Recent progress on heavy hadron spectroscopy in LHCb

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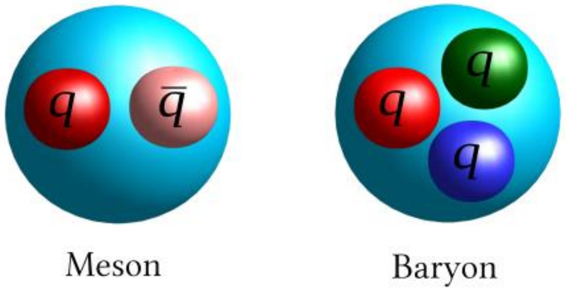
on behalf of the LHCb collaboration

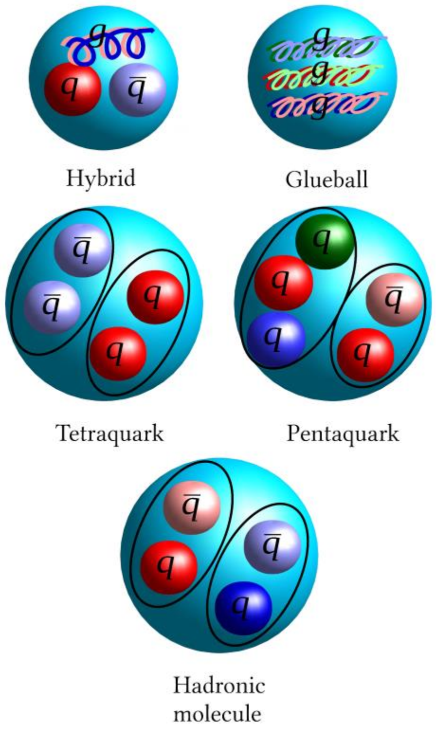
Introduction

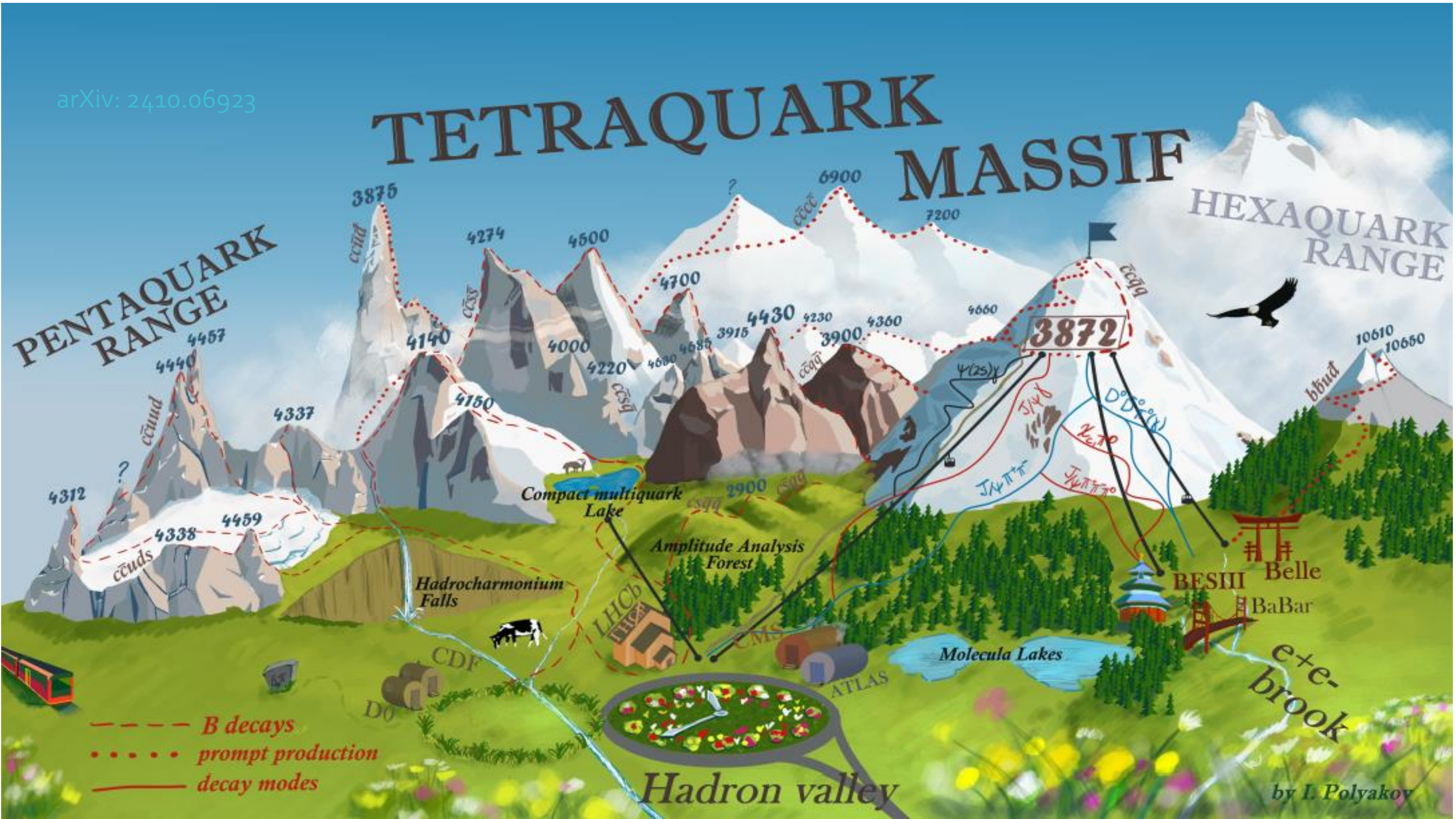
- Study the mass spectrum and properties of hadrons containing heavy quarks (charm and beauty)
  - Lattice QCD, phenomenological approaches…
- Understanding QCD in low energies, the strong force, and the nature of exotic states such as pentaquarks and tetraquarks.
  - Predicted in quark model, molecule, compact multiple quarks, hybrid…

Conventional hadrons



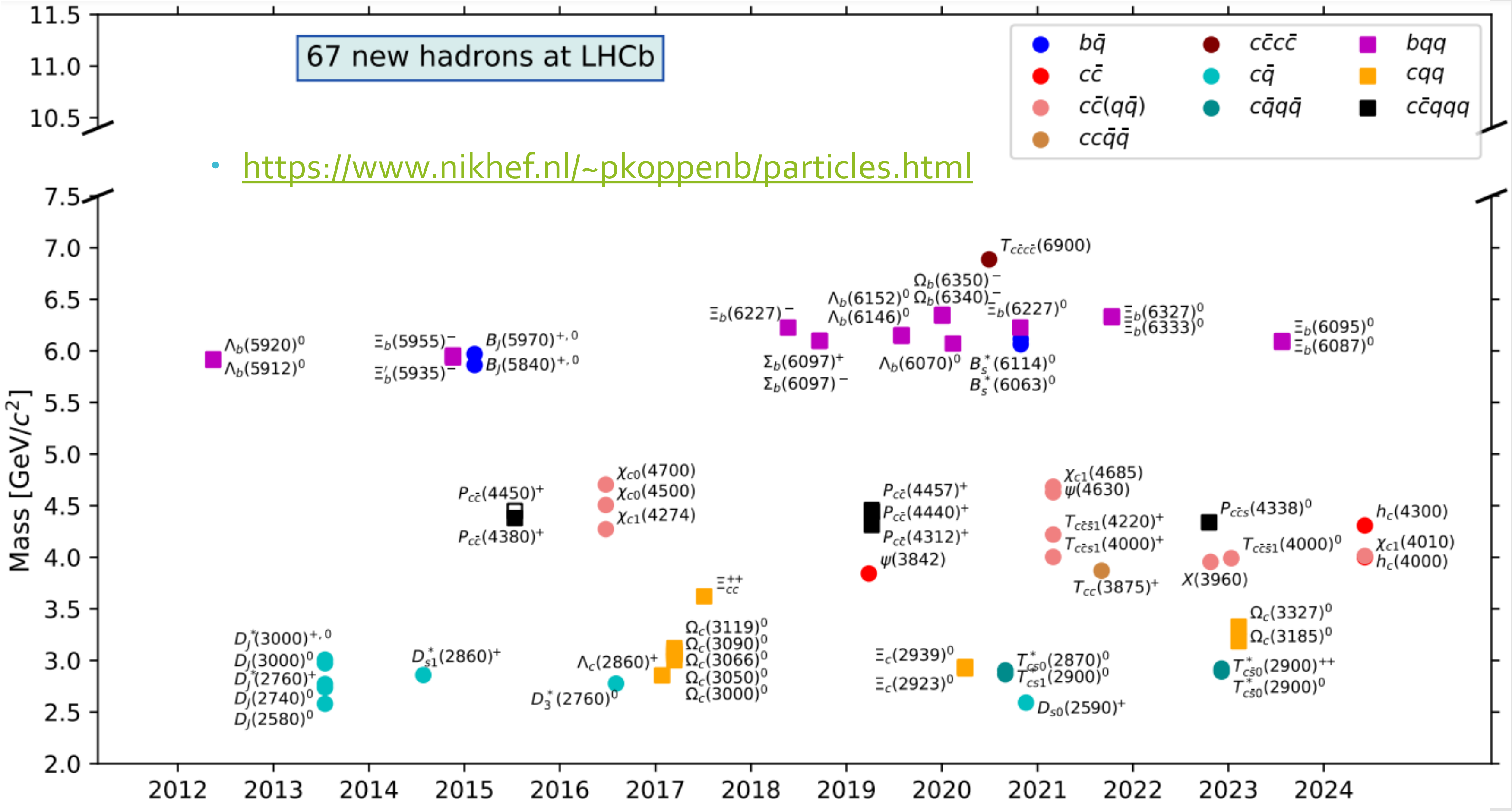
Exotic states





arXiv: 2410.06923
TETRAQUARK MASSIF
PENTAQUARK RANGE
HEXAQUARK RANGE
3872
3875
4274
4500
6900
7200
4700
4140
4000
4220
4150
4630
4685
3915
4430
4230
3900
4360
4660
4457
4440
4337
4312
4338
4459
2900
10610
10650
Compact multiquark Lake
Amplitude Analysis Forest
Hadrochamonium Falls
Molecula Lakes
Hadron valley
LHCb
CMS
ATLAS
CDF
D0
BESIII
Belle
BaBar
e+e- brook
B decays
prompt production
decay modes
by I. Polyakov

New Particles



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

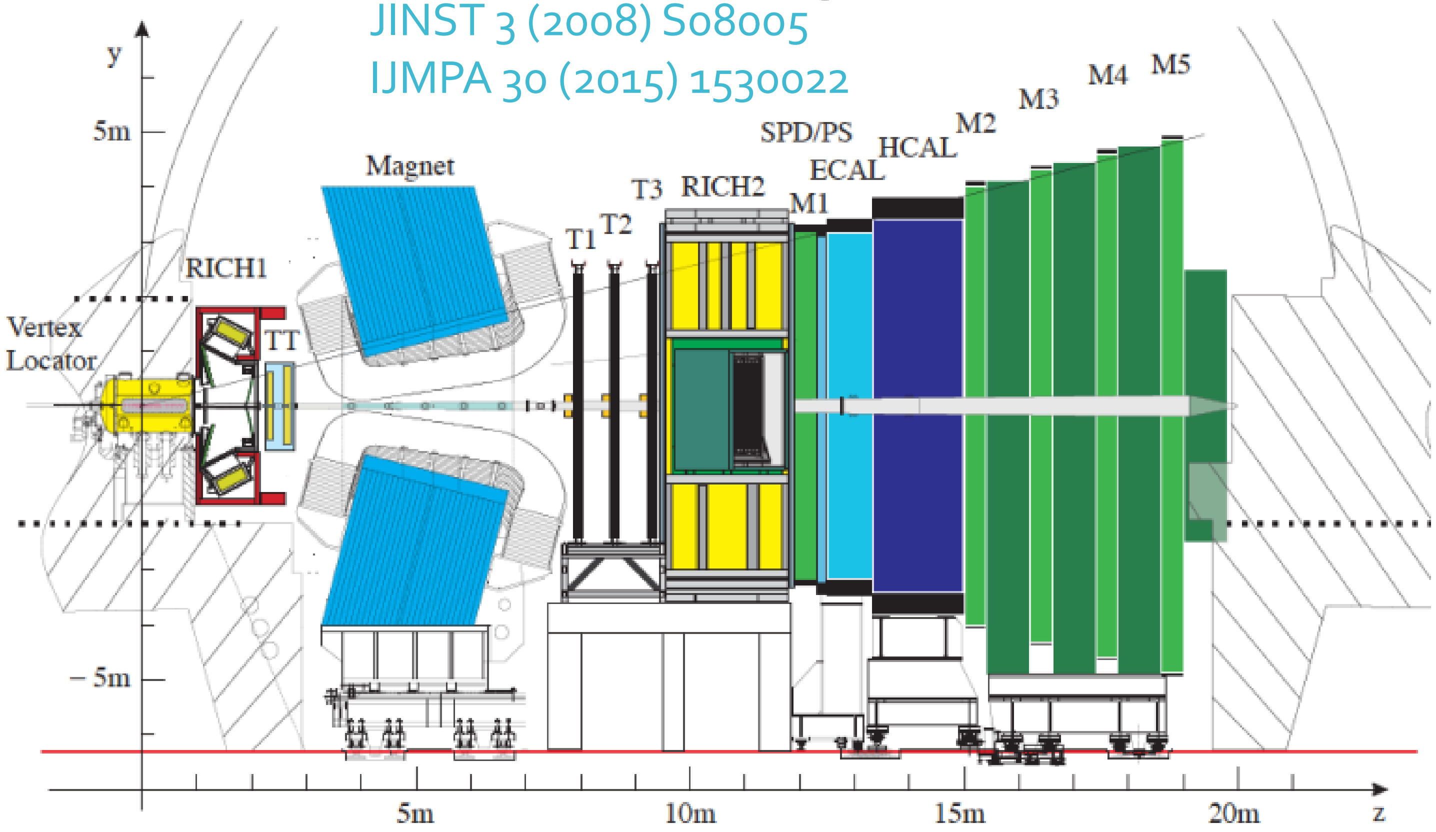
Overview

- LHCb Results on Heavy Hadrons
  - Probing the nature of the $\chi_{c1}(3872)$ state using radiative decays (*arXiv:2406.17006*)
  - New charmonium(-like) states in $B^+ \to D^{*\pm}D^{\mp}K^+$ decays (arXiv:2406.03156)
  - Amplitude Analysis of $B^+ \to D^{*-} D_s^+\pi^+$, *arXiv:2405.00098*
  - Observation of the open-charm tetraquark state $T^*_{cs0}(2870)^0$ in $B^- \to D^-D^0K_S^0$ decay
  - Search for prompt production of pentaquarks in open charm final states (arXiv: 2404.07131)
  - First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-}K^-$ decays and measurement of their relative branching fractions, *PRD 110 (2024) L031104*
  - Observation of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0}K^-$ *and* $\Lambda_b^0 \to \Lambda_c^+ D_s^-$ decays, *EPJC 84 (2024) 575*
  - Observation of exotic J/ψϕ resonances in diffractive processes (arXiv:2407.14301)
  - First determination of the spin-parity of the $\Xi_c(3055)^+$ baryons (arXiv:2409.05440)
  - Observation of muonic Dalitz decays of χ_b mesons (arXiv:2408.05134)

- Not mentioned
  - Observation of the $B_c^+ \to J/\psi\pi^+\pi^0$ *decay*, (arXiv *:2402.05523)*
  - Observation of $\Lambda_b^0 \to D^+D^-\Lambda$ [arXiv :2403.03586)
  - Ξ_b^- baryon lifetime measurement (arXiv :2406.12111)

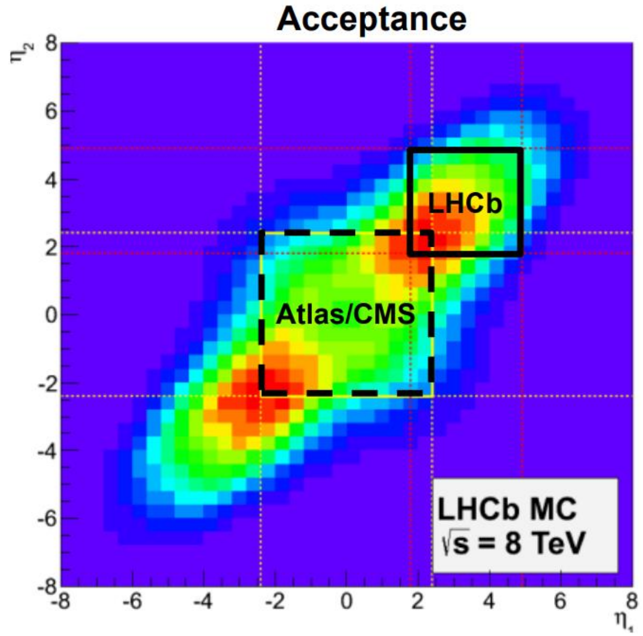
The LHCb detector at the LHC

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



Vertex Locator	$\sigma_{PV,x/y} \sim 10\ \mu m$, $\sigma_{PV,z} \sim 60\ \mu m$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1 - 3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

- LHCb is a dedicated flavour physics experiment at the LHC
  - Access to all b-hadrons: B^+, B^0, B_s^0, B_c^+, b-baryons
  - Larger b production rate than B factories (@ $\Upsilon(4S)$)
- Int lumi: 3 fb^{-1} at 7/8 TeV, 6 fb^{-1} at 13 TeV
- Can also study hadron spectroscopy and exotic states

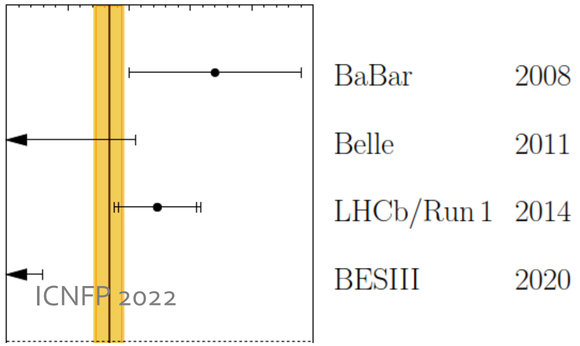


Acceptance optimised for forward production

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

Reference		$\mathscr{R}_{\psi\gamma} = \frac{\mathcal{B}_{B^+\to(\chi_{c1}(3872)\to\psi(2S)\gamma)K^+}}{\mathcal{B}_{B^+\to(\chi_{c1}(3872)\to J/\psi\gamma)K^+}}$	
T. Barnes and S. Godfrey	[67]	5.8	$c\bar{c}$
T. Barnes, S. Godfrey and S. Swanson	[69]	2.6	$c\bar{c}$
F. De Fazio	[84]	(1.64 ± 0.25)	$c\bar{c}$
B.-Q. Li and K. T. Chao	[85]	1.3	$c\bar{c}$
Y. Dong *et al.*	[86]	$1.3 - 5.8$	$c\bar{c}$
A. M. Badalian *et al.*	[87]	(0.8 ± 0.2)	$c\bar{c}$
J. Ferretti, G. Galata and E. Santopinto	[88]	6.4	$c\bar{c}$
A. M. Badalian, Yu. A. Simonov and B. L. G. Bakker	[89]	2.4	$c\bar{c}$
W. J. Deng *et al.*	[90]	1.3	$c\bar{c}$
F. Giacosa, M. Piotrowska and S. Goito	[71]	5.4	$c\bar{c}$/vc
E. S. Swanson	[81]	0.38 %	$D\bar{D}^*$
Y. Dong *et al.*	[86]	0.33 %	$D\bar{D}^*$
D. P. Rathaud and A. K. Rai	[91]	0.25	$D\bar{D}^*$
R. F. Lebed and S. R. Martinez	[92]	0.33 %	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	[93]	3.6 %	$D\bar{D}^*$
F.-K. Guo *et al.*	[82]	$0.21(g_2'/g_2)^2$	$D\bar{D}^*$
D. A.-S. Molnar, R. F. Luiz and R. Higa	[83]	$2 - 10$	$D\bar{D}^*$
E. Cincioglu *et al.*	[94]	< 4	$D\bar{D}^*$
S. Takeuchi, M. Takizawa and K. Shimizu	[95]	$1.1 - 3.4$	$D\bar{D}^*$
B. Grinstein, L. Maiani and A. D. Polosa	[93]	$> (0.95^{+0.01}_{-0.07})$	$c\bar{c}q\bar{q}$

- Meson molecule: (3~4)$\times 10^{-4}$
  - conflict with high production cross-section result
- Charmonium: 1.5~15
  - Significant isopin violation
- Molecule-charmonium mix: 0.5~5
- Virtual companion pole ~5.5

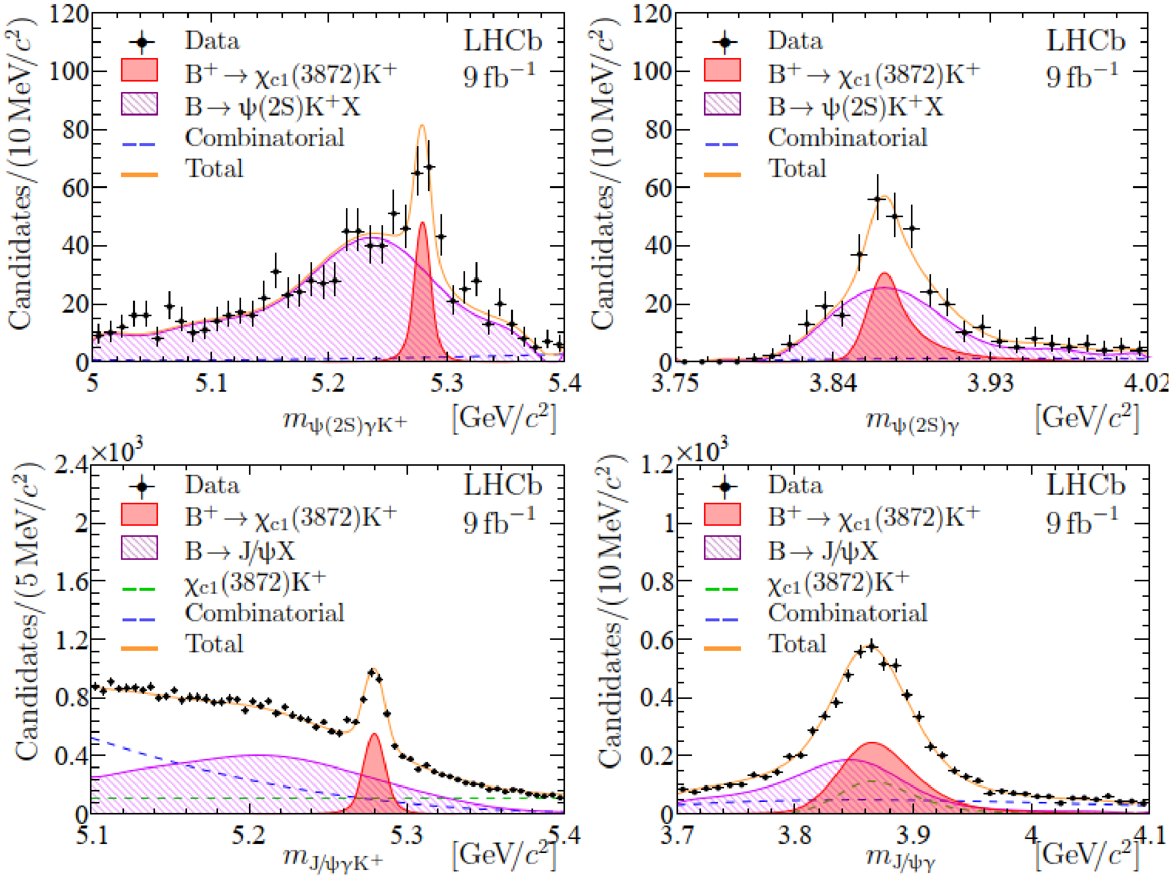


- Observed two decades ago, $\chi_{c1}(3872)$'s internal structure is yet understood, while study of radiative decays provides a way to probe it
- Only evidence of $\chi_{c1}(3872) \to \psi(2S)\gamma$ was seen experimentally before

[arXiv: 2406.17006]

Update at LHCb using $B^+ \to \chi_{c1} K^+$ decay with 9 fb^{-1} RUN1+ RUN2 data

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



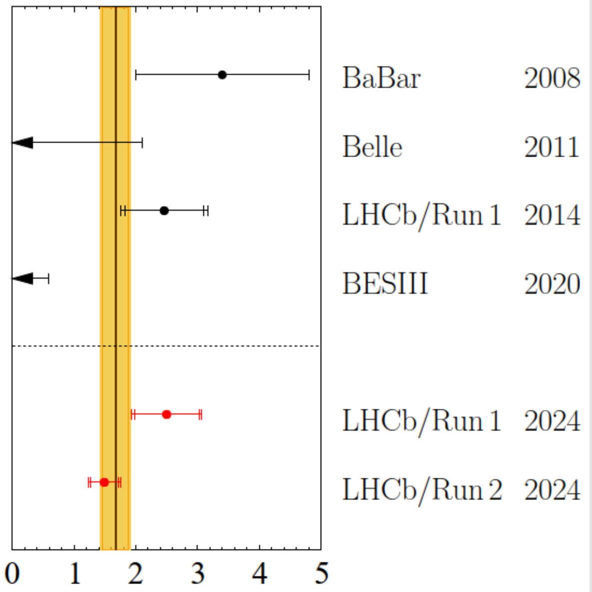
$$\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$

- LHCb meets Theory

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

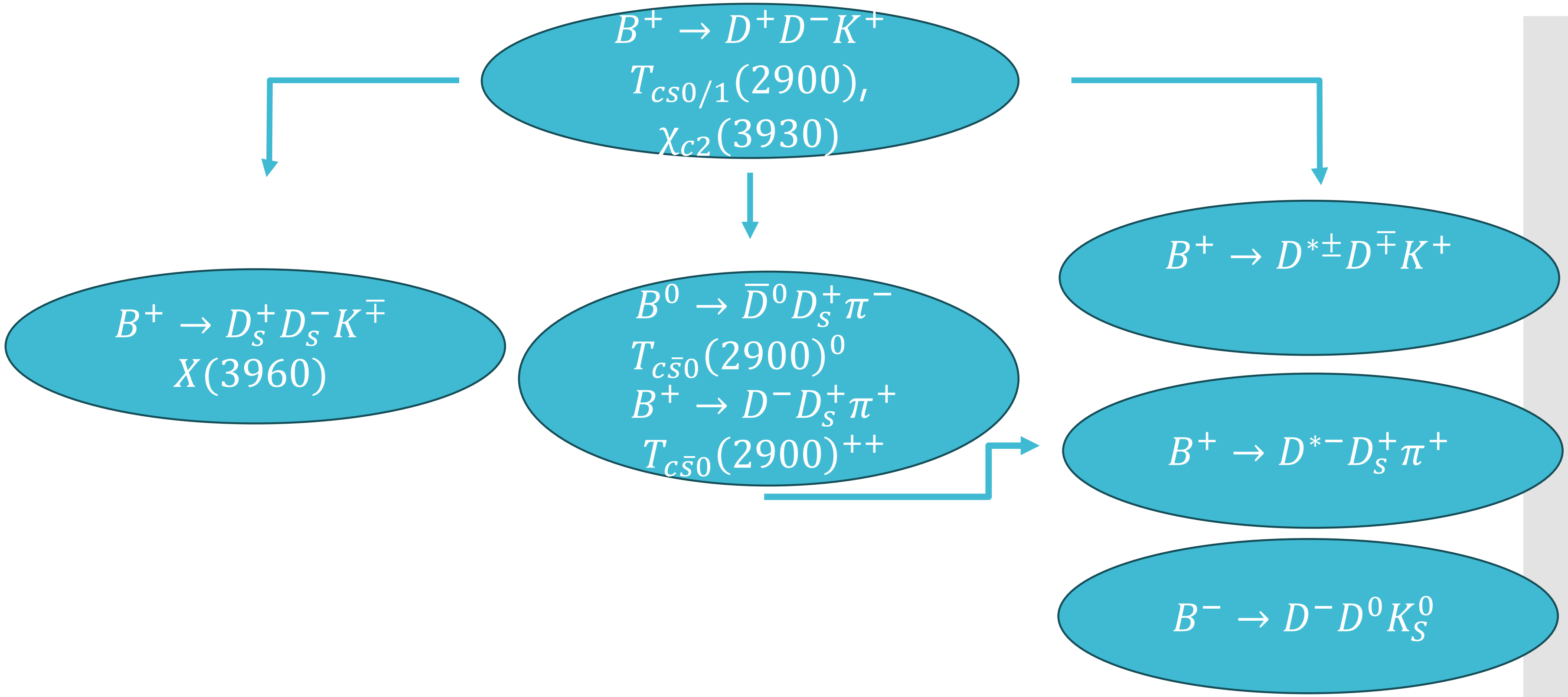
- Run1: 40 ± 8 (5.3σ)
- Run2: 63 ± 10 (6.7σ)

LHCb average



[arXiv: 2406.17006]

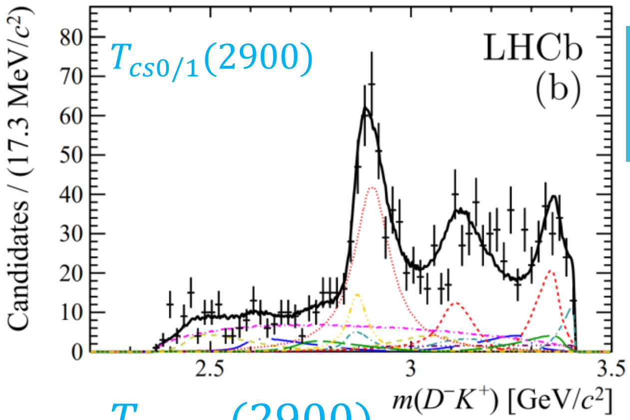
B $\rightarrow D\bar{D}h$ studies at LHCb



- $B^+ \rightarrow D^+D^-K^+$ open an avenue for the study of $B^+ \rightarrow D\bar{D}h$ study in LHCb
- Huge family of topologically similar decays and abundantly produced at LHC
- Large samples anticipated for many $B^+ \rightarrow D\bar{D}h$ decays

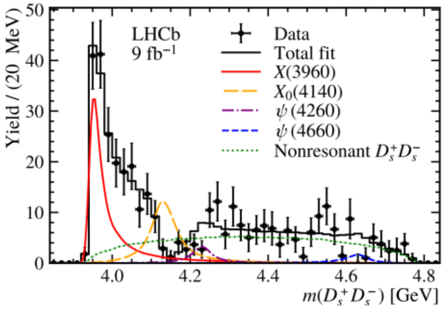
$T^{*}_{\bar{c}\bar{s}}$ states

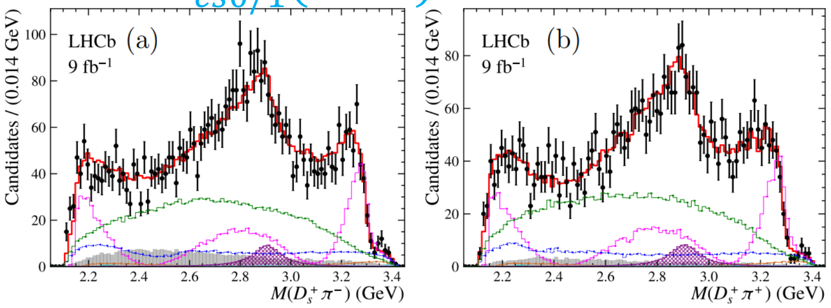
The puzzling χ(2900)



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

$T_{cs0/1}(2900)$





PRL 131 (2023) 071901

PRL 131 (2023) 041902

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

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

$B^- \to D^- D^0 K_S^0$

- $SU(3)_F$ partners? $T_{c\bar{s}0}(2900)^{0/++}[c\bar{s}d\bar{u}]/[c\bar{s}u\bar{d}]$ and $T_{cs0}(2900)^0[\bar{c}\bar{s}du]$
- compact tetraquarks? $D^{(*)}K^{(*)}$Molecular? Or just cusps, triangle singularities
  2008.05993,2108.06222 2008.11171 2008.07190, 2009.05352.

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

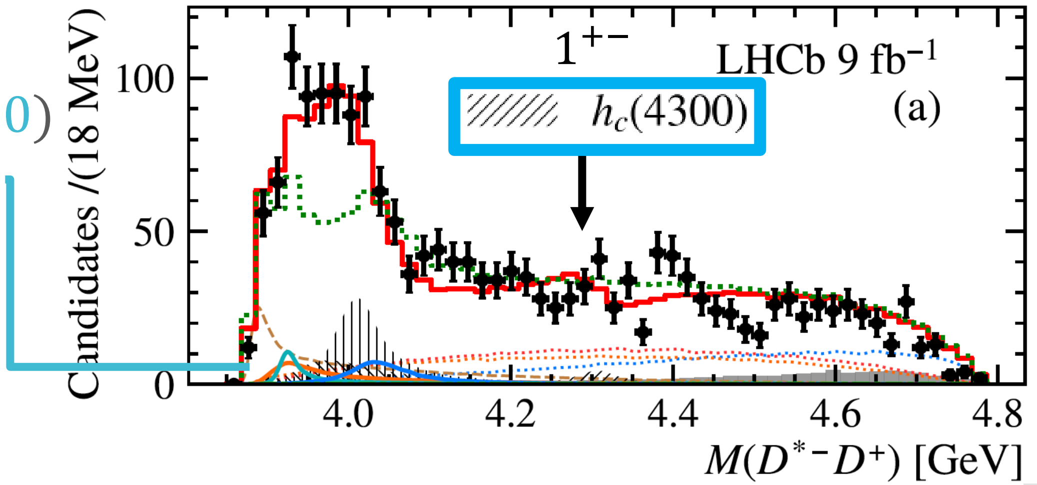
$$\mathcal{A}(x) = \frac{1+d}{2}\left\{\sum_{i\in R(D^{*\pm}D^{\mp})} c_i A_i(x) + \sum_{j\in R(D^{*-}K^+,D^+K^+)} c_j A_j(x)\right\} + \frac{1-d}{2}\left\{\sum_{i\in R(D^{*\pm}D^{\mp})} C\times c_i A_i(x) + \sum_{k\in R(D^{*+}K^+,D^-K^+)} c_k A_k(x)\right\}$$

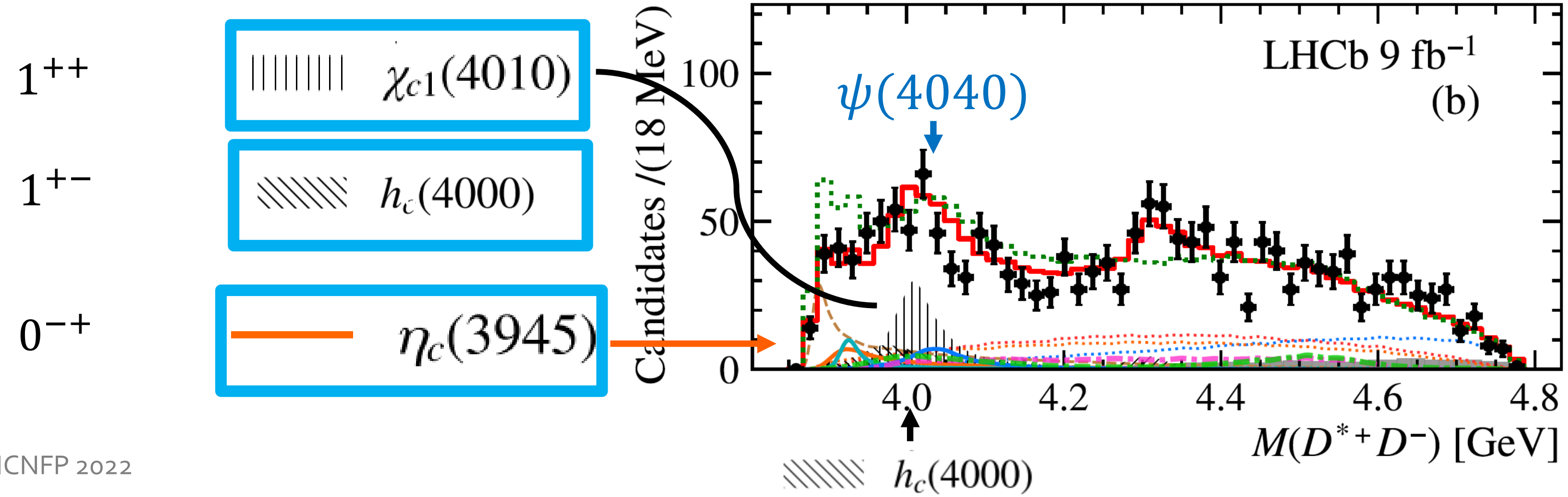
- d=1 $B^+ \to D^{*+}D^-K^+$
- d=-1 $B^+ \to D^{*-}D^+K^+$

- C-parity phase linked allowing determination of C-parities of resonances

clear different interference behaviors

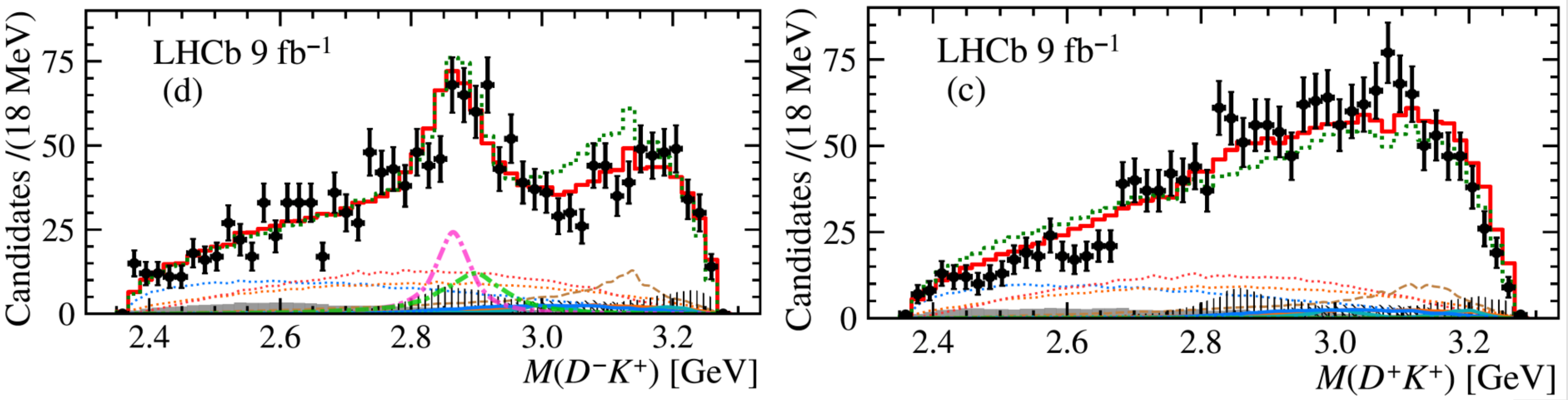
$\chi_{c2}(3930)$





[Phys. Rev. Lett. 133 (2024) 131902]

$T^*_{\bar{c}\bar{s}}$ states



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

Tensions

✓ 11 σ

✓ 9.2 σ

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

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

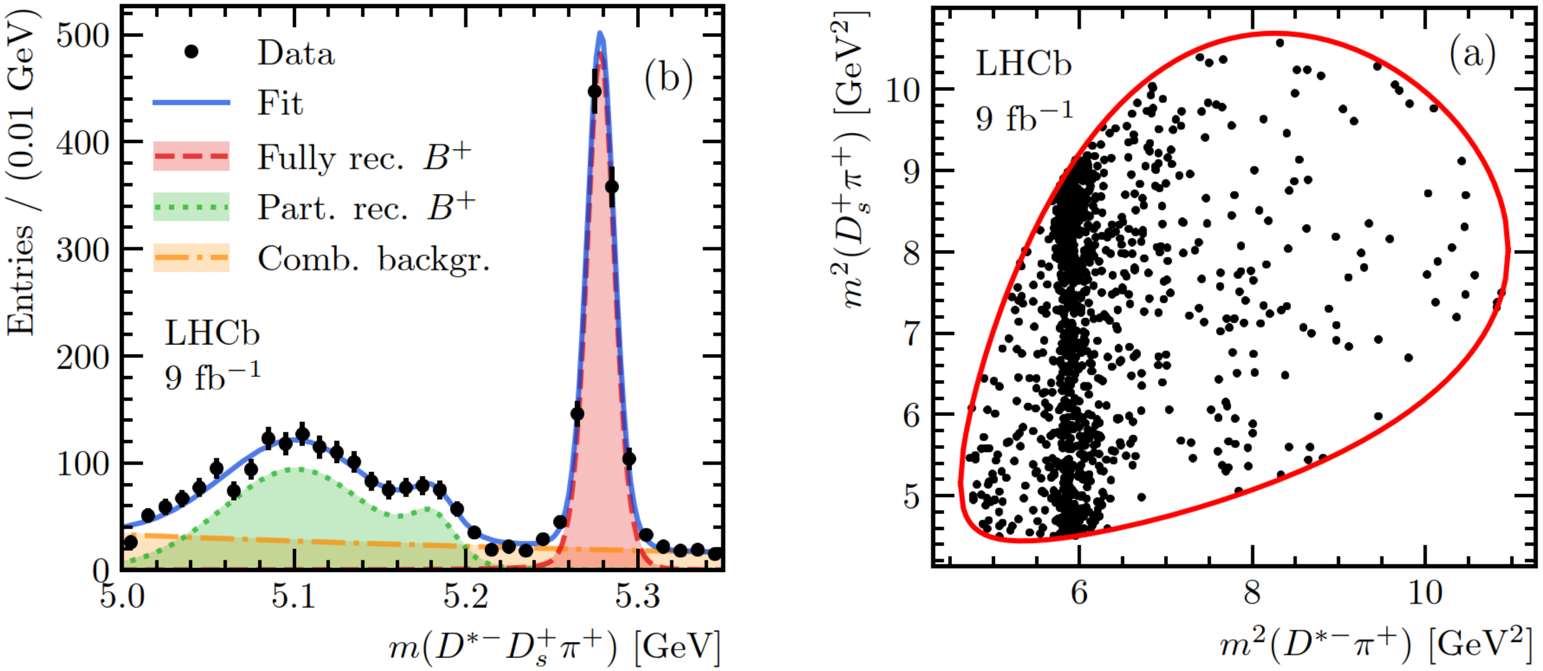
$\mathcal{B}(T^*_{\bar{c}\bar{s}1}(2900)^0 \to D^{*-}K^+)/\mathcal{B}(T^*_{\bar{c}\bar{s}1}(2900)^0 \to D^{*-}K^+)$<0.21 @ 95% C.L.

[Phys. Rev. Lett. 133 (2024) 131902]

Branching fraction $B^+ \to D^{*-} D_s^{(*)+} \pi^+$

[JHEP 08 (2024) 165]

- Detailed amplitude analyses reveal quantum numbers and decay dynamics.
- Measurement performed using the full LHCb dataset of 9 fb^{-1}



$|m(D^{*-}D_s^+\pi^+) - m(B^+)| < 30\ MeV/c^2$

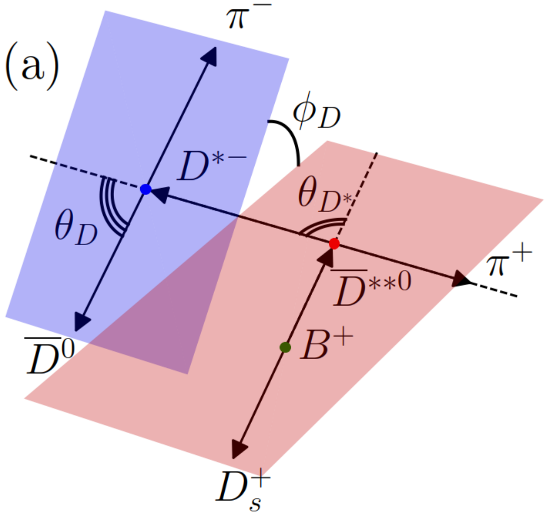
$$\mathcal{R} = \frac{\mathcal{B}(B^+ \to D^{*-} D_s^+ \pi^+)}{\mathcal{B}(B^0 \to D^{*-} D_s^+)} = 0.173 \pm 0.006 \pm 0.010$$

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

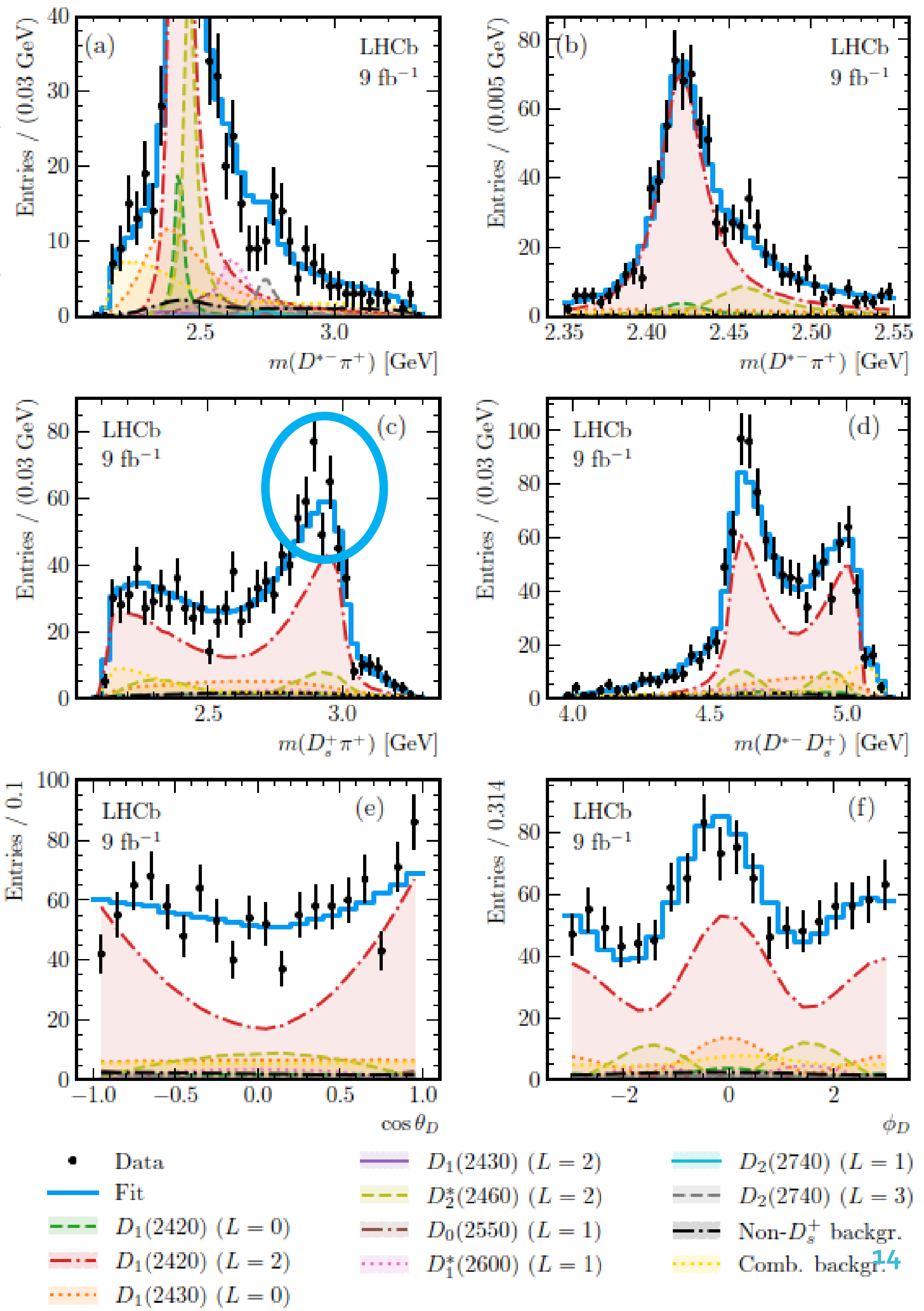
Amplitude analysis of $B^+ \to D^{*-} D_s^+ \pi^+$

[JHEP 08 (2024) 165]

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
$D_0(2550)$	0^-	$2\,549 \pm 19$	165 ± 24
$D_1^*(2600)$	1^-	$2\,627 \pm 10$	141 ± 23
$D_2(2740)$	2^-	$2\,747 \pm 6$	88 ± 19
$D_3^*(2750)$	3^-	$2\,763.1 \pm 3.2$	66 ± 5

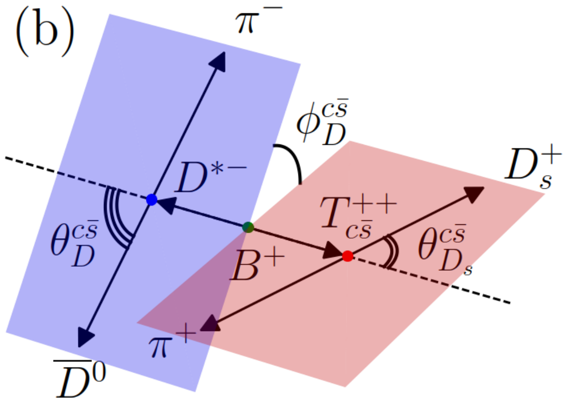


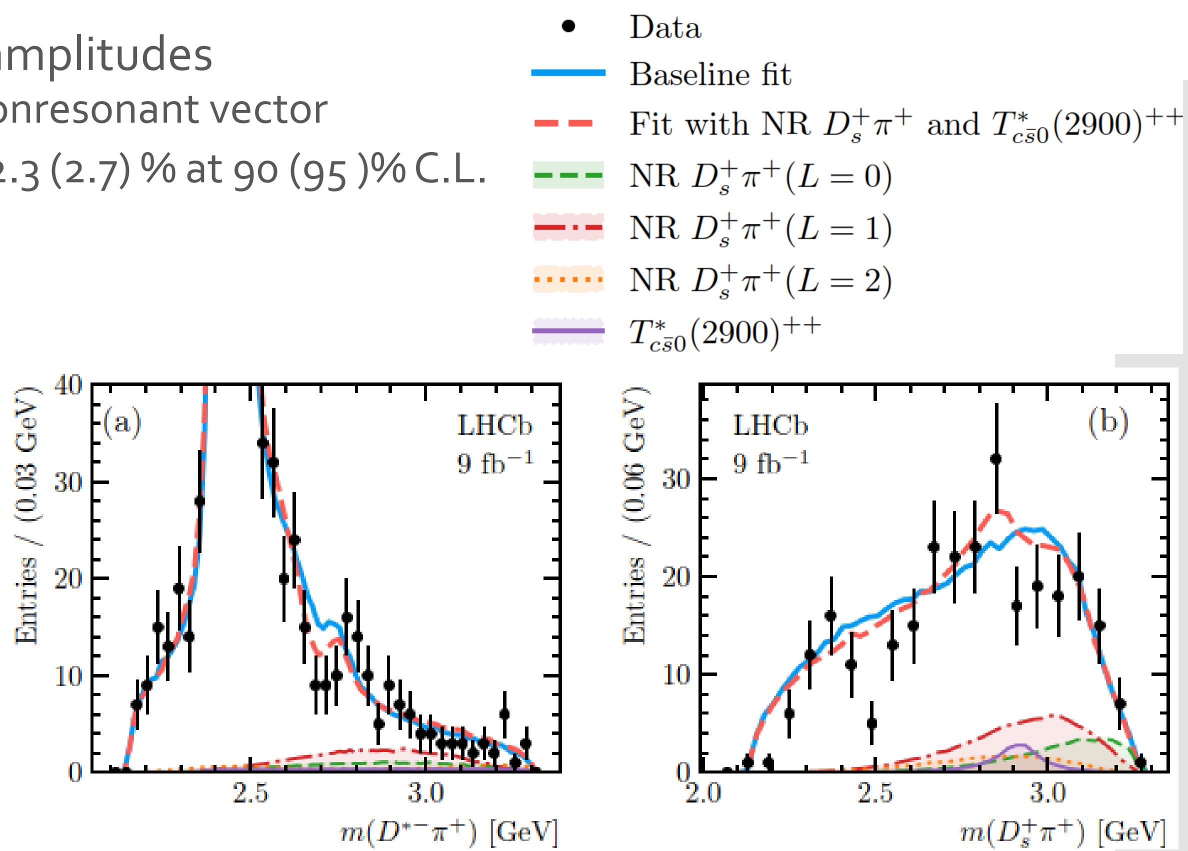
- (a) Baseline fit with $\overline{D}^{**0} \to D^{*-}\pi^+$
  - $D_0(2550)$: 6.5 σ
  - $D_1^*(2600)$: 6.8 σ



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

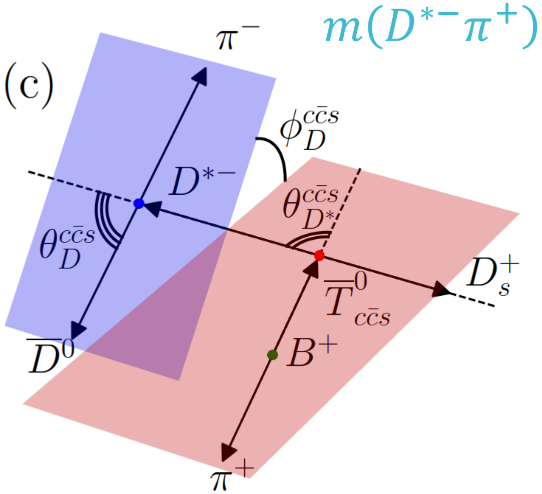
- (b) Fits incorporating $D_s^+\pi^+$ amplitudes
  - best fit: $T_{c\bar{s}0}^*(2900)^{++}$+ nonresonant vector
  - Upper limit of fit fraction 2.3 (2.7) % at 90 (95)% C.L. with 2.6 σ





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

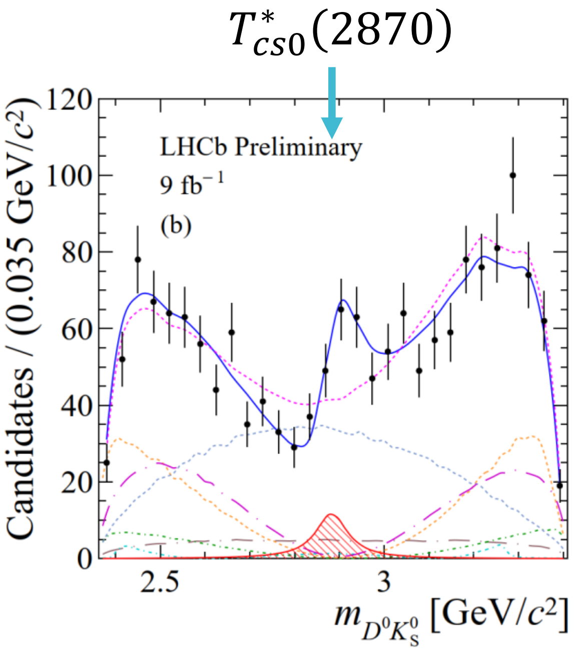
- (c) Fits incorporating $D_s^+ D^{*-}$amplitudes
  - none provides a physical description

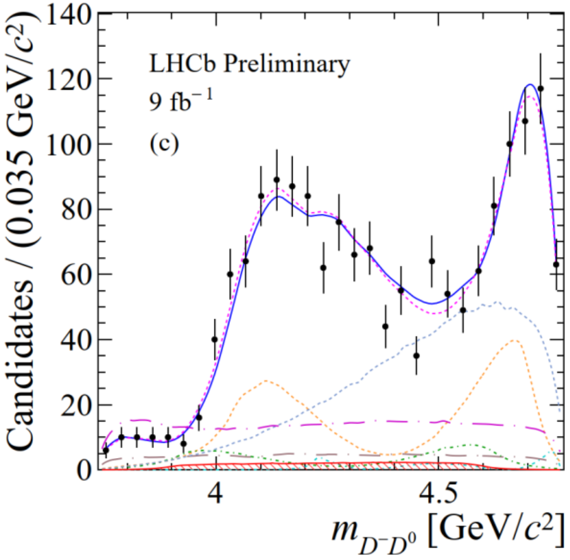


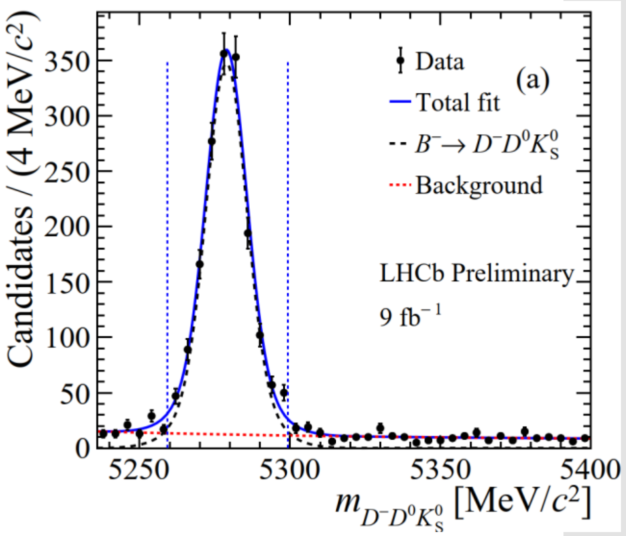
[JHEP 08 (2024) 165]

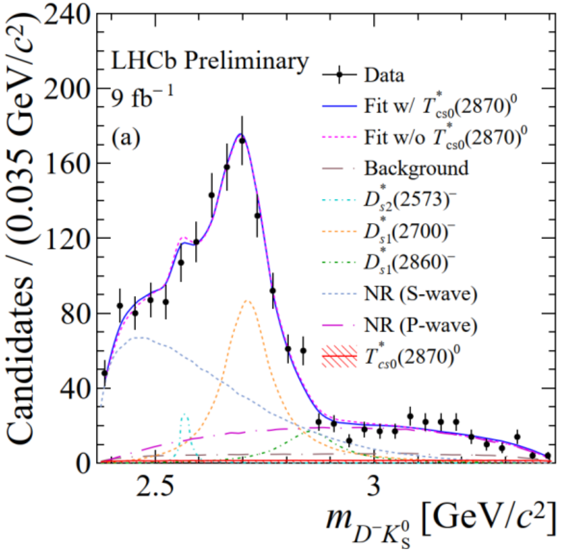
$B^- \to D^- D^0 K_S^0$

PRELIMINARY









Resonance	J^P	Mass (MeV/c^2)	Width (MeV)
$D^*_{s2}(2573)^-$	2^+	2569.1 ± 0.8	16.9 ± 0.7
$D^*_{s1}(2700)^-$	1^-	2714 ± 5	122 ± 10
$D^*_{s1}(2860)^-$	1^-	2859 ± 27	160 ± 80

$B^- \to D^- D^0 K_S^0$

PRELIMINARY

- Individual:
  - $T_{cs0}^*(2870)$ 5.3σ
  - $T_{cs1}^*(2900)$1.8σ
- Combined:
  - $T_{cs0}^*(2870)$+ $T_{cs1}^*(2900)$: 6.1 σ

$$M(T_{cs0}^{*0}) = 2883 \pm 11 \pm 7\,\mathrm{MeV}/c^2$$

$$\Gamma(T_{cs0}^{*0}) = 87^{+22}_{-47} \pm 6\,\mathrm{MeV}$$

Triangle Singularities? Threshold enhanced ?

$$R_\mathrm{I}(T_{cs}^{*0}) = \frac{\mathcal{B}(B^- \to D^- D^0 \overline{K}^0)\mathrm{FF}(T_{cs}^{*0} \to D^0 K_\mathrm{S}^0)}{\mathcal{B}(B^- \to D^- D^+ K^-)\mathrm{FF}(T_{cs}^{*0} \to D^+ K^-)}$$

Should $\approx$ 1 required by isospin symmetry

$$R_\mathrm{FF}(D^0 K_\mathrm{S}^0) \equiv \mathrm{FF}(T_{cs1}^{*0} \to D^0 K_\mathrm{S}^0)/\mathrm{FF}(T_{cs0}^{*0} \to D^0 K_\mathrm{S}^0)$$

Should equal to D^+K^-

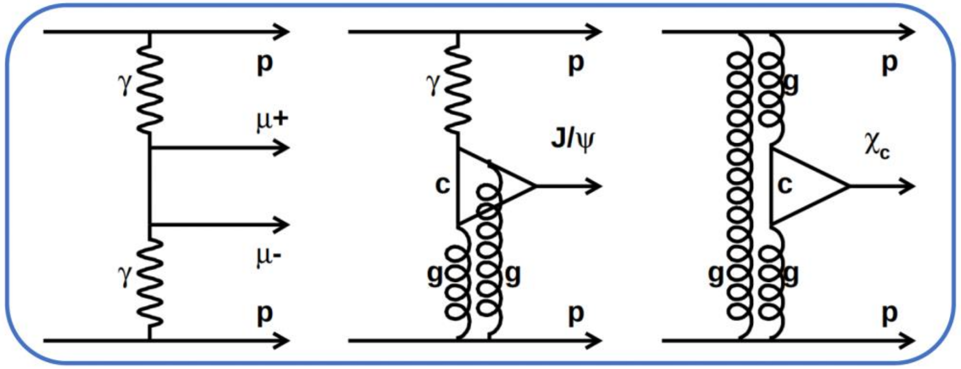
Observable	Result				
$R_\mathrm{I}(T_{cs0}^*(2870)^0)$	3.3	± 1.1	± 1.1	± 1.1	supports
$R_\mathrm{I}(T_{cs1}^*(2900)^0)$	0.15	± 0.15	± 0.05	± 0.05	Not support
$R_\mathrm{FF}(D^0 K_\mathrm{S}^0/D^+K^-)$	$0.044 \pm 0.035 \pm 0.020$				

Conclusion: Triangle Singularities or spin-1 state does not have a definite isospin

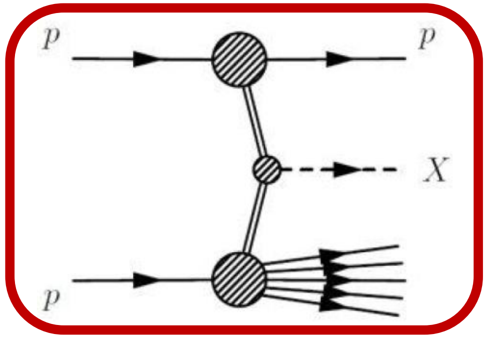
Arxiv:2009.05352

Central exclusive production

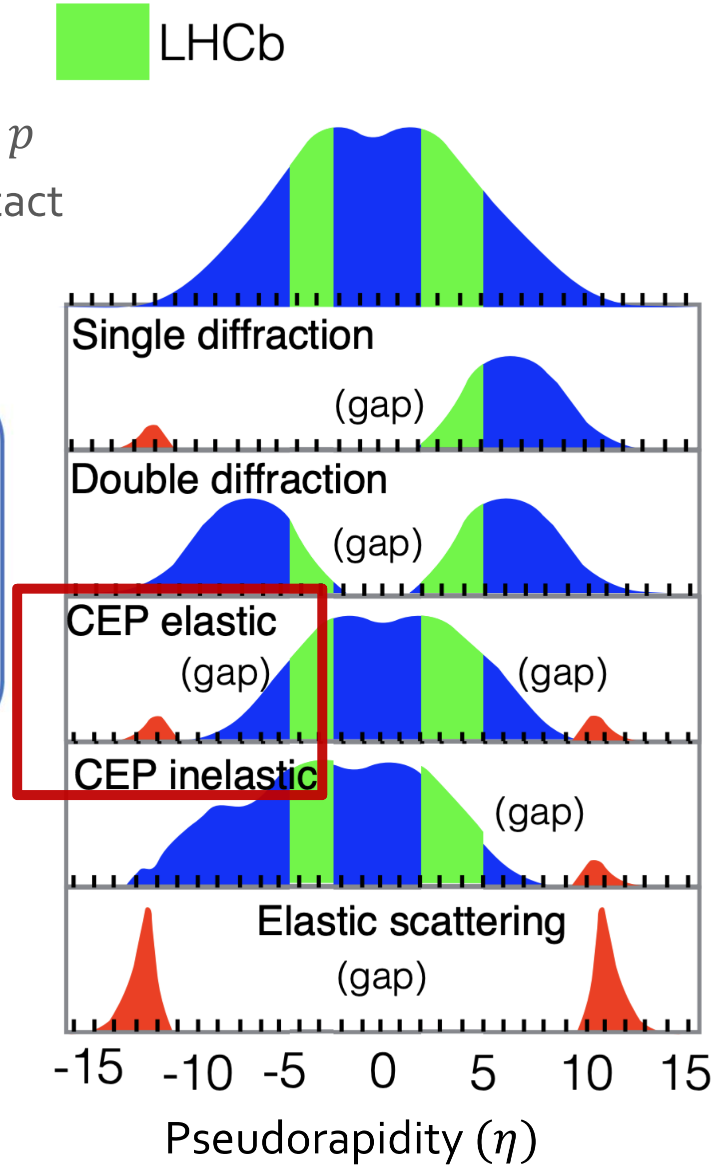
- Study J/ψϕ resonances in CEP
  - Diffractive process of the form $pp \rightarrow p + X + p$
  - Experimentally clean even @LHC, protons intact
  - Spin-parity option narrowed down
  - But Much smaller rate



γ-γ γ-pomeron pomeron-pomeron

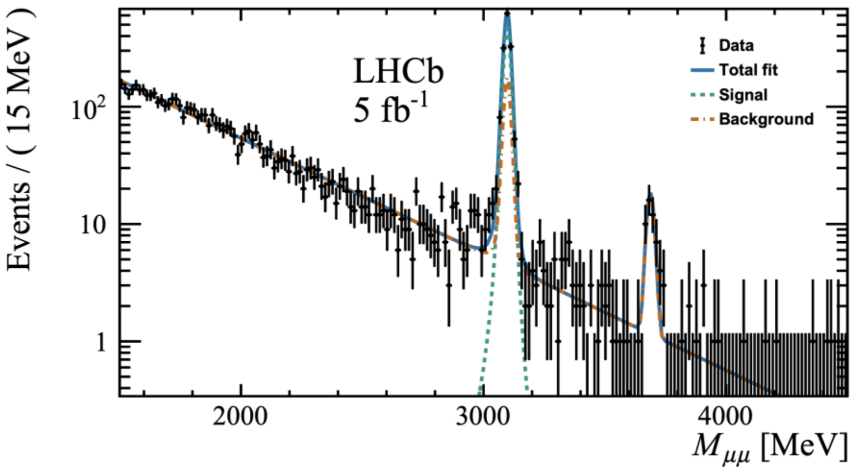


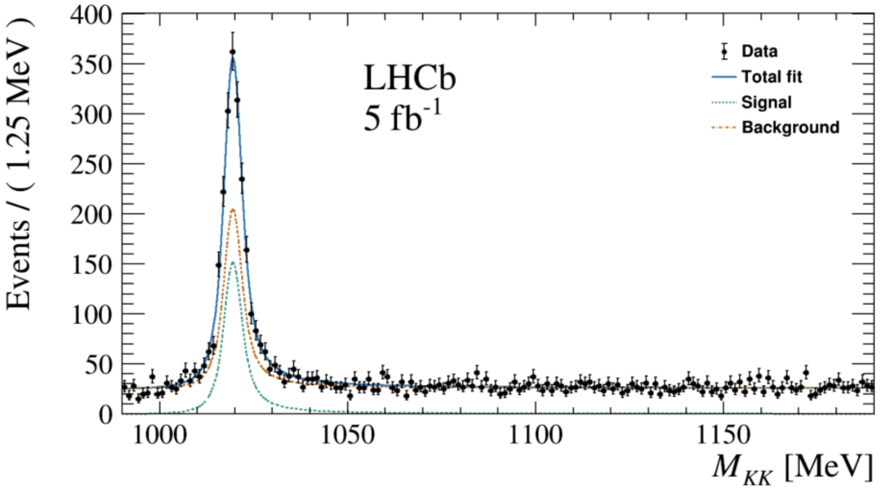
Inelastic CEP

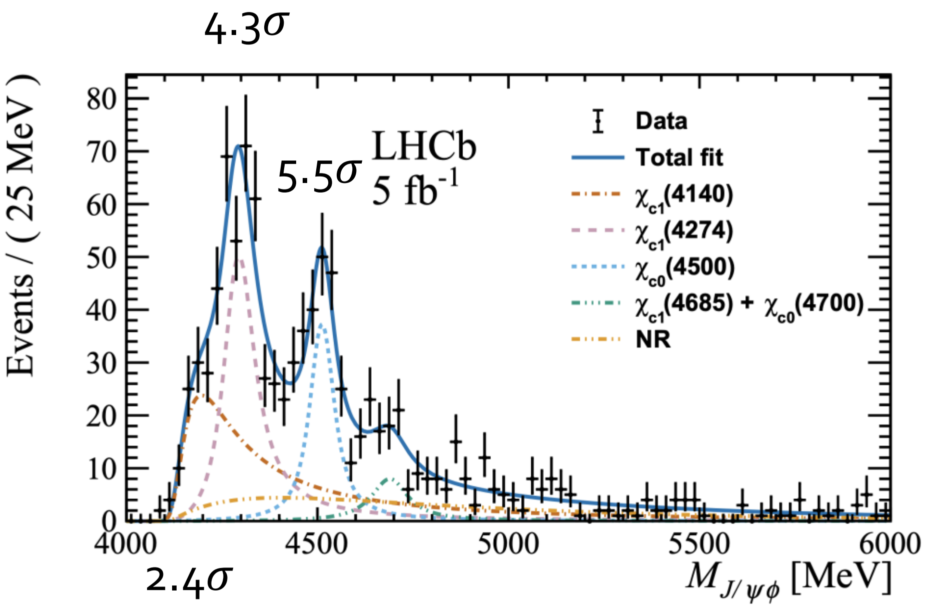


[arXiv:2407.14301]

χ->J/ψϕ in CEP







- first observation of $X \to J/\psi\phi$ in CEP
- five resonant and one nonresonant components

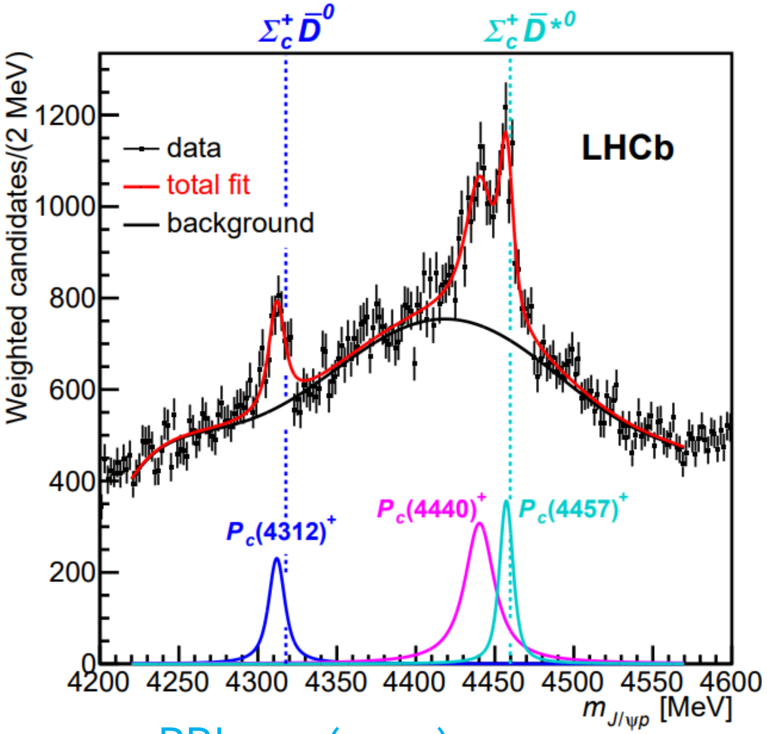
$$\sigma_{J/\psi\phi} \times \mathcal{B}(J/\psi \to \mu^+\mu^-) \times \mathcal{B}(\phi \to K^+K^-) = (2.52 \pm 0.08 \pm 0.12 \pm 0.05)\,\text{pb}$$

Parameter [MeV]	Current analysis	Ref. [13]
$M_{\chi_{c1}(4274)}$	$4298 \pm 6 \pm 9$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18} \pm 57$	$53 \pm 5 \pm 5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16} \pm 32$	$77 \pm 6^{+10}_{-8}$

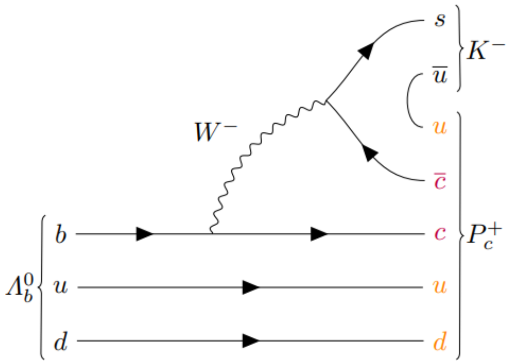
[arXiv:2407.14301]

Pentaquark study

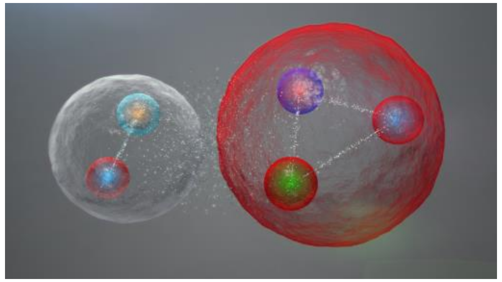
- The observation of new decay modes can shed light on the binding scheme of the exotic hadrons



PRL 122 (2019) 222001



Search through open charm modes



molecular state prediction is likely in nature

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

Search for pentaquarks via open charm

[Phys. Rev. D110 (2024) 032001]

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

hidden-charm pentaquarks

Hadron 1	Hadron 2	Charge	I_3	Y	C	Limit Set
Λ_c^+	$\overline{D}^0$	+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	✓

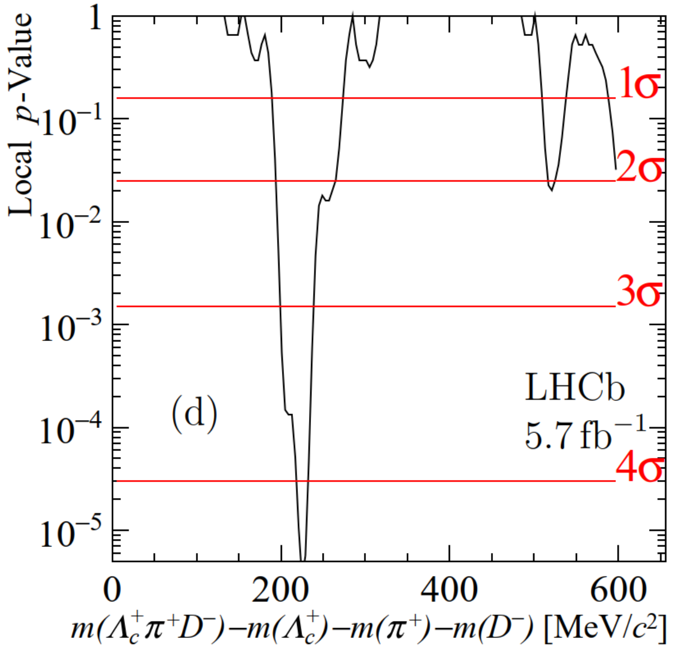
doubly-charmed pentaquarks & excited

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

- No significant signals are found
- Upper limits set on $R(\Lambda_c^+) = \frac{N_{P_c}}{N_{\Lambda_c^+}} \times \frac{\epsilon_{\Lambda_c^+}}{\epsilon_{P_c}}$



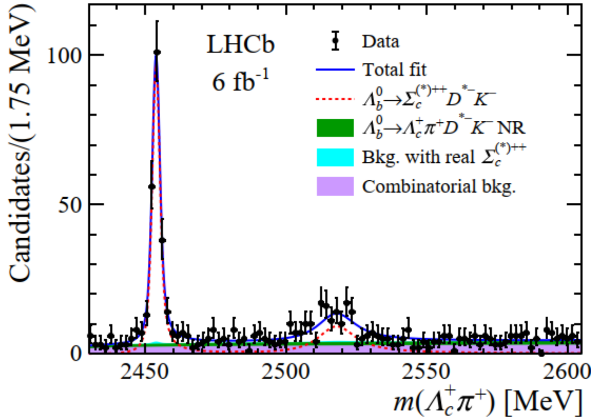
Largest significant modes:

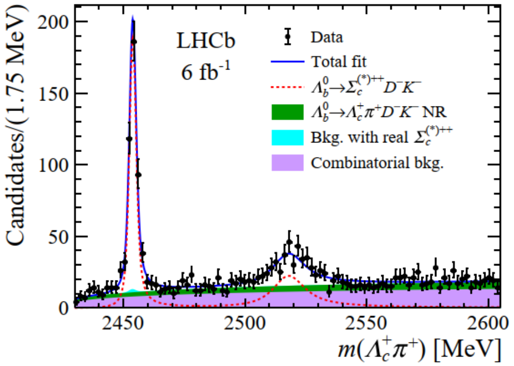
Decay Mode	Width (MeV/c^2)	Lowest p-value Local	Lowest p-value Corrected	Significance (σ) Local	Significance (σ) Corrected	Q-value (MeV/c^2)	Signal Yield	UL ($\times 10^{-3}$) 90% CL	UL ($\times 10^{-3}$) 95% CL
$\Lambda_c^+\pi^+\overline{D}^0$	0	7.4×10^{-4}	0.06	3.18	1.58	245	41.9 ± 13.7	2.87	3.06
	5	9.69×10^{-5}	5.76×10^{-3}	3.73	2.53	245	67.6 ± 19.2	3.22	3.35
	10	2.46×10^{-5}	1.12×10^{-3}	4.06	3.06	245	91.6 ± 24.1	3.29	3.39
	15	8.61×10^{-6}	3.11×10^{-4}	4.30	3.42	245	115.0 ± 28.5	3.30	3.40
$\Lambda_c^+\pi^+D^-$	0	1.6×10^{-4}	0.01	3.59	2.21	225	41.6 ± 12.6	3.95	4.19
	5	3.03×10^{-5}	1.96×10^{-3}	4.01	2.89	225	64.7 ± 17.4	4.43	4.69
	10	8.61×10^{-6}	4.44×10^{-4}	4.30	3.32	225	87.1 ± 21.6	4.64	4.85
	15	3.36×10^{-6}	1.45×10^{-4}	4.50	3.62	225	108.2 ± 25.3	4.72	4.90
$\Lambda_c^+\pi^-\overline{D}^0$	0	4.8×10^{-4}	0.04	3.30	1.72	597	54.0 ± 17.2	2.79	2.98
	5	9.65×10^{-5}	7.11×10^{-3}	3.73	2.45	597	78.8 ± 21.9	3.02	3.20
	10	2.71×10^{-5}	1.63×10^{-3}	4.04	2.94	597	104.0 ± 26.3	3.15	3.30
	15	9.50×10^{-6}	4.83×10^{-4}	4.28	3.30	597	128.5 ± 30.4	3.20	3.33

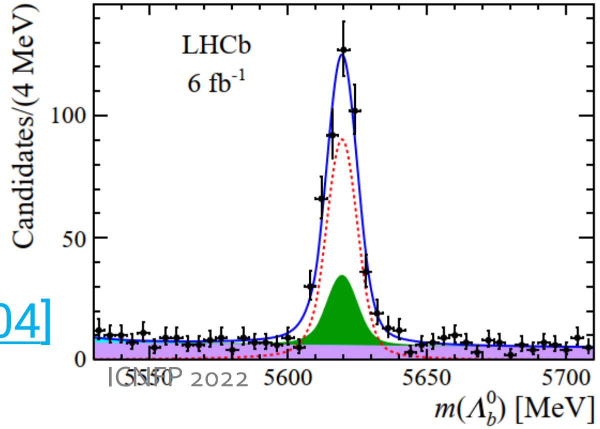
[Phys. Rev. D110 (2024) 032001]

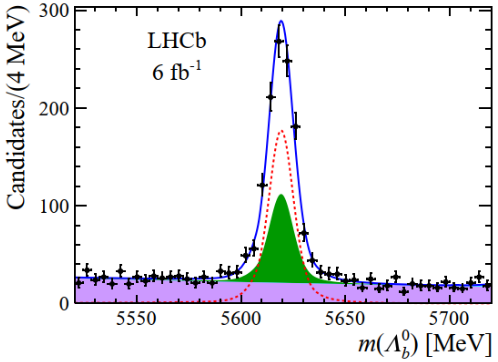
Observation of Λ_b^0 Decays

- First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ in pp collision
  - Four modes observed with overwhelming significance
- Provides insight into pentaquark searches in these modes.









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

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

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

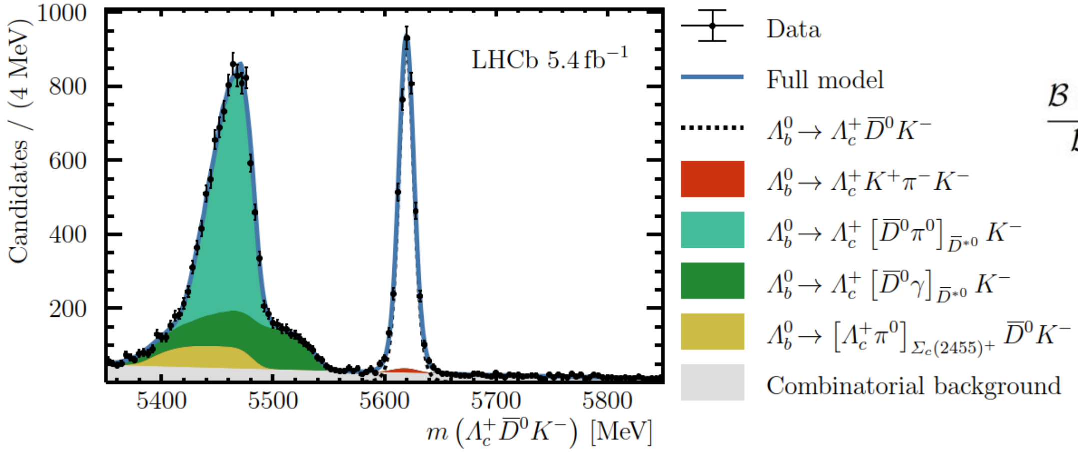
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{*++} D^{*-} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{++} D^- K^-)} = 0.896 \pm 0.137 \pm 0.066 \pm 0.018,$$

[Phys. Rev. D 110 (2024) L031104]

Larger dataset needed to amplitude analysis

Observation of Λ_b^0 Decays

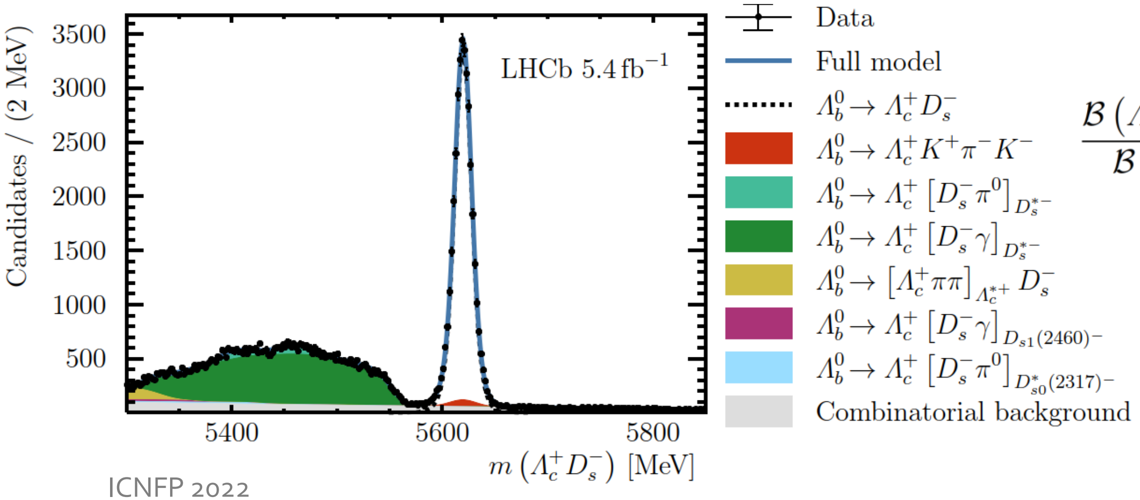
- First observation of $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{(*)0} K^-$
  - These decays can pave the way for future penta-quark search in $\Lambda_c^+ \bar{D}^{(*)0}$ systems
  - open-charm equivalent of $J/\psi p$
  - $\bar{D}^{(*)0}$ is partially reconstructed with missing π^0/γ



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

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.1908^{+0.0036+0.0016}_{-0.0034-0.0018} \pm 0.0038$$

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



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

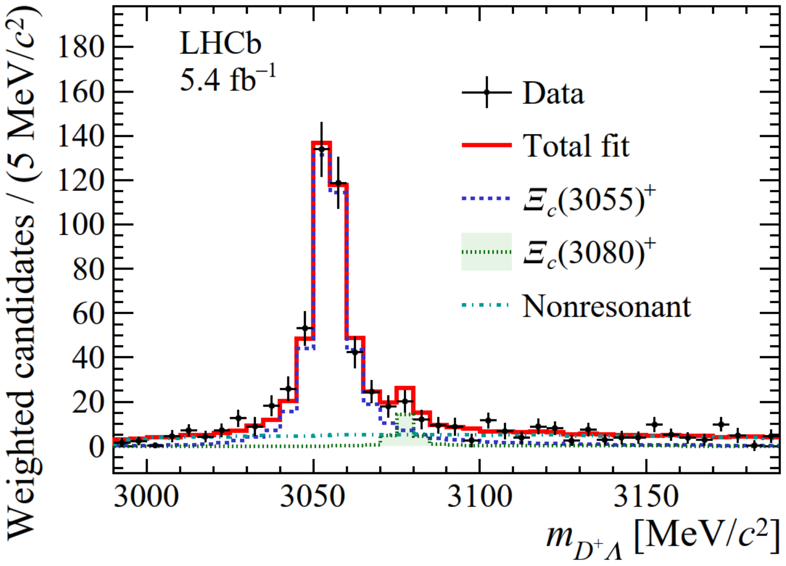
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.589^{+0.018+0.017}_{-0.017-0.018} \pm 0.012$$

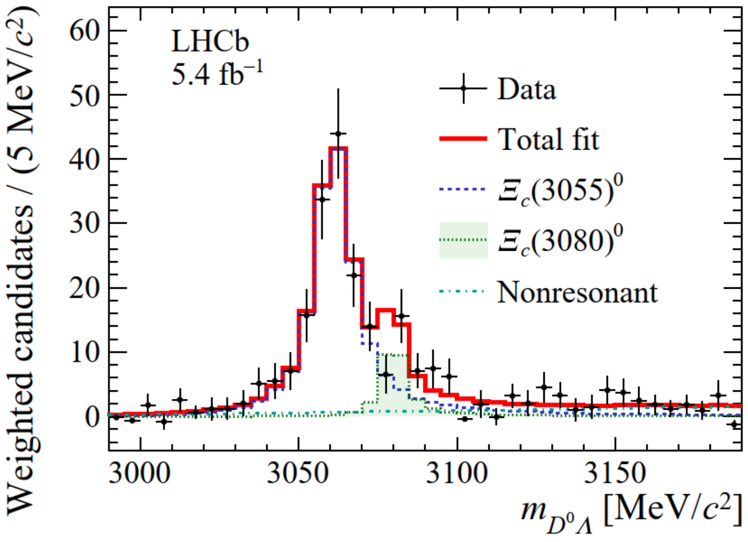
$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-)} = 0.049^{+0.011}_{-0.009}$$

[EPJ C 84 (2024) 575]

Baryon Spin-Parity Determination

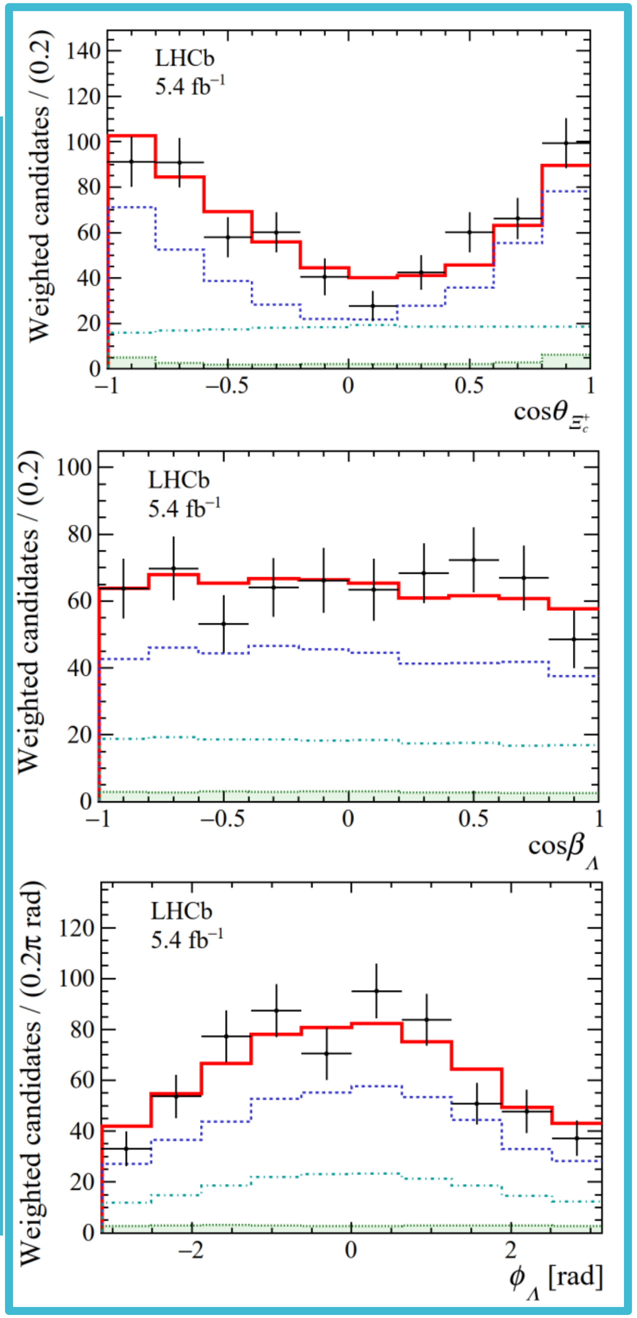
- First determination of the spin-parity of $\Xi_c(3050)^{+,0}$ using $\Xi_b^{0/(-)} \rightarrow \Xi_c(3050)^{+,0}$.
  - Hadron molecular state 1/2- or 3/2 –
  - D-wave excitation 3/2+, 5/2+ or 2S excitation with ½+, 3/2+
- Using amplitude analysis to determine quantum numbers.
- Important for understanding charm baryon spectroscopy.

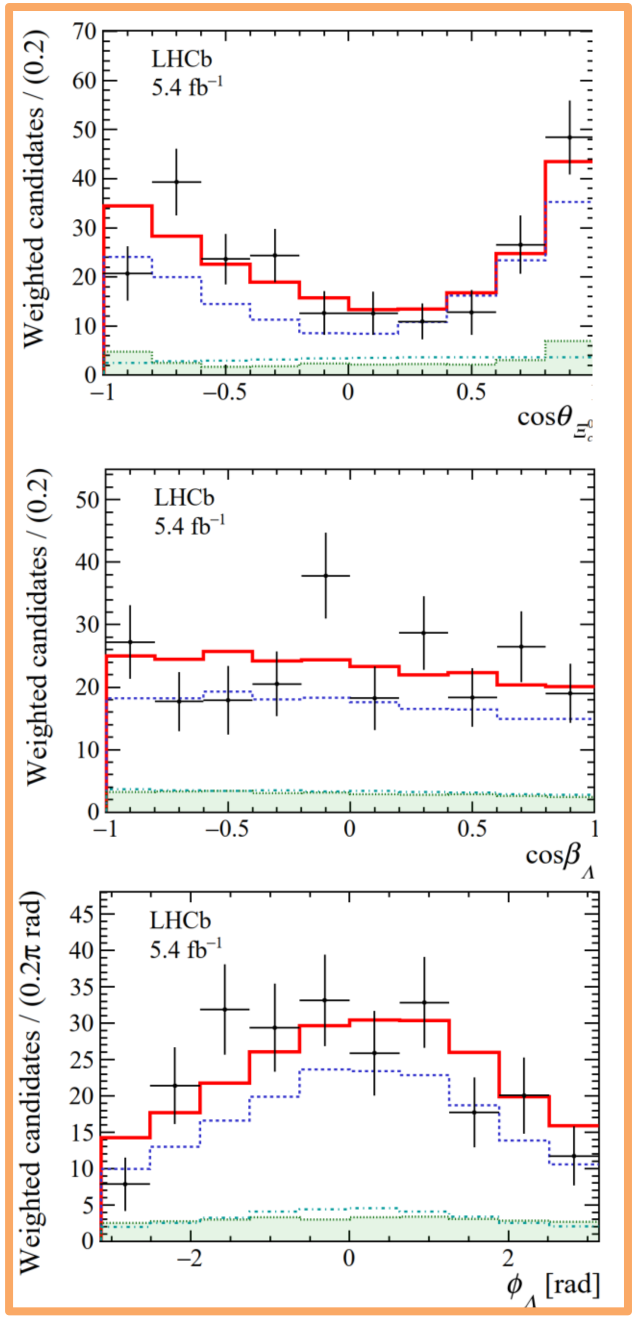




[arXiv:2409.05440]

Baryon Spin-Parity Determination





- $\Xi_c(3050)^+$:3/2+ (6.5σ)
- $\Xi_c(3050)^0$: 3/2+ (3.5σ)

Support excitation of D-wave or 2S

[arXiv:2409.05440]

hidden beauty spectroscopy

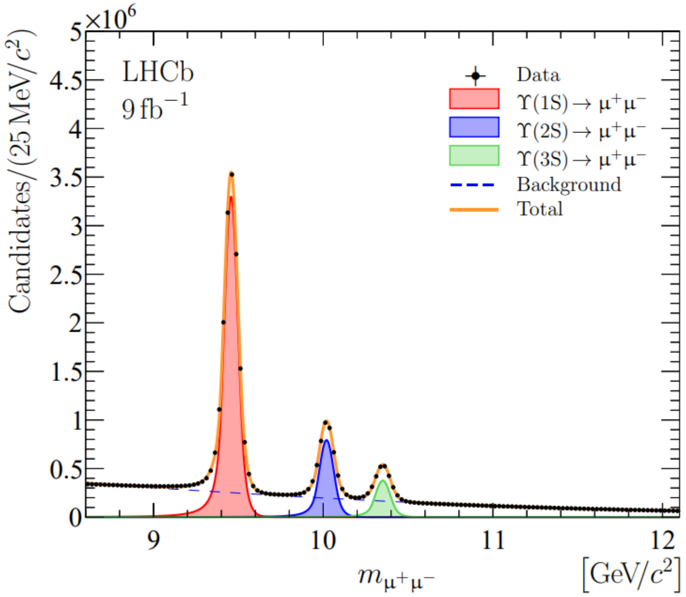
- Υ states
  - Masses measured in 1990s (CESR, DORIS, VEPP) , relied on photon energy of Y(2S) and Y(3S)
  - Standing tensions between CESR and DORIS on Y(1S) mass
  - Shamov et al resolved by reanalysing the data with interference and radiative corrections considered correctly
  - Quoted error in PDG 2024 for Y(1S) decreased: 0.26 MeV → 0.1 MeV
  - DORIS data is removed for Y (2S) , error increased: 0.31 MeV → 0.5 MeV
  - Measurement of mass splitting are dominated by BarBar experiment

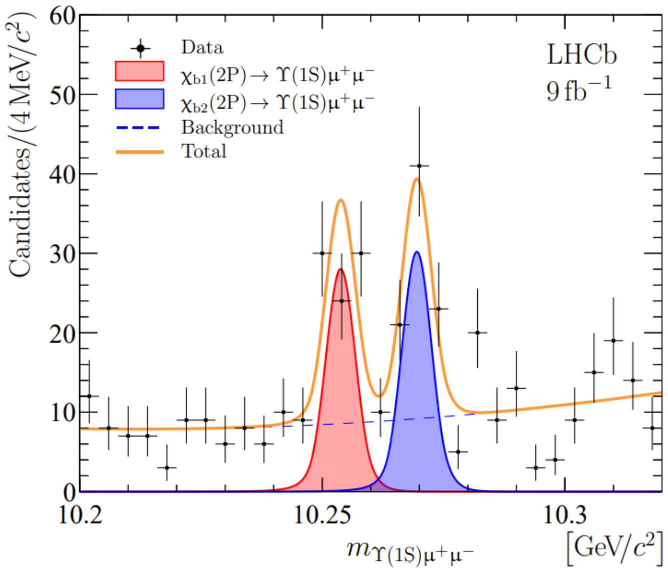
- Observe χb→ $\Upsilon\mu^+\mu^-$
  - Exploit the low Q-value for these decays to measure precisely χb masses
  - First observation of χb meson decays to muonic Dalitz decays.
- Precision spectroscopy of hidden beauty states.

State	Measured mass $[\mathrm{MeV}/c^2]$ PDG2024	PDG2022
$\Upsilon(1S)$	9460.4 ± 0.1	9460.30 ± 0.26
$\Upsilon(2S)$	10023.4 ± 0.5	10023.26 ± 0.31
$\Upsilon(3S)$	10355.2 ± 0.5	10355.2 ± 0.5

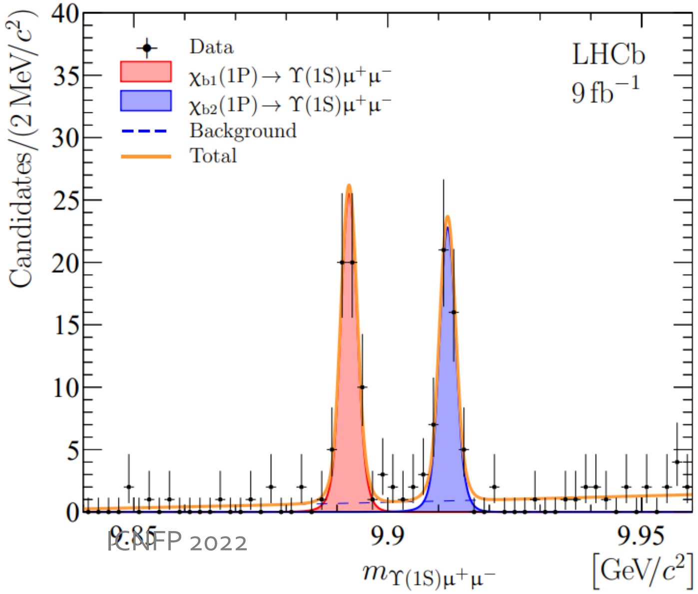
[arXiv: 2408.05134]

hidden beauty spectroscopy





- World best value for $m_{\chi_{b1}}(1P)$ and $m_{\chi_{b2}}(1P)$

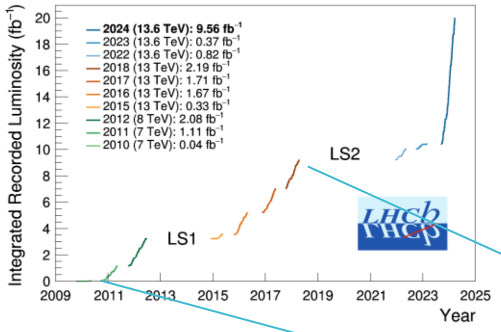


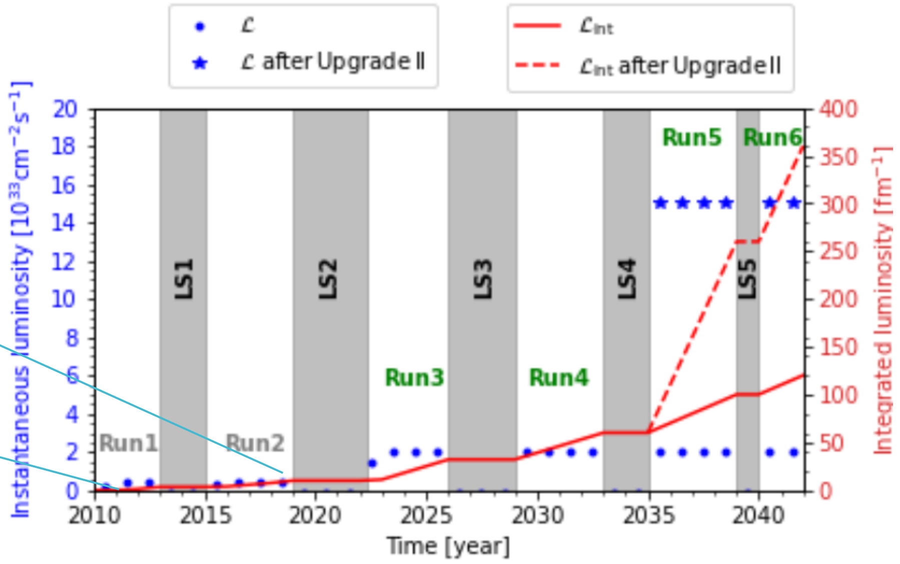
$$m_{\chi_{b1}}(1P) = 9892.50 \pm 0.26 \pm 0.10 \pm 0.10\ \mathrm{MeV/c^2}$$
$$m_{\chi_{b2}}(1P) = 9911.92 \pm 0.29 \pm 0.11 \pm 0.10\ \mathrm{MeV/c^2}$$
$$m_{\chi_{b1}}(2P) = 10253.97 \pm 0.75 \pm 0.22 \pm 0.09\ \mathrm{MeV/c^2}$$
$$m_{\chi_{b2}}(2P) = 10269.67 \pm 0.67 \pm 0.22 \pm 0.09\ \mathrm{MeV/c^2}$$

[arXiv: 2408.05134]

Summary && Prospects

- LHCb keeps making important contributions to heavy hadron spectroscopy, both for conventional or exotic hadrons
  - Exotic hadron spectroscopy: pentaquark search; Radiative decays of $\chi_{c1}(3872)$; $B \to D\bar{D}h$ study, the Tcs puzzle; first exotic study in diffractive processes…
  - Conventional hadron spectroscopy: $\chi_b$spectroscopy;$\Xi_c^{0/+}$ J^P
- Improved detectors and software-only trigger system will allow more precise measurements and discoveries.
- In Run 3, Expected to significantly increase the data sample for heavy hadron searches.





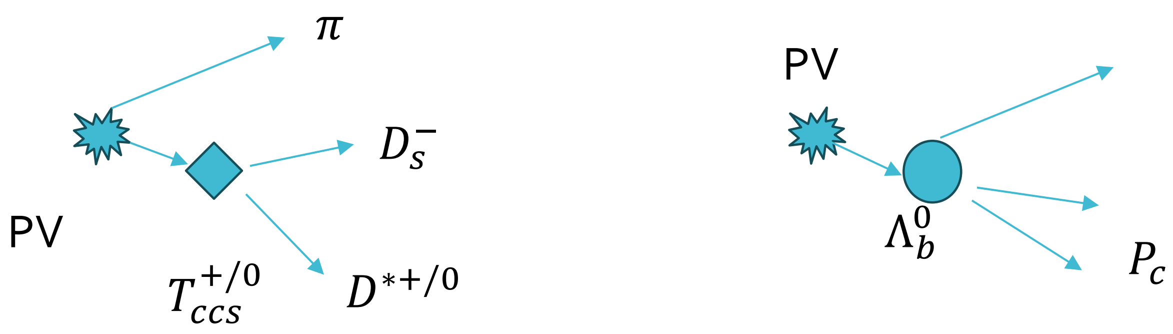
More exciting results are to come!
More data, more chances & challenges!

Thanks for your attention!

Backup

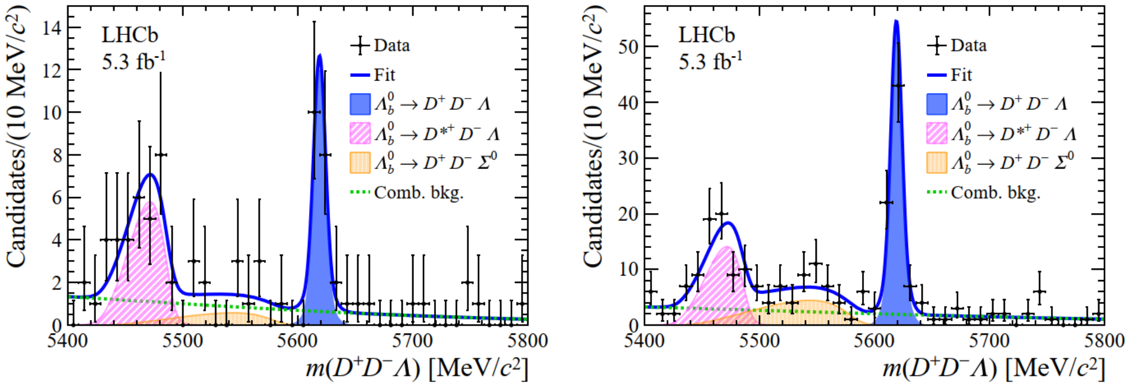
Two methods for spectroscopy

- Direct production in EE 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 quantum number 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



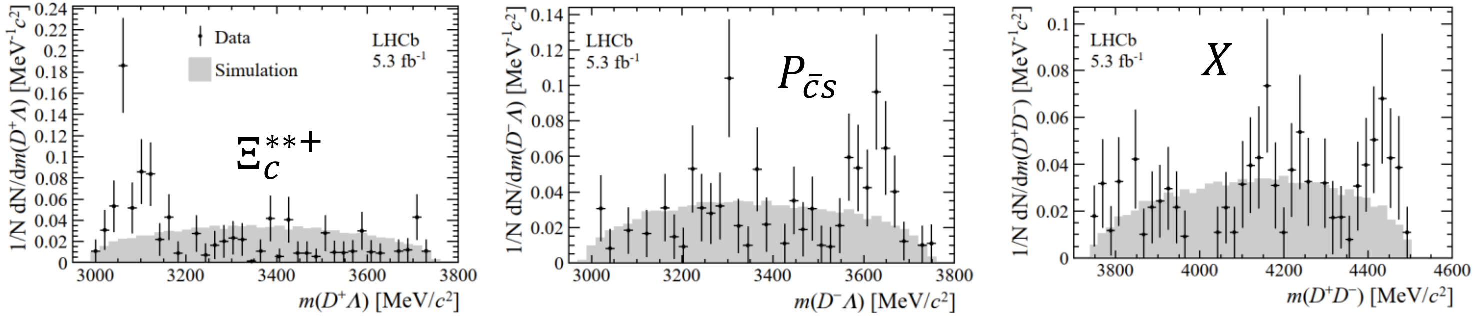
Observation of $\Lambda_b^0 \to D^+D^-\Lambda$

- First observation of with significance of 16 '



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

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



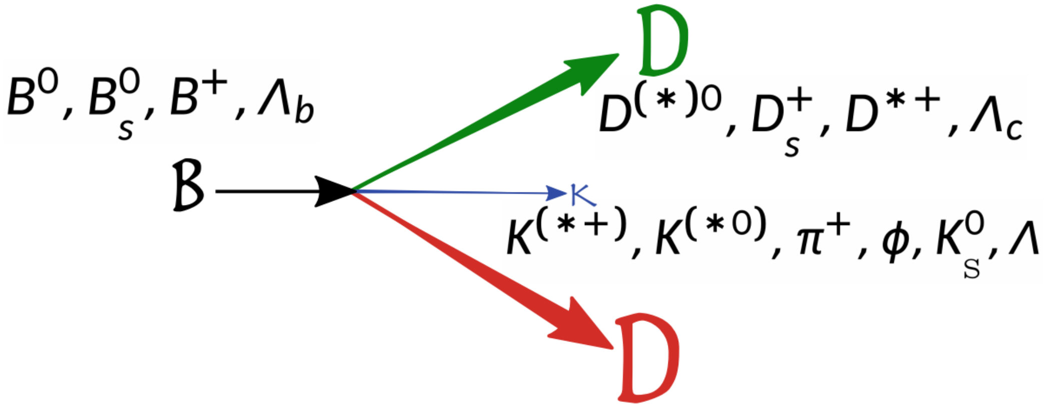
JHEP 07 (2024) 140

Spectroscopy

- **First determination of the spin-parity of the $\Xi_c(3055)^{+,0}$ baryons**
  LHCb-PAPER-2024-018, arXiv:2409.05440 (Charm)
- **Observation of muonic Dalitz decays of χ_b mesons and precise spectroscopy of hidden beauty**
  LHCb-PAPER-2024-025, arXiv:2408.05134 (B&Q)
- **Observation of exotic $J/\psi\phi$ resonances in diffractive processes in proton-proton collisions**
  LHCb-PAPER-2023-043, arXiv:2407.14301 (QEE)
- **Observation of new charmonium(-like) states in $B^+ \to D^{*\pm} D^{\mp} K^+$ decays**
  LHCb-PAPER-2023-047, arXiv:2406.03156 (B2OC)
- **Probing the nature of the $\chi_{c1}(3872)$ state using radiative decays**
  LHCb-PAPER-2024-015, arXiv:2406.17006 (B&Q)
- **Amplitude Analysis of $B^+ \to D^{*-} D_s^+ \pi^+$**
  LHCb-PAPER-2024-001, arXiv:2405.00098 (B2OC)
- **Search for prompt production of pentaquarks in open charm hadron final states**
  LHCb-PAPER-2023-018, arXiv:2404.07131 (B&Q)
- **Observation of the $B_c^+ \to J/\psi \pi^+ \pi^0$ decay**
  LHCb-PAPER-2023-046, arXiv:2402.05523 (B&Q)
- **Observation of $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ decays**
  LHCb-PAPER-2023-039, arXiv:2311.14088, EPJC 84 (2024) 575
- **First observation of $\Lambda_b^0 \to \Sigma_c^{(*)++} D^{(*)-} K^-$ decays and measurement of their relative branching fractions**
  LHCb-PAPER-2023-044, arXiv:2404.19510, PRD 110 (2024) L031104

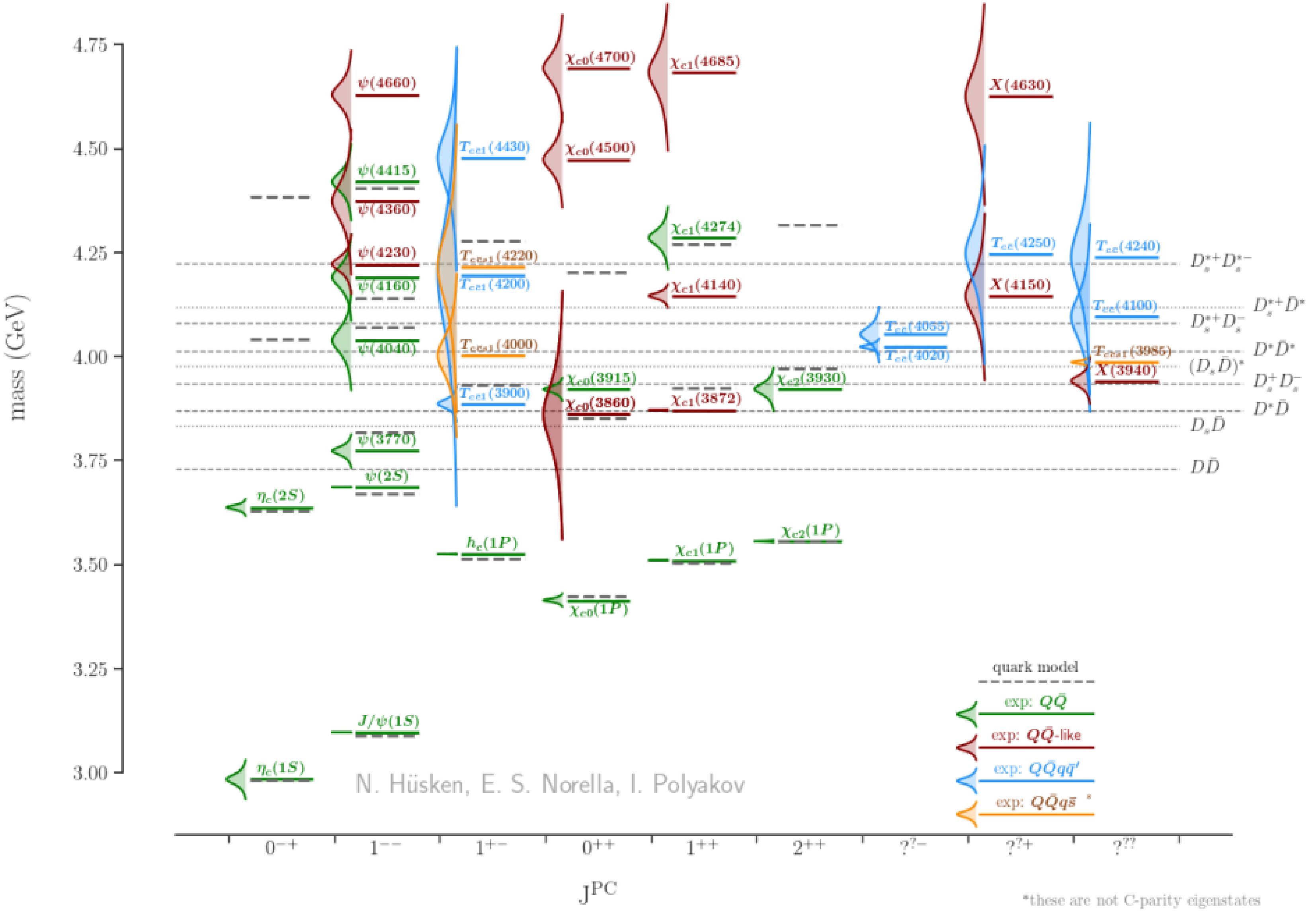
New Charmonium-like States

- **Rich opportunities for spectroscopy study in the new laboratory since $B \to D\bar{D}K$ (Belle PRL 100.092001 and LHCb PRL 125 (2020) 242001)**
  - **charmonium(-like) states in $D^*\bar{D}^{(*)}$, $\Lambda_c\bar{D}^{(*)}$, $\Lambda_c\bar{\Lambda}_c$**
  - **excited $D^0, D^+, D_s^+, \Lambda_c$ state from $D^{(*)}h, \Lambda_c h$**
  - **exotic states from $\bar{D}^{(*)}h, \bar{\Lambda}h$.**
- Adds to the growing list of potential exotic hadrons.
  - search for tetraquark candidates $(DK, \bar{D}^{(*)}K)$



[Phys. Rev. Lett. 133 (2024) 131902]

Conventional prediction && experiment



Layout of Hershel