$\Lambda_c^+ \to p^+ h^+ h^-$ BF Studies

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

- Λ_c^+ decay modes currently poorly understood in terms of Branching Fractions ($\mathcal{BF}$s) and resonance structure.
- All Λ_c^+ $\mathcal{BF}$ measurements made relative to Cabibbo-favoured (CF) $\Lambda_c^+ \to p^+ K^- \pi^+$ mode - has absolute $\mathcal{BF}$ uncertainty 26%.
- Doubly-Cabibbo Suppressed (DCS) decay $\Lambda_c^+ \to p^+ \pi^- K^+$ not yet 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.

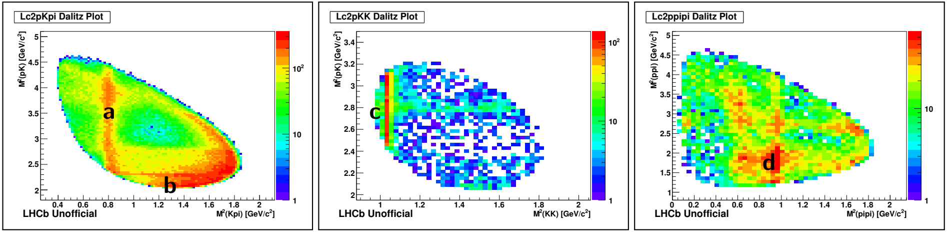
- Understanding these decays key to other analyses:
  - doubly-charmed baryon searches through $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$.
  - CPV searches in Cabibbo-suppressed Λ_c^+ decays.
- **High statistics in charm - LHCb can improve our understanding of these decays.**

$\Lambda_c^+ \to p^+ K^- \pi^+$ absolute $\mathcal{BF}$ measurements

Would be nice to include something here, need to include some info on analyses underway and contact points. Currently looking this up.

Resonant Structure of decays

- Shown below: charge opposite daughter pairs from semileptonic modes.
- Plots from Glasgow $\Lambda_c^+ \to p^+ h^- h^+$ analysis, sWeighted for sideband subtraction.



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

- Variety of resonances clearly seen: $K^*(892)$ (a), $\Lambda(1520)$ (b), $\phi(1020)$ (c), $f_0(980)$ (d).
- LHCb can perform comprehensive amplitude analysis of these poorly understood decays.
- IF AN ANALYSIS UNDERWAY IN THIS AREA - E.G. RIO, I CAN MENTION THEM HERE.

Relative $\Lambda_c^+ \to p^+ h^- h^+$ measurements

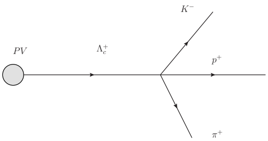
- Two independent analyses in this area underway.
  - Glasgow analysis measuring the following quantities:

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

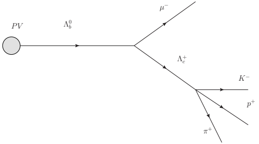
  - Analysis by Thomas Ruf measuring WS/RS ratios:

$$\frac{\mathcal{BF}_{\Lambda_c^+ \to p^+ \pi^- K^+}}{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- \pi^+}}, \frac{\mathcal{BF}_{\Lambda_c^+ \to p^+ \overline{K}^{*0}}}{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^{*0}}}$$

- Glasgow analysis makes independent measurements with two sources of Λ_c^+:
  - promptly produced
  - from semileptonic $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}$.
- WS/RS analysis using semileptonic stream.



Prompt production.



Semileptonic production

Glasgow - Analysis Outline

- Today will present:
  - Selections and mass fits.
  - Treatment of efficiencies.
  - Treatment of systematics.
  - Description of future work.
- Using full 2011 dataset, Stripping 17b.
- Keeping DCS mode blind until agreement in other relative $\mathcal{BF}$ measurements between prompt and semileptonic can be established.

Glasgow - Trigger

- Semileptonic chain:
  - μ L0Muon TOS
  - μ Hlt1TrackMuon TOS
  - Λ_b^0 Hlt2TopoMuNBodyBBDT TOS
- Measure the TOS candidates with respect to the reconstruction, using MCMATCH.
- At L0 and Hlt1, TOS on μ, trigger effs are consistent across modes.
- At Hlt2 Λ_c^+ decay kinematics become relevant.
- TOS chain gives well defined trigger efficiencies.

- Prompt Chain:
  - Λ_c^+ L0Global TIS
  - Λ_c^+ Hlt1TrackAllL0 TIS
  - Λ_c^+ Hlt2Phys TIS
- No TOS prompt data in 2011 for CS/DCS modes.
- Take TIS efficiencies from MC, but signal MC has very low TIS efficiency.
- Efficiencies of entire chain:

Mode	$N_{\mathrm{SEL}\mid\mathrm{TIS}}$	$\epsilon_{\mathrm{SEL}\mid\mathrm{TIS}}(\%)$
$\Lambda_c^+ \rightarrow p^+ K^- \pi^+$	65|12301	0.53 ± 0.13
$\Lambda_c^+ \rightarrow p^+ K^- K^+$	34|6401	0.53 ± 0.18
$\Lambda_c^+ \rightarrow p^+ \pi^- \pi^+$	52|10720	0.49 ± 0.13

- No evidence of differing TIS efficiencies but test is very imprecise.
- Other cross checks being carried out e.g. Λ_c^+ kinematic differences between modes.

Glasgow - Stripping and Offline

Semileptonic:

- Stripping lines:
  - `Strippingb2LcMuXB2DMuNuX`
  - `Strippingb2Lc2pKKMuXB2DMuNuX`
  - `Strippingb2Lc2pPiPiMuXB2DMuNuX`
  - `Strippingb2LcDCSMuXB2DMuNuX`
- Offline selection:
  - Kinematic vetoes on daughter tracks for PIDCalib - more later.
  - Tighter PID cuts on kaon/proton daughters.
  - Additional vertex quality cuts.

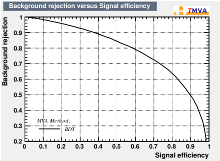
Prompt:

- Stripping lines:
  - `Lambdac2PHHLambdac2PKPi`
  - `Lambdac2PHHLambdac2PKK`
  - `Lambdac2PHHLambdac2PPiPi`
  - `Lambdac2PHHLambdac2PPiKWS`
- Offline selection:
  - Kinematic vetoes on daughter tracks for PIDCalib.
  - Tighter PID cuts on kaon/proton daughters.
  - BDT selection to reject combinatorics.

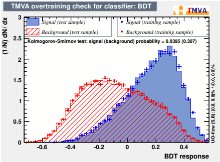
- Full list of stripping cuts in backup.
- Offline selections trained with global signal weighting $\frac{|V_{ud}|^2|V_{cs}|^2}{|V_{cd}|^2|V_{us}|^2} = 0.003$ for max sensitivity to DCS $\Lambda_c^+ \to p^+\pi^-K^+$.

Glasgow - Offline prompt BDT

- Combinatoric background low in SL but not in prompt - due to short Λ_c^+ TOF.
- Use BDT to select prompt events, trained on CF data, weighted with sPlots method.
- Recursively optimised in conjunction with offline PID cuts.

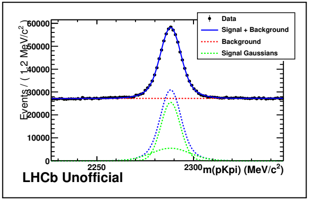


ROC curve for BDT.

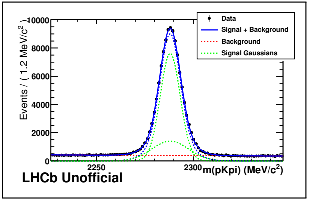


Cut ↑

Overtraining check for BDT.



Prompt sample before BDT/PID.

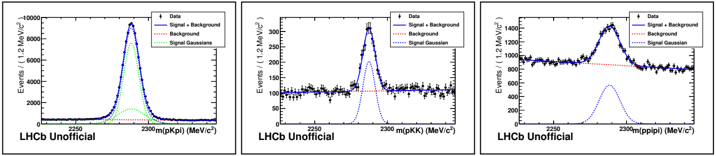


Prompt sample after BDT/PID.

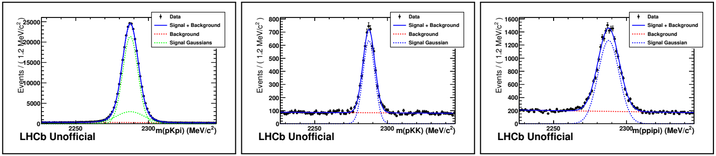
- BDT and further PID cuts reduce combinatorics by 98%.
- Projected signal significance $\frac{S}{\sqrt{S+B}}$ for prompt DCS $= 4.4\sigma$.
- Projected signal significance for semileptonic DCS $= 8.4\sigma$.

Glasgow - Mass Fits and Signal Yields

Prompt



Semileptonic



- 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	Semileptonic 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

Glasgow - Efficiencies

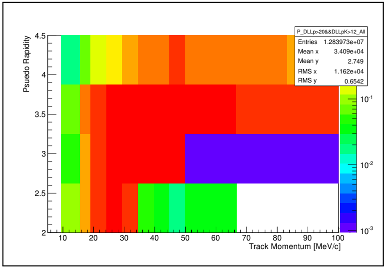
- Primary concern in this analysis is accurate assessment of efficiencies.
- Efficiency chain:

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

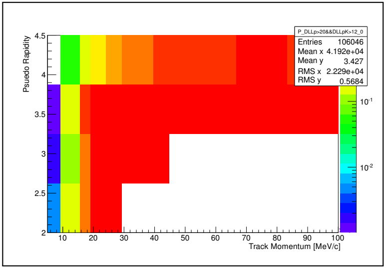
  - $N_{phh_{Final}}$ - Number of candidates passing stripping, final PID cuts, kinematic vetoes on daughter tracks, offline selection.
  - $\epsilon_{gen|reco}, \epsilon_{reco|trig}, \epsilon_{trig|reco}$ - Efficiency from generation to trigger, all taken from MC with a no-PID version of stripping. Includes kinematic vetoes necessary for PIDCalib.
  - $\epsilon_{strip|PID}$ - Efficiency of the PID cuts with respect to the no-PID stripping, evaluated with PIDCalib package.
  - $\epsilon_{PID|offline}$ - Efficiency of offline BDT, extracted from data in CF and applied to DCS mode.

Glasgow - PIDCalib Systematic I

- PID response varies more rapidly across kinematic space with protons than K/π
- Therefore higher systematics - likely to be our dominant contribution.
- Measuring relative $\mathcal{BF}$s - measure the ratio of the PID cut effs in PIDCalib with MC and compare this to the ratio of the true effs.
- No available proton calibration $\Lambda^0 \rightarrow p^+\pi^-$ MC11 - have produced a sample from the inclusive charm MC, soon publicly available via internal note.



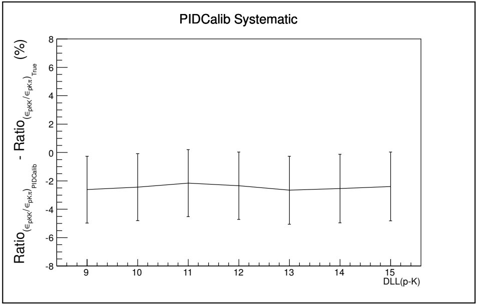
PIDCalib PerfHist of $\Lambda^0 \rightarrow p^+\pi^-$ calibration data.



PIDCalib PerfHist of $\Lambda^0 \rightarrow p^+\pi^-$ calibration MC.

Glasgow - PIDCalib Systematic II

- Proper assessment of systematic scans over all DLL cuts used, and combines these taking into account correlations between DLL variables.
- For now vary proton DLLs and take maximum discrepancy as our systematic - dominant contribution so good approximation.



Variation of systematic with PID cut

- Very low numbers of events passing both stripping and kinematic vetoes - 10k.
- Therefore statistical uncertainty on the discrepancies are very high.
- Assign systematic of 3%, can improve with higher MC stats.

Glasgow - Current Results

- All systematic errors shown from PIDCalib - 3%, should be dominant.

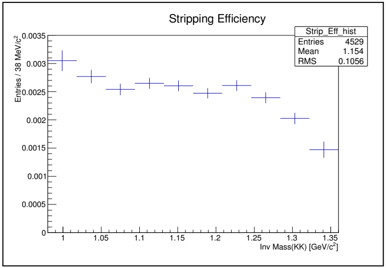
Current results

Measurement	Prompt [%]	Semileptonic [%]	Discrepancy
$\frac{BF_{pKK}}{BF_{pK\pi}}$	$2.124 \pm 0.102 \pm 0.063$	$1.595 \pm 0.032 \pm 0.047$	4.41σ
$\frac{BF_{p\pi\pi}}{BF_{pK\pi}}$	$6.967 \pm 0.278 \pm 0.209$	$6.907 \pm 0.097 \pm 0.207$	0.20σ
$\frac{BF_{p\phi}}{BF_{pK\pi}}$	$0.926 \pm 0.064 \pm 0.028$	$0.862 \pm 0.022 \pm 0.026$	0.91σ

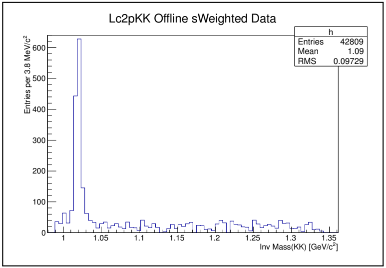
- Current results for $\Lambda_c^+ \to p^+\pi^-\pi^+$ and $\Lambda_c^+ \to p^+(\phi \to K^-K^+)$ are in agreement.
- Discrepancy in $\Lambda_c^+ \to p^+K^-K^+$ is high, but agreement in $\Lambda_c^+ \to p^+(\phi \to K^-K^+)$ tells us the likely cause of this.

Glasgow - Resonant Structure Re-weighting

- Resonant structure not modelled in prompt MC, poorly modelled in SL MC.
- Results in biases in phase space averaged efficiencies derived from MC.
- Variation in stripping acceptance observed in variables characterising the resonant structure.
- e.g. KK invariant mass in prompt $\Lambda_c^+ \to p^+ K^- K^+$ shown below.



Stripping acceptance variations in KK invariant mass.



Offline data population in KK invariant mass.

- Necessitates re-weighting of efficiencies derived from MC.
- Currently devising a binning schema in the 5 dimensions characterising resonant structure (2 invariant mass daughter combinations, 3 polarisation angles).

Glasgow - Future Work and Outlook

- Efficiency re-weighting currently underway.
- Systematics to be assessed:
    - Fit model
    - Data/MC Agreement
    - Tracking Efficiency
- Further issues to be examined:
    - Candidate Multiplicity
    - Cross checks on prompt trigger efficiencies.
- Analysis note under construction.
- Have the potential to make a number of world-best measurements. Current best measurements relative to CF $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$:
    - $\Lambda_c^+ \rightarrow p^+ K^- K^+$: $(1.4 \pm 0.2 \pm 0.2)\%$ - BELLE [PL B524 33]
    - $\Lambda_c^+ \rightarrow p^+ \phi$: $(1.5 \pm 0.2 \pm 0.2)\%$ - BELLE [PL B524 33]
    - $\Lambda_c^+ \rightarrow p^+ \pi^- \pi^+$: $(6.9 \pm 3.6)\%$ - NA32 [Z. Phys. C 48 (1990) 29-46]
- And in conjunction with WS/RS analysis observation of $\Lambda_c^+ \rightarrow p^+ \pi^- K^+$.

WS/RS - Outline and Selection

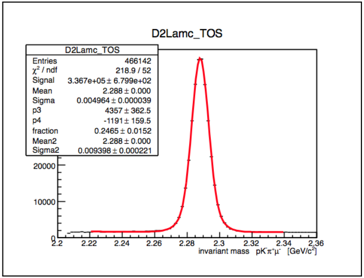
- Analysis conducted by Thomas Ruf.
- Reminder: PDG limit on $\mathcal{BF}$ of DCS $\Lambda_c^+ \to p^+\pi^-K^+$: $< 2.3 \times 10^{-4}$ at 90% CL.
- Analysis uses full 2011 dataset, stripping 17b semileptonic stream.

- Trigger chain fully TOS:
  - L0MuonDecision on μ
  - Hlt1TrackAllL0Decision or Hlt1TrackMuonDecision on μ
  - Hlt2TopoMuNBodyBBDTDecision [N=2,3,4] or Hlt2SingleMuonDecision on Λ_b^0
- Using following stripping lines:
  - `Lambdac2PHHLambdac2PKPi`
  - `Lambdac2PHHLambdac2PPiKWS`

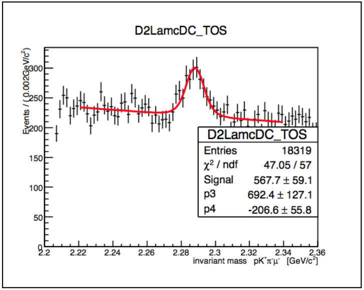
- Offline Selection:

Quantity	Cut Value
μ p_T	$> 1.8 GeV/c^2$
Λ_c^+ p_T	$> 1.5 GeV/c^2$
B mass	$[3.5 - 5.3] GeV/c^2$
CF: $Q(K) \times Q(\mu)$	> 0
DCS: $Q(K) \times Q(\mu)$	< 0
VZ(Λ_c^+)-VZ(B)	> 0
$pDLL_{p-K}$	> 10
$KDLL_{K-\pi}$	> 10
$\pi DLL_{K-\pi}$	< -5

WS/RS - Mass Fits and Yields



Right sign μ $\Lambda_c^+ \to p^+K^-\pi^+$ fit

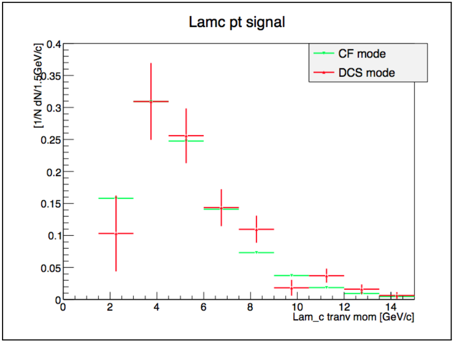


Right sign μ $\Lambda_c^+ \to p^+\pi^-K^+$ fit

- Clear peak in $p^+\pi^-K^+$ mass distribution observed.
- 567.7 ± 61 events observed - 9.3σ observation (statistical uncertainty only).
- Variety of studies (see backup) indicate this peak is unlikely to be a reflection.
- First observation of $\Lambda_c^+ \to p^+\pi^-K^+$.

WS/RS - Systematics

- Systematics arise from different reconstruction efficiencies between CF and DCS modes. Sources:
  - PID efficiency differences, evaluated with RICH PID tables.
  - Variations in efficiency across resonant structure.
  - Examination of Λ_c^+ p_T distributions (right).
- Summarised below as correction factors to $\frac{\mathcal{BF}_{\Lambda_c^+ \to p^+\pi^- K^+}}{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- \pi^+}}$. Differences from unity in corrections taken as systematics.



Λ_c^+ p_T differences between CF and DCS modes

Contribution	Correction Factor
PID Eff	0.993 ± 0.007
Resonance	0.981 ± 0.046
Λ_c^+ p_T	1.00 ± 0.05

- Add effects in quadrature - overall systematic of 7%

WS/RS - Results

Final results:

- $\frac{\mathcal{BF}_{\Lambda_c^+ \to p^+ \pi^- K^+}}{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^- \pi^+}} = (1.65 \pm 0.18_{stat.} \pm 0.11_{sys.}) \times 10^{-3}$.
- $\frac{\mathcal{BF}_{\Lambda_c^+ \to p^+ \overline{K}^{*0}}}{\mathcal{BF}_{\Lambda_c^+ \to p^+ K^{*0}}} = (6.79 \pm 0.88_{stat.} \pm 0.48_{sys.}) \times 10^{-3}$.
- Analysis note available here.
- First observation of new decay mode $\Lambda_c^+ \to p^+ \pi^- K^+$.

Future Prospects for $\Lambda_c^+ \to p^+ h^- h^+$

Need to say something here about how to bring the two relative BF analyses together. Not sure if timescales for absolute BF analyses would be available at present...