Charmed baryons from LHCb

Charm 2015 Detroit
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on behalf of the LHCb collaboration

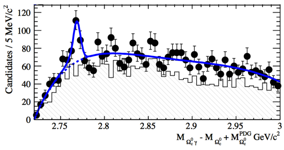
University of Glasgow

Outline

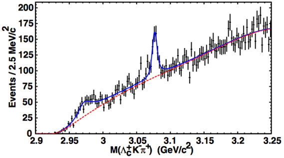
- The LHCb charmed baryon programme
- Recent results:
  - Λ_c^+ production
  - Doubly-charmed baryon searches
- Analyses underway with Run I data:
  - Precision measurements - lifetimes, branching fractions...
  - *CP*- violation and amplitude analyses
  - Searches for new states
  - Rare Λ_c decays
- And some prospects for the future

Charm baryon spectra - experiment

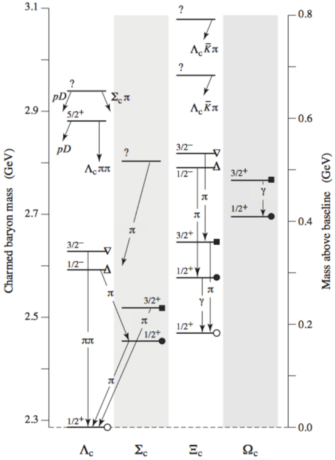
- Considerable progress in past 10 years on measuring charm baryon spectra.
- Variety of Σ_c, Ω_c and Ξ_c states identified by the B factories.
- Quark model has been very successful in predicting masses of singly charmed states, and mass splittings.
- Still an open question if calculations will work equally well on double and triple charm baryons.



$\Omega_c(2770)^0$ at BaBar - Phys. Rev. Lett. 97, 232001



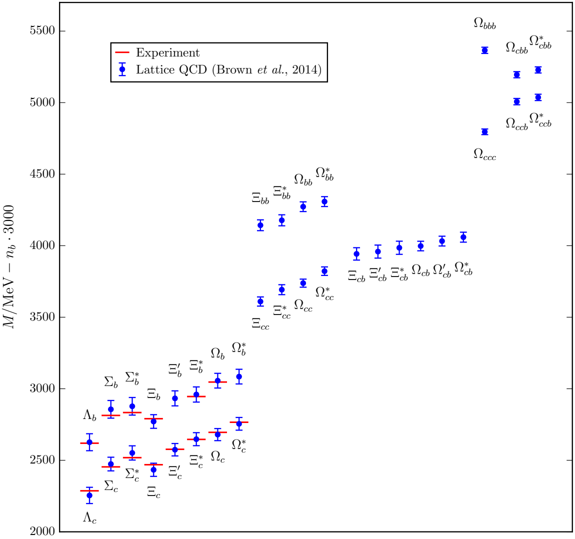
$\Xi_c(2980)$ and $\Xi_c(3077)$ at BELLE - Phys. Rev. Lett. 97, 162001



Baryon Spectra - Phys. Rev. D86, 010001 (2012)

Charm baryon spectra - theory

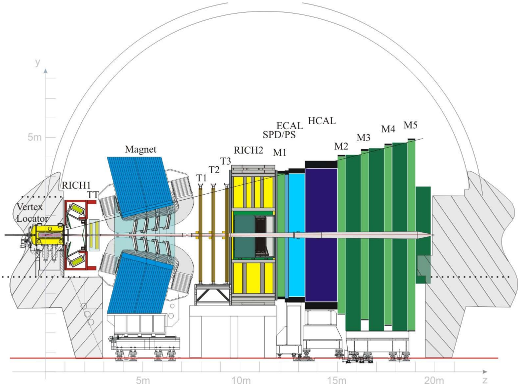
- Shown: predicted charm/beauty baryon states from lattice QCD (Brown, Detmold, Meinel, Orginos)
- Where observed states shown in red.
- Huge menagerie of states to still be found!
- Large number of HQET calculations - lifetimes, decay widths, masses.
- Experiment needs to catch up!

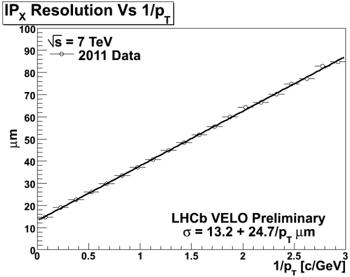


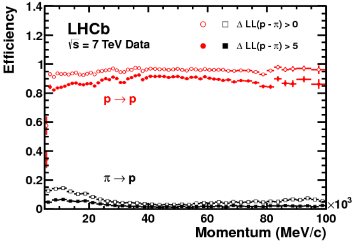
Phys. Rev. D 90, 094507 (2014)

JINST 3 (2008) S08005

- Forward arm spectrometer designed for precision flavour measurements

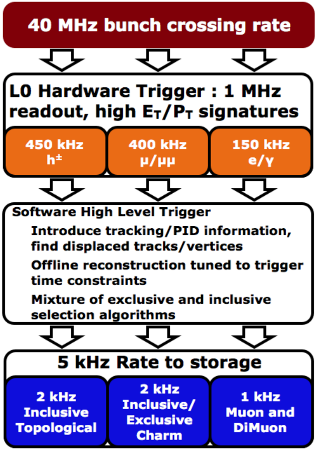






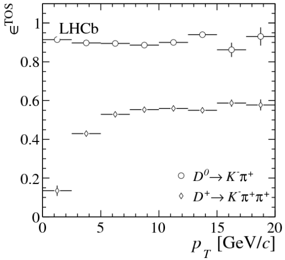
The LHCb trigger in Run I

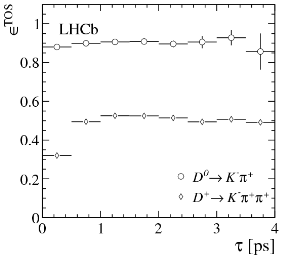
- Huge $c\bar{c}$ production at LHC relative to B factories.
- $\sigma(c\bar{c})_{p_{\mathrm{T}}<8\,\mathrm{GeV}/c,2.0<y<4.5} = 1419 \pm 12\,(\mathrm{stat}) \pm 116\,(\mathrm{syst}) \pm 65(\mathrm{fragmentation})\,\mu\mathrm{b}$



- *But only get what we trigger!*.
- For hadrons in L0, calorimeter cluster $E_{\mathrm{T}} > 3.5\ \mathrm{GeV}$
- For hadrons in HLT1 require single charged track:
  - *IP* wrt PV $> 0.1\ \mathrm{mm}$
  - $p_{\mathrm{T}} > 1.7\ \mathrm{GeV}/c$
  - Track quality criteria
- At HLT2 employ full event reconstruction.

Triggering on charm



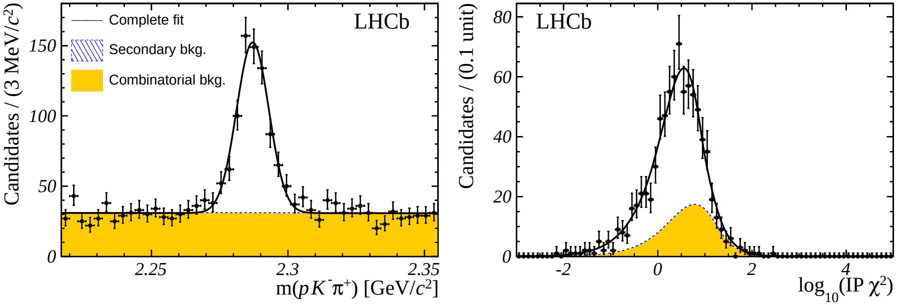


JINST 8 (2013) P04022

- Prompt charm reconstructed using exclusive lines.
- Secondary charm from b-hadron decays with inclusive b triggers
- Primary concerns for charm baryon exclusive triggers:
  - Hadronic - acceptance strongly dependent on p_{T} and lifetime
  - Use variety of data-driven techniques to correct for acceptance
  - Higher backgrounds than for muon final states - PID selection vital
- Shown: Trigger On Signal (TOS) efficiency - signal decay alone sufficient to fire HLT2 trigger line.

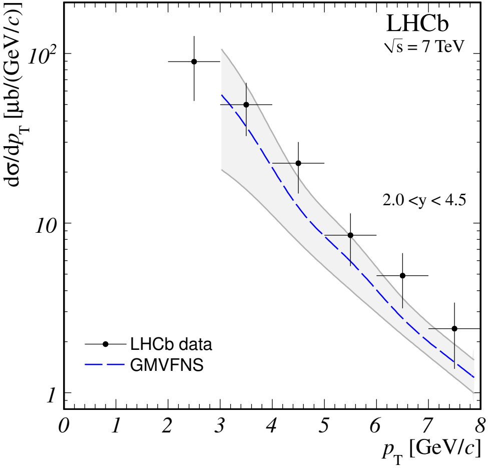
Open charm production at LHCb

- Open charm cross sections at $\sqrt{s} = 7$ TeV measured with 15 nb^{-1} of 2010 data.
- Production of strictly prompt particles measured.
  - From either open charm at PV or excited charm from PV.
  - Isolated from b-hadron decays through $\log(IP\chi^2)$ distributions.
- Mainly charmed mesons but includes $\Lambda_c^+ \to pK^-\pi^+$ differential cross section.



 NUCL.PHYS.B871(2013)1-20

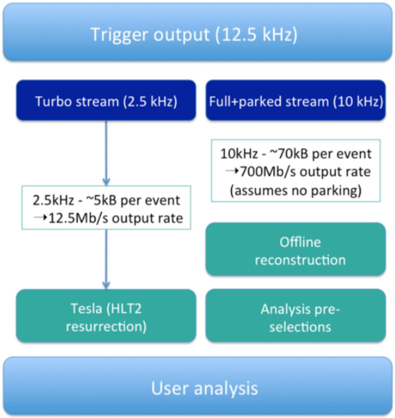
- Differential cross section in LHCb acceptance shown in p_T bins.
- Compared with predictions from Generalized Mass Variable Flavour Number Scheme (GMVFNS, Eur.Phys.J.C72(2012)2082).



Future cross section measurements

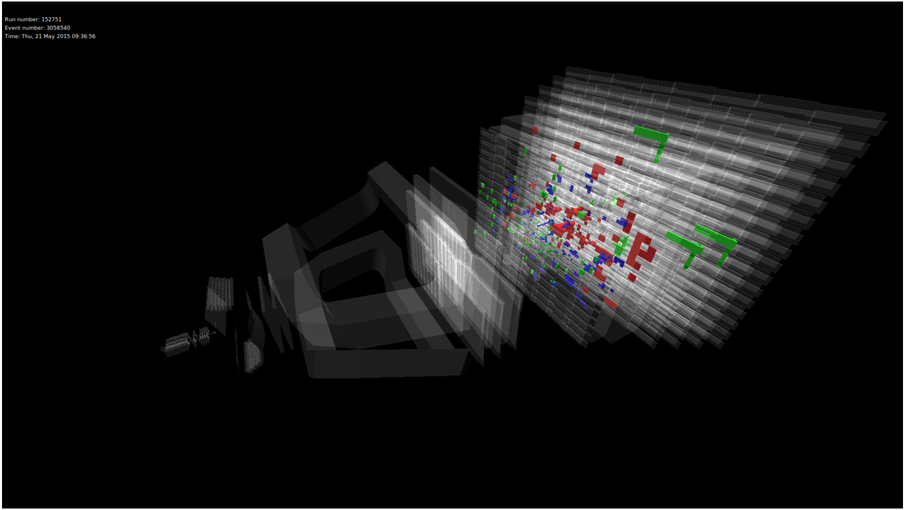
- For Run II, July 15: early measurements programme - includes open charm cross section at $\sqrt{s} = 13$ TeV
- Expanded suite of baryons - Λ_c^+, Σ_c^0, Σ_c^{++}, Ξ_c^+, Ξ_c^0.

- Employ SCS mode cross checks
- New trigger developments - Turbo stream (see Sean Benson's CHEP 2015 talk here).
- Core idea: reconstruct full signal candidates in trigger, not offline.
- Smaller events - more yield per bandwidth.
- Especially useful to charm, trigger output was a limitation in Run I

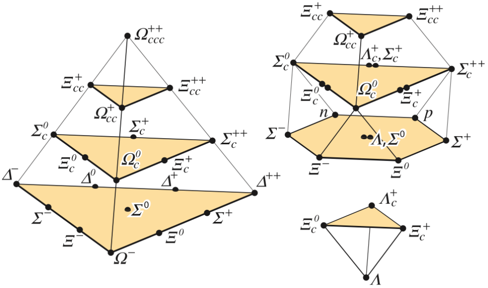


13 TeV!

- First collisions at $\sqrt{s} = 13\ \mathrm{TeV}$ today!



Double and triple charmed states

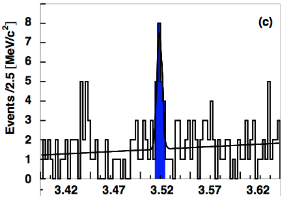


Phys. Rev. D86, 010001 (2012)

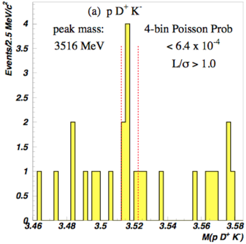
- Baryons with u,d,s,c form SU(4) multiplets
- Ground state baryons shown
- Three weakly decaying $C = 2, J^P = 1/2^+$ states:
  - Ξ_{cc} isodoublet (ccu, ccd)
  - Ω_{cc} singlet (ccs)

- Numerous predictions for $\Xi_{cc}^{+/++}$ masses and lifetimes:
  - $m(\Xi_{cc}^{+})$: $3500 - 3700\ \mathrm{MeV}/c^2$ - Phys. Rev. D70 (2004) 094004
  - $\tau(\Xi_{cc}^{+})$: $100 - 250\ \mathrm{fs}$ - Eur. Phys. J. A45 (2010) 267
  - Production relative to Λ_c^+ generally expected to be highly suppressed - e.g. Physics-Uspekhi 45 (2002), no. 5 455

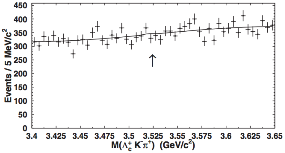
- SELEX reported signals in $\Lambda_c^+ K^- \pi^+$ and $p^+ D^+ K^-$ final states
  - $m(\Xi_{cc}^{+})$: (3519 ± 2) MeV/c^2, $\tau(\Xi_{cc}^{+})$: < 30 fs @ 90 % CL
  - SELEX calculate 20 % of their Λ_c produced in Ξ_{cc}^{+} decays



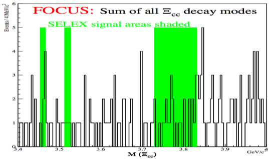
SELEX - Phys.Rev.Lett.89:112001



SELEX - Phys.Lett.B628:18-24



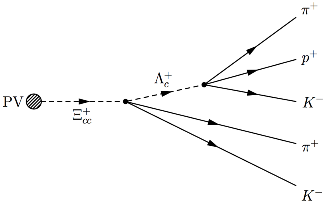
BELLE - PhysRevLett.97.162001



FOCUS - NuclPhysB 115:33-36

LHCb 2011 Ξ_{cc}^{+} search

JHEP1312(2013)090



- Search for particle in decay $\Xi_{cc}^{+} \to \Lambda_c^{+}(pK^{-}\pi^{+})K^{-}\pi^{+}$
- Using 0.65 fb^{-1} of 2011 data at $\sqrt{s} = 7$ TeV.
- Measure production ratio relative to control channel $\Lambda_c^{+} \to pK^{-}\pi^{+}$

$$R \equiv \frac{\sigma(\Xi_{cc}^{+})\mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+})}{\sigma(\Lambda_c^{+})} = \frac{N_{\text{signal}}}{N_{\text{control}}}\frac{\epsilon_{\text{control}}}{\epsilon_{\text{signal}}}$$

- Measured LHCb Λ_c cross-section at $\sqrt{s} = 7$ TeV ≈ 230 μb NUCL.PHYS.B871,1-20
- Predicted LHC Ξ_{cc}^{+} cross-section at $\sqrt{s} = 7$ TeV $\approx (30 - 900)$ nb.
- Assume $\mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+}) \approx \mathcal{B}(\Lambda_c^{+} \to p^{+}K^{-}\pi^{+}) \approx 5$ %
  - expected value of R at LHCb is of order $10^{-5} - 10^{-4}$

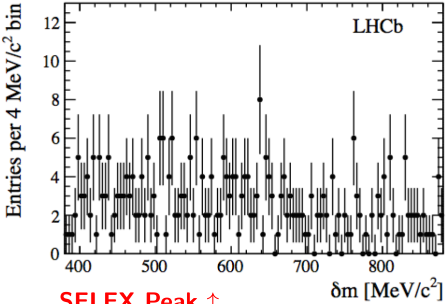
Ξ_{cc}^{+} search results

JHEP1312(2013)090

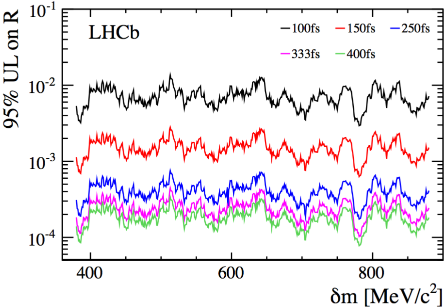
- Define:

$$\delta m \equiv m(\Lambda_c^+ K^- \pi^+) - m_{meas}(\Lambda_c^+) - m(K^-) - m(\pi^+)$$

- Perform 2D fit in $m(\Lambda_c)$ and δm to extract signal yields.
- No observed excess in δm spectrum in data - set upper limits on R.
- Calculate 95% CL_s ULs of R as function of δm for variety of lifetime hypotheses.



SELEX Peak ↑

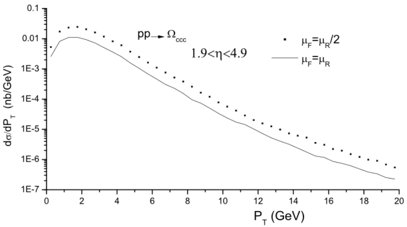


Double charm at LHCb

- 2011 analysis a strong proof of concept
- Full 2 fb^{-1} at $\sqrt{s} = 8$ TeV under analysis, with improved triggers
- Now searching for Ξ_{cc} in multiple final states
  - Notable inclusion: $\Xi_{cc}^{+} \to (D^{+} \to K^{-}\pi^{+}\pi^{+})p^{+}K^{-}$.
  - High D^{+} lifetime ($1\ \text{ps}$) vs. Λ_c^{+} (0.2 ps) - more efficient selections
- Estimated production in LHCb acceptance and $p_{\mathrm{T}} > 5\ \mathrm{GeV}/c$:

- 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`

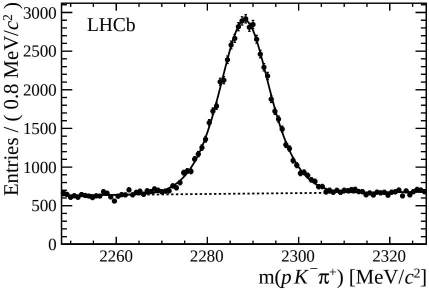
Charmed baryon analyses underway at LHCb

- Extensive charmed baryon programme underway at LHCb.
- Our early efforts in charm have focused on mesons, which are:
  - theoretically more precise
  - often experimentally cleaner than baryons.
  - often provide more access to new physics.
- Beginning to change - considerably more work now in charmed baryons
- Large number of charmed baryon decays gathered during Run I
- Will now discuss some analyses underway with this dataset.

$\Lambda_c^+ \to phh'$ branching fractions

- $\Lambda_c^+ \to phh'$ decays have imprecisely measured branching fractions.
- Most precise to-date:
  - $\mathcal{B}(\Lambda_c^+ \to pK^-K^+)/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$: $(1.4 \pm 0.2 \pm 0.2)$ % (Belle) Phys.Lett.B524:33-43,2002
  - $\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+)/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$: (6.9 ± 3.6) % (NA32) Z. Phys. C48 (1990) 29.

- Shown: 30 pb^{-1} of normalisation $\Lambda_c^+ \to pK^-\pi^+$ from Ξ_{cc}^+ search.
- 818×10^3 yield in just 0.65 fb^{-1}
- Far more than this recorded in Run I.
- Copious samples of Cabibbo suppressed samples recorded $\mathcal{O}(10^5)$.



JHEP1312(2013)090

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]:

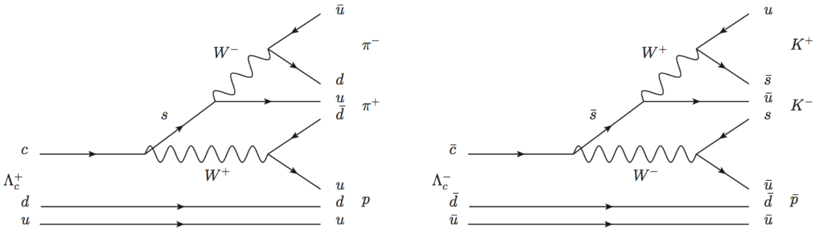
$$\mathcal{A}^{CP}(\Lambda_c^+ \to f) = \frac{\Gamma(\Lambda_c^+ \to f^+) - \Gamma(\Lambda_c^+ \to f^-)}{\Gamma(\Lambda_c^+ \to f^+) + \Gamma(\Lambda_c^+ \to f^-)} \sim |r| \sin(\Delta_s) \sin(\Theta)$$

- 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



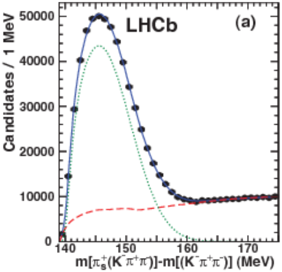
- Production and detector asymmetries mostly cancelled by taking difference:

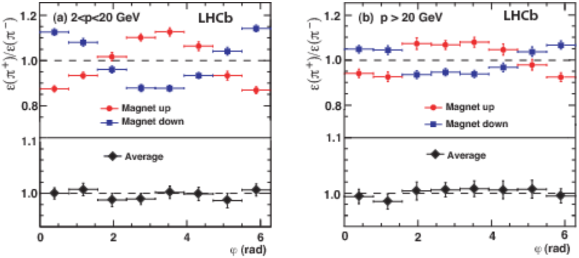
$$\Delta A_{CP}^{\Lambda_c} = A_{Raw}^{\Lambda_c}(K) - A_{Raw}^{\Lambda_c}(\pi) \approx A_{CP}^{\Lambda_c}(K) - A_{CP}^{\Lambda_c}(\pi)$$

- 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.

Proton detection asymmetry

- Precision measurments on D and D_s^+ production asymmetries performed at LHCb
  PLB 713 186 (2012), PLB 718 902 (2013)
- Recent theoretical interest in baryon production asymmetries
  Phys. Rev. D 91, 054022 (2015)
- Where are they? Detection asymmetries complicate things.
- 0.1 % precision acquired in K/π from partially reconstructed decays.
- Eg: $D^{*+} \to D^0(K^-\pi^+\pi^-\pi^+)\pi_s^+$ and calculate missing mass.



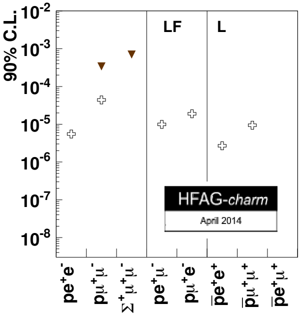


- For protons more difficult - less abundant decay modes, lower efficiencies.
- But work in progress now using:
  - $B^0 \to \bar{p}\pi^+\pi^-\pi^+$, $\Lambda_b^0 \to \Lambda_c^+\pi^-$, $\Sigma_c^0 \to \Lambda_c^+\pi^-$ and more.

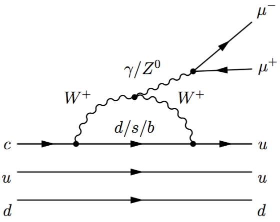
Rare and Forbidden Λ_c Decays

- 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:

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



- 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 $\mathcal{O}(10^{-8})$



Charmed baryon amplitude analysis

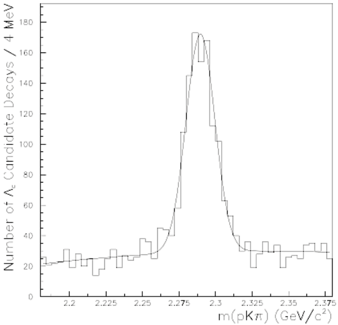
- First multidimensional amplitude analysis of a charmed baryon decay from E791.
- Analysis published back in 2000 (Phys.Lett.B471:449-459) - no advances since
- Experimentally challenging: three-body $D \to hhh$ meson decays fully parameterised by $m(h_1 h_2)$ and $m(h_2 h_3)$.
- But baryons carry spin. Differential rate as function of Λ_c polarisation $\mathbf{P_{\Lambda_c}}$:

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

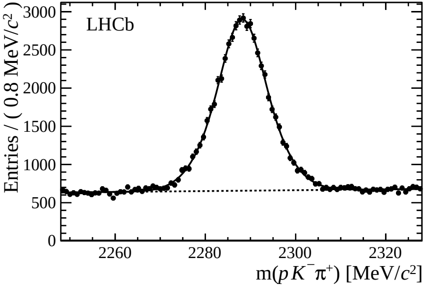
- $\alpha_{r,m,\lambda_\mathrm{p}}$ is complex decay amplitude for resonance r with spin m (Λ_c spin projection onto beam-axis) and proton helicity λ_p in Λ_c rest frame, $B_r(m_r)$ Breit-Wigner amplitude.
- Need 5 vars to parameterise decay - $m(h_1 h_2)$, $m(h_2 h_3)$ and *3 helicity angles*.

Amplitude analysis at LHCb

- Such analysis at LHCb looks promising.
- 10^3 $\Lambda_c^+ \to pK^-\pi^+$ recorded at E791, $\mathcal{O}(10^6)$ recorded at LHCb in 2011 alone.
- Huge body of amplitude analysis expertise at LHCb.
- Cabibbo-favoured and singly suppressed modes tentatively seem possible with already gathered data.



E791 - Phys. Lett. B471 (2000) 449



JHEP1312(2013)090

Summary

- LHCb starting to realise our capabilities with charmed baryons.
- This far published a modest number of production analyses...
  - .. but have datasets to conduct wide variety of analyses
  - Main barrier has been lack of analyst time, now far more being invested.

- Analyses with curent dataset underway:
  - $\Lambda_c^+ \to phh'$ branching fractions
  - Ξ_c branching fractions
  - $\Delta\mathcal{A}^{CP}$ in SCS Λ_c^+ decays
  - Expanded Ξ_{cc}^+ searches
  - Excited charm spectroscopy.
- $\sqrt{s} = 13\ \mathrm{TeV}$ cross sections in Run II early measurements

- Possible with current data, but longer term prospects:
  - Rare Λ_c decays
  - Amplitude analysis in Λ_c decays
  - Other *CP* violation in $\Lambda_c^+ \to phh'$.

- Possible we have some new charmed baryon publications for later this summer.