

Heavy flavor spectroscopy

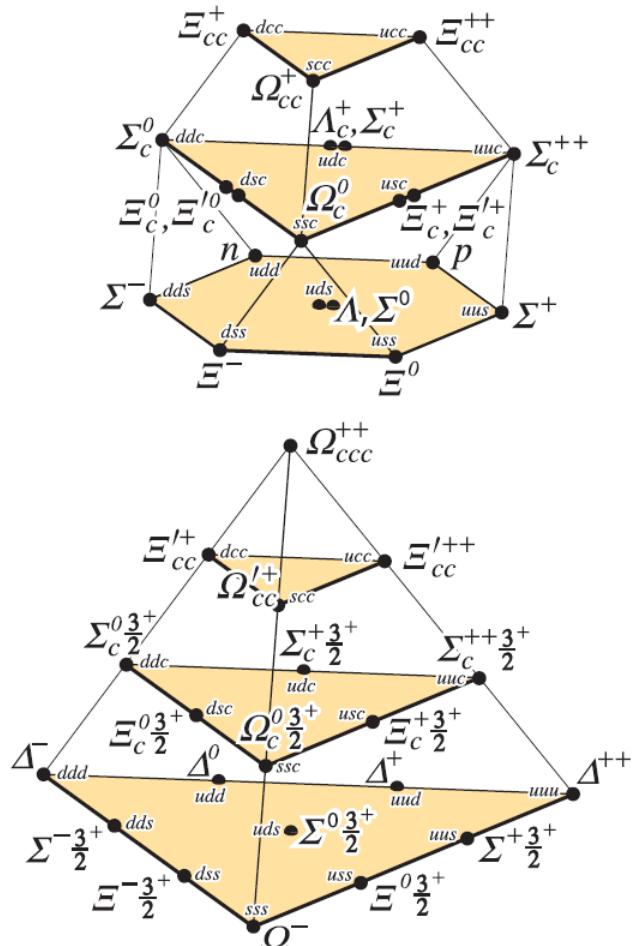
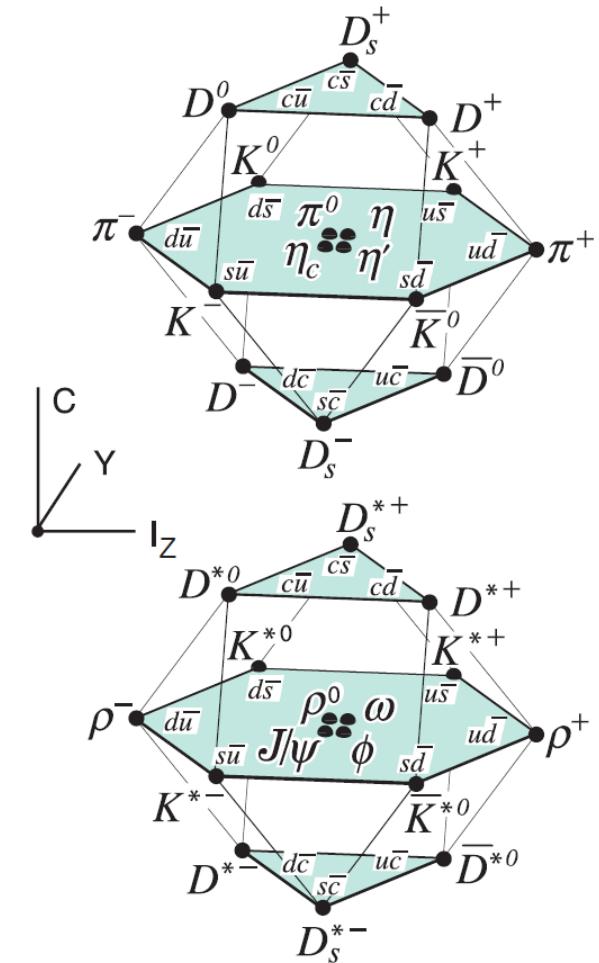
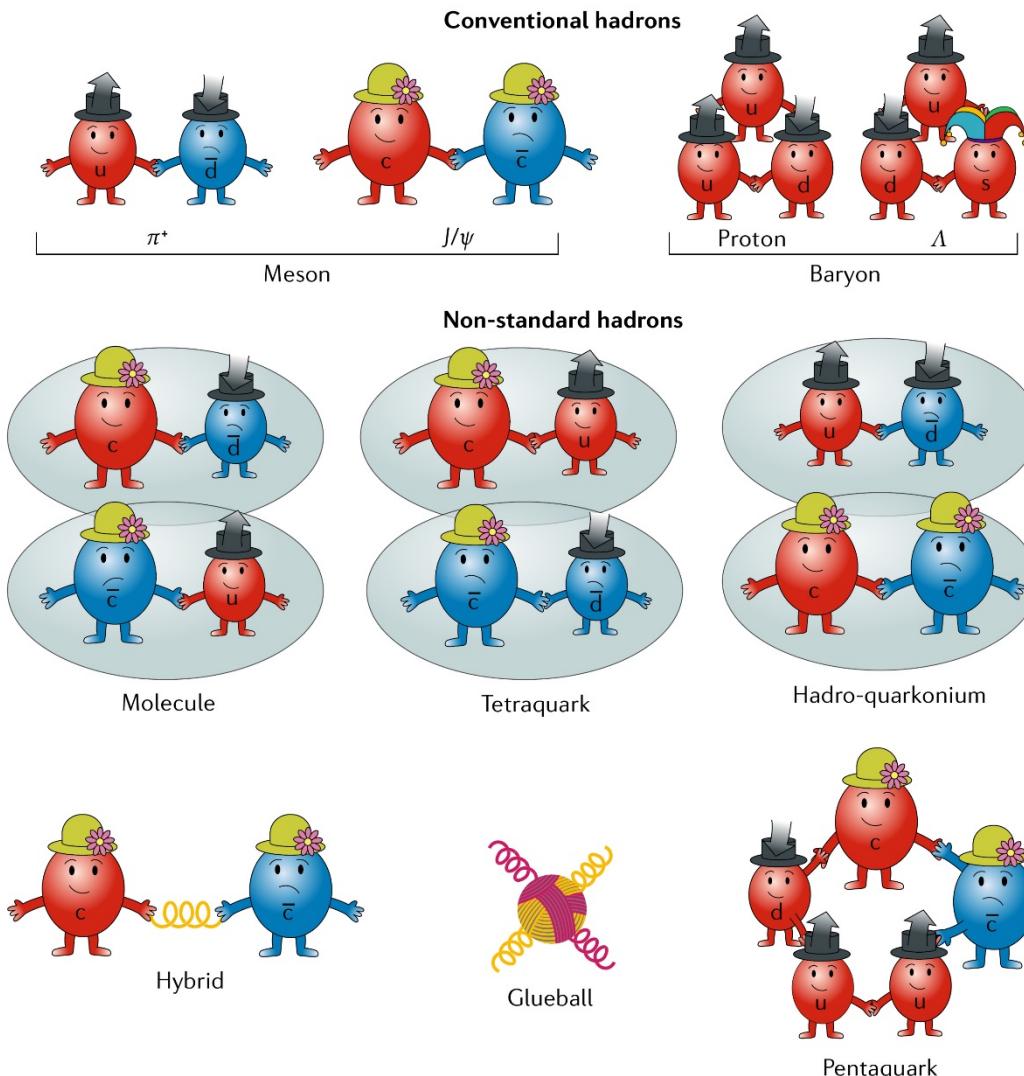
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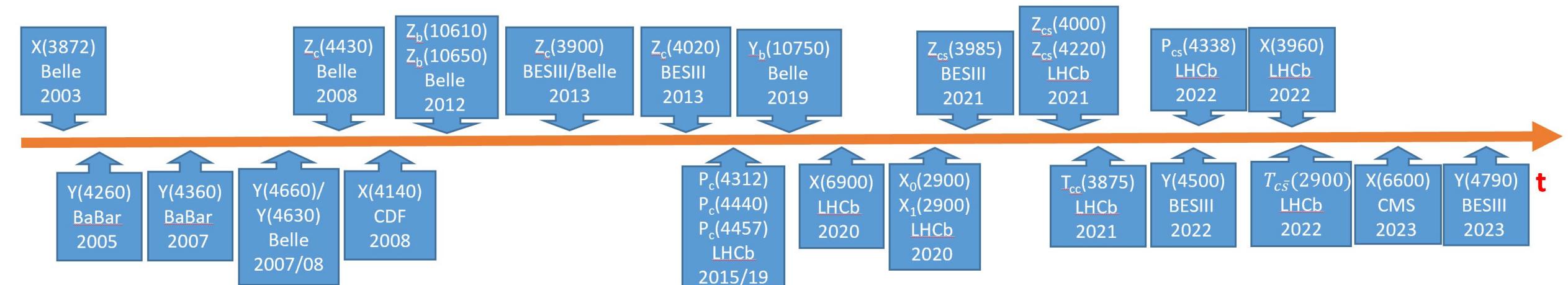
31st Lepton Photon Conference 2023
MELBOURNE CONVENTION
& EXHIBITION CENTRE
17 - 21 JULY

Hadrons: conventional & exotic



$SU(4)$ multiplets of mesons & baryons

- 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

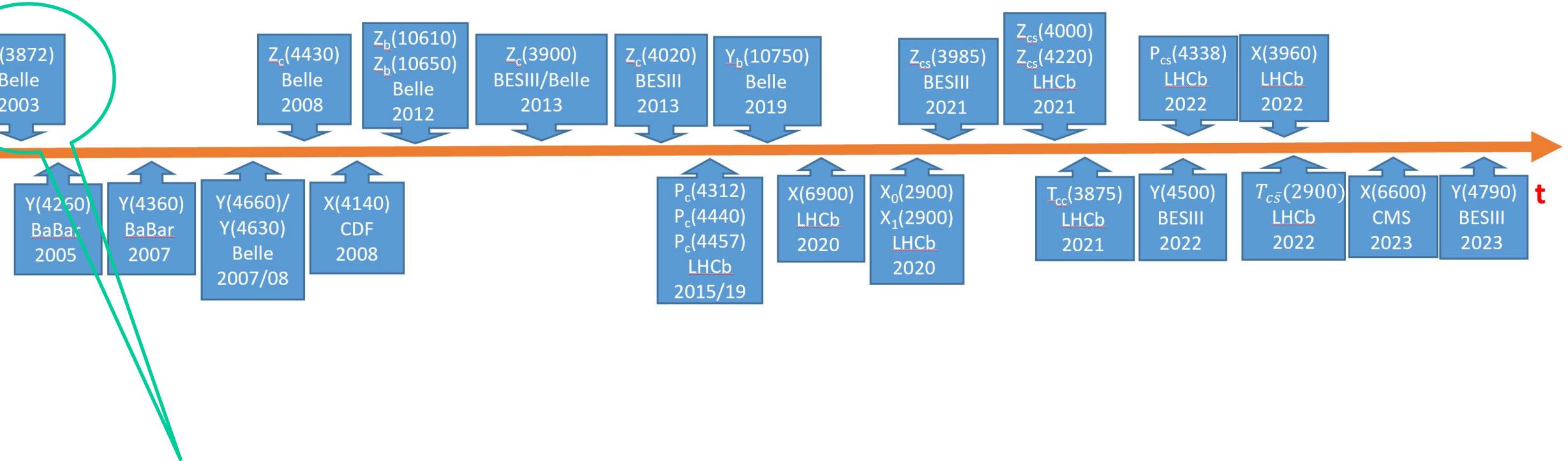
P_Q : I=1/2 & a $Q\bar{Q}$ pair

Y : $J^{PC}=1^{--}$

T_{QQ} : tetraquark state

X : other states

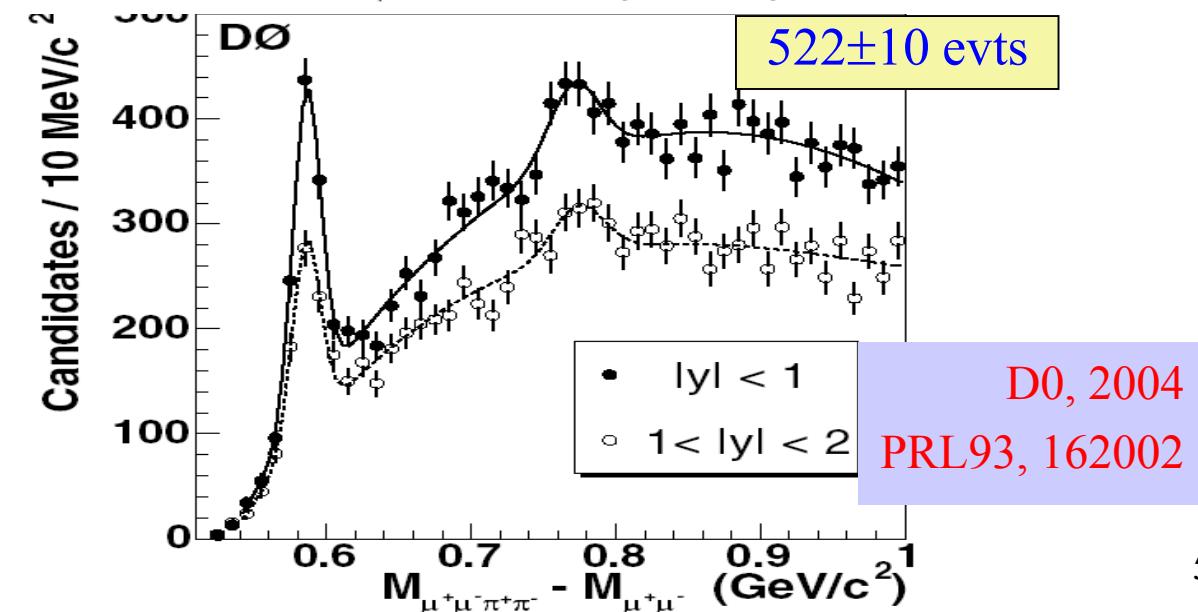
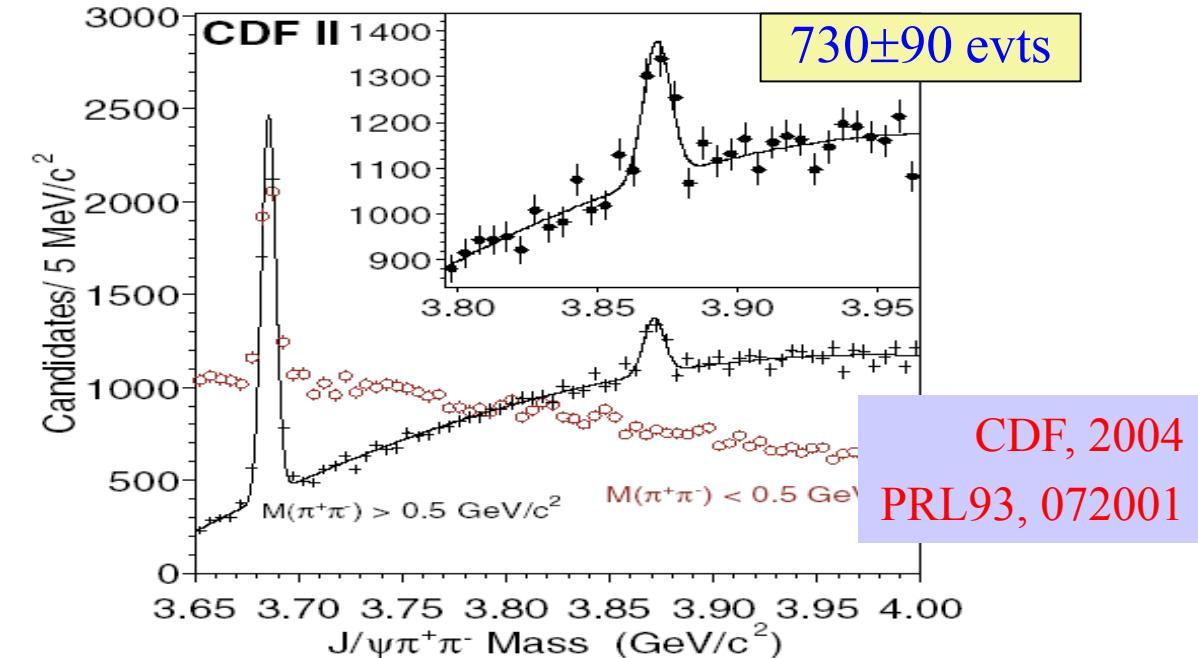
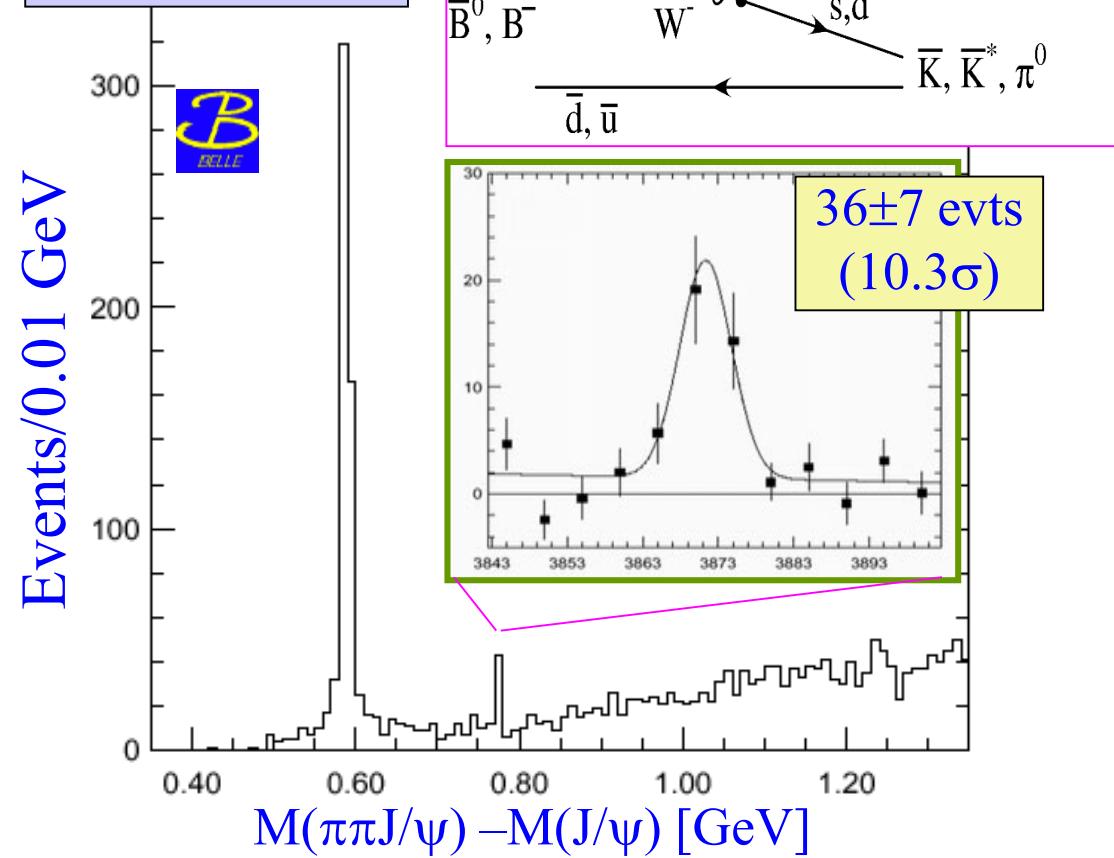
New spectrum emerges although more effort is needed to understand the nature of them.



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



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 $B^+ \rightarrow J/\psi \pi^+ \pi^- K^+$
3871.9 ± 0.7 ± 0.2		20	ABLIKIM	2014	BES3 $e^+ e^- \rightarrow J/\psi \pi^+ \pi^- \gamma$
3871.95 ± 0.48 ± 0.12		0.6k	AAIJ	2012H	LHCb $p p \rightarrow J/\psi \pi^+ \pi^- X$
3871.85 ± 0.27 ± 0.19		170	2 CHOI	2011	BELL $B \rightarrow K \pi^+ \pi^- J/\psi$
3873 ^{+1.8} _{-1.6} ± 1.3		27	3 DEL-AMO-SANCH..	2010B	BABR $B \rightarrow \omega J/\psi K$
3871.61 ± 0.16 ± 0.19		6k	4, 3 AALTONEN	2009AU	CDF2 $p \bar{p} \rightarrow J/\psi \pi^+ \pi^- X$
3871.4 ± 0.6 ± 0.1		93.4	AUBERT	2008Y	BABR $B^+ \rightarrow K^+ J/\psi \pi^+ \pi^-$
3868.7 ± 1.5 ± 0.4		9.4	AUBERT	2008Y	BABR $B^0 \rightarrow K_S^0 J/\psi \pi^+ \pi^-$
3871.8 ± 3.1 ± 3.0		522	5, 3 ABAZOV	2004F	D0 $p \bar{p} \rightarrow J/\psi \pi^+ \pi^- X$

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

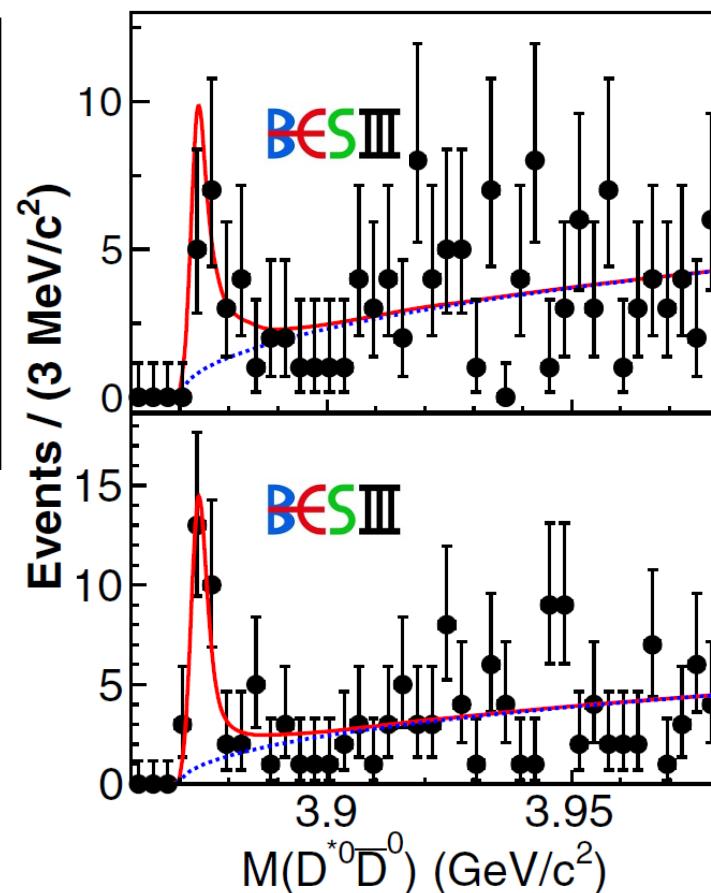
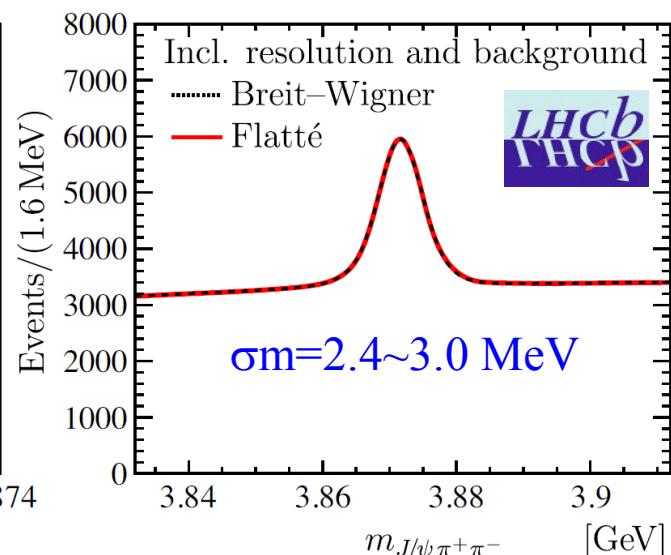
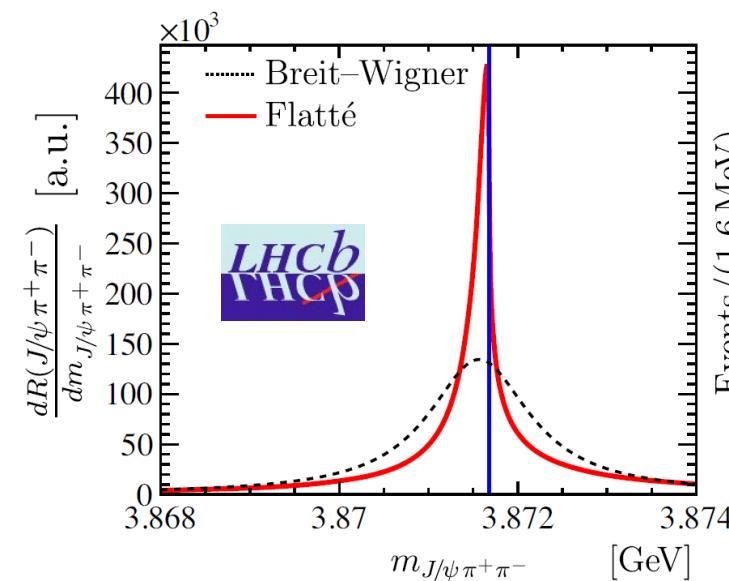
$$E_b = -0.04 \pm 0.12 \text{ MeV}$$

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

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

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 ± 0.24 ± 0.10		15.6k	¹ AAJ	2020AD LHCb	$p p \rightarrow J/\psi \pi^+ \pi^- X$
0.96 ^{+0.19} _{-0.18} ± 0.21	BW width!	4.2k	² AAJ	2020S LHCb	$B^+ \rightarrow J/\psi \pi^+ \pi^- K^+$



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 $\bar{D}^0 D^{*0}$!

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

BESIII may supply crucial information on g & line shape.

Mass resolution $\sigma_m < 1 \text{ MeV}$!

PRL124, 242001
(2020)

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

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

$$\frac{d\text{Br}(D^0 \bar{D}^0 \pi^0)}{dE} = B \frac{1}{2\pi} \times \frac{\textcolor{red}{g} * k_{\text{eff}}(E)}{|D(E)|^2} \times \text{Br}(D^{*0} \rightarrow D^0 \pi^0)$$

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

$$D(E) = E - \textcolor{red}{E}_X + \frac{1}{2} \textcolor{red}{g} * (\kappa_{\text{eff}}(E) + ik_{\text{eff}}(E) + \kappa_{\text{eff}}^c(E) + ik_{\text{eff}}^c(E)) + \frac{i}{2} \Gamma_0$$

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

$$\begin{aligned} \kappa_{\text{eff}}(E) = & -\sqrt{\mu_p} \sqrt{\sqrt{(E - E_R)^2 + \Gamma^2/4} - E + E_R} \\ & + \sqrt{\mu_p} \sqrt{\sqrt{(E_X - E_R)^2 + \Gamma_X^2/4} - E_X + E_R} \end{aligned}$$

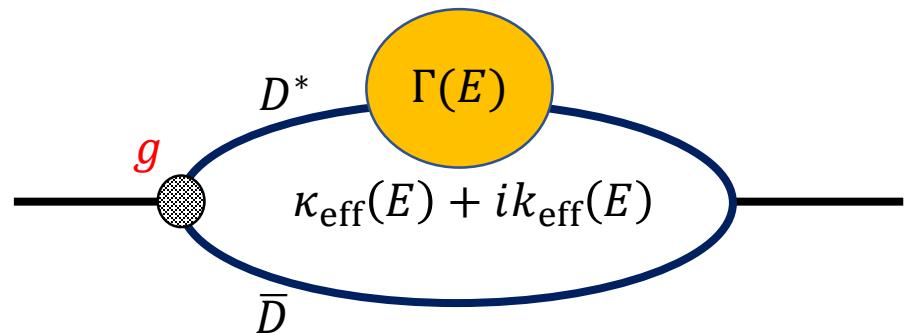
$$\Gamma_0 = \Gamma_{\pi^+ \pi^- J/\psi} + \Gamma_{\text{known}} + \Gamma_{\text{unknown}}$$

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

superscript c: charged $D^{+} D^-$

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

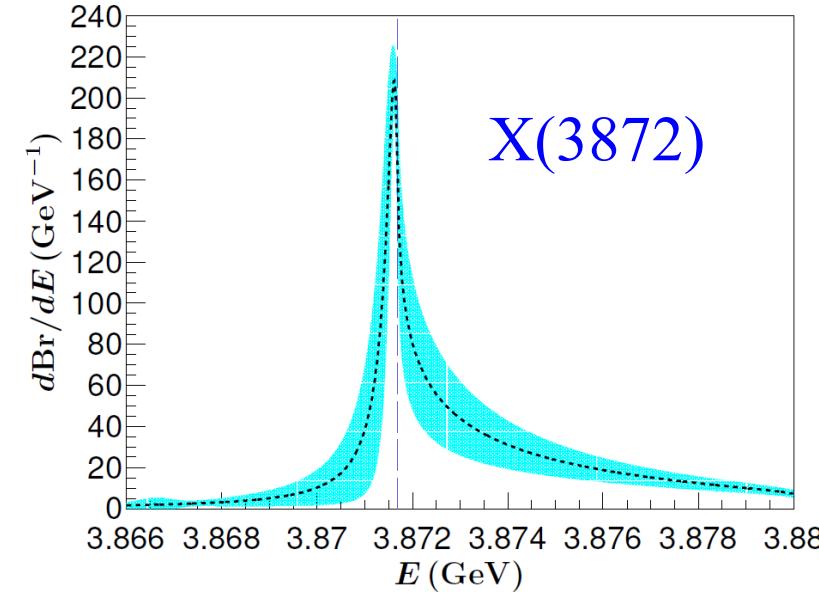
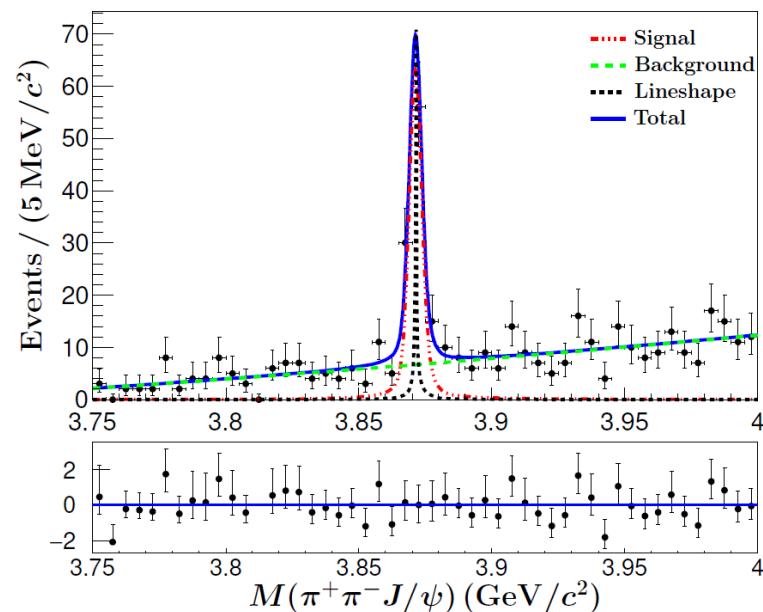
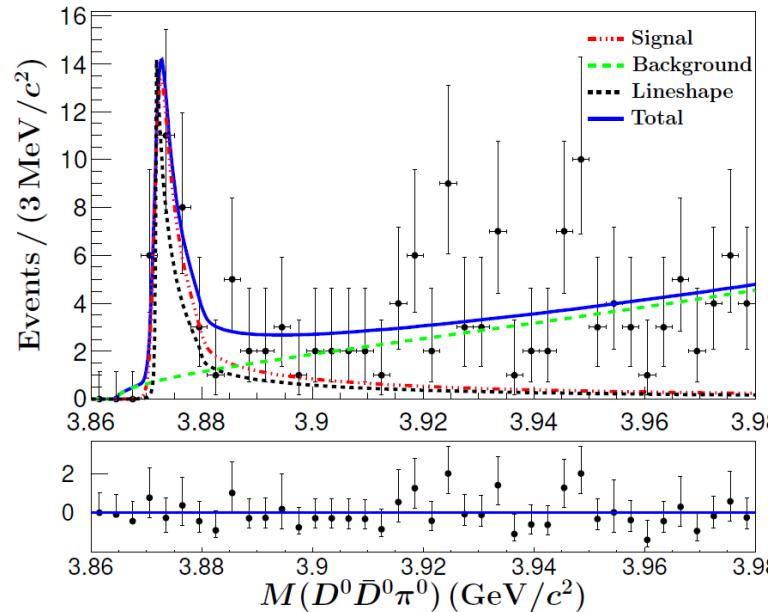
[Chunhua Li, Chang-Zheng Yuan, PRD 100, 094003 (2019)]



Key features:

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

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

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

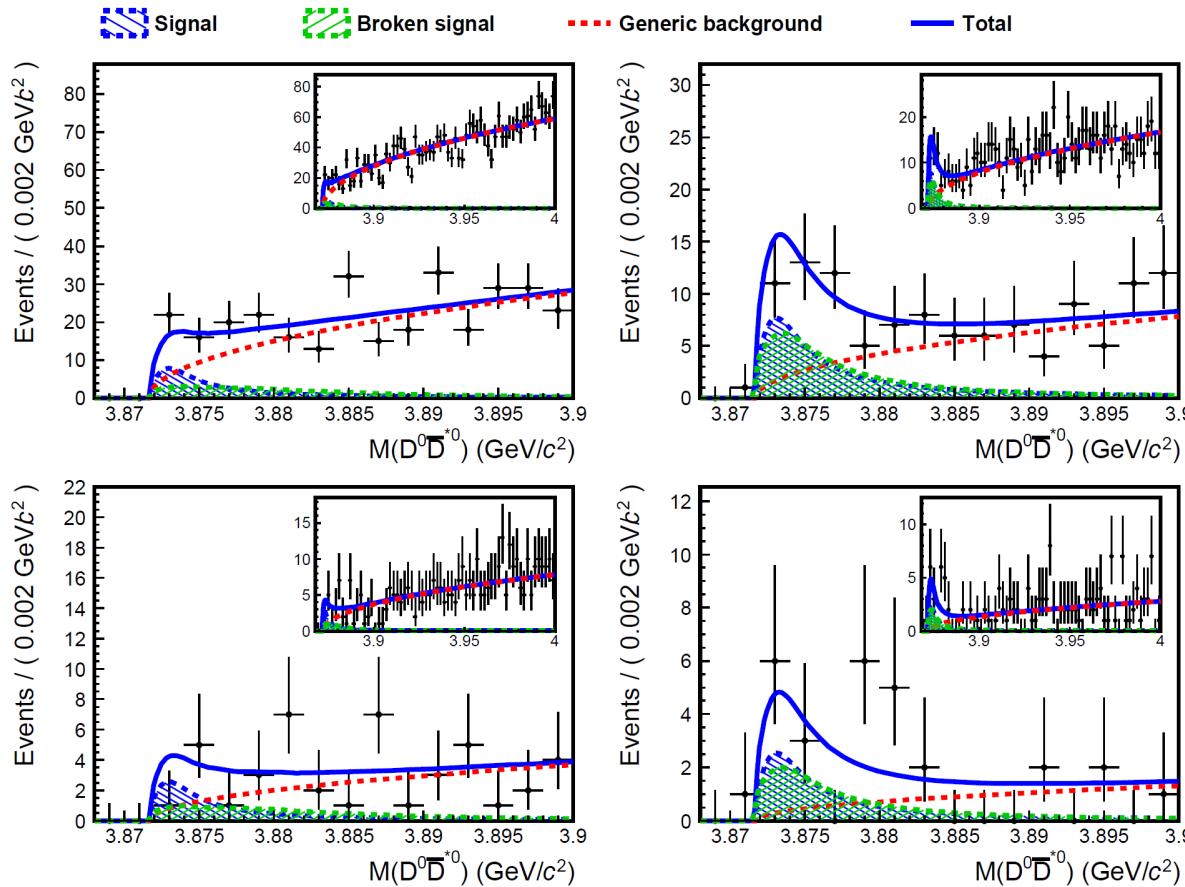
$$E_{II} = (0.26 \pm 5.74^{+5.14}_{-38.32}) + (-1.71 \pm 0.90^{+0.60}_{-1.96})i \text{ MeV}$$

Parameters	BESIII (<i>prelim.</i>)	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

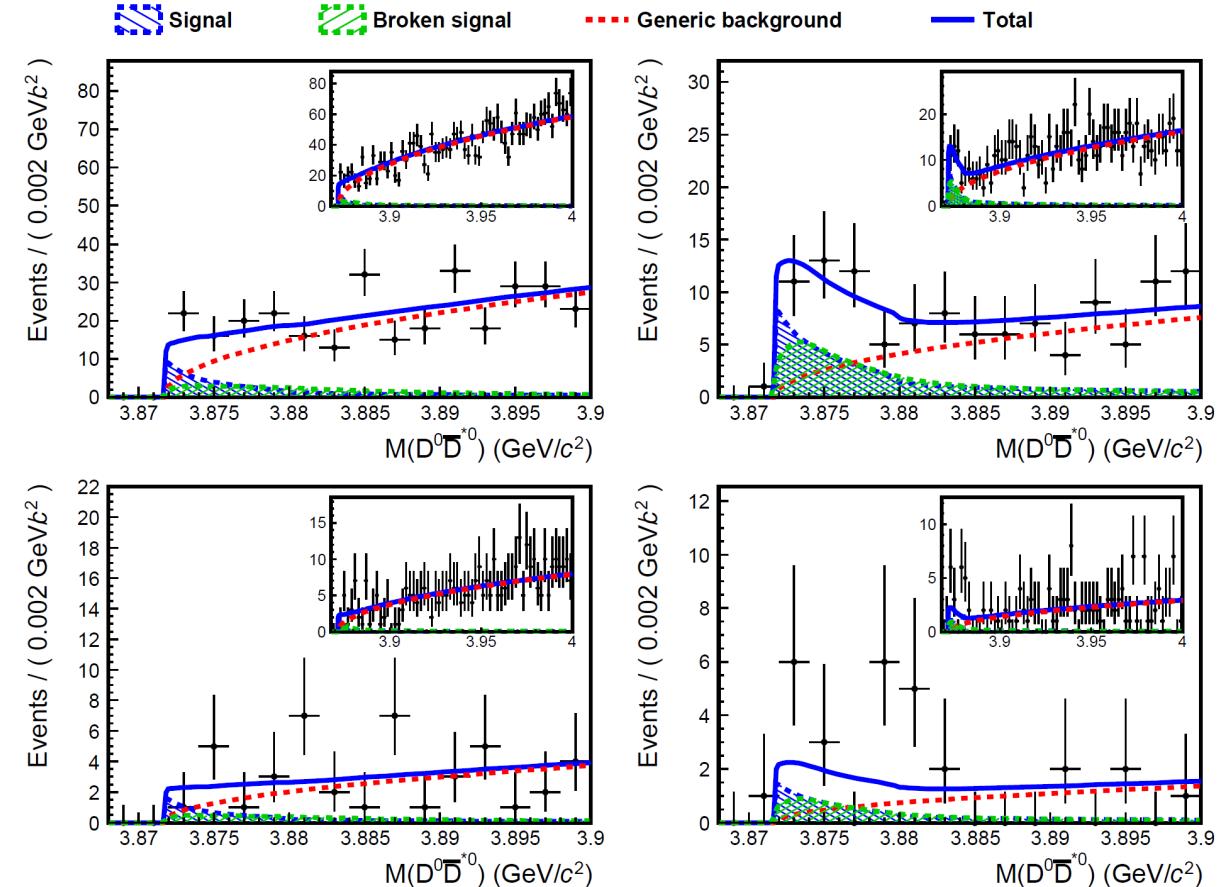
Weinberg's compositeness: $Z = 1$: pure elementary state; $Z = 0$: pure bound (composite) state.

X(3872) line shape @ Belle

BW parametrization

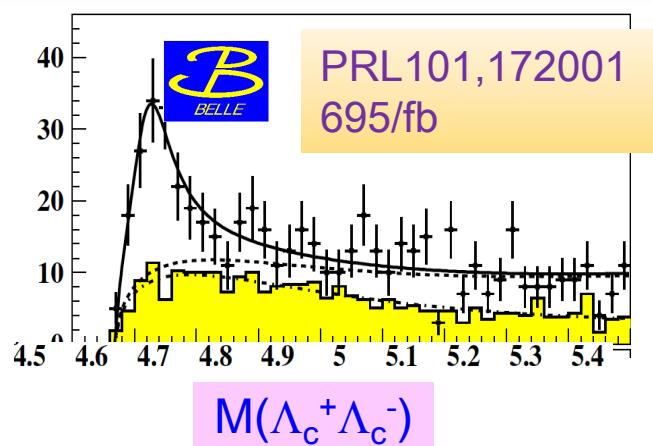
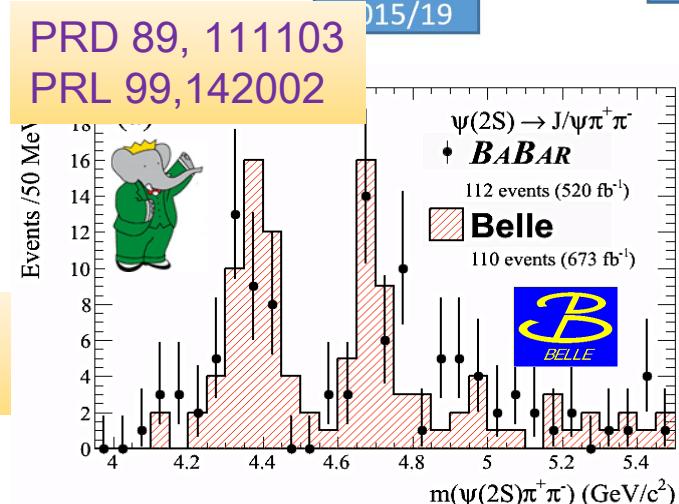
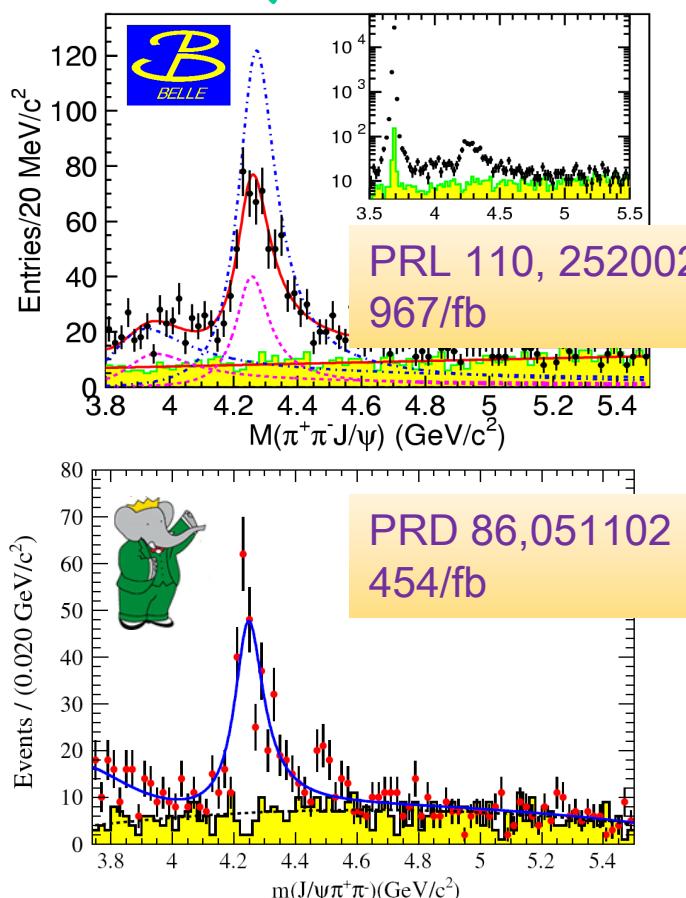
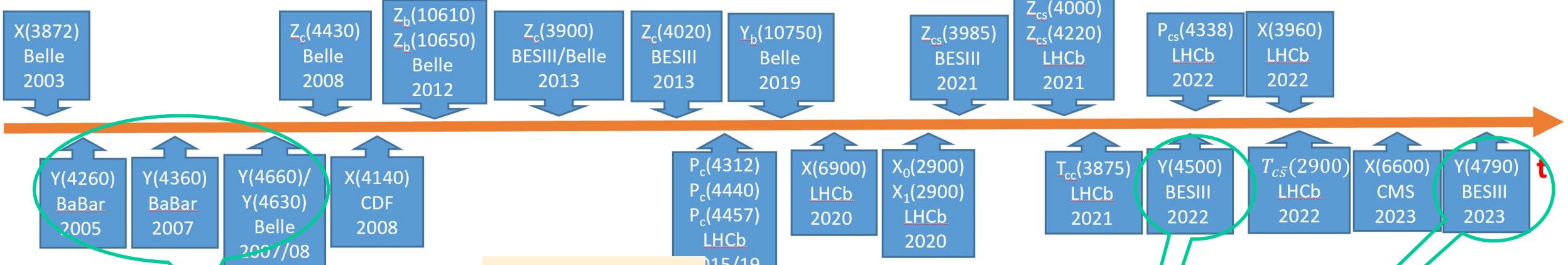


Flatté parametrization

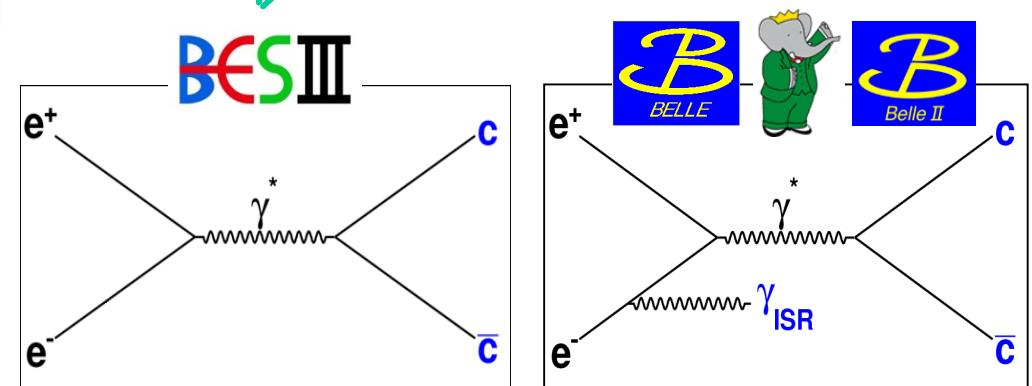


$m_{\text{BW}} = 3873.71^{+0.56}_{-0.50}(\text{stat}) \pm 0.13(\text{syst}) \text{ MeV}/c^2$,
 $\Gamma_{\text{BW}} = 5.2^{+2.2}_{-1.5}(\text{stat}) \pm 0.4(\text{syst}) \text{ MeV}$.

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

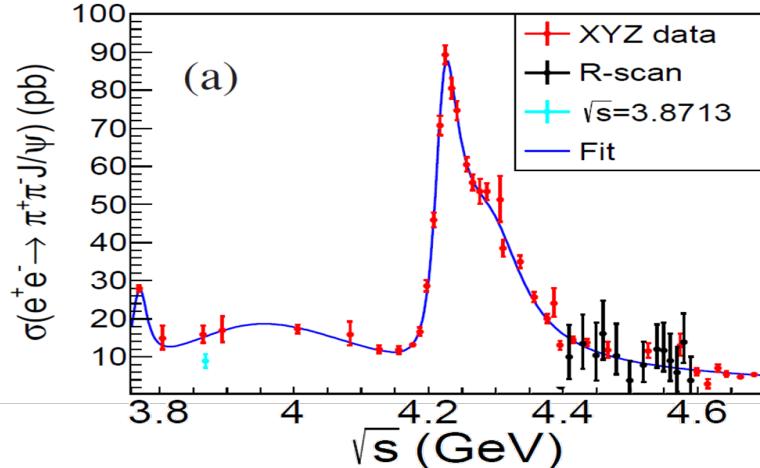


The Y states discovered via initial state radiation (ISR) in e^+e^- annihilation have $J^{PC}=1^{--}$. Direct e^+e^- annihilation experiment BESIII can measure them in higher precision.

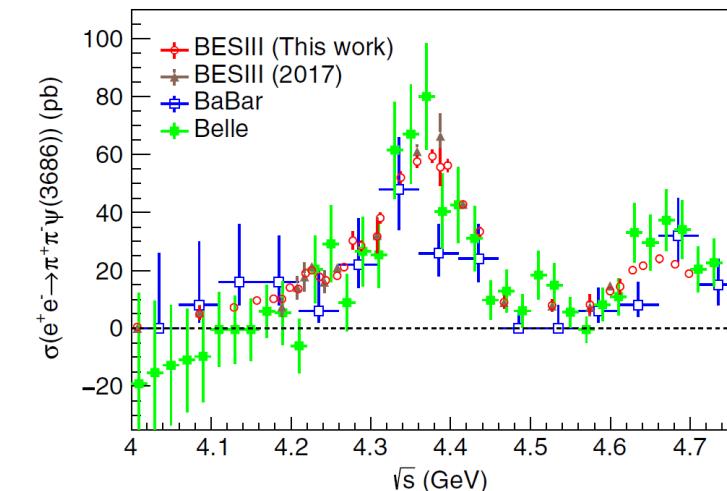


Y(4260) is now Y(4230) [$\psi(4230)$ in PDG2023]

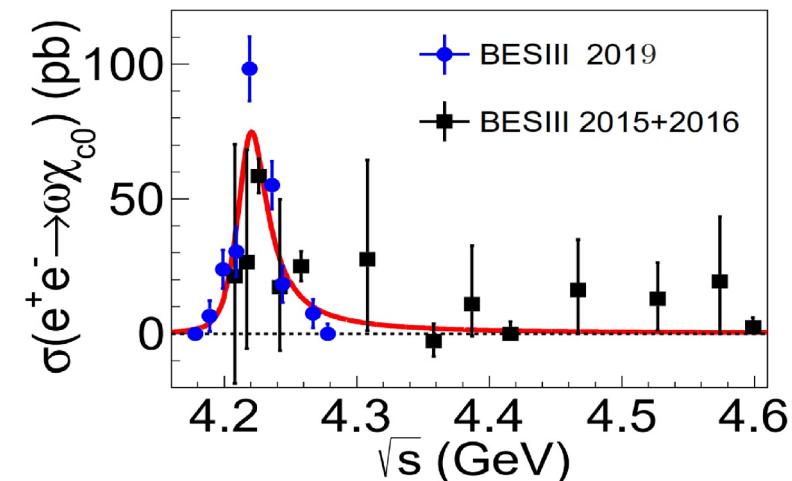
PRD106, 072001 (2022)



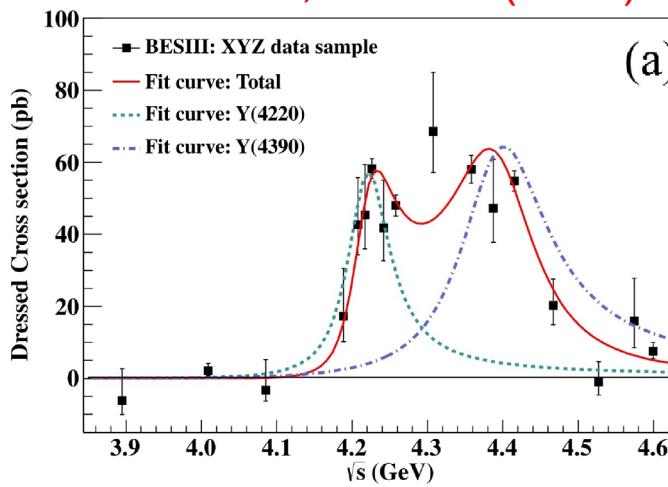
PRD104, 052102 (2021)



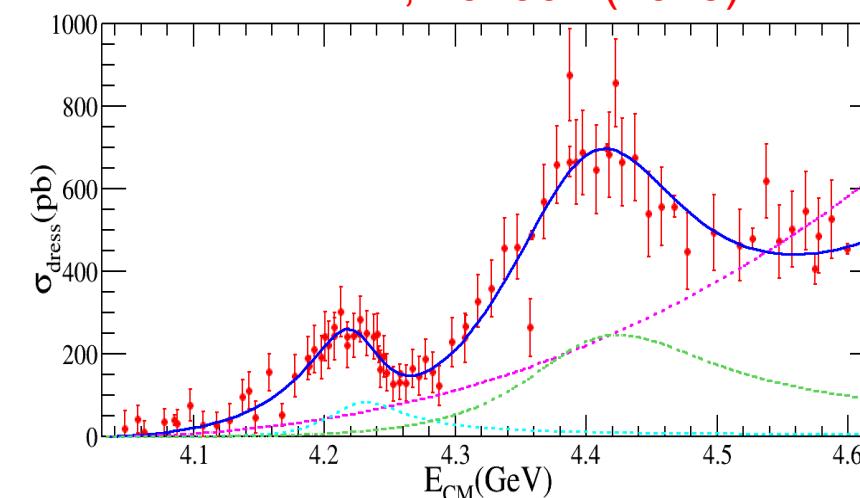
PRD99, 091103 (2019)



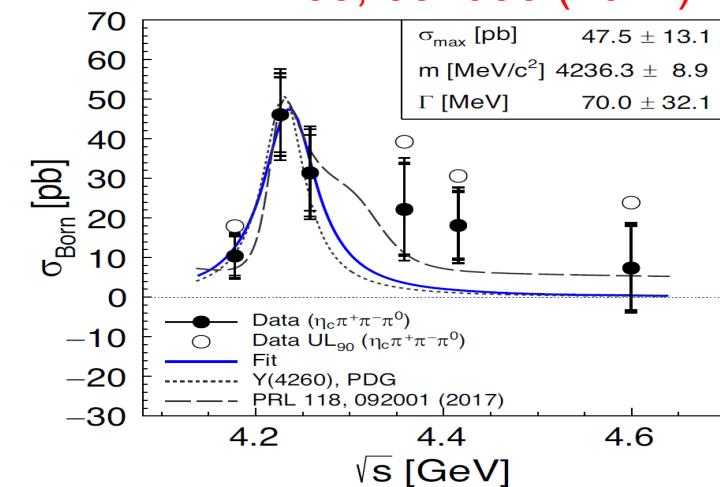
PRL118, 092002 (2017)



PRL122, 102002 (2019)



PRD 103, 032006 (2021)

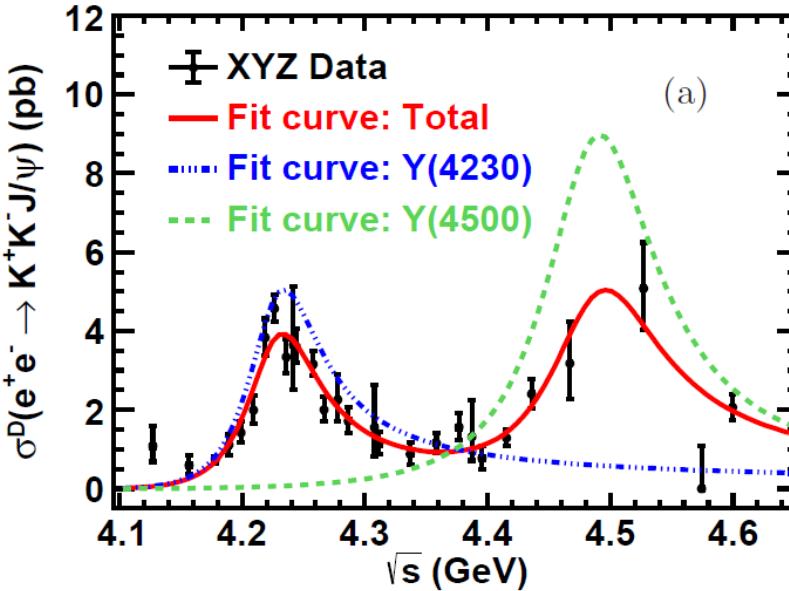


$Y(4230)$ appears in $\omega\chi_{c0}$, $\pi^+\pi^-J/\psi$, $\pi^+\pi^-\psi'$, $\pi^+\pi^-h_c$, $D^0D^{*-}\pi^+$, $\eta_c\pi^+\pi^-\pi^0$, K^+K^-J/ψ , $D^{*0}D^{*-}\pi^+$,

Mass~4220 MeV, width~ 50 MeV!

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

CPC46, 111002 (2022)

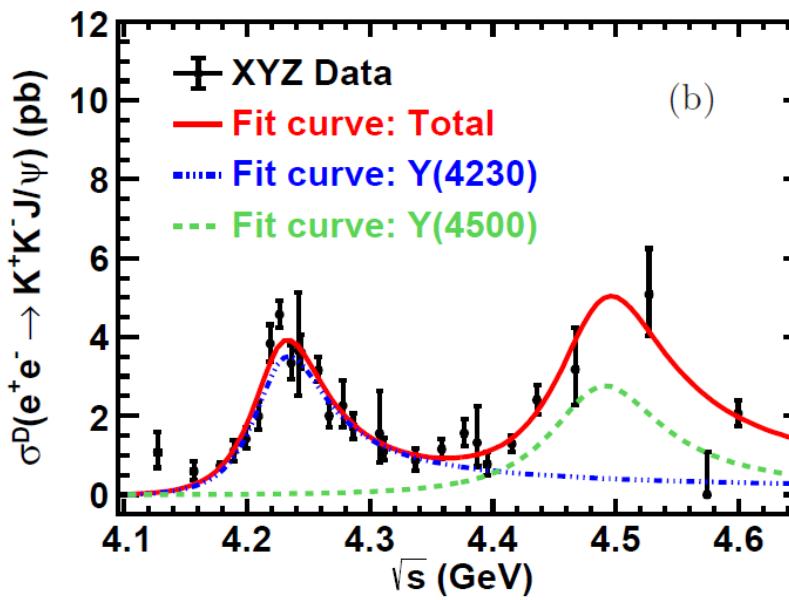


✓ First observation of $Y(4230) \rightarrow K^+K^-J/\psi$ (29σ)

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

✓ Significance of the $Y(4500) > 8\sigma$

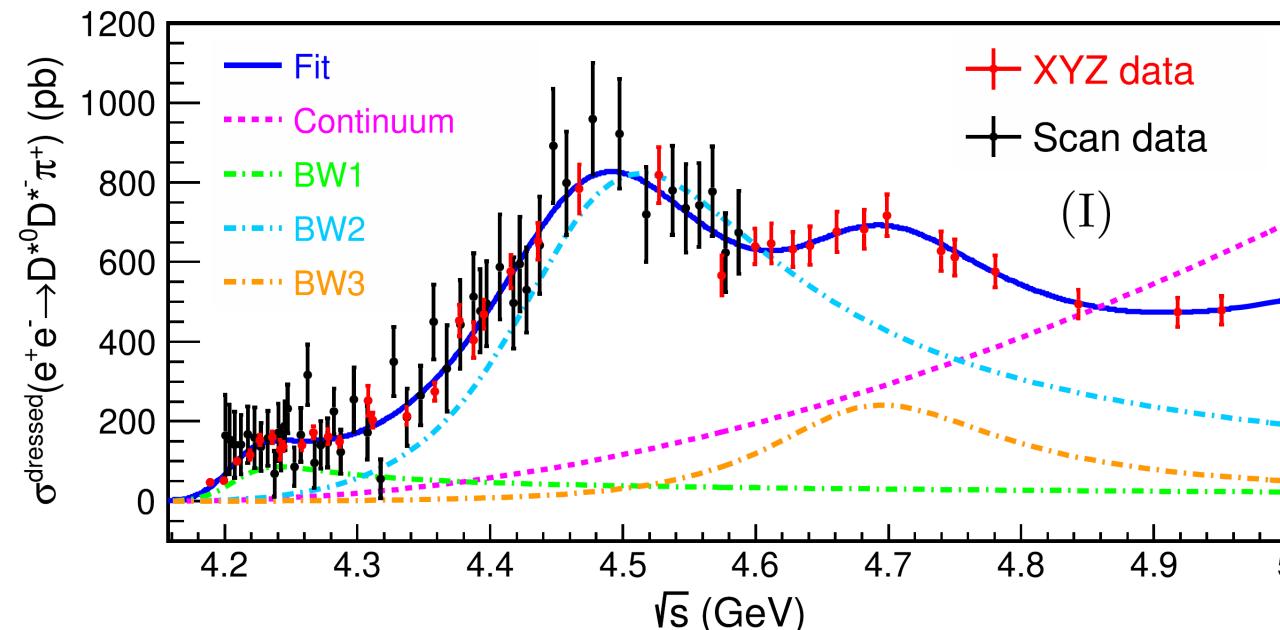
- A 5S-4D mixing state (J. Z. Wang et al., PRD 99, 114003 (2019))
- A heavy-antiheavy hadronic molecule
(X. K. Dong et al., Prog. Phys. 41, 65 (2021))
- A $(c\bar{s}\bar{c}\bar{s})$ state on LQCD (T. W. Chiu et al., PRD 73, 094510 (2006))



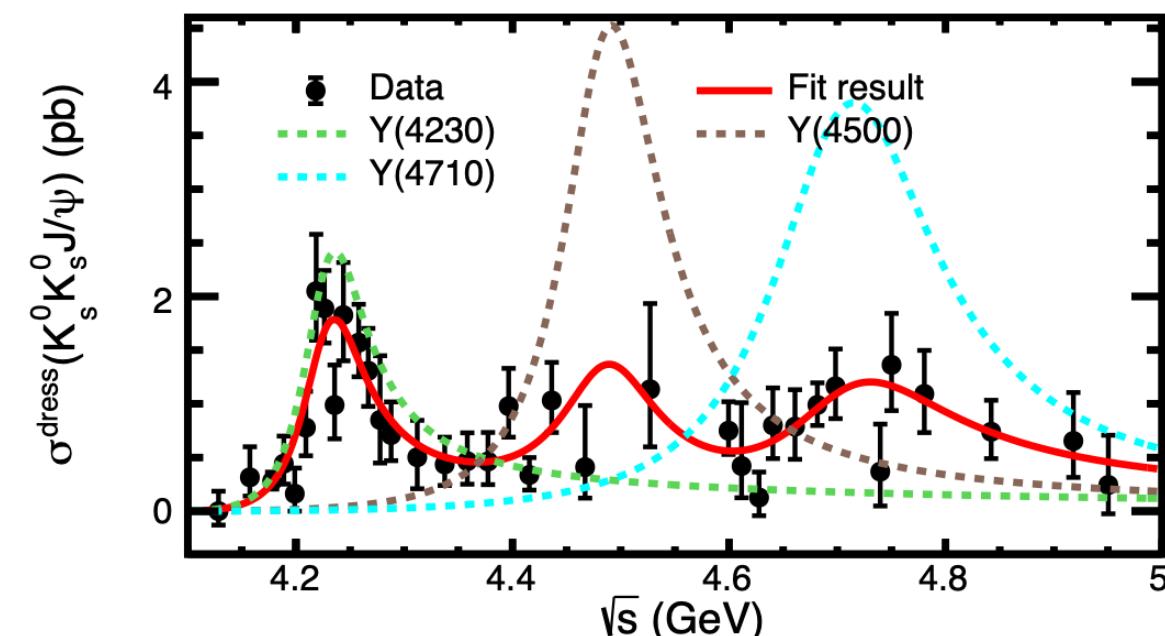
	Parameters	Solution I	Solution II
$Y(4230)$	$M(\text{MeV})$	$4225.3 \pm 2.3 \pm 21.5$	
	$\Gamma_{tot}(\text{MeV})$	$72.9 \pm 6.1 \pm 30.8$	
	$\Gamma_{ee}\mathcal{B}(\text{eV})$	$0.42 \pm 0.04 \pm 0.15$	$0.29 \pm 0.02 \pm 0.10$
$Y(4500)$	$M(\text{MeV})$	$4484.7 \pm 13.3 \pm 24.1$	
	$\Gamma_{tot}(\text{MeV})$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

Confirmation of $\Upsilon(4500)$ and evidence for $\Upsilon(4710)$

PRL130, 121901 (2023)

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

PRD107, 092005 (2023)

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

resonance	mass (MeV)	width (MeV)	note
BW1	$4210 \pm 5 \pm 6$	$82 \pm 18 \pm 9$	agree with $\Upsilon(4230)$
BW2	$4469 \pm 26 \pm 4$	$246 \pm 37 \pm 9$	agree with $\Upsilon(4500)$
BW3	$4675 \pm 30 \pm 4$	$218 \pm 73 \pm 9$	agree with $\Upsilon(4660)$

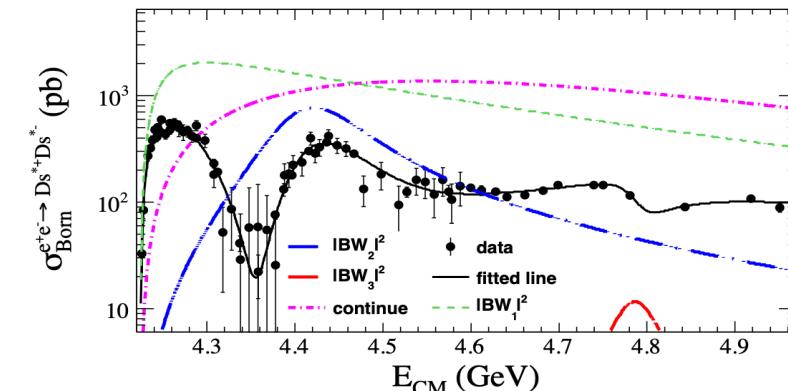
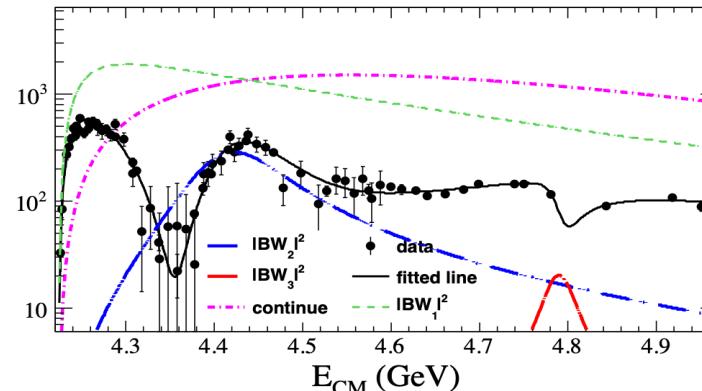
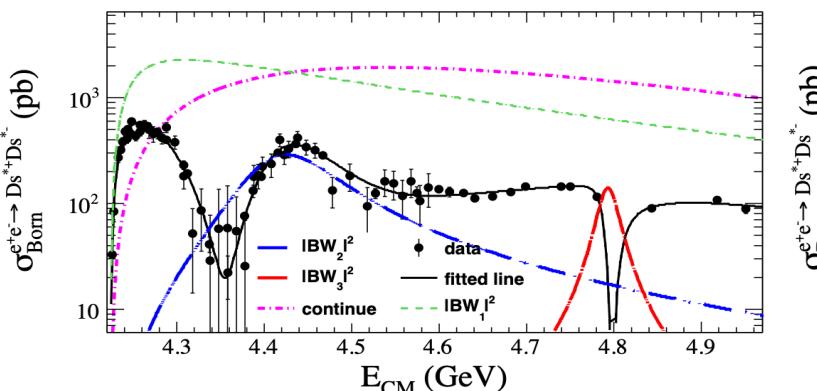
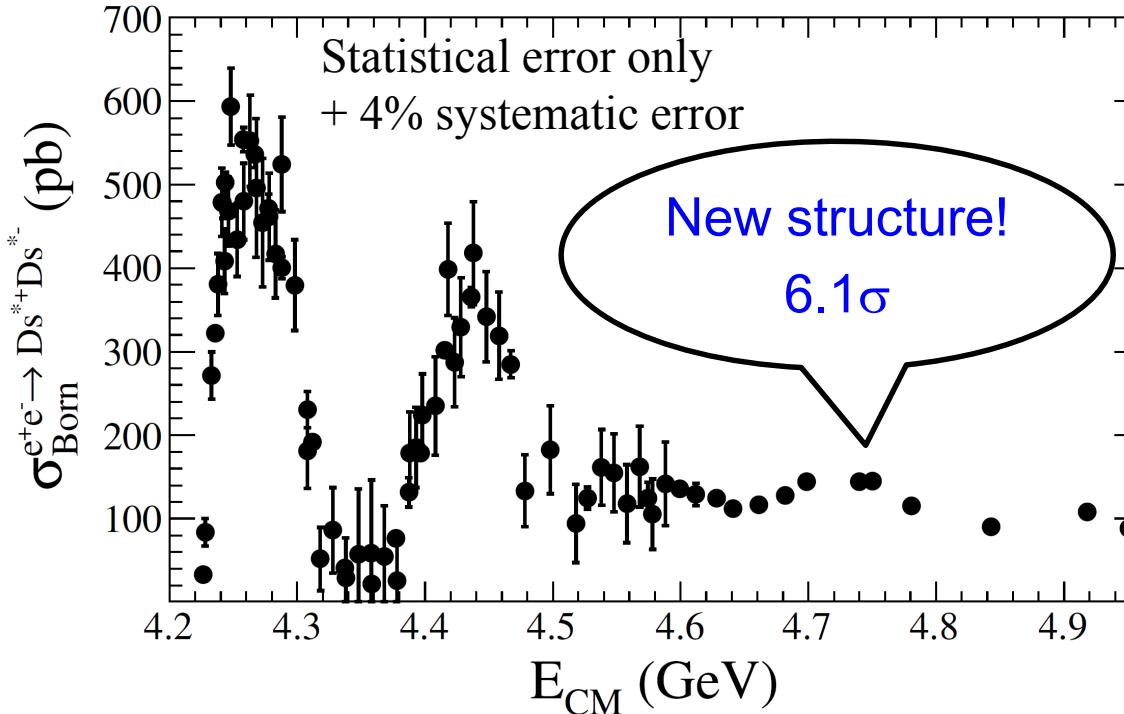
Contributions from the $\psi(4360)$, $\psi(4415)$ and $\Upsilon(4710)$?

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

Waiting for update on $e^+e^- \rightarrow K^+K^- J/\psi$ from BESIII!

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

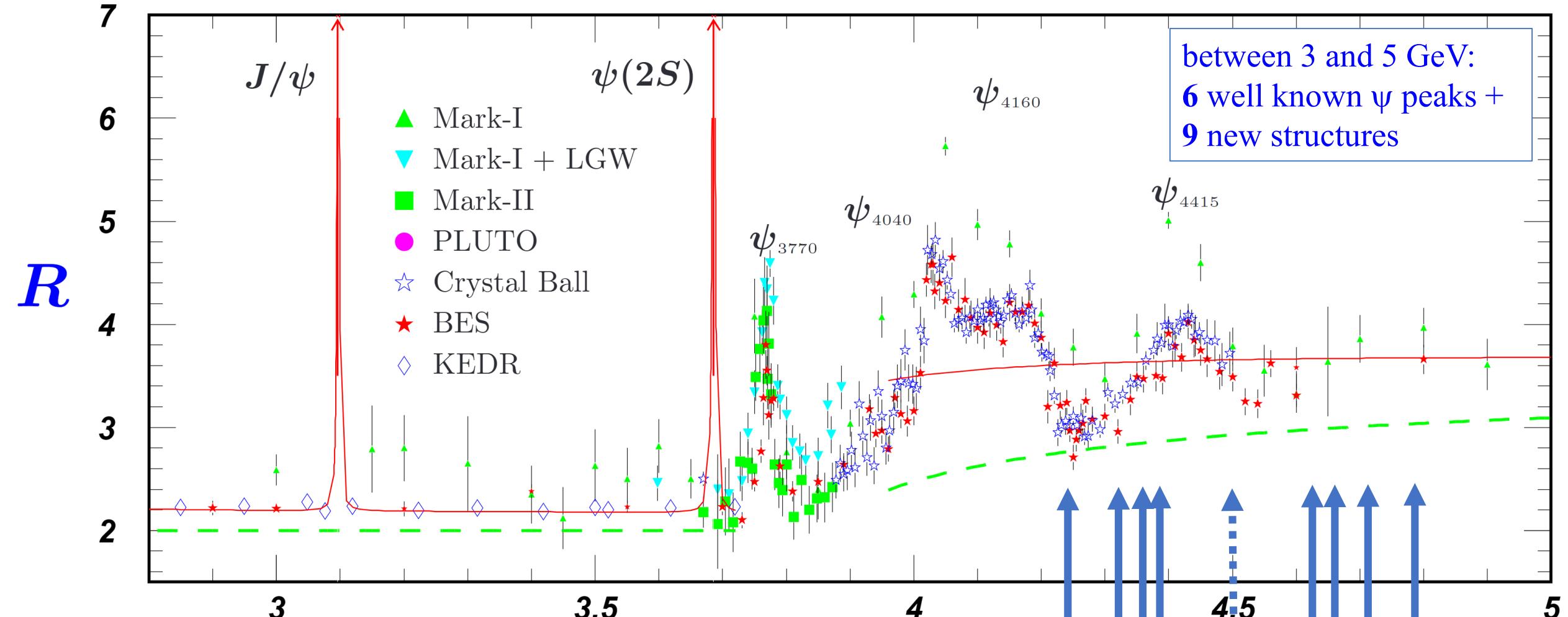
arXiv: 2305.10789, submitted to PRL



- 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 $\Upsilon(4710)$ in K_SK_SJ/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

How many vectors in charmonium energy region?



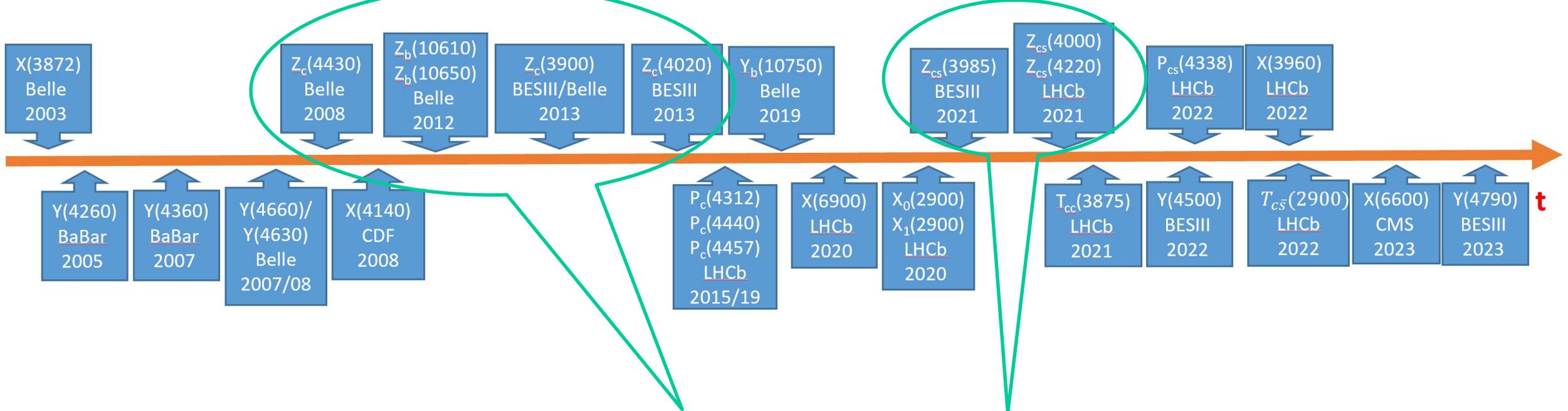
Besides vector charmonium ($c\bar{c}$) states, we also expect $c\bar{c}g$ hybrids, and $c\bar{c}q\bar{q}$ tetraquark states. Have they already been observed?

→ More theoretical/experimental efforts necessary!

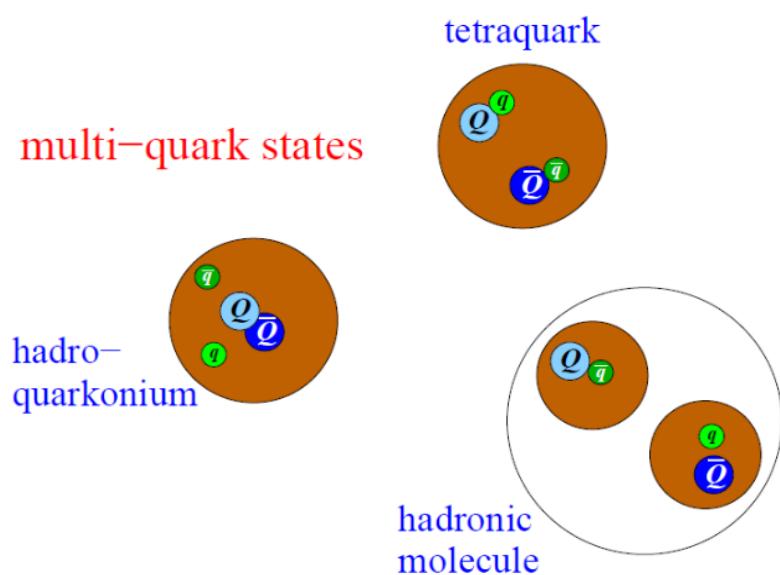
$Y(4230), Y(4320),$
 $Y(4360), Y(4390)$

$Y(4500)$

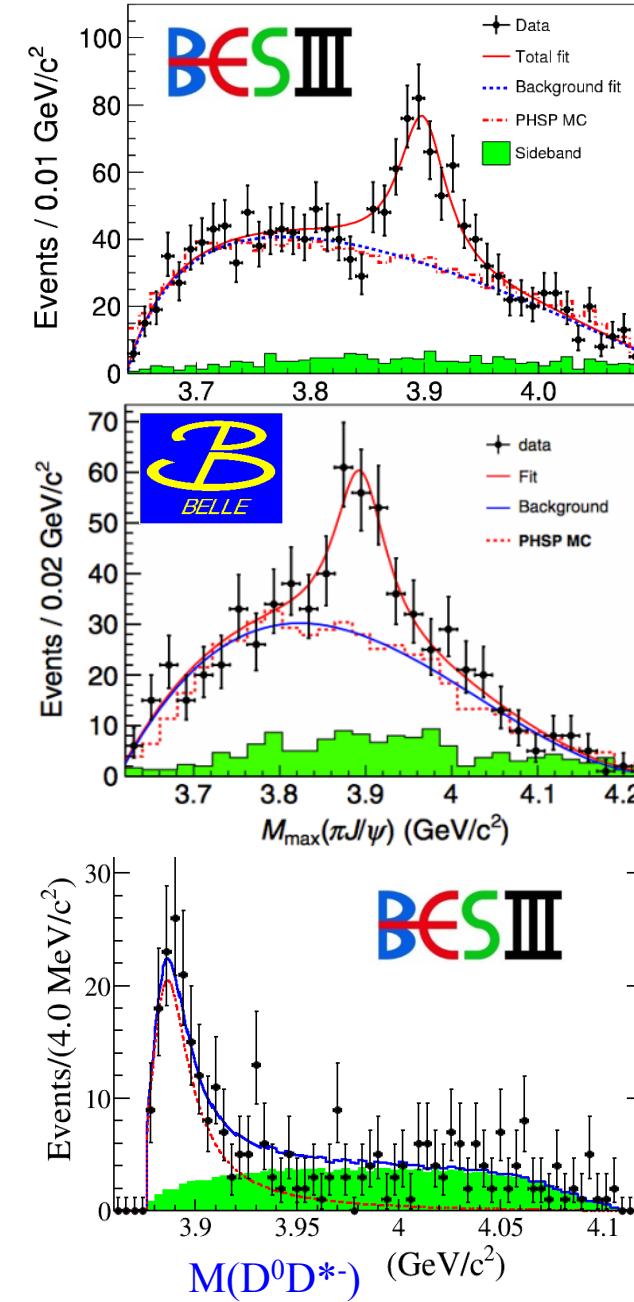
$Y(4630), Y(4660),$
 $Y(4710), Y(4790)$



Charged quarkoniumlike states must have at least 4 quarks!

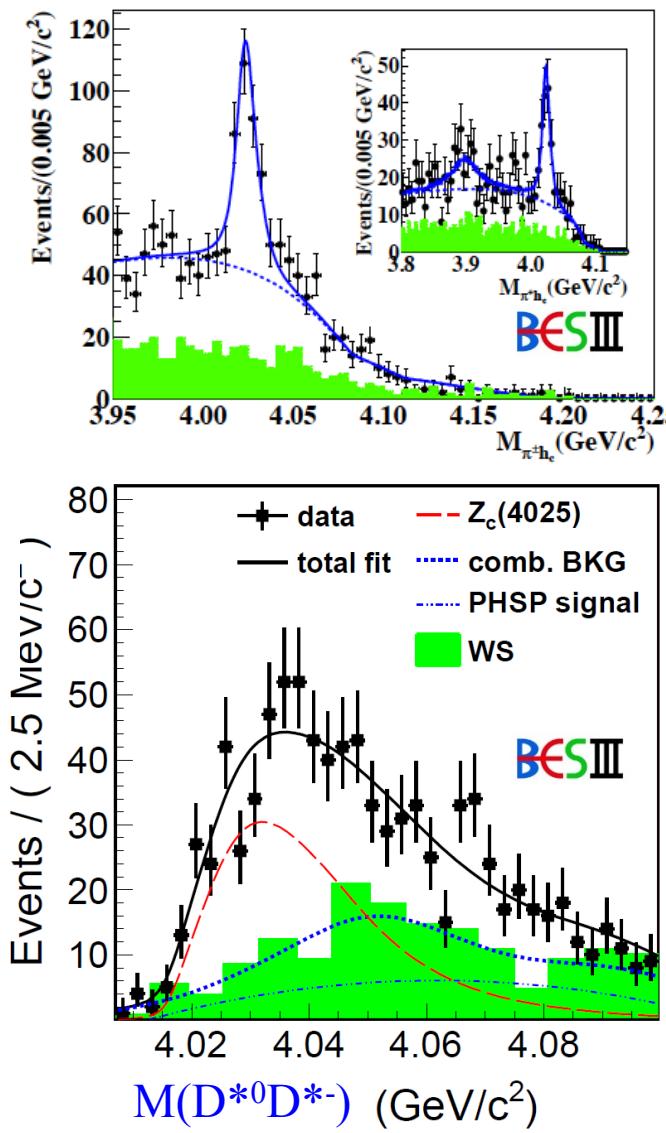


$Z_c(3900)$, 2013

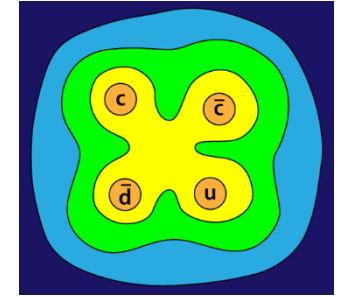
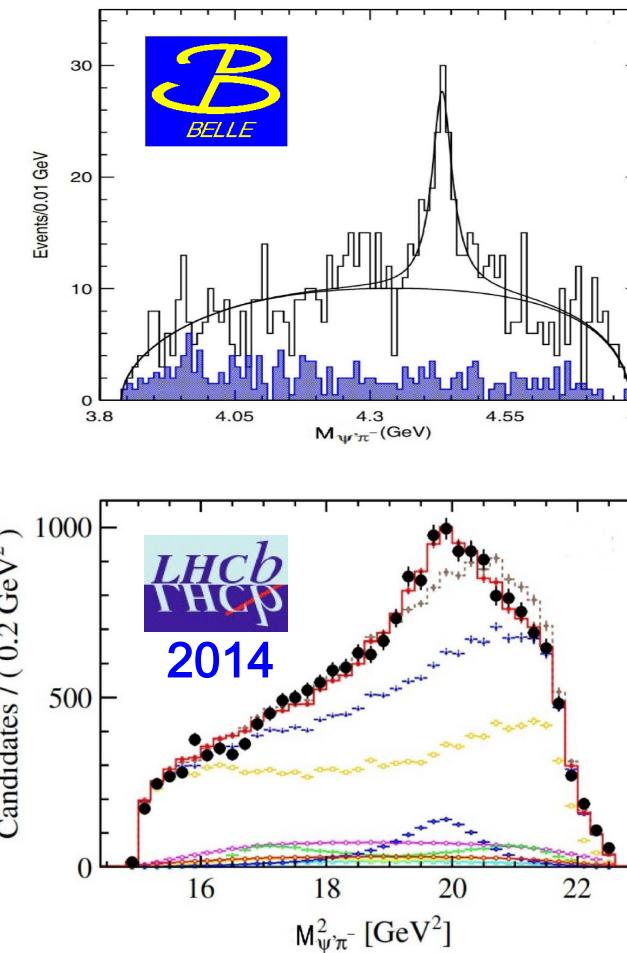


The Z_c states with u,d-quark

$Z_c(4020)$, 2013

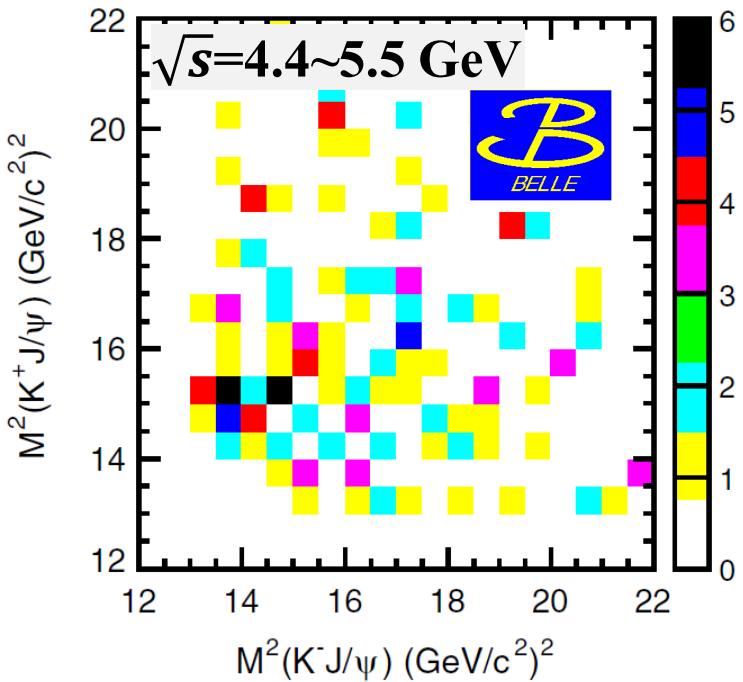


$Z_c(4430)$, 2008



All are observed in $\pi +$ 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 $K^\pm J/\psi$,
 $\bar{D}^* D_s + \bar{D} D_s^*$!

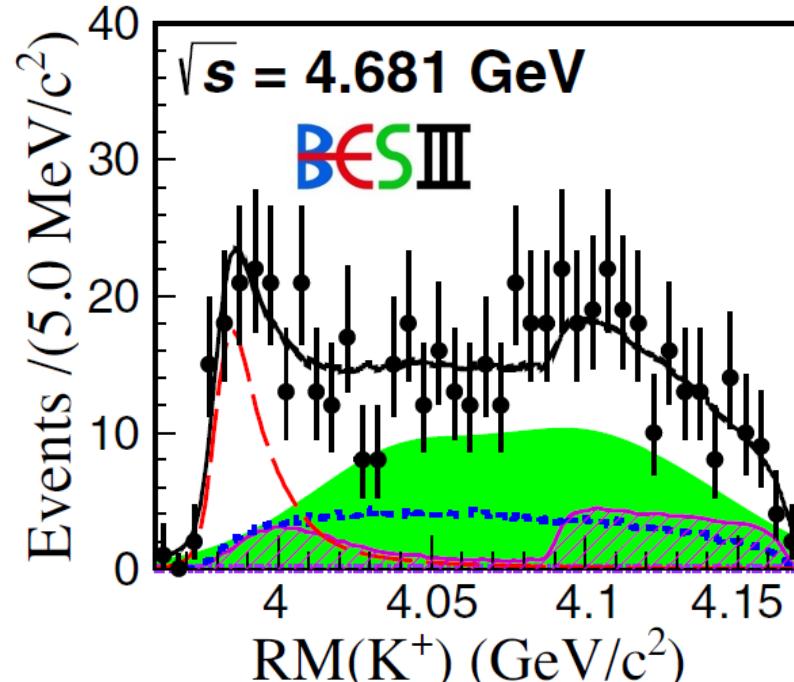
$e^+e^- \rightarrow K^+K^-J/\psi$



PRD 89, 072015 (2014)

No significant signal in
 $K^\pm J/\psi$ decay mode!
(statistics low!)

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

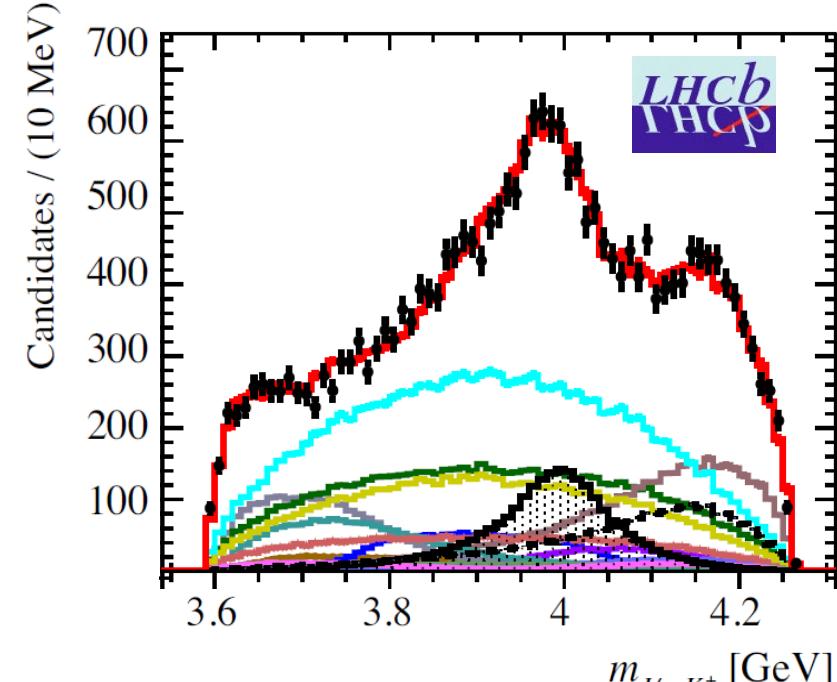


PRL 126, 102001 (2021)

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

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	$1+$	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$

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



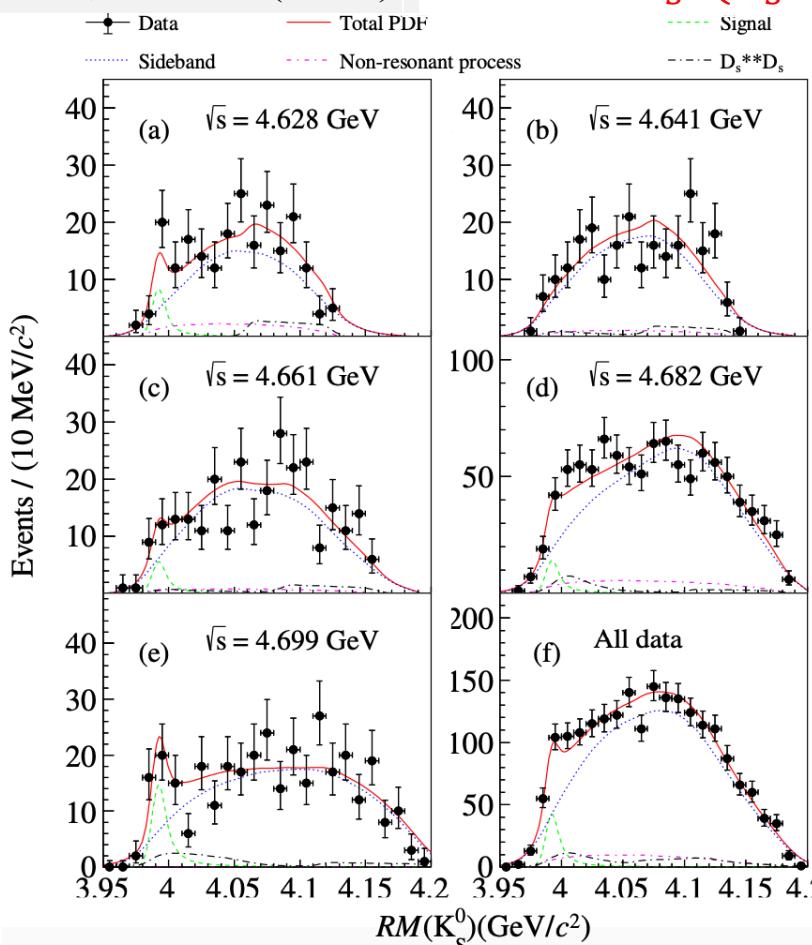
PRL 127, 082001 (2021)

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

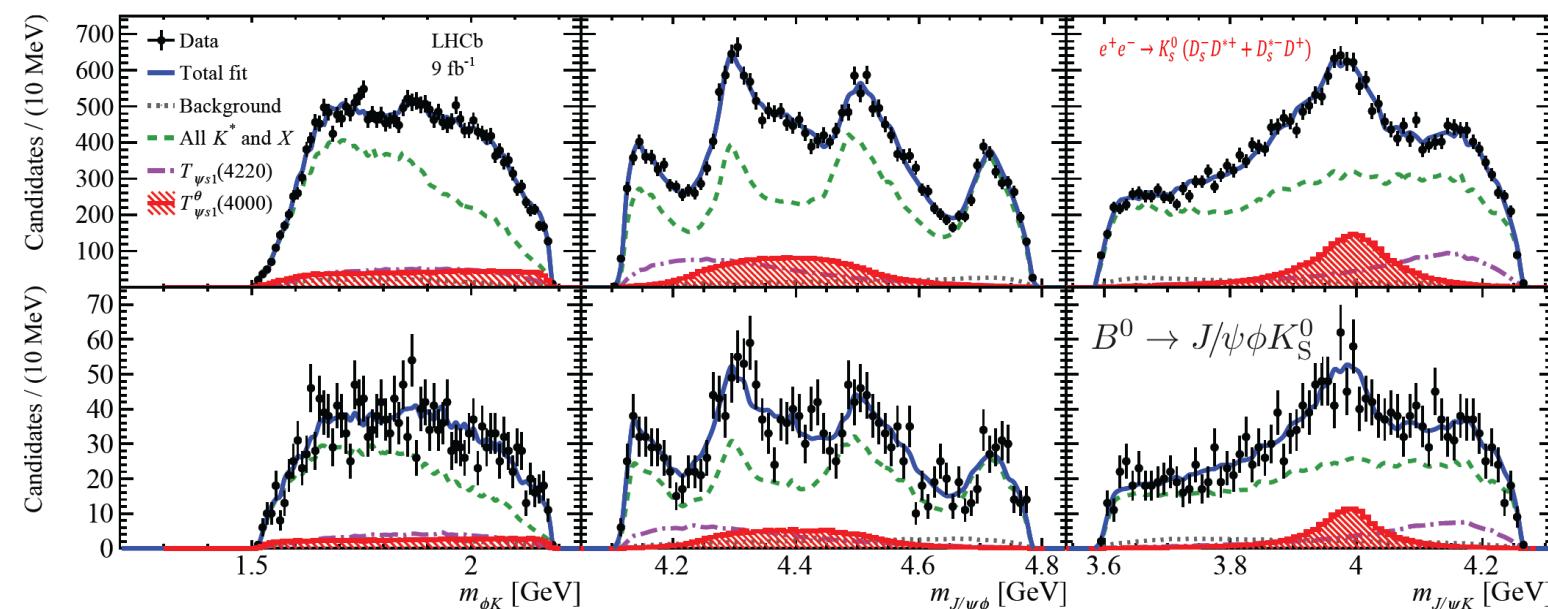
Widths very different,
not the same state!

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

PRL129, 112003 (2022)

 $e^+e^- \rightarrow K_S^0 (D_s^- D^{*+} + D_s^{*-} D^+)$  $B^0 \rightarrow J/\psi \phi K_S^0$

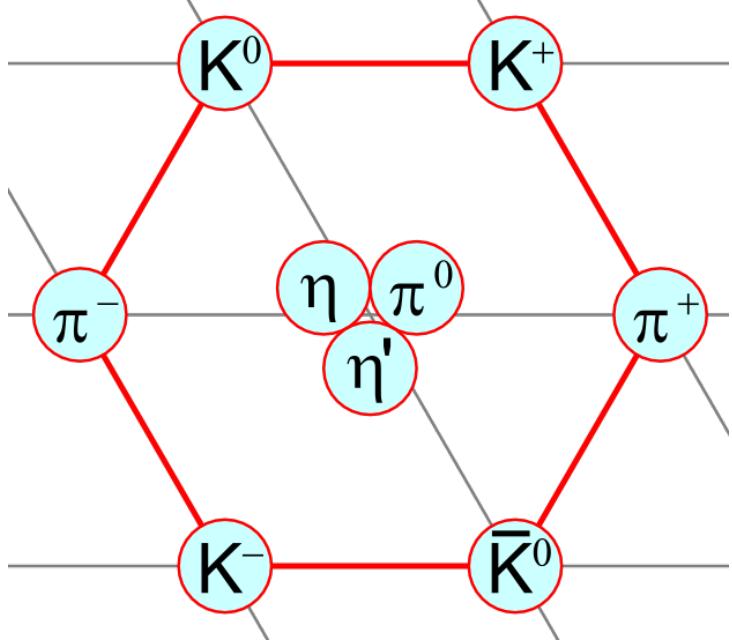
arXiv:2301.04899v2

Significance $>4.0\sigma$ after including systematic uncertaintiesSignificance 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

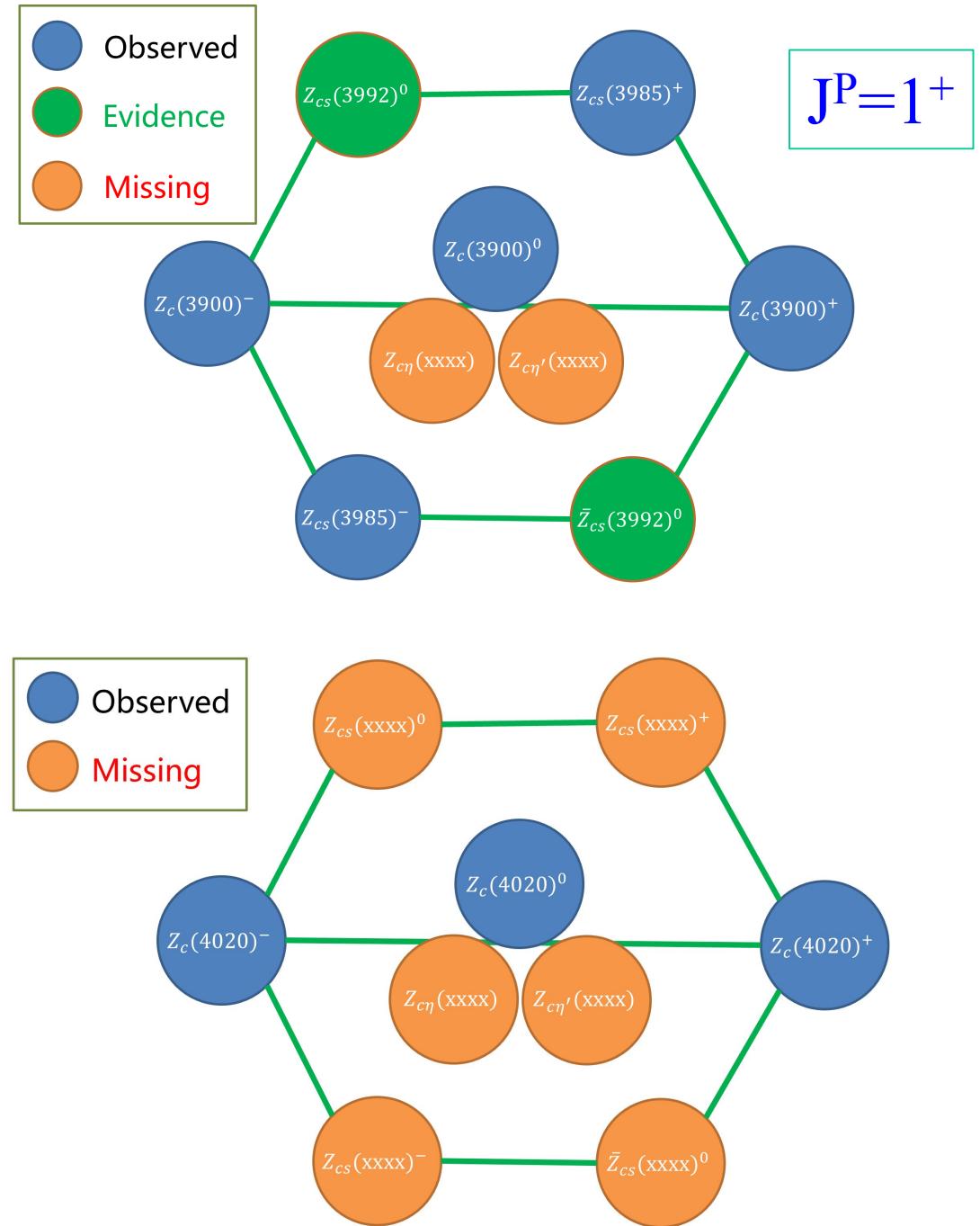
Mass (MeV)	Width (MeV)	Fit fraction (%)	ΔM (MeV)
$3991^{+12}_{-10} {}^{+9}_{-17}$	$105^{+29}_{-25} {}^{+17}_{-23}$	$7.9 \pm 2.5 {}^{+3.0}_{-2.8}$	$-12^{+11}_{-10} {}^{+6}_{-4}$

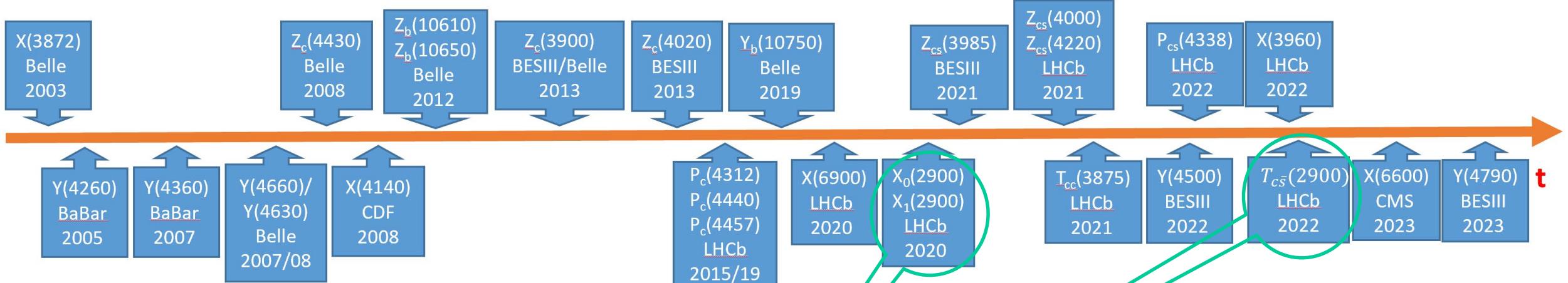
➤ Minimal quark content $c\bar{c}s\bar{d}$? Mass and width consistent with charged $Z_{cs} \rightarrow$ isospin partner



+ J/ψ

+ h_c





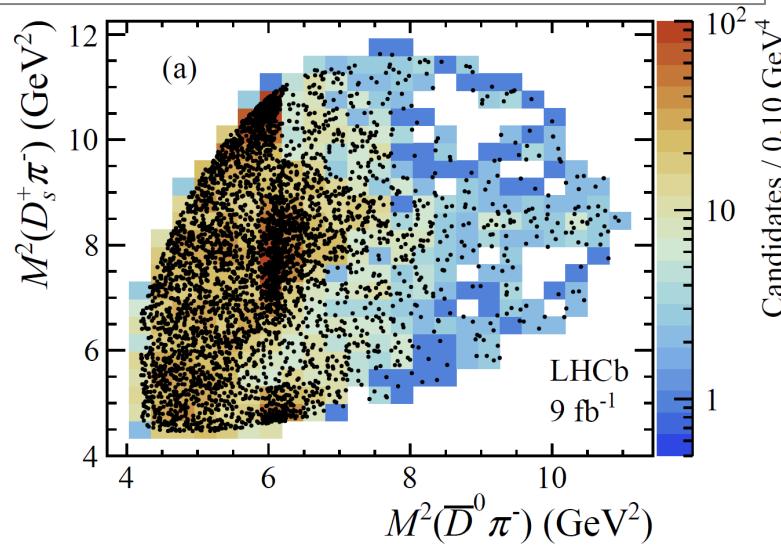
States with 4 different flavors (T_{cs} and $T_{c\bar{s}}$)

$$c\bar{d}s\bar{u} \quad c\bar{d}\bar{s}u$$

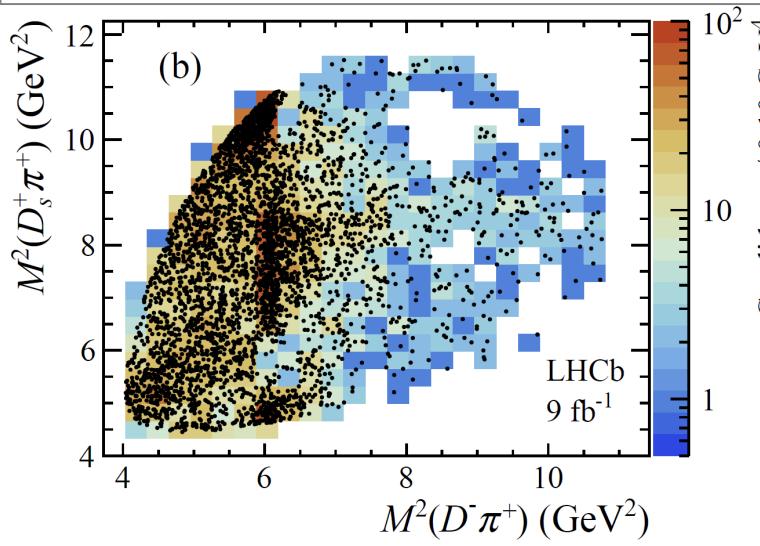
9 fb⁻¹ Run 1 & Run 2 data

Observation of $T_{c\bar{s}}$ states decay into $D_s^+ \pi^\pm$

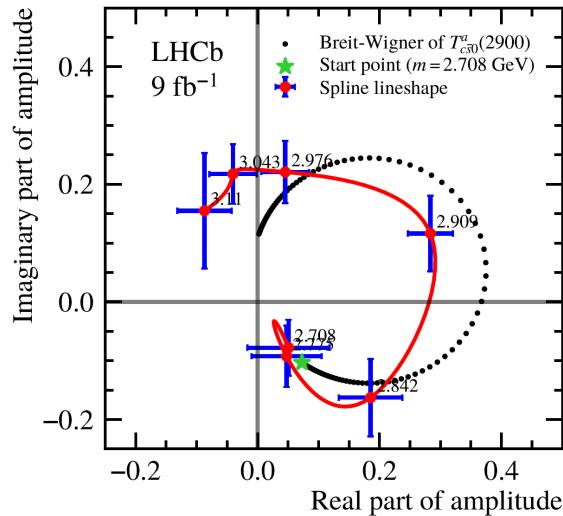
4009 selected $B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ decays,
purity $\sim 90\%$



3750 selected $B^+ \rightarrow D^- D_s^+ \pi^+$ decays,
purity $\sim 95\%$



Assuming isospin symmetry
→ combined amplitude analysis
of the 2 channels



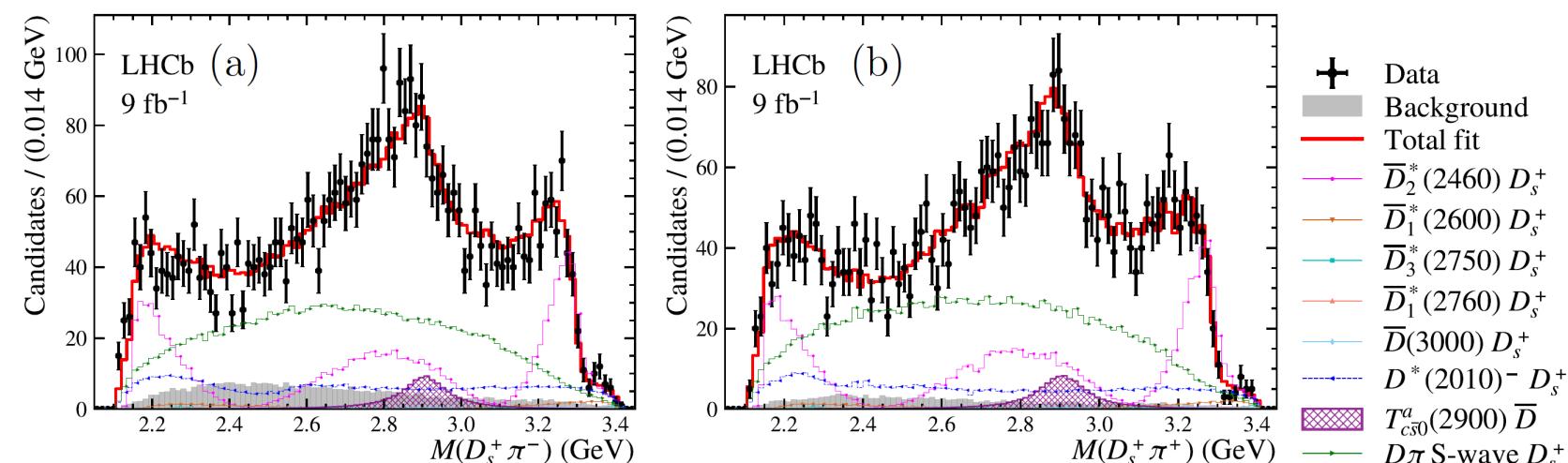
$$M = 2.908 \pm 0.011 \pm 0.020 \text{ GeV}$$

$$\Gamma = 0.136 \pm 0.023 \pm 0.013 \text{ GeV}$$

Significance $>9\sigma$, taking into account
the systematic uncertainties & the
look-elsewhere effect.

$$J^P = 0^+$$

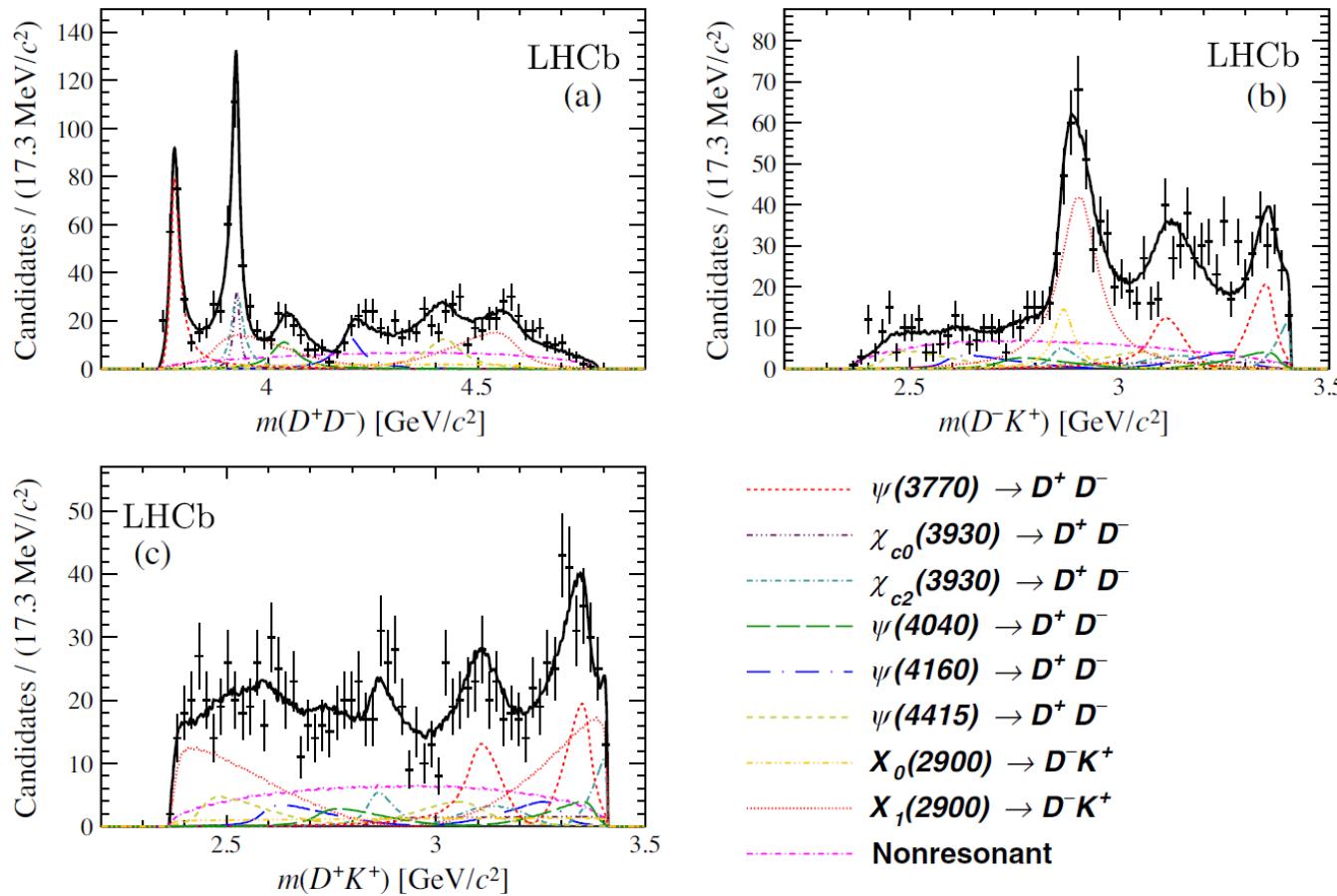
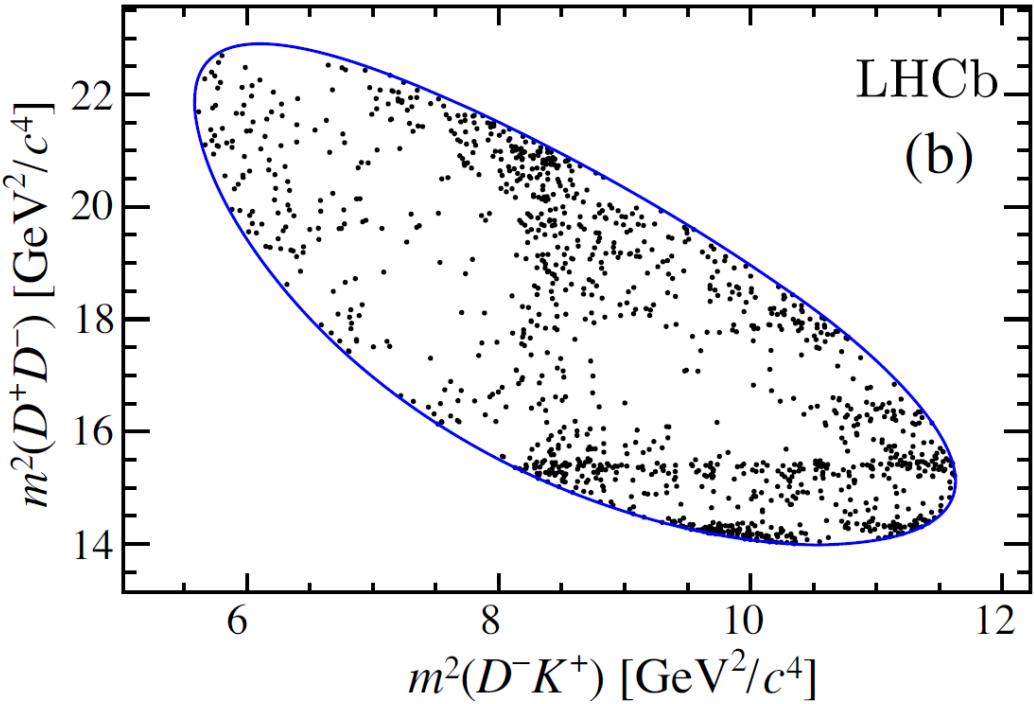
I=1 → search for $D_s^+ \pi^0$ state



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

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

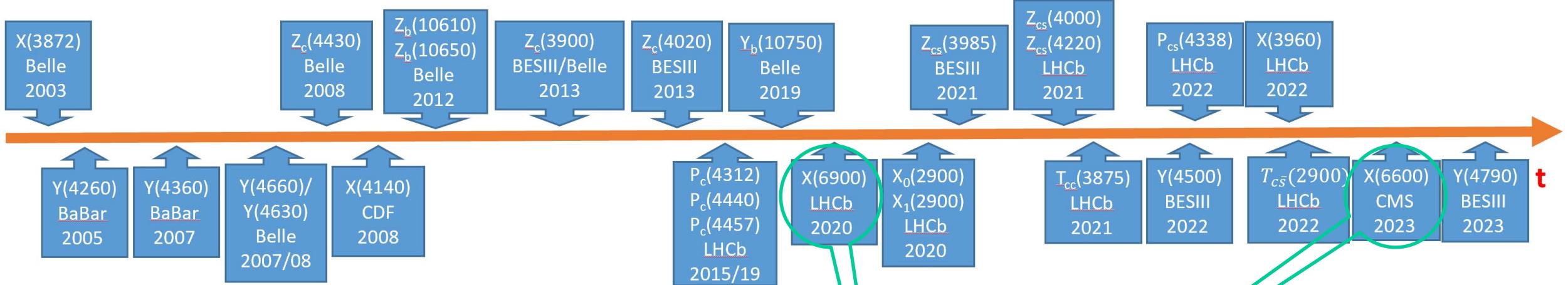
LHCb
 WHCP



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.

SU(3) flavor partners of the T_{cs} states? $J^P=1^+$ partners?

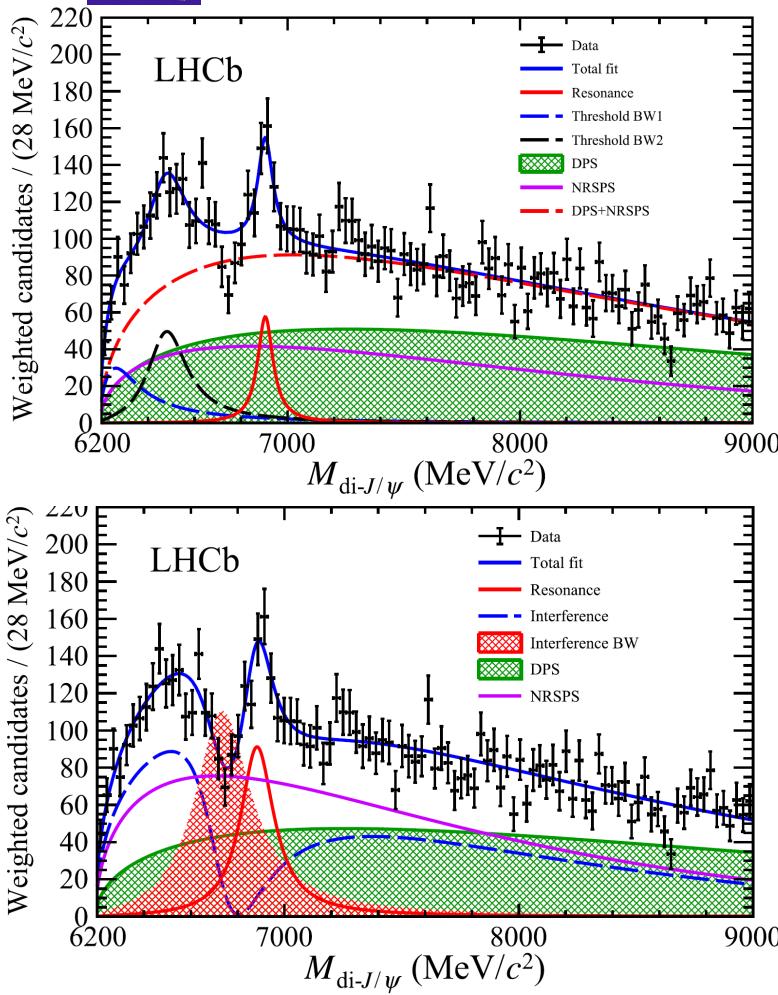


States with two pairs of $c\bar{c}$

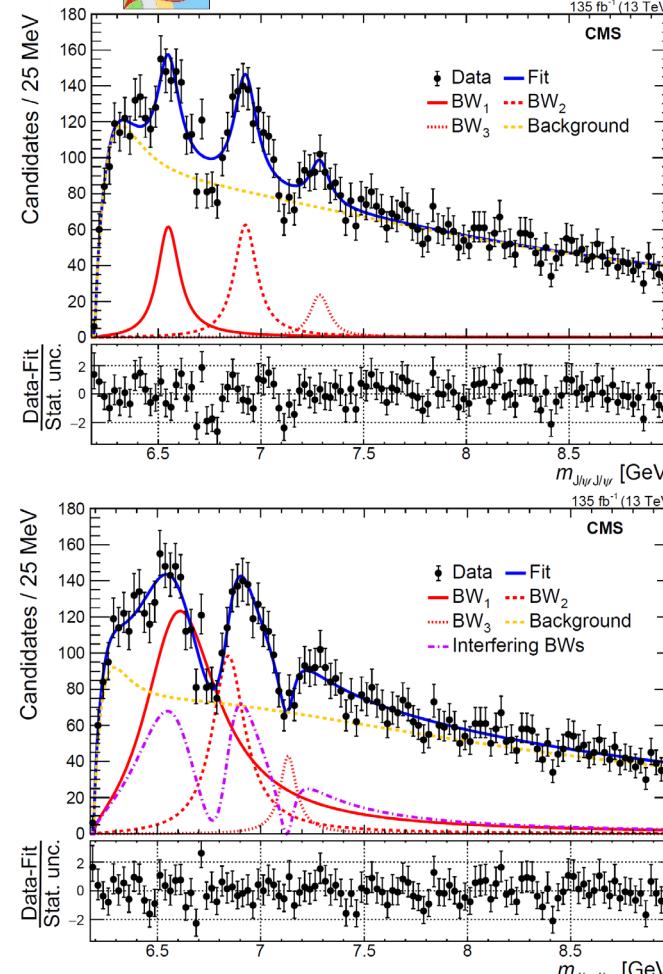
$X \rightarrow J/\psi J/\psi$: states with $c\bar{c}c\bar{c}$



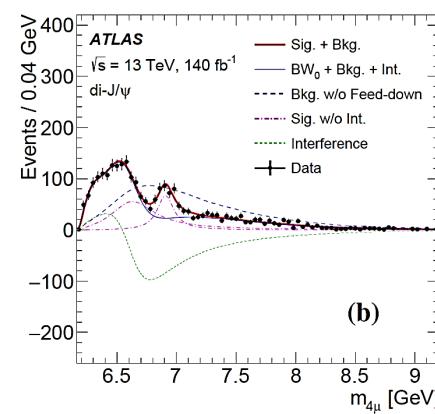
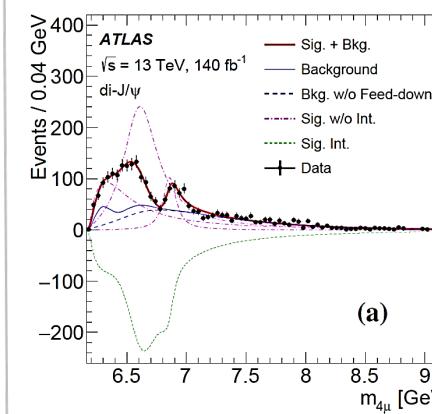
Sci.Bull. 65 (2020) 1983



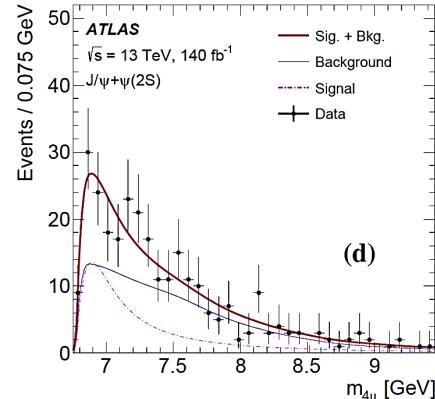
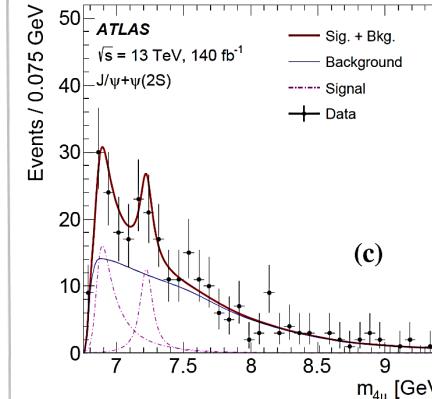
arXiv:2306.07164



arXiv:2304.08962



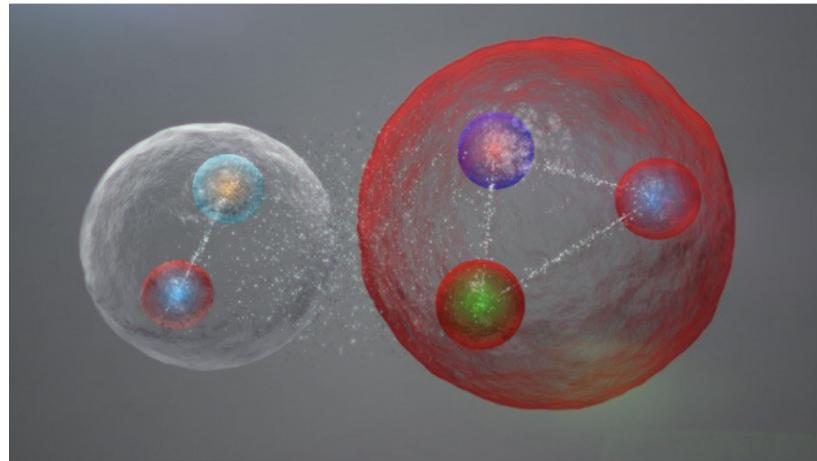
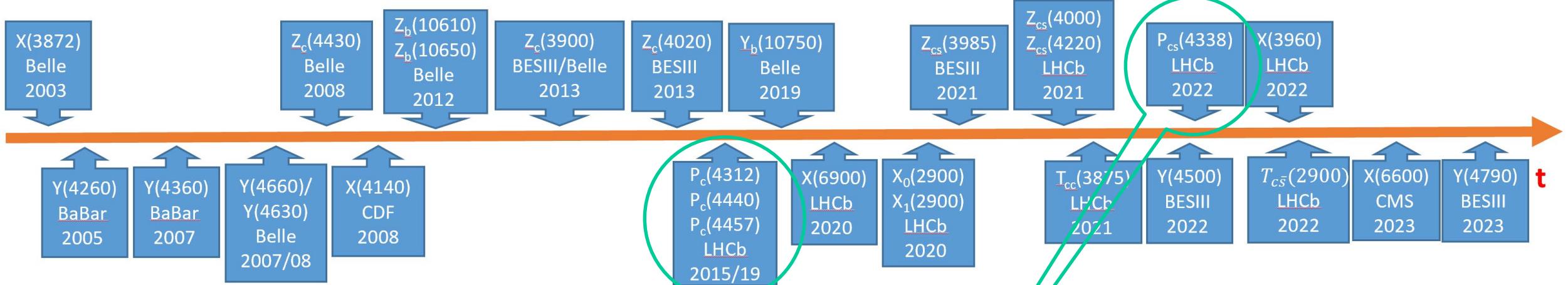
$X \rightarrow J/\psi \psi(2S)$



- Narrow structure at 6.9 GeV, $>5\sigma$
- $X(6900)$: $M \sim 6900$ MeV, $\Gamma \sim 100$ MeV
- Structure just above $J/\psi J/\psi$ threshold

- $X(6900)$ consistent with LHCb
- New state $X(6600)$ with 6.5σ
- Evidence for $X(7300)$ with 4.1σ

- $X(6900)$ consistent with LHCb
- Evidence for states in $M(J/\psi \psi(2S))$



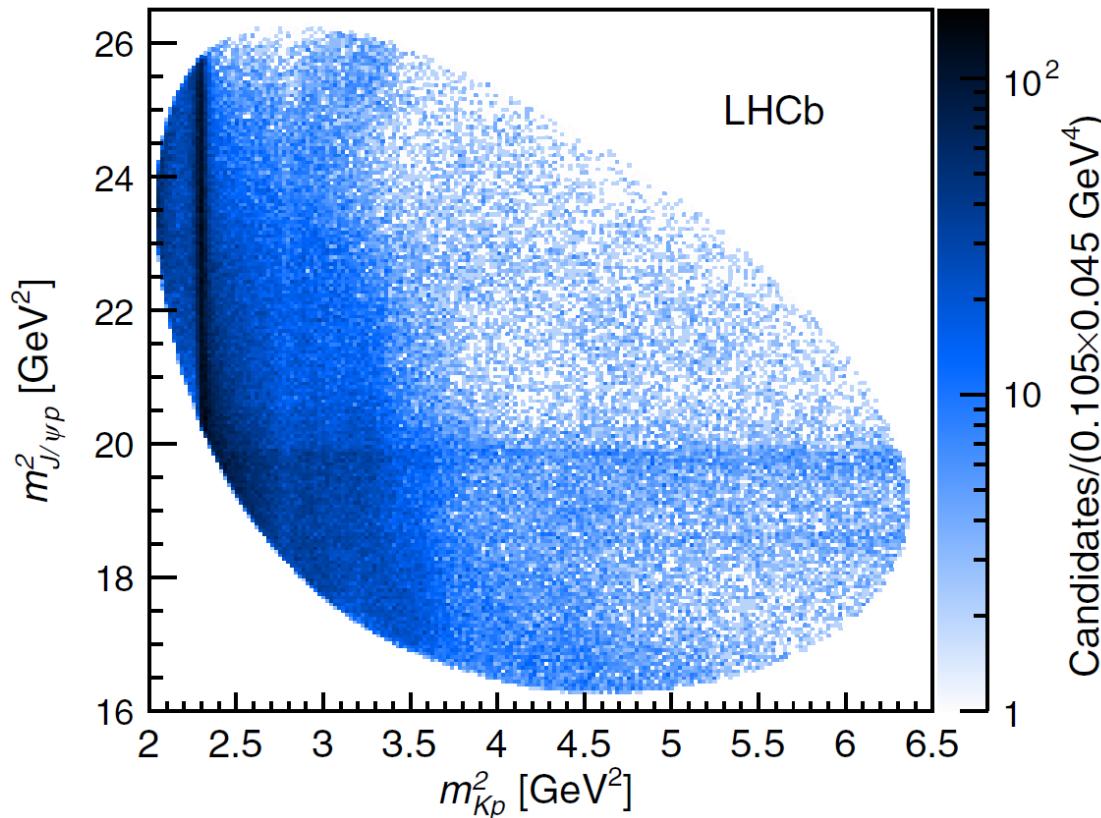
pentaquark states

Observation of pentaquark states $P_c \rightarrow J/\psi p$

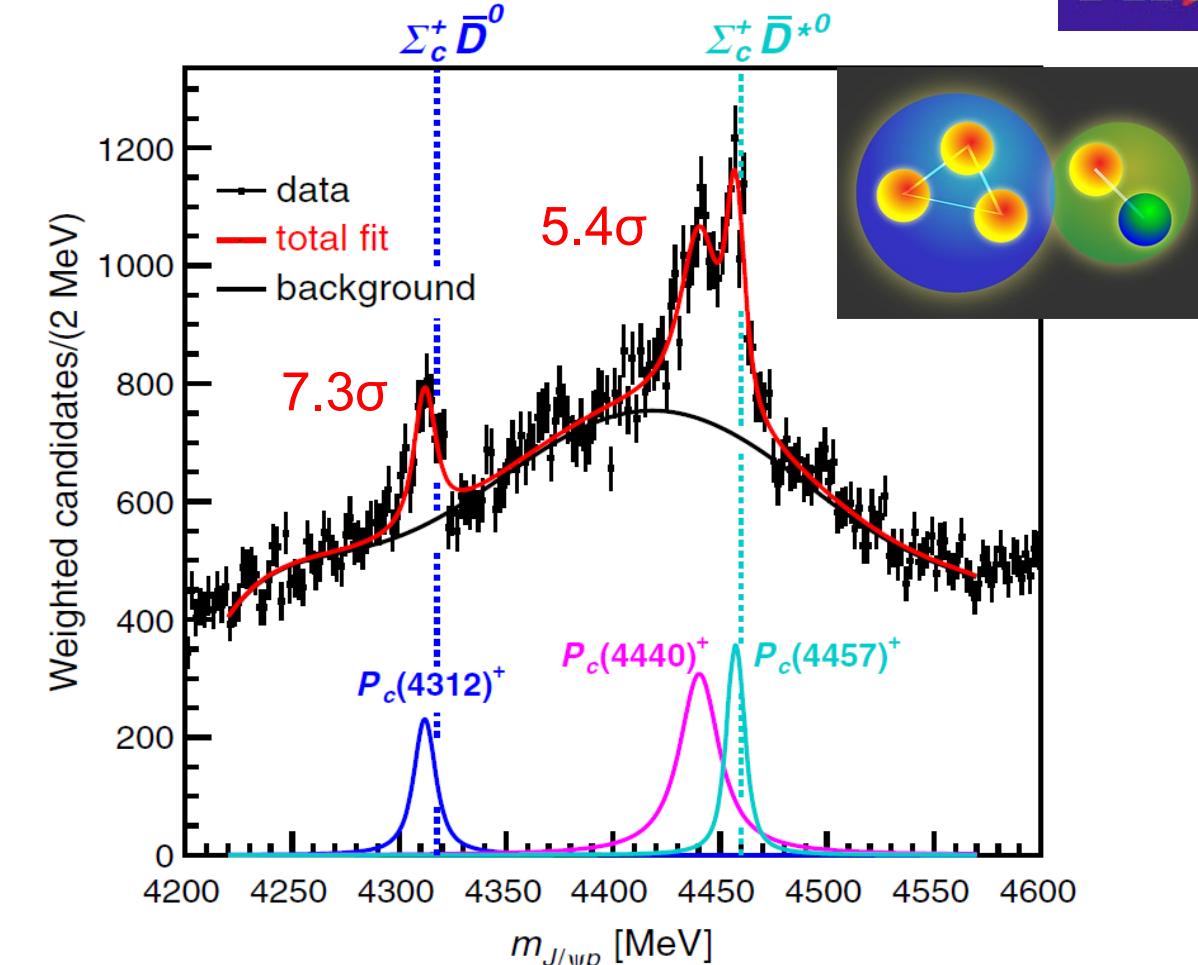
LHCb
VHCf

PRL 122, 222001 (2019)

9 fb^{-1} Run 1 & Run 2 data; 246k selected $\Lambda_b \rightarrow J/\psi p K^-$ decays

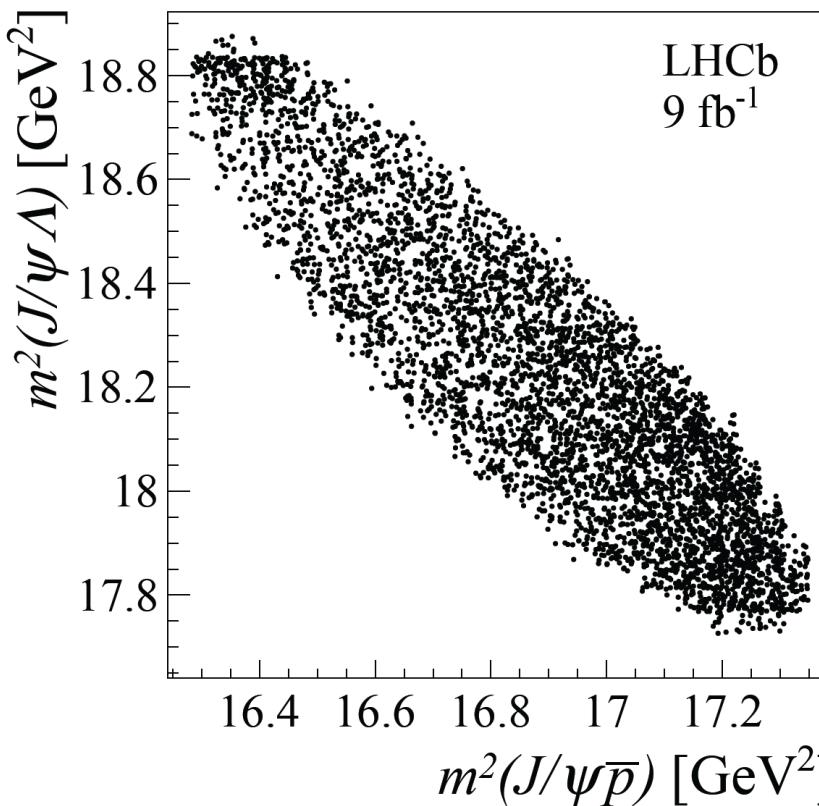


State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$



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.

Observation of $P_{\text{cs}} \rightarrow J/\psi \Lambda$

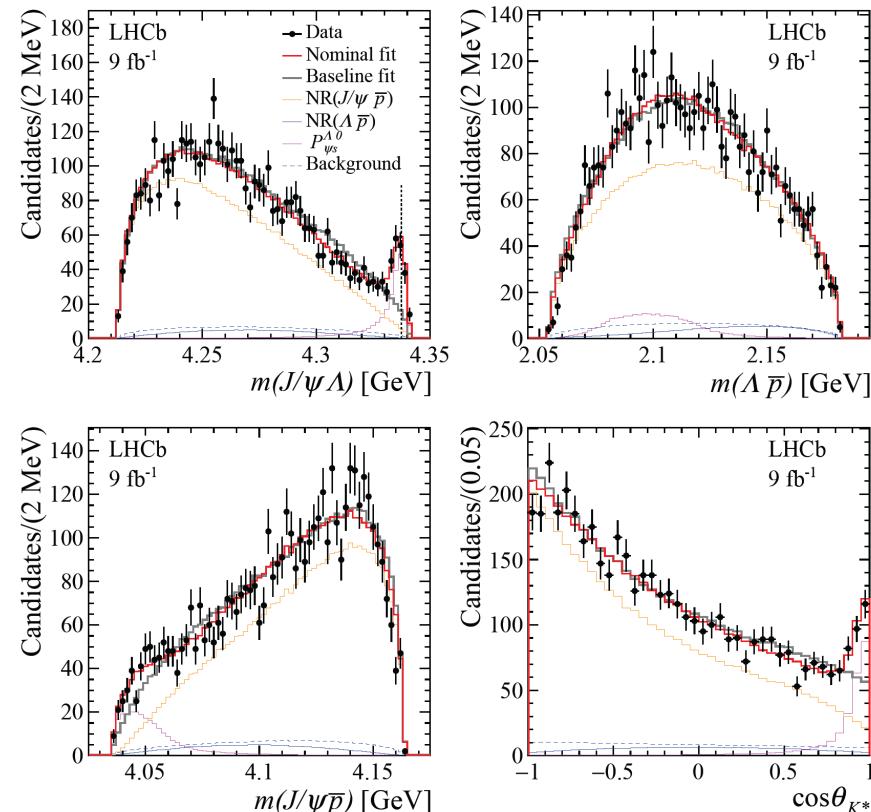


$J=1/2, P = -1$ favored. Significance $>10\sigma$

$M = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$ ($\Xi_c^+ D^-$ threshold 4337.4 MeV)

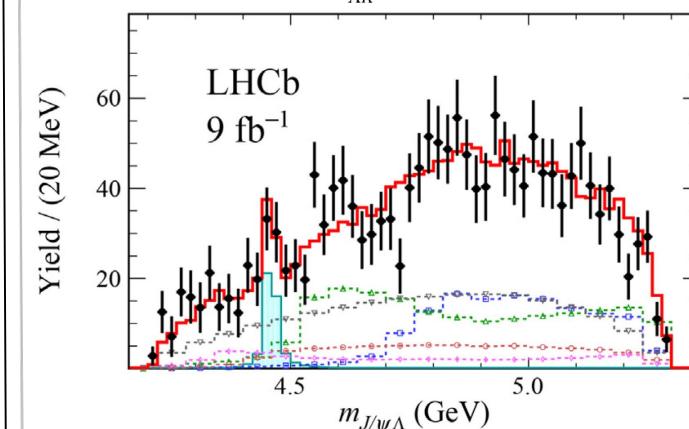
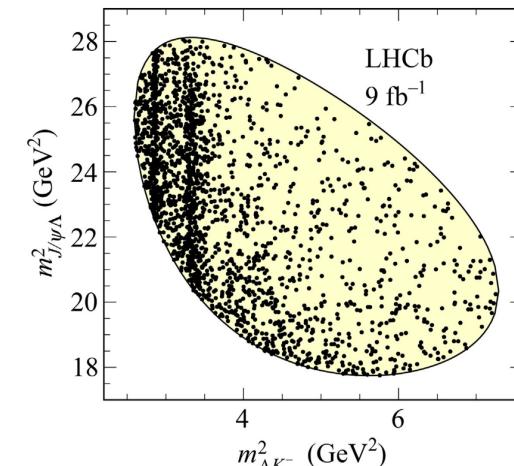
$\Gamma = 7.0 \pm 1.2 \pm 1.3 \text{ MeV}$ (very narrow)

S-wave $\Xi_c^+ D^-$ molecule? Also expect S-wave $\Xi_c^+ D^{*-}$ molecules?



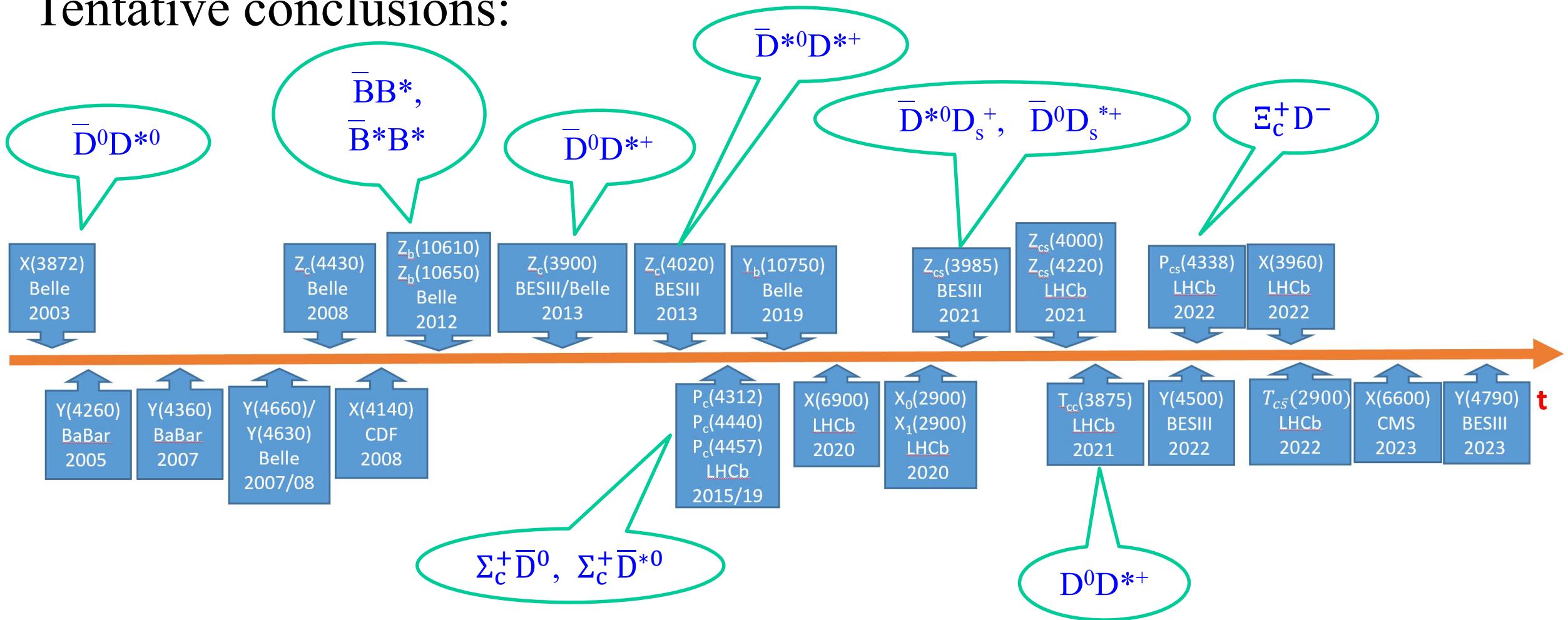
Sci.Bull. 66 (2021) 1278

1750 selected $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decays



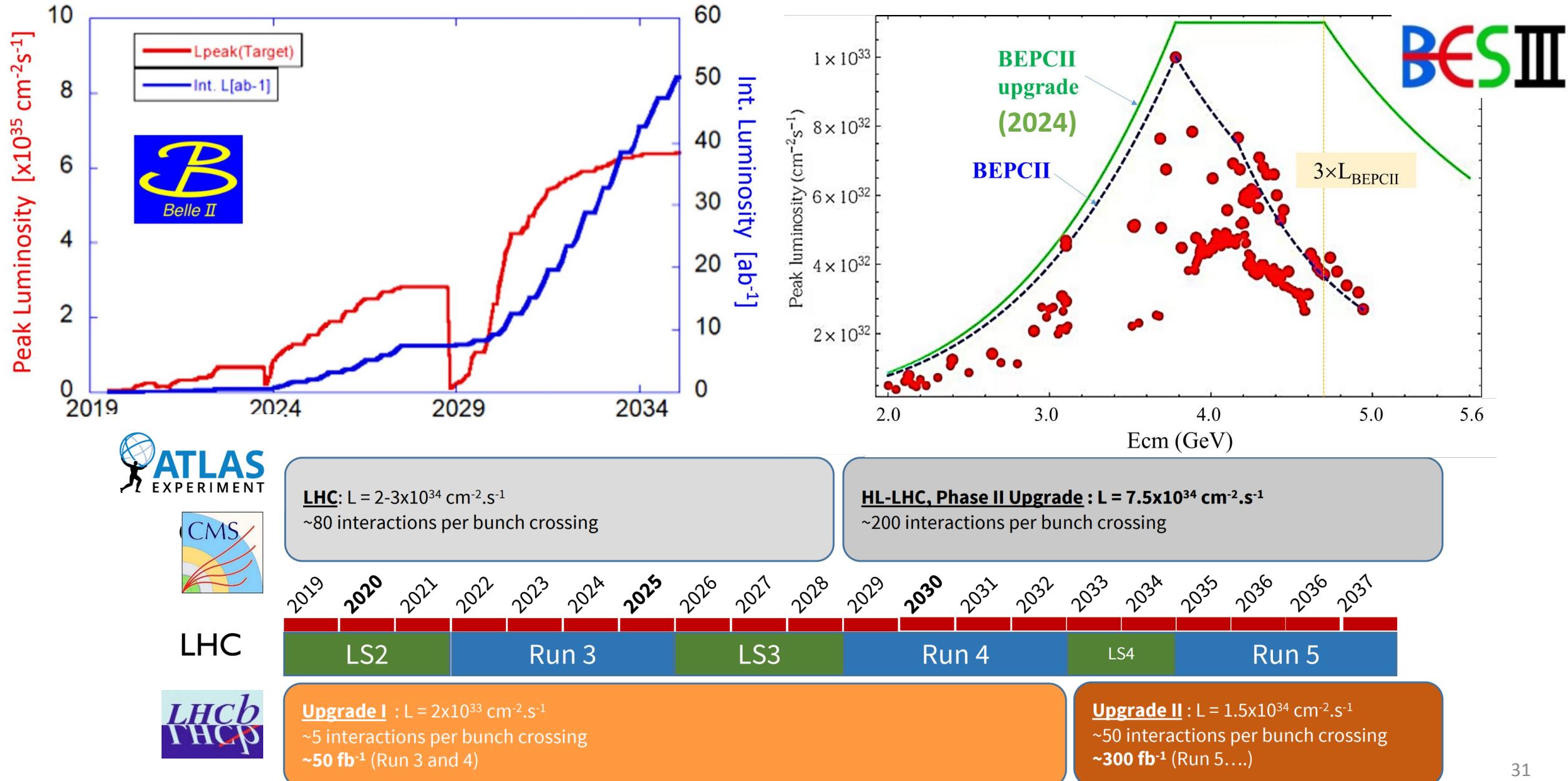
- 3.1σ evidence for $P_{\text{cs}}(4459)$ close to $\Xi_c^+ D^{*-}$ threshold.
- Two states?

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



Summary

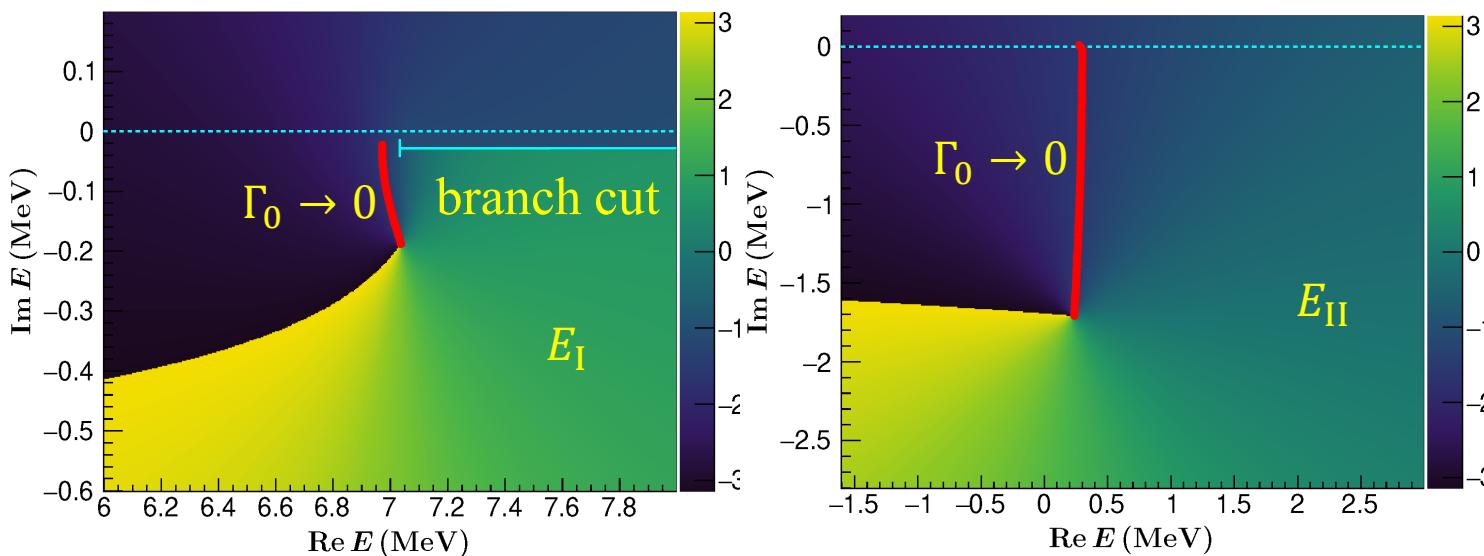
- Lots of progress in the experimental study of hadron spectroscopy.
- Spectroscopy of hadronic molecules to be further investigated.
- States formed by other dynamics may have been discovered.
- More results to come (Belle II, BESIII, LHCb, ...), and lots of opportunities and challenges ahead.
- Theoretical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

Thank you very much!

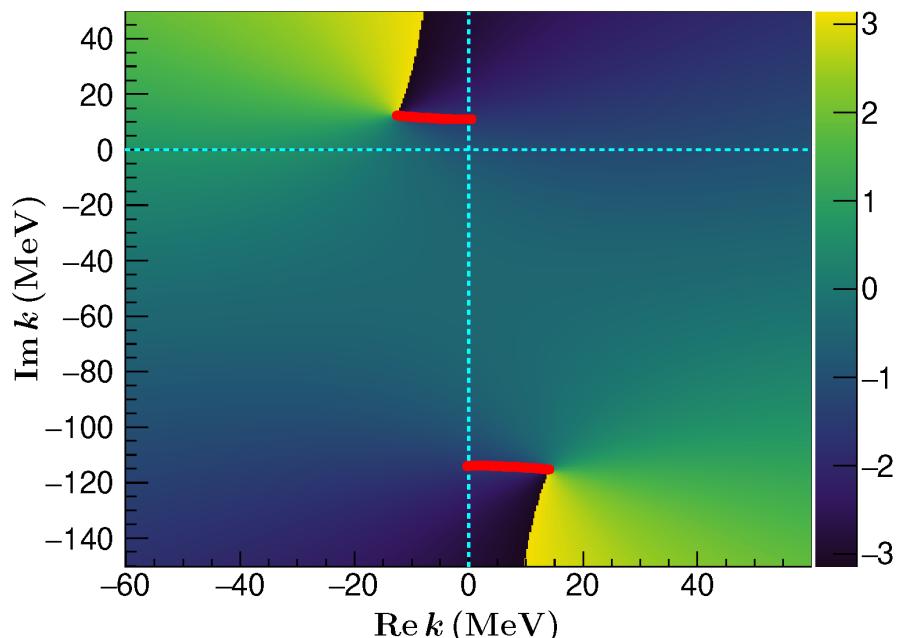
Backup slides

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: $E - E_X + g\sqrt{-2\mu(E - E_R + i\Gamma/2)}$
- $E_I = (7.04 \pm 0.15^{+0.07}_{-0.08}) + (-0.19 \pm 0.08^{+0.14}_{-0.19})i$ MeV
- $E_{II} = (0.26 \pm 5.74^{+5.14}_{-38.32}) + (-1.71 \pm 0.90^{+0.60}_{-1.96})i$ 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 $\Gamma_0 \rightarrow 0$ and stable D^*
 - scattering length $a = (-16.5^{+7.0+5.6}_{-27.6-27.7})$ fm
 - effective range: $r_e = (-4.1^{+0.9+2.8}_{-3.3-4.4})$ fm



The effective range expansion

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

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

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

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	$-16.5^{+7.0}_{-27.6} {}^{+5.6}_{-27.7}$ fm	-5.41 fm
r_e	$-4.1^{+0.9}_{-3.3} {}^{+2.8}_{-4.4}$ 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

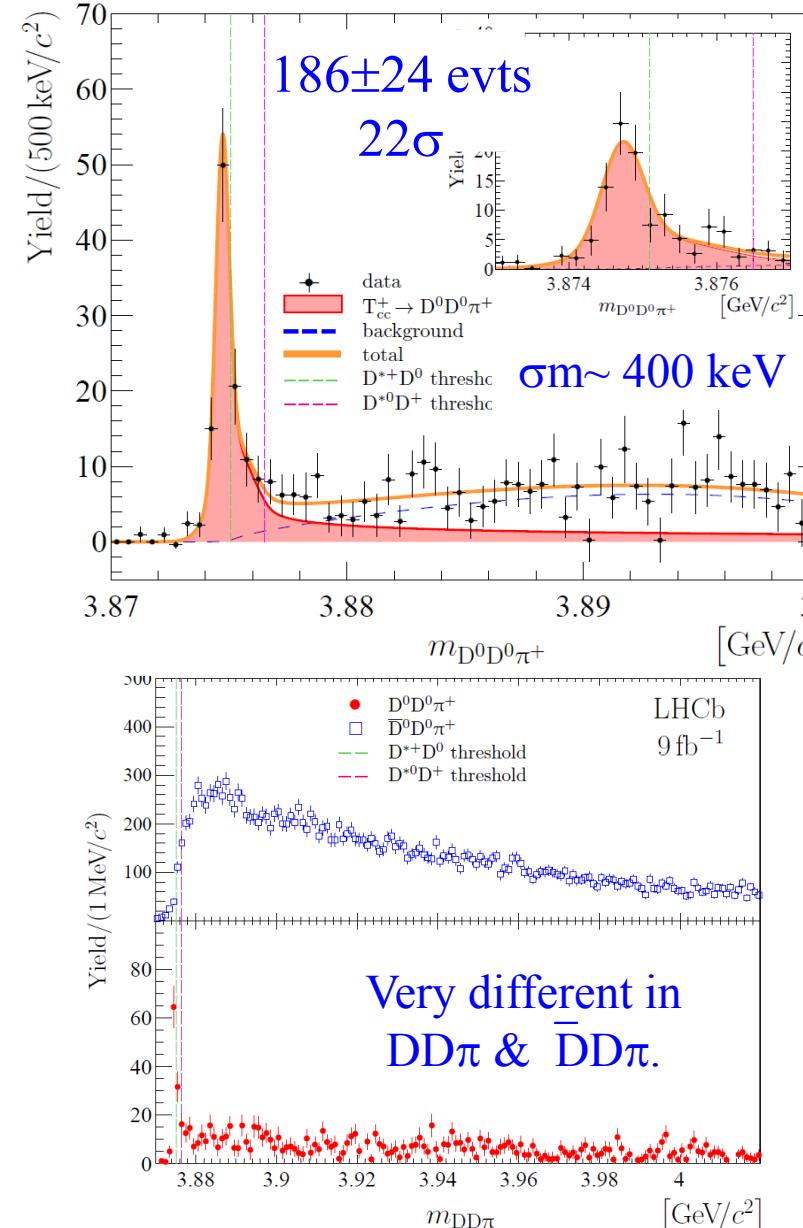
Effective Range Expansion → scattering length a and effective range r_e

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, *PPNP* 107 (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/>

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

9 fb^{-1} Run 1 & Run 2 data



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

$$\tilde{\mathcal{F}}_f^U(s) = \varrho_f(s) |\mathcal{A}_U(s)|^2, \quad f \in \{D^0\bar{D}^0\pi^+, D^0\bar{D}^+\pi^0, D^0\bar{D}^+\gamma\}$$

$$\mathcal{A}_U(s) = \frac{1}{m_U^2 - s - im_U \hat{\Gamma}(s)}, \quad J^P=1^+ \text{ & } I=0 \text{ assumed.}$$

Relative to $D^0\bar{D}^{*+}$ threshold:

$$\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0} \text{ keV}/c^2$$

$$\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14} \text{ keV},$$

$$\delta m_{\text{BW}} = -273 \pm 61 \pm 5^{+11}_{-14} \text{ keV}/c^2$$

$$\Gamma_{\text{BW}} = 410 \pm 165 \pm 43^{+18}_{-38} \text{ keV},$$

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

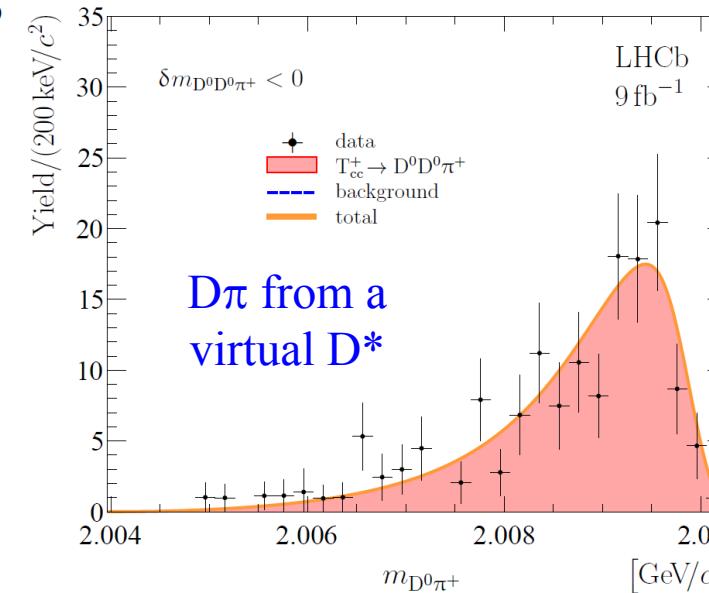
$$R_{\Delta E} \equiv \frac{1}{\gamma} = 7.5 \pm 0.4 \text{ fm}$$

The compositeness

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

$Z < 0.52 (0.58)$ at 90 (95)% CL.

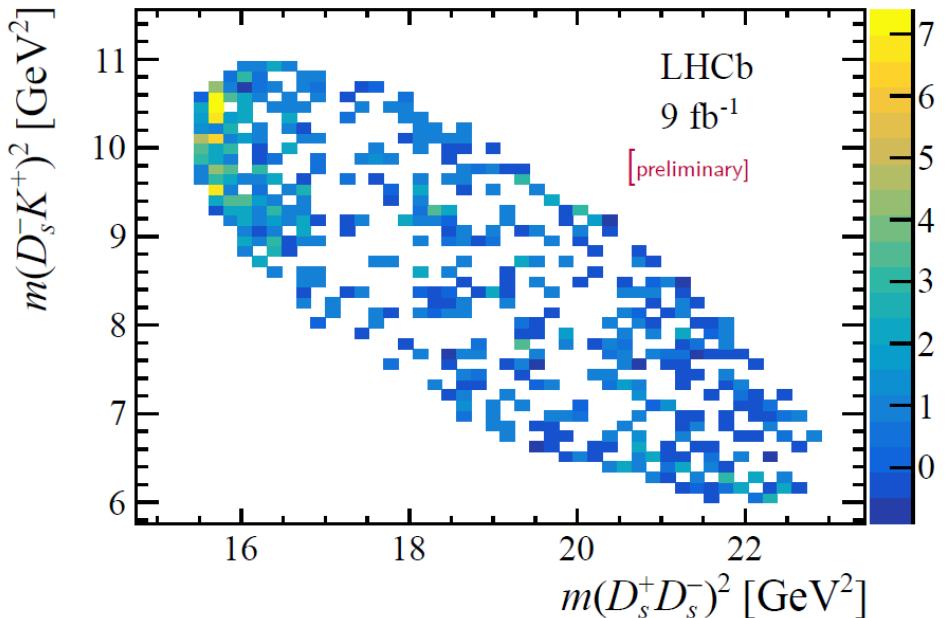
($Z=0$ for molecular states).



9 fb⁻¹ Run 1 & Run 2 data
360 $B^+ \rightarrow D_s^+ D_s^- K^+$ evts, 84% purity

$X(3960)$ in $B^+ \rightarrow D_s^+ D_s^- K^+$

LHCb
VHCf



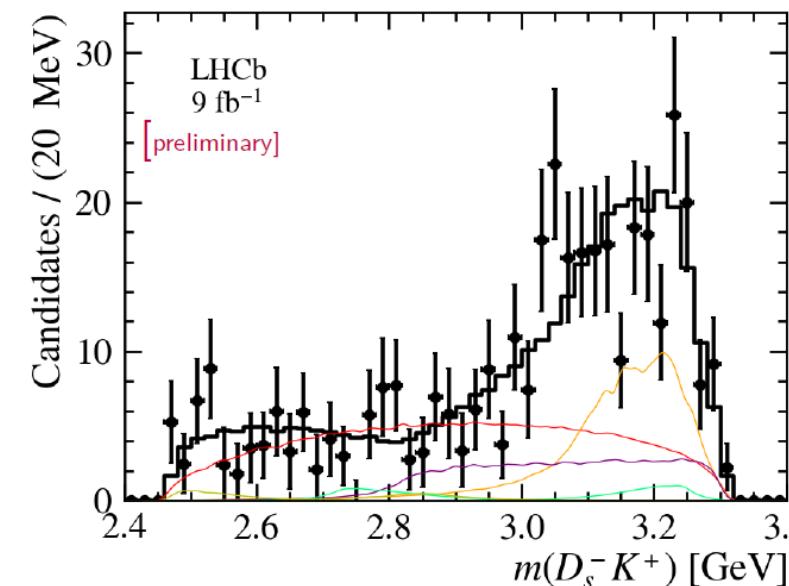
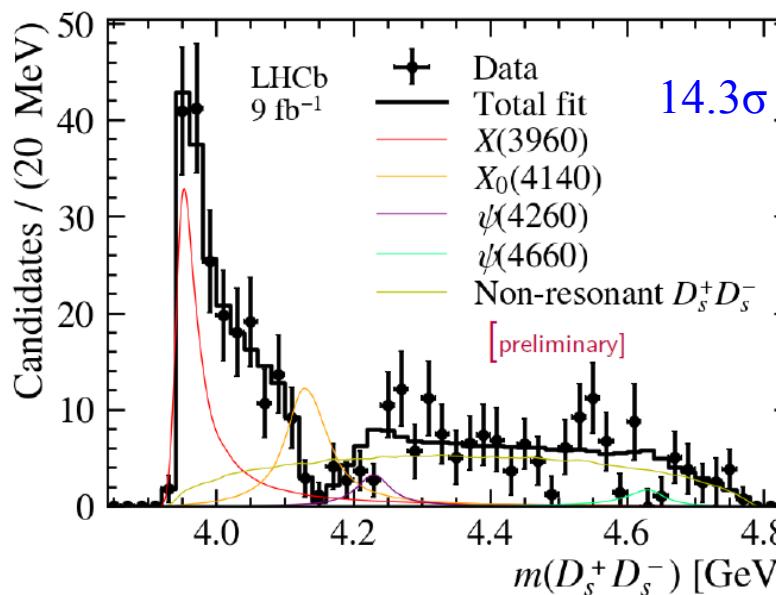
Baseline model: $D_s^+ D_s^-$ resonances

- 1^{--} : $\psi(4260) \sim 4\%$, $\psi(4660) \sim 2\%$
- 0^{++} : $X(3960) \sim 24\%$, $X(4140) \sim 18\%$, NR $\sim 50\%$

Coupled channels $D_s^+ D_s^- / J/\psi \phi$

Two K-matrix poles

Gives equally good fit



$X(3960)$, 14.3σ , $J^{PC}=0^{++}$:

$$m = 3956 \pm 5 \pm 11 \text{ MeV}$$

$$\Gamma = 43 \pm 13 \pm 8 \text{ MeV}$$

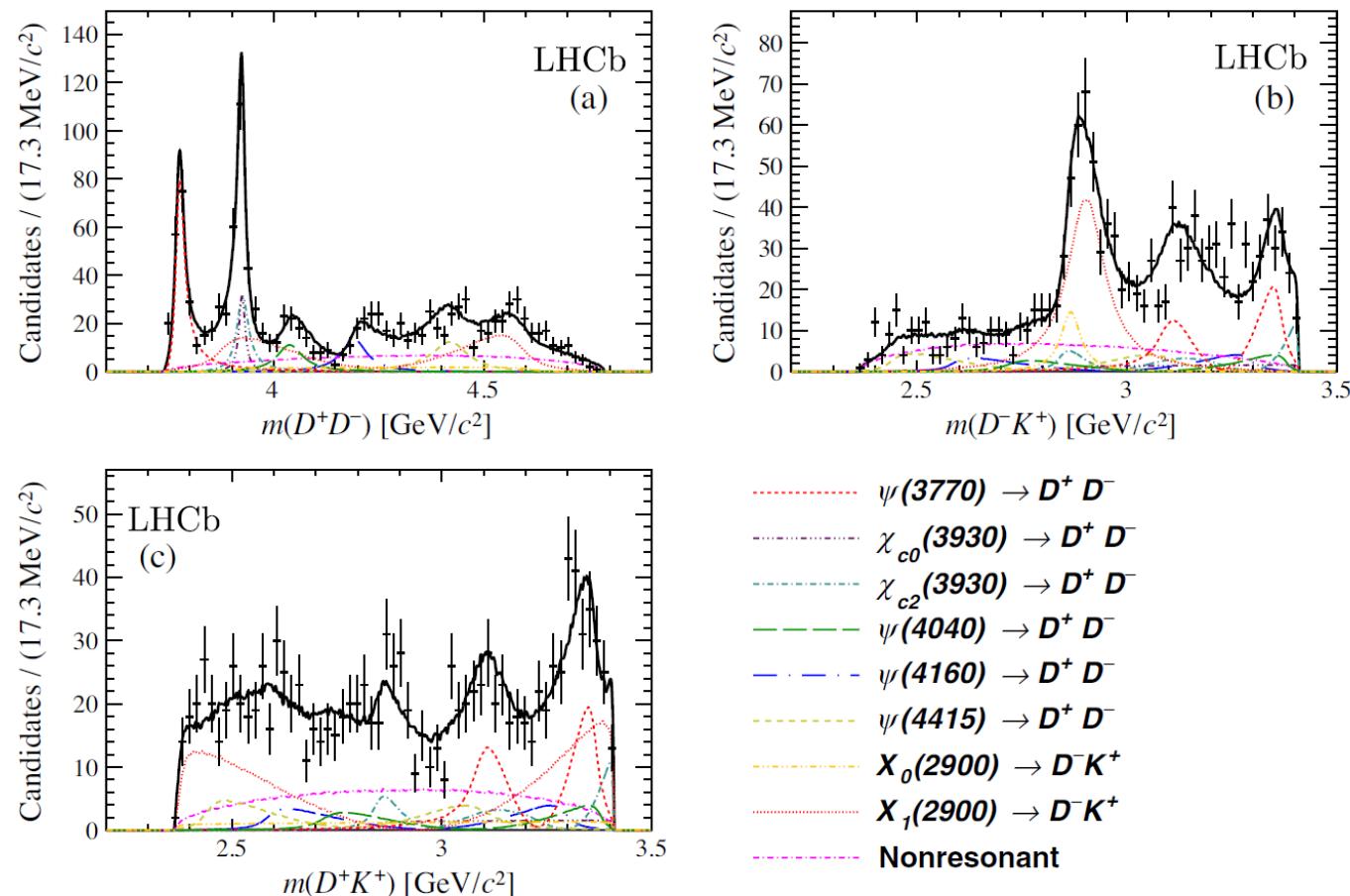
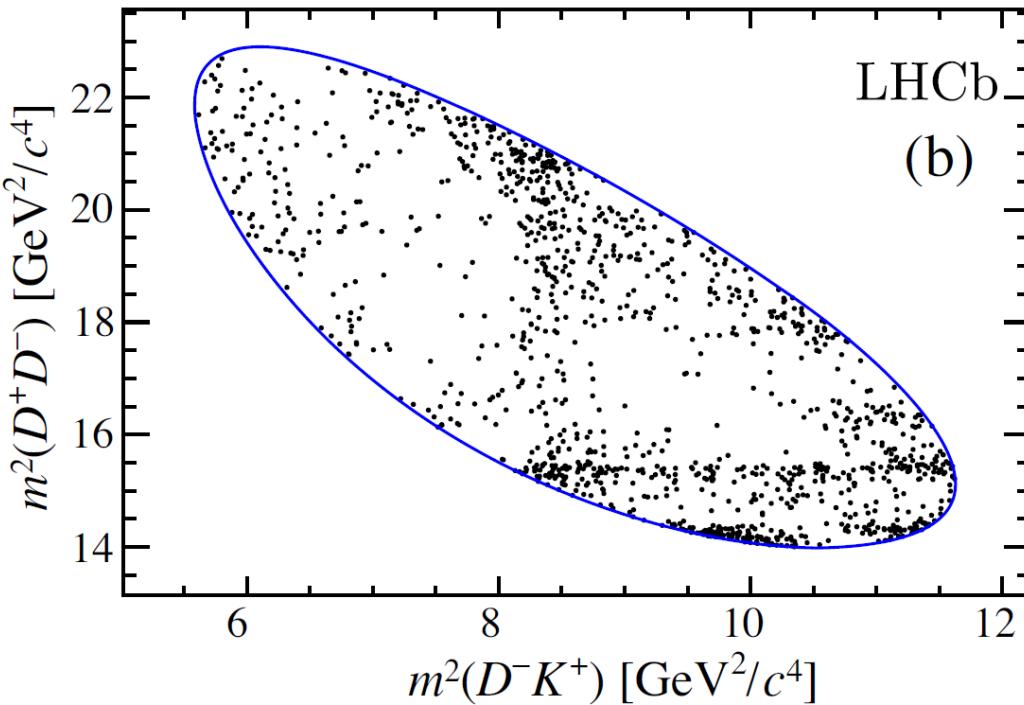
Evidence for the $Y(4140)$, $Y(4260)$, and $Y(4660)$

PRD 102, 112003 (2020)

PRL 125, 242001 (2020)

9 fb^{-1} Run 1 & Run 2 data1260 selected $B^+ \rightarrow D^+ D^- K^+$ decays

$X(3930)$ in $B^+ \rightarrow D^+ D^- K^+$



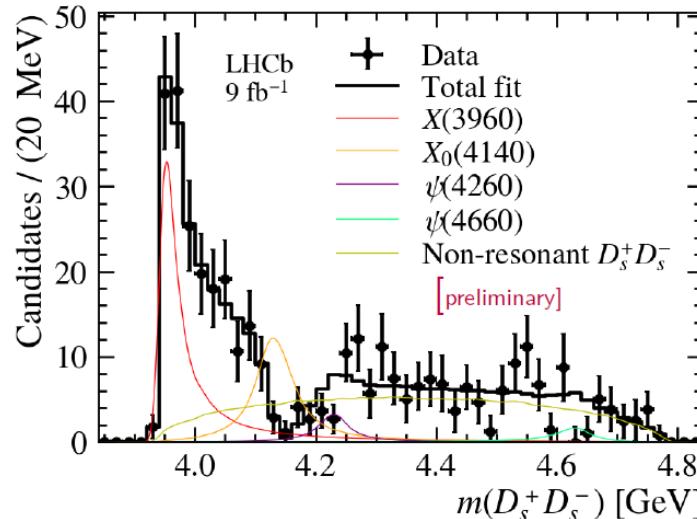
Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
$X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
$X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11 \pm 4$

Resonance	Magnitude	Phase (rad)	Fit fraction (%)
$D^+ D^-$ resonances			
$\psi(3770)$	1 (fixed)	0 (fixed)	$14.5 \pm 1.2 \pm 0.8$
$\chi_{c0}(3930)$	$0.51 \pm 0.06 \pm 0.02$	$2.16 \pm 0.18 \pm 0.03$	$3.7 \pm 0.9 \pm 0.2$
$\chi_{c2}(3930)$	$0.70 \pm 0.06 \pm 0.01$	$0.83 \pm 0.17 \pm 0.13$	$7.2 \pm 1.2 \pm 0.3$
$\psi(4040)$	$0.59 \pm 0.08 \pm 0.04$	$1.42 \pm 0.18 \pm 0.08$	$5.0 \pm 1.3 \pm 0.4$
$\psi(4160)$	$0.67 \pm 0.08 \pm 0.05$	$0.90 \pm 0.23 \pm 0.09$	$6.6 \pm 1.5 \pm 1.2$
$\psi(4415)$	$0.80 \pm 0.08 \pm 0.06$	$-1.46 \pm 0.20 \pm 0.09$	$9.2 \pm 1.4 \pm 1.5$

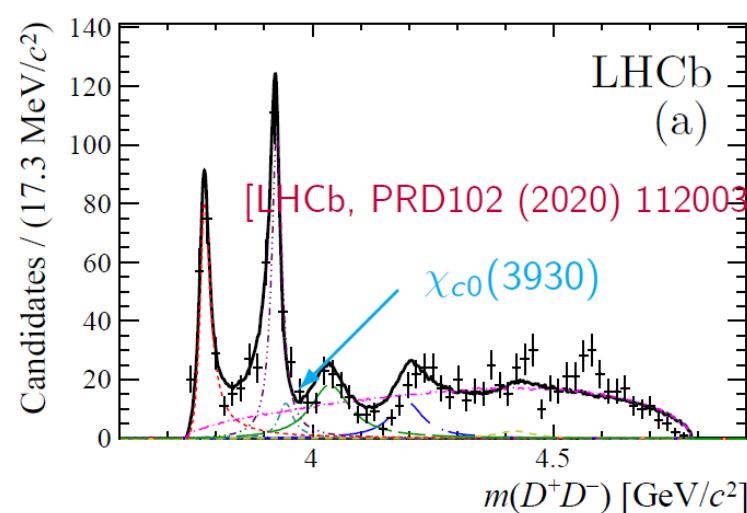
$X(3960)=X(3930)? \quad X(3960)=X(3915)?$

Is $X(3960)$ the same as $\chi_{c0}(3930)$ from D^+D^- ?

$B^+ \rightarrow (D_s^+ D_s^-) K^+$ by LHCb:

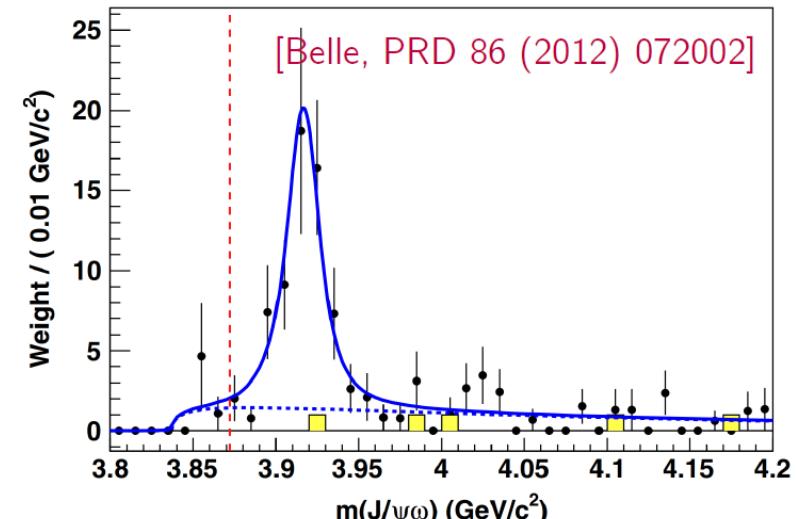


$B^+ \rightarrow (D^+ D^-) K^+$ by LHCb:



Is $X(3960)$ the same as $\chi_{c0}(3915)$?

$\gamma\gamma \rightarrow J/\psi\omega$ by Belle:



- Assuming to be the same, $\mathcal{B}(\chi_{c0} \rightarrow D^+ D^-)/\mathcal{B}(\chi_{c0} \rightarrow D_s^+ D_s^- P) \sim 0.3$
large molecular component, or large tetraquark component, $T_{\psi\phi}$
- [JHEP 06 (2021) 035] finds a state coupled to $D_s^+ D_s^-$ on the lattice

- Belle sees a clean state in $J/\psi\omega$ with $J^P = 0^+$
- The $D_s^+ D_s^-$ signal might be a tail of the $\chi_{c0}(3915)$ state

Very puzzling scalars, some of them could be non- $q\bar{q}$ states:

- Light hadrons: $f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, ...
- Charmonium(likes): $\chi_{c0}(3415)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c0}(3930)$, $\chi_{c0}(3960)$, ...