LHCb实验上最新强子谱学研究

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第四届中国格点量子色动力学研讨会

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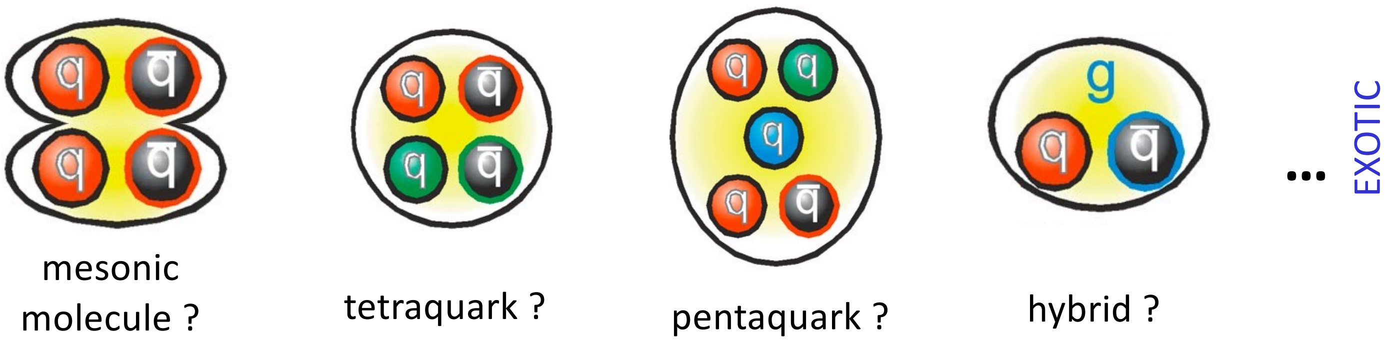
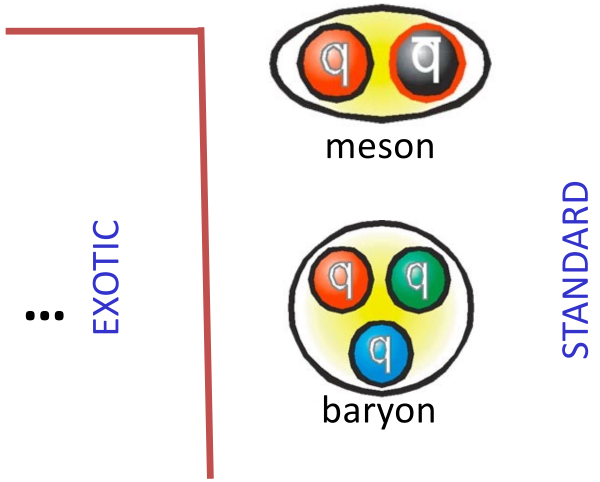
Outline

- Amplitude analysis of $B^+ \to D^{*\pm}D^{\mp}K^+$ [arXiv: 2404.19510]
- Exotic $J/\psi\phi$ resonances in diffractive processes in pp collisions [arXiv: 2407.14301]
- Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$ [arXiv: 2407.12475]
- Study of radiative decays of $\chi_{c1}(3872)$ [arXiv: 2406.17006]
- First determination of J^P of $\Xi_c(3055)$ baryons [arXiv: 2409.05440]
- $\Lambda_b^0, \Lambda_c^+, \Lambda$ decay parameters [arXiv: 2409.02759]
- Search for prompt production of pentaquarks in open charm final states [PRD 110 (2024) 032001]
- Observation of $\Lambda_b^0 \to \Sigma_c^{(*)++}D^{(*)-}K^-$ [PRD 110 (2024) L031104]

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

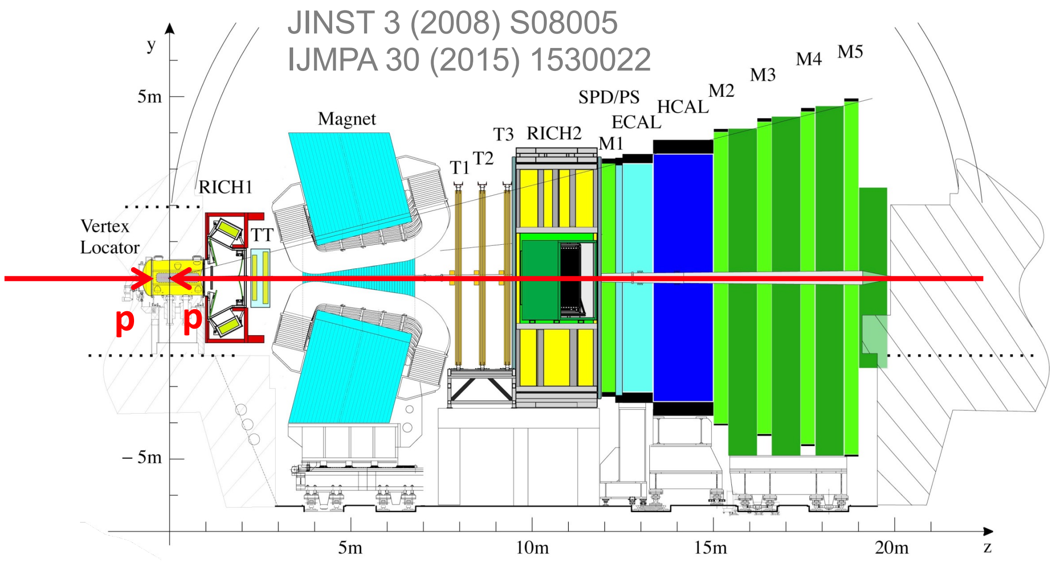


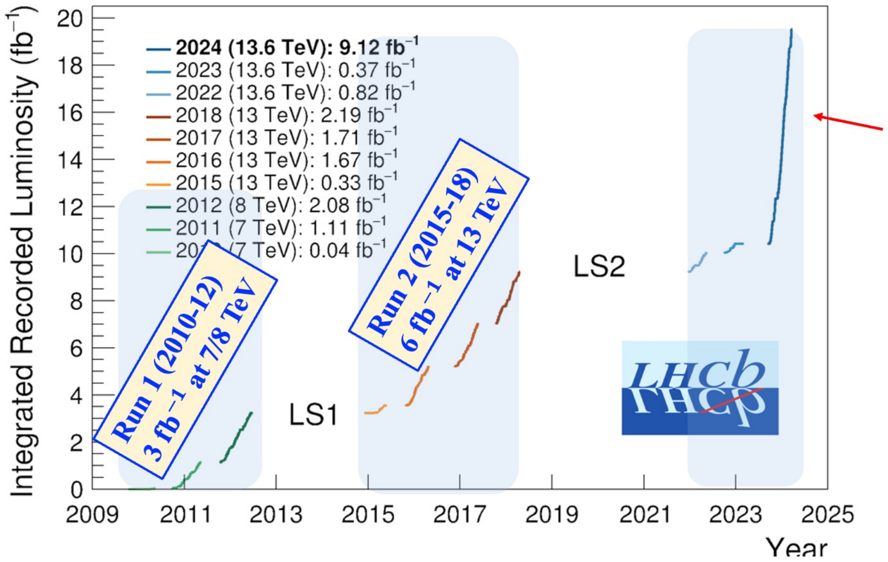


The LHCb Experiment

- 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

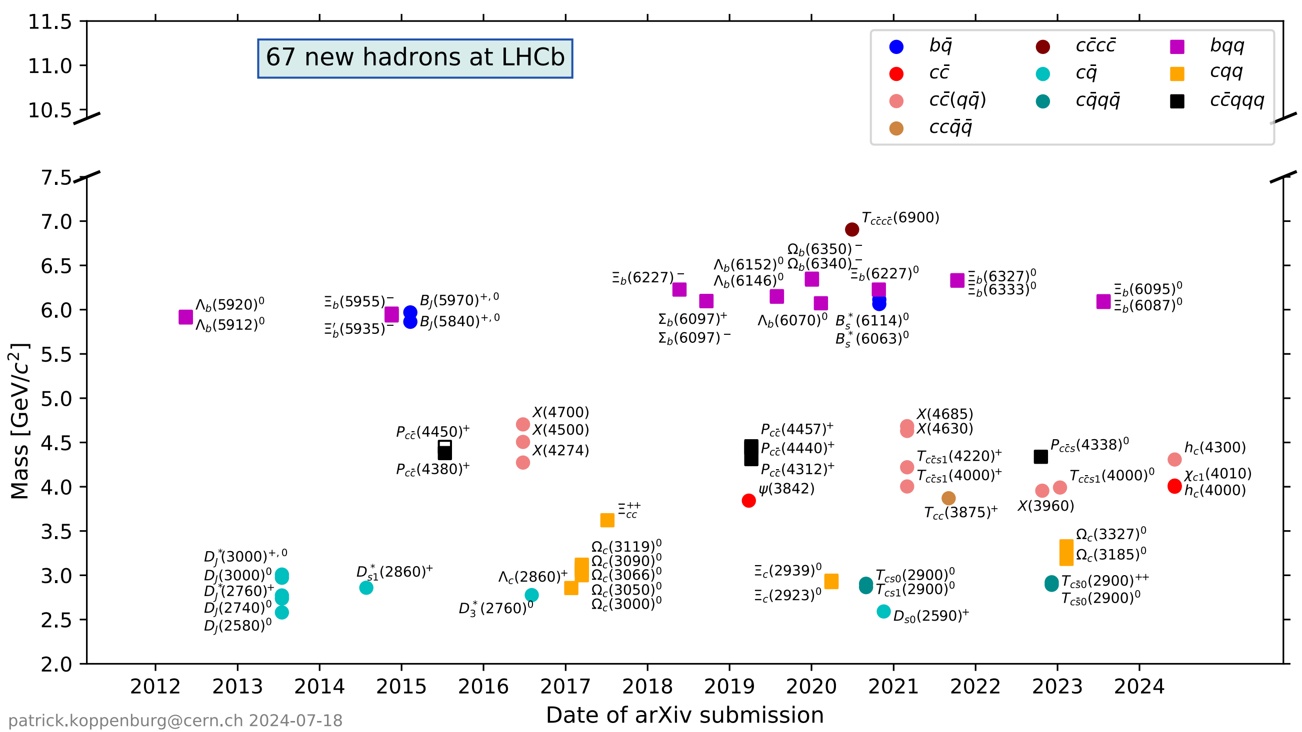




New particles in a glance

- 67 new hadrons discovered by LHCb!

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

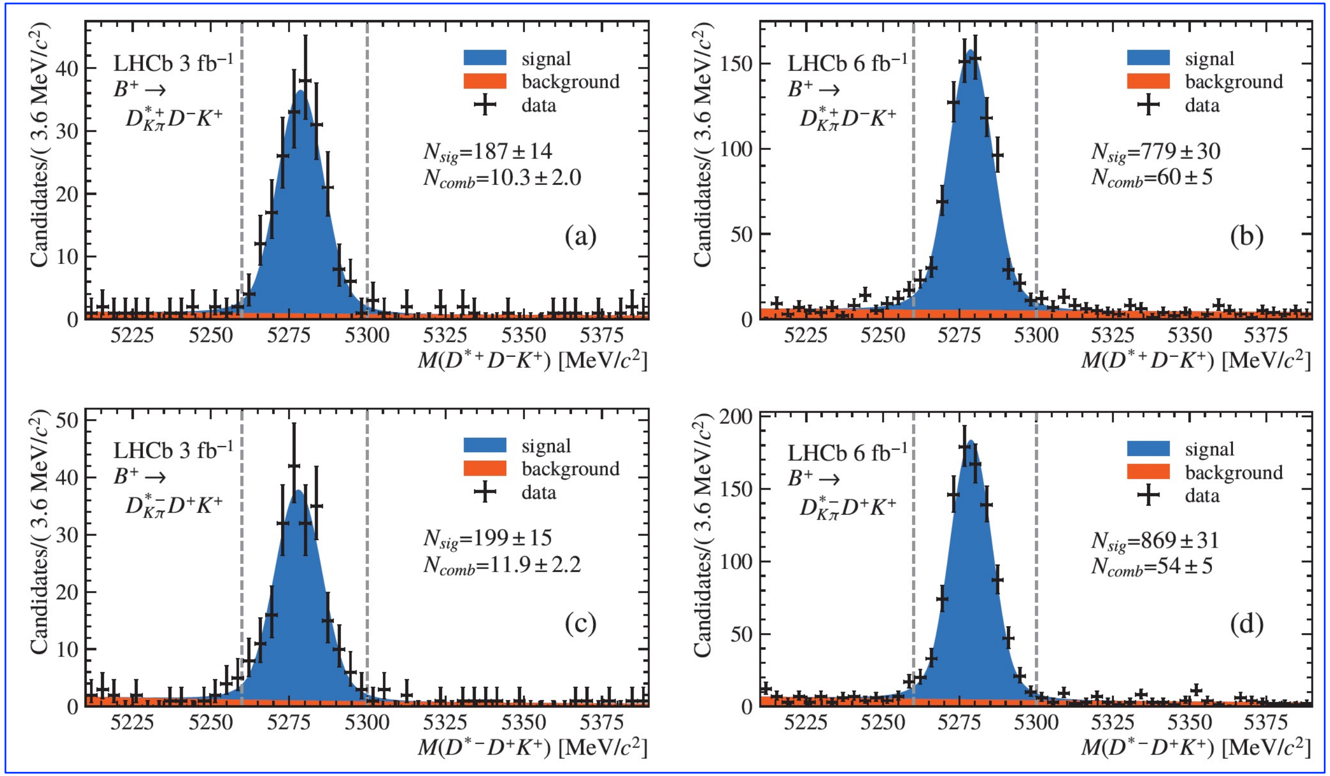


Exotic hadron naming convention: PDG2024 $Z_c \to T^{(*)}_{c\bar{c}J}$ $Z_{cs} \to T^{(*)}_{c\bar{c}\bar{s}J}$ $P_c \to P_{c\bar{c}}$

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

[arXiv: 2406.03156]
accepted by PRL

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



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

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

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

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

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

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

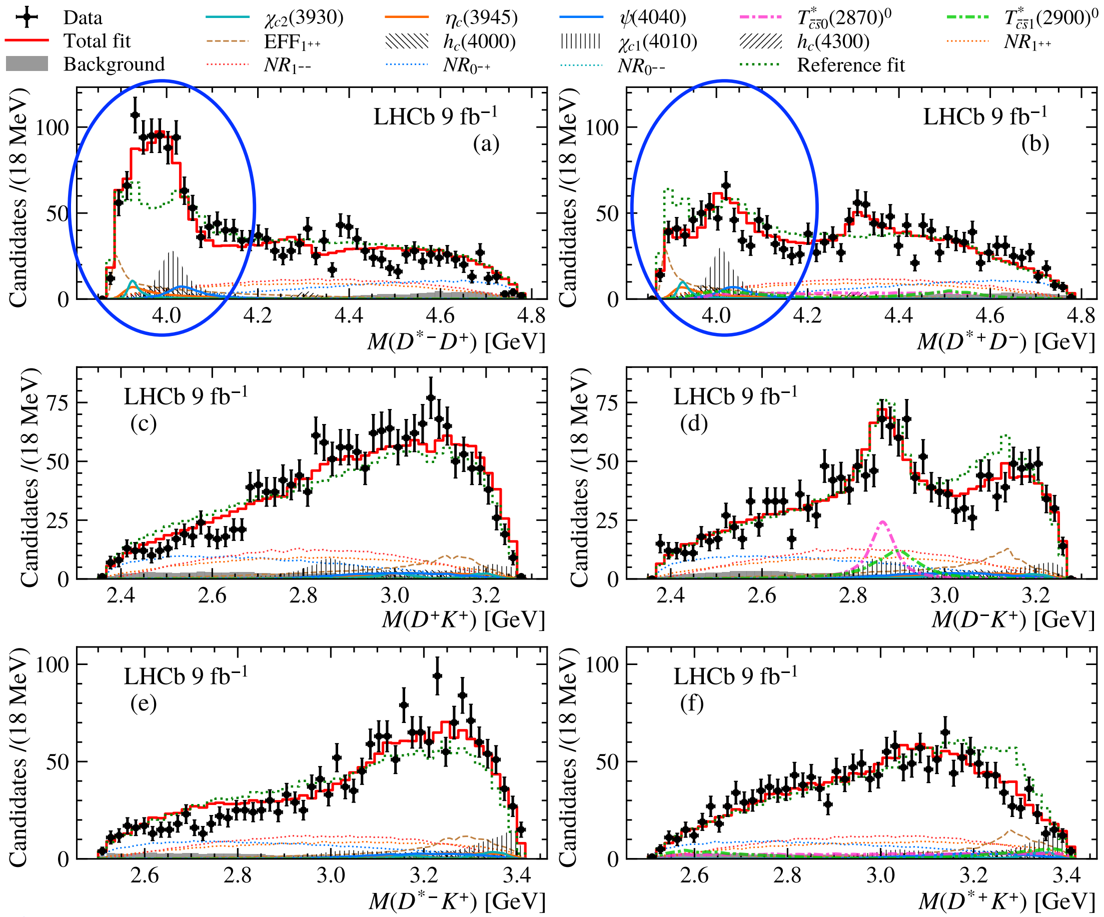
$$
f_{R,S/D}(m) = \frac{\gamma_{S/D}}{m_0^2 - m^2 - i m_0[\gamma_S^2 \Gamma_S(m) + \gamma_D^2 \Gamma_D(m)]}
$$

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

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

[arXiv: 2406.03156]
accepted by PRL

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



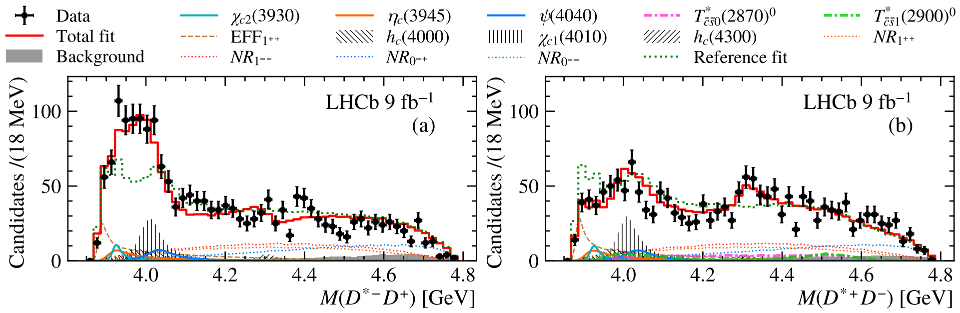
Component	$J^{P(C)}$
EFF$_{1^{++}}$	1^{++}
$\eta_c(3945)$	0^{-+}
$\chi_{c2}(3930)^\dagger$	2^{++}
$h_c(4000)$	1^{+-}
$\chi_{c1}(4010)$	1^{++}
$\psi(4040)^\dagger$	1^{--}
$h_c(4300)$	1^{+-}
$T^*_{c\bar{s}0}(2870)^{0\,\dagger}$	0^+
$T^*_{c\bar{s}1}(2900)^{0\,\dagger}$	1^-
NR$_{1^{--}}(D^{*\mp}D^{\pm})$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

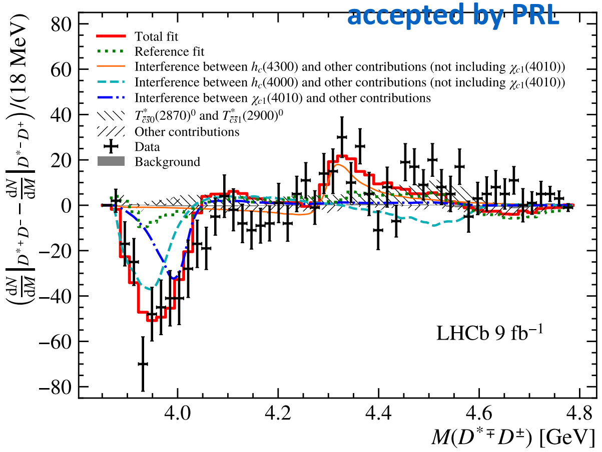
*Fit fractions in paper

✓clear different interference behaviors

$B^+ \to D^{*\pm} D^{\mp} K^+$: $D^{*\pm} D^{\mp}$ 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)?	$\eta_c(3945)$	$J^{PC} = 0^{-+}$	$\eta_c(3S)$	$J^{PC} = 0^{-+}$
	$m_0 = 3945\,^{+28}_{-17}\,^{+37}_{-28}$	$\Gamma_0 = 130\,^{+92}_{-49}\,^{+101}_{-70}$	$m_0 = 4064$	$\Gamma_0 = 80$
	$h_c(4000)$	$J^{PC} = 1^{+-}$	$h_c(2P)$	$J^{PC} = 1^{+-}$
	$m_0 = 4000\,^{+17}_{-14}\,^{+29}_{-22}$	$\Gamma_0 = 184\,^{+71}_{-45}\,^{+97}_{-61}$	$m_0 = 3956$	$\Gamma_0 = 87$
	$\chi_{c1}(4010)$	$J^{PC} = 1^{++}$	$\chi_{c1}(2P)$	$J^{PC} = 1^{++}$
	$m_0 = 4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$	$\Gamma_0 = 62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$	$m_0 = 3953$	$\Gamma_0 = 165$
	$h_c(4300)$	$J^{PC} = 1^{+-}$	$h_c(3P)$	$J^{PC} = 1^{+-}$
	$m_0 = 4307.3\,^{+6.4}_{-6.6}\,^{+3.3}_{-4.1}$	$\Gamma_0 = 58\,^{+28}_{-16}\,^{+28}_{-25}$	$m_0 = 4318$	$\Gamma_0 = 75$

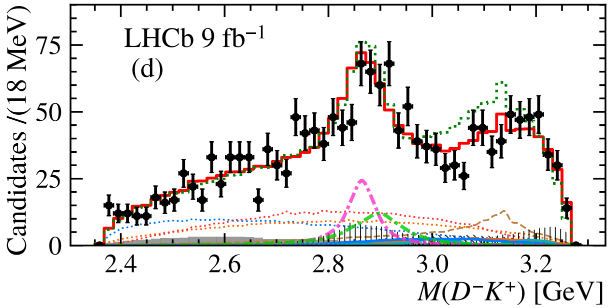
GI model
hep-ph/0505002

- 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]

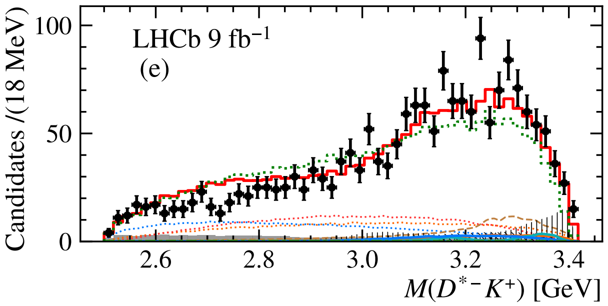
$B^+ \to D^{*\pm} D^{\mp} K^+$: $T^*_{\bar{c}\bar{s}}$ states

[arXiv: 2406.03156]
accepted by PRL

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



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



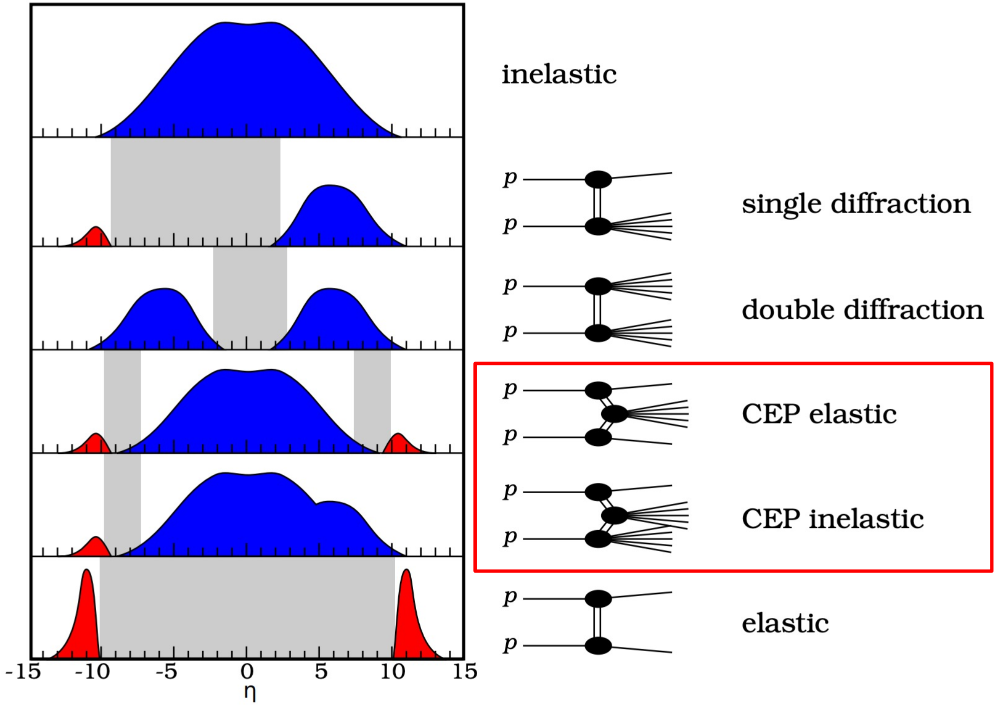
	Property	This work		Previous work
11σ	$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$		2866 ± 7
$X_0(2900)$	$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	2σ ↔	57 ± 13
9.2σ	$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$		2904 ± 5
$X_1(2900)$	$T^*_{\bar{c}\bar{s}1}(2900)^0$ 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

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

Central exclusive production (CEP)

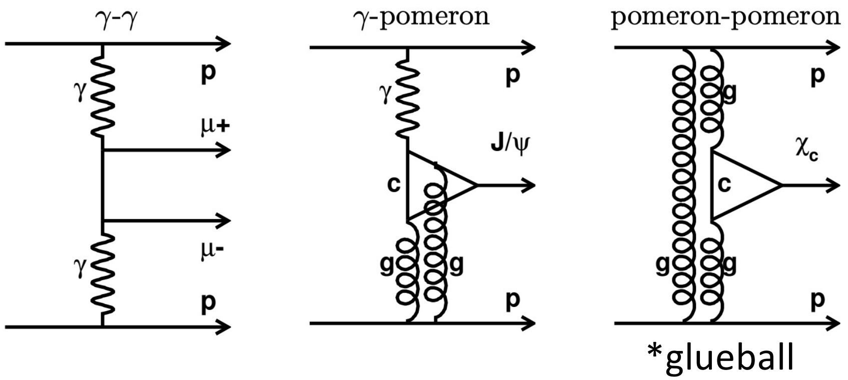
- Study *J/ψϕ resonances in CEP*



✓ Experimentally clean even @LHC

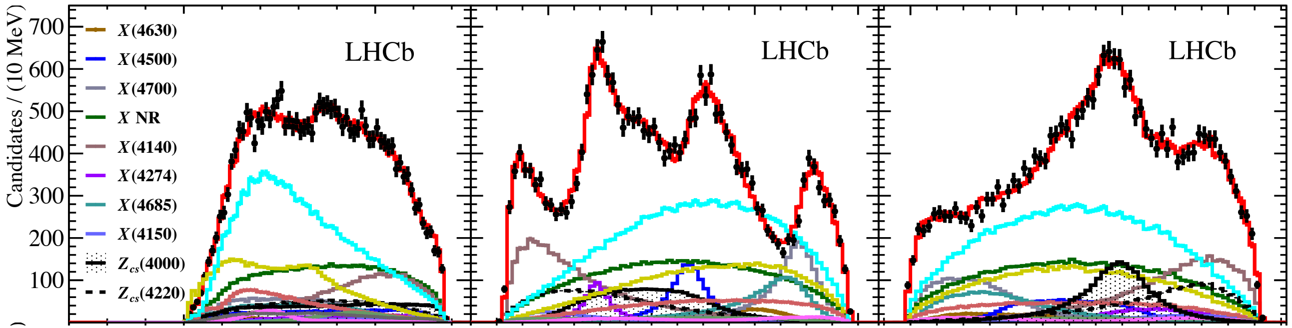
✓ Spin-parity option narrowed down

✘ Much smaller rate



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

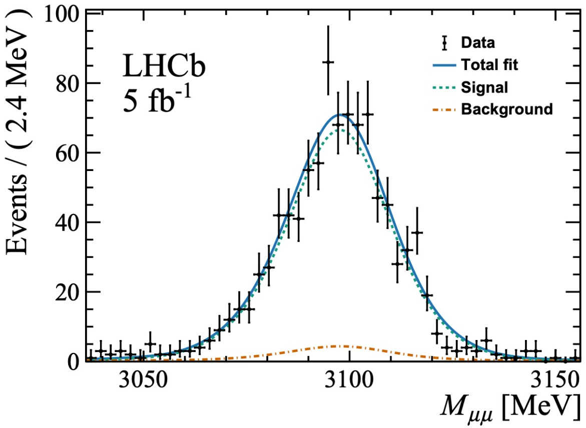
[PRL 127 (2021) 082001]

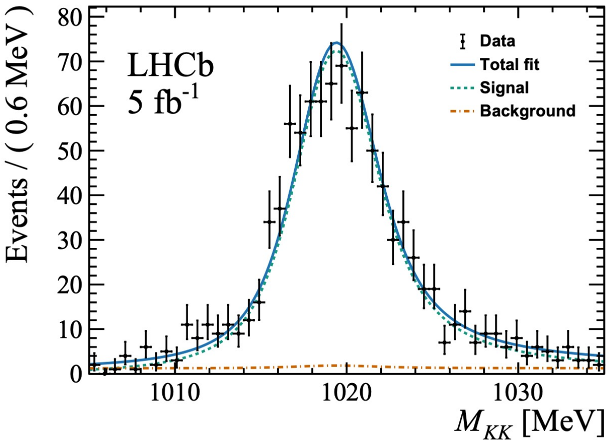


$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
$X(4700)$	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)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

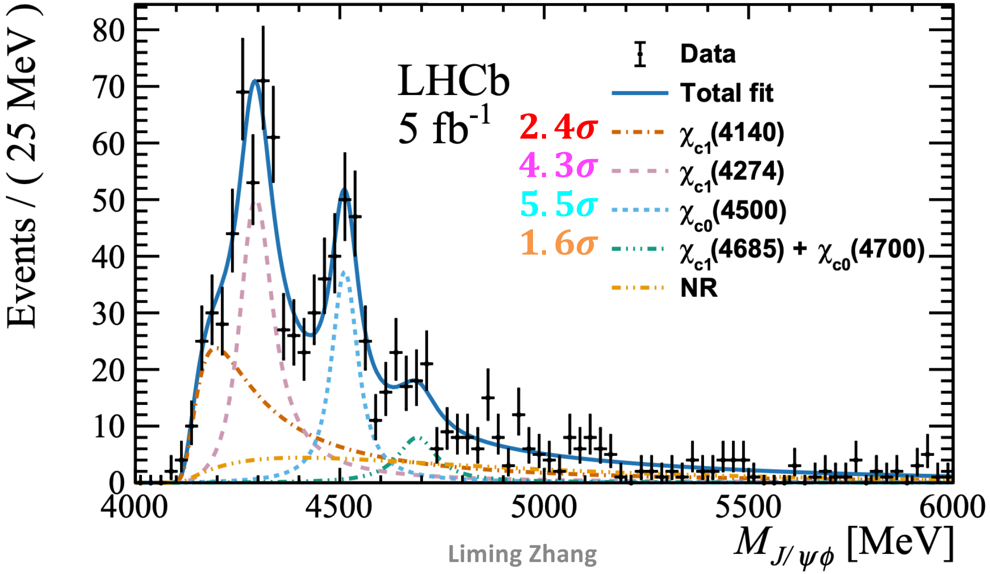
$X \to J/\psi\phi$ in CEP

[arXiv: 2407.14301]



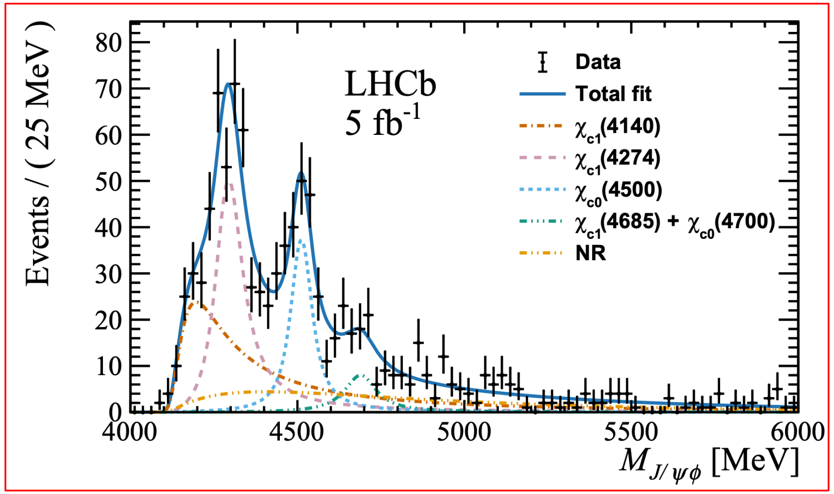


$N = 989$
purity $= (93.0 \pm 0.5)\%$

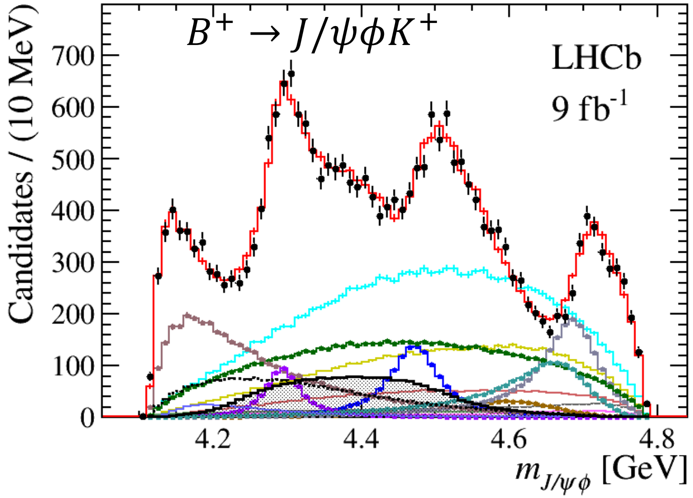


First exotic hadron measurement in CEP!

[arXiv: 2407.14301]



[PRL 127 (2021) 082001]



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

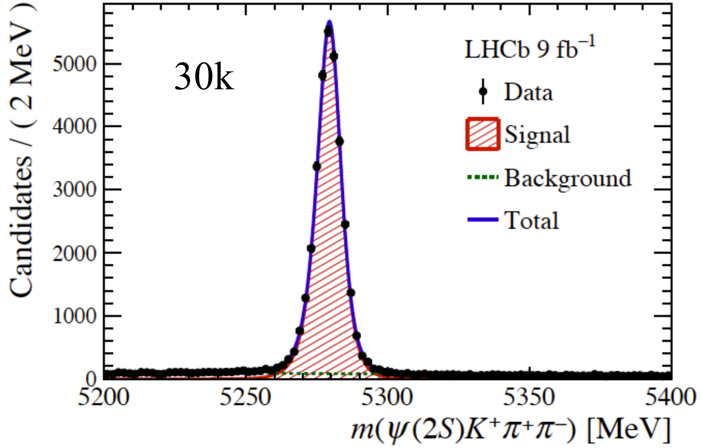
Parameter (MeV)	This Letter	Ref. [12]
$M_{\chi_{c1}(4274)}$	$4298 \pm 6 \pm 9$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18} \pm 57$	$53 \pm 5 \pm 5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16} \pm 32$	$77 \pm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

- Cross-section measurements:

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

$B^+ \to \psi(2S)K^+\pi^+\pi^-$: 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 I think 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

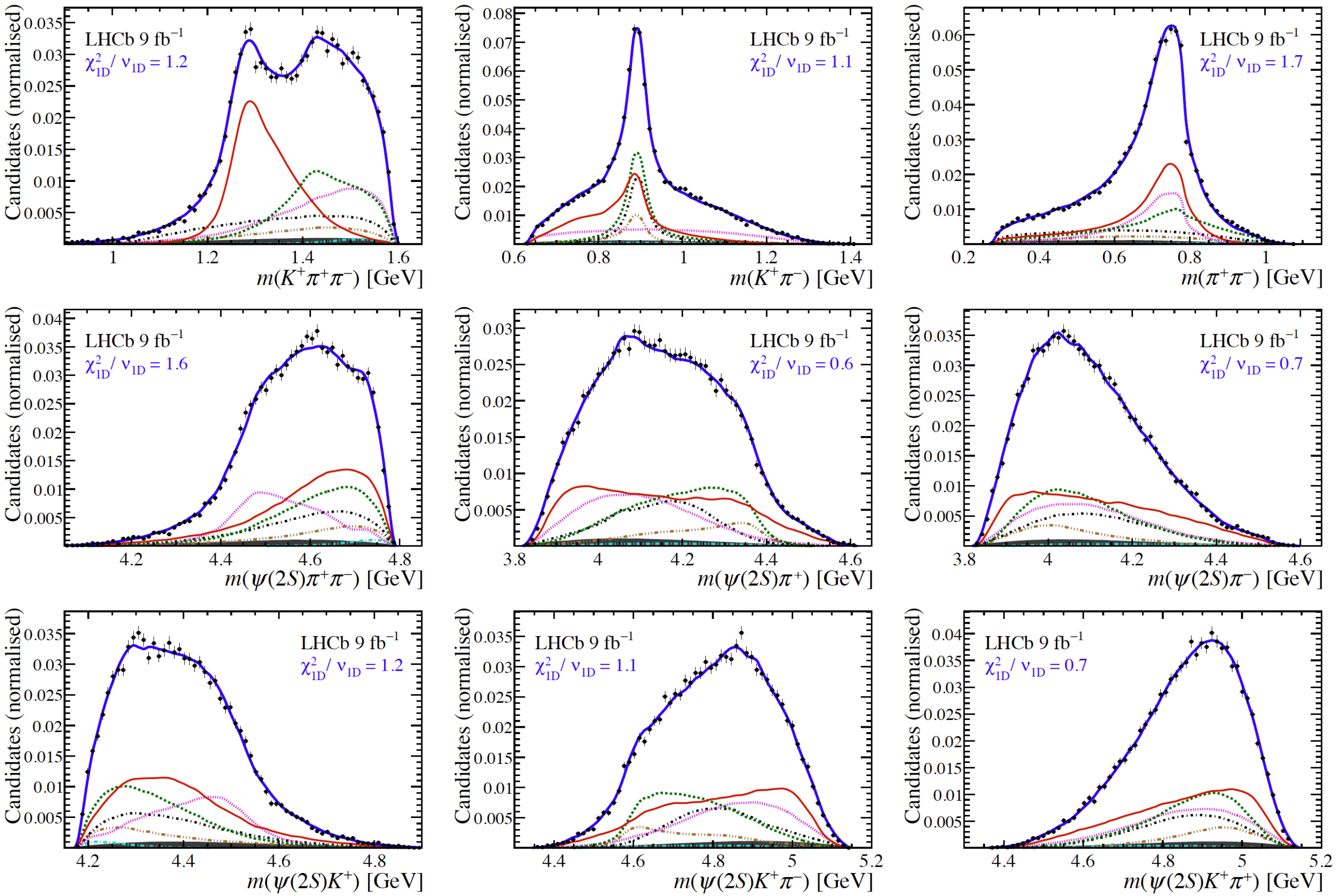
Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Res. PDG	m_0 [MeV]	Γ_0 [MeV]
$\chi_{c0}(4475)$	0^+	$4475\pm 7\pm12$	$231\pm19\pm32$	$\chi_{c0}(4500)$	4474 ± 4	77^{+12}_{-10}
$\chi_{c1}(4650)$	1^+	$4653\pm14\pm27$	$227\pm26\pm22$	$\chi_{c1}(4685)$	4684^{+15}_{-17}	126 ± 40
$\chi_{c0}(4710)$	0^+	$4710\pm 4\pm5$	$64\pm 9\pm10$	$\chi_{c0}(4700)$	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

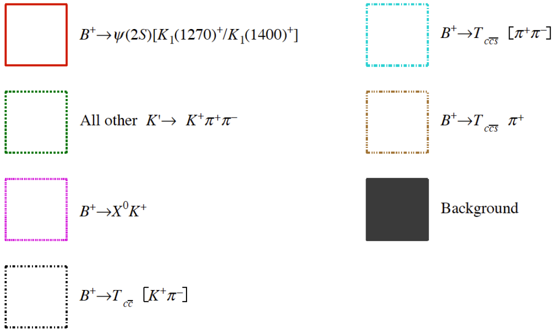
new

Fit projections

[arXiv: 2407.12475]

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



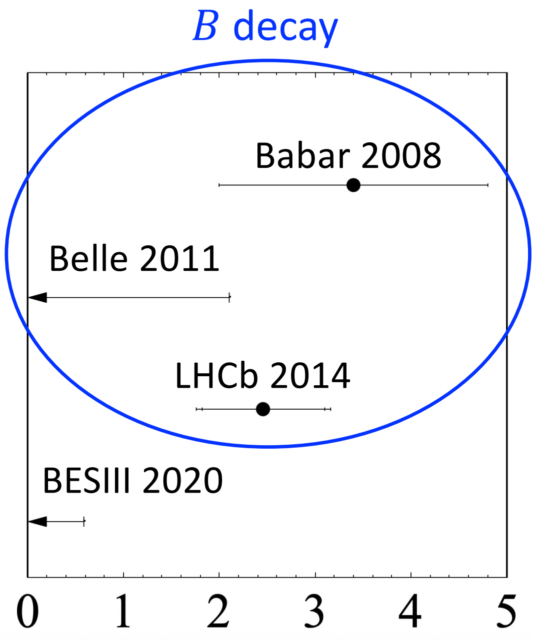


Radiative decays of $\chi_{c1}(3872)$

[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		$\mathscr{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$		
T. Barnes and S. Godfrey		[67]	5.8	$c\bar{c}$
T. Barnes, S. Godfrey and S. Swanson		[69]	2.6	$c\bar{c}$
F. De Fazio		[84]	(1.64 ± 0.25)	$c\bar{c}$
B.-Q. Li and K. T. Chao		[85]	1.3	$c\bar{c}$
Y. Dong *et al.*	$\gtrsim 1$	[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		[91]	0.25	$D\bar{D}^*$
R. F. Lebed and S. R. Martinez	$\ll 1$	[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]	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$

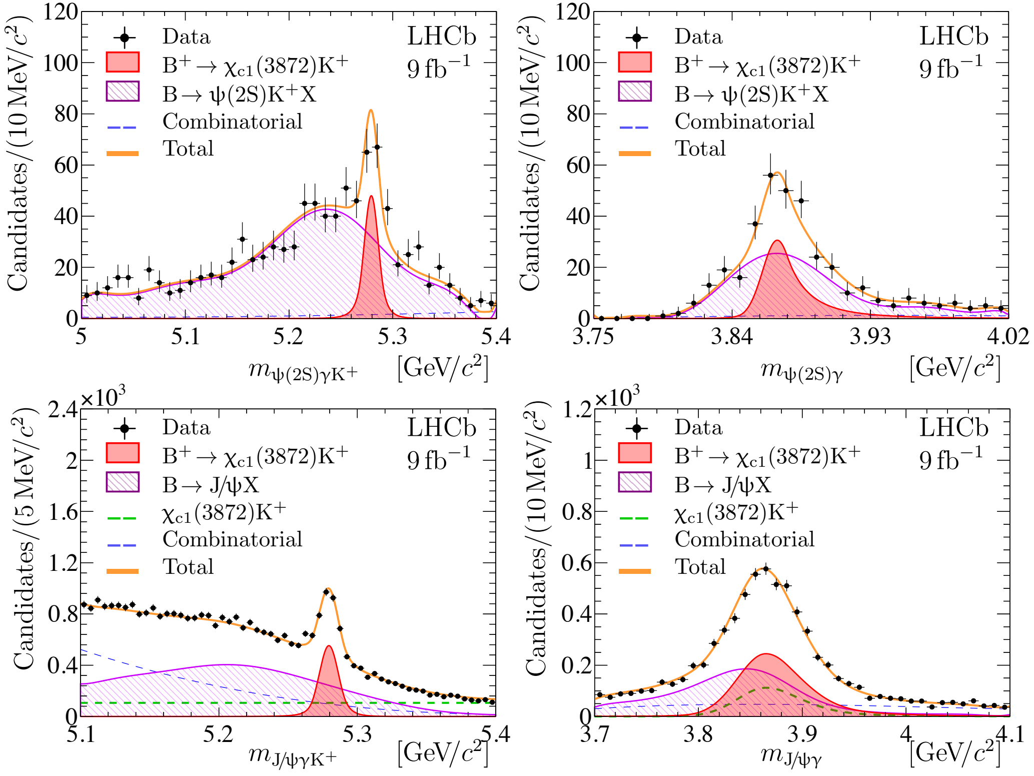


$$\mathscr{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$$

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



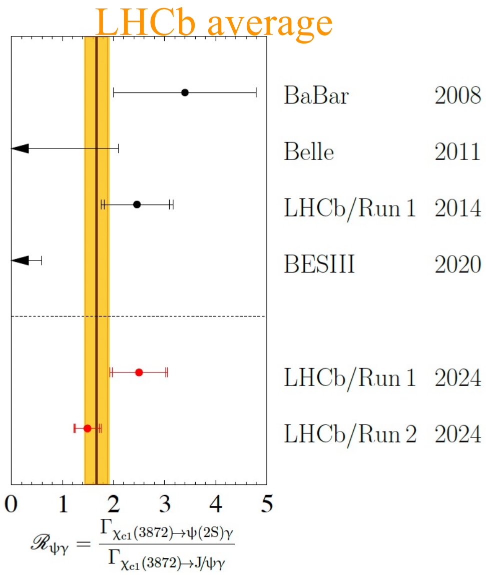
$$\mathscr{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04 \quad (15\%)$$

LHCb meets theory workshop

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

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

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



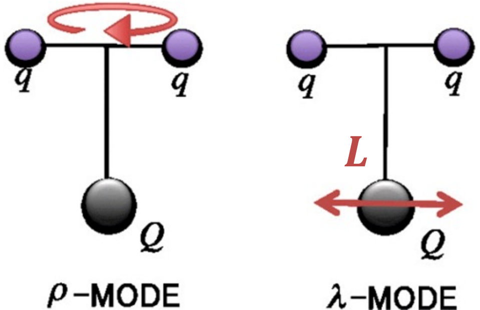
1st determination of J^P for $\Xi_c(3055)^{+,0}$

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

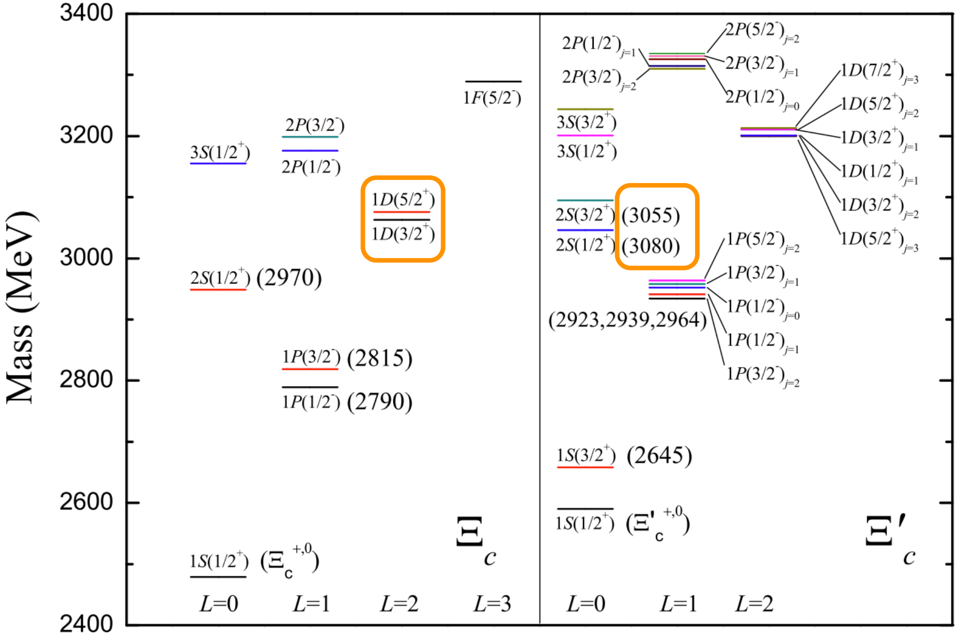
Configuration	$J^P_{[qq]} = 0^+$	$J^P_{[qq]} = 1^+$
Naming	Ξ_Q	Ξ'_Q

  - ✓ ρ-mode: no firm assignment yet

[PRD 92 (2015) 114029]



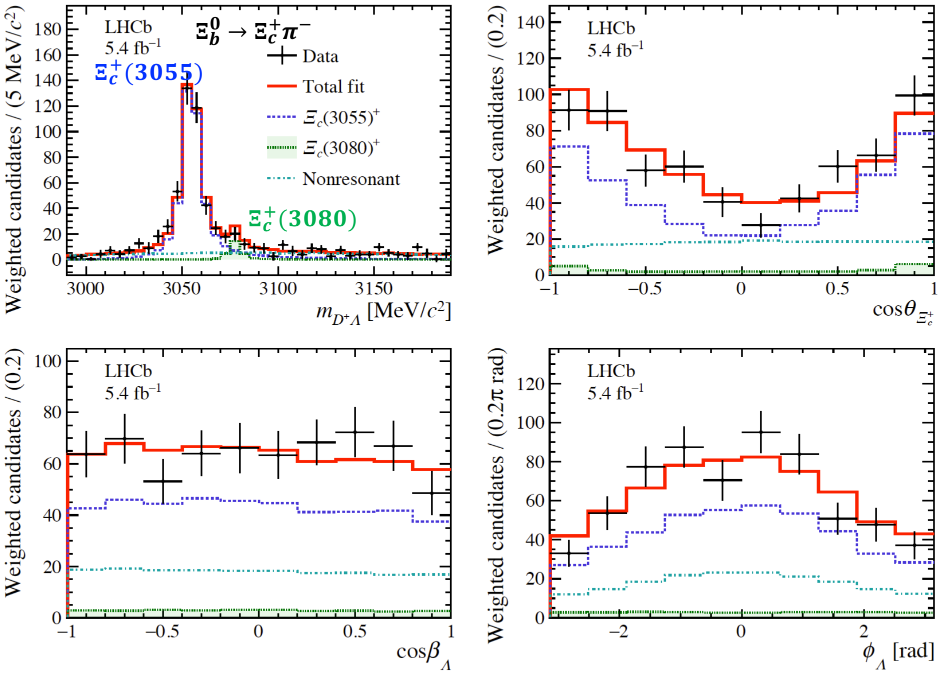
$\Xi_c(3055)$'s mass can fit into 1D or 2S states

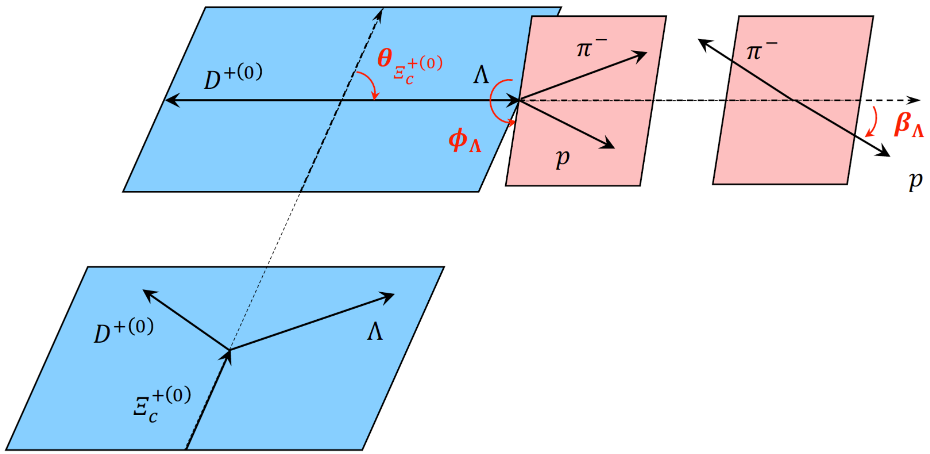


Chinese Phys. C **47** (2023) 073105

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 $(m_{D\Lambda}, \theta_{\Xi_c}, \beta_\Lambda, \theta_\Lambda)$



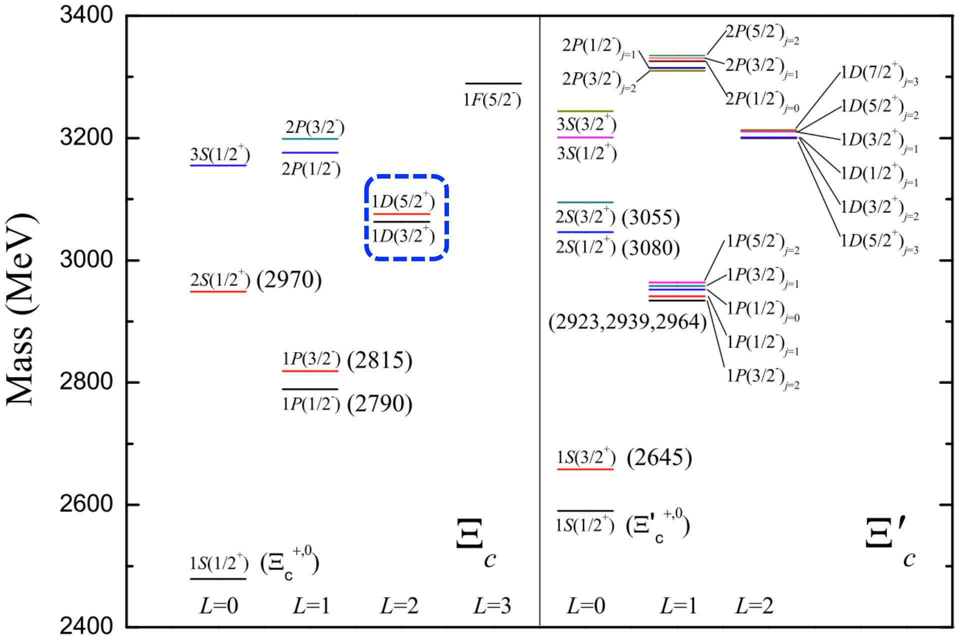


1st determination of J^P for $\Xi_c(3055)^{+,0}$ [arXiv: 2409.05440]

- $J^P = 3/2^+$ 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 [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	$-0.92 \pm 0.10 \pm 0.05$	$-0.92 \pm 0.16 \pm 0.22$
$R_{\mathcal{B}}$	$0.045 \pm 0.023 \pm 0.006$	$0.14 \pm 0.06 \pm 0.04$

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



Chinese Phys. C **47** (2023) 073105

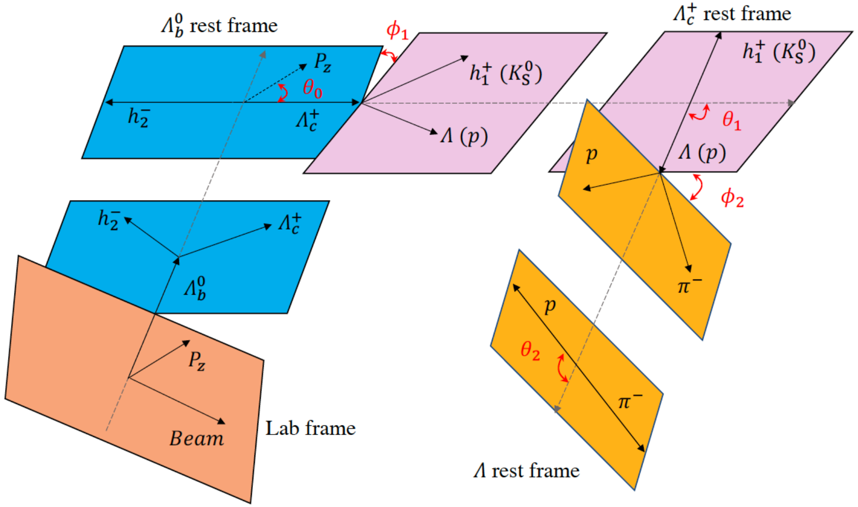
$\Lambda_b^0, \Lambda_c^+, \Lambda$ decay parameters

- 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]

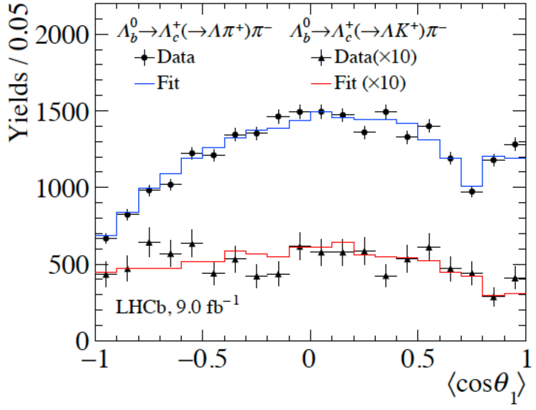
- Parameters are determined for Λ_b^0 and $\overline{\Lambda}_b^0$
- No significant CP violation is found

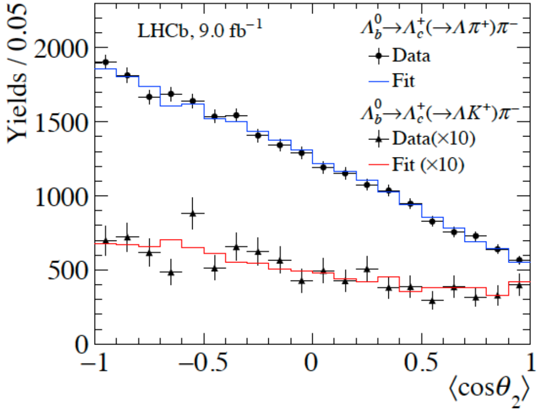
Other paramaters can found in the paper

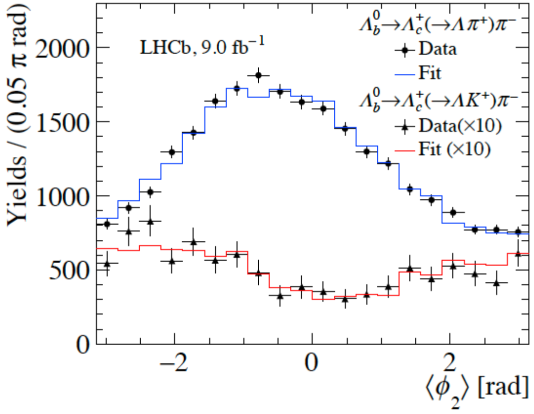
Decay	α	$\bar{\alpha}$	$\langle\alpha\rangle$	A_α
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	$-1.010 \pm 0.011 \pm 0.003$	$0.996 \pm 0.011 \pm 0.003$	$-1.003 \pm 0.008 \pm 0.005$	$0.007 \pm 0.008 \pm 0.005$
$\Lambda_b^0 \to \Lambda_c^+ K^-$	$-0.933 \pm 0.042 \pm 0.014$	$0.995 \pm 0.036 \pm 0.013$	$-0.964 \pm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

1st measurments

Most precise



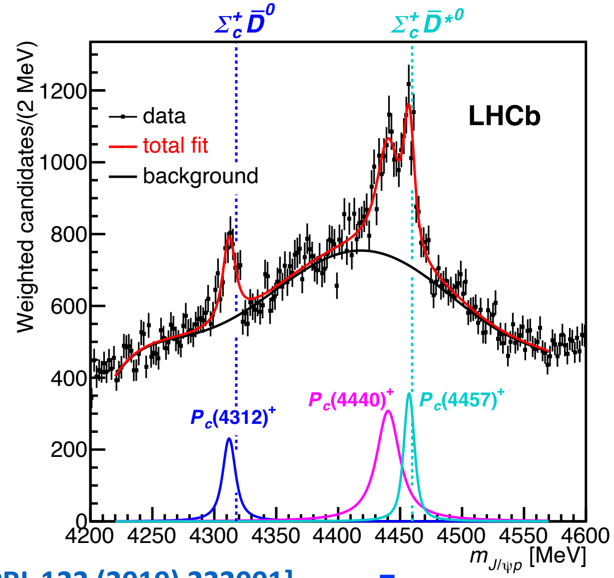




Pentaquark study

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

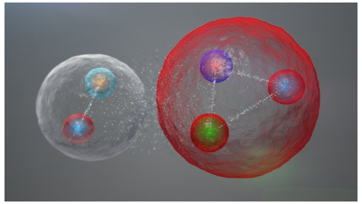
$\Lambda_b^0 \to [J/\psi\, p]K^-$



[PRL 122 (2019) 222001]

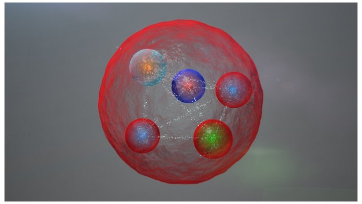
Proximity of $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$ thresholds to the peaks suggests they play an important role in the dynamics

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	✓

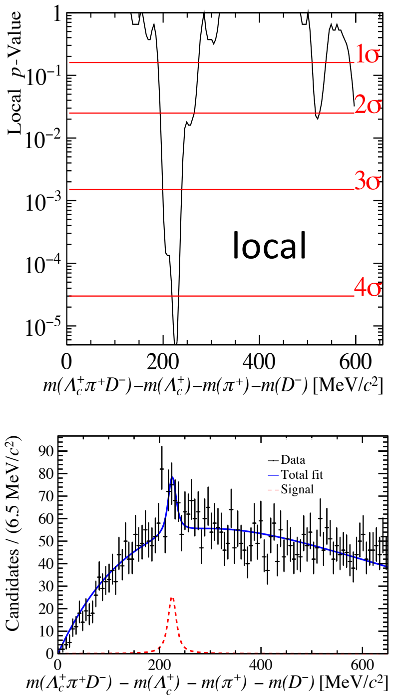
✓doubly-charmed pentaquarks & excited Ξ_{cc}

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 $R = \frac{N_{P_c}}{N_{\Lambda_c^+}} \times \frac{\varepsilon_{\Lambda_c^+}}{\varepsilon_{P_c}} \rightarrow \frac{\sigma(P_c)\times\mathcal{B}\left(P_c\rightarrow\Lambda_c^+D(\pi)\right)\times\mathcal{B}(D)}{\sigma(\Lambda_c^+)}$
- Largest significant modes:

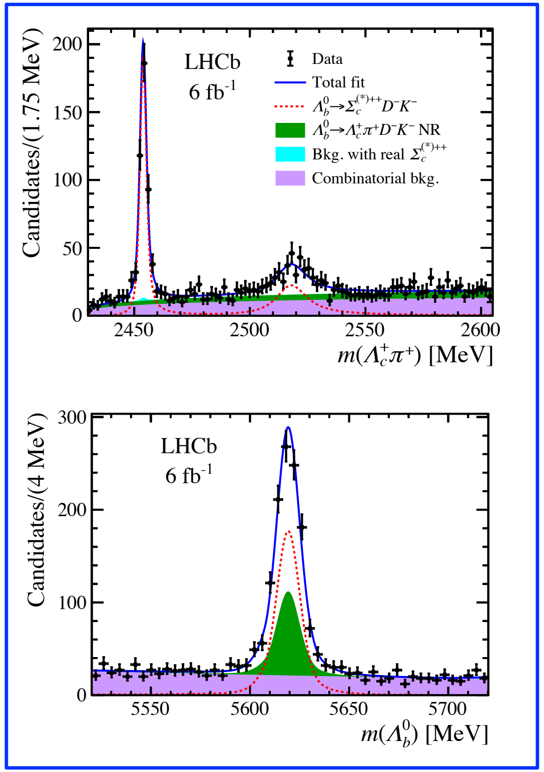
*Complete list in paper

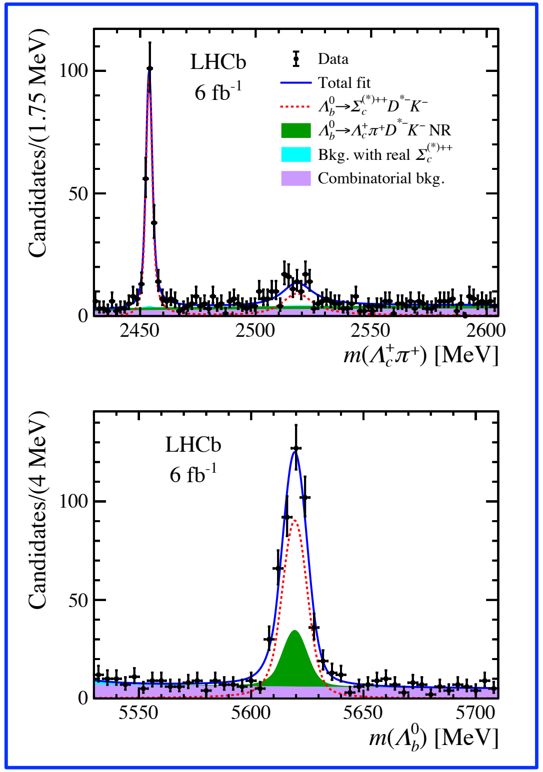
Decay Mode	Width (MeV/c^2)	Significance (σ) Local	Significance (σ) Corrected	Q-value (MeV/c^2)	Signal Yield	UL ($\times10^{-3}$) 90% CL	UL ($\times10^{-3}$) 95% CL
$\Lambda_c^+\pi^+D^-$	0	3.59	2.21	225	41.6 ± 12.6	3.95	4.19
	5	4.01	2.89	225	64.7 ± 17.4	4.43	4.69
	10	4.30	3.32	225	87.1 ± 21.6	4.64	4.85
	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
$\Lambda_c^+\pi^+\overline{D}^0$	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

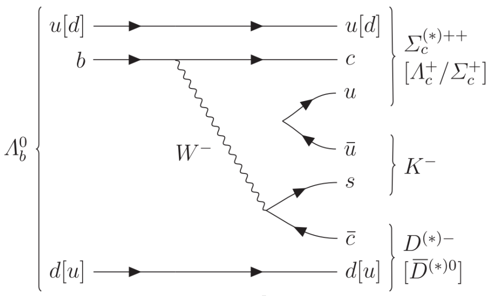
$\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$: observation

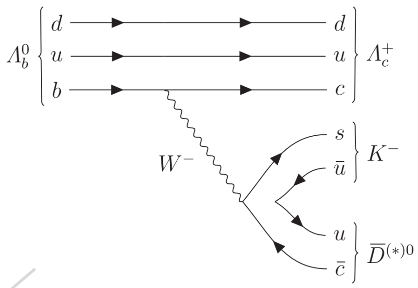
[PRD **110** (2024) L031104]

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









$$\frac{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^-K^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\overline{D}^0K^-)} = 0.282\pm0.016\pm0.016\pm0.005,$$

$$\frac{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{*++}D^-K^-)}{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^-K^-)} = 0.460\pm0.052\pm0.028,$$

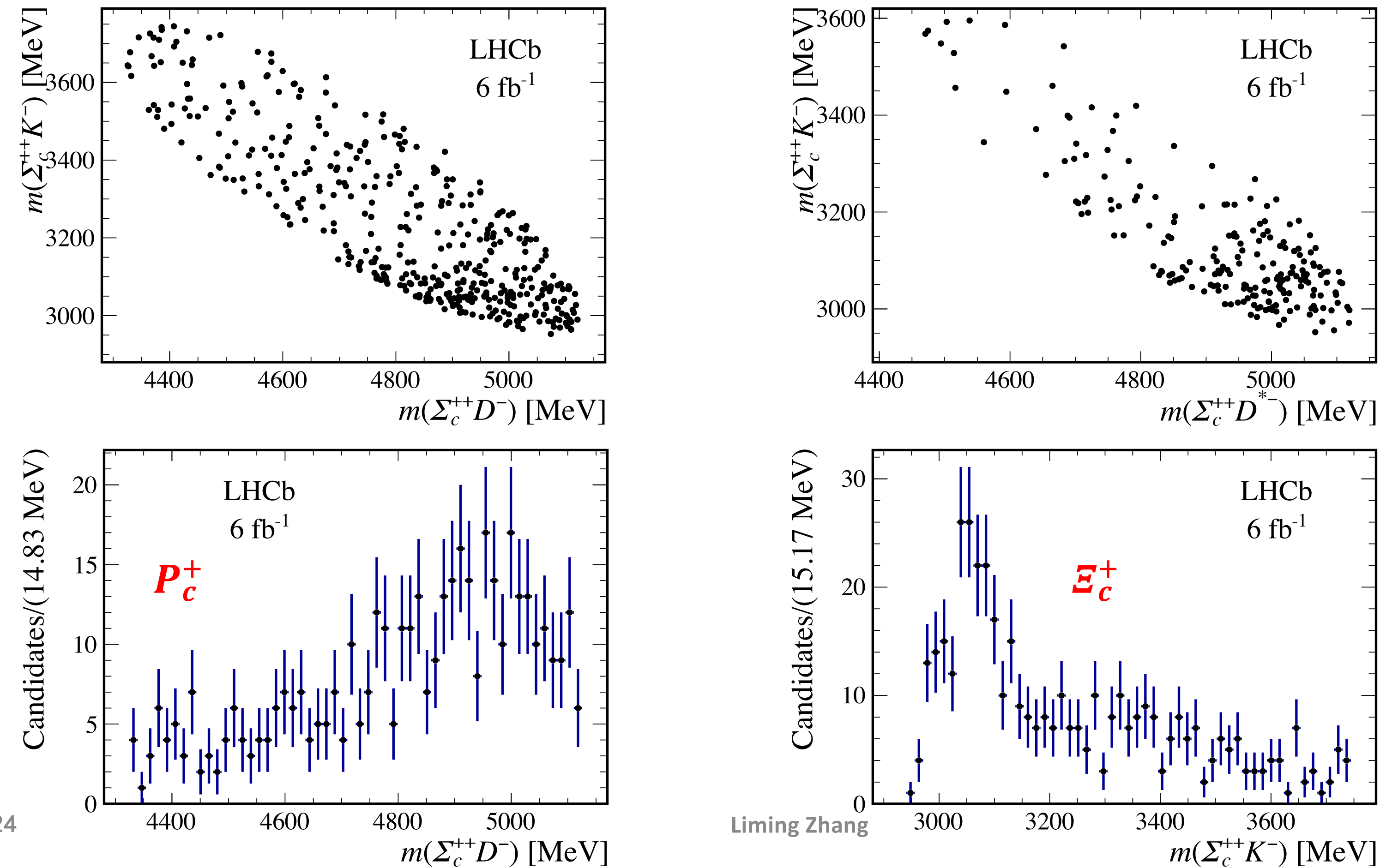
$$\frac{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^{*-}K^-)}{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^-K^-)} = 2.261\pm0.202\pm0.129\pm0.046,$$

$$\frac{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{*++}D^{*-}K^-)}{\mathcal{B}(\Lambda_b^0\to\Sigma_c^{++}D^-K^-)} = 0.896\pm0.137\pm0.066\pm0.018,$$

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

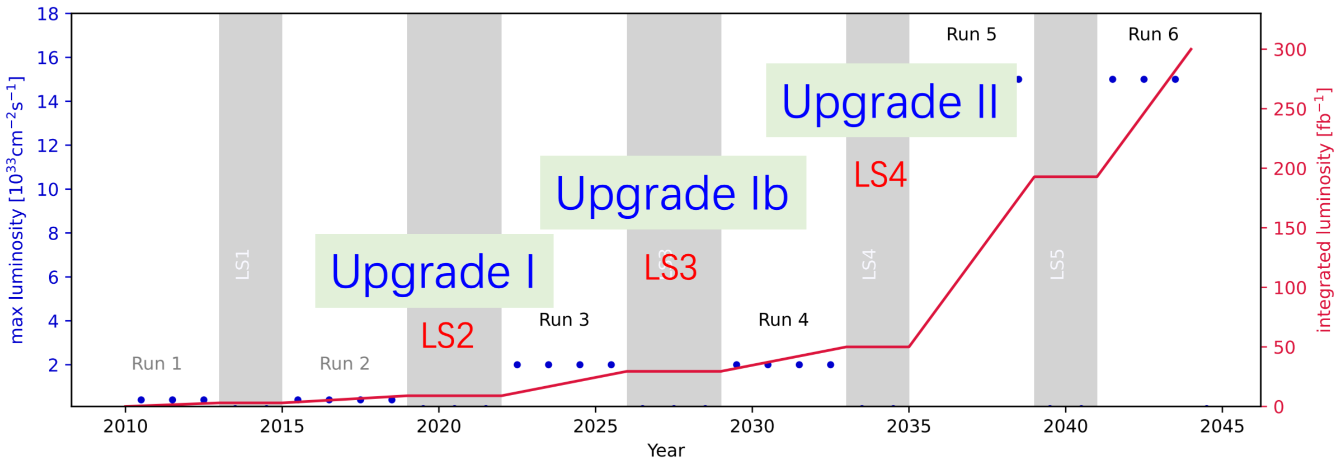
[PRD **110** (2024) L031104]

- Larger dataset needed to draw a definitive conclusion



Summary and prospects

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



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

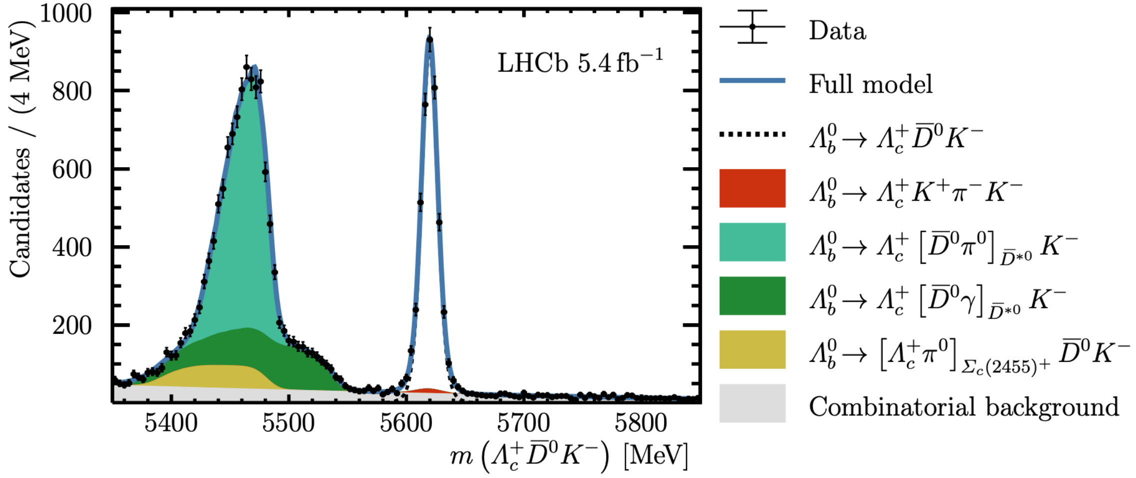
BACKUP

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

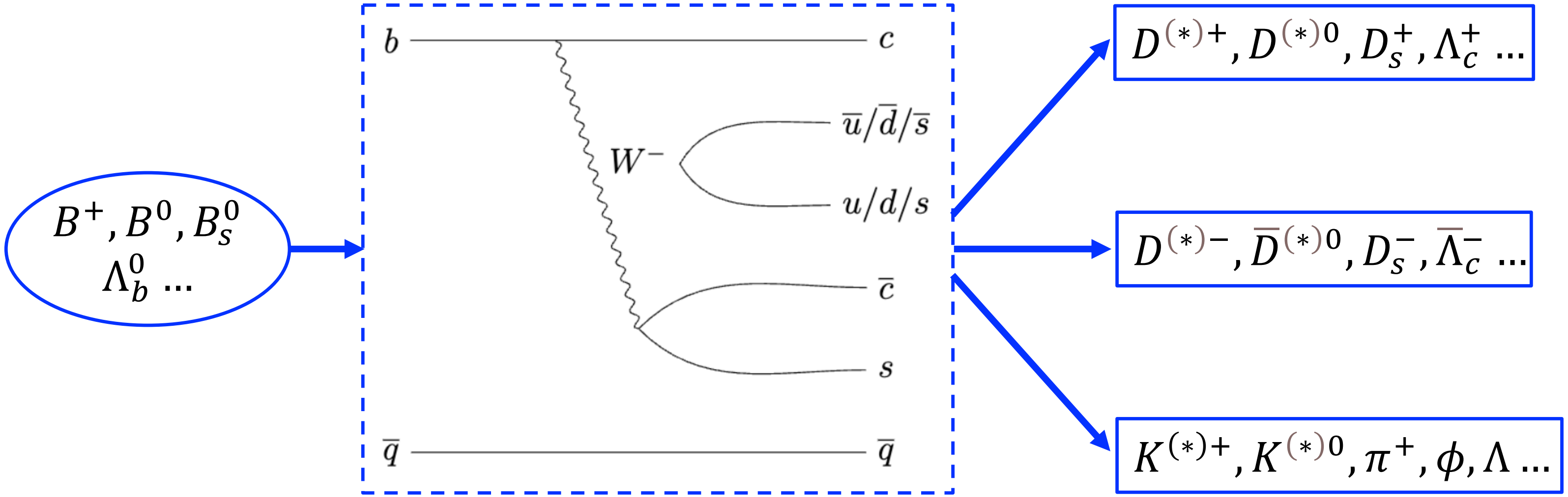
$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)} = (15.2^{+3.2}_{-2.8})\%$$

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

[arXiv:2311.14088]

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

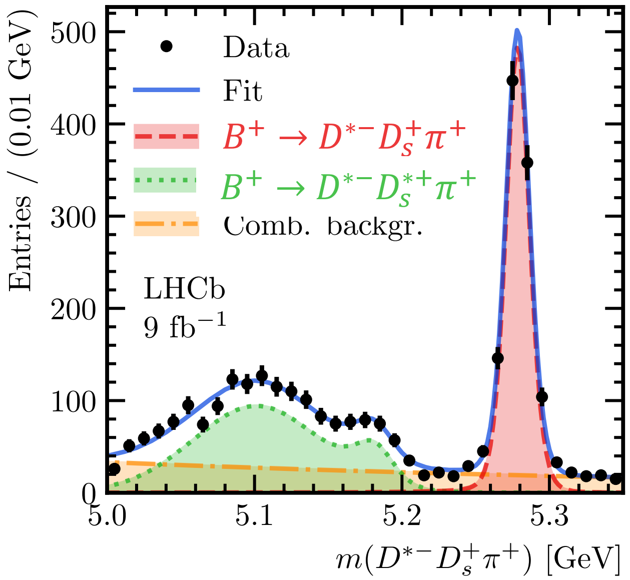
- Rich opportunities for spectroscopy study
  - **charmonium(-like)** states in $D^{(*)}\bar{D}^{(*)}, \Lambda_c^+\bar{D}^{(*)}, \Lambda_c^+\bar{\Lambda}_c^-$ ...
  - **excited $D^+, D^0, D_s^+, \Lambda_c^+$** states from $D^{(*)}h, \Lambda_c^+ h$ ...
  - **exotic** states from $\bar{D}^{(*)}h, \bar{\Lambda}_c^-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



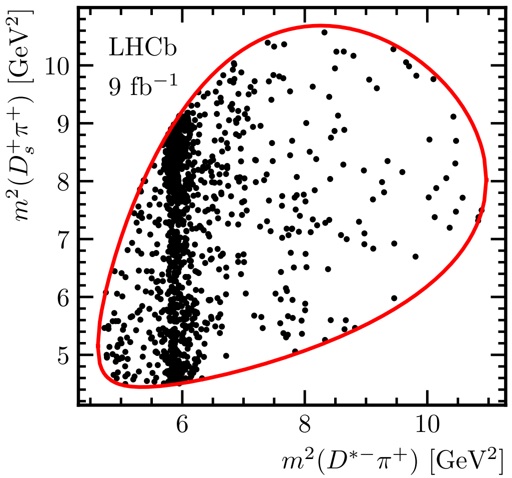
$B^+ \to D^{*-} D_s^{(*)+} \pi^+$: branching fractions

[arXiv: 2405.00098]

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



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



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

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

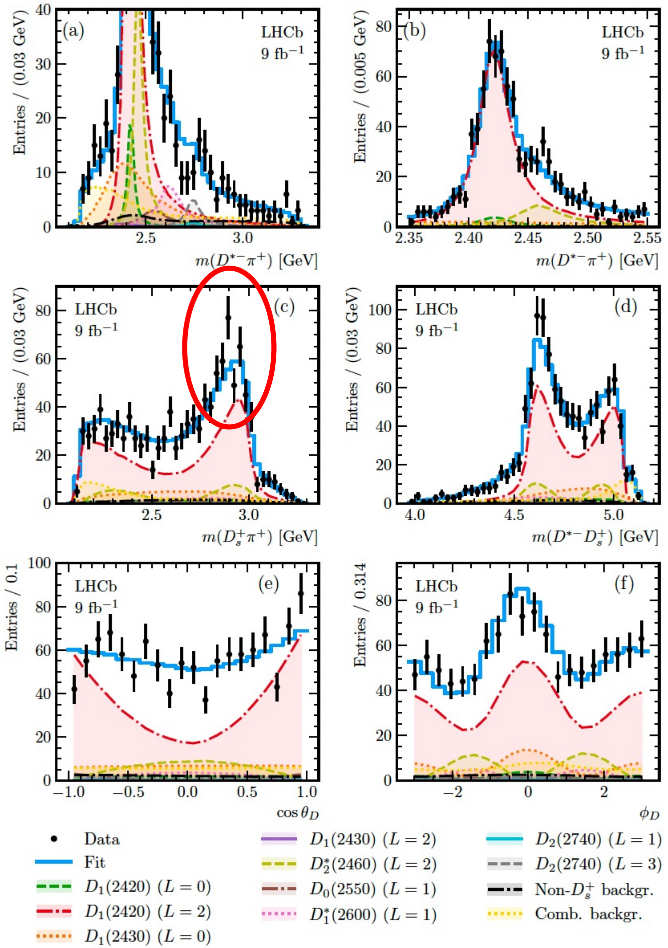
$B^+ \to D^{*-} D_s^+ \pi^+$: amplitude analysis

[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^+	$2\,412 \quad \pm 9$	314 ± 29
	$D_2^*(2460)$	2^+	$2\,461.1\ ^{+0.7}_{-0.8}$	47.3 ± 0.8
6.5σ	$D_0(2550)$	0^-	$2\,549 \quad \pm 19$	165 ± 24
6.8σ	$D_1^*(2600)$	1^-	$2\,627 \quad \pm 10$	141 ± 23
4.6σ	$D_2(2740)$	2^-	$2\,747 \quad \pm 6$	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

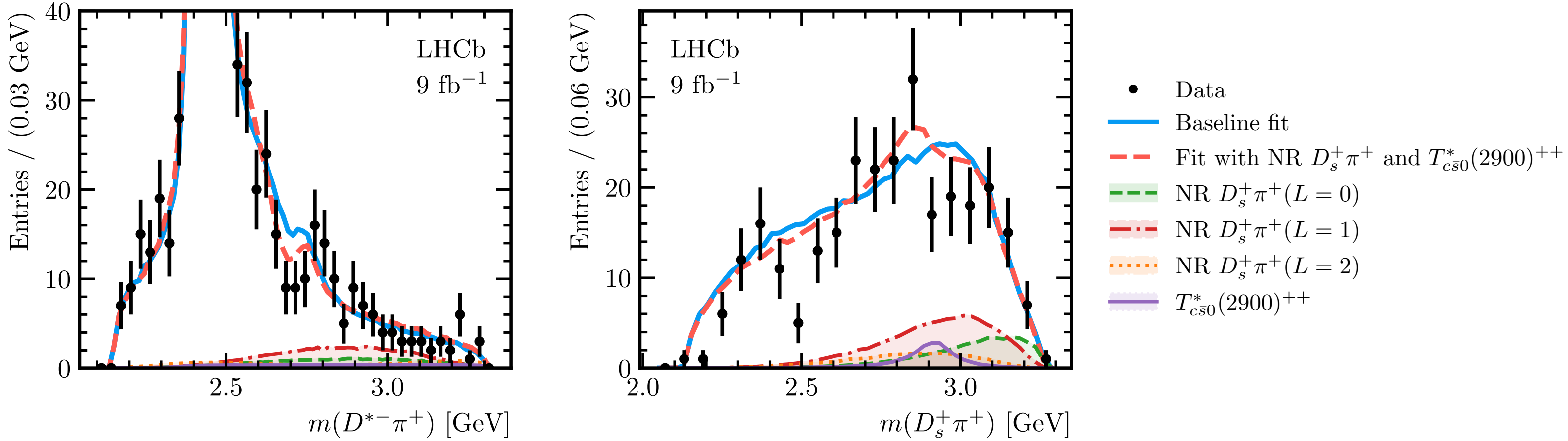
[arXiv: 2405.00098]

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

$2.6\,\sigma$, 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 $B^+ \to D^- D_s^+ \pi^+$

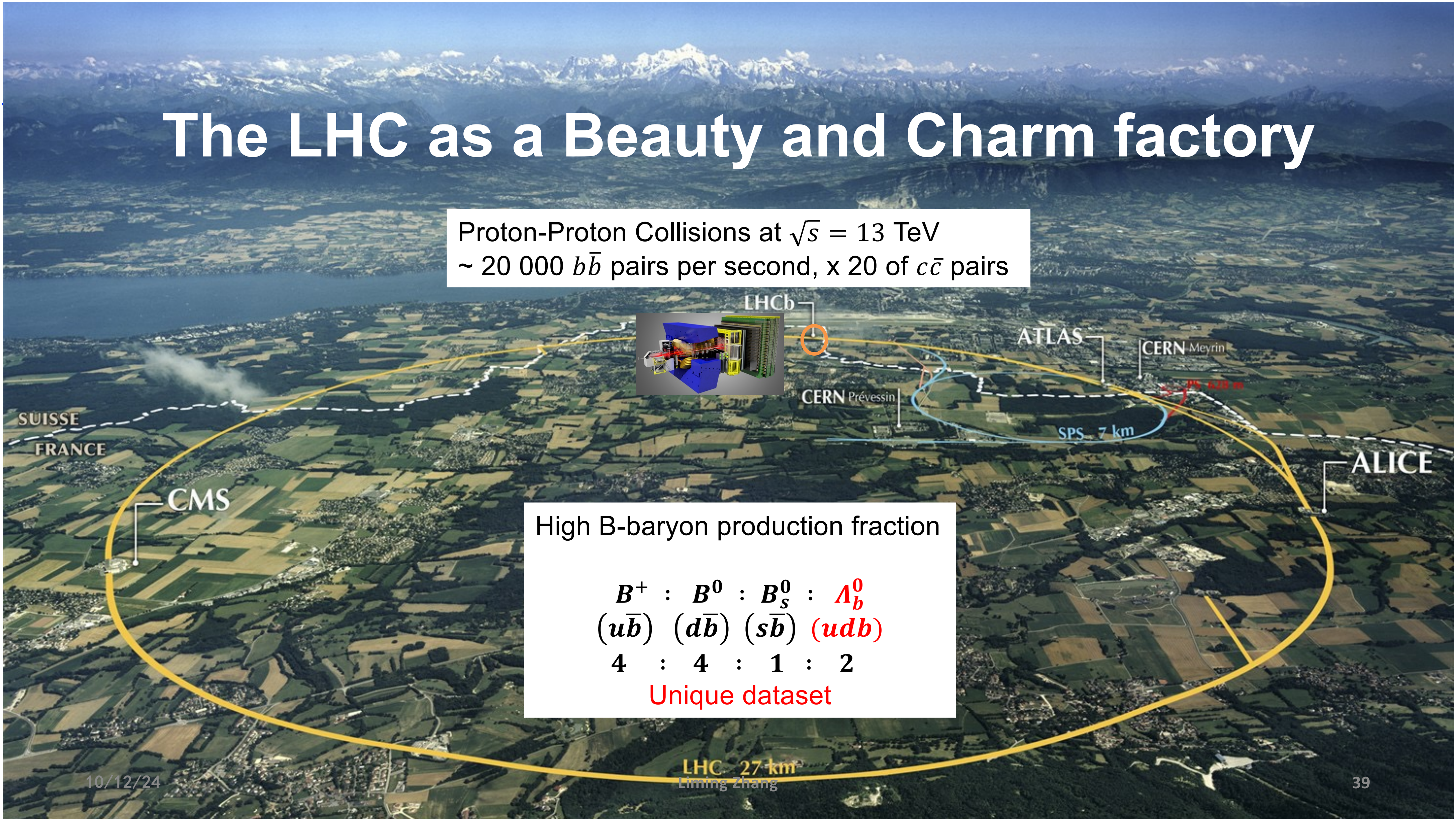
$m(D^{*-}\pi^+) > 2.5$ GeV



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

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

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

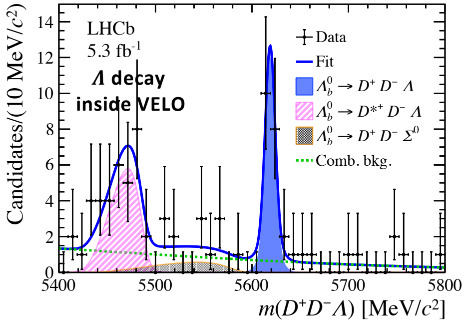
Unique dataset

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

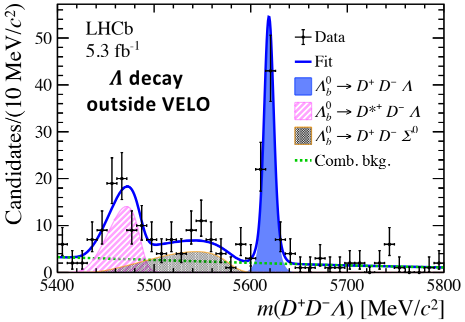
[arXiv: 2403.03586]

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

$N = 19 \pm 5$



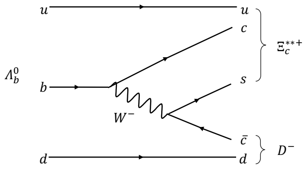
$N = 73 \pm 9$

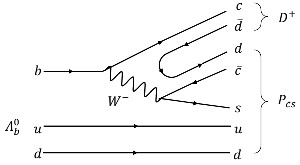


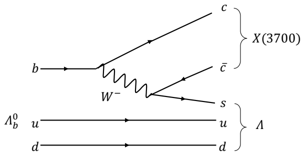
$$\frac{\sigma_{\Lambda_b^0}}{\sigma_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \to D^+ D^- \Lambda)}{\mathcal{B}(B^0 \to D^+ D^- K_S^0)} = 0.179 \pm 0.022 \pm 0.014$$

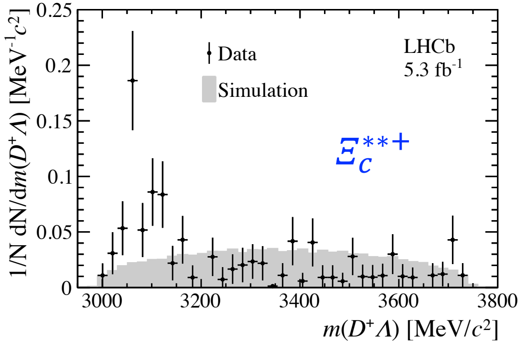
$$\mathcal{B}(\Lambda_b^0 \to D^+ D^- \Lambda) = (1.24 \pm 0.15 \pm 0.10 \pm 0.28 \pm 0.11) \times 10^{-4}$$

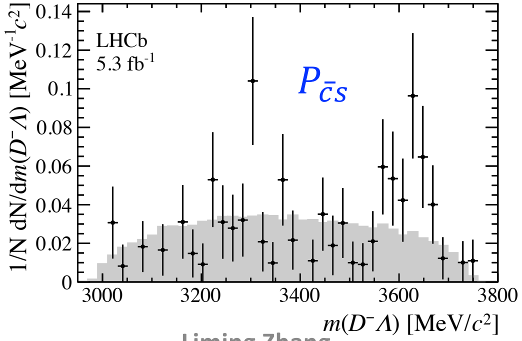
[PRD 103 (2021) 114013]

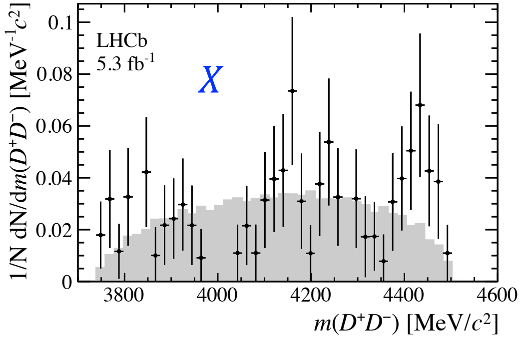






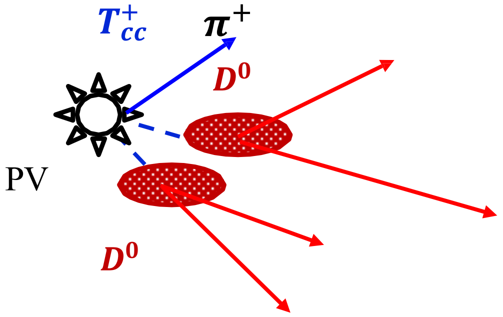


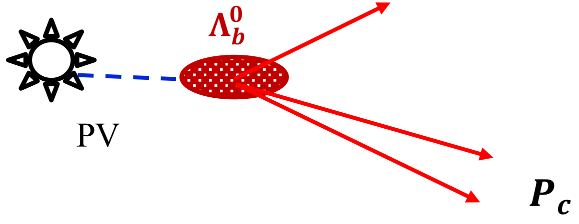




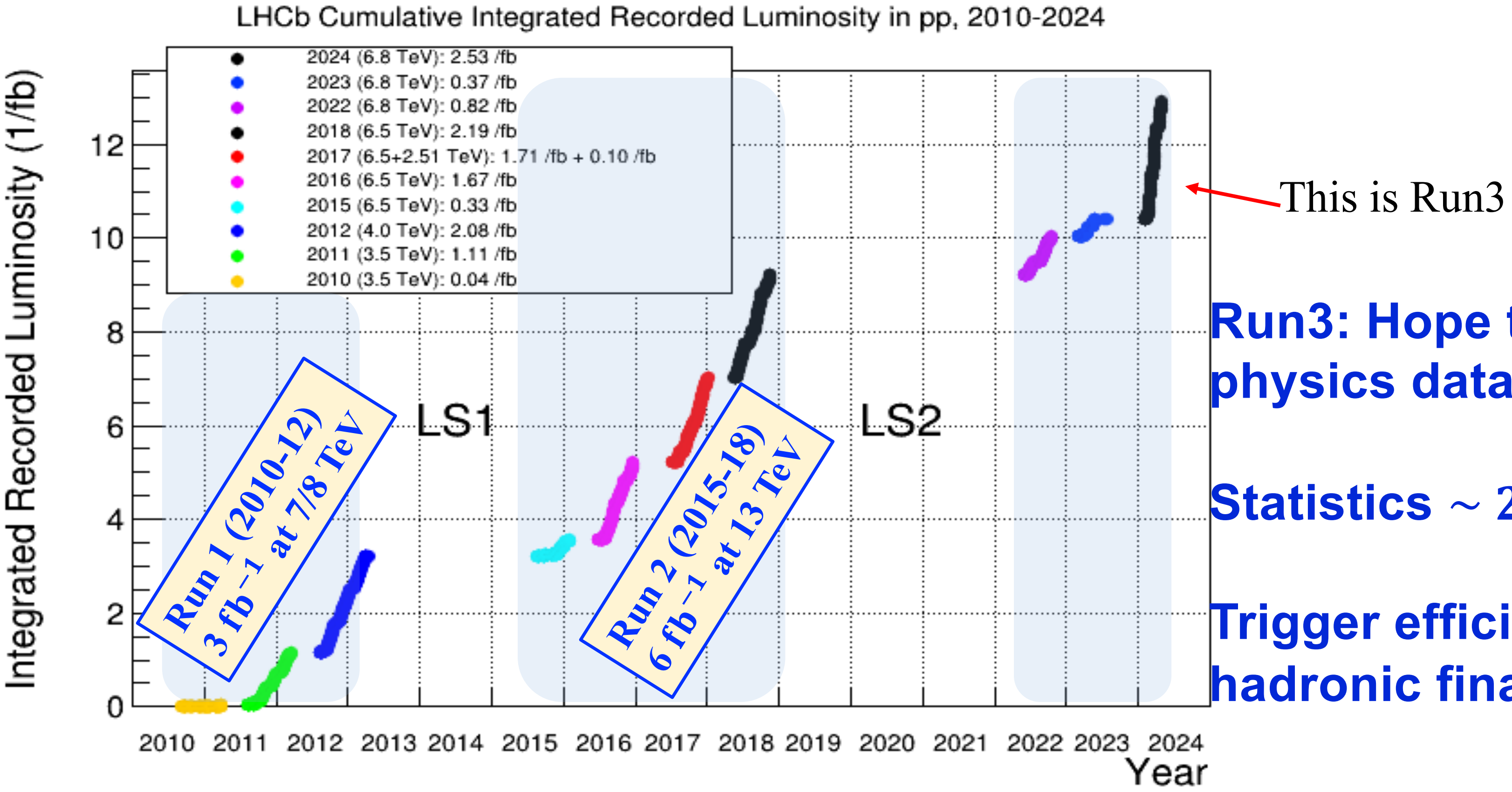
Two methods for spectroscopy

- Direct production in pp collisions
  - Combine a heavy flavour hadron with one or more light particles
  - Pros: High statistics, in principle can study all states
  - Cons: Large combinatorial background, hard to determine J^P
- Production by a heavier particle decay
  - Usually with amplitude analysis
  - Pros: Low background, Better determination of J^P
  - Cons: Low cross-section, limited mass range





LHCb collected luminosity

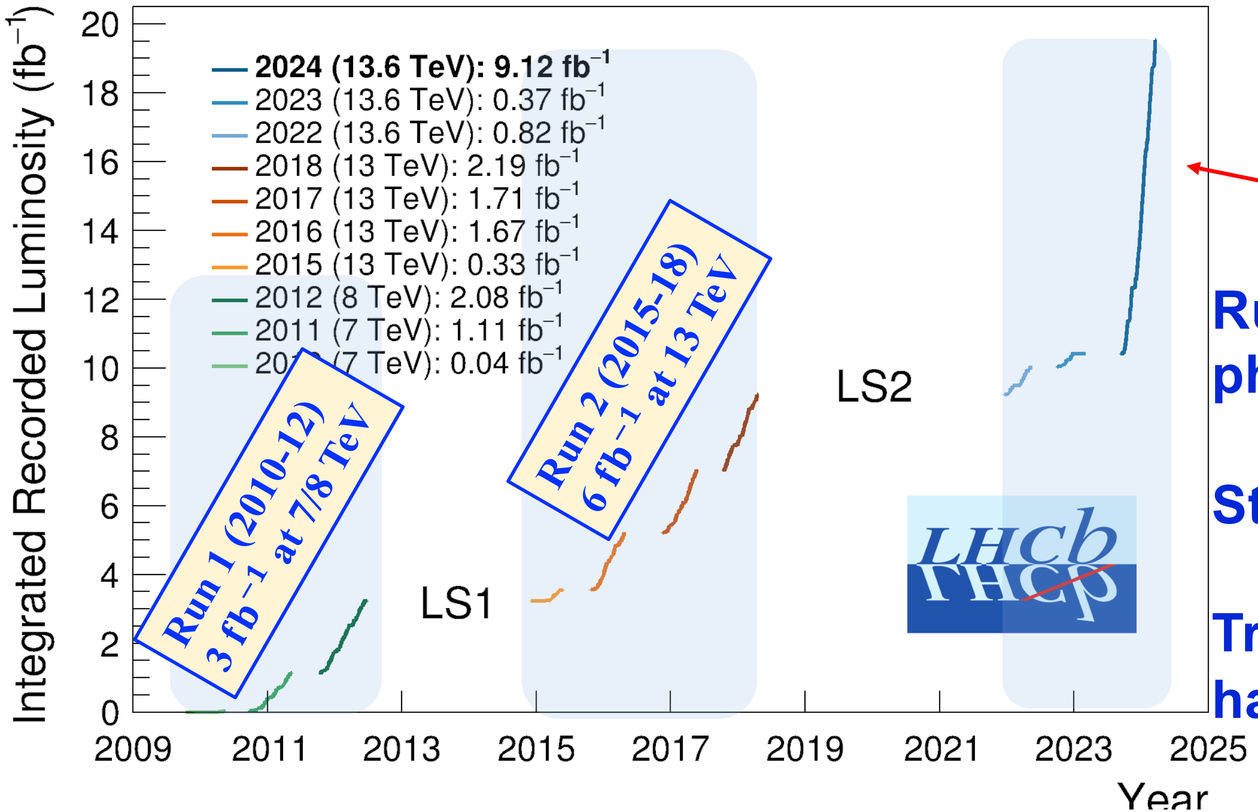


Run3: Hope to collect ~15 fb^{-1} physics data in 2024&2025

Statistics ~ 2× run1+2

Trigger efficiency 2× for hadronic final state

LHCb collected luminosity



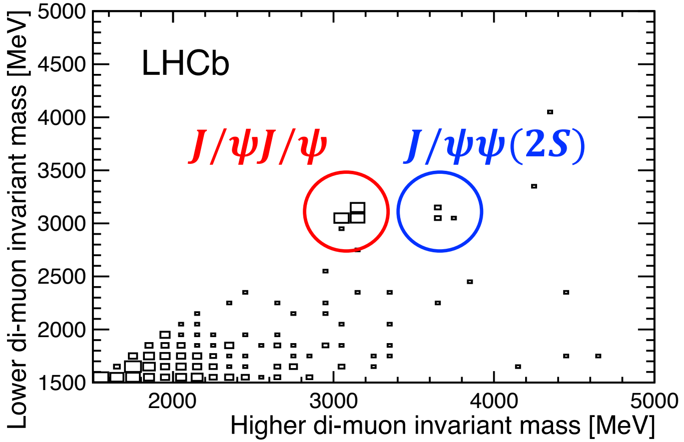
Run3: Hope to collect ~15 fb^{-1} physics data in 2024&2025

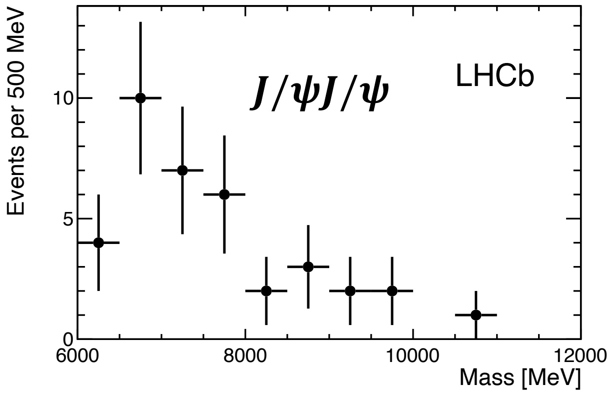
Statistics ~ 2× run1+2

Trigger efficiency 2× for hadronic final state

Other exotics in CEP

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

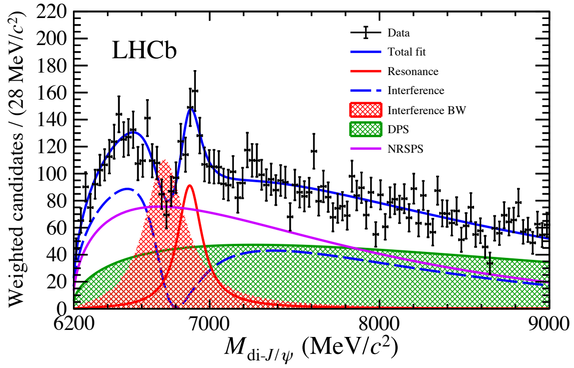




[J. Phys. G: Nucl. Part. Phys. 41 (2014) 115002]

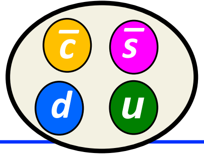
$$\begin{aligned}
\sigma^{J/\psi\, J/\psi} &= 58 \pm 10(\mathrm{stat}) \pm 6(\mathrm{syst})\,\mathrm{pb},\\
\sigma^{J/\psi\,\psi(2S)} &= 63^{+27}_{-18}(\mathrm{stat}) \pm 10(\mathrm{syst})\,\mathrm{pb},\\
\sigma^{\psi(2S)\psi(2S)} &< 237\,\mathrm{pb},\\
\sigma^{\chi_{c0}\chi_{c0}} &< 69\,\mathrm{nb},\\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

[Science Bulletin 65 (2020) 1983]



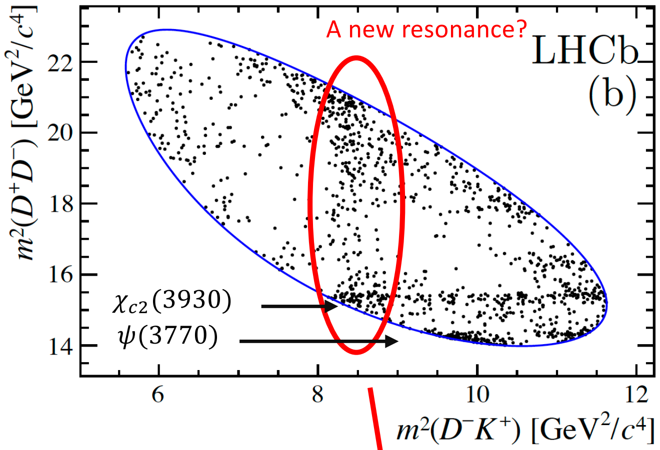
- ➢ $\chi_{c1}(3872)$? Other suggestions?

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



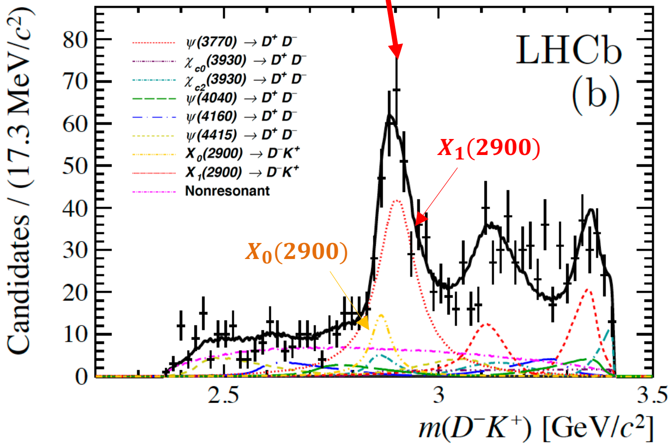
[PRL 125 (2020) 242001]
[PRD 102 (2020) 112003]

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



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

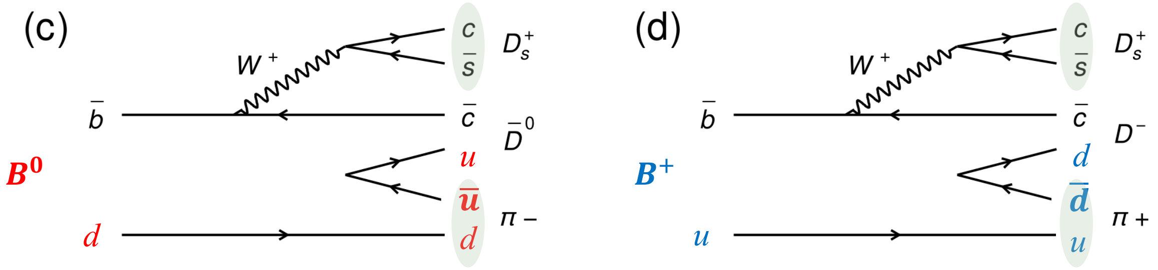
Resonance	Mass (GeV/c^2)	Width (MeV)
new $\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
new $X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
new $X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11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

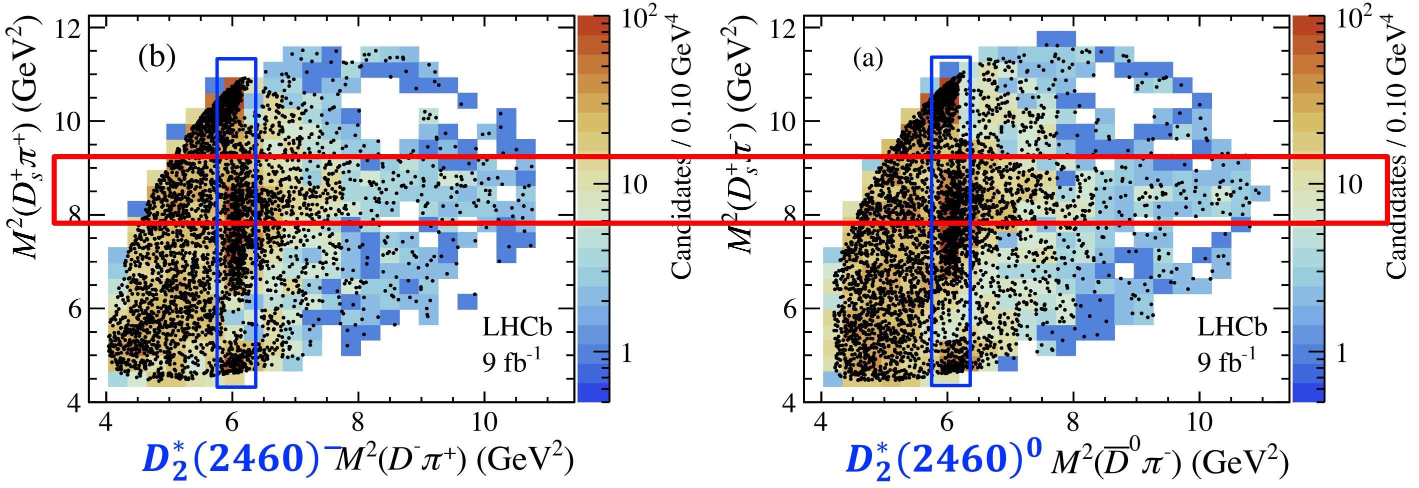


Study of $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

[PRL 131 (2023) 041902]

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



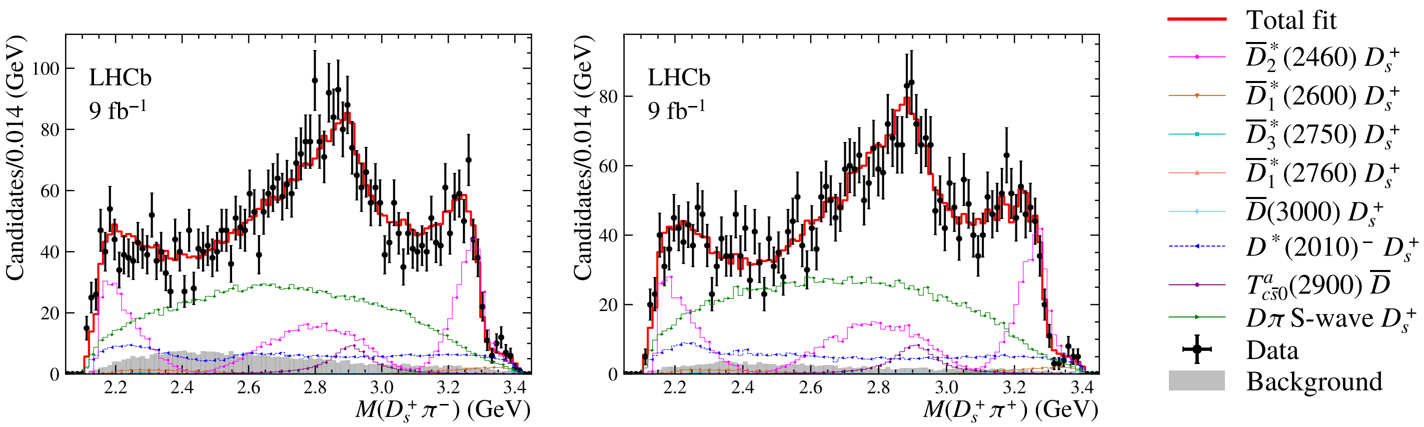


$\Rightarrow$ Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

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

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

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

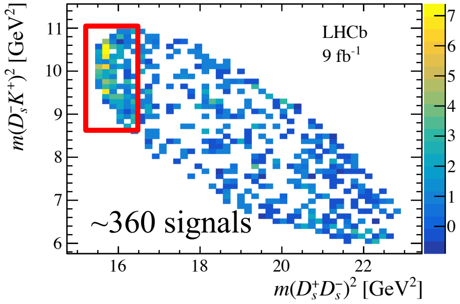
$$\text{Fit fraction} = (2.45 \pm 0.65 \pm 0.84)\%$$

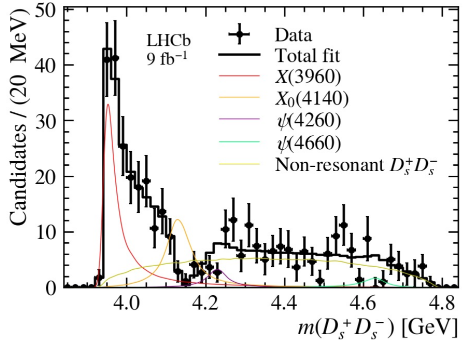
$X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$ decays

[PRL 131 (2023) 071901]

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

Charmonia in an unquenched quark model

arXiv: 2312.10296

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