LHCb实验重味强子谱学研究

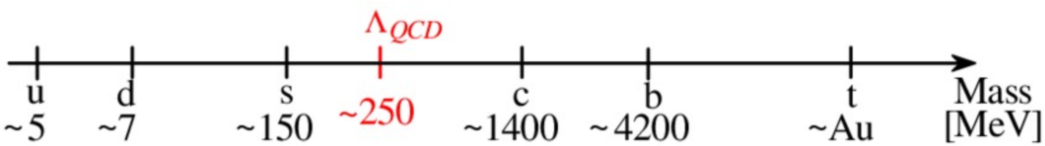
Liupan An (安刘攀)
On behalf of the LHCb collaboration

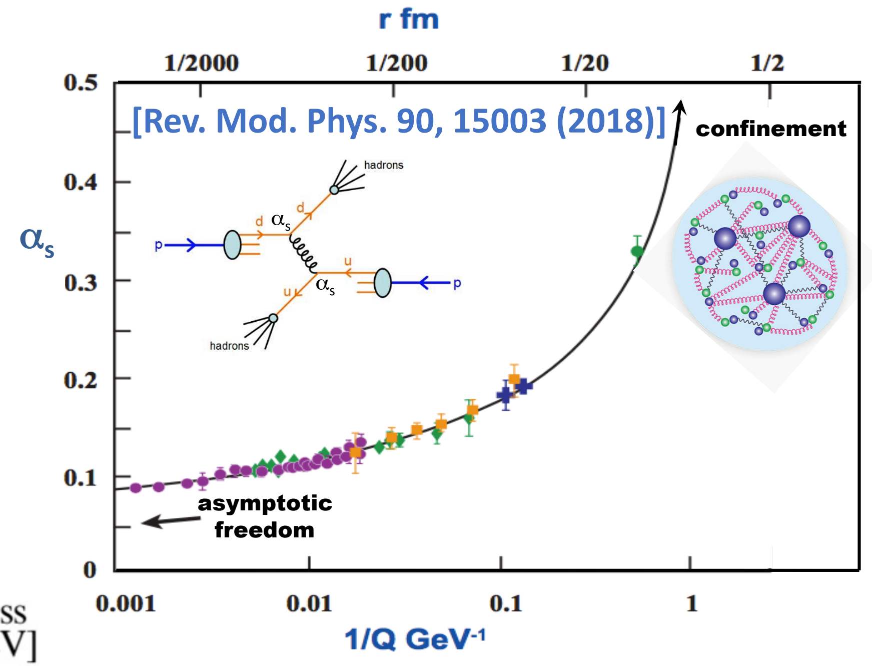
Peking University (北京大学)

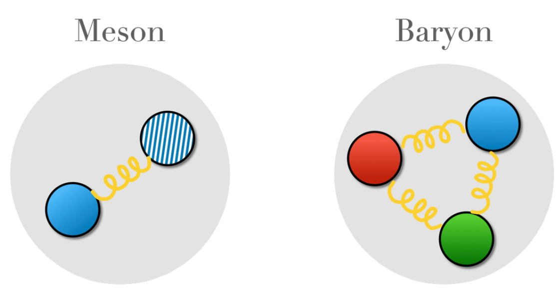
第二届强子物理新发展研讨会 @ 中国科学技术大学, 2024.07.02

Introduction

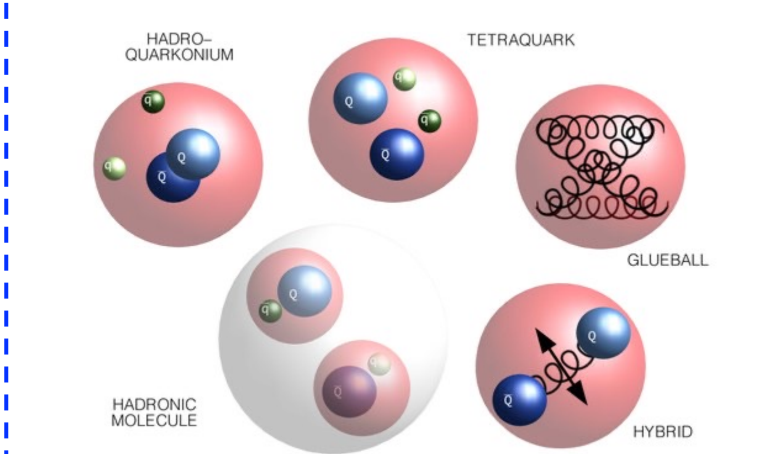
- ***QCD dilemma***: understanding the non-perturbative property of QCD at low-energy scale
- ***Hadron spectroscopy***: a main tool to probe QCD at low-energy regime
  - ✓ ***heavy quarks*** bring advances both experimentally and theoretically







conventional hadrons

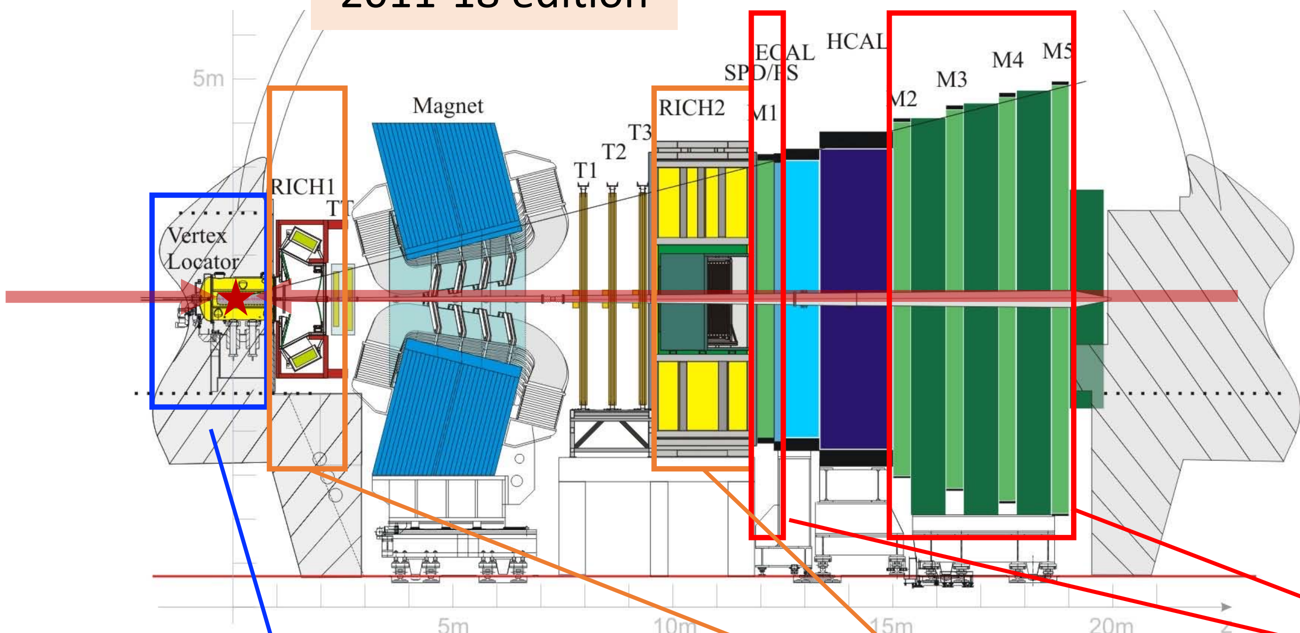


exotic hadrons

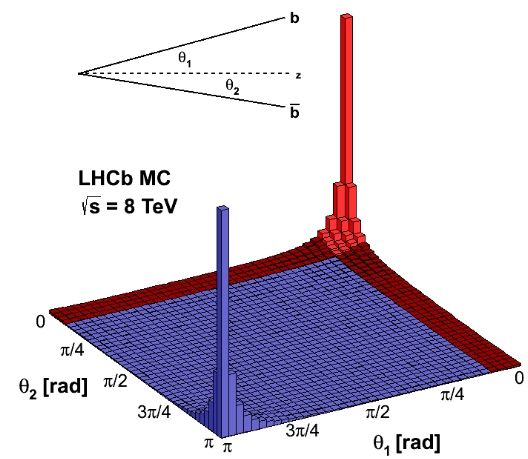
The LHCb detector

- LHCb is a single-arm forward region spectrometer covering $2 < \eta < 5$, dedicated to heavy flavor physics at the Large Hadron Collider

2011-18 edition



2.4% 4π angle
$\Rightarrow$ 25% $b\bar{b}$



Vertex Locator: high precision; capable of separating b/c hadron production and decay vertices

$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$

RICHs: efficient identification of pions, kaons and protons

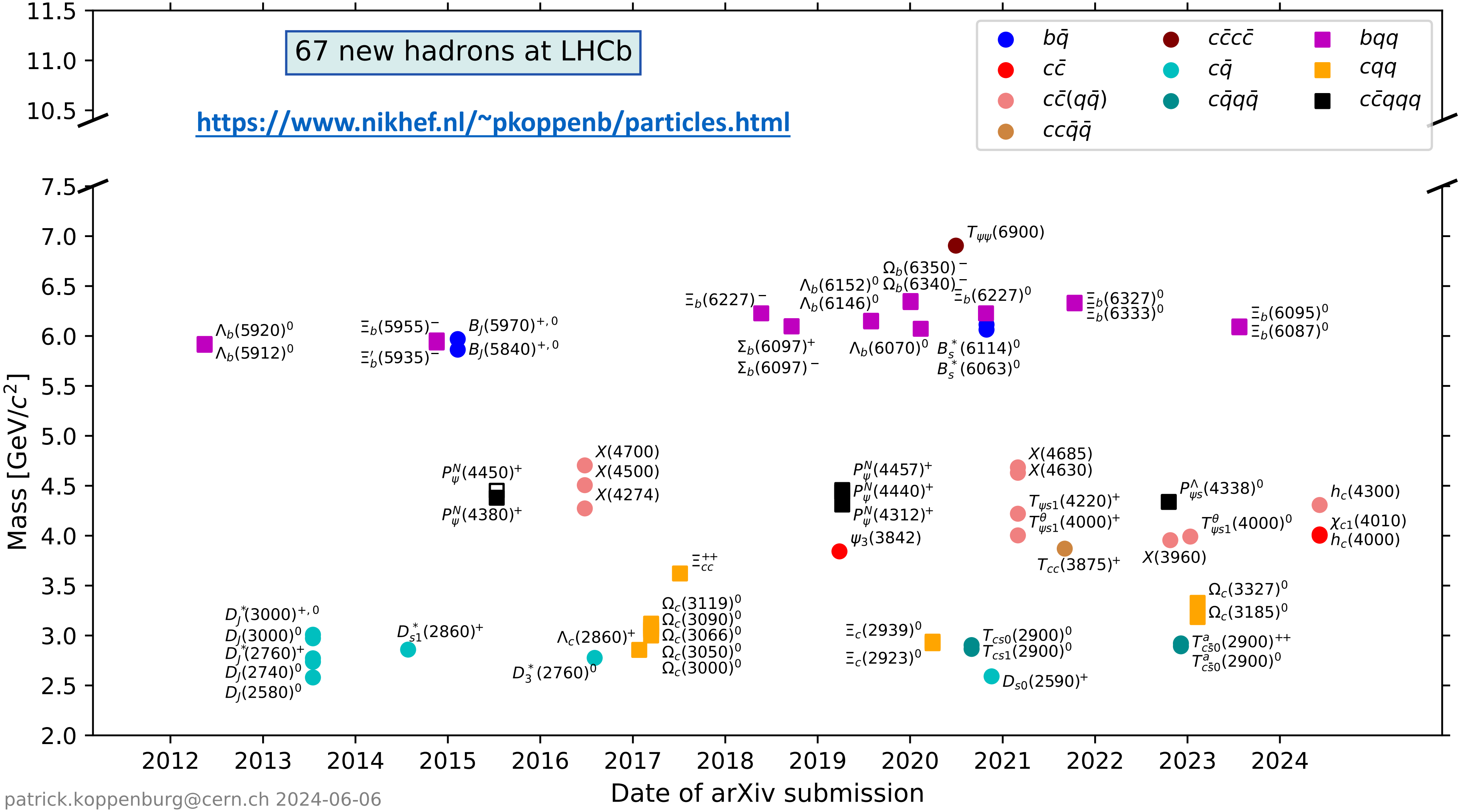
$\varepsilon(K \to K) \sim 95\%$
@ misID rate $(\pi \to K) \sim 5\%$

Muon system (M1-M5): efficient muon identification and trigger

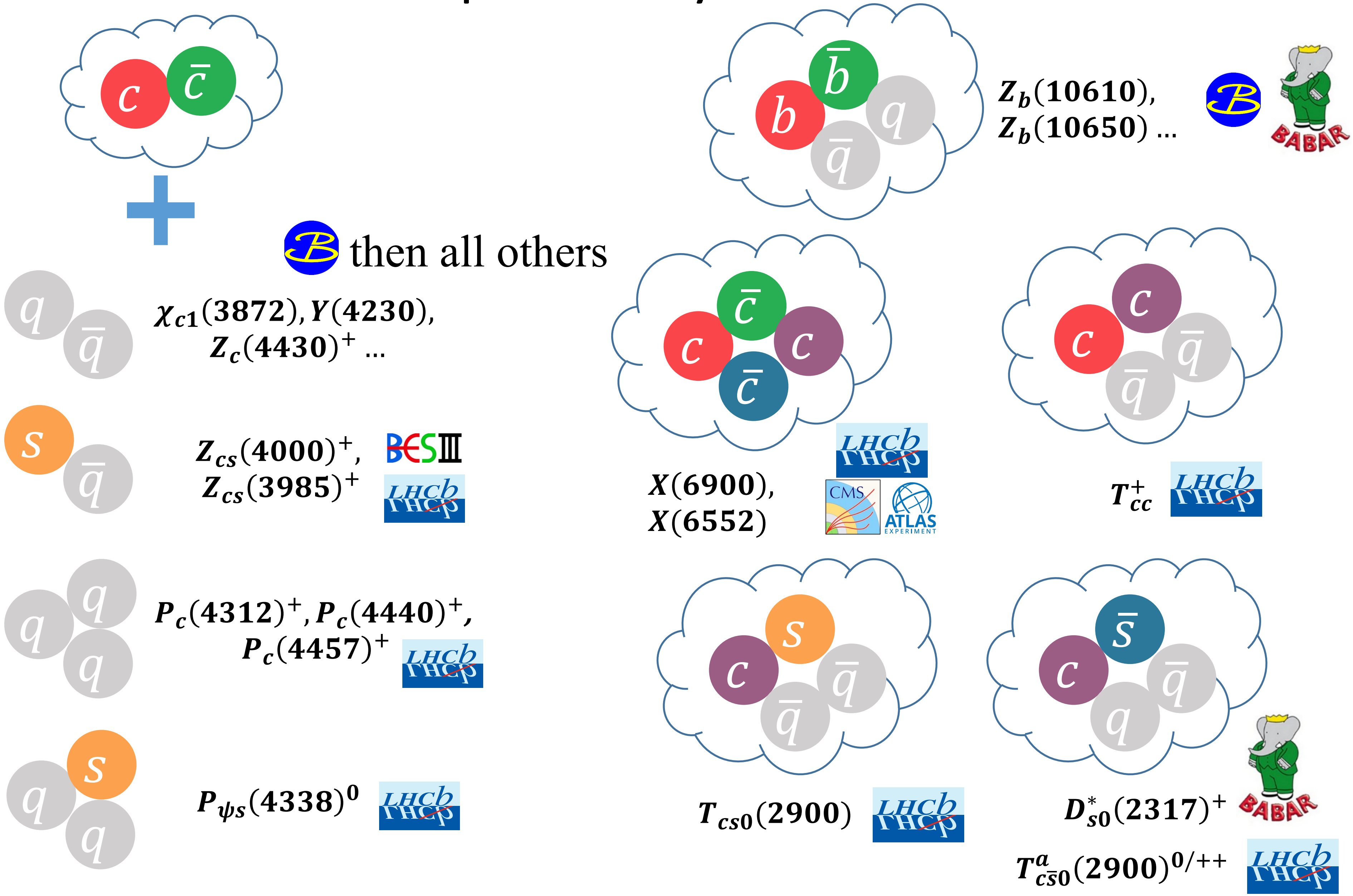
$\varepsilon(\mu \to \mu) \sim 97\%$
@ misID rate $(\pi \to \mu) \sim 1 - 3\%$

[JINST 3 (2008) S08005]

Hadrons observed at LHCb



Map of heavy exotics



Selected new measurements

- Study of radiative decays of $\chi_{c1}(3872)$ [arXiv: 2406.17006]
- Ξ_b^- baryon lifetime measurement [arXiv: 2406.12111]
- Amplitude analysis of $B^+ \to D^{*-} D_s^+ \pi^+$ [arXiv: 2405.00098]
- Amplitude analysis of $B^+ \to D^{*\pm} D^{\mp} K^+$ [arXiv: 2404.19510]
- Observation of $\Lambda_b^0 \to D^+ D^- \Lambda$ [arXiv: 2403.03586]
- Observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ [arXiv: 2404.19510]

(the four items above: $B \to D\bar{D}h$)

- Modification of $\chi_{c1}(3872)$ production in pPb collisions [PRL 132 (2024) 242301]
- First measurement of $J/\psi\phi$ production in pp collisions with no additional activity [LHCb-PAPER-2023-043] in preparation
- Search for prompt production of pentaquarks in open charm final states [arXiv: 2404.07131]
- ...

*Doubly heavy hadron covered by Prof. Jibo He yesterday

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 $\chi_{c1}(3872) \to \psi(2S)\gamma$ was seen experimentally before

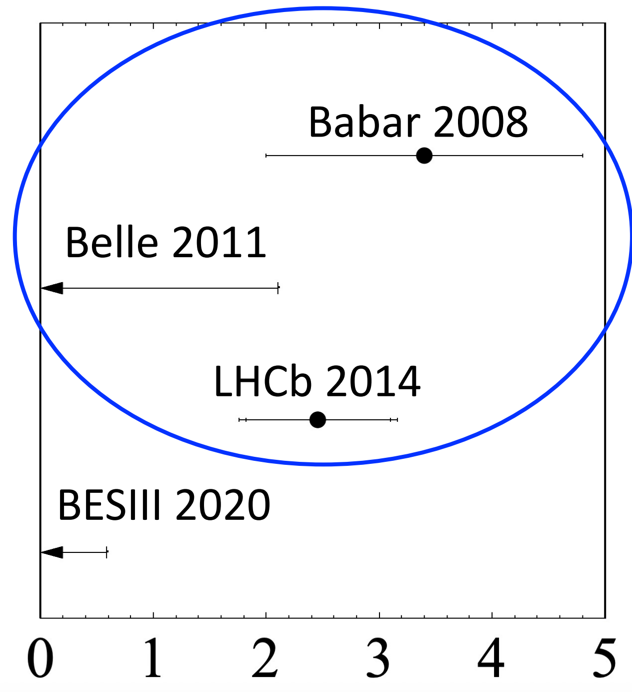
Reference		$\mathscr{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$	
T. Barnes and S. Godfrey	[67]	5.8	$c\bar{c}$
T. Barnes, S. Godfrey and S. Swanson	[69]	2.6	$c\bar{c}$
F. De Fazio	[84]	(1.64 ± 0.25)	$c\bar{c}$
B.-Q. Li and K. T. Chao	[85]	1.3	$c\bar{c}$
Y. Dong *et al.*	[86]	$1.3 - 5.8$	$c\bar{c}$
A. M. Badalian *et al.*	[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 *et al.*	[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 *et al.*	[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 *et al.*	[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 *et al.*	[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]	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$

$\gtrsim 1$

$\ll 1$

mixed

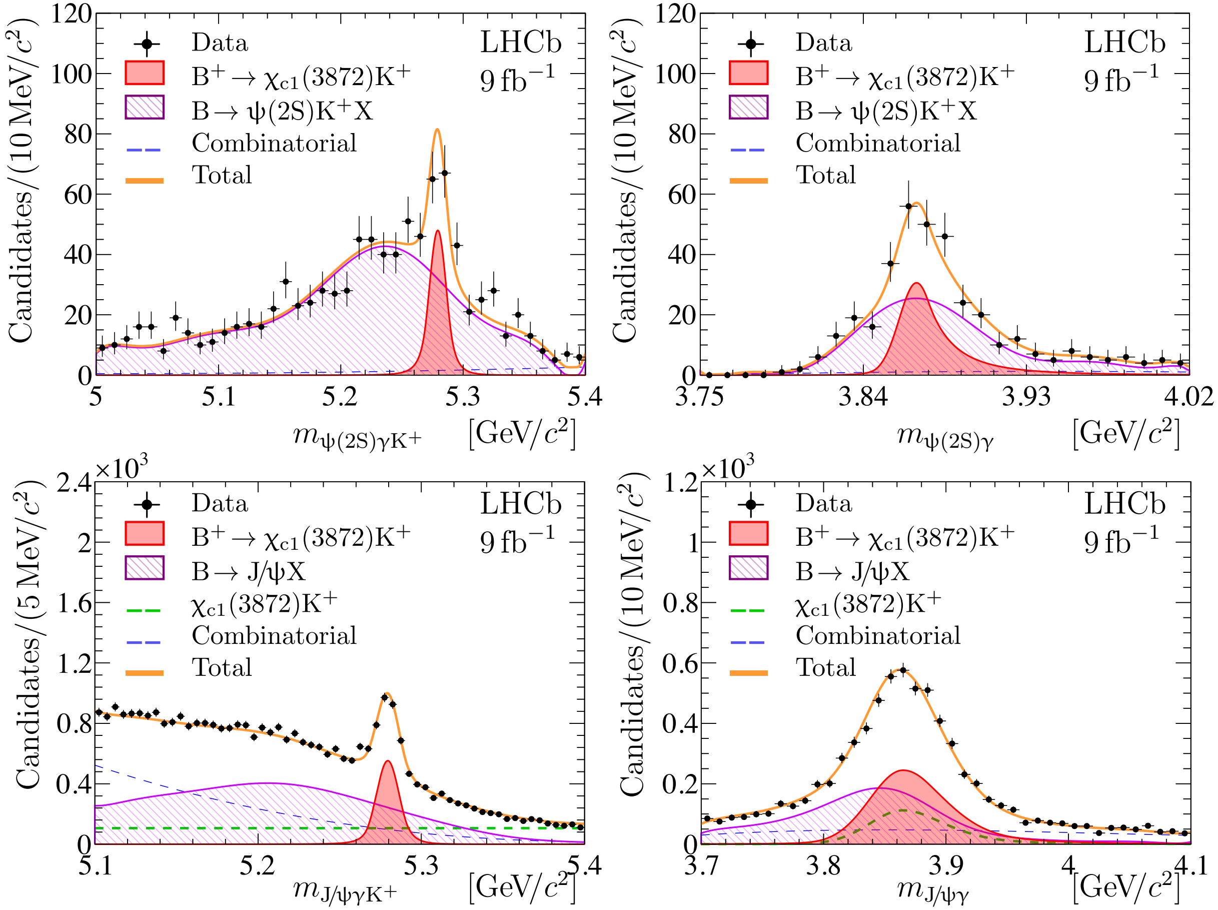
B decay



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

[arXiv: 2406.17006]

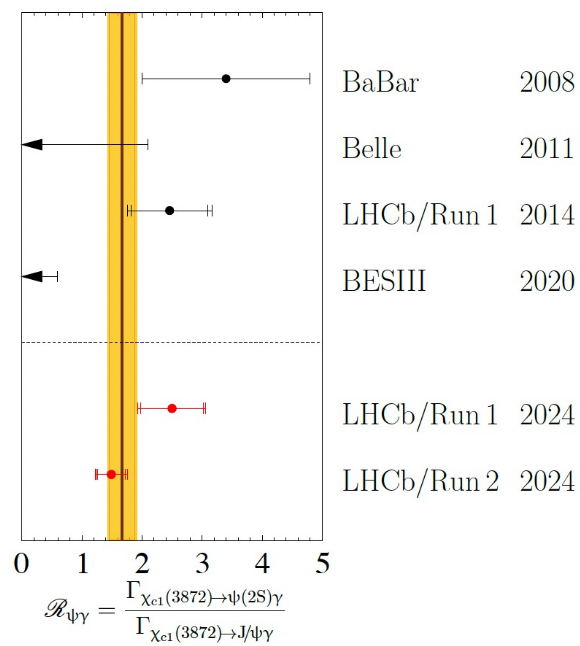
- Update at LHCb using $B^+ \to \chi_{c1}(3872)K^+$ decay with 9 fb^{-1} Run1+Run2 data



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

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

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



$$\mathscr{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$

Ξ_b^- baryon lifetime

[arXiv: 2406.12111]

- b-hadron lifetime measurements provide a direct quantitative test of Heavy Quark Expansion (HQE) higher-order corrections

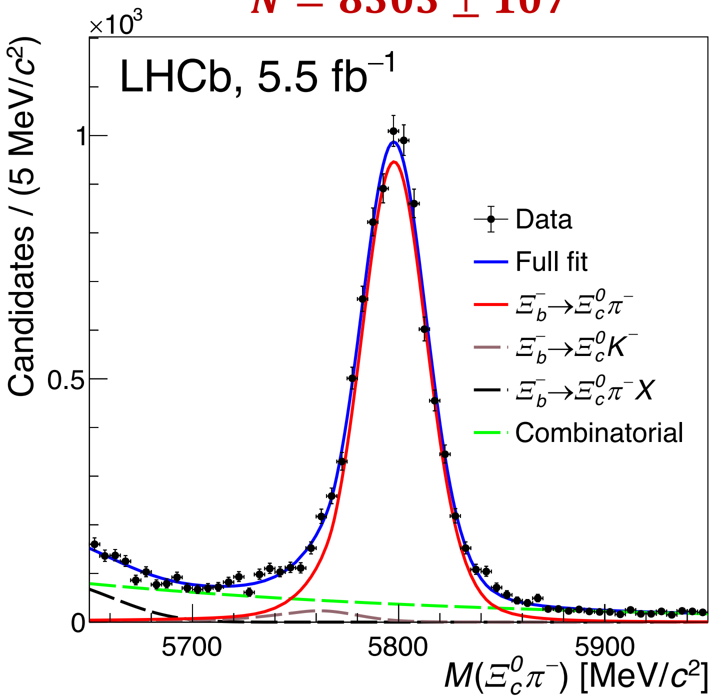
$\tau(\Xi_b^-)/\tau(\Lambda_b^0)$

theoretical: 1.078 ± 0.021, $\boldsymbol{\delta \sim 1.9\%}$

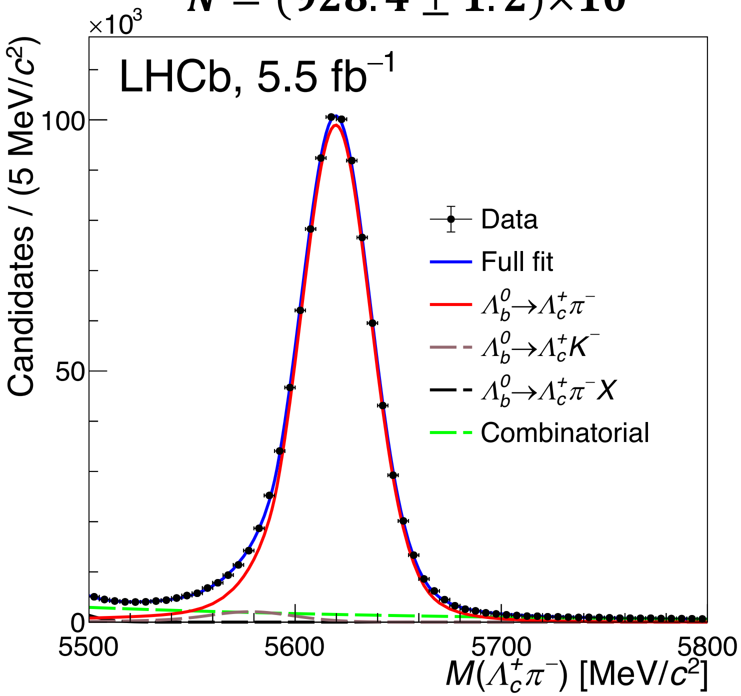
experimental: 1.089 ± 0.028, $\boldsymbol{\delta \sim 2.5\%}$

- Ξ_b^- baryon lifetime measured with 5.5 fb^{-1} LHCb data at $\sqrt{s} = 13$ TeV, using $\Xi_b^- \to \Xi_c^0(\to pK^-K^-\pi^+)\pi^+$ wrt $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^+$

$\boldsymbol{N = 8303 \pm 107}$



$\boldsymbol{N = (928.4 \pm 1.2)\times 10^3}$



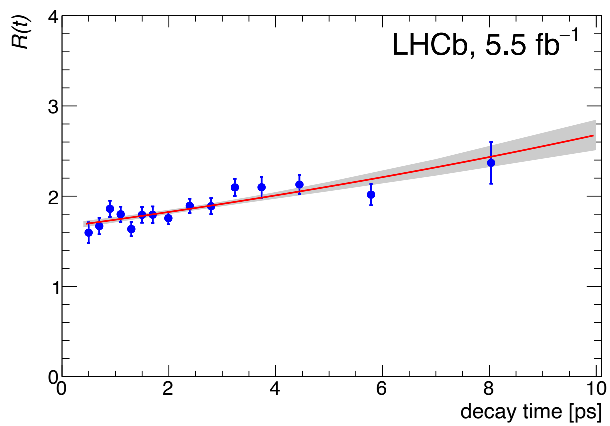
Ξ_b^- baryon lifetime (cont.)

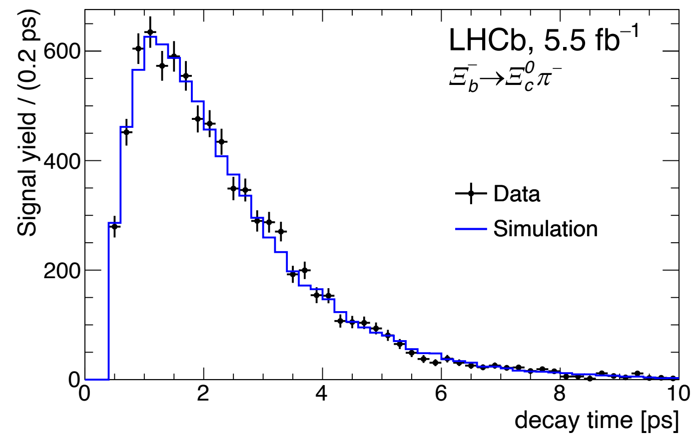
[arXiv: 2406.12111]

$$R(t) \equiv \frac{N[\Xi_b^- \to \Xi_c^0 \pi^-](t)}{N[\Lambda_b^0 \to \Lambda_c^+ \pi^-](t)} \cdot \frac{\varepsilon[\Lambda_b^0 \to \Lambda_c^+ \pi^-](t)}{\varepsilon[\Xi_b^- \to \Xi_c^0 \pi^-](t)} = R_0 \exp(\lambda t),$$

$$\lambda \equiv \frac{1}{\tau_{\Lambda_b^0}} - \frac{1}{\tau_{\Xi_b^-}}$$

$$r_\tau \equiv \frac{\tau_{\Xi_b^-}}{\tau_{\Lambda_b^0}} = \frac{1}{1 - \lambda \tau_{\Lambda_b^0}}$$





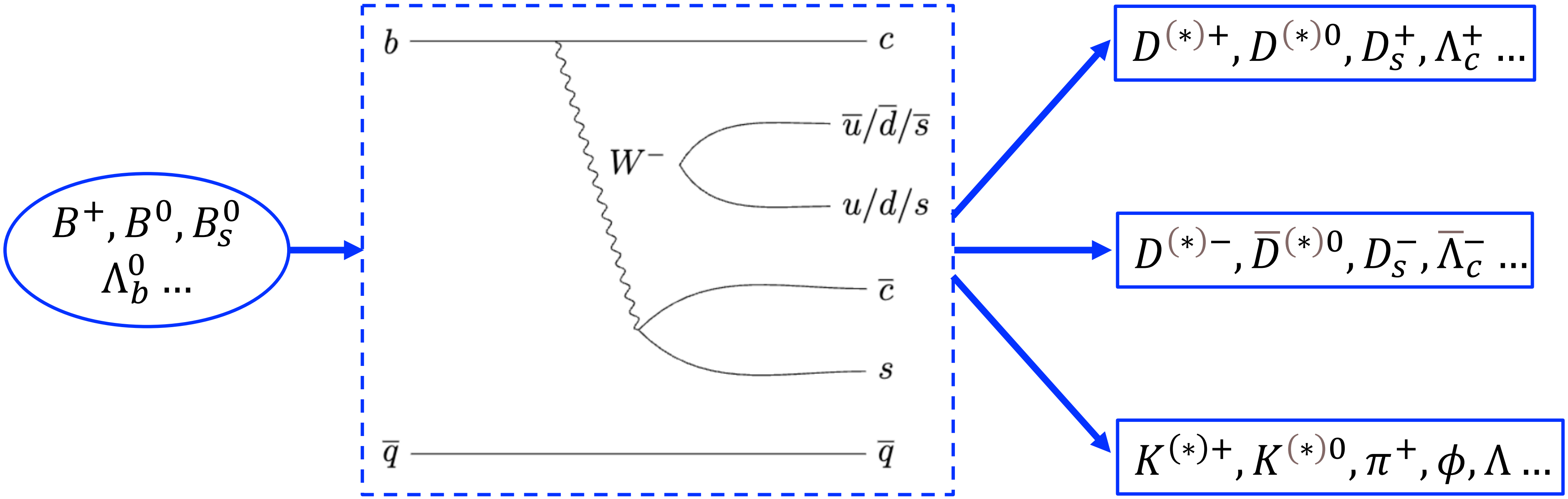
$$r_\tau^{\mathrm{Run\,2}} = 1.076 \pm 0.013 \pm 0.006$$

$$r_\tau^{\mathrm{Run\,1,2}} = 1.078 \pm 0.012 \pm 0.007,$$
$$\tau_{\Xi_b^-}^{\mathrm{Run\,1,2}} = 1.578 \pm 0.018 \pm 0.010 \pm 0.011 \text{ ps}$$

theoretical		experimental
1.078 ± 0.021 $\boldsymbol{\delta \sim 1.9\%}$	$\boldsymbol{\tau(\Xi_b^-)/\tau(\Lambda_b^0)}$	1.078 ± 0.014 $\boldsymbol{\delta \sim 1.3\%}$

✓Nice agreement with HQE prediction (additional $s \to u\bar{u}d$ transition would reduce the prediction by ~1%)

$B \to D\overline{D}h$ studies



- Rich opportunities for heavy spectroscopy study
  - ✓ **charmonium(-like)** states in $D^{(*)}\overline{D}^{(*)}, \Lambda_c^+\overline{D}^{(*)}, \Lambda_c^+\overline{\Lambda}_c^-$ ...
  - ✓ **excited $D^+, D^0, D_s^+, \Lambda_c^+$** states from $D^{(*)}h, \Lambda_c^+ h$ ...
  - ✓ **exotic** states from $D^{(*)}h, \Lambda_c^+ h$ ...
- Useful for studies of semileptonic decays for search of New Physics

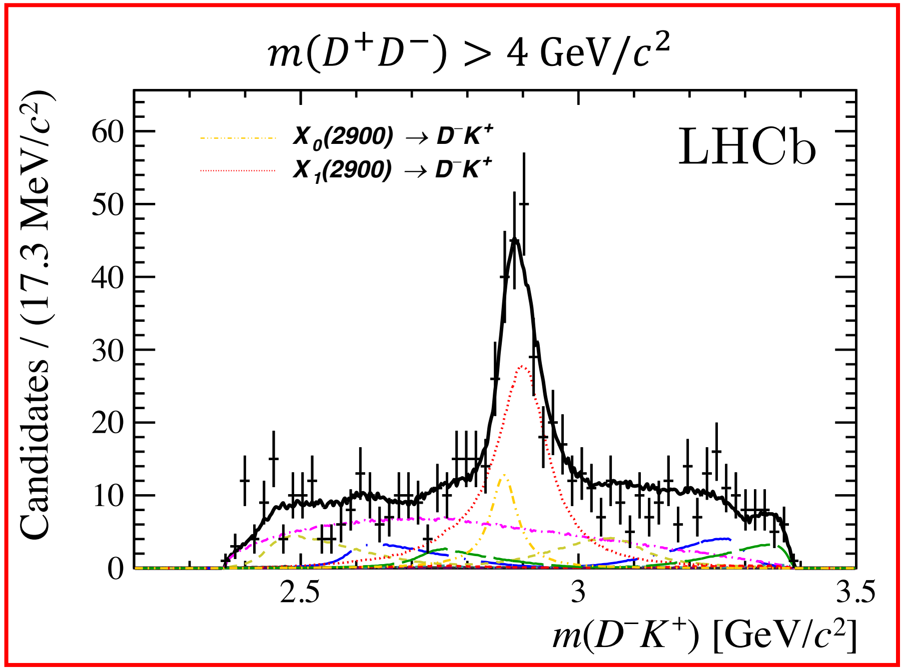
$B \to D\bar{D}h$ studies at LHCb

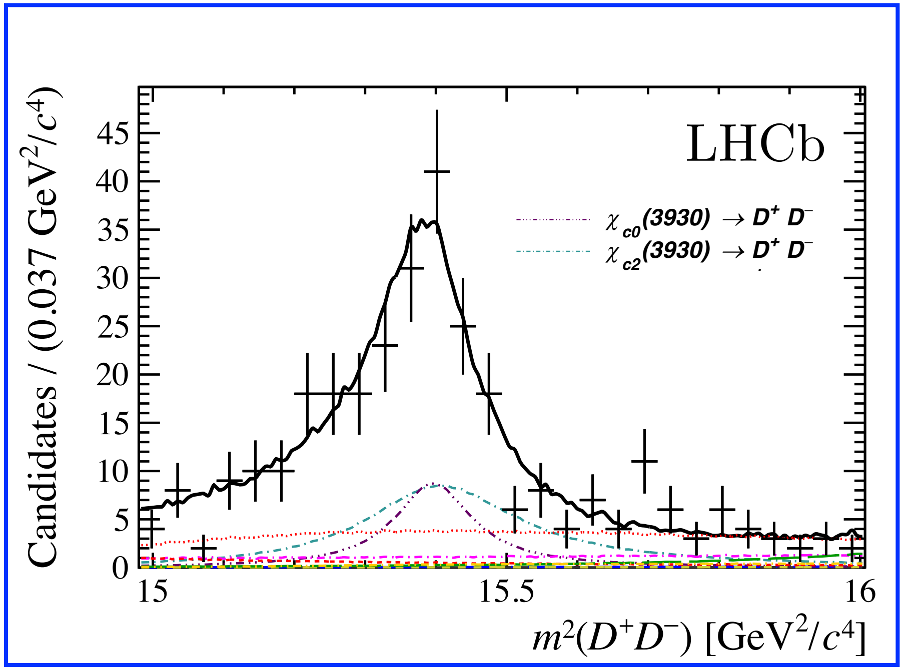
$B^+ \to D^+D^-K^+$

T_{cs} in $B^+ \to D^+D^-K^+$

[PRL 125 (2020) 242001]
[PR D102 (2020) 112003]

- Resonant structures observed in the D^-K^+ and D^+D^- systems from an amplitude analysis of the $B^+ \to D^+D^-K^+$ decay





	Resonance	Mass (GeV/c^2)	Width (MeV)
	$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
	$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
$T^*_{\bar{c}\bar{s}0}(2870)^0$	$X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
$T^*_{\bar{c}\bar{s}1}(2900)^0$	$X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11 \pm 4$

- First discovery of open-charm tetraquarks with four different flavors $[cs\bar{u}\bar{d}]$!

$B \to D\overline{D}h$ studies at LHCb

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

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

$B^+ \to D^- D_s^+ \pi^+$ & $B^0 \to \overline{D}^0 D_s^+ \pi^-$

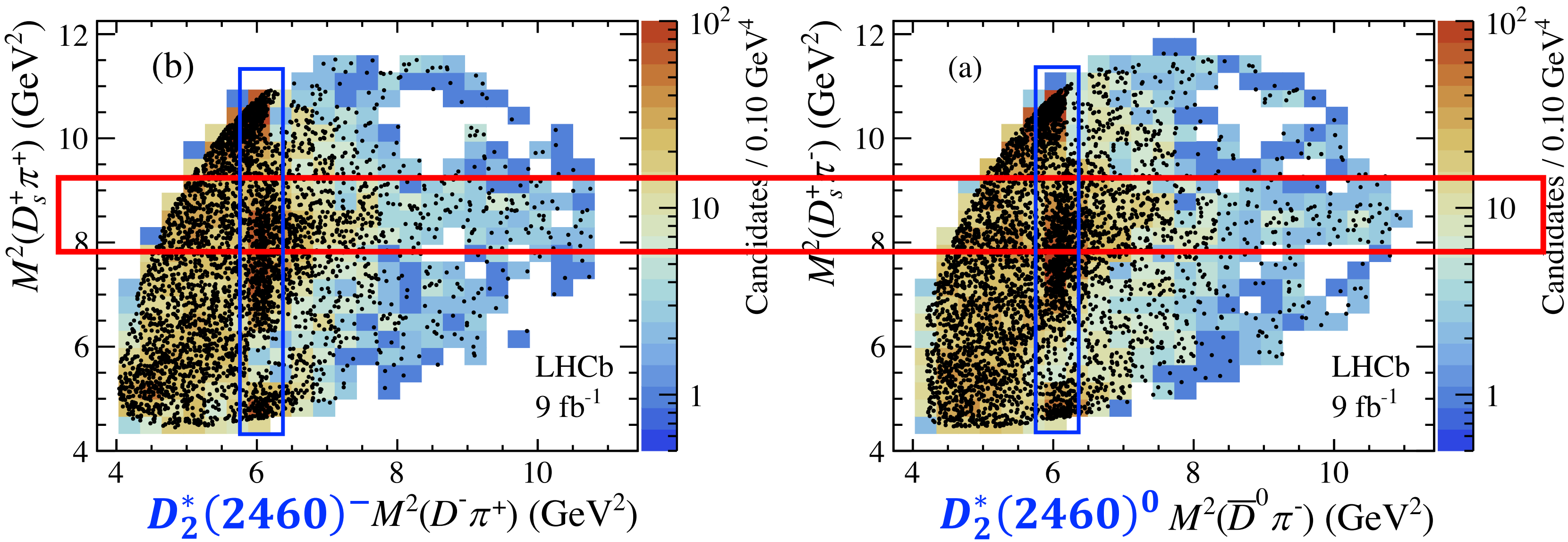
Study of $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

[PRL 131 (2023) 041902]

- Full 9 fb^{-1} Run1+Run2 LHCb data

$\Rightarrow$ 4420 $B^0 \to \bar{D}^0 D_s^+ \pi^-$ candidates with signal purity of 90.7%

3940 $B^+ \to D^- D_s^+ \pi^+$ candidates with signal purity of 95.2%



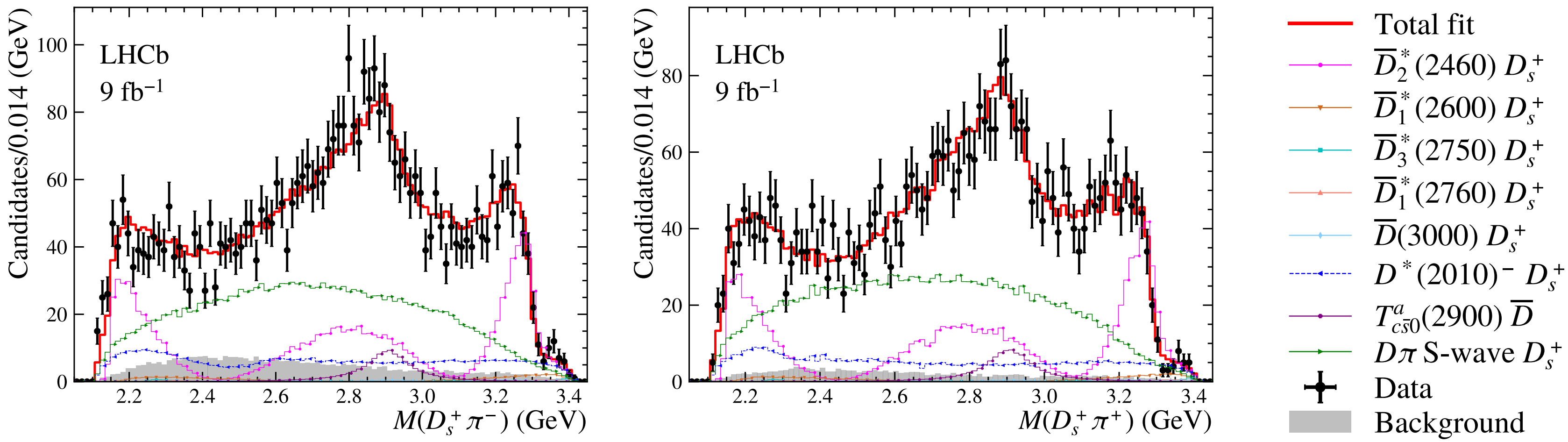
✓Faint horizontal band at $M^2(D_s^+\pi) \approx 8.5\ \text{GeV}^2$ indicating $T_{c\bar{s}}$ candidates

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

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

[PRL 131 (2023) 041902]

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



- $T^{a}_{c\bar{s}0}(2900)^{0} \to D_s^+\pi^-$ & $T^{a}_{c\bar{s}0}(2900)^{++} \to D_s^+\pi^+$ 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

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

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

- Flavor partner of $T_{cs0}(2900)$? Multiplets to be revealed in the future.

$B \to D\overline{D}h$ studies at LHCb

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

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

$T_{cs0/1}(2900), \chi_{c2}(3930)$

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

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

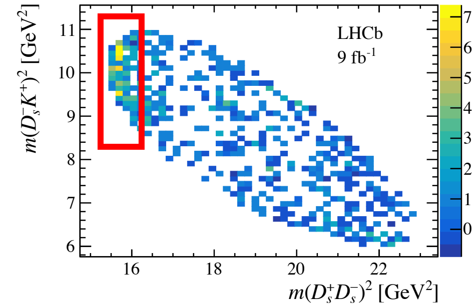
&

$B^0 \to \overline{D}^0 D_s^+ \pi^-$

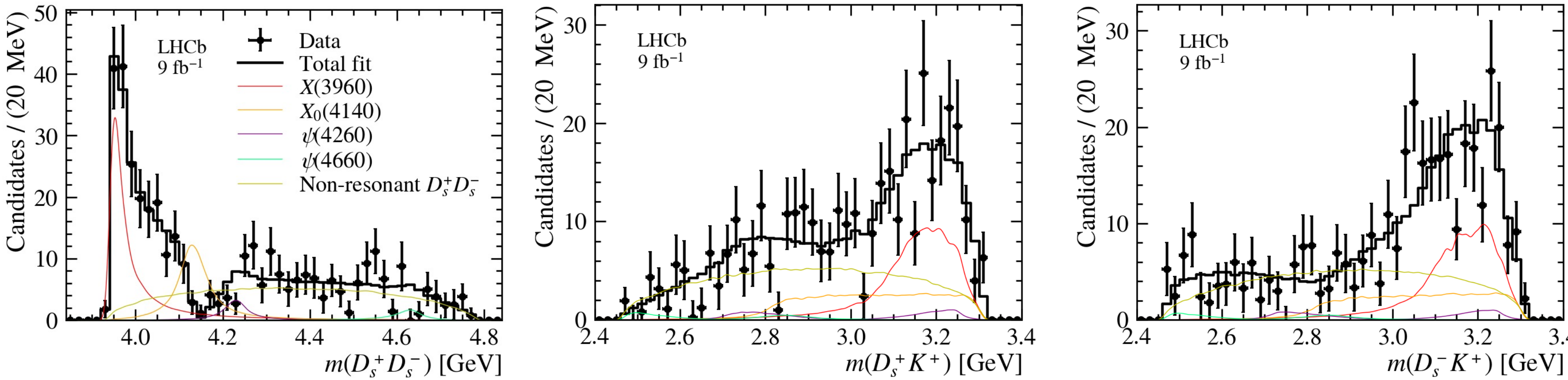
$T_{c\bar{s}0}^{a}(2900)^0$

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

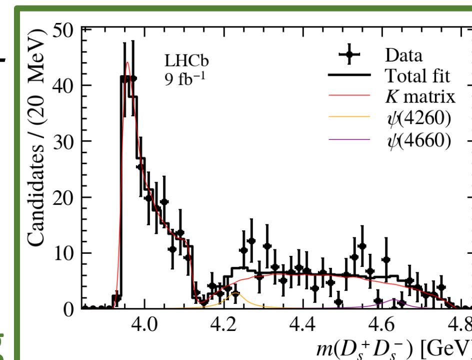
[PRL 131 (2023) 071901]



- New exotic X states needed to describe data
  - ✓0^{++}: $X(3960)$ (14.3σ), $X_0(4140)$ (3.9σ), Non-resonant
  - ✓1^{--}: $\psi(4260), \psi(4660)$



- $X(3960)$: threshold enhancement
  - ✓$J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 9.3σ and 12.3σ
- $X_0(4140)$: dip at $\sim$4.14 GeV via interference
  - ✓ $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 3.5σ and 4.2σ
  - ✓the dip can also be described by $J/\psi\phi \to D_s^+ D_s^-$ scattering



$X(3960)$ and $\chi_{c0}(3930)$

[PRL 131 (2023) 071901]

	M [MeV]	Γ [MeV]	J^{PC}
$X(3960)$	$3955 \pm 6 \pm 12$	$48 \pm 17 \pm 10$	0^{++}
$\chi_{c0}(3930)$	3924 ± 2	17 ± 5	

- Same particle?

$\mathcal{FF}$: Fit fraction

$$\frac{\Gamma(X \to D^+D^-)}{\Gamma(X \to D_s^+D_s^-)} = \frac{\mathcal{B}(B^+ \to D^+D^-K^+)\times\mathcal{FF}^X_{B^+\to D^+D^-K^+}}{\mathcal{B}(B^+ \to D_s^+D_s^-K^+)\times\mathcal{FF}^X_{B^+\to D_s^+D_s^-K^+}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$$

✓Creation of $s\bar{s}$ from vacuum is suppressed wrt $u\bar{u}$ or $d\bar{d}$

✓$X \to D_s^+D_s^-$ has smaller phase-space factor than $X \to D^+D^-$

$\Rightarrow$ X has an exotic nature! Candidate for $c\bar{c}s\bar{s}$

- Different particles?

✓No obvious candidate within conventional charmonium multiplets for them; likely to be exotic

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

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

$X(3960)$

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

$T_{cs0/1}(2900), \chi_{c2}(3930)$

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

$T^a_{c\bar{s}0}(2900)^{++}$

&

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

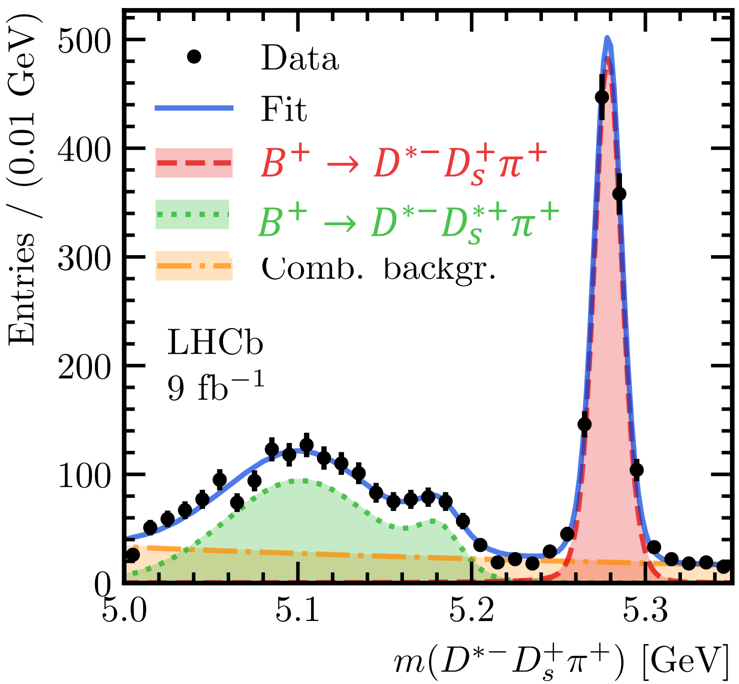
$T^a_{c\bar{s}0}(2900)^0$

$B^+ \to D^{*-} D_s^+ \pi^+$

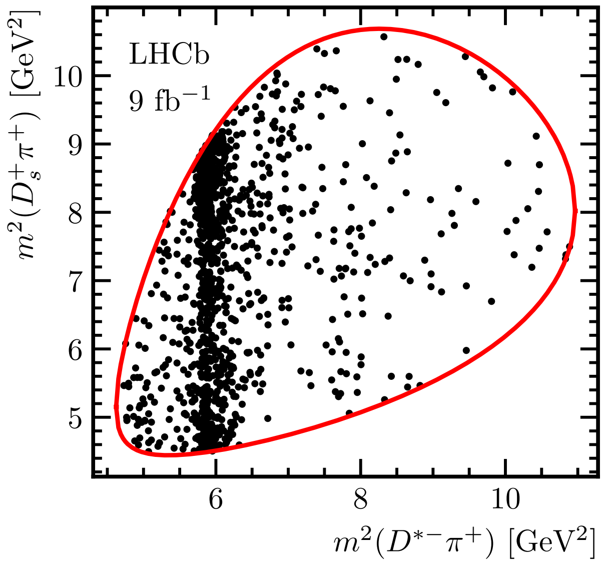
$B^+ \to D^{*-} D_s^{(*)+} \pi^+$: branching fractions

[arXiv: 2405.00098]

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



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



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

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

$B^+ \to D^{*-} D_s^+ \pi^+$: amplitude analysis

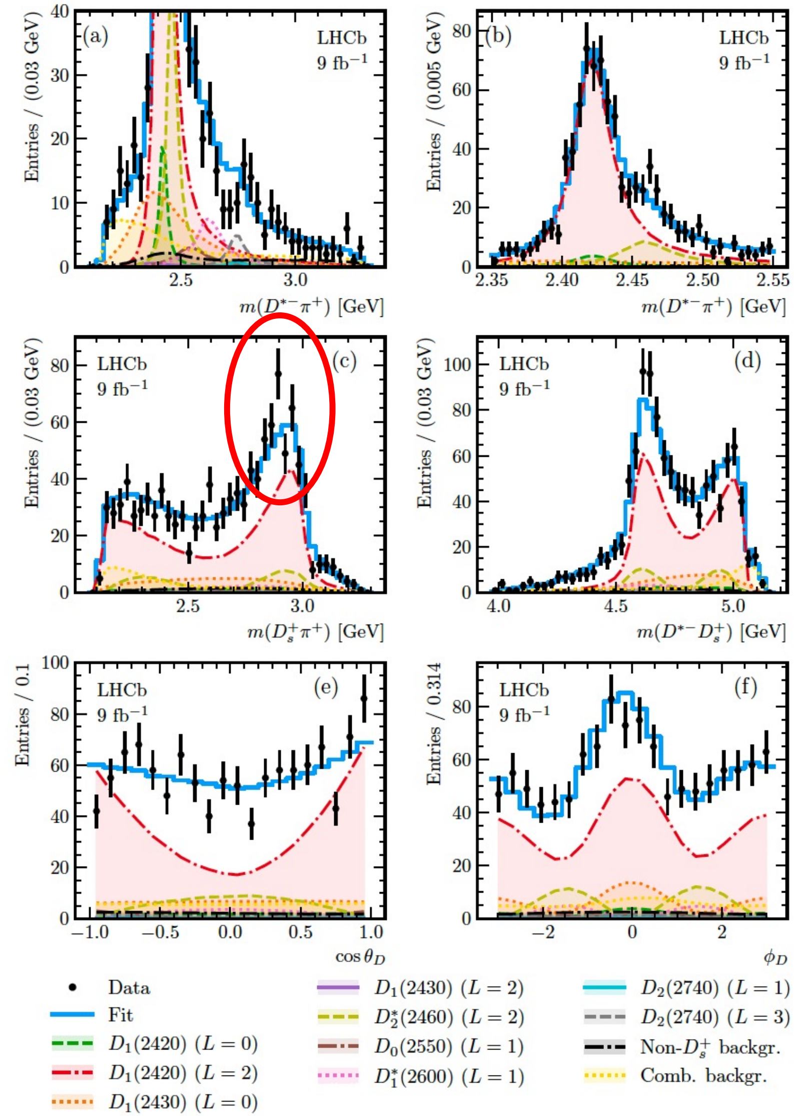
[arXiv: 2405.00098]

➢Baseline fit with $D^{**0} \to D^{*-}\pi^+$ contributions

	Resonance	J^P	Mass [MeV]	Width [MeV]
default	$D_1(2420)$	1^+	$2\,422.1 \pm 0.6$	31.3 ± 1.9
default	$D_1(2430)$	1^+	$2\,412 \pm 9$	314 ± 29
default	$D_2^*(2460)$	2^+	$2\,461.1\,^{+0.7}_{-0.8}$	47.3 ± 0.8
6.5σ	$D_0(2550)$	0^-	$2\,549 \pm 19$	165 ± 24
6.8σ	$D_1^*(2600)$	1^-	$2\,627 \pm 10$	141 ± 23
4.6σ	$D_2(2740)$	2^-	$2\,747 \pm 6$	88 ± 19
	~~$D_3^*(2750)$~~	3^-	$2\,763.1 \pm 3.2$	66 ± 5

➢Alternative parametrisations do not give significant improvement

- ✓Quasi-model-independent description of 1^+ S-wave amplitude
- ✓set mass and width of $D_1(2430)$ free
- ✓inclusion of additional broad nonresonant contributions

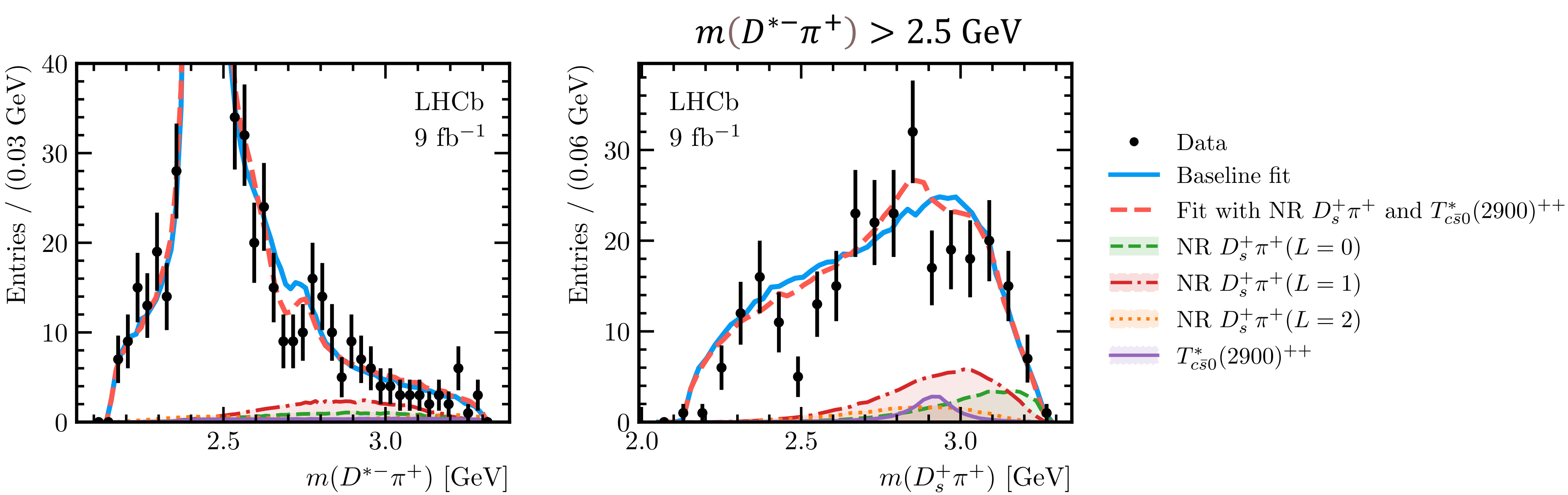


$B^+ \to D^{*-} D_s^+ \pi^+$: amplitude analysis

[arXiv: 2405.00098]

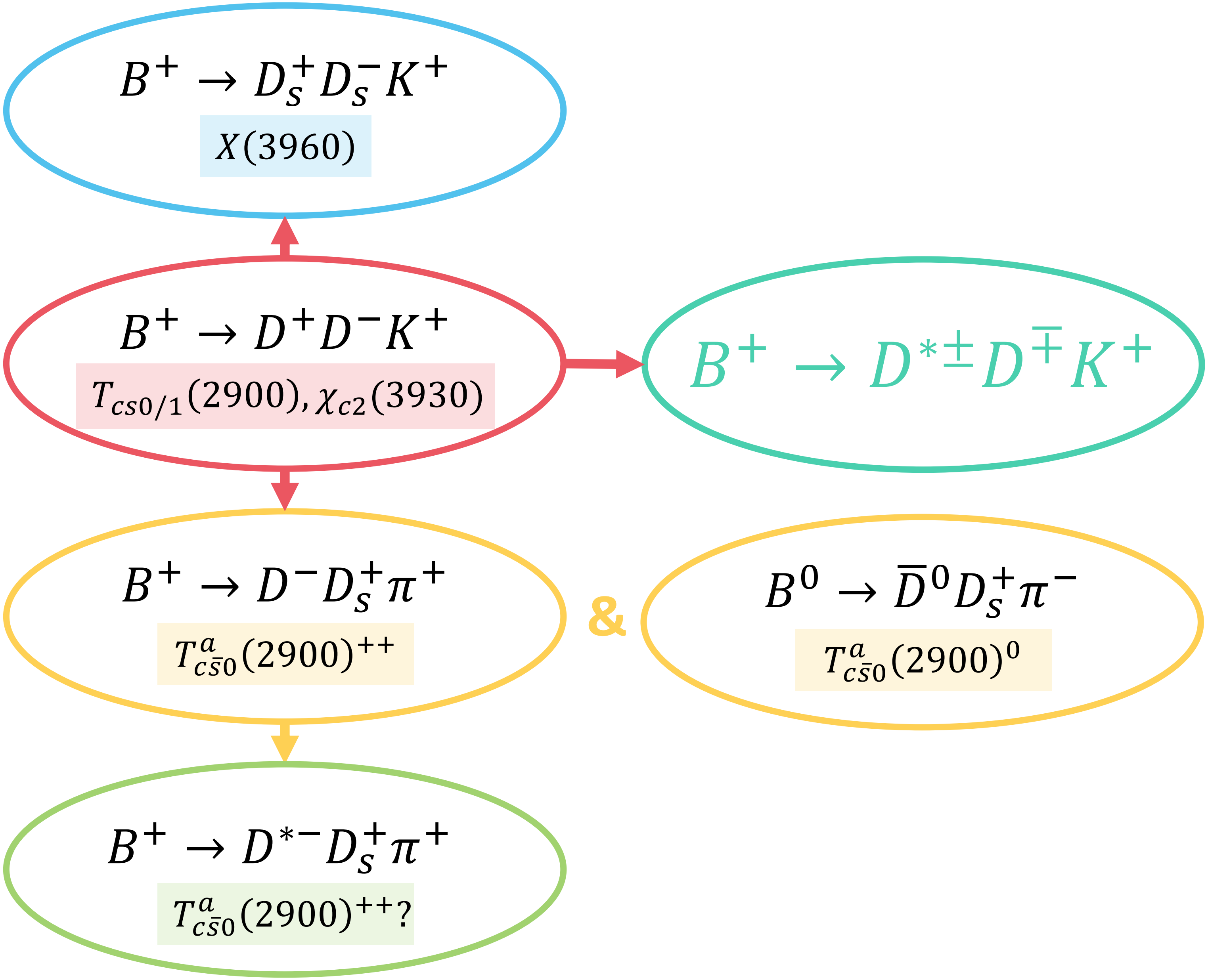
- Fits incorporating $D_s^+\pi^+$ amplitudes
  - ✓Adding $T_{c\bar{s}0}^{a}(2900)^{++}$ with mass and width fixed: fit fraction ~0.1%, negligible
  - ✓All combinations of scalar/vector/tensor & resonant/nonresonant amplitudes
    ⇒best fit: $\boldsymbol{T_{c\bar{s}0}^{a}(2900)^{++}}$ + **nonresonant vector**

> $\boldsymbol{2.6\,\sigma}$, fit fraction = $\boldsymbol{1.2 \pm 0.8\%}$, upper limit 2.3(2.7)% at 90(95)% CL
> - consistent with $\boldsymbol{(2.25 \pm 0.67 \pm 0.77)\%}$ in $B^+ \to D^- D_s^+ \pi^+$



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

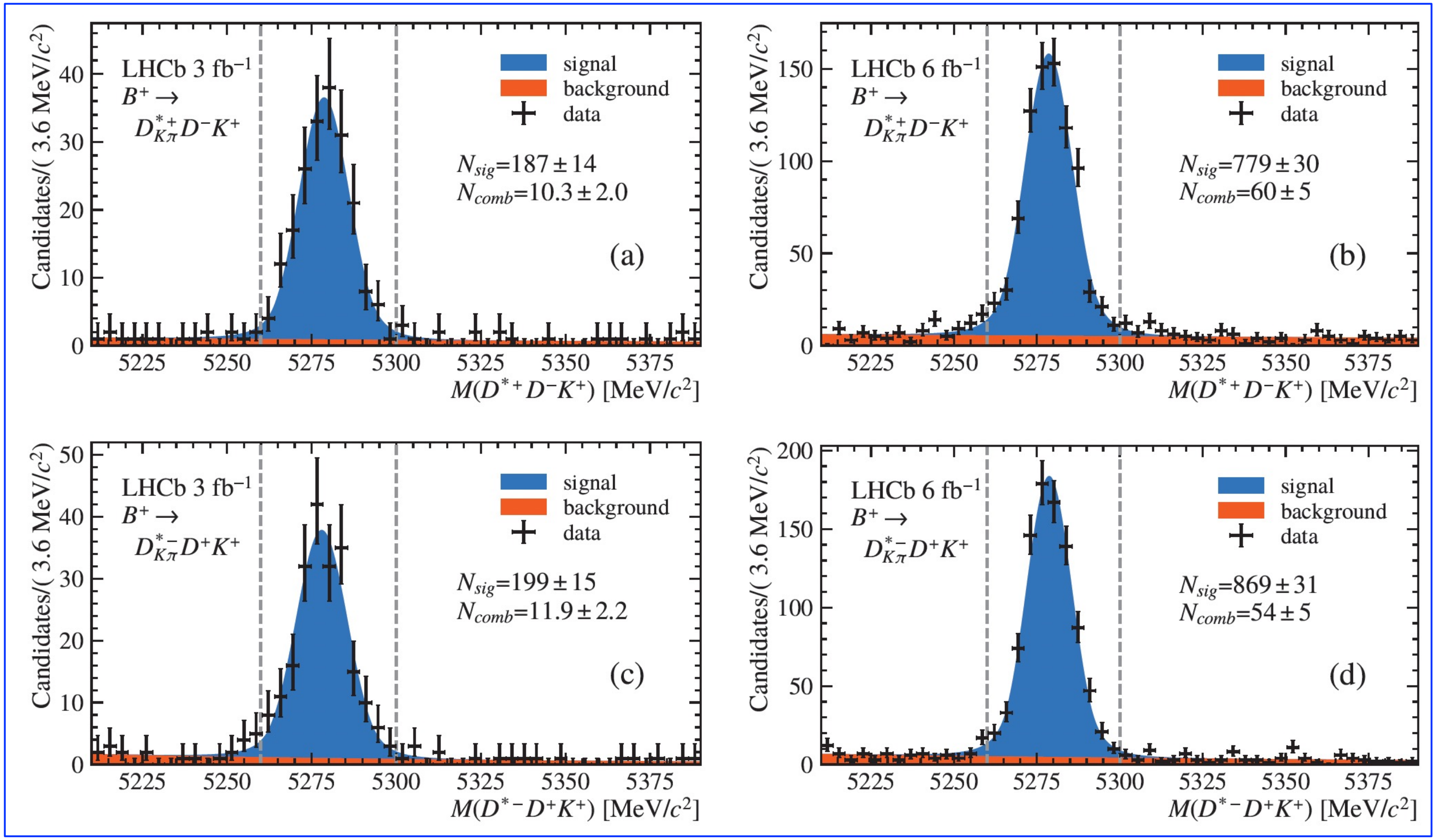
$B \to D\bar{D}h$ studies at LHCb



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

[arXiv: 2406.03156]

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



✓ $B^+ \to D^{*+} D^- K^+$: **1636 ± 43**

✓ $B^+ \to D^{*-} D^+ K^+$: **1772 ± 44**

both with bkg fraction ~5%

$B^+ \to D^{*\pm}D^{\mp}K^+$: amplitude analysis [arXiv: 2406.03156]

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

$$\mathcal{A}(x) = \frac{1+d}{2}\left\{\sum_{j\in R(D^{*\pm}D^{\mp})} \boxed{c_j A_j(x)} + \sum_{k\in R(D^{*-}K^+,\ D^+K^+)} c_k A_k(x)\right\} + \frac{1-d}{2}\left\{\sum_{j\in R(D^{*\pm}D^{\mp})} \boxed{C_j \times c_j A_j(x)} + \sum_{l\in R(D^{*+}K^+,\ D^-K^+)} c_l A_l(x)\right\}$$

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

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

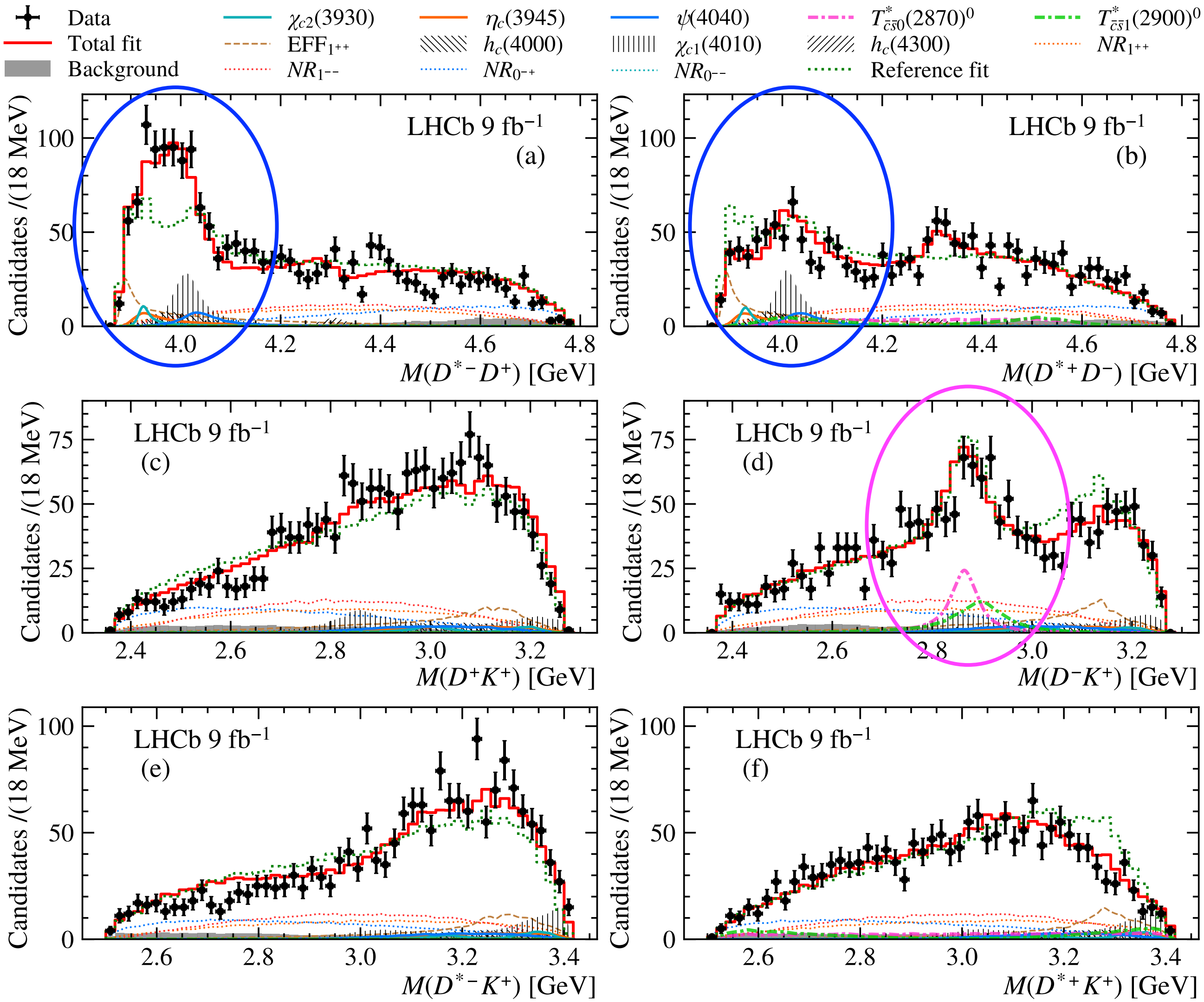
$$f_{R,S/D}(m) = \frac{\gamma_{S/D}}{m_0^2 - m^2 - i m_0[\gamma_S^2\Gamma_S(m) + \gamma_D^2\Gamma_D(m)]}$$

- Other resonances: Breit-Wigner
- Nonresonant contributions to $D^{*\pm}D^{\mp}$:
  $f_R(m) = e^{(\alpha+\beta i)(m^2-m_0^2)}$ for $NR_{0^{-+}}$; otherwise $f_R(m) = 1$

$B^+ \to D^{*\pm} D^{\mp} K^+$: 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^{+-}
$T^*_{\bar{c}\bar{s}0}(2870)^{0\,\dagger}$	0^+
$T^*_{\bar{c}\bar{s}1}(2900)^{0\,\dagger}$	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^{-+}

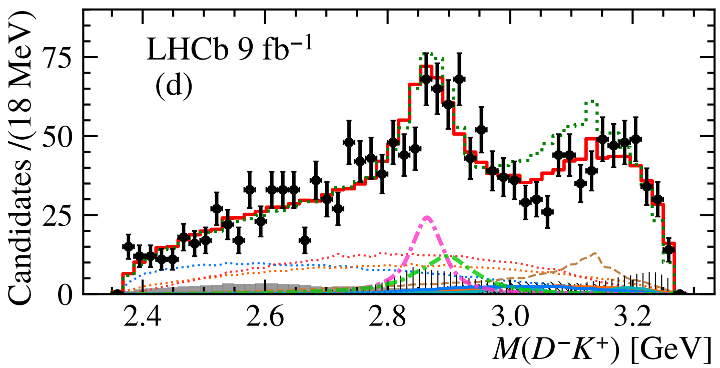
*Fit fractions in paper

✓clear different interference behaviours

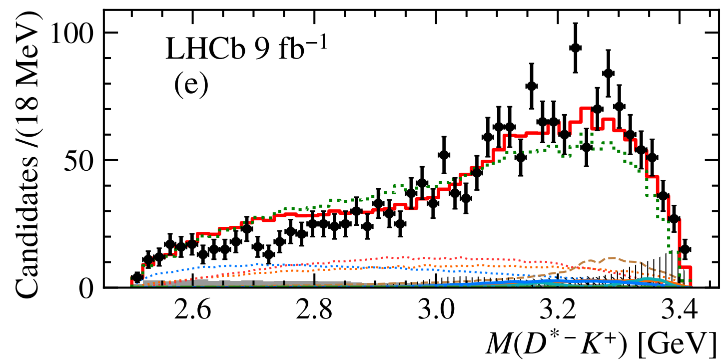
$B^+ \to D^{*\pm} D^{\mp} K^+$: $T^*_{\bar{c}\bar{s}}$ states

[arXiv: 2406.03156]

- $B^+ \to D^{*+} D^- K^+$



- $B^+ \to D^{*-} D^+ K^+$



11σ **$X_0(2900)$**

9.2σ **$X_1(2900)$**

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
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

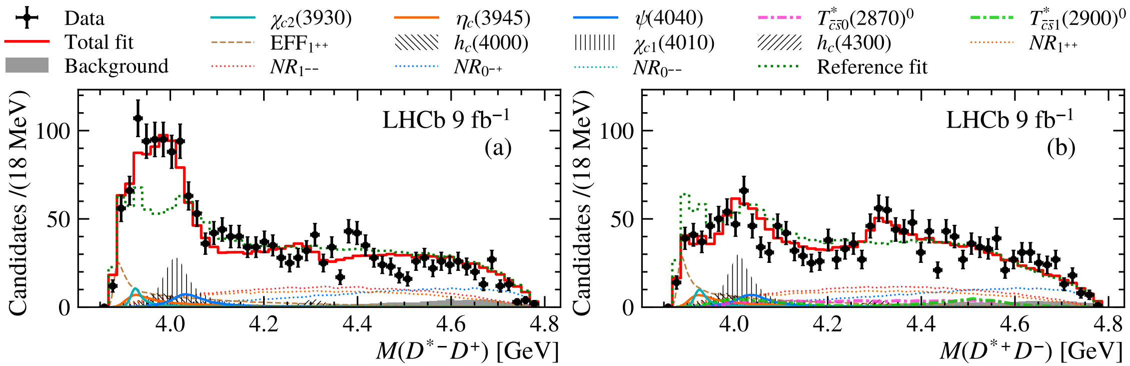
2σ

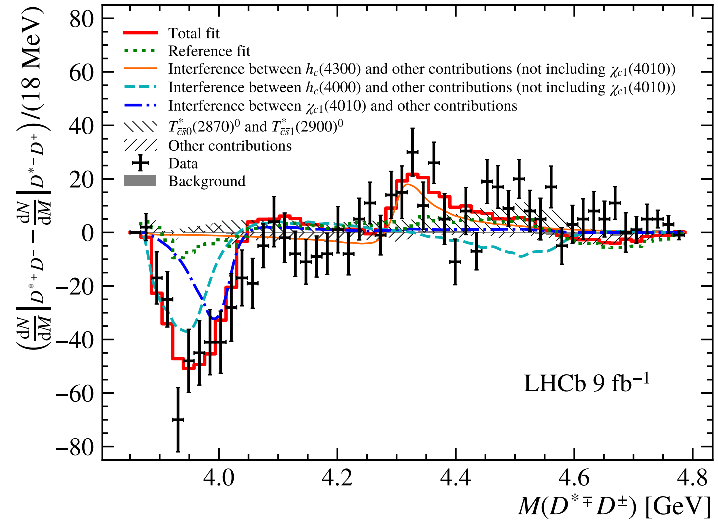
✓ $T^*_{\bar{c}\bar{s}0}(2870)^0 \to D^{*-} K^+$ forbidden

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

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

[arXiv: 2406.03156]



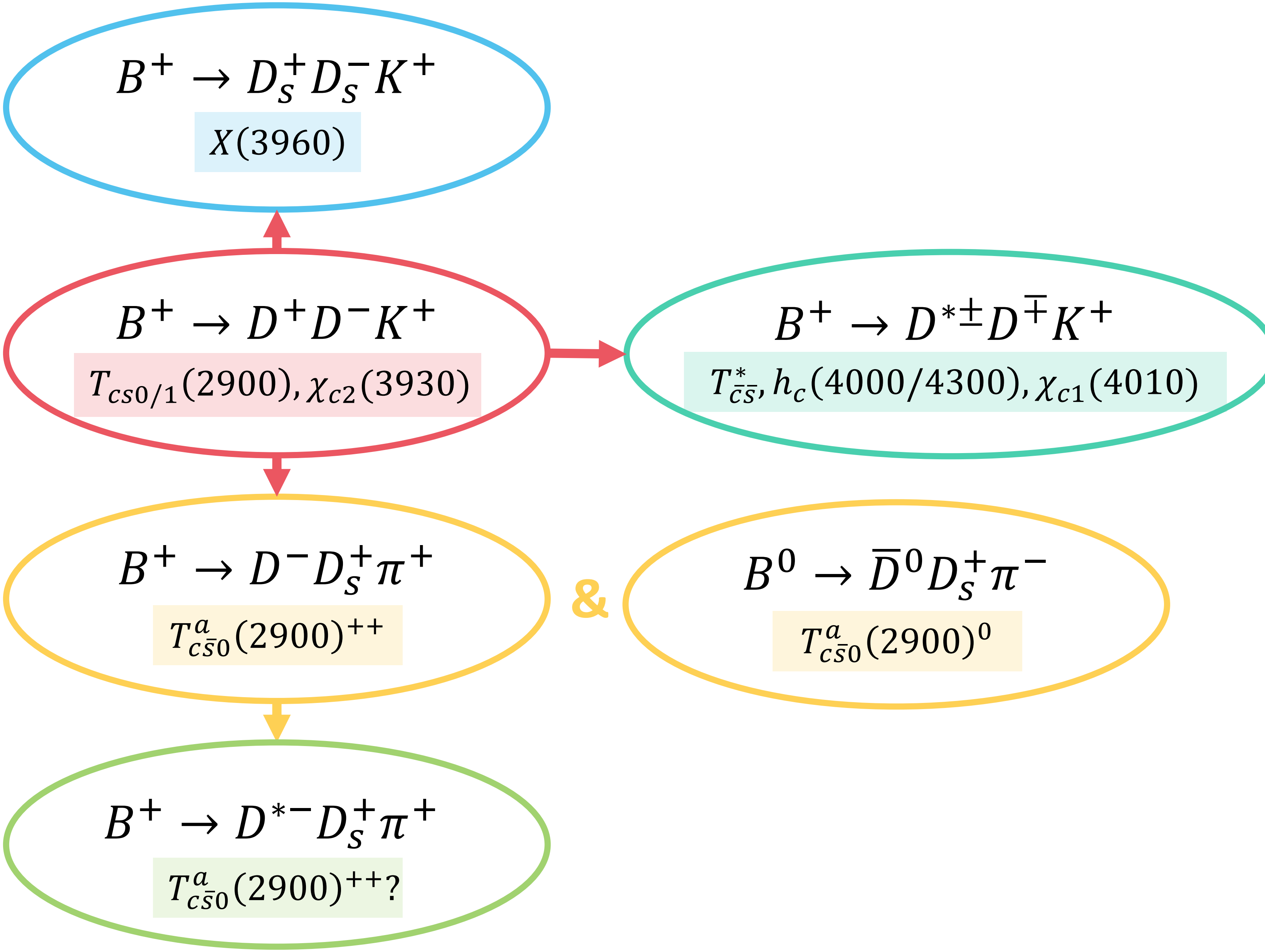


✓Reference fit without $h_c(4000), \chi_{c1}(4010), h_c(4300)$: necessary to describe discrepancy between $M(D^{*-}D^+)$ and $M(D^{*+}D^-)$

Component	$J^{P(C)}$
EFF$_{1^{++}}$	1^{++}
$\chi_{c2}(3930)^\dagger$	2^{++}
$\psi(4040)^\dagger$	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^{-+}

This work	Known states [6]	$c\bar{c}$ prediction [34]
$\eta_c(3945)$ $J^{PC}=0^{-+}$ $m_0 = 3945^{+28}_{-17}{}^{+37}_{-28}$ $\Gamma_0 = 130^{+92}_{-49}{}^{+101}_{-70}$	$X(3940)$ [9,10] $J^{PC}=?^{??}$ $m_0 = 3942 \pm 9$ $\Gamma_0 = 37^{+27}_{-17}$	$\eta_c(3S)$ $J^{PC}=0^{-+}$ $m_0 = 4064$ $\Gamma_0 = 80$
$h_c(4000)$ $J^{PC}=1^{+-}$ $m_0 = 4000^{+17}_{-14}{}^{+29}_{-22}$ $\Gamma_0 = 184^{+71}_{-45}{}^{+97}_{-61}$ $\chi_{c1}(4010)$ $J^{PC}=1^{++}$ $m_0 = 4012.5^{+3.6}_{-3.9}{}^{+4.1}_{-3.7}$ $\Gamma_0 = 62.7^{+7.0}_{-6.4}{}^{+6.4}_{-6.6}$	$T_{c\bar{c}}(4020)^0$ [35] $J^{PC}=?^{?-}$ $m_0 = 4025.5^{+2.0}_{-4.7} \pm 3.1$ $\Gamma_0 = 23.0 \pm 6.0 \pm 1.0$ [arXiv: 2406.08313]	$h_c(2P)$ $J^{PC}=1^{+-}$ $m_0 = 3956$ $\Gamma_0 = 87$ $\chi_{c1}(2P)$ $J^{PC}=1^{++}$ $m_0 = 3953$ $\Gamma_0 = 165$
$h_c(4300)$ $J^{PC}=1^{+-}$ $m_0 = 4307.3^{+6.4}_{-6.6}{}^{+3.3}_{-4.1}$ $\Gamma_0 = 58^{+28}_{-16}{}^{+28}_{-25}$	$\chi_c(4274)$ [36] $J^{PC}=1^{++}$ $m_0 = 4294 \pm 4^{+6}_{-3}$ $\Gamma_0 = 53 \pm 5 \pm 5$	$h_c(3P)$ $J^{PC}=1^{+-}$ $m_0 = 4318$ $\Gamma_0 = 75$ $\chi_{c1}(3P)$ $J^{PC}=1^{++}$ $m_0 = 4317$ $\Gamma_0 = 39$

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



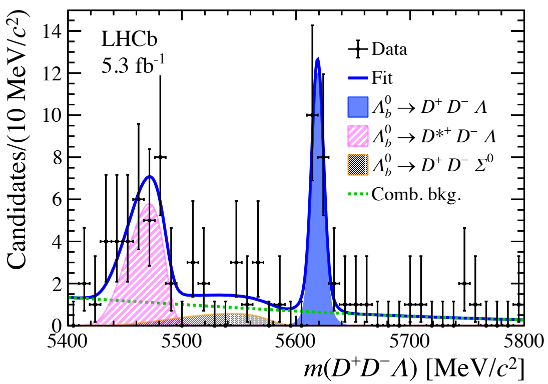
Observation of $\Lambda_b^0 \to D^+ D^- \Lambda$

[arXiv: 2403.03586]

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

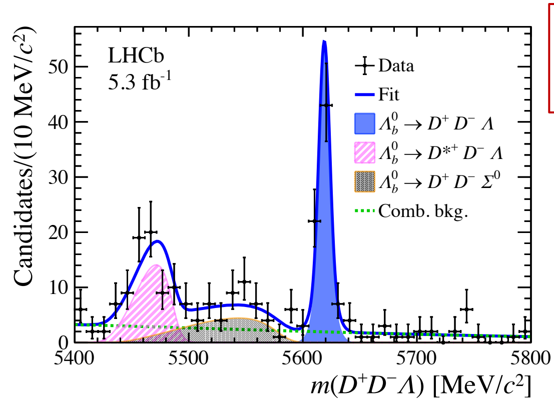
✓ Λ decay inside VELO

$N = 19 \pm 5$



✓ Λ decay outside VELO

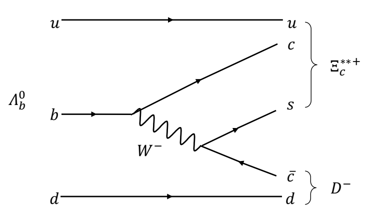
$N = 73 \pm 9$

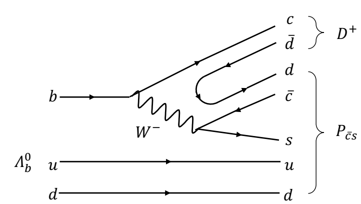


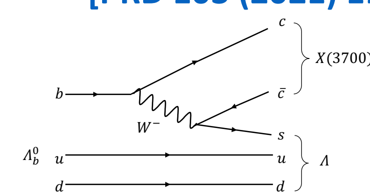
$$\frac{\sigma_{\Lambda_b^0}}{\sigma_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \to D^+ D^- \Lambda)}{\mathcal{B}(B^0 \to D^+ D^- K_S^0)} = 0.179 \pm 0.022 \pm 0.014$$

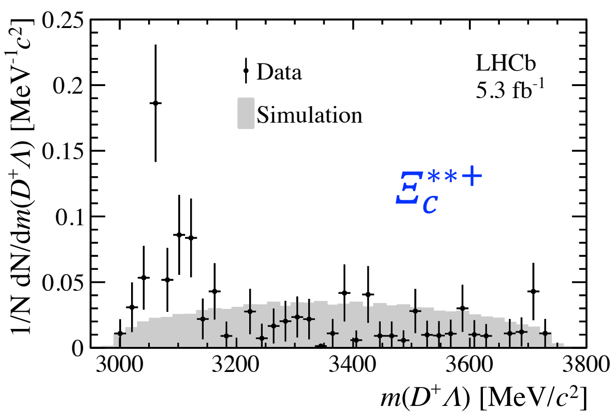
$$\mathcal{B}(\Lambda_b^0 \to D^+ D^- \Lambda) = (1.24 \pm 0.15 \pm 0.10 \pm 0.28 \pm 0.11) \times 10^{-4}$$

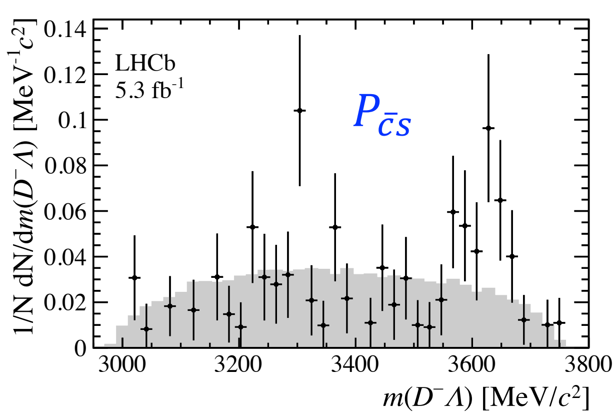
[PRD 103 (2021) 114013]

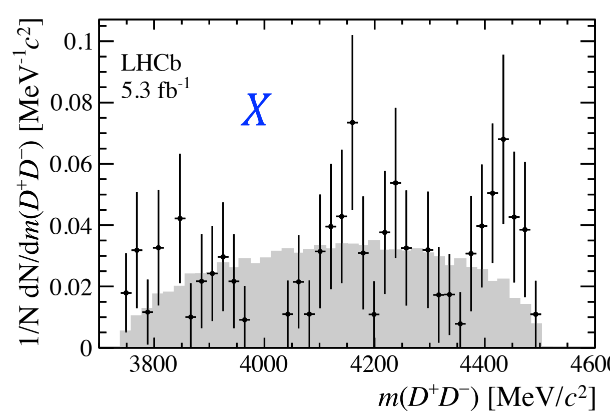






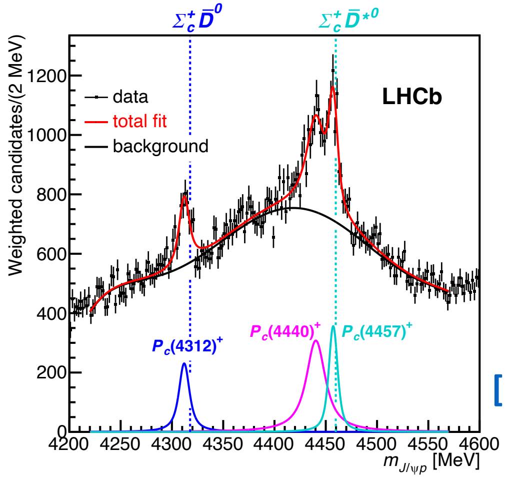






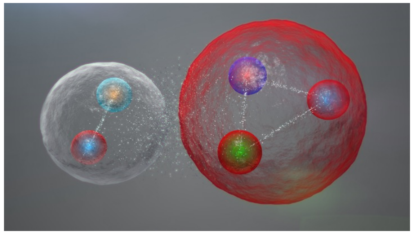
$\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$: motivation

- A step towards pentaquark search in $\Sigma_c^{(*)}\overline{D}$ system

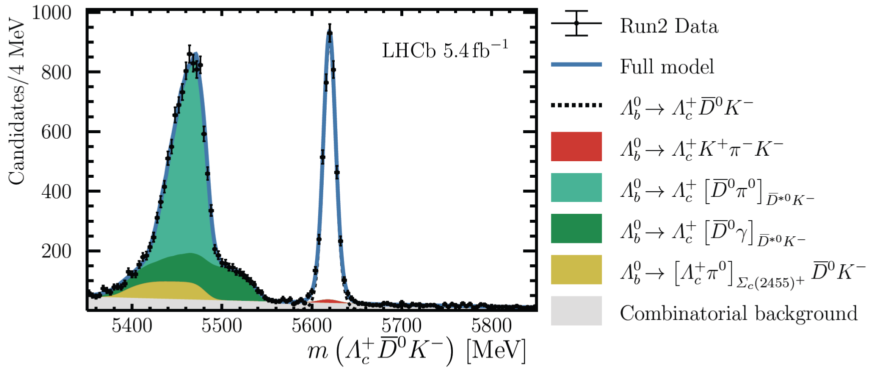


✓ Proximity of $\Sigma_c^+\overline{D}^0$ and $\Sigma_c^+\overline{D}^{*0}$ thresholds to the peaks suggests they play an important role in the dynamics

[PRL 122 (2019) 222001]



- $\mathcal{B}\left(\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-\right)$ measured relative to $\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-\right)$



[EPJC 84 (2024) 575]

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to J/\psi p K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-\right)} = 0.152^{+0.032}_{-0.028},$$

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to J/\psi p K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-\right)} = 0.049^{+0.011}_{-0.009},$$

*Fit fraction of P_c^+ in $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$

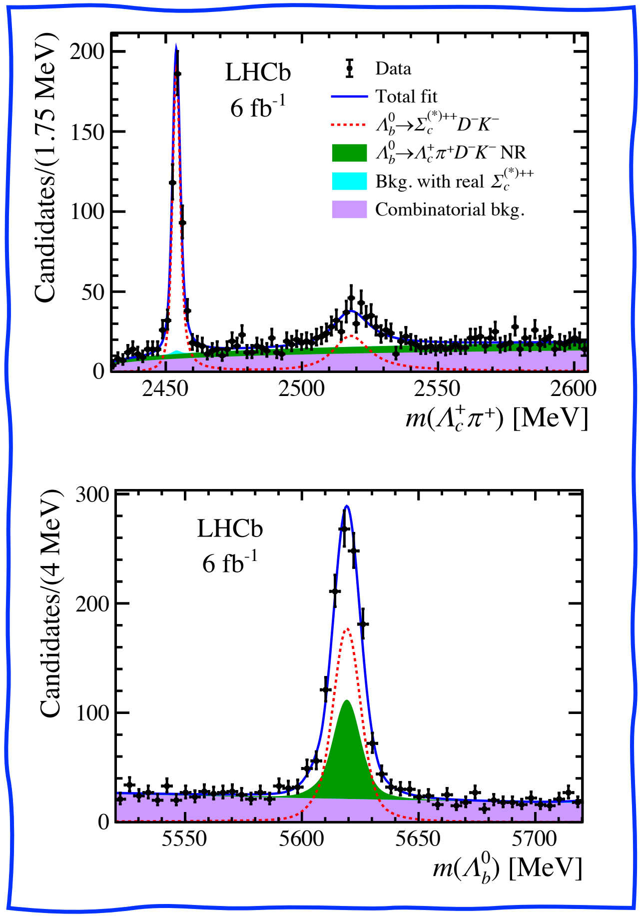
$$f_{\Lambda_c^+ \overline{D}^{(*)0}}(P_c^+) = f_{J/\psi p}(P_c^+) \cdot \frac{\mathcal{B}\left(\Lambda_b^0 \to J/\psi p K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-\right)} \cdot \frac{\mathcal{B}\left(P_c^+ \to \Lambda_c^+ \overline{D}^{(*)0}\right)}{\mathcal{B}\left(P_c^+ \to J/\psi p\right)}$$

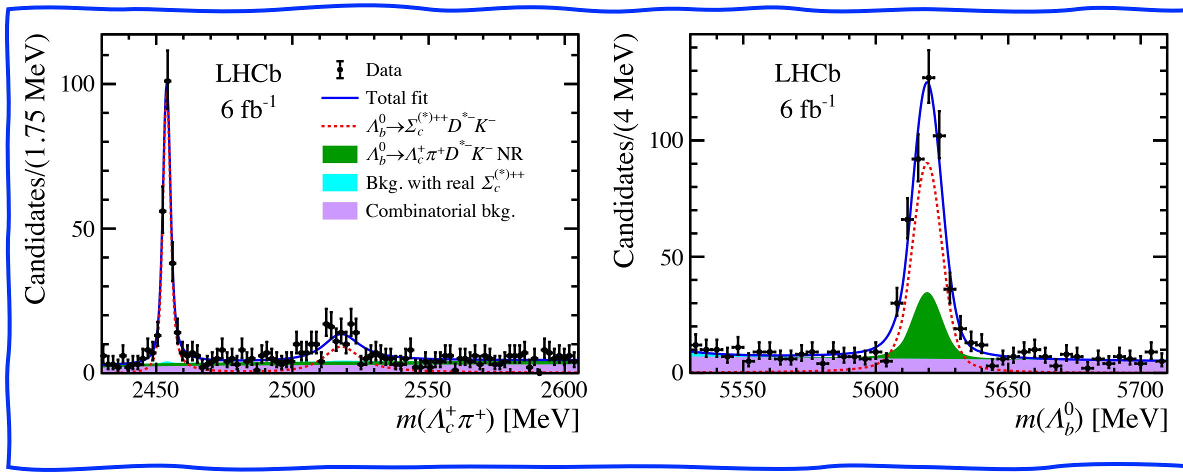
future study — measured — theoretically interesting

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

[arXiv: 2404.19510]

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





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

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

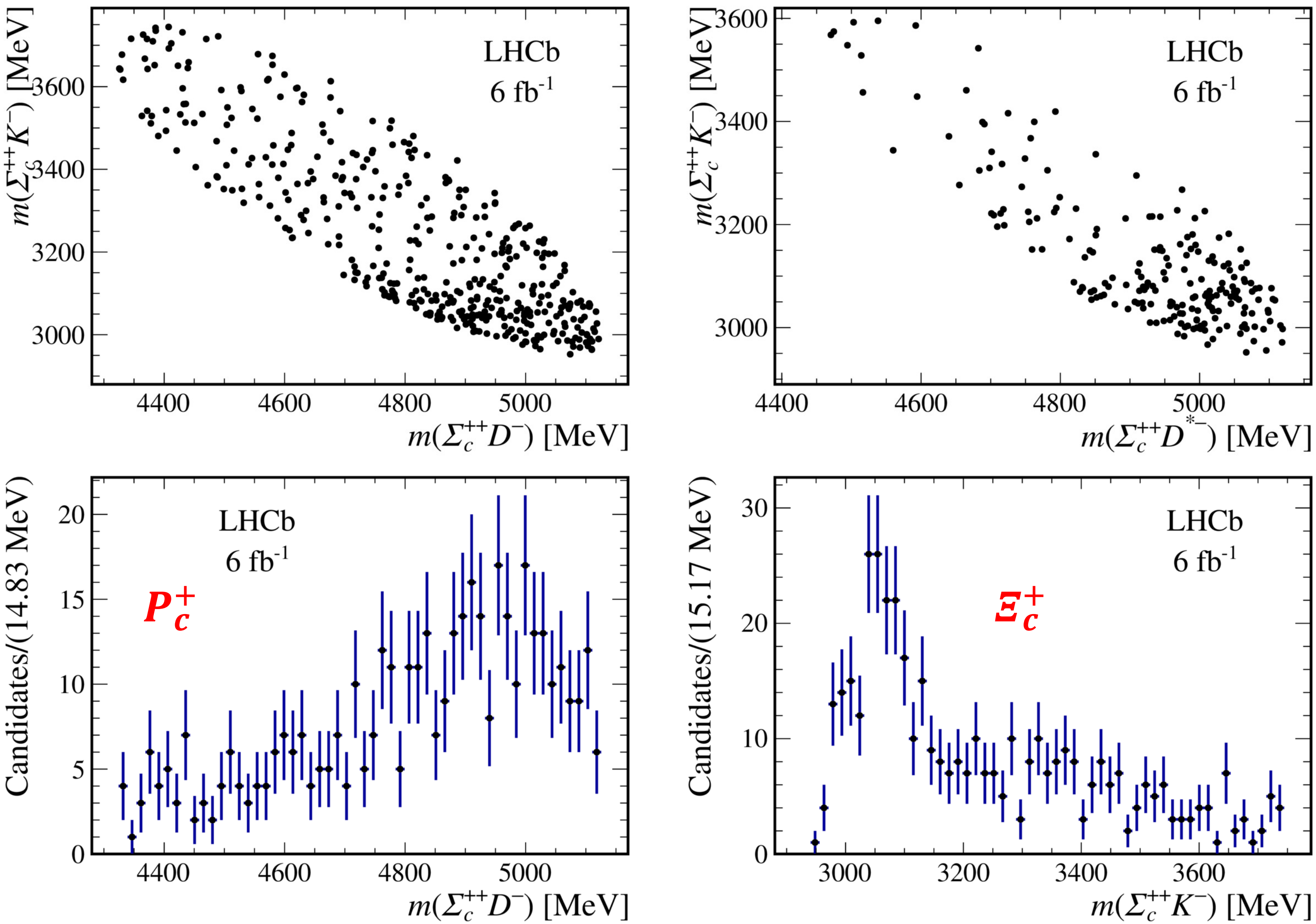
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)} = 2.261 \pm 0.202 \pm 0.129 \pm 0.046,$$

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

$\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$: intermediate states

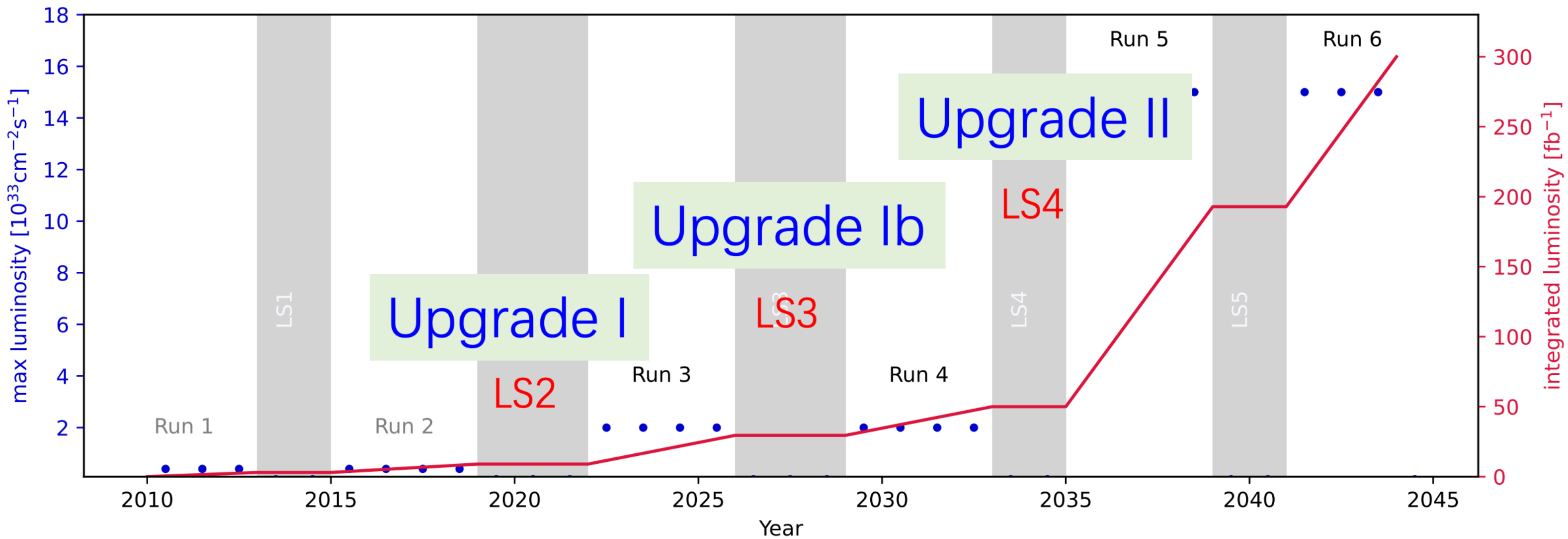
[arXiv: 2404.19510]

- ➢Larger dataset needed to draw a definitive conclusion



Summary and prospects

- LHCb keeps making important contributions to spectroscopy study
  - ✓ $B \to D\bar{D}h$: exotic candidates emerging from amplitude analysis; new decay modes with potential of exotic discovery being observed, e.g. $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$, $\Lambda_b^0 \to D^+ D^- \Lambda$
  - ✓ Looking further into $\chi_{c1}(3872)$
  - ✓ Ξ_b^- baryon lifetime measurement
- In Run 3, upgraded sub-detectors & software-only trigger system
  - ✓ trigger efficiency for fully hadronic modes largely improved



More data, more chances!

Back up