



Hadron spectroscopy from LHCb

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Outline

- Introduction
- Review of $B \rightarrow D\bar{D}h(h')$ studies
- Other quarkonium(like) studies
- Baryon spectroscopy
- Summary

Introduction

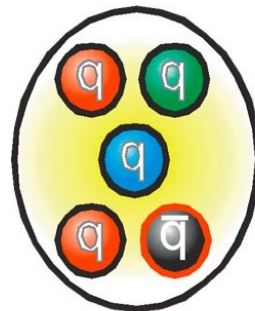
- Hadron spectroscopy provides opportunities to study QCD in the non-perturbative region
 - Extensive and precise spectroscopy combined with a thorough theoretical analysis, will add substantially to our knowledge of QCD
- Exotic hadrons provide unique probe to QCD
 - Predicted in quark model
 - Recent results show strong evidence for their existence



mesonic molecule ?



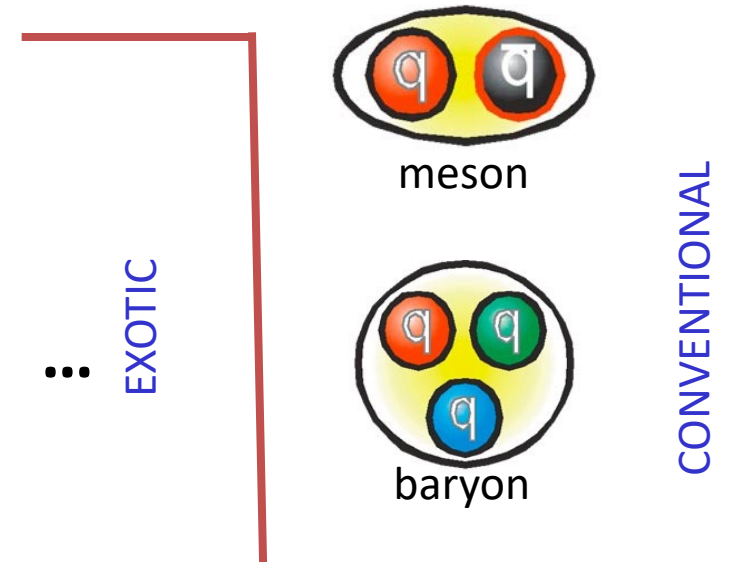
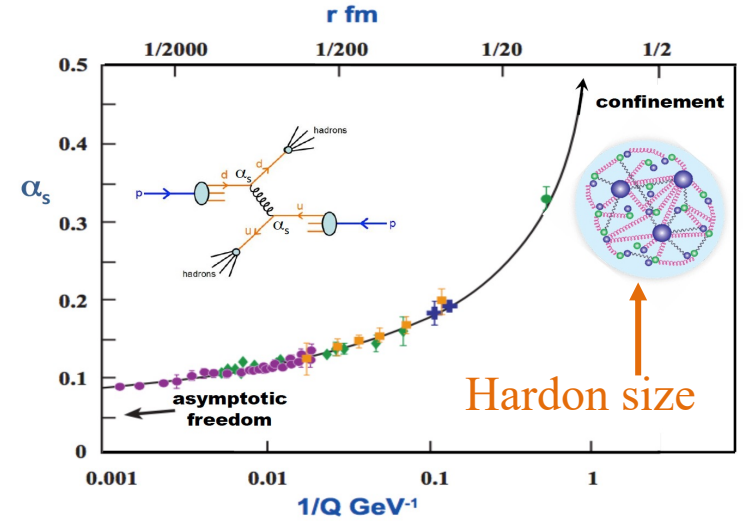
tetraquark ?



pentaquark ?

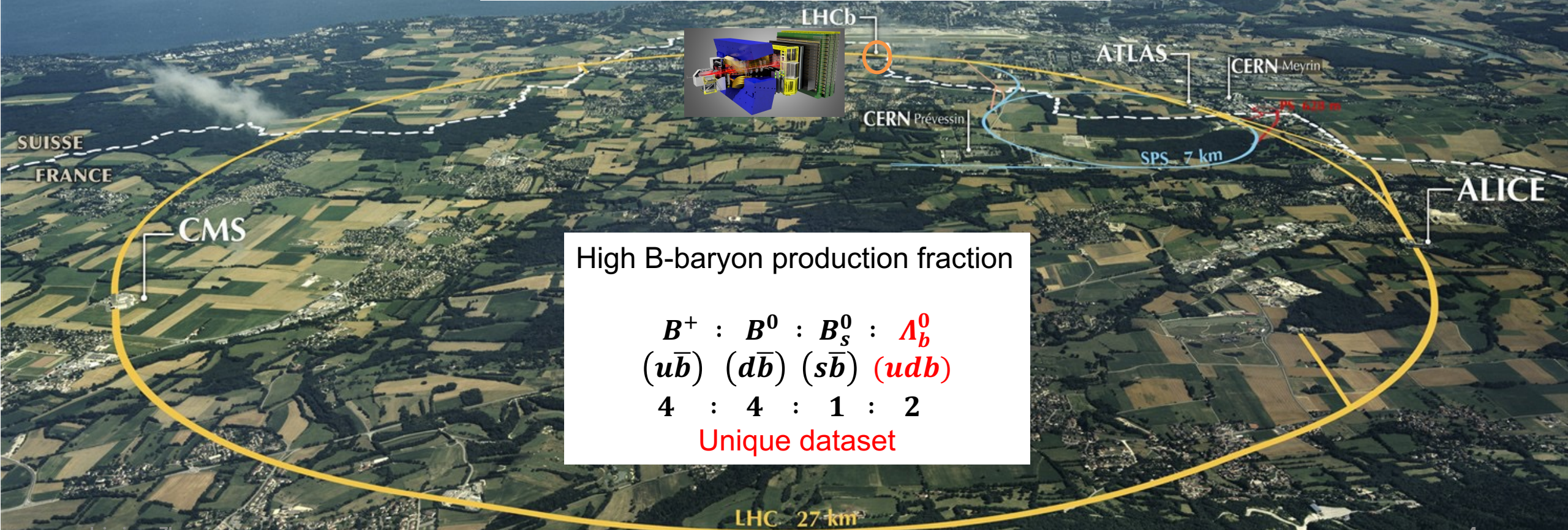


hybrid ?



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



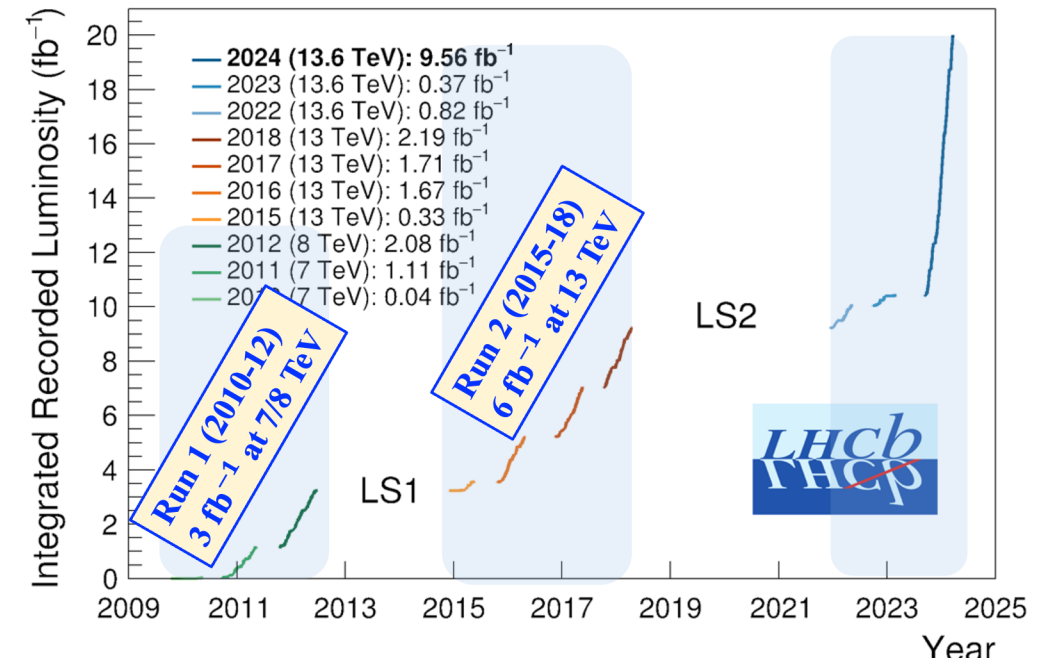
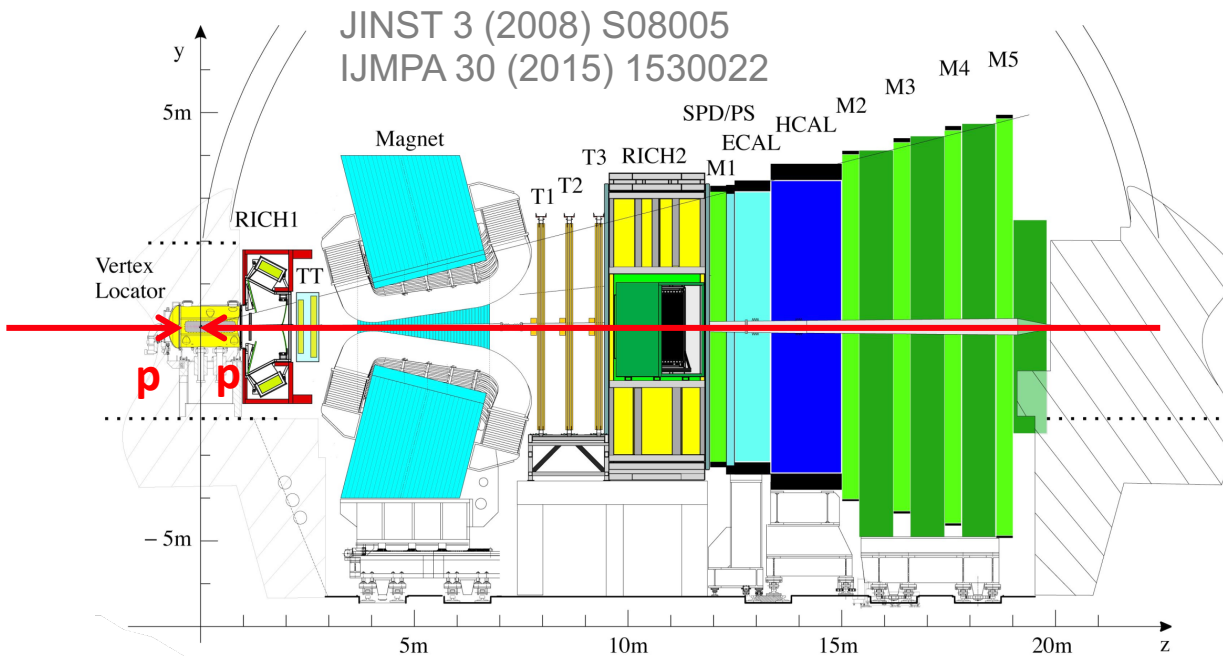
High B-baryon production fraction

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

The LHCb Experiment

- LHCb is a dedicated flavour physics experiment at the LHC
 - $>10^4 \times$ larger b production rate than the B factories @ Y(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

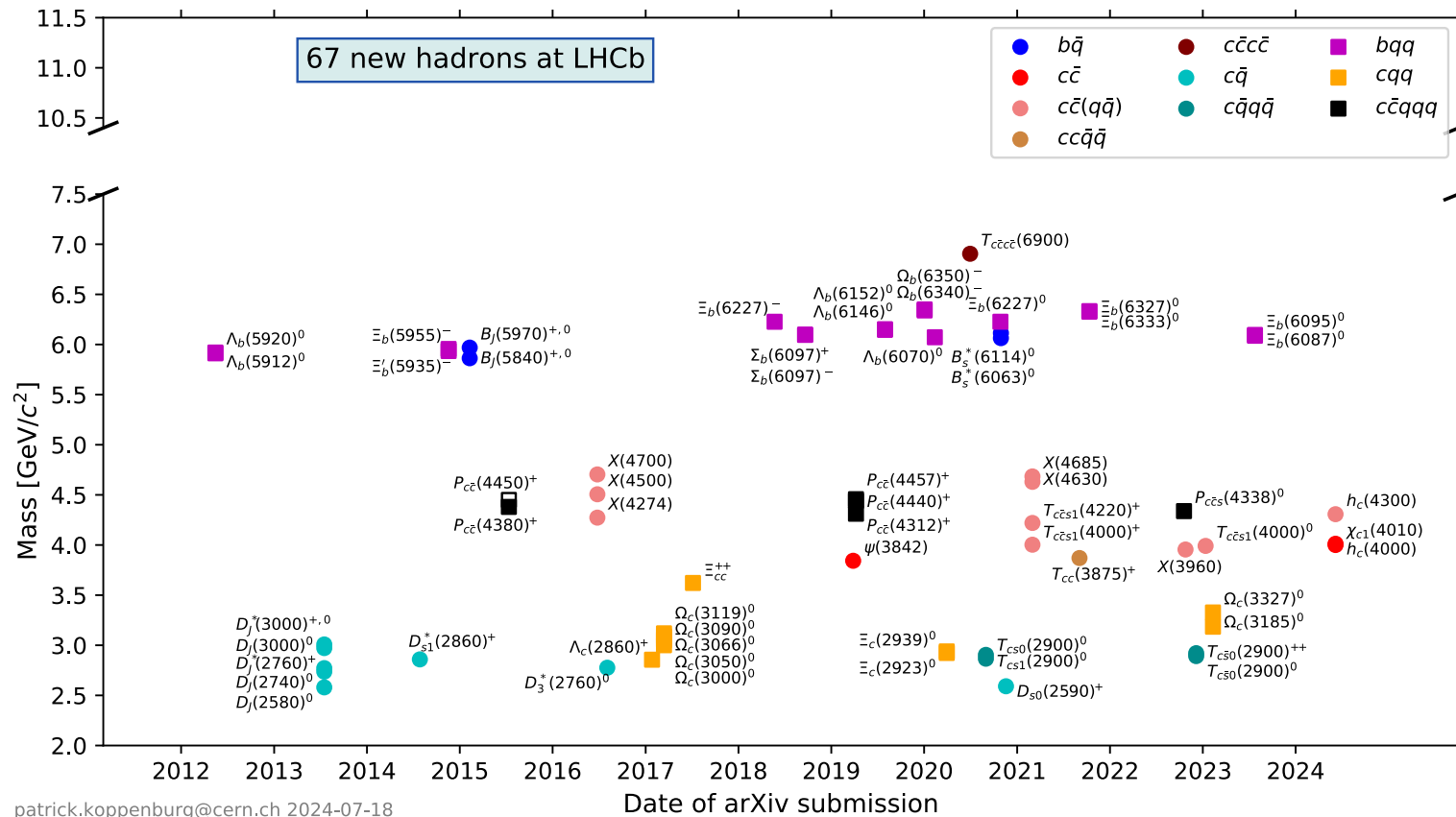
➤ All results based on full or part of run-1 and run-2 datasets



New particles in a glance

■ 67 new hadrons discovered by LHCb!

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



Exotic hadron naming convention: [PDG2024](#)

$$Z_c \rightarrow T_{c\bar{c}J}^{(*)} \quad Z_{cs} \rightarrow T_{c\bar{c}sJ}^{(*)} \quad P_c \rightarrow P_{c\bar{c}}$$

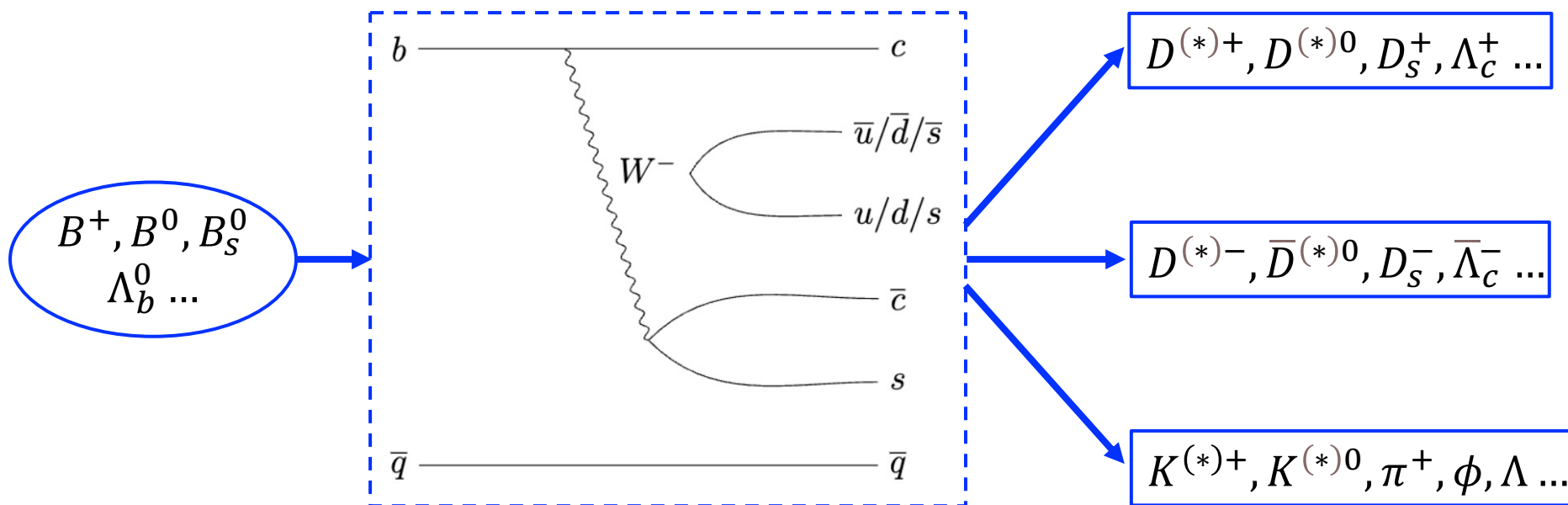
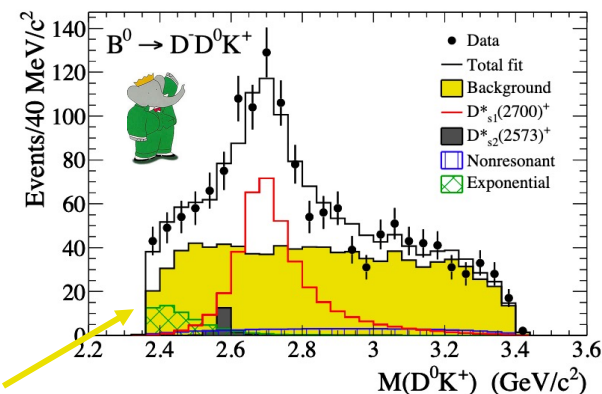
Normal and exotic hadrons in

$$B \rightarrow D\bar{D}h(h')$$

Why $B \rightarrow D\bar{D}h(h')$ decays

- Rich opportunities for spectroscopy study
 - **charmonium(-like) states in $D^{(*)}\bar{D}^{(*)}, \Lambda_c^+\bar{D}^{(*)}, \Lambda_c^+\bar{\Lambda}_c^-$...**
 - **excited $D^+, D^0, D_s^+, \Lambda_c^+$ states from $D^{(*)}h, \Lambda_c^+h$...**
 - **Open-flavour exotic states from $\bar{D}^{(*)}h, \bar{\Lambda}_c^-h$...**
- Previous Babar study show low signal and large background

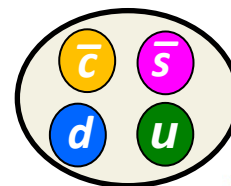
[Babar, PRD 91 (2015) 052002]



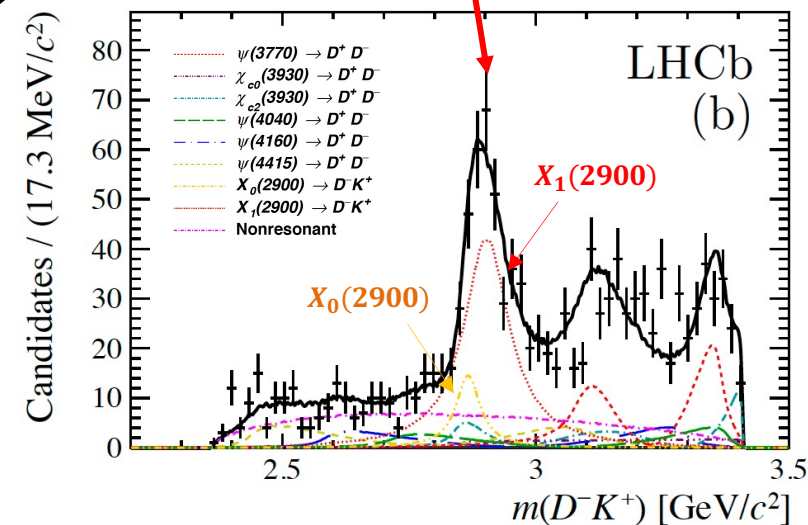
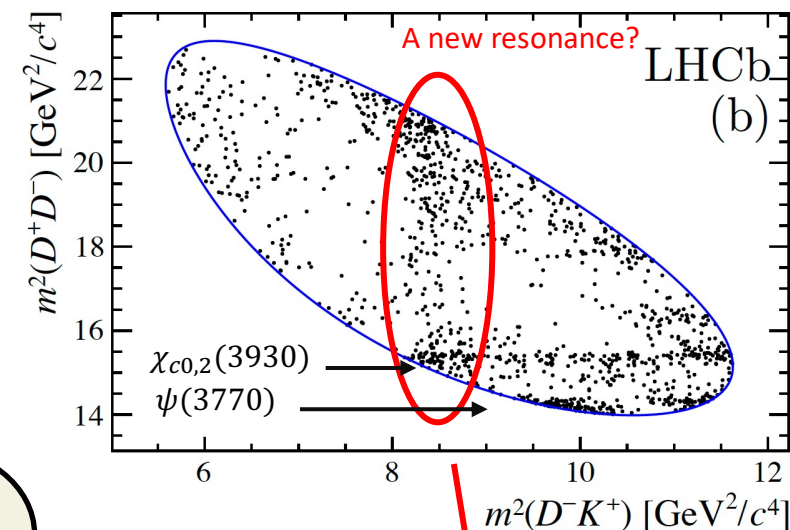
$B \rightarrow D\bar{D}h$ studies at LHCb

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

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

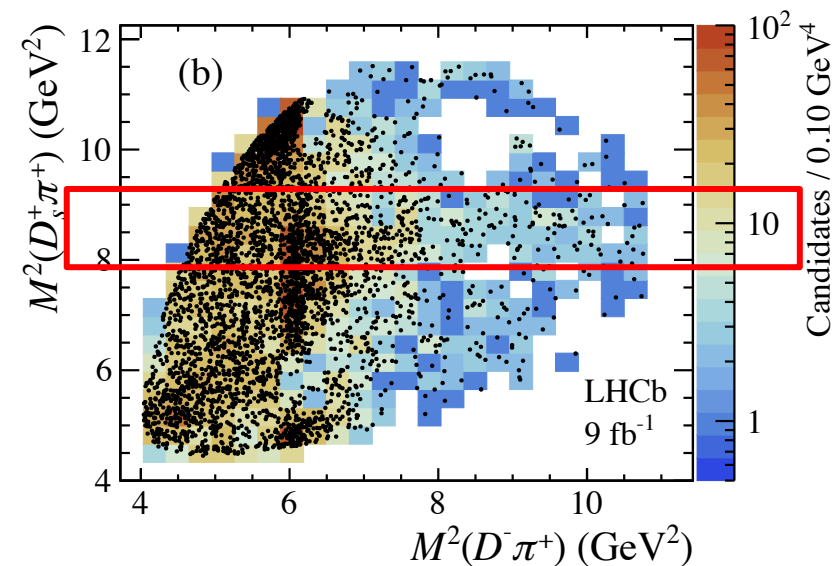
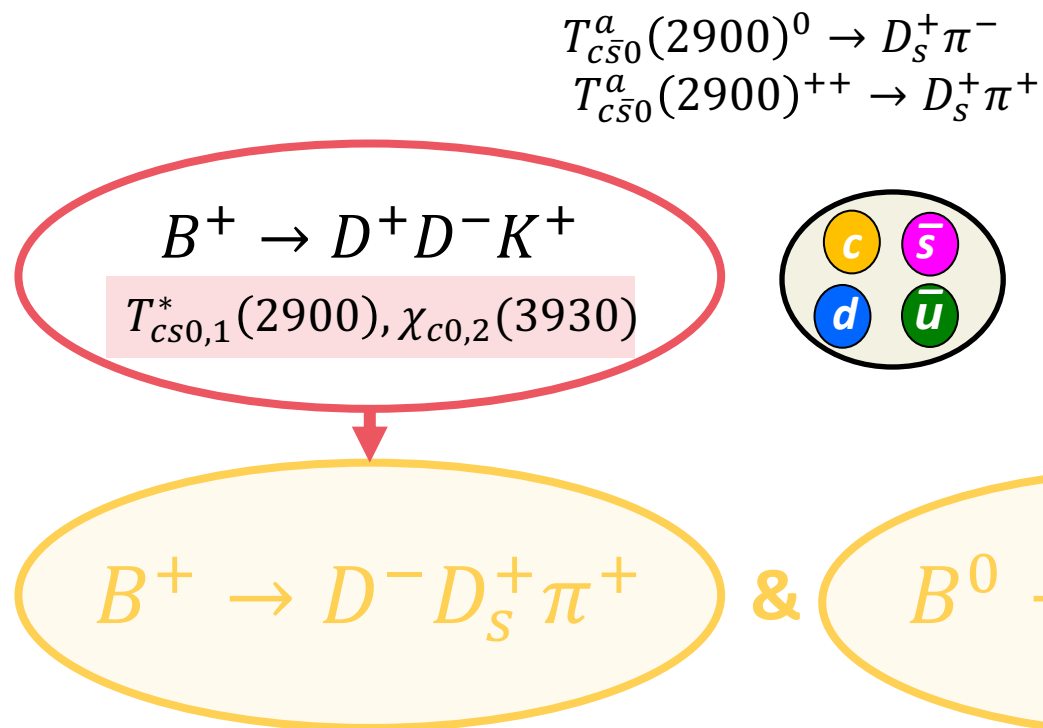


First discovery of **open-charm tetraquarks**
with four different flavors [$\bar{c}\bar{s}ud$]!



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

[PRL 131 (2023) 041902]



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

[PRL 131 (2023) 071901]

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

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

$$T_{cs0,1}^*(2900), \chi_{c0,2}(3930)$$

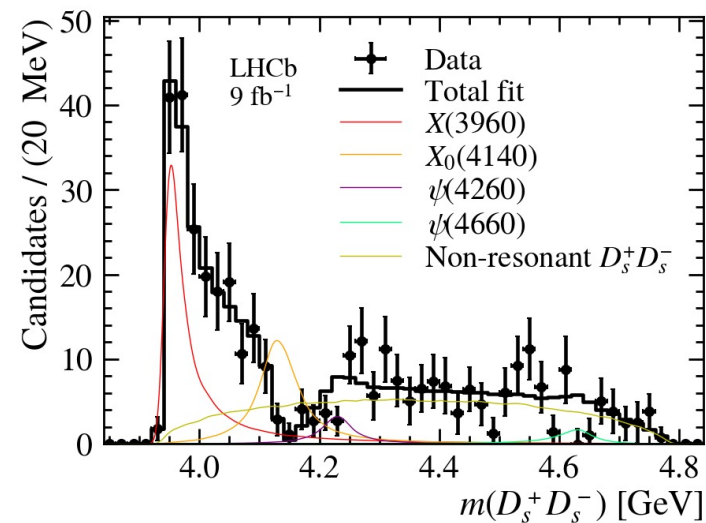
$$B^+ \rightarrow D^- D_s^+ \pi^+$$

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

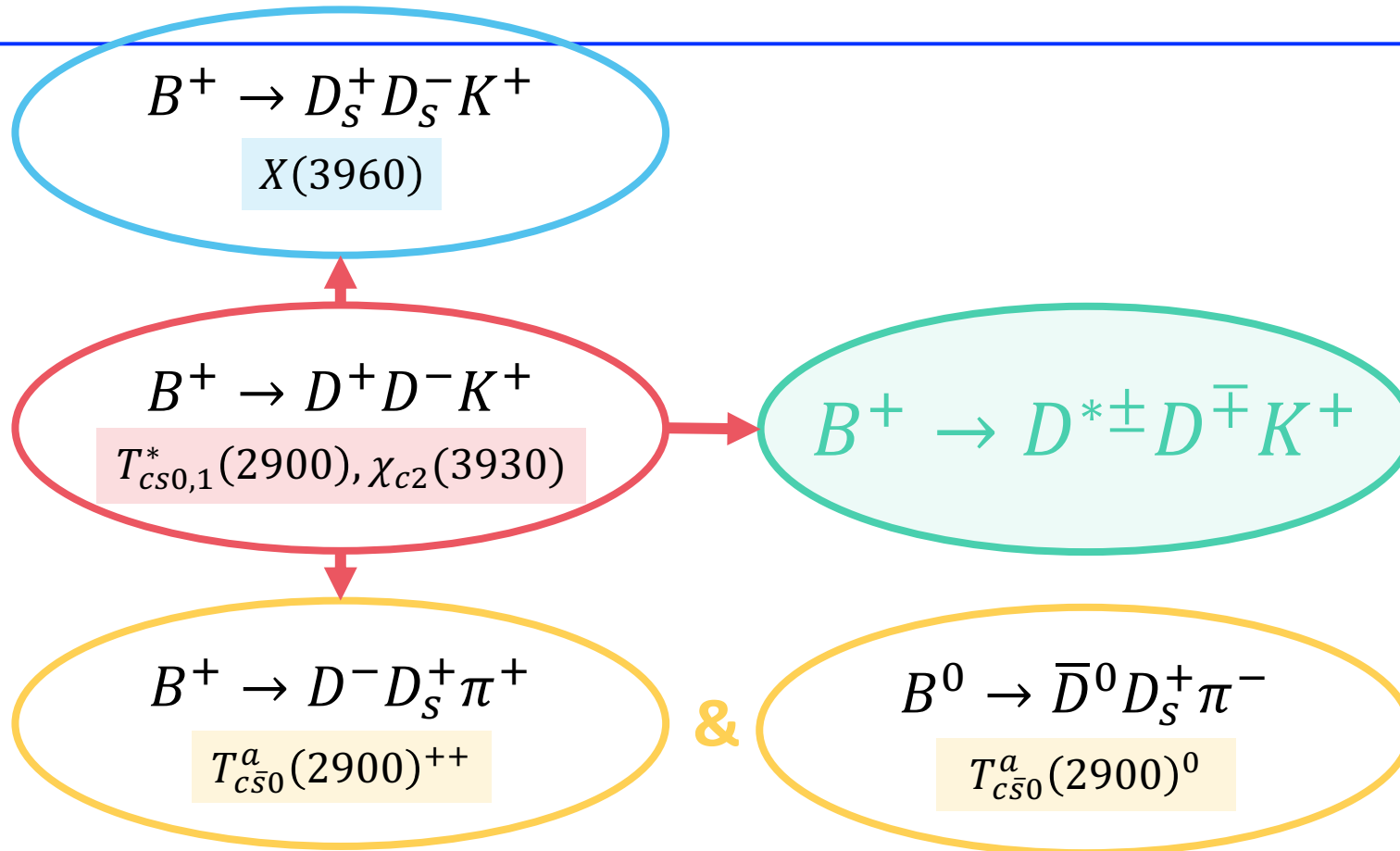
&

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

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



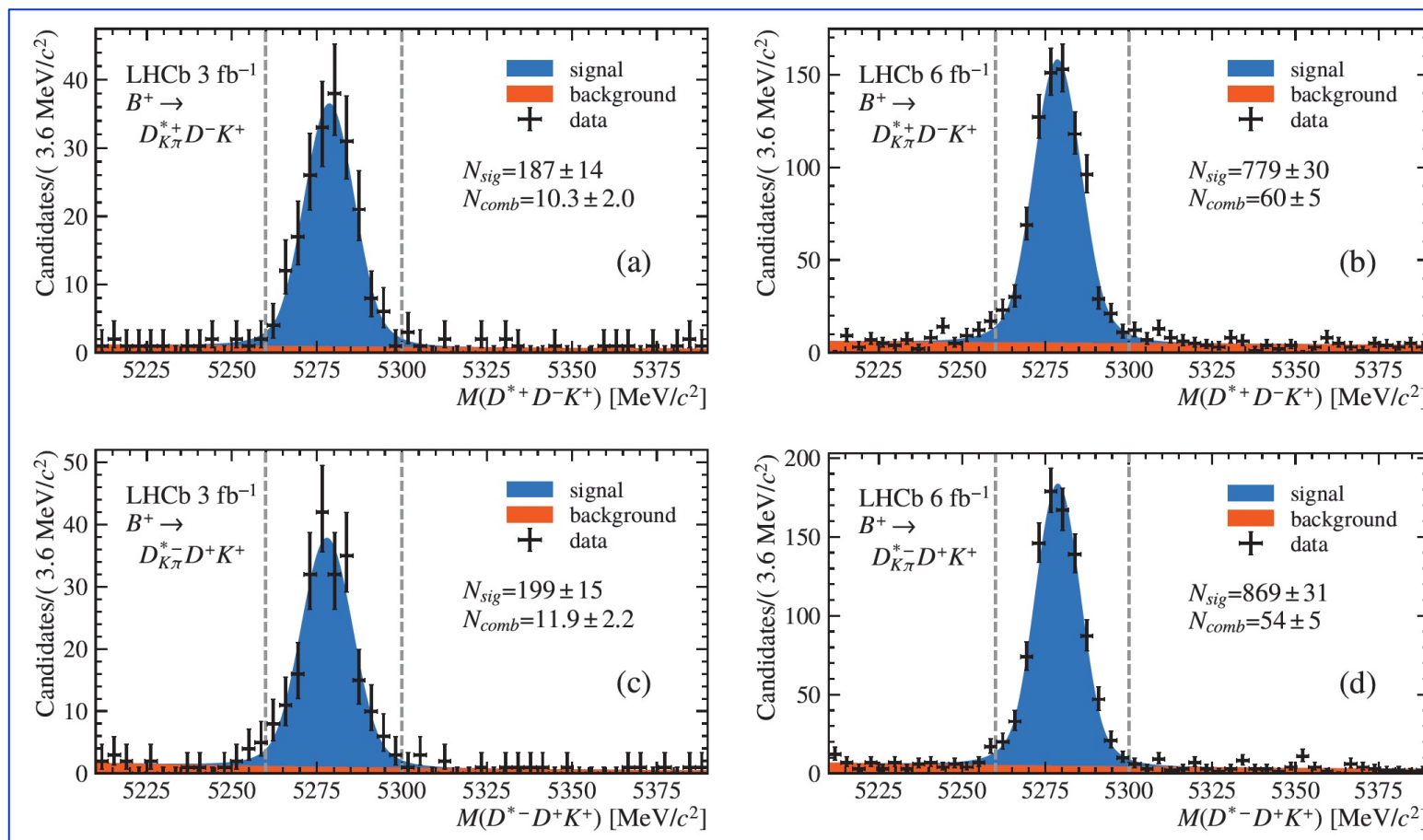
$B \rightarrow D\bar{D}h$ studies at LHCb



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

[PRL 133 (2024) 131902]

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



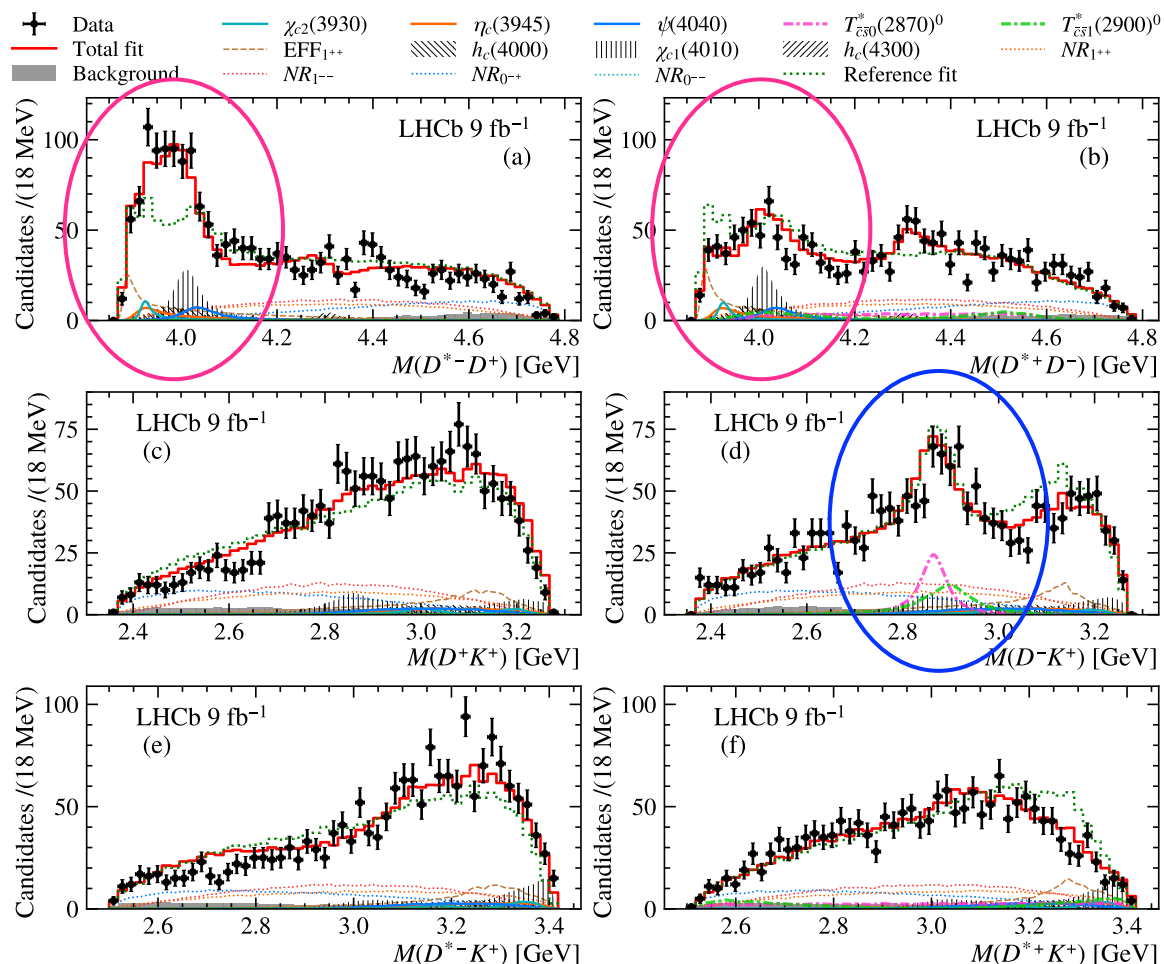
✓ $B^+ \rightarrow D^{*+} D^- K^+$: **966**

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

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

[PRL 133 (2024) 131902]

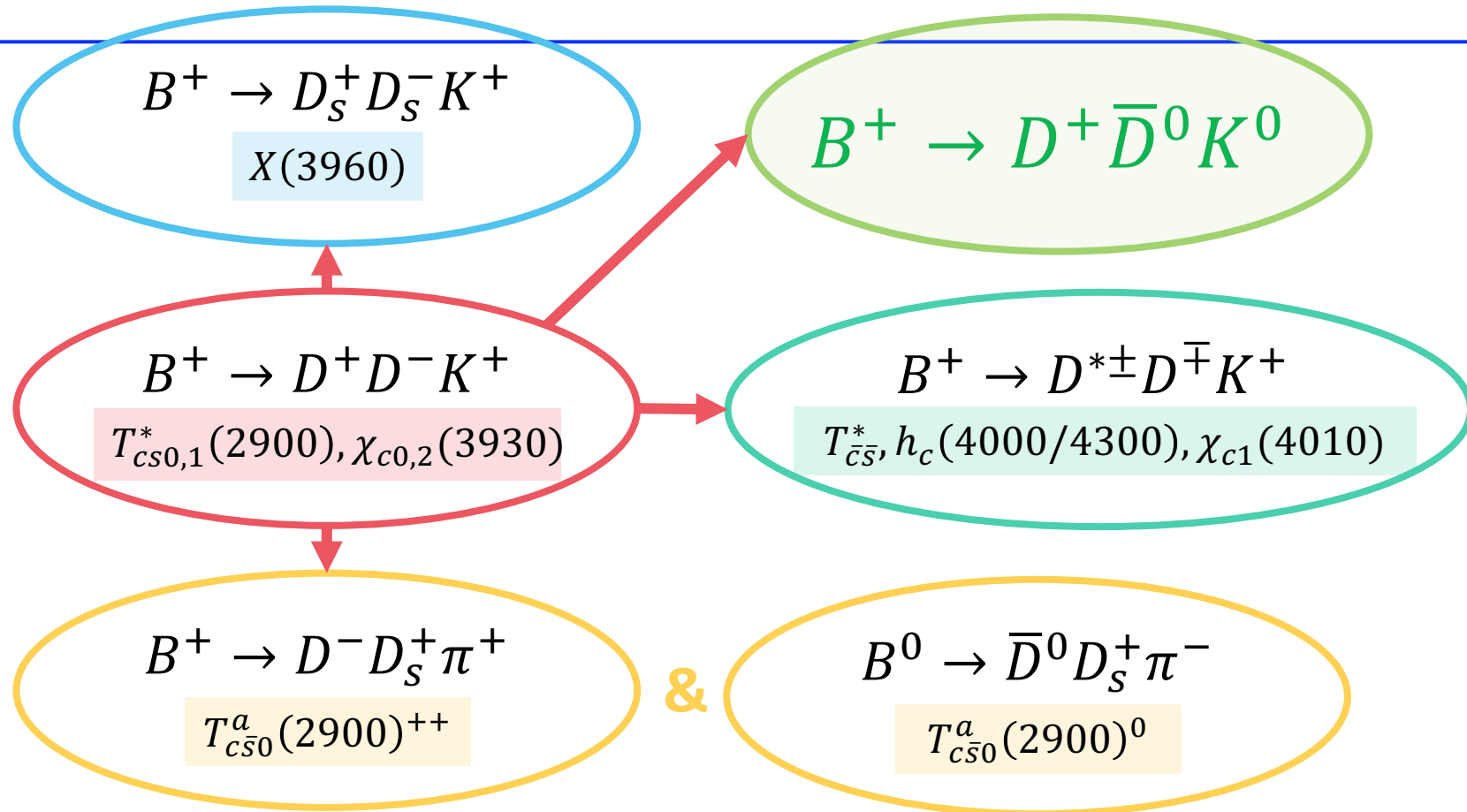
- Amplitudes of $R \rightarrow D^{*+} D^-$ and $R \rightarrow D^{*-} D^+$ linked by **C-parity**
 $\Rightarrow$ allowing determination of C-parities of R resonances



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 ⁺⁻
$T_{\bar{c}s0}^*(2870)^{0\dagger}$	0 ⁺
$T_{\bar{c}s1}^*(2900)^{0\dagger}$	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 ⁻⁺

- Four charmonium(-like) states are observed decaying to $D^* \bar{D}$ for $>6.1\sigma$
- At least the three of them are new
- J^{PC} for each state is determined for $>5.7\sigma$
- $T_{\bar{c}\bar{s}}^*$ states, seen in $B^+ \rightarrow D^+ D^- K^+$, are confirmed in $B^+ \rightarrow D^{*+} D^- K^+$ decays

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



$B^+ \rightarrow D^+ \bar{D}^0 K^0: T_{\bar{c}\bar{s}0}^*(2870)^0$ new decay mode

LHCb-PAPER-2024-040
in preparation

- Amplitude analysis of $B^+ \rightarrow D^+ \bar{D}^0 K_S^0$ finding $T_{\bar{c}\bar{s}0}^*(2870)^0$, but not $T_{\bar{c}\bar{s}1}^*(2900)^0$ to $D^0 K_S^0$

- $T_{cs0}^*(2870)^0$

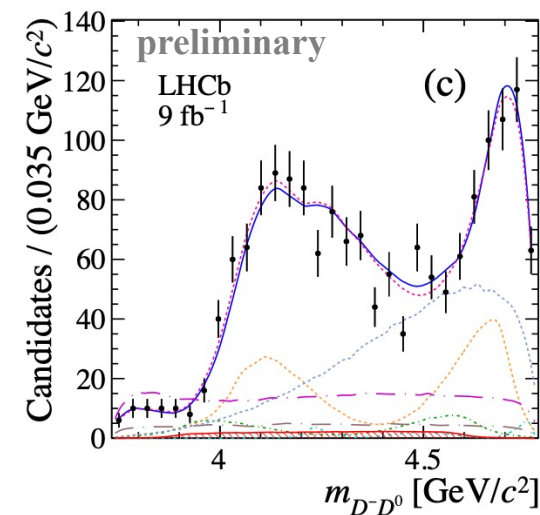
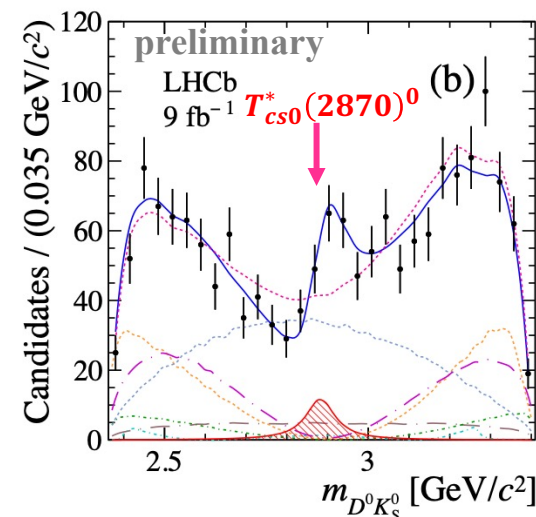
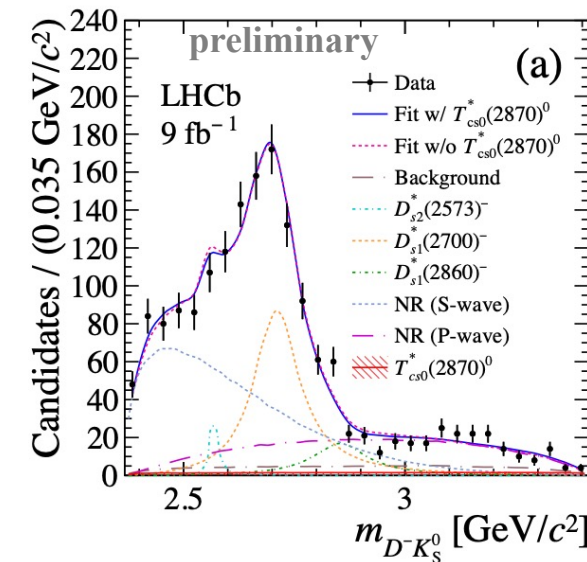
- Significance of 5.3σ
- $m = 2883 \pm 11 \pm 6 \text{ MeV}$
- $\Gamma = 87_{-47}^{+22} \pm 6 \text{ MeV}$

- Branching fraction ratio

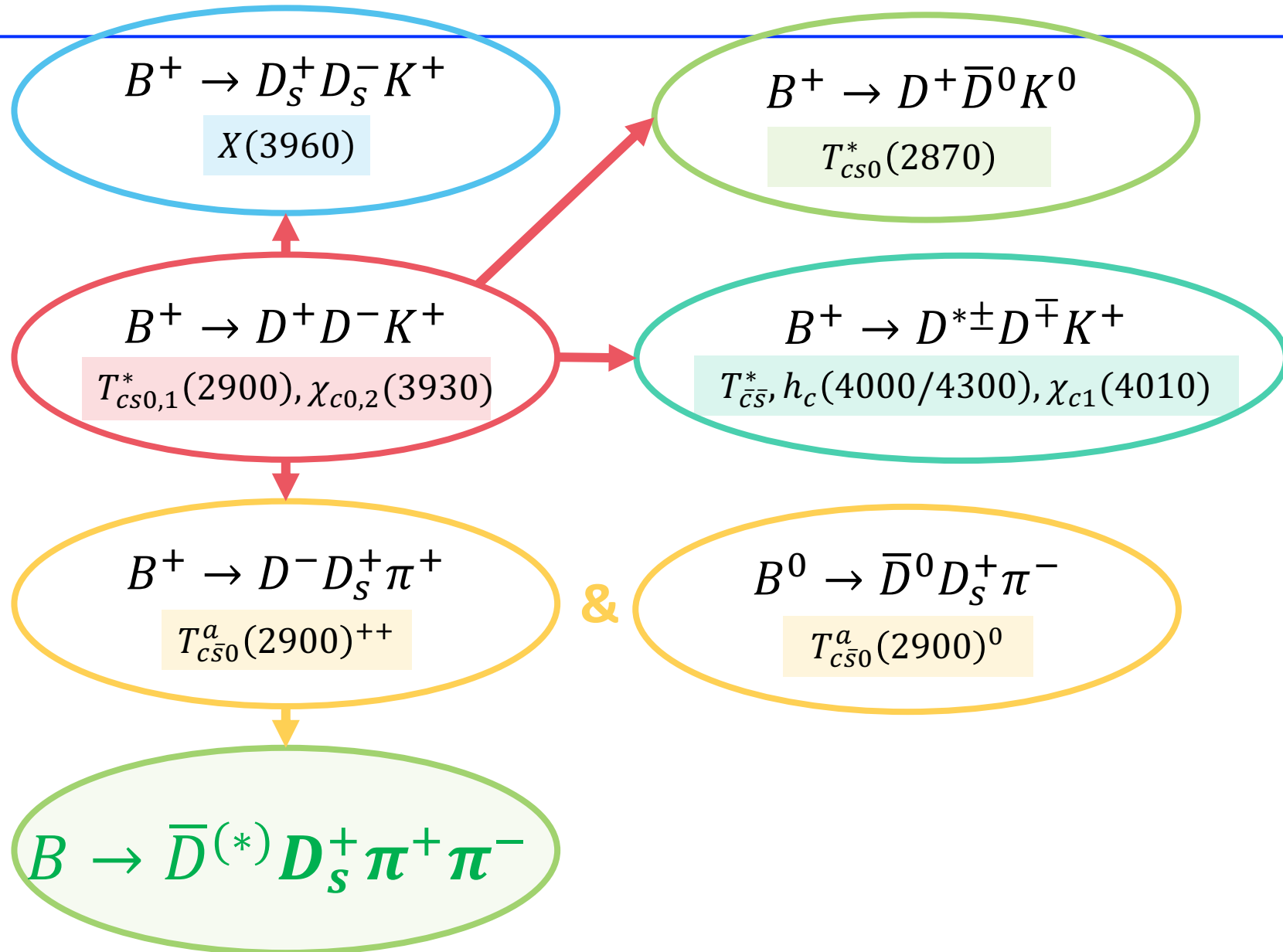
$$\frac{T_{cs0}^*(2870)^0 \rightarrow D^0 \bar{K}^0}{T_{cs0}^*(2870)^0 \rightarrow D^+ K^-} = 3.3 \pm 1.9$$

$$\frac{T_{cs1}^*(2900)^0 \rightarrow D^0 \bar{K}^0}{T_{cs1}^*(2900)^0 \rightarrow D^+ K^-} = 0.15 \pm 0.17$$

Isospin symmetry: two ratio should be 1



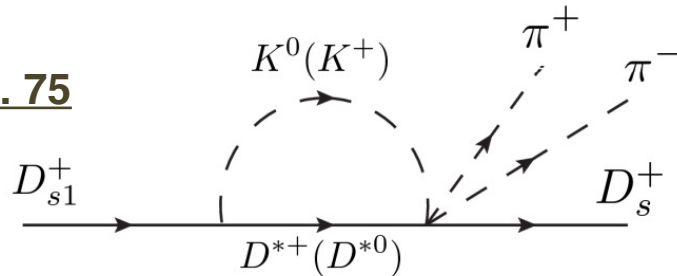
$B \rightarrow D\bar{D}h$ studies at LHCb



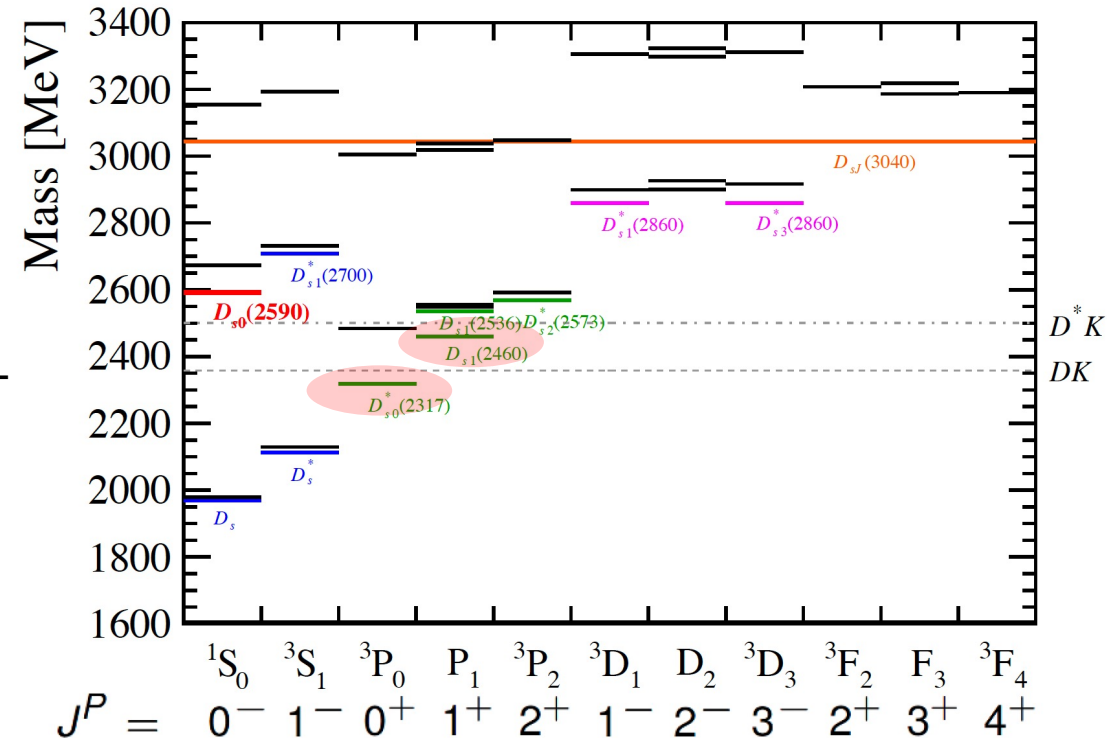
Study of $D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ decay

- $D_{s0}^*(2317)$ and $D_{s1}(2460)$ are very special
 - Masses ~ 100 MeV below expectation
 - Isospin-violating decay $D_s^{(*)+} \pi^0$ dominate
- Propose to study of $D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$
 - Double-bump lineshape in $m(\pi\pi)$ if $D_{s1}(2460)^+$ is a D^*K hadronic molecule

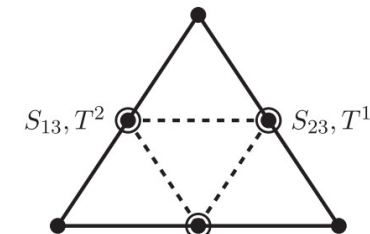
[Tang et. al.
Commun. Theor. Phys. 75
055203]



- $I=1$ partners of $D_{s0}^*(2317)$ are proposed, inspired by observation of $I=1$ tetraquark $T_{c\bar{s}}(2900)^{++/0} \rightarrow D_s^+ \pi^\pm$ [PRL 131 (2023) 041902]



$S_{33}(2335 \pm 100) \rightarrow \bar{D}^0 K^0, K^+ K^0 \pi^-$ (weak decay)



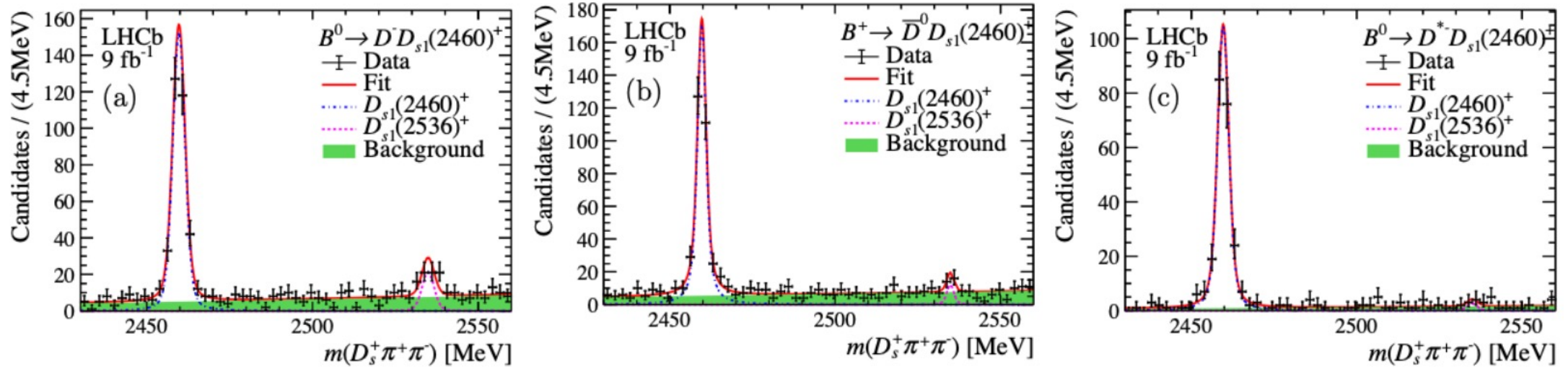
$S_{11}(2367 \pm 10) \rightarrow \bar{D}_s^- \pi^-$ or $\bar{D}^- K^-$ $D_{s0}^*(2317)$ + second state $S_{22}(2367 \pm 10) \rightarrow \bar{D}_s^- \pi^+$ or $\bar{D}^0 \bar{K}^0$

[L. Maiani et. al.
Phys. Rev. D 110,
034014]

Study of $D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ decay

[arXiv:2411.03399]

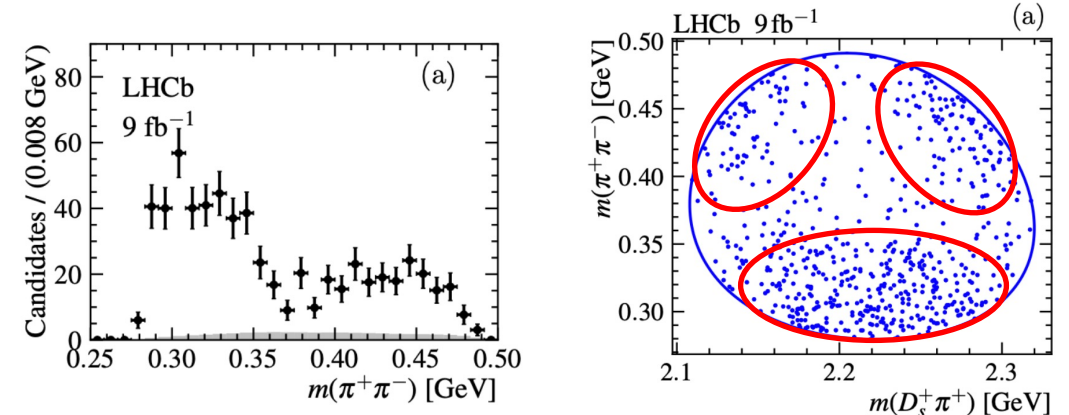
- ~ 800 $D_{s1}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$ decays from three $B \rightarrow D_{s1}(2460)^+ \bar{D}^{(*)}$ decays



- Double-bump structure in $m(\pi\pi)$

- Amplitude analysis performed

- $f_0(500) + f_0(980)$ and $\pi\pi$ K-matrix cannot describe the data well
- The model in paper [Tang *et. al.*] also cannot describe the data well



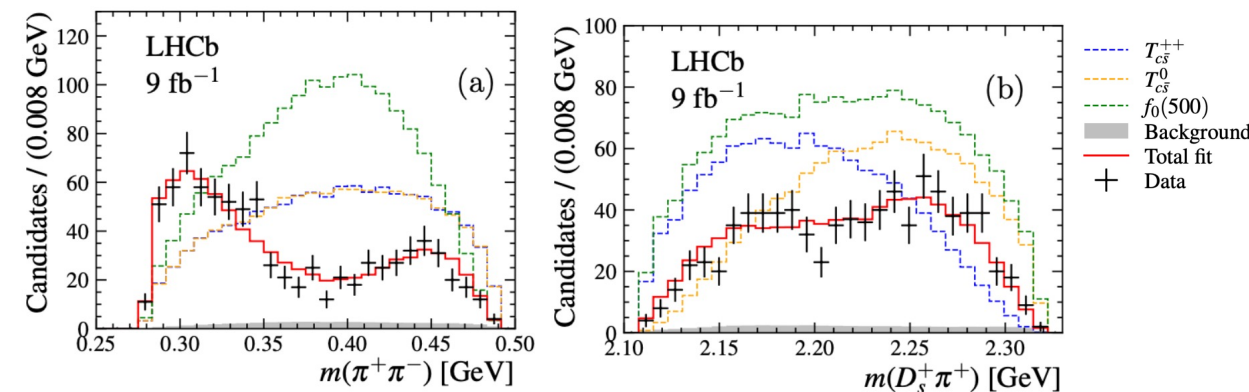
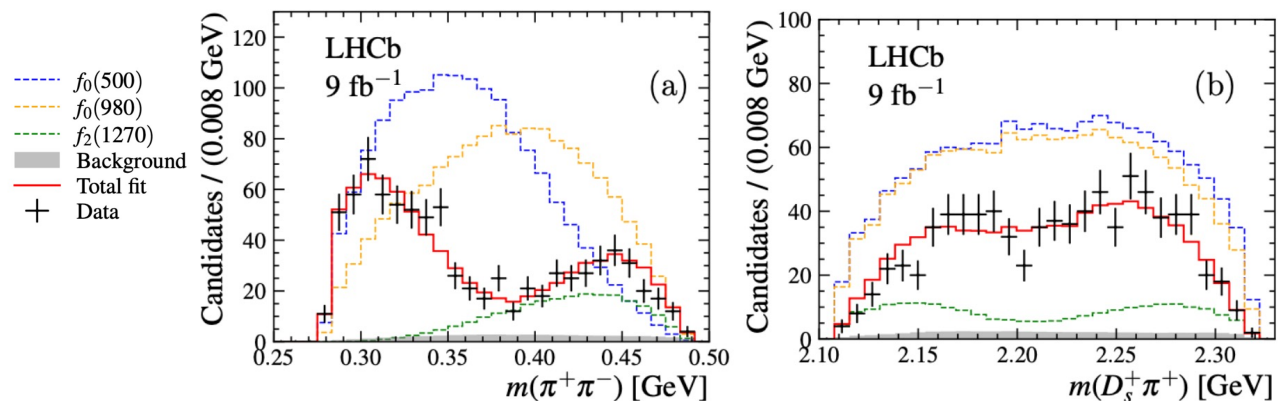
Two resonance models can fit the data well [arXiv:2411.03399]

- $f_0(500) + f_0(980) + f_2(1270)$
 - Large contribution from $f_0(980)$ and $f_2(1270)$ above PHSP of $m(\pi\pi)$
 - This model cannot be rejected, but **implausible**

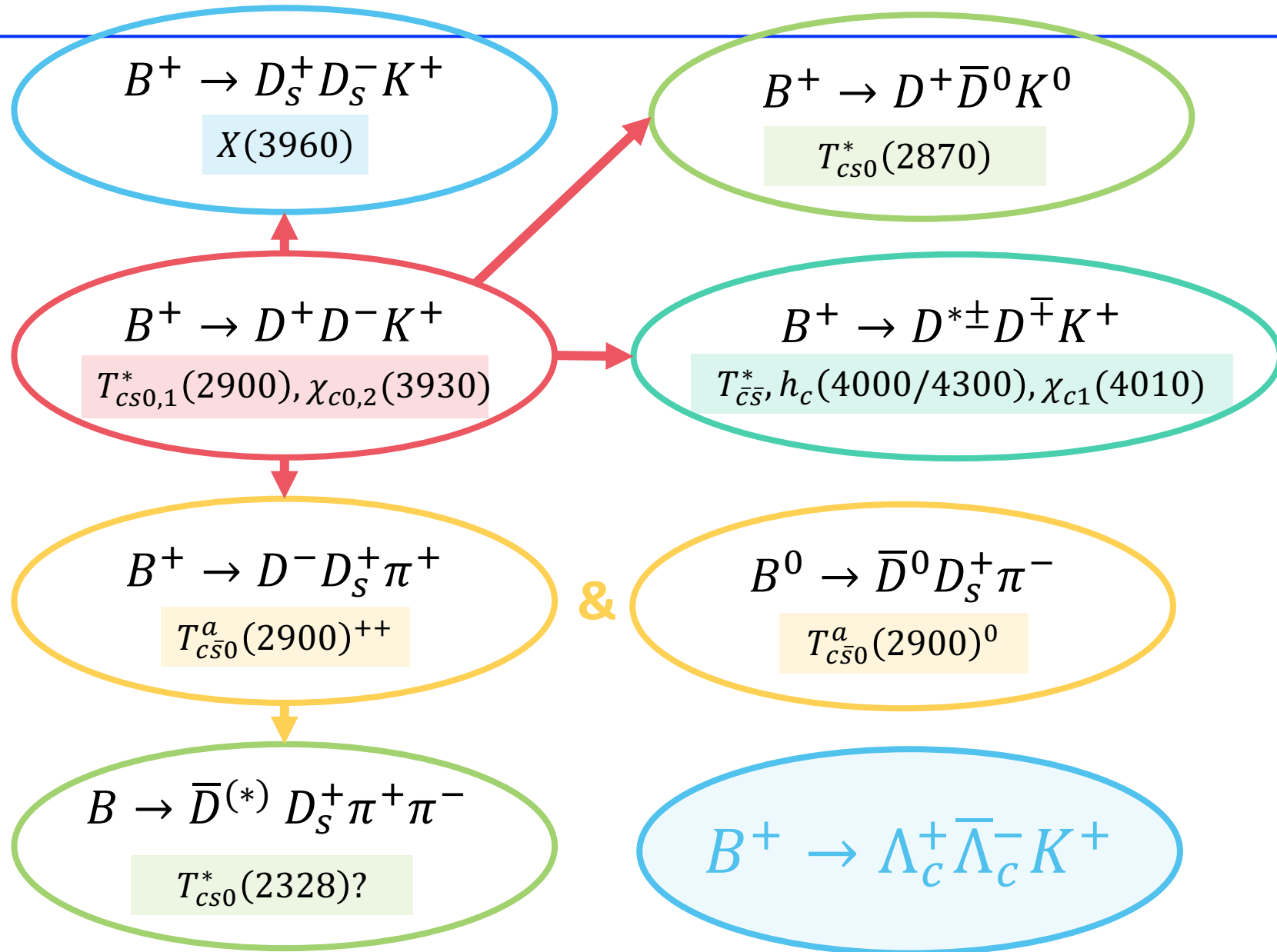
Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$376 \pm 9 \pm 16$	$175 \pm 23 \pm 16$	$197 \pm 35 \pm 23$
$f_0(980)$	945.5	167	$187 \pm 38 \pm 43$
$f_2(1270)$	1275.4	186.6	$29 \pm 2 \pm 1$

- $f_0(500) + T_{c\bar{s}}^{++} + T_{c\bar{s}}^0$ (new exotics)

Resonance	Mass (MeV)	Width (MeV)	FF (%)
$f_0(500)$	$472 \pm 32 \pm 19$	$226 \pm 24 \pm 18$	$237^{+51}_{-43} \pm 42$
$T_{c\bar{s}}$	$2328 \pm 12 \pm 12$	$96 \pm 16^{+170}_{-23}$	$151^{+31}_{-33} \pm 25$



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



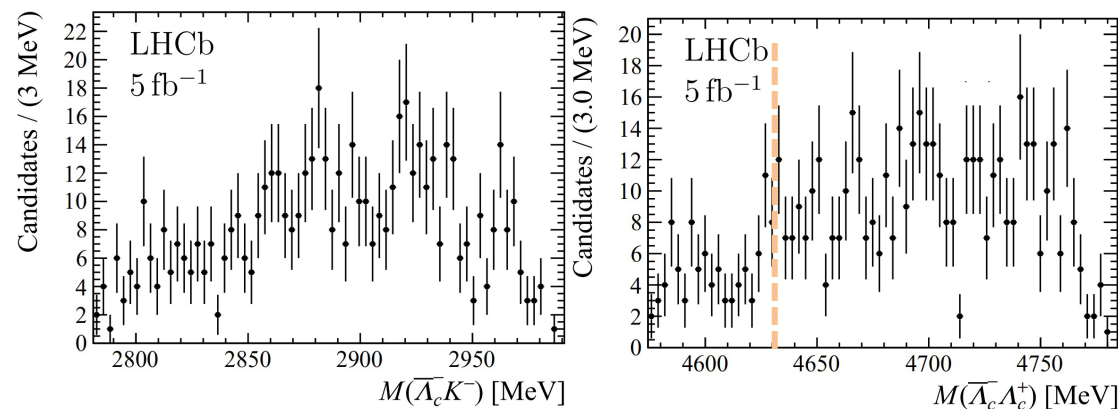
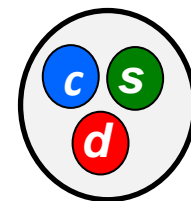
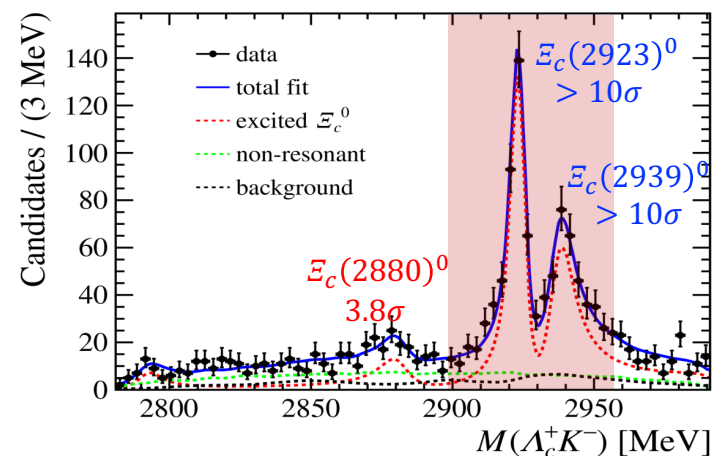
The $B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^-$ decay

[PRD 108 (2023) 012020]

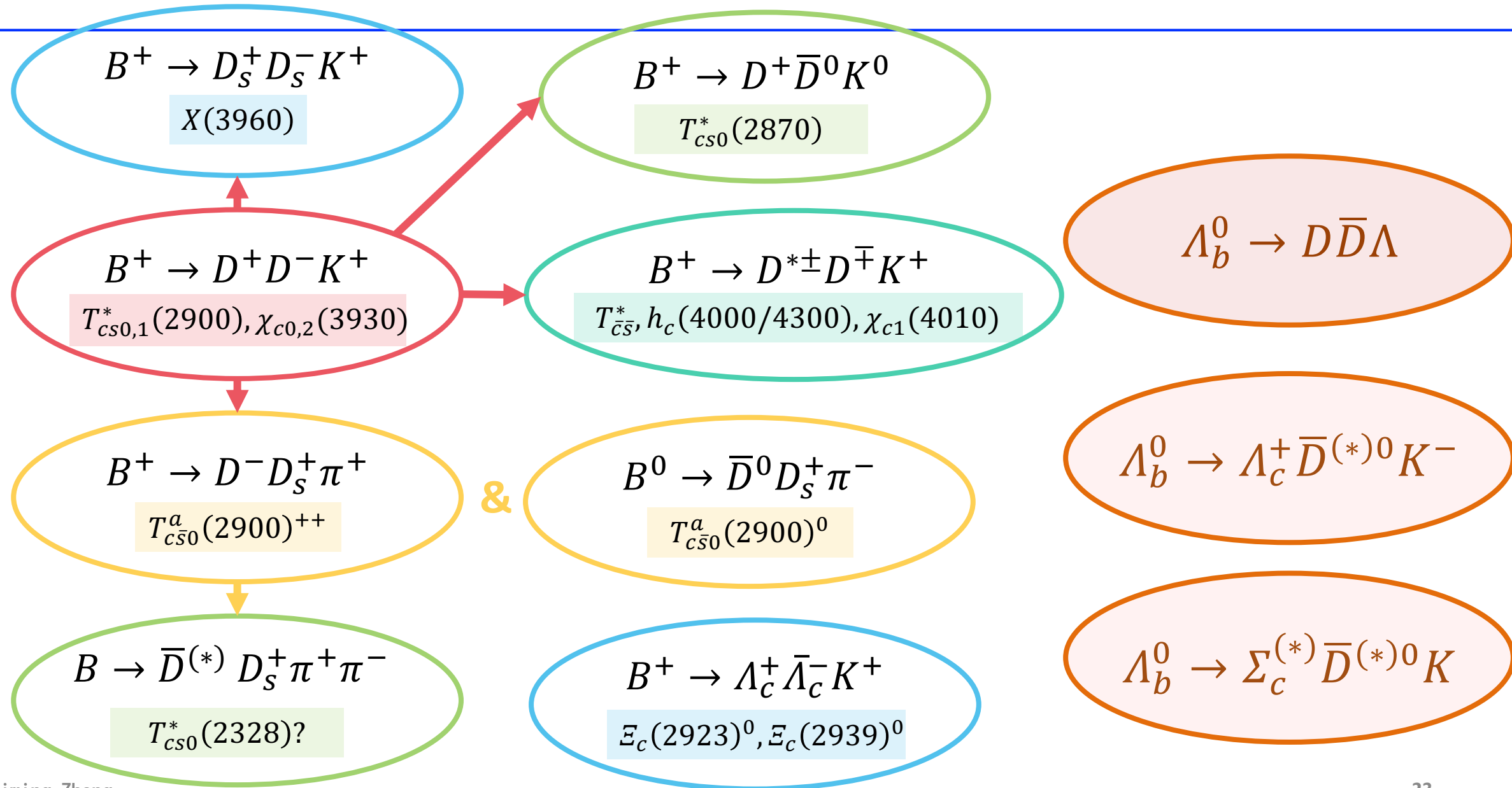
- Interesting for conventional & exotic studies
 - $\Xi_c^{0**} \rightarrow \Lambda_c^+ K^-$; exotic hadrons in $\Lambda_c^+ \bar{\Lambda}_c^-$ and $\bar{\Lambda}_c^- K^-$?
- High-purity sample, with $N_{\text{sig}} = 1365 \pm 42$
- $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ are confirmed
- Evidence of a new $\Xi_c(2880)^0$

State	Mass (MeV)	Width (MeV)
$\Xi_c(2880)^0$	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.2 \pm 5.8$
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$

- No significant hint for exotic hadrons in $\Lambda_c^+ \bar{\Lambda}_c^-$ or $\bar{\Lambda}_c^- K^-$ mass spectra

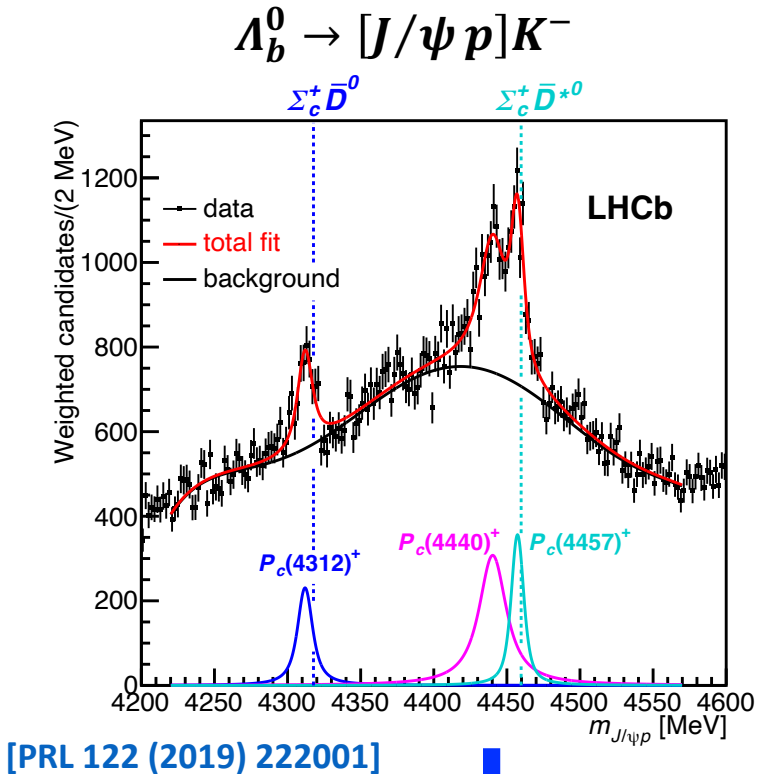


$B \rightarrow D\bar{D}h$ studies at LHCb



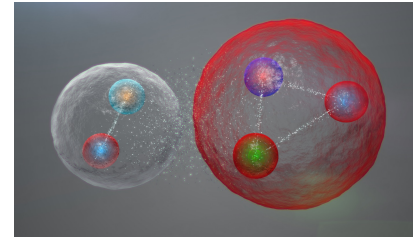
Pentaquark study

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



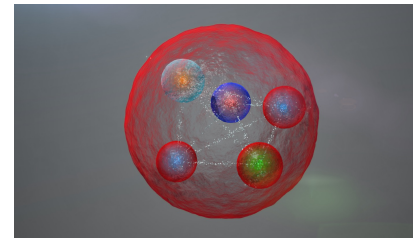
Proximity of $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$ thresholds to the peaks suggests they play an important role in the dynamics

Hadron molecule



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

Compact multiquark



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

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

[EPJC 84 (2024) 575]

- 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

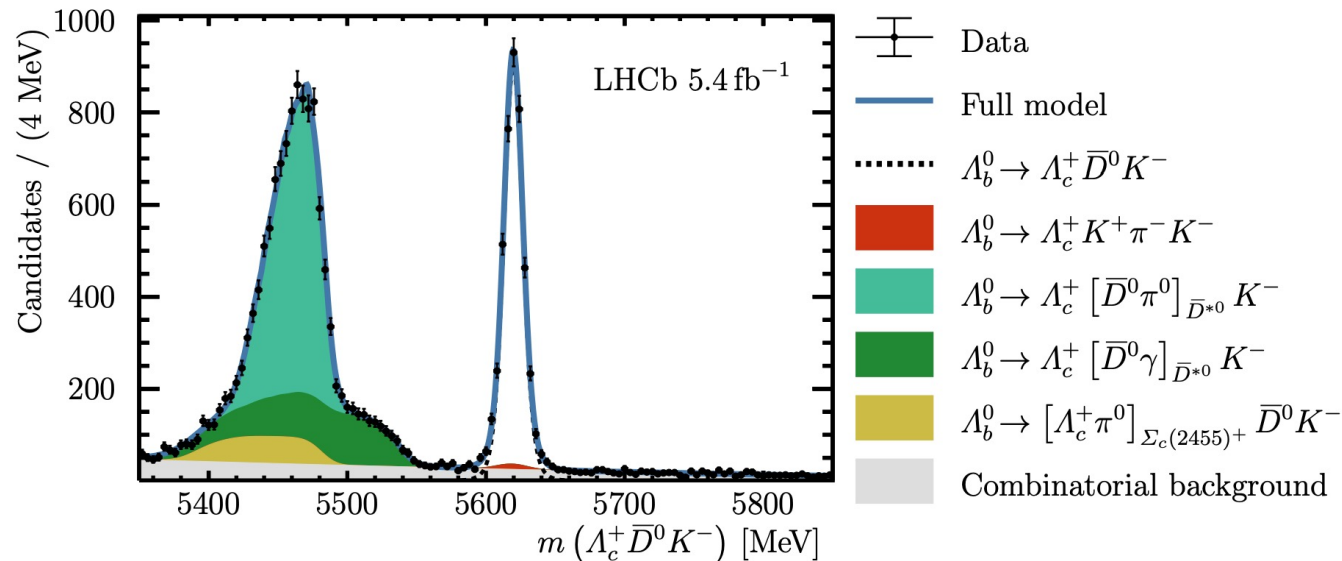
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} = (19.08_{-0.34-0.18}^{+0.36+0.16} \pm 0.38)\%$$

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

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

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

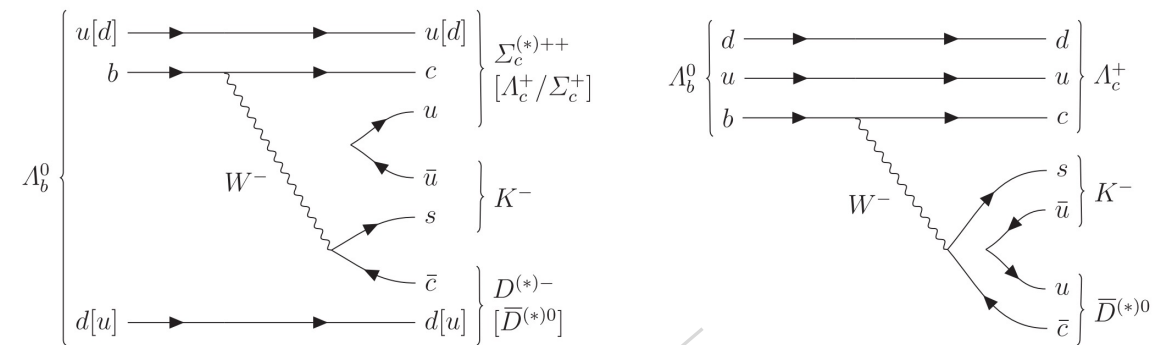
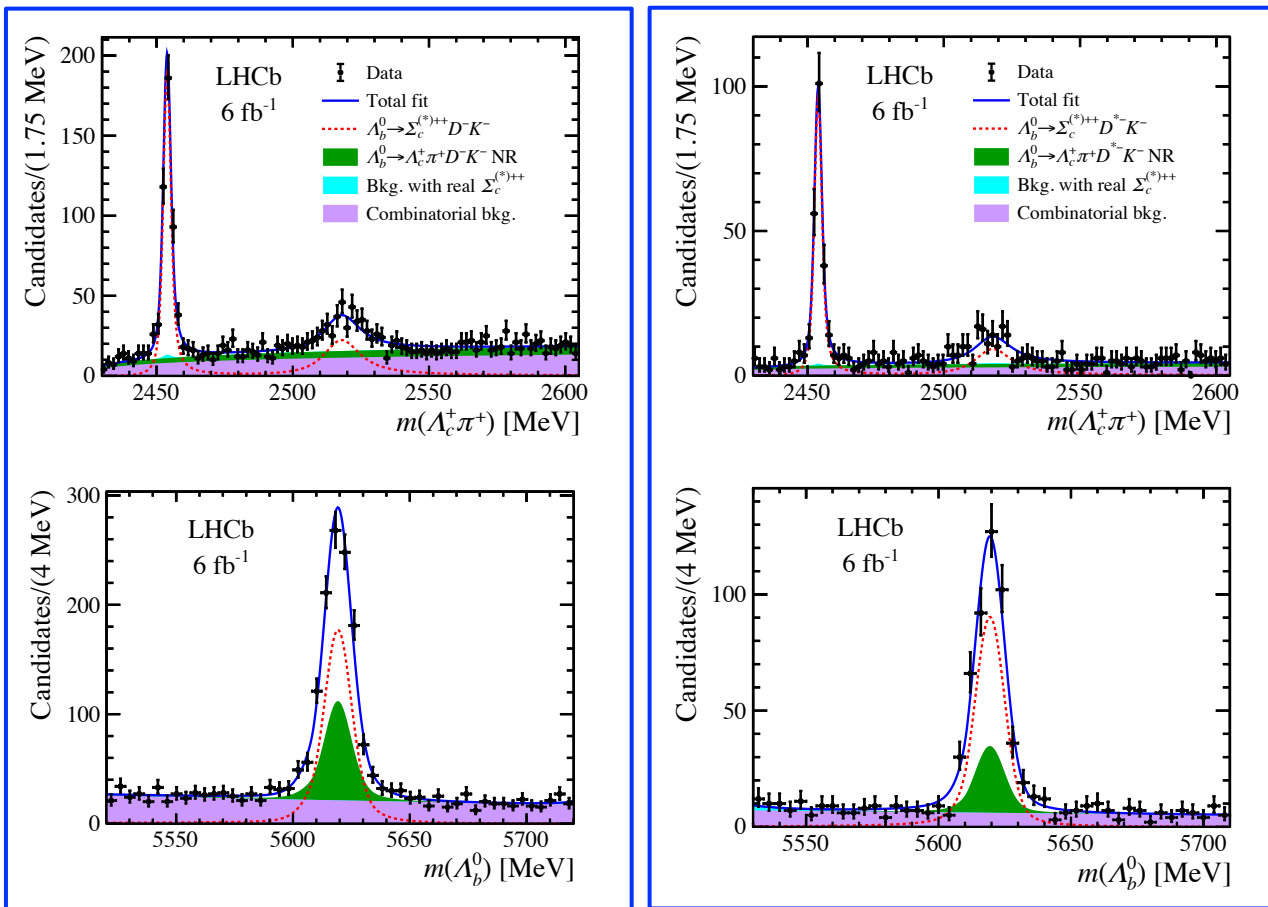
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{*0} K^-)} = (4.9_{-0.9}^{+1.1})\%$$



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

[PRD 110 (2024) L031104]

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



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

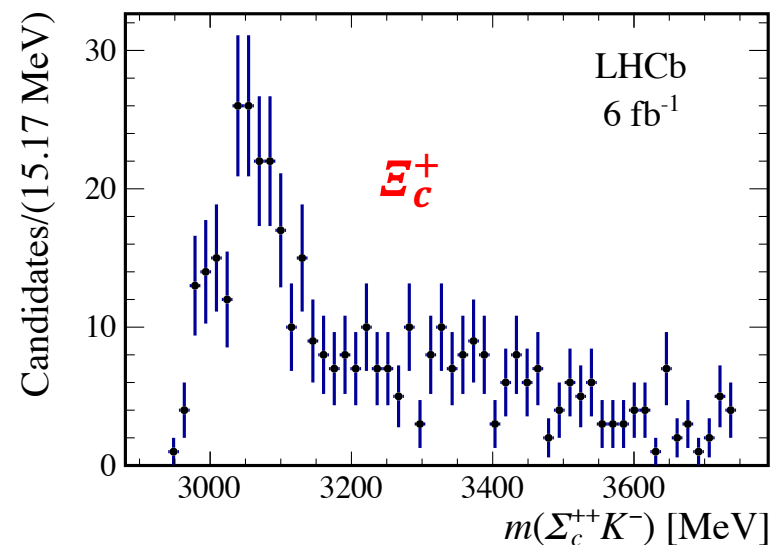
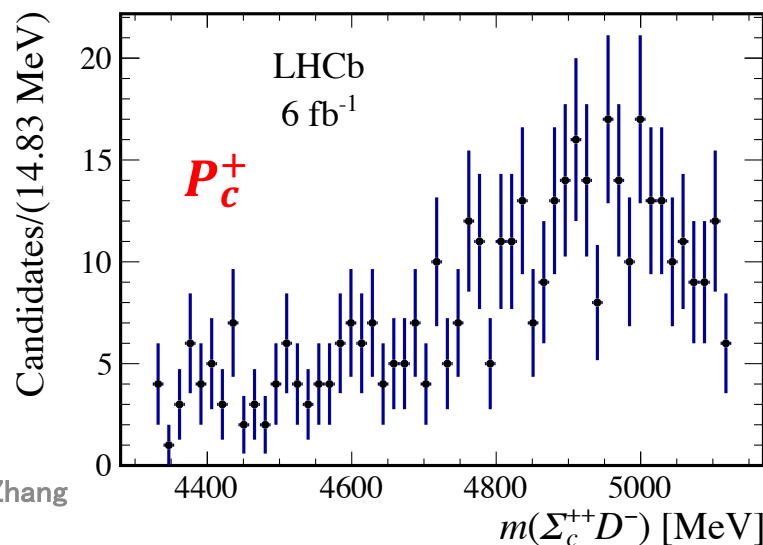
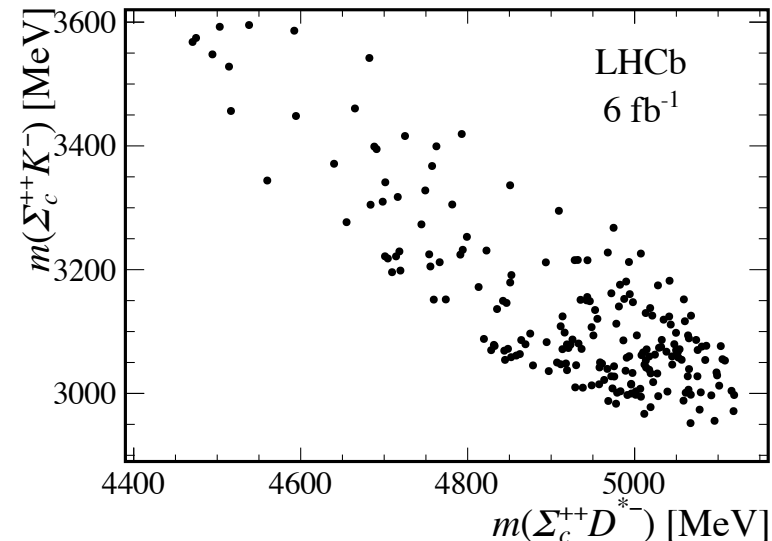
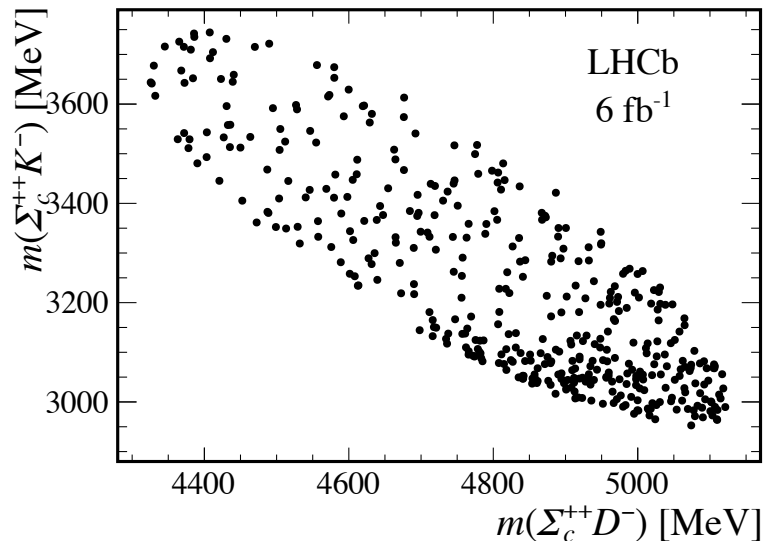
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{*++} D^- K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-)} = 0.460 \pm 0.052 \pm 0.028,$$

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

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

$\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$: intermediate states [PRD 110 (2024) L031104]

- Larger dataset needed to draw a definitive conclusion



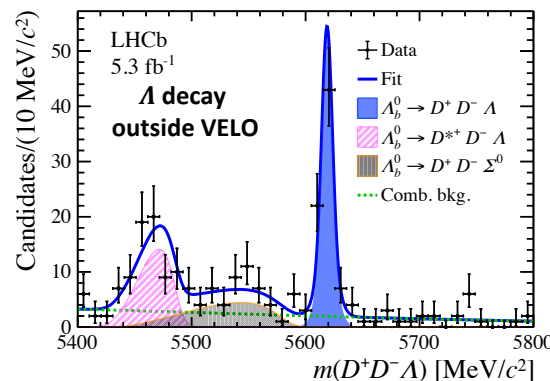
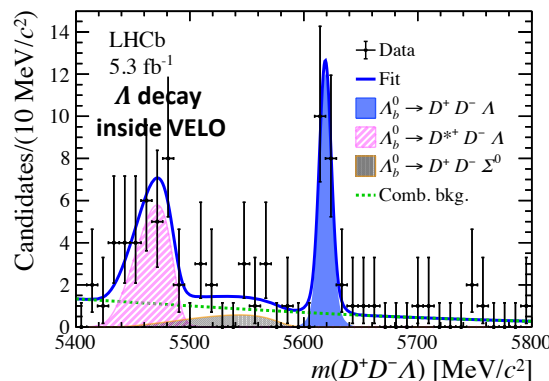
Observation of $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$

[JHEP 07 (2024) 140]

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

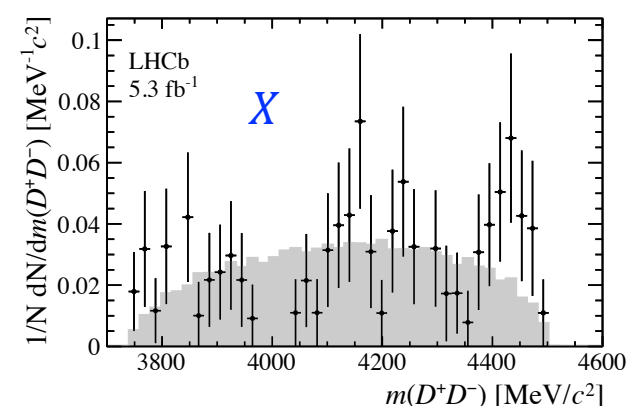
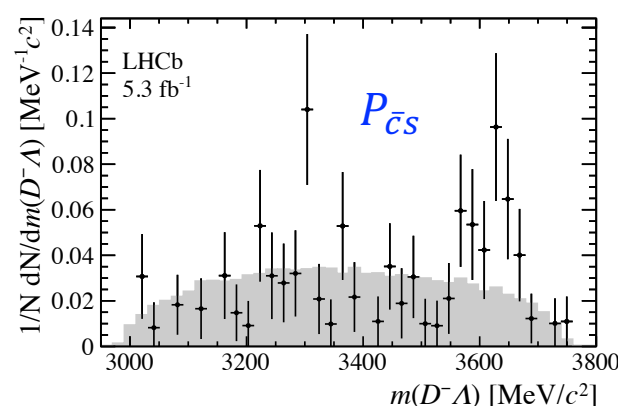
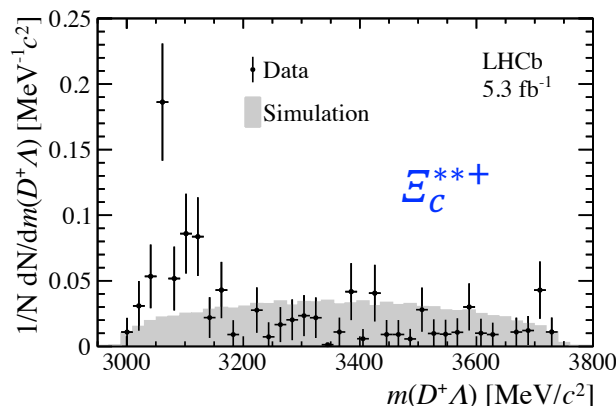
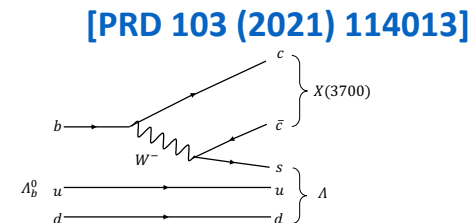
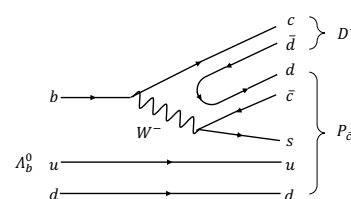
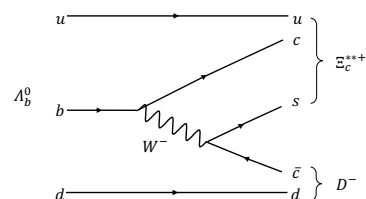
$N = 19 \pm 5$

$N = 73 \pm 9$



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

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



Other quarkonium(like) studies

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

[arXiv: 2406.17006]

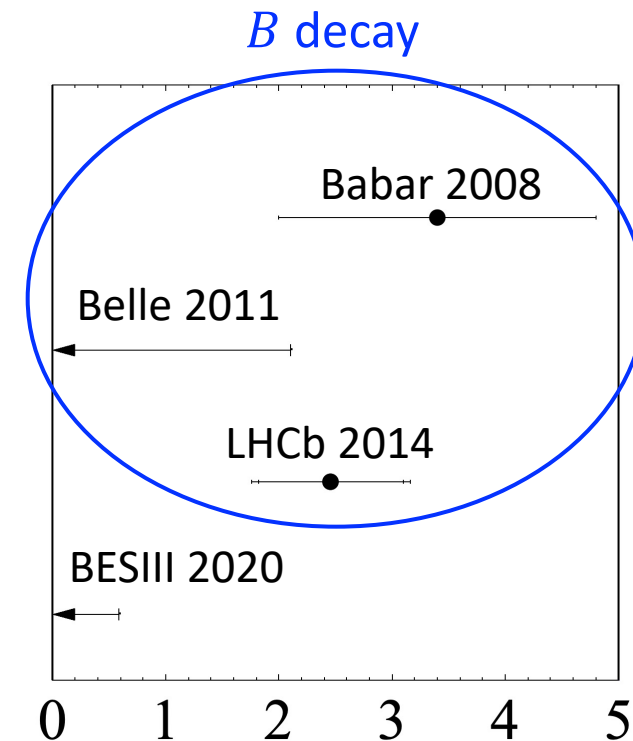
- Nature of $\chi_{c1}(3872)$ still under debate, while study of radiative decays provides a way to probe it
- Only evidence of $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$ was seen experimentally before

Reference		$\mathcal{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872) \rightarrow \psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872) \rightarrow J/\psi\gamma}}$	
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 <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	$c\bar{c}/\psi c$
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	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$

$\gtrsim 1$

$\ll 1$

mixed



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

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

[arXiv: 2406.17006]

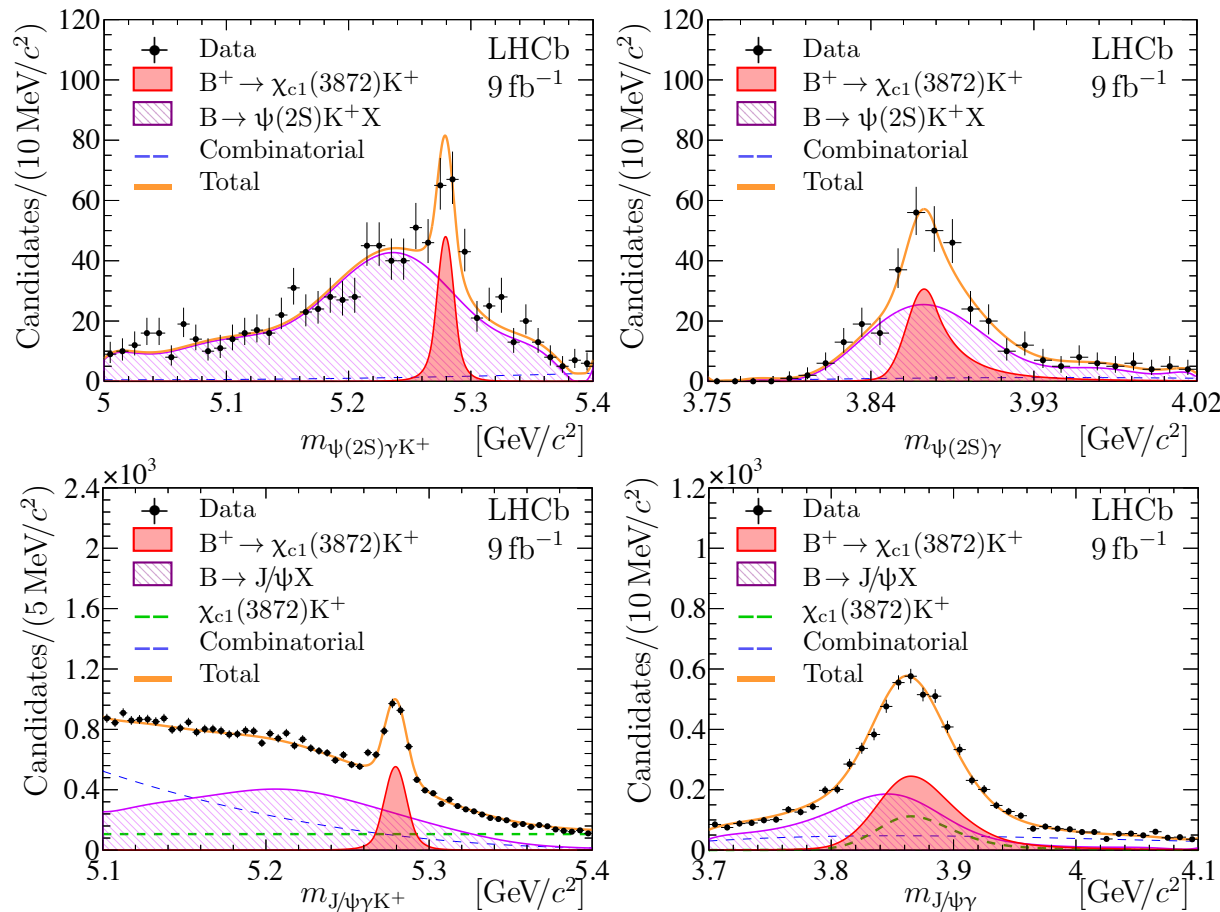
- Update at LHCb using $B^+ \rightarrow \chi_{c1}(3872)K^+$ decay with 9 fb^{-1} Run1+Run2 data

[LHCb meets theory workshop](#)

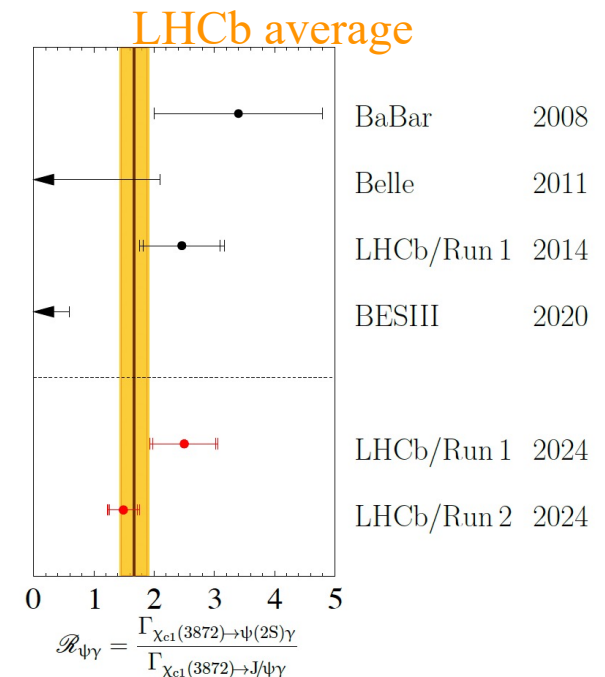
$$\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$$

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

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



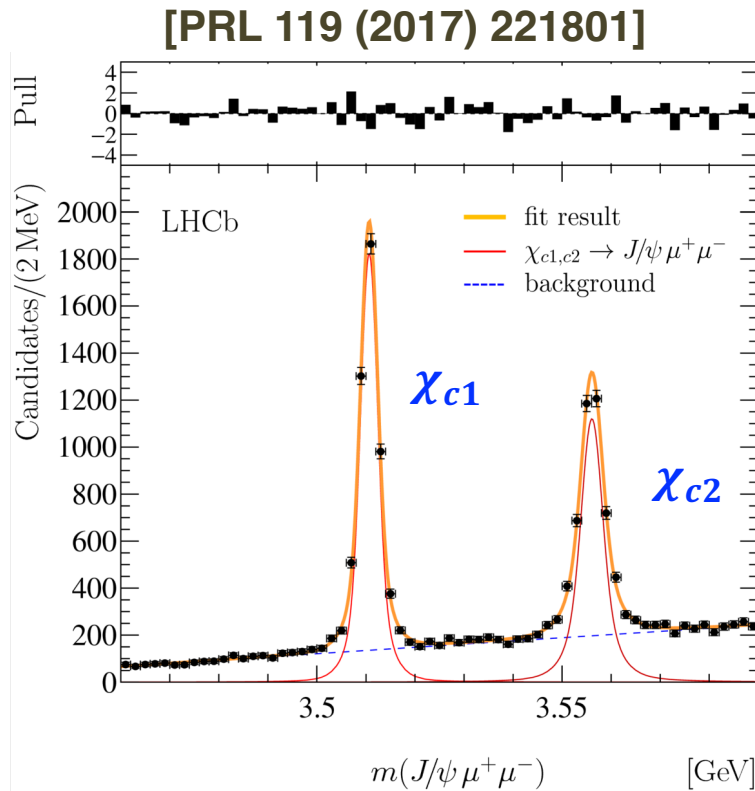
$$\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04 \quad (15\%)$$



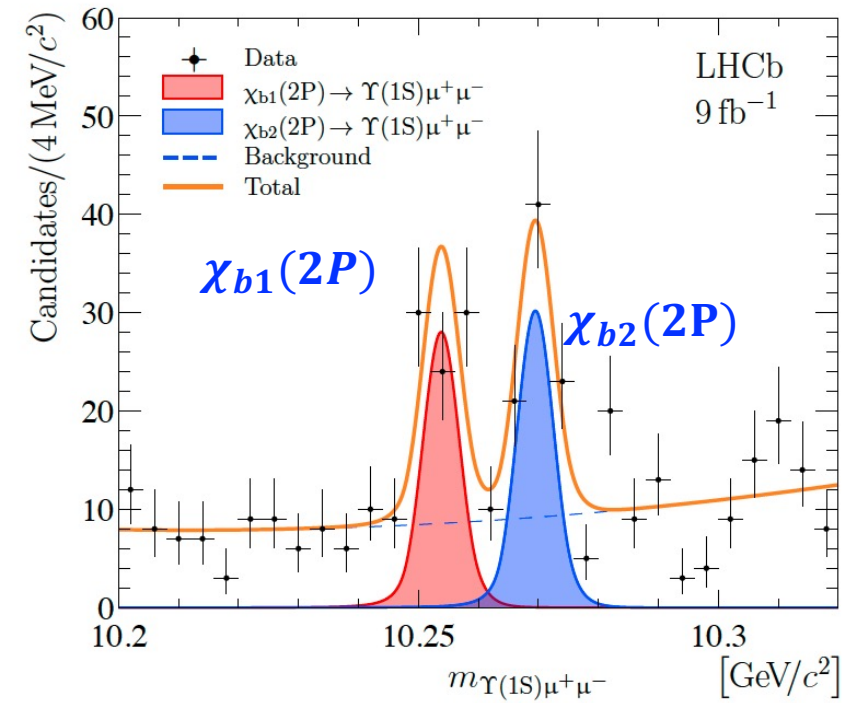
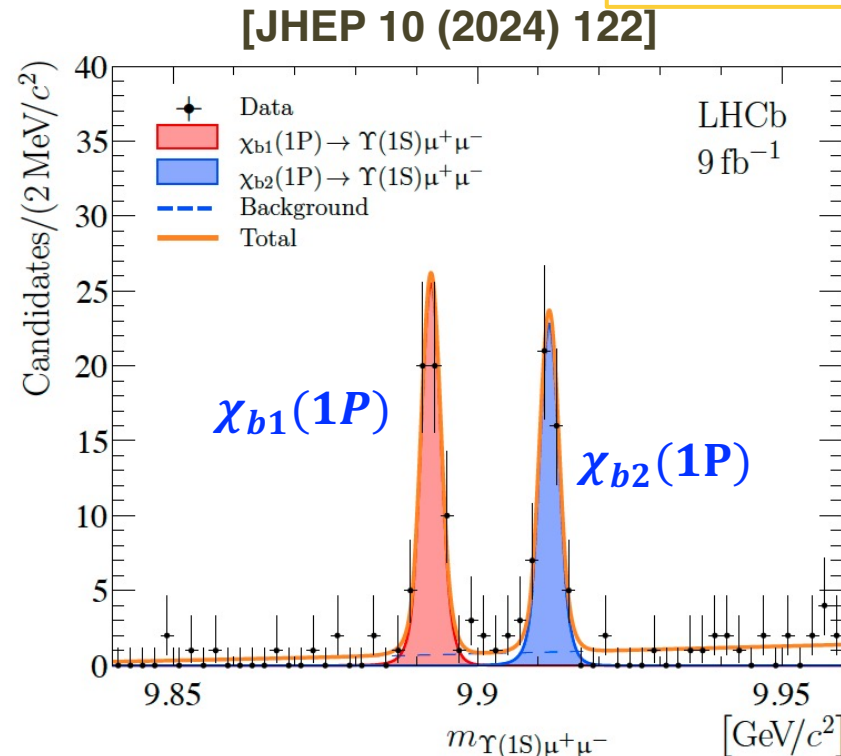
Muonic decays of $\chi_{c1,2}(1P)$ and $\chi_{b1,2}(1P, 2P)$

- 1st observation of $\chi_{c1,2} \rightarrow J/\psi \mu^+ \mu^-$ in 2017
- 1st observation of $\chi_{b1,2} \rightarrow \Upsilon(1S) \mu^+ \mu^-$ in 2024
- Competitive mass and width measurements

$$\begin{aligned}
 m_{\chi_{b1}(1P)} &= 9892.50 \pm 0.26 \pm 0.10 \pm 0.10 \text{ MeV}/c^2, \\
 m_{\chi_{b2}(1P)} &= 9911.92 \pm 0.29 \pm 0.11 \pm 0.10 \text{ MeV}/c^2, \\
 m_{\chi_{b1}(2P)} &= 10253.97 \pm 0.75 \pm 0.22 \pm 0.09 \text{ MeV}/c^2, \\
 m_{\chi_{b2}(2P)} &= 10269.67 \pm 0.67 \pm 0.22 \pm 0.09 \text{ MeV}/c^2,
 \end{aligned}$$

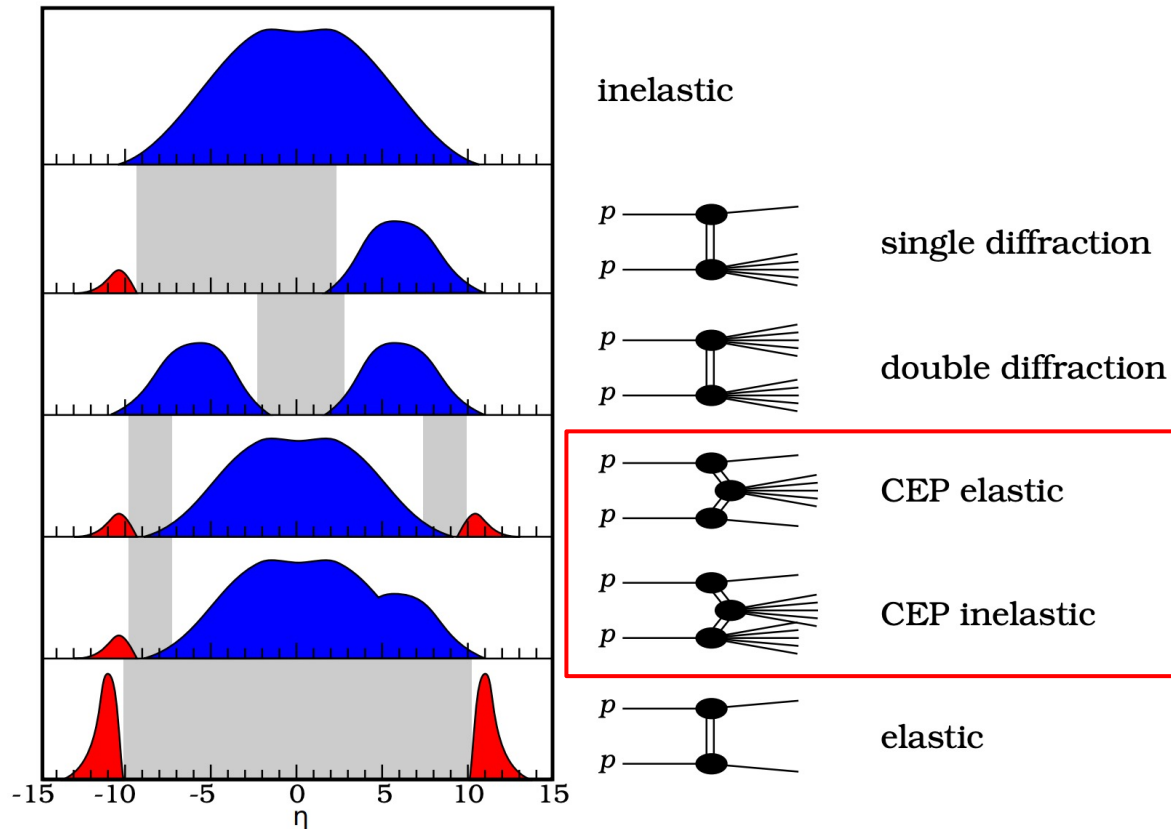


Liming Zhang

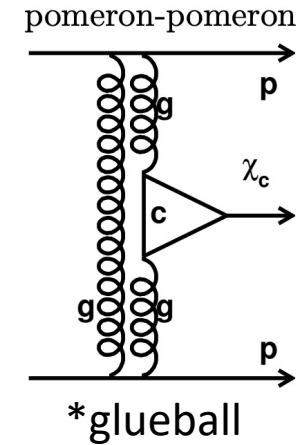
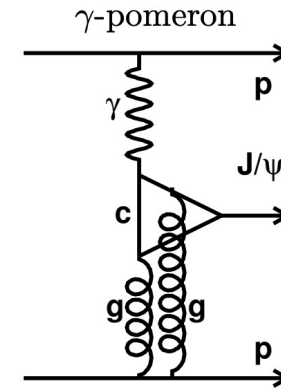
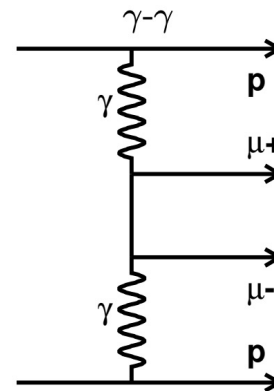


Central exclusive production (CEP)

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

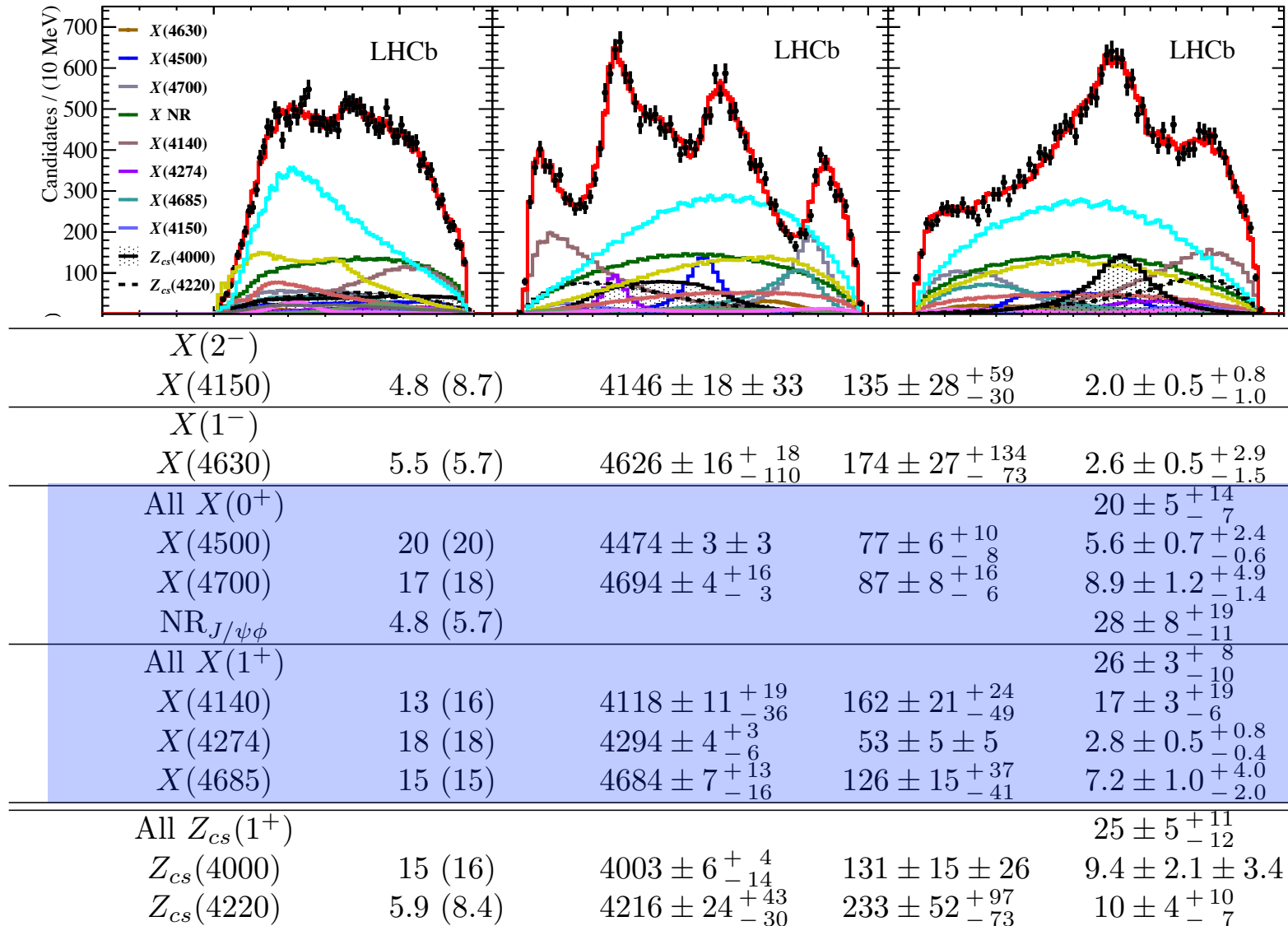


- ✓ Experimentally clean even @LHC
- ✓ Spin-parity option narrowed down
- ✗ Much smaller rate



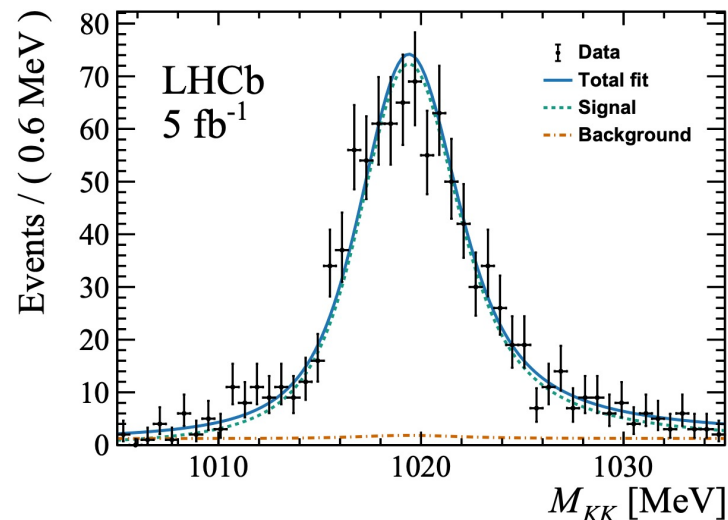
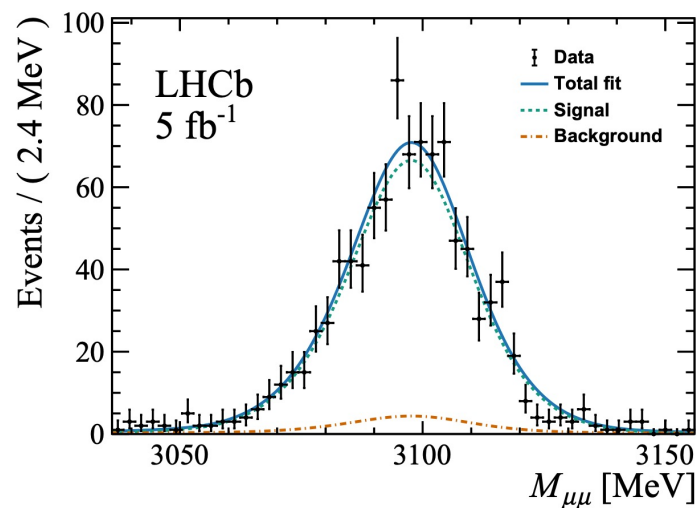
X in $B^+ \rightarrow J/\psi \phi K^+$

[PRL 127 (2021) 082001]

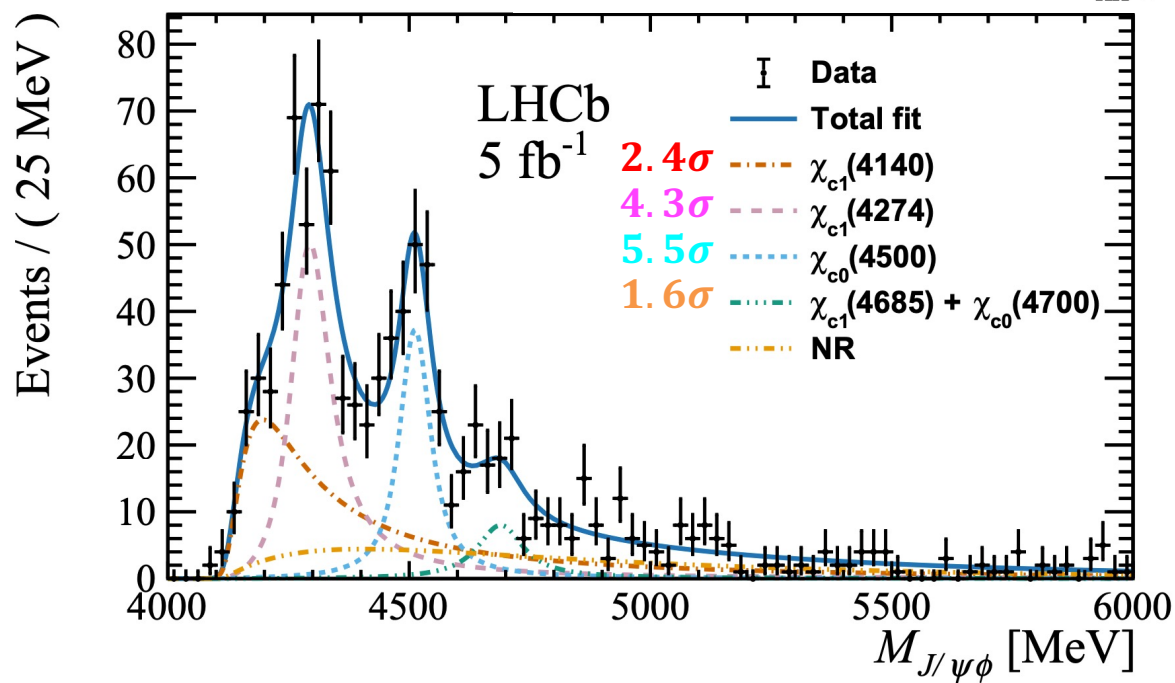


$X \rightarrow J/\psi\phi$ in CEP

[arXiv: 2407.14301]

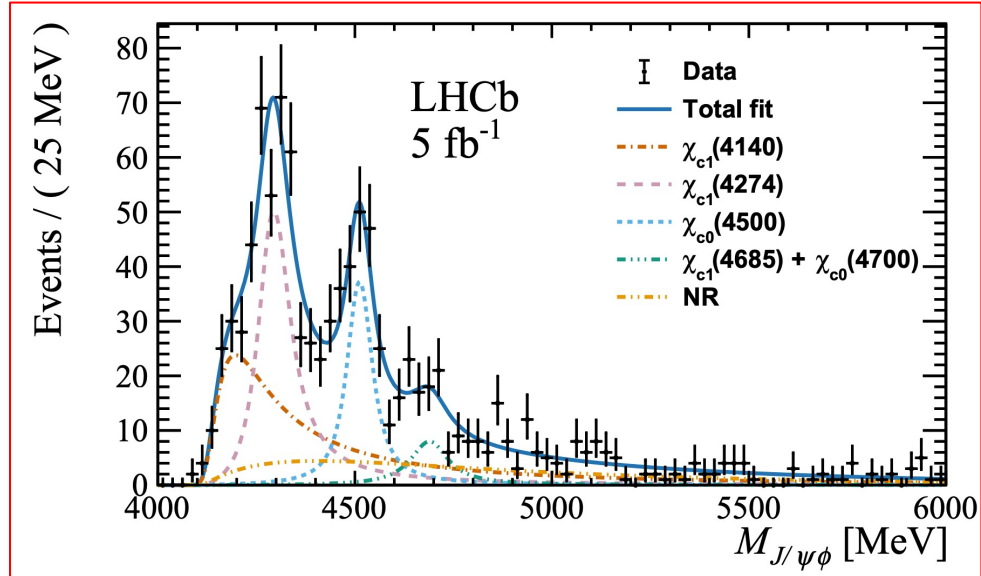


$N = 989$
purity = $(93.0 \pm 0.5)\%$



First exotic hadron measurement in CEP!

[arXiv: 2407.14301]

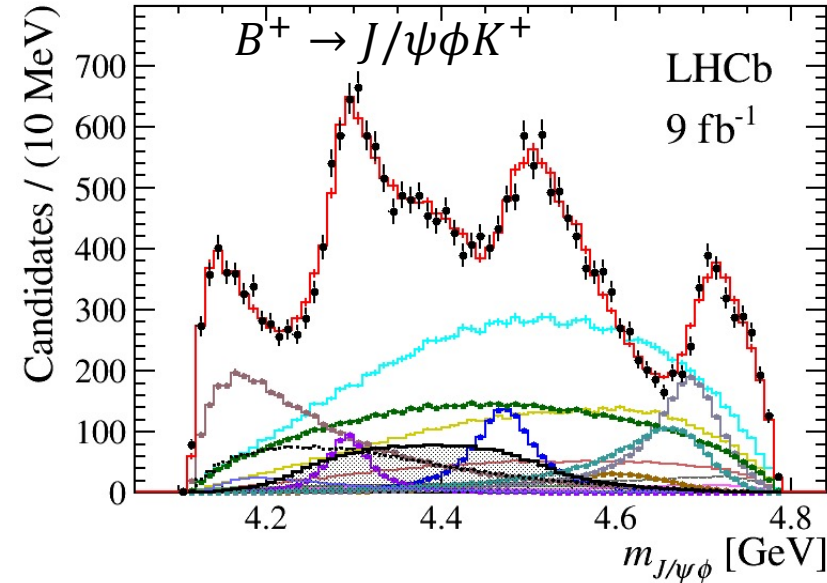


- Mass & width measurements: slightly higher mass of $X(4500)$

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

Liming Zhang

[PRL 127 (2021) 082001]



- Cross-section measurements:

$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4140)} = (0.80 \pm 0.15 \pm 0.28) \text{ pb},$$

$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4274)} = (0.73 \pm 0.08 \pm 0.17) \text{ pb},$$

$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\text{eff}}^{\chi_{c0}(4500)} = (0.42^{+0.09}_{-0.08} \pm 0.06) \text{ pb},$$

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

$$\sigma_{\text{NR}} \times \mathcal{B}_{\text{eff}}^{\text{NR}} = (0.43^{+0.24}_{-0.18} \pm 0.20) \text{ pb},$$

Baryon spectroscopy

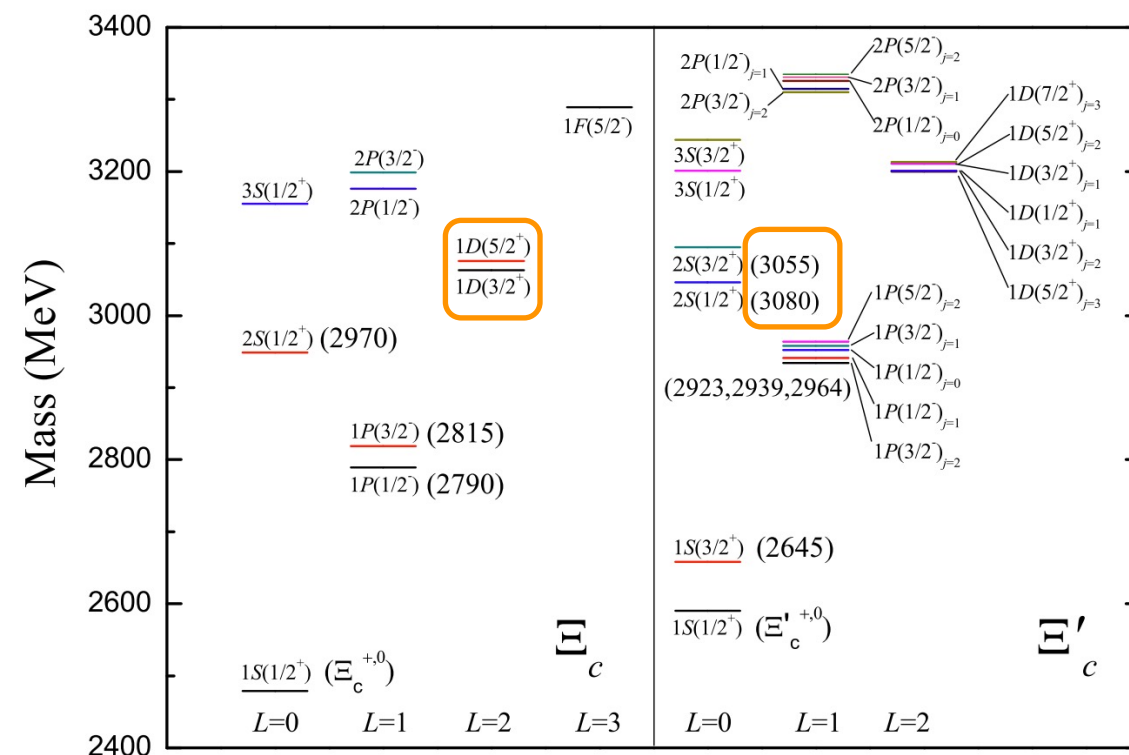
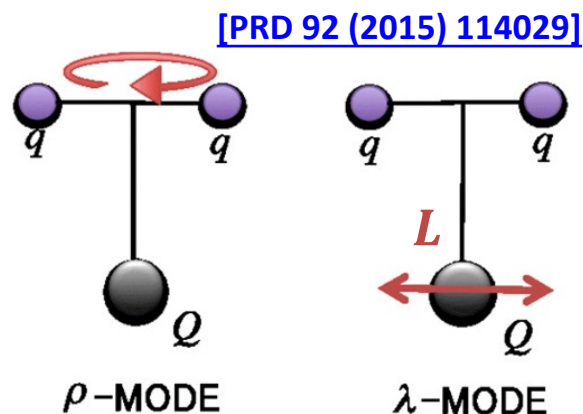
Singly heavy baryons

- Qqq baryons is well described by heavy quark-light diquark $Q[qq]$ model
- ✓ λ -mode: can describe almost all observed states



Configuration	$J_{[qq]}^P = 0^+$	$J_{[qq]}^P = 1^+$
Naming	Ξ_Q	Ξ'_Q

- ✓ ρ -mode: no firm assignment yet

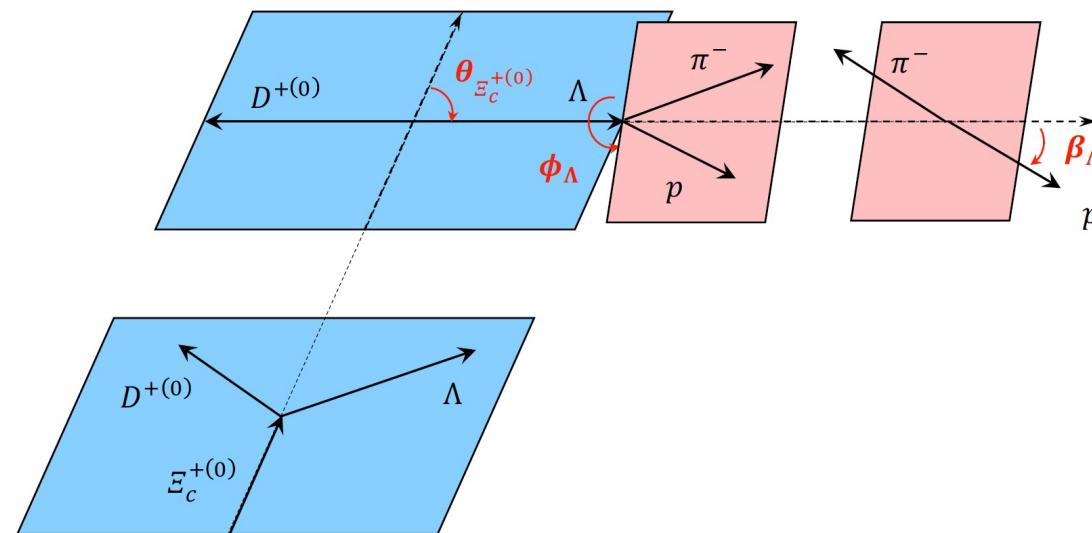
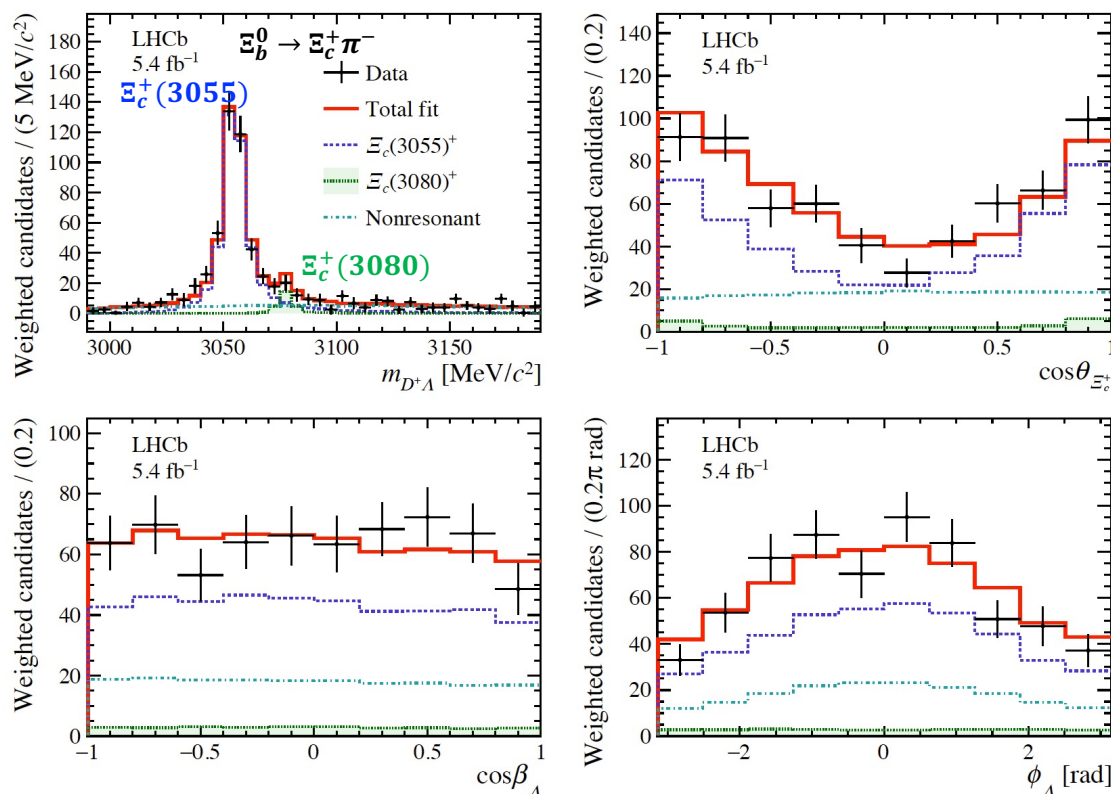
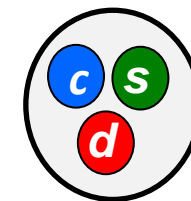


Zhen-Yu Li, Guo-Liang Yu, Zhi-Gang Wang, Jian-Zhong Gu, Jie Lu
Chinese Phys. C **47** (2023) 073105

1st determination of J^P for $\Xi_c(3055)^{+,0}$

[arXiv:2409.05440]

- $\Xi_b^{0(-)} \rightarrow \Xi_c^{+(0)}(3055/3080)(\rightarrow D\Lambda)\pi^-$ decays are used to study of the properties of charm baryons
- Amplitude analysis performed to four observables ($m_{D\Lambda}$, θ_{Ξ_c} , β_Λ , θ_Λ)



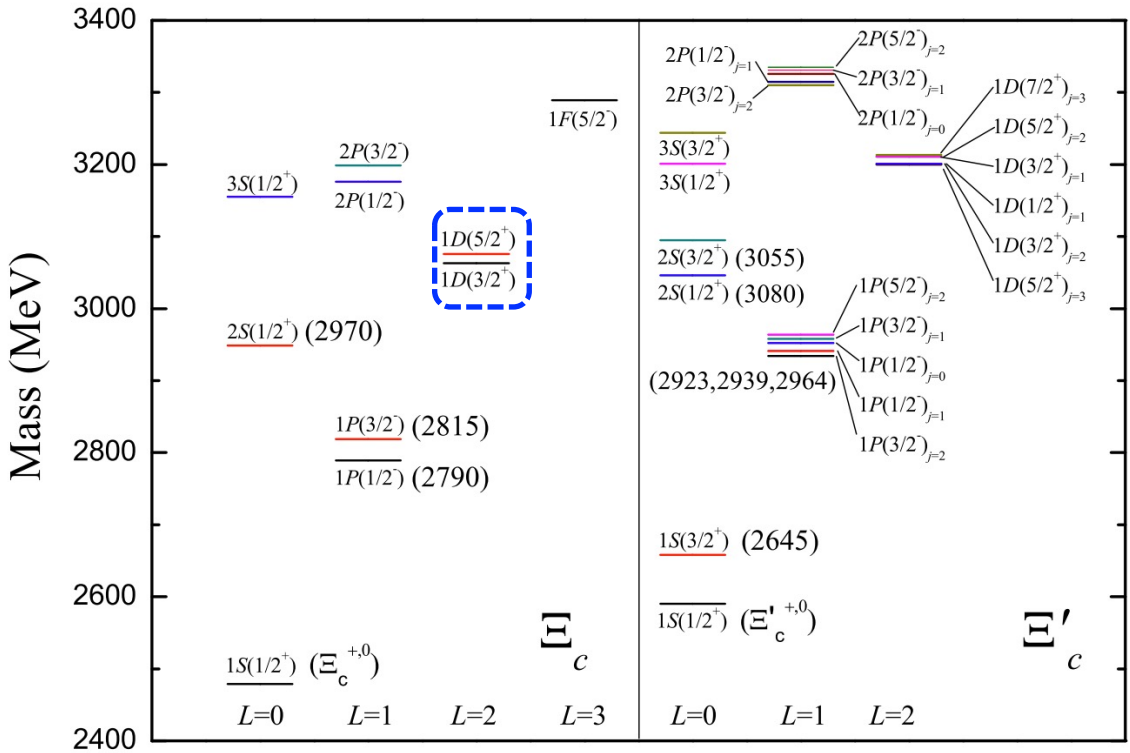
1st determination of J^P for $\Xi_c(3055)^{+,0}$

[arXiv:2409.05440]

- $J^P = 3/2^+$ is determined for $\Xi_c(3055)^{+,0}$ with significances of more than 6.5σ (3.5σ) against other hypotheses
- Evidence found for $\Xi_c(3080)^{+,0}$ in the $\Xi_b^{0(-)}$ decays
- Mass, width, Ξ_b decay parameter α , and relative rate for 3080/3055 R_B

$J^P = 3/2^+$ and narrow width for $\Xi_c(3055)$ may favor it as a 1D state

Quantity	$\Xi_c(3055)^+$	$\Xi_c(3055)^0$
m [MeV/ c^2]	$3054.52 \pm 0.36 \pm 0.17$	$3061.00 \pm 0.80 \pm 0.23$
Γ [MeV/ c^2]	$8.01 \pm 0.76 \pm 0.34$	$12.4 \pm 2.0 \pm 1.1$
α	$-0.92 \pm 0.10 \pm 0.05$	$-0.92 \pm 0.16 \pm 0.22$
R_B	$0.045 \pm 0.023 \pm 0.006$	$0.14 \pm 0.06 \pm 0.04$



Zhen-Yu Li, Guo-Liang Yu, Zhi-Gang Wang, Jian-Zhong Gu, Jie Lu
Chinese Phys. C **47** (2023) 073105

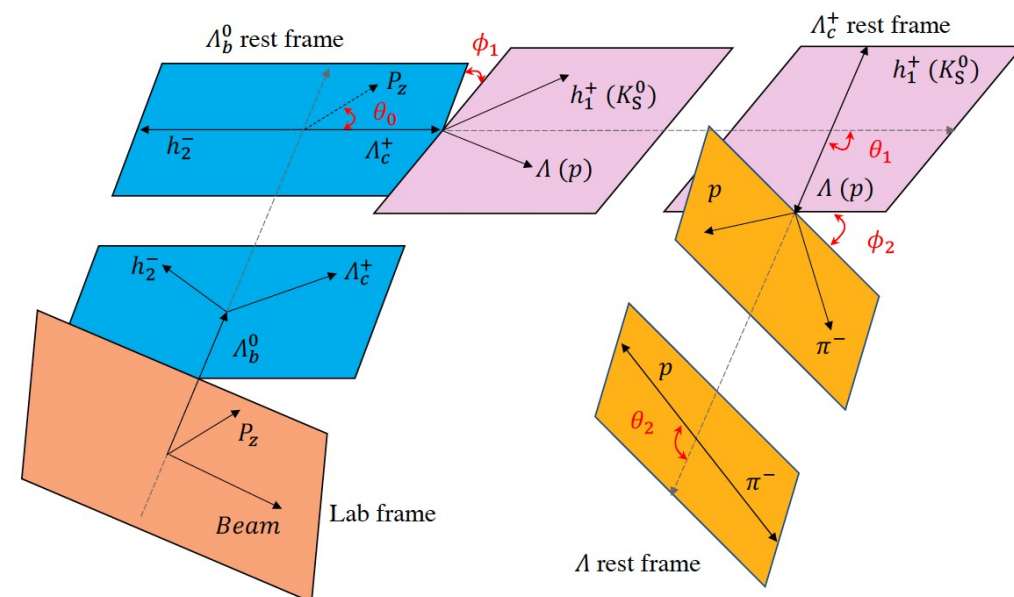
$\Lambda_b^0, \Lambda_c^+, \Lambda$ decay parameters

[arXiv: 2409.02759]

- Decay parameters of baryon are first proposed by Lee and Yang to search for parity violation, with s and p as S- and P-wave amplitude $\alpha^2 + \beta^2 + \gamma^2 = 1$

$$\alpha \equiv \frac{2\Re(s^*p)}{|s|^2 + |p|^2}, \quad \beta \equiv \frac{2\Im(s^*p)}{|s|^2 + |p|^2}, \quad \gamma \equiv \frac{|s|^2 - |p|^2}{|s|^2 + |p|^2},$$

- Two $\Lambda_b^0 \rightarrow \Lambda_c^+ h^-$ ($h = \pi, K$) decays and three $\Lambda_c^+ \rightarrow \Lambda h^+$ or $\Lambda_c^+ \rightarrow p K_S^0$ decays are studied
- The decay parameters are encoded in the angular distributions of these decays
 - The Λ_b^0 is unpolarized, shown by previous study



$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi_2} \propto (1 + \alpha_{\Lambda_b^0} \alpha_{\Lambda_c^+} \cos\theta_1 + \alpha_{\Lambda_c^+} \alpha_{\Lambda} \cos\theta_2 + \alpha_{\Lambda_b^0} \alpha_{\Lambda} \cos\theta_1 \cos\theta_2 - \alpha_{\Lambda_b^0} \gamma_{\Lambda_c^+} \alpha_{\Lambda} \sin\theta_1 \sin\theta_2 \cos\phi_2 + \alpha_{\Lambda_b^0} \beta_{\Lambda_c^+} \alpha_{\Lambda} \sin\theta_1 \sin\theta_2 \sin\phi_2)$$

$\Lambda_b^0, \Lambda_c^+, \Lambda$ decay parameters

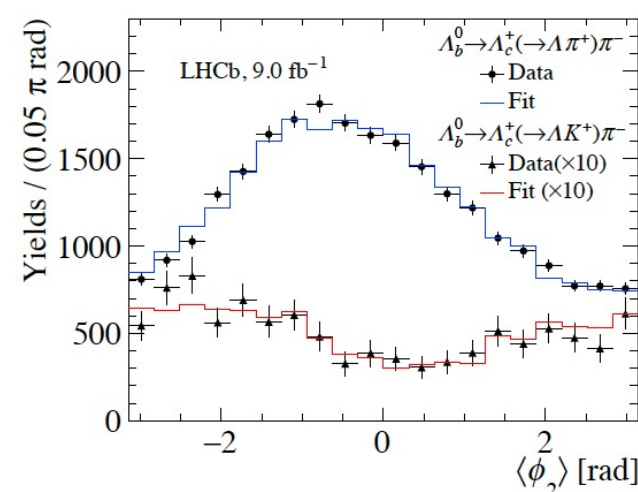
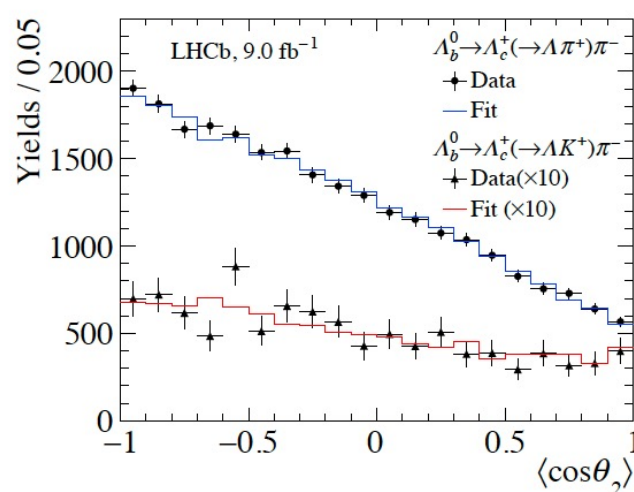
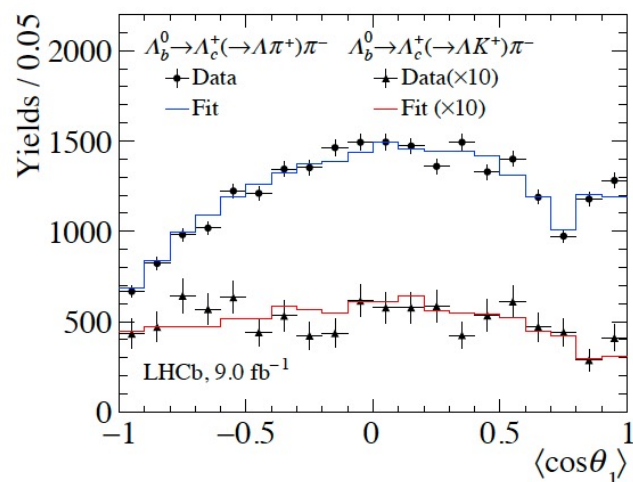
[arXiv: 2409.02759]

- Parameters are determined for Λ_b^0 and $\bar{\Lambda}_b^0$
- No significant CP violation is found

Other parameters can be found in the paper

Decay	α	$\bar{\alpha}$	$\langle\alpha\rangle$	A_α
$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$	$-1.010 \pm 0.011 \pm 0.003$	$0.996 \pm 0.011 \pm 0.003$	$-1.003 \pm 0.008 \pm 0.005$	$0.007 \pm 0.008 \pm 0.005$
$\Lambda_b^0 \rightarrow \Lambda_c^+ K^-$	$-0.933 \pm 0.042 \pm 0.014$	$0.995 \pm 0.036 \pm 0.013$	$-0.964 \pm 0.028 \pm 0.015$	$-0.032 \pm 0.029 \pm 0.006$
$\Lambda_c^+ \rightarrow \Lambda \pi^+$	$-0.782 \pm 0.009 \pm 0.004$	$0.787 \pm 0.009 \pm 0.003$	$-0.785 \pm 0.006 \pm 0.003$	$-0.003 \pm 0.008 \pm 0.002$
$\Lambda_c^+ \rightarrow \Lambda K^+$	$-0.569 \pm 0.059 \pm 0.028$	$0.464 \pm 0.058 \pm 0.017$	$-0.516 \pm 0.041 \pm 0.021$	$0.102 \pm 0.080 \pm 0.023$
$\Lambda_c^+ \rightarrow p K_S^0$	$-0.744 \pm 0.012 \pm 0.009$	$0.765 \pm 0.012 \pm 0.007$	$-0.754 \pm 0.008 \pm 0.006$	$-0.014 \pm 0.011 \pm 0.008$
$\Lambda \rightarrow p \pi^-$	$0.717 \pm 0.017 \pm 0.009$	$-0.748 \pm 0.016 \pm 0.007$	$0.733 \pm 0.012 \pm 0.006$	$-0.022 \pm 0.016 \pm 0.007$

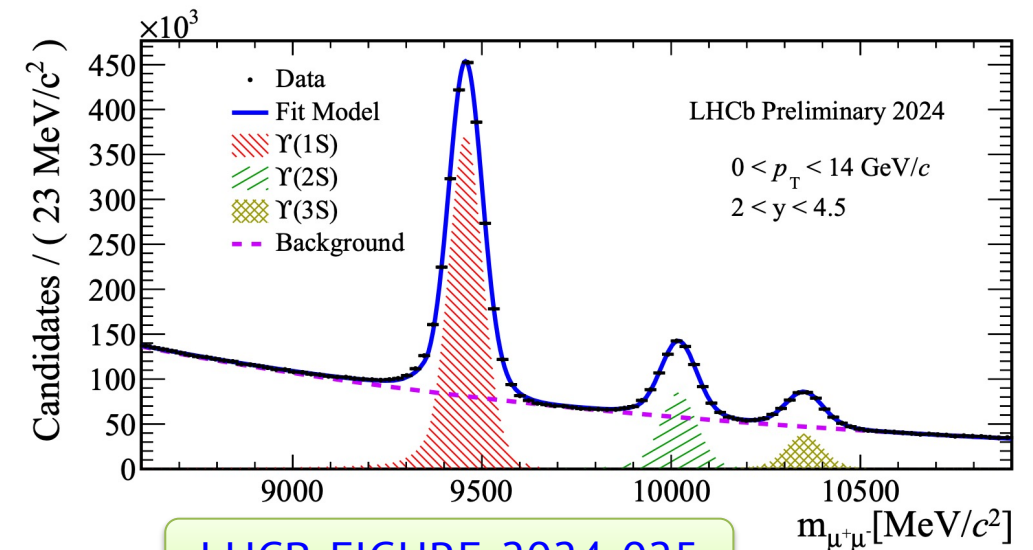
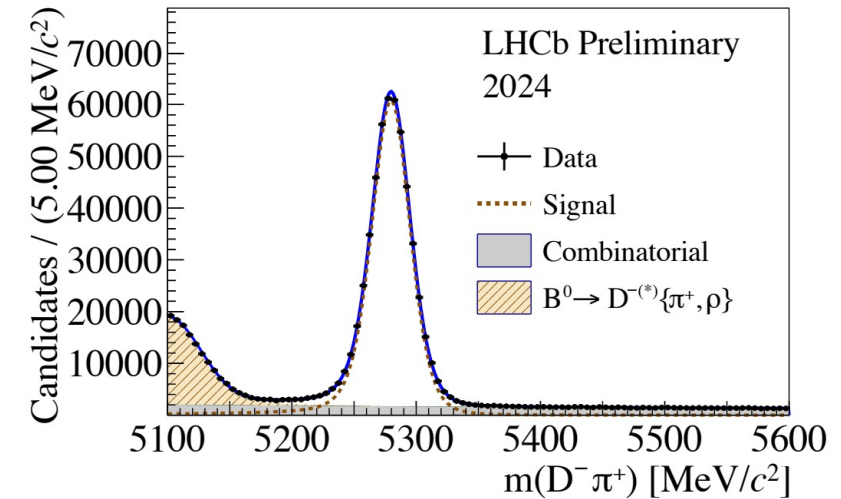
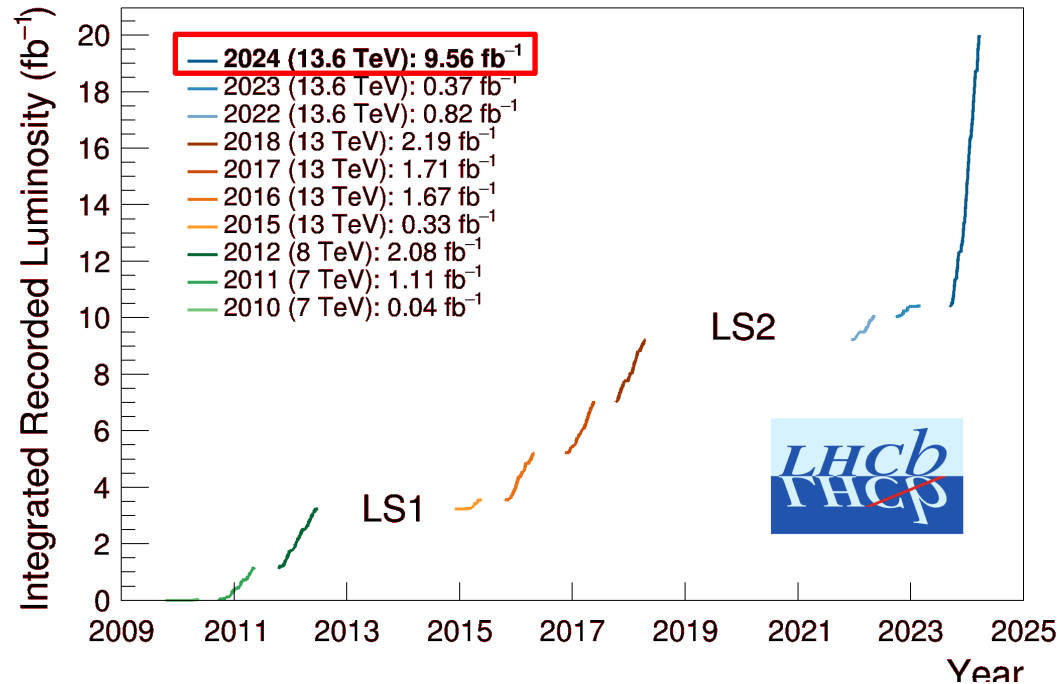
1st measurements
Most precise



Run3 performance

LHCb-FIGURE-2024-021

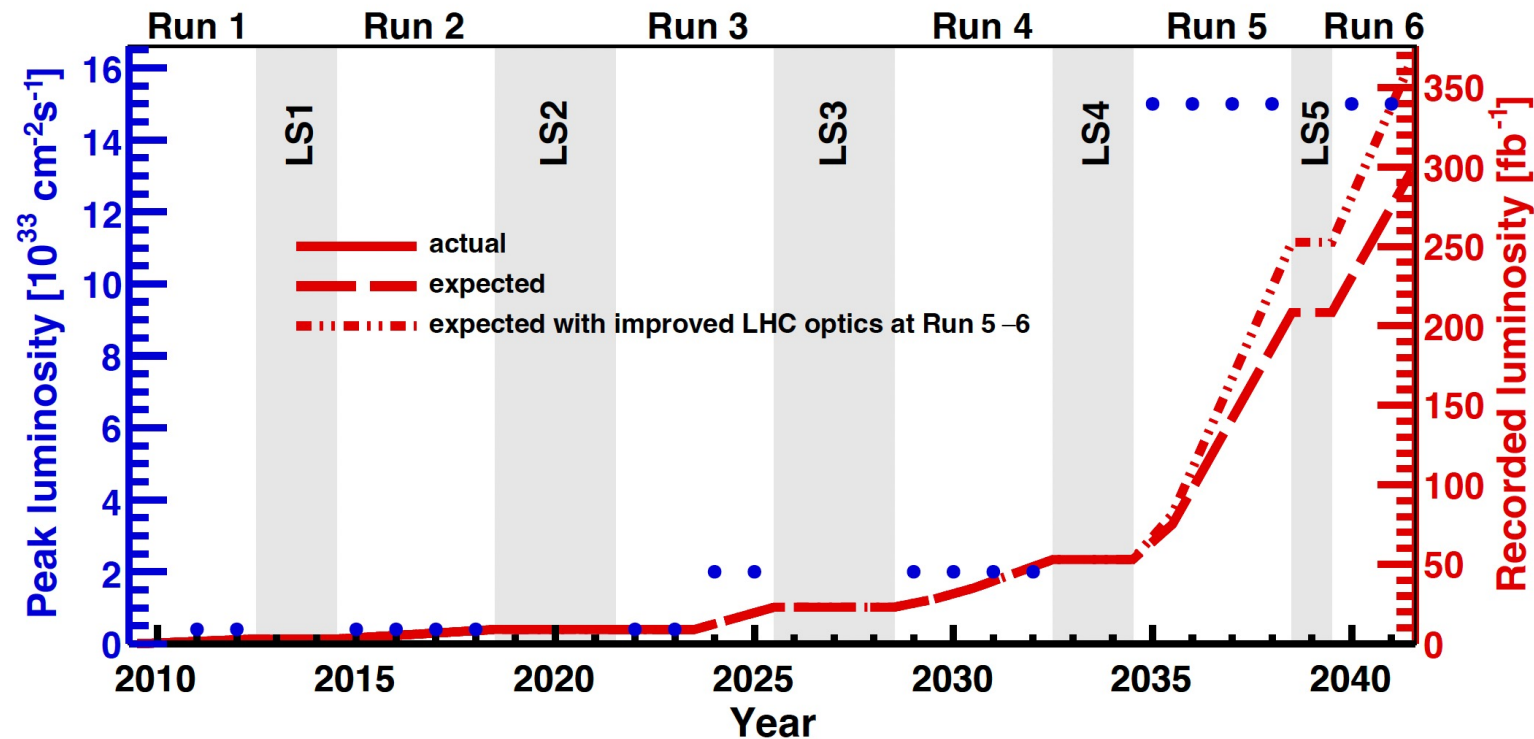
- Reaching Run 2 performance in mass resolution



LHCb-FIGURE-2024-025

Summary

- LHCb keeps making important contributions to heavy hadron spectroscopy with run1 and run2 data
- Run 3 this year has taken 9.5 fb^{-1} data, same luminosity as run1&2
- Stay tuned for more exciting results



BACKUP

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

- 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

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

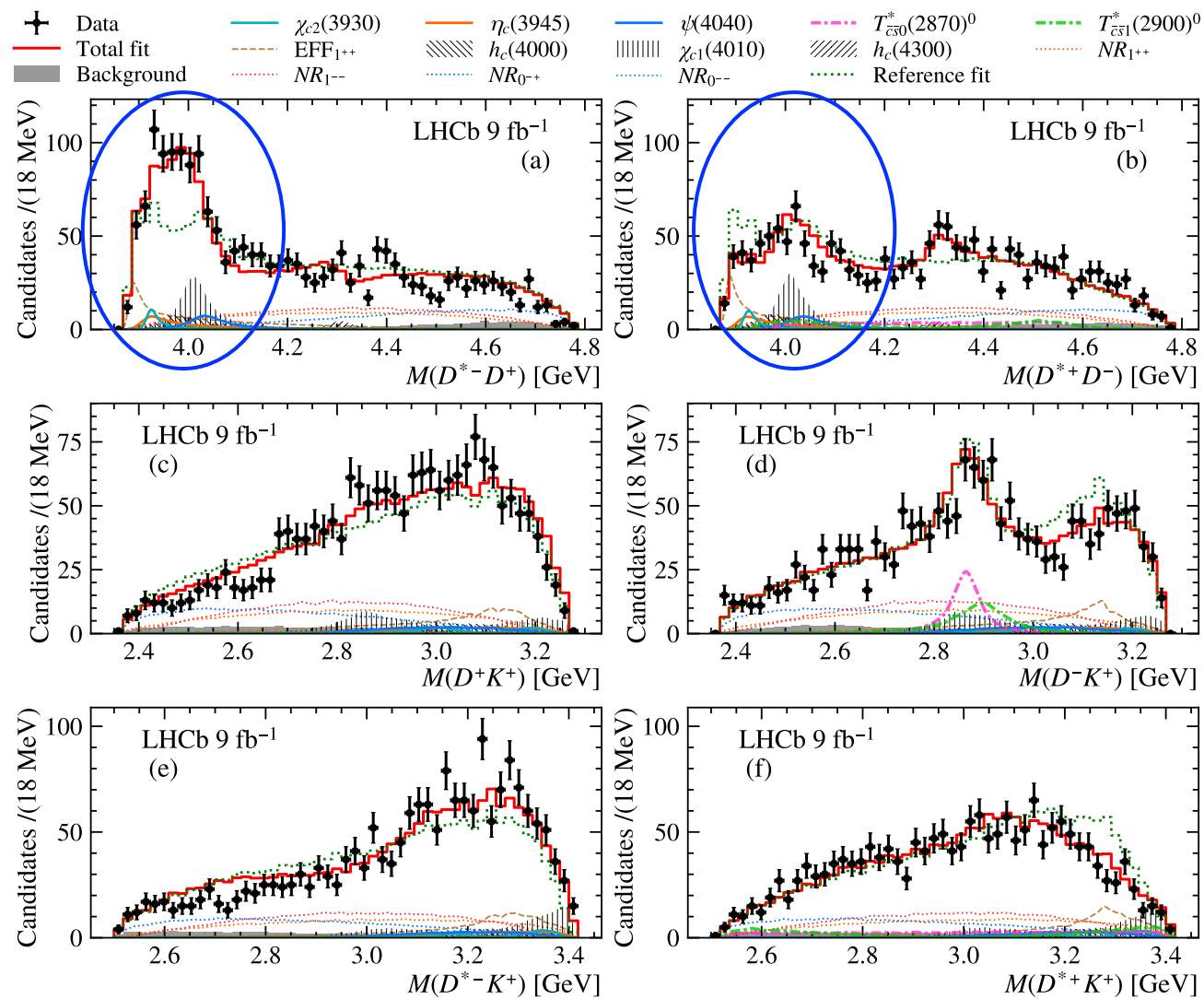
□ Other resonances: Breit-Wigner

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

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

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

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

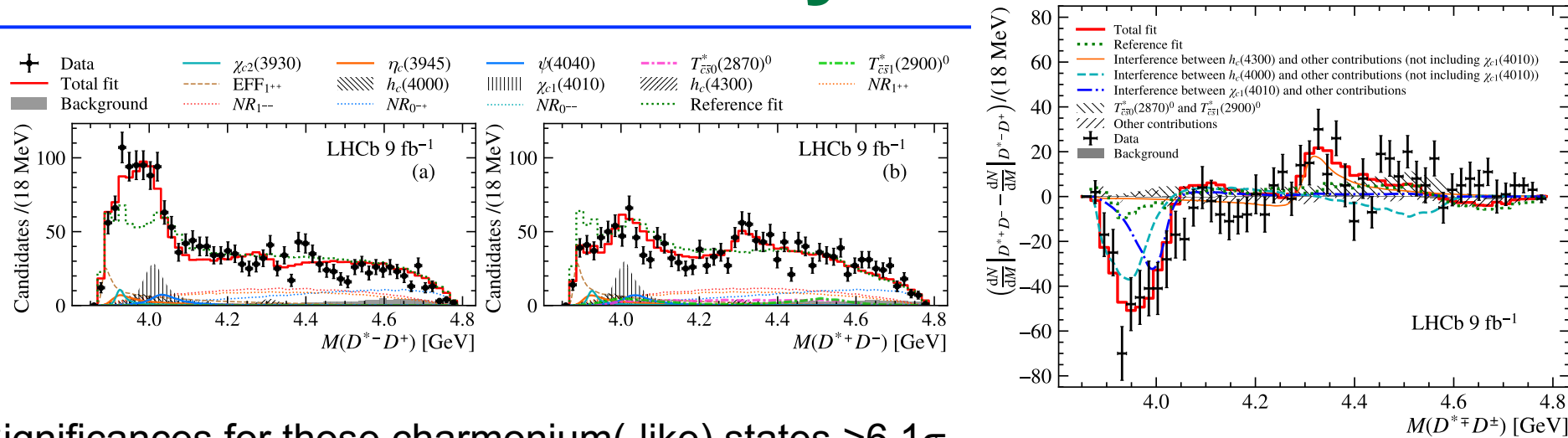


Component	$J^{P(C)}$
EFF ₁₊₊	1 ⁺⁺
$\eta_c(3945)$	0 ⁻⁺
$\chi_{c2}(3930)^{\dagger}$	2 ⁺⁺
$h_c(4000)$	1 ⁺⁻
$\chi_{c1}(4010)$	1 ⁺⁺
$\psi(4040)^{\dagger}$	1 ⁻⁻
$h_c(4300)$	1 ⁺⁻
$T_{\bar{c}s0}^*(2870)^{0\dagger}$	0 ⁺
$T_{\bar{c}s1}^*(2900)^{0\dagger}$	1 ⁻
NR ₁₋₋ ($D^{*\mp}D^{\pm}$)	1 ⁻⁻
NR ₀₋₋ ($D^{*\mp}D^{\pm}$)	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

[PRL 133 (2024) 131902]



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

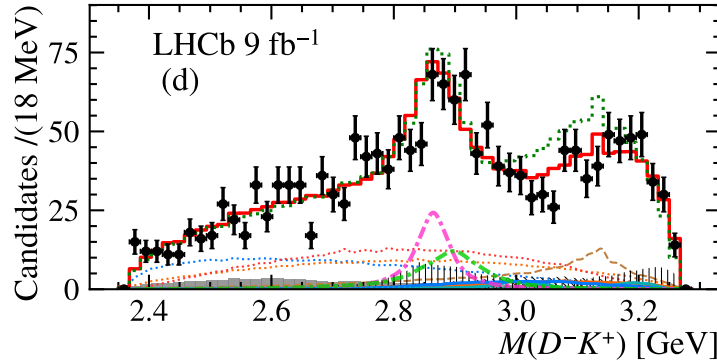
GI model
hep-ph/0505002

- 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]

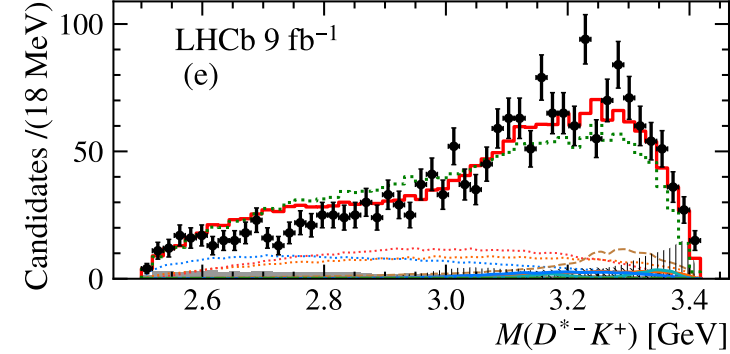
$B^+ \rightarrow D^{*\pm} D^{\mp} K^+ : T_{\bar{c}\bar{s}}^*$ states

[PRL 133 (2024) 131902]

➤ $B^+ \rightarrow D^{*+} D^- K^+$



➤ $B^+ \rightarrow D^{*-} D^+ K^+$



	Property	This work	Previous work
11σ	$T_{\bar{c}\bar{s}0}^*(2870)^0$ 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
9.2σ	$T_{\bar{c}\bar{s}1}^*(2900)^0$ 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

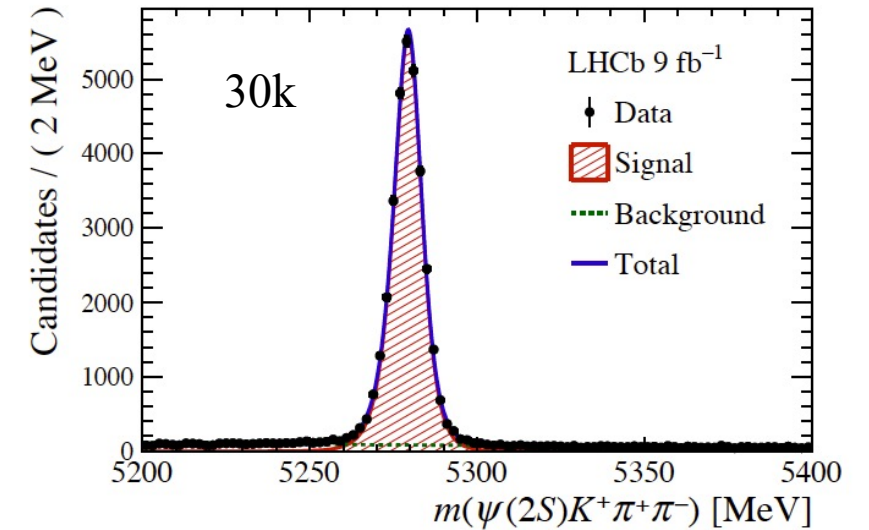
✓ $T_{\bar{c}\bar{s}0}^*(2870)^0 \rightarrow D^{*-} K^+$ forbidden

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

$B^+ \rightarrow \psi(2S)K^+\pi^+\pi^-$: amplitude analysis

[arXiv: 2407.12475]

- Can study $K^+\pi^+\pi^-$ system, crucial for NP studies of $B \rightarrow K\pi\pi(\gamma/\mu\mu)$
- Can also study charmonium-like exotic states
- With ~ 1000 signal decays, Belle only studied the $K^+\pi^+\pi^-$ system [PRD 83 (2011) 032005]
- LHCb performed the first full amplitude analysis on this decay
- Baseline fit contributions
 - 6 K'^+ states
 - 11 exotic states: most are very broad



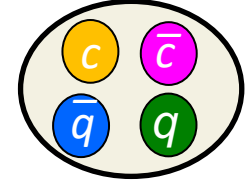
Decay channel	Fit fraction [%]
$B^+ \rightarrow \chi_{c0}(4475)K^+$	$18.45 \pm 1.31 \pm 2.92$
$B^+ \rightarrow \psi(2S) K^*(1680)^+$	$8.15 \pm 1.31 \pm 3.51$
$B^+ \rightarrow \psi(2S) K_1(1270)^+$	$7.60 \pm 0.85 \pm 1.35$
$B^+[P] \rightarrow \psi(2S) K_1(1270)^+$	$7.52 \pm 0.60 \pm 1.08$
$B^+[D] \rightarrow \psi(2S) K_1(1270)^+$	$6.81 \pm 0.45 \pm 1.18$
$B^+ \rightarrow \psi(2S) K_1(1400)^+$	$5.78 \pm 0.62 \pm 0.92$
$B^+ \rightarrow \psi(2S) K(1460)^+$	$5.26 \pm 0.48 \pm 0.87$
$B^+[P] \rightarrow T_{c\bar{c}1}(4200)^+ K^*(892)^0$	$4.60 \pm 0.54 \pm 2.17$
$B^+ \rightarrow T_{c\bar{c}1}(4600)^0 \pi^+$	$4.42 \pm 0.98 \pm 2.17$

.....

Exotic contributions

[arXiv: 2407.12475]

- 4 $X^0 \rightarrow \psi(2S)\pi^+\pi^-$ states are identified



- Main decay mode is $\psi(2S)\rho^0$
- Similar but broader than the states observed in $B^+ \rightarrow J/\psi\phi K^+$
- But they might not be the same, $\psi(2S)\rho^0$ has $L=1$, $J/\psi\phi$ has $L=0$

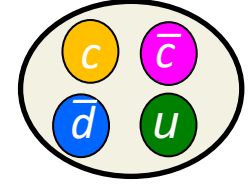
Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Res. PDG	m_0 [MeV]	Γ_0 [MeV]
$\chi_{c0}(4475)$	0^+	$4475 \pm 7 \pm 12$	$231 \pm 19 \pm 32$	$\chi_{c0}(4500)$	4474 ± 4	77^{+12}_{-10}
$\chi_{c1}(4650)$	1^+	$4653 \pm 14 \pm 27$	$227 \pm 26 \pm 22$	$\chi_{c1}(4685)$	4684^{+15}_{-17}	126 ± 40
$\chi_{c0}(4710)$	0^+	$4710 \pm 4 \pm 5$	$64 \pm 9 \pm 10$	$\chi_{c0}(4700)$	4694^{+16}_{-5}	87^{+18}_{-10}
$\eta_{c1}(4800)$	1^-	$4785 \pm 37 \pm 119$	$457 \pm 93 \pm 157$	$X(4630)$	4626^{+24}_{-110}	174^{+140}_{-80}
$T_{c\bar{c}1}^*(4055)^+$	1^-	4054 (fixed)	45 (fixed)	$T_{c\bar{c}}(4055)^+$	4054 ± 3.2	45 ± 13
$T_{c\bar{c}1}(4200)^+$	1^+	$4257 \pm 11 \pm 17$	$308 \pm 20 \pm 32$	$T_{c\bar{c}1}(4200)^+$	4196^{+35}_{-32}	370^{+100}_{-150}
$T_{c\bar{c}1}(4430)^+$	1^+	$4468 \pm 21 \pm 80$	$251 \pm 42 \pm 82$	$T_{c\bar{c}1}(4430)^+$	4478^{+15}_{-18}	181 ± 31
$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	$4578 \pm 10 \pm 18$	$133 \pm 28 \pm 69$			
$T_{c\bar{c}\bar{s}1}(4900)^0$	1^+	$4925 \pm 22 \pm 47$	$255 \pm 55 \pm 127$			
$T_{c\bar{c}\bar{s}1}^*(5200)^0$	1^-	$5225 \pm 86 \pm 181$	$226 \pm 76 \pm 374$			
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	$T_{c\bar{c}\bar{s}1}(4000)^+$	4003^{+7}_{-15}	131 ± 30

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

Exotic contributions

[arXiv: 2407.12475]

■ $3 T_{c\bar{c}}^{(*)} \rightarrow \psi(2S)\pi$ states are identified



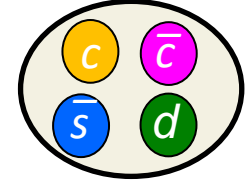
- Confirmed $Z_c(4430)^+$ seen in $\bar{B}^0 \rightarrow \psi(2S)\pi^+K^-$
- Confirmed $Z_c(4200)^+$ seen in $\bar{B}^0 \rightarrow J/\psi\pi^+K^-$, and $J^P = 1^+$ is determined for the 1st time
- $T_{c\bar{c}}(4055)^+$ seen in $e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$ is also needed

Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Res. PDG	m_0 [MeV]	Γ_0 [MeV]
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$T_{c\bar{c}1}^*(4055)^+$	1^-	4054 (fixed)	45 (fixed)	$T_{c\bar{c}}(4055)^+$	4054 ± 3.2	45 ± 13
$T_{c\bar{c}1}(4200)^+$	1^+	$4257 \pm 11 \pm 17$	$308 \pm 20 \pm 32$	$T_{c\bar{c}1}(4200)^+$	4196^{+35}_{-32}	370^{+100}_{-150}
$T_{c\bar{c}1}(4430)^+$	1^+	$4468 \pm 21 \pm 80$	$251 \pm 42 \pm 82$	$T_{c\bar{c}1}(4430)^+$	4478^{+15}_{-18}	181 ± 31
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$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	$T_{c\bar{c}\bar{s}1}(4000)^+$	4003^{+7}_{-15}	131 ± 30

Exotic contributions

[arXiv: 2407.12475]

- 3 new $T_{c\bar{c}\bar{s}} \rightarrow \psi(2S)K\pi$ states are observed



- $\psi(2S)K$ mass above $Z_{cs}(4000)^+$, only tail of $Z_{cs}(4000)^+$ can contribute

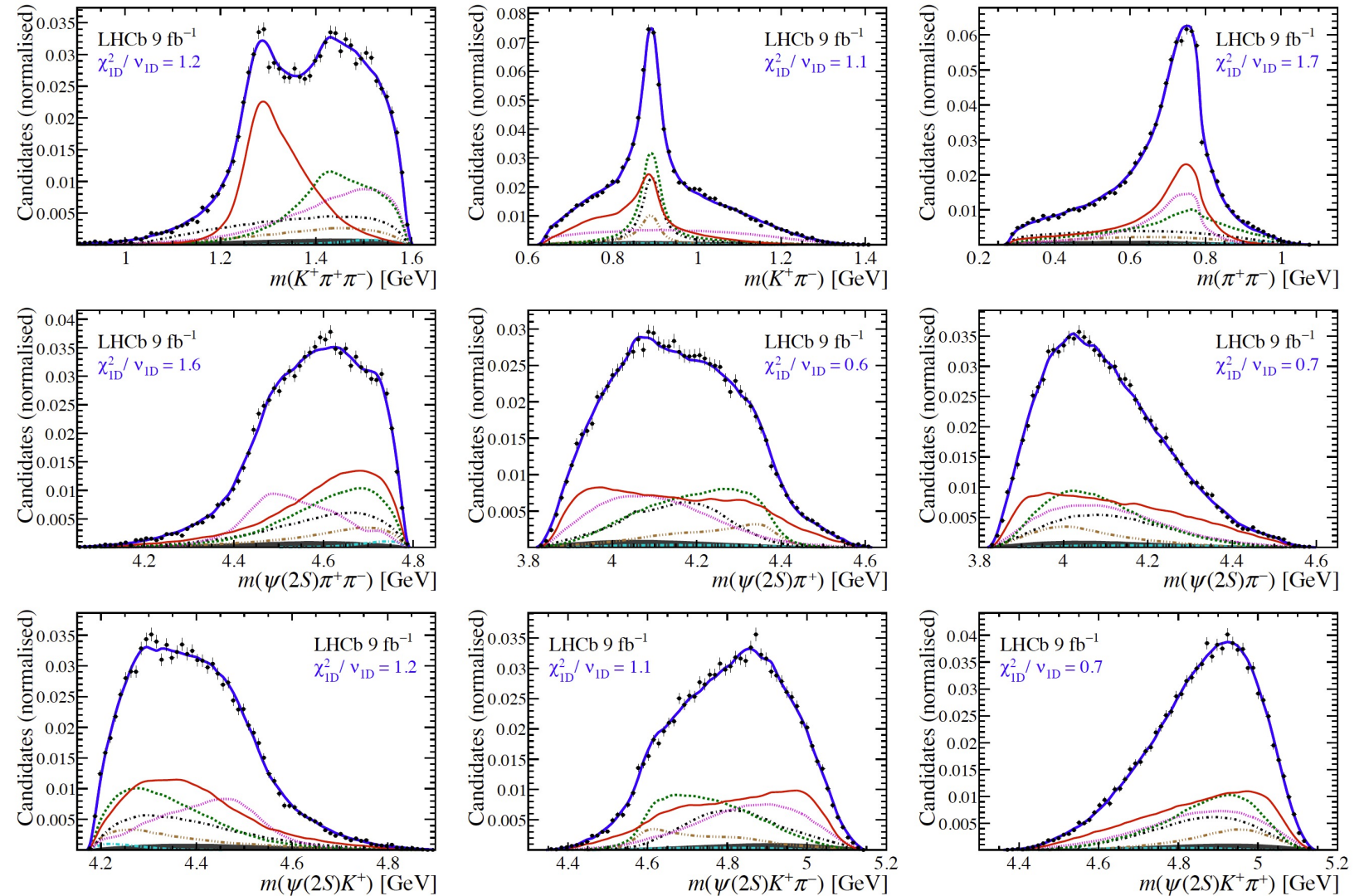
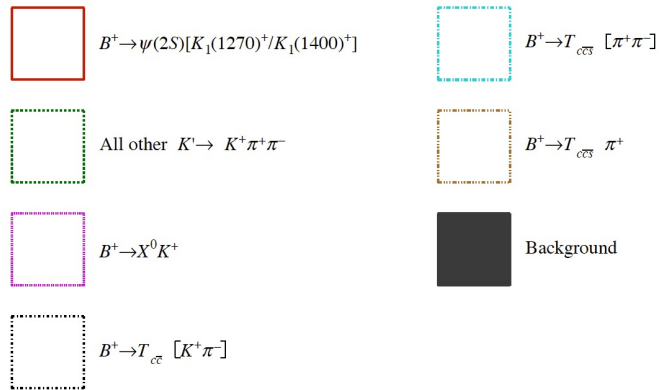
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$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	$T_{c\bar{c}\bar{s}1}(4000)^+$	4003^{+7}_{-15}	131 ± 30

new

Fit projections

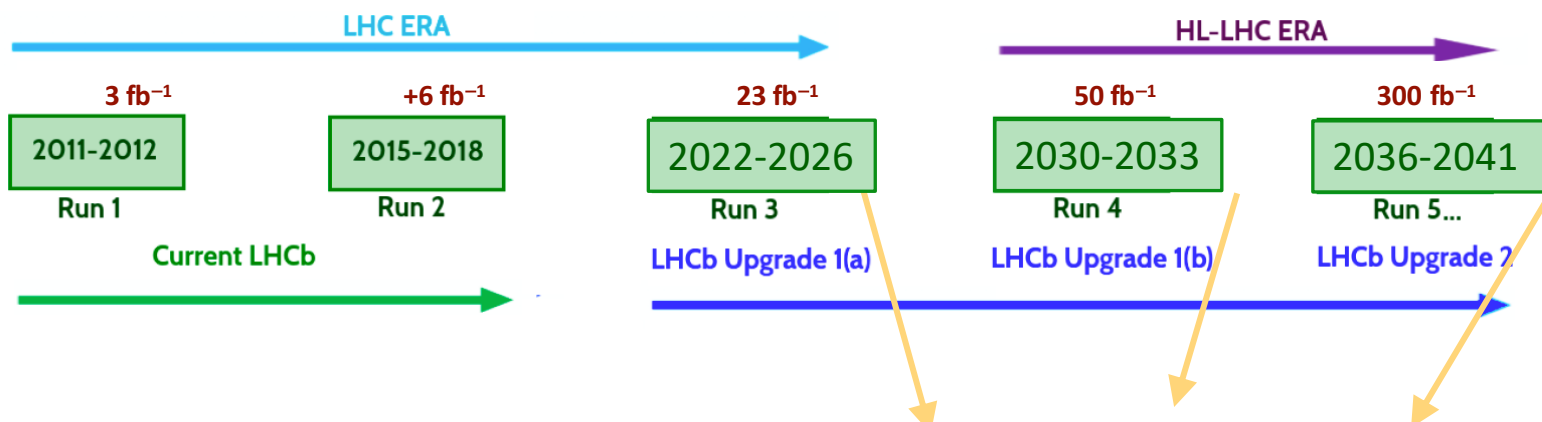
[arXiv: 2407.12475]

- Fit quality is acceptable, 7D $\chi^2/\text{ndof} = 1.2$
- Resonances are generally broad



Prospects

[arXiv:1808.08865]



LHCb is now boosting the data to a new level

- Expect to **3x** data (**5x hadronic events**) by 2026
- Opportunity for decays with hadronic final state, such as $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{(*)0} K^+$

Decay mode	LHCb		
	23 fb ⁻¹	50 fb ⁻¹	300 fb ⁻¹
$B^+ \rightarrow X(3872)(\rightarrow J/\psi \pi^+ \pi^-) K^+$	14k	30k	180k
$B^+ \rightarrow X(3872)(\rightarrow \psi(2S) \gamma) K^+$	500	1k	7k
$B^0 \rightarrow \psi(2S) K^- \pi^+$	340k	700k	4M
$B_c^+ \rightarrow D_s^+ D^0 \bar{D}^0$	10	20	100
$\Lambda_b^0 \rightarrow J/\psi p K^-$ [*]	680k	1.4M	8M
$\Xi_b^- \rightarrow J/\psi \Lambda K^-$	4k	10k	55k
$\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^+$	23k	58k	390k

$\chi_{c1}(3872)$ lineshape from multi-channels

$Z_c(4430)$

Doubly-charmed tetraquark $\mathcal{T}_{cc\bar{s}}^+ \rightarrow D_s^+ D^0$

More information for pentaquarks

Search for pentaquarks via open charm

[PRD 110 (2024) 032001]

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

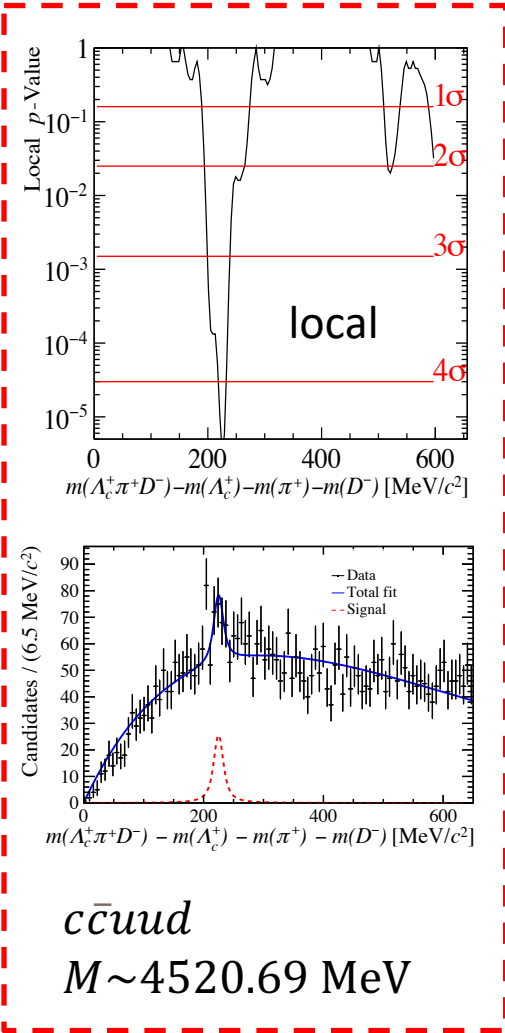
✓hidden-charm pentaquarks

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	✓

✓doubly-charmed pentaquarks & excited Ξ_{cc}

Hadron 1	Hadron 2	Charge	I_3	Y	C	Limit Set
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



- No significant signals are found
- Upper limits set on $R = \frac{N_{P_c}}{N_{\Lambda_c^+}} \times \frac{\epsilon_{\Lambda_c^+}}{\epsilon_{P_c}} \rightarrow \frac{\sigma(P_c) \times \mathcal{B}(P_c \rightarrow \Lambda_c^+ D(\pi)) \times \mathcal{B}(D)}{\sigma(\Lambda_c^+)}$
- Largest significant modes:

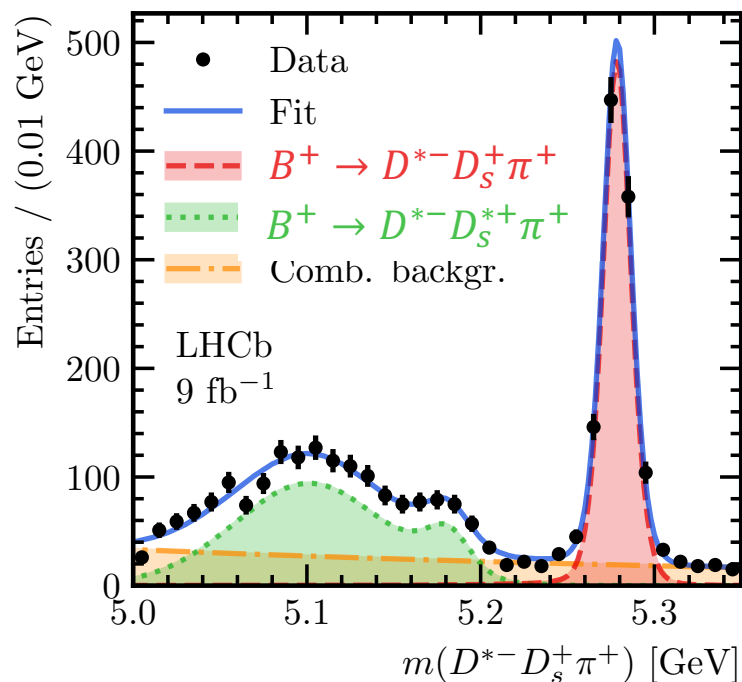
*Complete list in paper

Decay Mode	Width (MeV/c ²)	Significance (σ)		Q-value (MeV/c ²)	Signal Yield	UL (×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

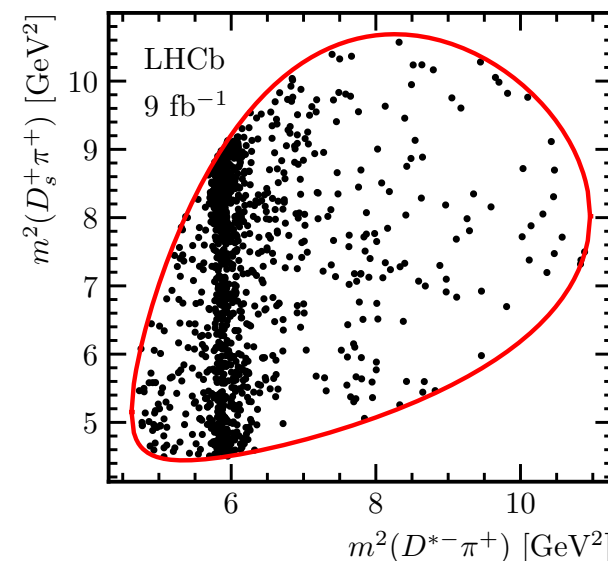
$B^+ \rightarrow D^{*-} D_s^{(*)+} \pi^+ : \text{branching fractions}$

[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]

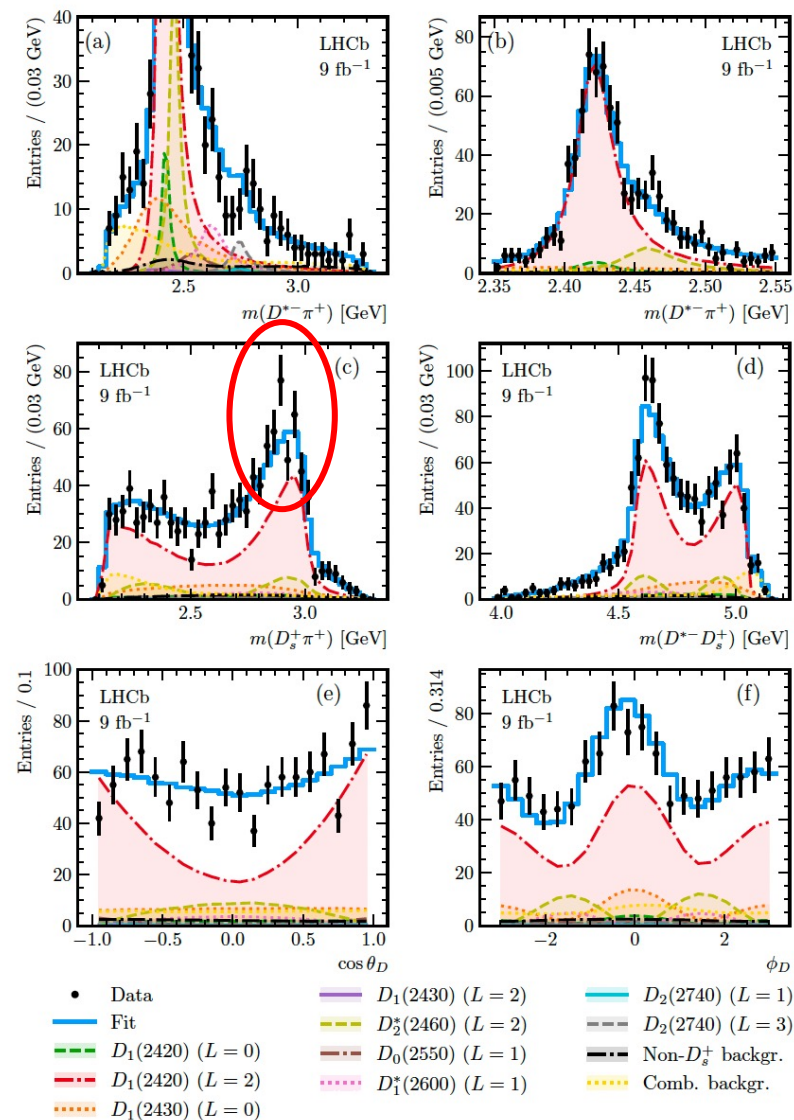
■ Baseline fit with $\bar{D}^{**0} \rightarrow D^{*-} \pi^+$ contributions

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

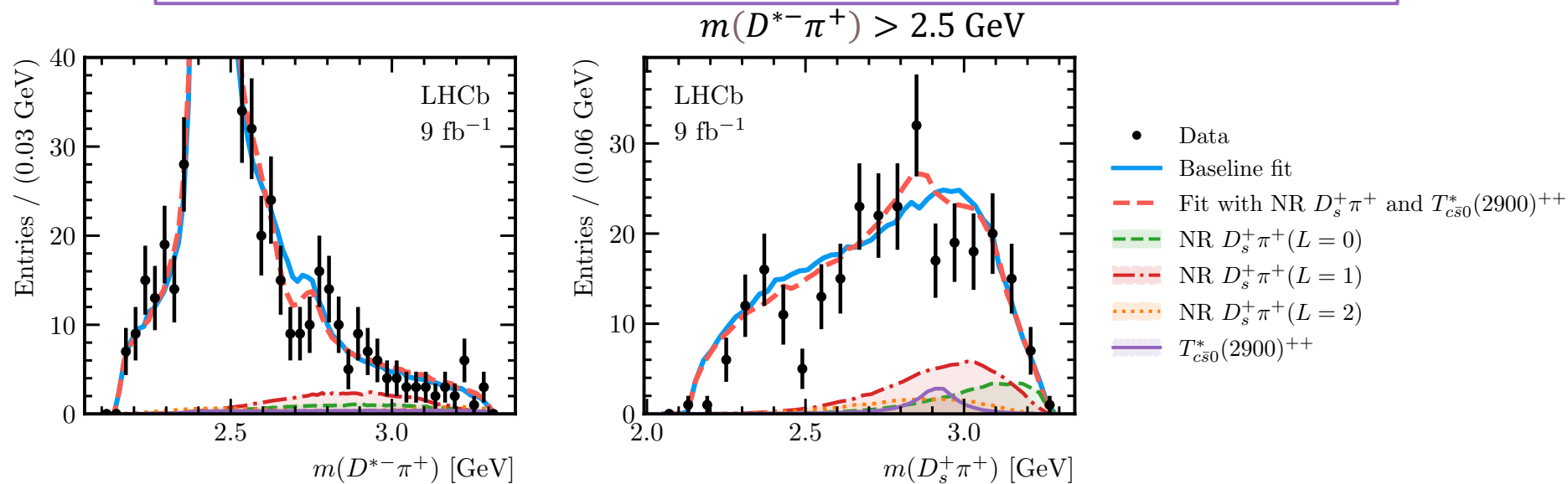
[arXiv: 2405.00098]

■ 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 $B^+ \rightarrow D^- D_s^+ \pi^+$

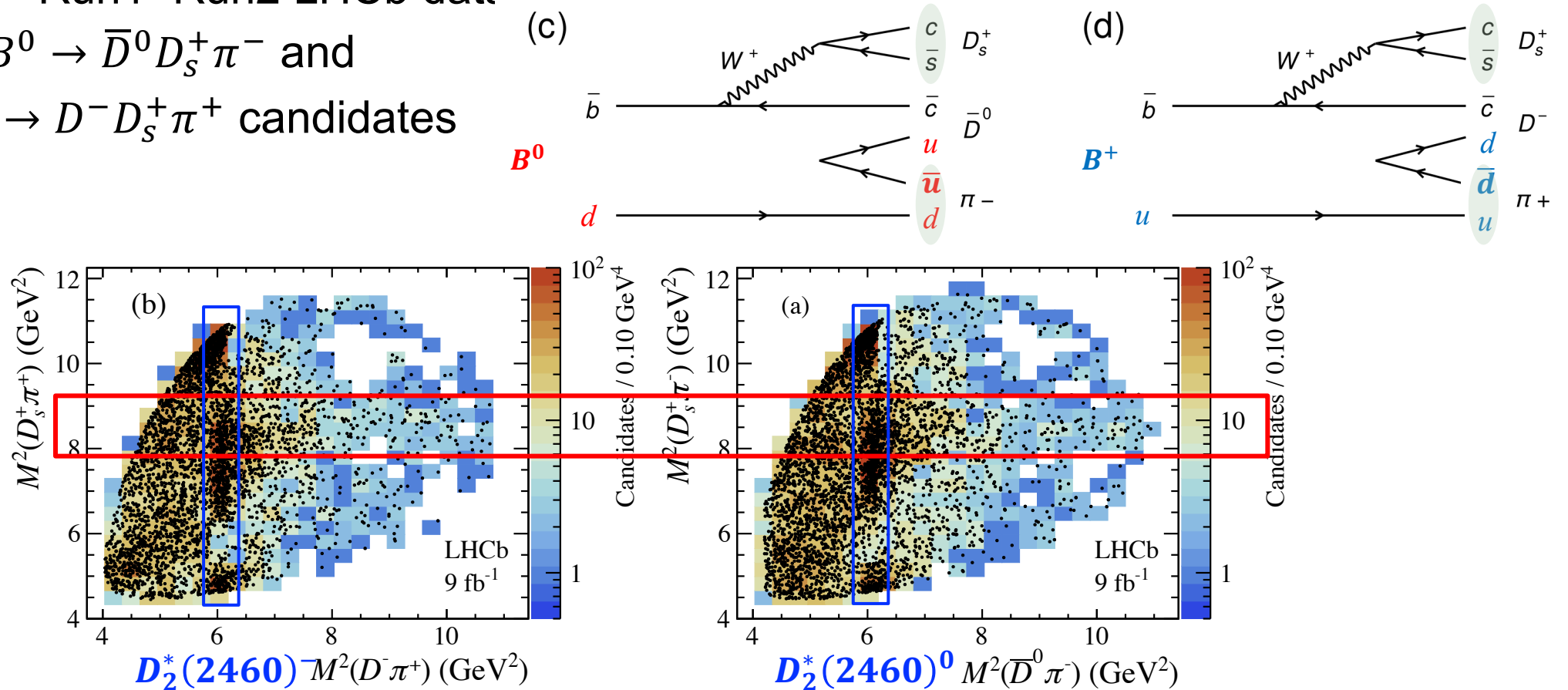


■ Fits incorporating $D^{*-} D_s^+$ amplitudes: none provides a physical description

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

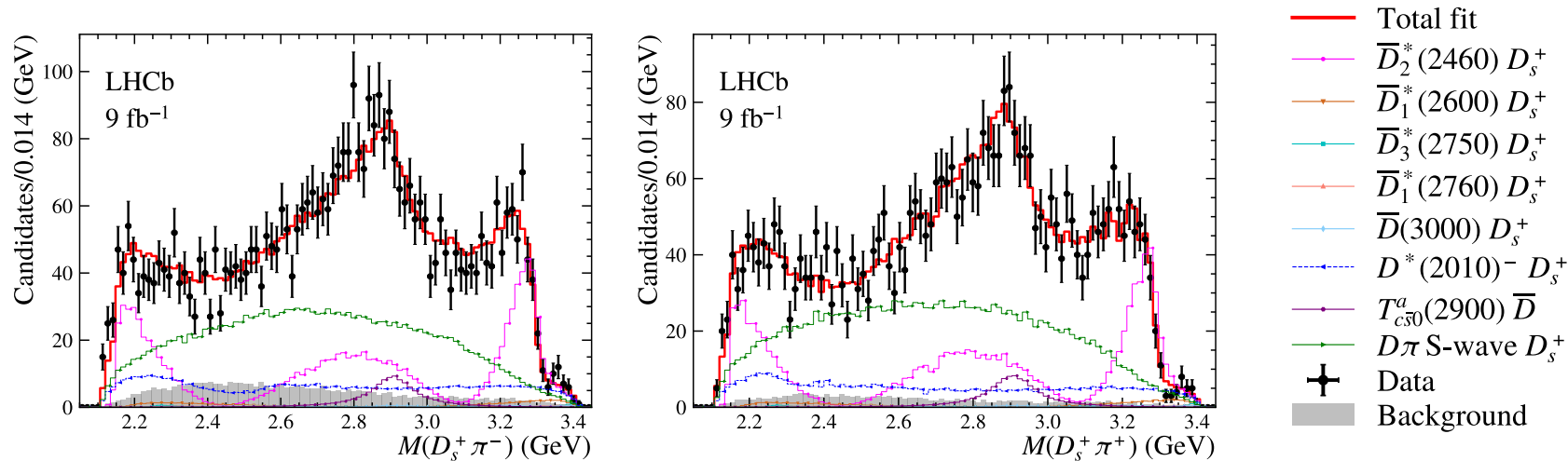


$\Rightarrow$ Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

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

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

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

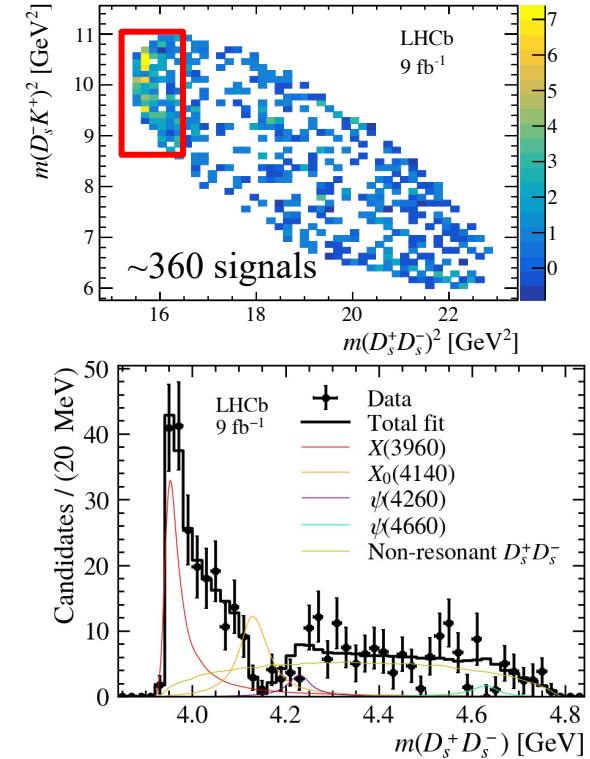
$$\text{Fit fraction} = (2.45 \pm 0.65 \pm 0.84)\%$$

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

[PRL 131 (2023) 071901]

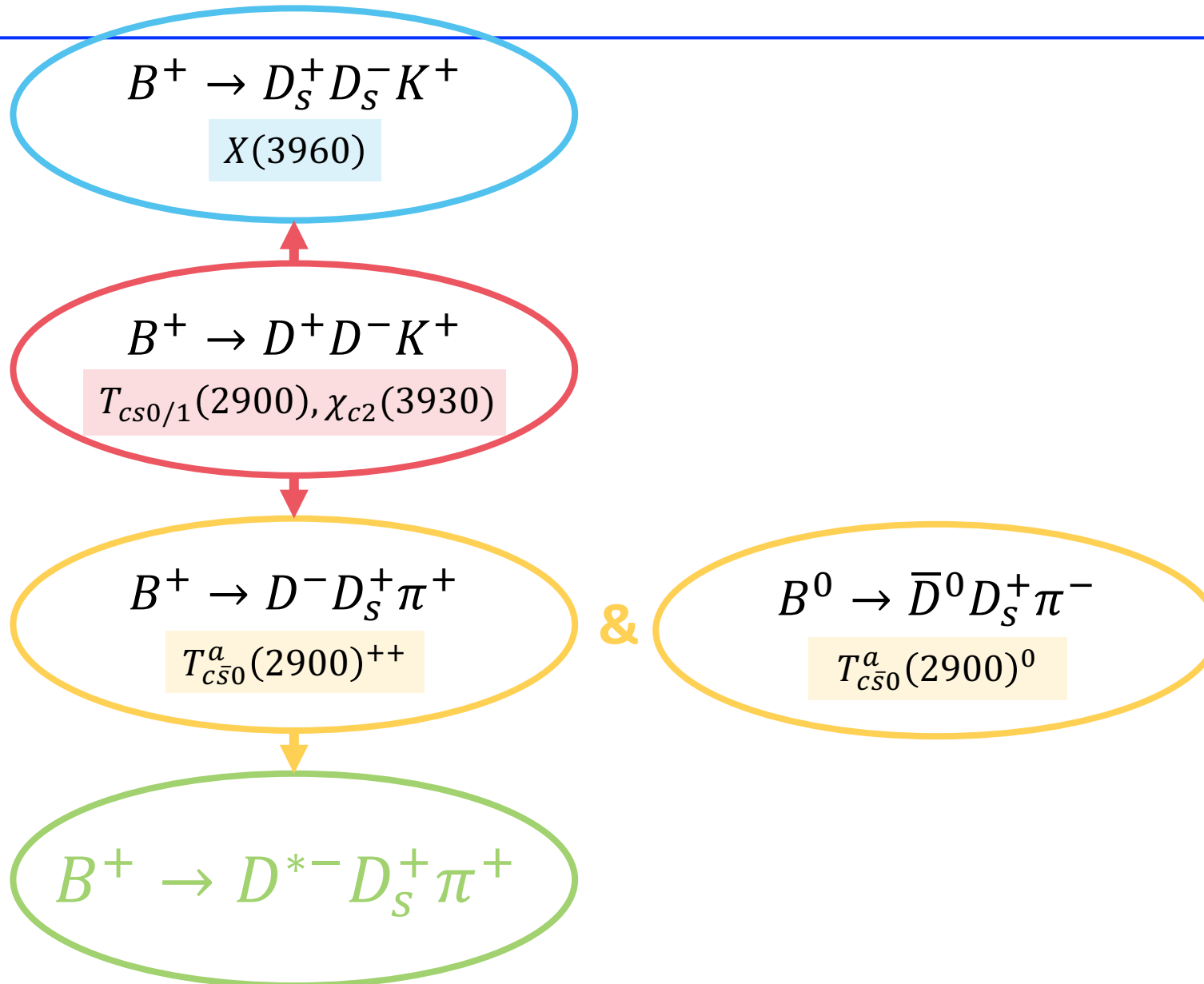
- Strong threshold enhancement found in $D_s^+ D_s^-$ system
- Amplitude analysis is performed
- **$X(3960)$** : threshold enhancement
 - $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 9.3σ and 12.3σ
 - Could be a $c\bar{c}s\bar{s}$ tetraquark predicted by Lattice QCD
- Resonance parameters are 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)

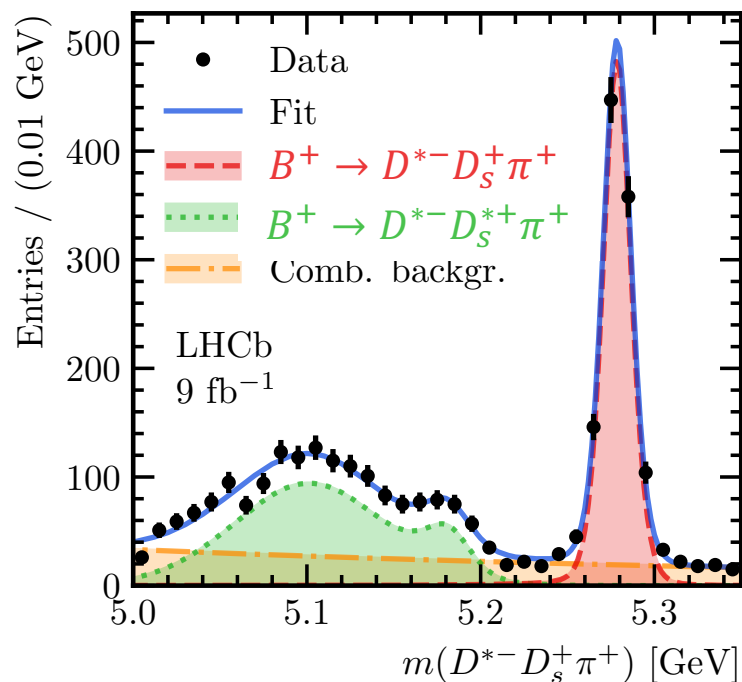
$B \rightarrow D\bar{D}h$ studies at LHCb



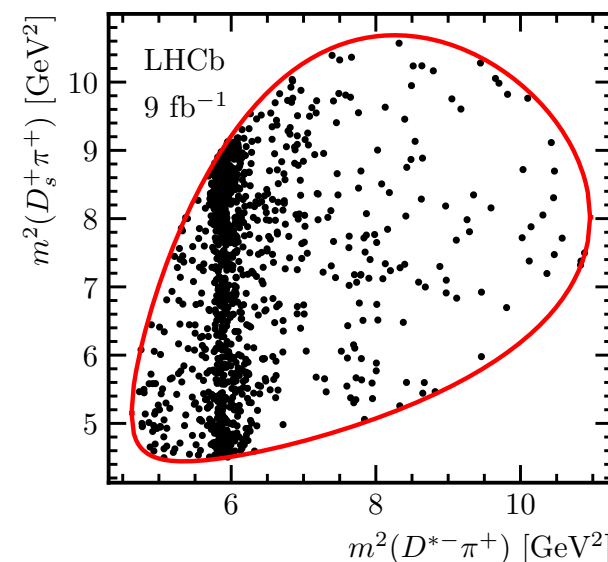
$B^+ \rightarrow D^{*-} D_s^{(*)+} \pi^+ : \text{branching fractions}$

[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]

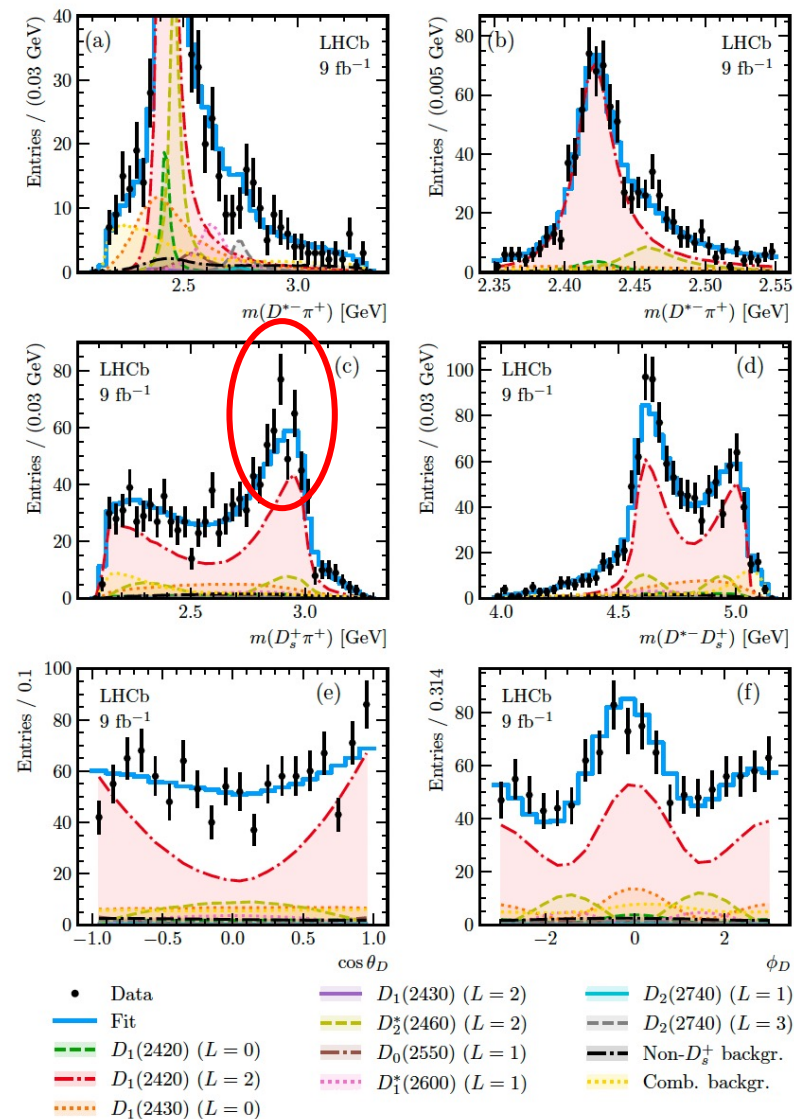
■ Baseline fit with $\bar{D}^{**0} \rightarrow D^{*-} \pi^+$ contributions

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	$0.5 \pm 0.9 \pm 1.5^{+0.2}_{-0.5}$	$-2.99 \pm 0.42 \pm 0.84^{+0.23}_{-0.55}$
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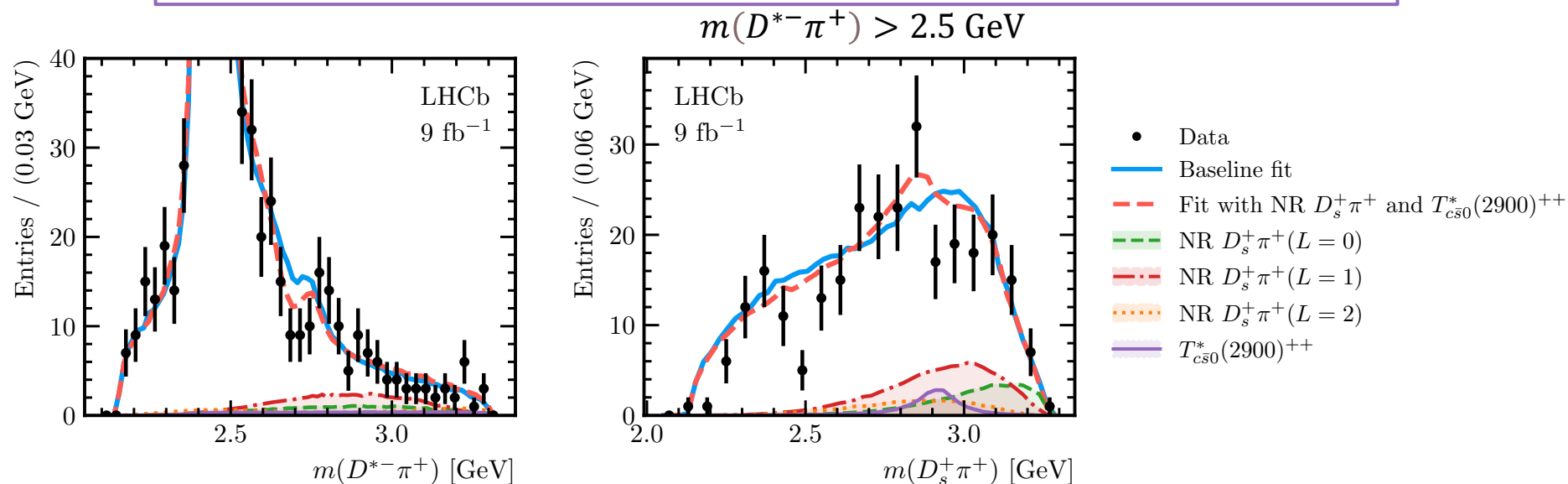
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