Λ Production in $\bar{\nu}_\mu$ - Ar Interactions in MicroBooNE

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Neutrino Cross Section Physics

- Neutrinos oscillation provides evidence of physics beyond the Standard Model.
- Big push to measure oscillation parameters with different baselines/detector technologies.
- Good cross section physics enables good oscillation physics.

Figure: Neutrino cross section measurements [1].
Direct Hyperon Production

The focus of this talk is on direct (Cabibbo suppressed) hyperon production: $W$ boson converts an up quark into a strange quark inside a nucleon:

\[ \bar{\nu}_l \rightarrow l^+ \]

\[ N = p, n, \quad Y = \Lambda, \Sigma^0, \Sigma^- \]

Figure: Direct hyperon production. $N = p, n, \ Y = \Lambda, \Sigma^0, \Sigma^-$. 

Other production mechanisms are resonance excitation/decay and deep inelastic scattering.
Direct Hyperon Production

- This process is very poorly constrained by existing measurements.
- Sensitive to a range of effects: $\bar{\nu}$-nucleon cross section parameters and unique final state interactions.
- Measuring multiple channels can help disentangle these effects.
- Only generated by anti-neutrinos.

Figure: Predictions from NuWro compared with entire $\Lambda$ production dataset [2].
LArTPCs

Figure: Operational principle of the MicroBooNE LArTPC.

Figure: Example (signal) event display.
Flux

- Hyperon production is purely $\bar{\nu}$ driven, influences our choice of flux.
- BNB has run exclusively in neutrino mode for MicroBooNE’s data taking period.
- NuMI has run in a mix of neutrino/anti-neutrino mode.
- Off axis $\rightarrow$ stronger $\bar{\nu}$ flux even when in neutrino mode.
- We use NuMI.

Figure: Fluxes from BNB (top) [3] and NuMI (bottom) [4].
The Analysis

- We wish to measure $\Lambda$ production in $\bar{\nu}_\mu$ interactions:
  \[ \bar{\nu}_\mu + \text{Ar} \rightarrow \mu^+ + \Lambda + X \]  
  (1)
- Search for the $\Lambda \rightarrow p + \pi^-$ decay, leaves a very distinctive “track + V” topology.
- Expect 12 interactions among 650k triggers before applying any selection in data from our 1st year of data taking.
- Challenging selection!

Figure: Selected signal event from MicroBooNE simulation.
Selection Strategy

- Selection identifies a muon candidate and a pair of tracks consistent with a proton and pion.
- Check if the kinematics of the proton + pion are consistent with a $\Lambda$ decay.
- Do the proton + pion form a separate “island” of activity to the muon?
- See MicroBooNE public note 1097 for details.

No selection:

**Signal = 12 events.**
**BG = 650k events.**

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Figure: Selected signal event from MicroBooNE simulation.
Preselection and Muon ID

- Apply a preselection to remove any events outside fiducial volume or with fewer than three tracks.
- Vast majority of the time muon is longest track.
- Muon is longest track satisfying PID and quality requirements.

After preselection + Muon ID:
Signal = 2.7 events.
BG = 3000 events.

Figure: Log-likelihood ratio PID used in muon selection [5].
Decay Track Selection

- Want to calculate useful quantities like invariant mass.
- Need the pair of tracks belonging to the $\Lambda \rightarrow p + \pi^-$ decay for these things to mean anything.
- Need to get the tracks in the right order.

**Figure:** Selected $\Lambda$ event from MicroBooNE simulation.
**Decay Track Selection**

- Employ an array of BDTs that utilises 7 variables to produce a response score for each combination.
- Variables used include PIDs, track/shower classification scores.
- Select correct pair of tracks in $\approx 95\%$ of signal events.

**Figure:** Some variables used in decay track selection.

**Correct combination. Wrong combination.**
Decay Analysis

- Two variables to check consistency of kinematics and geometry with that of a real \( \Lambda \) decay including invariant mass.
- Feed these into a second set of BDTs alongside the response from the selector.

After decay analysis:
- **Signal = 0.9 events.**
- **BG = 6.1 events.**

**Figure:** Variables used to analyse decay kinematics.
“Island” Finding

- Main distinguishing feature of signal is small gap between muon and decay.
- Purpose made software that analyses event display, checks if activity from decay forms a separate region of activity to muon.

After island finding:
Signal = 0.8 events.
BG = 0.7 events.

Figure: Different stages of island finding algorithm, tested on a signal event.
Background

- Main remaining background consists of other hyperon production channels.
- Some background from neutron interactions.

Figure: Selected $n + Ar \rightarrow 2\pi + X$ event.
Systematics

Consider four sources of systematic uncertainty:

1. Flux simulation.
2. Event generator modelling.
4. Detector effects.

Dominant source of uncertainty from detector modelling.

Figure: Breakdown of fractional errors for signal and three main categories of background.
Cross Section Extraction

- Aim to publish a restricted phase space total cross section.
- Related to number of observed events by:

\[
\sigma_* = \frac{N_{\text{Obs}} - B}{T \Phi \Gamma \epsilon}
\]  

\( T \) = number of targets.
\( \Phi = \bar{\nu}_\mu \) flux.
\( \Gamma = 0.64 = \Lambda \to p + \pi^- \) branching fraction.
\( \epsilon \) = selection efficiency.
\( B \) = predicted background.

- Calculate covariance matrix of \( B, \epsilon \) and \( \Phi \).
Cross Section Extraction - Statistical Errors

- Use Bayesian method for propagating data/MC statistical uncertainties.
- Obtain posterior distribution on the background acceptance and efficiency using TEfficiency class from Root [6]:

\[
\phi_\epsilon(\epsilon) = P(\epsilon|\epsilon_{MC}) \tag{3}
\]

\[
\phi_B(B) = P(B|B_{MC}) \tag{4}
\]

- Posterior distribution on data event rate:

\[
P(N|N_{Obs}) = \frac{P(N_{Obs}|N)P(N)}{\int_a^b P(N_{Obs}|N)P(N)dN} \tag{5}
\]

- Use uniform priors.
Throw many values of $\epsilon$, $B$ and $N$ from their respective posterior distributions.

Throw fluctuations on these using $B$, $\epsilon$, $\Phi$ covariance matrix to propagate systematic uncertainties.

Build the posterior distribution on $\sigma_\ast$.

**Figure:** Bayesian posterior distributions on extracted cross section for a given number of data events.
Summary

- Analysis of $\Lambda$ production in $\bar{\nu}_\mu$ interactions is ready for application to MicroBooNE data.
- Finishing off analysing $\bar{\nu}$ mode data (approx. $2.5 \times$ the exposure shown here), then perform final unblinding.
- Early stages of preparing publication.

Figure: Selected signal event.
References I


References II


Parameter

- Angle between the direction of the \( \Lambda \)'s momentum vector and the line connecting the primary vertex to the decay vertex.

Figure: Values for signal and BG.

Figure: \( \alpha \) angle calculation.
Flux Systematics

- Flux systematics fall into two categories:
  1. Hadron production modelling. Handled using PPFX [7].
  2. Beamline geometry.
- Hadron production dominates.
- Overall uncertainty approx 10%.

Figure: Fractional errors from flux.
Cross Section Systematics

- Generator uncertainties performed using GENIE reweighting tools
  1. Large collection of parameters varied using multisim technique incl. vector/axial masses, FSI cross sections.
  2. 8 alternative models tested.
- See [8] for details.

Figure: Fractional errors from background cross sections.
Geant 4 Systematics

- proton, $\pi^\pm$ and $\Lambda$ uncertainties propagated with Geant 4 Reweight [9].
- 26% neutron uncertainty extracted from CAPTAIN data [10], used to rescale this background.

**Figure:** Fractional errors from Geant 4 modelling.
Detector Systematics

- Calculated by running a set of events through different detector response models.
- Four groups of uncertainties:
  1. Scintillation light yield (3 models).
  2. Wire response (4 models).
  3. Space charge effect (SCE) modelling.

Figure: Fractional errors from detector uncertainties.