300 fb^{-1} Charm - Baryons

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Outline

- Charm physics at LHCb has been incredibly successful.
- Less work in charmed baryons to date - but this is changing.
- Many analyses we can and should be doing.
- Which of these are possible now?
- Which need the 300 fb^{-1} upgrade?
- What is likely to limit our results?

Current topics in charmed baryons

- Spectroscopy:
  - Double and triple heavy baryons - is SELEX candidate real? Opportunities to study HQET in new quark configurations.
  - Single charm - branching fractions, lifetimes, excited states.
- Rare Λ_c^+ decays. Can probe:
  - $|\mathrm{B}-\mathrm{L}| = 0$ (e.g. $\Lambda_c \to 3\mu$)
  - FCNC (e.g. $\Lambda_c^+ \to \mu^-\mu^+$)
- Amplitude analysis. First charmed baryon decay 15 years ago ($\Lambda_c^+ \to pK^-\pi^+$ from E791 - Phys.Lett.B471:449-459) - nothing else from any other experiment! LHCb can study a huge number of new decays for the first time.
- *CP*-violation - both global asymmetries ($\Delta\mathcal{A}^{CP}$) or "Dalitz" (but with helicity).

What needs more data?

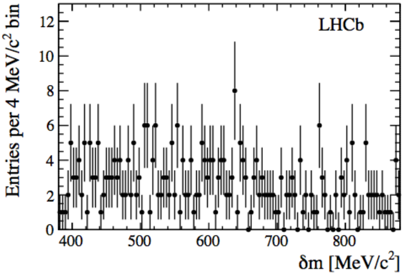
- Most of these analyses are *probably* possible to world best precision with Run I data alone.
- But one or two channels which stand out to me as probably being quite lucrative with a huge dataset.
- Will try to cover each topic and see what LHCb's "end game" consists of.

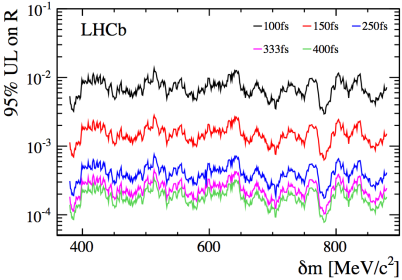
Spectroscopy - single charm

- Single charm lifetimes, branching fractions - can probe nearly all to WB with Run I.
  - Few exceptions - absolute branching fractions where BES3, Belle etc. beat us.
  - For everything else Λ_c, Σ_c etc. our dataset is the largest and will continue to grow in Run II.
  - No lifetimes or non-rare branching fractions which are strongly affected by any potential NP.
- I don't think any single charm channel would benefit from 300 fb^{-1} **for spectroscopy purposes.**

Spectroscopy - double charm

- What about double charm? LHCb already published 2011 search. Probes ratio of Λ_c^+ to Ξ_{cc}^+ production (called R). 95 % ULs shown right for multiple Ξ_{cc}^+ lifetime hypotheses.
- Expected value of R at LHCb is of order $10^{-5} - 10^{-4}$





- Ability to probe this very dependent on Ξ_{cc}^+ lifetime.
- Predicted to be $\tau(\Xi_{cc}^+)$: 100 – 250 (Eur. Phys. J. A45 (2010) 267)
- But SELEX candidate has lifetime consistent with zero.

Spectroscopy - double charm prospects

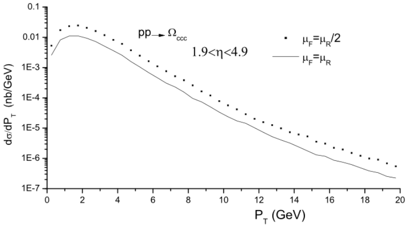
- Search with full Run I data already underway. Expect many improvements over 2011 analysis.
  - Improvements to trigger selection for $\Xi_{cc}^{+} \rightarrow \Lambda_{c}^{+}(pK^{-}\pi^{+})K^{-}\pi^{+}$.
  - Inclusion of new modes like $\Xi_{cc}^{+} \rightarrow (D^{+} \rightarrow K^{-}\pi^{+}\pi^{+})p^{+}K^{-}$, which should be considerably more efficient.
  - My naive expectation - should increase sensitivity by around factor 10 - decent chance of finding a longer lifetime Ξ_{cc}^{+}.
- Even if shorter lifetime - production cross section should roughly double at 14 TeV.
- Would expect even a short lifetime Ξ_{cc}^{+} candidate to be observable in Run II data.

Spectroscopy - triple heavy baryons

- What about the triple heavy baryons?
- Very interesting place to study HQET - entirely new regime to explore.

- Using calculated cross sections from Chen, Wu (JHEP 1108 (2011) 144) and Chang et. al (J.Phys. G34 (2007) 845).

	Run I	Run II	Run III
Ξ_{cc}^{+}	1.5×10^8	7×10^8	1.5×10^9
Ω_{ccc}^{+++}	5×10^3	3×10^4	6×10^4
Ω_{ccb}^{+++}	2×10^2	1.5×10^3	3×10^3



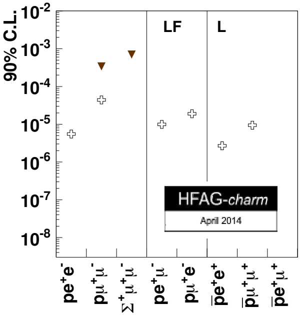
- Ω_{ccc}^{+++} production at LHCb from JHEP 1108 (2011) 144

- We likely produce too little triple charm to be studied with planned dataset.
- With 300 fb^{-1} we could remedy this.
- But next to no work been done on feasibility studies.
- Decays are cascading weak decays with pions - could be a nightmare to reconstruct, especially in high luminosity environment.
- **My feeling - these are worth exploring, at least in a preliminary fashion, as part of the Charm 300 fb^{-1} remit (even if likely to be ruled out)**

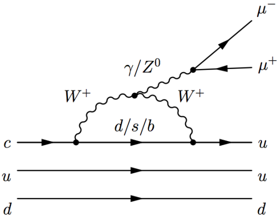
Rare decays

- LHCb published $\tau \to 3\mu$ and $\tau \to p\mu\mu$ searches
  Phys.Lett.B724(2013), JHEP 02 (2015) 121
- First direct experimental limits on
  $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^+\mu^-$
- Analogous channels for Λ_c:

$$\begin{aligned} \tau \to 3\mu \ (\mathrm{LFV}) \ &: \Lambda_c \to 3\mu \ (|\mathrm{B}-\mathrm{L}| = 0) \\ \tau^+ \to p\mu^-\mu^+ \ (|\mathrm{B}-\mathrm{L}| = 0) \ &: \Lambda_c^+ \to \mu^-\mu^+ \ (\mathrm{FCNC}) \\ \tau^+ \to \bar{p}\mu^+\mu^+ \ (|\mathrm{B}-\mathrm{L}| = 0) \ &: \Lambda_c^+ \to \bar{p}\mu^+\mu^+ \ (|\mathrm{B}-\mathrm{L}| = 0) \end{aligned}$$



- Current limits at 90% CL:
  - $\mathcal{B}(\Lambda_c^+ \to p\mu^-\mu+) < 4.4 \times 10^{-5}$
    $\mathcal{B}(\Lambda_c^+ \to \bar{p}\mu^+\mu^+ < 9.4 \times 10^{-6}$
    Babar - Phys. Rev. D84 (2011) 072006
  - $\mathcal{B}(\Lambda_c^+ \to 3\mu)$ - no constraints.
- LHCb should probe $\Lambda_c^+ \to p\mu^-\mu^+$ to $\mathcal{O}(10^{-7})$ with current dataset.
- After Run III down to $\mathcal{O}(10^{-8})$ - level at which interesting effects may be observed.



Rare decays

- Still some scope for investigation here.
- Questions needing answered.
  - What exact NP are these sensitive to? Long distance interaction, W emission - does this count out too many interesting channels relative to rare charm meson and τ decays?
  - Channels are often very clean - dimuon and proton signatures, trimuon signatures should be very clean, even in high lumi environment.
- My feeling - these rare charm baryon decays should be considered by our experts on rare decays. I don't feel too qualified to make any definitive statements here.

Charmed baryon amplitude analysis

- First multidimensional amplitude analysis of a charmed baryon decay from E791 15 years ago.
- Experimentally challenging: three-body $D \rightarrow hhh$ meson decays fully parameterised by $m(h_1 h_2)$ and $m(h_2 h_3)$.
- But baryons carry spin. Differential rate as function of Λ_c polarisation $\mathbf{P}_{\mathbf{\Lambda_c}}$:

$$\mathrm{d}\Gamma \sim \frac{1+\mathbf{P}_{\mathbf{\Lambda_c}}}{2}\left(|\sum_r B_r(m_r)\alpha_{r,\frac{1}{2},\frac{1}{2}}|^2 + |\sum_r B_r(m_r)\alpha_{r,\frac{1}{2},-\frac{1}{2}}|^2\right) + \frac{1-\mathbf{P}_{\mathbf{\Lambda_c}}}{2}\left(|\sum_r B_r(m_r)\alpha_{r,-\frac{1}{2},\frac{1}{2}}|^2 + |\sum_r B_r(m_r)\alpha_{r,-\frac{1}{2},-\frac{1}{2}}|^2\right)$$

- $\alpha_{r,m,\lambda_{\mathrm{p}}}$ is complex decay amplitude for resonance r with spin m (Λ_c spin projection onto beam-axis) and proton helicity λ_{p} in Λ_c rest frame, $B_r(m_r)$ Breit-Wigner amplitude.
- Need 5 vars to parameterise decay - $m(h_1 h_2)$, $m(h_2 h_3)$ and *3 helicity angles*.
- **We probably are already systematically limited here by acceptance effects. Statstics should already be sufficient with Run I data.**

CPV in charmed baryons

- Weakly decaying baryons: Λ_c^+, Ξ_c^0, Ξ_c^+, Ω_c^0.
- Complementary to charmed mesons, direct asymmetries in their decays see Bigi, arXiv:1206.4554 [hep-ph]:

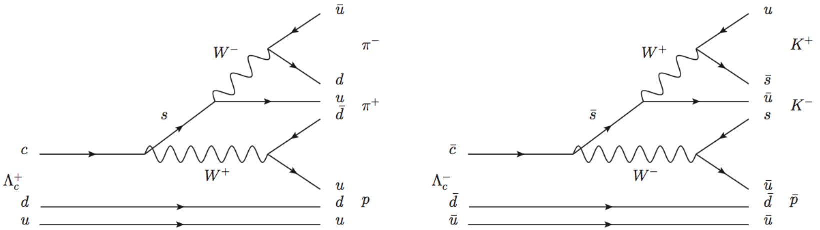
$$\mathcal{A}^{CP}(\Lambda_c^+ \to f) = \frac{\Gamma(\Lambda_c^+ \to f^+) - \Gamma(\Lambda_c^+ \to f^-)}{\Gamma(\Lambda_c^+ \to f^+) + \Gamma(\Lambda_c^+ \to f^-)} \sim |r| \sin(\Delta_s) \sin(\Theta)$$

- where Δ_s/Θ are differences between strong/CPV phases of SM and NP contributions
- May provide access to NP: SM backgrounds lower than meson sector.
- Can access experimentally via:

$$A_{Raw}^{\Lambda_c}(h) = \frac{N(\Lambda_c^+ \to ph^+h^-) - N(\Lambda_c^- \to ph^+h^-)}{N(\Lambda_c^+ \to ph^+h^-) + N(\Lambda_c^- \to ph^+h^-)}$$

- But underlying production and detection assymetries too.

$\Delta\mathcal{A}^{CP}$ in $\Lambda_c^+ \to phh'$ Decays



- Production and detector asymmetries mostly cancelled by taking difference:

$$\Delta A_{CP}^{\Lambda_c} = A_{Raw}^{\Lambda_c}(K) - A_{Raw}^{\Lambda_c}(\pi) \approx A_{CP}^{\Lambda_c}(K) - A_{CP}^{\Lambda_c}(\pi)$$

- In SCS modes should be close to zero in SM: $\mathcal{O}(10^{-4})$
- First studies well underway with Run I data.
- Limiting factor - how well do proton asymmetries cancel?
- Longer term prospects:
  - CPV in DCS - SM even smaller CP asymmetry than SCS - possible window to NP?
  - Examine local assymetries in “Dalitz” plot, e.g. Miranda method (Phys.Rev.D80 (2009) 096006) - local asymmetries stronger than global.

CP-violation in DCS $\Lambda_c^+ \to p\pi^- K^+$ decays

- Bigi thinks that the DCS mode would be an excellent probing ground for new physics:
    - "SM produces only one quark amplitude for DCS transitions; therefore SM cannot produce CP asymmetry. Furthermore the size of SM amplitudes are very much suppressed to give more sensitivity to the impact of ND"
- Exchange amplitudes are short range - plenty of interesting NP that can be probed.
- But not much quantitative theoretical work has gone on here.
- For this mode, expect visible peaks in 2011 search (currently ongoing), but small.
- To probe these possible asymmetries we could need a very large dataset, but i have no idea how much.
- Limiting factor in present SCS $\Lambda_c^+ \to phh'$ analyses looks to be the proton detection asymmetry.
- But that may be scalable with luminosity! More data will yield more viable calibration channels - possibly more precision on systematics.
- **Merits some further study - one of the few charmed baryon channels with keen access to new physics.**

Conclusions

- Despite the huge number of charmed baryon analyses avaiable to LHCb, limited data is rarely a problem.
- More likely to be systematically limited, or just not need more precision on a result than we can presently obtain.
- Despite this, some interesting prospects for a potential 300 fb^{-1} upgrade.
  - Triple heavy baryons may become a possibility.
  - Some rare charm decays *could* be theoretically interesting enough, and probe interesting limits.
  - *CP*-violation in suppressed Λ_c decays could be of remarkable interest for exploring NP - if we can keep systematics under control.
- But all of these of course need further study. Many or all may be unfeasible in high lumi environment.
- And of course, are they swept away by other, more promising benchmark decays which the collaboration may wish to prioritise?