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.

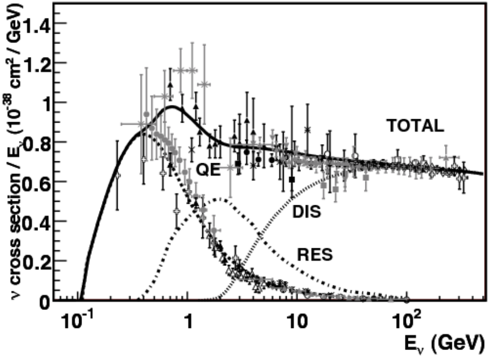


Figure: Neutrino cross section measurements [1].

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:

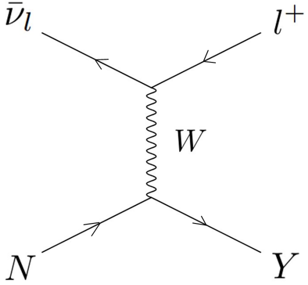


Figure: Direct hyperon production. $N = p, n$, $Y = \Lambda, \Sigma^0, \Sigma^-$.

- 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.

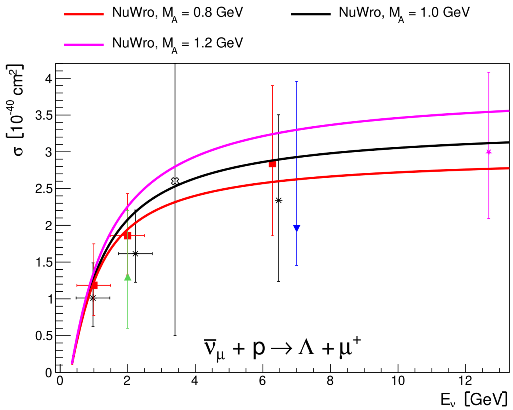


Figure: Predictions from NuWro compared with entire Λ production dataset [2].

LArTPCs

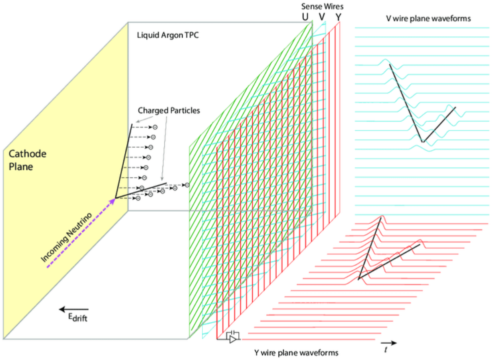


Figure: Operational principle of the MicroBooNE LArTPC.

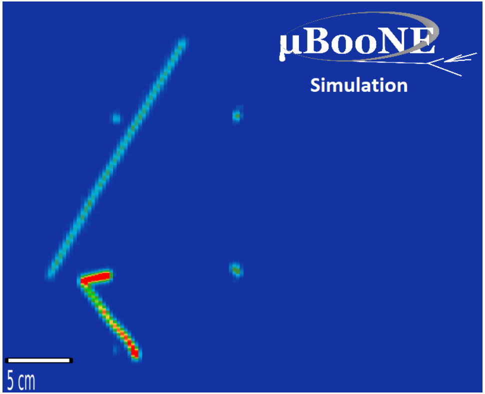
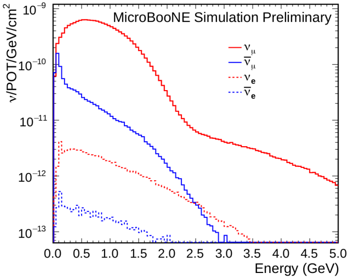


Figure: Example (signal) event display.

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.**



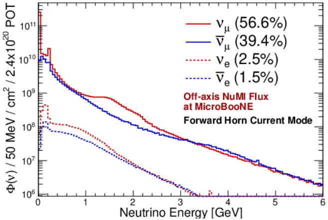


Figure: Fluxes from BNB (top) [3] and NuMI (bottom) [4].

The Analysis

- We wish to measure Λ production in $\bar{\nu}_\mu$ interactions:
$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \Lambda + X \qquad (1)$$
- 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!

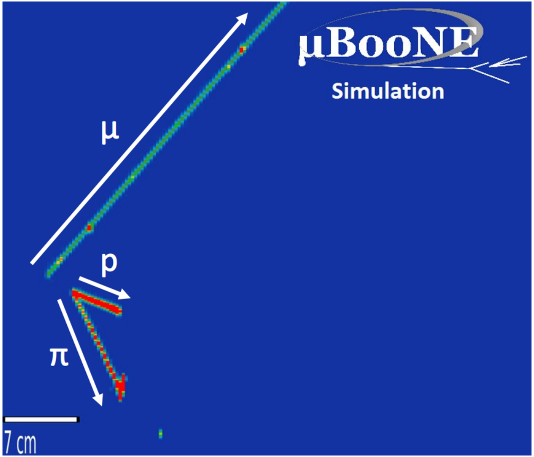


Figure: Selected signal event from MicroBooNE simulation.

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 Λ 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.

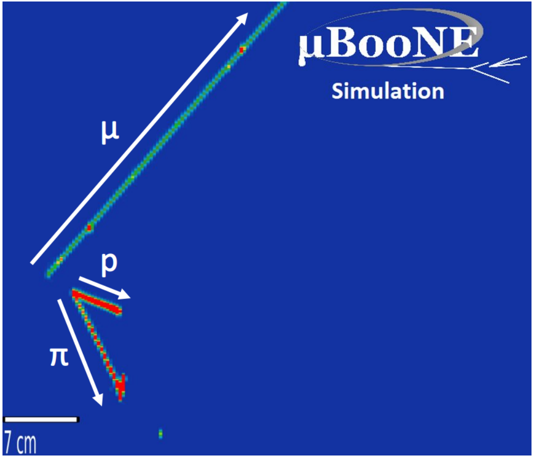


Figure: Selected signal event from MicroBooNE simulation.

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.

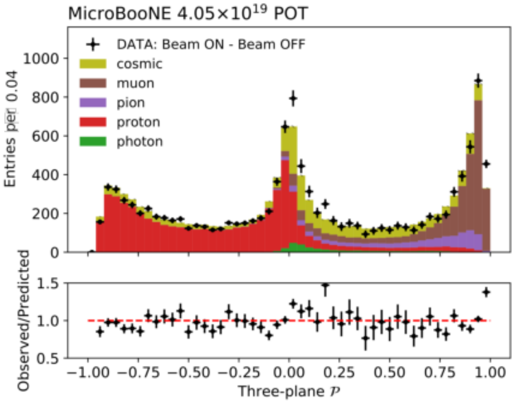


Figure: Log-likelihood ratio PID used in muon selection [5].

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

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*.

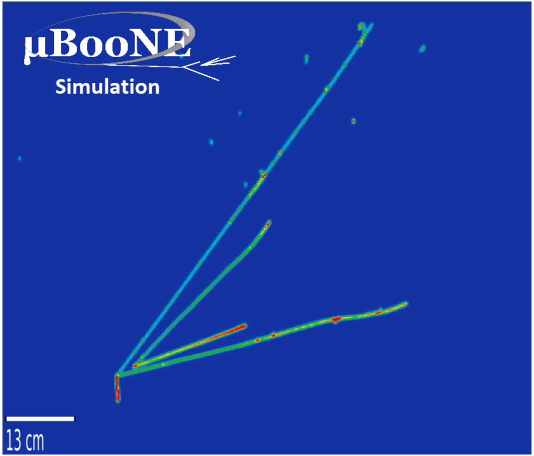


Figure: Selected Λ event from MicroBooNE simulation.

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.

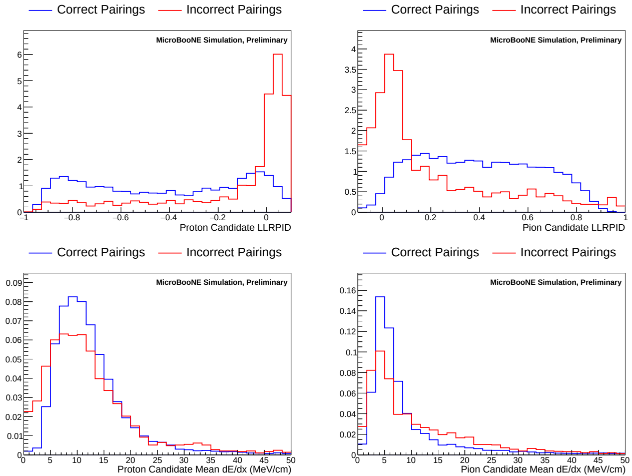


Figure: Some variables used in decay track selection. Correct combination. Wrong combination.

Decay Analysis

- Two variables to check consistency of kinematics and geometry with that of a real Λ 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.

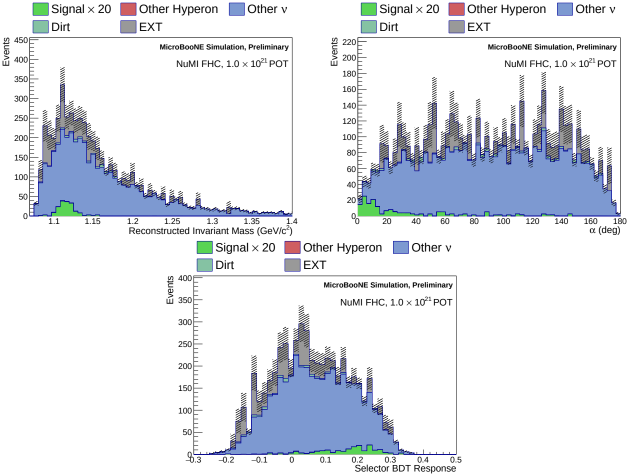


Figure: Variables used to analyse decay kinematics.

“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.

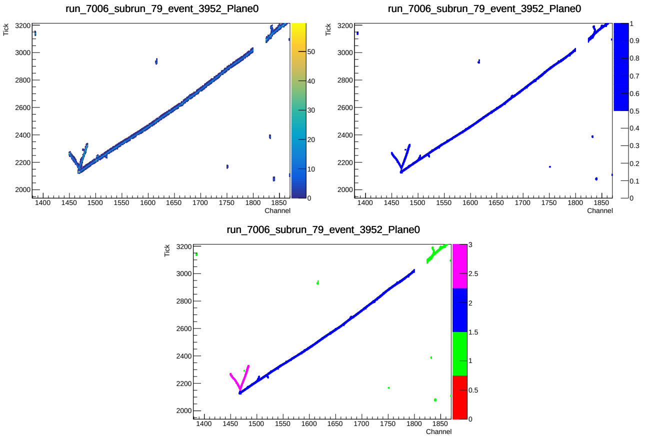


Figure: Different stages of island finding algorithm, tested on a signal event.

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

Background

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

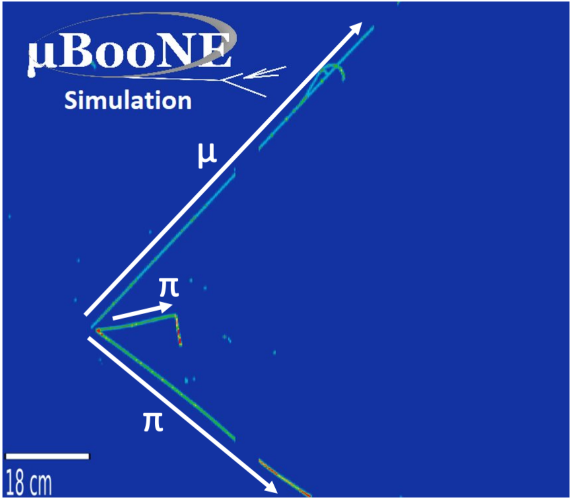


Figure: Selected $n + \mathrm{Ar} \to 2\pi + X$ event.

Systematics

- Consider four sources of systematic uncertainty:

1. Flux simulation.
2. Event generator modelling.
3. Secondary interactions.
4. Detector effects.

- Dominant source of uncertainty from detector modelling.

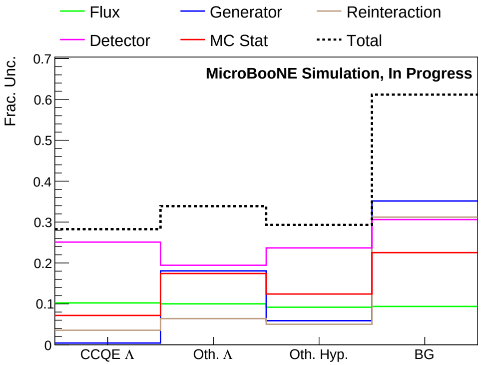


Figure: Breakdown of fractional errors for signal and three main categories of background.

Cross Section Extraction

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

$$\sigma_* = \frac{N_{\mathrm{Obs}} - B}{T\Phi\Gamma\epsilon} \tag{2}$$

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

- Calculate covariance matrix of B, ϵ and Φ.

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]:

$$\varphi_{\epsilon}(\epsilon) = P(\epsilon|\epsilon_{\mathrm{MC}}) \quad (3)$$

$$\varphi_B(B) = P(B|B_{\mathrm{MC}}) \quad (4)$$

- Posterior distribution on data event rate:

$$P(N|N_{\mathrm{Obs}}) = \frac{P(N_{\mathrm{Obs}}|N)P(N)}{\int_a^b P(N_{\mathrm{Obs}}|N)P(N)dN} \quad (5)$$

- Use uniform priors.

Cross Section Extraction - Complete

- Throw many values of ϵ, B and N from their respective posterior distributions.
- Throw fluctuations on these using B, ϵ, Φ covariance matrix to propagate systematic uncertainties.
- Build the posterior distribution on σ_*.

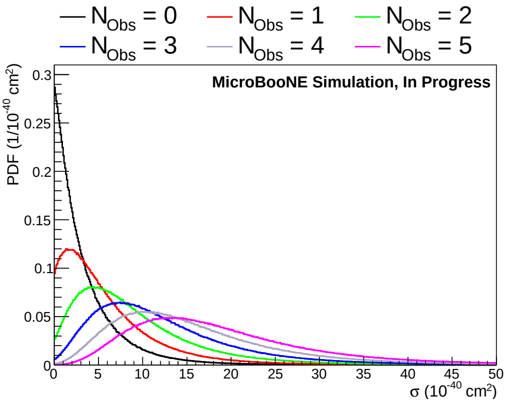


Figure: Bayesian posterior distributions on extracted cross section for a given number of data events.

Summary

- Analysis of Λ 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.

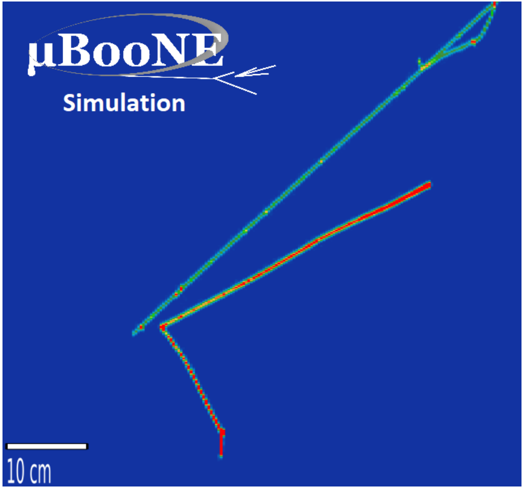


Figure: Selected signal event.

References I

[1] J. A. Formaggio and G. P. Zeller, Rev. Mod. Phys. **84** (2012), 1307-1341

[2] C. Thorpe, J. Nowak, K. Niewczas, J. T. Sobczyk and C. Juszczak, Phys. Rev. C **104** (2021) no.3, 035502

[3] MicroBooNE Public Note 1031.

[4] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. D **104** (2021) no.5, 052002

[5] P. Abratenko *et al.* [MicroBooNE], JHEP **12** (2021), 153

[6] https://root.cern.ch/doc/master/classTEfficiency.html. Accessed August 2021. Root version 6.16 used.

[7] L. Aliaga Soplin, PhD Thesis, William-Mary Coll.

[8] P. Abratenko *et al.* [MicroBooNE], [arXiv:2110.14028 [hep-ex]].

References II

[9] J. Calcutt, C. Thorpe, K. Mahn and L. Fields, JINST **16** (2021) no.08, P08042

[10] B. Bhandari *et al.* [CAPTAIN], Phys. Rev. Lett. **123** (2019) no.4, 042502

α Parameter

- Angle between the direction of the Λ's momentum vector and the line connecting the primary vertex to the decay vertex.

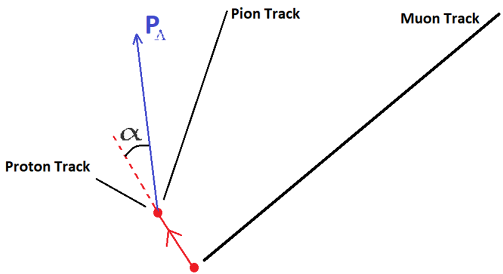


Figure: α angle calculation.

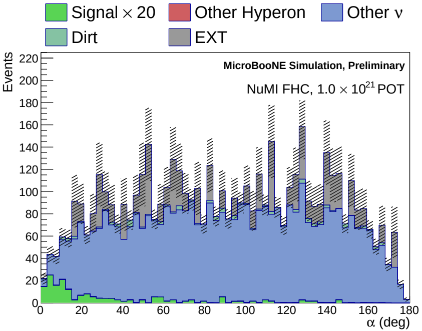


Figure: Values for signal and BG.

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%.

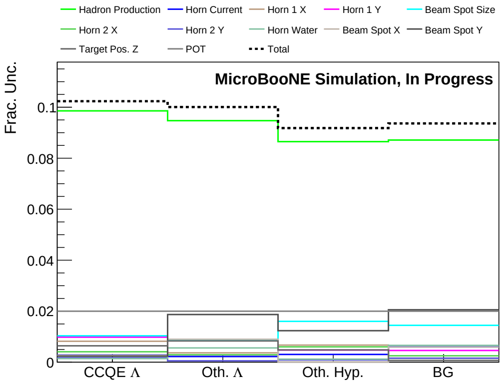


Figure: Fractional errors from flux.

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.

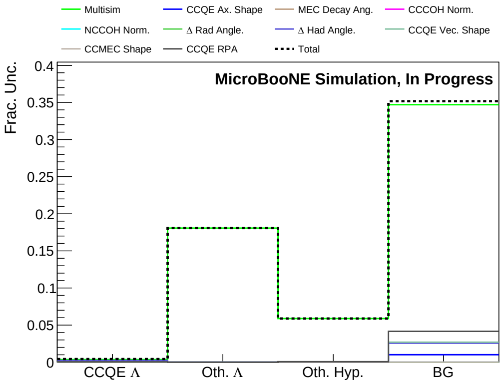


Figure: Fractional errors from background cross sections.

Geant 4 Systematics

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

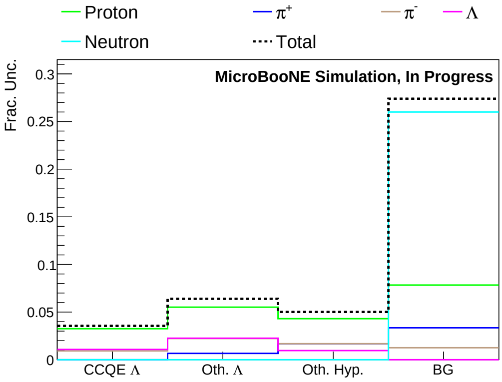


Figure: Fractional errors from Geant 4 modelling.

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.
  4. Recombination modelling.

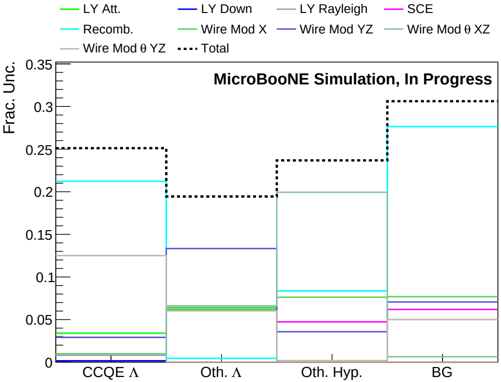


Figure: Fractional errors from detector uncertainties.