Measurements of $\Lambda_c^+ \to p^+ h^+ h^-$ $\mathcal{BF}s$ with LHCb 2011 Data

Stephen Ogilvy[1], Thomas Ruf[2], Paul Soler[1], Patrick Spradlin[1]

1. University of Glasgow, UK 2. CERN

University of Glasgow | Experimental Particle Physics

LHCb

Overview

Existing $\Lambda_c^+ \to p^+ h^- h^+$ Measurements

- Λ_c^+ decay modes currently poorly understood in terms of Branching Fractions ($\mathcal{BF}$s), decay amplitudes and resonance structure.
- All Λ_c^+ $\mathcal{BF}$ measurements are currently made relative to the Cabibbo-favoured (CF) $\Lambda_c^+ \to p^+ K^- \pi^+$ mode, which has absolute $\mathcal{BF}$ uncertainty 26%.
- Current PDG $\mathcal{BF}$s shown below, the doubly-Cabibbo Suppressed (DCS) decay $\Lambda_c^+ \to p^+ \pi^- K^+$ has not been observed.

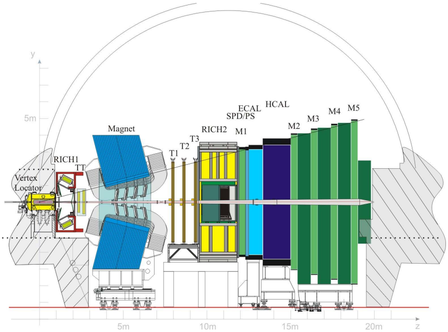
Decay Mode	**PDG Branching Fraction**
$\Lambda_c^+ \to p^+ K^- \pi^+$ (CF)	0.05 ± 0.013
$\Lambda_c^+ \to p^+ K^- K^+$ (SCS)	$(7.7 \pm 3.5) \times 10^{-4}$
$\Lambda_c^+ \to p^+ \pi^- \pi^+$ (SCS)	$(3.5 \pm 2.0) \times 10^{-3}$
$\Lambda_c^+ \to p^+ K^+ \pi^-$ (DCS)	$< 2.3 \times 10^{-4}$ @ 90% CL

The $\Lambda_c^+ \to p^+ h^- h^+$ decay modes and their branching fractions.

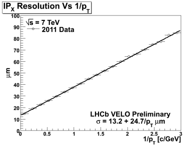
- Understanding these decays key to other analyses:
  - doubly-charmed baryon searches through $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$.
  - CPV searches in Cabibbo-suppressed Λ_c^+ decays (see Alex Pearce's talk).
- With its high statistics in charm LHCb can improve our understanding of these decays.

The LHCb Detector

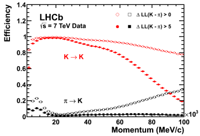
- LHCb is a forward arm spectrometer designed for precision flavour measurements.
- Requires powerful particle identification (PID), secondary vertex discrimination and high momentum and energy resolution.



Cross-section of the LHCb Detector.



IP Resolution vs $1/p_T$.

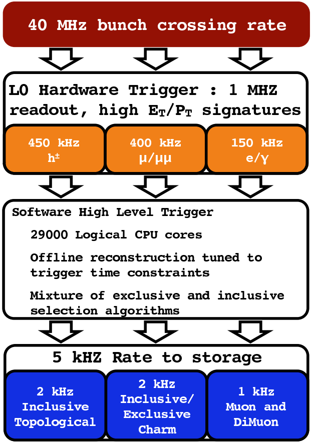


Kaon ID and $\pi - K$ misID rates.

- VELO and trackers give secondary vertex discrimination to trigger on decays of interest. Momentum resolution: $\Delta p/p = 0.4\%$ at $5 GeV/c$ to 0.6% at $100 GeV/c$.
- RICH provides daughter particle discrimination: Kaon ID efficiency $\sim 95\%$ for $\sim 5\%$ $\pi \to K$ mis-id probability.

The LHCb Trigger

- Trigger has multiple stages, hardware $L0$ and software HLT.
- L0 reconstructs:
    - the highest transverse energy (E_T) hadron, electron and photon clusters in the calorimeters.
    - the two highest transverse momentum (p_T) muons in the muon chambers.
- Reduces rate to $1MHz$ for HLT.
    - HLT1 rejects bulk of events with partial reconstruction.
    - HLT2 filters events using full event reconstruction for use in physics analyses. $5kHz$ rate written to tape.



Scheme of the LHCb trigger.

2011 Dataset and Measurements

- In 2011 LHCb gathered an integrated luminosity of $1.0 fb^{-1}$ at $\sqrt{s} = 7\,TeV$.
- Utilise two sources of Λ_c^+ production: those produced promptly and those from semileptonic $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}$ decays. Treat these independently.
- Measuring $\mathcal{BF}$s of the modes relative to the CF $\Lambda_c^+ \to p^+ K^- \pi^+$ mode:

$$\frac{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- K^+}}{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- \pi^+}}, \frac{\mathcal{BF}_{\Lambda_c^+ \to p^+ \pi^- \pi^+}}{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- \pi^+}}, \frac{\mathcal{BF}_{\Lambda_c^+ \to p^+ \pi^- K^+}}{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- \pi^+}}.$$

- Lack of suitable cross-check modes for these decays - keeping the unobserved DCS mode blind until we can demonstrate agreement between ratios of SCS/CF in the prompt and semileptonic.
- Also check $\Lambda_c^+ \to p^+ \phi(K^+ K^-)$: easy to isolate due to relatively low non-resonant production.
- Aim to resolve some existing experimental tension regarding $\frac{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- K^+}}{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- \pi^+}}$:
  - Belle: $0.014 \pm 0.002(stat) \pm 0.002(syst)$ [PL B524 33].
  - CLEO II: $0.039 \pm 0.009(stat) \pm 0.007(syst)$ [PR D53 R1013].

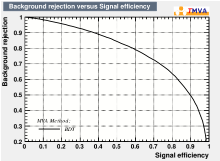
Trigger and Stripping Selection

- Trigger:
  - Lack of prompt trigger lines in HLT2 in 2011 necessitates different approaches to trigger chain (L0, HLT1, HLT2 requirements) in prompt and semileptonic.
  - In prompt require that events triggered regardless of inclusion of signal event (trigger independently of signal) - same trigger efficiency across modes.
  - In semileptonic require signal decay within the event fired the trigger, not other feature of the underlying event (trigger on signal); can measure well-defined trigger efficiencies for modes.
- "Stripping" is the central processing of the data to extract interesting events from tape.

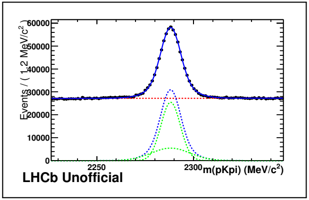
  Utilise sequential cuts on a variety of quantities:
  - PID information from the RICH.
  - Kinematic cuts on mother and daughters.
  - Quality cuts on track reconstruction and vertexing.
- Efficiencies of trigger and stripping can be calculated from MC.

Offline Selection

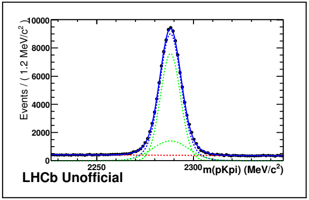
- In semileptonic low combinatoric background. Minimal additional vertex quality cuts made offline. In prompt much higher combinatoric background.
- Use a BDT to select prompt events, trained on 10% of the CF data (weighted with the sPlots method - arXiv:physics/0402083) with additional global signal weighting of $\frac{|V_{ud}|^2|V_{cs}|^2}{|V_{cd}|^2|V_{us}|^2} = 0.003$ for max sensitivity to DCS mode.



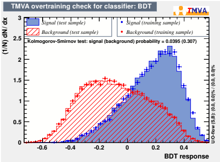
ROC curve for BDT.



Prompt sample before BDT.



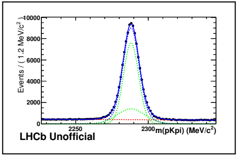
Prompt sample after BDT.



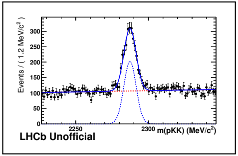
Overtraining check for BDT.

- Green lines gaussians, blue line double gaussian signal, red combinatorics.
- BDT in conjunction with further PID cuts reduce the prompt CF combinatoric background by 98%.
- Projected signal significance $\frac{S}{\sqrt{S+B}}$ for prompt DCS $= 4.4\sigma$.
- Projected signal significance for semileptonic DCS $= 8.4\sigma$.

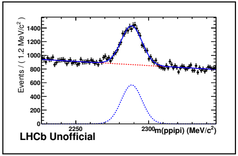
Mass Fits and Signal Yields



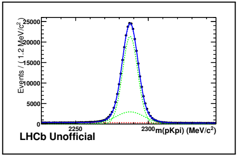
Prompt $\Lambda_c^+ \to p^+ K^- \pi^+$.



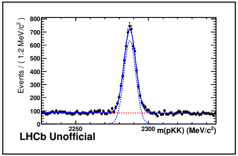
Prompt $\Lambda_c^+ \to p^+ K^- K^+$.



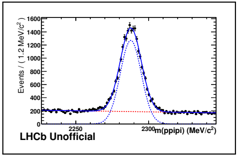
Prompt $\Lambda_c^+ \to p^+ \pi^- \pi^+$.



SL $\Lambda_c^+ \to p^+ K^- \pi^+$.



SL $\Lambda_c^+ \to p^+ K^- K^+$.



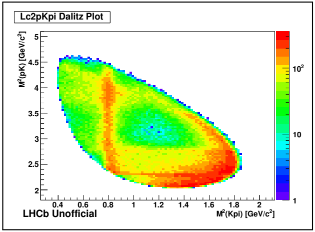
SL $\Lambda_c^+ \to p^+ \pi^- \pi^+$.

- Data yields after final selection.
- All fits unbinned extended likelihood fits.
- Signal models: double gaussian with shared mean for CF, single gaussian for CS. All backgrounds linear.

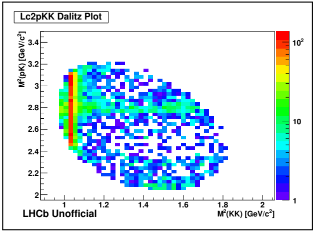
Mode	Prompt Yield	SL Yield
$\Lambda_c^+ \to p^+ K^- \pi^+$	109779 ± 397	292499 ± 578
$\Lambda_c^+ \to p^+ K^- K^+$	1773 ± 67	5390 ± 87
$\Lambda_c^+ \to p^+ \pi^- \pi^+$	8465 ± 225	19125 ± 175

Resonance Structure

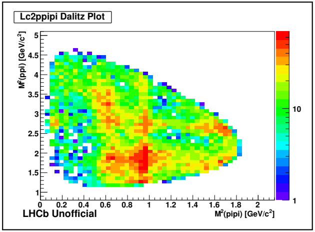
- Shown below: charge opposite daughter pairs from semileptonic modes.
- s-Weighted for sideband subtraction.



$\Lambda_c^+ \to p^+ K^- \pi^+$ Dalitz Plot



$\Lambda_c^+ \to p^+ K^- K^+$ Dalitz Plot



$\Lambda_c^+ \to p^+ \pi^- \pi^+$ Dalitz Plot

- Variety of resonances can be clearly seen: $K^*(892)$, $\Lambda(1520)$, $\phi(1020)$, $f_0(980)$.
- LHCb has the expertise, high statistics and low backgrounds for a comprehensive amplitude analysis of these poorly understood decays.

Efficiencies and Systematics Overview

Efficiencies to be determined:

$$\frac{BF_{phh}}{BF_{pK\pi}} = \frac{N_{phh_{measured}}}{N_{pK\pi_{measured}}} \times \frac{\epsilon_{trig|pK\pi}}{\epsilon_{trig|phh}} \times \frac{\epsilon_{strip|pK\pi}}{\epsilon_{strip|phh}} \times \frac{\epsilon_{offline|pK\pi}}{\epsilon_{offline|phh}} \times \frac{\epsilon_{PID|pK\pi}}{\epsilon_{PID|phh}}$$

- Trigger and stripping efficiencies taken from MC.
- Offline (BDT in prompt, cut-based in SL) efficiency taken from data.
- PID cuts used in stripping, but badly modelled in MC. Use a data-driven calibration to evaluate the PID efficiency separately from stripping and offline efficiencies.
- All efficiencies have been calculated.

Systematics:

- Dominant systematic associated with our PID calibration - $\sim 3\%$. Evaluated with MC and limited by MC stats - could improve before publication.
- Some sources of systematic uncertainty still to be evaluated, e.g. fit model, but expected to be small.

Outlook

- Results in prompt and semileptonic:

- agreement in $\frac{\mathcal{BF}_{\Lambda_c^+ \to p^+ \pi^- \pi^+}}{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- \pi^+}}$.
- $\sim 4\sigma$ disagreement in $\frac{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- K^+}}{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- \pi^+}}$.

- Working to find this source of disagreement before unblinding $\Lambda_c^+ \to p^+ \pi^- K^+$ and presenting all results to public.
- Significance projections indicate we should make first observation of $\Lambda_c^+ \to p^+ \pi^- K^+$.
- Should have lower final systematics than previous measurements: Belle 14%, CLEO II 18% for $\frac{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- K^+}}{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- \pi^+}}$.
- After this result have another $2 fb^{-1}$ at $\sqrt{s} = 8 TeV$ of data to analyse!