Prompt/SL $\Lambda_c^+ \to p^+ h^+ h^-$ BF Update

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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.**

Analysis Outline

- Glasgow analysis underway measuring the following quantities:

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

- Analysis makes independent measurements with two sources of Λ_c:
  - those promptly produced
  - from semileptonic $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}$.
- DCS mode blind in both channels in this analysis.
- Using full 2011 dataset at $\sqrt{s} = 7\mathrm{TeV}$.
- Stripping17b, Reco14.

Selection Outline

- Semileptonic trigger chain:
  - μ L0Muon TOS
  - μ Hlt1TrackMuon TOS
  - Λ_b^0 Hlt2TopoMuNBodyBBDT TOS
- StrippingB2DMuNuX module lines

- Prompt trigger chain:
  - Λ_c^+ L0Global TIS
  - Λ_c^+ Hlt1TrackAllL0 TIS
  - Λ_c^+ Hlt2Phys TIS
- Pass dedicated lines e.g. Lambdac2PHHLambdac2PKPiLines
- Offline BDT for DCS selection.

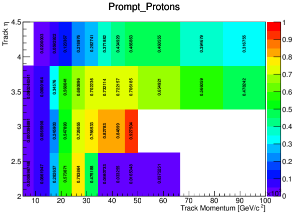
Common elements in both selections:

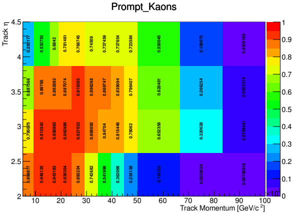
- Tighter PID cuts used in both offline selections.
- Kinematic vetoes used to eliminate signal candidates outside of valid PID calibration region.
- DecayTreeFitter applied with no PV constraint and Λ_c mass constraint - fit convergence required.

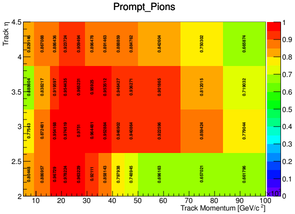
Offline PID Requirements

Selection	Particle	PID Cuts
Prompt $\Lambda_c^+ \to phh'$	p	$\mathrm{DLL}_{(\mathrm{p}-\pi)} > 20, \mathrm{DLL}_{(\mathrm{p}-\mathrm{K})} > 12$
	K	$\mathrm{DLL}_{(\mathrm{K}-\pi)} > 10, \mathrm{DLL}_{(\mathrm{K}-\mathrm{p})} > -8$
	π	$\mathrm{DLL}_{(\mathrm{K}-\pi)} < 0$
SL $\Lambda_c^+ \to p\pi^-\pi^+$	p	$\mathrm{DLL}_{(\mathrm{p}-\pi)} > 20, \mathrm{DLL}_{(\mathrm{p}-\mathrm{K})} > 9$
	π	$\mathrm{DLL}_{(\mathrm{K}-\pi)} < 0$
Other SL $\Lambda_c^+ \to phh'$	p	$\mathrm{DLL}_{(\mathrm{p}-\pi)} > 20, \mathrm{DLL}_{(\mathrm{p}-\mathrm{K})} > 9$
	K	$\mathrm{DLL}_{(\mathrm{K}-\pi)} > 10$
	π	$\mathrm{DLL}_{(\mathrm{K}-\pi)} < 10$

Prompt Tracks

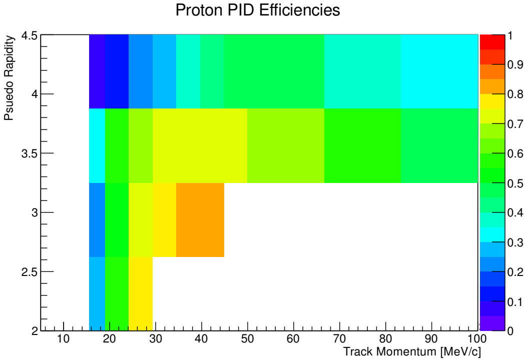






Kinematic Vetoes for PIDCalib

- Necessary due to low populations of PID calibration data in these regions of phase space.
- Shown for protons below. White = vetoed.
- For π and K $5\,\mathrm{GeV} < \mathrm{P} < 100\,\mathrm{GeV}, 2.0 < \eta < 4.5.$



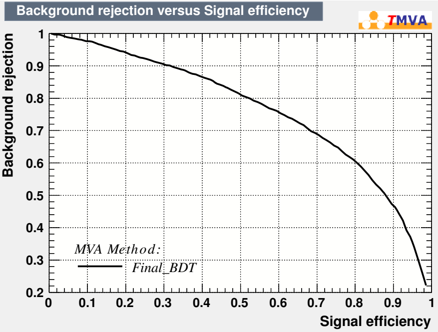
(a)

Improving Data-driven PIDCalib

the vetoes on the MC outside our data region i discuss go here

Offline BDT for Prompt DCS

- Have recently reoptimised following selection revision.
- Necessary as vetoes lead to lower signal efficiency.
- Reoptimised tree architecture and response cutoff.
- Projected significance now 3.27σ for prompt, 8.66σ for SL.



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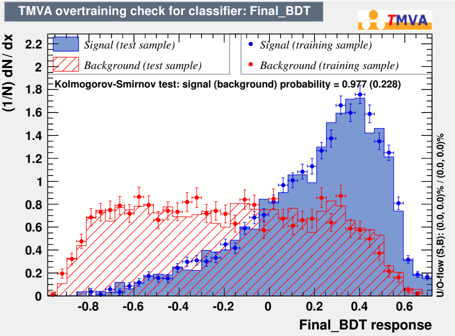

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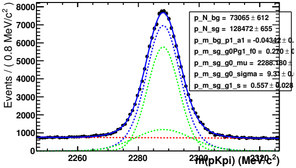
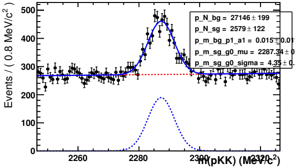
Mass Fits - Prompt

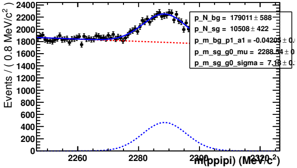
- Fit model:
  - Single Gaussian for SCS modes, double Gaussian shared mean for CF.
  - All combinatorics are first order Chebbychev polynomials.



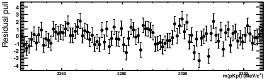
(a) $\Lambda_c^+ \to pK^-\pi^+$



(b) $\Lambda_c^+ \to pK^-K^+$



(c) $\Lambda_c^+ \to p\pi^-\pi^+$



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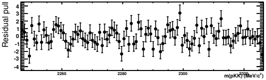

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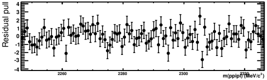

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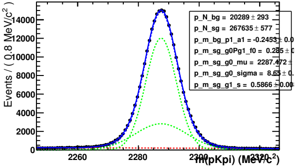
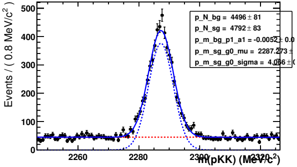
Mass Fits - SL

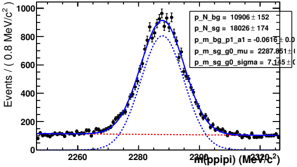
- Fit model:
  - Single Gaussian for SCS modes, double Gaussian shared mean for CF.
  - All combinatorics are first order Chebbychev polynomials.



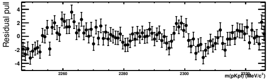
(a) $\Lambda_c^+ \to pK^-\pi^+$



(b) $\Lambda_c^+ \to pK^-K^+$



(c) $\Lambda_c^+ \to p\pi^-\pi^+$



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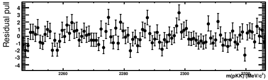

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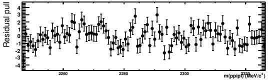


(f)

MC Modelling - The Problem

- Three body baryonic decays parameterised in helicity formalism by 5 resonant variables. All in In Λ_c rest frame:

  Inv. Mass $(ph_1)(h_1h_2)$

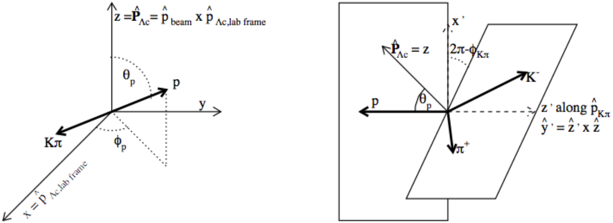
  $\cos\theta_p$ - angle between proton momentum and Λ_c polarisation.

  $\cos\phi_p$ - angle between Λ_c polarisation and lab frame Λ_c momentum vector.

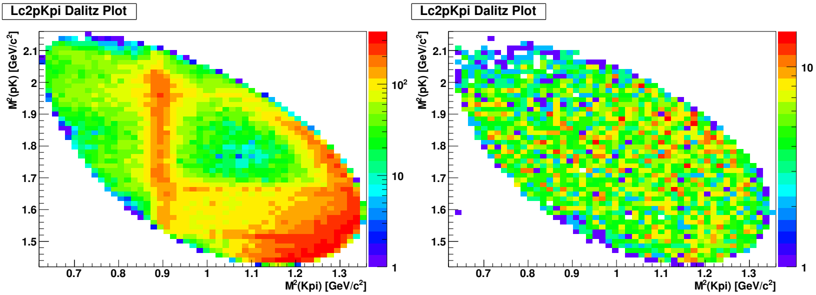
  $\cos\theta_{h_1h_2}$ - angle between plane containing proton momentum vector and the Λ_c polarisation and plane containing the two meson momenta.

- But only one resonance model for $\Lambda_c^+ \to pK^-\pi^+$ from E791, none for other modes - our MC by necessity is imperfect, yet needed for efficiency corrections.

1.



MC Modelling - The Solution



(a) Stripped Data (b) Stripped MC

- Examine each stage of our efficiency which is derived from MC
- If both of the following are true:
  - acceptance variations over these variables.
  - disagreements in data/MC distributions
- then average efficiencies over phase space not valid.
- Necessitates re-weighting, described later.

Efficiencies in Analysis

- expression for the efficiency-adjusted ratio of branching fractions is the following:

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

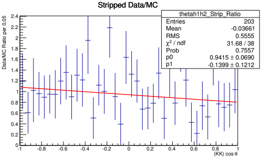
- all terms explained in ANA.
- $\epsilon_{acc|gen}, \epsilon_{reco|acc}, \epsilon_{trig|reco}, \epsilon_{strip|trig}$ all taken from MC.
- Investigate these for acceptance flatness w.r.t. resonant variables.
- First three are fine, stripping efficiency is problematic.
- Other efficiencies taken from data.

Strip eff re-weighting - I

- Want to re-weight stripping efficiency based on data populations.
- However, selections are very inefficient - few MC events survive.
  - Around $5-8K$ for prompt, $25k$ for SL.
- Full re-weighting in 5D impossible.
- So take steps to reduce binning dimensionality.
- Use prompt $\Lambda_c^+ \rightarrow pK^-K^+$ as example.

Strip eff re-weighting - II

- Examine each resonant variable for good data/MC agreement.
- Distributions of angular variables flat here (although test is imprecise). Inv. mass variables are not.



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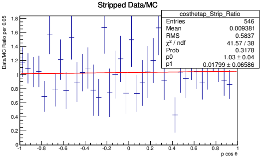
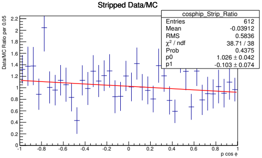


(b)



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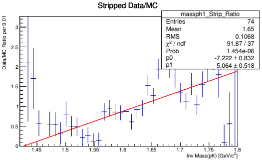

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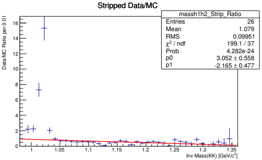
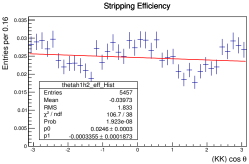


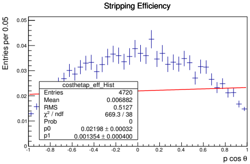
(e)

Strip eff re-weighting - III

- Next, check if the acceptances vary w.r.t. these variables.
- None flat - so perform 2D re-weighting in invariant mass variables.



(a)



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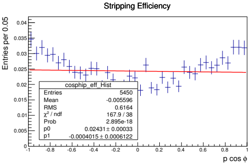
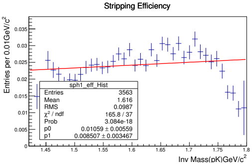


(c)



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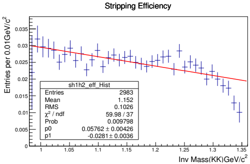
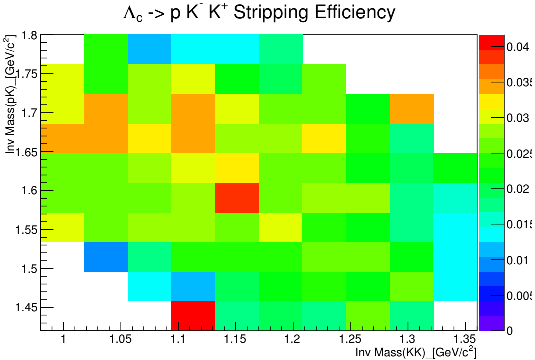


(e)

Strip eff re-weighting - IV

- Construct binned efficiencies using MC
- Use these to assign event-by-event efficiencies to the data.



(a)

- Fluctuations due to low bin stats present. Are considering smarter binning schemas, possibly adaptive.

Adjusted Yields

The final expression for the adjusted yield is:

$$\mathrm{M} = (\sum_{\mathrm{i}}^{\mathrm{n}} \mathrm{w_i w_{i_{PID}} w_{i_{Strip}}}) \times \frac{1}{\epsilon_{\mathrm{trig|reco}} \times \epsilon_{\mathrm{acc|gen}} \times \epsilon_{\mathrm{BDT|PID}}}$$

where the sum is over n events passing selection, and where:

- $\mathrm{w_i}$ - sWeight of event.
- $\mathrm{w_{i_{PID}}}$ - PID weight of event, the inverse of `PIDCalib` event efficiency.
- $\mathrm{w_{i_{Strip}}}$ - stripping weight of event, the inverse of the event's local efficiency in the resonant phase space.
- $\epsilon_{\mathrm{trig|reco}}$ - The average trigger efficiency w.r.t. reconstruction of the mode.
- $\epsilon_{\mathrm{acc|gen}}$ - The average acceptance of the detector geometry for the mode.
- $\epsilon_{\mathrm{BDT|PID}}$ - The average BDT efficiency w.r.t. rest of selection. Equal to 1 for all modes except prompt $\Lambda_c^+ \to p\pi^- K^+$.

Updated Results

Results before efficiency re-weighting

Measurement	Prompt [%]	Semileptonic [%]	Difference
$\frac{BF_{pKK}}{BF_{pK\pi}}$	$2.124 \pm 0.102 \pm 0.063$	$1.595 \pm 0.032 \pm 0.047$	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

Results after efficiency re-weighting

Measurement	Prompt [%]	Semileptonic [%]	Difference
$\frac{BF_{pKK}}{BF_{pK\pi}}$	$1.819 \pm 0.103 \pm 0.055$	$1.865 \pm 0.042 \pm 0.055$	0.39σ
$\frac{BF_{p\pi\pi}}{BF_{pK\pi}}$	$6.751 \pm 0.291 \pm 0.202$	$6.866 \pm 0.105 \pm 0.205$	0.32σ

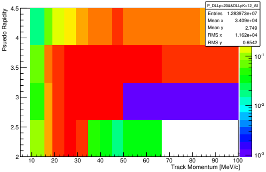
- Second errors correspond to PIDCalib systematics only.
- Results in agreement, but still work to do.
- Will now discuss work on the central values, systematics and cross checks.

Regarding BF central values

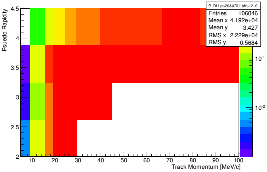
- Results are in agreement right now - but not finalised yet!
  - Tracking efficiency corrections to be applied - should have minimal effect.
  - As mentioned checking smarter bin schemas to minimise systematic uncertainty on stripping efficiency re-weighting - expect this to have some effect on efficiency weights.
- No other effects expected to alter central BF values after these.

Systematics - PIDCalib I

- Systematic has two sources:
  - Limited statistical precision in calibration bins
  - Acceptance variations over calibration bins
- Using MC: scan across DLLs, assess max difference between true PID eff and PIDCalib eff.
- Measure ratio of true/PIDCalib PID cut effs to eliminate effects from nTracks.
- No publicly available proton calibration $\Lambda^0 \to p^+\pi^-$ MC11 - have produced a private sample from the inclusive charm MC.



(a) Calib proton data

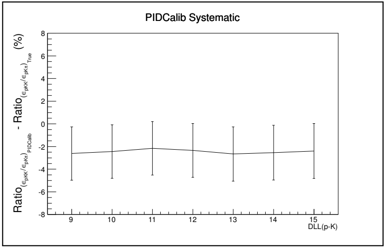


(b) Calib proton MC

- For more info on proton MC sample see LHCb-INT-2013-028.

Systematics - PIDCalib II

- Again prompt $\Lambda_c^+ \to pK^-K^+$ proton scan shown as example.



- Low numbers of MC events passing stripping and kinematic vetoes - 10k.
- Have not applied trigger chain, less than 1k after this.
- Therefore statistical uncertainty on the discrepancies are very high.
- Assign conservative systematic of 3%.

Systematics - efficiency re-weighting

x

Systematics - MC modelling

x

Systematics - Overview

x

Cross checks in progress

background studies, mis-ID etc.

Analysis Note

x