Hadron spectroscopy from LHCb

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On behalf of the LHCb collaboration

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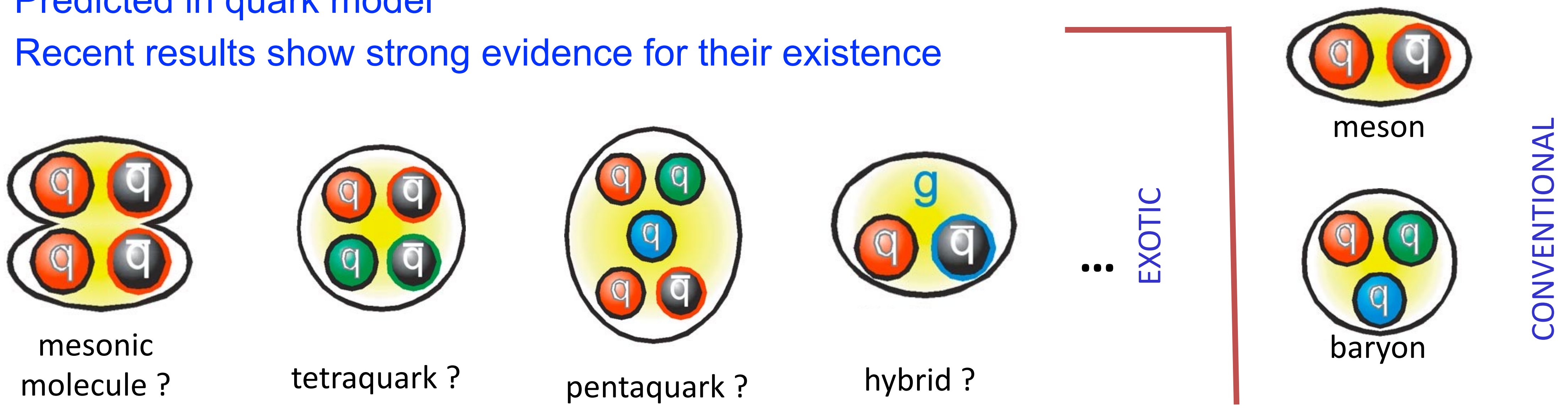
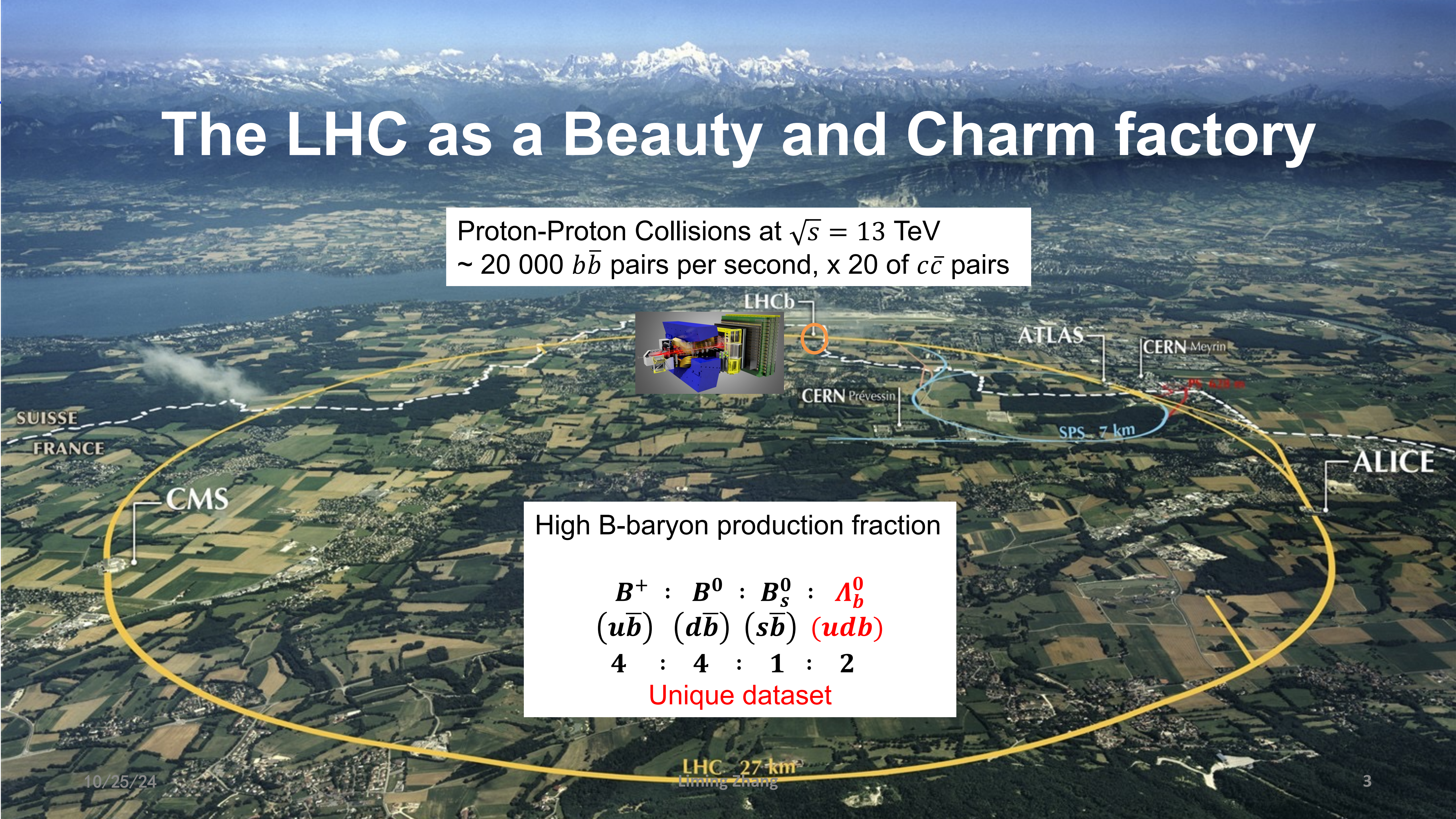
Introduction

- 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



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

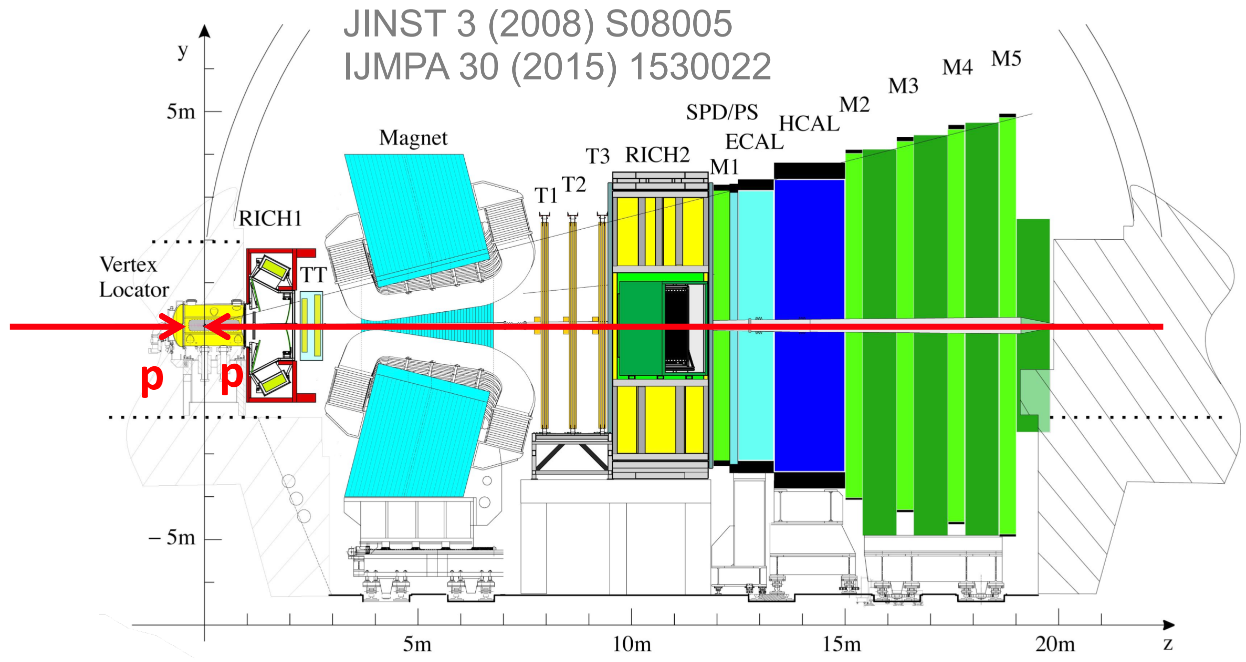
$$\begin{array}{ccccccc} B^+ & : & B^0 & : & B_s^0 & : & \Lambda_b^0 \\ (u\bar{b}) & & (d\bar{b}) & & (s\bar{b}) & & (udb) \\ 4 & : & 4 & : & 1 & : & 2 \end{array}$$

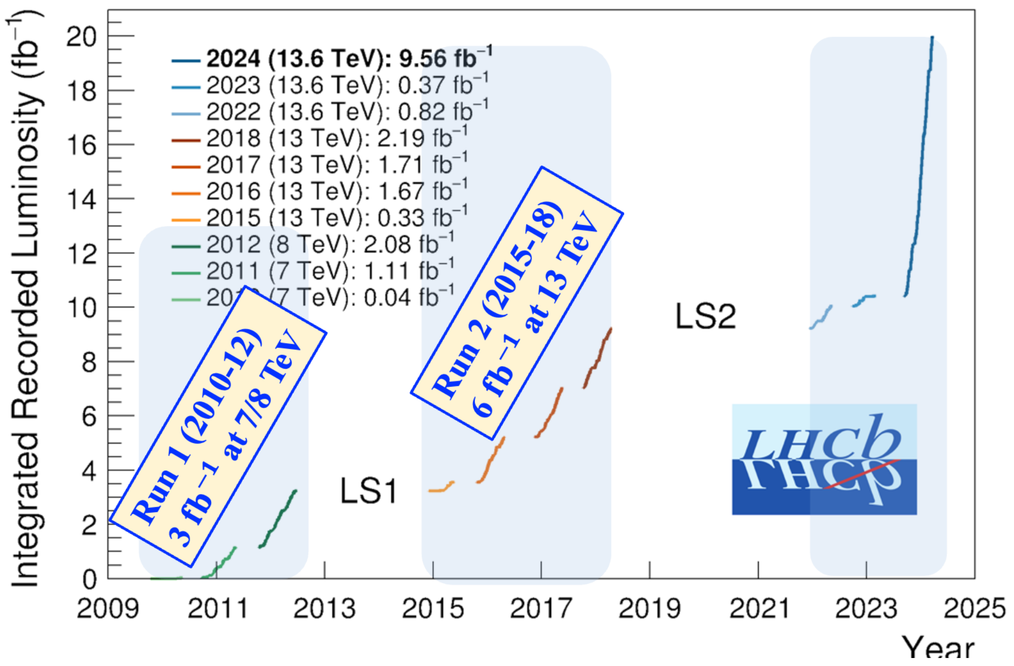
Unique dataset

The LHCb Experiment

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

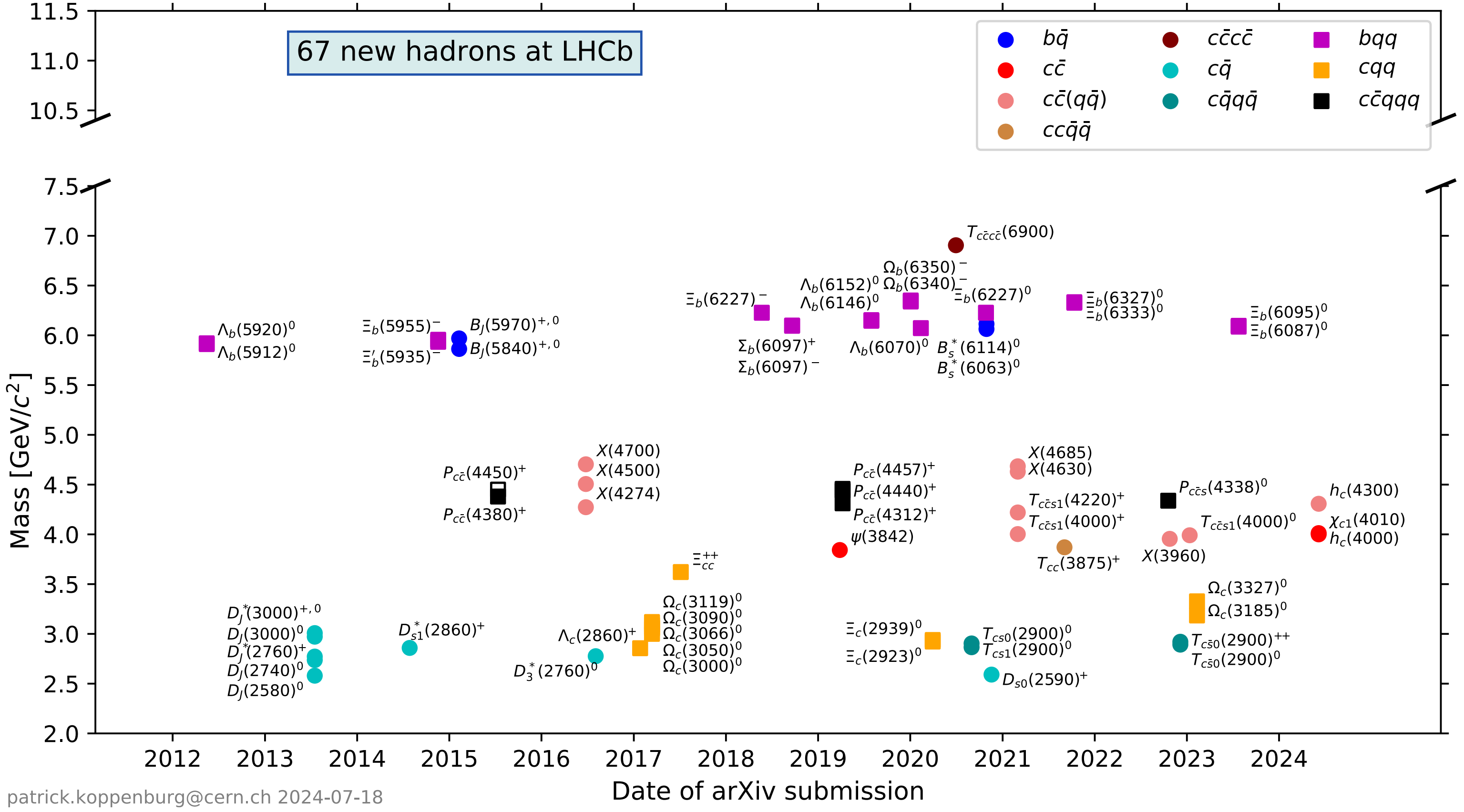




New particles in a glance

- 67 new hadrons discovered by LHCb!

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



Exotic hadron naming convention: PDG2024 $\quad Z_c \rightarrow T_{c\bar{c}J}^{(*)} \quad Z_{cs} \rightarrow T_{c\bar{c}\bar{s}J}^{(*)} \quad P_c \rightarrow P_{c\bar{c}}$

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

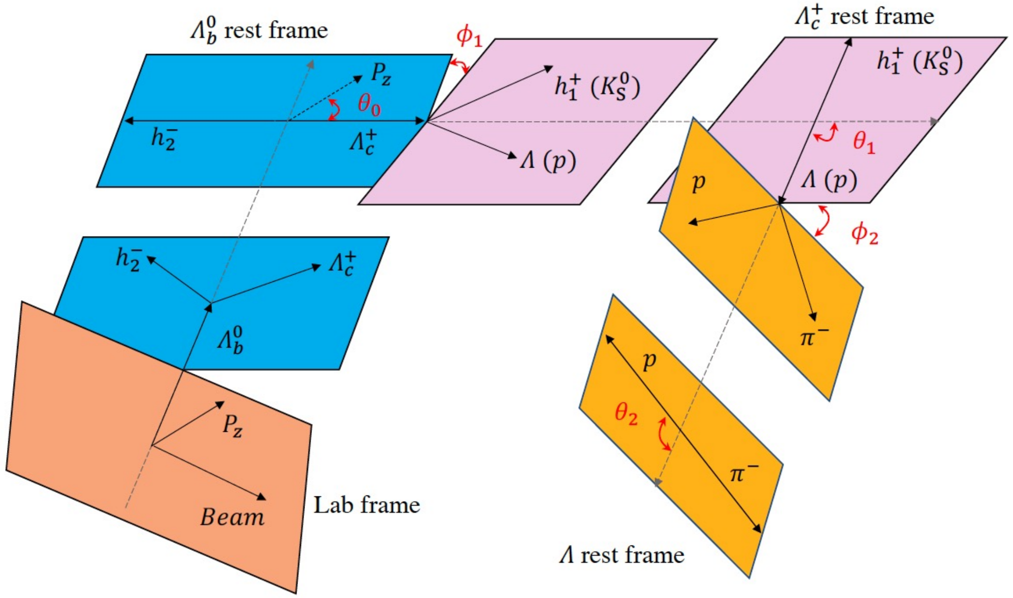
[arXiv: 2409.02759]

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

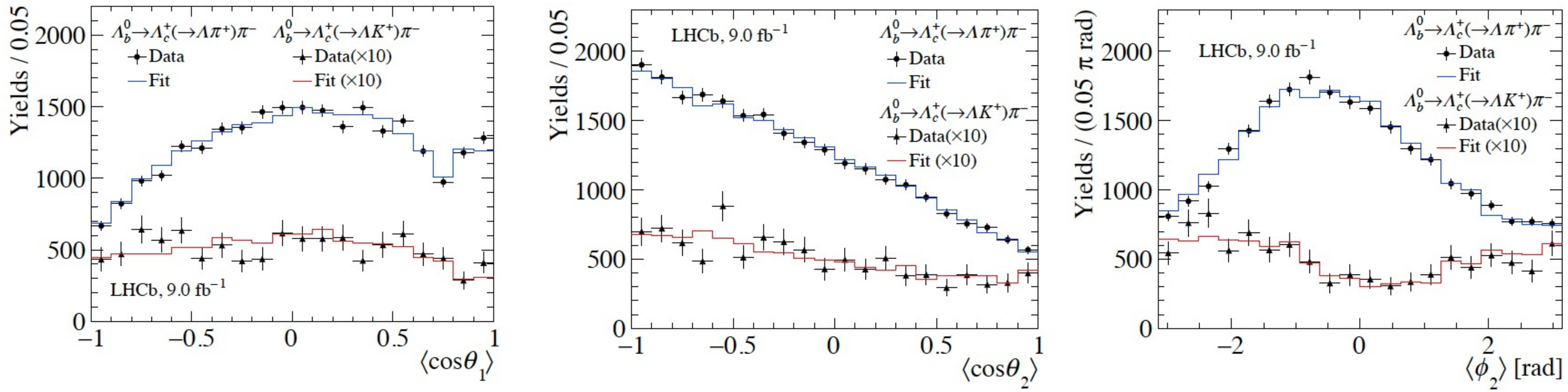
- Parameters are determined for Λ_b^0 and $\overline{\Lambda}_b^0$
- No significant CP violation is found

Other paramaters can found in the paper

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

1st measurments

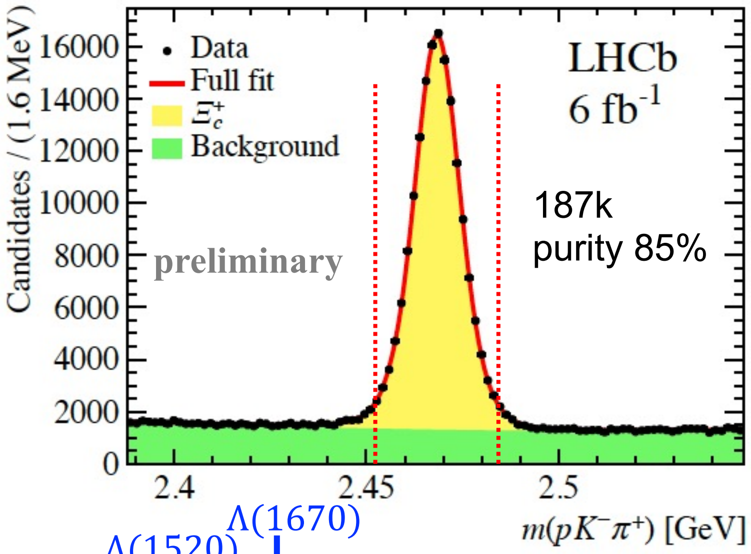
Most precise

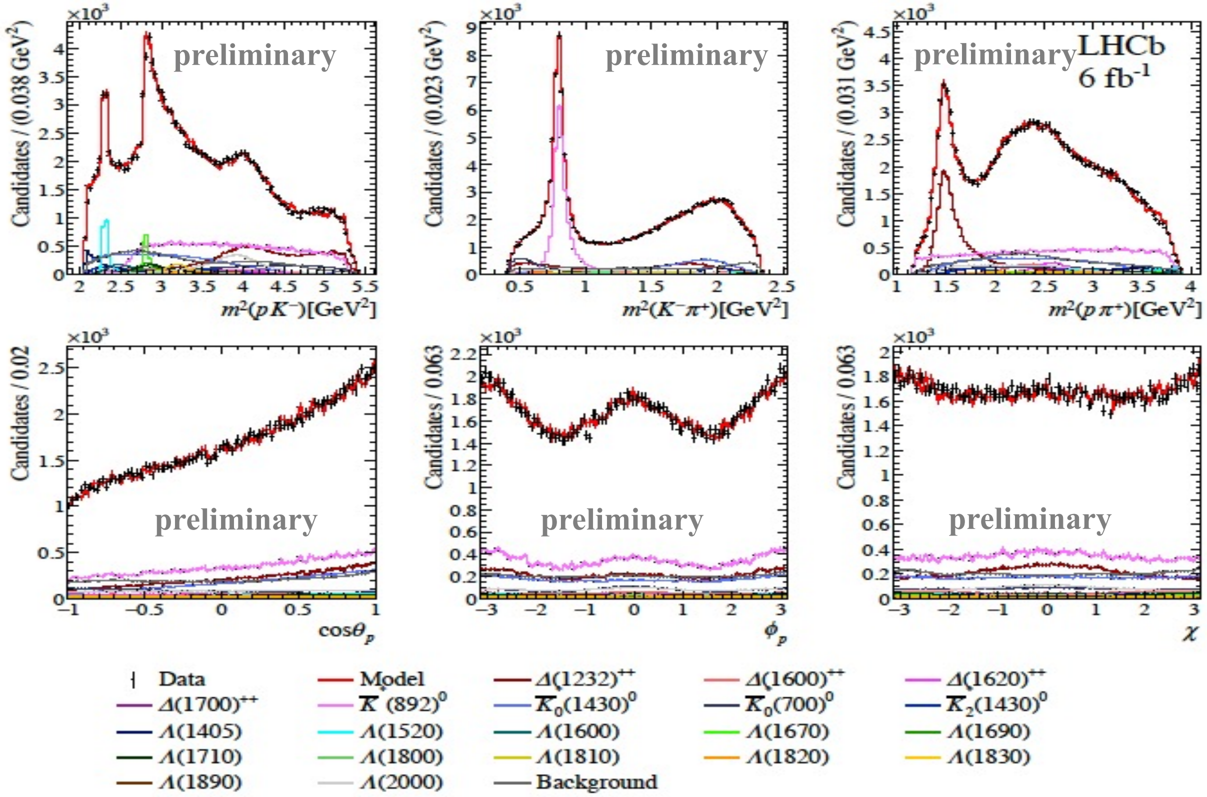


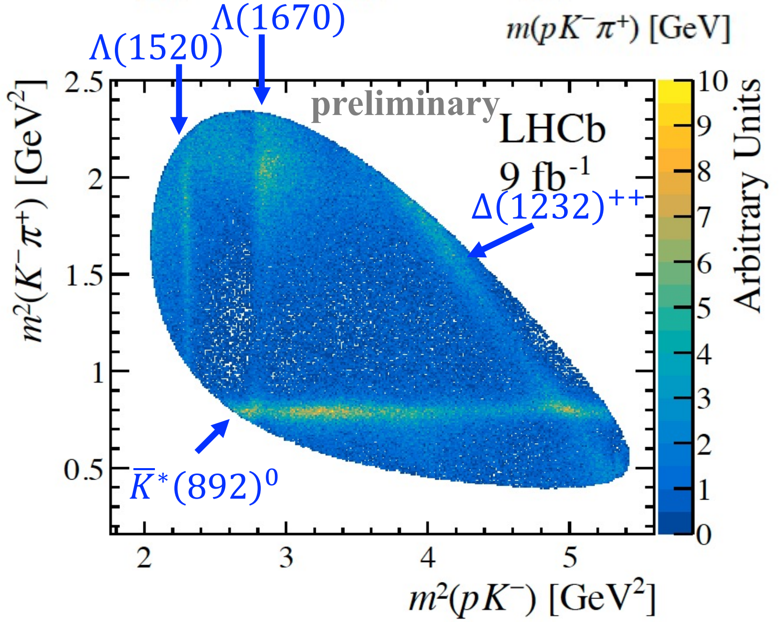
Amplitude analysis of $\Xi_c^+ \to pK^-\pi^+$ decay

LHCb-PAPER-2024-034
in preparation

- Ξ_c^+ from *B-hadron* semileptonic decay
- An amplitude model is provided, which is useful for polarization measurement of Ξ_c^+ in multiple production processes







Amplitude analysis of $\Xi_c^+ \to pK^-\pi^+$ decay

LHCb-PAPER-2024-034
in preparation

- Fit fraction

Resonance	Fit fraction (%)	Stat. unc.	Model unc.	Syst. unc.
$\Lambda(1405)$	3.1	0.2	1.5	0.2
$\Lambda(1520)$	2.69	0.08	0.10	0.04
$\Lambda(1600)$	2.4	0.3	1.4	1.0
$\Lambda(1670)$	1.85	0.09	0.17	0.11
$\Lambda(1690)$	1.51	0.12	0.18	0.42
$\Lambda(1710)$	2.6	0.3	1.1	0.4
$\Lambda(1800)$	0.42	0.13	0.54	0.15
$\Lambda(1810)$	2.04	0.28	0.86	0.17
$\Lambda(1820)$	0.806	0.086	0.053	0.079
$\Lambda(1830)$	0.24	0.05	0.10	0.03
$\Lambda(1890)$	0.24	0.05	0.17	0.04
$\Lambda(2000)$	6.88	0.34	0.86	0.82
$\overline{K}_0^*(700)^0$	6.6	0.4	1.1	0.7
$\overline{K}^*(892)^0$	28.28	0.28	0.53	0.80
$\overline{K}_0^*(1430)^0$	14.2	0.7	3.2	1.9
$\overline{K}_2^*(1430)^0$	3.07	0.21	0.65	0.68
$\Delta(1232)^{++}$	17.73	0.35	0.48	0.45
$\Delta(1600)^{++}$	4.17	0.27	0.96	0.91
$\Delta(1620)^{++}$	3.29	0.21	0.42	0.27
$\Delta(1700)^{++}$	2.03	0.17	0.36	0.15

preliminary

- Polarization and decay parameters

Resonance	α	Stat. unc.	Model unc.	Syst. unc.
Model $\sqrt{3}S$	0.6801	0.0055	0.0093	0.0088
$\overline{K}^*(892)^0$ $\sqrt{3}S$	0.608	0.016	0.010	0.014
$\overline{K}_2^*(1430)^0$ $\sqrt{3}S$	0.42	0.05	0.10	0.08
$\Lambda(1405)$	−0.67	0.09	0.14	0.08
$\Lambda(1520)$	−0.759	0.038	0.052	0.056
$\Lambda(1600)$	−0.06	0.11	0.21	0.08
$\Lambda(1670)$	−0.65	0.06	0.06	0.11
$\Lambda(1690)$	−0.65	0.07	0.07	0.12
$\Lambda(1710)$	−0.83	0.09	0.12	0.06
$\Lambda(1800)$	−0.10	0.30	0.71	0.71
$\Lambda(1810)$	0.86	0.06	0.11	0.08
$\Lambda(1820)$	0.70	0.07	0.13	0.21
$\Lambda(1830)$	−0.01	0.19	0.91	0.41
$\Lambda(1890)$	−0.27	0.19	0.35	0.21
$\Lambda(2000)$	0.51	0.04	0.12	0.05
$\overline{K}_0^*(700)^0$	0.648	0.038	0.065	0.058
$\overline{K}_0^*(1430)^0$	−0.745	0.028	0.078	0.054
$\Delta(1232)^{++}$	−0.743	0.020	0.040	0.019
$\Delta(1600)^{++}$	0.33	0.06	0.17	0.06
$\Delta(1620)^{++}$	0.11	0.06	0.10	0.22
$\Delta(1700)^{++}$	0.30	0.07	0.17	0.24

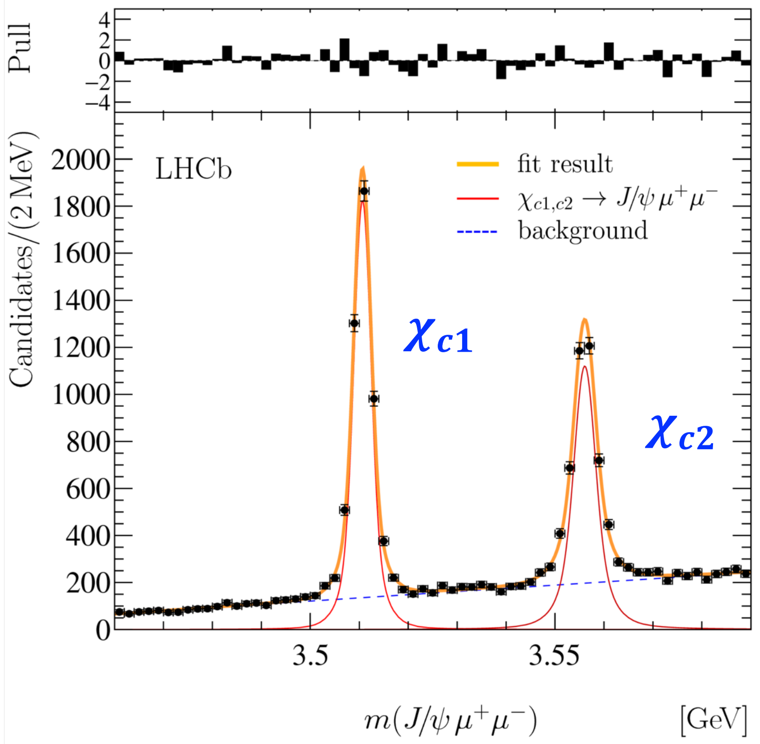
preliminary

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

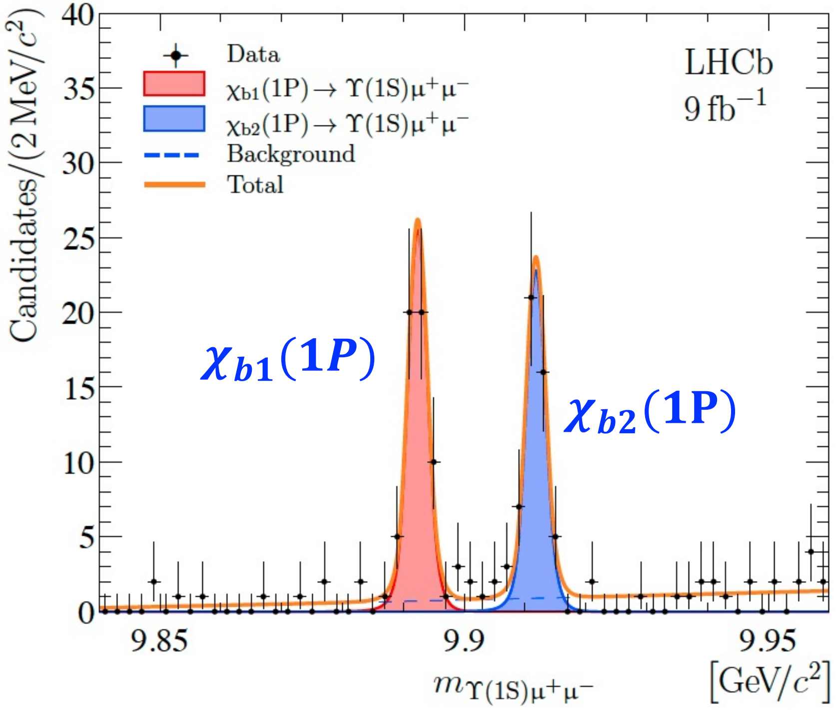
- 1st observation of $\chi_{c1,2} \to J/\psi\mu^+\mu^-$ in 2017
- 1st observation of $\chi_{b1,2} \to \Upsilon(1S)\mu^+\mu^-$ in 2024
- Competitive mass and width measurements

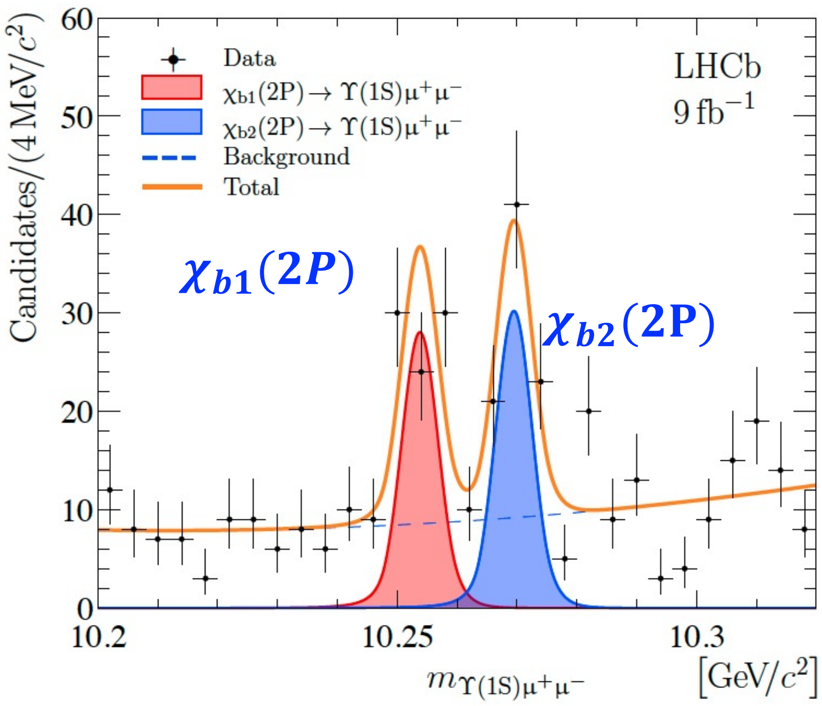
$$m_{\chi_{b1}(1P)} = 9\,892.50 \pm 0.26 \pm 0.10 \pm 0.10\,\mathrm{MeV}/c^2\,,$$
$$m_{\chi_{b2}(1P)} = 9\,911.92 \pm 0.29 \pm 0.11 \pm 0.10\,\mathrm{MeV}/c^2\,,$$
$$m_{\chi_{b1}(2P)} = 10\,253.97 \pm 0.75 \pm 0.22 \pm 0.09\,\mathrm{MeV}/c^2\,,$$
$$m_{\chi_{b2}(2P)} = 10\,269.67 \pm 0.67 \pm 0.22 \pm 0.09\,\mathrm{MeV}/c^2\,,$$

[PRL 119 (2017) 221801]

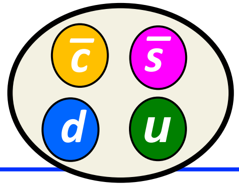


[JHEP 10 (2024) 122]



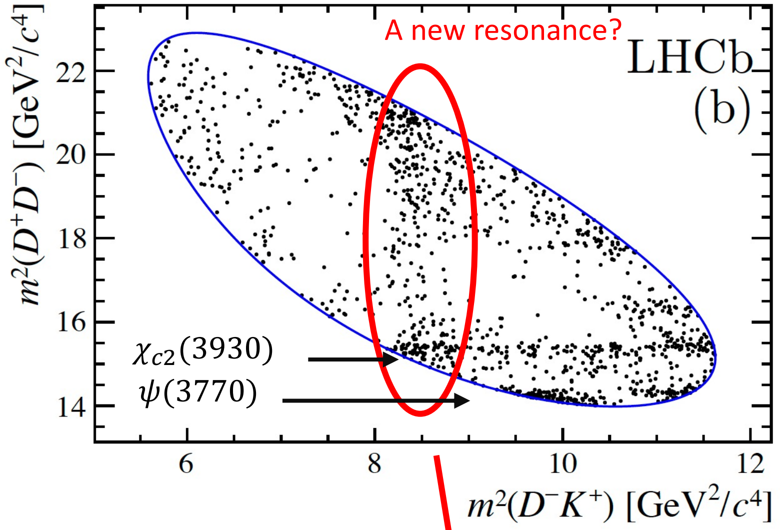


Observation of $T_{cs} \to D^- K^+$



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

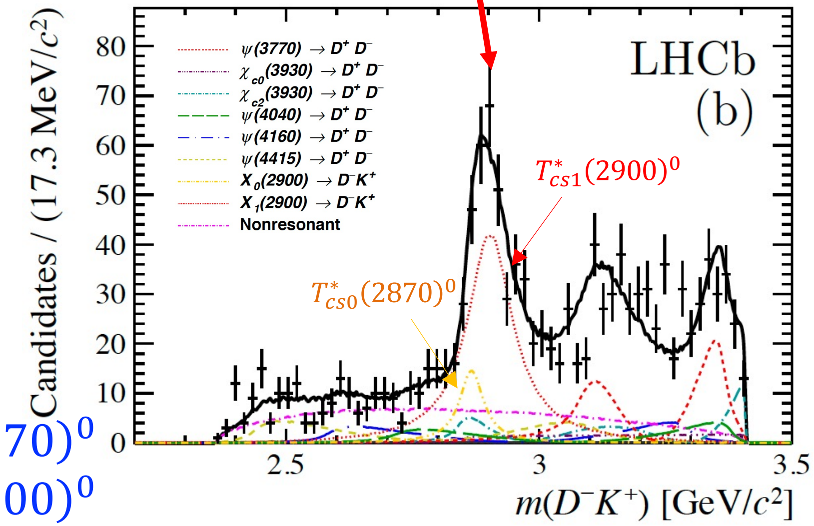
- Amplitude analysis of $\boldsymbol{B^+ \to D^+ D^- K^+}$ decays
  - ~1300 signals with purity 99.5% (9fb^{-1})
- Enhancement in $m^2(D^- K^+)$~8.5GeV^{-2}
- Described by $X_1(2900)$ and $X_0(2900)$
- **First discovery of open-charm tetraquarks with four different flavors $[cs\bar{u}\bar{d}]$!**



- The observation motivates study of $B \to \bar{D} D_s \pi$

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

$T^*_{c\bar{s}0}(2870)^0$
$T^*_{c\bar{s}1}(2900)^0$



$T^*_{cs0}(2870)^0$ decay into a different channel

LHCb-PAPER-2024-040
in preparation

- **Amplitude analysis of $B^+ \to D^- D^0 K^0_S$ finding $T^*_{\bar{c}\bar{s}0}(2870)^0$, but not $T^*_{\bar{c}\bar{s}1}(2900)^0$ to $D^0 K^0_S$**

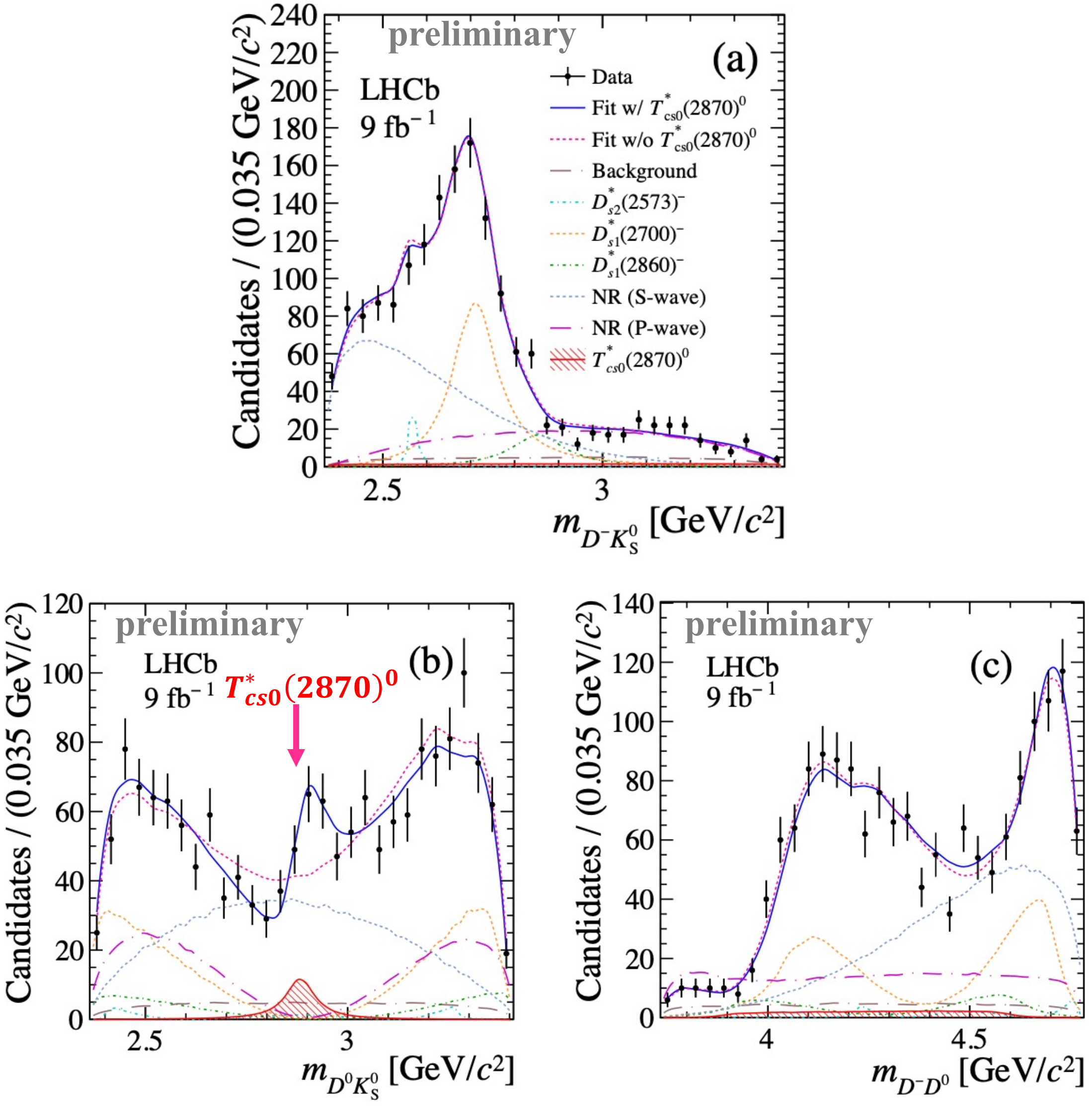
- **$T^*_{cs0}(2870)^0$**
  - **Significance of 5.3 σ**
  - **$m = 2883 \pm 11 \pm 6$ MeV**
  - **$\Gamma = 87^{+22}_{-47} \pm 6$ MeV**

- Branching fraction ratio

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

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

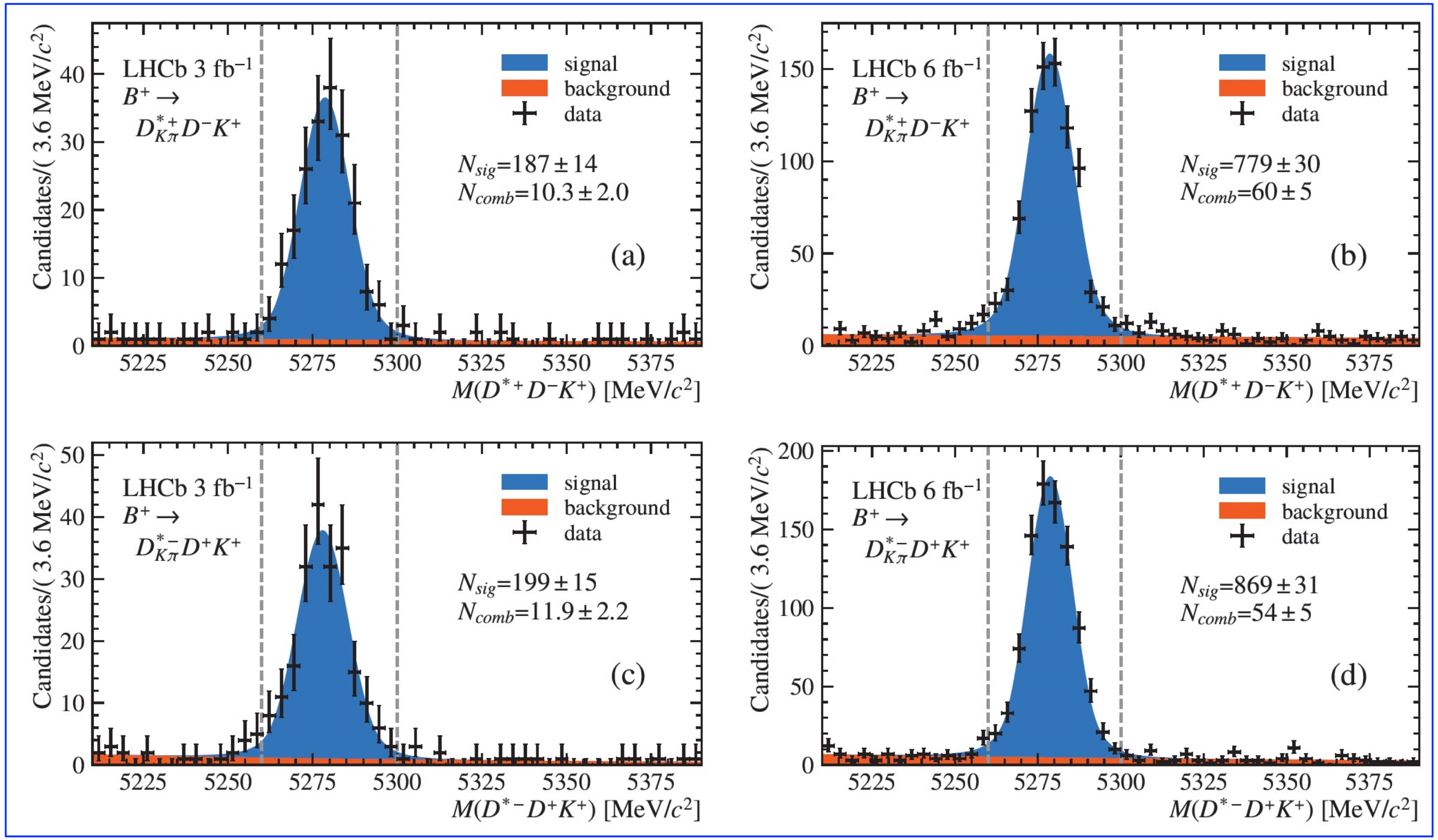
Isospin symmetry: two ratio should be 1



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

[arXiv: 2406.03156]
accepted by PRL

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

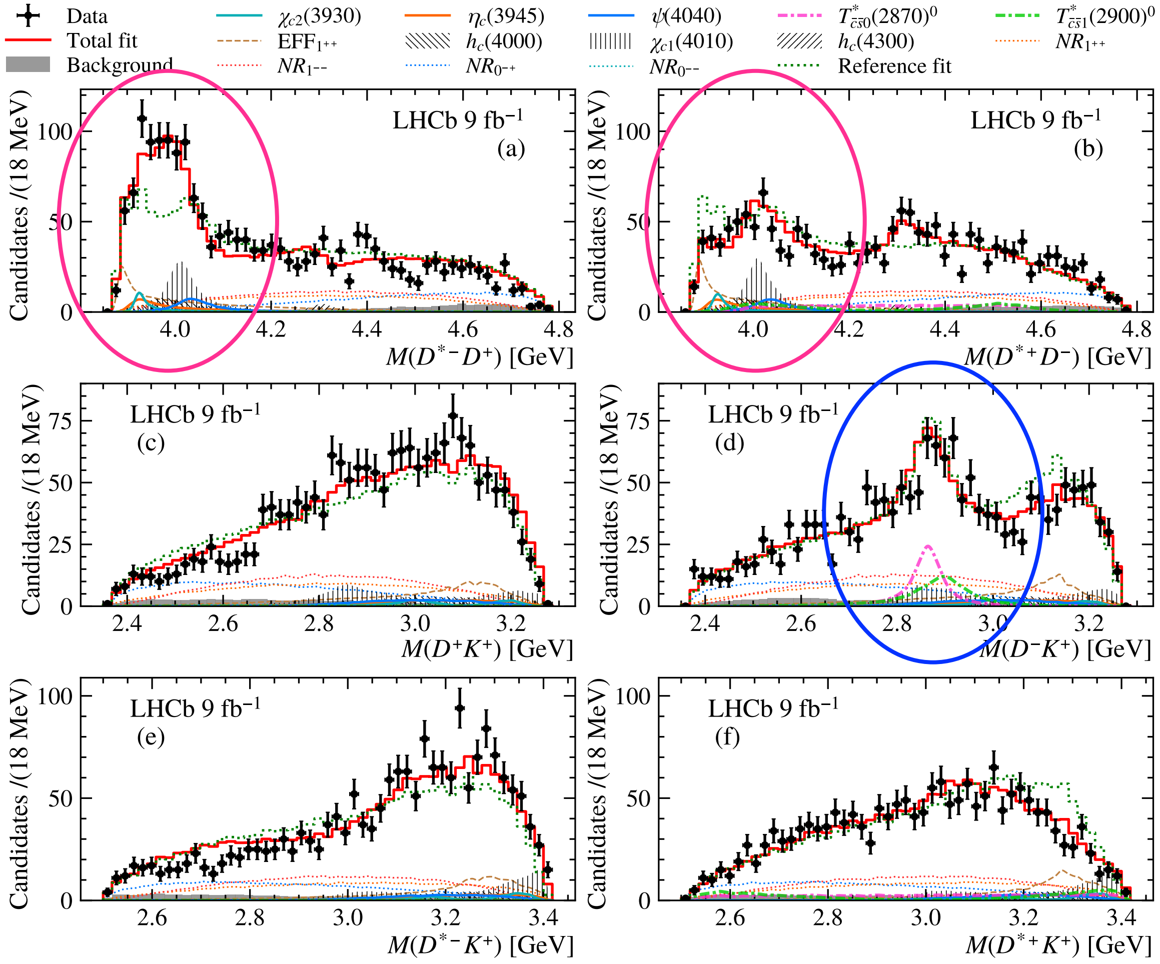


✓ $B^+ \to D^{*+} D^- K^+$: **966**
✓ $B^+ \to D^{*-} D^+ K^+$: **1068**

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

[arXiv: 2406.03156]
accepted by PRL

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



Component	$J^{P(C)}$
$\mathrm{EFF}_{1^{++}}$	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^-
$\mathrm{NR}_{1^{--}}(D^{*\mp}D^\pm)$	1^{--}
$\mathrm{NR}_{0^{--}}(D^{*\mp}D^\pm)$	0^{--}
$\mathrm{NR}_{1^{++}}(D^{*\mp}D^\pm)$	1^{++}
$\mathrm{NR}_{0^{-+}}(D^{*\mp}D^\pm)$	0^{-+}

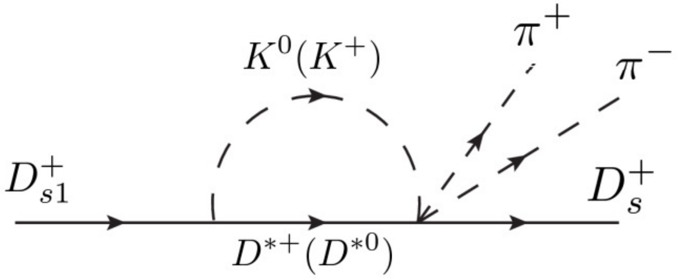
- Four new charmonium (-like) states are observed for >6.1σ
- J^{PC} for each state is determined for >5.7σ

- $T^*_{\bar{c}\bar{s}}$ states, seen in $B^+ \to D^+D^-K^+$, are confirmed in $B^+ \to D^{*+}D^-K^+$ decays

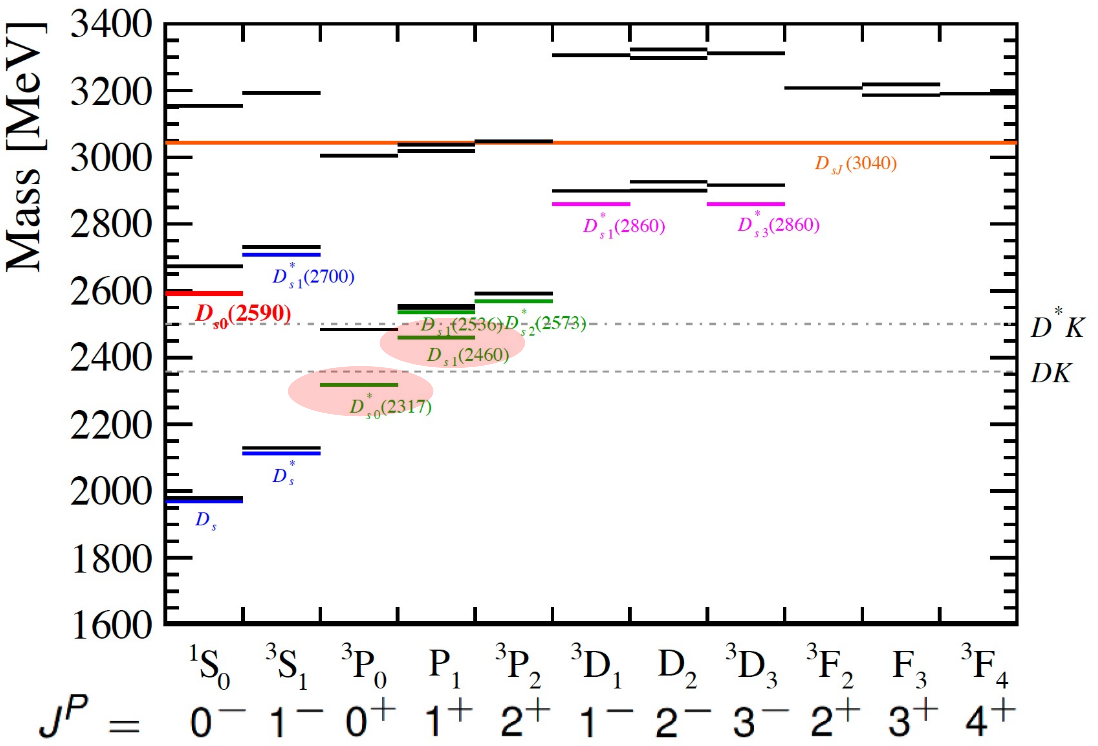
Study of $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ decay

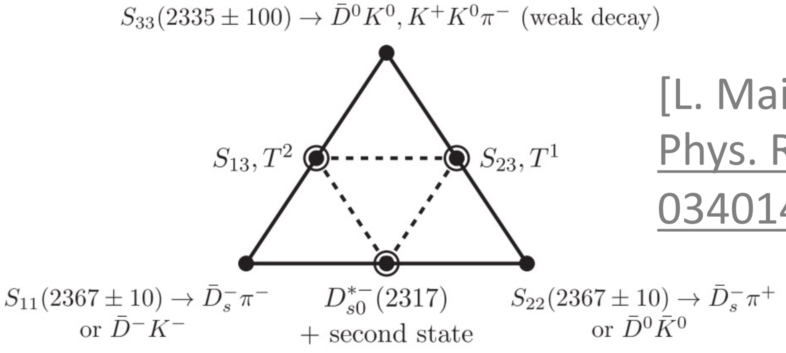
- $D_{s0}^*(2317)$ and $D_{s1}(2460)$ are very special
  - Masses ~100 MeV below expectation
  - Isospin-violating decay $D_s^{(*)+}\pi^0$ dominate
- Propose to study of $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$
  - Double-bump lineshape in $m(\pi\pi)$ if $D_{s1}(2460)^+$ is a D^*K hadronic molecule

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



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



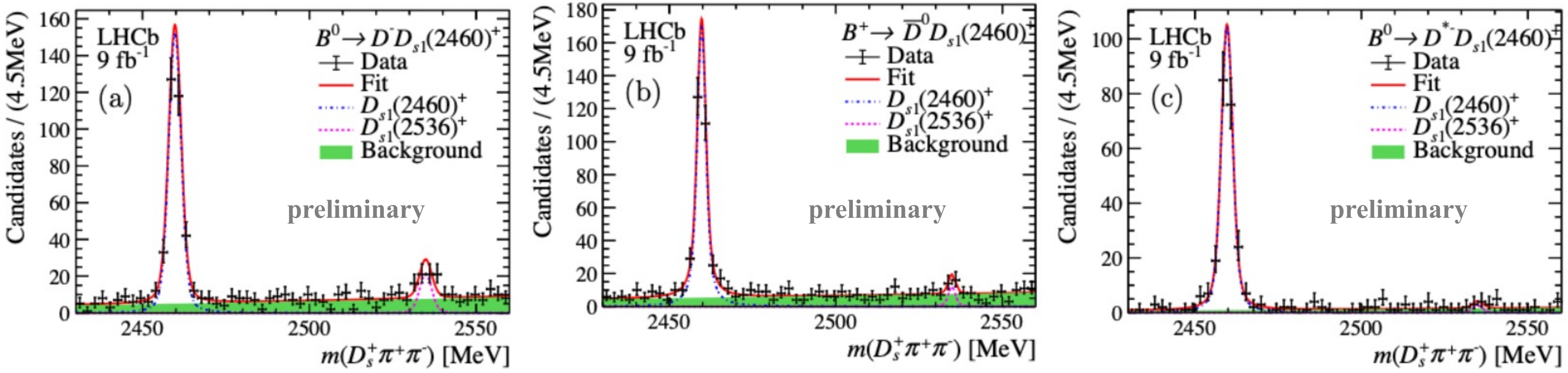


[L. Maiani *et. al.* Phys. Rev. D **110**, 034014]

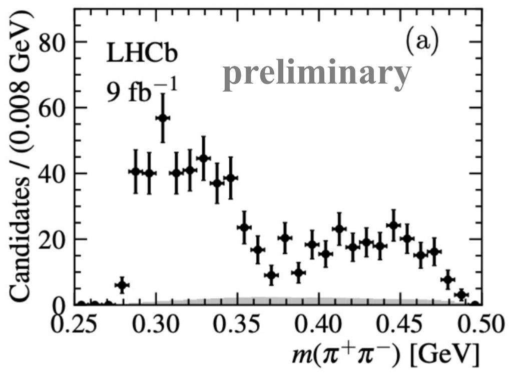
Study of $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$ decay

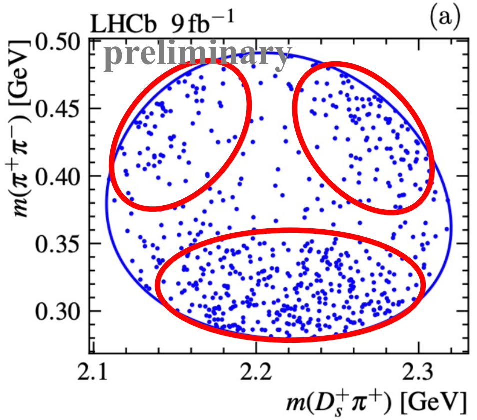
LHCb-PAPER-2024-033
in preparation

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



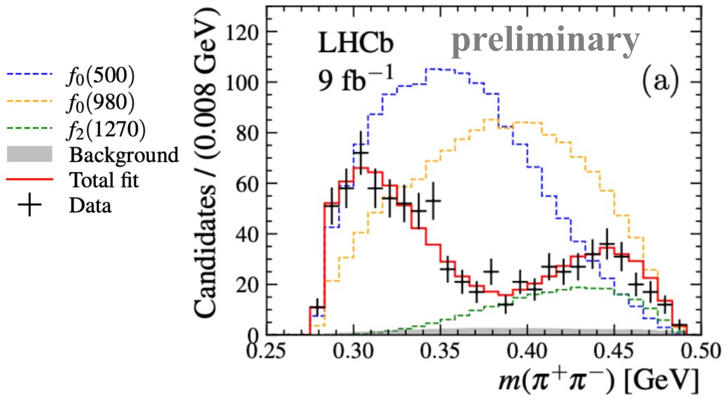


Two resonance models can fit the data well

LHCb-PAPER-2024-033
in preparation

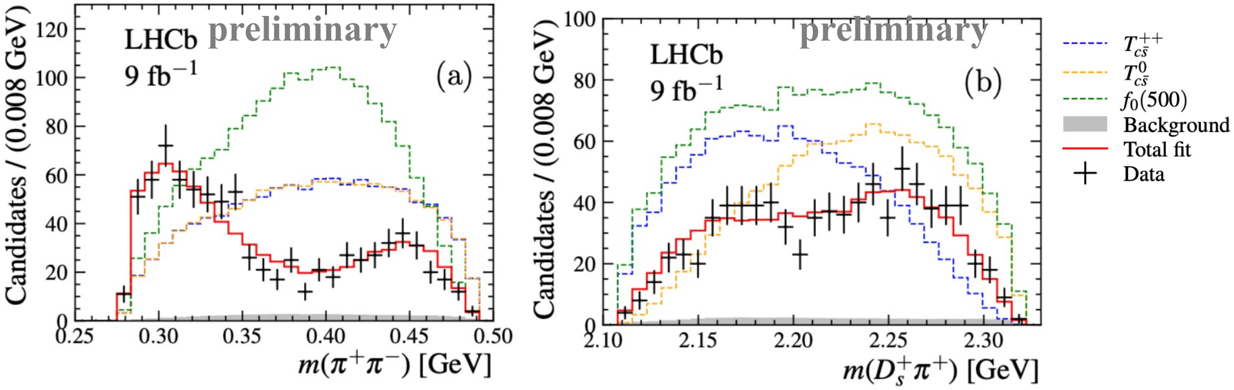
- $f_0(500) + f_0(980) + f_2(1270)$
  - Large contribution from $f_0(980)$ and $f_2(1270)$ above PHSP of $m(\pi\pi)$
  - This model cannot rejected, but implausible

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	$29 \pm 2 \pm 1$



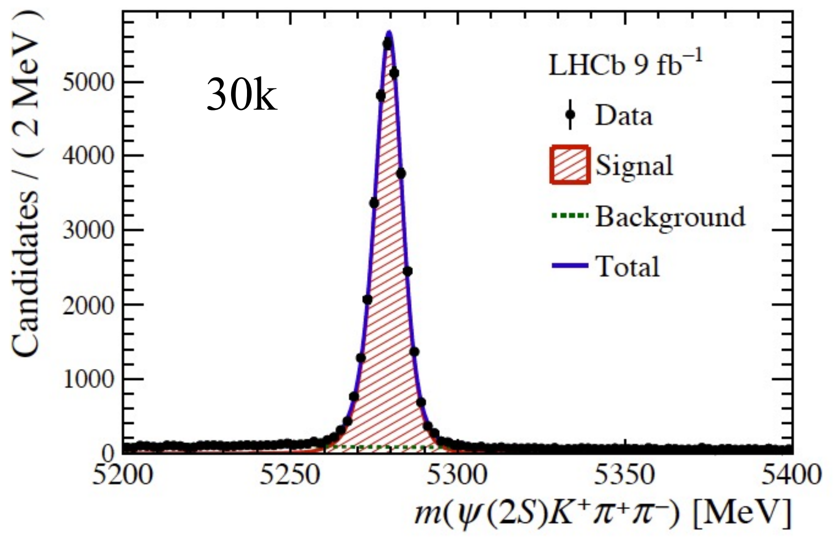
- $f_0(500) + T_{c\bar{s}}^{++} + T_{c\bar{s}}^{0}$ (new exotics)

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



$B^+ \to \psi(2S)K^+\pi^+\pi^-$: amplitude analysis [arXiv: 2407.12475]

- Can study $K^+\pi^+\pi^-$ system, crucial for NP studies of $B \to K\pi\pi(\gamma/\mu\mu)$
- 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

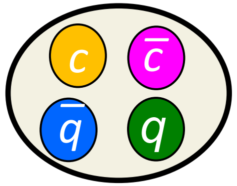


Decay channel	Fit fraction [%]
$B^+ \to \chi_{c0}(4475)K^+$	$18.45 \pm 1.31 \pm 2.92$
$B^+ \to \psi(2S)\, K^*(1680)^+$	$8.15 \pm 1.31 \pm 3.51$
$B^+ \to \psi(2S)\, K_1(1270)^+$	$7.60 \pm 0.85 \pm 1.35$
$B^+[P] \to \psi(2S)\, K_1(1270)^+$	$7.52 \pm 0.60 \pm 1.08$
$B^+[D] \to \psi(2S)\, K_1(1270)^+$	$6.81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

……

Exotic contributions

[arXiv: 2407.12475]



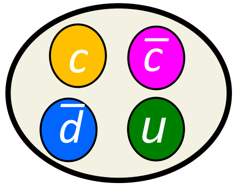
- 4 $X^0 \to \psi(2S)\pi^+\pi^-$ states are identified
  - Main decay mode is $\boldsymbol{\psi(2S)\rho^0}$
  - Similar but broader that the states observed in $B^+ \to \boldsymbol{J/\psi\phi}K^+$
  - But they might not the same, $\psi(2S)\rho^0$ has I=1, $J/\psi\phi$ has I=0

Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Res. PDG	m_0 [MeV]	Γ_0 [MeV]
$\chi_{c0}(4475)$	0^+	$4475\pm 7\pm12$	$231\pm19\pm32$	$\chi_{c0}(4500)$	4474 ± 4	77^{+12}_{-10}
$\chi_{c1}(4650)$	1^+	$4653\pm14\pm27$	$227\pm26\pm22$	$\chi_{c1}(4685)$	4684^{+15}_{-17}	126 ± 40
$\chi_{c0}(4710)$	0^+	$4710\pm 4\pm5$	$64\pm 9\pm10$	$\chi_{c0}(4700)$	4694^{+16}_{-5}	87^{+18}_{-10}
$\eta_{c1}(4800)$	1^-	$4785\pm37\pm119$	$457\pm93\pm157$	$X(4630)$	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^+	$4257\pm11\pm17$	$308\pm20\pm32$	$T_{c\bar{c}1}(4200)^+$	4196^{+35}_{-32}	370^{+100}_{-150}
$T_{c\bar{c}1}(4430)^+$	1^+	$4468\pm21\pm80$	$251\pm42\pm82$	$T_{c\bar{c}1}(4430)^+$	4478^{+15}_{-18}	181 ± 31
$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	$4578\pm10\pm18$	$133\pm28\pm69$			
$T_{c\bar{c}\bar{s}1}(4900)^0$	1^+	$4925\pm22\pm47$	$255\pm55\pm127$			
$T^*_{c\bar{c}\bar{s}1}(5200)^0$	1^-	$5225\pm86\pm181$	$226\pm76\pm374$			
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	$T_{c\bar{c}\bar{s}1}(4000)^+$	4003^{+7}_{-15}	131 ± 30

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

Exotic contributions

[arXiv: 2407.12475]



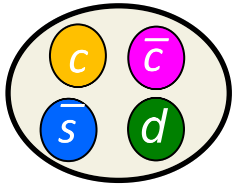
- 3 $T_{c\bar{c}}^{(*)} \to \psi(2S)\pi$ states are identified
  - Confirmed $\boldsymbol{Z_c(4430)^+}$ seen in $\bar{B}^0 \to \psi(2S)\pi^+K^-$
  - Confirmed $\boldsymbol{Z_c(4200)^+}$ seen in $\bar{B}^0 \to J/\psi\pi^+K^-$, and $J^P = 1^+$ is determined for the 1st time
  - $T_{c\bar{c}}(4055)^+$ seen in $e^+e^- \to \psi(2S)\pi^+\pi^-$ is also needed

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

Exotic contributions

[arXiv: 2407.12475]

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



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

Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Res. PDG	m_0 [MeV]	Γ_0 [MeV]
$\chi_{c0}(4475)$	0^+	$4475\pm 7\pm12$	$231\pm19\pm32$	$\chi_{c0}(4500)$	4474 ± 4	77^{+12}_{-10}
$\chi_{c1}(4650)$	1^+	$4653\pm14\pm27$	$227\pm26\pm22$	$\chi_{c1}(4685)$	4684^{+15}_{-17}	126 ± 40
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$\eta_{c1}(4800)$	1^-	$4785\pm37\pm119$	$457\pm93\pm157$	$X(4630)$	4626^{+24}_{-110}	174^{+140}_{-80}
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$T_{c\bar{c}1}(4200)^+$	1^+	$4257\pm11\pm17$	$308\pm20\pm32$	$T_{c\bar{c}1}(4200)^+$	4196^{+35}_{-32}	370^{+100}_{-150}
$T_{c\bar{c}1}(4430)^+$	1^+	$4468\pm21\pm80$	$251\pm42\pm82$	$T_{c\bar{c}1}(4430)^+$	4478^{+15}_{-18}	181 ± 31
$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	$4578\pm10\pm18$	$133\pm28\pm69$			
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$T^*_{c\bar{c}\bar{s}1}(5200)^0$	1^-	$5225\pm86\pm181$	$226\pm76\pm374$			
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	$T_{c\bar{c}\bar{s}1}(4000)^+$	4003^{+7}_{-15}	131 ± 30

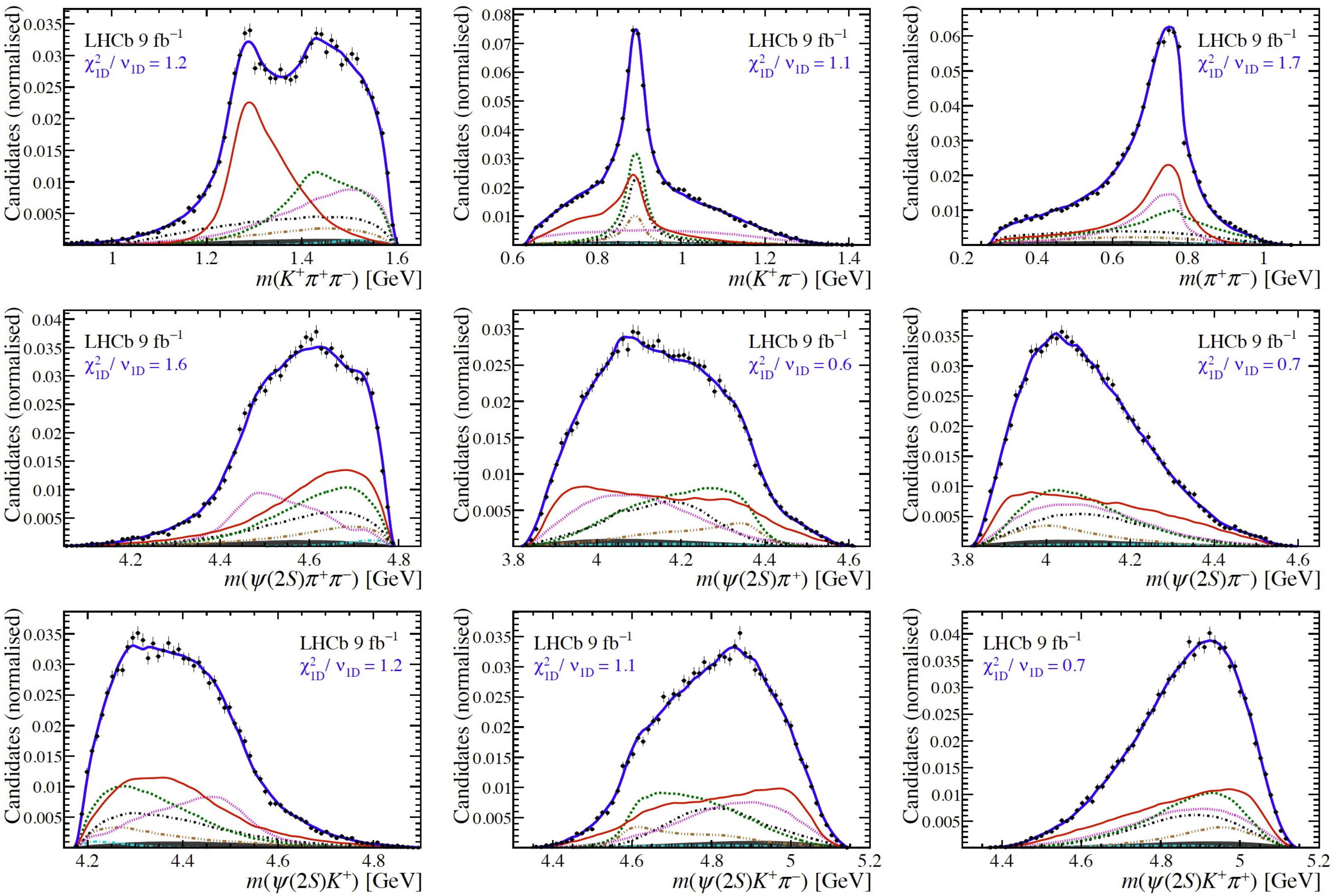
new

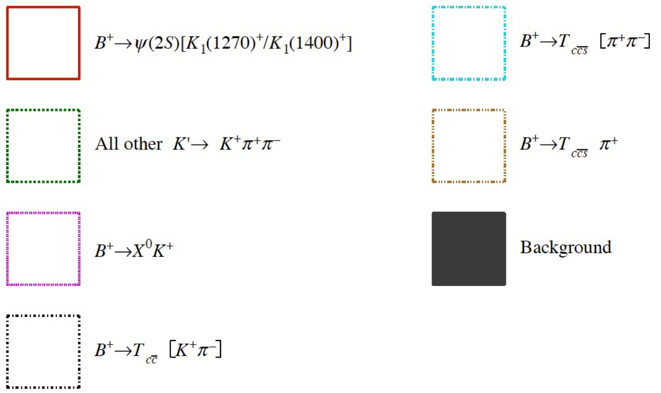
Fit projections

[arXiv: 2407.12475]

- Fit quality is acceptable, 7D $\chi^2/\mathrm{ndof} = 1.2$

- Resonances are generally broad



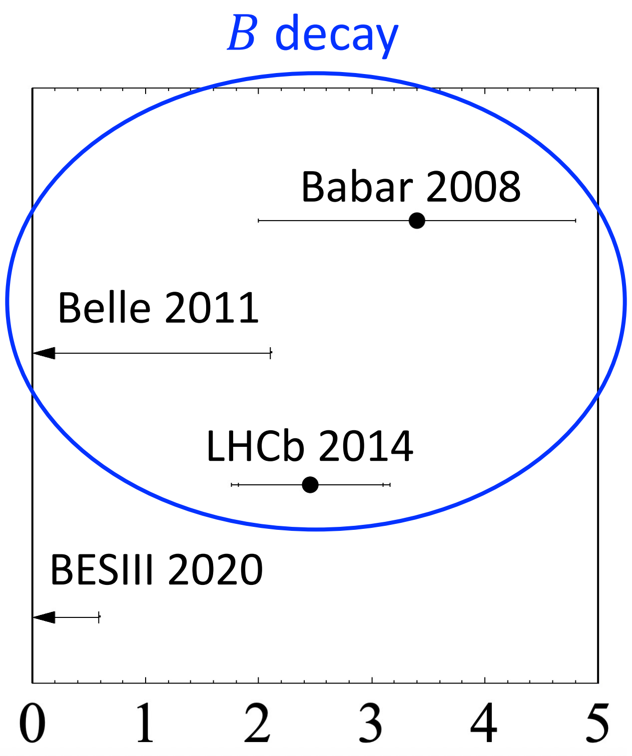


Radiative decays of $\chi_{c1}(3872)$

[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			$\mathcal{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$	
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.*	$\gtrsim 1$	[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	$\ll 1$	[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.*	mixed	[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]	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$

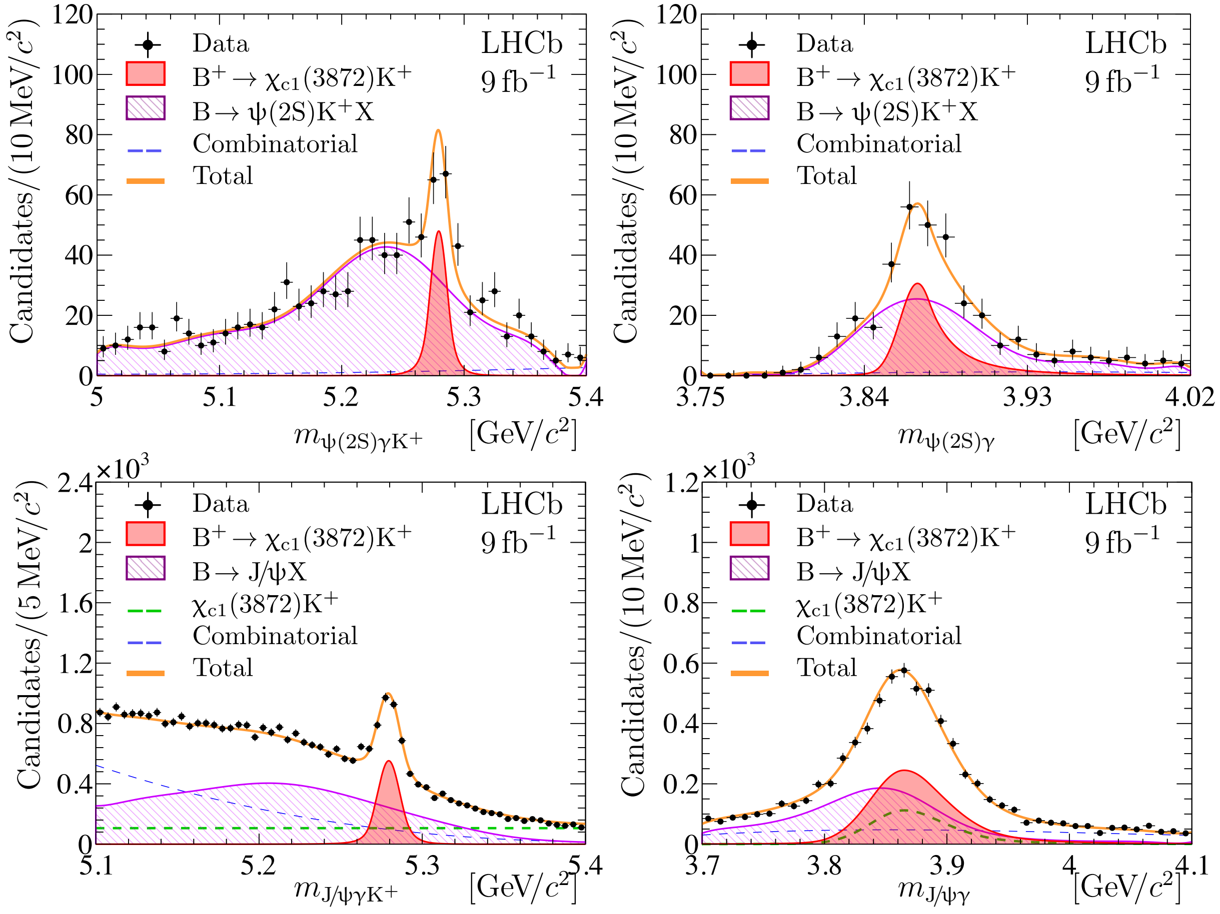


$$\mathcal{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$$

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

[arXiv: 2406.17006]

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



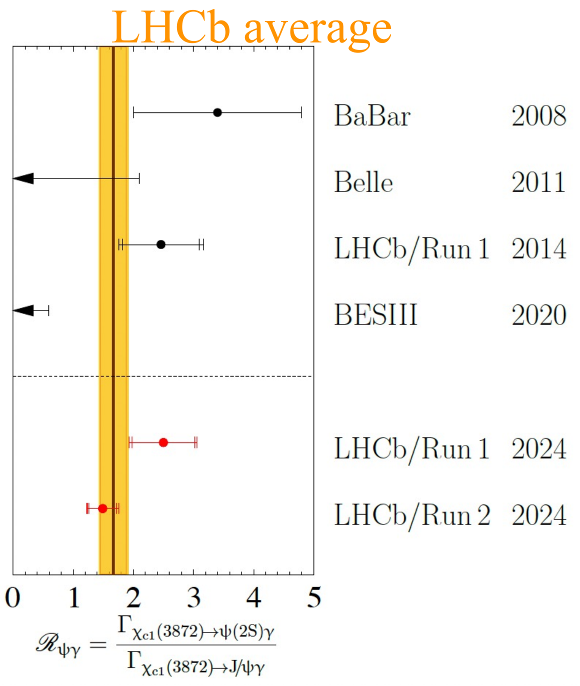
$$\mathscr{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04 \quad (15\%)$$

LHCb meets theory workshop

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

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

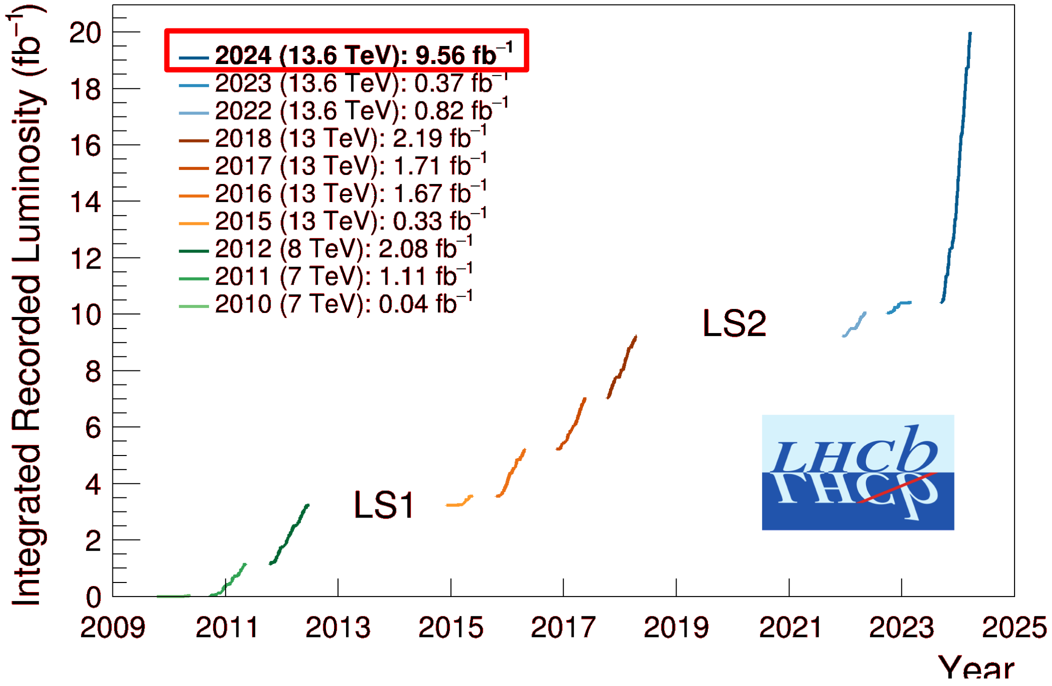
Run2: $N = 63 \pm 10$; $\mathbf{6.7\sigma}$

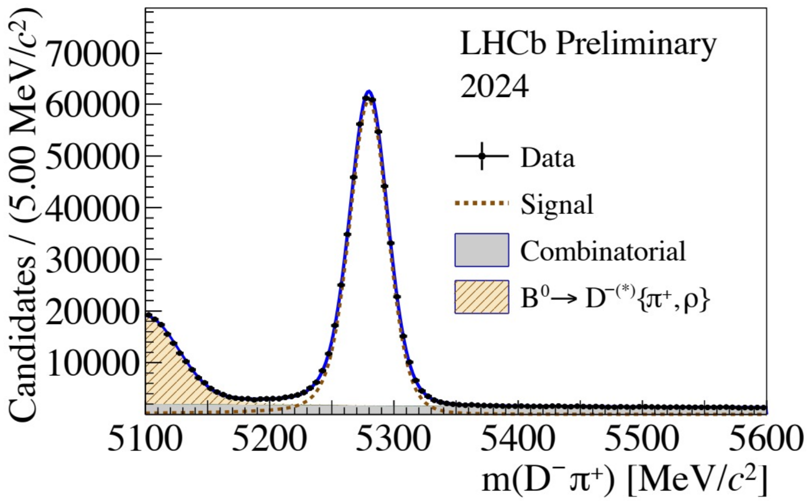


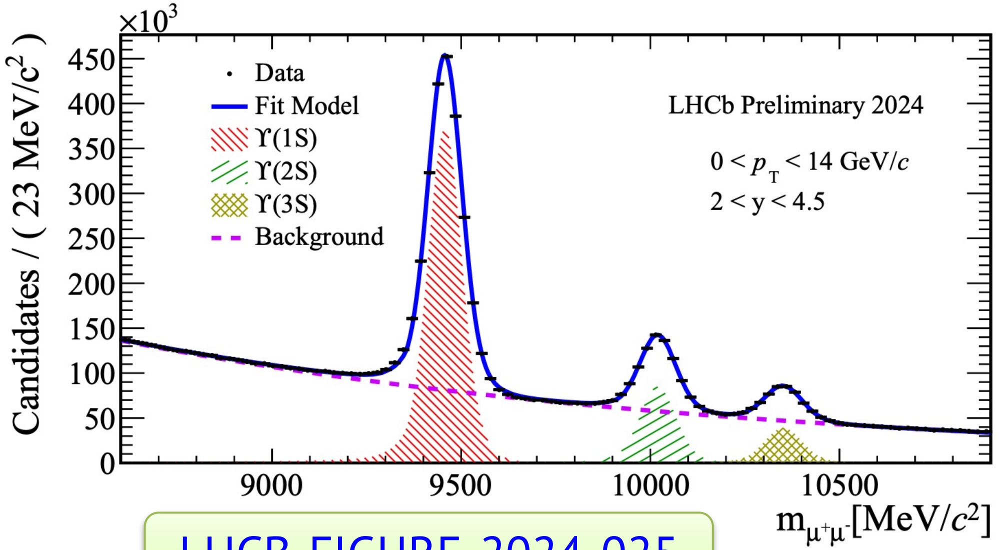
Run3 performance

LHCB-FIGURE-2024-021

- Reaching Run 2 performance in mass resolution



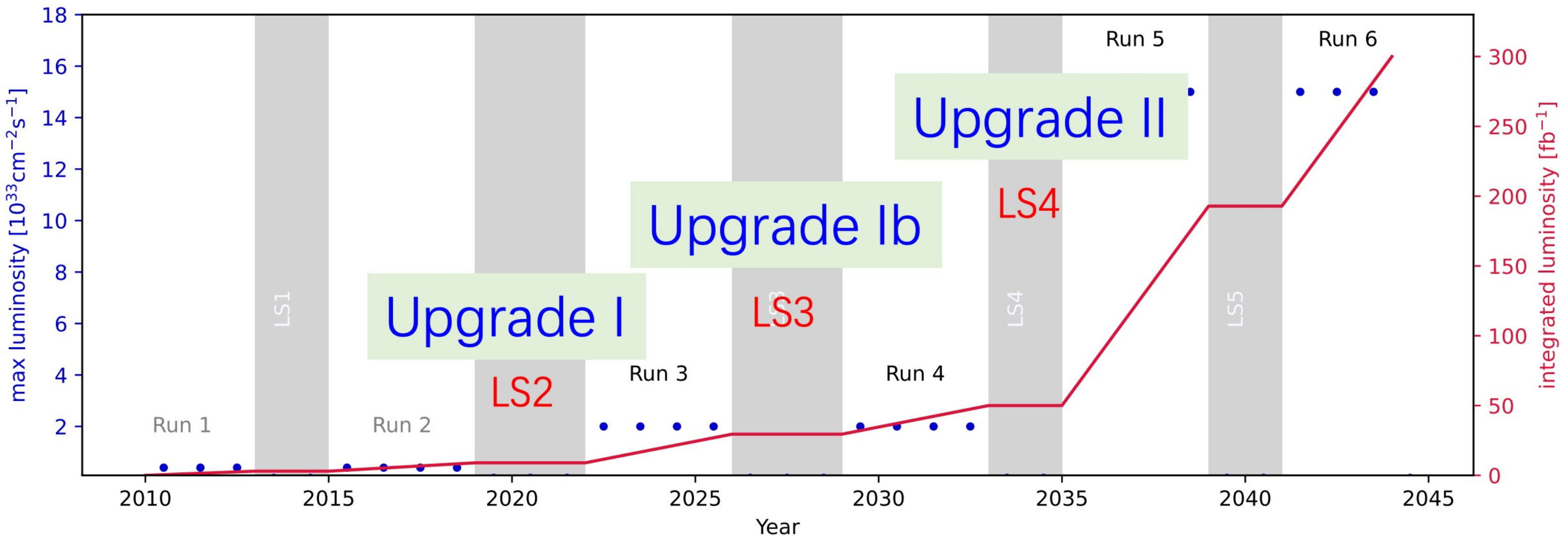




LHCB-FIGURE-2024-025

Summary

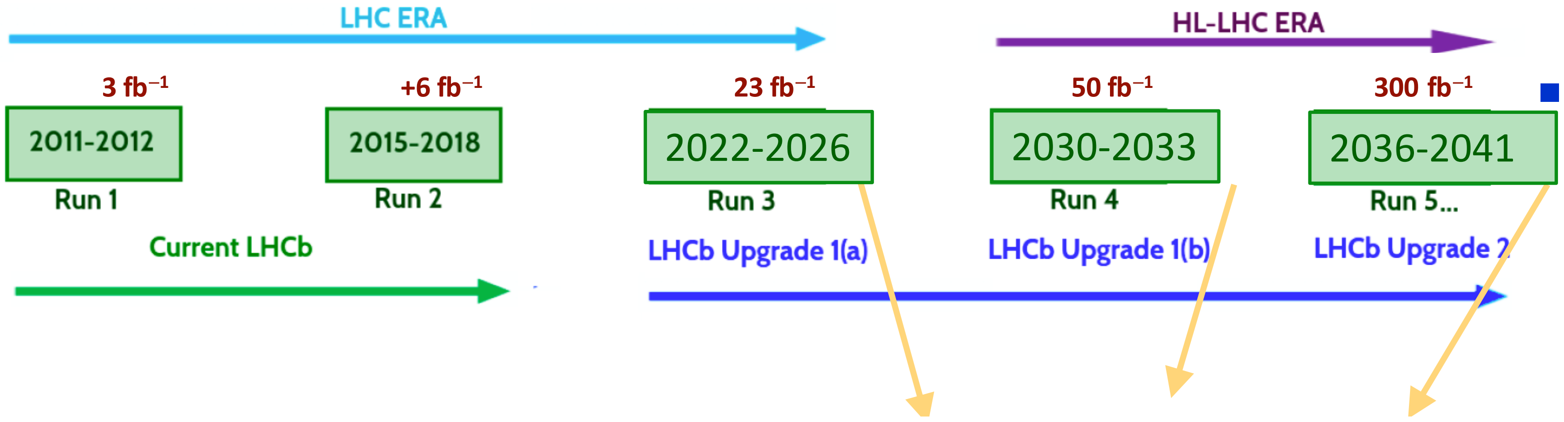
- LHCb keeps making important contributions to heavy hadron spectroscopy with run1 and run2 data
- Run 3 this year has taken 9.5 fb^{-1} data, same luminosity as run1&2
- Stay tuned for more exciting results



BACKUP

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 $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^+$

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

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

$Z_c(4430)$

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

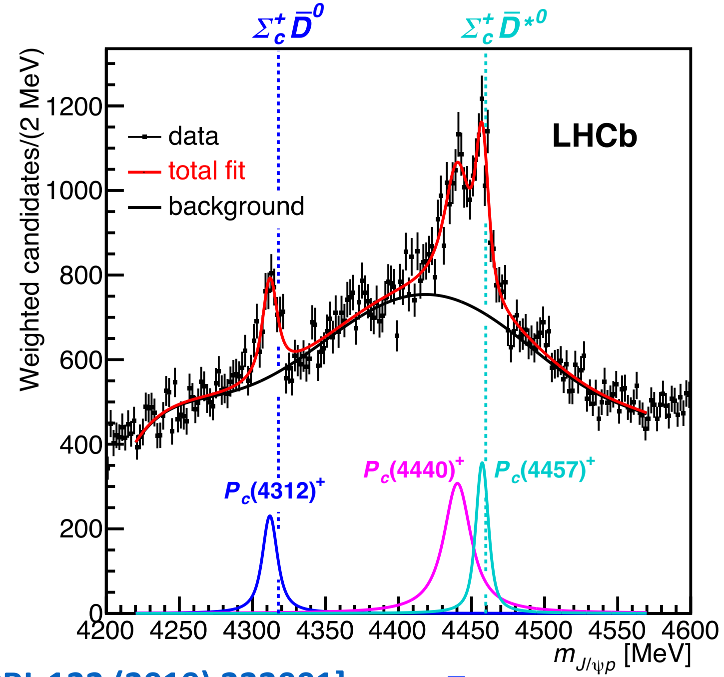
More information for pentaquarks

[*] updated according to the latest result

Pentaquark study

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

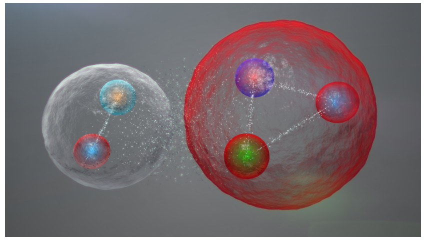
$\Lambda_b^0 \to [J/\psi\, p]K^-$



[PRL 122 (2019) 222001]

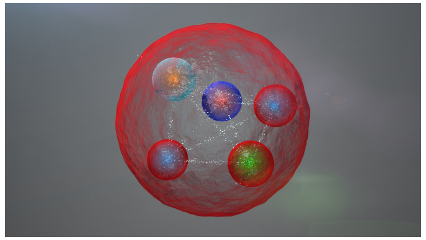
Proximity of $\Sigma_c^+\bar{D}^0$ and $\Sigma_c^+\bar{D}^{*0}$ thresholds to the peaks suggests they play an important role in the dynamics

Hadron molecule



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

Compact multiquark



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

Search for pentaquarks via open charm

[PRD 110 (2024) 032001]

- Inclusive search performed using $5.7\ \mathrm{fb}^{-1}$ 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^+	$\overline{D}^0$	+1	$1/2$	1	0	✓
Λ_c^+	D^-	0	$-1/2$	1	0	✓
Λ_c^+	D^{*-}	0	$-1/2$	1	0	✓
Σ_c^{++}	$\overline{D}^0$	+2	$3/2$	1	0	✓
Σ_c^{++}	D^-	+1	$1/2$	1	0	✓
Σ_c^{++}	D^{*-}	+1	$1/2$	1	0	×
Σ_c^0	$\overline{D}^0$	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^{*++}	$\overline{D}^0$	+2	$3/2$	1	0	✓
Σ_c^{*++}	D^-	+1	$1/2$	1	0	✓
Σ_c^{*++}	D^{*-}	+1	$1/2$	1	0	✓
Σ_c^{*0}	$\overline{D}^0$	0	$-1/2$	1	0	✓
Σ_c^{*0}	D^-	−1	$-3/2$	1	0	✓
Σ_c^{*0}	D^{*-}	−1	$-3/2$	1	0	✓

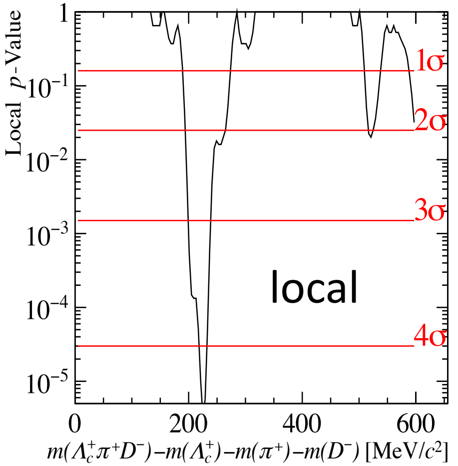
✓doubly-charmed pentaquarks & excited Ξ_{cc}

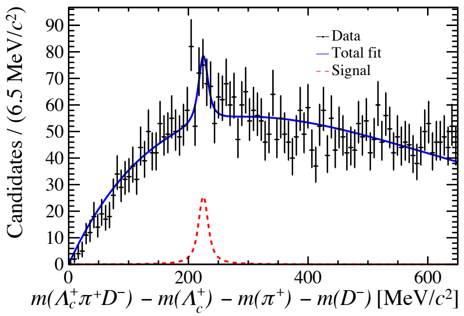
Hadron 1	Hadron 2	Charge	I_3	Y	C	Limit Set
Λ_c^+	D^0	+1	$-1/2$	3	2	✓
Λ_c^+	D^+	+2	$1/2$	3	2	✓
Λ_c^+	D^{*+}	+2	$1/2$	3	2	✓
Σ_c^{++}	D^0	+2	$1/2$	3	2	×
Σ_c^{++}	D^+	+3	$3/2$	3	2	×
Σ_c^{++}	D^{*+}	+3	$3/2$	3	2	×
Σ_c^0	D^0	0	$-3/2$	3	2	×
Σ_c^0	D^+	+1	$-1/2$	3	2	×
Σ_c^0	D^{*+}	+1	$-1/2$	3	2	×
Σ_c^{*++}	D^0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

Results

[PRD 110 (2024) 032001]





$c\bar{c}uud$

$M{\sim}4520.69$ MeV

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

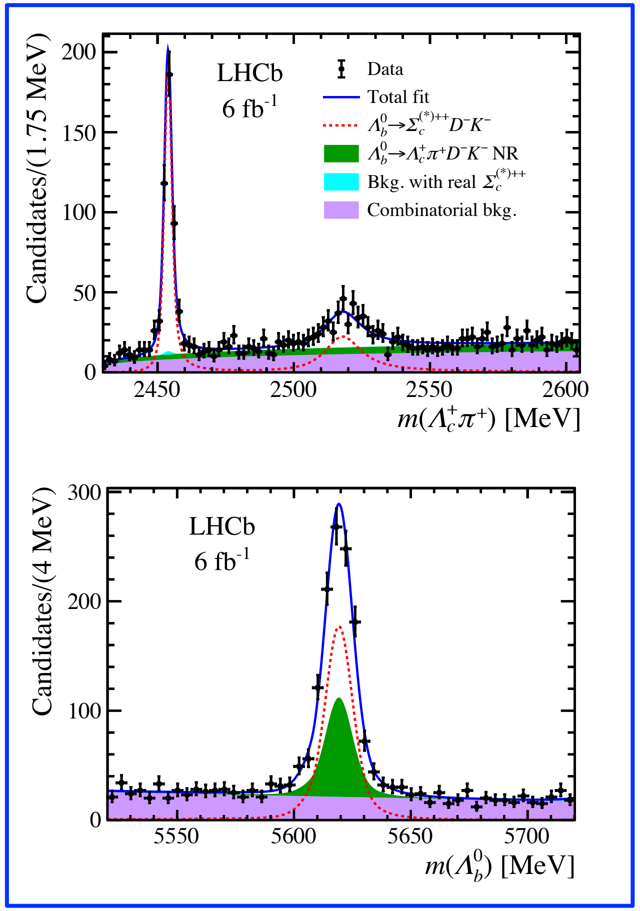
*Complete list in paper

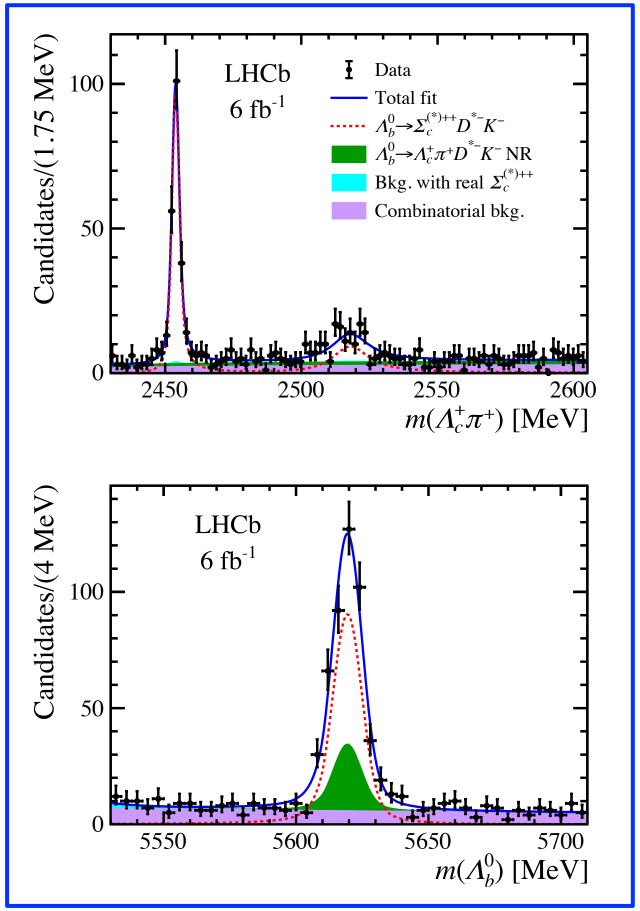
Decay Mode	Width (MeV/c^2)	Significance (σ) Local	Significance (σ) Corrected	Q-value (MeV/c^2)	Signal Yield	UL ($\times 10^{-3}$) 90% CL	UL ($\times 10^{-3}$) 95% CL
$\Lambda_c^+\pi^+D^-$	0	3.59	2.21	225	41.6 ± 12.6	3.95	4.19
	5	4.01	2.89	225	64.7 ± 17.4	4.43	4.69
	10	4.30	3.32	225	87.1 ± 21.6	4.64	4.85
	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

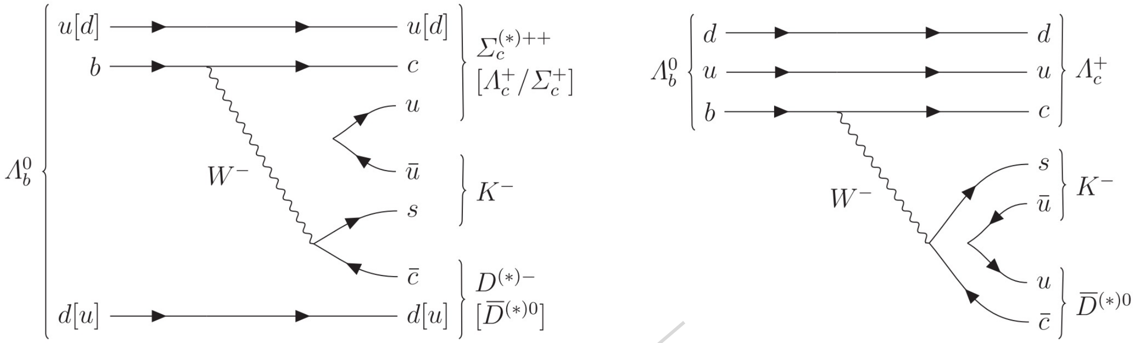
$\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$: observation

[PRD **110** (2024) L031104]

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







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

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

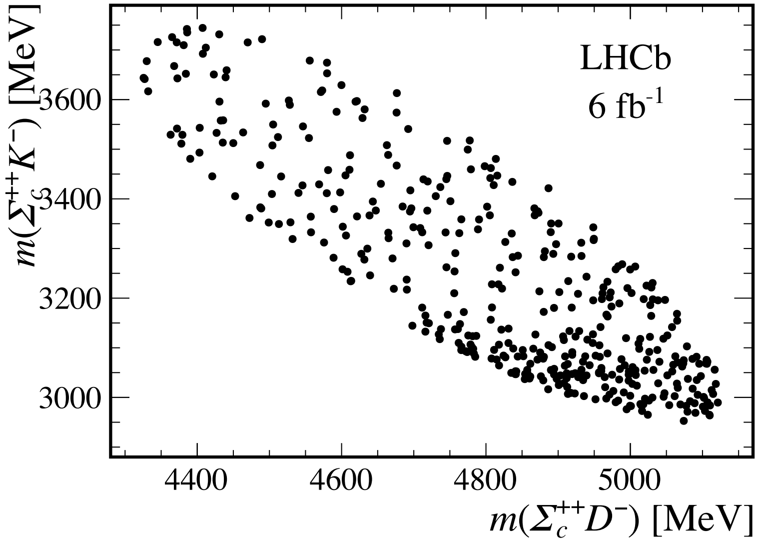
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)} = 2.261 \pm 0.202 \pm 0.129 \pm 0.046,$$

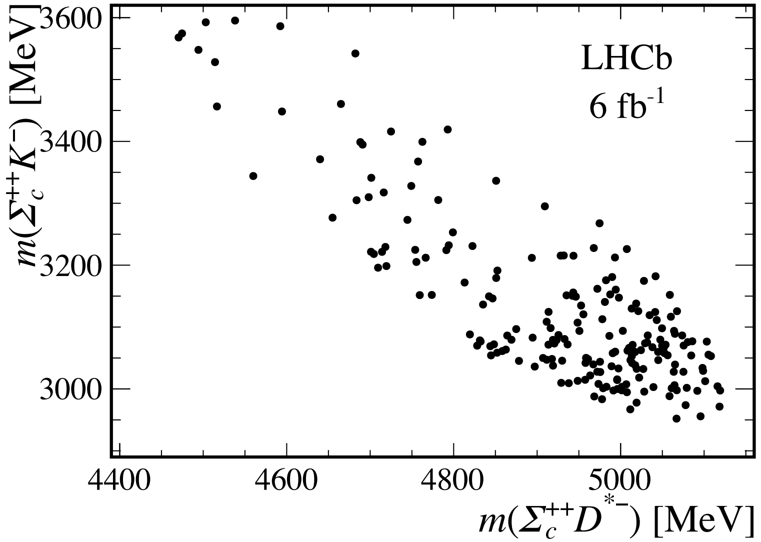
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{*++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)} = 0.896 \pm 0.137 \pm 0.066 \pm 0.018,$$

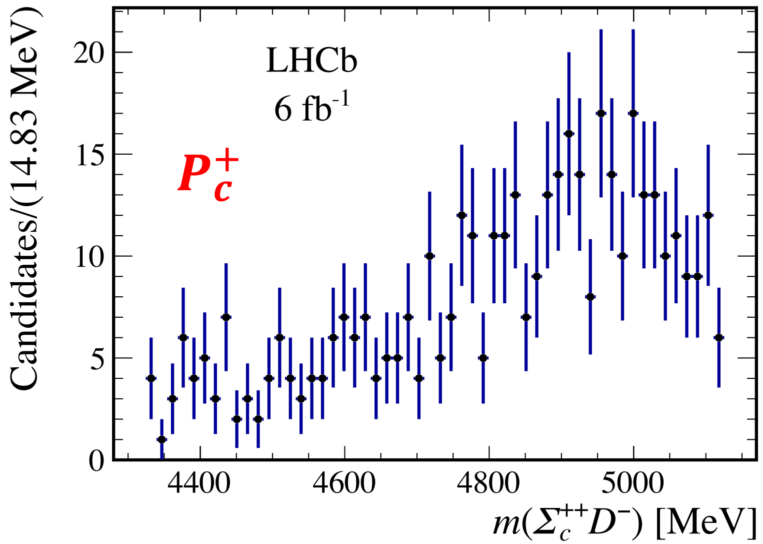
$\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$: intermediate states

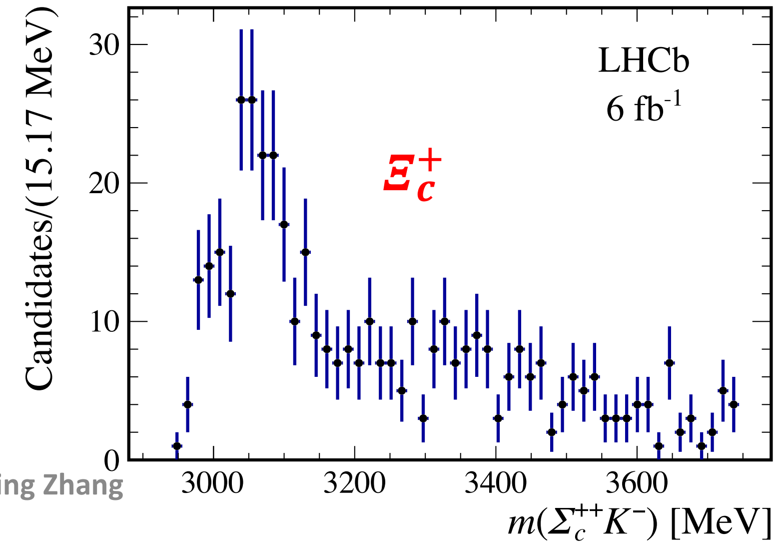
[PRD **110** (2024) L031104]

- Larger dataset needed to draw a definitive conclusion



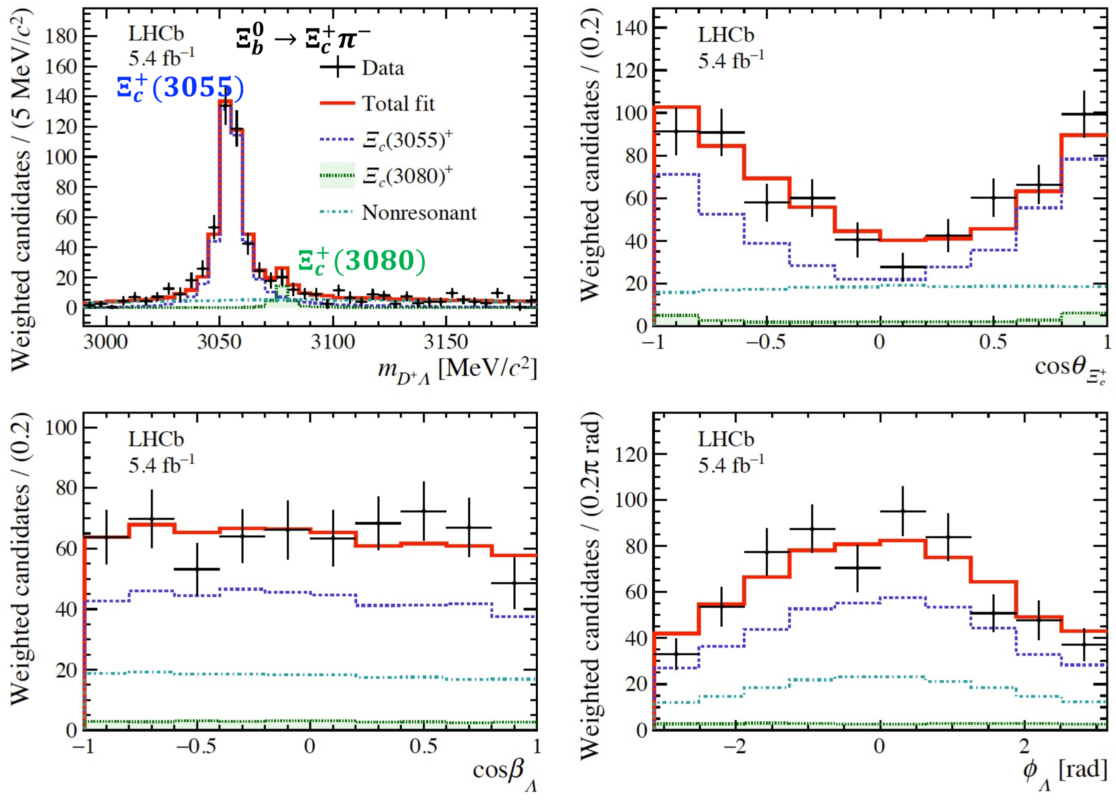


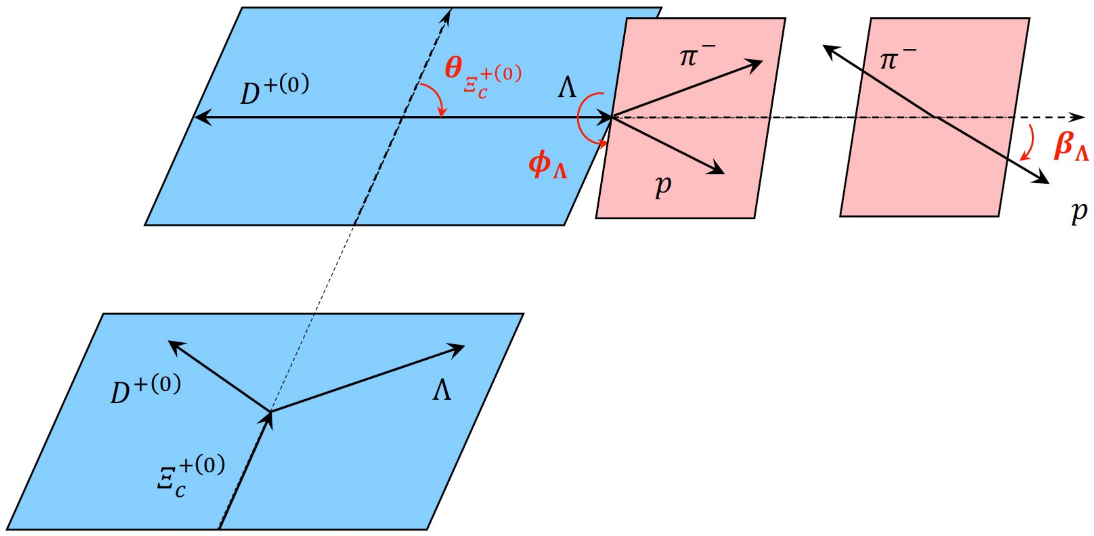




1st determination of J^P for $\Xi_c(3055)^{+,0}$ [arXiv: 2409.05440]

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



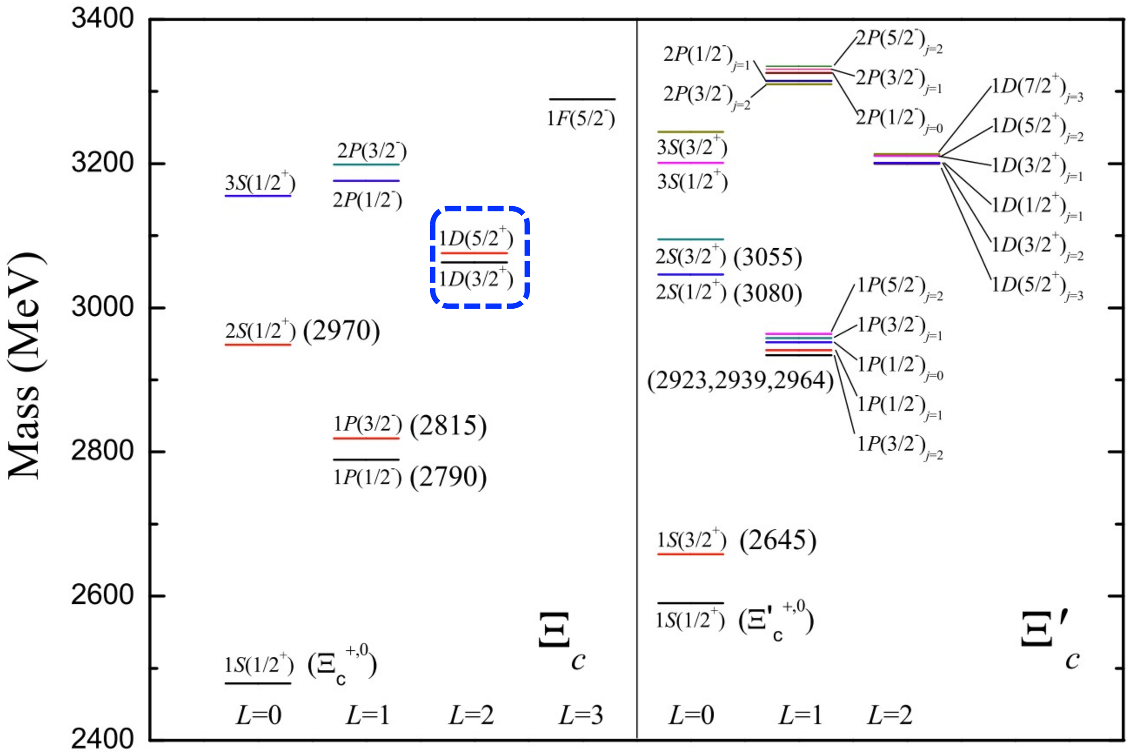


1st determination of J^P for $\Xi_c(3055)^{+,0}$ [arXiv: 2409.05440]

- $J^P = 3/2^+$ 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 $R_{\mathcal{B}}$

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

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



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 $\Xi_c(3055)^{+,0}$

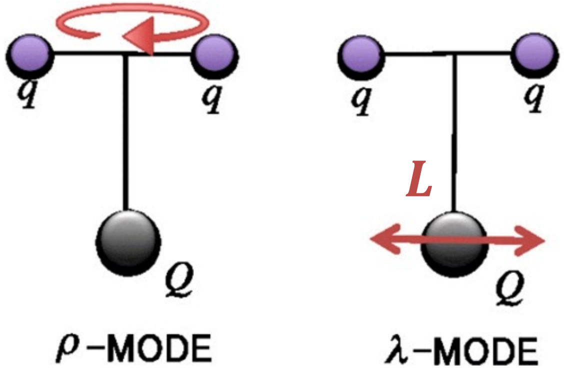
- Qqq baryons is well described by heavy quark-light diquark $Q[qq]$ model

✓ λ-mode: can describe almost all observed states

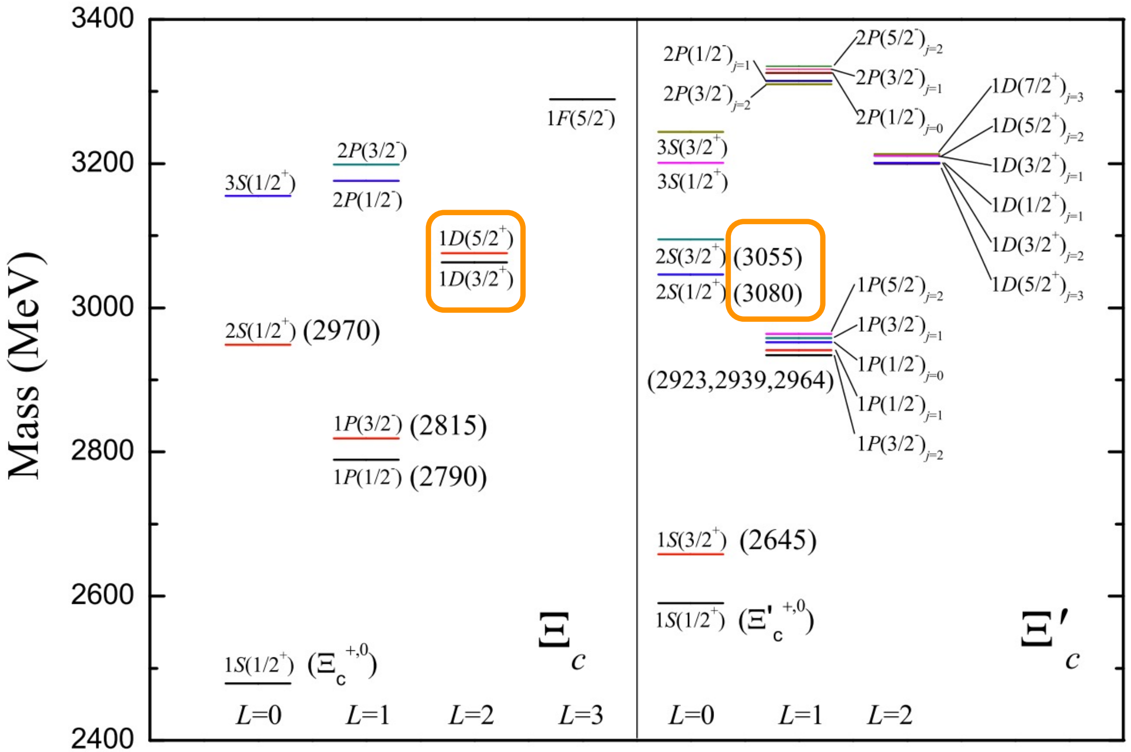
Configuration	$J^P_{[qq]} = 0^+$	$J^P_{[qq]} = 1^+$
Naming	Ξ_Q	Ξ'_Q

✓ ρ-mode: no firm assignment yet

[PRD 92 (2015) 114029]



$\Xi_c(3055)$'s mass can fit into 1D or 2S states

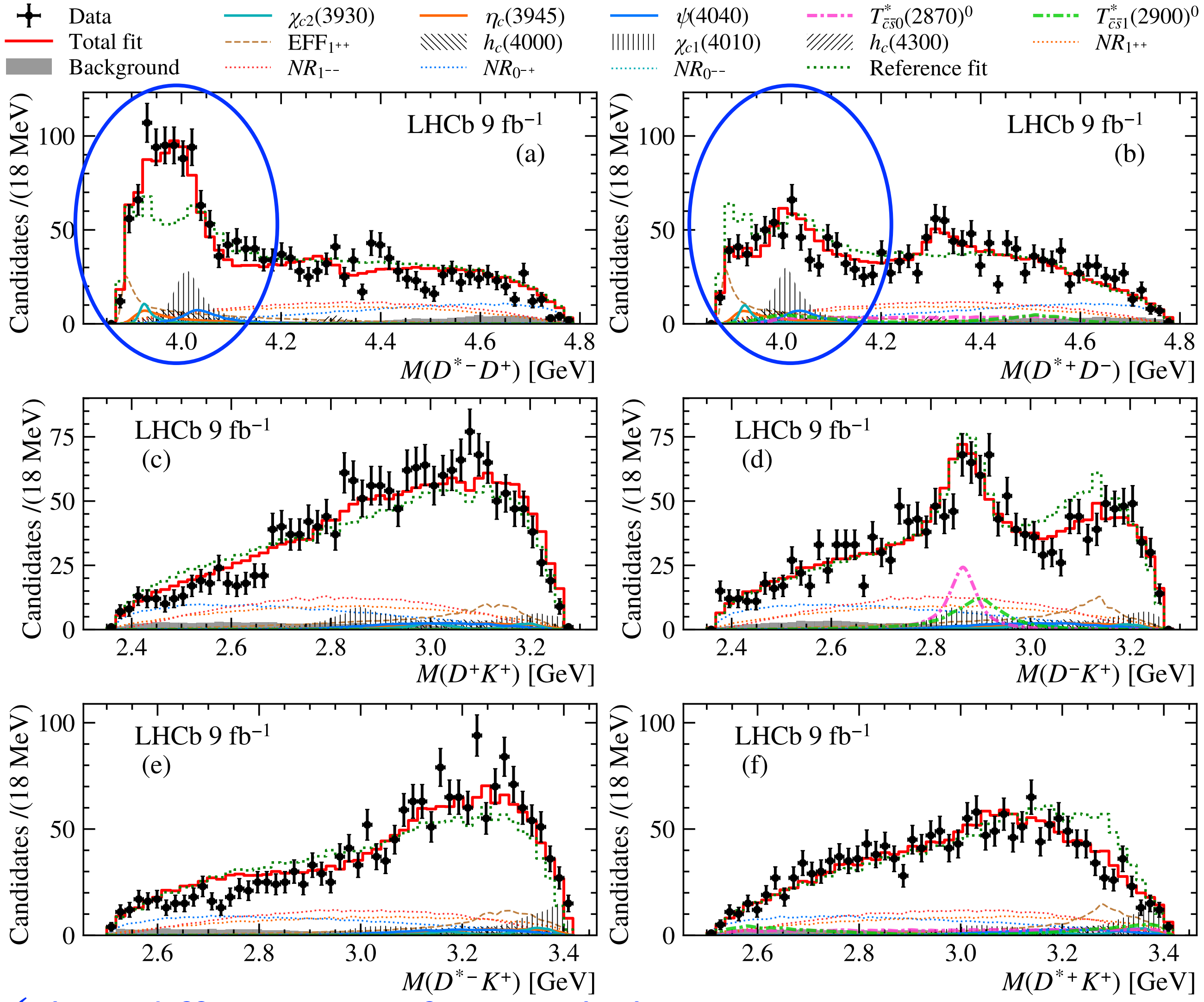


Zhen-Yu Li, Guo-Liang Yu, Zhi-Gang Wang, Jian-Zhong Gu, Jie Lu
Chinese Phys. C **47** (2023) 073105

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

[arXiv: 2406.03156]
accepted by PRL

- 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^{-+}

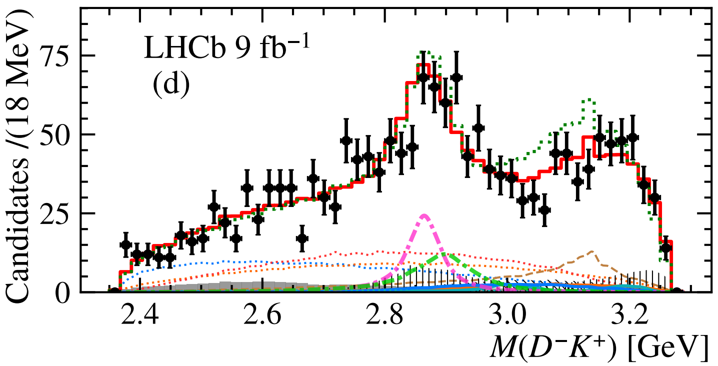
*Fit fractions in paper

✓clear different interference behaviors

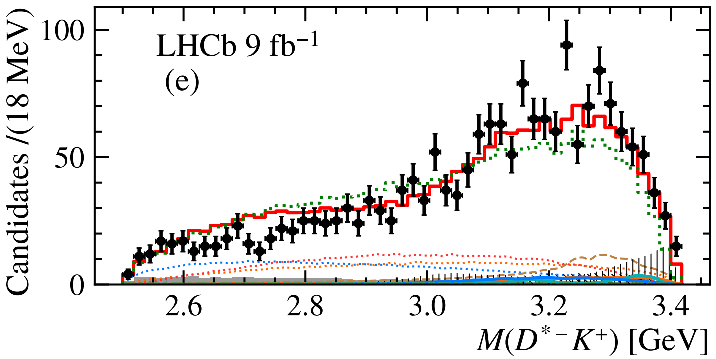
$B^+ \to D^{*\pm} D^{\mp} K^+$: $T^*_{\bar{c}s}$ states

[arXiv: 2406.03156]
accepted by PRL

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



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



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

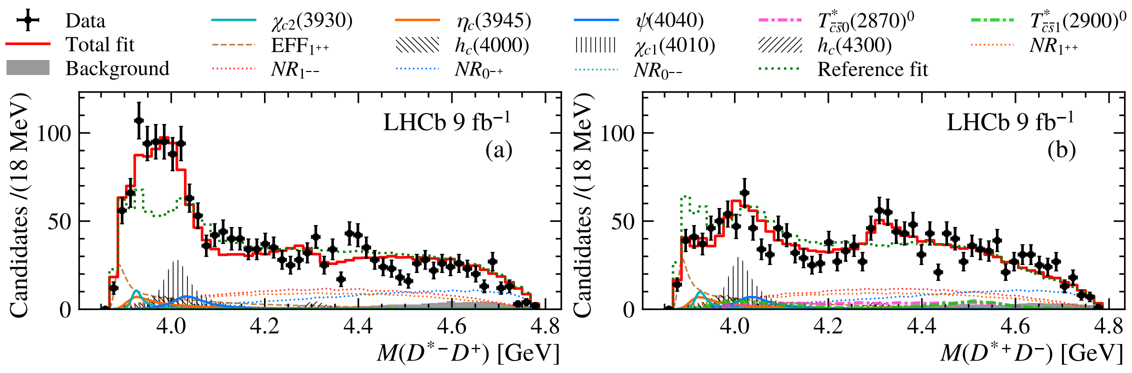
2σ

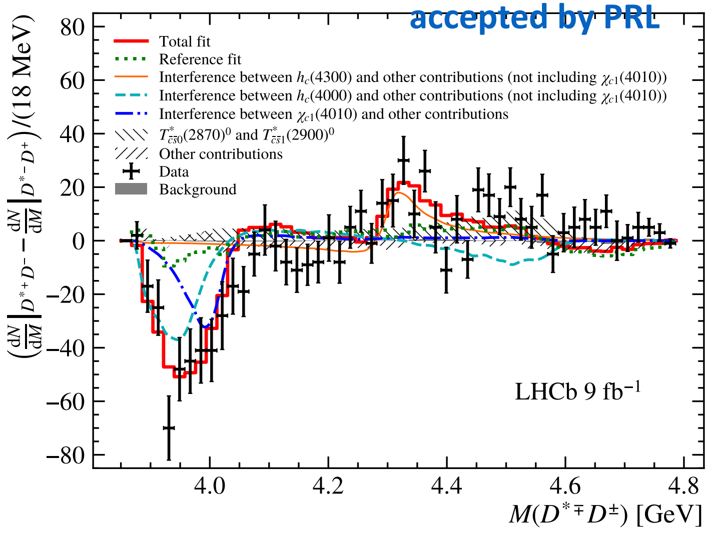
✓$T^*_{\bar{c}\bar{s}0}(2870)^0 \to D^{*-}K^+$ forbidden

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

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

[arXiv: 2406.03156]
accepted by PRL





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

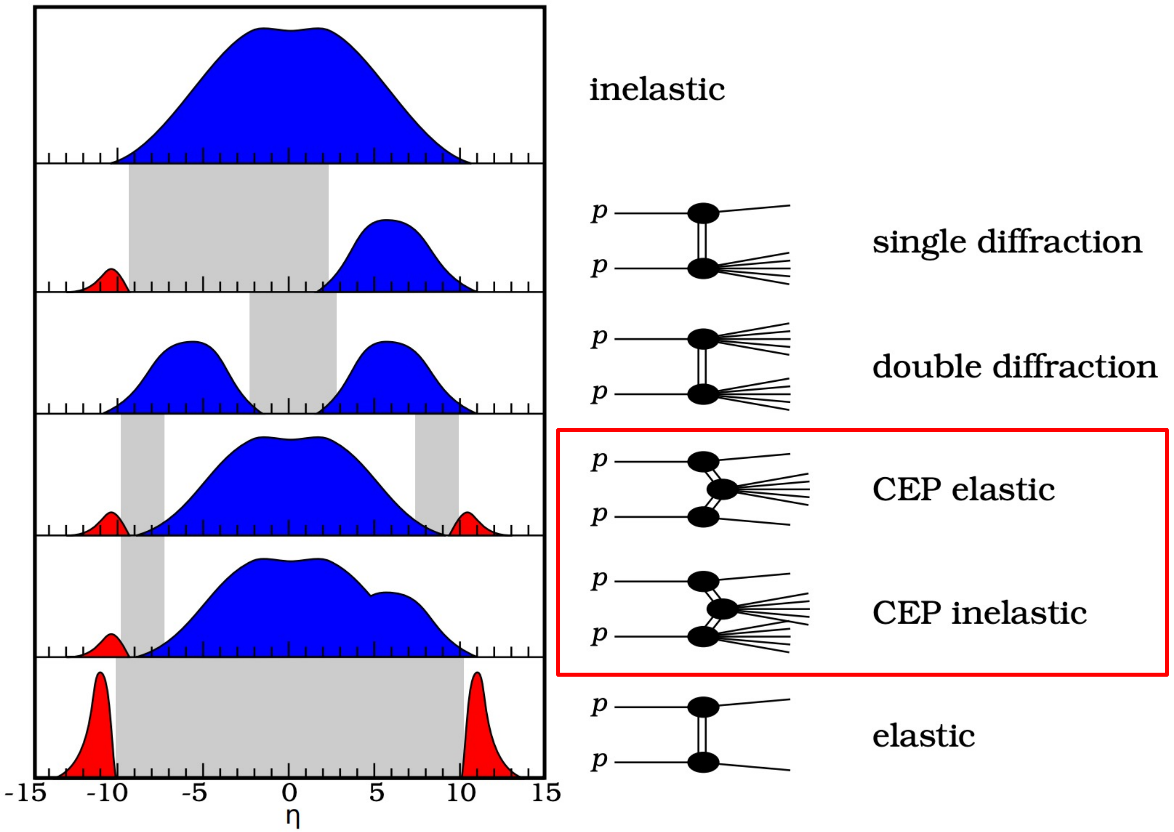
	This work		$c\bar{c}$ prediction [34]	
X(3940)?	$\eta_c(3945)$	$J^{PC}=0^{-+}$	$\eta_c(3S)$	$J^{PC}=0^{-+}$
	$m_0 = 3945\,^{+28\,+37}_{-17\,-28}$	$\Gamma_0 = 130\,^{+92\,+101}_{-49\,-70}$	$m_0 = 4064$	$\Gamma_0 = 80$
	$h_c(4000)$	$J^{PC}=1^{+-}$	$h_c(2P)$	$J^{PC}=1^{+-}$
	$m_0 = 4000\,^{+17\,+29}_{-14\,-22}$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

GI model
hep-ph/0505002

- States can fit into Charmonia, and mass more consistent with the prediction with unquenched quark model [Qian Deng, Ru-Hui Ni, Qi Li, Xian-Hui Zhong, arXiv: 2312.10296]
- $\chi_{c1}(4010)$ could be the partner of $\chi_{c1}(3872)$, predicted both in the unquenched model and Lattice [Haozheng Li, Chunjiang Shi, Ying Chen, Ming Gong, Juzheng Liang, Zhaofeng Liu, Wei Sun, arXiv:2402.14541]

Central exclusive production (CEP)

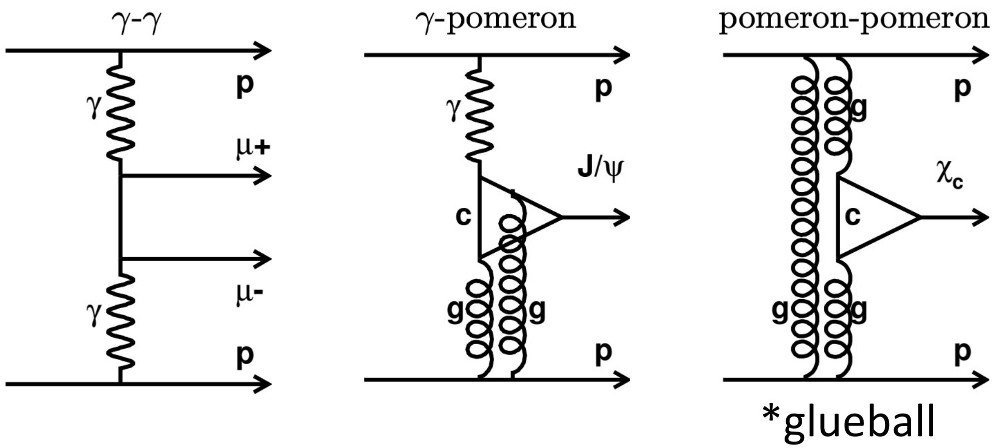
- Study *J/ψϕ resonances in CEP*



✓ Experimentally clean even @LHC

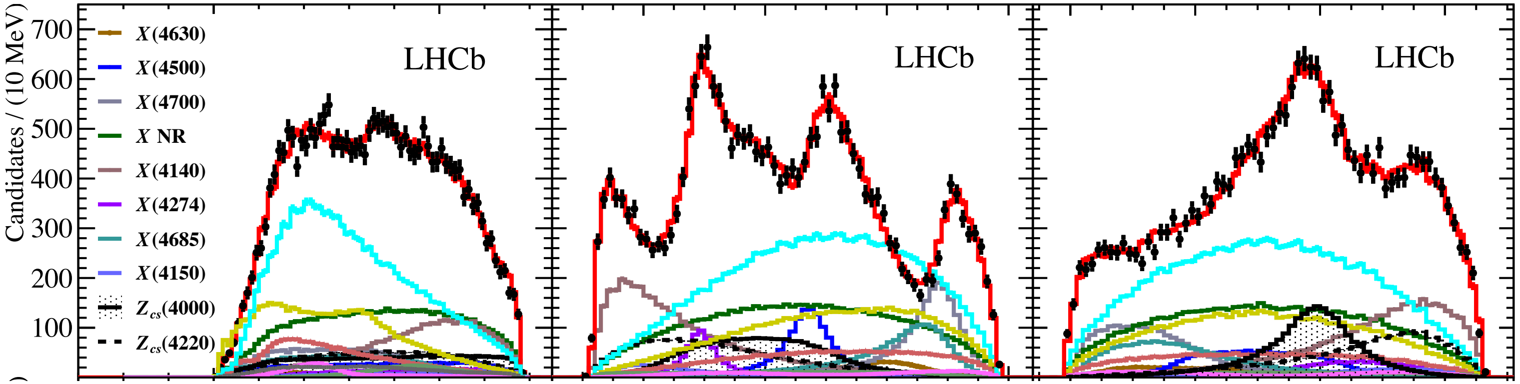
✓ Spin-parity option narrowed down

✘ Much smaller rate



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

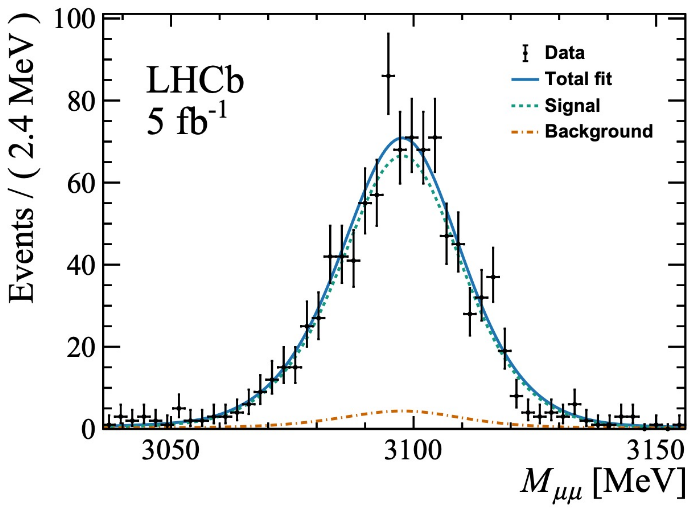
[PRL 127 (2021) 082001]

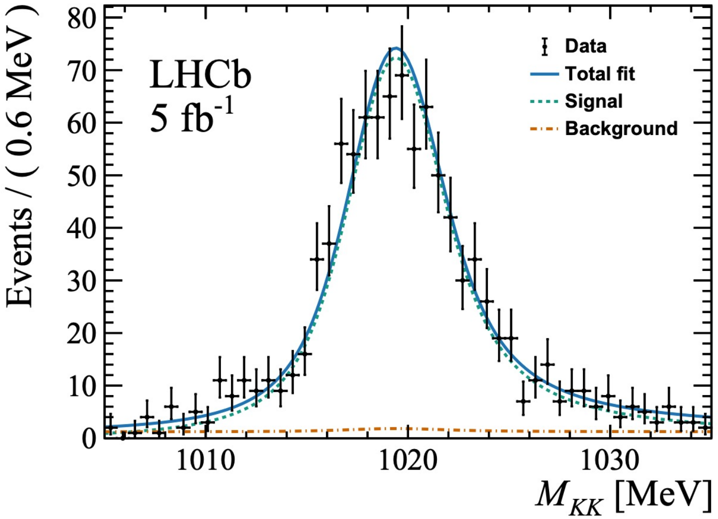


$X(2^-)$				
$X(4150)$	$4.8\ (8.7)$	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+\,59}_{-\,30}$	$2.0 \pm 0.5\,^{+\,0.8}_{-\,1.0}$
$X(1^-)$				
$X(4630)$	$5.5\ (5.7)$	$4626 \pm 16\,^{+\,18}_{-\,110}$	$174 \pm 27\,^{+\,134}_{-\,73}$	$2.6 \pm 0.5\,^{+\,2.9}_{-\,1.5}$
All $X(0^+)$				$20 \pm 5\,^{+\,14}_{-\,7}$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

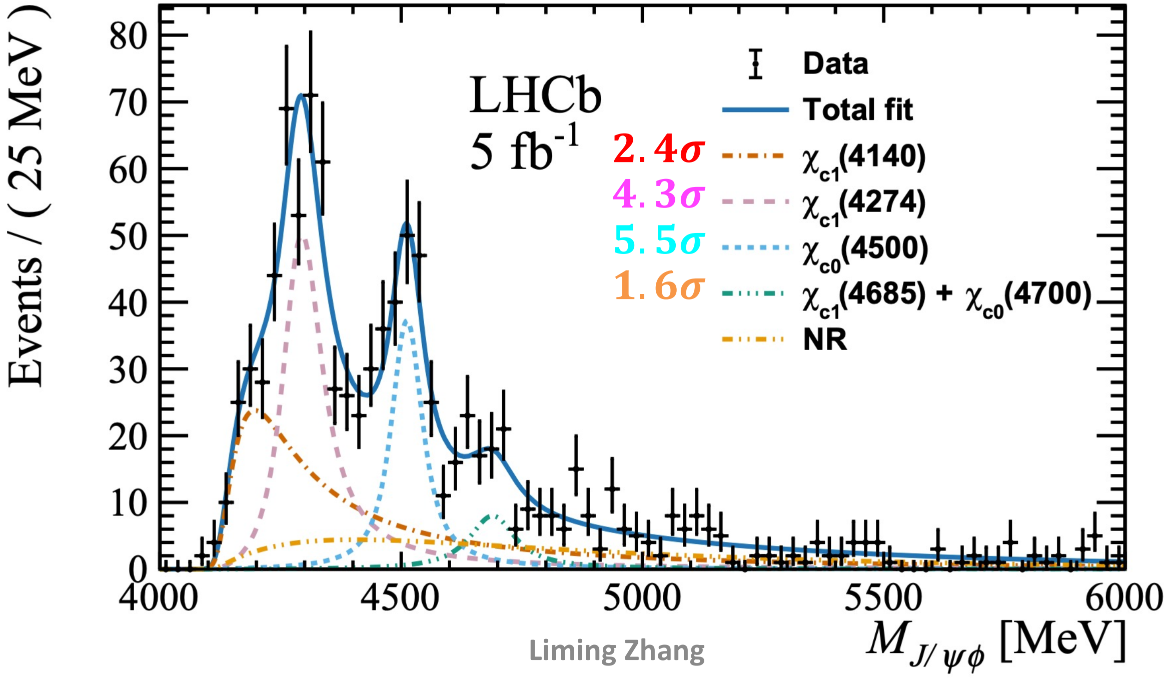
$X \to J/\psi\phi$ in CEP

[arXiv: 2407.14301]



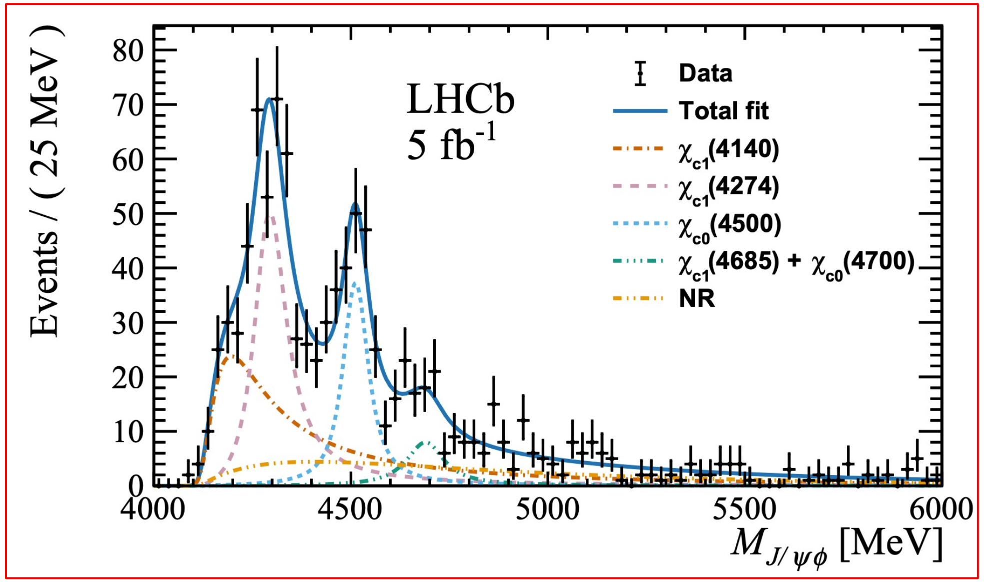


$N = 989$
purity $= (93.0 \pm 0.5)\%$

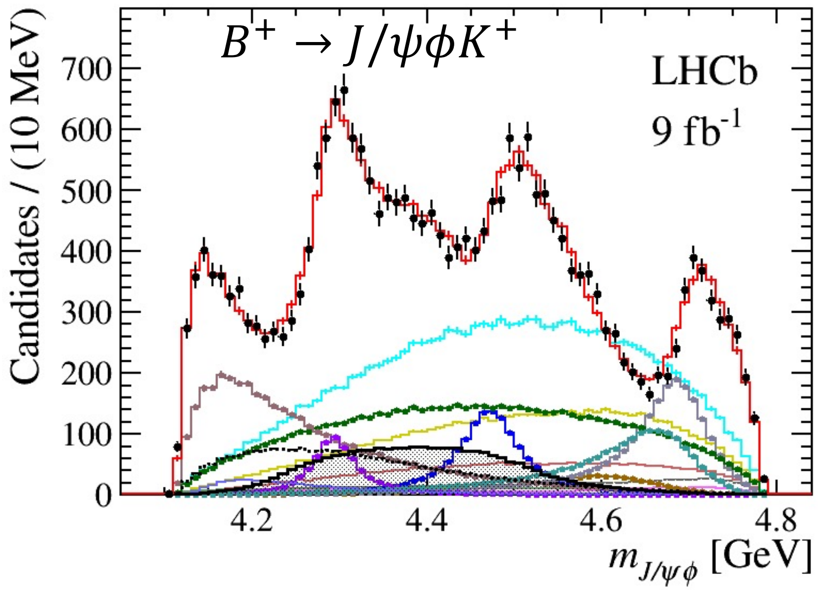


First exotic hadron measurement in CEP!

[arXiv: 2407.14301]



[PRL 127 (2021) 082001]



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

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

- Cross-section measurements:

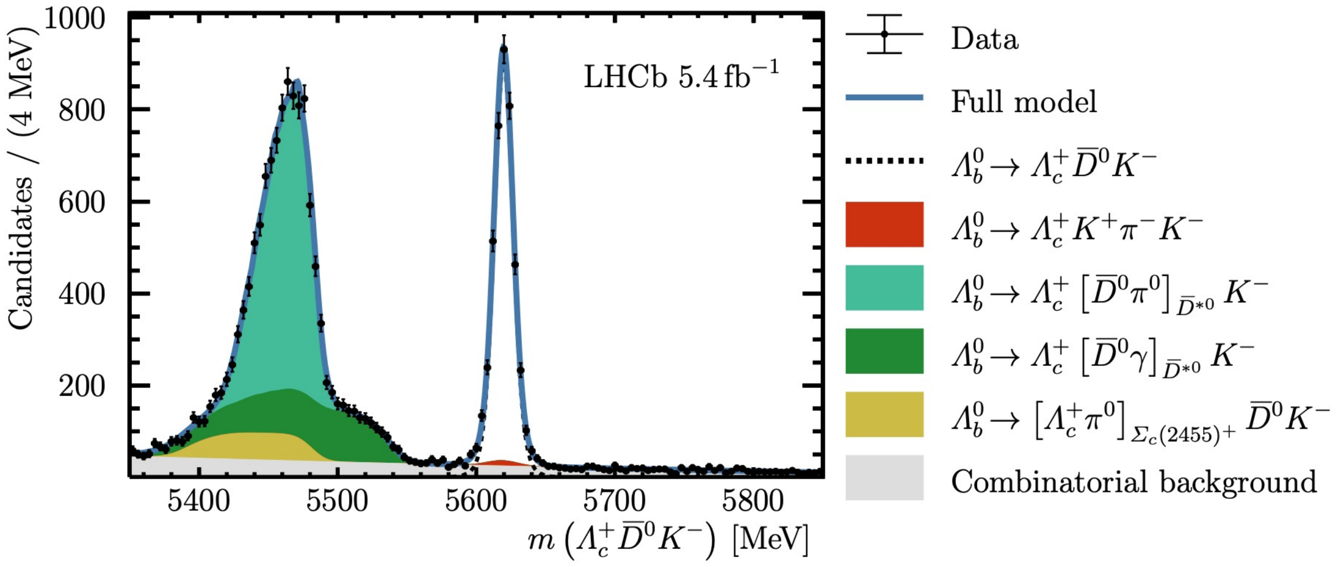
$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4140)} = (0.80 \pm 0.15 \pm 0.28)\,\text{pb},$$
$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4274)} = (0.73 \pm 0.08 \pm 0.17)\,\text{pb},$$
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\rm eff}^{\chi_{c0}(4500)} = (0.42^{+0.09}_{-0.08} \pm 0.06)\,\text{pb},$$
$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\,\text{pb},$$
$$\sigma_{\rm NR} \times \mathcal{B}_{\rm eff}^{\rm NR} = (0.43^{+0.24}_{-0.18} \pm 0.20)\,\text{pb},$$

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

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

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

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



- Branching fractions

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

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

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

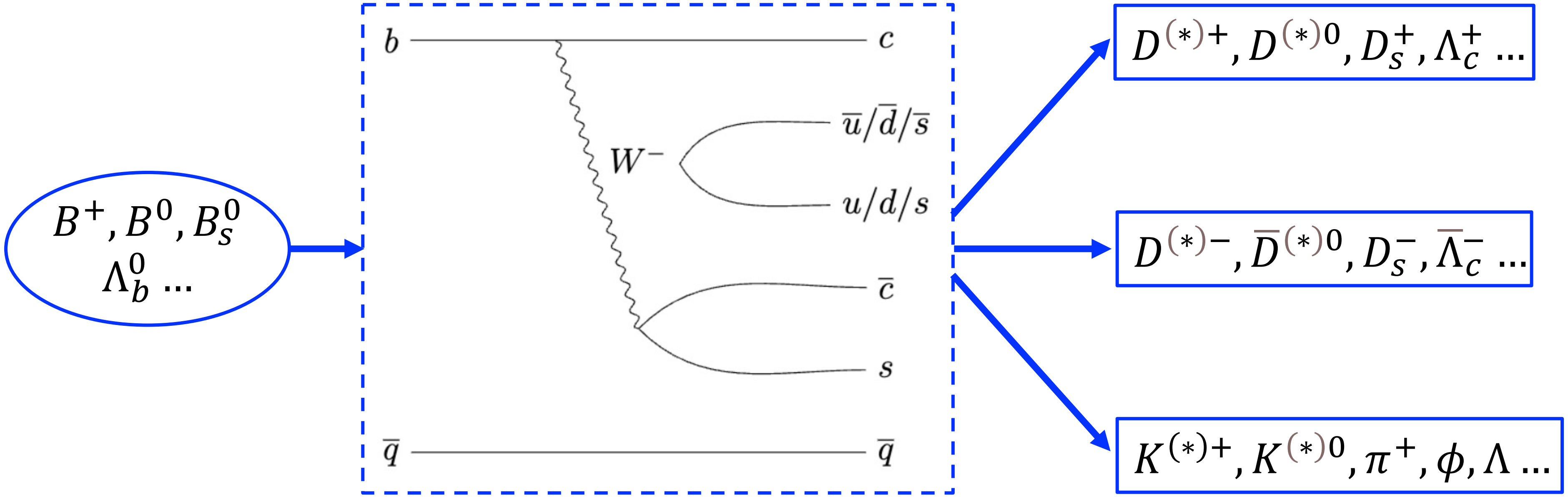
$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)} = (15.2^{+3.2}_{-2.8})\%$$

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

[arXiv:2311.14088]

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

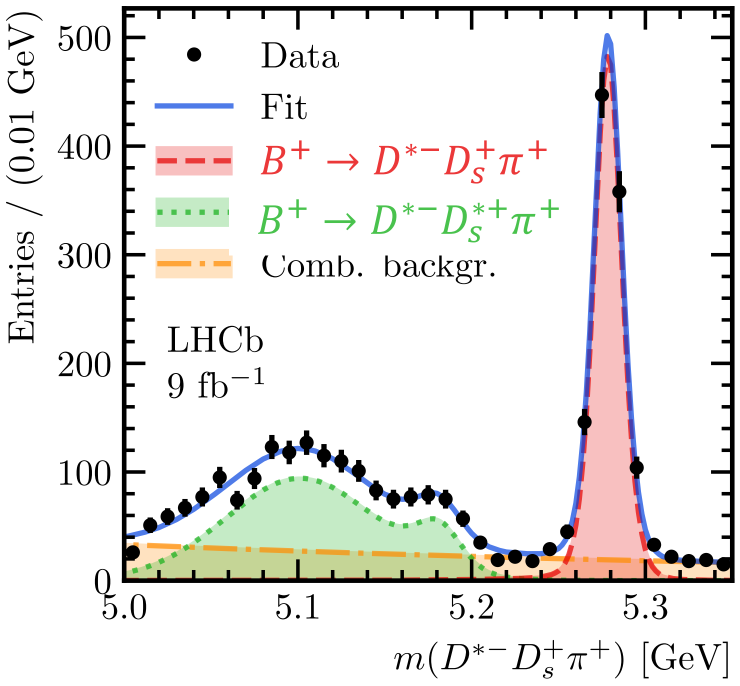
- Rich opportunities for spectroscopy study
  - **charmonium(-like)** states in $D^{(*)}\bar{D}^{(*)}, \Lambda_c^+\bar{D}^{(*)}, \Lambda_c^+\bar{\Lambda}_c^-$ ...
  - **excited $D^+, D^0, D_s^+, \Lambda_c^+$** states from $D^{(*)}h, \Lambda_c^+ h$ ...
  - **exotic** states from $\bar{D}^{(*)}h, \bar{\Lambda}_c^-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



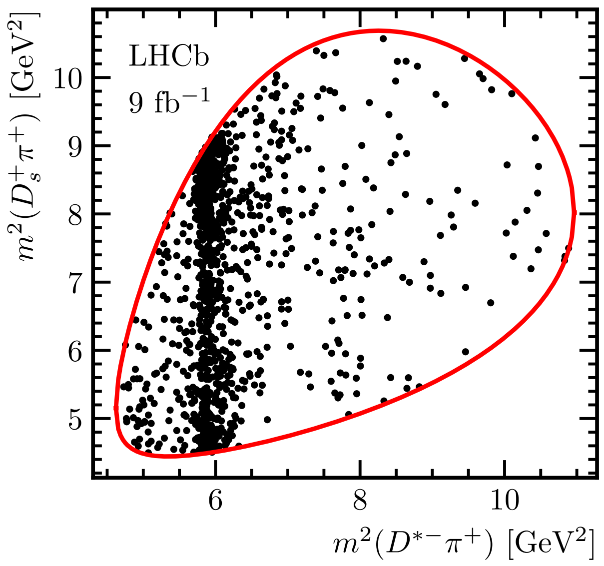
$B^+ \to D^{*-} D_s^{(*)+} \pi^+$: branching fractions

[arXiv: 2405.00098]

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



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



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

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

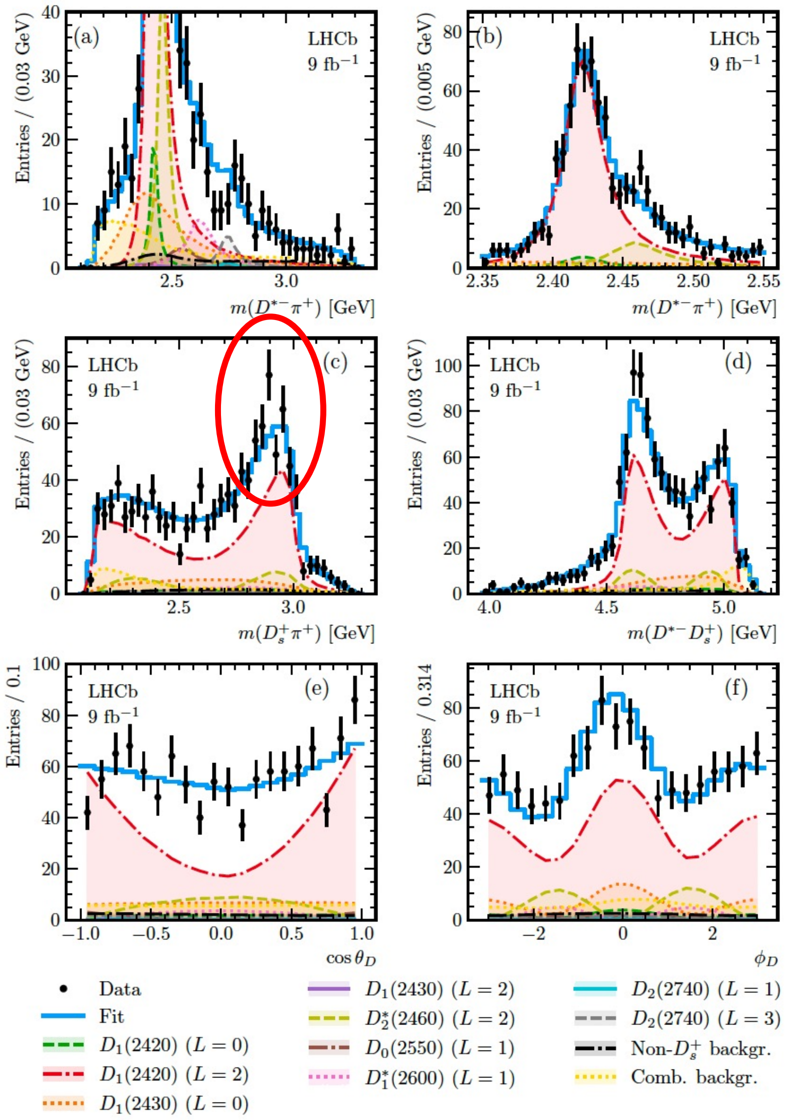
$B^+ \to D^{*-} D_s^+ \pi^+$: amplitude analysis

[arXiv: 2405.00098]

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

	Resonance	J^P	Mass [MeV]	Width [MeV]
	$D_1(2420)$	1^+	$2\,422.1 \pm 0.6$	31.3 ± 1.9
	$D_1(2430)$	1^+	$2\,412 \pm 9$	314 ± 29
	$D_2^*(2460)$	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

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	$111.0 \pm 5.2 \pm 4.2$	



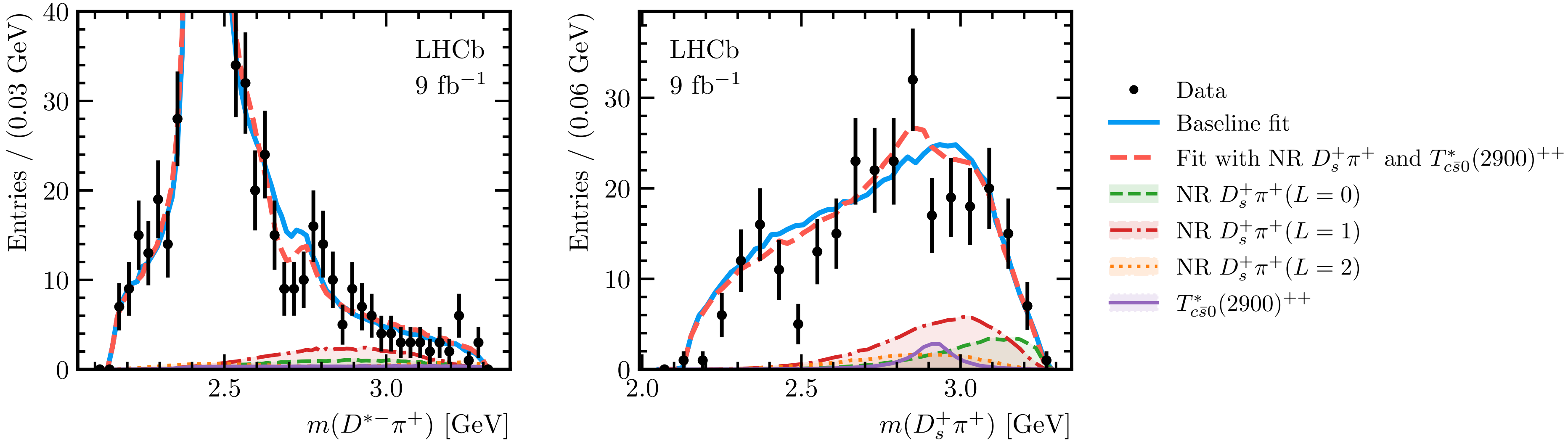
$B^+ \to D^{*-} D_s^+ \pi^+$: amplitude analysis

[arXiv: 2405.00098]

- Fits incorporating $D_s^+\pi^+$ amplitudes
  - best fit: $T^a_{c\bar{s}0}(2900)^{++}$ + **nonresonant vector**

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

$m(D^{*-}\pi^+) > 2.5$ GeV



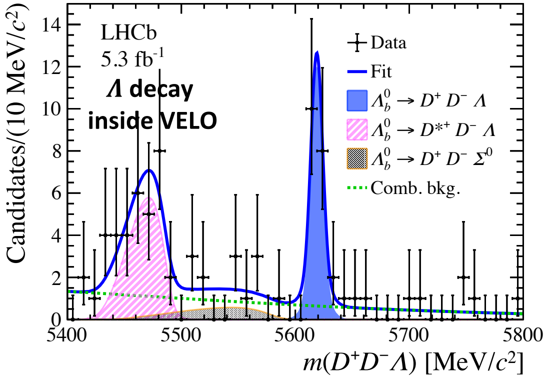
- Fits incorporating $D^{*-}D_s^+$ amplitudes: none provides a physical description

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

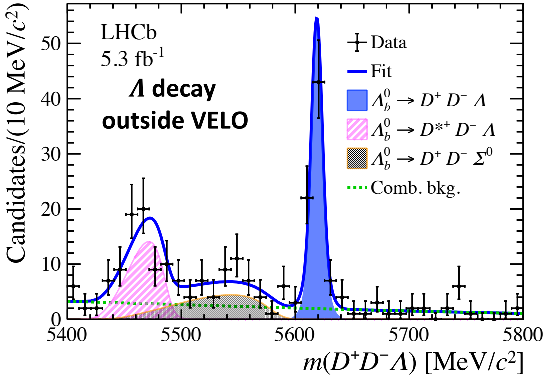
[arXiv: 2403.03586]

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

$N = 19 \pm 5$



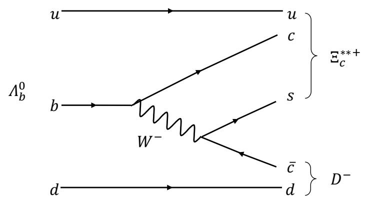
$N = 73 \pm 9$

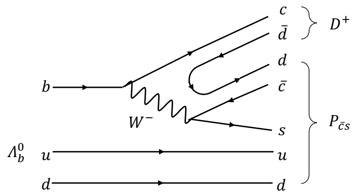


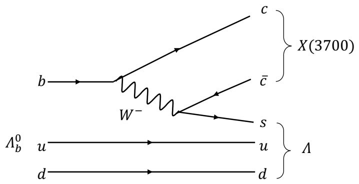
$$\frac{\sigma_{\Lambda_b^0}}{\sigma_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \to D^+ D^- \Lambda)}{\mathcal{B}(B^0 \to D^+ D^- K_S^0)} = 0.179 \pm 0.022 \pm 0.014$$

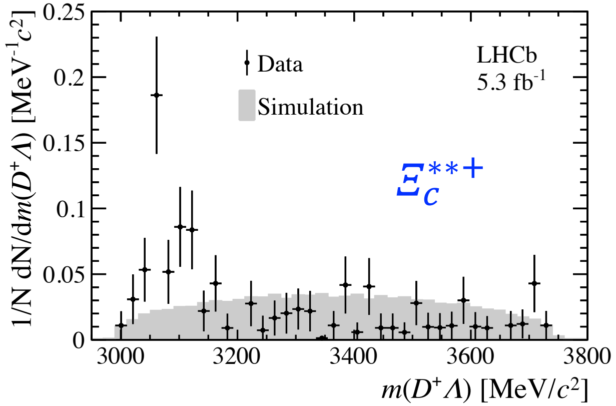
$$\mathcal{B}(\Lambda_b^0 \to D^+ D^- \Lambda) = (1.24 \pm 0.15 \pm 0.10 \pm 0.28 \pm 0.11) \times 10^{-4}$$

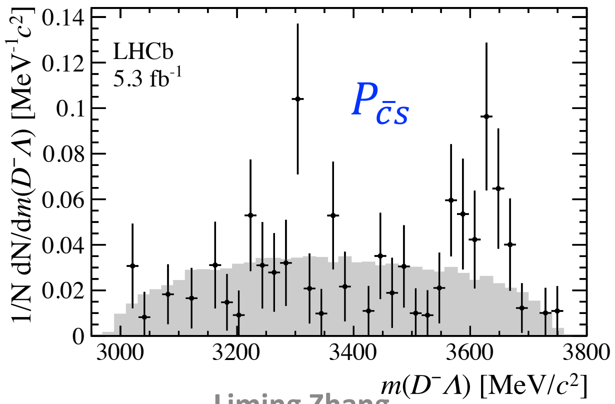
[PRD 103 (2021) 114013]

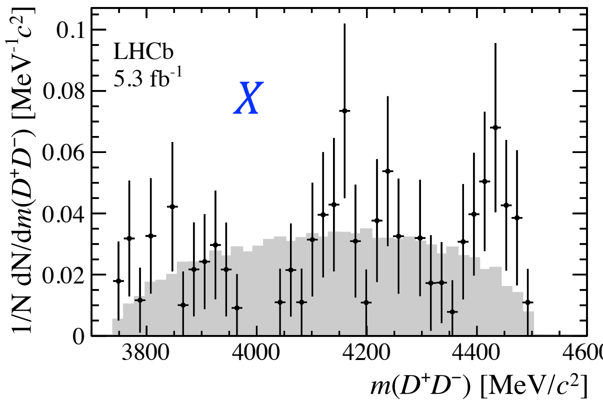








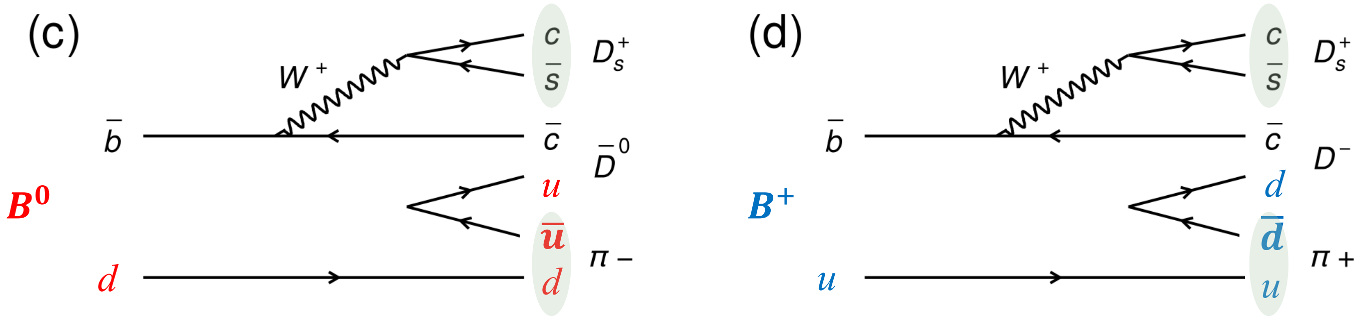


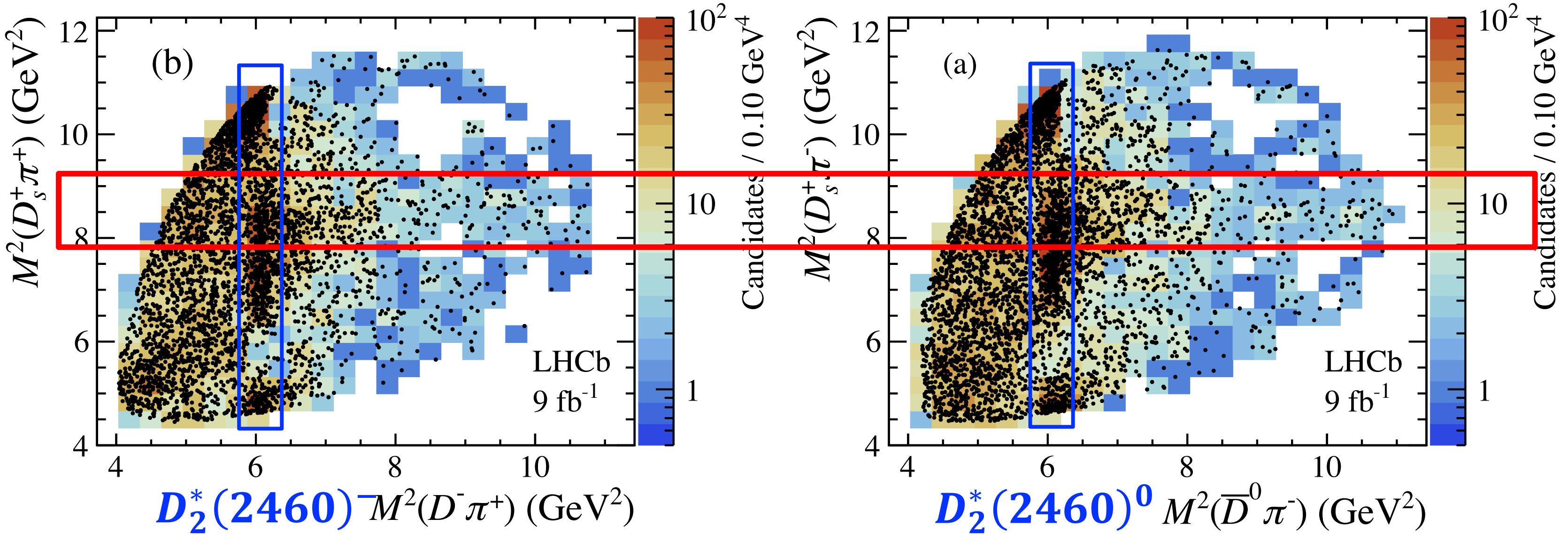


Study of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

[PRL 131 (2023) 041902]

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



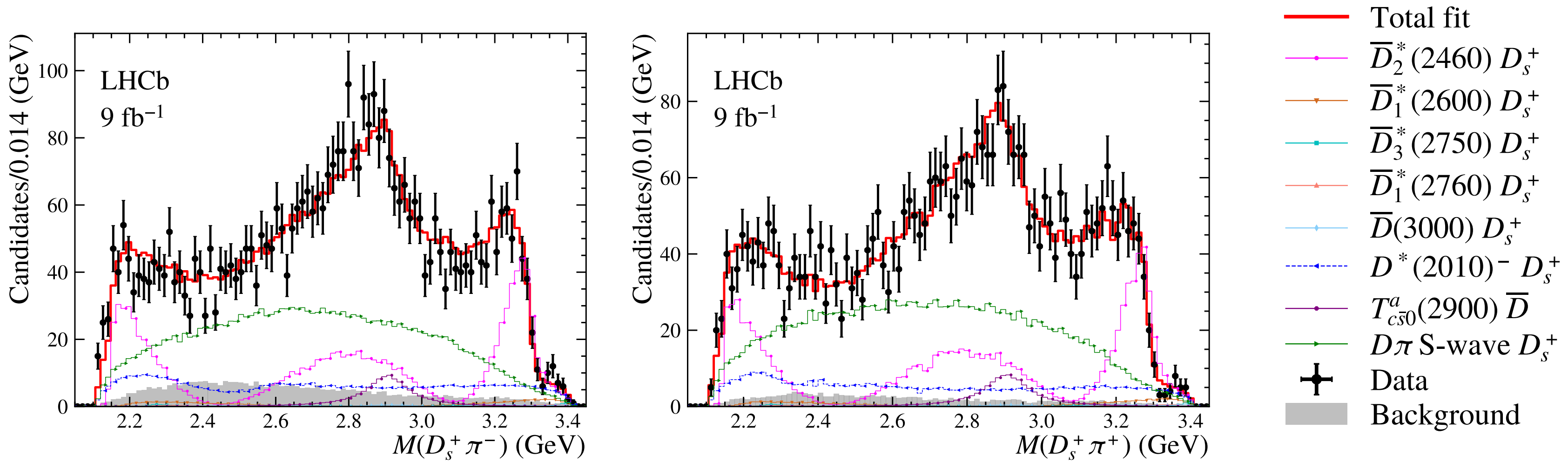


$\Rightarrow$ Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

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

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

[PRL 131 (2023) 041902]



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

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

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

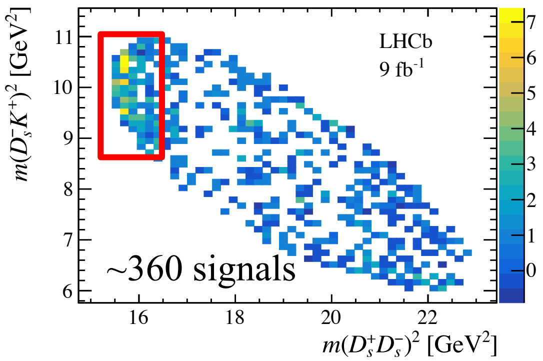
$$\text{Fit fraction} = (2.45 \pm 0.65 \pm 0.84)\%$$

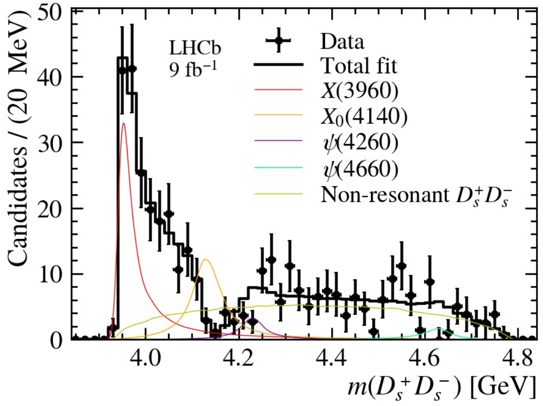
$X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$ decays

[PRL 131 (2023) 071901]

- Strong threshold enhancement found in $D_s^+ D_s^-$ system
- Amplitude analysis is performed
- $\boldsymbol{X(3960)}$: 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

    [JHEP 06 (2021) 035]
  - Resonance parameters are consistent with $\chi_{c0}(3930)$ within 3σ
- More data need to study the lineshape for $X(3960)$





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)