Search for the doubly charmed baryon Ξ_{cc}^{+} with the upgraded LHCb detector

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60^{th} Rencontres de Moriond

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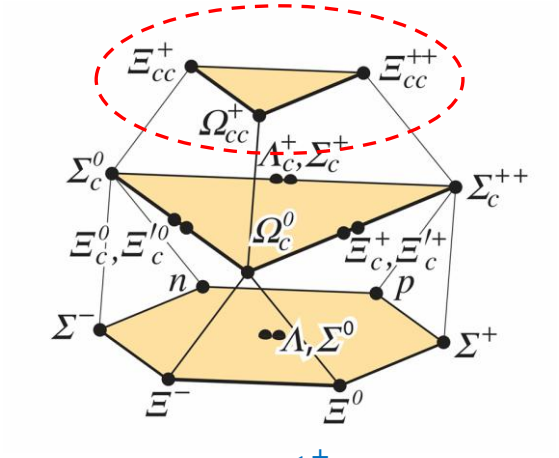
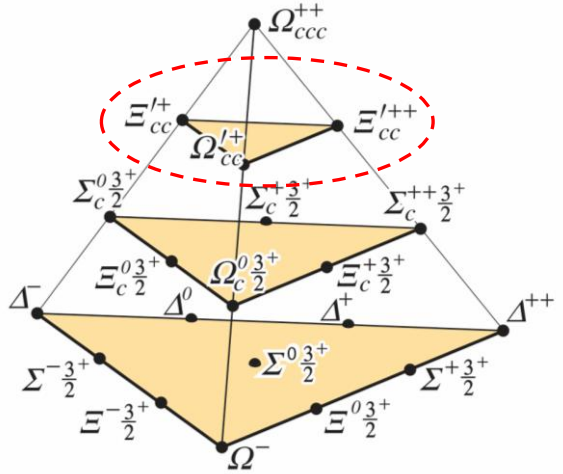
Introduction: Doubly charmed baryons

- Isospin doublet $\boldsymbol{\Xi_{cc}^{+}(ccd)}$, $\boldsymbol{\Xi_{cc}^{++}(ccu)}$ and isospin singlet $\boldsymbol{\Omega_{cc}^{+}(ccs)}$.

- Lifetime prediction: $\tau(\Xi_{cc}^{++})/\tau(\Xi_{cc}^{+}) \sim 6.7$, $\boldsymbol{\tau(\Xi_{cc}^{+}) = 45\ \mathrm{fs}}$ used in this analysis. [RBI-ThPhys-2023-9] [PhysRevD.98.113005]
- ΔM prediction: $\boldsymbol{M(\Xi_{cc}^{+}) - M(\Xi_{cc}^{++})} \in [-0.4, -2.3]\ \mathrm{MeV}/c^2$.



$J^P = \frac{1^+}{2}$

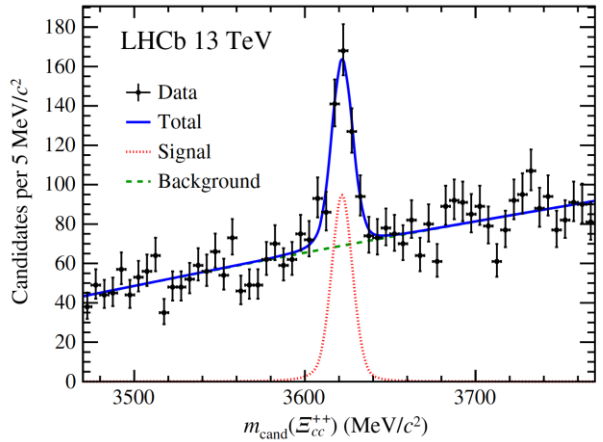


$J^P = \frac{3^+}{2}$

Introduction: Ξ_{cc}^{+}

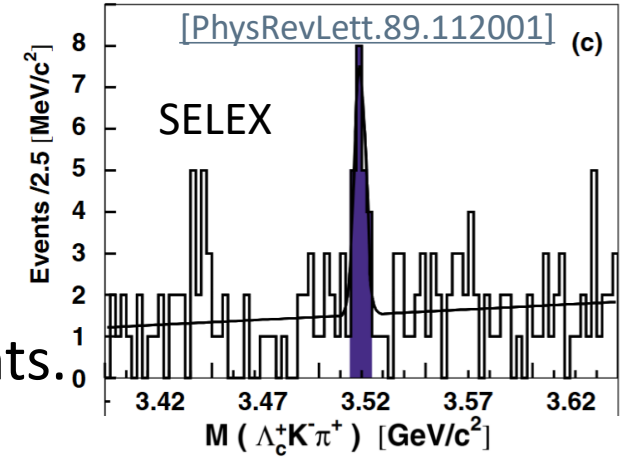
- Its isospin partner Ξ_{cc}^{++}:
  - Observed with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ in 2017.
  - $M(\Xi_{cc}^{++}) = 3621.55 \pm 0.23\ (\text{stat}) \pm 0.30\ (\text{syst})\ \text{MeV}/c^2$ [JHEP 02 (2020) 049]
  - $\tau(\Xi_{cc}^{++}) = 256^{+24}_{-22}(\text{stat}) \pm 14\ (\text{syst})\ \text{fs}$ [PhysRevLett.121.052002]

[PhysRevLett.119.112001]



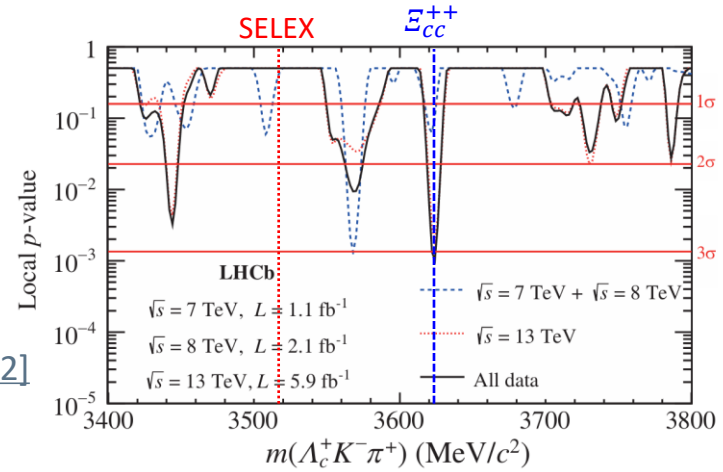
- Previous search for Ξ_{cc}^{+}:
  - SELEX: $3518.7 \pm 1.7\ \text{MeV}/c^2$
    Not confirmed by other experiments.

[PhysRevLett.89.112001]



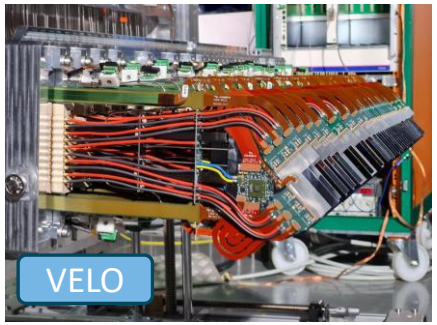
  - LHCb: $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ full Run 1 + Run 2 data ($\mathcal{L} = 9.0\ \text{fb}^{-1}$).
    3.0σ local significance near observed Ξ_{cc}^{++} mass peak.

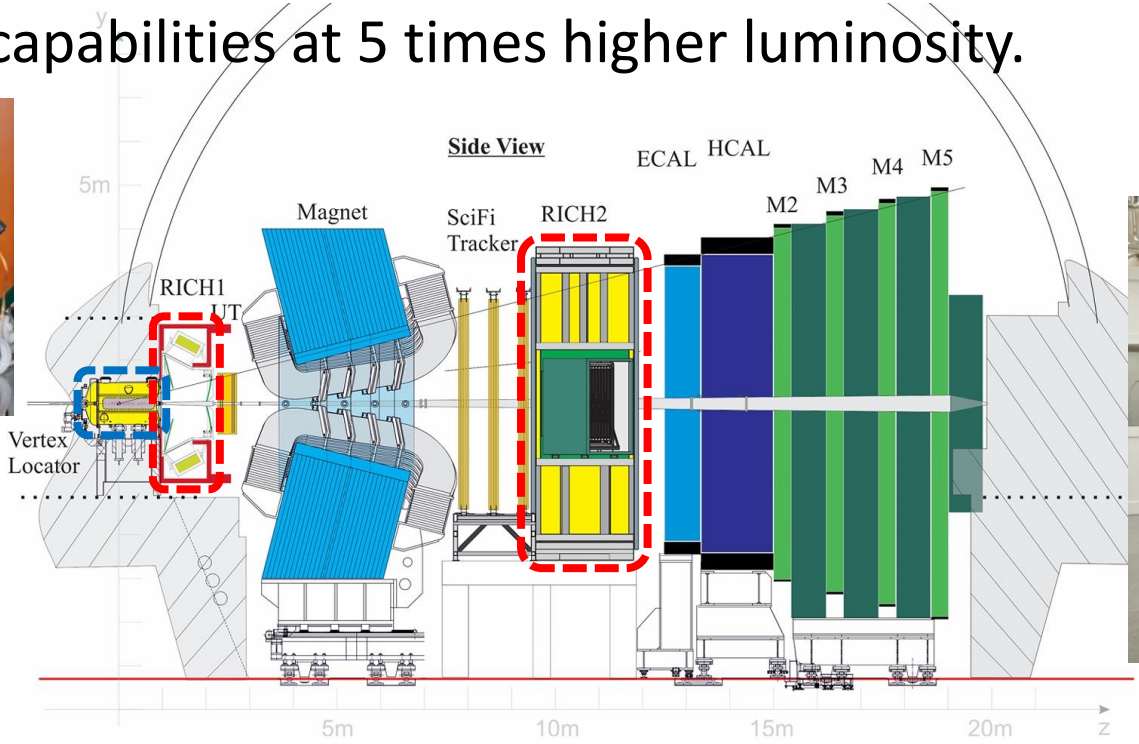
[SCPMA 63(2020) 221062]



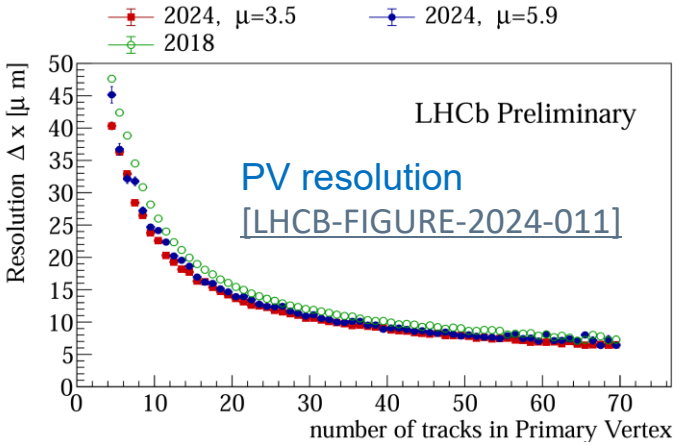
Upgraded LHCb detector

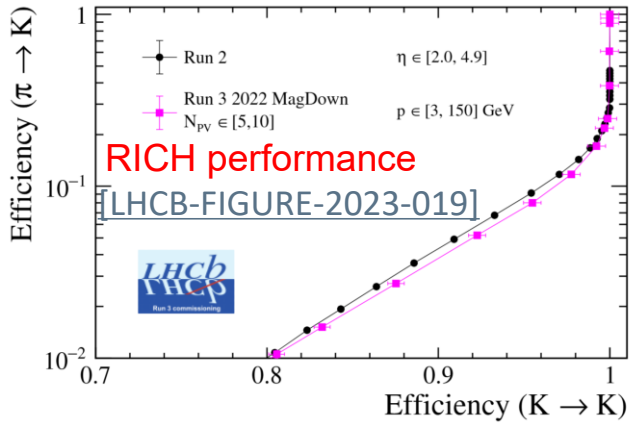
- LHCb Upgrade I: changed 90% of the sensitive detector elements.
- Vertex Locator: new silicon-pixel detector
  - Identify hadrons containing b/c from characteristically long flight distances.
- Ring-imaging Cherenkov detectors: new optics and photon detectors
  - Good discrimination of charged hadron.
- Enhanced capabilities at 5 times higher luminosity.

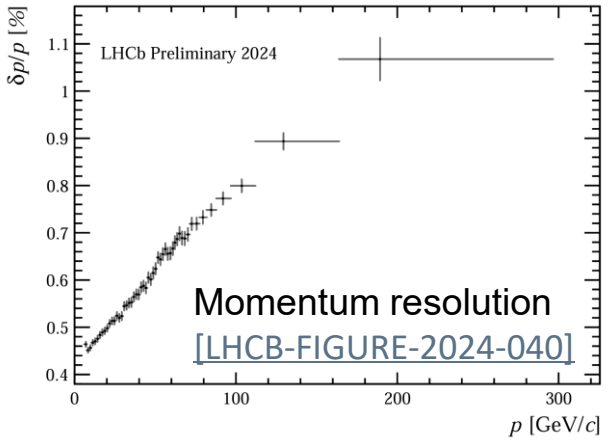




[LHCb-DP-2022-002]

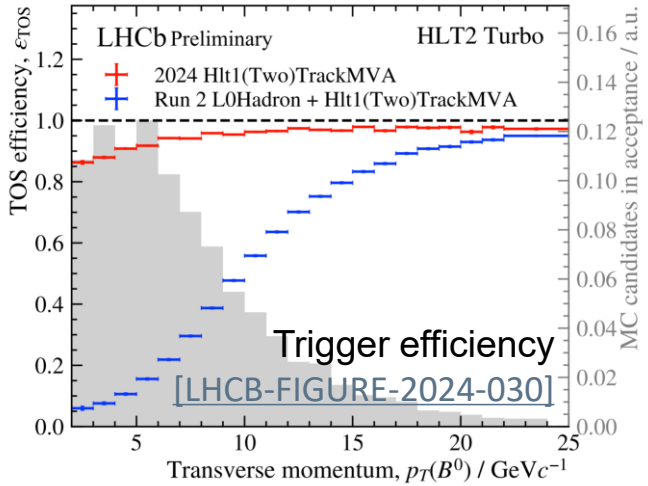






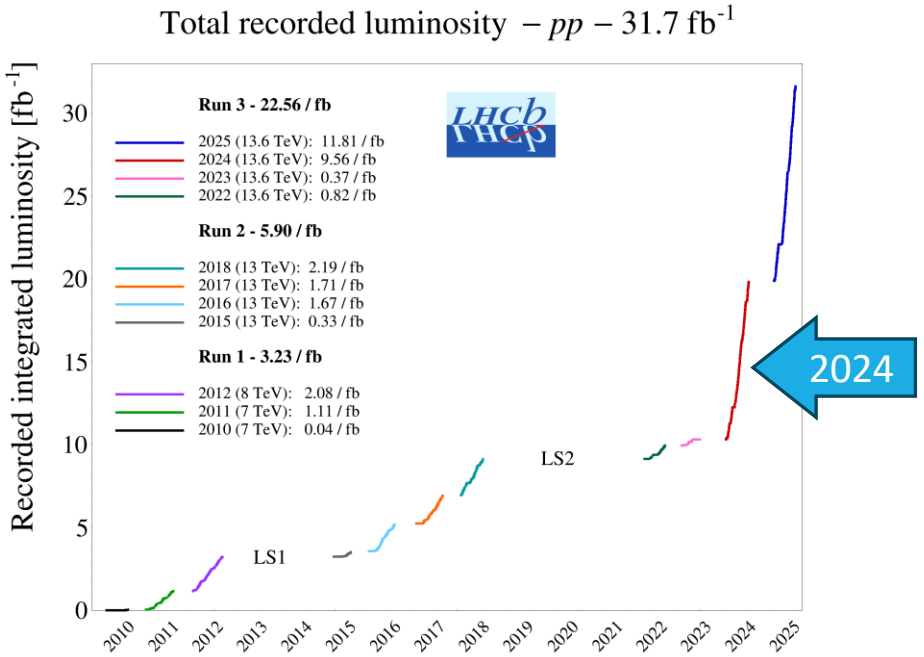
Upgraded LHCb detector

- Run 3 data (2024): luminosity increased by a factor 5.



- Upgraded readout system: 40 MHz
- Upgraded trigger system: hardware trigger removed.
  - **All-software trigger** enables reconstruction and event selection in real time.
  - Efficiency of hadronic final states increased by a factor 2-4.

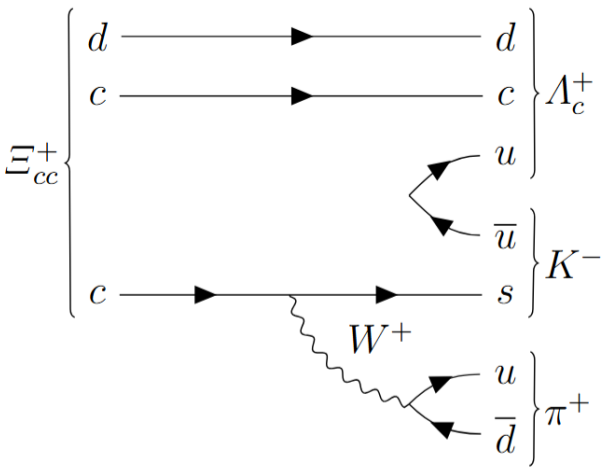
- 2024 after June Technical Stop data:
  - $\sqrt{s} = \mathbf{13.6\ TeV,\ 6.9\ fb^{-1}}$



Analysis strategy

[LHCb-PAPER-2026-009, in preparation]

- Search Ξ_{cc}^{+} in the decay mode: $\boldsymbol{\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+} (\Lambda_c^{+} \to p K^{-} \pi^{+})}$
  - MC sample: $\boldsymbol{\tau(\Xi_{cc}^{+})}$ **= 45 fs**, considering first Dim-7 calculation.
  - $\tau(\Xi_{cc}^{+})$ assumed in the range **15-160 fs** based on $\tau(\Xi_{cc}^{+})/\tau(\Xi_{cc}^{++})$ predictions and $\tau(\Xi_{cc}^{++})$ measured by LHCb.



- Off-line selection based on **MVA** method (BDT).
  - MVA trained with data and simulation.

- Keep signal window (3.5-3.65 GeV) **blinded**.
  - Measure the mass of Ξ_{cc}^{+}, if global significance > 3σ or local significance > 5σ.

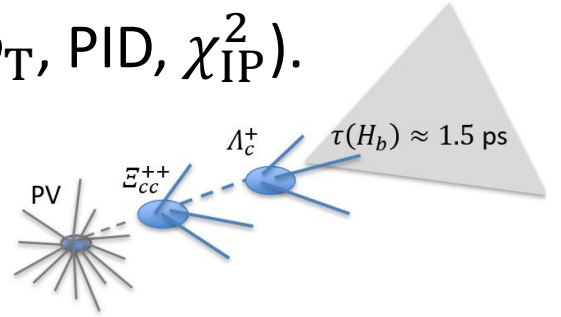
- Use $\boldsymbol{\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}}$ as control channel to optimize algorithm: study about uncertainties and cross-check the performance of the detectors
  - Event-selection of Ξ_{cc}^{+} is very similar to Ξ_{cc}^{++}, except one less pion, and shorter lifetime.

- Run 2 data (2016-2018) as cross-check.

[LHCb-PAPER-2026-009, in preparation]

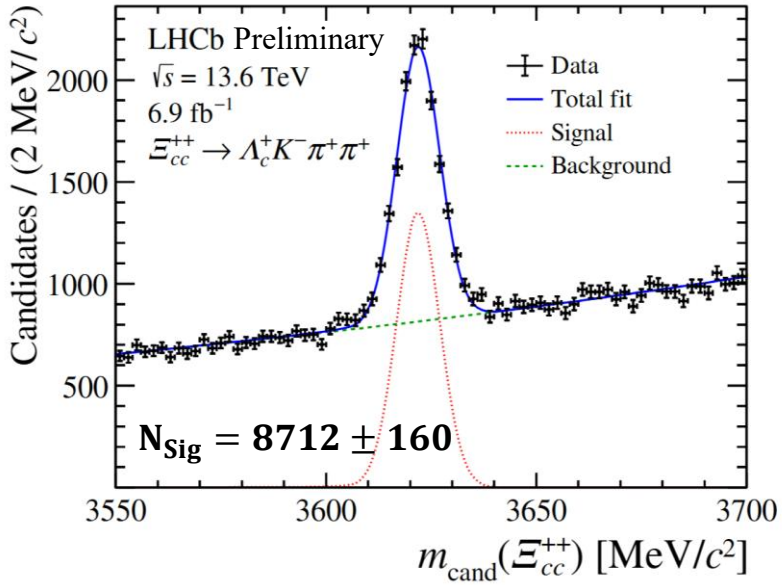
Validation with control channel

- Output of a MVA trained with Λ_c^+ data is included in the MVA for Ξ_{cc}^{++} (p_{T}, PID, χ^2_{IP}).
  - To mitigate the difference of particle-identification variables in data and simulation.

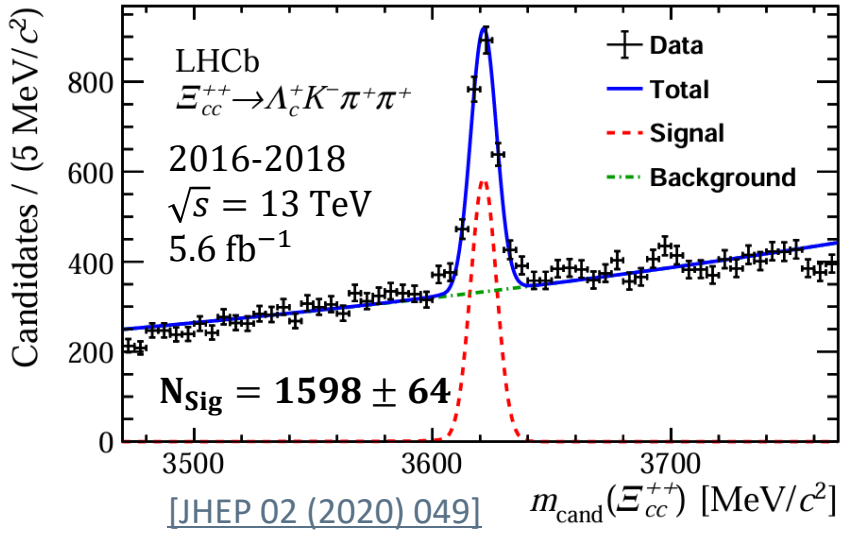


- Efficiency increased by a factor 4, compared with Run 2.
  - Signal yield per fb^{-1} is 1262 in 2024 data, 285 in Run 2 data.
  - Thanks to removal of hardware trigger and improved event-selection.

- Corrected mass: $M(\Xi_{cc}^{++}) = 3621.74 \pm 0.10\ \mathrm{MeV}/c^2$(stat. only), consistent with Run 2 result.



$M(\Xi_{cc}^{++}) = 3621.55 \pm 0.23\ (\mathrm{stat}) \pm 0.30\ (\mathrm{syst})\ \mathrm{MeV}/c^2$



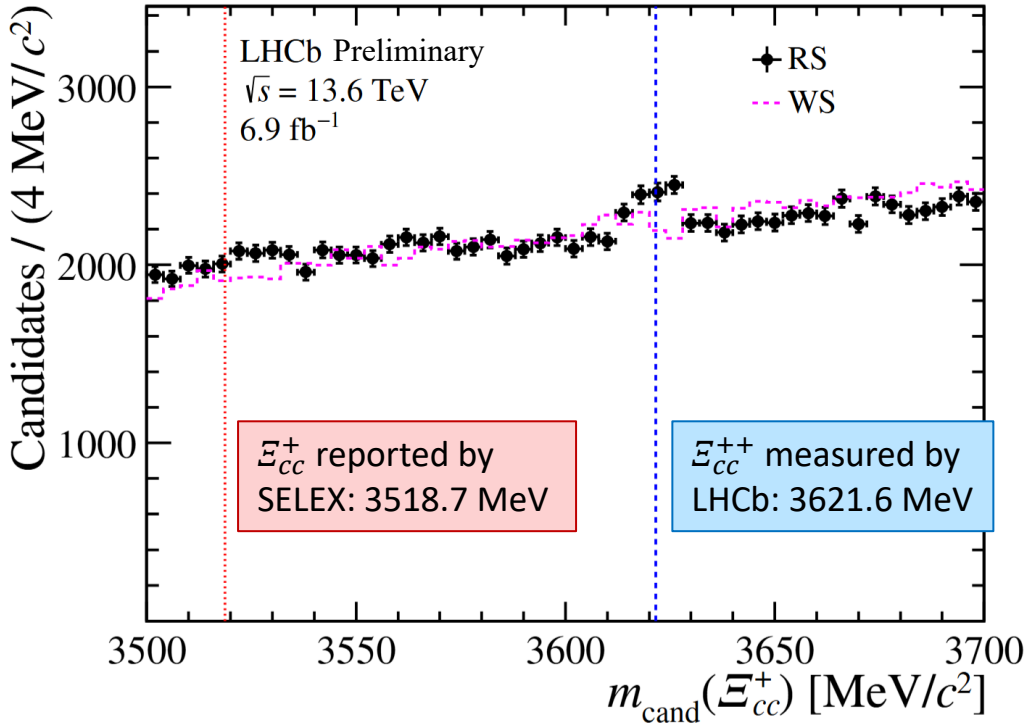
[JHEP 02 (2020) 049]

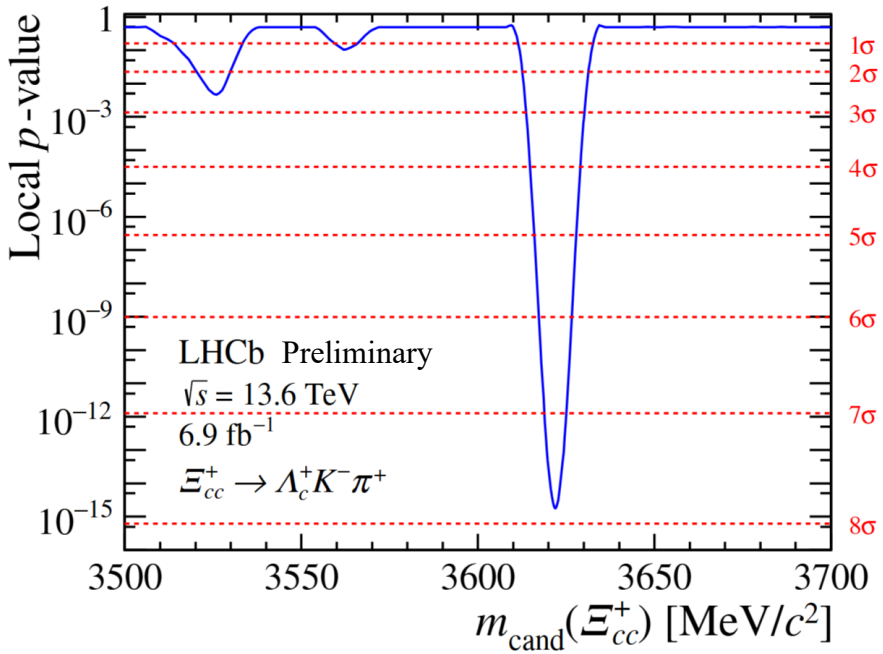
[LHCb-PAPER-2026-009, in preparation]

Results of Ξ_{cc}^{+} in 2024 data

- No fake peak in the Wrong-Sign sample, or at the $m(\Xi_{cc}^{+})$ reported by SELEX.
- The local significance around $3622\ \mathrm{MeV}/c^2$ **exceeds 7σ**, evaluated with a likelihood ratio test.

- Efficiency increased by a factor 2.5, compared with Run 2.
  - Signal yield per fb^{-1} is 133 in 2024 data, 54 in Run 2 data.

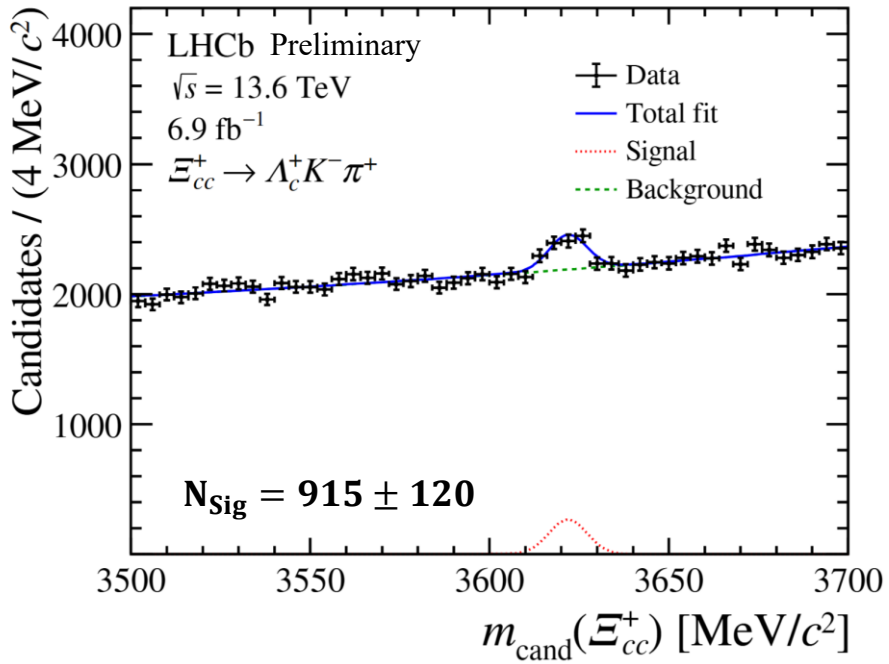




[LHCb-PAPER-2026-009, in preparation]

Mass measurement of Ξ_{cc}^{+}

- Precise measurement:
  - Correct the mass bias caused by event selection(backup) and final-state photon radiation.
- Ξ_{cc}^{+} mass with correction: $3619.97 \pm 0.83\,(\text{stat}) \pm 0.26\,(\text{syst})^{+1.90}_{-1.30}\,(\text{lifetime})\,\text{MeV}/c^2$.
- Mass difference: $\Delta M \equiv M(\Xi_{cc}^{+}) - M(\Xi_{cc}^{++}) = -1.77 \pm 0.84\,(\text{stat}) \pm 0.15\,(\text{syst})^{+1.90}_{-1.30}\,(\text{lifetime})\,\text{MeV}/c^2$.
  - Prediction: -0.4 to -2.3 MeV/c^2.



Systematic uncertainties (in MeV/c^2) on the $M(\Xi_{cc}^{+})$ mass and mass difference ΔM

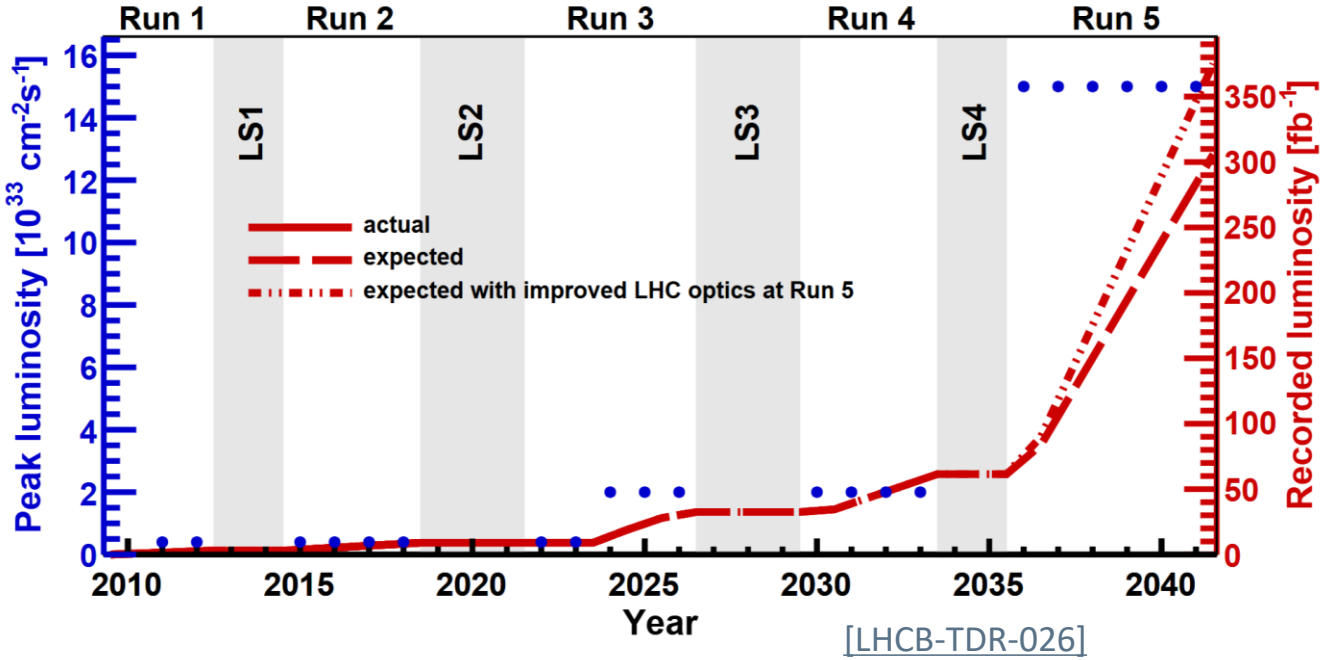
Source	$M(\Xi_{cc}^{+})$	ΔM
Momentum-scale calibration	0.14	0.03
Energy loss	0.10	0.05
Selection bias correction	0.10	0.10
Mass fit model	0.10	0.10
Λ_c^{+} mass uncertainty	0.14	–
Sum in quadrature	0.26	0.15
Unknown Ξ_{cc}^{+} lifetime	$^{+1.90}_{-1.30}$	$^{+1.90}_{-1.30}$

The bias due to event selection strongly depends on the lifetime.

Prospects

[LHCb-PAPER-2026-009, in preparation]

- Run 1 & 2: $9\ \mathrm{fb}^{-1}$
  - Ξ_{cc}^{++}: first observation.
- Run 3: $\sim 30\ \mathrm{fb}^{-1}$
  - Ξ_{cc}^{++}: with $\mathcal{O}(10\mathrm{k})$ signal.
  - Ξ_{cc}^{+}: first observation, with $\mathcal{O}(1\mathrm{k})$ signal.
  - Next: search for Ω_{cc}^{+}.

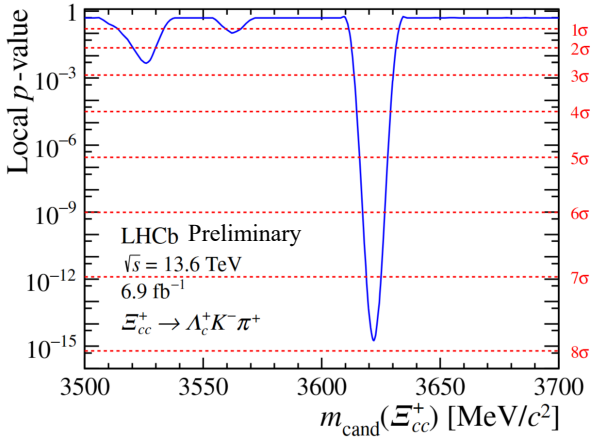


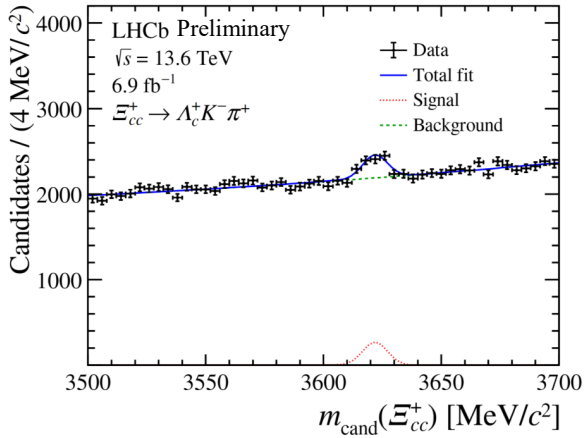
[LHCB-TDR-026]

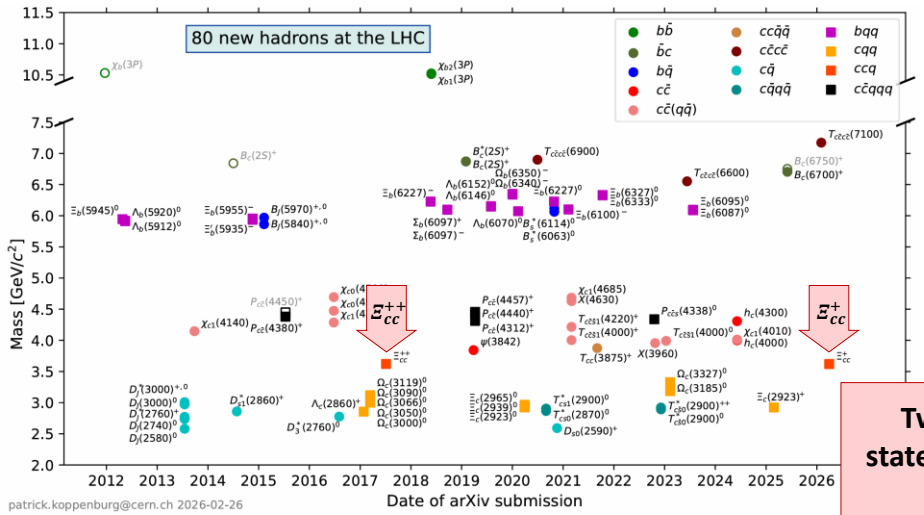
- Run 4: $\sim 30\ \mathrm{fb}^{-1}$
  - Precise determination of lifetime, branching ratios, and study of additional decay modes.
- With Upgrade II: $\sim 300\ \mathrm{fb}^{-1}$
  - Triple-charm baryons?

Summary

- Thanks to the enhanced capabilities of the **upgraded LHCb detector** and trigger system, **efficiency of hadronic final states increased** by a factor of 2-4.
- Ξ_{cc}^{++}: with a factor of 4 signal yield per fb^{-1} of data, compared with Run 2.
- **Ξ_{cc}^{+}: first new particle observed with the upgraded LHCb detector.**
  - Local significance larger than 7σ.
  - Ξ_{cc}^{+} mass: $3619.97 \pm 0.83\,(\text{stat}) \pm 0.26\,(\text{syst})^{+1.90}_{-1.30}\,(\text{lifetime})\,\text{MeV}/c^2$.
  - Mass difference: $\Delta M \equiv M(\Xi_{cc}^{+}) - M(\Xi_{cc}^{++}) = -1.77 \pm 0.84\,(\text{stat}) \pm 0.15\,(\text{syst})^{+1.90}_{-1.30}\,(\text{lifetime})\,\text{MeV}/c^2$.
    - Consistent with prediction.







Two weakly decaying states observed at the LHC to date.

BACKUP

MVA for $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$

- Training samples:
  - Signal from simulation (available blocks)
  - Background from WS (3.6-3.64 GeV)

- Training variables:
  - Λ_c^{+} MVA (after requiring > -0.55)
  - p_T, χ^2_{IP} of all particles
  - PID of Ξ_{cc} daughters
  - Ξ_{cc} and Λ_c^{+}: vertex fit χ^2, Flight distance $\chi^2 + \rho$, DIRA, DTF χ^2 with PV constraint

- Working point determined using Punzi FoM: $\varepsilon / (\frac{5}{2} + \sqrt{B})$

Event-selection: Clone and multiple candidate removal

- Clone candidate study:
  - In the distributions of opening angles of tracks with the same charge: in 2024 WS, the opening angle peak near zero is rightward shifted.
  - Remove events where the opening angle between two tracks in the VELO is **< 0.7 mrad** (same track reconstructed twice, using different hits).

- Multiple candidate: more than one Ξ_{cc} candidate in an event
  - Swapping two final state tracks (K^- from Λ_c^+ or Ξ_{cc}): randomly choose one candidate to retain.
  - Different combination (same Λ_c^+ with different π^+): 8% of Ξ_{cc}^{++} signal (6% of Ξ_{cc}^{+}), not removed.

Bias due to event-selection

- Multiple scattering can alter the values of the reconstructed mass and flight distance.
- Event selection tends to retain candidates with long flight distances → larger opening angle and mass biased towards larger values.
  - Particularly important for short-lived particles.
  - Estimated by comparing fitted mass before and after applying all selection cuts in simulation.

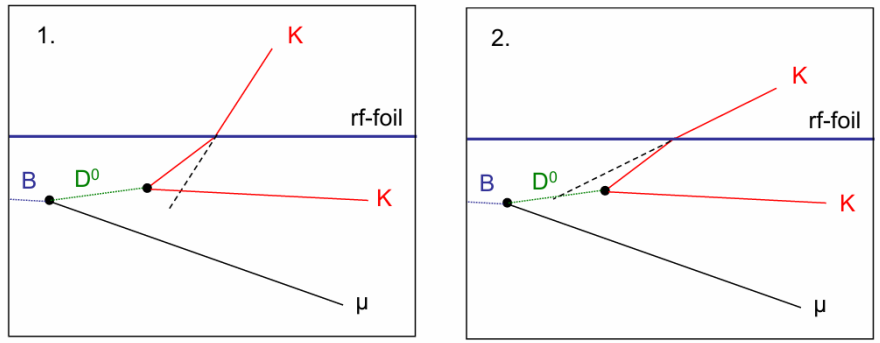
- In control channel:

$$\Delta M = M_{\text{fitted}} - M_{\text{input}}(3621.40\,\text{MeV}/c^2)$$

$$\delta\mu = \Delta M_{\text{sel}}(\Xi_{cc}^{++}) - \Delta M_{\text{rec}}(\Xi_{cc}^{++}) = 0.261 \pm 0.029\,\text{MeV}/c^2$$

- For Ξ_{cc}^{+}:
  - Mass bias depends on the unknown lifetime.
  - 45 fs: $\delta\mu = 2.04 \pm 0.09\ \text{MeV}/c^2$
  - Lifetime range causes uncertainty on the correction (15 fs: $-1.3\text{MeV}/c^2$, 160 fs: $+1.9\text{MeV}/c^2$).

Two examples of multiple scattering



• Opening angle larger → higher mass
• Reconstructed decay distance too long

• Opening angle smaller → lower mass
• Reconstructed decay distance too short

Reconstructed decay distance and mass are correlated

Cross check with Run 2 result

- The local significance around $3622\ \mathrm{MeV}/c^2$ is over 4σ.
  - Thanks to improved event-selection enabled by using inclusive Λ_c^+ line.

- Ξ_{cc}^+ mass with correction: $3620.8 \pm 2.2\,(\mathrm{stat})^{+1.5}_{-1.2}\,(\mathrm{lifetime})\ \mathrm{MeV}/c^2$
- Consistent with 2024 result. $3619.97 \pm 0.83\,(\mathrm{stat}) \pm 0.26\,(\mathrm{syst})^{+1.90}_{-1.30}\,(\mathrm{lifetime})\ \mathrm{MeV}/c^2$.