Observation of the doubly charmed $\Omega_{cc}^{+}(scc)$ baryon

[LHCb-PAPER-2026-022, to be submitted to PRL]

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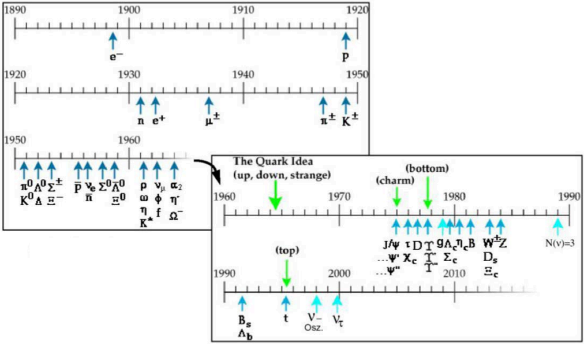
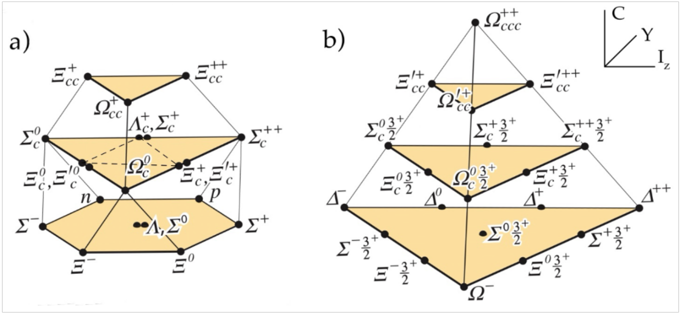
强子物理在线论坛
2026 年 6 月 15 日

- Hundreds of sub-atomic particles have been observed over the past century



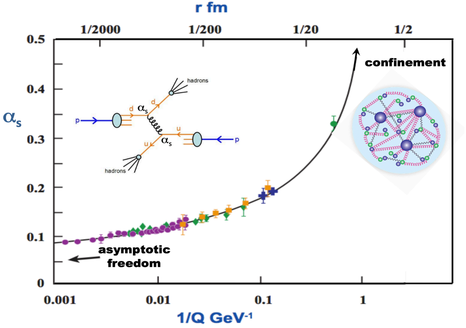
Quark model

- Hadrons are bound states of quarks: mesons ($q\bar{q}$), baryons (qqq), exotics ($q\bar{q}q\bar{q}$, $qqqq\bar{q}$, *etc.*)
- Ground-state hadrons are classified into multiplets according to the symmetry property of flavour, spin, color, and space
  - $\mathrm{SU}(4)_f$ baryon $J^P = 1/2^+$ 20-plets and $J^P = 3/2^+$ 20-plets



Quantum ChromoDynamics (QCD)

- The theory of strong interaction in the Standard Model
  - Quarks interact with gluons, which also interact among themselves
- Running coupling constant α_s
  - Confinement: perturbation theory breaks down at low energy scale



[Rev.Mod.Phys. 90 (2018) 015003]

- Experimental data are essential to test and refine theoretical technologies for the description of hadron properties

A little bit of history

[FERMILAB-Conf-85/69]

- J. D. Bjorken explored the possibility of the experimental observation of $\Omega_{ccc}^{++}(ccc)$ baryon in 1985

IS THE CCC A NEW DEAL FOR BARYON SPECTROSCOPY?

J. D. Bjorken
Fermi National Accelerator Laboratory, Batavia, IL 60510

ABSTRACT

The possibility of experimental observation of the triply charmed ccc baryon Ω_{ccc}^{++} is explored. The conclusion is that it is very difficult, but not unthinkable.

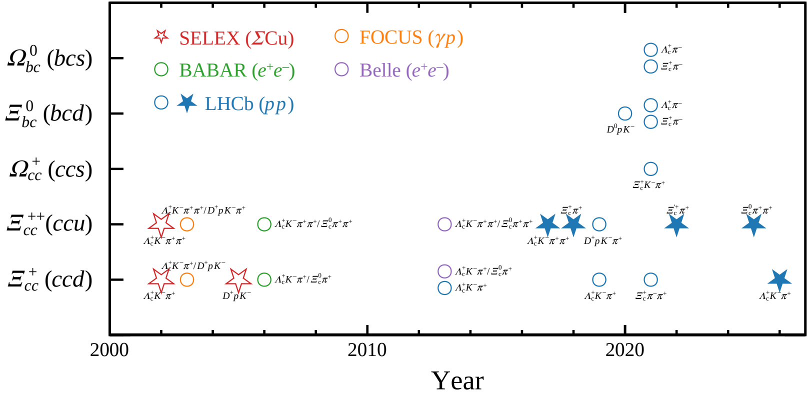
- Doubly charmed baryons as the consolation prizes along the way
  - $\Xi_{cc}^{++}(ucc)$, $\Xi_{cc}^{+}(dcc)$, $\Omega_{cc}^{+}(scc)$

CONCLUSIONS

Finding the (ccc) baryon would seem a worthwhile goal, were it not so obviously painfully difficult. Study of the baryonic analogue of charmonium might yield sharp tests for QCD. But irrespective of that, there are consolation prizes along the way, most notably the (ccu). Just the observation of a doubly

We have tried, A LOT

- Experimental studies of doubly heavy baryons

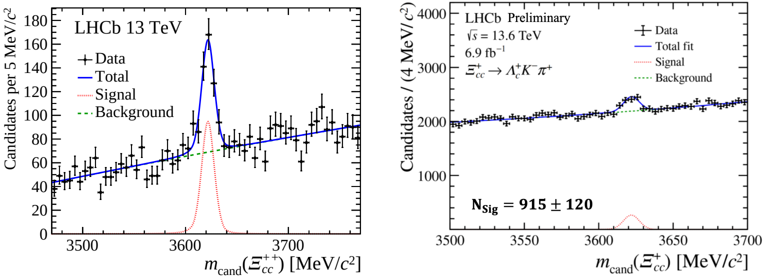


[CERN-THESIS-2022-271]

We have won the prize, TWICE!

- LHCb observed $\Xi_{cc}^{++}(ucc)$ baryon in 2017 and $\Xi_{cc}^{+}(dcc)$ baryon this year

[PRL 119 (2017) 112001, LHCb-PAPER-2026-009, accepted by PRL]



$$M(\Xi_{cc}^{++}) = 3621.24 \pm 0.65\,(\text{stat}) \pm 0.31\,(\text{syst})\,\text{MeV}$$

$$M(\Xi_{cc}^{+}) - M(\Xi_{cc}^{++}) = -1.77 \pm 0.84(\text{stat}) \pm 0.15(\text{syst})^{+1.90}_{-1.30}(\text{lifetime})\,\text{MeV}$$

And a new PDG sector is building up

- For Ξ_{cc}^{++} baryon, the lifetime and four decay channels have been measured

DOUBLY CHARMED BARYONS
($C = +2$)
$\Xi_{cc}^{++} = ucc$, $\Xi_{cc}^{+} = dcc$, $\Omega_{cc}^{+} = scc$

PDGID:S068 JSON INSPIRE

Ξ_{cc}^{++} $I(J^P) = ?(?^?)$

Ξ_{cc}^{++} MASS	3621.6 ± 0.4 MeV
Ξ_{cc}^{++} MEAN LIFE	$(2.56 \pm 0.27) \times 10^{-13}$ s

Ξ_{cc}^{++} DECAY MODES

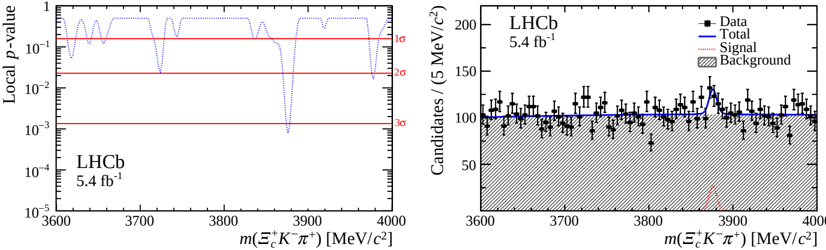
	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\Lambda_c^+ K^- \pi^+ \pi^+$	DEFINED AS 1		880
Γ_2	$\Xi_c^+ \pi^+$, $\Xi_c^+ \to p K^- \pi^+$	0.0022 ± 0.0006		
Γ_3	$\Xi_c^{\prime +} \pi^+$, $\Xi_c^{\prime +} \to \Xi_c^+ \gamma$, $\Xi_c^+ \to p K^- \pi^+$	0.0031 ± 0.0010		
Γ_4	$\Xi_c^0 \pi^+ \pi^+$, $\Xi_c^0 \to p K^- K^- \pi^+$	0.0067 ± 0.0010		
Γ_5	$D^+ p K^- \pi^+$	<0.017	CL=90%	562

But what about $\Omega_{cc}^{+}(scc)$ baryon?

- Production cross-section of Ξ_{cc}^{++} and Ξ_{cc}^{+} baryons have been proved to be large at LHC
- Fragmentation fraction

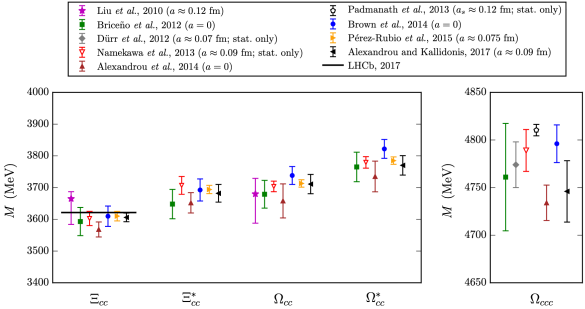
$$\sigma(\Xi_{cc}^{++}) : \sigma(\Xi_{cc}^{+}) : \sigma(\Omega_{cc}^{+}) \sim 3 : 3 : 1$$

- Search for $\Omega_{cc}^{+} \to \Xi_{c}^{+} K^{-} \pi^{+}$ with LHCb Run 2 data [SCPMA64(2021)101062]
  - A hint seen around 3880 MeV, but less significant after LEE correction



Prediction of Ω_{cc}^{+} properties

- Theoretical predictions become much more reliable with knowledge of Ξ_{cc} baryons as input
- $M(\Omega_{cc}^{+}) - M(\Xi_{cc}) \sim 100\,\mathrm{MeV}$



- Lifetime hierarchy

$$\tau(\Xi_{cc}^{+}) \sim 50\,\mathrm{fs} < \tau(\Omega_{cc}^{+}) \sim 150\,\mathrm{fs} < \tau(\Xi_{cc}^{++}) \approx 300\,\mathrm{fs}$$

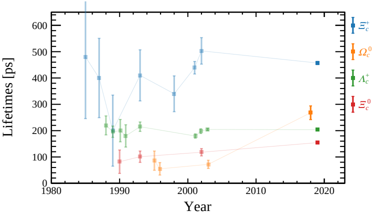
[See LHCb-PAPER-2026-022 for detailed references]

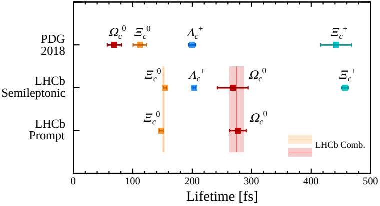
Search for Ω_{cc}^{+} with LHCb Run 3 data

- Search for Ω_{cc}^{+} in a new channel $\Omega_c^0\pi^+$ is performed
- The $\Omega_c^0\pi^+$ mode is expected to have a leading hadronic branching fraction

[See LHCb-PAPER-2026-022 for detailed references]

- Ω_c^0 baryon turns out to be longer lived than previously known, and hence have a more significant experimental signature
  - LHCb established new lifetime hierarchy of charmed baryons

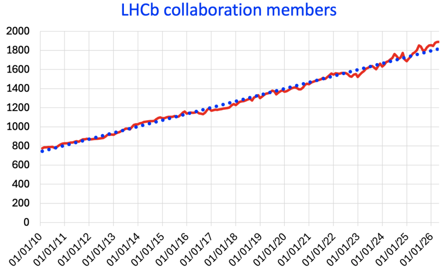


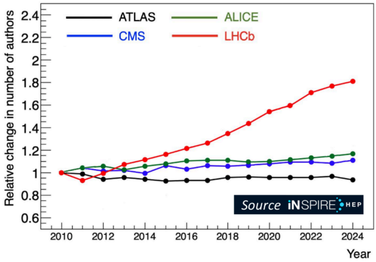


[Sci.Bull. 67 (2022) 479]

LHCb experiment

- LHCb experiment is a 「Flavour factory」 at LHC
- LHCb collaboration comprises 29 countries, 110 institutes, and around 1800 members

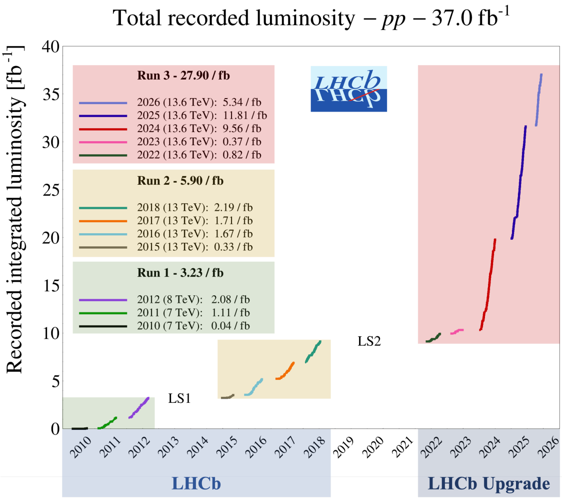




- LHCb China group comprises 12 institutes and around 200 members

LHCb operation and data sets

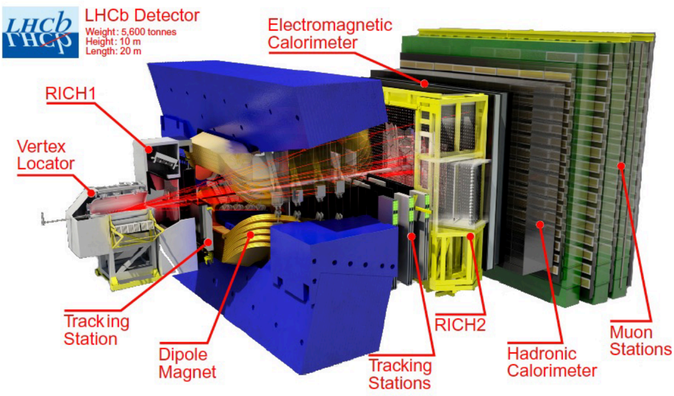
- $37\,\text{fb}^{-1}$ pp collision data in Run 1–3
- A major upgrade during LS2
  - New major sub-detectors
  - $5 \times \mathcal{L}(t)$
- Various heavy-ion data are collected as well



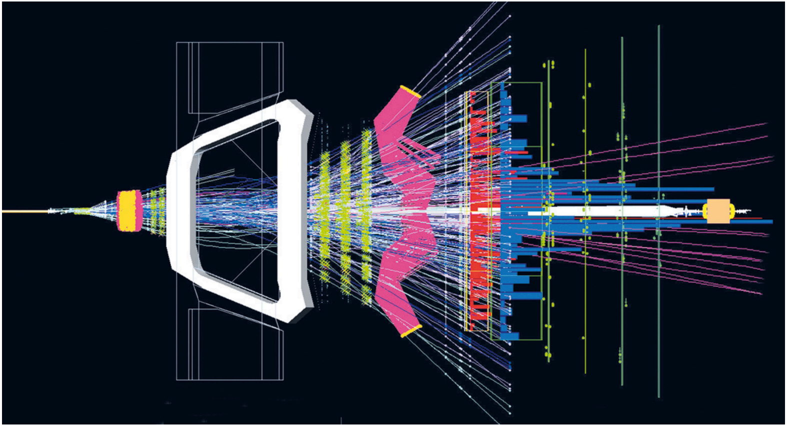
LHCb detector

[JINST 3 (2008) S08005]

- A single-arm forward spectrometer



Display of a typical pp collision event



- Require excellent vertex resolution and PID to reconstruct clean heavy flavour hadronic decays

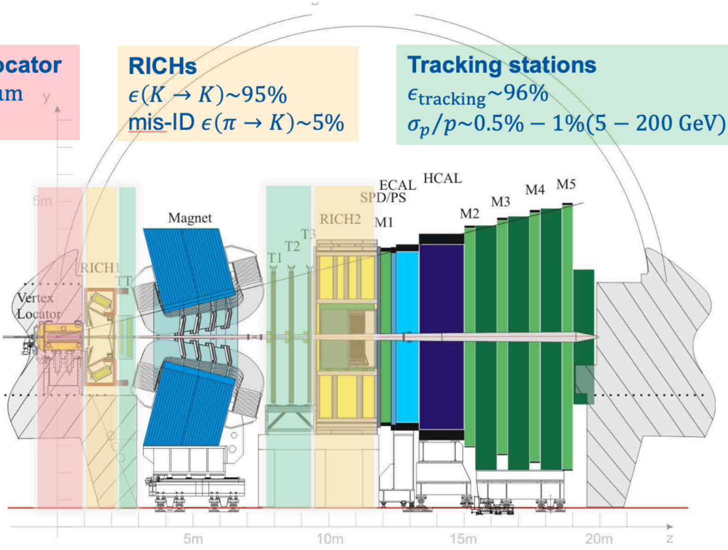
LHCb detector performance

[JINST 14 (2019) P04013]

Vertex Locator
$\sigma_{\mathrm{IP}} = 20\ \mu\mathrm{m}$
$\sigma_\tau = 45$ fs

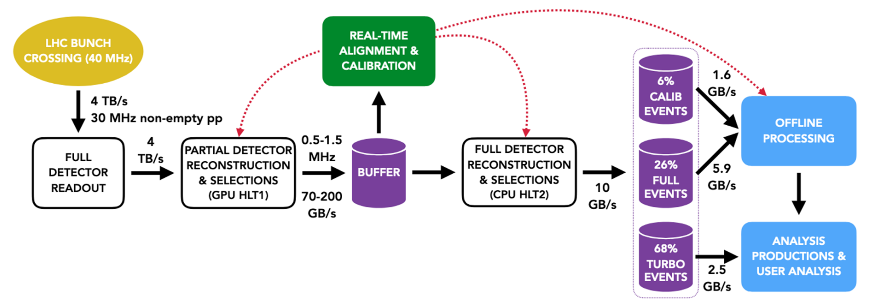
RICHs
$\epsilon(K \to K) \sim 95\%$
mis-ID $\epsilon(\pi \to K) \sim 5\%$

Tracking stations
$\epsilon_{\mathrm{tracking}} \sim 96\%$
$\sigma_p/p \sim 0.5\% - 1\% (5 - 200\ \mathrm{GeV})$



LHCb data flow and real-time analysis

- Trigger system is essential to reconstruct and select heavy flavour decays efficiently, within limited computing resources
- LHCb Run 3 adopted a fully software two-stage trigger system
  - Only interesting events and/or their interesting parts saved for offline analysis



Take action even before data taking

- Trigger algorithms for the study of doubly charmed baryons were developed in 2022, before the data taking
  - Exclusive DCB hadronic and hyperon decays
  - Inclusive single-charmed baryon decays

LHCb / Moore / Merge requests / **!1508**

Add exclusive hadronic doubly charmed baryon lines

Merged **Ao Xu** requested to merge `axu_charm_xicc` into `master` 19 Apr 2022

Overview 89 Commits 10 Pipelines 31 Changes 4

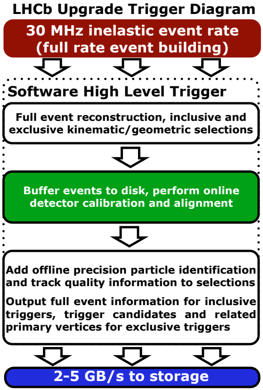
Add exclusive hadronic doubly charmed baryon lines based on the Run2 implementations, including:

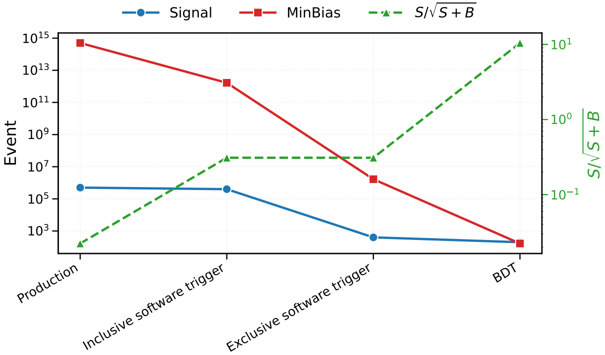
- Xi_cc++
- Xi_cc+
- Omega_cc+

decays to charmed-baryon and charmed-meson final states. Wrong-sign and doubly-Cabbibo-suppressed lines are also added for background study. There are 46 lines in total.

Event selection in a nutshell

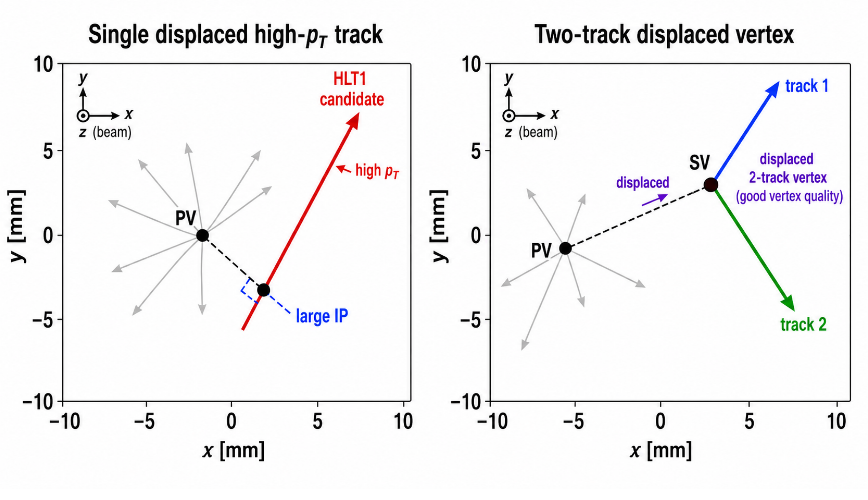
- Efficiency and significance at each selection stage
  - Signal: $\Omega_{cc}^{+} \to \Omega_c^0 \pi^+$, $\Omega_c^0 \to p K^- K^- \pi^+$
  - Minbias: Inelastic pp collisions





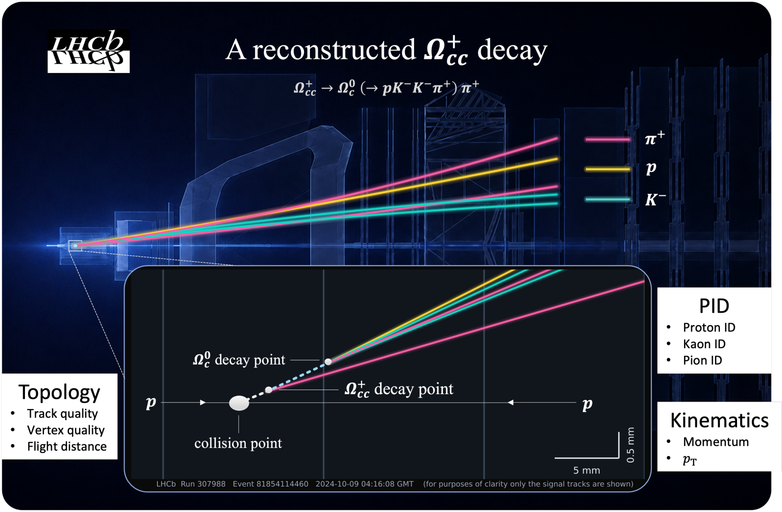
Inclusive software trigger

- First trigger stage mainly exploits vertex and momentum signatures
  - No PID information is available at this stage



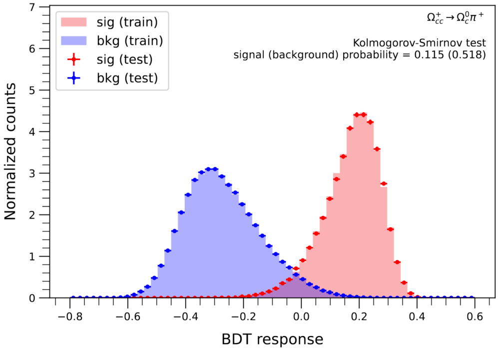
Exclusive software trigger

- Second trigger stage exploits more information with rectangular cuts



Offline selection

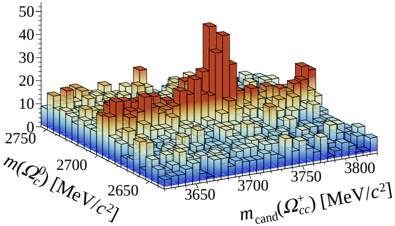
- Boosted Decision Tree exploits full information to further suppress background due to random combination of tracks

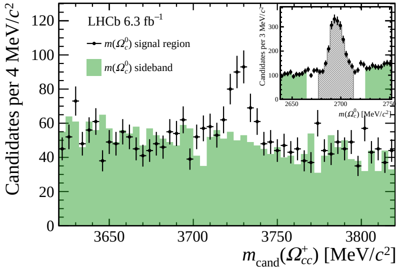


- Background with physics origin, *e.g.* due to particle misidentification or partial reconstruction, is also examined extensively

Invariant-mass distributions in 2024 data

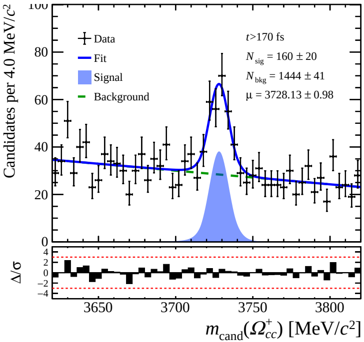
- A significant (global 8.7σ) peaking structure in the Ω_{cc}^{+} mass distribution is seen in 2024 data
  - The structure only appears for candidates within the mass signal window of the intermediate Ω_c^0 baryon





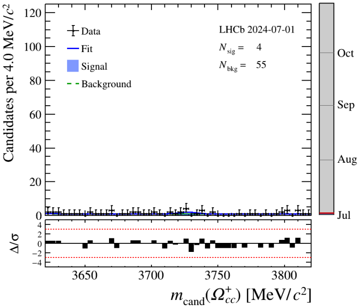
Is it a weakly-decaying particle?

- An additional requirement of $t > 170\,\mathrm{fs}$, corresponding to $3 \times \sigma_t(\Omega_{cc}^{+})$, is applied to the signal candidates
- Local significance of the signal is still above 9σ
- This confirms the weakly-decaying nature of the observed signal

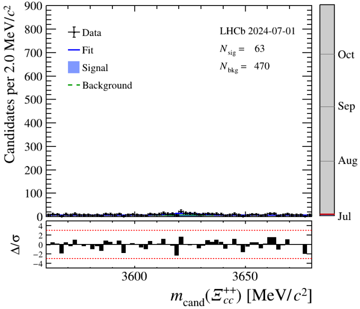


Consistency between data-taking periods

- Growth of mass distributions with data-taking time is visualised, along with fitted curves
  - Mass-peak position is stable over time



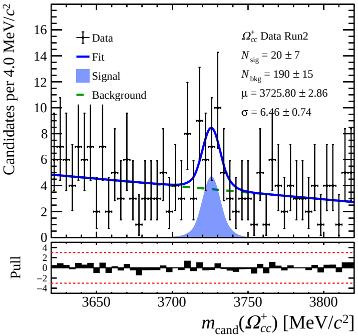
$\Omega_{cc}^{+} \to \Omega_c^0 \pi^+$



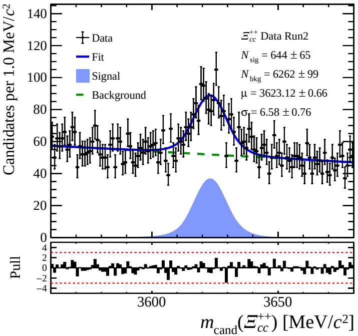
$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

How about Run 2 data?

- An evidence (local 3.2σ) of Ω_{cc}^{+} baryon also seen in Run 2 data
  - Consistent with expectation from luminosity and efficiency



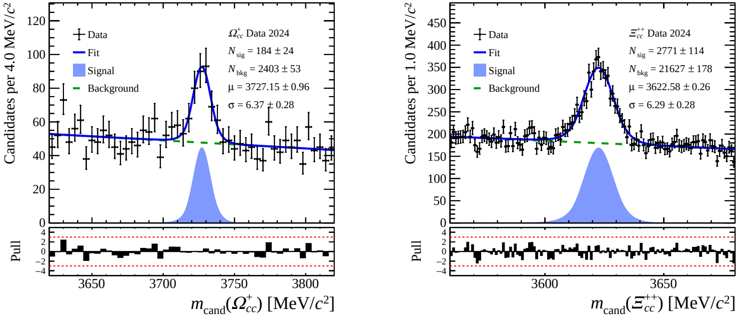
$\Omega_{cc}^{+} \to \Omega_{c}^{0}\pi^{+}$



$\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+}$

First determination of the mass difference

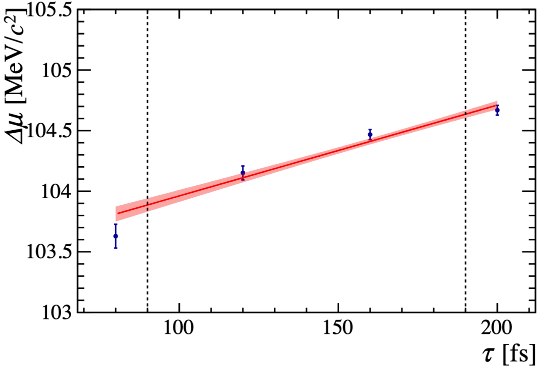
- Mass difference between the signal (Ω_{cc}^{+}) and control (Ξ_{cc}^{++}) mode is determined with simultaneous fits to the mass distributions
  - Difference from $\Xi_{cc}^{++} \to \Xi_c^{+}(\to pK^-\pi^+)\pi^+$ reduces systematic uncertainties due to selection bias, momentum scale calibration, and energy loss significantly



$$N_{\rm sig} = 184 \pm 24, \quad \Delta\mu_{\rm fit} = 104.56 \pm 0.99\,(\rm stat)\ MeV$$

Correction of bias

- Event selection favors candidates with larger flight distances
- In the presence of multiple scattering, this biases the opening angles between the decay products and therefore the reconstructed mass
- Correction evaluated with simulation samples



Result and discussion

- Mass of Ω_{cc}^{+} baryon is then determined using the known Ξ_{cc}^{++} mass
- The measured value is in general compatible with theoretical predictions
- Regge phenomenology $(J = a + \alpha M^2) \Rightarrow$

$$\left(M_{\Omega_{cc}}^2 - M_{\Xi_{cc}}^2\right) + \left(M_{\Xi}^2 - M_{\Sigma}^2\right) = \left(M_{\Omega_c}^2 - M_{\Sigma_c}^2\right)$$

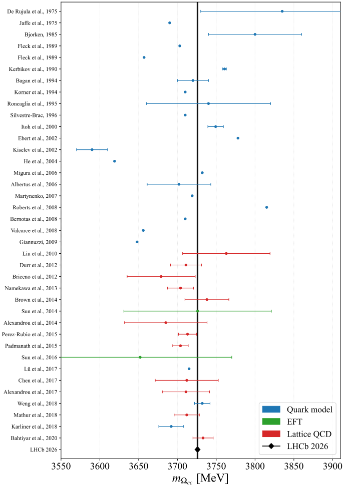
$\Longrightarrow M(\Omega_{cc}^{+}) = 3719\,\mathrm{MeV}$ [Phys.Scripta 97(2022)5 054001]

- Light-quark-heavy-diquark picture

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

$M(D_s^{+}) - M(D) \approx 100\,\mathrm{MeV}$

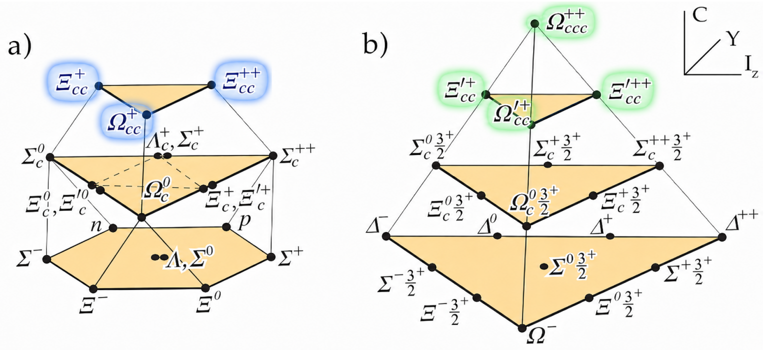
$M(B_s^{0}) - M(B) \approx 90\,\mathrm{MeV}$



$$3725.9 \pm 1.0\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst}) \pm 0.4\,(\mathrm{lifetime}) \pm 0.6\,(\mathrm{ext})\,\mathrm{MeV}$$

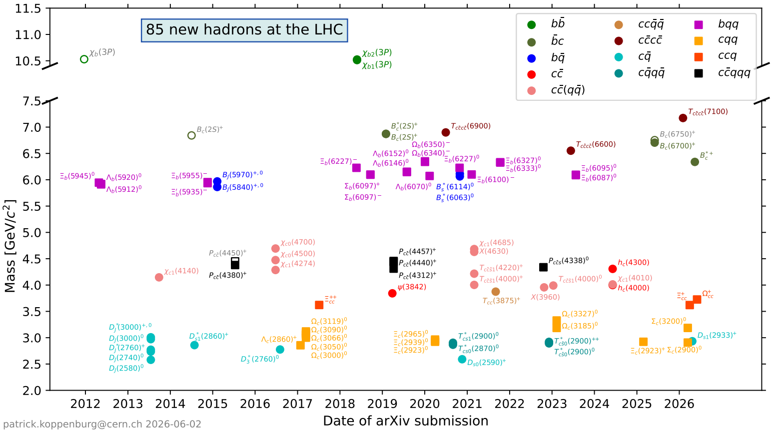
Observation of the doubly charmed baryon family

- This observation completes the last piece of $J^P = 1/2^+$ baryon $\mathrm{SU}(4)_f$ 20-plet



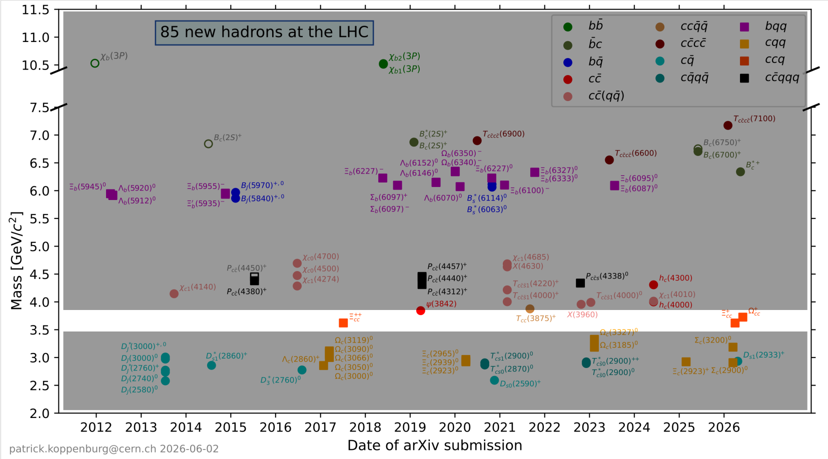
New hadrons discovered at LHC

- 85 new hadrons discovered at LHC so far



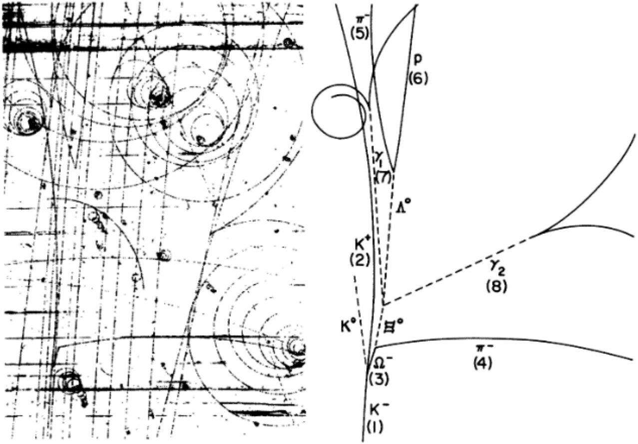
New hadrons discovered at LHC

- But only 3 of them decay weakly!



A historical perspective

- $\Omega^-(sss)$ discovery: 1 out of 80000 bubble-chamber photographs



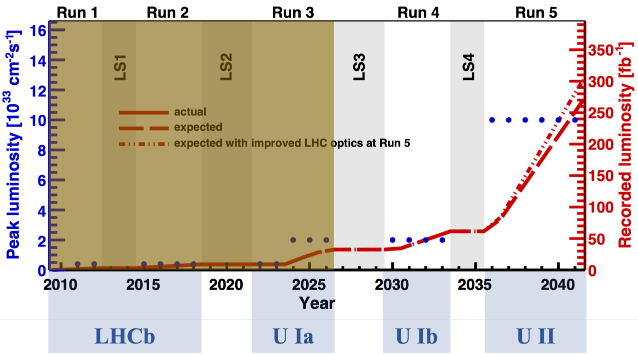
- $\Omega_{cc}^+(scc)$ discovery: a hundred out of trillions of pp collisions

What is next?

Plan for LHCb upgrade

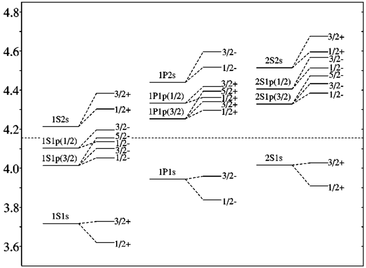
[CERN-LHCC-2021-012]
[CERN-LHCC-2018-027]

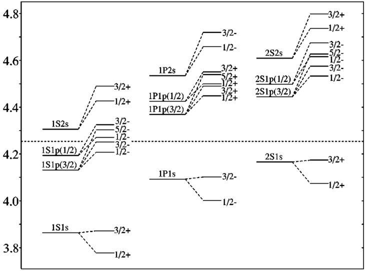
- Upgrade Ib: enhancement of DAQ and PID systems
- Upgrade II: the ultimate flavour experiment at LHC
  - $5 \times \mathcal{L}_{\text{Upgrade I}}(t)$



Opportunities with LHCb Run 3 data

- Ξ_{cc}^{+} and Ω_{cc}^{+} baryons
  - Measurement of lifetime and production times branching fraction
  - More decay channels
- Ξ_{cc}^{++} baryon: semi-leptonic and Cabibbo suppressed decays
- Excited states: fight against combinatorial background





[PRD 61 (2000) 057502]

- Ξ_{bc} and Ω_{ccc}^{+} baryons require LHCb Run 4 and 5 data

Opportunities beyond LHCb

- Complementary to pp collision
  - Measurement of absolute branching fractions at e^+e^- colliders
  - Unique probe of quark-gluon plasma (QGP) at heavy-ion colliders
- Projection of produced doubly charmed baryons at future colliders
  - Branching fractions and detection efficiency NOT accounted

Programs	Production per year
Belle II	2×10^6
CEPC	1×10^6
FCC	8×10^6
ILC	3×10^4
CLIC	5×10^4
LHeC	5×10^5
ALICE Upgrade	1×10^9

[CERN-THESIS-2022-271]

Summary

- LHCb recently reported the observation of Ω_{cc}^{+} baryon

$$3725.9 \pm 1.0\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.4\,(\text{lifetime}) \pm 0.6\,(\text{ext})\,\text{MeV}$$

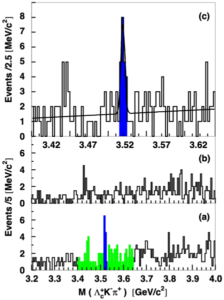
- Together with early observations of Ξ_{cc}^{++} and Ξ_{cc}^{+} baryons, LHCb puts in place the final pieces of $\text{SU}(4)_f$ baryon $J^P = 1/2^+$ 20-plet puzzle
- LHCb has just finished Run 3 data-taking, with a large data set to be further explored

Thanks for the continuing support from theory community on the predictions and generator development!

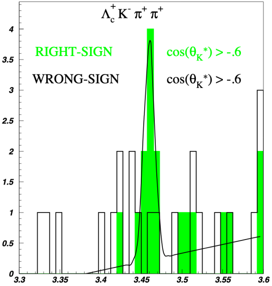
Backup

Early experimental searches

- Fixed-target SELEX experiment @ Fermilab reported first observation of both Ξ_{cc}^{+} and Ξ_{cc}^{++} baryons in 2002 [PRL89(2002)112001, hep-ex/0209075]
  - Large isospin split: $M_{\text{SELEX}}(\Xi_{cc}^{+}/\Xi_{cc}^{++}) \sim 3520/3460\,\text{MeV}$
  - Short lifetime: $\tau_{\text{SELEX}}(\Xi_{cc}^{+}) < 33\,\text{fs}$ @ 90% CL
  - Large production: 22 Ξ_{cc}^{+} signals out of 1630 Λ_c^{+} signals



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



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

FOCUS (γp)
BaBar ($e^{+}e^{-}$)
Belle ($e^{+}e^{-}$)
failed to confirm in the following 10 years