中国科学院大学
University of Chinese Academy of Sciences

Latest results of conventional states at LHCb

Zan Ren

University of Chinese Academy of Sciences

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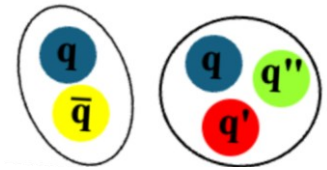
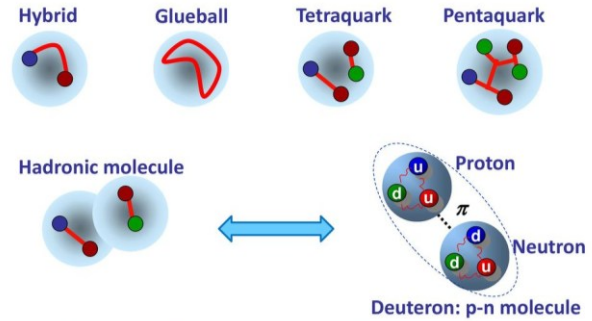
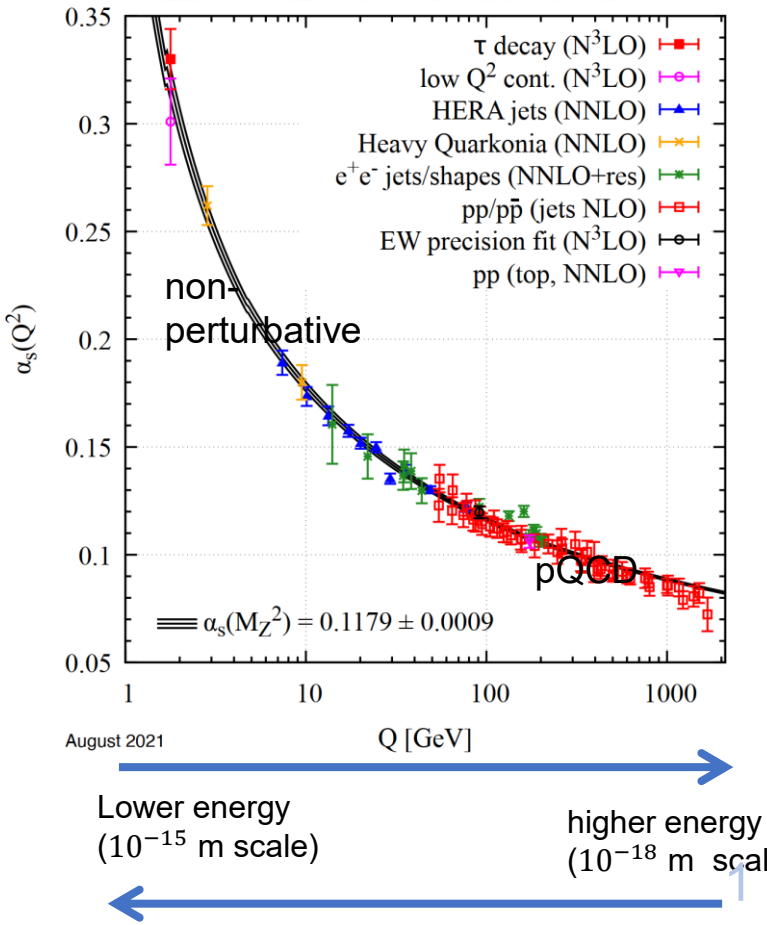
第九届强子谱和强子结构研讨会

About hadron spectroscopy

- QCD shows non-perturbative behavior at the energy scale of hadrons.
- Hadron: conventional or exotic
- Spectroscopy of conventional hadrons (mesons and baryons) enriched in the past decades.
- Why conventional heavy-flavour states?
  - Probe non-perturbative QCD: the cleanest laboratory for strong dynamics
  - Heavy-quark symmetry: ($m_b \gg m_c \gg \mathrm{m_q}$) enables precise effective theories (HQET, NRQCD, …)
  - Narrow, clean signals: Lower-lying excitations below open-flavour thresholds → narrower width → easy to resolve
- LHCb is designed for this!

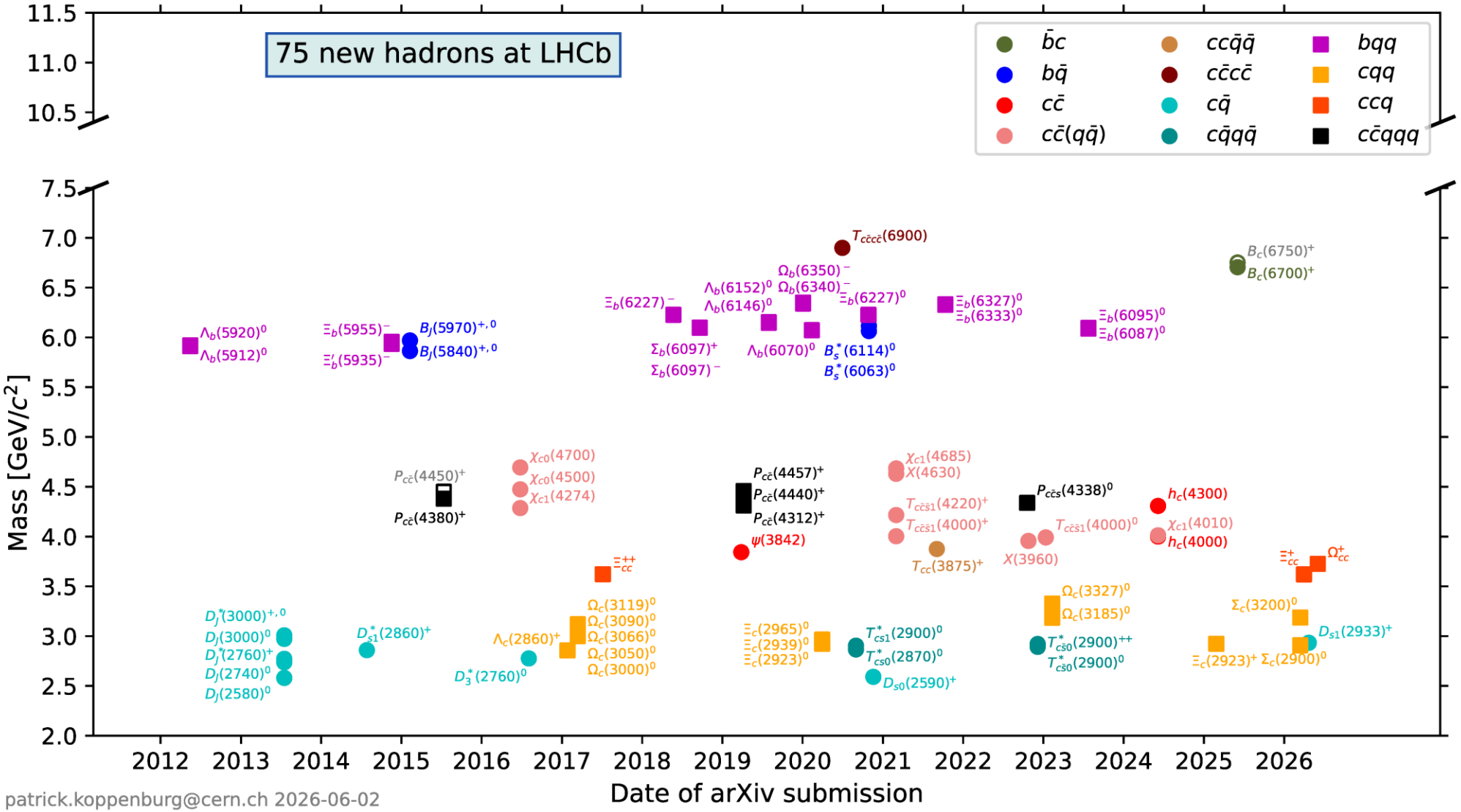






Hadrons discovered by LHCb

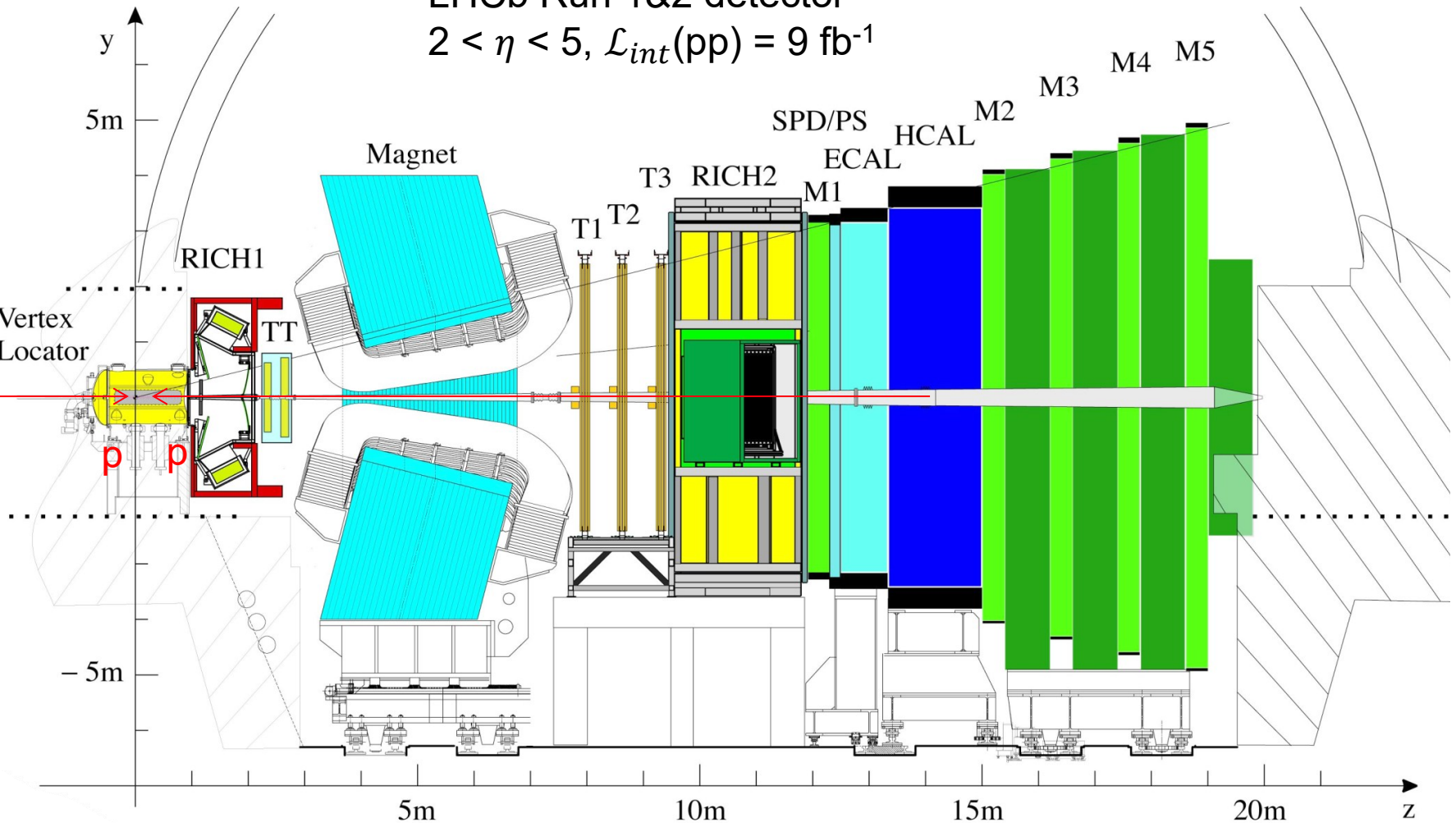
https://www.koppenburg.ch/particles.html



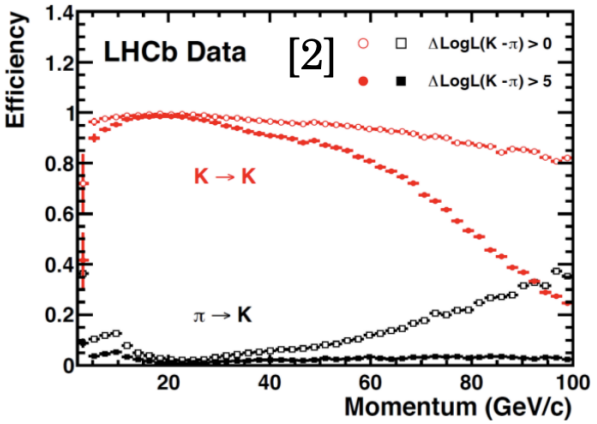
LHCb detector: Run1 & Run2

- Single-arm, forward. Specifically designed for heavy-flavour physics.

LHCb Run 1&2 detector
$2 < \eta < 5$, $\mathcal{L}_{int}$(pp) = 9 fb^{-1}



- **Excellent tracking and vertexing**
  - $\sigma(p)/p < 1\%$ @ $\epsilon_{\text{track}} > 96\%$
  - $\sigma(\text{IP}) = (15 + 29/p_T)\ \mu m$
- **Excellent PID**
  - $\epsilon_{\text{PID}}(K) \approx 95\%$ @ $\text{MisID}(\pi \to K) \approx 5\%$
  - $\epsilon_{\text{PID}}(\mu) \approx 97\%$ @ $\text{MisID}(\pi \to \mu) \approx 3\%$



JINST3 (2008) S08005
IJMPA 30 (2015) 1530022

LHCb detector: Run3

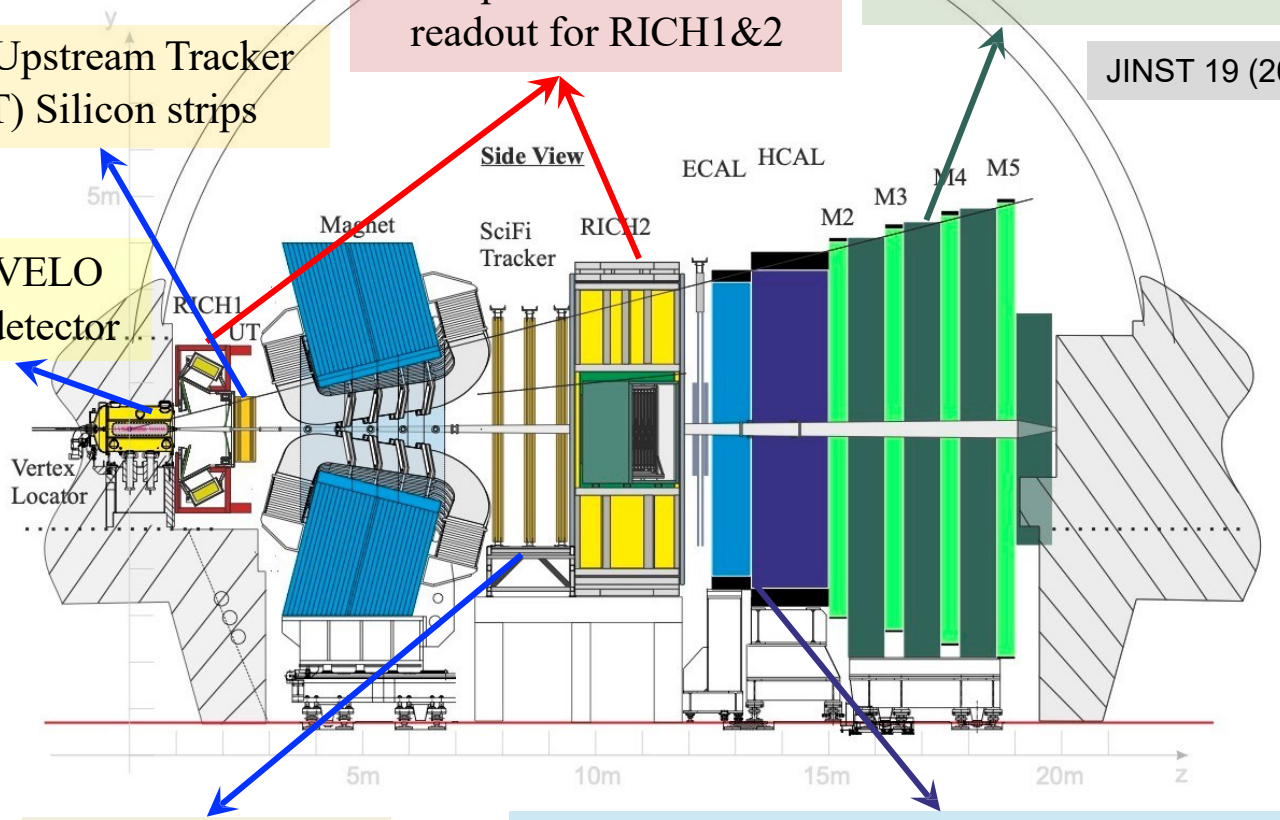
New RICH1 optics
New photodetectors and readout for RICH1&2

Muon: removed M1 and new readout

New Upstream Tracker (UT) Silicon strips

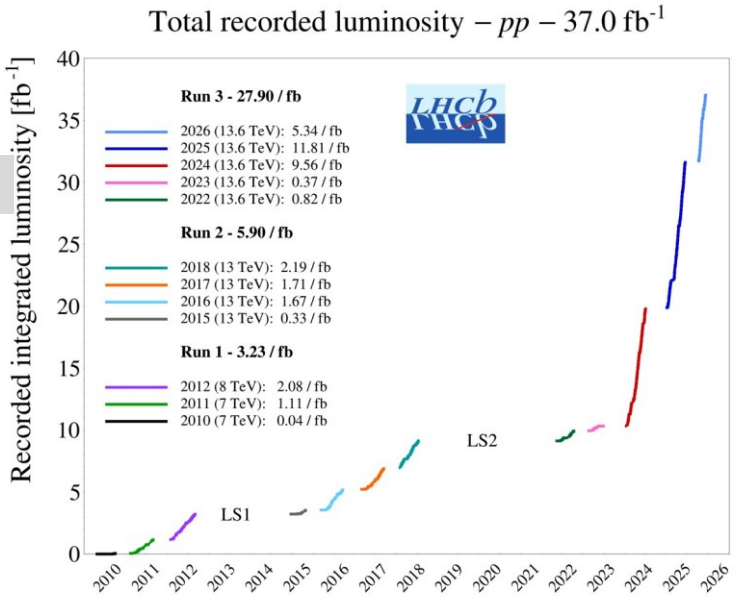
JINST 19 (2024) P05065

New VELO Pixel detector

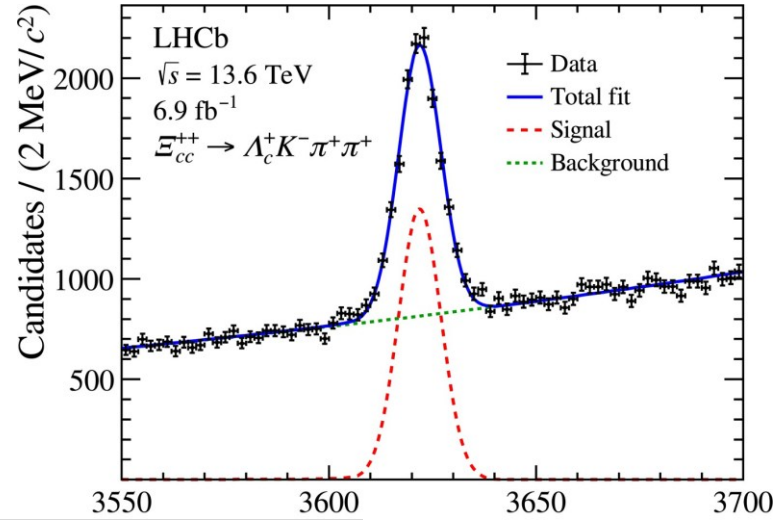


New SciFi Tracker Scintillating fibres

Calorimeters: removed PreShower (PS) and Scintillating Pad Detector (SPD), new readout



✓ Ξ_{cc}^{++} yield/fb^{-1}: 285 @ Run2 → 1262 @ 2024



PRL 137, 021902 (2026)

- **Luminosity**: 9 fb^{-1} Run 1 & Run 2 → **37 fb^{-1}** by Run 3
- **Software-only trigger**: efficiency of hadronic modes **×2 to 4**

New results covered by this talk

- Lots of exciting results form LHCb this year:
  - Observation of doubly charmed baryons: Ξ_{cc}^{+} and Ω_{cc}^{+}
  - Observation of $D_{s1}(2933)^{+}$ in $B^{+} \rightarrow D^{+}D^{-}K^{+}\pi^{-}$ decays
  - Discovery of an unexpectedly light narrow beauty-strange state $B_{s0}^{*}(5700)^{0}$
  - Observation of new excited Σ_{c}^{0} states in the $B^{-} \rightarrow \Lambda_{c}^{+}\,\overline{p}\,\pi^{-}$ decay

Ξ_{cc}^{+} PRL 137, 021902 (2026)
Ω_{cc}^{+} LHCb-PAPER-2026-022 in preparation

arXiv:2604.21257

LHCb-PAPER-2026-021 in preparation

arXiv:2607.10595

Some of the newly discovered states need further theoretical investigation:
➔ They cannot be interpreted as pure conventional states.

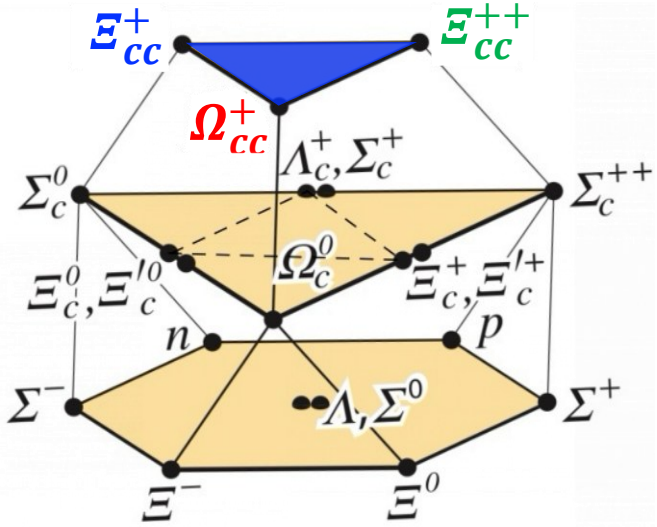
Red: Analysis mainly completed by Chinese groups/people.

Doubly heavy flavour hadrons

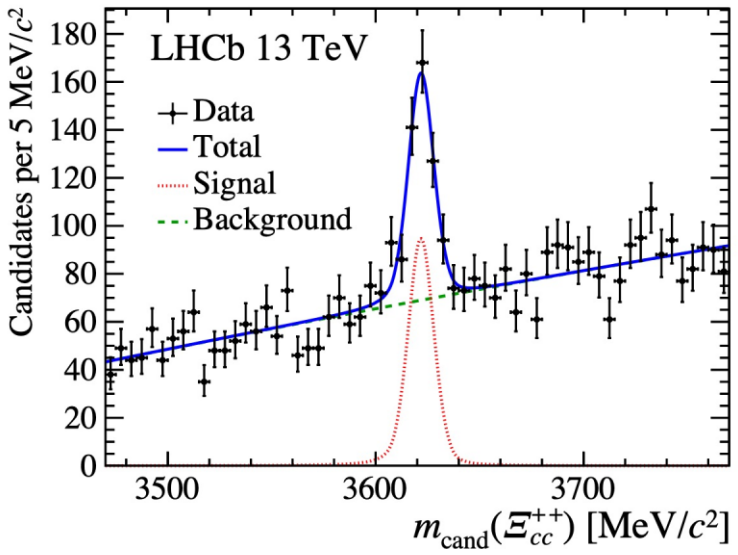
History of doubly charmed baryons

- Doubly charmed baryons remained a missing piece in baryon sector
  ➔ until the firm observation of Ξ_c^{++} in $\Lambda_c^+ K^- \pi^+ \pi^+$
- Search for Ξ_c^+ and Ω_c^+ with LHCb Run1&2 data yields no observation

$$\tau\ \Xi_{cc}^{++} > \tau(\Omega_{cc}^+) > \tau(\Xi_{cc}^+)$$
$$\sigma(\Xi_{cc}^{++}) \sim \sigma(\Xi_{cc}^+) \sim 3\times\sigma(\Omega_{cc}^+)$$

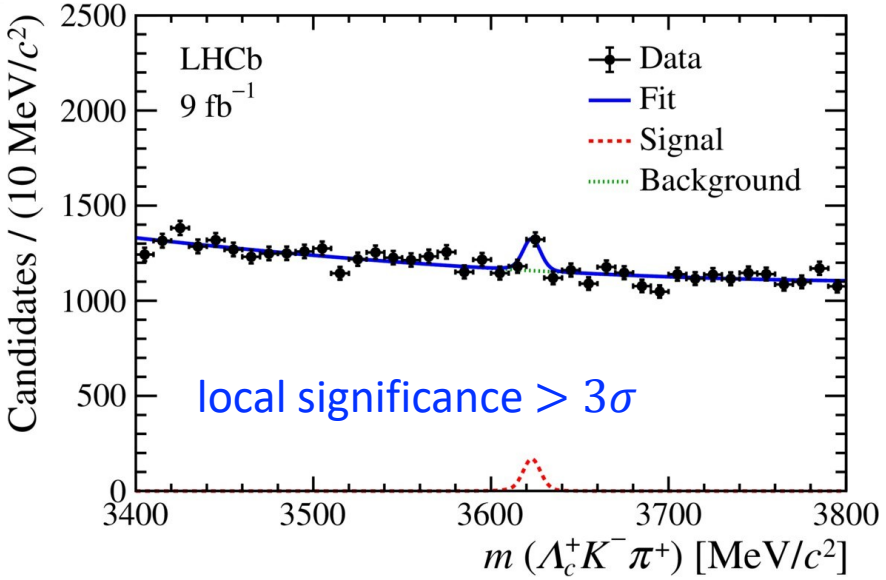


Observation of Ξ_{cc}^{++}



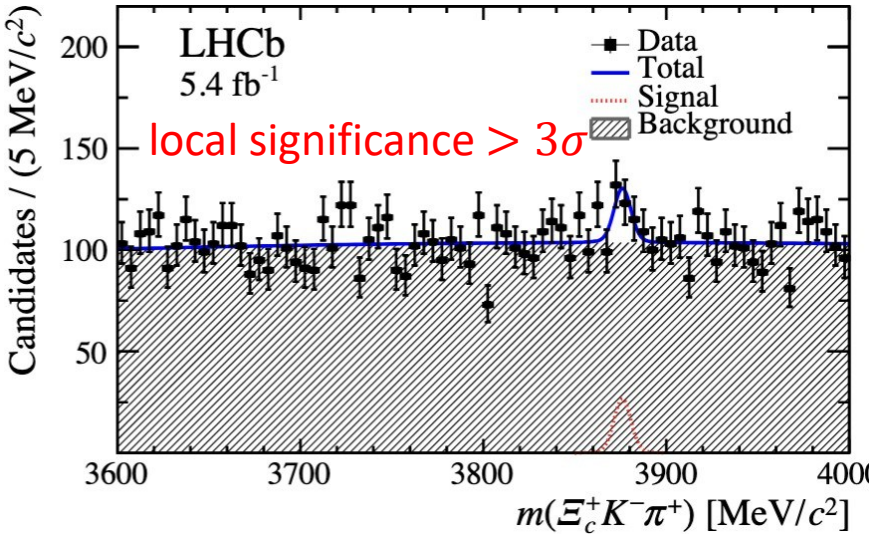
PRL 119 (2017) 112001

Search for $\Xi_c^+ \to \Lambda_c^+ K^- \pi^+$



JHEP 12 (2021) 107

Search for $\Omega_c^+ \to \Xi_c^+ K^- \pi^+$



SCPMA 64 (2021), 101062

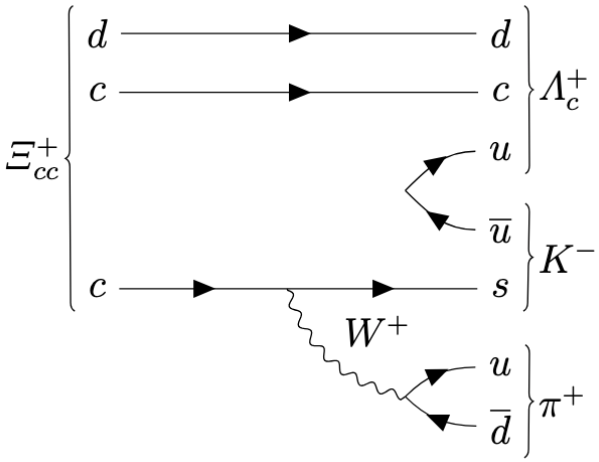
Observation of $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$

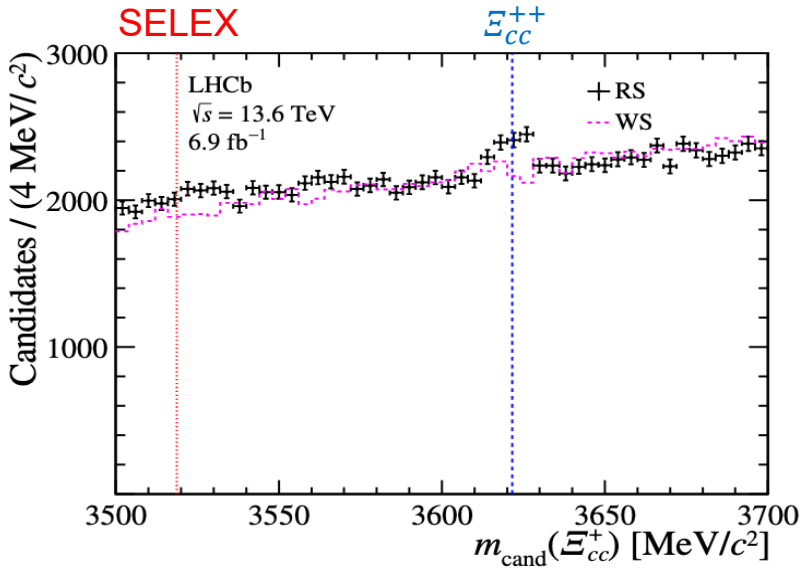
JHEP07(2023)061

- Isospin-partner with Ξ_{cc}^{++} with shorter lifetime: ~60 ps
- First claimed by SELEX collaboration:
  - Reported in $\Lambda_c^{+} K^{-} \pi^{+}$ and $D^{+} p K^{-}$ at 3520 MeV

PRL 89, 112001 (2002)
PRL 95, 232001 (2005)

  - Not confirmed by FOCUS, BABAR, Belle and LHCb Run1/2
- Local significance $> 3\sigma$ in LHCb Run 1&2 data
  - but not significant considering Look Elsewhere Effect (LEE)
- Target: search for Ξ_{cc}^{+} via $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ in LHCb 2024 data
  - Control mode: $\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$
- Two-stage multivariate classifiers:
  - BDT for Λ_c^{+} selection
  - BDT for $\Xi_{cc}^{+}(\Xi_{cc}^{++})$ with the first BDT as an input
- Mass distributions of the selected Ξ_{cc}^{+} candidates
  - Peak near Ξ_{cc}^{++} mass
  - No structure at SELEX-claimed 3520 MeV





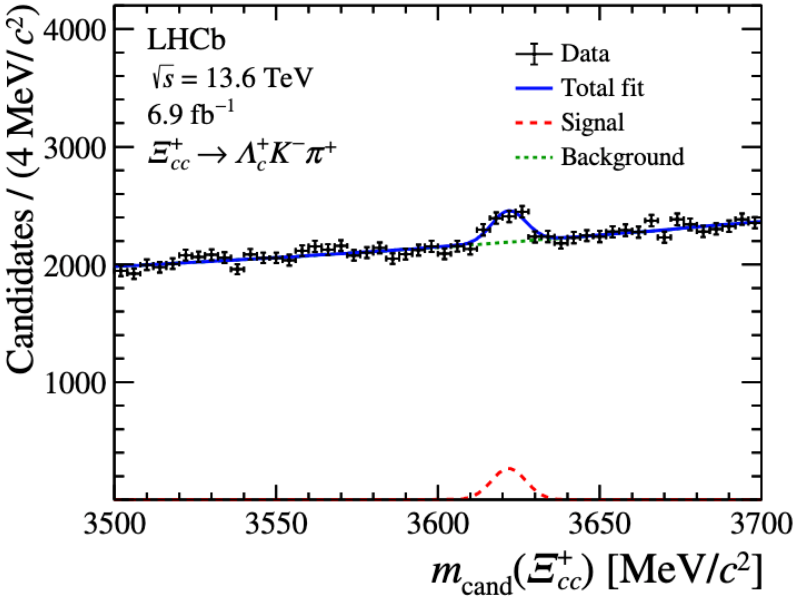
PRL 137, 021902 (2026)

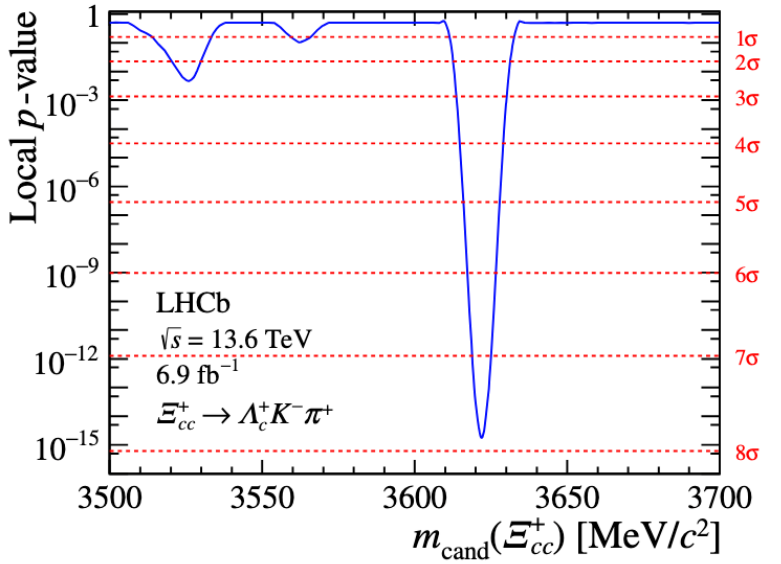
Observation of $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$

PRL 137, 021902 (2026)

- An unbinned extended maximum-likelihood fit
  - Signal model: Double sided Crystal Ball distribution
  - Background model: 2nd order polynomial
  - $N_{\mathrm{sig}} = 915 \pm 120$
  - Local significance: > 7σ
- Mass bias caused by
  - Event selection
  - Final-state photon radiation
- Corrected Ξ_{cc}^{+} mass:
  - $M(\Xi_{cc}^{+}) = 3619.97 \pm 0.83(\mathrm{stat}) \pm 0.26(\mathrm{syst})^{+1.90}_{-1.30}(\mathrm{lifetime})$ MeV
  - 100 MeV higher than the SELEX results
- Mass difference $\Delta M = M(\Xi_{cc}^{++}) - M(\Xi_{cc}^{+})$
  - $1.77 \pm 0.84(\mathrm{stat}) \pm 0.15(\mathrm{syst})^{+1.90}_{-1.30}(\mathrm{lifetime})$ MeV
  - Consistent with predicted isospin splitting

First Observation!

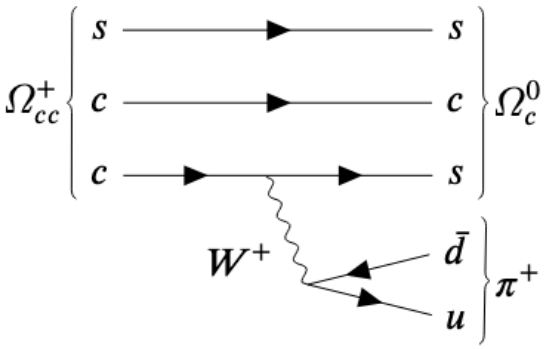


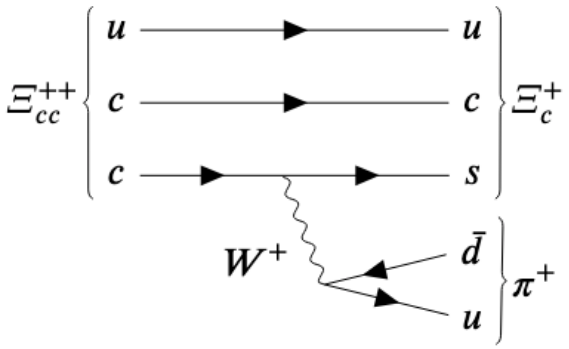


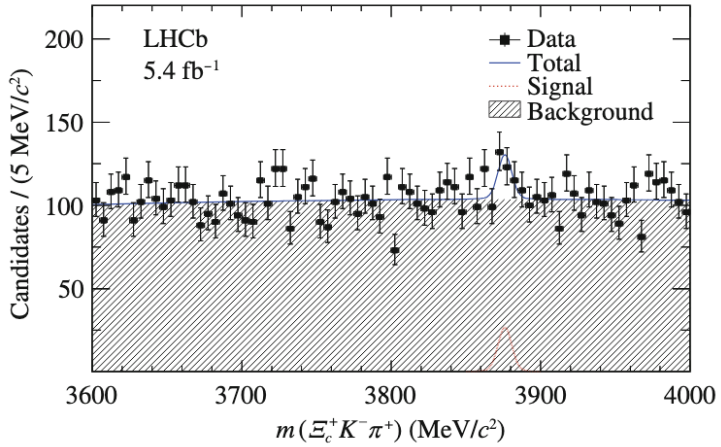
PRD96(2017)033004

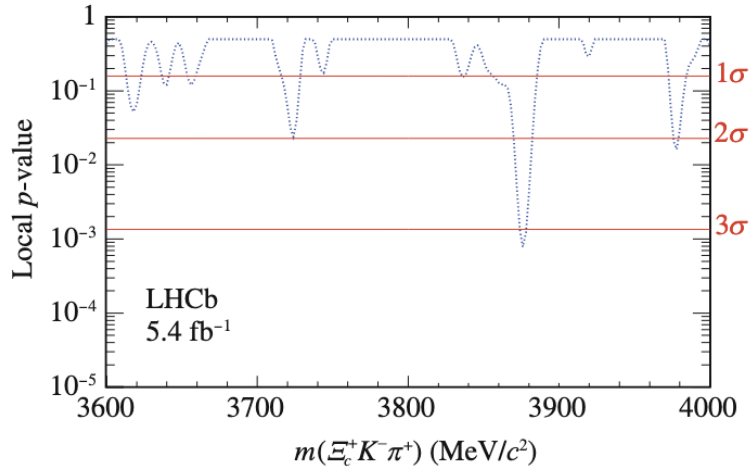
Observation of doubly charmed baryon Ω_{cc}^{+}

- About Ω_{cc}^{+}:
  - Isospin-singlet
  - Lifetime: ~160 ps
  - Predicted fragmentation fraction $\frac{\sigma(\Omega_{cc}^{+})}{\sigma(\Xi_{cc})} \sim \frac{1}{3}$
- Global significance <3σ in LHCb Run 2 data
- Target: search for Ω_{cc}^{+} via $\Omega_{cc}^{+} \to \Omega_{c}^{0}\pi^{+}$ in LHCb 2024 data
  - $\Omega_{c}^{0} \to pK^{-}K^{-}\pi^{+}$
  - Control mode: $\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+}$









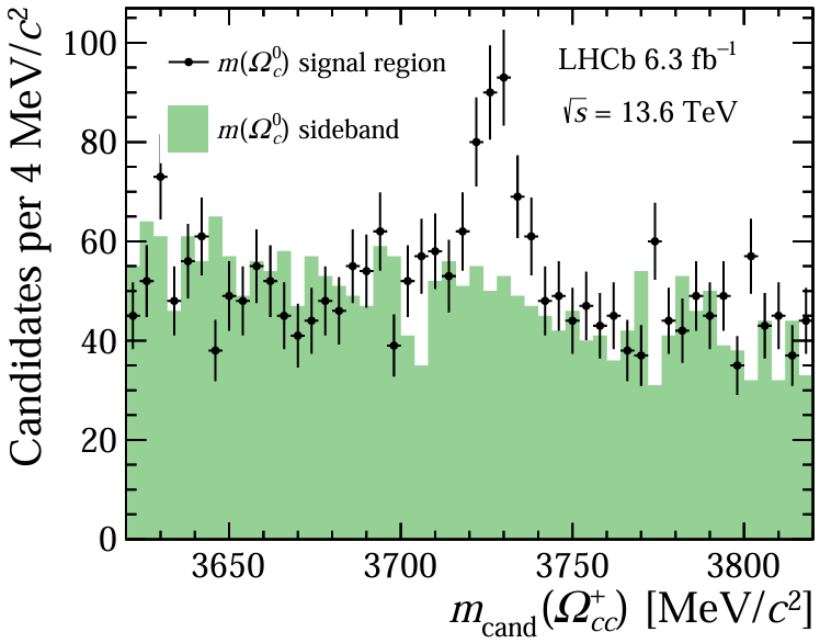
SCPMA 64 (2021), 101062

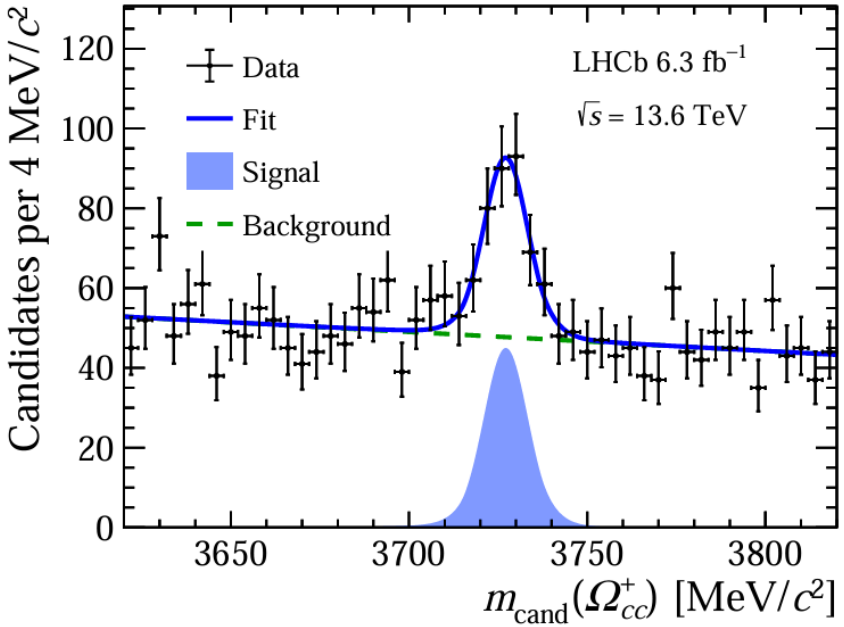
Observation of Ω_{cc}^{+} via $\Omega_{cc}^{+} \to \Omega_{c}^{0}\pi^{+}$

LHCb-PAPER-2026-022 in preparation

First Observation!

- Kinematical, topological, PID, and BDT based cuts
- Fit: signal described by a Gaussian plus a Double-sided Crystal ball
  - Global significance 8.7σ with 184 ± 24 signals
- The final part of the ground-state spin-1/2 baryon in SU(4) quark model





Observation of Ω_{cc}^{+} via $\Omega_{cc}^{+} \to \Omega_{c}^{0}\pi^{+}$

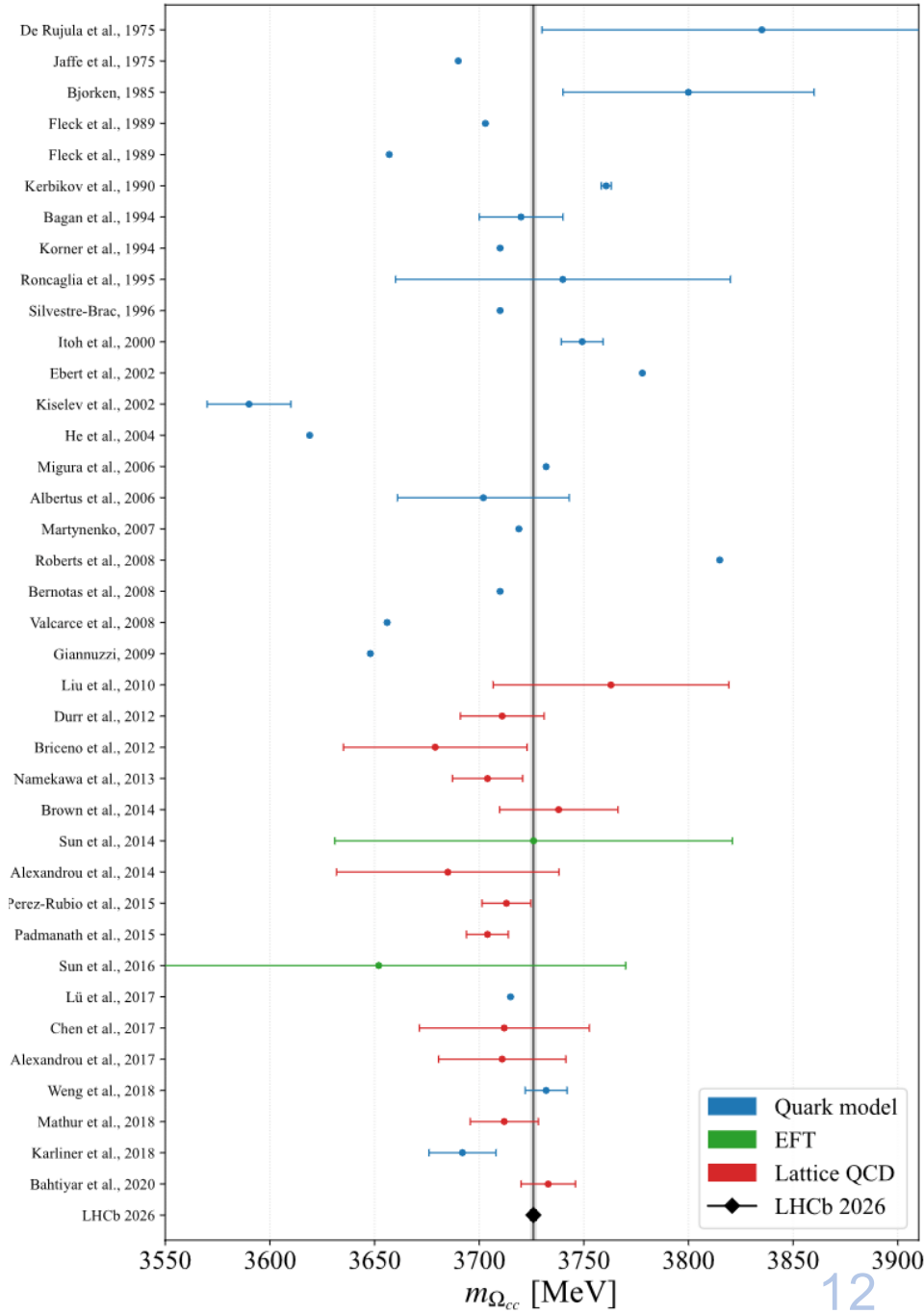
- Mass difference:$\Delta M = M(\Omega_{cc}^{+}) - M(\Xi_{cc}^{++})$
  - $104.3 \pm 1.0(\text{stat}) \pm 0.2(\text{syst}) \pm 0.4(\tau) \pm 0.5(\text{ext})\text{MeV}$
- Ω_{cc}^{+} mass:

  LHCb-PAPER-2026-022 in preparation
  - $M(\Omega_{cc}^{+}) =$
    $3725.9 \pm 1.0(\text{stat}) \pm 0.2(\text{syst}) \pm 0.4(\tau) \pm 0.6(\text{ext})\ \text{MeV}$
- The measured mass is in general compatible with lots of theoretical predictions
- Light-quark-heavy-diquark $[q][QQ]$ picture

$$M(\Omega_{cc}^{+}) - M(\Xi_{cc}) \approx 105\,\text{MeV}$$

$$M(D_{s}^{+}) - M(D) \approx 100\,\text{MeV}$$

$$M(B_{s}^{0}) - M(B) \approx 90\,\text{MeV}$$

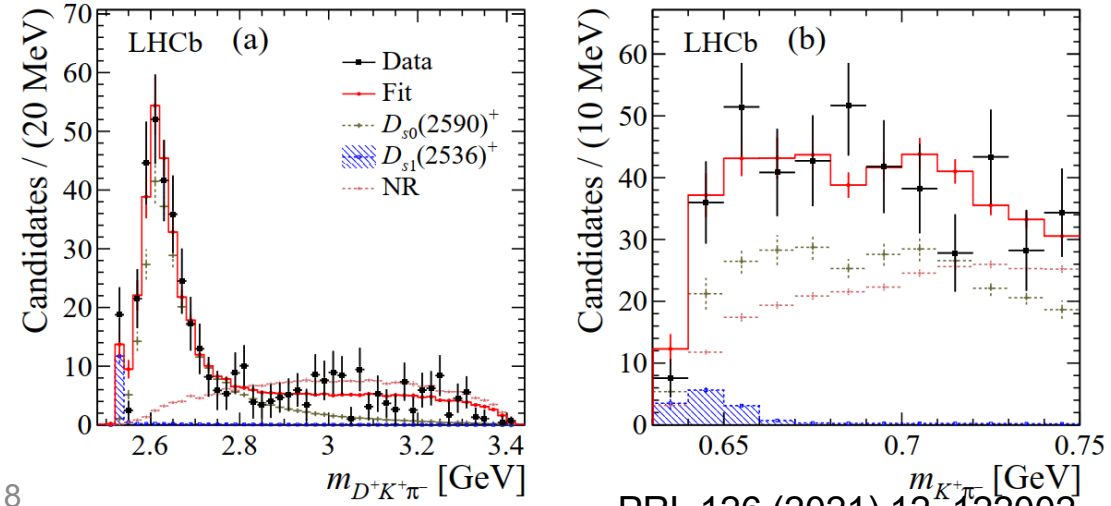


Singly heavy flavour hadrons

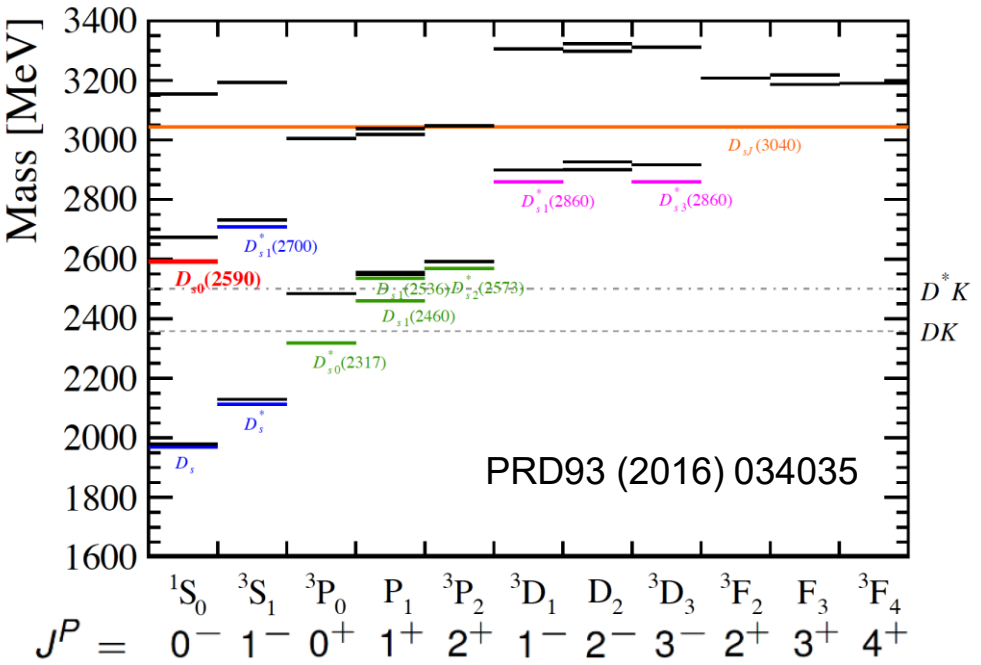
Observation of $D_{s1}(2933)^+$ in $B^+ \to D^+D^-K^+\pi^-$ decays

https://arxiv.org/abs/2604.21257

- The $D_s^{(*)+}$ spectrum is complicated:
  - Several predicted states (below 3.1GeV) haven't yet been observed
  - $D_{s0}(2317)$ and $D_{s1}(2460)$ puzzle: $D^{(*)}K$ threshold
- The D_s^{*+} search benefits from using the $D^+K^+\pi^-$ (inc. D^+K^{*0}) final state
  - can access both natural $(0^+, 1^-, ...)$ and unnatural $(0^-, 1^+, ...)$ J^P configurations
  - No π^0 or γ, benefit from good PID of charged tracks
- Previous study ($m_{K^+\pi^-} < 0.75$ GeV):
  - $D_{s0}(2590)^+$ $J^P = 0^-$ observed $m_R = 2591 \pm 6 \pm 7$ MeV, $\Gamma_R = 89 \pm 16 \pm 12$ MeV



PRL 126 (2021) 12, 122002

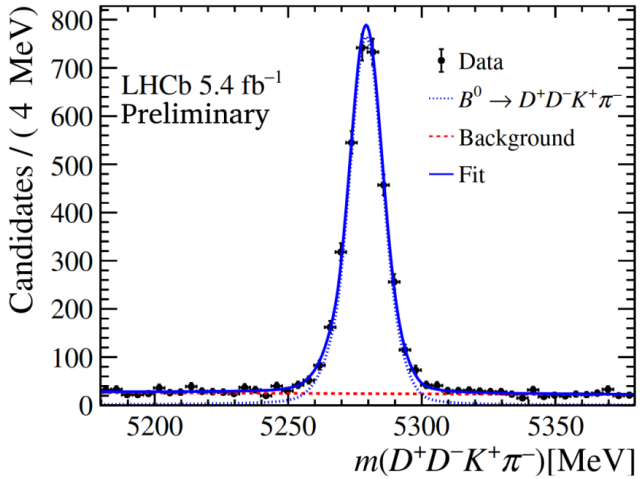


spectrum of $c\bar{s}$ mesons

Observation of $D_{s1}(2933)^+$ in $B^+ \to D^+D^-K^+\pi^-$ decays

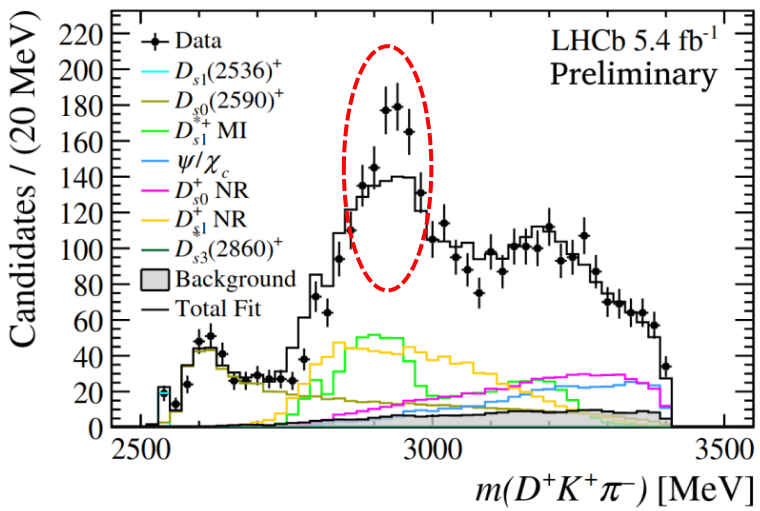
https://arxiv.org/abs/2604.21257

- This study: same dataset but full phase space region (no cut on $m_{K\pi}$)
  - Full 4D amplitude analysis

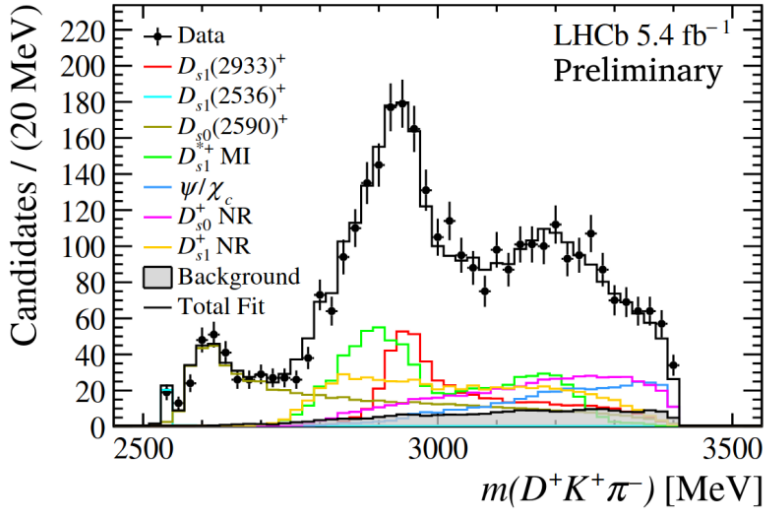


~3260 $B^{\pm}$ signal

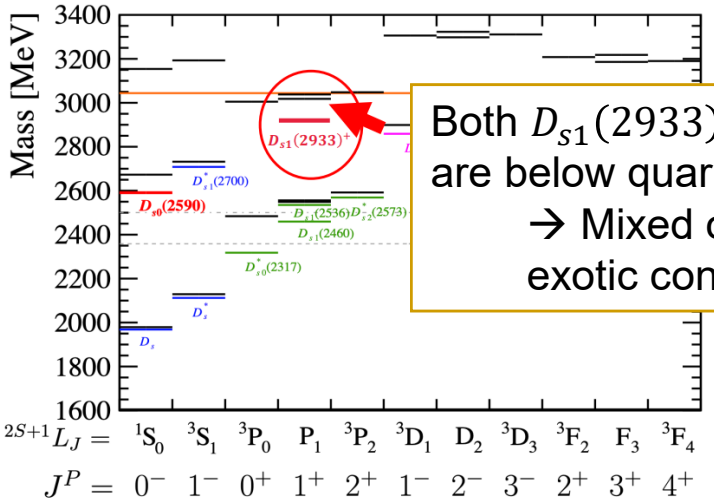
Only known K^* and D_s^* and ψ/χ_c do not correctly describe the data



Add a new state $D_{s1}(2933)^+$



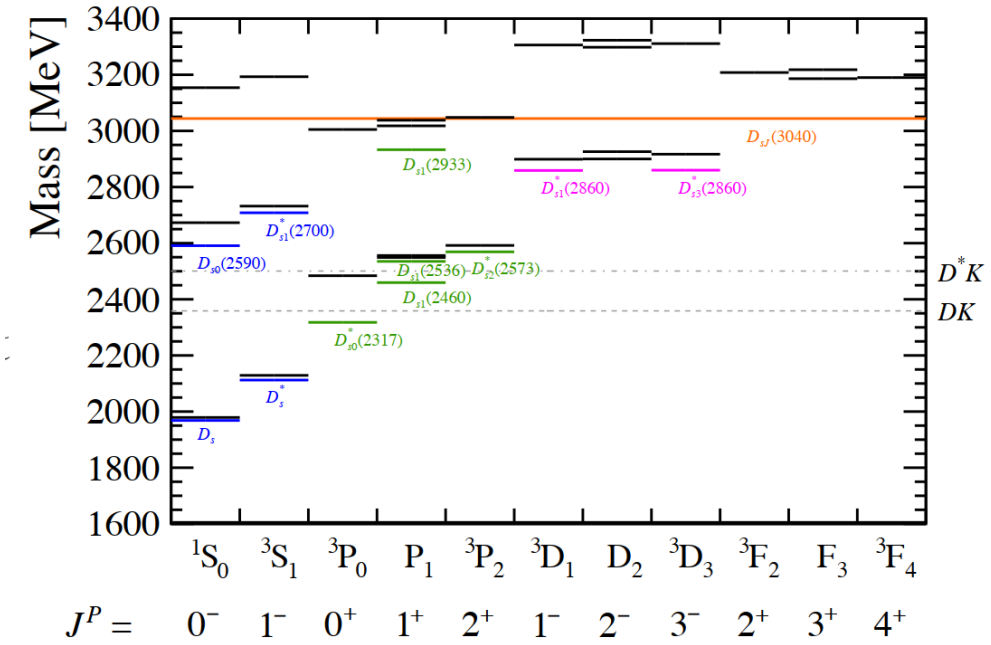
- About the new $D_{s1}(2933)^+$ state:
  - $m = 2933^{+6}_{-5}(\text{stat})^{+4}_{-3}(\text{syst})$ MeV
  - $\Gamma = 72^{+18}_{-12}(\text{stat})^{+7}_{-10}(\text{syst})$ MeV
  - Significance > 10σ
  - $J^P = 1^+$ preferred by 5σ
  - Candidate for the conventional $D_s(2P')$ state
- $D_{s0}(2590)^+$mass and width consistent with previous measurements



Both $D_{s1}(2933)^+$ and $D_{s0}(2590)^+$ are below quark-model prediction
→ Mixed of conventional and exotic contribution?

Search for the counterpart of $D_{s0}(2317)^+$ in the excited B_s-meson spectrum

- Let's go back to the D_s spectrum, the P-wave states
  - $j_q = \frac{3}{2}$ doublet $(1^+, 2^+)$ $D_{s1}(2536)$ and $D_{s2}(2573)$ ➔ consistent with HQET prediction
  - $j_q = \frac{1}{2}$ doublet $(0^+, 1^+)$ $D_{s0}(2317)$ and $D_{s1}(2460)$
    - ➔ masses are much lower than HQET calculation
    - ➔ mass difference $140\,\mathrm{MeV} \simeq M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)} \neq M_{D^*_{s2}(2573)} - M_{D_{s1}(2536)} \simeq 40\,\mathrm{MeV}$



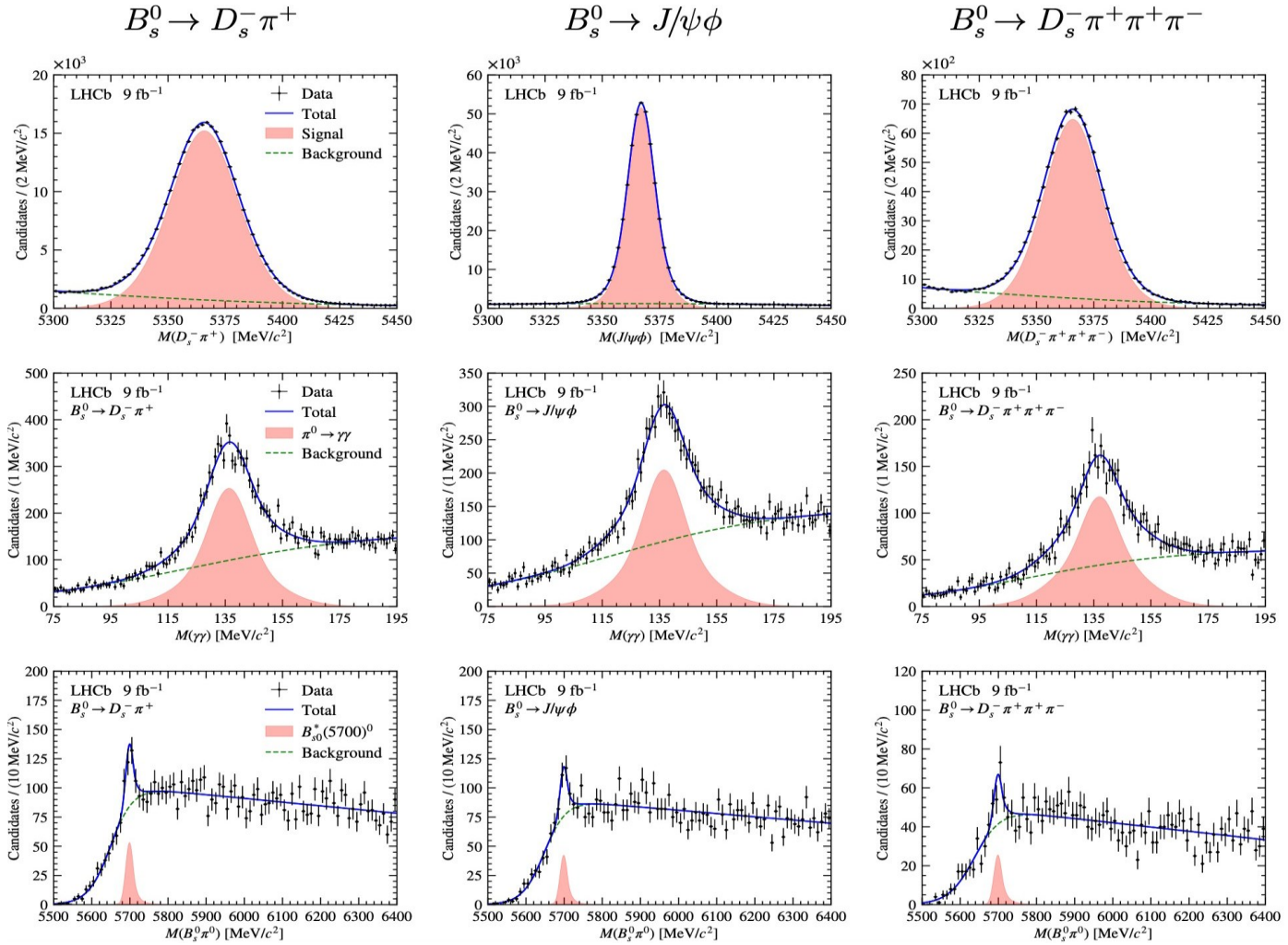
In $b\bar{s}$ system:

- $j_q = \frac{3}{2}$ doublet $(1^+, 2^+)$: candidates are $B_{s1}(5830)$ and $B^*_{s2}(5840)$
- $j_q = \frac{1}{2}$ double $(0^+, 1^+)$: not yet observed

Discovery of an unexpectedly light narrow beauty-strange state $B^*_{s0}(5700)^0$

- LHCb Run1&Run2 dataset
- Building the $B^0_s\pi^0$ invariant mass via three different B^0_s decays
- π^0s are reconstructed via $\gamma\gamma$
- Two BDTs are trained and applied.
- Kinematic refits applied to improve the mass resolution.
- Clear peaking structure is seen in all three decay channels
  - No peaks are seen in event-mixing samples

LHCb-PAPER-2026-021 in preparation



Discovery of an unexpectedly light narrow beauty-strange state $B_{s0}^{*}\,(5700)^{0}$

- Signal model is a S-wave Breit-Wigner with shared parameters convolved with channel-dependent resolution function
- Simultaneous fit to all 3 B_s^0 channels:

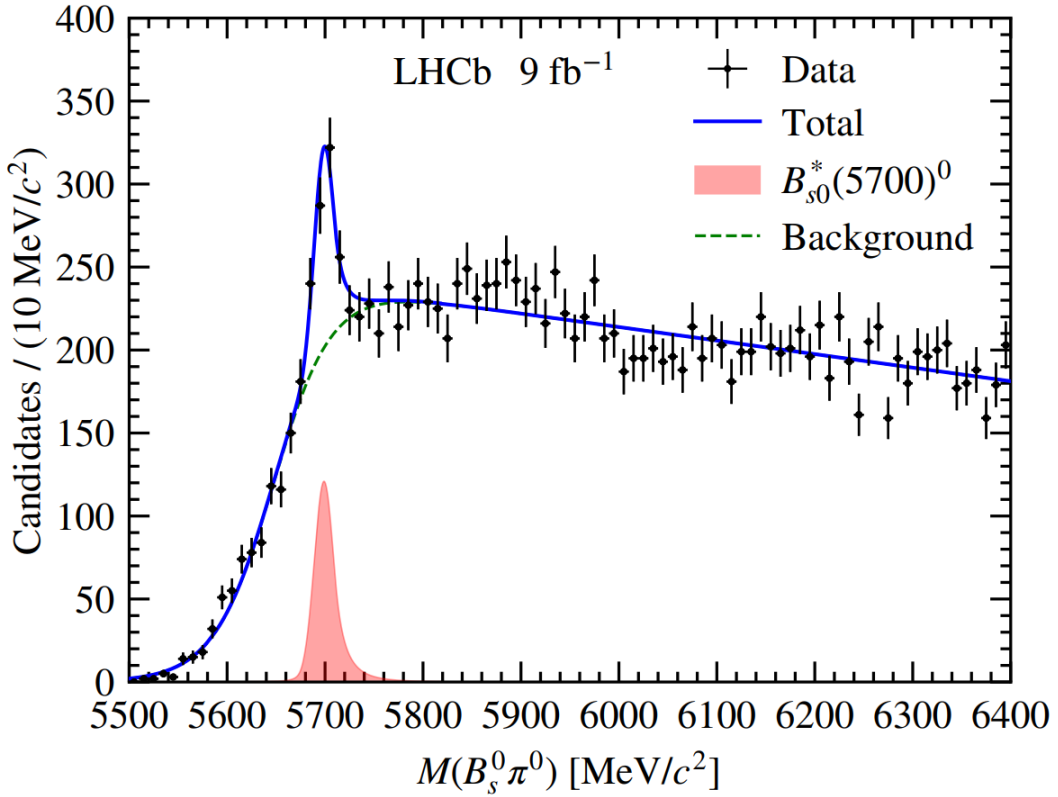
$$m = 5698.9 \pm 1.5 \pm 0.6 \pm 0.1\ \text{MeV}$$

$$\Gamma < 9.8\ (11.8)\ \text{MeV}\ at\ 90\ (95)\ \%\ CL$$

- Mass ~130 MeV below quark model prediction
- $m(B_{s0}^{*}(5700)^{0}) - m(B_{s0}) = 332.0 \pm 1.5 \pm 0.6$ MeV
  - Consistent with predictions from chiral doubling theory and with mass splitting in the charm sector $D_{s0}(2317)^{+}$
- Mass, width, and decay mode also consistent with the state being the first single-beauty hadron molecule
- Also compatible with feed-down from a new $B_{s1}^{\prime 0} \rightarrow (B_{s0}^{*0} \rightarrow B_s^0\gamma)\pi^0$, which provides equivalent experimental support

LHCb-PAPER-2026-021 in preparation

First Observation!



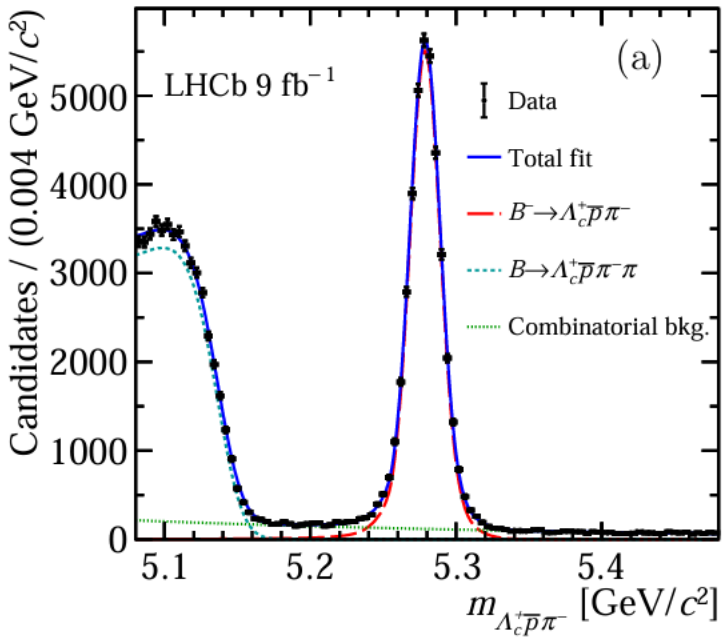
Observation of new excited Σ_c^0 states in the $B^- \to \Lambda_c^+ \bar{p} \pi^-$ decay

arXiv:2607.10595

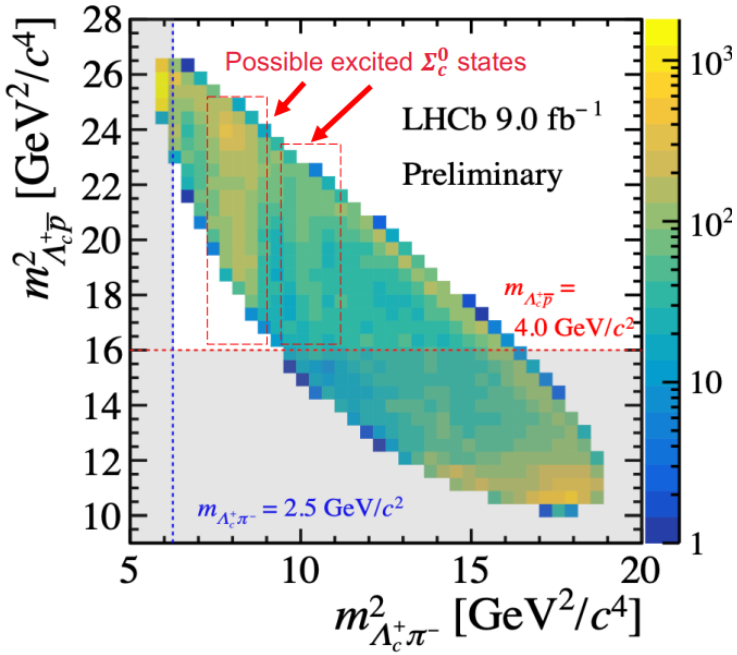
- Excited charmed baryons:
  - $\Sigma_c^0(2800)$ reported by Belle and BABAR is inconsistent
    PRL94 (2005) 122002, PRD 78 112003

Fit Parameter	BaBar	Belle
m_R (GeV/c^2)	2.846 ± 0.008	$2.802^{+0.004}_{-0.007}$
Γ_R (MeV)	86^{+33}_{-22}	61^{+28}_{-18}

- This work: search for Σ_c^0 in the $\Lambda_c^+\pi^-$ system of the $B^- \to \Lambda_c^+ \bar{p}\pi^-$ decay using LHCb Run 1+2 data



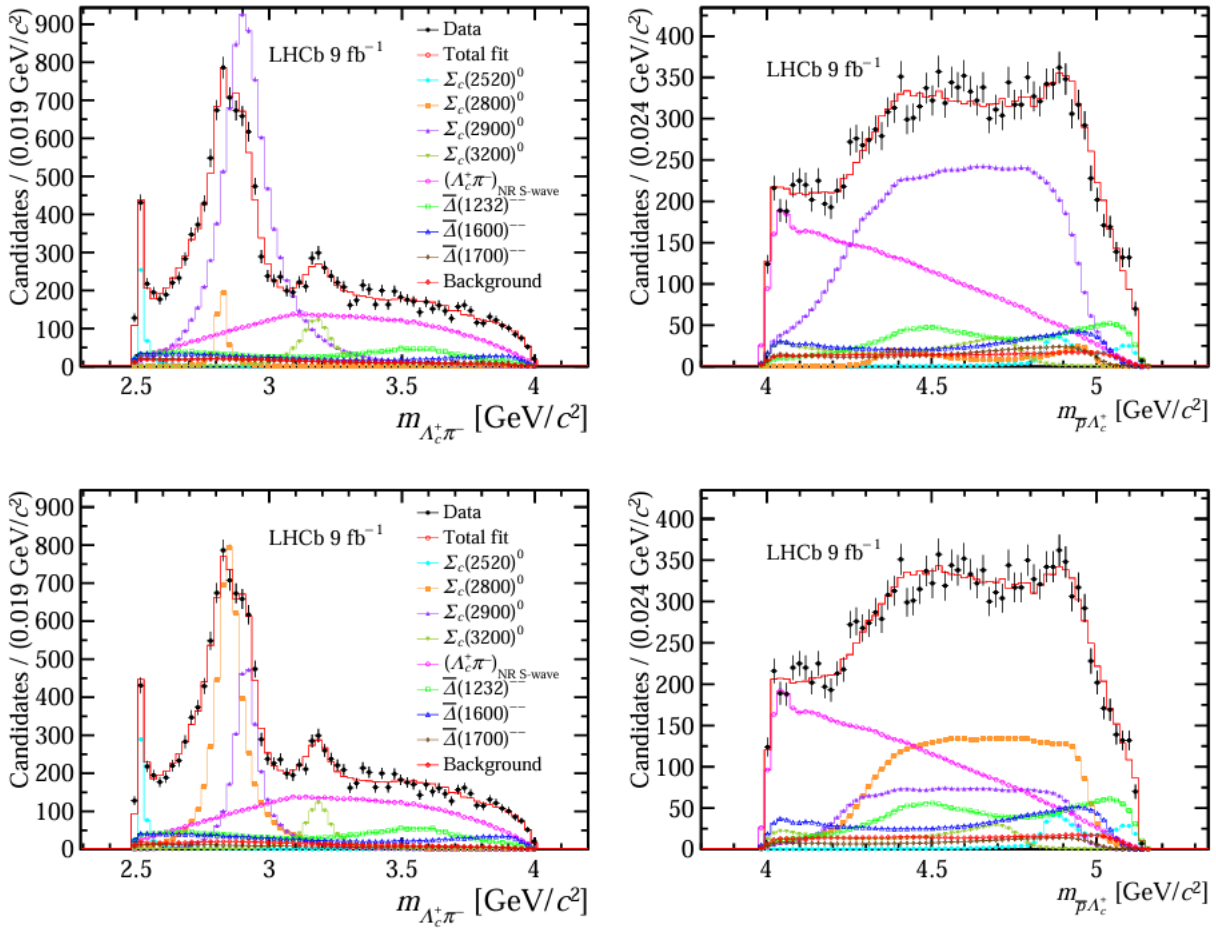
~3.7×10^4 signal



Data in red dashed square:
Used in the amplitude fit

Observation of new excited Σ_c^0 states in the $B^- \to \Lambda_c^+ \bar{p} \pi^-$ decay

- In addition to $\Sigma_c(2520)^0$ and $\Sigma_c(2800)^0$, two new states $\Sigma_c^0(2900)$ and $\Sigma_c^0(3200)$ are found.
- Two solution groups show identically fit quality but exhibit significant differences.



Parameter	Group A	Group B
$m_{\Sigma_c(2800)^0}$ [GeV/c^2]	$2.819 \pm 0.006 \pm 0.002$	$2.848 \pm 0.004 \pm 0.006$
$\Gamma_{\Sigma_c(2800)^0}$ [GeV]	$0.033 \pm 0.007 \pm 0.008$	$0.099 \pm 0.007 \pm 0.021$
$m_{\Sigma_c(2900)^0}$ [GeV/c^2]	$2.908 \pm 0.005 \pm 0.009$	$2.914 \pm 0.003 \pm 0.008$
$\Gamma_{\Sigma_c(2900)^0}$ [GeV]	$0.175 \pm 0.008 \pm 0.023$	$0.092 \pm 0.006 \pm 0.023$
$m_{\Sigma_c(3200)^0}$ [GeV/c^2]	$3.186 \pm 0.006 \pm 0.014$	$3.190 \pm 0.005 \pm 0.011$
$\Gamma_{\Sigma_c(3200)^0}$ [GeV]	$0.133 \pm 0.018 \pm 0.027$	$0.100 \pm 0.015 \pm 0.032$
$\mathcal{R}(\Sigma_c(2520)^0)$	$0.09 \pm 0.01 \pm 0.02$	$0.11 \pm 0.01 \pm 0.03$
$\mathcal{R}(\Sigma_c(2800)^0)$	$0.09 \pm 0.02 \pm 0.05$	$0.86 \pm 0.07 \pm 0.42$
$\mathcal{R}(\Sigma_c(2900)^0)$	$1.68 \pm 0.07 \pm 0.29$	$0.50 \pm 0.04 \pm 0.19$
$\mathcal{R}(\Sigma_c(3200)^0)$	$0.21 \pm 0.03 \pm 0.05$	$0.17 \pm 0.03 \pm 0.05$
$\mathcal{R}((\Lambda_c^+\pi^-)_{\text{NR S-wave}})$	$2.19 \pm 0.14 \pm 0.22$	$2.23 \pm 0.11 \pm 0.30$

For $\Sigma_c(2800)^0$:

- Solution A consistent with the Belle
- Solution B consistent with the BABAR

➔ Need further investigation!

arXiv:2607.10595

Summary and prospects

- Remarkable recent progress at LHCb in conventional hadron spectroscopy
- Run 3 high statistics open new possibilities
  - Search for Ξ_{bc}, …
  - Search for more decay modes of $\Xi_{cc}^{+(+)}$ and Ω_{cc}^{+}
  - Search for $B_{s1}^{\prime 0} \rightarrow B_s^0 \pi^+ \pi^-$, and similar processes
  - Measure the decay properties or lifetime of Ξ_{cc}/Ω_{cc}
  - ……
- Deep collaboration between theorists and experimentalists is essential to fully interpret these states.

Thanks for your listening!

Backup

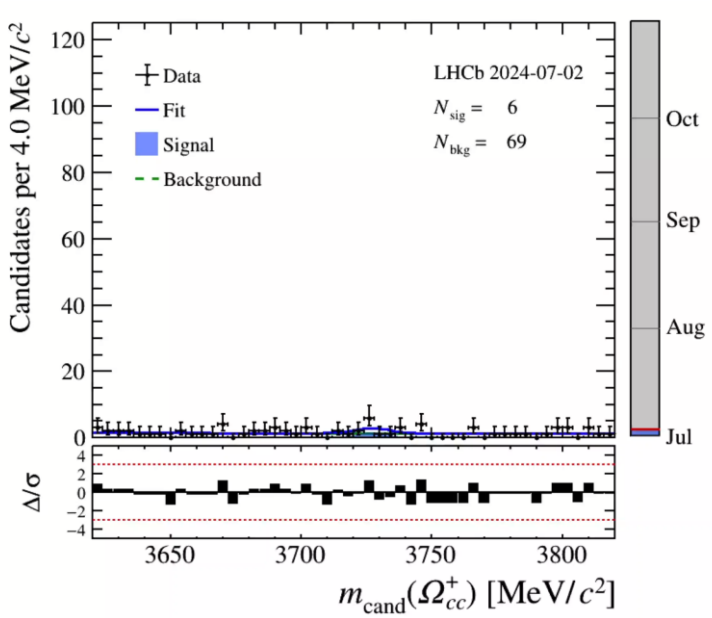
$B_{s0}^{*}(5700)^{0}$: Compare with theories

Table 1: Masses of the excited B_{s0}^{*0} and $B_{s1}^{\prime 0}$ from several theoretical works and lattice QCD.

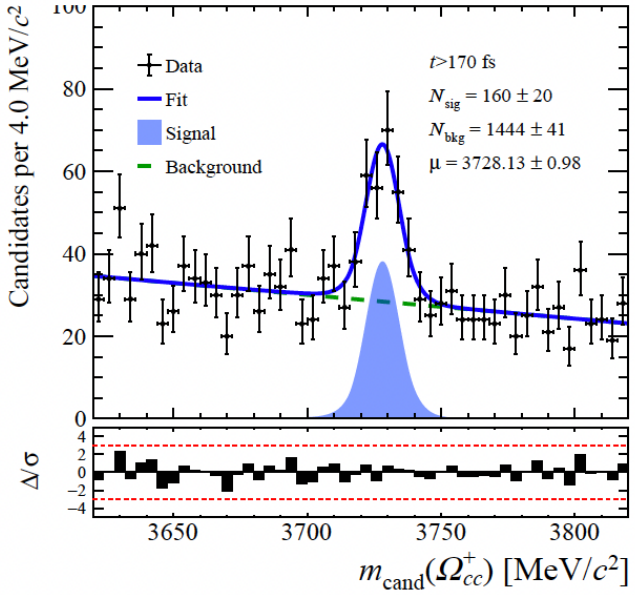
	Mass [MeV]	
	B_{s0}^{*0}	$B_{s1}^{\prime 0}$
rel. quark model [2]	5804	5842
rel. quark model [14]	5833	5865
rel. quark model [15]	5830	5858
nonrel. quark model [16]	5788	5810
quark model (KKMT) [17]	5719	5765
LO $\chi - SU(3)$ [18]	5643	5690
Bardeen, Eichten, Hill [19]	5718 ± 35	5765 ± 35
LO UChPT [20, 21]	5725 ± 39	5778 ± 7
NLO UHMChPT [22]	$5696 \pm 20 \pm 30$	$5742 \pm 20 \pm 30$
NLO UHMChPT [23]	5720^{+16}_{-23}	5772^{+15}_{-21}
HQET + ChPT [24]	5706.6 ± 1.2	5765.6 ± 1.2
Covariant ChPT [25]	5726 ± 28	5778 ± 26
local hidden gauge [26]	$5475.4 \sim 5457.5$	$5671.2 \sim 5663.6$
heavy meson chiral unitary [27]	5709 ± 8	5755 ± 8
lattice QCD [28]	$5752 \pm 16 \pm 5 \pm 25$	$5806 \pm 15 \pm 5 \pm 25$
lattice QCD [29]	$5713 \pm 11 \pm 19$	$5750 \pm 17 \pm 19$
Rel. quark model + Lattice [30]	$5730.2^{+2.4}_{-1.5}$	$5769.6^{+2.4}_{-1.6}$

Ω_{cc}^{+}: Consistency and cross-checks

- Mass-peak position is stable with data-taking time
- An additional requirement of $t > 170$ fs, corresponding to $3\sigma(\tau_{\Omega_{cc}^{+}})$, is applied to the signal candidates
  - ➢ Confirms the weakly-decaying nature of the observed signal



$\Omega_{cc}^{+} \to \Omega_c^0 \pi^+$

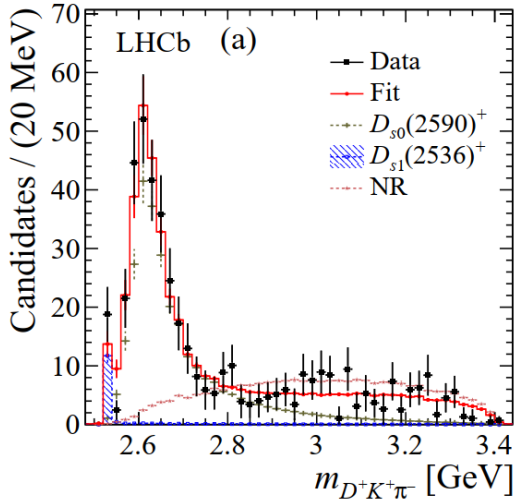


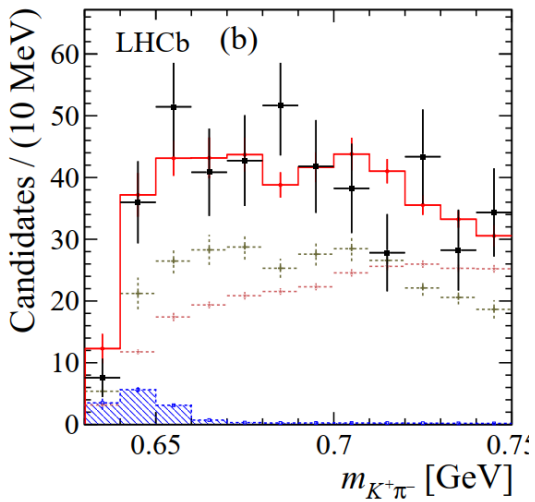
$t > 170$ fs

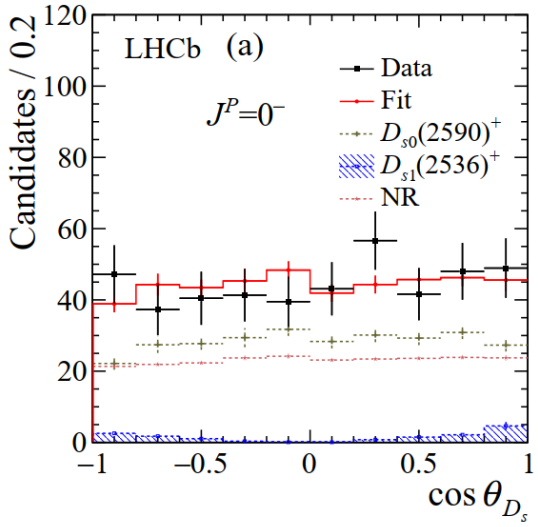
Study of the $B^0 \to D^+D^-K^+\pi^-$ decay (previous)

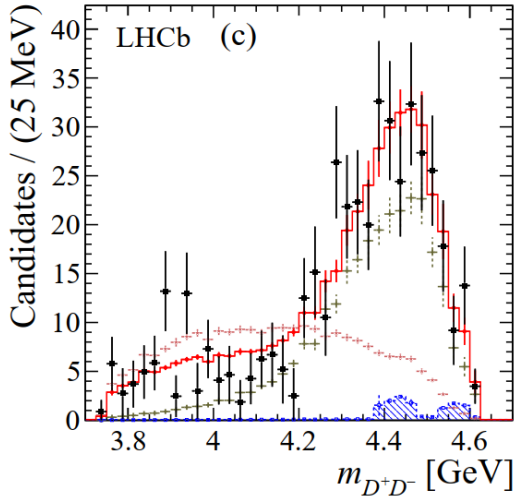
- Fit results

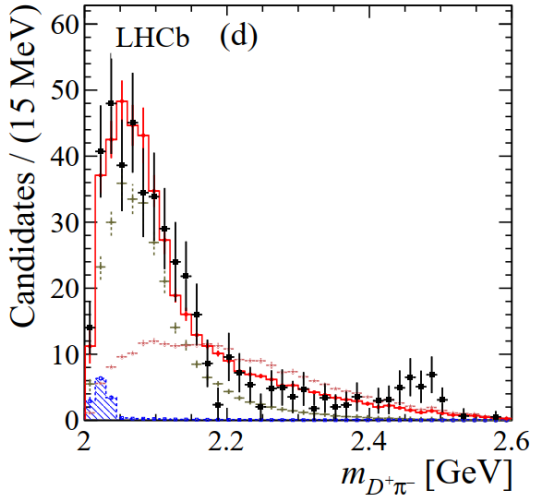
PRL 126 (2021) 12, 122002











- Systematics

Source	m_R [MeV]	Γ_R [MeV]
$D_{s0}(2590)^+$ width model	6.1	8.0
$D_{s1}(2536)^+$ mass shape	0.3	4.3
$K^+\pi^-$ mass shape	2.7	2.6
Blatt-Weisskopf factor	0.7	3.4
Including $c\bar{c}$ resonances	1.1	5.4
$D^+\pi^-$ resonance veto	2.4	2.1
Simulation correction	0.2	1.1
Momentum calibration	0.5	0.4
Total	7.2	11.7

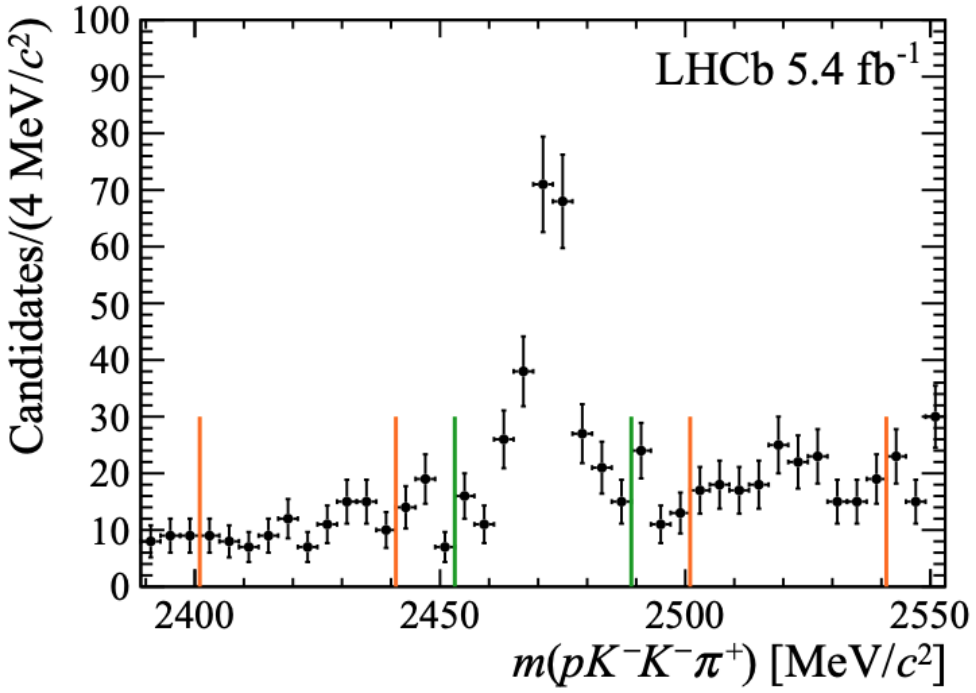
- $m_R = 2591 \pm 6 \pm 7$ MeV
- $\Gamma_R = 89 \pm 16 \pm 12$ MeV
- $J^P = 0^-$
- While 1^+ and 2^- are rejected by >10σ

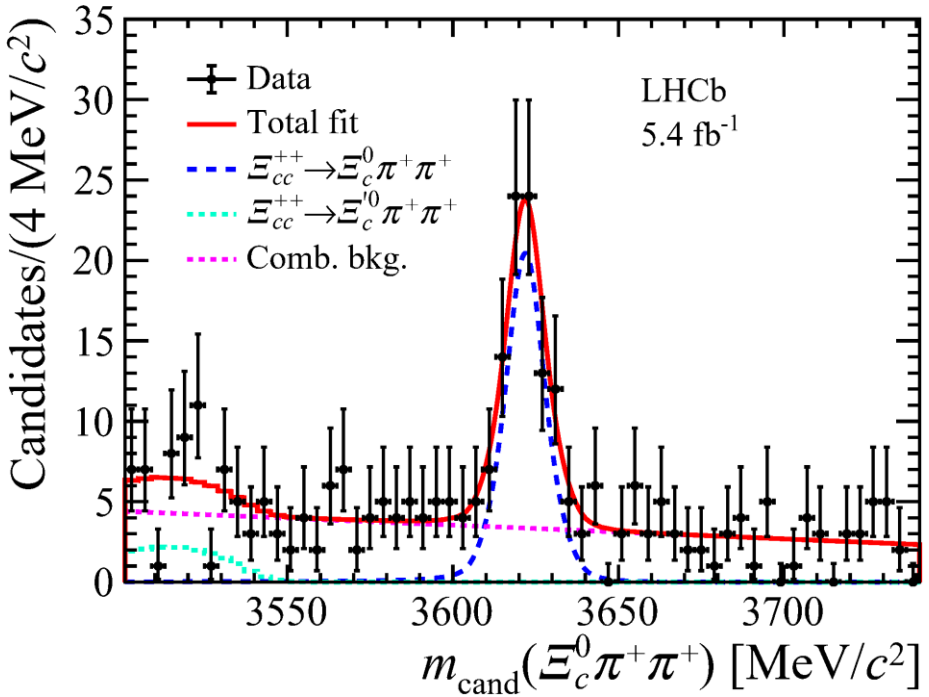
	Fit fraction ($\times 10^{-2}$)
$D_{s0}(2590)^+$	63 ± 9 (stat) ± 9 (syst)
$D_{s1}(2536)^+$	3.9 ± 1.4 (stat) ± 0.8 (syst)
NR	51 ± 11 (stat) ± 19 (syst)
D_{s0}^+–NR	-18 ± 18 (stat) ± 24 (syst)
D_{s1}^+/D_{s0}^+	6.1 ± 2.4 (stat) ± 1.4 (syst)

Observation of the decay $\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+$

arXiv:2504.05063,
Submitted to JHEP

- Measurements of additional Ξ_{cc}^{++} decay modes provide essential information to better understand the decay dynamics of doubly charmed baryons.



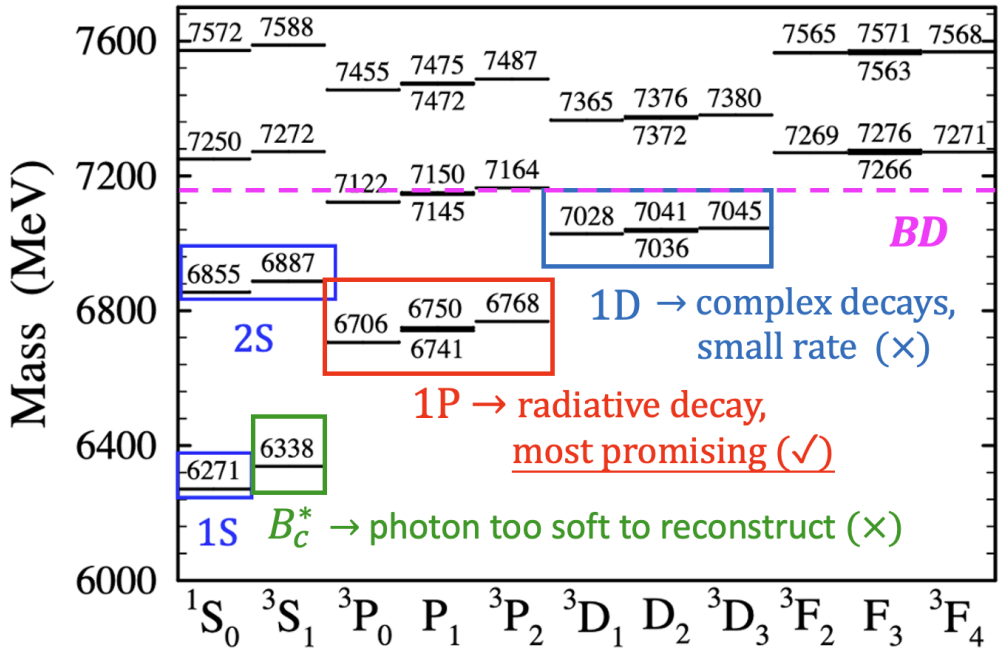


$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} = 1.37 \pm 0.18(\text{stat}) \pm 0.09(\text{syst}) \pm 0.35(\text{ext})$$

Observation of the orbitally excited B_c^+ states

- The B_c^+ meson family is the only mesons composed of two different heavy quarks $(\bar{b}c)$
- Despite its ground state, only the 2S excitations have been observed at the LHC PRL 113 (2014) 212004
- The 1P excited states are predicted to decay solely via radiative transitions
  - most likely to be the next excitations to be observed, with predicted masses in the range of $(340, 520)$ MeV
  - four states are expected, leading to six peaks due to unreconstructed photons from B_c^* decays

PRD 70 (2004) 054017



$$(L=1)\otimes(S=0,1)\begin{cases} S=0 \rightarrow & 1^1P_1 \\ S=1 \rightarrow & 1^3P_0,\ 1^3P_1,\ 1^3P_2 \end{cases}$$

mixing

Four physical states

$$1^3P_0,\ 1^3P_2 \quad \begin{pmatrix} 1P_1' \\ 1P_1 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1^1P_1 \\ 1^3P_1 \end{pmatrix}$$

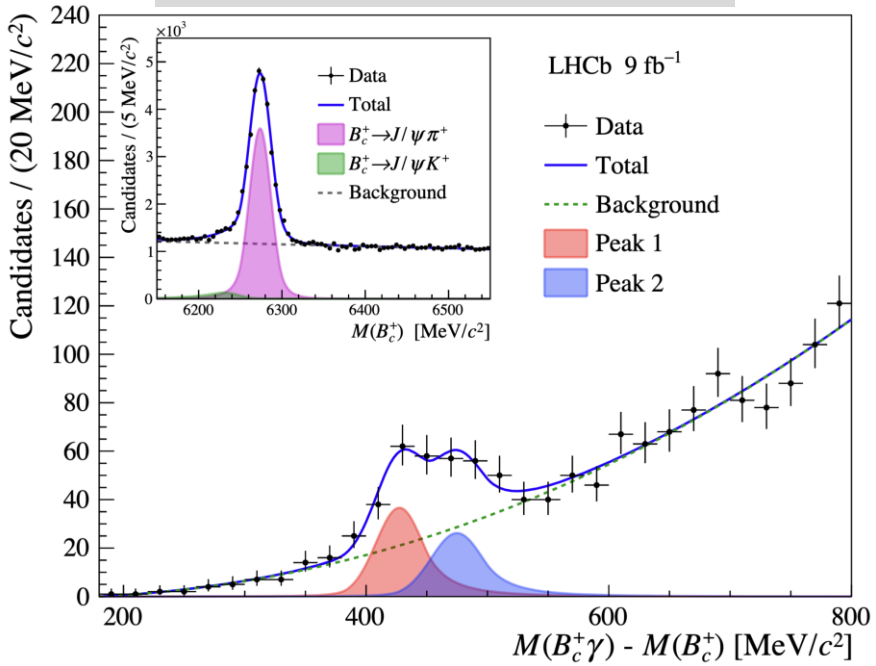
States	1^3P_0	$1P_1$	$1P_1'$	1^3P_2
Decays	$B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^+\gamma$	$B_c^+\gamma$	$B_c^{*+}(\to B_c^+\gamma)\gamma$
		$B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^{*+}(\to B_c^+\gamma)\gamma$	
#peaks	1	2	2	1

Observation of the orbitally excited B_c^+ states

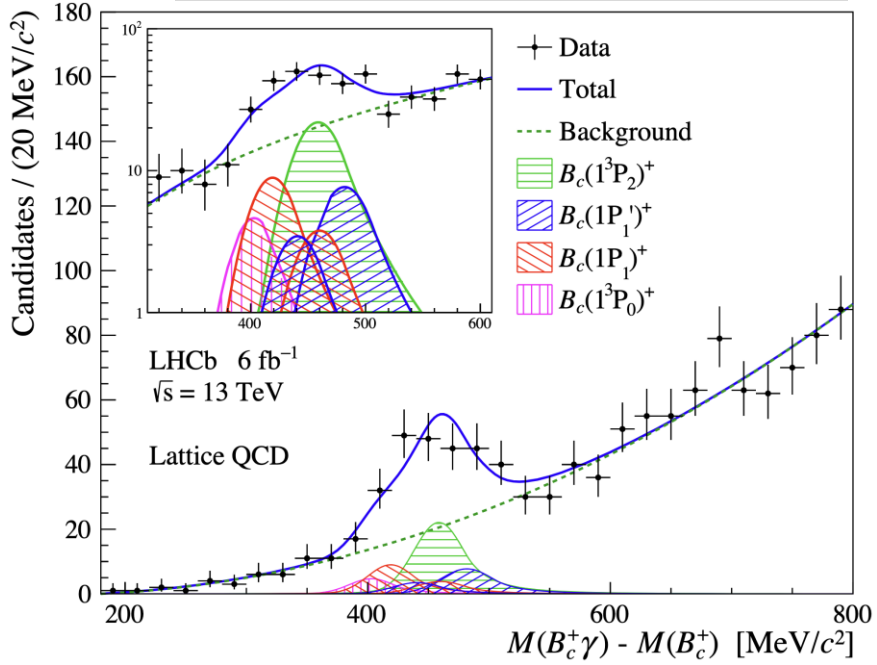
- $B_c(1P)^+ \to B_c^+\gamma$, where $B_c^+ \to J/\psi\,(\to \mu^+\mu^-)\pi^+$ and photon reconstructed from calorimeter
- A pronounced wide peaking structure is seen within the predicted mass range (significance $> 7\sigma$)
- The visible width exceed the expectation of single-peak interpretation ⇒ a minimal effective **two-peak** model used
- By fixing the peak positions and relative yields to theory, different theoretical models were investigated ⇒ all generally good
- The relative production rate, representing the fraction of B_c^+ comes from $B_c(1P)^+$ is determined using the LQCD model

$$R = \frac{N(B_c(1P)^+ \to B_c^+\gamma)}{N(B_c^+)} \cdot \frac{\varepsilon(B_c^+)}{\varepsilon(B_c(1P)^+ \to B_c^+\gamma)} = 0.20 \pm 0.03 \pm 0.02 \pm 0.03$$ (choice of theoretical models)

arXiv:2507.02149, Submitted to PRL



arXiv:2507.02142, Submitted to PRD

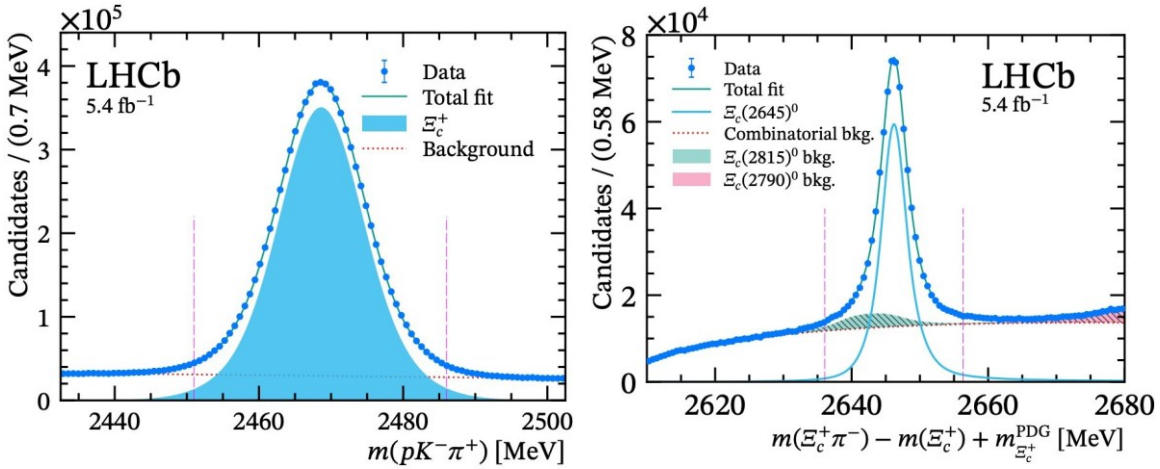


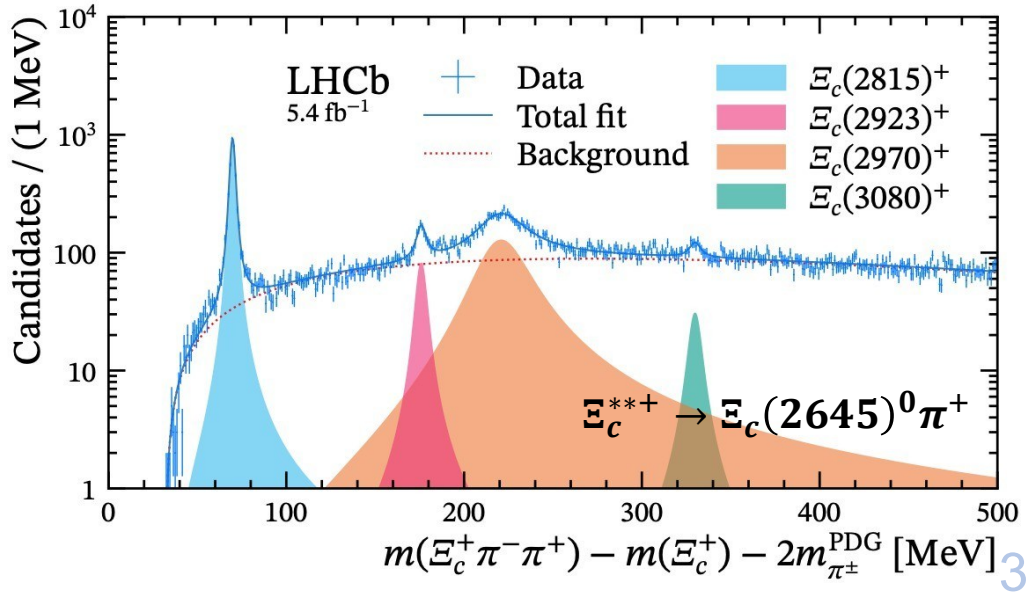
Observation of $\Xi_c(2923)^+$ decaying to $\Xi_c^+ \pi^- \pi^+$

arXiv: 2502.18987, Submitted to PRL

- Four peaks with high significance
  - $\Xi_c(2923)^+$
    - observed for the first time
  - $\Xi_c(3080)^+$
    - seen in this decay mode for the first time
  - $\Xi_c(2970)^+$ with ~30 MeV width
    - confirms different to $\Lambda_c K\pi$ peak

$$m[\Xi_c(2815)^+] = 2816.65 \pm 0.03 \pm 0.03 \pm 0.23\,\text{MeV},$$
$$\Gamma[\Xi_c(2815)^+] = 2.07 \pm 0.08 \pm 0.12\,\text{MeV},$$
$$m[\Xi_c(2923)^+] = 2922.8 \pm 0.3 \pm 0.5 \pm 0.2\,\text{MeV},$$
$$\Gamma[\Xi_c(2923)^+] = 5.3 \pm 0.9 \pm 1.4\,\text{MeV},$$
$$m[\Xi_c(2970)^+] = 2968.6 \pm 0.5 \pm 0.5 \pm 0.2\,\text{MeV},$$
$$\Gamma[\Xi_c(2970)^+] = 31.7 \pm 1.7 \pm 1.9\,\text{MeV},$$
$$m[\Xi_c(3080)^+] = 3076.8 \pm 0.7 \pm 1.3 \pm 0.2\,\text{MeV},$$
$$\Gamma[\Xi_c(3080)^+] = 6.8 \pm 2.3 \pm 0.9\,\text{MeV},$$

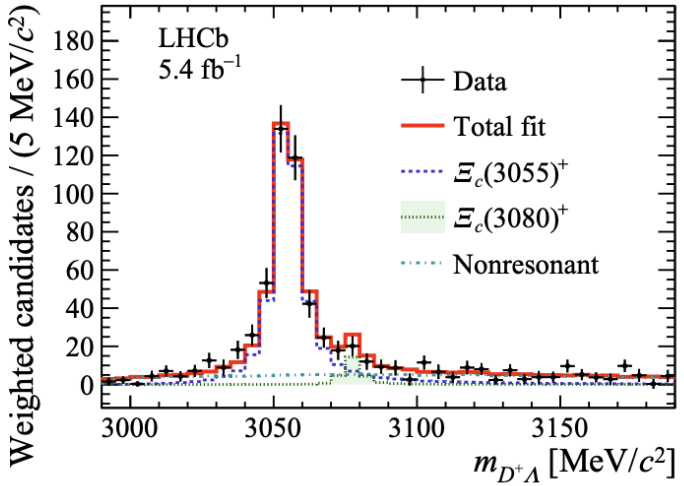


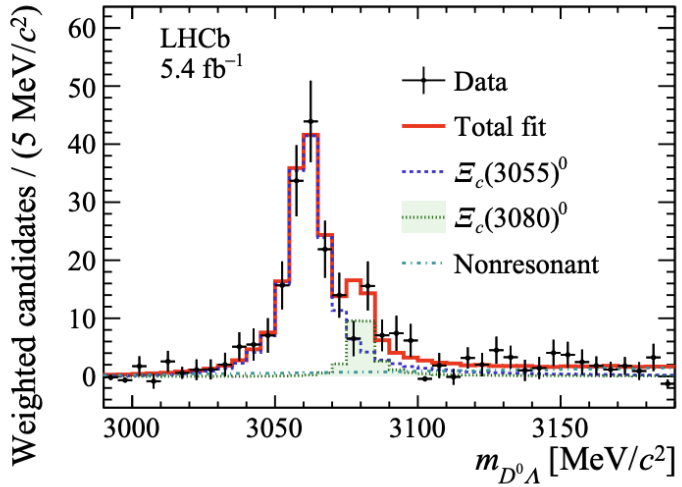


First determination of the spin-parity of $\Xi_c(3055)^{+,0}$

PRL 134 (2025) 081901

- Study $\Xi_c^{**+(0)}$ in the $\Xi_b^{0(-)} \to D^{+(0)}\Lambda\pi^+$ processes
  - Dominated by $\Xi_c(3055)^{+(0)} \to D^{+(0)}\Lambda$ contributions
  - Using LHCb Run2 dataset of 5.4 fb^{-1}
- $\Xi_c(3055)^+$ and $\Xi_c(3055)^0$ observed, first time in Ξ_b decays
- Evidence of $\Xi_c(3080)^{+(0)}$, significance $4.4(3.6)\sigma$
- Mass, width of $\Xi_c(3055)$, relative branching fraction
- $R_{\mathcal{B}} = Br\big(\Xi_c(3080)\big) \,/\, Br\big(\Xi_c(3055)\big)$ measured



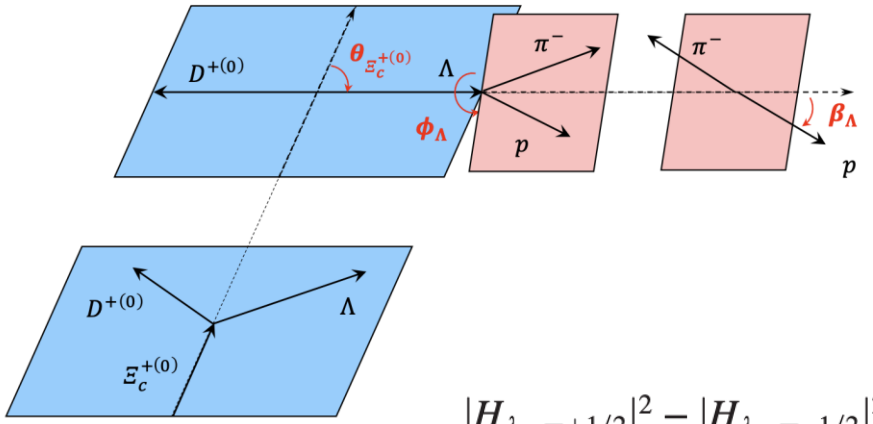


Quantity	$\Xi_c(3055)^+$	$\Xi_c(3055)^0$
m [MeV/c^2]	$3054.52 \pm 0.36 \pm 0.17$	$3061.00 \pm 0.80 \pm 0.23$
Γ [MeV/c^2]	$8.01 \pm 0.76 \pm 0.34$	$12.4 \pm 2.0 \pm 1.1$
$R_{\mathcal{B}}$	$0.045 \pm 0.023 \pm 0.006$	$0.14 \pm 0.06 \pm 0.04$

First determination of the spin-parity of $\Xi_c(3055)^{+,0}$

PRL 134 (2025) 081901

- $\Xi_b^{0(-)} \to \Xi_c^{**+(0)}(\to D\Lambda(\to p\pi))\pi^-$ amplitude analysis
  - 4-dimensional fit to $m(D\Lambda)$, helicity angles θ, β, ϕ
  - J^P of $\Xi_c(3055)^{+(0)}$ determined to be $\mathbf{3/2^+}$ for the first time
    - $6.5(3.5)\sigma$ significance w.r.t. other hypotheses
    - $5/2^+$ of $\Xi_c(3080)^{+(0)}$ also favored, but not significant
  - Decay parameter $\alpha_{\Xi_b \to \Xi_c(3055)\pi^-}$ (up-down asymmetry)
    - Consistent with maximal parity violation
    - Indicates the light quarks are spectating in $b \to c$ transition



$$\alpha \equiv \frac{|H_{\lambda_{\Xi_b^0}=+1/2}|^2 - |H_{\lambda_{\Xi_b^0}=-1/2}|^2}{|H_{\lambda_{\Xi_b^0}=+1/2}|^2 + |H_{\lambda_{\Xi_b^0}=-1/2}|^2},$$

- Identified $\Xi_c(3055)$ as the first D-wave, λ-mode excitation of the Ξ_c triplet