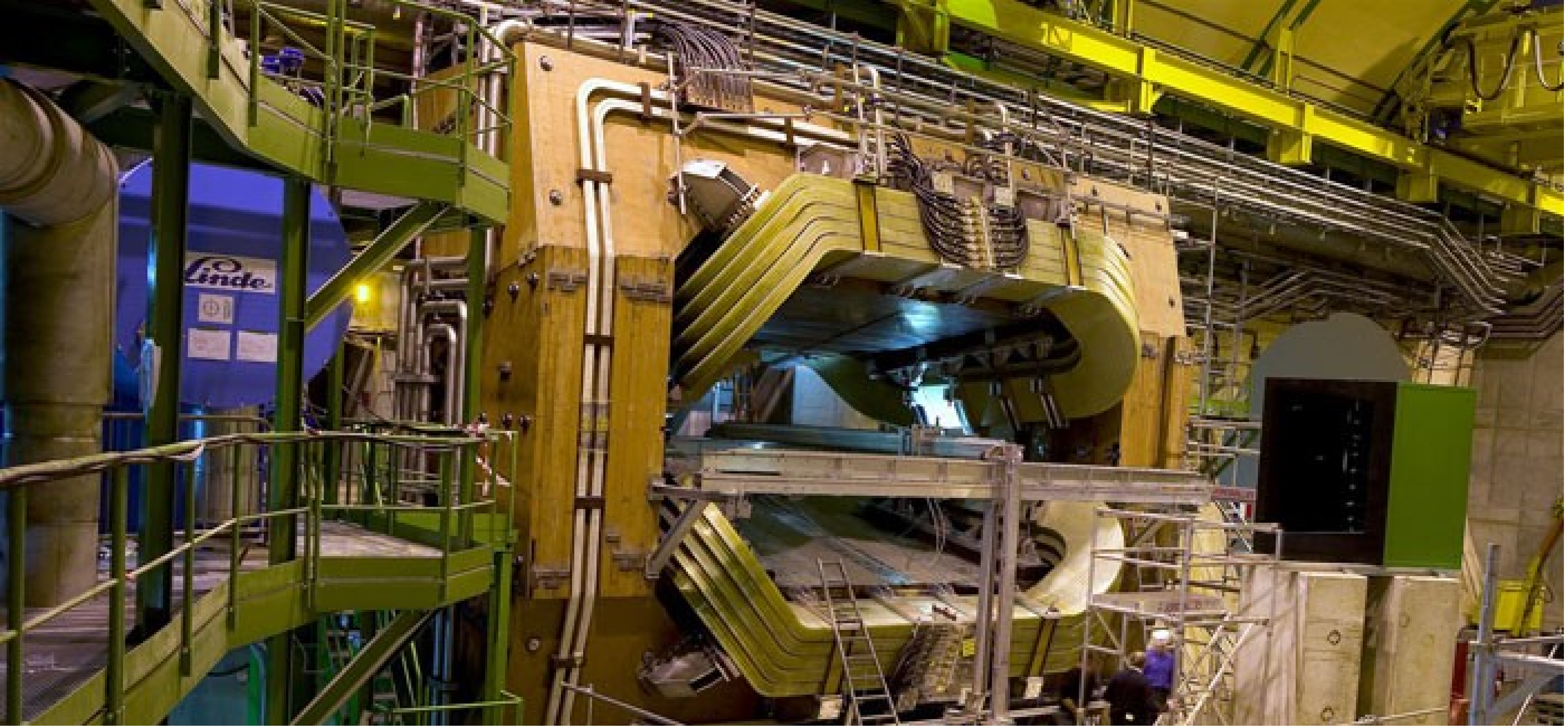


Charm decays at LHCb

Louis Henry, on behalf of the LHCb collaboration
CERN, 25/11/2021

A (quick) overview of charm physics at LHCb

- LHCb (see next slide) is a charm factory as much as a beauty one.
  - Especially true in the upgrade: ~1 MHz charm production rate has informed the trigger choices.

- Charm physics at LHCb roughly fall in 3 categories, with overlaps:
  - Spectroscopy and measurement of decay rates (mostly this talk)
  - Charm mixing and CPV (see Daniel Cervenkov's talk and Andrea Contu's talk)
  - Rare charm decays (see Davide Brundu' talk)

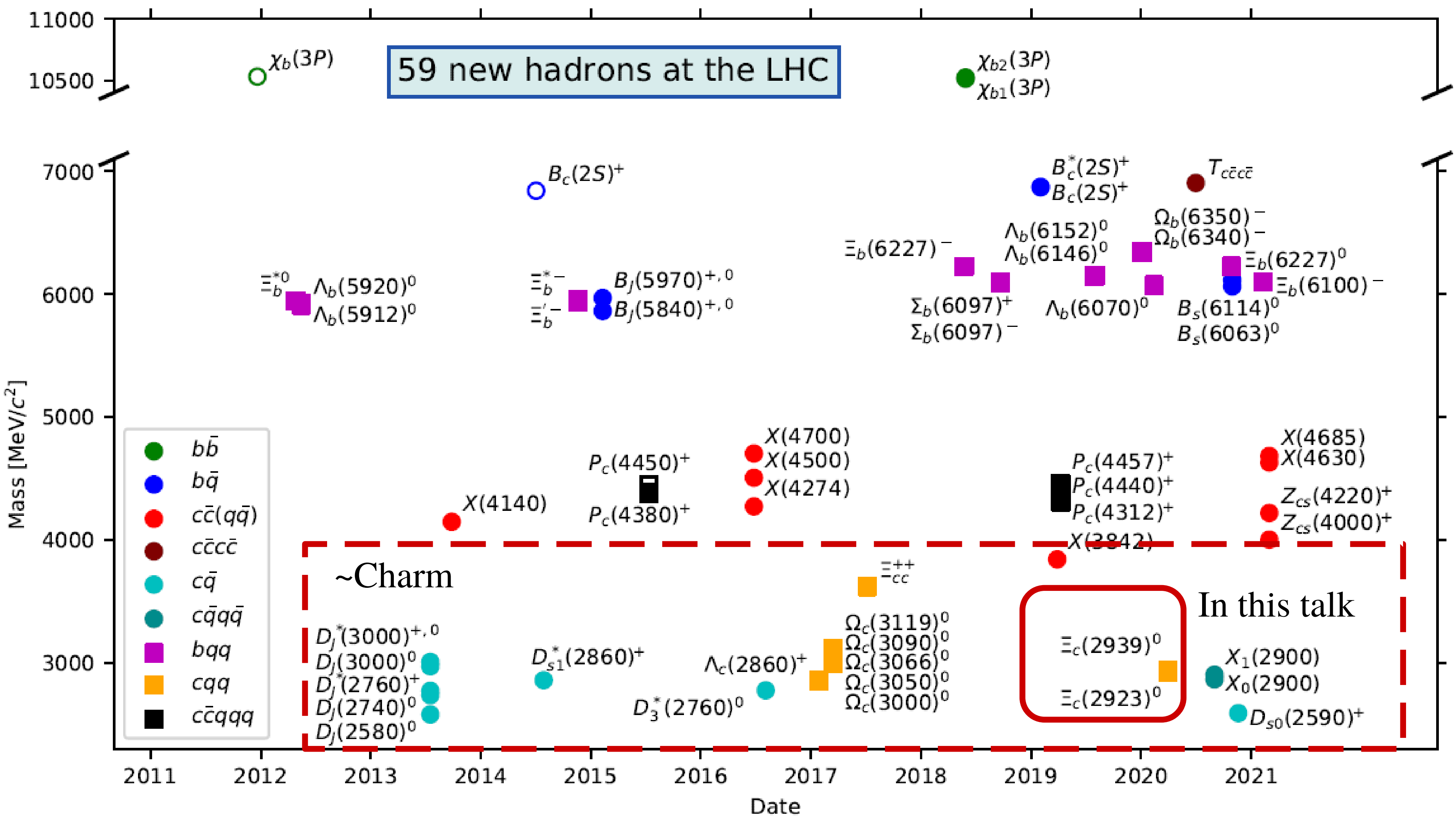
- We focus in this talk on recent results of charm physics at LHCb, particularly in the domain of baryon searches.

- In terms of physics, QCD + weak physics interplay.

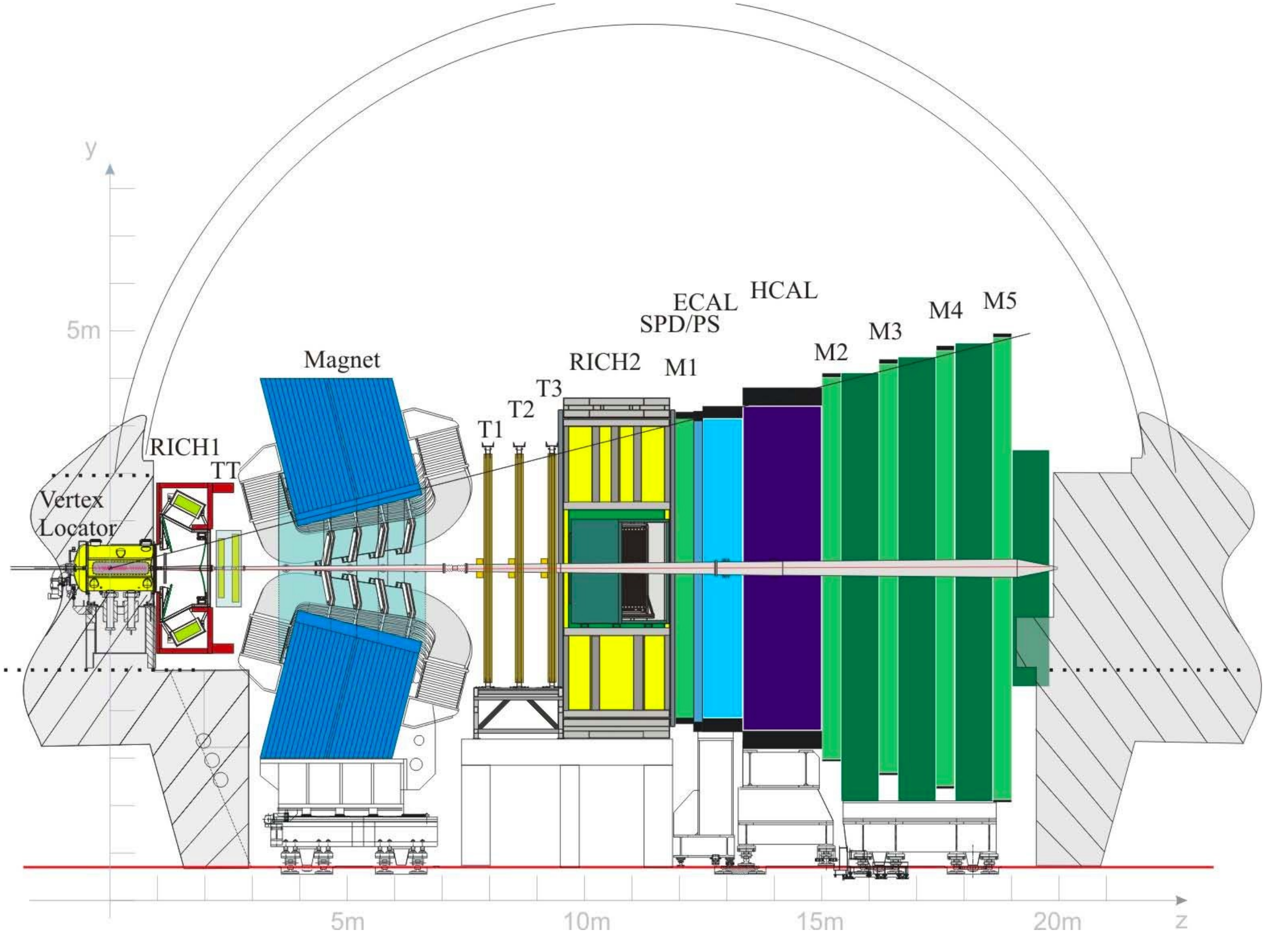
- There will be baryons: not just zoology, but future playgrounds for searches (e.g. Ξ_{cc}^{++}).

Overview of past discoveries

- Large contribution from LHCb.
  - Source: https://www.nikhef.nl/~pkoppenb/particles.html

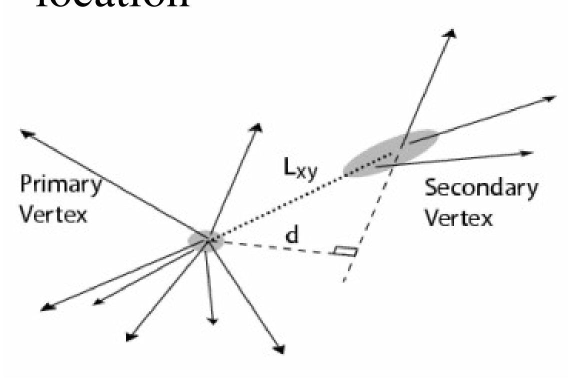


We could have called it LHCc



Int. J. Mod. Phys. A 30, 1530022 (2015)

(Secondary) vertex location



Momentum measurement

$\delta p/p \sim 0.5\%$
for Long tracks

95% K/π separation efficiency for 5% misID

- Production of charm pairs dwarves that of beauty pairs by a factor >10.
  - And no huge difference of acceptance.
- Much smaller flight distance and transverse momentum → harder to trigger on.

Measurement of the lifetimes of promptly produced Ω_c^0 and Ξ_c^0 baryons

arXiv:2109.01334

- 7σ inconsistency between LHCb measurement and world average for the Ω_c lifetime.
  - Also goes against 'naive' expectations for baryon lifetime hierarchy

$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}, \quad \text{(expected)}$$

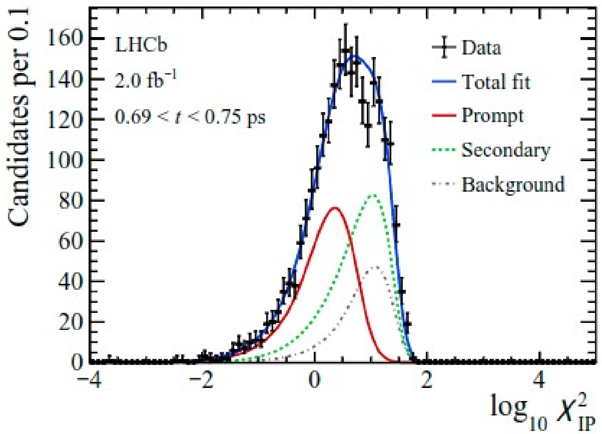
$$\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}. \quad \text{(measured)}$$

- This tests the higher orders of heavy-quark expansion (weak W-annihilation, Pauli interference).
  - Both "expected" and "measured" hierarchies can be obtained through different higher-order effects. See [Front. Phys. (Beijing) 10(2015) 101406] and [arXiv:hep-ph/9311331].

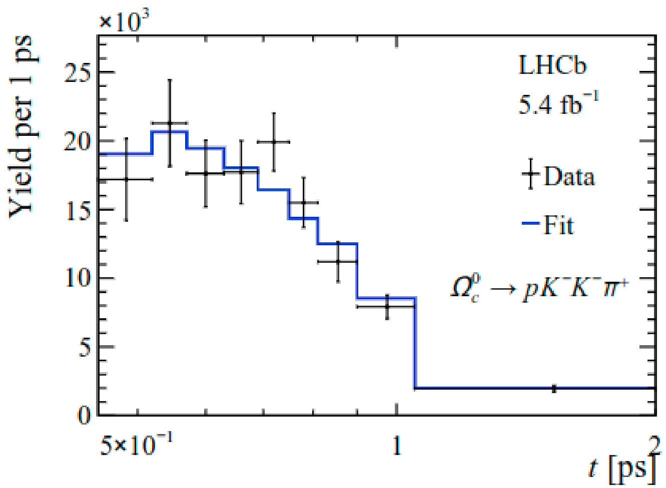
- Motivation for a combined analysis.
- Charm at LHCb can be prompt or produced in SL B decays, which lead to different systematics and experimental effects → important to crosscheck when possible.
  - The previous, most precise result was obtained using SL decays.
- Using D^0 as a control mode.

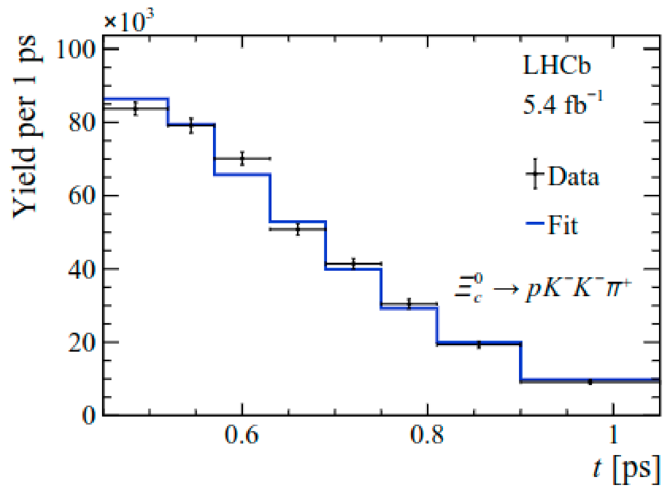
Measurement of the lifetimes of promptly produced Ω_c^0 and Ξ_c^0 baryons

arXiv:2109.01334



- Selecting promptly produced baryons relies on χ^2(IP) cuts
  - Difficult to model as there are simulation discrepancies
- Lifetime fit using a template.



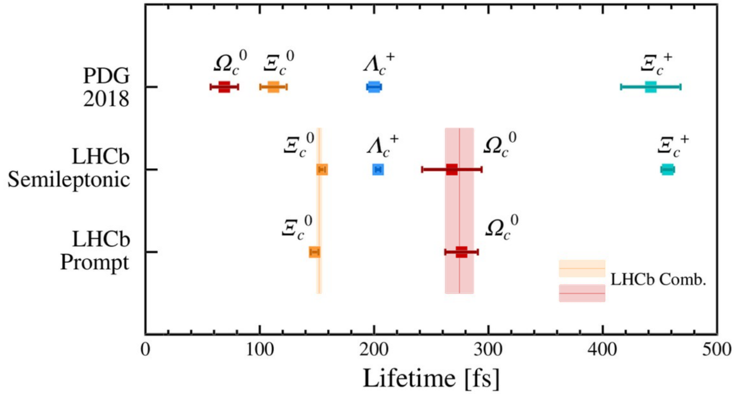


- Measured lifetimes: $\tau_{\Omega_c^0} = 276.5 \pm 13.4 \pm 4.4 \pm 0.7\,\text{fs}$, and $\tau_{\Xi_c^0} = 148.0 \pm 2.3 \pm 2.2 \pm 0.2\,\text{fs}$,
- Confirms previous measurement and hierarchy, precision doubled for Ω_c.

Combined LHCb result:

$$\tau_{\Omega_c^0} = 274.5 \pm 12.4\,\text{fs},$$
$$\tau_{\Xi_c^0} = 152.0 \pm 2.0\,\text{fs}.$$

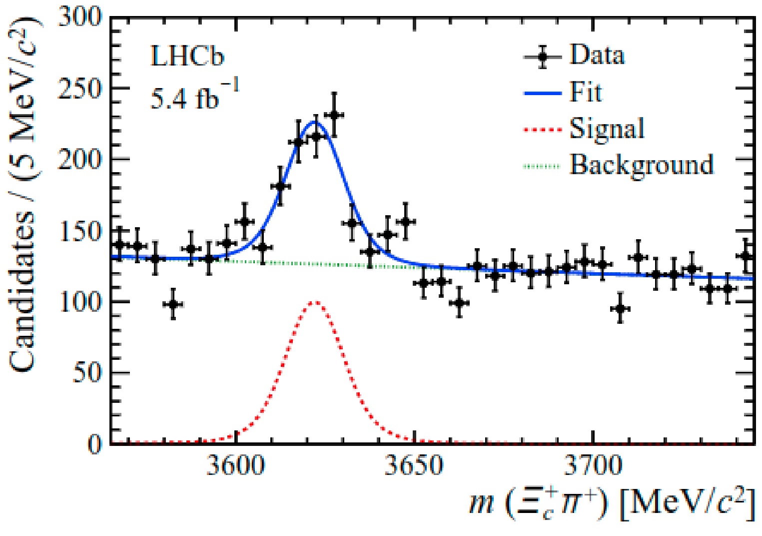
Hierarchy confirmed, discrepancy with PDG increasing.



Search for Ξ_{cc}^{+} in the $\Xi_c^{+}\pi^{-}\pi^{+}$ final state

arXiv:2109.07292

- Existence predicted by the SM and reported by SELEX in the $\Xi_{cc}^{+}\to\Lambda_c^{+}K^{-}\pi^{+}$ and $\Xi_{cc}^{+}\to pD^{+}K^{-}$ modes [Phys. Rev. Lett.89(2002) 112001, Phys.Lett.B628:18-24,2005]
  - No subsequent confirmations by Babar [Phys.Rev.D74:011103,2006], Belle [Phys.Rev.Lett.97:162001,2006] , FOCUS [Nucl.Phys.B Proc.Suppl. 115 (2003) 33-36], and LHCb [JHEP 1312 (2013) 090, Sci. China-Phys. Mech. Astron. 63, 221062 (2020)]
- Isospin partner to the well-established Ξ_{cc}^{++} baryon → most predictions constrain the lifetime ratio of the two states.
  - Using $\Xi_{cc}^{++}\to\Xi_c^{+}\pi^{+}$ as a normalisation channel.
- Using 2016-2018 dataset: 5.4 fb^{-1}.
- Also using 9 fb^{-1} of the previously studied $\Xi_{cc}^{+}\to\Lambda_c^{+}cK^{-}\pi^{+}$ in a combined search.



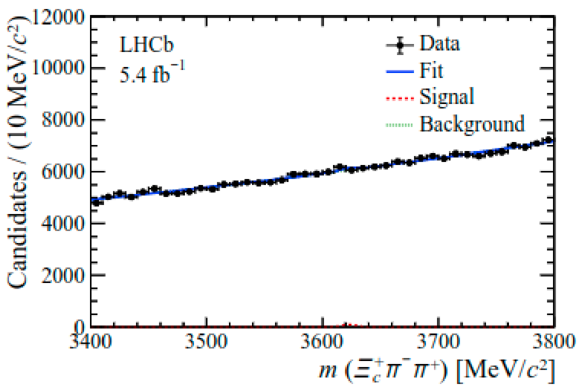
- Searches complicated by a priori shorter lifetime than that of Ξ_{cc}^{++} . Aim to measure this lifetime too.

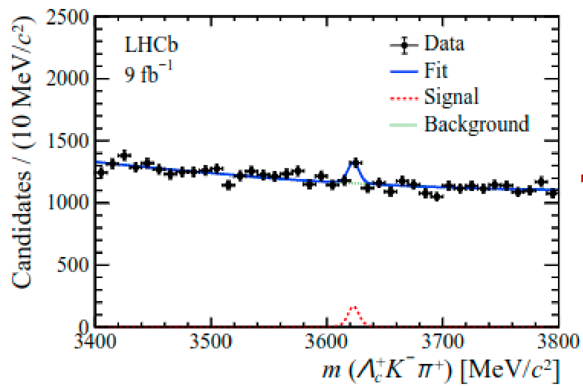
$$R \equiv \frac{\sigma(\Xi_{cc}^{+}) \times \mathcal{B}(\Xi_{cc}^{+}\to \Xi_c^{+}\pi^{-}\pi^{+})}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++}\to \Xi_c^{+}\pi^{+})} = \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}}\frac{N_{\rm sig}}{N_{\rm norm}} \equiv \alpha N_{\rm sig},$$

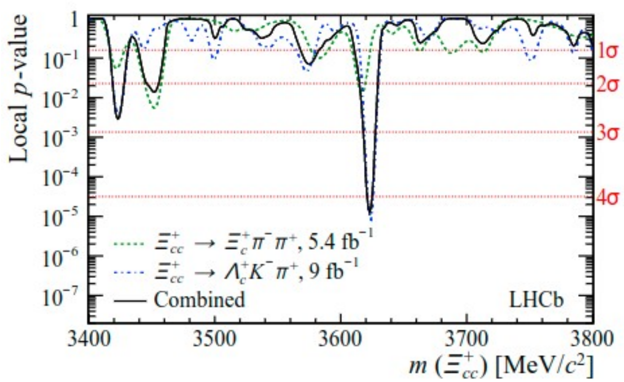
Search for Ξ_{cc}^{+} in the $\Xi_c^{+}\pi^{-}\pi^{+}$ final state

arXiv:2109.07292

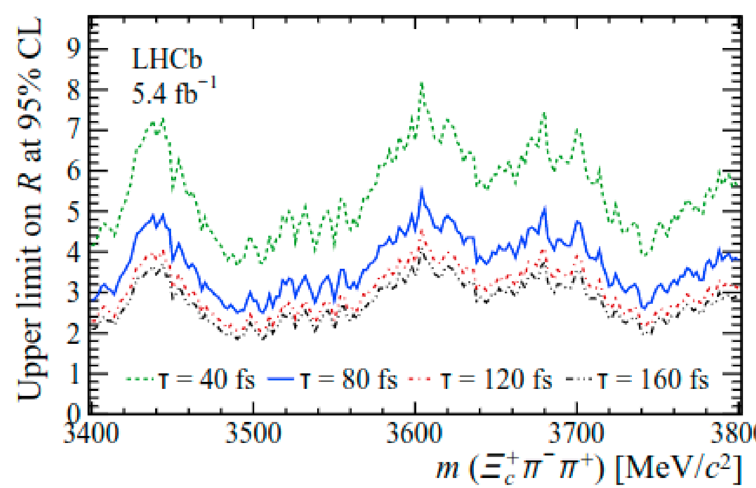
- Simultaneous fit to the two signal samples → challenging because of different purities.







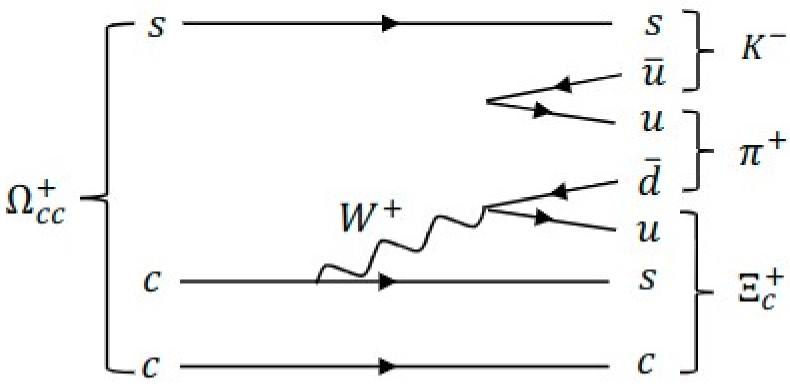
- No clear bump but possible signal around 3600 MeV/c^2.
- Evaluated combined local and global significances are determined to be 4.0 σ and 2.9 σ, respectively (window was 3.5-3.7 GeV).
- Ratio of production ratios with respect to that of Ξ_{cc}^{++} changes as a function of the Ξ_{cc}^{+} lifetime hypothesis.



Intriguing results, but no observation yet

Search for the doubly charmed baryon Ω_{cc}^{+}

SCI.CHINA PHYS.MECH.ASTRON. 64, 101062 (2021)



- Search in the $\Omega_{cc}^{+} \rightarrow \Xi_{c}^{+} K^{-} \pi^{+}$ final state.
- Mass predicted to be in the 3.6–3.9GeV/c^2 range and lifetime is predicted to be 75 – 180 fs.
- Destructive Pauli interference → lifetime expected to be larger than that of the Ξ_{cc}^{+} baryon [Phys. Rev. D 98, 113005 (2018)]:

$$\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+}) \quad \text{(expected)}$$

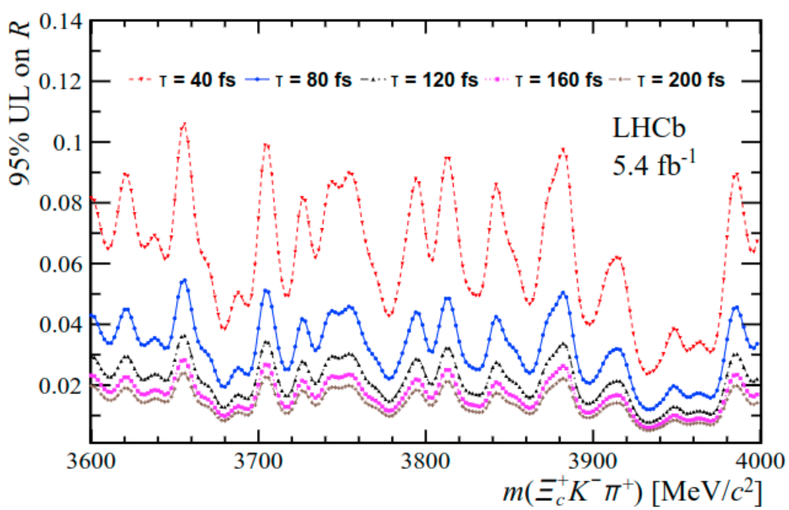
- Search using 2016-2018 data, using Ξ_{cc}^{++} as control.
- Two selections are used: selection A to maximise sensitivity to potential signal, and selection B to maximise sensitivity to the production ratio:

$$R \equiv \frac{\sigma(\Omega_{cc}^{+}) \times \mathcal{B}(\Omega_{cc}^{+} \rightarrow \Xi_{c}^{+} K^{-} \pi^{+}) \times \mathcal{B}(\Xi_{c}^{+} \rightarrow p K^{-} \pi^{+})}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_{c}^{+} K^{-} \pi^{+} \pi^{+}) \times \mathcal{B}(\Lambda_{c}^{+} \rightarrow p K^{-} \pi^{+})}$$

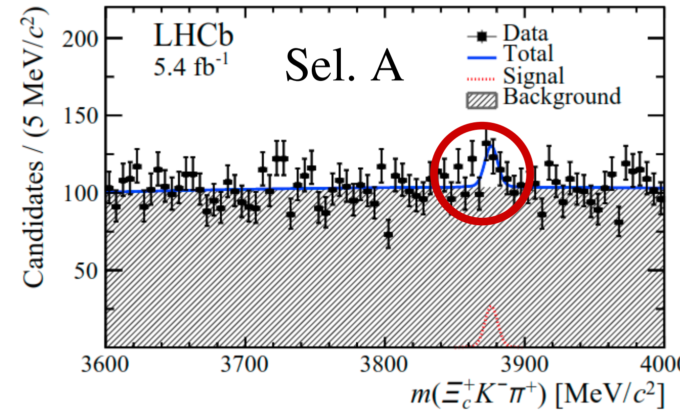
Search for the doubly charmed baryon Ω_{cc}^{+}

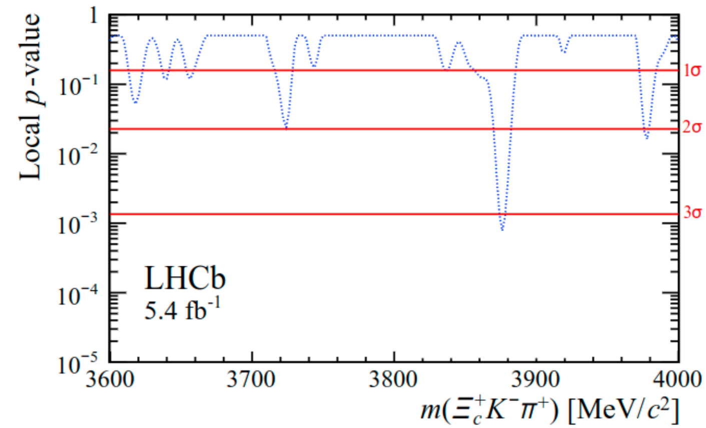
SCI.CHINA PHYS.MECH.ASTRON. 64, 101062 (2021)

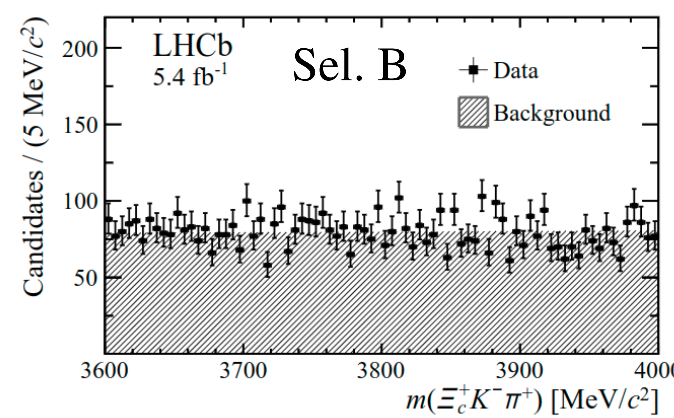
- Local > 3σ excess found near 3900 MeV/c^2, but with low (1.8σ) global significance
  - Using Selection B to set upper limit on R.
- As with the Ξ_{cc}^{+} search, the unknown lifetime of the state complicates the ratio calculation.
  - Lifetimes are varied in the simulation and efficiency ratios are corrected.



- Dominant systematics are the Ξ_{cc}^{++} lifetime and the hardware trigger.



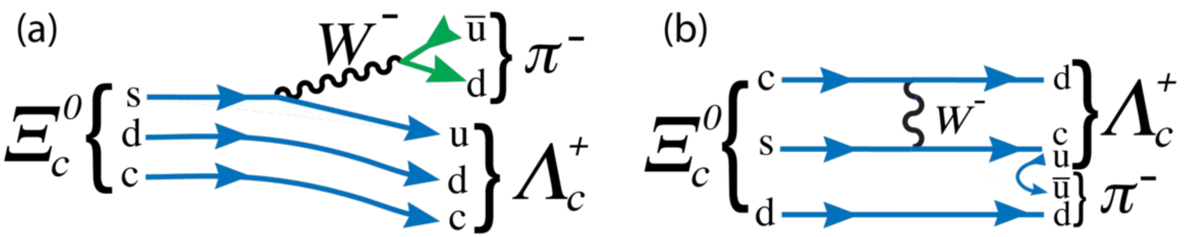




First branching fraction measurement of the suppressed decay $\Xi_c^0 \to \pi^- \Lambda_c^+$

PHYS. REV. D102 (2020) 071101(R)

- Ξ_c^0 usually decays to charmless final states but can decay to Λ_c^+ via s quark decay (a) or cs→cd scattering (b).



- Depending on the interference patterns of the two amplitudes, different predictions, for instance $B(\Xi_c^0 \to \pi^- \Lambda_c^+) = (0.14 \pm 0.07)\%$ or $< (0.018 \pm 0.015)\%$.
- Analysis using 2017 and 2018 data (3.8 fb^{-1}), and prompt-produced Ξ_c^0 baryons.
- Two normalisations:
  - Method 1 uses the LHCb measurement of relative production fractions of the Ξ_b^- and Λ_b^0
  - Method 2 uses Belle measurement of $B(\Xi_c^+ \to pK^-\pi^+) = (0.45 \pm 0.21 \pm 0.07)\%$ [Phys. Rev.D100(2019) 031101].

$$\mathcal{R}_1 \equiv \frac{N(\Xi_c^0)}{N(\Lambda_c^+)} = \frac{f_{\Xi_c^0}}{f_{\Lambda_c^+}} \cdot \mathcal{B}(\Xi_c^0 \to \pi^- \Lambda_c^+) = (0.095 \pm 0.003 \pm 0.012)\%,$$

$$\mathcal{R}_2 \equiv \frac{N(\Xi_c^0)}{N(\Xi_c^+)} = \frac{f_{\Xi_c^0}}{f_{\Xi_c^+}} \cdot \frac{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)} \cdot \mathcal{B}(\Xi_c^0 \to \pi^- \Lambda_c^+) = (5.70 \pm 0.19 \pm 0.77)\%$$

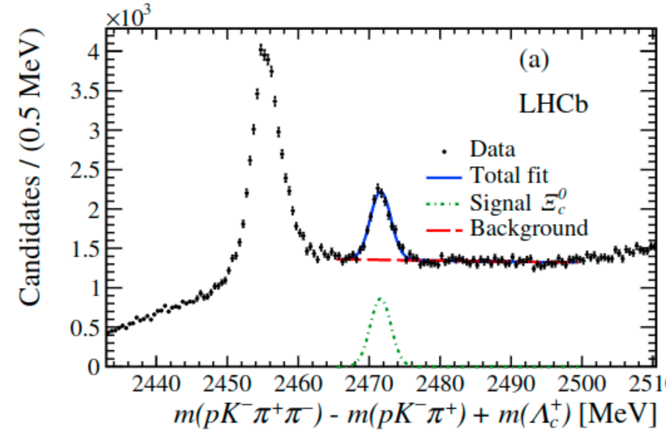
First branching fraction measurement of the suppressed decay $\Xi_c^0 \to \pi^- \Lambda_c^+$

PHYS. REV. D102 (2020) 071101(R)

- Bonus: we also measure $B(\Xi_c^+ \to pK^-\pi^+)$ using:

$$\mathcal{R}_3 \equiv \frac{N(\Xi_c^+)}{N(\Lambda_c^+)} = \frac{f_{\Xi_c^+}}{f_{\Lambda_c^+}} \cdot \frac{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.753 \pm 0.003 \pm 0.107)\%$$

- Right: clear signal observed.

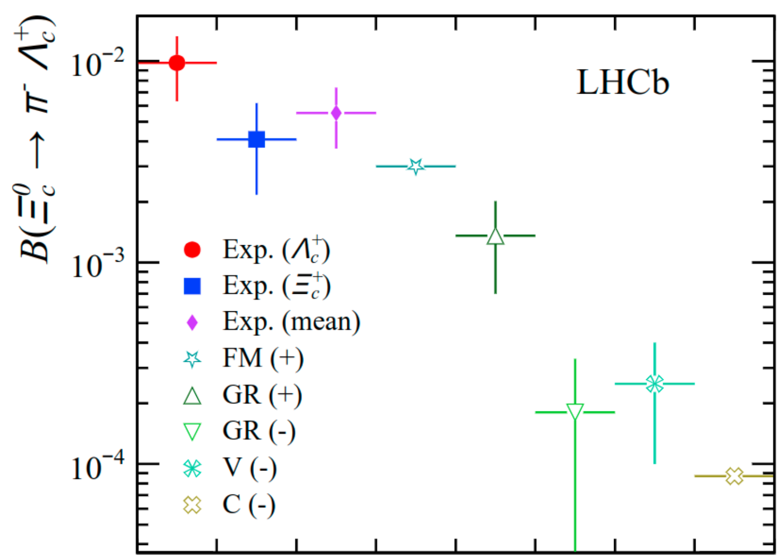


- We combine the three ratios using their correlation matrix, obtaining:

$$\mathcal{B}(\Xi_c^0 \to \pi^- \Lambda_c^+) = (0.55 \pm 0.02 \pm 0.18)\%$$
$$\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = (1.135 \pm 0.002 \pm 0.387)\%$$

- Results are consistent with **constructive** interference.

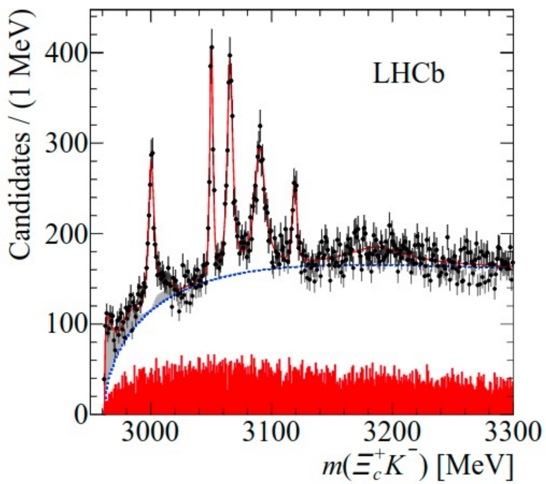
- Ξ_c^+ branching fraction larger, but in agreement with previous Belle measurement, with better relative precision.



Observation of new Ξ_c^0 baryons decaying to $\Lambda_c^+K^-$

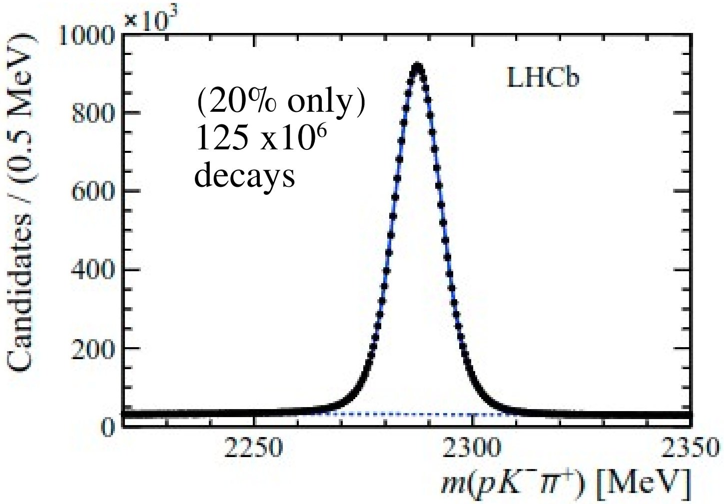
PHYS. REV. LETT. 124 (2020) 222001

- In 2017, observation of 5 new Ωc baryons [Phys. Rev. Lett. 118, 182001 (2017)]
  - narrow widths not clearly understood.
  - similar trend in excited Ω_b^- states decaying to $\Xi_b^0K^-$ [Phys. Rev. Lett. 124, 082002 (2020)]



- Investigating a different charmed mass spectrum could lead to a better understanding of this feature.
  - $\Xi_c(2930)^0$ already possibly seen by Babar and Belle.

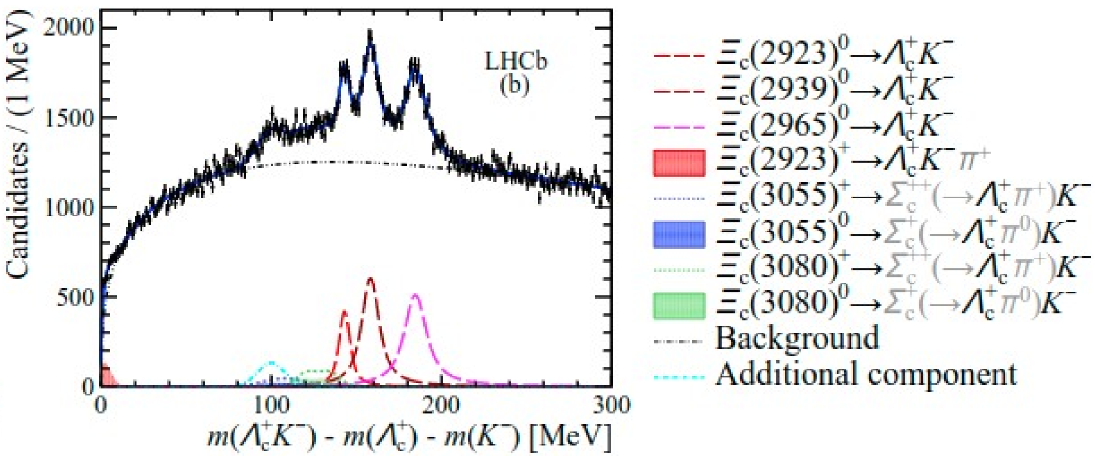
- Analysis of 2016-2018 data → 5.8 fb^{-1}.
  - Still more than 100 millions Λ_c decays.



Observation of new Ξ_c^0 baryons decaying to $\Lambda_c^+K^-$

PHYS. REV. LETT. 124 (2020) 222001

- Three narrow structures observed in the invariant-mass distribution.
  - Not seen in the "wrong-sign" sample, nor in the Λ_c sidebands



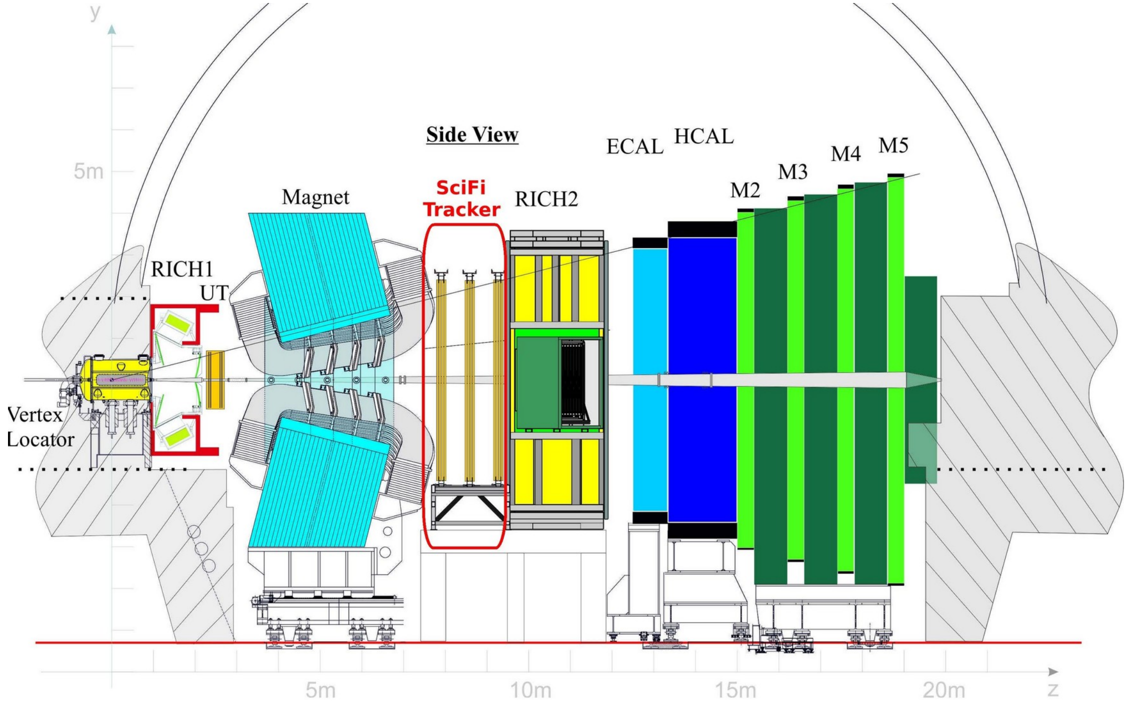
$$
\begin{aligned}
m(\Xi_c(2923)^0) &= 2923.04 \pm 0.25 \pm 0.20 \pm 0.14\,\text{MeV}, \\
\Gamma(\Xi_c(2923)^0) &= 7.1 \pm 0.8 \pm 1.8\,\text{MeV}, \\
m(\Xi_c(2939)^0) &= 2938.55 \pm 0.21 \pm 0.17 \pm 0.14\,\text{MeV}, \\
\Gamma(\Xi_c(2939)^0) &= 10.2 \pm 0.8 \pm 1.1\,\text{MeV}, \\
m(\Xi_c(2965)^0) &= 2964.88 \pm 0.26 \pm 0.14 \pm 0.14\,\text{MeV}, \\
\Gamma(\Xi_c(2965)^0) &= 14.1 \pm 0.9 \pm 1.3\,\text{MeV},
\end{aligned}
$$

- $\Xi_c(2930)^0$ not seen → overlap between $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$?
- $\Xi_c(2965)^0$ width very different from that of $\Xi_c(2970)^0$ → different baryon?
- Equal spacing rule seems to hold

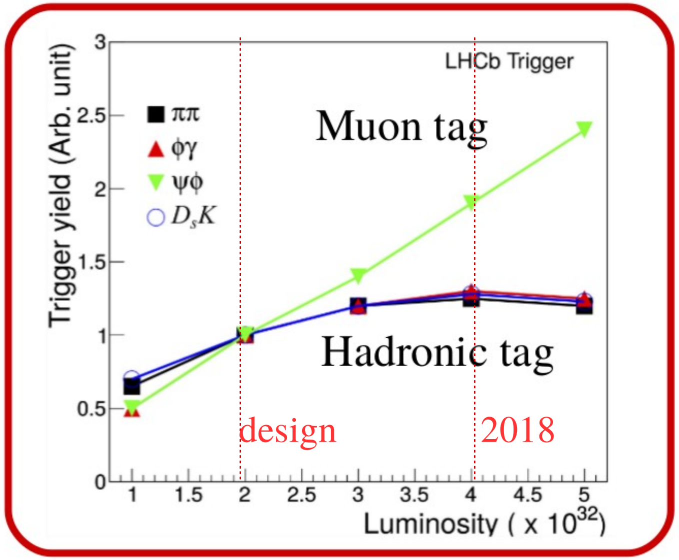
  → related to the newly discovered Ω_c baryons?

$$
\begin{aligned}
m(\Omega_c(3050)^0) - m(\Xi_c(2923)^0) \simeq m(\Xi_c(2923)^0) - m(\Sigma_c(2800)^0) &\simeq 125\,\text{MeV}, \\
m(\Omega_c(3065)^0) - m(\Xi_c(2939)^0) &\simeq 125\,\text{MeV}, \\
m(\Omega_c(3090)^0) - m(\Xi_c(2965)^0) &\simeq 125\,\text{MeV}.
\end{aligned}
$$

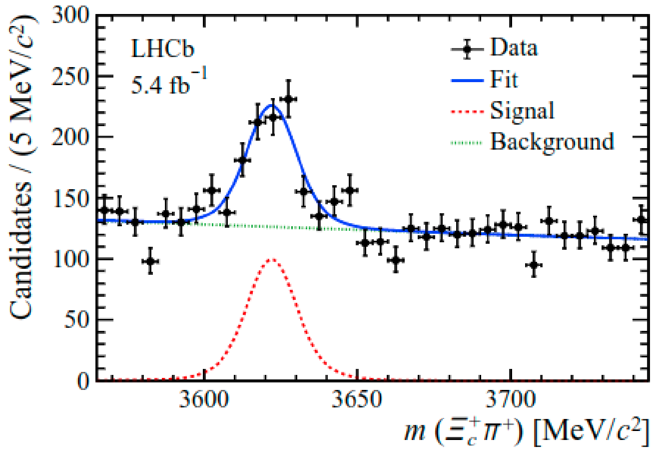
A glimpse into the future: the LHCb upgrade



- LHCb Upgrade is around the corner → more proper to call it a new detector.
- New VELO: better lifetime resolution.
- Different subdetectors and improved technologies: able to withstand larger luminosities than before.
- Overhauled, fully software trigger: increased trigger efficiencies, especially on charm and low-p_T modes.
  - Bonus: potentially easier systematic errors as previous trigger relied heavily on the CALO and its corrections.



Conclusion



- Lots of new charm results in the last years.
- New observations become normalisation channels with increasing statistics.
- LHCb upgrade will produce much, much more data

  → are we statistically limited? Which are the systematics of tomorrow?

- No single answer: reported results cover very different regimes.
  - Baron lifetimes is dominated by fit model, kinematic corrections and decay-time resolution → first two should go down with more statistics, the third with the new VELO [LHCB-TDR-013].
  - The search for Ξ_{cc}^{+} is completely dominated by statistics, and the ratio of production by the Ξ_{cc}^{++} lifetime.
- Whether in search for new modes, exploration of recently discovered hadrons, or precision measurements, lots of new results to be expected with Run 3.