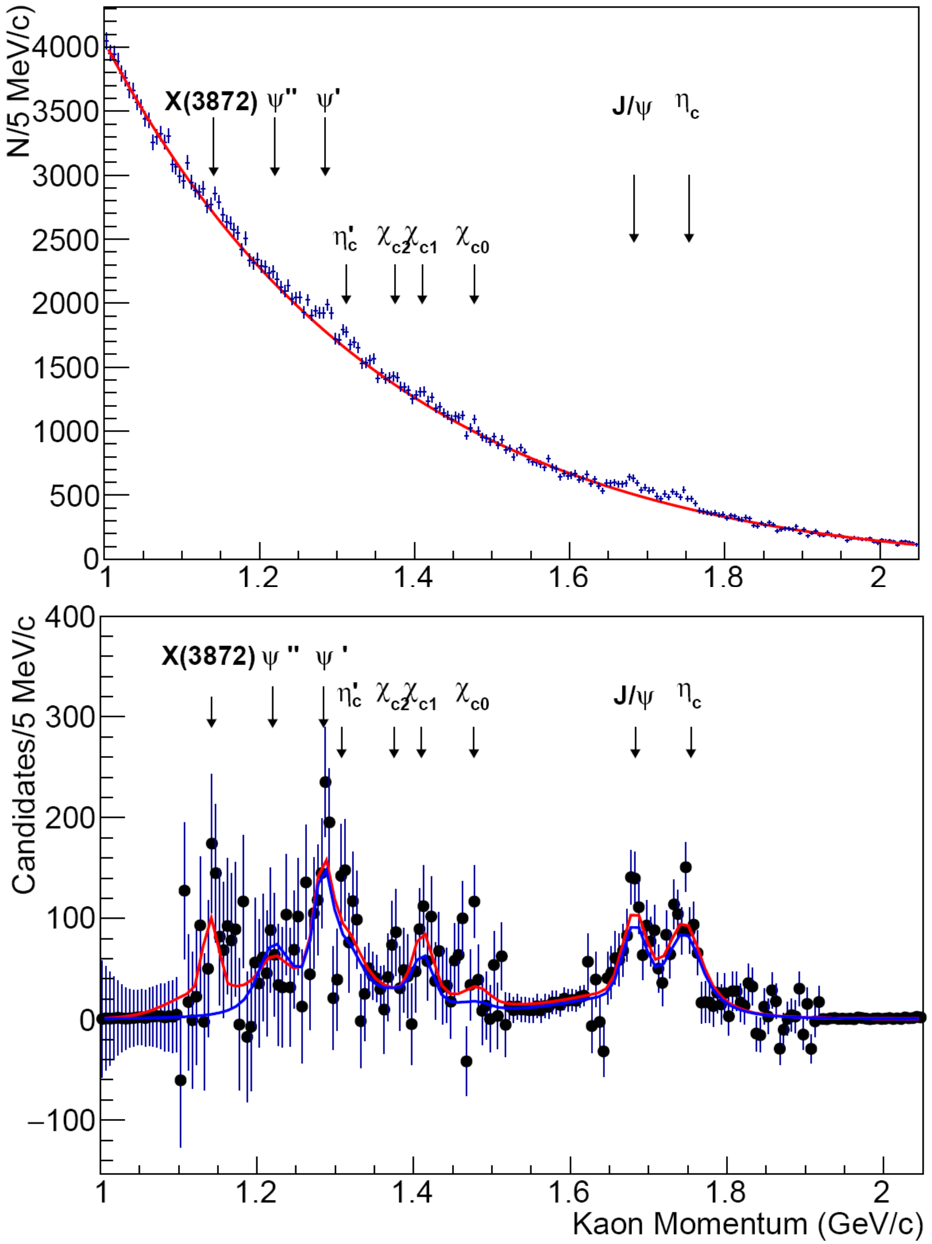
PRL122, 232002 (2019)



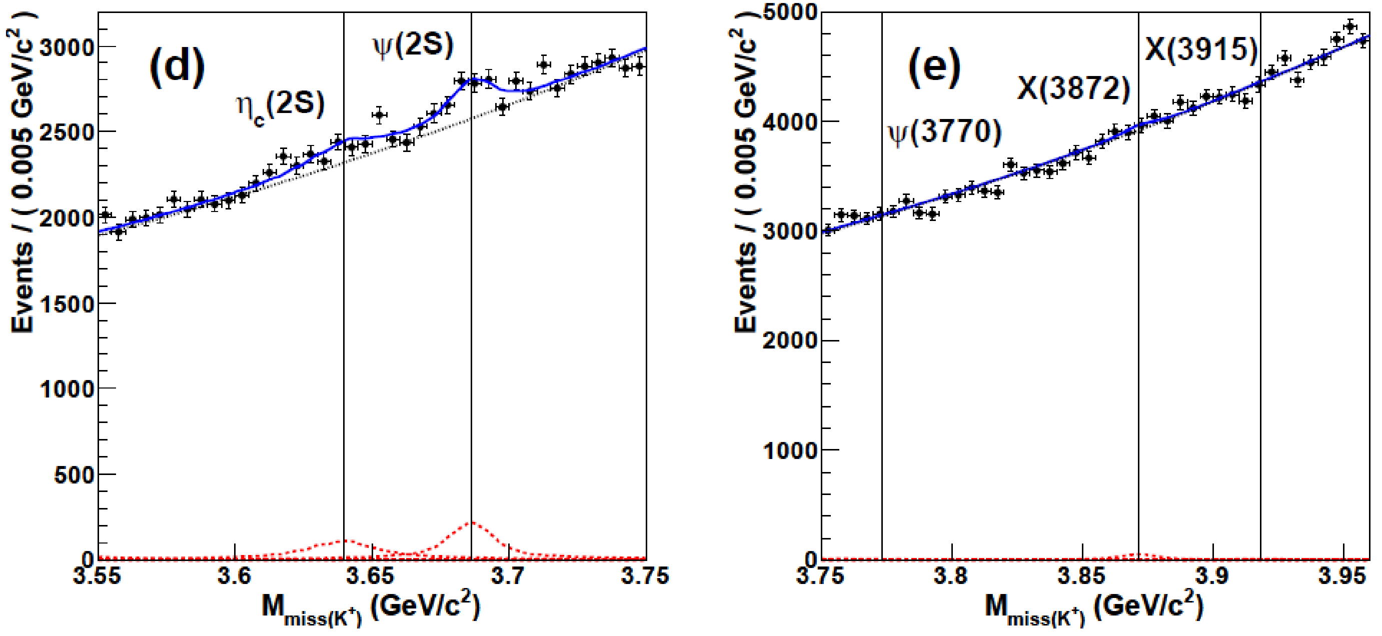
11.6 fb^{-1}, 79±9 evts

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

PRL 124, 152001 (2020)



PRD 97, 012005 (2018)

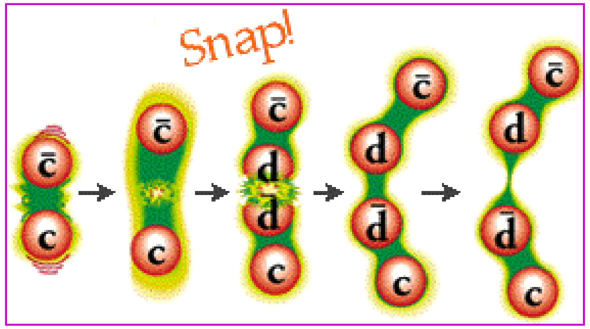


	N^{signal}	Signif.	$B(B^+ \to K^+X)$
BaBar	992±285	3.0σ	$(2.1\pm0.6\pm0.3)\times10^{-4}$
Belle	260±230	1.1σ	$(1.2\pm1.1\pm0.1)\times10^{-4}$

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

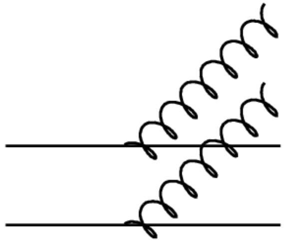
Decay of the X(3872)

- Open charm



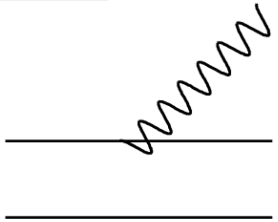
$\bar{D}^0 D^{*0}$? Threshold?
$\bar{D}^0 D^0 \pi^0$ (non $\bar{D}^0 D^{*0}$)
$\bar{D}^0 D^0 \gamma$ (non $\bar{D}^0 D^{*0}$)
$D^+ D^- \gamma$

- Transitions
  - Hadronic transitions



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

  - Radiative transitions



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

- Hadronic decays
- Radiative decays

New measurements
from BESIII & Belle.

Global fit to X(3872) decays

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	$\frac{\mathcal{B}(X(3872)\to D^{*0}\bar{D}^0+c.c.)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	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]

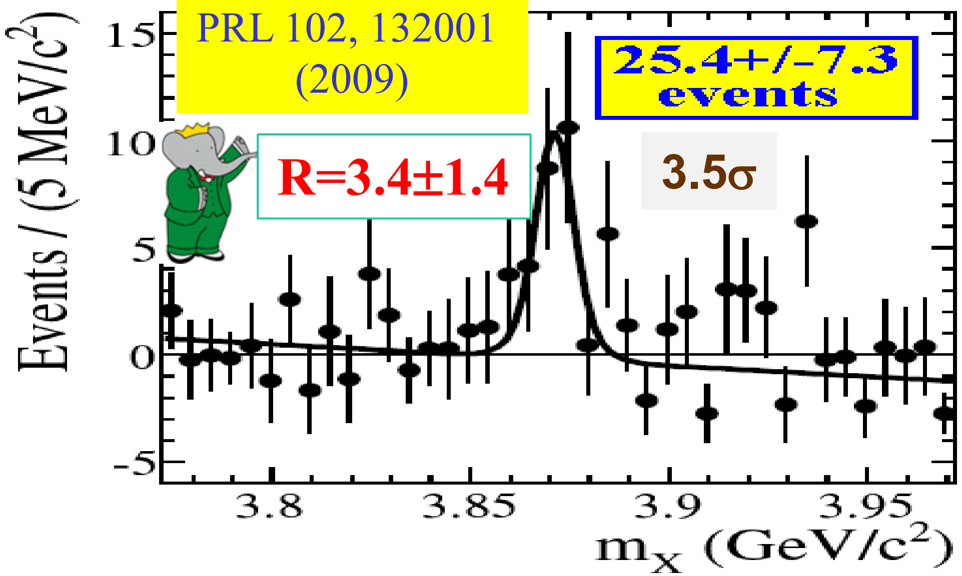
- $B(X(3872) \to D^{*0}\bar{D}^0 + c.c.) = (52^{+25}_{-14})\%$
- $B(X(3872) \to \pi^+\pi^- J/\psi) = (4.1^{+1.9}_{-1.1})\%$
- $B(X(3872) \to \omega J/\psi) = (4.4^{+2.3}_{-1.3})\%$
- $B(X(3872) \to \gamma J/\psi) = (1.1^{+0.6}_{-0.3})\%$
- $B(X(3872) \to \pi^0\chi_{c1}) = (3.6^{+2.2}_{-1.6})\%$
- $B(X(3872)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

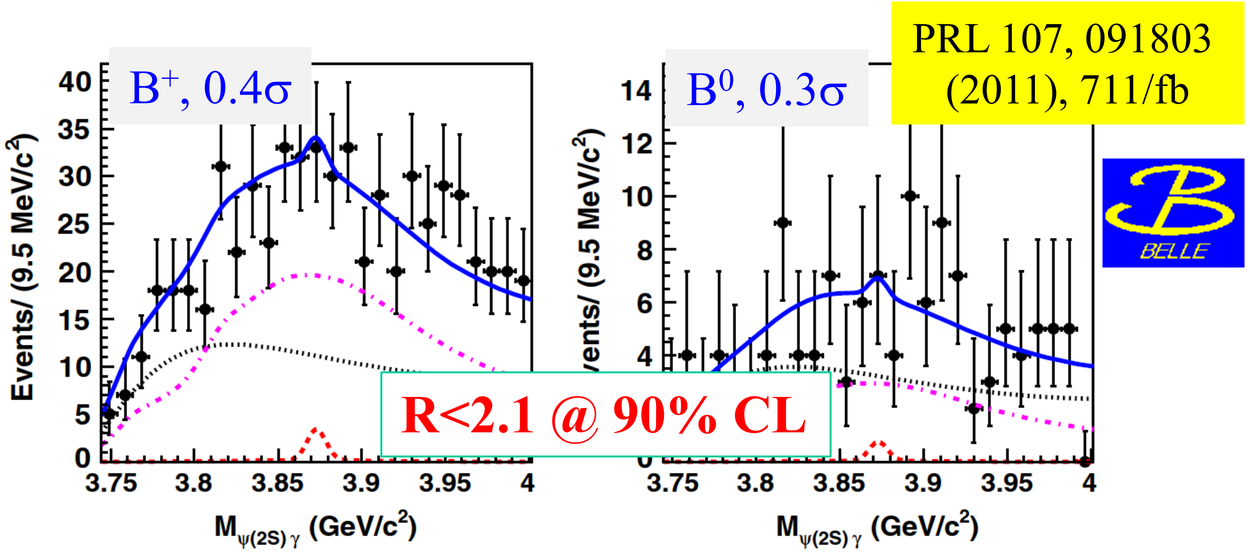
Parameter index	1	2	3	4	5	6	7	8
1	1	0.87	0.84	0.75	0.64	0.79	-0.95	-0.87
2		1	0.79	0.71	0.56	0.74	-0.90	-0.77
3			1	0.78	0.54	0.73	-0.88	-0.78
4				1	0.49	0.65	-0.79	-0.69
5					1	0.51	-0.61	-0.56
6						1	-0.82	-0.72
7							1	0.84

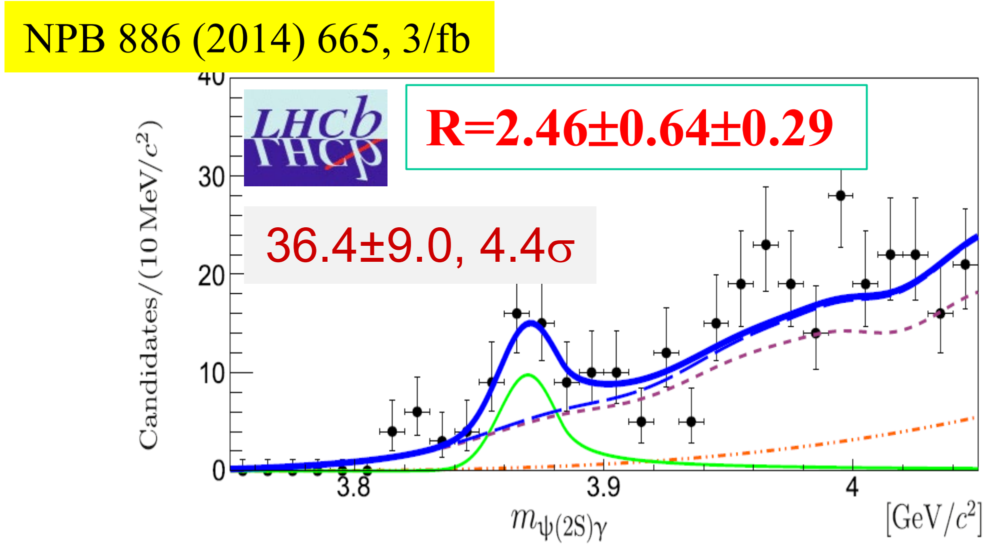
Chunhua Li and CZY, PRD 100, 094003 (2019)

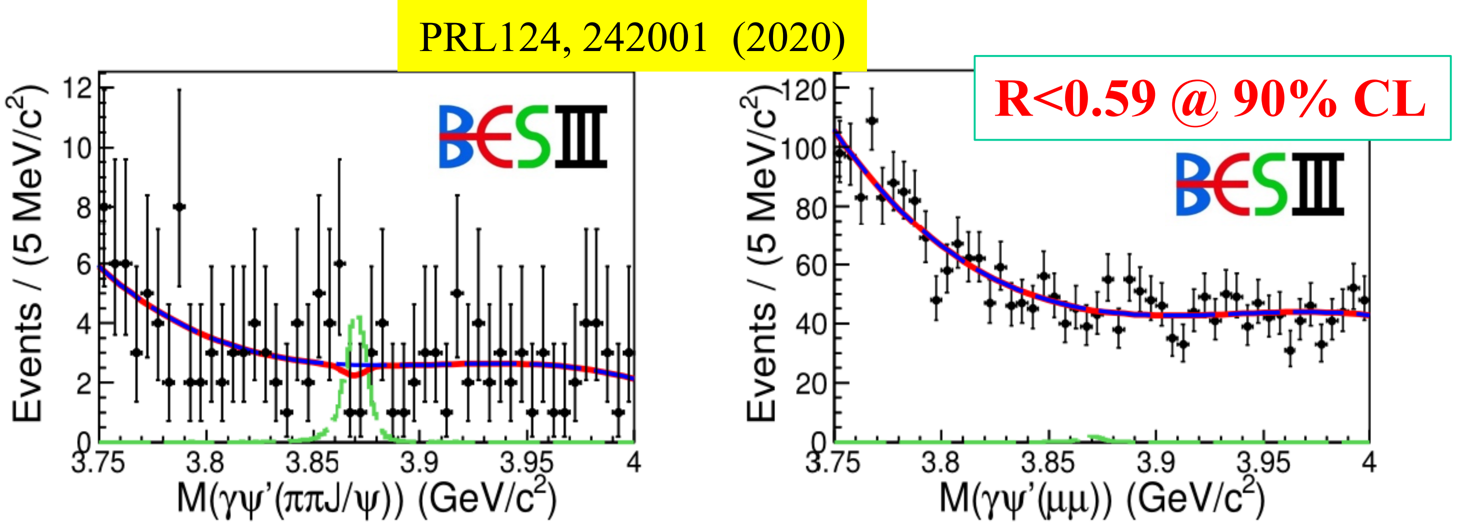
$$R=\frac{B[X(3872)\to\gamma\psi(2S)]}{B[X(3872)\to\gamma J/\psi]}$$

X(3872) → γψ(2S) puzzle

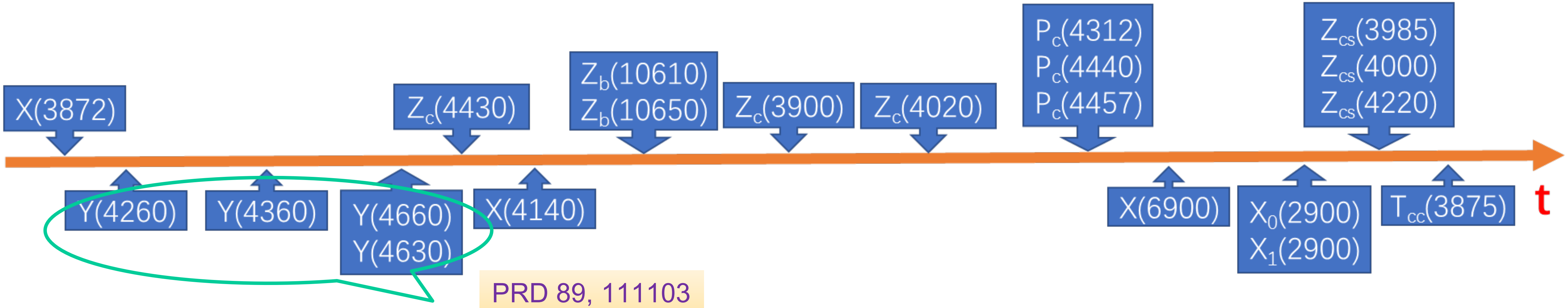


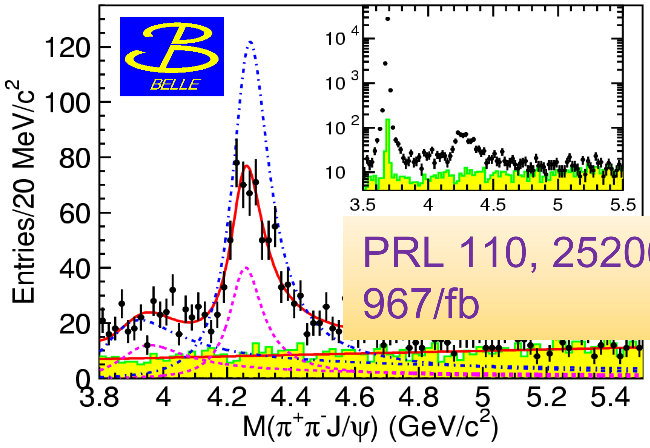






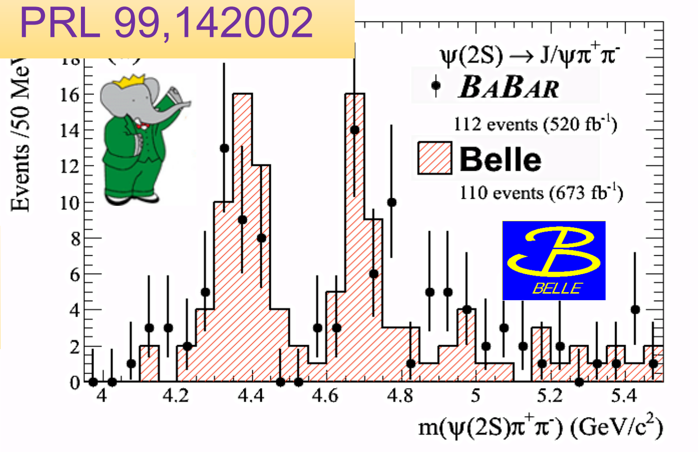
It is still not clear if X(3872)→γψ(2S) exists or not!





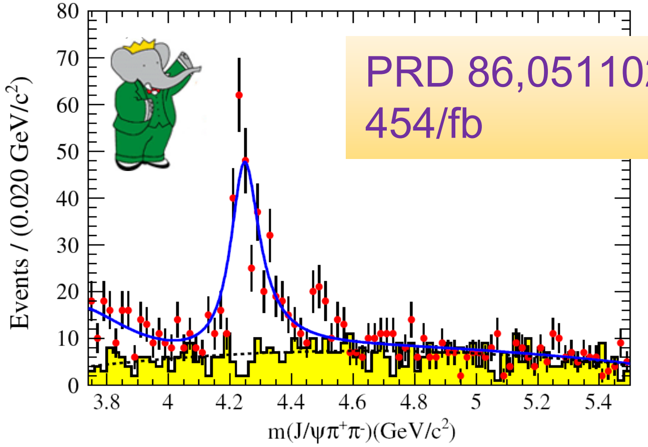
PRL 110, 252002
967/fb

PRD 89, 111103
PRL 99,142002

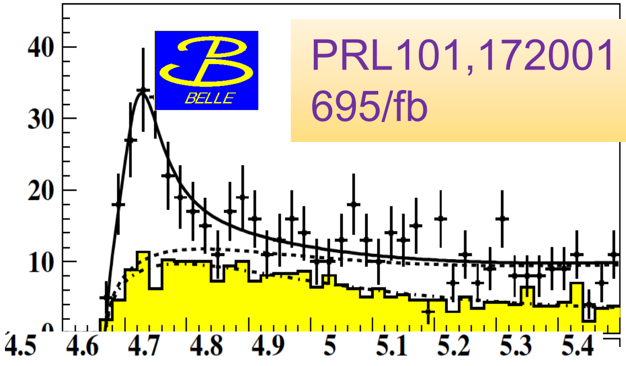


The Y states discovered via initial states radiation (ISR) in e^+e^- annihilation have $J^{PC}=1^{--}$.

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

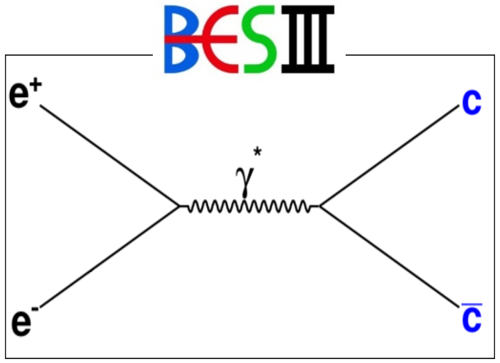


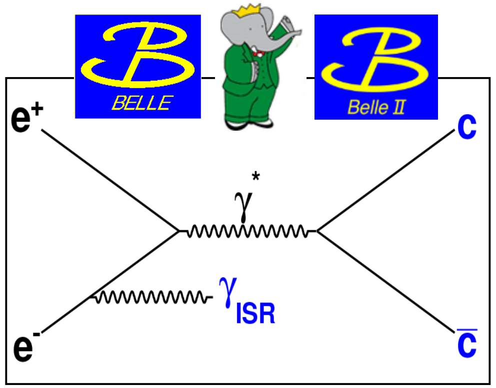
PRD 86,051102
454/fb



PRL101,172001
695/fb

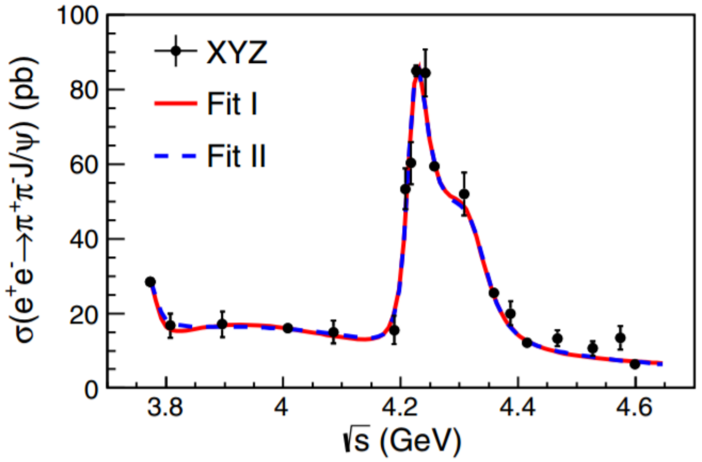
$M(\Lambda_c^+\Lambda_c^-)$



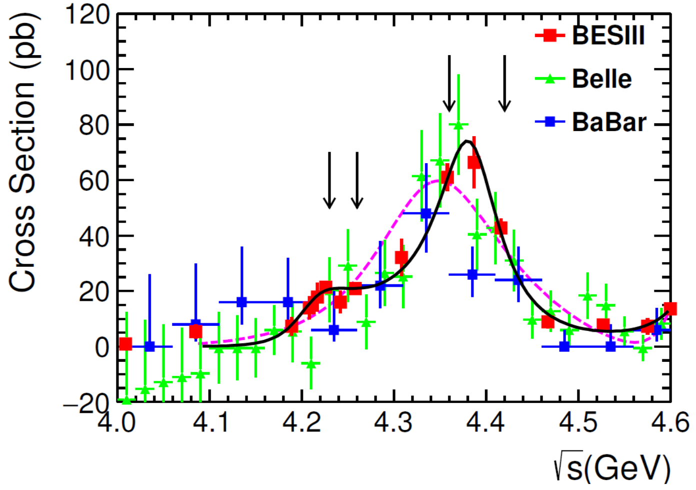


Y(4260) is now Y(4220)

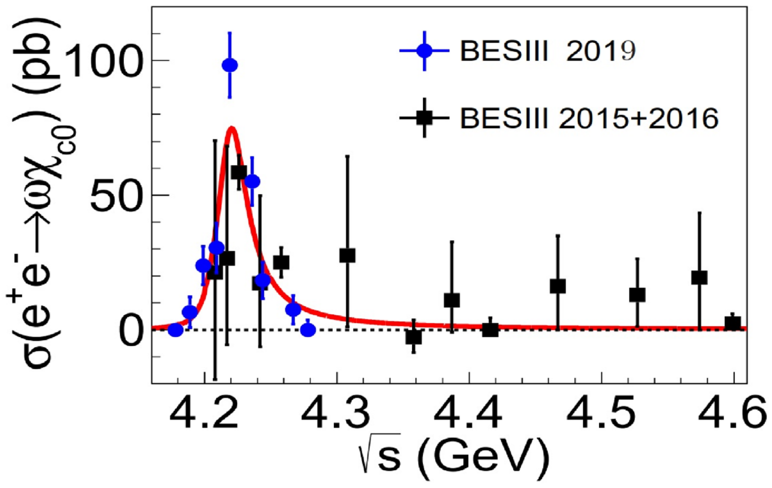
PRL118, 092001 (2017)



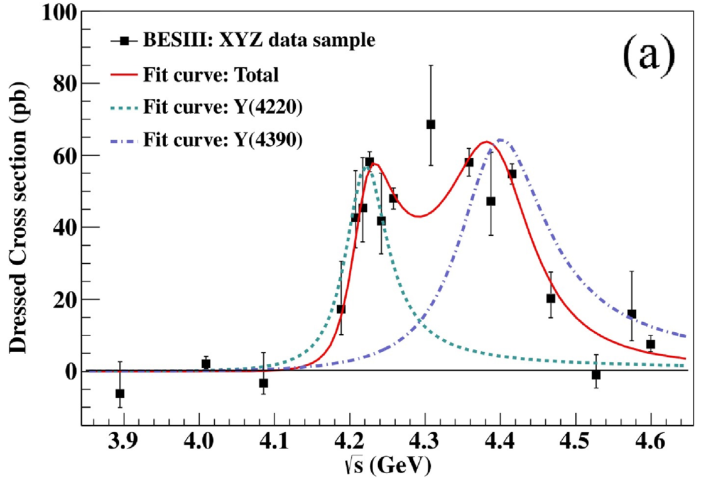
PRD96, 032004 (2017)



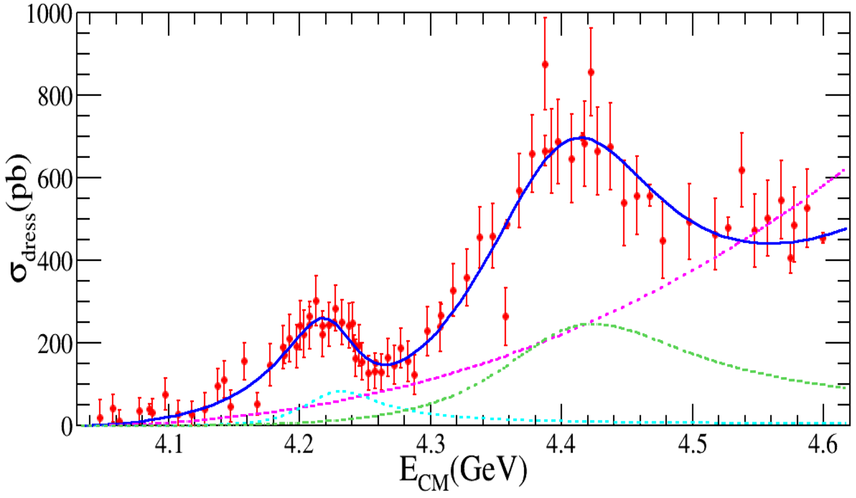
PRD99, 091103 (2019)



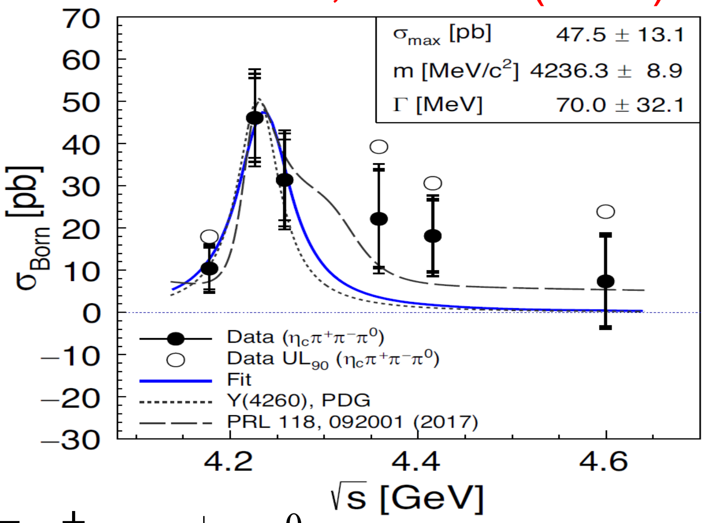
PRL118, 092002 (2017)



PRL122, 102002 (2019)



PRD 103, 032006 (2021)



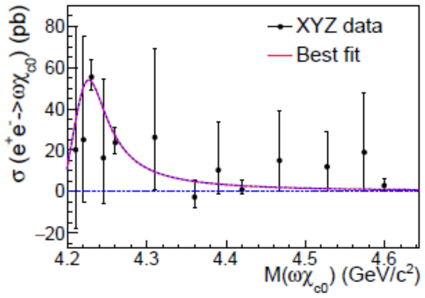
Y(4220) appears in $\omega\chi_{c0}$, $\pi^+\pi^-J/\psi$, $\pi^+\pi^-\psi'$, $\pi^+\pi^-h_c$, $D^0D^{*-}\pi^+$, $\eta_c\pi^+\pi^-\pi^0$

Mass~4220 MeV, width~ 60 MeV!

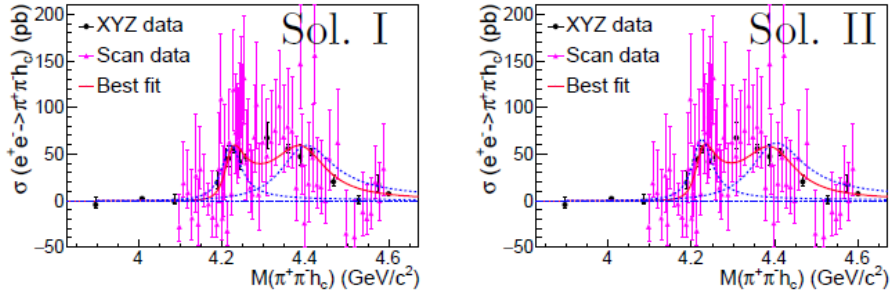
Combined fit results

X. Y. Gao, C. P. Shen, CZY
PRD 95, 092007 (2017)

$\omega\chi_{c0}$

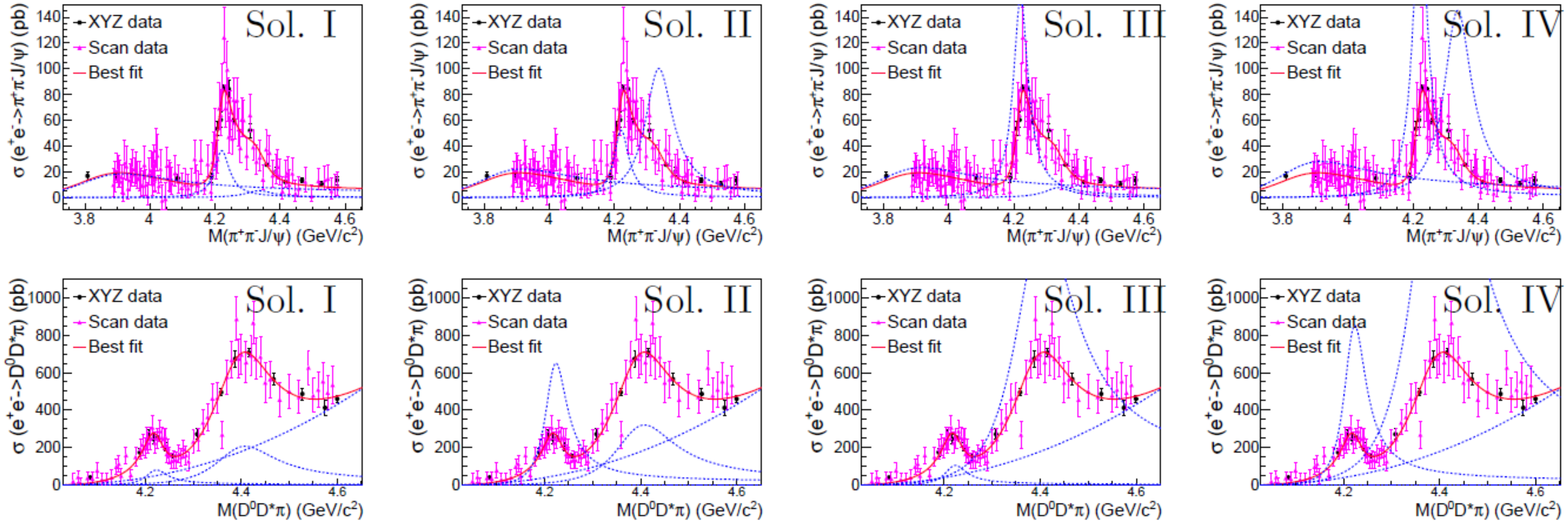


$\pi^+\pi^-h_c$



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

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



- $\mathrm{M} = 4219.6 \pm 3.3(stat) \pm 5.1(sys)$ MeV
- $\Gamma = 56.0 \pm 3.6(stat) \pm 6.9(sys)$ MeV

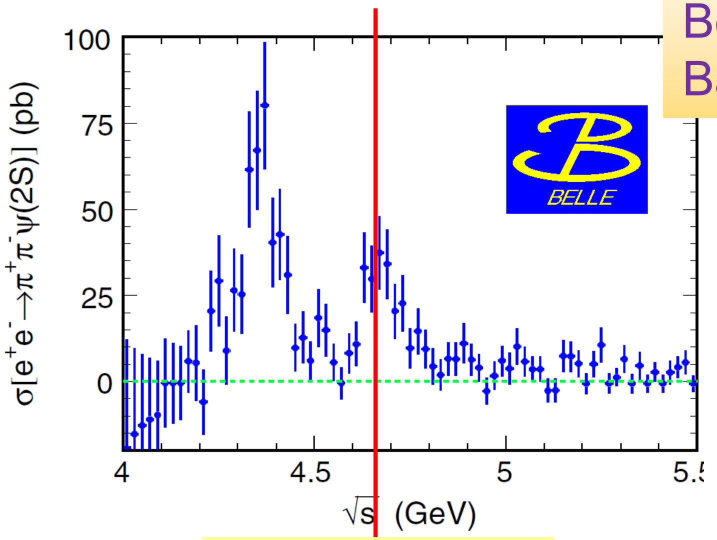
$2 \times m(D_s^*) = 4224 \pm 1$ MeV

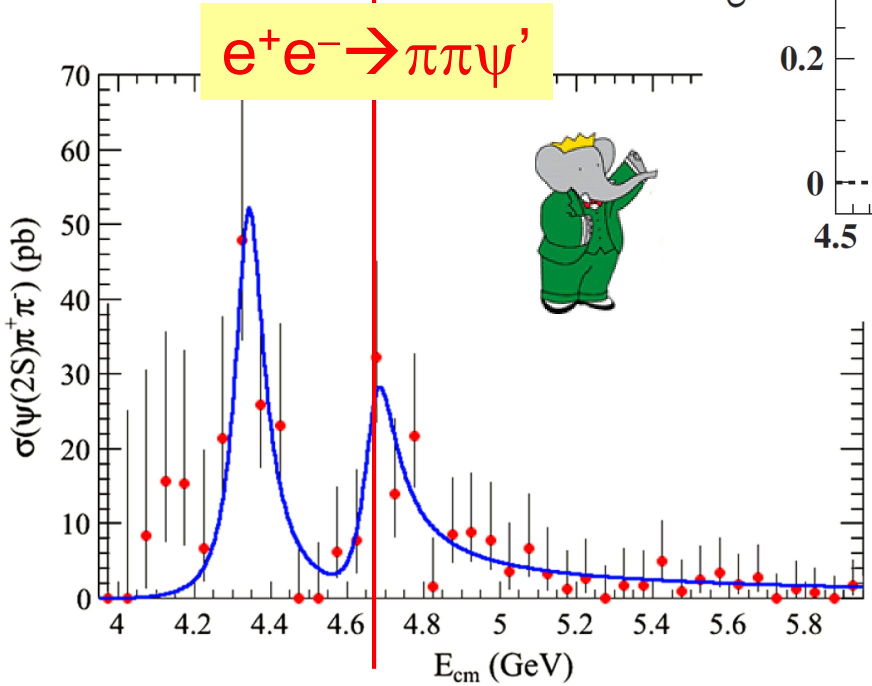
The fit could be updated with more processes.

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

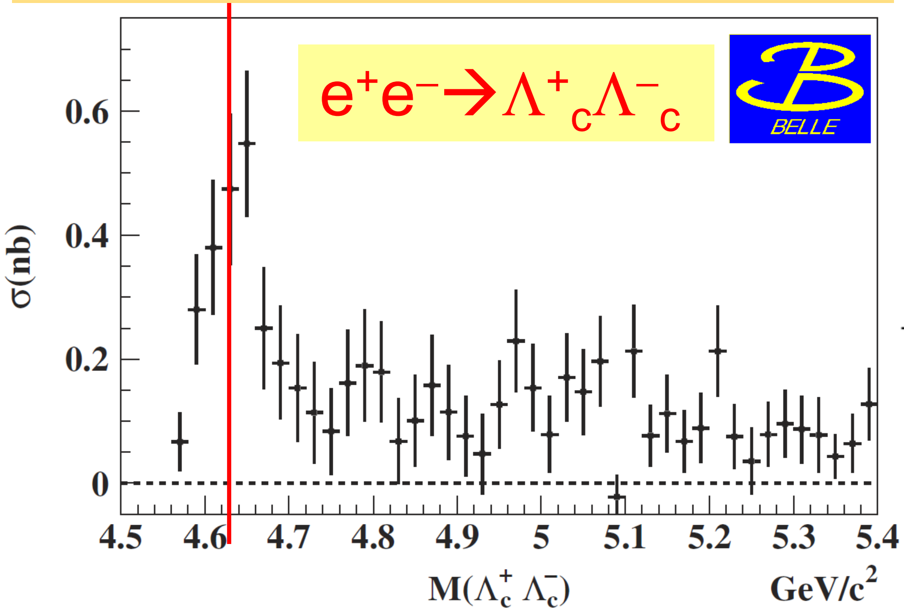
Belle: PRD91, 112007 (2015), 980/fb
BaBar: PRD89, 111103 (2014), 520/fb

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

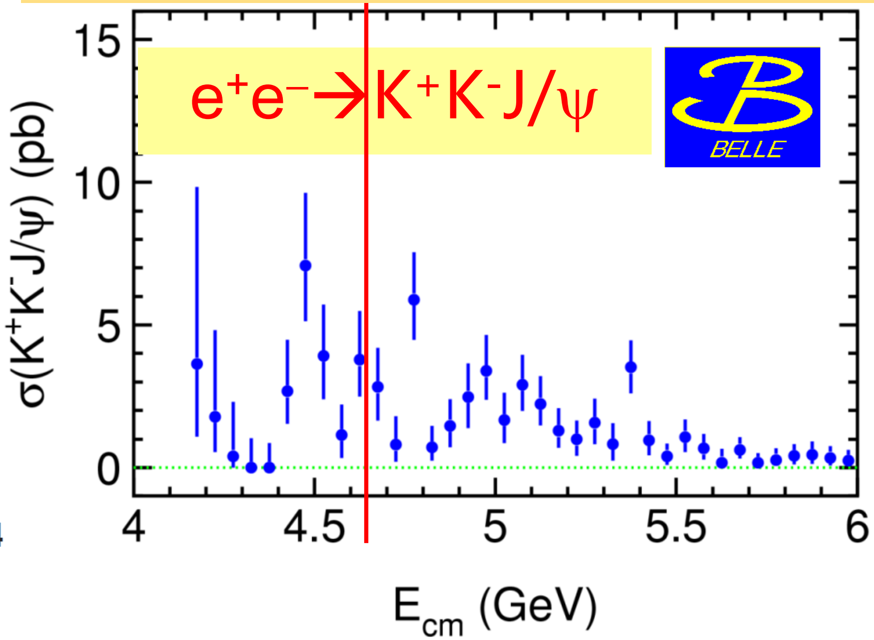




Belle: PRL101, 172001 (2008), 695/fb



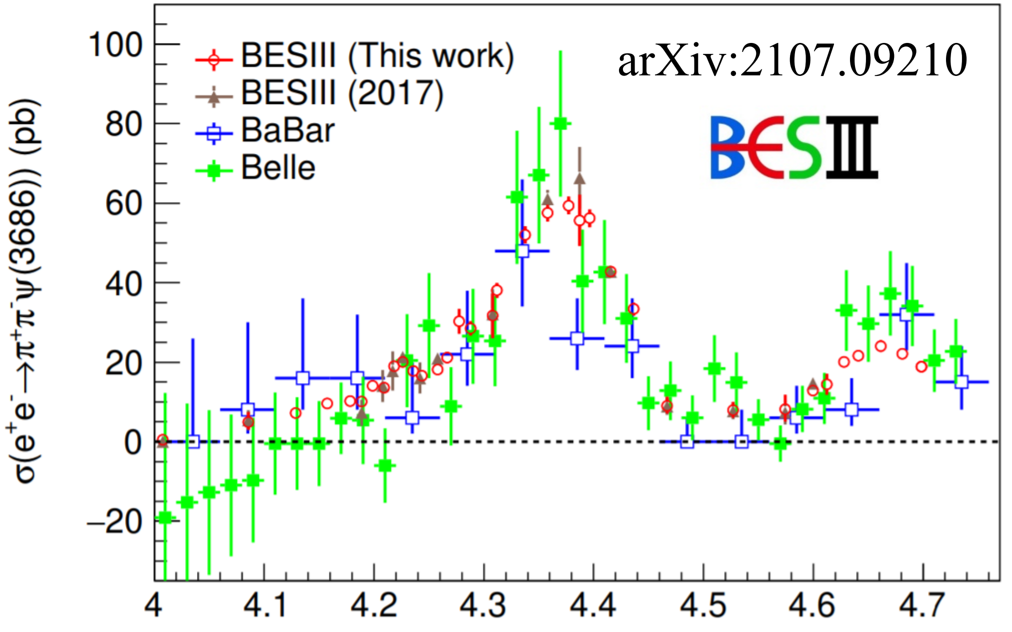
Belle: PRD89, 072015 (2014), 980/fb

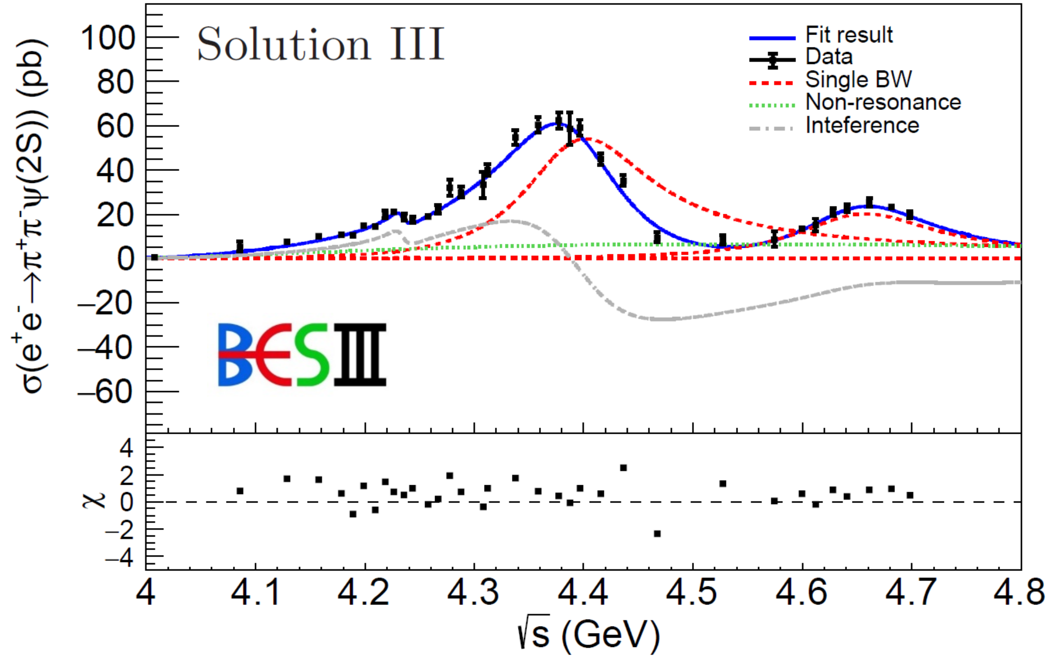


Experiment	Mass (MeV)	Width (MeV)
Belle, $\Lambda^+_c\Lambda^-_c$	$4634^{+8}_{-7}{}^{+5}_{-8}$	$92^{+40}_{-24}{}^{+10}_{-21}$
Belle, $\pi\pi\psi'$	4652±10±8	68±11±1
BaBar, $\pi\pi\psi'$	4669±21±3	104±48±10

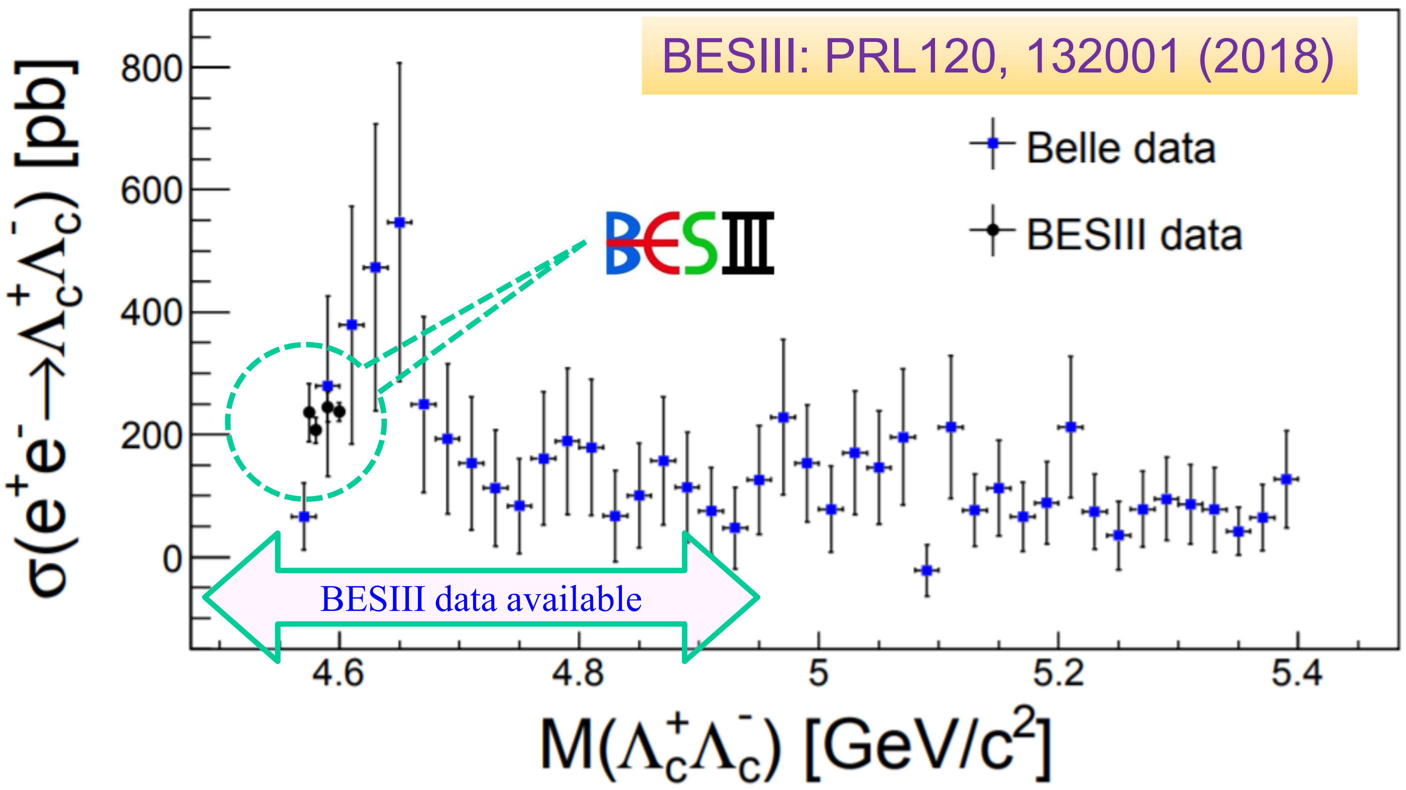
Recent measurements

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





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



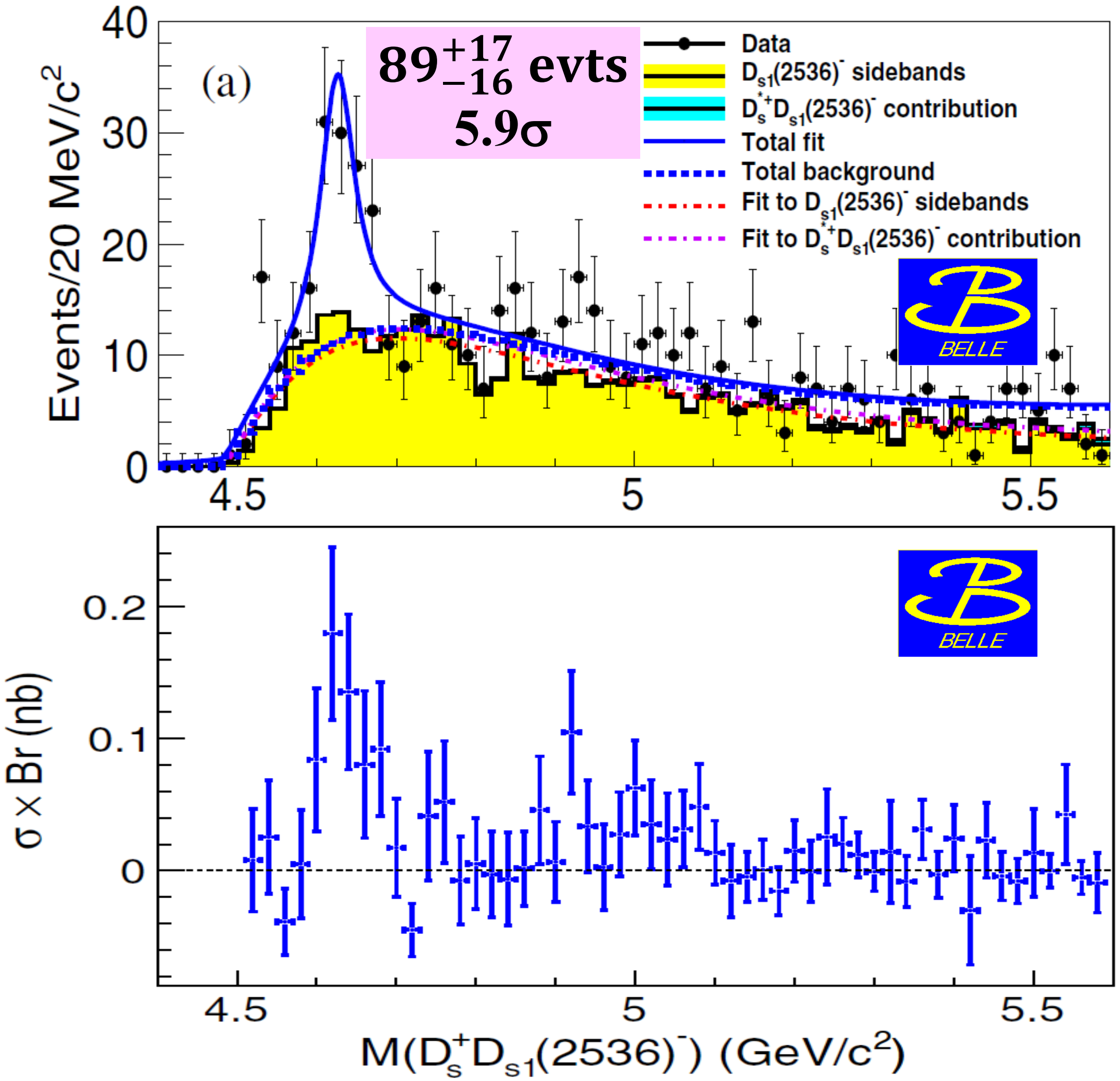
BESIII data confirmed Belle & BaBar measurements with much improved precision!

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

Recent measurements

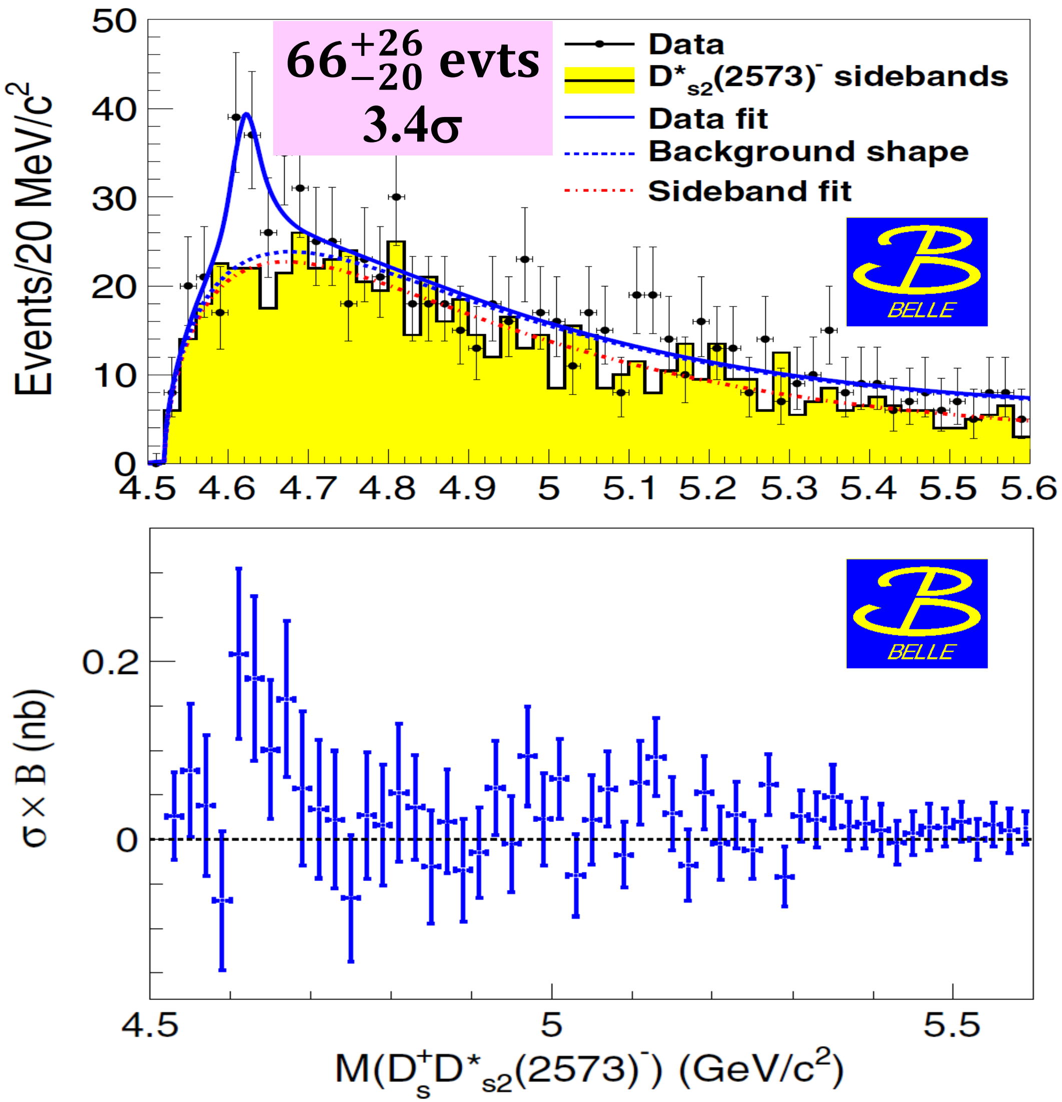
PRD 100, 111103 (2019)

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



PRD 101, 091101 (2020)

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

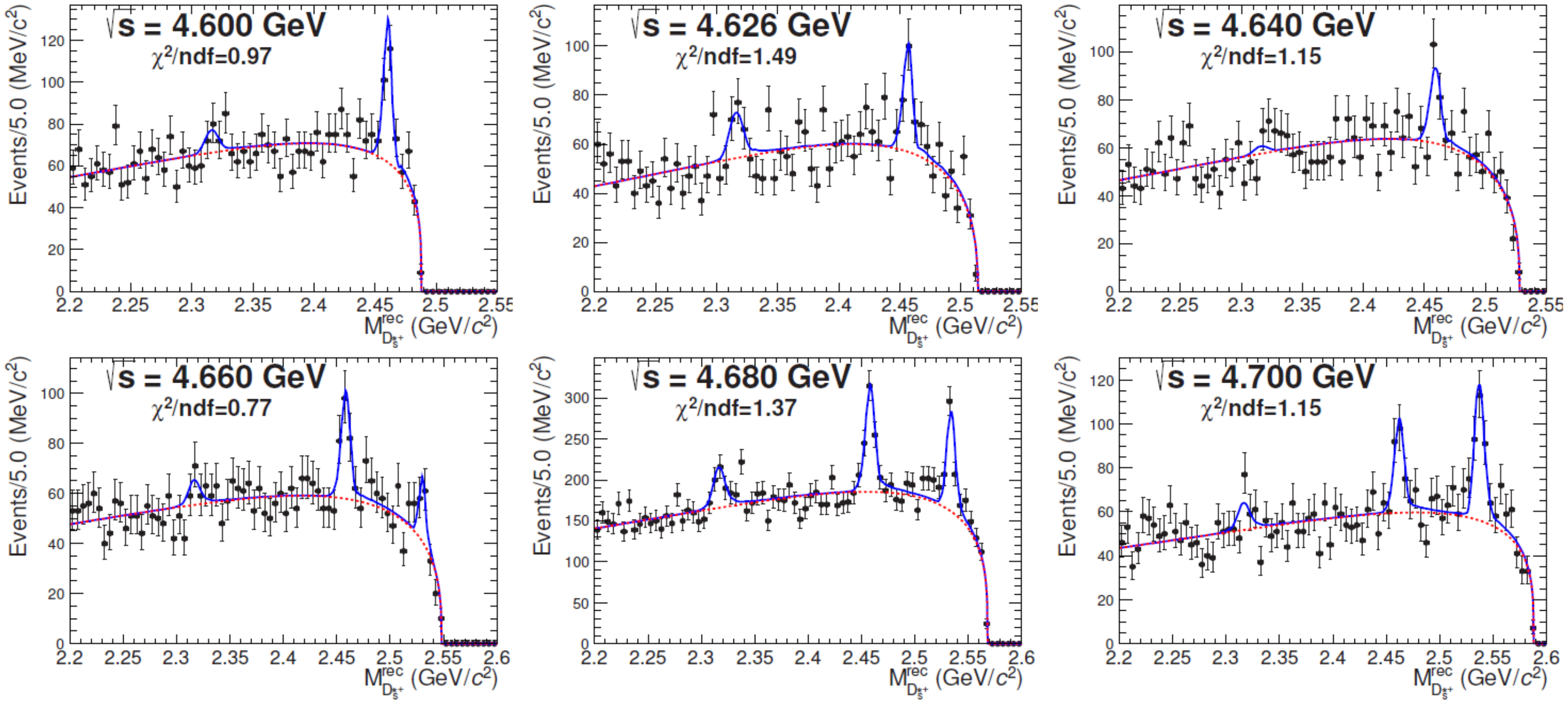


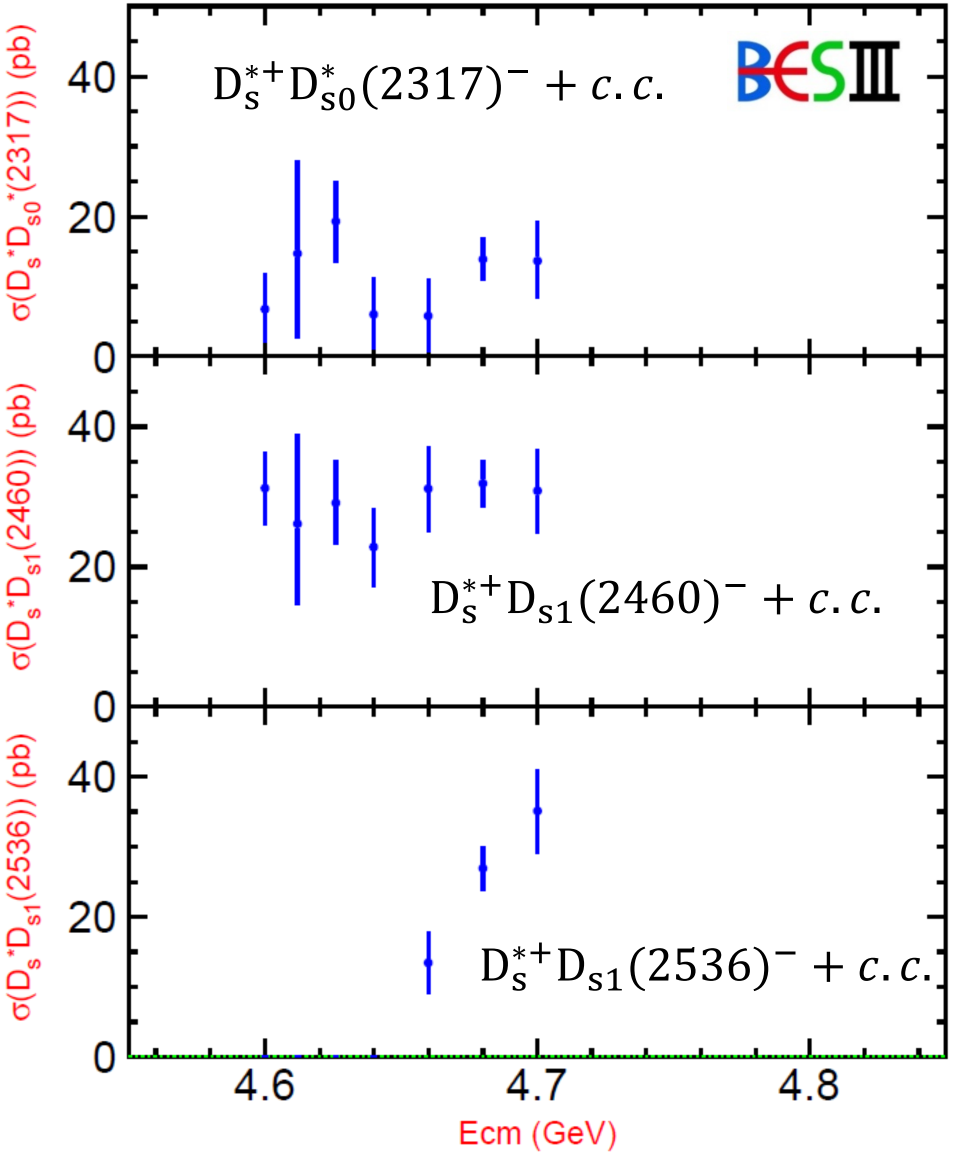
BESIII has data from threshold to 4.95 GeV, improved measurements are expected!

Recent measurements

arXiv: 2106.02298
PRD 104, 032012 (2021)

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



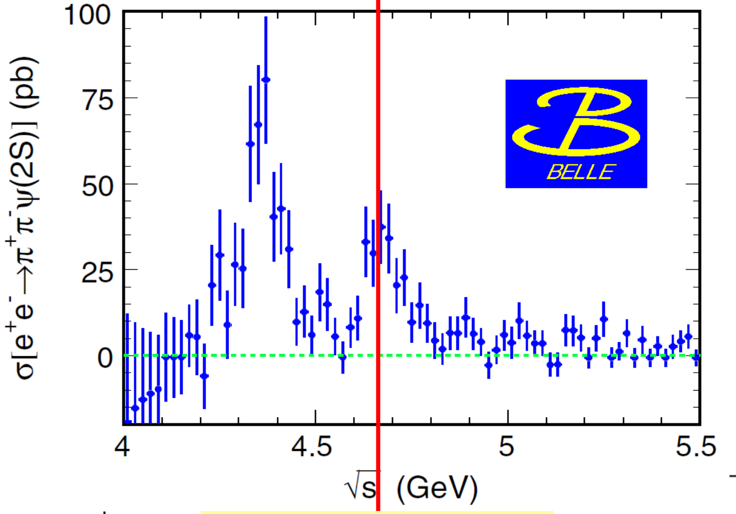


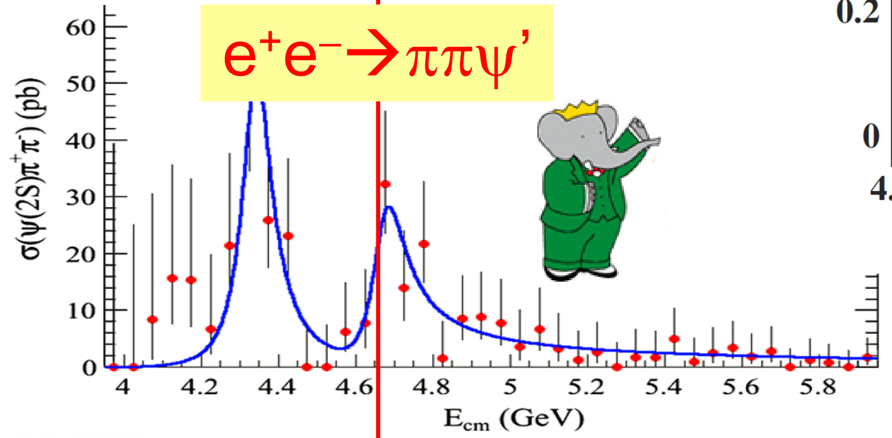
Clear e^+e^-→$D_s^*D_{sJ}$ production between 4.6 and 4.7 GeV.

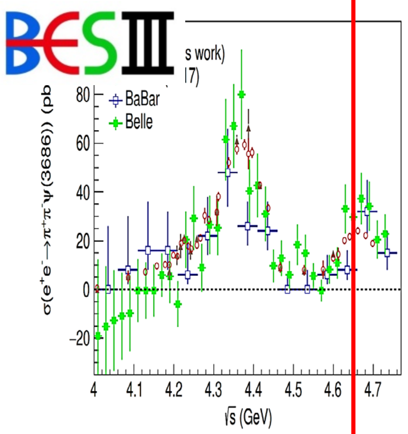
No significant Y(46xx)→$D_s^*D_{sJ}$ signal

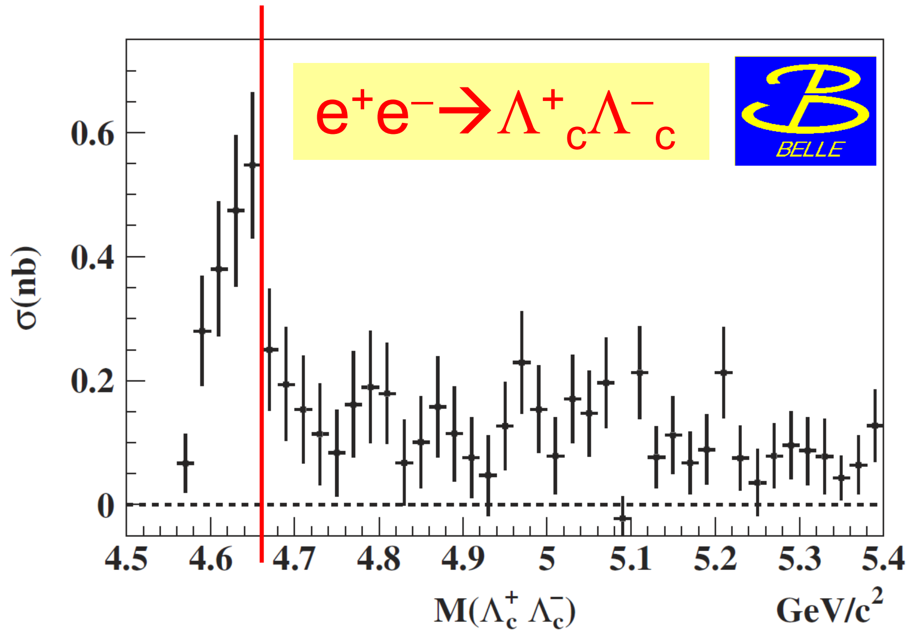
BESIII has data from threshold to 4.95 GeV, improved measurements are expected!

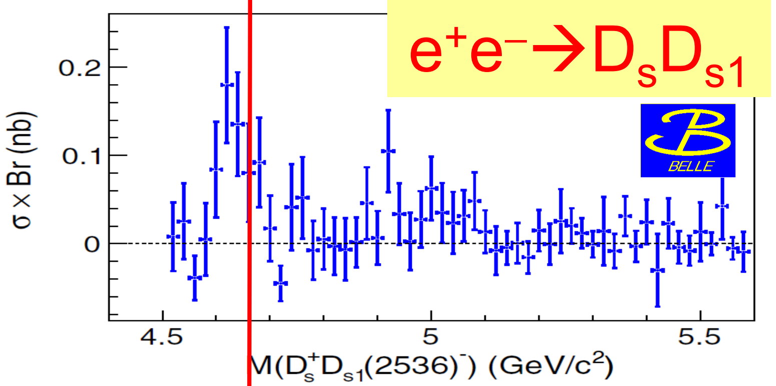
Y(4630)? Y(4660)?

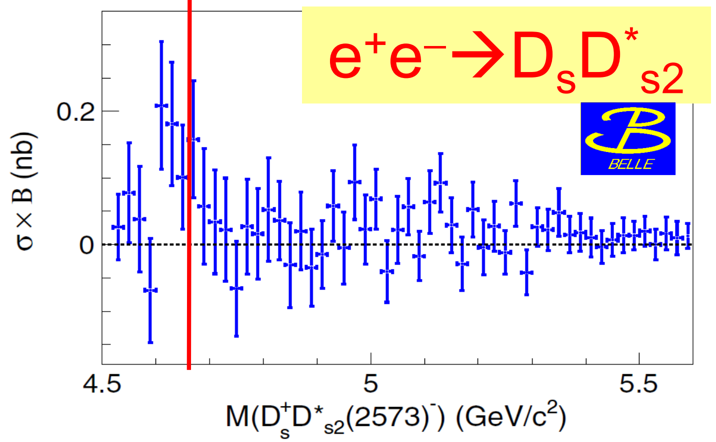








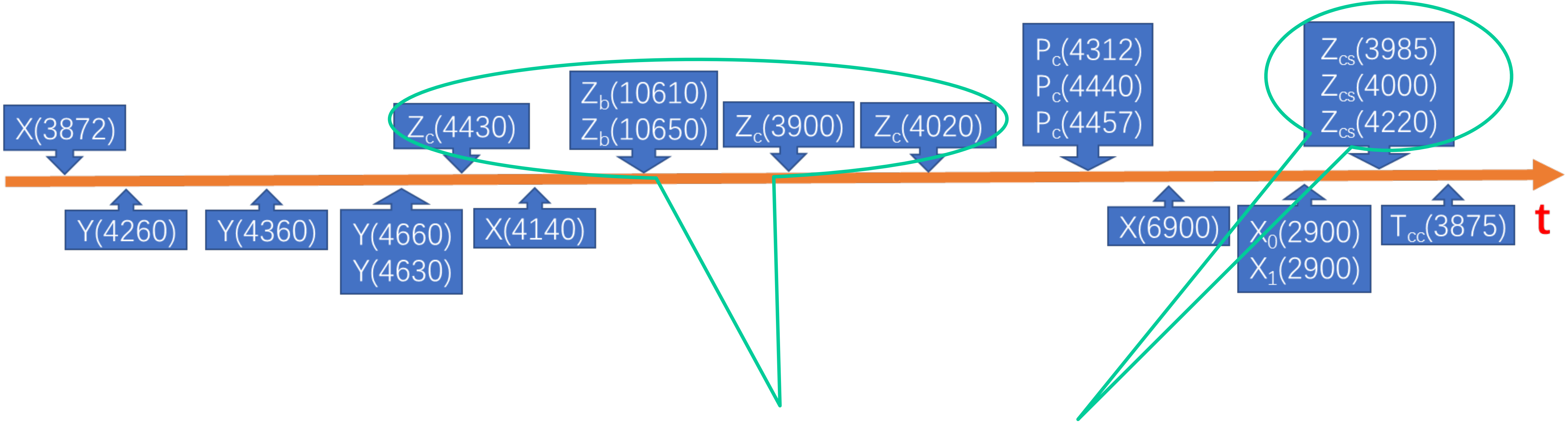




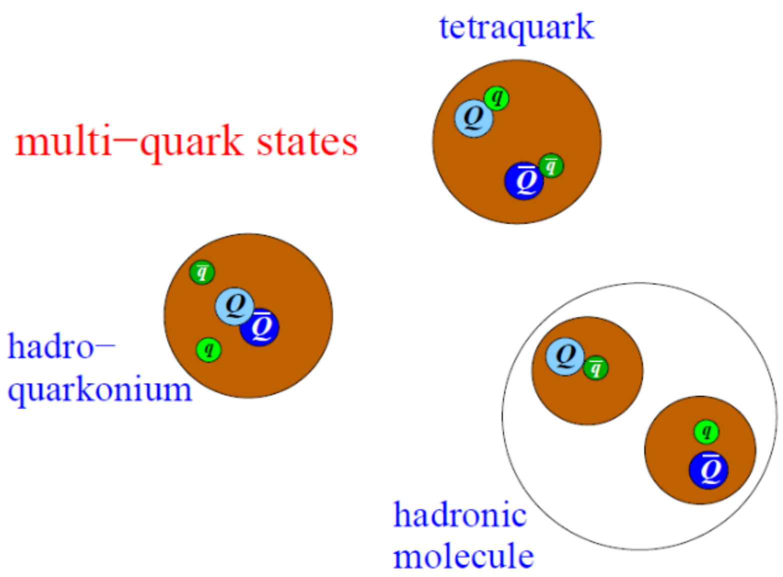
Tension between open charm & charmonium modes.

Parametrization affects the resonance parameters.

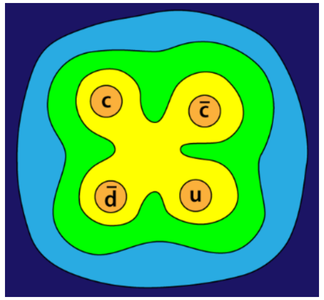
Experiment	Mass (MeV)	Width (MeV)
Belle, $\pi\pi\psi'$	$4652\pm10\pm8$	$68\pm11\pm1$
BaBar, $\pi\pi\psi'$	$4669\pm21\pm3$	$104\pm48\pm10$
BESIII, $\pi\pi\psi'$	$4651\pm38\pm2$	$155\pm25\pm1$
Belle, $\Lambda^+_c\Lambda^-_c$	$4634^{+8}_{-7}{}^{+5}_{-8}$	$92^{+40}_{-24}{}^{+10}_{-21}$
Belle, D_sD_{s1}	$4625.9^{+6.2}_{-6.0}\pm0.4$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



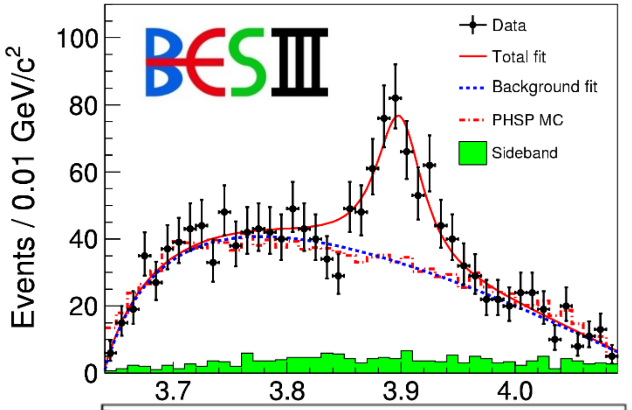
Charged quarkoniumlike states must have at least 4 quarks!

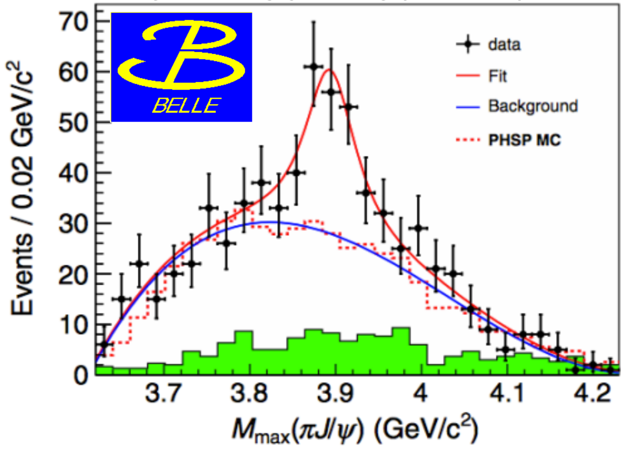


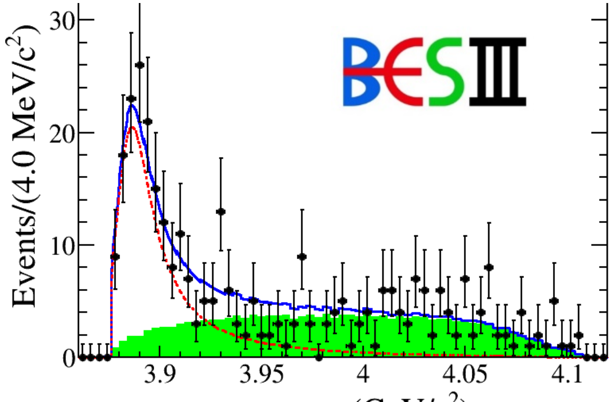
The Z_c states with u,d-quark



$Z_c(3900)$, 2013

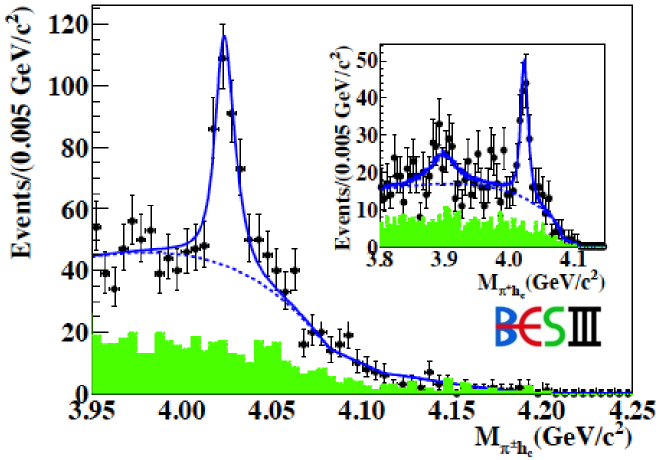


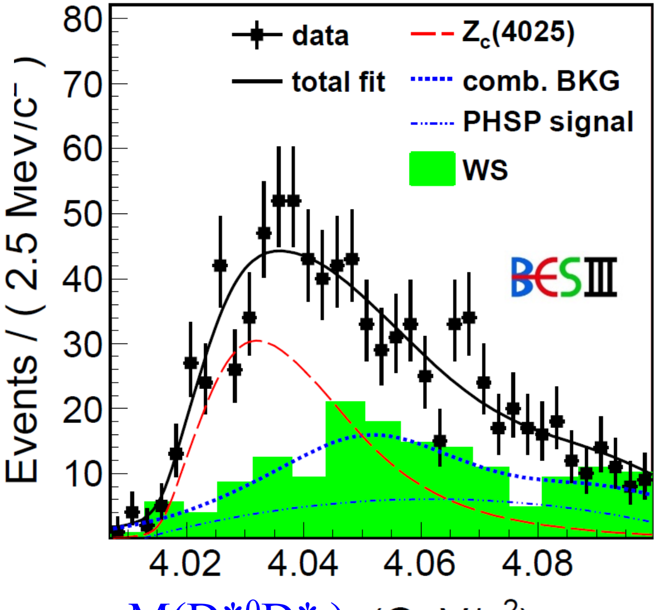




$M(D^0D^{*-})$

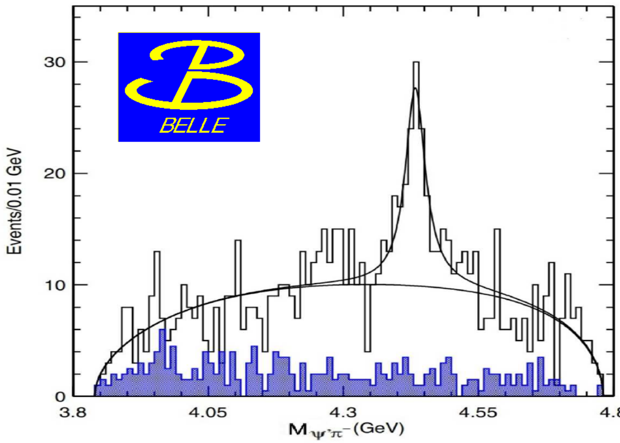
$Z_c(4020)$, 2013

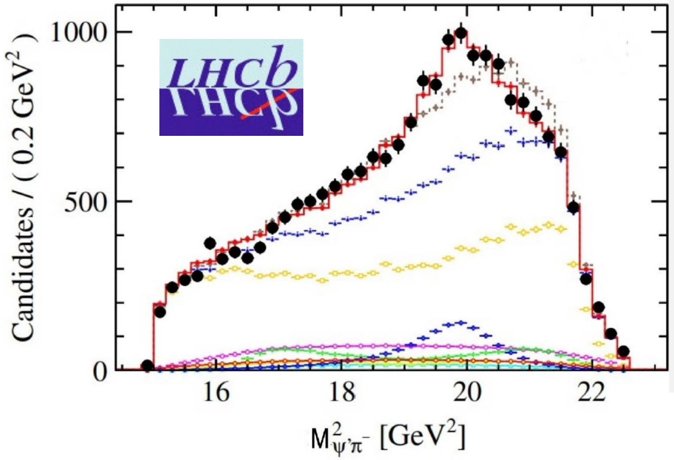




$M(D^{*0}D^{*-})$ (GeV/c²)

$Z_c(4430)$, 2008



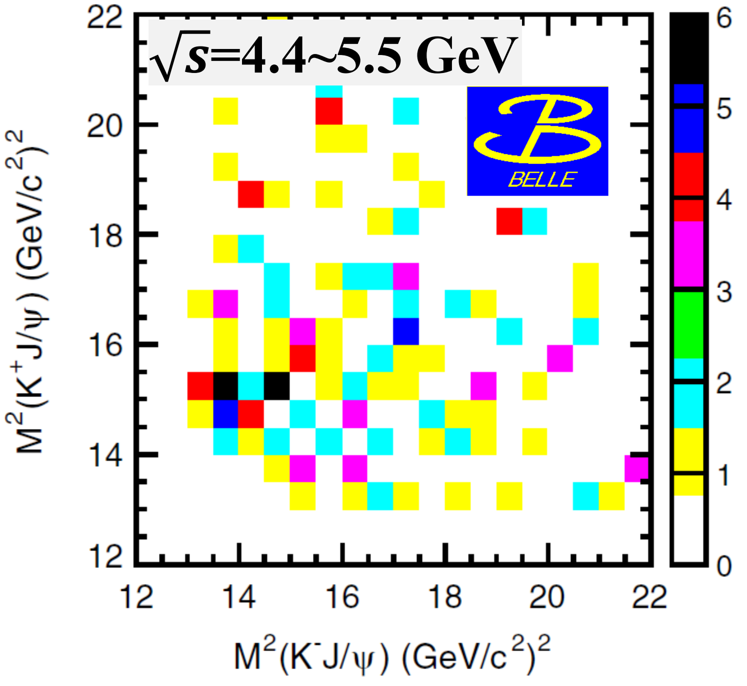


All are observed in π+charmonium (J/ψ, h_c, $\psi(2S)$) final states, candidate $\bar{c}\,c\,\bar{d}\,u$ tetraquark states

➔ Existence of states with $d \rightarrow s$?

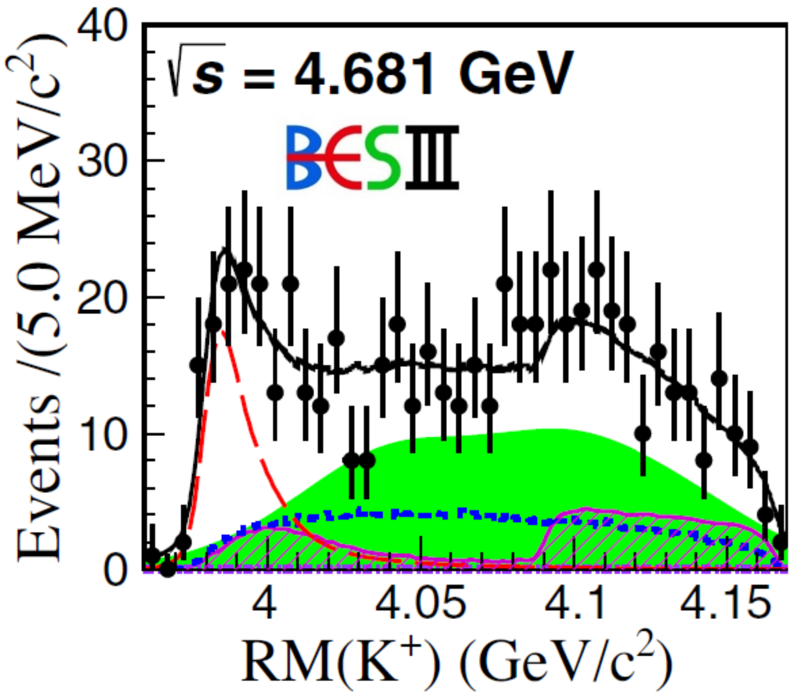
➔ Search for states decay into $K^{\pm}J/\psi$, $\bar{D}^*D_s + \bar{D}D^*_s$!

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



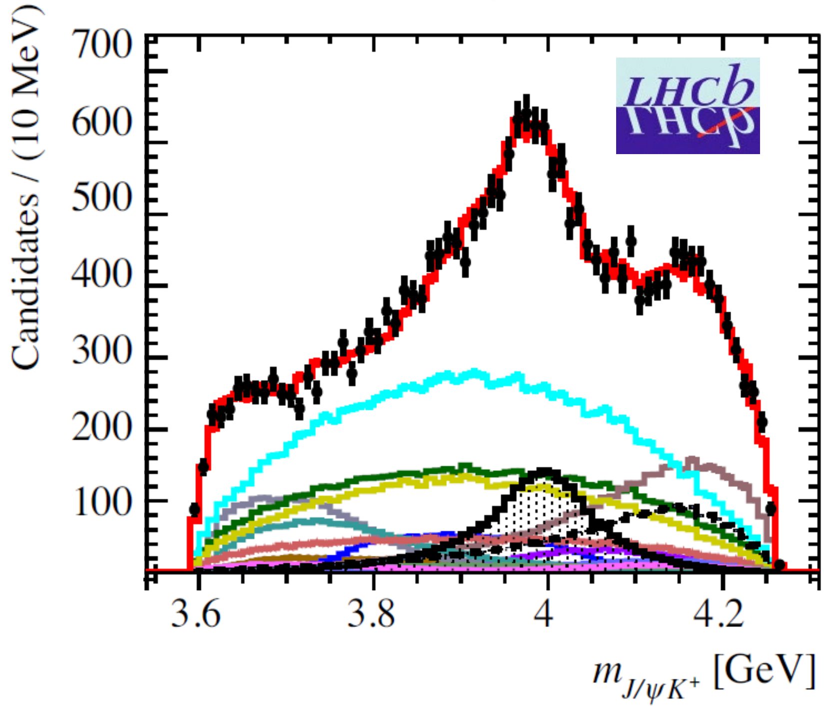
PRD 89, 072015 (2014)

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



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!)

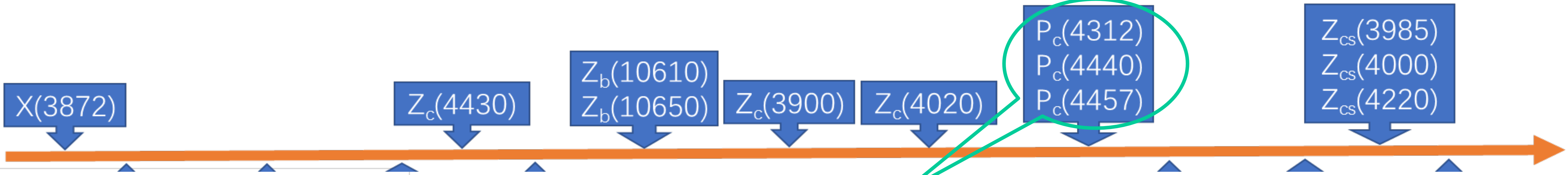
$Z_{cs}(3985)$ in $\bar{D}^* D_s$ + $\bar{D} D^*_s$ mode!

$Z_{cs}(4000)$ 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!

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



PRL 122, 222001 (2019)
9 fb^{-1} Run 1 & Run 2 data
246k selected $\Lambda_b \to J/\psi p K^-$ decays

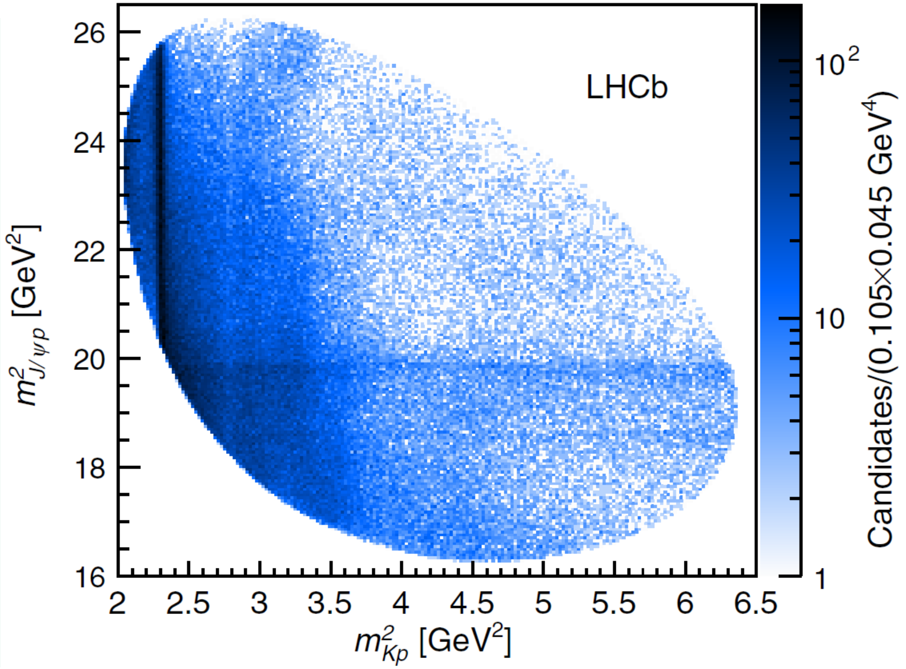
Pentaquark states close to charmed baryon-meson thresholds

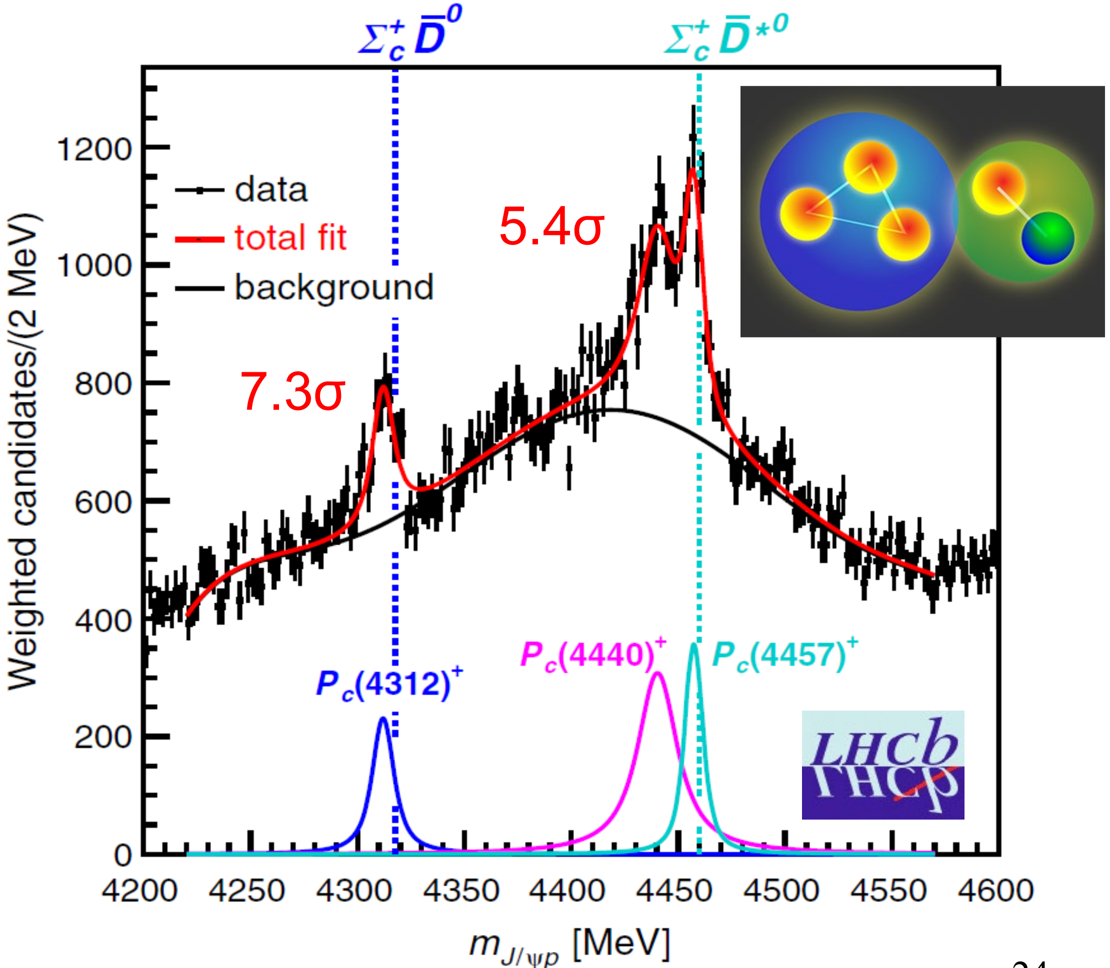
Spin and parity not determined yet.

Partial wave analysis of the full data sample is in progress.

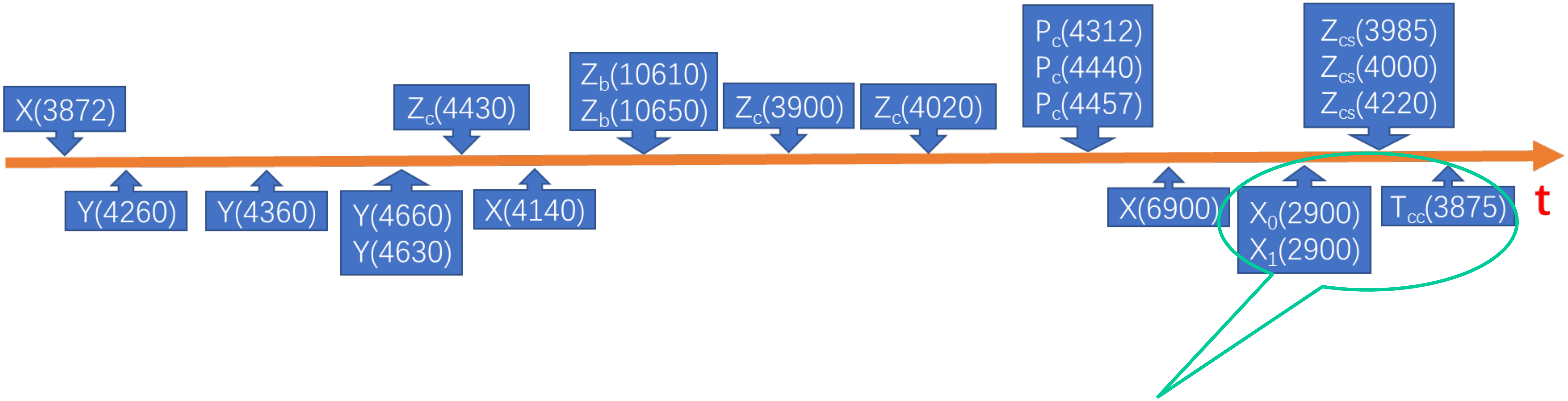
Good hadronic molecule candidates.

More states may exist close to other thresholds.





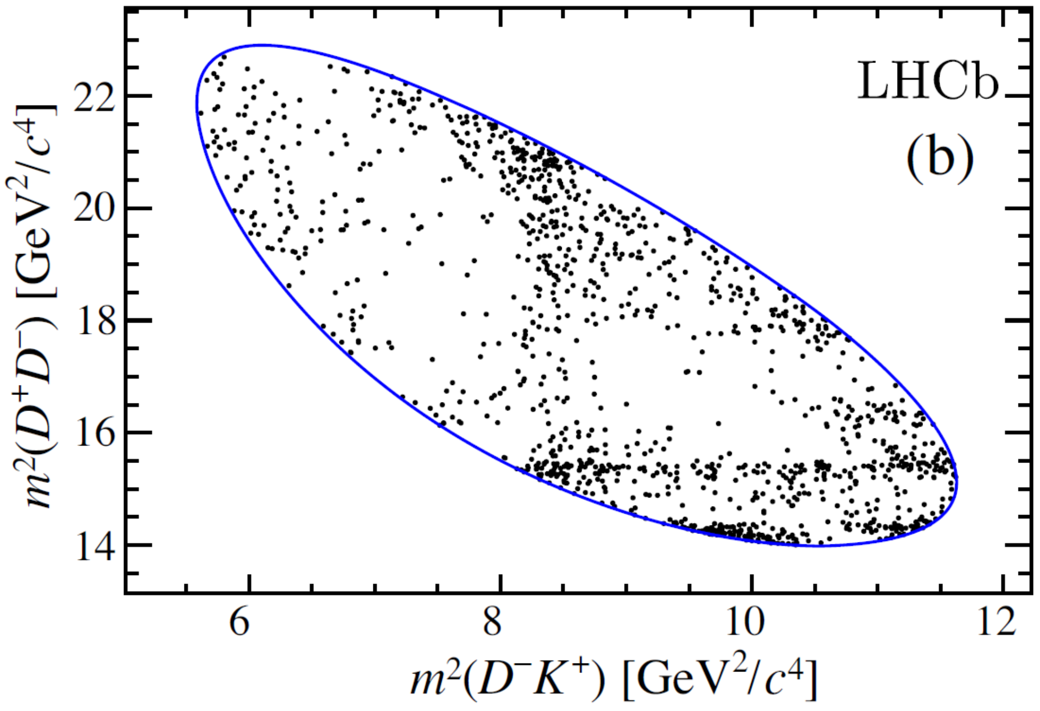
State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$

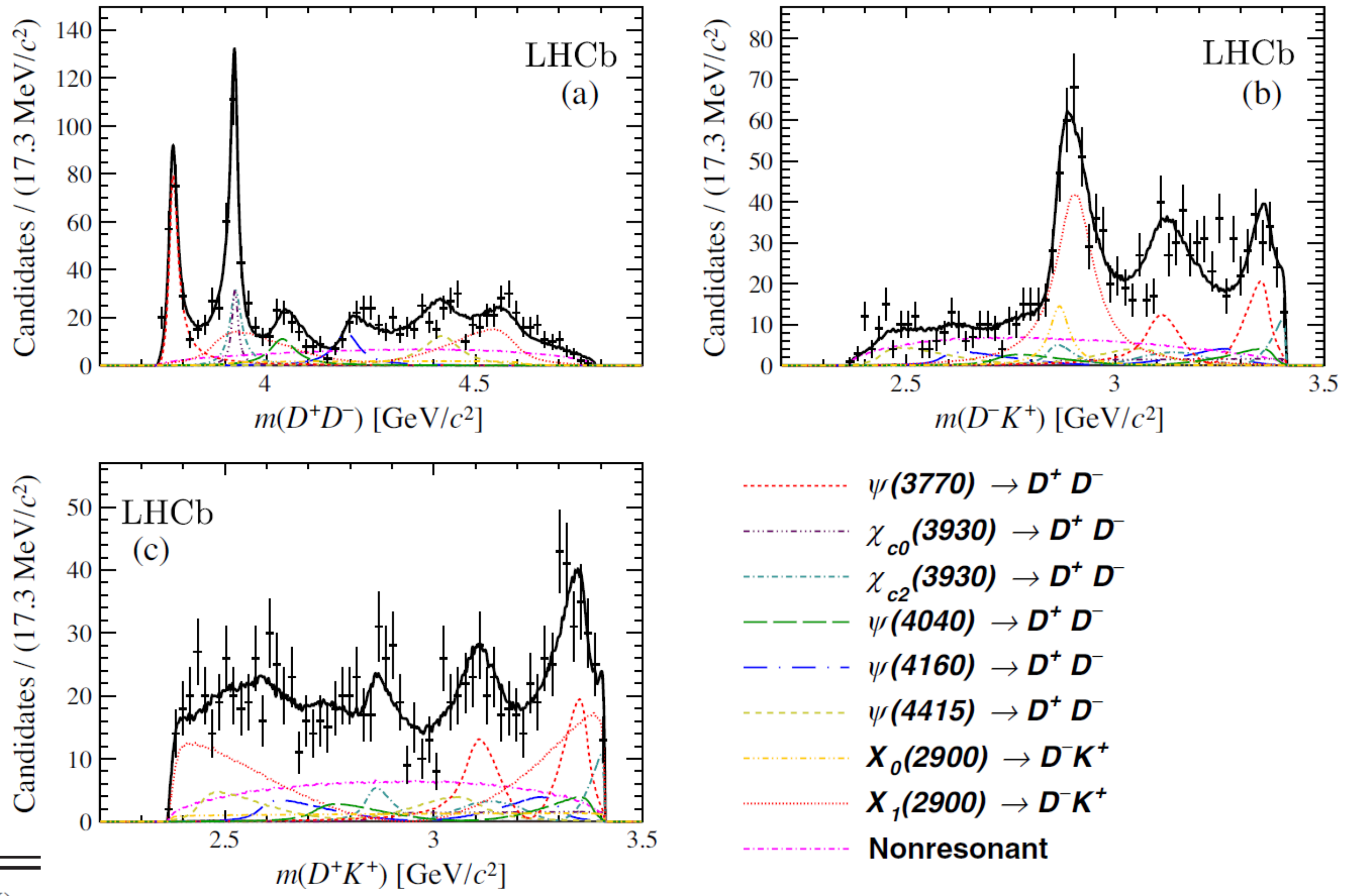


States with 4 flavors (T_{cs}) or two heavy quarks (T_{cc})

Evidence for T_{cs} states decay into D^-K^+

PRD 102, 112003 (2020)
PRL 125, 242001 (2020)
9 fb^{-1} Run 1 & Run 2 data
1260 selected $B^+ \to D^+D^-K^+$ decays



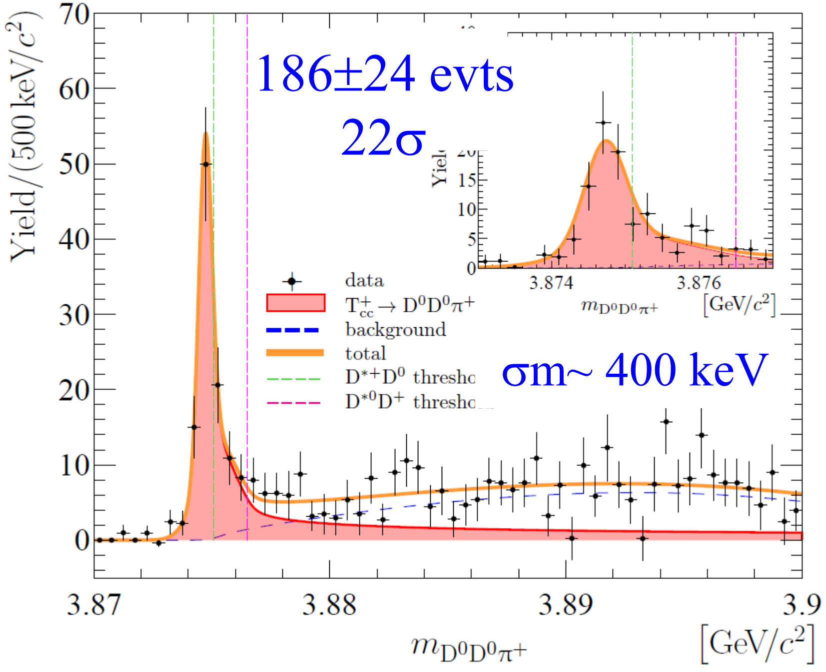


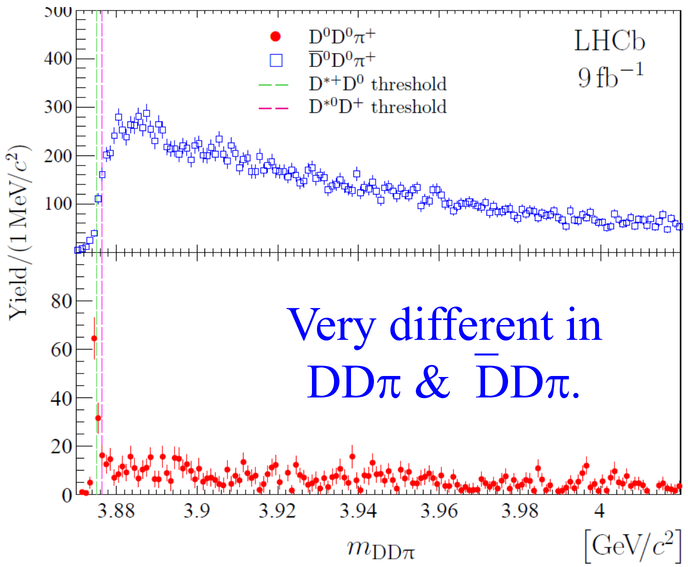
Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
$X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
$X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11 \pm 4$

The significance of the disagreement in the $m(D^-K^+)$ distribution is 3.9σ and is most apparent in the region $m(D^-K^+)$=2.9 GeV. This discrepancy could be explained by a new, manifestly exotic, charm-strange resonance decaying to the D^-K^+ final state.

arXiv:2109.01038
arXiv:2109.01056
9 fb^{-1} Run 1 & Run 2 data

The $T_{cc}(3875)$ state decays into $D^0D^0\pi^+$





Fit with a unitarized three-body Breit–Wigner function:

$$\mathfrak{F}_f^{\mathrm{U}}(s) = \varrho_f(s)\,|\mathcal{A}_{\mathrm{U}}(s)|^2\,, \qquad f \in \{D^0D^0\pi^+, D^0D^+\pi^0, D^0D^+\gamma\}$$

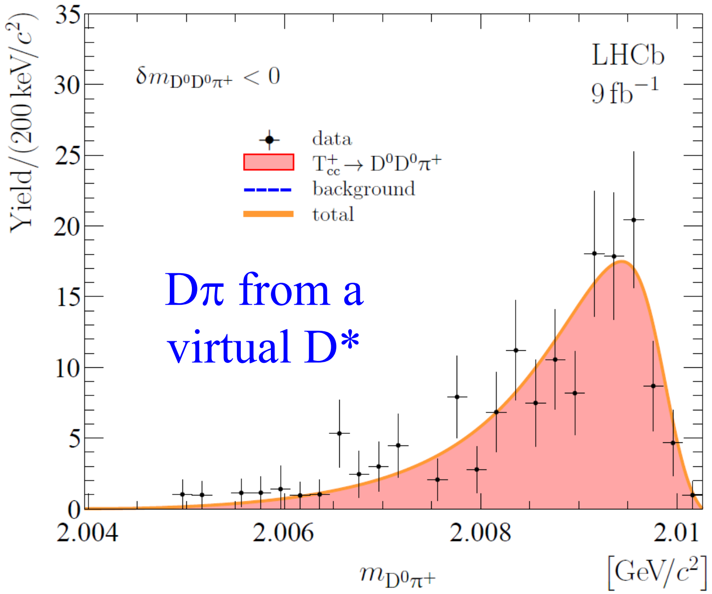
$$\mathcal{A}_{\mathrm{U}}(s) = \frac{1}{m_{\mathrm{U}}^2 - s - i m_{\mathrm{U}}\hat{\Gamma}(s)}\,,$$

$J^P=1^+$ & I=0 assumed.

Relative to D^0D^{*+} threshold:

$$\delta m_{\mathrm{pole}} = -360 \pm 40\,^{+4}_{-0}\ \mathrm{keV}/c^2$$
$$\Gamma_{\mathrm{pole}} = 48 \pm 2\,^{+0}_{-14}\ \mathrm{keV}\,,$$

$$\delta m_{\mathrm{BW}} = -273 \pm 61 \pm 5\,^{+11}_{-14}\ \mathrm{keV}/c^2$$
$$\Gamma_{\mathrm{BW}} = 410 \pm 165 \pm 43\,^{+18}_{-38}\ \mathrm{keV}\,,$$



Characteristic size of a D^0D^{*+} molecule

$$R_{\Delta E} \equiv \frac{1}{\gamma} = 7.5 \pm 0.4\,\mathrm{fm}$$

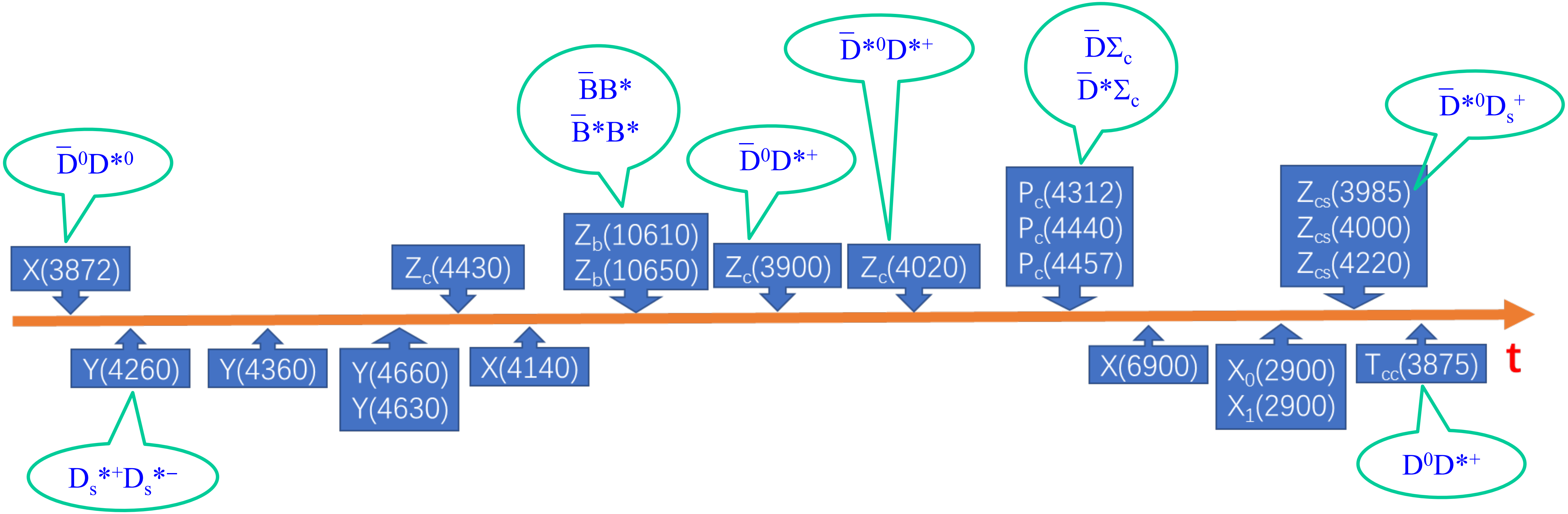
The compositeness

$$Z = 1 - \sqrt{\frac{1}{1 + 2\,|r/\Re\,a|}}$$

$$Z < 0.52\,(0.58)\ \text{at}\ 90\,(95)\%\ \text{CL}\,.$$

(*Z=0* for molecular states).

Tentative conclusions:

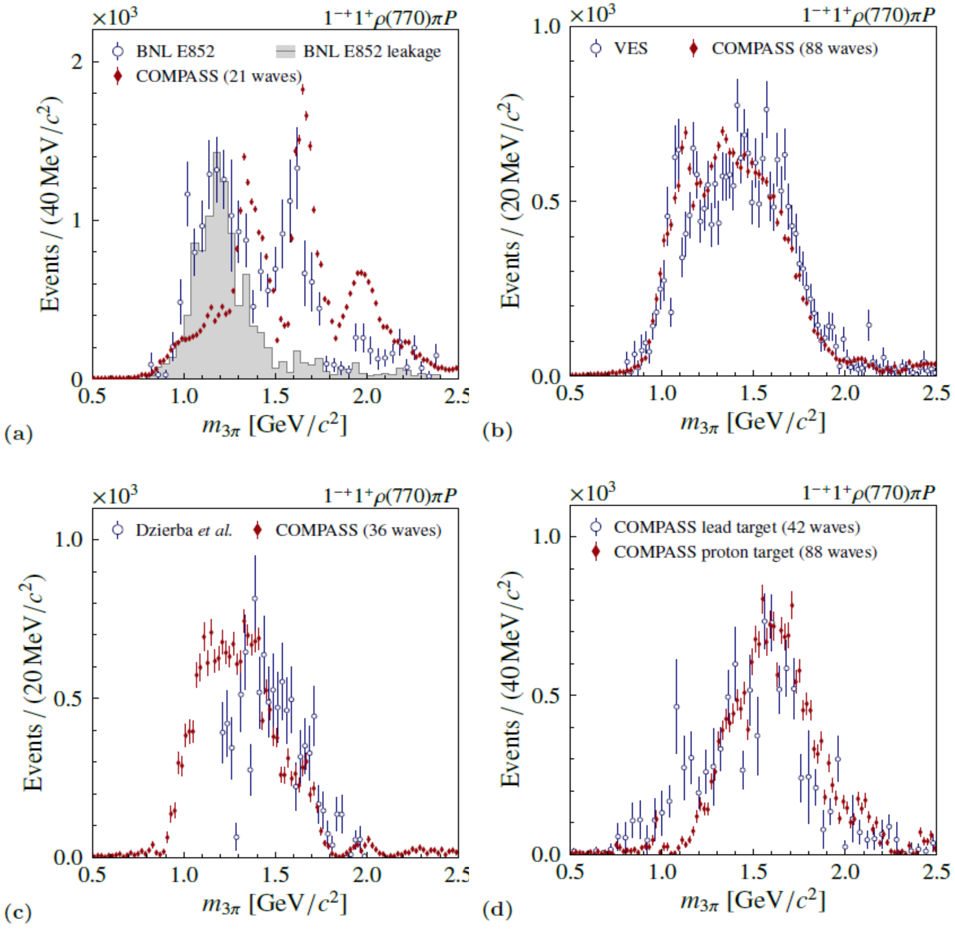


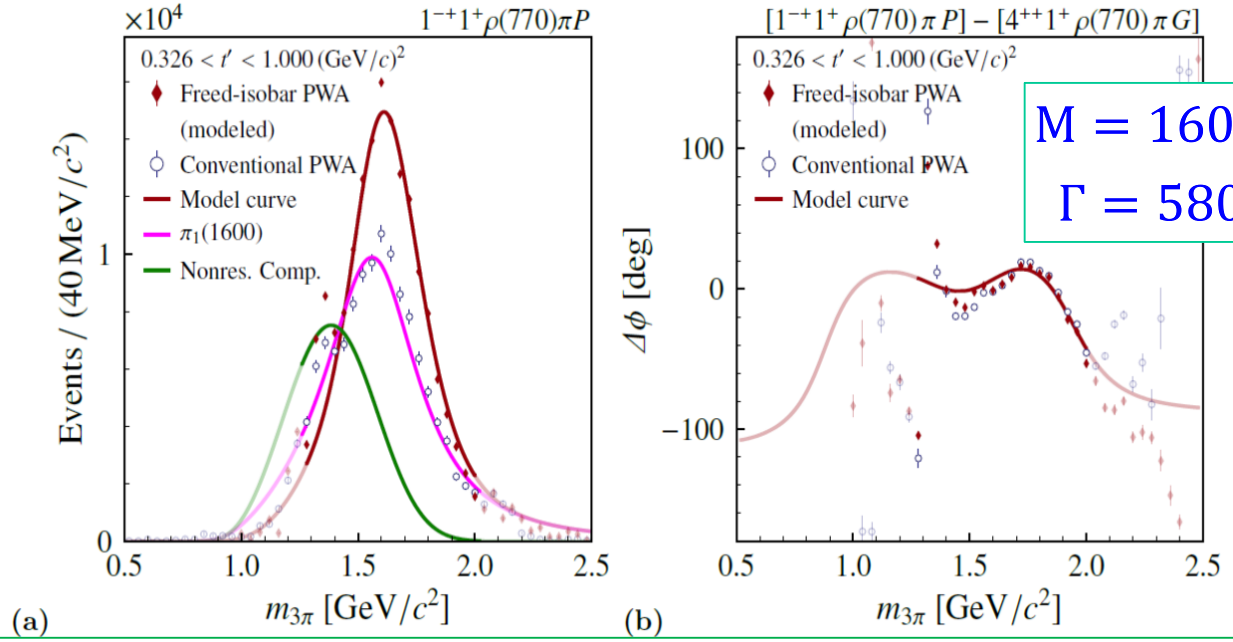
1. We do observed hadronic molecules close to the thresholds
2. There must be dynamics beyond molecule to explain many other states far from thresholds of narrow hadrons
3. Similar states in light quark sector (u,d,s) may also exist

arXiv:2108.01744
PRD 98, 092003 (2018)
190 GeV $\pi^- p \to \pi^- \pi^+ \pi^- p$
46 million selected events

$J^{PC}=1^{-+}$ state $\pi_1(1600)$

Tensions between different experiments:





COMPASS

$M = 1600^{+110}_{-60}$ MeV
$\Gamma = 580^{+100}_{-230}$ MeV

- Conflicting conclusions from previous studies can be attributed to different models and treatment of t'-dependence of the amplitudes.
- Deck model can describe data in spectral shape and t'-dependence for the $J^{PC}=1^{-+}$ and other amplitudes.
- Freed-isobar fit results indicate that the P-wave $\pi^+\pi^-$ amplitude is dominated by $\rho(770)$ for both the $\pi_1(1600)$ and the nonresonant $J^{PC}=1^{-+}$ amplitudes.

"These findings largely confirm the underlying assumptions for the isobar model used in all previous partial-wave analyses addressing the $J^{PC}=1^{-+}$ amplitude." ➔ $\pi_1(1600)$ exists!

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

BESIII

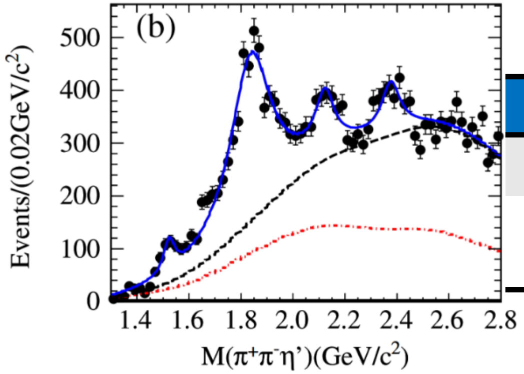
X(1835) observed in $J/\psi\to\gamma\eta'\pi^+\pi^-$

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

0.2B J/ψ events

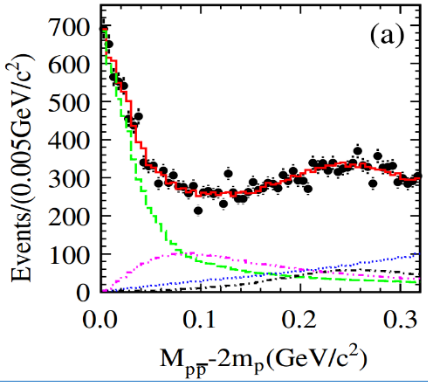
X($p\bar{p}$) observed in $J/\psi\to\gamma p\bar{p}$

PRL 108, 112003 (2012); PRL 115, 091803 (2015)



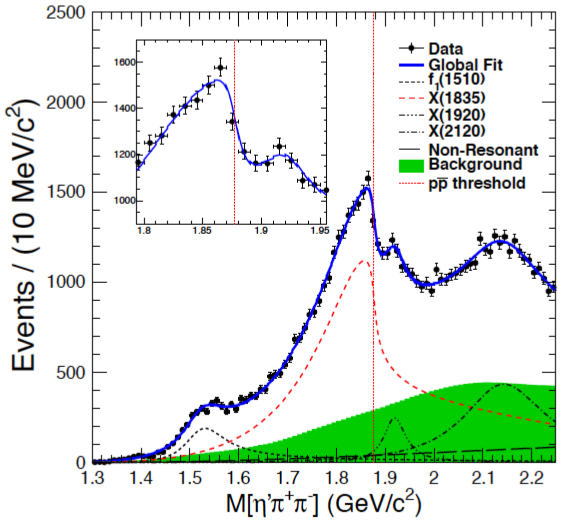
X(1835) $J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2

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.)



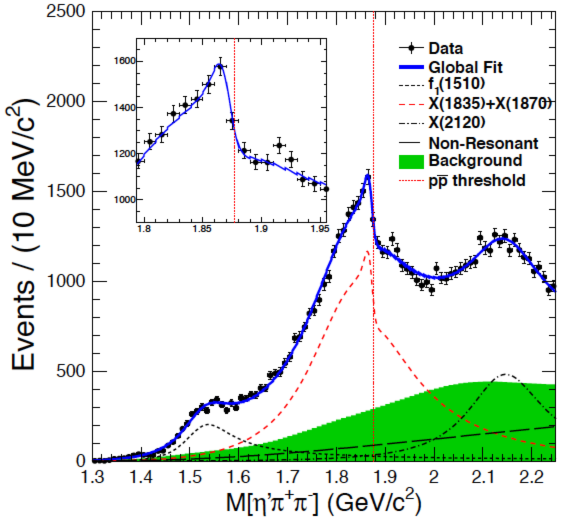
1.3B J/ψ events

PRL 117, 042002 (2016)



Model I:
Flatté line shape with strong coupling to $p\bar{p}$ and one additional narrow BW at ~ 1920 MeV

Model II:
Two coherent BWs, X(1835) and one additional, narrow BW at ~ 1870 MeV significance > 7σ



- Existence of a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold
- Existence of a $p\bar{p}$ molecule-like state or bound state?

Search for X(1835)'s other decay modes

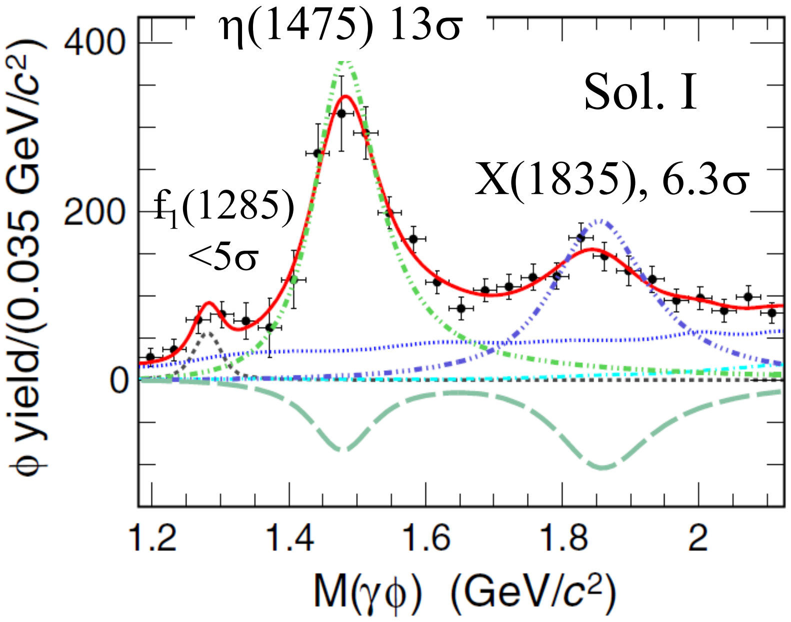
$J/\psi \rightarrow \gamma\gamma\phi$:

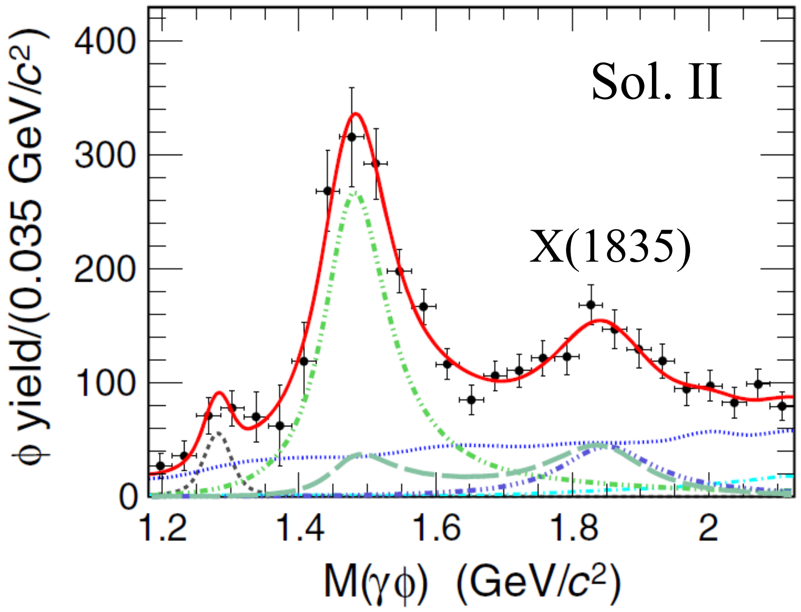
- ✓ First observation of $\eta(1475)/X(1835) \rightarrow \gamma\phi$.
- ✓ Angular distribution favor $J^{PC} = 0^{-+}$.
- ✓ Sizeable $s\bar{s}$ components in X(1835): more complicated than a pure $N\overline{N}$ state

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

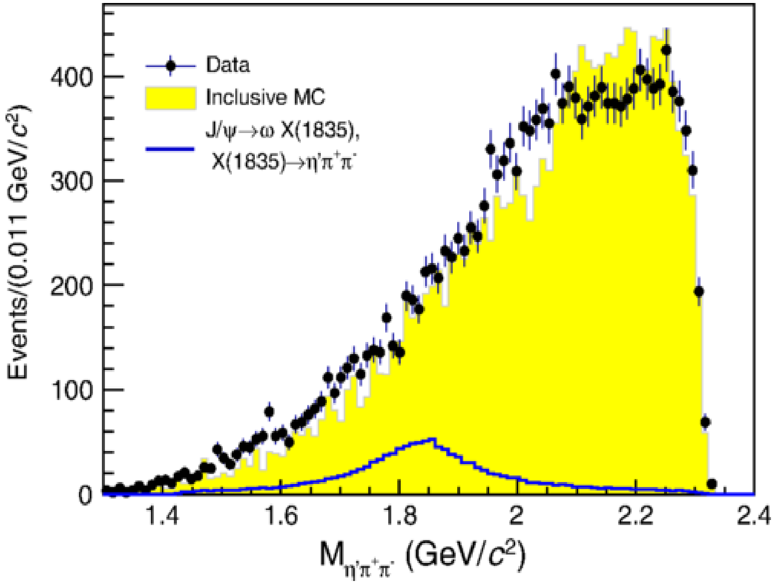
- ✓ No obvious signal of X(1835) is found.
- ✓ B.R.< 6.2×10^{-5} @ 90% C. L.

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





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



More in parallel talk of Tingting Han on Sunday.

Summary

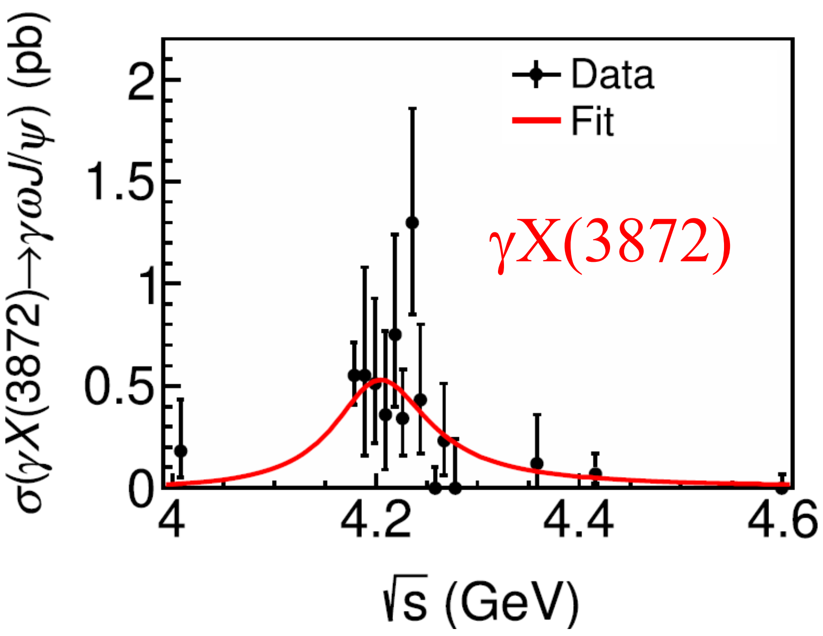
- Lots of progress in the experimental study of hadron spectroscopy.
- Spectroscopy of hadronic molecules to be further investigated.
- States formed by other dynamics may have been discovered.
- Study of similar states in the light quark sector (u,d,s) may reveal even richer phenomenon of strong interaction.
- More results to come (Belle II, BESIII, COMPASS, GlueX, LHCb, …), and lots of opportunities and challenges ahead.

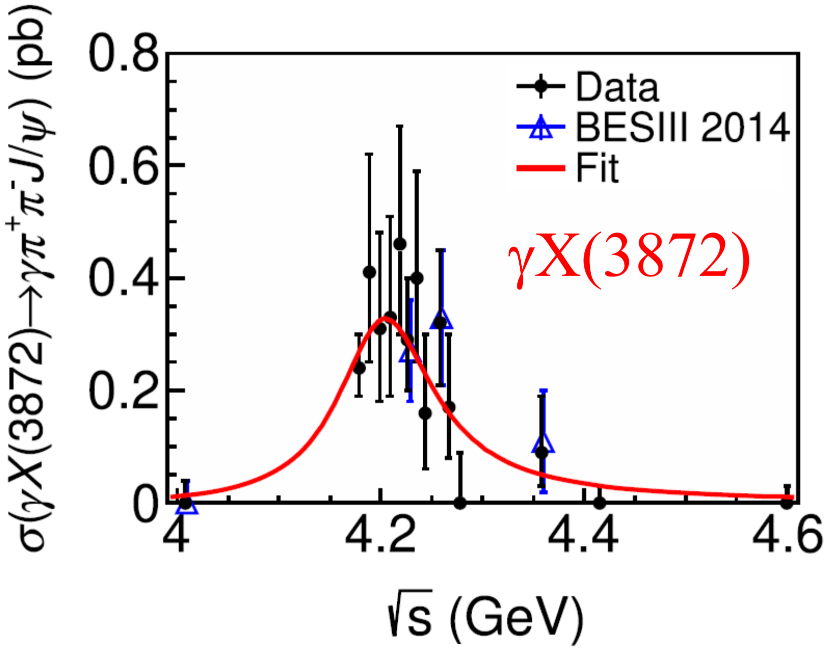
Thank you very much!

Backup slides

Y(4220) → γ + X(3872) ?

PRL 122, 232002 (2019)





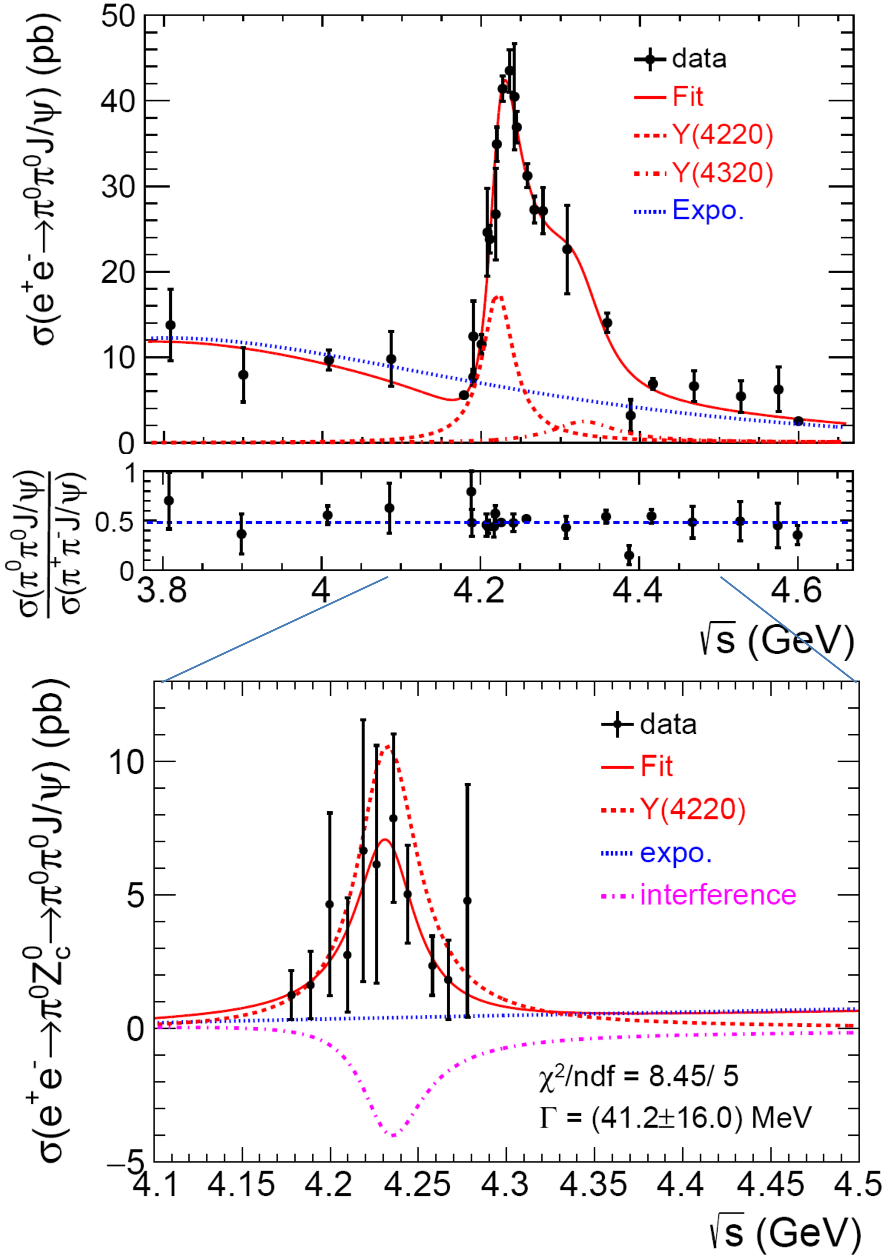
$$M[Y(4200)] = 4200.6^{+7.9}_{-13.3} \pm 3.0 \ \mathrm{MeV}/c^2$$

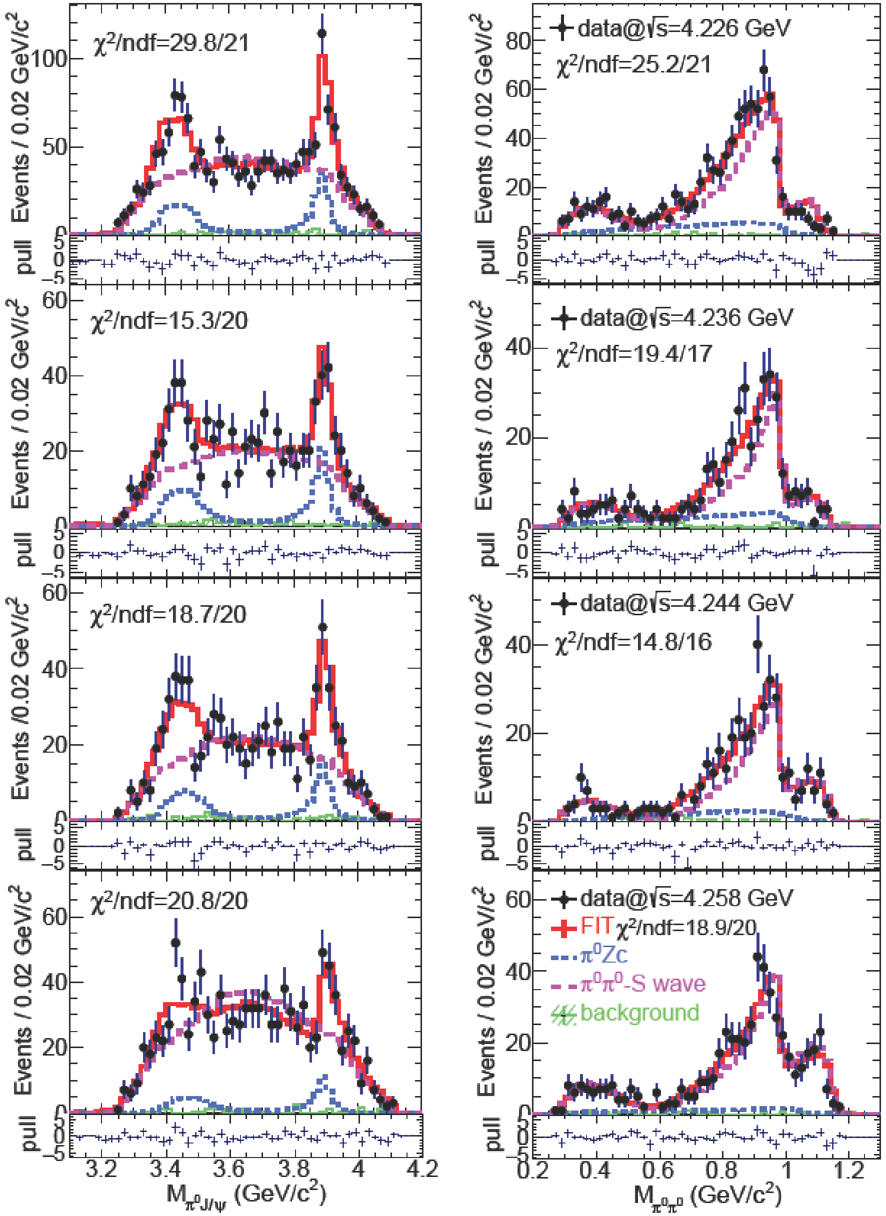
$$\Gamma[Y(4200)] = 115^{+38}_{-26} \pm 12 \ \mathrm{MeV}$$

Need data between 4 and 4.16 GeV to check if there is contribution from ψ(4040).

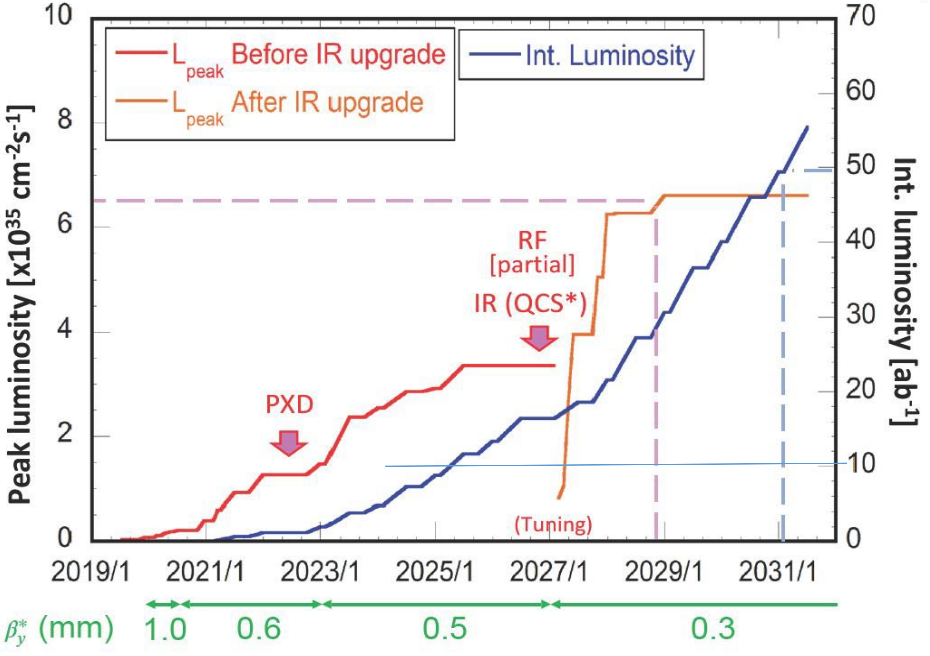
Y(4220)→π Z_c(3900)→ππJ/ψ

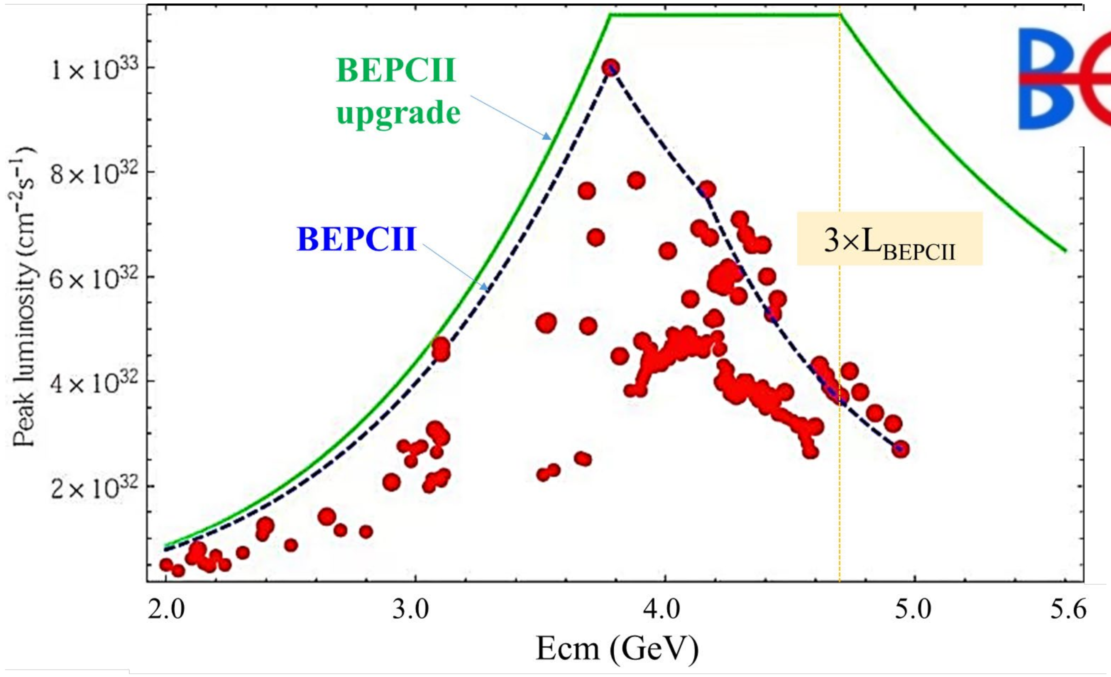
PRD 102, 012009 (2020)





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		$L=1\text{-}2 \times 10^{34}$ $300\ fb^{-1}$	
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								$3000\ fb^{-1}$	