

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



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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%.
 - Recent preliminary result from Belle with 5% precision
- 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:
- **High statistics in charm - LHCb can improve our understanding of these decays.**

Analysis Outline

- Glasgow analysis underway measuring the following quantities:

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

- Analysis makes independent measurements with two sources of Λ_c :
 - those promptly produced
 - from semileptonic $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}$.
- DCS mode blind in both channels in this analysis.
- Using full 2011 dataset at $\sqrt{s} = 7\text{TeV}$.
- Stripping17b, Reco14.
- Also exists independent DCS/CF analysis by Thomas Ruf - aim to combine with this analysis at paper -

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.

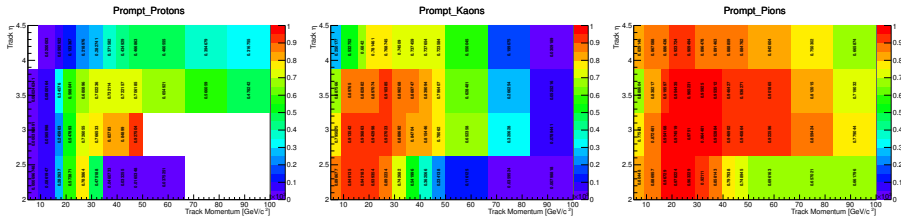
Common elements in both selections:

- 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

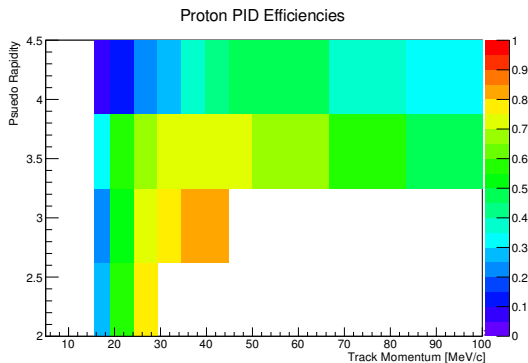
Selection	Particle	PID Cuts
Prompt $\Lambda_c^+ \rightarrow phh'$	p	$DLL_{(p-\pi)} > 20, DLL_{(p-K)} > 12$
	K	$DLL_{(K-\pi)} > 10, DLL_{(K-p)} > -8$
	π	$DLL_{(K-\pi)} < 0$
SL $\Lambda_c^+ \rightarrow p\pi^-\pi^+$	p	$DLL_{(p-\pi)} > 20, DLL_{(p-K)} > 9$
	π	$DLL_{(K-\pi)} < 0$
Other SL $\Lambda_c^+ \rightarrow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

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 $5 \text{ GeV} < P < 100 \text{ GeV}$, $2.0 < \eta < 4.5$.



(a)

Improving fully data-driven PIDCalib - I

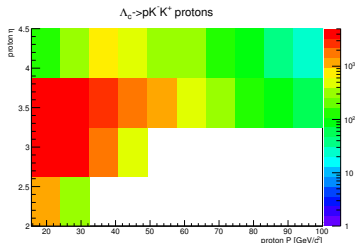
- PIDCalib procedure using data reference samples:
 - k = number of events passing PID cuts.
 - n = number of events before PID cuts.
 -

$$\epsilon^{sig} = \frac{k^{sig}}{\sum_{i=1}^{nbins} \frac{k^{sig}}{\epsilon^{sig}}}$$

- How do we know our k^{sig} in a given bin is reliable?
- PID cuts can sculpt fringes of distribution
- *if we have empty/close to empty bins around the edges of the PIDCalib phase space this is not imply a reliable k^{sig} , and does not imply a zero n^{sig} !*

Improving fully data-driven PIDCalib - II

- Employ method to explicitly deal with this effect.
- Bin your signal data in same schema as your calibration data.
- Test binning schema shown below.



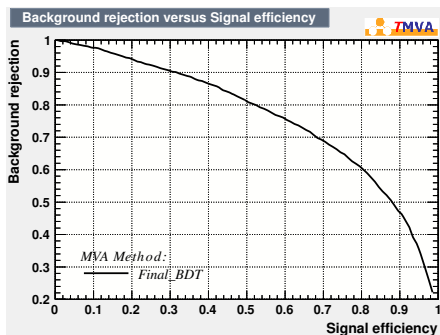
(a)

- Identify bins with population below some threshold, or zero.
- Explicitly veto bins from selection and calculate efficiency of these vetos in MC.

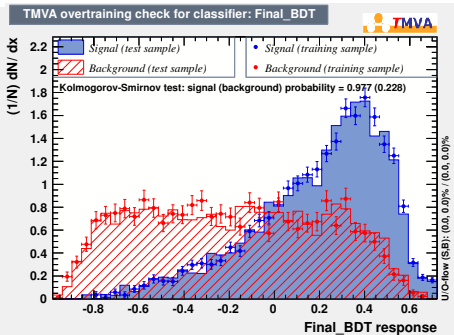
- If MC variables are well modelled this lets you know the extent of the sculpting at the fringes of your distributions.
 - Good assumption in case of P, P_t, η .
 - Not so for nTracks.
- Does not affect this analysis significantly - due to our required vetos on low calibration data population regions.
 - Most of our bins passing selection already have high stats.
- Analyses should be looking at this! Will be described in PIDCalib documentation from Philip, Andrea, Alex and myself.

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.



(a)

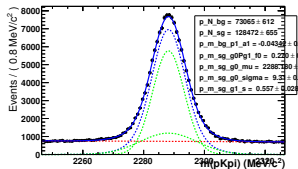


(b)

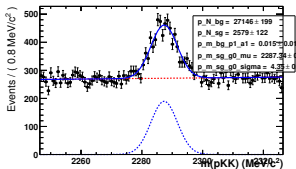
Mass Fits - Prompt

- Fit model:

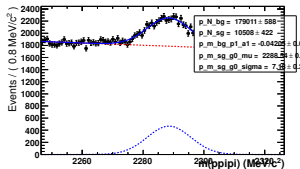
- Single Gaussian for SCS modes, double Gaussian shared mean for CF.
- All combinatorics are first order Chebyshev polynomials.



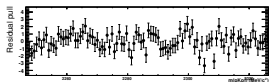
(a) $\Lambda_c^+ \rightarrow pK^- \pi^+$



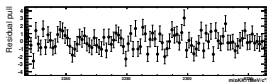
(b) $\Lambda_c^+ \rightarrow pK^- K^+$



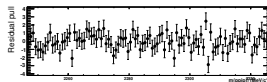
(c) $\Lambda_c^+ \rightarrow p\pi^- \pi^+$



(d)



(e)

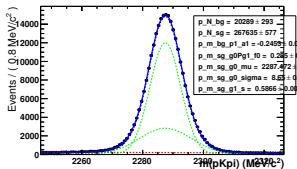


(f)

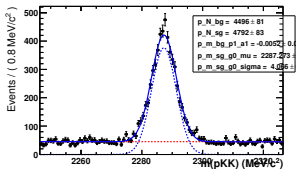
Mass Fits - SL

- Fit model:

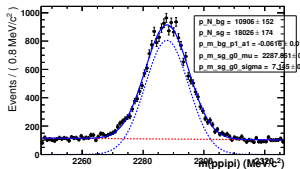
- Single Gaussian for SCS modes, double Gaussian shared mean for CF.
- All combinatorics are first order Chebbychev polynomials.



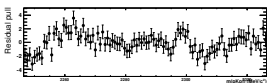
(a) $\Lambda_c^+ \rightarrow pK^- \pi^+$



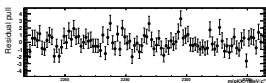
(b) $\Lambda_c^+ \rightarrow pK^- K^+$



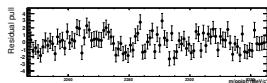
(c) $\Lambda_c^+ \rightarrow p\pi^- \pi^+$



(d)



(e)



(f)

MC Modelling - The Problem

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

Inv. Mass ($p h_1$)($h_1 h_2$)

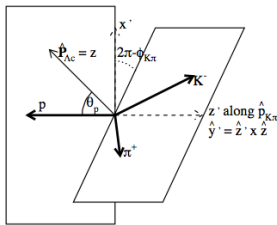
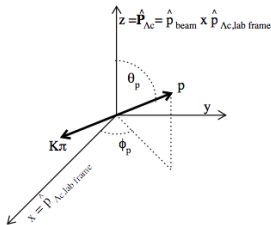
$\cos \theta_p$ - angle between proton momentum and Λ_c polarisation.

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

$\cos \theta_{h_1 h_2}$ - angle between plane containing proton momentum vector and the Λ_c polarisation and plane containing the two meson momenta.

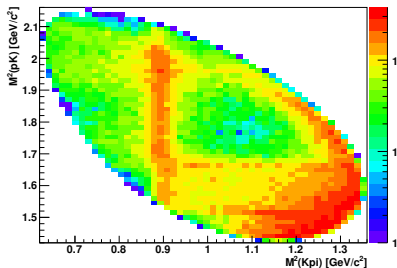
- But only one resonance model for $\Lambda_c^+ \rightarrow p K^- \pi^+$ from E791, none for other modes - our MC by necessity is imperfect, yet needed for efficiency corrections.

1.



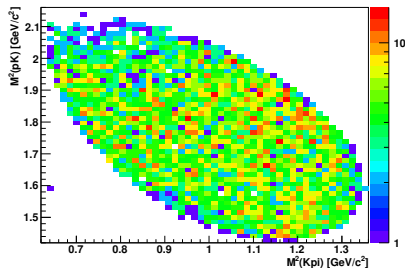
MC Modelling - The Solution

Lc2pKpi Dalitz Plot



(a) Stripped Data

Lc2pKpi Dalitz Plot



(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:

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

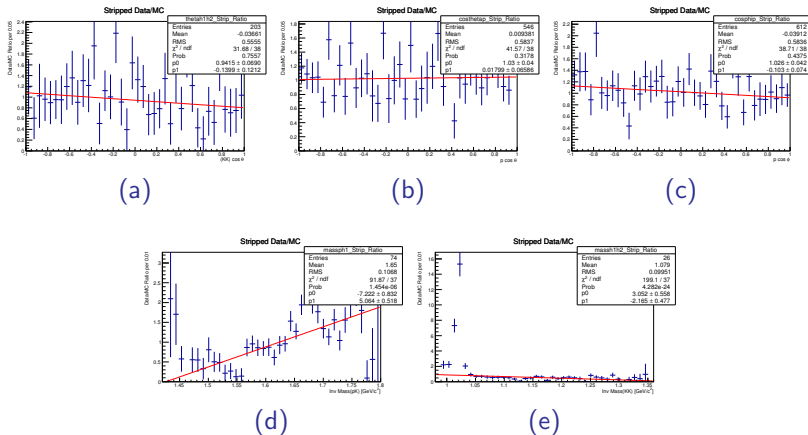
- all terms explained in ANA.
- $\epsilon_{acc|gen}$, $\epsilon_{reco|acc}$, $\epsilon_{trig|reco}$, $\epsilon_{strip|trig}$ all taken from MC.
- Investigate these for acceptance flatness w.r.t. resonant variables.
- First three are fine, stripping efficiency is problematic.
- Other efficiencies taken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

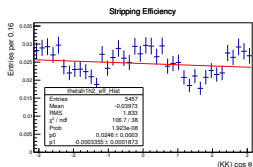
Strip eff re-weighting - II

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

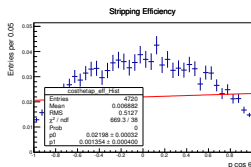


Strip eff re-weighting - III

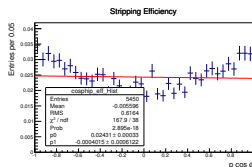
- Next, check if the acceptances vary w.r.t. these variables.
- None flat - so perform 2D re-weighting in invariant mass variables.



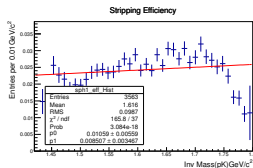
(a)



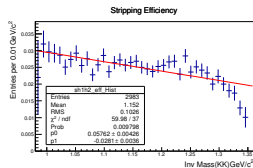
(b)



(c)



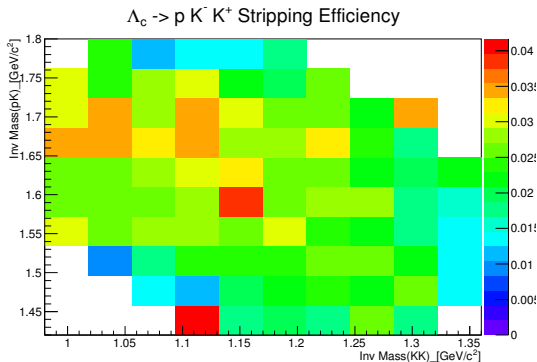
(d)



(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:

$$M = \left(\sum_i^n w_i w_{i\text{PID}} w_{i\text{Strip}} \right) \times \frac{1}{\epsilon_{\text{trig|reco}} \times \epsilon_{\text{acc|gen}} \times \epsilon_{\text{BDT|PID}}}$$

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

w_i - sWeight of event.

$w_{i\text{PID}}$ - PID weight of event, the inverse of PIDCalib event efficiency.

$w_{i\text{Strip}}$ - stripping weight of event, the inverse of the event's local efficiency in the resonant phase space.

$\epsilon_{\text{trig|reco}}$ - The average trigger efficiency w.r.t. reconstruction of the mode.

$\epsilon_{\text{acc|gen}}$ - The average acceptance of the detector geometry for the mode.

$\epsilon_{\text{BDT|PID}}$ - The average BDT efficiency w.r.t. rest of selection. Equal to 1 for all modes except prompt $\Lambda_c^+ \rightarrow p\pi^- K^+$.

Results before efficiency re-weighting

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

Results after efficiency re-weighting

	Prompt [%]	Semileptonic [%]	Difference	PDG [%]
$\frac{BF_{\rho KK}}{BF_{\rho K\pi}}$	$1.819 \pm 0.103 \pm 0.055$	$1.865 \pm 0.042 \pm 0.055$	0.39σ	1.5 ± 0.6
$\frac{BF_{\rho\pi\pi}}{BF_{\rho K\pi}}$	$6.751 \pm 0.291 \pm 0.202$	$6.866 \pm 0.105 \pm 0.205$	0.32σ	6.9 ± 3.6

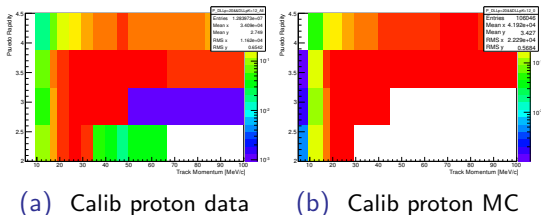
- Second errors correspond to PIDCalib systematics only.
- Results in agreement, but still work to do.
- Will now discuss work on the central values, systematics and cross checks.

Regarding BF central values

- Results are in agreement right now - but not finalised yet!
 - Tracking efficiency corrections to be applied - should be 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.
 - Some peaking backgrounds still to be investigated - more on this later.
- No other effects expected to alter central BF values after these.

Systematics - PIDCalib I

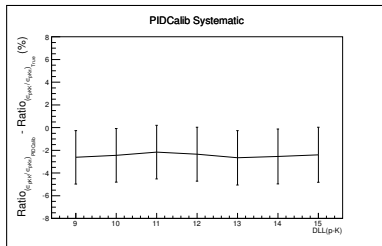
- Systematic has two sources:
 - Limited statistical precision in calibration bins
 - Acceptance variations over calibration bins
- Account for first with poisson errors on calib bins.
- For second: using MC scan across DLLs, assess max difference between true PID eff and PIDCalib eff.
- Measure ratio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



- For more info on proton MC sample see [LHCb-INT-2013-028](#).

Systematics - PIDCalib II

- Prompt $\Lambda_c^+ \rightarrow pK^-K^+$ 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 due to acceptance variations of 3%.

- Stripping efficiency re-weighting procedure has two systematic sources:
 - Limited statistical precision in MC bins
 - Acceptance variations over efficiency bins
- Account for the first with poisson errors on each bin.
- Account for the second by varying bin limits and schema in a semi-random way and measure the adjustment to derived efficiency.

- Use MC generated with flat phase space in prompt, pseudo-resonance model in SL.
- Different phase space modelling could lead to different efficiencies derived in MC.
- Can evaluate by weighting MC11a in analysis with generator level MC of different models.

- Full table of systematics in analysis below

Source	Effect [%]
PIDCalib binning schema	3.0
PIDCalib finite calibration stats	1.2
Finite MC statistics	1.5
Strip Eff Re-weighting	-
MC Modelling	-
Peaking Backgrounds	-

- Calculation of remaining systematics underway - methods in place to evaluate effects.
- PIDCalib still expected to be one of the largest systematics.
- If we keep them under control, should have world best measurements on all relative branching fractions in analysis.

- Work by Thomas investigated backgrounds - mis-ID'd D, D_s decays.
- Double Mis-ID CF \rightarrow DCS also investigated.
- No peaking backgrounds discovered in relevant mass window.
- Our SL selections are very similar but not identical!
- Work currently underway to replicate these checks using both our selections.
 - Use $D, D_s \rightarrow hhh$ MC decays, reassign mass hypotheses to look for single and triple mis-ID peaking backgrounds.
 - Use CF data/PIDCalib to estimate double mid-ID feed to DCS. If significant, account for in fit of DCS mode.

Analysis Note and Outlook

- Analysis note *very* close to v0 for public consumption!
 - Had planned for release today but have some polishing to do.
- Will release v0 by Monday at the very latest.
- Analysis in mature stage, systematics and cross checks ongoing with fixed methods in place.
- Hope to enter WG review proper by next week when ANA v0 released.