



Recent results on hadron spectroscopy at LHCb

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QCD24 27th HIGH-ENERGY PHYSICS
INTERNATIONAL CONFERENCE
IN QUANTUM CHROMODYNAMICS



Outline

- Study of radiative decays of $\chi_{c1}(3872)$ [arXiv: 2406.17006]
- First measurement of $J/\psi\phi$ production in pp collisions with no additional activity [LHCb-PAPER-2023-043] in preparation
- Amplitude analysis of $B^+ \rightarrow D^{*-} D_S^+ \pi^+$ [arXiv: 2405.00098]
- Amplitude analysis of $B^+ \rightarrow D^{*\pm} D^{\mp} K^+$ [arXiv: 2404.19510] } $B \rightarrow D\bar{D}h$
- Search for prompt production of pentaquarks in open charm final states [arXiv: 2404.07131]
- Observation of $\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$ [arXiv: 2404.19510]
- Modification of $\chi_{c1}(3872)$ production in $p\text{Pb}$ collisions [PRL 132 (2024) 242301]
- Ξ_b^- baryon lifetime measurement [arXiv: 2406.12111]
- Observation of $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ [arXiv: 2403.03586]
- ...

Introduction

- QCD describing strong interaction between quarks and gluons is not well understood due to its non-perturbative nature at low energy scale
- Hadron spectroscopy provides opportunities to test QCD and its effective models
 - e.g. lattice QCD, diquark model, potential model ...
- Exotic hadrons provide unique probe to QCD
 - Predicted in quark model
 - Recent results show strong evidence for their existence



mesonic molecule ?



tetraquark ?



pentaquark ?



hybrid ?



meson



baryon



...

EXOTIC



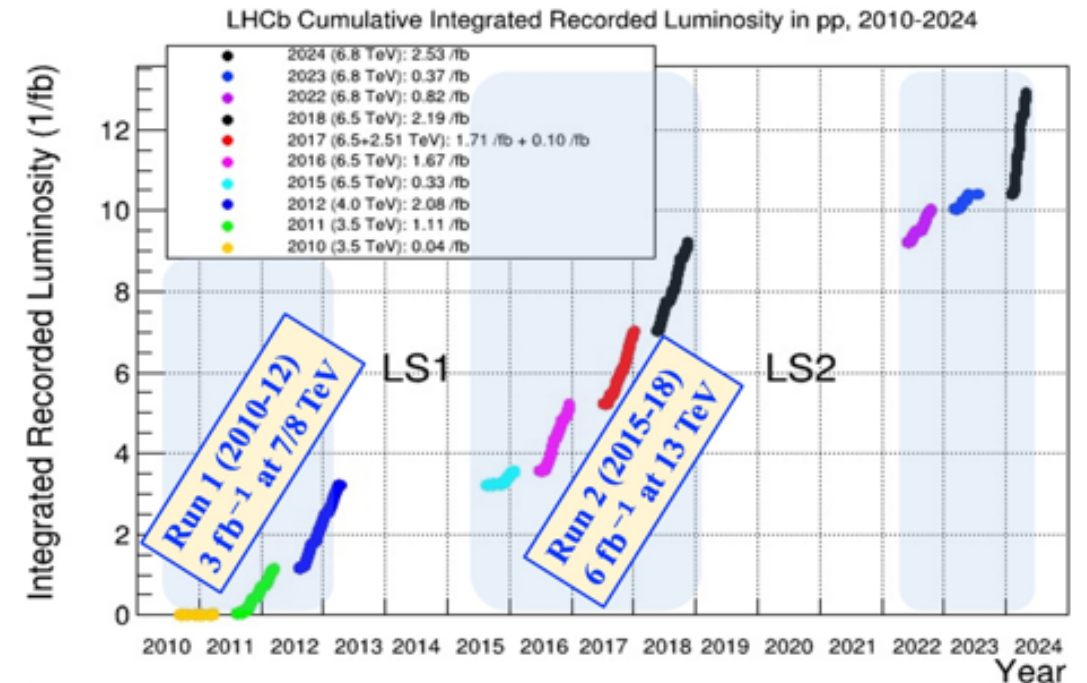
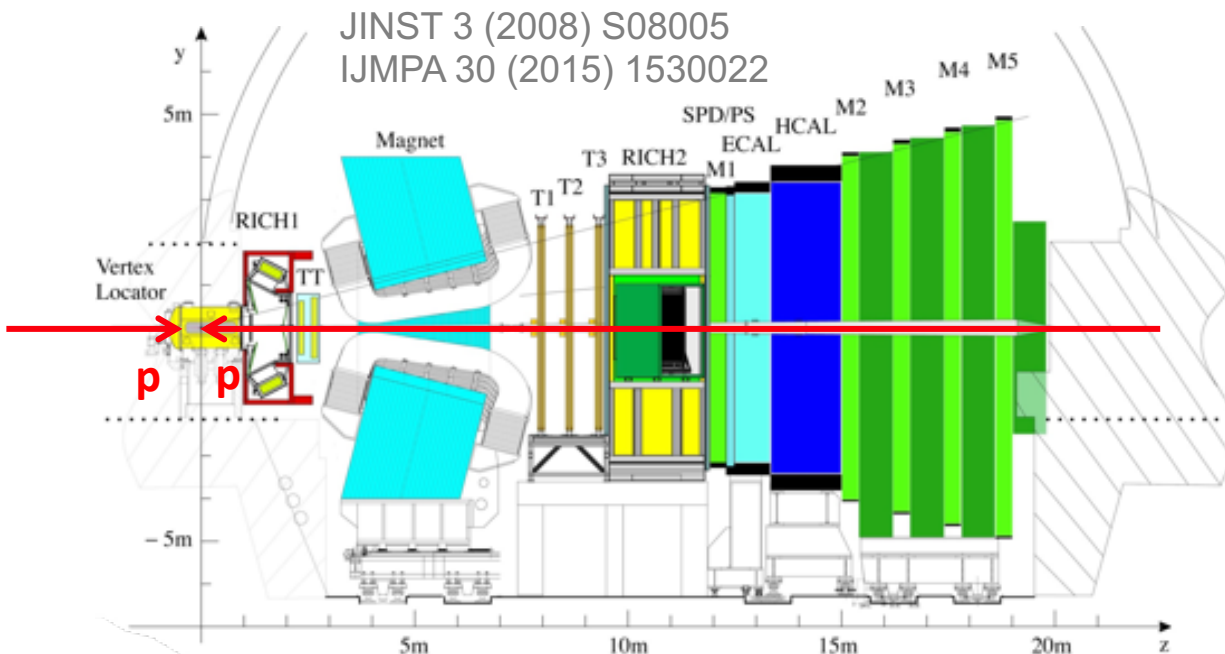
e.g. deuteron

STANDARD

The LHCb Experiment

- LHCb is a dedicated flavour physics experiment at the LHC
 - $>10^4 \times$ larger b production rate than the B factories @ $\sqrt{s}=4S$
 - Access to all b -hadrons: B^+ , B^0 , B_s^0 , B_c^+ , b -baryons
- Can also study hadron spectroscopy and exotic states
- Acceptance optimised for forward $b\bar{b}$ production

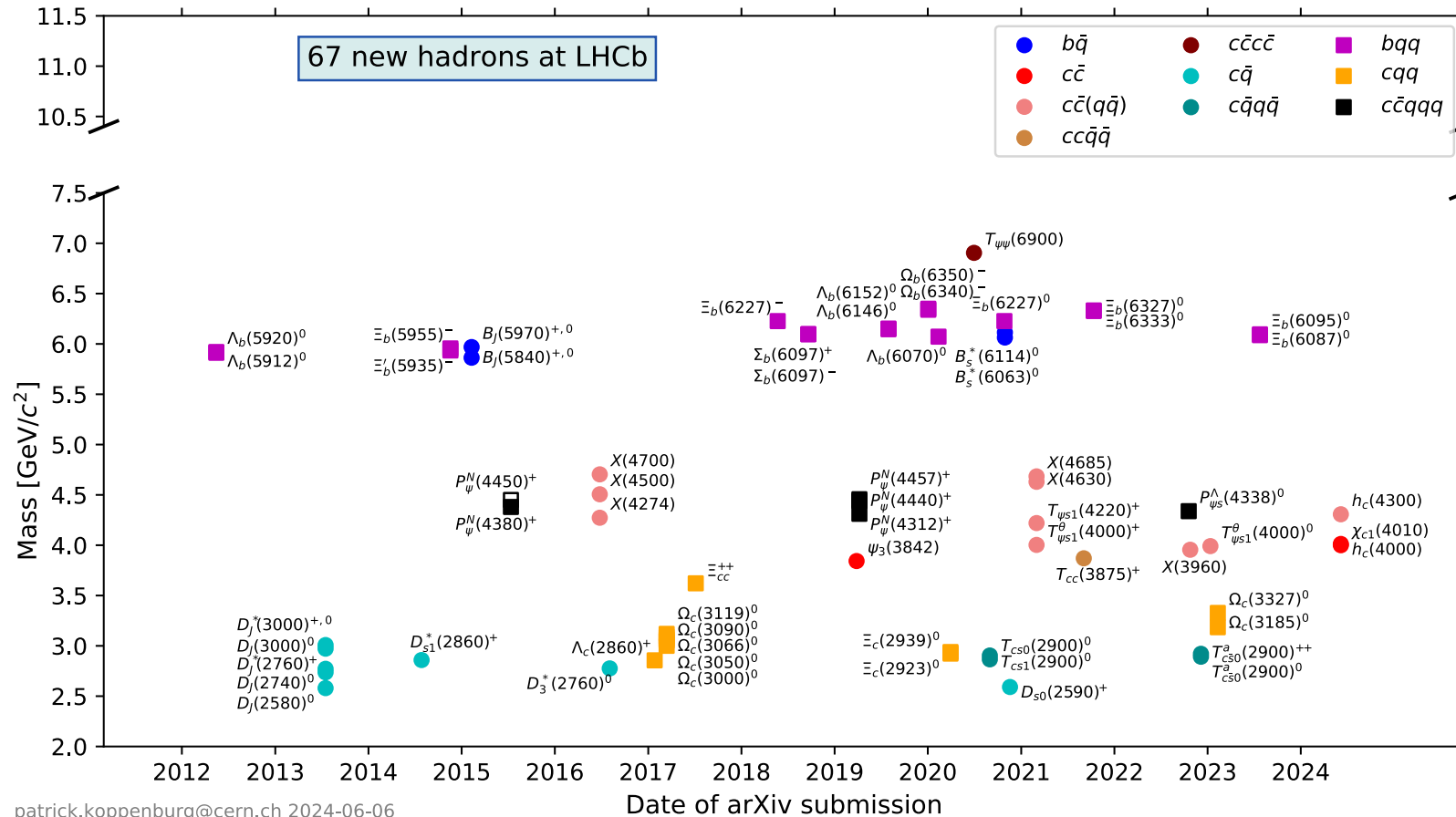
➤ All results based on full or part of run-1 and run-2 datasets



New particles in a glance

67 new hadrons discovered by LHCb!

<https://www.nikhef.nl/~pkoppenb/particles.html>



Radiative decays of $\chi_{c1}(3872)$

[arXiv: 2406.17006]

- Nature of $\chi_{c1}(3872)$ still under debate, while study of radiative decays provides a way to probe it
- Only evidence of $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$ was seen experimentally before

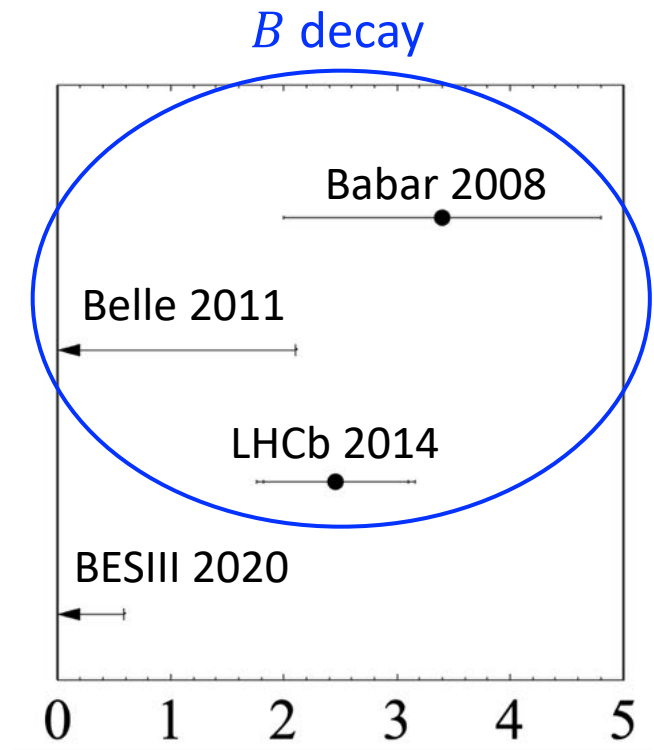
$$\mathcal{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872) \rightarrow \psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872) \rightarrow J/\psi\gamma}}$$

Reference			
T. Barnes and S. Godfrey	67	5.8	$c\bar{c}$
T. Barnes, S. Godfrey and S. Swanson	69	2.6	$c\bar{c}$
F. De Fazio	84	(1.64 ± 0.25)	$c\bar{c}$
B.-Q. Li and K. T. Chao	85	1.3	$c\bar{c}$
Y. Dong <i>et al.</i>	86	1.3 – 5.8	$c\bar{c}$
A. M. Badalian <i>et al.</i>	87	(0.8 ± 0.2)	$c\bar{c}$
J. Ferretti, G. Galata and E. Santopinto	88	6.4	$c\bar{c}$
A. M. Badalian, Yu. A. Simonov and B. L. G. Bakker	89	2.4	$c\bar{c}$
W. J. Deng <i>et al.</i>	90	1.3	$c\bar{c}$
F. Giacosa, M. Piotrowska and S. Goito	71	5.4	$c\bar{c}/vc$
E. S. Swanson	81	0.38 %	$D\bar{D}^*$
Y. Dong <i>et al.</i>	86	0.33 %	$D\bar{D}^*$
D. P. Rathaud and A. K. Rai	91	0.25	$D\bar{D}^*$
R. F. Lebed and S. R. Martinez	92	0.33 %	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	93	3.6 %	$D\bar{D}^*$
F.-K. Guo <i>et al.</i>	82	$0.21(g_2'/g_2)^2$	$D\bar{D}^*$
D. A.-S. Molnar, R. F. Luiz and R. Higa	83	2 – 10	$D\bar{D}^*$
E. Cincioglu <i>et al.</i>	94	< 4	$D\bar{D}^*$
S. Takeuchi, M. Takizawa and K. Shimizu	95	1.1 – 3.4	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	93	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$

≈ 1

$\ll 1$

mixed



Radiative decays of $\chi_{c1}(3872)$ (cont.)

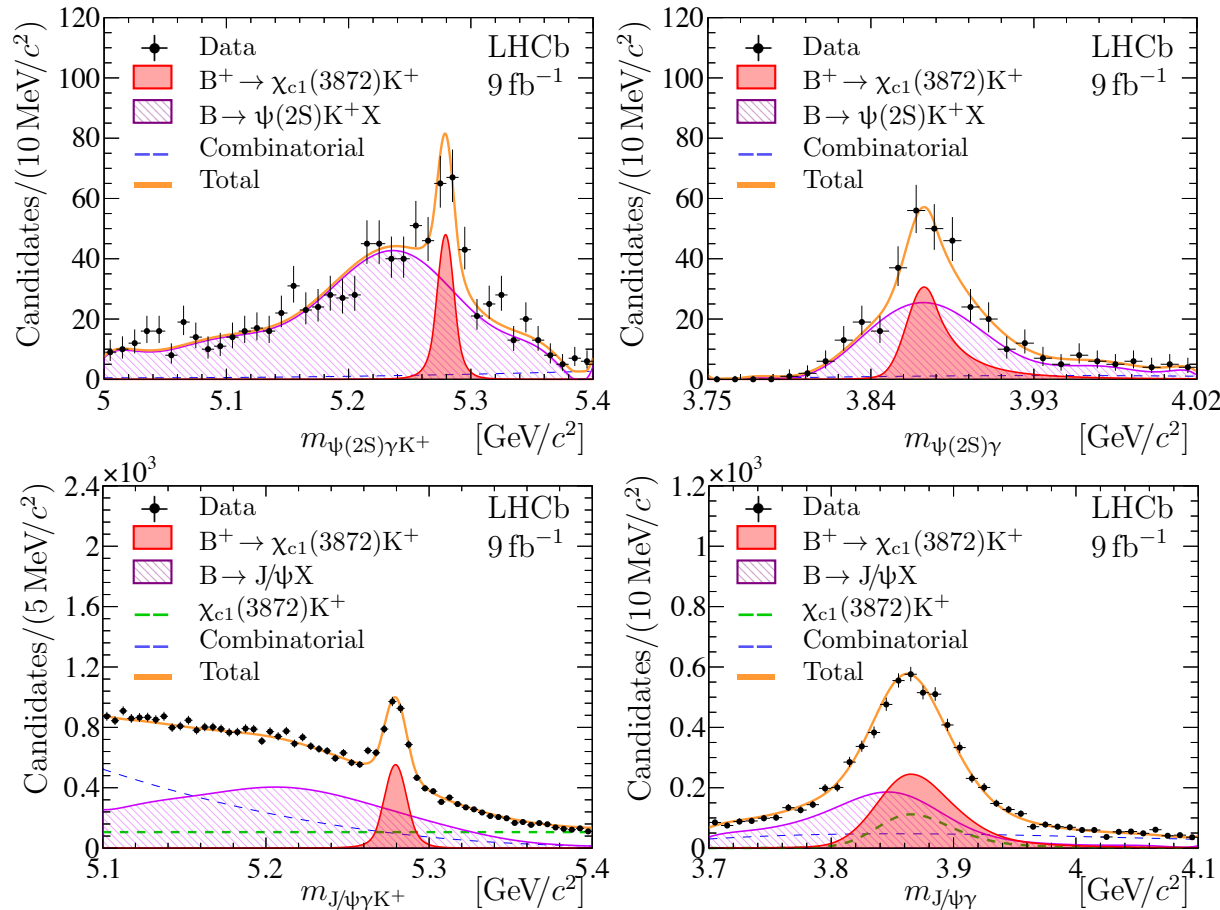
- Update at LHCb using $B^+ \rightarrow \chi_{c1}(3872)K^+$ decay with 9 fb^{-1} Run1+Run2 data

[LHCb meets theory workshop](#)

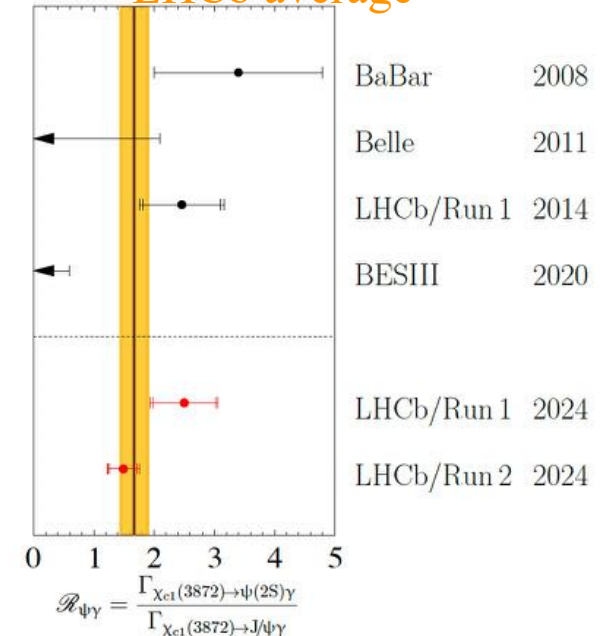
$$\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$$

Run1: $N = 40 \pm 8; 5.3\sigma$

Run2: $N = 63 \pm 10; 6.7\sigma$



LHCb average

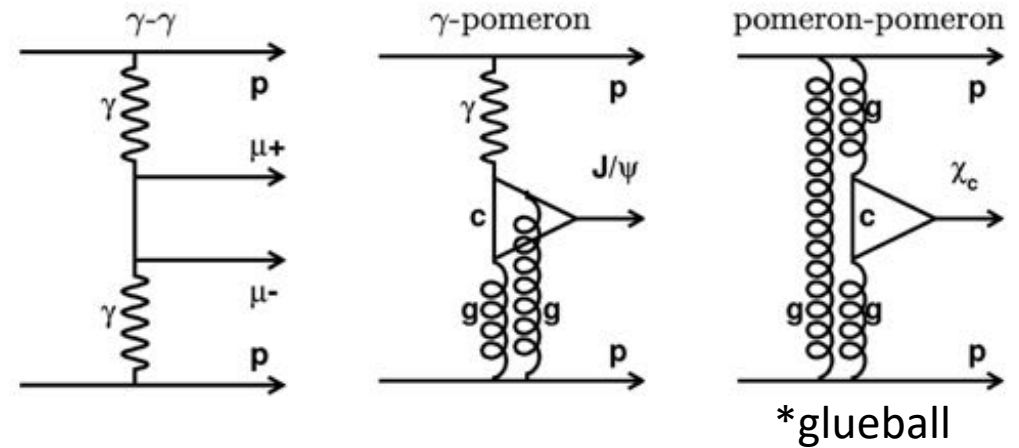
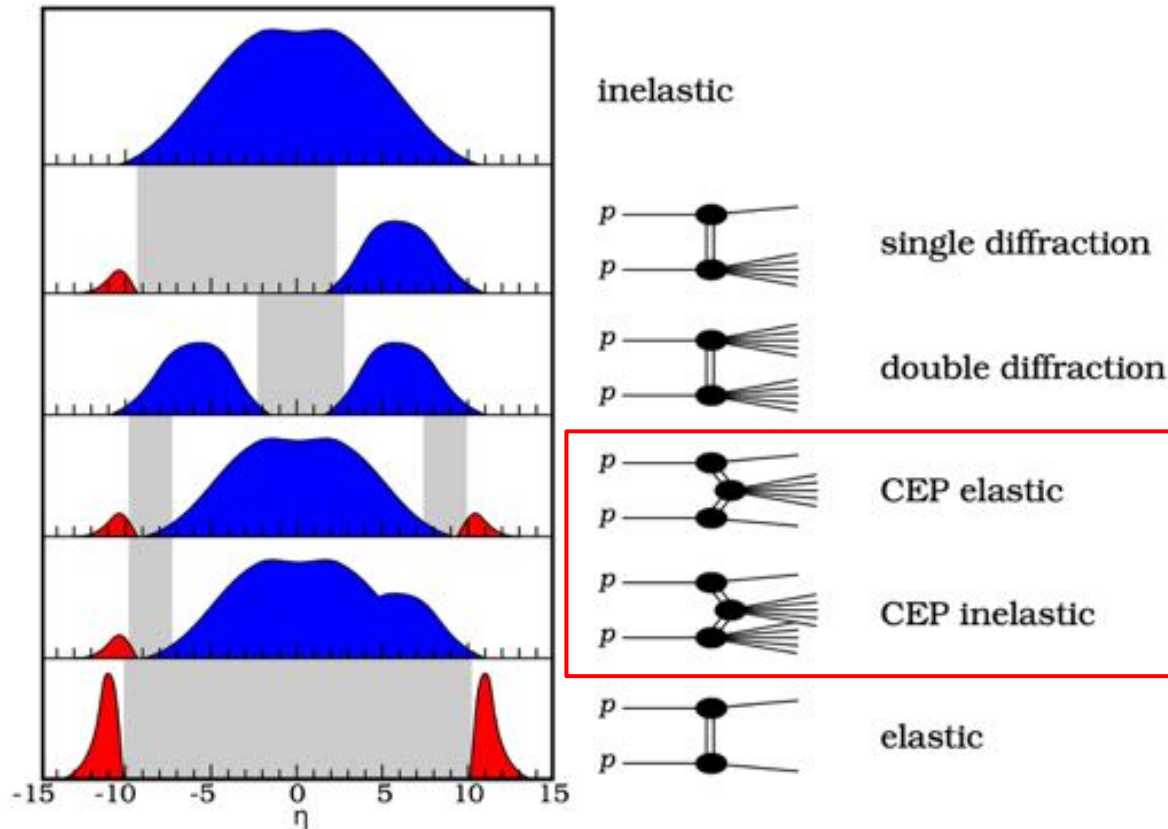


$$\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04 \quad (15\%)$$

Central exclusive production (CEP)

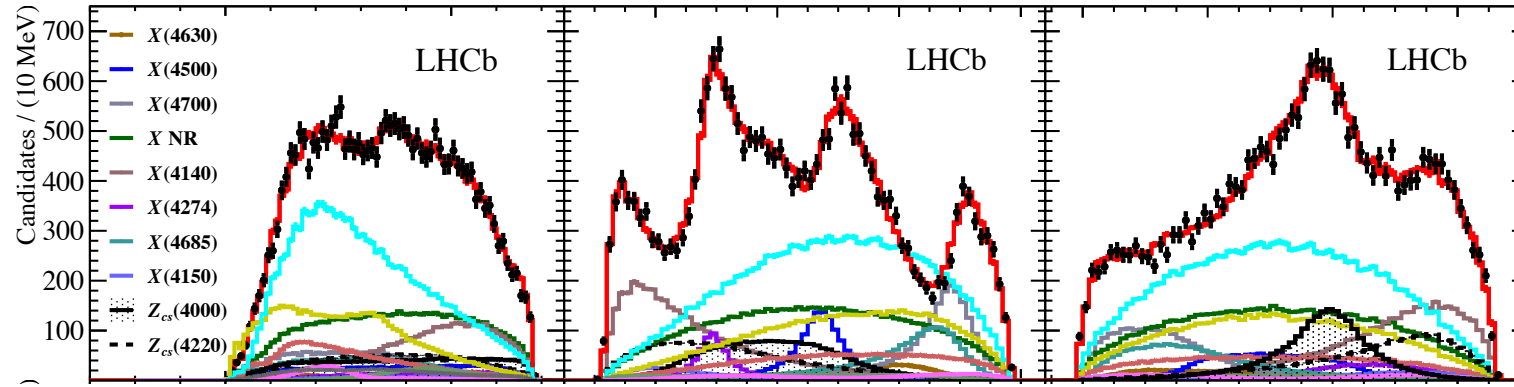
■ Study $J/\psi\phi$ resonances in CEP

- ✓ Experimentally clean even @LHC
- ✓ Spin-parity option narrowed down
- ✗ Much smaller rate



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

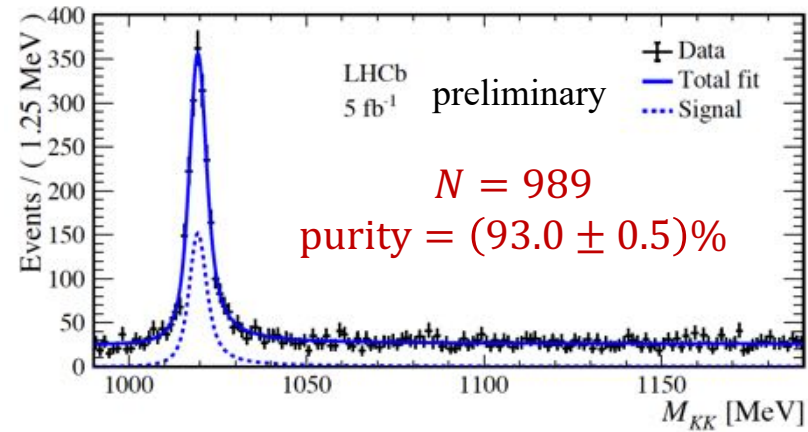
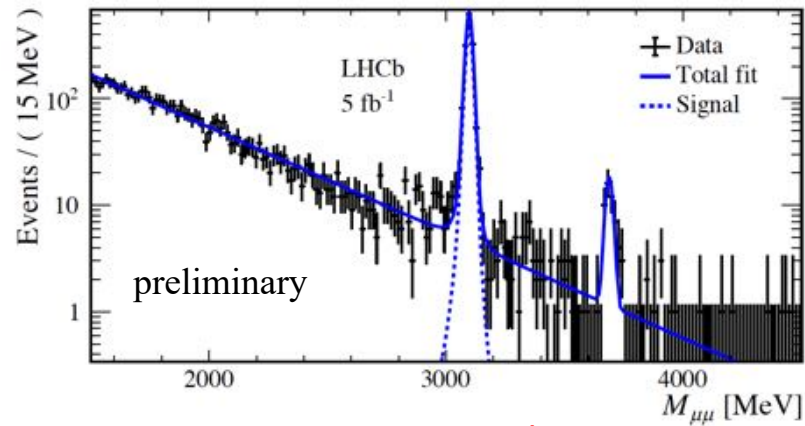
[PRL 127 (2021) 082001]



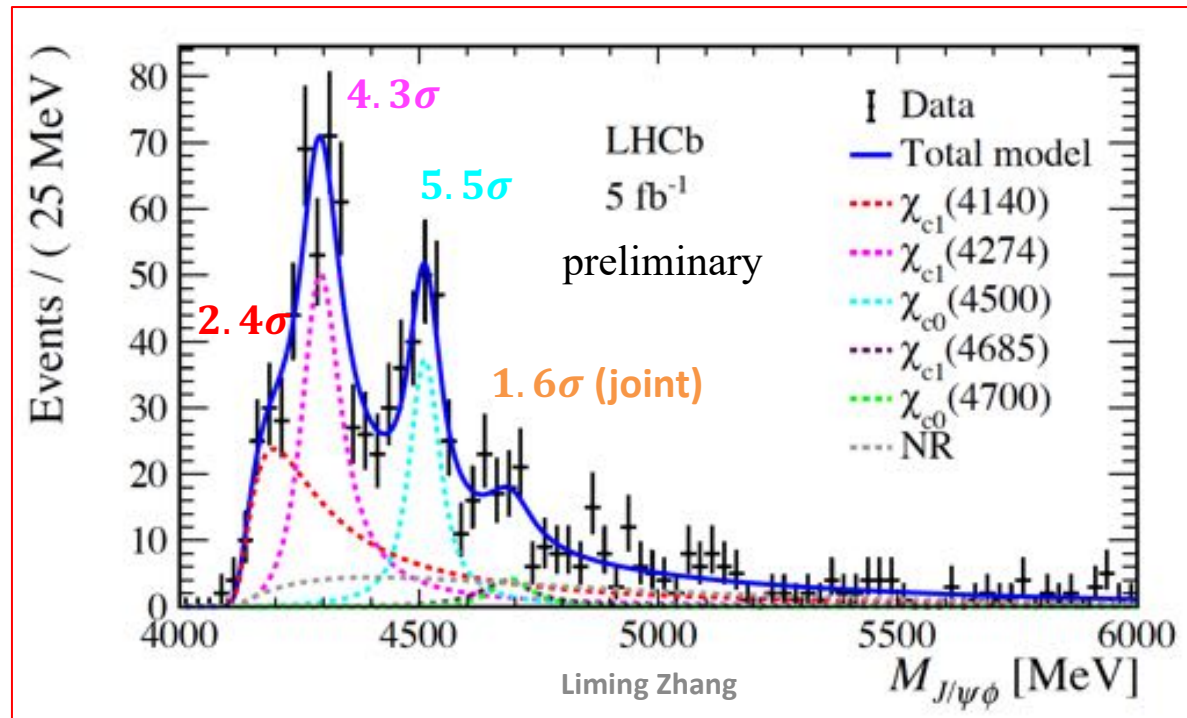
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
$\text{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	$17 \pm 3^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$
All $Z_{cs}(1^+)$				$25 \pm 5^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

$X \rightarrow J/\psi\phi$ in CEP

[LHCb-PAPER-2023-043]
in preparation

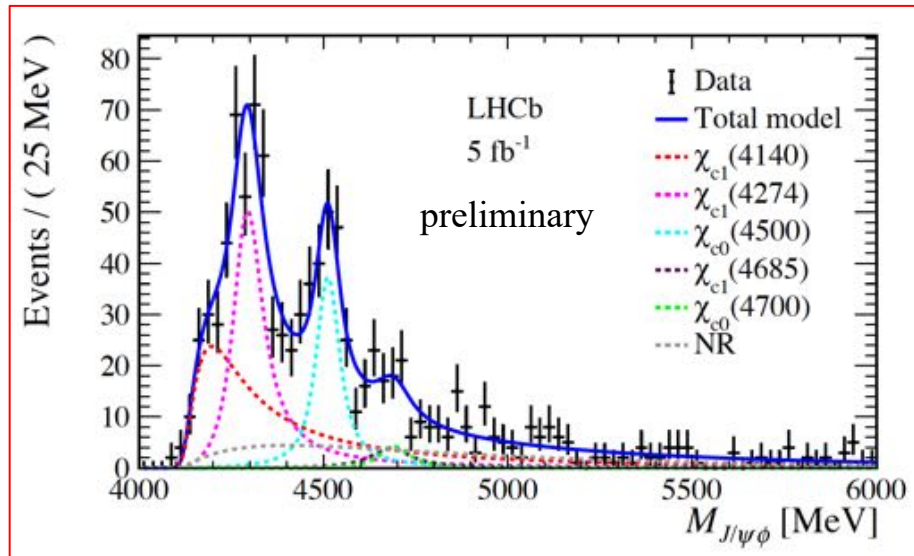


4 tracks



First exotic hadron measurement in CEP!

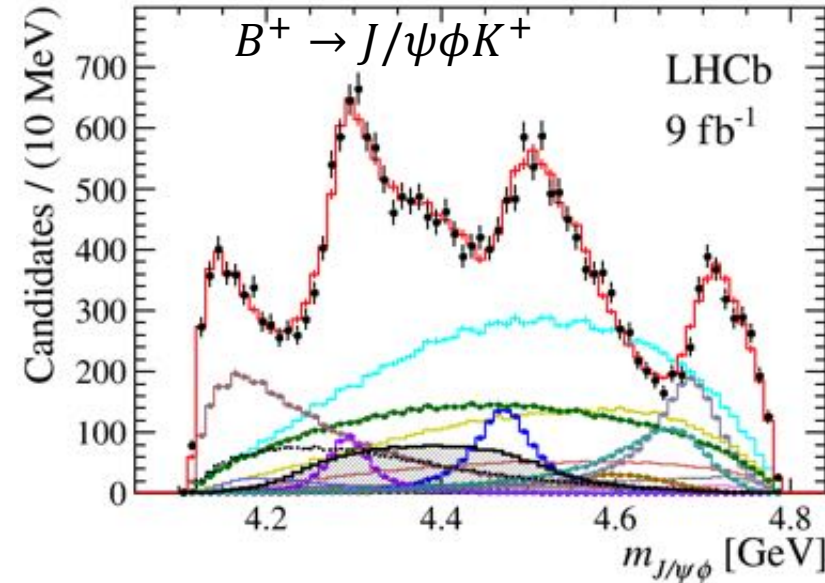
[LHCb-PAPER-2023-043] in preparation



- Mass & width measurements: slightly higher mass of $X(4500)$

Parameter (MeV)	This Letter	Ref. [12]
$M_{\chi_{c1}(4274)}$	$4298 \pm 6 \pm 9$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18} \pm 57$	$53 \pm 5 \pm 5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16} \pm 32$	$77 \pm 6^{+10}_{-8}$

[PR1 127 (2021) 082001]



- Cross-section measurements:

$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4140)} = (0.85 \pm 0.16 \pm 0.30) \text{ pb},$$

$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4274)} = (0.77^{+0.14}_{-0.13} \pm 0.18) \text{ pb},$$

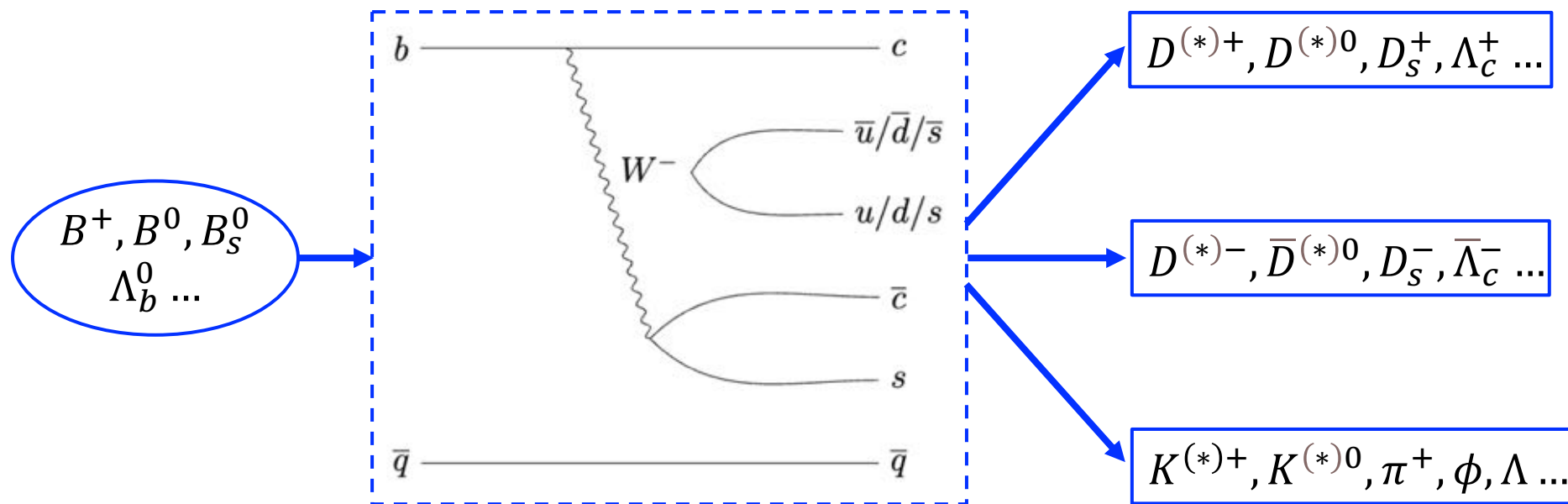
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\text{eff}}^{\chi_{c0}(4500)} = (0.44^{+0.09}_{-0.08} \pm 0.07) \text{ pb},$$

$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06) \text{ pb},$$

$$\sigma_{NR} \times \mathcal{B}_{\text{eff}}^{NR} = (0.46^{+0.25}_{-0.19} \pm 0.21) \text{ pb},$$

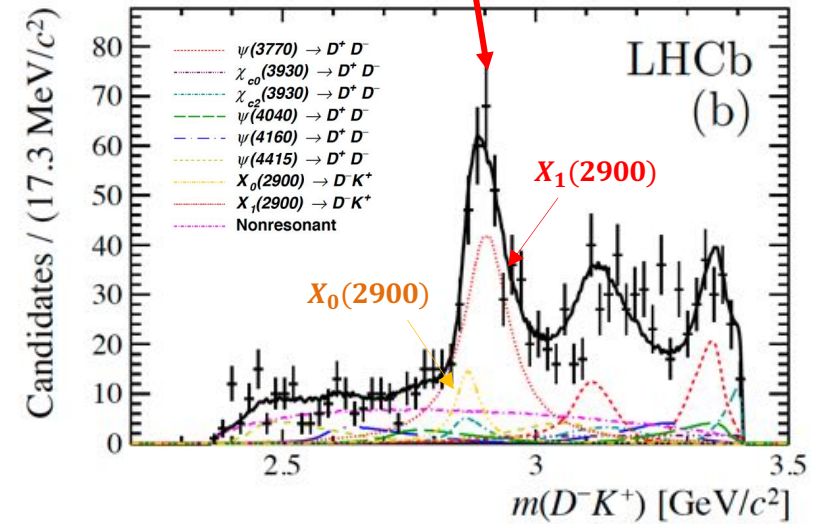
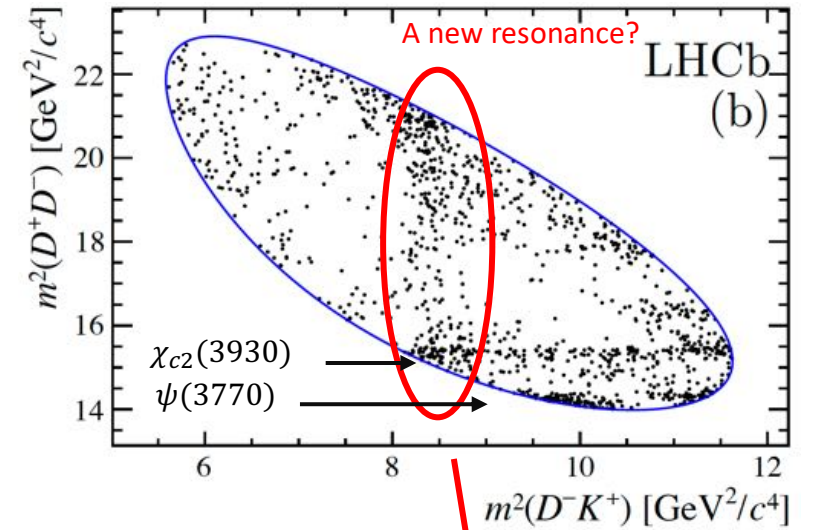
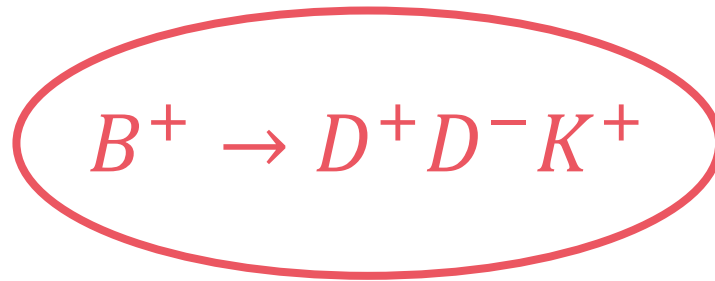
$B \rightarrow D\bar{D}h$ studies

- Rich opportunities for spectroscopy study
 - **charmonium(-like)** states in $D^{(*)}\bar{D}^{(*)}, \Lambda_c^+\bar{D}^{(*)}, \Lambda_c^+\bar{\Lambda}_c^- \dots$
 - **excited** $D^+, D^0, D_s^+, \Lambda_c^+$ states from $D^{(*)}h, \Lambda_c^+h \dots$
 - **exotic** states from $\bar{D}^{(*)}h, \bar{\Lambda}_c^-h \dots$



$B \rightarrow D\bar{D}h$ studies at LHCb

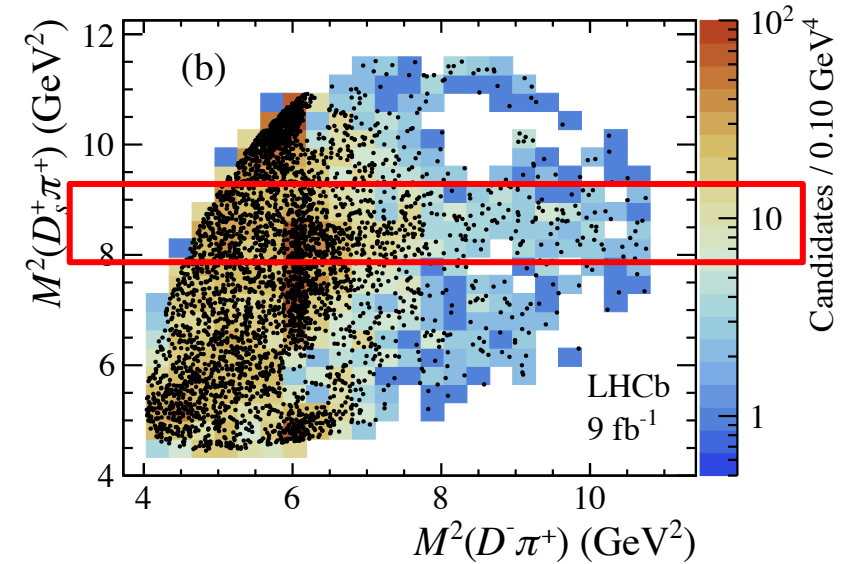
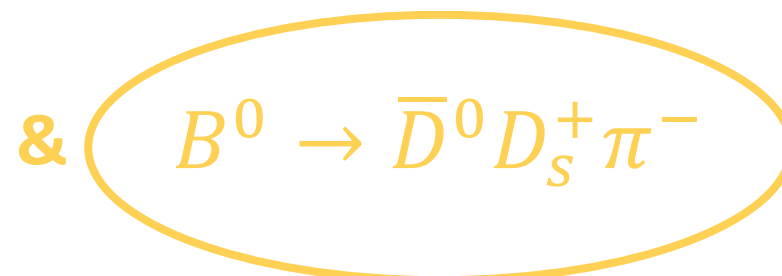
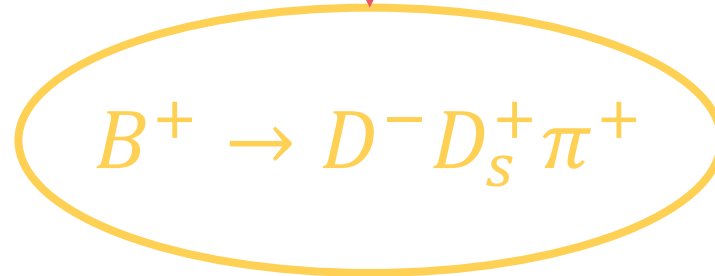
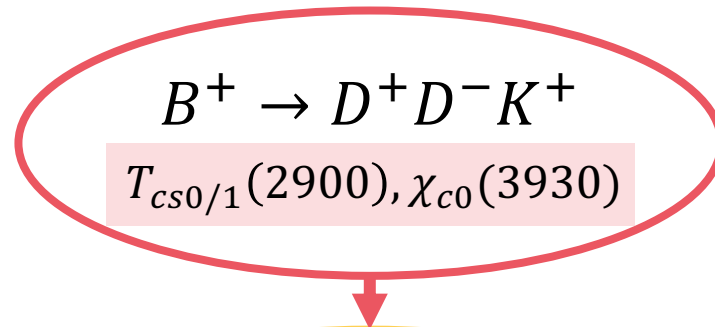
[PRL 125 (2020) 242001]
[PRD 102 (2020) 112003]



$B \rightarrow D\bar{D}h$ studies at LHCb

[PRL 131 (2023) 041902]

$$T_{c\bar{s}0}^a(2900)^0 \rightarrow D_s^+ \pi^-$$
$$T_{c\bar{s}0}^a(2900)^{++} \rightarrow D_s^+ \pi^+$$



$B \rightarrow D\bar{D}h$ studies at LHCb

[PRL 131 (2023) 071901]

$$B^+ \rightarrow D_s^+ D_s^- K^+$$

$$B^+ \rightarrow D^+ D^- K^+$$

$T_{cs0/1}(2900), \chi_{c0}(3930)$

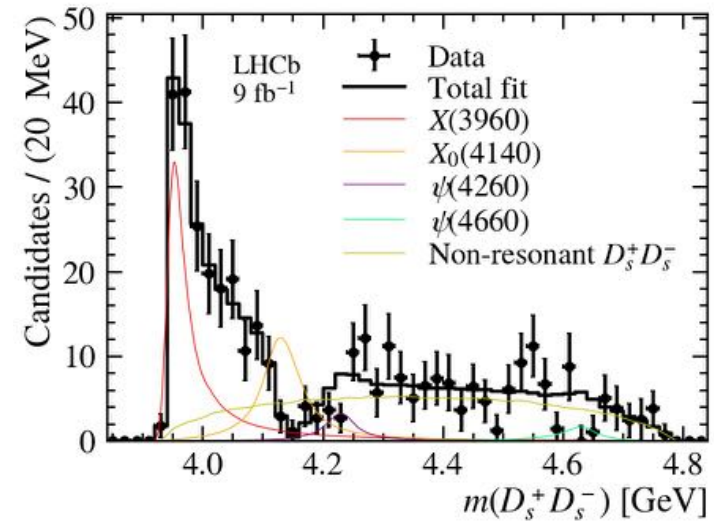
$$B^+ \rightarrow D^- D_s^+ \pi^+$$

$T_{c\bar{s}0}^a(2900)^{++}$

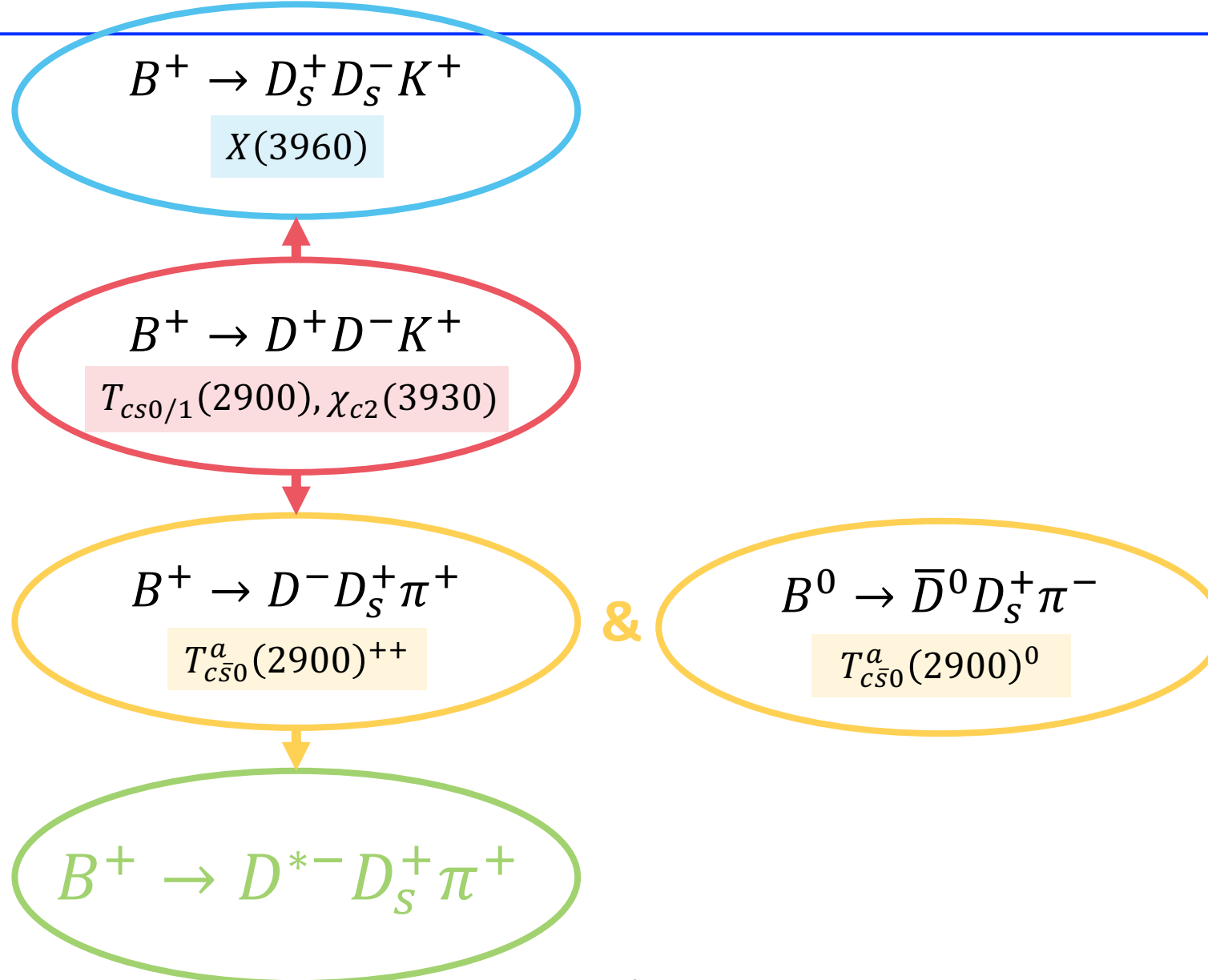
&

$$B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$$

$T_{c\bar{s}0}^a(2900)^0$



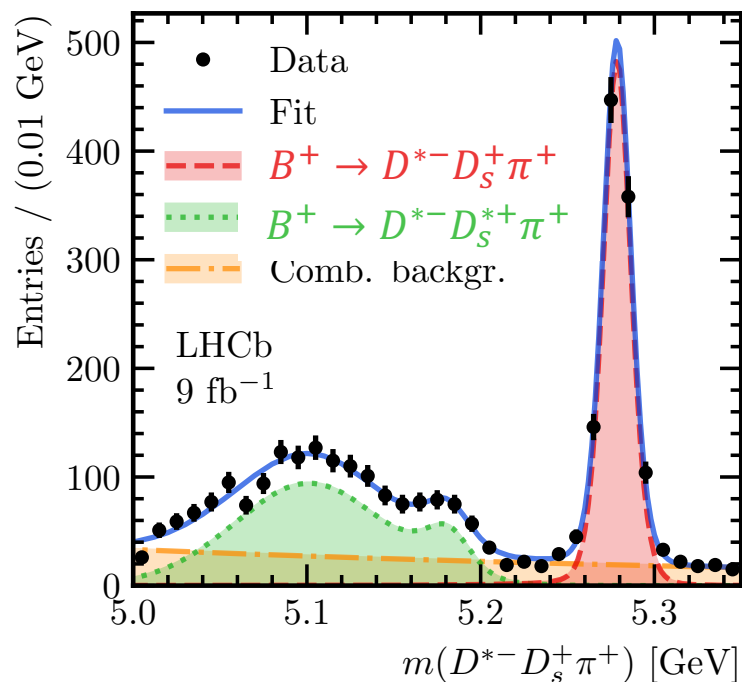
$B \rightarrow D\bar{D}h$ studies at LHCb



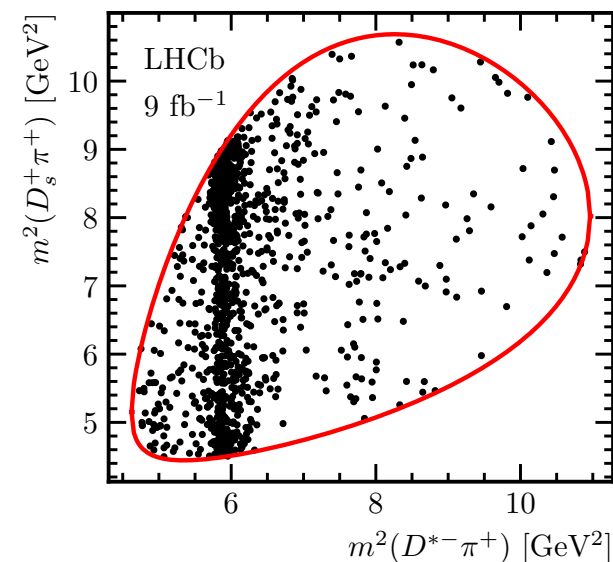
$B^+ \rightarrow D^{*-} D_s^{(*)+} \pi^+$: branching fractions

[arXiv: 2405.00098]

- Measurement performed using the full LHCb dataset of 9 fb^{-1}



$$|m(D^{*-} D_s^+ \pi^+) - m_{B^+}| < 30 \text{ MeV}$$



$$\mathcal{R} = \frac{\mathcal{B}(B^+ \rightarrow D^{*-} D_s^+ \pi^+)}{\mathcal{B}(B^0 \rightarrow D^{*-} D_s^+)} = 0.173 \pm 0.006 \pm 0.010$$

$$\mathcal{R}^* = \frac{\mathcal{B}(B^+ \rightarrow D^{*-} D_s^{*+} \pi^+)}{\mathcal{B}(B^+ \rightarrow D^{*-} D_s^+ \pi^+)} = 1.32 \pm 0.07 \pm 0.14$$

$B^+ \rightarrow D^{*-} D_S^+ \pi^+$: amplitude analysis

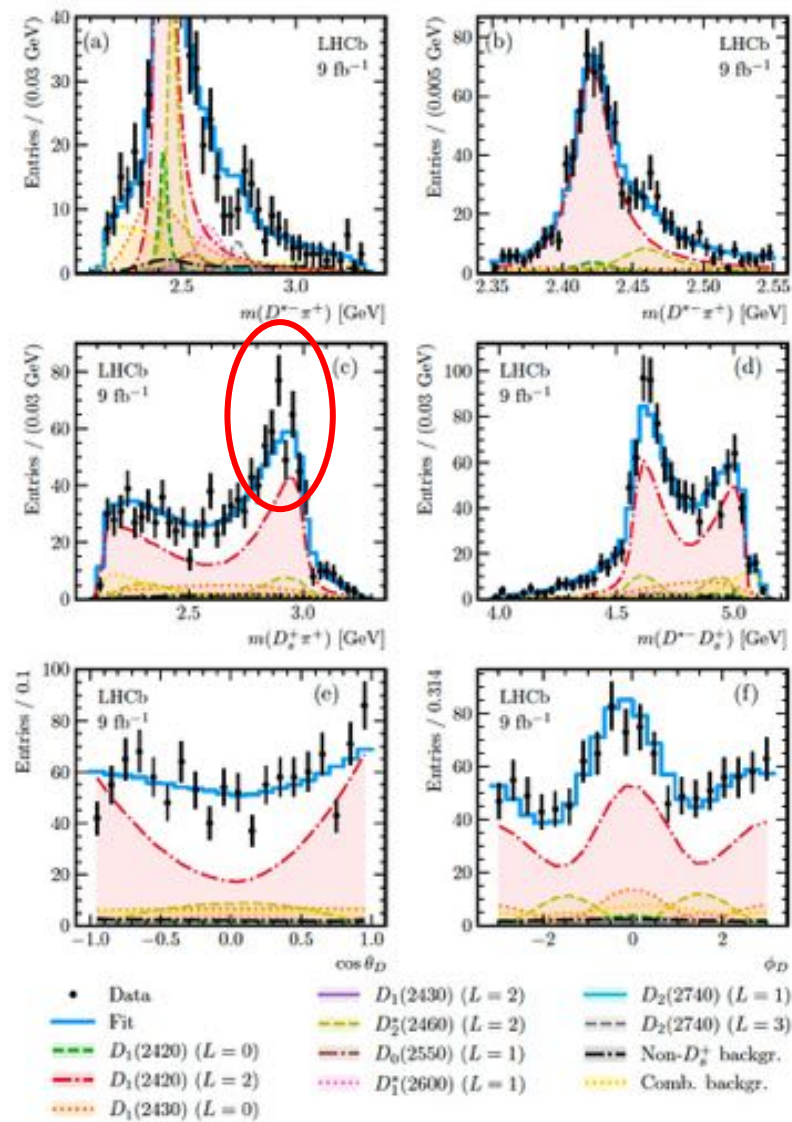
[arXiv: 2405.00098]

■ Baseline fit with $\bar{D}^{**0} \rightarrow D^{*-} \pi^+$ contributions

Resonance	J^P	Mass [MeV]	Width [MeV]
$D_1(2420)$	1^+	2422.1 ± 0.6	31.3 ± 1.9
$D_1(2430)$	1^+	2412 ± 9	314 ± 29
$D_2^*(2460)$	2^+	$2461.1^{+0.7}_{-0.8}$	47.3 ± 0.8

6.5σ	$D_0(2550)$	0^-	2549 ± 19	165 ± 24
6.8σ	$D_1^*(2600)$	1^-	2627 ± 10	141 ± 23
4.6σ	$D_2(2740)$	2^-	2747 ± 6	88 ± 19
	$D_3^*(2750)$	3^-	2763.1 ± 3.2	66 ± 5

Component	Fit fraction [%]	Phase [rad]
$D_1(2420)$ S-wave	$3.8 \pm 1.7 \pm 0.8^{+1.3}_{-0.1}$	$-1.96 \pm 0.16 \pm 0.10^{+0.17}_{-0.05}$
$D_1(2420)$ D-wave	$71.0 \pm 4.4 \pm 4.6^{+0.0}_{-6.0}$	0 (fixed)
$D_1(2430)$ S-wave	$14.2 \pm 2.5 \pm 2.4^{+3.1}_{-2.0}$	$+0.14 \pm 0.11 \pm 0.13^{+0.06}_{-0.18}$
$D_1(2430)$ D-wave	$0.5 \pm 0.9 \pm 1.5^{+0.2}_{-0.5}$	$-2.99 \pm 0.42 \pm 0.84^{+0.23}_{-0.55}$
$D_2^*(2460)$	$11.7 \pm 1.4 \pm 0.8^{+0.0}_{-0.7}$	$+3.14 \pm 0.11 \pm 0.14^{+0.05}_{-0.04}$
$D_0(2550)$	$2.3 \pm 0.8 \pm 0.7^{+0.3}_{-1.7}$	$-2.24 \pm 0.21 \pm 0.26^{+0.05}_{-0.25}$
$D_1^*(2600)$	$4.8 \pm 1.0 \pm 0.9^{+1.1}_{-2.0}$	$+0.32 \pm 0.16 \pm 0.16^{+0.37}_{-0.01}$
$D_2(2740)$ P-wave	$0.4 \pm 0.4 \pm 0.2^{+0.1}_{-0.1}$	$-0.02 \pm 0.56 \pm 0.32^{+0.16}_{-0.59}$
$D_2(2740)$ F-wave	$2.3 \pm 0.7 \pm 0.9^{+0.4}_{-0.1}$	$-0.09 \pm 0.27 \pm 0.21^{+0.08}_{-0.23}$
Sum of fit fractions	$111.0 \pm 5.2 \pm 4.2$	



$B^+ \rightarrow D^{*-} D_S^+ \pi^+$: amplitude analysis

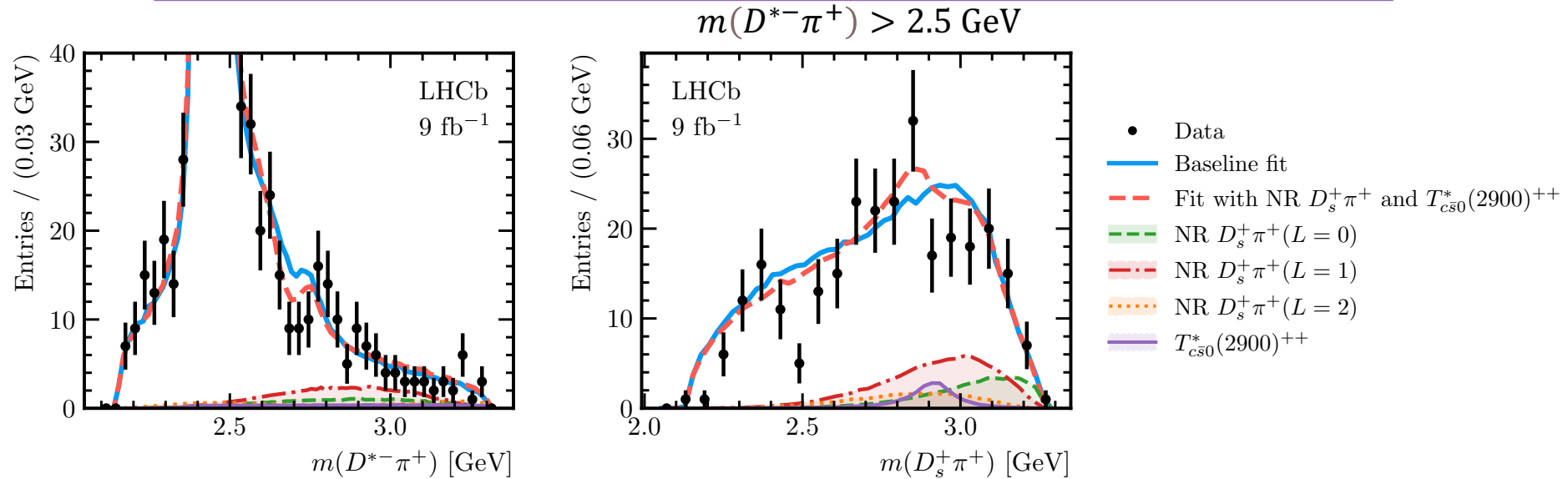
[arXiv: 2405.00098]

■ Fits incorporating $D_S^+ \pi^+$ amplitudes

- best fit: $T_{c\bar{s}0}^a(2900)^{++}$ + nonresonant vector

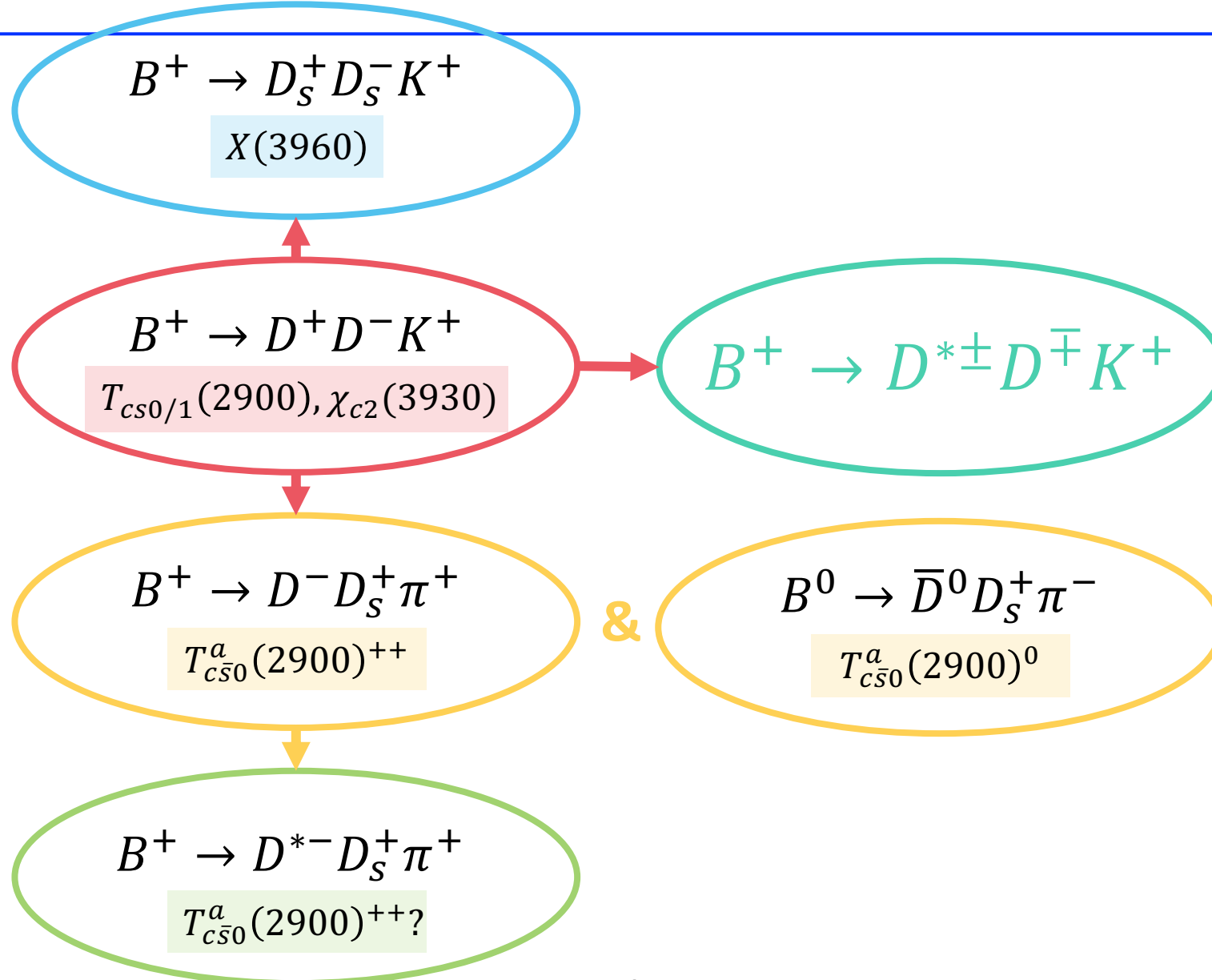
2.6 σ , fit fraction = **$1.2 \pm 0.8\%$** , upper limit 2.3(2.7)% at 90(95)% CL

- consistent with **$(2.25 \pm 0.67 \pm 0.77)\%$** in $B^+ \rightarrow D^- D_S^+ \pi^+$



■ Fits incorporating $D^{*-} D_S^+$ amplitudes: none provides a physical description

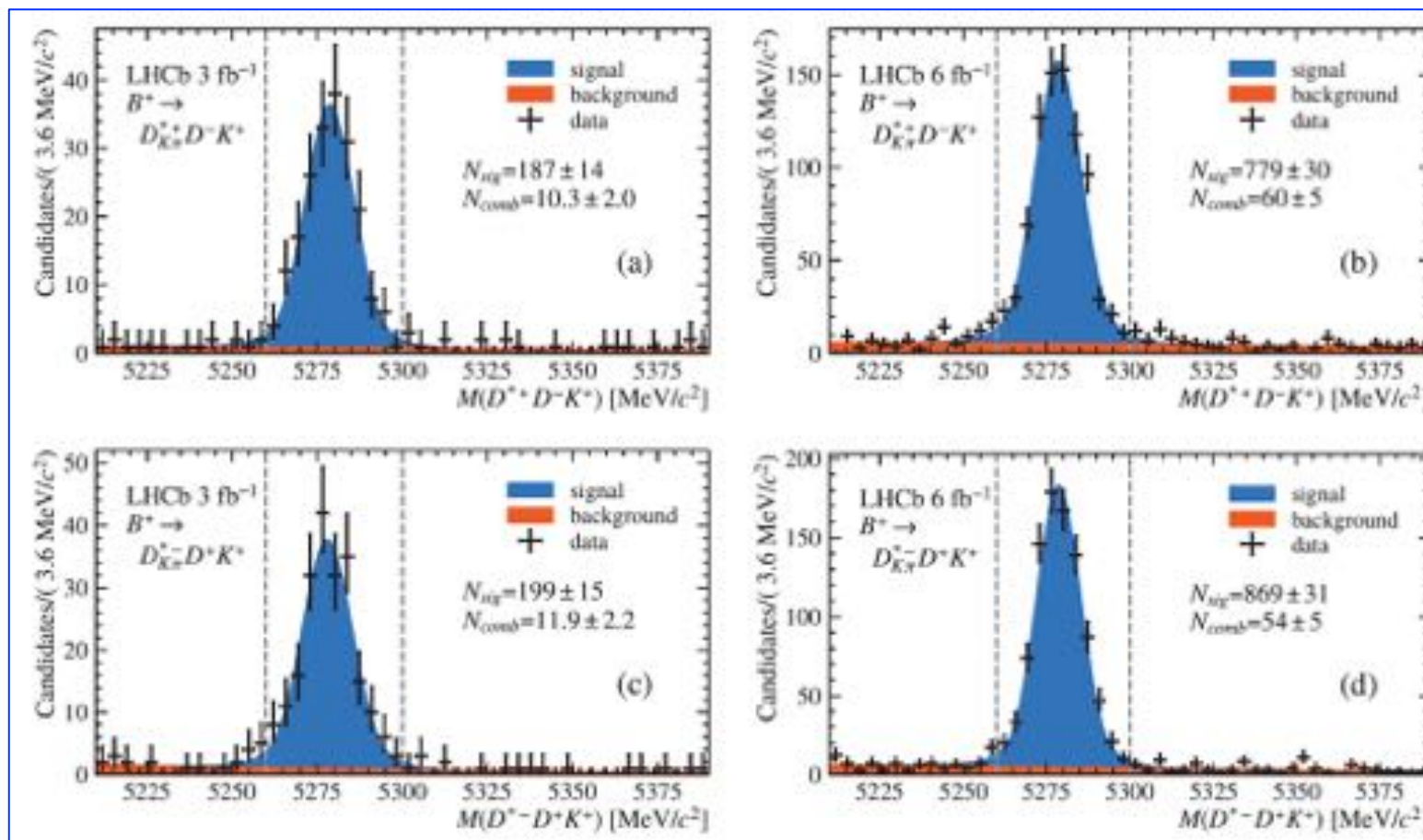
$B \rightarrow D\bar{D}h$ studies at LHCb



$B^+ \rightarrow D^{*\pm} D^{\mp} K^+$: signal yields

[arXiv: 2406.03156]

- Using the full LHCb dataset of 9 fb^{-1} : $D^{*-} \rightarrow \bar{D}^0 (\rightarrow K^+ \pi^- \& K^+ \pi^- \pi^- \pi^+) \pi^-$



- ✓ $B^+ \rightarrow D^{*+} D^- K^+$: **966**
- ✓ $B^+ \rightarrow D^+ D^{*-} K^+$: **1068**

$B^+ \rightarrow D^{*\pm} D^{\mp} K^+$: amplitude analysis

[arXiv: 2406.03156]

- Amplitudes of $B^+ \rightarrow R(D^{*+}D^-)K^+$ and $B^+ \rightarrow R(D^+D^{*-})K^+$ linked by **C-parity**
 \Rightarrow allowing determination of C-parities of R resonances

$$\mathcal{A}(x) = \frac{1+d}{2} \left\{ \sum_{j \in R(D^{*\pm}D^{\mp})} c_j A_j(x) + \sum_{k \in R(D^{*-}K^+, D^+K^+)} c_k A_k(x) \right\} \quad \leftarrow B^+ \rightarrow D^+ D^{*-} K^+$$

$$+ \frac{1-d}{2} \left\{ \sum_{j \in R(D^{*\pm}D^{\mp})} C_j \times c_j A_j(x) + \sum_{l \in R(D^{*+}K^+, D^-K^+)} c_l A_l(x) \right\} \quad \leftarrow B^+ \rightarrow D^{*+} D^- K^+$$

✓ $d = 1$ for $B^+ \rightarrow D^+ D^{*-} K^+$; $d = -1$ for $B^+ \rightarrow D^{*+} D^- K^+$

- R resonances with $J^P = 1^+$: S -wave & D -wave

$$f_{R,S/D}(m) = \frac{\gamma_{S/D}}{m_0^2 - m^2 - im_0[\gamma_S^2 \Gamma_S(m) + \gamma_D^2 \Gamma_D(m)]}$$

- Other resonances: Breit-Wigner

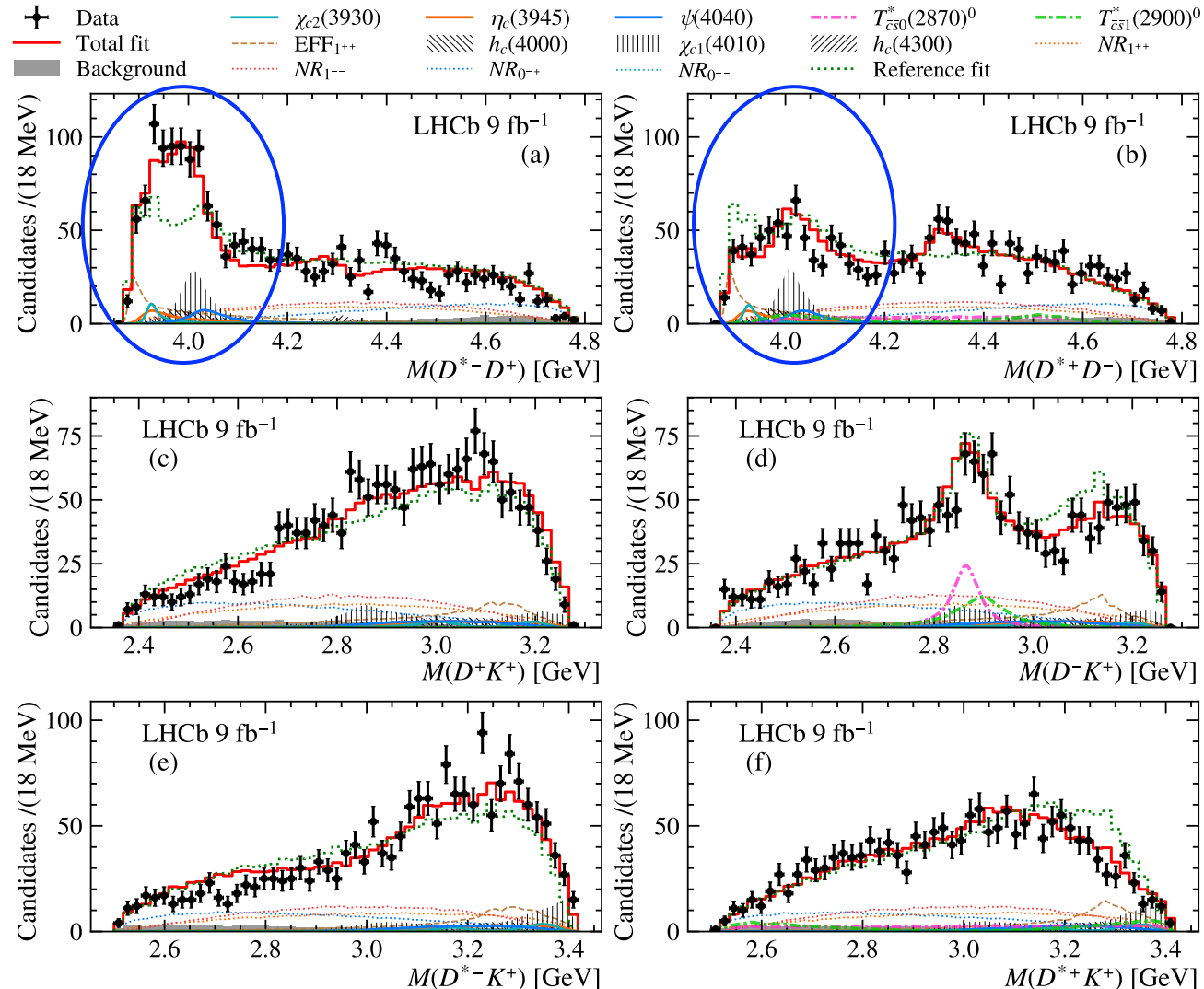
- Nonresonant contributions to $D^{*\pm} D^{\mp}$:

$$f_R(m) = e^{(\alpha+\beta i)(m^2-m_0^2)} \text{ for } NR_{0^-+}; \text{ otherwise } f_R(m) = 1$$

$B^+ \rightarrow D^{*\pm} D^{\mp} K^+$: fit results

[arXiv: 2406.03156]

- All components in baseline fit have significance $> 5\sigma$

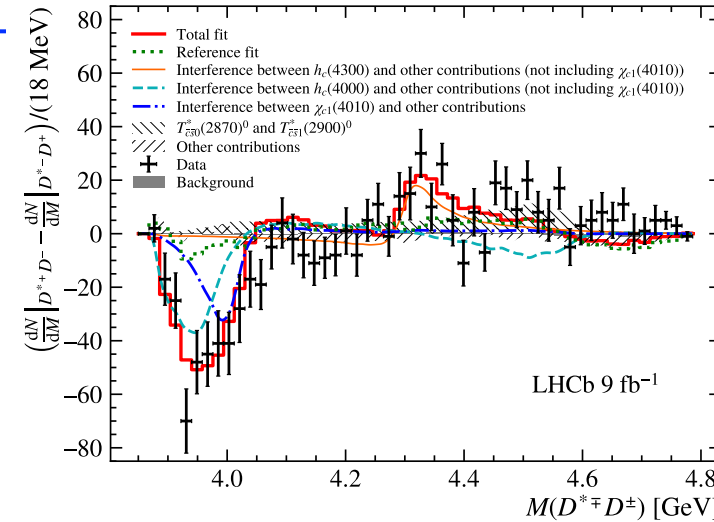
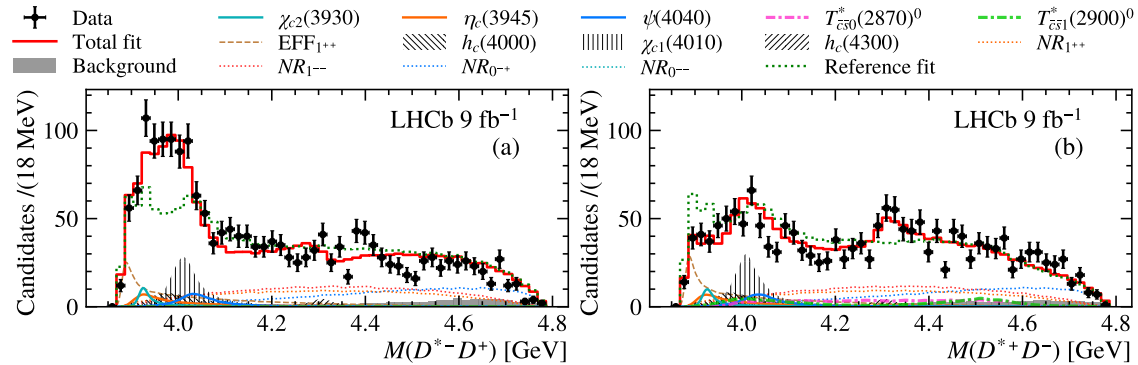


Component	$J^{P(C)}$
EFF_{1++}	1^{++}
$\eta_c(3945)$	0^{-+}
$\chi_{c2}(3930)^\dagger$	2^{++}
$h_c(4000)$	1^{+-}
$\chi_{c1}(4010)$	1^{++}
$\psi(4040)^\dagger$	1^{--}
$h_c(4300)$	1^{+-}
$T_{c\bar{s}0}^*(2870)^{0\dagger}$	0^+
$T_{c\bar{s}1}^*(2900)^{0\dagger}$	1^-
$NR_{1--}(D^{*\mp}D^\pm)$	1^{--}
$NR_{0--}(D^{*\mp}D^\pm)$	0^{--}
$NR_{1++}(D^{*\mp}D^\pm)$	1^{++}
$NR_{0-+}(D^{*\mp}D^\pm)$	0^{-+}

*Fit fractions in paper

$B^+ \rightarrow D^{*\pm} D^{\mp} K^+ : D^{*\pm} D^{\mp}$ system

[arXiv: 2406.03156]



- Significances for those charmonium(-like) states $>6.1\sigma$
- J^{PC} for each state is determined to be $>5.7\sigma$ better than other hypotheses

Component	J^{PC}
$\text{EFF}_{1^{++}}$	1^{++}
$\chi_{c2}(3930)^\dagger$	2^{++}
$\psi(4040)^\dagger$	1^{--}
$\text{NR}_{1^{--}}(D^{*\mp} D^\pm)$	1^{--}
$\text{NR}_{0^{--}}(D^{*\mp} D^\pm)$	0^{--}
$\text{NR}_{1^{++}}(D^{*\mp} D^\pm)$	1^{++}
$\text{NR}_{0^{++}}(D^{*\mp} D^\pm)$	0^{++}

	This work		$c\bar{c}$ prediction [34]
$X(3940)?$	$\eta_c(3945)$	$J^{PC} = 0^{++}$	$\eta_c(3S)$ $J^{PC} = 0^{++}$
	$m_0 = 3945^{+28+37}_{-17-28}$	$\Gamma_0 = 130^{+92+101}_{-49-70}$	$m_0 = 4064$ $\Gamma_0 = 80$
	$h_c(4000)$	$J^{PC} = 1^{+-}$	$h_c(2P)$ $J^{PC} = 1^{+-}$
	$m_0 = 4000^{+17+29}_{-14-22}$	$\Gamma_0 = 184^{+71+97}_{-45-61}$	$m_0 = 3956$ $\Gamma_0 = 87$
	$\chi_{c1}(4010)$	$J^{PC} = 1^{++}$	$\chi_{c1}(2P)$ $J^{PC} = 1^{++}$
	$m_0 = 4012.5^{+3.6+4.1}_{-3.9-3.7}$	$\Gamma_0 = 62.7^{+7.0+6.4}_{-6.4-6.6}$	$m_0 = 3953$ $\Gamma_0 = 165$
	$h_c(4300)$	$J^{PC} = 1^{+-}$	$h_c(3P)$ $J^{PC} = 1^{+-}$
	$m_0 = 4307.3^{+6.4+3.3}_{-6.6-4.1}$	$\Gamma_0 = 58^{+28+28}_{-16-25}$	$m_0 = 4318$ $\Gamma_0 = 75$

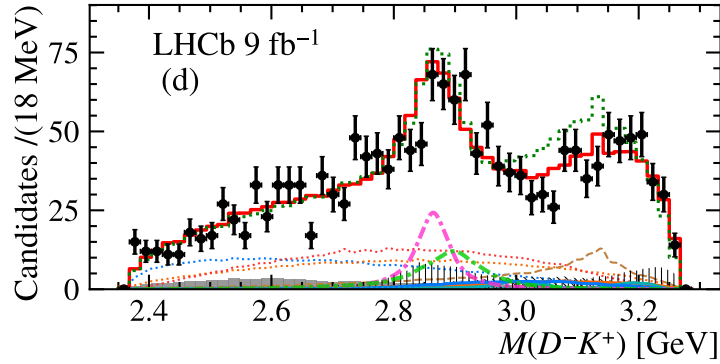
GI model
hep-ph/0505002

- States can fit into Charmonia, and mass more consistent with the prediction with unquenched quark model [arXiv: 2312.10296]
- $\chi_{c1}(4010)$ could be the partner of $\chi_{c1}(3872)$, predicted both in the unquenched model and Lattice [arXiv:2402.14541]

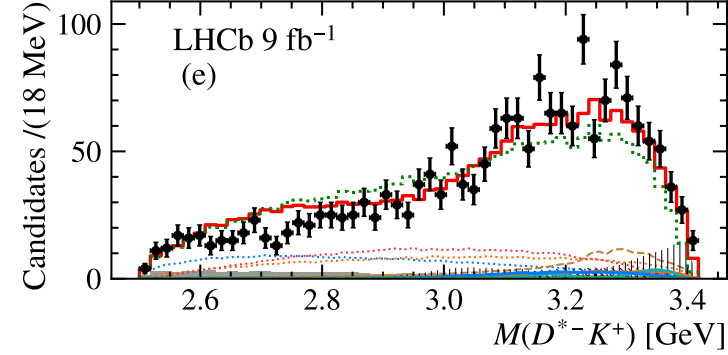
$B^+ \rightarrow D^{*\pm} D^{\mp} K^+ : T_{\bar{c}\bar{s}}^*$ states

[arXiv: 2406.03156]

➤ $B^+ \rightarrow D^{*+} D^- K^+$



➤ $B^+ \rightarrow D^{*-} D^+ K^+$



11 σ

$X_0(2900)$

9.2 σ

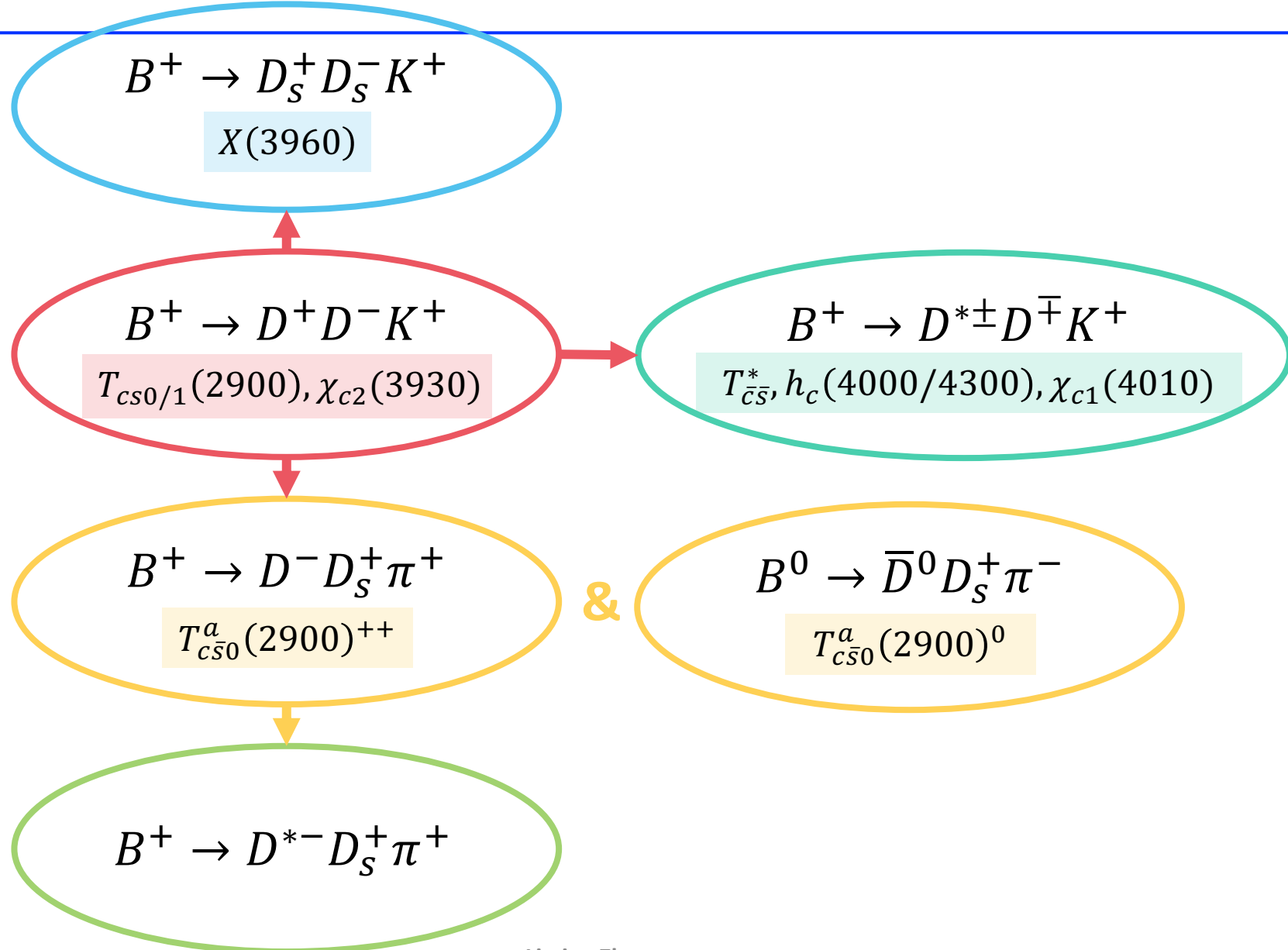
$X_1(2900)$

Property	This work	Previous work
$T_{\bar{c}\bar{s}0}^*(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T_{\bar{c}\bar{s}0}^*(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T_{\bar{c}\bar{s}1}^*(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T_{\bar{c}\bar{s}1}^*(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$	110 ± 12
$\mathcal{B}(B^+ \rightarrow T_{\bar{c}\bar{s}0}^*(2870)^0 D^{(*)+})$	$(4.5^{+0.6}_{-0.8} {}^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \rightarrow T_{\bar{c}\bar{s}1}^*(2900)^0 D^{(*)+})$	$(3.8^{+0.7}_{-1.0} {}^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \rightarrow T_{\bar{c}\bar{s}0}^*(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \rightarrow T_{\bar{c}\bar{s}1}^*(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

✓ $T_{\bar{c}\bar{s}0}^*(2870)^0 \rightarrow D^{*-} K^+$ forbidden

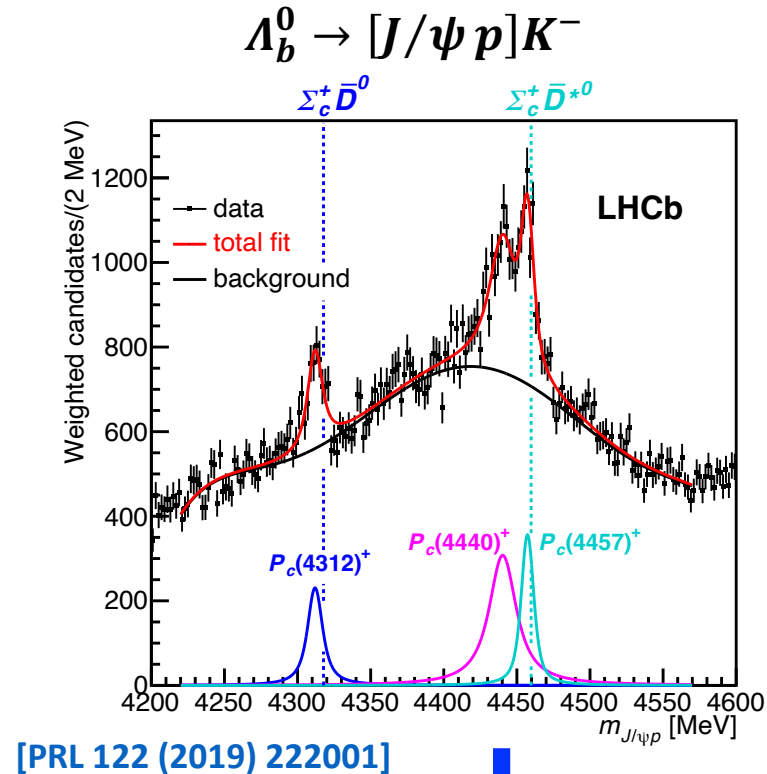
✓ $\mathcal{B}(T_{\bar{c}\bar{s}1}^*(2900)^0 \rightarrow D^{*-} K^+) / \mathcal{B}(T_{\bar{c}\bar{s}1}^*(2900)^0 \rightarrow D^- K^+) < 0.21$ @ 95% CL

$B \rightarrow D\bar{D}h$ studies at LHCb

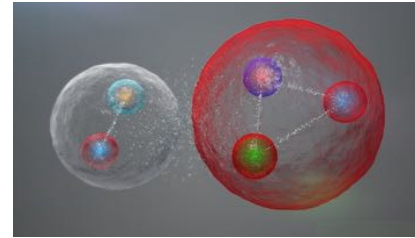


Background for pentaquark study

- The observation of new decay modes can shed light on the binding scheme of the exotic hadrons \Rightarrow search through open charm modes

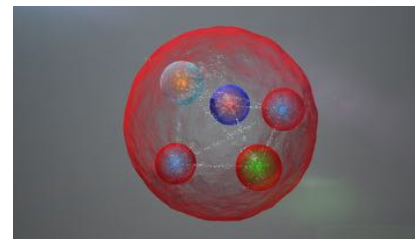


Hadron molecule



- Mass proximity to threshold **natural**
- Fall-apart decay **dominant**

Compact multiquark



- Mass proximity to threshold **accidental**
- No (strong) hierarchy of couplings

Proximity of $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$ thresholds to the peaks suggests they play an important role in the dynamics

Search for pentaquarks via open charm

[arXiv: 2404.07131]

- Inclusive search performed using 5.7 fb^{-1} data from 2016-2018
- Reconstruction: $\Lambda_c^+, D^-, D^0, \Sigma_c^{++(0)}, D^{*-}$

✓ hidden-charm pentaquarks

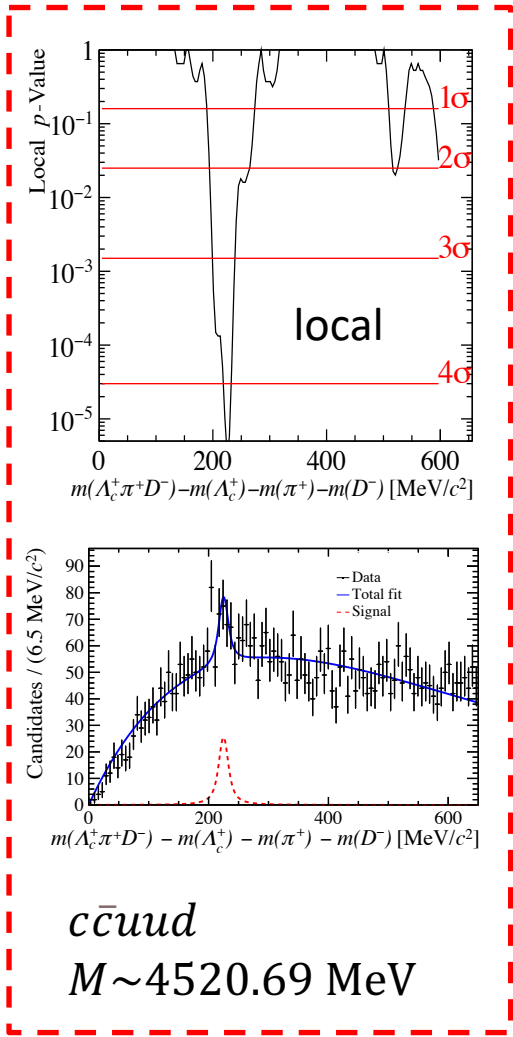
✓ doubly-charmed pentaquarks & excited Ξ_{cc}

Hadron 1	Hadron 2	Charge	I_3	Y	C	Limit Set
Λ_c^+	\bar{D}^0	+1	$1/2$	1	0	✓
Λ_c^+	D^-	0	$-1/2$	1	0	✓
Λ_c^+	D^{*-}	0	$-1/2$	1	0	✓
Σ_c^{++}	\bar{D}^0	+2	$3/2$	1	0	✓
Σ_c^{++}	D^-	+1	$1/2$	1	0	✓
Σ_c^{++}	D^{*-}	+1	$1/2$	1	0	×
Σ_c^0	\bar{D}^0	0	$-1/2$	1	0	✓
Σ_c^0	D^-	-1	$-3/2$	1	0	✓
Σ_c^0	D^{*-}	-1	$-3/2$	1	0	×
Σ_c^{*++}	\bar{D}^0	+2	$3/2$	1	0	✓
Σ_c^{*++}	D^-	+1	$1/2$	1	0	✓
Σ_c^{*++}	D^{*-}	+1	$1/2$	1	0	✓
Σ_c^{*0}	\bar{D}^0	0	$-1/2$	1	0	✓
Σ_c^{*0}	D^-	-1	$-3/2$	1	0	✓
Σ_c^{*0}	D^{*-}	-1	$-3/2$	1	0	✓
Λ_c^+	D^0	+1	$-1/2$	3	2	✓
Λ_c^+	D^+	+2	$1/2$	3	2	✓
Λ_c^+	D^{*+}	+2	$1/2$	3	2	✓
Σ_c^{++}	D^0	+2	$1/2$	3	2	×
Σ_c^{++}	D^+	+3	$3/2$	3	2	×
Σ_c^{++}	D^{*+}	+3	$3/2$	3	2	×
Σ_c^0	D^0	0	$-3/2$	3	2	×
Σ_c^0	D^+	+1	$-1/2$	3	2	×
Σ_c^0	D^{*+}	+1	$-1/2$	3	2	×
Σ_c^{*++}	D^0	+2	$1/2$	3	2	✓
Σ_c^{*++}	D^+	+3	$3/2$	3	2	✓
Σ_c^{*++}	D^{*+}	+3	$3/2$	3	2	×
Σ_c^{*0}	D^0	0	$-3/2$	3	2	✓
Σ_c^{*0}	D^+	+1	$-1/2$	3	2	✓
Σ_c^{*0}	D^{*+}	+1	$-1/2$	3	2	×

*10 modes too statistically limited to set upper limits

Results

[arXiv: 2404.07131]



- No significant signals are found

- Upper limits set on $R = \frac{N_{P_C}}{N_{\Lambda_C^+}} \times \frac{\epsilon_{\Lambda_C^+}}{\epsilon_{P_C}} \rightarrow \frac{\sigma(P_C) \times B(P_C \rightarrow \Lambda_C^+ D(\pi)) \times B(D)}{\sigma(\Lambda_C^+)}$

- Largest significant modes:

*Complete list in paper

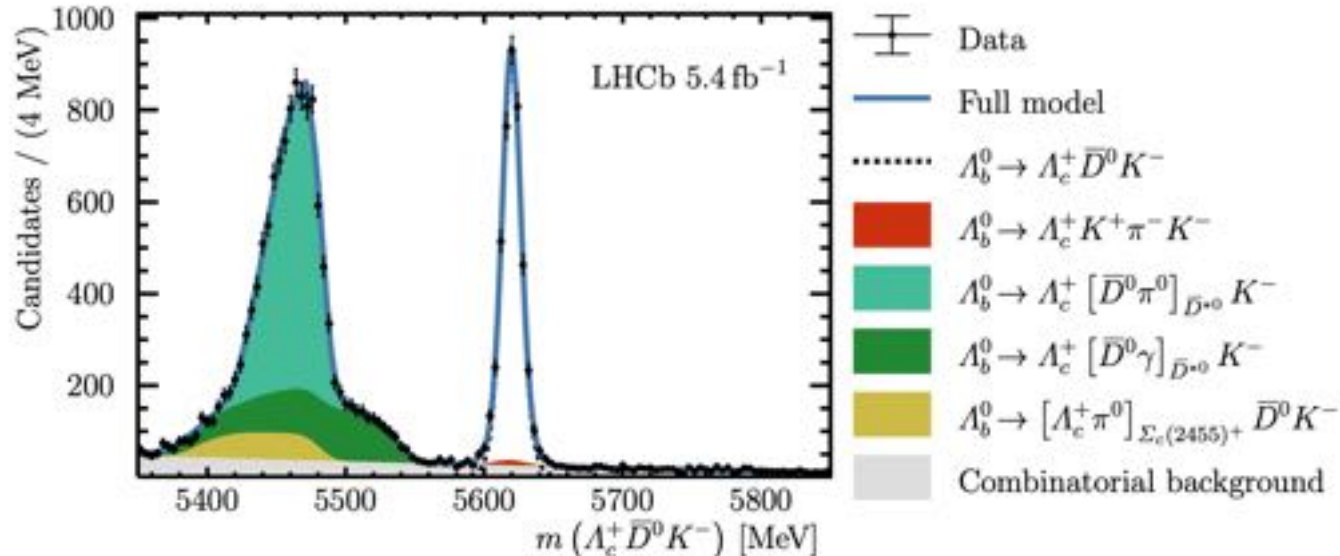
Decay Mode	Width (MeV/c ²)	Significance (σ)		Q-value (MeV/c ²)	Signal Yield	UL ($\times 10^{-3}$)	
		Local	Corrected			90% CL	95% CL
$\Lambda_c^+ \pi^+ D^-$	0	3.59	2.21	225	41.6 ± 12.6	3.95	4.19
	5	4.01	2.89	225	64.7 ± 17.4	4.43	4.69
	10	4.30	3.32	225	87.1 ± 21.6	4.64	4.85
	15	4.50	3.62	225	108.2 ± 25.3	4.72	4.90
$\Lambda_c^+ \pi^- D^-$	0	3.36	1.90	257	38.1 ± 12.4	4.28	4.56
	5	3.86	2.71	253	62.1 ± 17.1	4.62	4.83
	10	4.18	3.20	249	83.7 ± 21.2	4.72	4.88
	15	4.44	3.56	249	103.5 ± 24.6	4.77	4.92
$\Lambda_c^+ \pi^+ \bar{D}^0$	0	3.18	1.58	245	41.9 ± 13.7	2.87	3.06
	5	3.73	2.53	245	67.6 ± 19.2	3.22	3.35
	10	4.06	3.06	245	91.6 ± 24.1	3.29	3.39
	15	4.30	3.42	245	115.0 ± 28.5	3.30	3.40

Observations of $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{(*)0} K^-$ decays

- These decays can pave the way for future P_c^+ search in $\Lambda_c^+ \bar{D}^{(*)0}$ systems
 - which are open-charm equivalent of $J/\psi p$
 - \bar{D}^{*0} is partially reconstructed with missing π^0/γ

$$N^{\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-} = 4010 \pm 70,$$

$$N^{\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{*0} K^-} = 10\,560_{-290}^{+310}$$



- Branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} = (19.08_{-0.34-0.18}^{+0.36+0.16} \pm 0.38)\%$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} = (58.9_{-1.7-1.8}^{+1.8+1.7} \pm 1.2)\%$$

- Relative to $\Lambda_b^0 \rightarrow J/\psi p K^-$

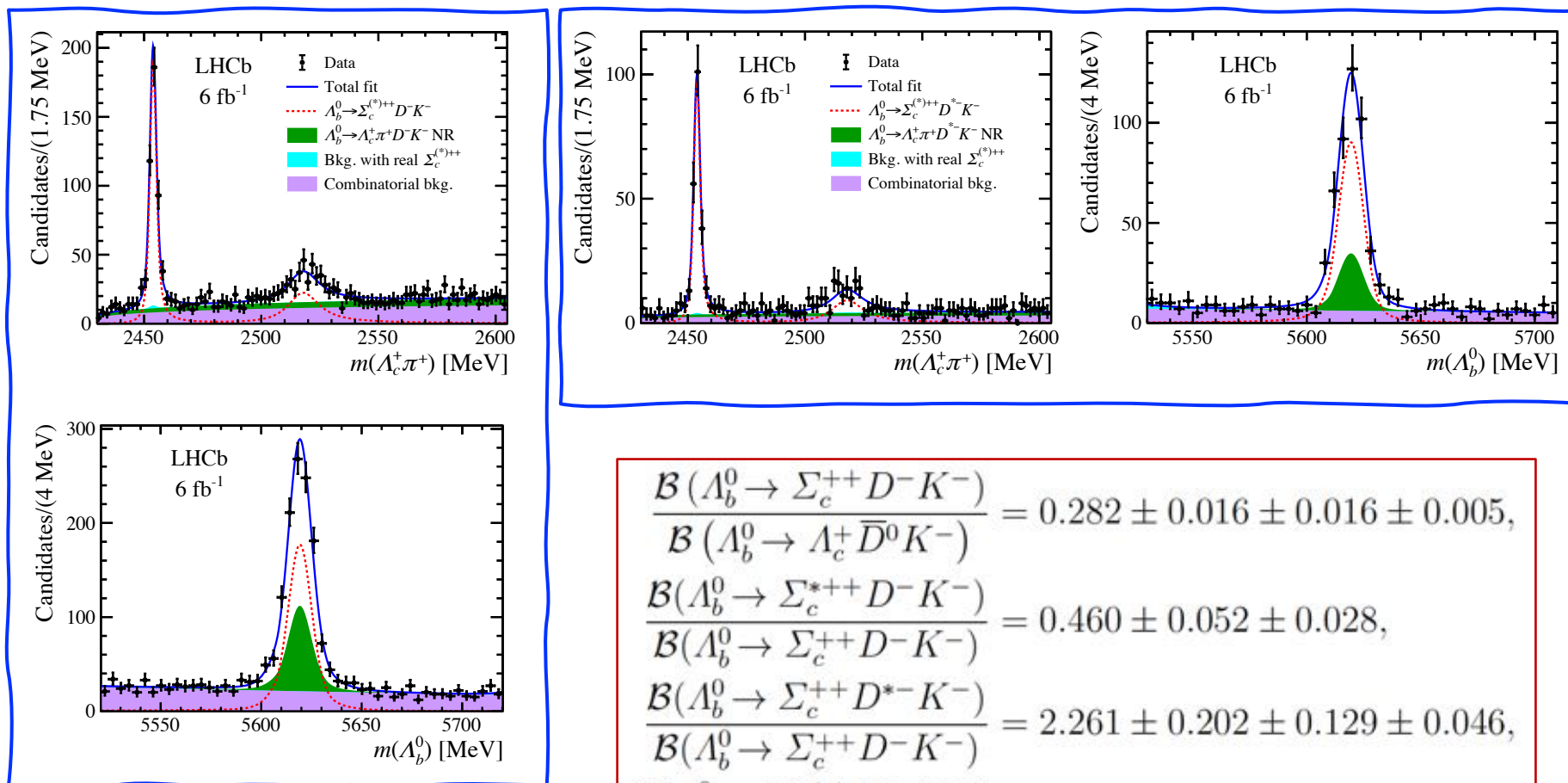
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-)} = (15.2_{-2.8}^{+3.2})\%$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{*0} K^-)} = (4.9_{-0.9}^{+1.1})\%$$

$\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$: observation

[arXiv: 2404.19510]

- Four $\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$ modes observed with overwhelming significance



$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-)} = 0.282 \pm 0.016 \pm 0.016 \pm 0.005,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{*++} D^- K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)} = 0.460 \pm 0.052 \pm 0.028,$$

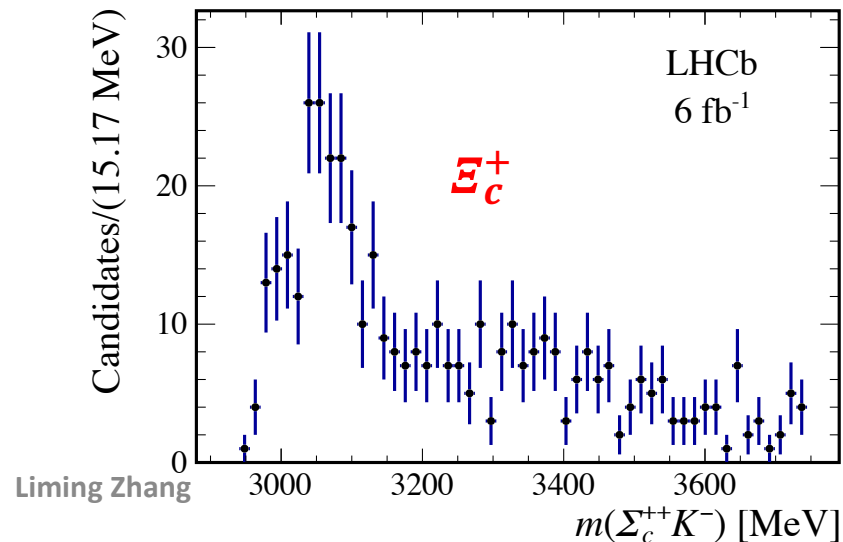
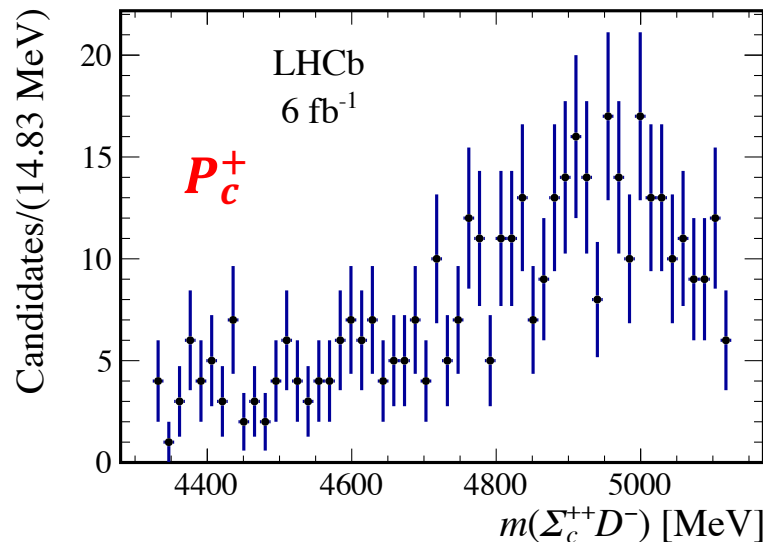
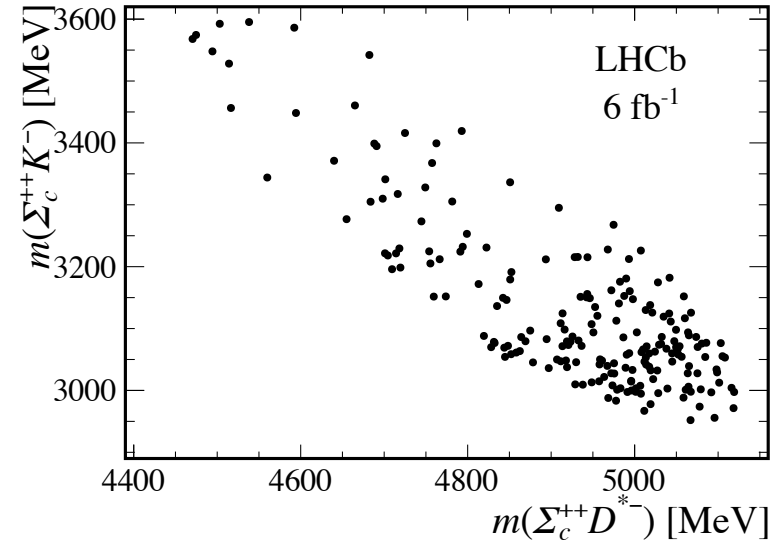
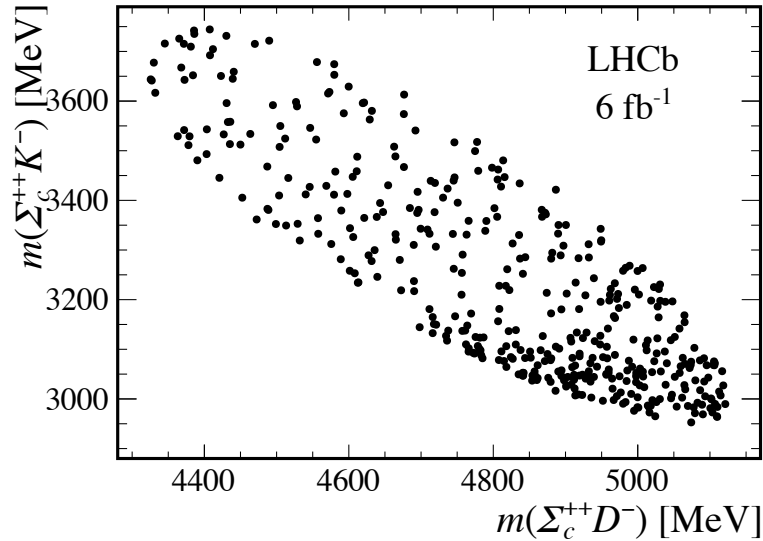
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)} = 2.261 \pm 0.202 \pm 0.129 \pm 0.046,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{*++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)} = 0.896 \pm 0.137 \pm 0.066 \pm 0.018,$$

Liming Zhang

$\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$: intermediate states [arXiv: 2404.19510]

- Larger dataset needed to draw a definitive conclusion



Summary and prospects

- LHCb keeps making important contributions to heavy hadron spectroscopy, both for conventional or exotic hadrons
- In Run 3, the upgraded LHCb detector and an improved software-only trigger system will be implemented

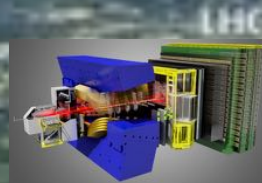


More exciting results are to come!
More data, more chances & challenges!

BACKUP

The LHC as a Beauty and Charm factory

Proton-Proton Collisions at $\sqrt{s} = 13$ TeV
~ 20 000 $b\bar{b}$ pairs per second, x 20 of $c\bar{c}$ pairs



High B-baryon production fraction

$$\begin{array}{cccc} B^+ & : & B^0 & : & B_s^0 & : & \Lambda_b^0 \\ (u\bar{b}) & & (d\bar{b}) & & (s\bar{b}) & & (udb) \\ 4 & : & 4 & : & 1 & : & 2 \\ & & & & \text{Unique dataset} & & \end{array}$$

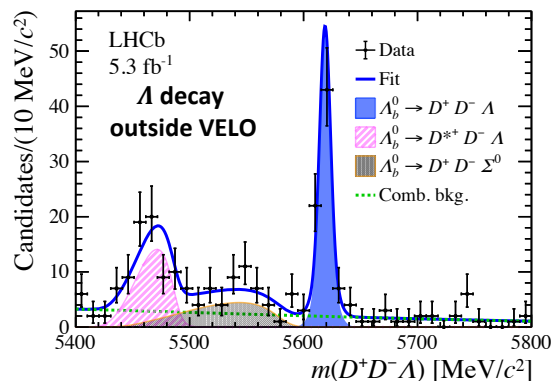
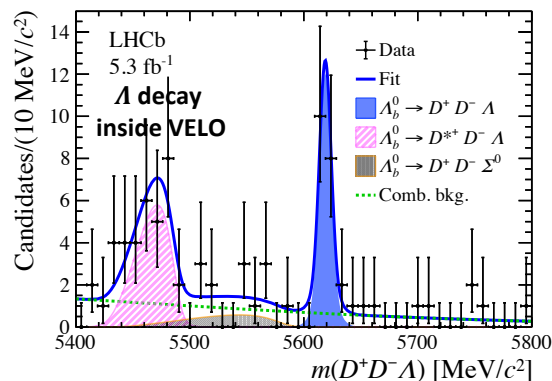
Observation of $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$

[arXiv: 2403.03586]

- First observation of $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ with significance of 16σ

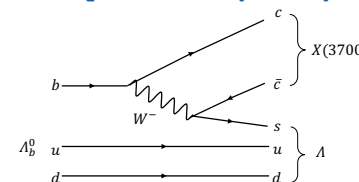
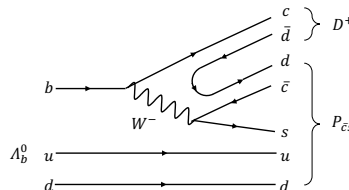
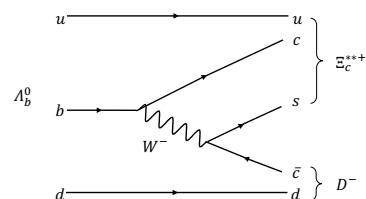
$N = 19 \pm 5$

$N = 73 \pm 9$

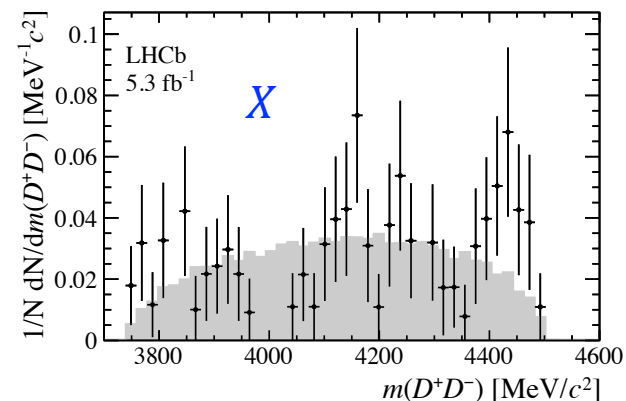
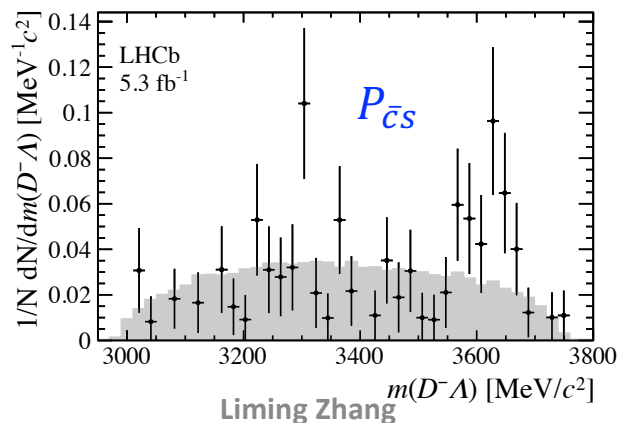
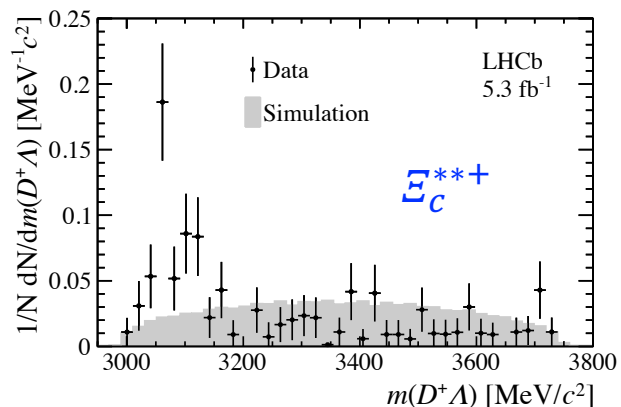


$$\frac{\sigma_{\Lambda_b^0}}{\sigma_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \rightarrow D^+ D^- \Lambda)}{\mathcal{B}(B^0 \rightarrow D^+ D^- K_S^0)} = 0.179 \pm 0.022 \pm 0.014$$

$$\mathcal{B}(\Lambda_b^0 \rightarrow D^+ D^- \Lambda) = (1.24 \pm 0.15 \pm 0.10 \pm 0.28 \pm 0.11) \times 10^{-4}$$

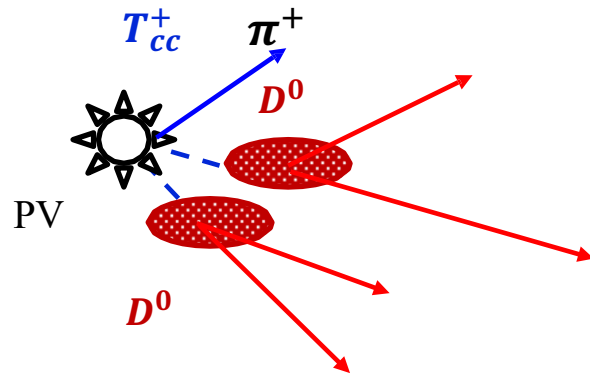


[PRD 103 (2021) 114013]

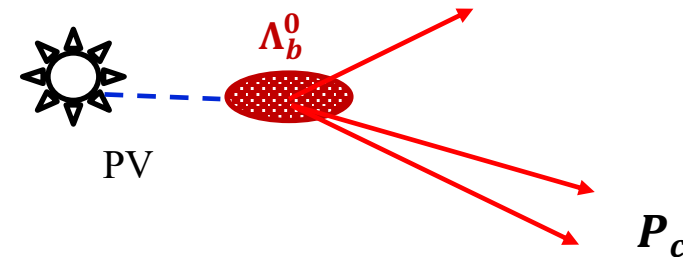


Two methods for spectroscopy

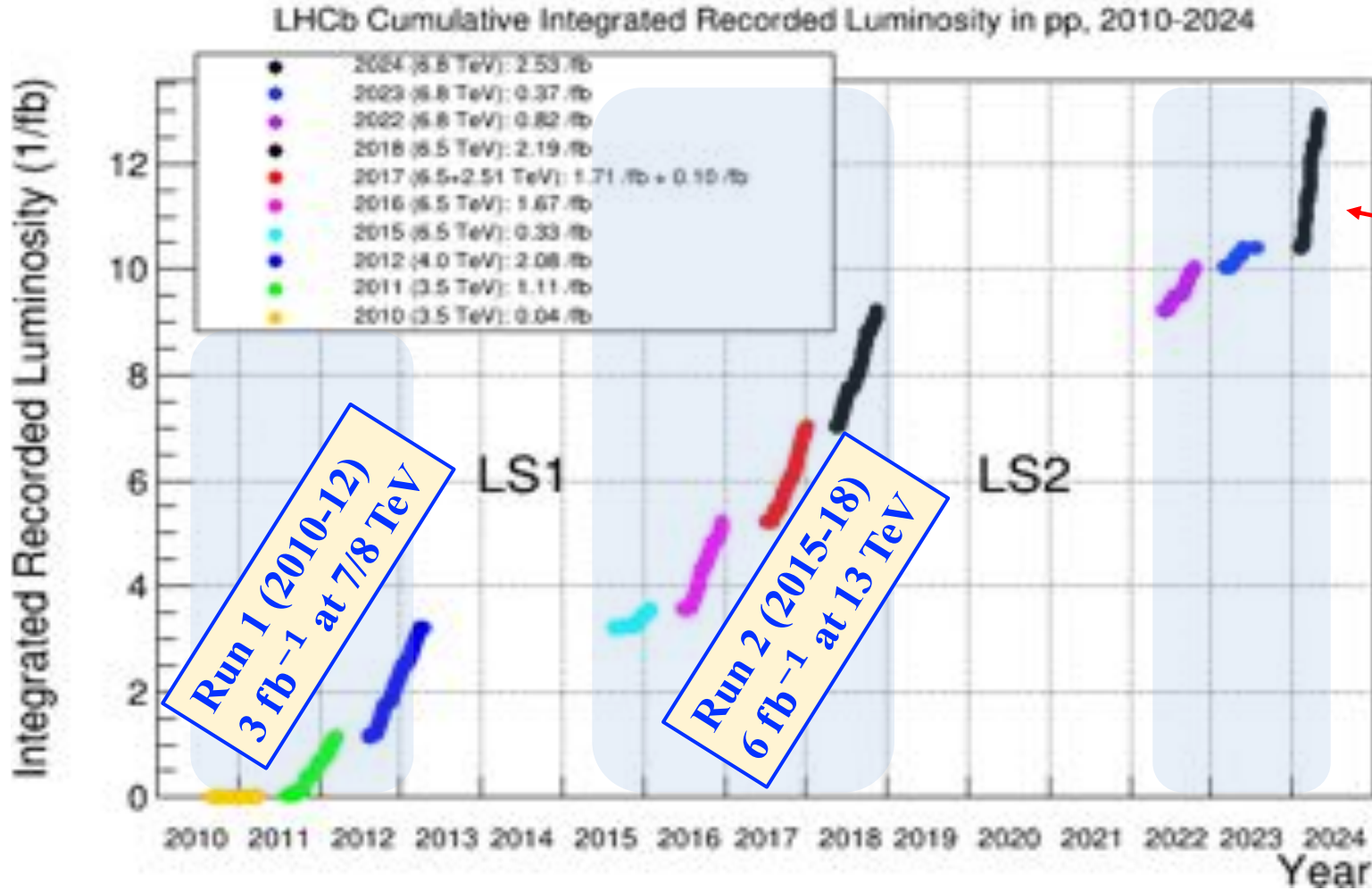
- Direct production in pp collisions
 - Combine a heavy flavour hadron with one or more light particles
 - Pros: High statistics, in principle can study all states
 - Cons: Large combinatorial background, hard to determine J^P



- Production by a heavier particle decay
 - Usually with amplitude analysis
 - Pros: Low background, Better determination of J^P
 - Cons: Low cross-section, limited mass range



LHCb collected luminosity



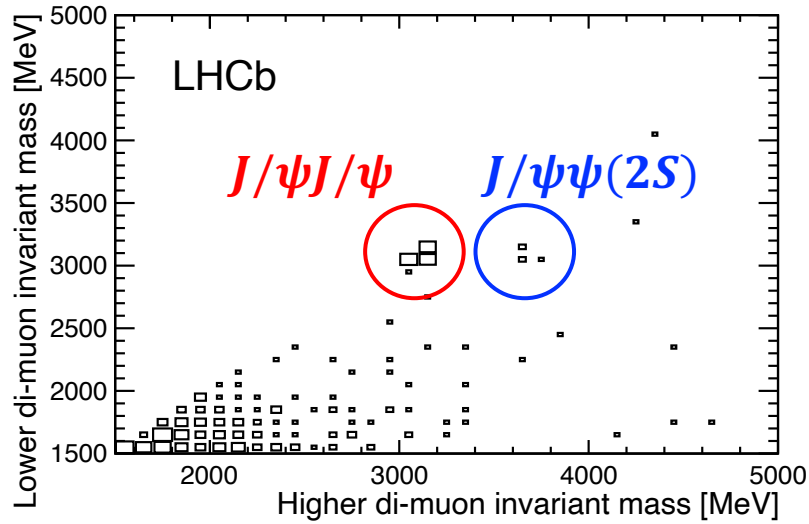
Run3: Hope to collect ~15 fb⁻¹ physics data in 2024&2025

Statistics ~ 2× run1+2

Trigger efficiency 2× for hadronic final state

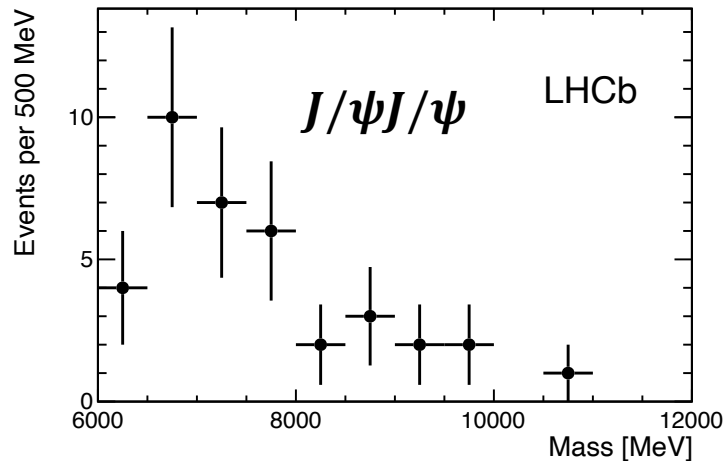
Other exotics in CEP

➤ $X \rightarrow J/\psi J/\psi$: CEP of charmonium pairs studied using 3 fb^{-1} Run1 data

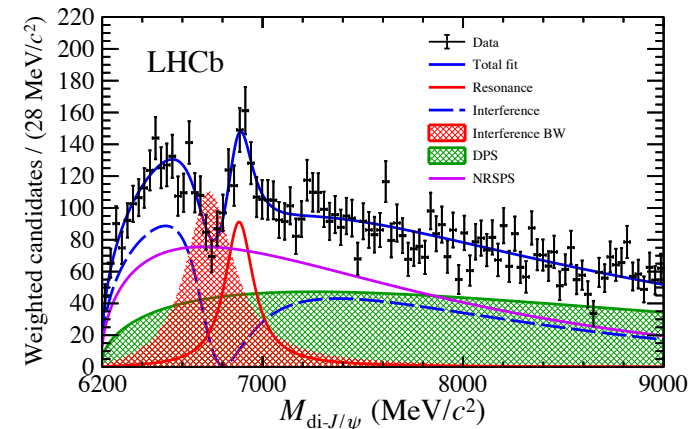


[J. Phys. G: Nucl. Part. Phys. 41 (2014) 115002]

$$\begin{aligned} \sigma^{J/\psi J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst}) \text{ pb}, \\ \sigma^{J/\psi \psi(2S)} &= 63_{-18}^{+27}(\text{stat}) \pm 10(\text{syst}) \text{ pb}, \\ \sigma^{\psi(2S)\psi(2S)} &< 237 \text{ pb}, \\ \sigma^{\chi_{c0}\chi_{c0}} &< 69 \text{ nb}, \\ \sigma^{\chi_{c1}\chi_{c1}} &< 45 \text{ pb}, \\ \sigma^{\chi_{c2}\chi_{c2}} &< 141 \text{ pb}, \end{aligned}$$

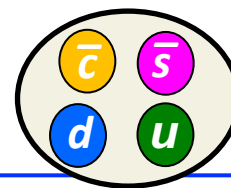


[Science Bulletin 65 (2020) 1983]



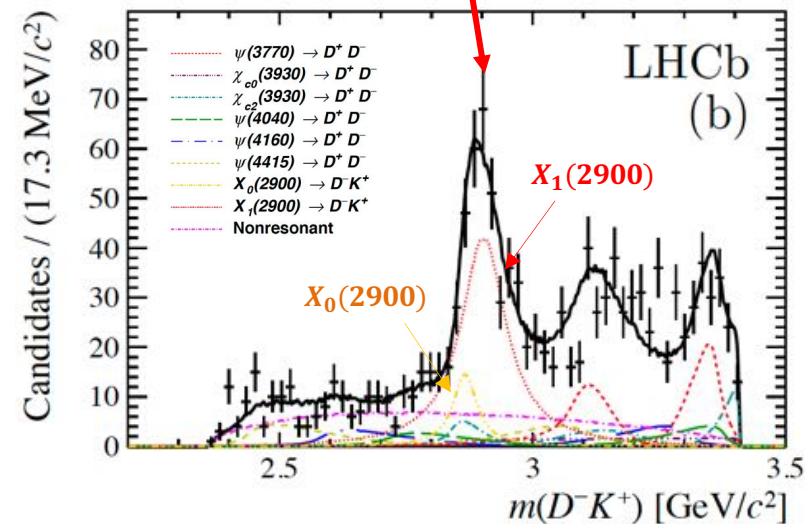
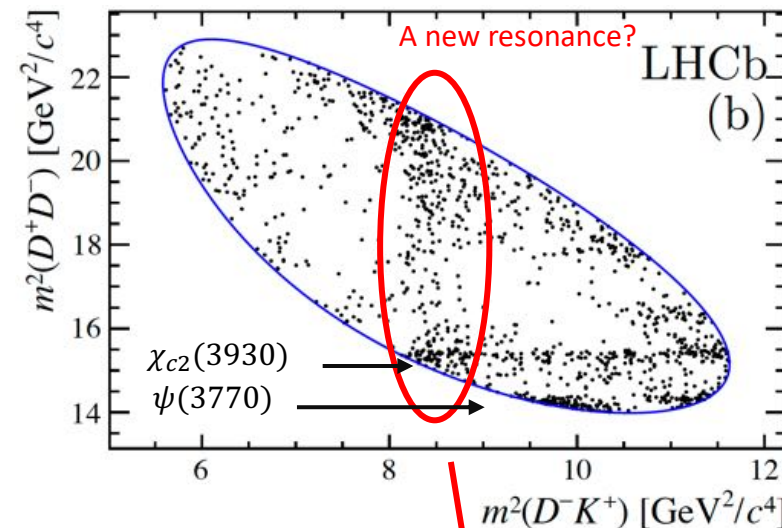
9/7/24 ➤ $\chi_{c1}(3872)$? Other suggestions?

Observation of $T_{cs} \rightarrow D^- K^+$



[PRL 125 (2020) 242001]
[PRD 102 (2020) 112003]

- Amplitude analysis of $B^+ \rightarrow D^+ D^- K^+$ decays
 - ~1300 signals with purity 99.5% (9fb⁻¹)
- Enhancement in $m^2(D^- K^+) \sim 8.5 \text{ GeV}^{-2}$
- Described by $X_1(2900)$ and $X_0(2900)$
- **First discovery of open-charm tetraquarks with four different flavors [$cs\bar{u}\bar{d}$]!**
- The observation motivates study of $B \rightarrow \bar{D} D_s \pi$

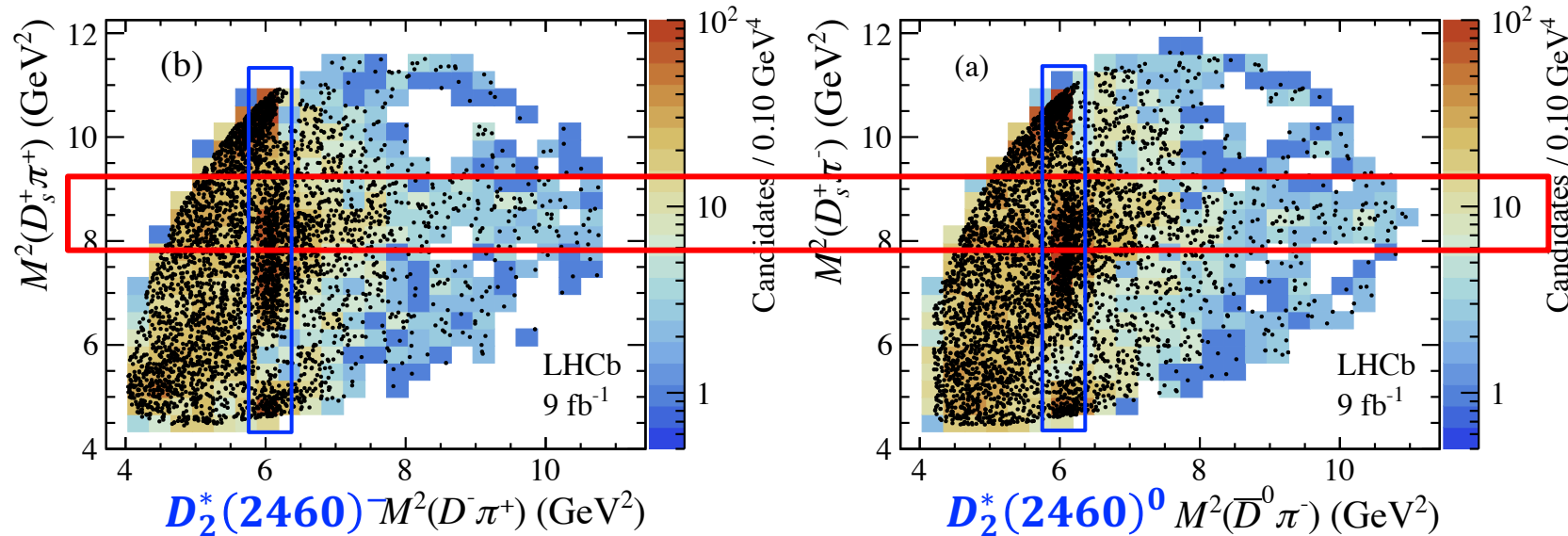
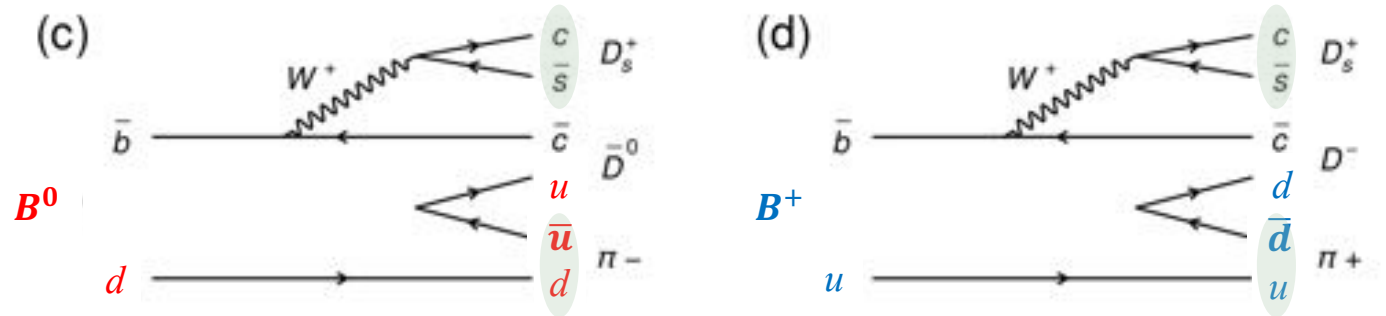


Resonance	Mass (GeV/c ²)	Width (MeV)
new $\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
new $X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
new $X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11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

Study of $B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ and $B^+ \rightarrow D^- D_s^+ \pi^+$

[PRL 131 (2023) 041902]

- Full 9 fb^{-1} Run1+Run2 LHCb data
 $\Rightarrow 4420 B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ and
 $3940 B^+ \rightarrow D^- D_s^+ \pi^+$ candidates

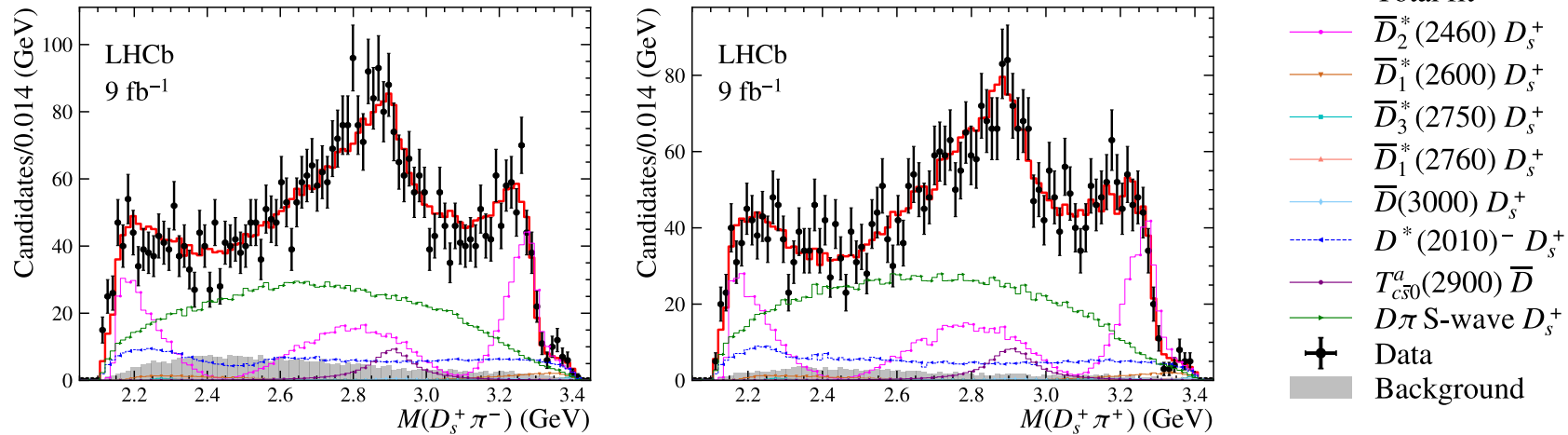


\Rightarrow Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

Observation of $T_{c\bar{s}0}^a(2900)^{0/++}$

- Fit with two $D_s^+ \pi$ states sharing resonance parameters

[PRL 131 (2023) 041902]



➤ $T_{c\bar{s}0}^a(2900)^0 \rightarrow D_s^+ \pi^-$ & $T_{c\bar{s}0}^a(2900)^{++} \rightarrow D_s^+ \pi^+$ **significance $> 9\sigma$**

✓ A second $1^- D_s^+ \pi$ state yields significance of only 1.3σ

✓ Additional $D\pi, D_s^+ \pi, DD_s^+$ resonances disfavored

➤ $J^P = 0^+$ favored over other spin-parity by more than 7.5σ

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

$$\Gamma = 0.136 \pm 0.023 \pm 0.011 \text{ GeV}$$

$$\text{Fit fraction} = (2.45 \pm 0.65 \pm 0.84)\%$$

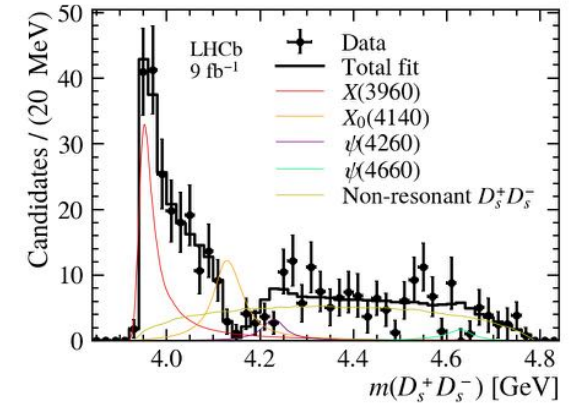
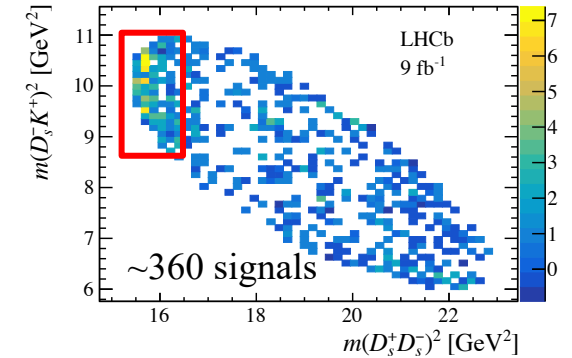
Liming Zhang

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

[PRL 131 (2023) 071901]

- Strong threshold enhancement found in $D_s^+ D_s^-$ system
- Amplitude analysis is performed
- **$X(3960)$** : threshold enhancement
 - $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 9.3σ and 12.3σ
 - Could be a $c\bar{c}s\bar{s}$ tetraquark predicted by Lattice QCD
- Resonance parameters are consistent with $\chi_{c0}(3930)$ within 3σ
- More data need to study the lineshape for $X(3960)$

[JHEP 06 (2021) 035]



Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	\mathcal{F} (%)	\mathcal{S} (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 5.0$	12.6 (14.6)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 6$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 3.9$	3.8 (4.1)
$\psi(4260)$	1^{--}	4230 [62]	55 [62]	$3.6 \pm 0.4 \pm 3.2$	3.2 (3.6)
$\psi(4660)$	1^{--}	4633 [32]	64 [32]	$2.2 \pm 0.2 \pm 0.8$	3.0 (3.2)
NR	0^{++}	-	-	$46.1 \pm 13.2 \pm 11.3$	3.1 (3.4)

Charmonia in an unquenched quark model

arXiv: 2312.10296

Experiment results		Theoretical predictions		
		GI	Unquenched	states
$\eta_c(3945)$	$m_0 = 3945_{-17-28}^{+28+37}$	4064	4022	$\eta_c(3S)$
0^{-+}	$\Gamma_0 = 130_{-49-70}^{+92+101}$	80	62	
$h_c(4000)$	$m_0 = 4000_{-14-22}^{+17+29}$	3956	3961	$h_c(2P)$
1^{+-}	$\Gamma_0 = 130_{-49-70}^{+92+101}$	87	66	
$\chi_{c1}(4010)$	$m_0 = 4012.5_{-3.9-3.7}^{+3.6+4.1}$	3953	3990	$\chi_{c1}(2P)$
1^{++}	$\Gamma_0 = 62.7_{-6.4-6.6}^{+7.0+6.4}$	165	60	
$h_c(4300)$	$m_0 = 4307.3_{-6.6-4.1}^{+6.4+3.3}$	4318	4307	$h_c(3P)$
1^{+-}	$\Gamma_0 = 58_{-16-25}^{+28+28}$	75	25	

