Charm decays at LHCb

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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. $\Xi_{cc}^{++}$).
Overview of past discoveries

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

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In this talk

59 new hadrons at the LHC

~Charm
We could have called it LHCc

- 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.

\[ \delta p/p \approx 0.5\% \]

for Long tracks

95% $K/\pi$ separation efficiency for 5% misID
Measurement of the lifetimes of promptly produced $\Omega_c^0$ and $\Xi_c^0$ baryons

- 7$\sigma$ inconsistency between LHCb measurement and world average for the $\Omega_c$ 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 $\Omega_c^0$ and $\Xi_c^0$ baryons

- Selecting promptly produced baryons relies on $\chi^2$(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 $\Omega_c$.

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 $\Xi_{cc}^{*+}$ in the $\Xi_{c}^{+}\pi^{-}\pi^{+}$ final state

- Existence predicted by the SM and reported by SELEX in the $\Xi_{cc}^{*+}\rightarrow\Lambda_{c}^{+}K^{-}\pi^{+}$ and $\Xi_{cc}^{*+}\rightarrow pD^{+}K^{-}$ modes [Phys. Rev. Lett.89(2002) 112001, Phys.Lett.B628:18-24,2005]

- Isospin partner to the well-established $\Xi_{cc}^{++}$ baryon $\rightarrow$ most predictions constrain the lifetime ratio of the two states.
  - Using $\Xi_{cc}^{++}\rightarrow\Xi_{c}^{+}\pi^{+}$ as a normalisation channel.

- Using 2016-2018 dataset: 5.4 fb$^{-1}$.

- Also using 9 fb$^{-1}$ of the previously studied $\Xi_{cc}^{*+}\rightarrow\Lambda_{c}^{+}cK^{-}\pi^{+}$ in a combined search.

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

$$R = \frac{\sigma(\Xi_{cc}^{*+}) \times B(\Xi_{cc}^{*+}\rightarrow\Xi_{c}^{+}\pi^{-}\pi^{+})}{\sigma(\Xi_{cc}^{++}) \times B(\Xi_{cc}^{++}\rightarrow\Xi_{c}^{+}\pi^{+})} = \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \frac{N_{\text{sig}}}{N_{\text{norm}}} \equiv \alpha N_{\text{sig}},$$
Search for $\Xi_{cc}^+$ in the $\Xi_c^+\pi^-\pi^+$ final state

- 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 $\sigma$ and 2.9 $\sigma$, respectively (window was 3.5-3.7 GeV).

- Ratio of production ratios with respect to that of $\Xi_{cc}^{++}$ changes as a function of the $\Xi_{cc}^+$ lifetime hypothesis.

Intriguing results, but no observation yet
Search for the doubly charmed baryon $\Omega_{cc}^+$

- Search in the $\Omega_{cc}^+ \to \Xi_c^+ K^−\pi^+$ final state.

- Mass predicted to be in the $3.6−3.9\text{GeV}/c^2$ range and lifetime is predicted to be $75 − 180$ fs.

- Destructive Pauli interference $\Rightarrow$ lifetime expected to be larger than that of the $\Xi_{cc}^+$ baryon [Phys. Rev. D 98, 113005 (2018)]:

  \[ \tau(\Xi^{++}_{cc}) > \tau(\Omega^+_{cc}) > \tau(\Xi^+_{cc}) \] (expected)

- Search using 2016-2018 data, using $\Xi_{cc}^{++}$ as control.

- Two selections are used: selection A to maximise sensitivity to potential signal, and selection B to maximise sensitivity to the production ratio:

  \[ R \equiv \frac{\sigma(\Omega^+_{cc}) \times \mathcal{B}(\Omega^+_{cc} \to \Xi_c^+ K^−\pi^+) \times \mathcal{B}(\Xi^+_{cc} \to pK^−\pi^+)}{\sigma(\Xi^{++}_{cc}) \times \mathcal{B}(\Xi^{++}_{cc} \to \Lambda_c^+ K^−\pi^+\pi^+) \times \mathcal{B}(\Lambda^+_{cc} \to pK^−\pi^+)} \]
Search for the doubly charmed baryon $\Omega_{cc}^+$

- Local $> 3\sigma$ excess found near 3900 MeV/c$^2$, but with low (1.8\sigma) global significance
  - Using Selection B to set upper limit on R.

- As with the $\Xi_{cc}^+$ 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 $\Xi_{cc}^{++}$ lifetime and the hardware trigger.
First branching fraction measurement of the suppressed decay $\Xi_c^0 \rightarrow \pi^- \Lambda_c^+$

- $\Xi_c^0$ usually decays to charmless final states but can decay to $\Lambda_c^+$ via $s$ quark decay (a) or $cs \rightarrow cd$ scattering (b).

- Depending on the interference patterns of the two amplitudes, different predictions, for instance $B(\Xi_c^0 \rightarrow \pi^- \Lambda_c^+) = (0.14 \pm 0.07)\%$ or $< (0.018 \pm 0.015)\%$.

- Analysis using 2017 and 2018 data ($3.8 \text{ fb}^{-1}$), and prompt-produced $\Xi_c^0$ baryons.

- Two normalisations:
  - Method 1 uses the LHCb measurement of relative production fractions of the $\Xi_b^-$ and $\Lambda_b^0$
  - Method 2 uses Belle measurement of $B(\Xi_c^+ \rightarrow pK^-\pi^+) = (0.45 \pm 0.21 \pm 0.07)\%$ [Phys. Rev.D100(2019) 031101].

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

\[
\mathcal{R}_2 \equiv \frac{N(\Xi_c^0)}{N(\Xi_c^+)} = \frac{f_{\Xi_c^0}}{f_{\Xi_c^+}} \cdot \frac{B(\Lambda_c^+ \rightarrow pK^-\pi^+)}{B(\Xi_c^+ \rightarrow pK^-\pi^+)} \cdot B(\Xi_c^0 \rightarrow \pi^- \Lambda_c^+) = (5.70 \pm 0.19 \pm 0.77)\%.
\]
First branching fraction measurement of the suppressed decay $\Xi_{c}^0 \rightarrow \pi^- \Lambda_{c}^+$

- Bonus: we also measure $B(\Xi_{c}^+ \rightarrow pK^- \pi^+)$ using:
  
  $$R_3 \equiv \frac{N(\Xi_{c}^+)}{N(\Lambda_{c}^+)} = \frac{f_{\Xi_{c}^+}}{f_{\Lambda_{c}^+}} \cdot \frac{B(\Xi_{c}^+ \rightarrow pK^- \pi^+)}{B(\Lambda_{c}^+ \rightarrow pK^- \pi^+)} = (1.753 \pm 0.003 \pm 0.107)\%$$

- Right: clear signal observed.

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

  $$B(\Xi_{c}^0 \rightarrow \pi^- \Lambda_{c}^+) = (0.55 \pm 0.02 \pm 0.18)\%$$

  $$B(\Xi_{c}^+ \rightarrow pK^- \pi^+) = (1.135 \pm 0.002 \pm 0.387)\%$$

- Results are consistent with constructive interference.

- $\Xi_{c}^+$ branching fraction larger, but in agreement with previous Belle measurement, with better relative precision.
Observation of new $\Xi_c^0$ baryons decaying to $\Lambda_c^+K^-$

- In 2017, observation of 5 new $\Omega_c$ baryons [Phys. Rev. Lett. 118, 182001 (2017)]
  - narrow widths not clearly understood.
  - similar trend in excited $\Omega_b^-$ 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 $\Lambda_c$ decays.
Observation of new $\Xi_c^0$ baryons decaying to $\Lambda_c^+K^-$

- Three narrow structures observed in the invariant-mass distribution.
  - Not seen in the “wrong-sign” sample, nor in the $\Lambda_c$ sidebands

$\Xi_c(2930)^0$ 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 $\Omega_c$ baryons?

$$ m(\Omega_c(3050)^0) - m(\Xi_c(2923)^0) \simeq m(\Xi_c(2923)^0) - m(\Sigma_c(2800)^0) \simeq 125 \text{ MeV}, $$

$$ m(\Omega_c(3065)^0) - m(\Xi_c(2939)^0) \simeq 125 \text{ MeV}, $$

$$ m(\Omega_c(3090)^0) - m(\Xi_c(2965)^0) \simeq 125 \text{ MeV}. $$
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 $\Xi_{cc}^{+}$ is completely dominated by statistics, and the ratio of production by the $\Xi_{cc}^{++}$ 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.