Charm Baryon Spectroscopy

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Charm Spectroscopy

Several analyses currently underway in Charm WG. Will cover three today.

- Branching fractions of $\Lambda_c^+ \to p^+ h^+ h^-$, $h = K, \pi$.
- Search for the doubly charmed baryons $\Xi_{cc}^{+(++)}$.
- Spectroscopy of $D^0 p$ final states.

Will focus today on Λ_c^+ BF analysis.

Lc Overview

- Physics Motivation
- Λ_c^+ Dataset.
- Mass Fits and Signal Yields
- Selections (cut based and MVA).
- Efficiencies
- Future Work

Physics Motivation

- $\Lambda_c^+ \rightarrow$ p h h modes still poorly understood in terms of Branching Fractions (BFs), decay amplitudes and resonance structure.
- Current PDG BFs shown below, the doubly-Cabibbo Suppressed decay $\Lambda_c^+ \rightarrow p^+ K^+ \pi^+$ has not been 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.

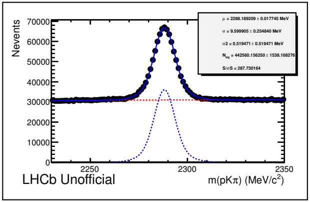
- Easy to get competitive measurements but makes cross checks more challenging.
- Work is ongoing with Rio to perform multi-dimensional resonance analysis with the CF and DCS modes. CPV in SCS Λ_c^+ decays by Sajan et al.

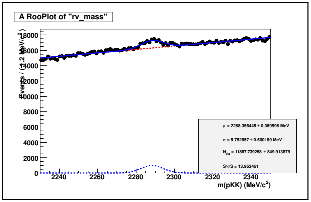
Λ_c^+ Stripping 17b 2011 Dataset

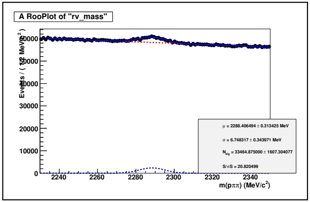
- Two sources of Λ_c^+ production: prompt and from semileptonic $\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu_\mu$ secondary decays.
- Expect more prompt production but prompt charm baryon triggers are inefficient. Dedicated $\Lambda_c^+ \to p^+ \pi^+ K^-$ TOS is 8.1% efficient. Partly due to the shorter time of flight for baryons than mesons: $\tau_{\Lambda_c} = 0.2$ps. $\tau_D = 0.4 - 1$ps.
- Compared to topological muon semileptonic lines, typically 80% TOS efficient.
- Both are important due to the lack of a suitable control mode for the decays. Treating both samples independently.
- Have chosen a TIS trigger chain for prompt as we have only had a prompt Cabibbo-Favoured dedicated trigger for half of 2011.
- We now have prompt dedicated triggers in place for all four modes.

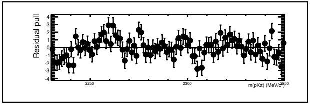
Mass Fits and Signal Yields I - Prompt

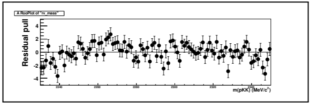
- Double (Single) Gaussian signal and linear background describe CF mode (DCS modes) well.

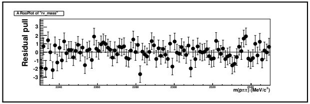






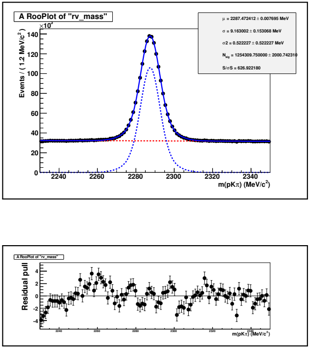




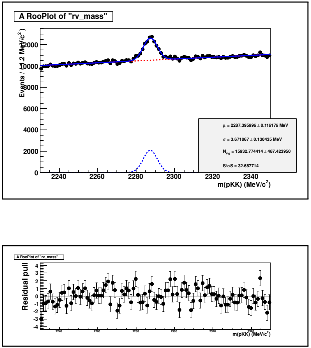


$\Lambda_c^+ \to p^+ K^- \pi^+$ $\quad$ $\Lambda_c^+ \to p^+ K^- K^+$ $\quad$ $\Lambda_c^+ \to p^+ \pi^- \pi^+$

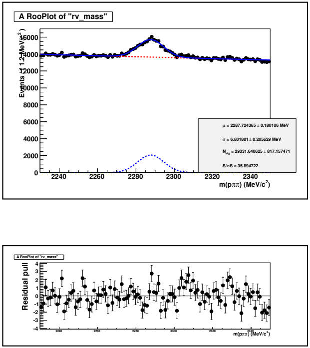
- Much higher raw yields from stripping than in prompt for CF, SCS modes comparible.
- Both datasets are being analysed in parallel.



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



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



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

Mass Fits and Signal Yields III - Overall

- The DCS prompt mode is being kept blind in prompt. Peaking backgrounds likely to be more important for DCS mode due to much lower expected yield.
- Main sources likely to be from D reflections and double mis-ID from CF. Currently under investigation.

-	Decay Mode	Signal Yield
Prompt	$\Lambda_c^+ \to p^+ K^- \pi^+$	442 k
	$\Lambda_c^+ \to p^+ K^- K^+$	11.8 k
	$\Lambda_c^+ \to p^+ \pi^- \pi^+$	33.4 k
Semileptonic	$\Lambda_c^+ \to p^+ K^- \pi^+$	1.25 M
	$\Lambda_c^+ \to p^+ K^- K^+$	15.9 k
	$\Lambda_c^+ \to p^+ \pi^- \pi^+$	29.3 k

The signal yields of the Λ_c^+ unblinded modes.

- From here on in will discuss only the prompt sample.

Offline Selections I - Outline

- Main strategy: make the selection as agnostic to the daughter properties as possible. This will make the application to a relative BF measurement much more amenable.
- Have trained 2 cut-based and two MLP selections for each channel. One for the CF mode and one for the DCS mode using sWeighted CF data.
- For DCS mode also use a global weighting on signal events of $\frac{|V_{ud}|^2|V_{cs}|^2}{|V_{cd}|^2|V_{us}|^2} = 0.003$.
- Variables utlised:
  - Λ_c^+:
    - Pt , MAXDOCA, Vertex χ^2 , IPχ^2, FD χ^2, DIRA
  - PID:
    - $p_{PIDp}, K_{PIDK}, K_{PIDp}, (p_{PIDp} - p_{PIDK})$
- Aware that discrimination achieved with PID may be in effect daughter Pt cuts which makes the selection less agnostic to daughters, under investigation.

Offline Selections II - Cut Based

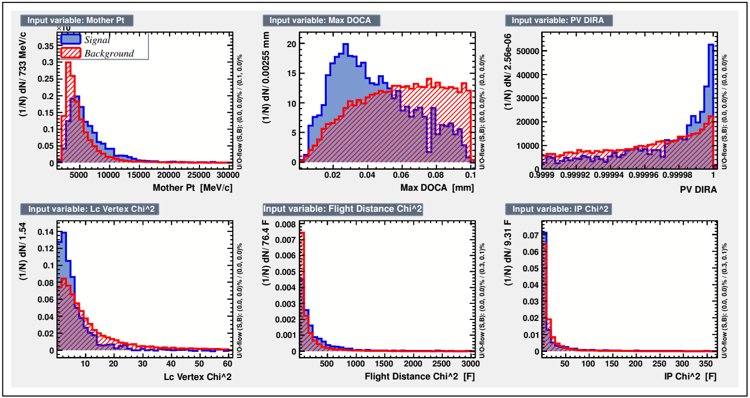
- Implement TIS trigger chain: L0, HLT1, HLT2Phys TIS.
- Conor Fitzpatrick's Cut Recursive Optimiser (CROP) used to acquire optimum $\frac{S}{\sqrt{S+B}}$ with rectangular cuts.
- Final yields for the CF mode shown below.

Post...	N_{sig}	% of raw
Raw	$442k \pm 1538$	-
TIS	$361k \pm 1935$	81.6 ± 0.9
Offline	$229k \pm 756$	51.86 ± 0.35

- With this selection expect for the DCS mode in the signal region ($\pm 15 MeV$) a significance of $\frac{S}{\sqrt{S+B}} = 3.27$.

Offline Selections III - MVA Setup

- To gain sensitivity we approached a full MVA selection using our non-PID discriminating variables.
- Variable input distributions for training below.

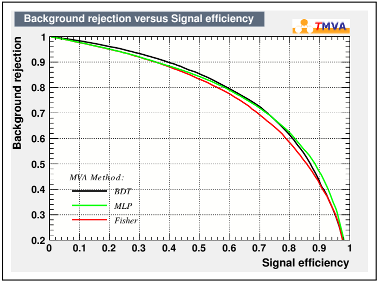


Input variables for MVA training.

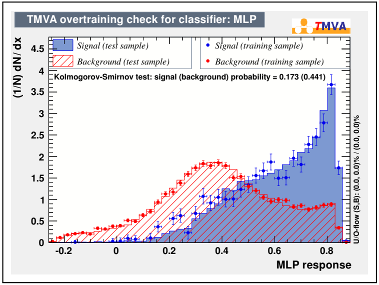
- bob

Offline Selections IV - MVA Training

- Investigated the use of a BDT, MLP and Fisher discriminant.
- BDT and MLP display the expected superior discrimination to the Fisher.
- However, MLP displays more robustness against overtraining.



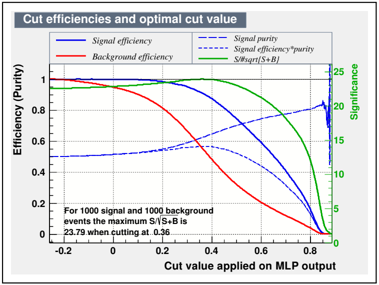
ROC curve for $\Lambda_c^+ \to p^+ K^- \pi^+$.



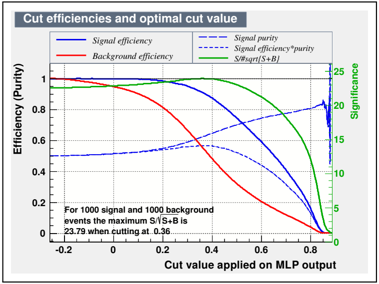
Overtraining check for the MLP.

Offline Selections V - MLP Performance

- High signal purity can be attained with an MLP.



MLP performance curves.



Mass plot for CF prompt after MLP goes here.

- Final signal yield with MLP: $x \pm y$ ($z\% \pm a$ retained).
- Final projected DCS $\frac{S}{\sqrt{S+B}}$: .
- Would/would not expect a discovery of this mode.

Efficiencies I

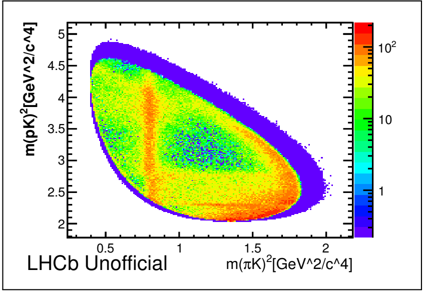
- Efficiencies composed of reconstruction and the full selection, incorporating the efficiencies of the trigger, stripping and offline.
- As usual, separate the PID efficiencies from our selection efficiencies to utilise Andrew Powell's PID reweighting. This prohibits the use of PID variables in MVA training.
- Relative BF between CF and other phh mode given by:

$$\frac{\mathcal{B}_{\Lambda_c^+ \to p^+ K^- \pi^-}}{\mathcal{B}_{\Lambda_c^+ \to p^+ h^- h^-}} = r \times \epsilon_{acc} \times \epsilon_{reco} \times \epsilon_{trigger} \times \epsilon_{sel}$$

  where r is the measured signal yield ratio.
- All decay modes of interest have a rich resonance structure. It therefore becomes necessary to consider the Dalitz space when calculating our efficiencies.
- In mesons invariant mass of daughter pairs is sufficient to parameterise the resonance structure, with baryons spin becomes a concern.

Efficiencies II

- The extension of the 2D Dalitz space in the meson sector to particles with spin incorporates an additional 3 angular parameters to make a 5D phase space.
- Strong resonance structures demonstrated in the sWeighted CF charge-opposite daughter pair invariant masses, below. Strong $K^*(892)$ and $\Lambda(1520)$ contributions can be seen.



CF prompt resonance structure for the TIS dataset.

- Take the reconstruction efficiency from MC with a binning in the 5D phase space such that there should be no strong variation of the resonance structure within each bin.
- Then calculate a bin by bin efficiency to apply to the data.
- Work ongoing in this area.

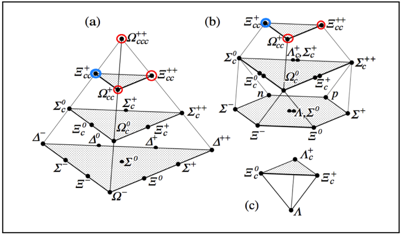
Future Work

- Have finalised an MVA selection for use in searching for the DCS mode.
- Would expect to see this mode in the prompt charm dataset.
- BF analysis progressing, moving onto efficiency techniques and calculations.
- Still requires a thorough consideration of physics backgrounds for the DCS mode and systematics for all modes.
- Analysis note currently under construction.
- When finished much of the groundwork for further analyses with Λ_c^+ will already be there.

Double Charm Baryon Searches - Motivation

- Baryons containing u,d,c,s form an SU(4) group, below.

- LHCb expected to produce Ξ_{cc}^{+} copiously:
  $\sigma(pp \rightarrow \Xi_{cc}^{+} X) = 300nb$.



SU(4) generated multiplets of charm baryons. Circled in blue, observed only by SELEX. Red not observed. From PDG [1].

- SELEX [2] measurements of the Ξ_{cc}^{+} properties disagree strongly with theory.
  - SELEX
    - $m = 3518.7 \pm 1.7 MeV/c^2$
    - $\tau < 0.33ps$ at $90\% CL$
    - 0.2 Λ_c^+ from Ξ_{cc}^{+} decays
  - Theory
    - $m = 3610 MeV/c^2$
    - $\tau < 0.07 - 0.20ps$
    - $10^{-5} \Lambda_c^+$ from Ξ_{cc}^{+} decays
- Belle, BaBar and FOCUS have searched for and not observed doubly charmed baryon production.

Double Charm Baryon Searches at LHCb

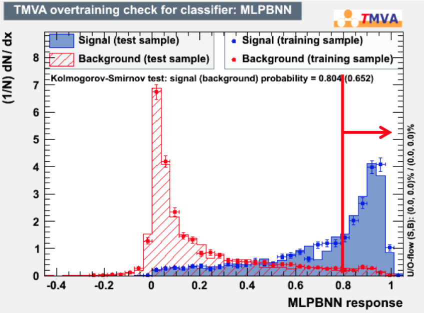
- Searches are underway for the particles through the decay modes using all the Stripping 17b data:
  - $\Xi_{cc}^{+} \to D^{+}(K^{-}\pi^{+}\pi^{+})p^{+}K^{-}$
  - $\Xi_{cc}^{+} \to D^{0}(K^{-}\pi^{+})p^{+}K^{-}\pi^{+}$
  - $\Xi_{cc}^{+} \to \Lambda_{c}^{+}\pi^{+}K^{-}$
  - And the corresponding Ξ_{cc}^{++} modes.
- The Ξ_{cc}^{+} mass window is blinded in the range $3.3 - 3.8$GeV.
- MC created with GenXicc2.0, a dedicated double heavy baryon generator.
- Simulated particle properties:
  - $m_{\Xi_{cc}^{+}} = 3.5 GeV$
  - $\tau_{\Xi_{cc}^{+}} = 330 fs$
  - $\Gamma_{\Xi_{cc}^{+}} = 7 MeV$
- If found intend to measure the production ratio relative to the Λ_c^{+}:

$$\frac{\sigma(\Xi_{cc}^{+}\to\Lambda_c^{+}K^{-}\pi^{+})\times\mathcal{B}(\Xi_{cc}^{+}\to\Lambda_c^{+}K^{-}\pi^{+})}{\sigma(\Lambda_c^{+}\to p^{+}K^{-}\pi^{+})}$$

Double Charm Baryon Searches - MVA Selection

- Before MVA additional cut applied:
  - Ξ_{cc}^{+} PVFit $\chi^2 < 50$, PVFit χ^2 is the DecayTreeFitter χ^2 with a PV constraint, no mass constraint.
  - Multilayer Perceptron with BFGS training method and bayesian regulator trained on MC for offline selection.

- Variables used in training:
  - Ξ_{cc}^{+} MAXDOCA
  - Ξ_{cc}^{+} IP χ^2
  - Ξ_{cc}^{+} Vertex χ^2
  - Ξ_{cc}^{+} P_t
  - Λ_c^{+} MAXDOCA
  - Λ_c^{+} IP χ^2
  - Λ_c^{+} Vertex χ^2
  - Λ_c^{+} Flight Distance χ^2



MLP response and overtraining plot.

Efficiencies and Preliminary Projections

- Derive all acceptance, reconstruction, trigger and selection efficiencies for signal from the MC.
- Use the cross section with the combined efficiency to predict N_{sig} in the signal region, use sidebands to estimate our N_{bkg}.
- Provisional $N_{sig} = 2.5$, $N_{bkg} = 36$.
- By measuring the ratio of the production of Ξ_{cc} and Λ_c^+ we cancel some systematics.
- Would expect from this a final production ratio of

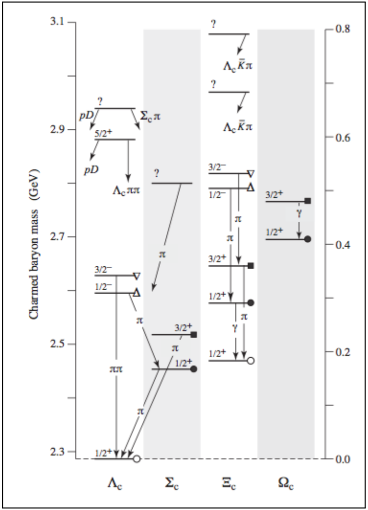
$$\frac{\sigma(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+ \to p^+ K^- \pi^+)} = 4.82 \times 10^-5$$

- Such a measurement would be consistent with theory.

Double Charm Baryon Searches - Future Work

Need some advice on what to say here. We could and probably should mention our background studies but my memory is a little foggy on what was being done...
What do we plan for the 2012 data if we do/don't observe anything in 2011?

D^0p Final State Spectroscopy - Motivation



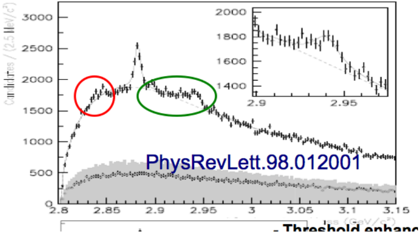
The spectra of the singly charmed baryons.

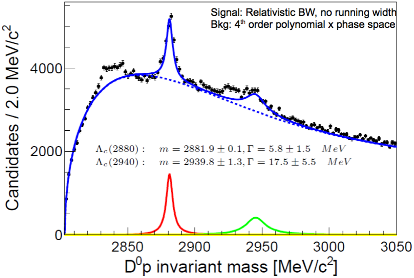
- Spectroscopy of excited charm baryons offers tests of HQET - approximate the heavy baryon as a stationary heavy quark interacting with a light quark dipole.
- $\Lambda_c(2880, 2940) \rightarrow D^0p$ first observed by BaBar.
- LHCb can make a significant contribution in this area of research.

$D^0 p$ Final State Spectroscopy - Cuts and Selection

- Using Stripping 17b prompt $D^0 p$ production.
- Standard set of offline cuts using variables with negligible correlations.
  - $\cos\theta > 0, \theta =$ angle between p momentum in $D^0 p$ frame and boost of $D^0 p$ frame in lab frame. Reduces combinatoric background by more than 95%.
  - All tracks associated to same PV.
  - PID $\mathrm{DLL}_{p-K} < 8$. Soft PID requirements on D^0 daughters.
  - $P_t(D^0 p) > 4.5 GeV$.
- All cuts are going to be optimised in the future, using the signal significance of the $\Lambda_c(2880)$.
- Vital to eliminate mis-ID crossfeed, eg. $D_{s2}^{+}(2573) \rightarrow D^0 K$

- Use same fit model as Babar: relativistic Breit-Wigner distribution for signals and 4*th* order polynomial background.
- Distributions from Babar's measurement (left) and our measurement shown below.

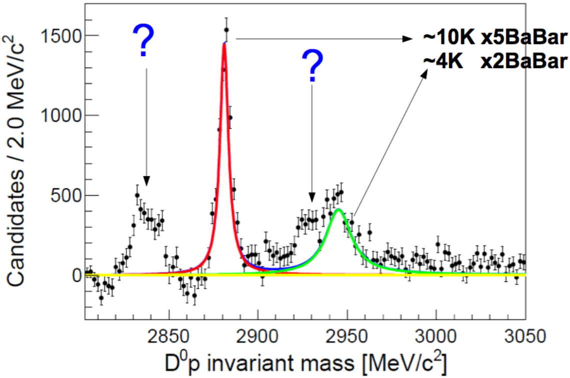




- $\Lambda_c(2880, 2940)$ resonances can be clearly seen in our data, but more structure emerges.

D^0p Final State Spectroscopy - Mass Spectrum II

- Background subtracted mass distribution shown below.



- The nature of this structure is at present unclear.
- Possible explanations include reflections (particularly $D_{s2}^{+}(2573) \rightarrow D^0K$ cross-feed), missing π^0/γ, distortion from pPID cut, clones, threshold enhancement...

D^0p Final State Spectroscopy - Future Work

- Selection Optimisation is underway.
- The auxiliary D*p decay mode requires further study to establish the possibility of crossfeed.
- This will enable us to find out the source of the new structure in the D^0p mass spectra.
- Note is being written, plans to release it to the Charm WG by the end of September.

Concluding Remarks

- Variety of work in progress with charmed baryons at LHCb.
- $\Lambda_c^+ \to p^+ h^- h^+$ BF measurement has finalised a selection. Now dealing with a thorough calculation of the relative efficiencies between the modes. Systematics and background studies for the DCS mode to follow.
- $\Xi_{cc}^{+(++)}$ search is continuing to refine an MVA selection for maximum sensitivity to the modes of interest. Background studies are in progress.
- $D^0 p$ final state spectroscopy is working with larger statistics than previous efforts at BaBar. Investigations into potential crossfeed from $D^* p$ decays are underway to establish the source of the new structure in the spectra observed.

Backup