

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



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Existing $\Lambda_c^+ \rightarrow p^+ h^- h^+$ 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)
 $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$ mode - has absolute \mathcal{BF} uncertainty 26%.
- Doubly-Cabibbo Suppressed (DCS) decay $\Lambda_c^+ \rightarrow p^+ \pi^- K^+$ not yet observed.

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

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

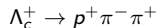
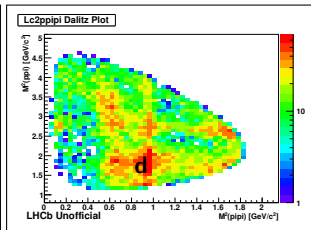
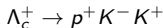
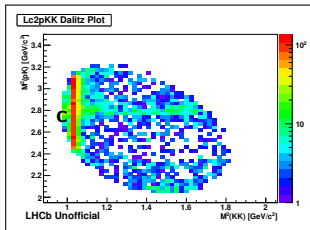
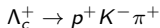
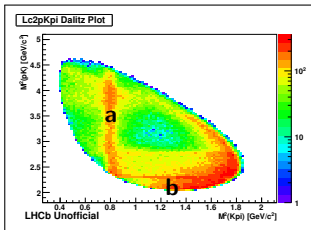
- Understanding these decays key to other analyses:
 - doubly-charmed baryon searches through $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$.
 - CPV searches in Cabibbo-suppressed Λ_c^+ decays.
- **High statistics in charm - LHCb can improve our understanding of these decays.**

$\Lambda_c^+ \rightarrow p^+ K^- \pi^+$ 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 $\Lambda_c^+ \rightarrow p^+ h^- h^+$ analysis, sWeighted for sideband subtraction.



- 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 $\Lambda_c^+ \rightarrow p^+ h^- h^+$ measurements

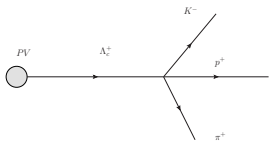
- Two independent analyses in this area:
 - Glasgow analysis underway measuring the following quantities:

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

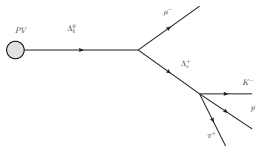
- Finished analysis by Thomas Ruf measuring WS/RS ratios:

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

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



Prompt production.



Semileptonic production

- 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.

- 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	$N_{\text{SEL TIS}}$	$\epsilon_{\text{SEL TIS}}(\%)$
$\Lambda_c^+ \rightarrow p^+ K^- \pi^+$	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.

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.
- Full list of stripping cuts in backup.
- Offline selections trained with global signal weighting

Prompt:

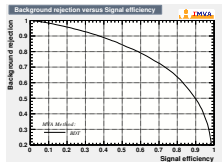
- Stripping lines:
 - Lambdac2PHHLambdac2PKPi
 - Lambdac2PHHLambdac2PKK
 - Lambdac2PHHLambdac2PPiPi
 - Lambdac2PHHLambdac2PPiKWS
- Offline selection:
 - Kinematic vetoes on daughter tracks for PIDCalib.
 - Tighter PID cuts on kaon/proton daughters.
 - BDT selection to reject combinatorics.

$$\frac{|V_{ud}|^2 |V_{cs}|^2}{|V_{cd}|^2 |V_{us}|^2} = 0.003 \text{ for max}$$

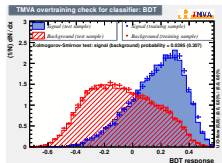
sensitivity to DCS $\Lambda_c^+ \rightarrow p^+ \pi^- K^+$.

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.

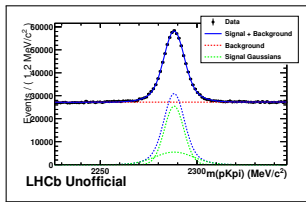


ROC curve for BDT.

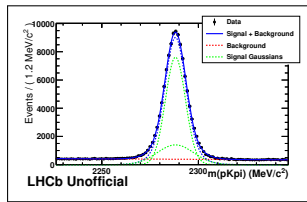


Cut \uparrow

Overtraining check for BDT.



Prompt sample before BDT/PID.

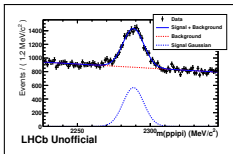
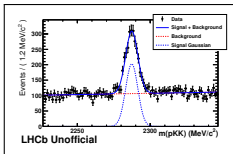
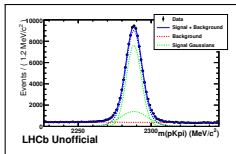


Prompt sample after BDT/PID.

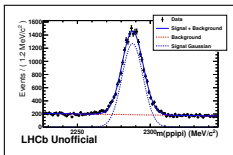
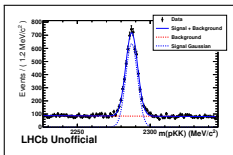
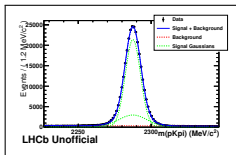
- BDT and further PID cuts reduce combinatorics by 98%.
- Projected signal significance $\frac{S}{\sqrt{S+B}}$ for prompt DCS = 4.4σ .
- Projected signal significance for semileptonic DCS = 8.4σ .

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
$\Lambda_c^+ \rightarrow p^+ K^- \pi^+$	109779 ± 397	292499 ± 578
$\Lambda_c^+ \rightarrow p^+ K^- K^+$	1773 ± 67	5390 ± 87
$\Lambda_c^+ \rightarrow p^+ \pi^- \pi^+$	8465 ± 225	19125 ± 175

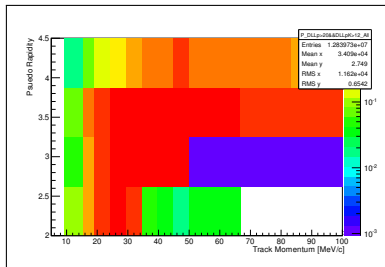
- Primary concern in this analysis is accurate assessment of efficiencies.
- Efficiency chain:

$$\frac{BF_{p hh}}{BF_{p K \pi}} = \frac{N_{p hh Final}}{N_{p K \pi Final}} \times \frac{\epsilon_{p K \pi gen|reco}}{\epsilon_{p hh gen|reco}} \times \frac{\epsilon_{p K \pi reco|trig}}{\epsilon_{p hh reco|trig}} \times \frac{\epsilon_{p K \pi trig|strip}}{\epsilon_{p hh trig|strip}} \times \frac{\epsilon_{p K \pi strip|PID}}{\epsilon_{p hh strip|PID}} \times \frac{\epsilon_{p K \pi PID|offline}}{\epsilon_{p hh PID|offline}}$$

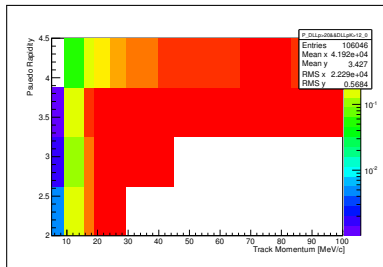
- $N_{p hh Final}$ - Number of candidates passing stripping, final PID cuts, kinematic vetoes on daughter tracks, offline selection.
- $\epsilon_{gen|reco}, \epsilon_{reco|trig}, \epsilon_{trig|reco}$ - Efficiency from generation to trigger, all taken from MC with a no-PID version of stripping. Includes 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.



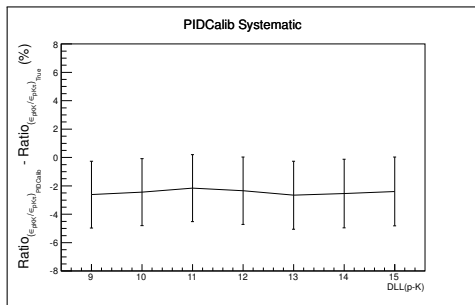
PIDCalib PerfHist of $\Lambda^0 \rightarrow p^+ \pi^-$ calibration data.



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.

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

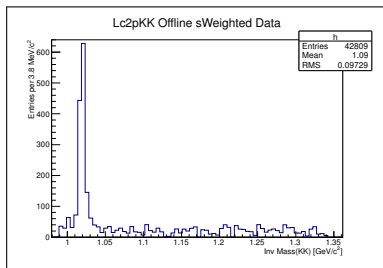
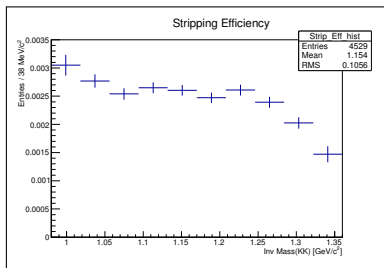
Current results

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

- Current results for $\Lambda_c^+ \rightarrow p^+ \pi^- \pi^+$ and $\Lambda_c^+ \rightarrow p^+(\phi \rightarrow K^- K^+)$ are in agreement.
- Discrepancy in $\Lambda_c^+ \rightarrow p^+ K^- K^+$ is high, but agreement in $\Lambda_c^+ \rightarrow p^+(\phi \rightarrow K^- K^+)$ 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 $\Lambda_c^+ \rightarrow p^+ K^- K^+$ shown below.



Striping acceptance variations in KK invariant mass.

Offline data population in KK invariant mass.

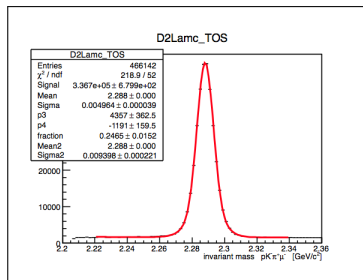
- Necessitates re-weighting of efficiencies derived from MC.
- Currently devising a binning schema in the 5 dimensions characterising resonant structure (2 invariant mass daughter combinations, 3 polarisation angles).

- 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 $\Lambda_c^+ \rightarrow p^+ \pi^- K^+$.

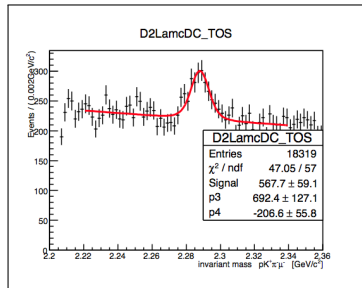
- Analysis conducted by Thomas Ruf.
 - Reminder: PDG limit on \mathcal{BF} of DCS $\Lambda_c^+ \rightarrow p^+ \pi^- K^+$: $< 2.3 \times 10^{-4}$ at 90% CL.
 - Analysis uses full 2011 dataset, stripping 17b semileptonic stream.
- Trigger chain fully TOS:
 - L0MuonDecision on μ
 - Hlt1TrackAllL0Decision 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
μp_T	$> 1.8 \text{ GeV}/c^2$
$\Lambda_c^+ p_T$	$> 1.5 \text{ GeV}/c^2$
B mass	$[3.5 - 5.3] \text{ GeV}/c^2$
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



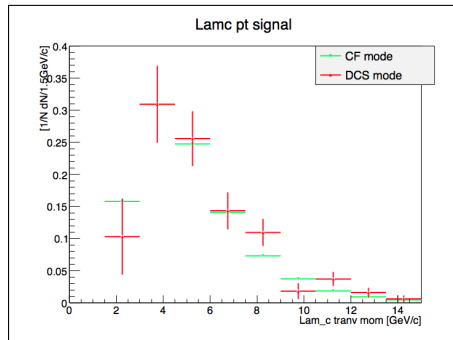
Right sign $\mu \Lambda_c^+ \rightarrow p^+ K^- \pi^+$ fit



Right sign $\mu \Lambda_c^+ \rightarrow p^+ \pi^- K^+$ 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 $\Lambda_c^+ \rightarrow p^+ \pi^- K^+$.

- 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 $\Lambda_c^+ p_T$ distributions (right).
- Summarised below as correction factors to $\frac{\mathcal{B}\mathcal{F}_{\Lambda_c^+ \rightarrow p^+ \pi^- K^+}}{\mathcal{B}\mathcal{F}_{\Lambda_c^+ \rightarrow p^+ K^- \pi^+}}$. Differences from unity in corrections taken as systematics.



$\Lambda_c^+ p_T$ differences between CF and DCS modes

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

- Add effects in quadrature - overall systematic of 7%

Final results:

- $\frac{\mathcal{BF}_{\Lambda_c^+ \rightarrow p^+ \pi^- K^+}}{\mathcal{BF}_{\Lambda_c^+ \rightarrow p^+ K^- \pi^+}} = (1.65 \pm 0.18_{stat.} \pm 0.11_{sys.}) \times 10^{-3}.$
- $\frac{\mathcal{BF}_{\Lambda_c^+ \rightarrow p^+ \bar{K}^{*0}}}{\mathcal{BF}_{\Lambda_c^+ \rightarrow p^+ K^{*0}}} = (6.79 \pm 0.88_{stat.} \pm 0.48_{sys.}) \times 10^{-3}.$
- Final \mathcal{BF} of $\Lambda_c^+ \rightarrow p^+ \pi^- K^+$:
 $(8.2 \pm 0.9 + stat. \pm 0.6 + sys. \pm 2.2_{pdg}) \times 10^{-5}.$
- Analysis note available [here](#).
- First observation of new decay mode $\Lambda_c^+ \rightarrow p^+ \pi^- K^+$.

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

- Strategy for relative \mathcal{BF} measurements:
 - Glasgow analysis converging on final results.
 - Once agreement demonstrated between prompt and SL and WG approval unblind on $\Lambda_c^+ \rightarrow p^+ \pi^- K^+$.
 - If we observe peak in both prompt and SL, and agreement in $\frac{\mathcal{BF}_{\Lambda_c^+ \rightarrow p^+ \pi^- K^+}}{\mathcal{BF}_{\Lambda_c^+ \rightarrow p^+ K^- \pi^+}}$, collaborate with Thomas to release one paper with all results.
- If things proceed smoothly with CS measurements release all results in one paper. Preferred option - BF(CS/CF) measurements serve as cross-check for new observation.
- If not option exists to publish first observation of $\Lambda_c^+ \rightarrow p^+ \pi^- K^+$ in independent paper, with measurements in prompt and SL.

BACKUP

Stripping 17b Cuts

Applies to...	Cut	Prompt	Semileptonic
Tracks	TRCHI2DOF<	5	4
	PT>	0.4GeV	0.3GeV
	P>	3.2GeV	2GeV
	MIPCHI2DV>	-	4
	BPVIPCHI2>	4	-
Muon	PT>	-	0.8GeV
	P>	-	3GeV
	TRCHI2DOF<	-	5
	MIPCHI2DV>	-	9
	PIDmu>	-	0
Pion	dIIK<	0	10
Kaon	dIIK>	5	4
Proton	dIIP>	5	4
	dIIP-K>	-	0
Combination	SumPt>	-	1.8GeV
	ADAMASS<	90MeV	-
	ADOCAMAX<	0.1mm	-
	AMAXCHILD(BPVIPCHI2)>	8	-
	AMAXCHILD(PT)>	1.2GeV	-
	ADOCACHI2CUT=	-	20
	VFASPF(VCHI2/VDOF)<	20	6
	BPVVDCHI2>	16	100
	SUMTREE(PT, ISBASIC)>	-	1.8GeV
	BPVLTIME('ProptimeFitter/properTime:PUBLIC')	$0.0 < t < 1.2ps$	-
	BPVDIRA>	0.9999	0.99

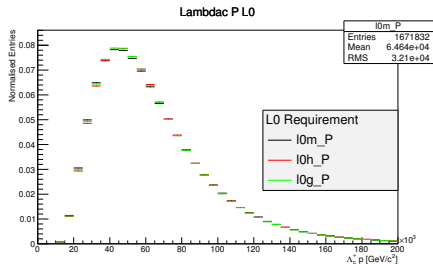
- Binning in Λ_c^+ lifetime gives way of checking trigger effects.
- Differing acceptances at trigger level may manifest here.
- Consistent measurements in prompt/SL.

Stream	Λ_c^+ Lifetime [ps]	$\frac{\mathcal{BF}_{\Lambda_c^+ \rightarrow p^+ K^- K^+}}{\mathcal{BF}_{\Lambda_c^+ \rightarrow p^+ K^- \pi^+}}$ [%]
Prompt	0.12 – 0.61	0.0257 ± 0.0019
	0.61 – 0.91	0.0251 ± 0.0020
	0.91 – 136	0.0209 ± 0.0024
SL	0.12 – 0.61	0.0181 ± 0.0005
	0.61 – 0.91	0.0195 ± 0.0018
	0.91 – 136	0.0194 ± 0.0036

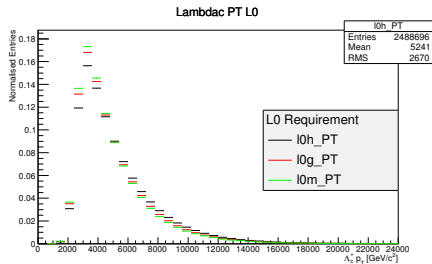
Relative $\Lambda_c^+ \rightarrow p^+ K^- K^+$ \mathcal{BF} s in bins of Λ_c^+ lifetime

Glasgow - L0 Trigger Requirements - II

$$\Lambda_c^+ \rightarrow p^+ K^- \pi^+ P$$



$$\Lambda_c^+ \rightarrow p^+ K^- \pi^+ P_T$$



Stripping output Λ_c^+ kinematics.

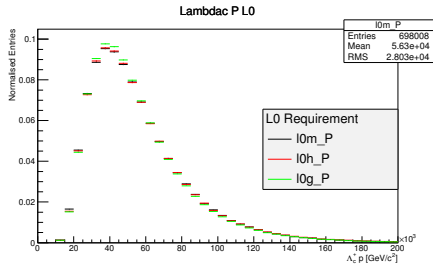
Green: L0 Global TIS

Red: L0 Hadron TIS

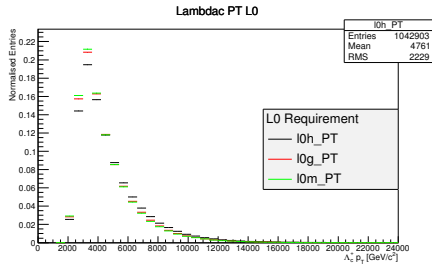
Black: L0 Muon TIS

Glasgow - L0 Trigger Requirements - III

$$\Lambda_c^+ \rightarrow p^+ K^- K^+ P$$



$$\Lambda_c^+ \rightarrow p^+ K^- K^+ P_T$$



Stripping output Λ_c^+ kinematics.

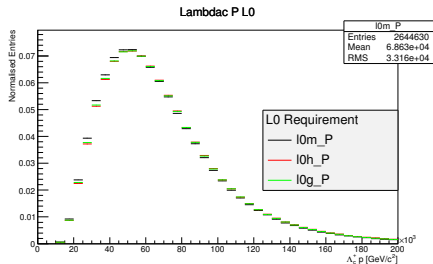
Green: L0 Global TIS

Red: L0 Hadron TIS

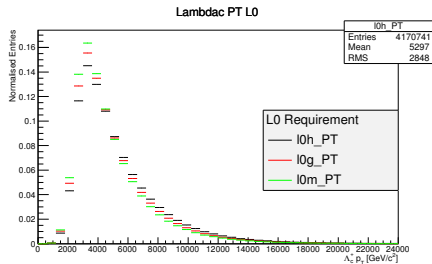
Black: L0 Muon TIS

Glasgow - L0 Trigger Requirements - IV

$$\Lambda_c^+ \rightarrow p^+ \pi^- \pi^+ P$$



$$\Lambda_c^+ \rightarrow p^+ \pi^- \pi^+ P_T$$



Stripping output Λ_c^+ kinematics.

Green: L0 Global TIS

Red: L0 Hadron TIS

Black: L0 Muon TIS

WS/RS - Reflection Studies

- Following cases studied:
 - Double mis-ID $K \rightarrow \pi, \pi \rightarrow K$, cross feed from CF.
 - Single mis-ID $K \rightarrow \pi, \pi \rightarrow K$, cross feed from D_s .
 - Triple mis-ID $p \rightarrow K, K \rightarrow \pi, \pi \rightarrow K$, cross feed from D_s .
- No significant peaks observed, except small excess (21 ± 9) near D_s mass in case of misidentifying two kaons as a proton and a pion for the DCS mode.
- Looking at $D_s \rightarrow KKK$ prompt MC and changing the mass assignments correspondingly does not give any excess at the Λ_c^+ mass. Assumed to be statistical fluctuation.

