

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.

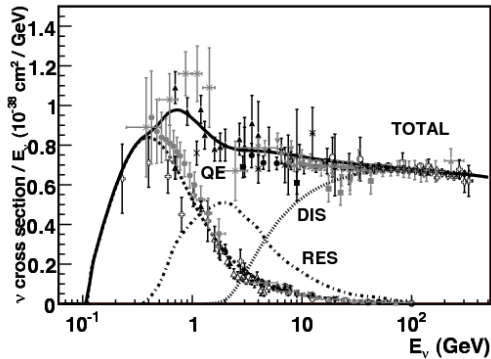


Figure: Neutrino cross section measurements [1].

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:

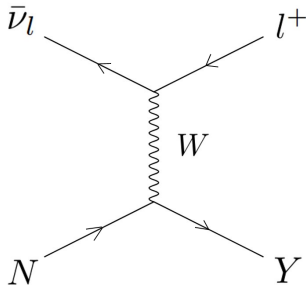


Figure: Direct hyperon production. $N = p, n$, $Y = \Lambda, \Sigma^0, \Sigma^-$.

- 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.

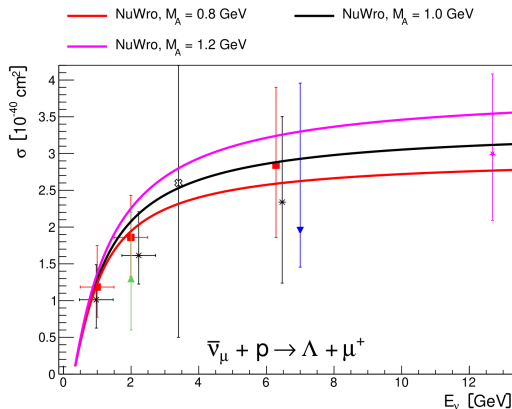


Figure: Predictions from NuWro compared with entire Λ production dataset [2].

LArTPCs

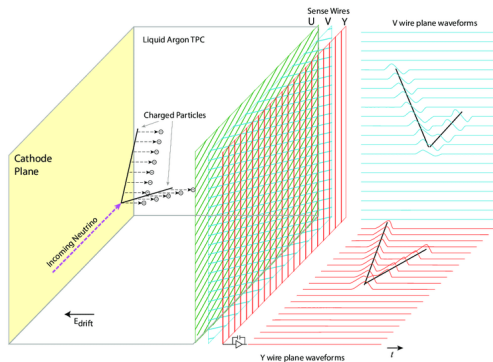


Figure: Operational principle of the MicroBooNE LArTPC.

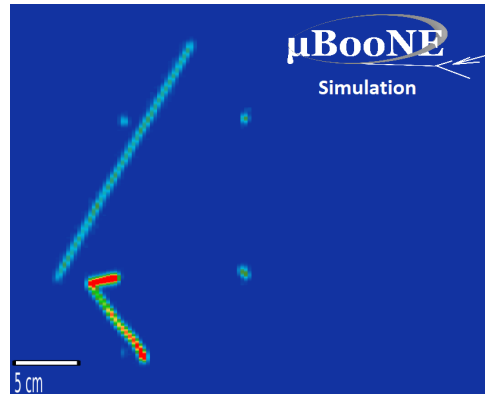


Figure: Example (signal) event display.

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.**

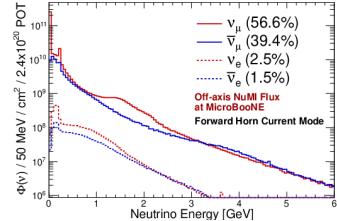
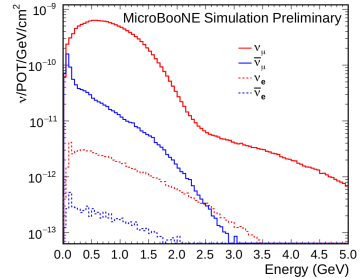
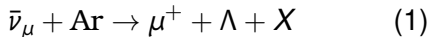


Figure: Fluxes from BNB (top) [3] and NuMI (bottom) [4].

The Analysis

- We wish to measure Λ production in $\bar{\nu}_\mu$ interactions:



- Search for the $\Lambda \rightarrow p + \pi^-$ decay, leaves a very distinctive “track + V” topology.
- Expect 37 interactions among 1.9M triggers before applying any selection to data from two periods in 2015/16 and 2017/18.
- Challenging selection!

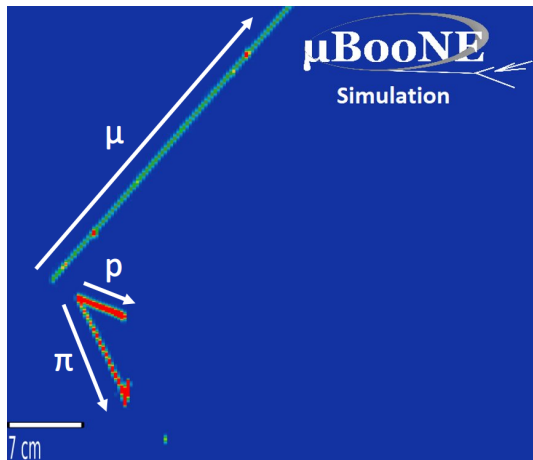


Figure: Selected signal event from MicroBooNE simulation.

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 = 37 events.

BG = 1.9M events.

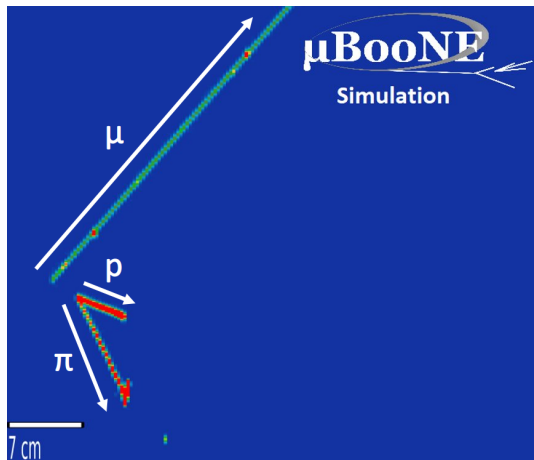


Figure: Selected signal event from MicroBooNE simulation.

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.

After preselection + Muon ID:
Signal = 9.2 events.
BG = 9600 events.

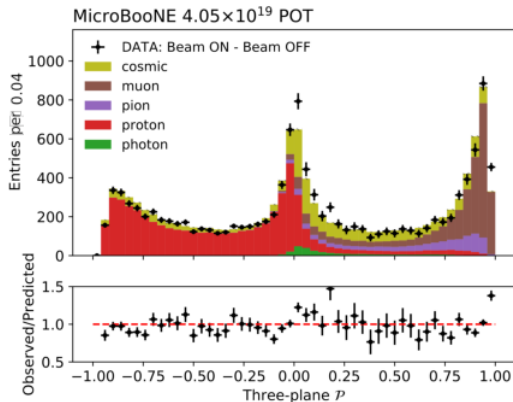


Figure: Log-likelihood ratio PID used in muon selection [5].

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*.

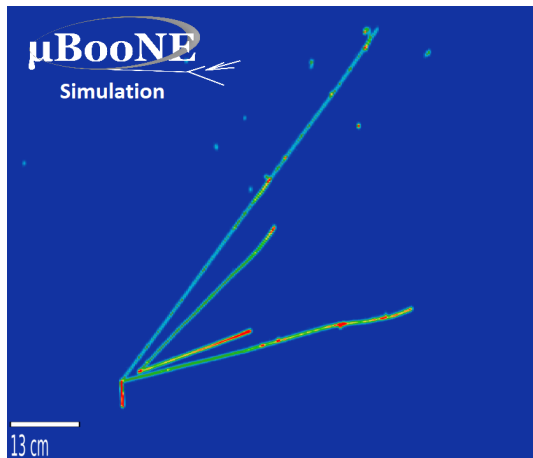


Figure: Selected Λ event from MicroBooNE simulation.

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.

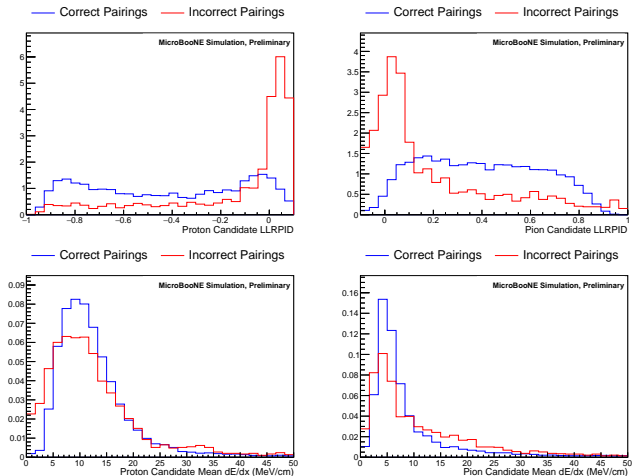


Figure: Some variables used in decay track selection.
Correct combination. Wrong combination.

Decay Analysis

- Two variables to check consistency of kinematics and geometry with that of a real Λ decay: Invariant mass W and angular deviation α (defined on slide 21).
- Keep events with $1.09 < W < 1.14$ GeV/c^2 and $\alpha < 14^\circ$.

After decay analysis:
Signal = 2.8 events.
BG = 41 events.

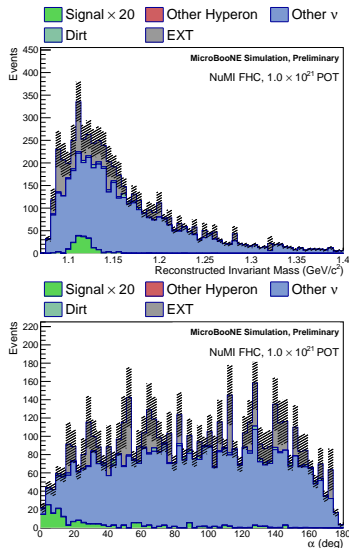


Figure: Variables used to analyse decay kinematics.

“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 = 2.5 events.
BG = 2.8 events.

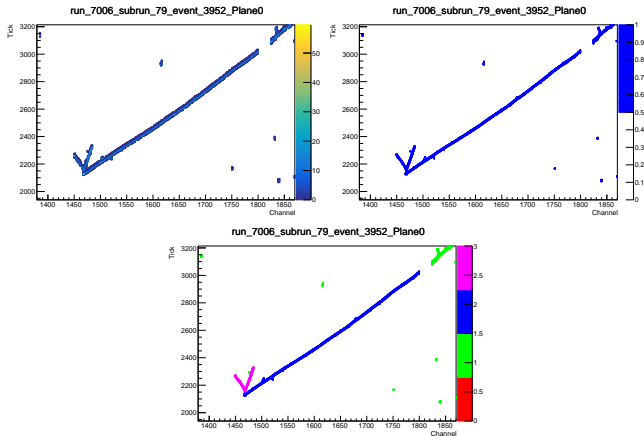


Figure: Different stages of island finding algorithm, tested on a signal event.

Background

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

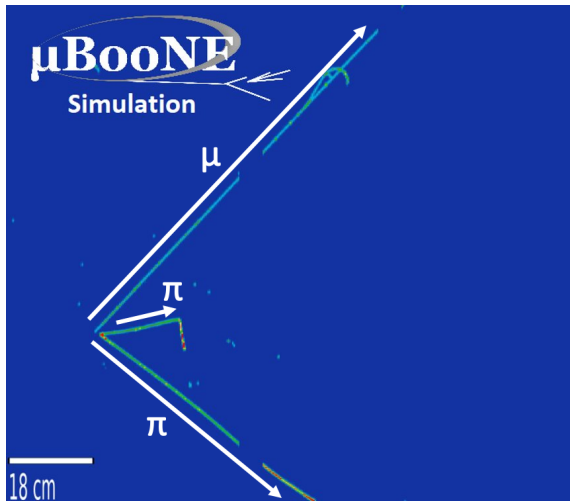


Figure: Selected $n + \text{Ar} \rightarrow 2\pi + X$ event.

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.

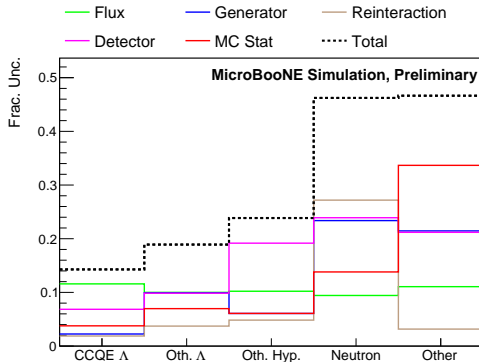


Figure: Breakdown of fractional errors for signal and four main categories of background.

Cross Section Extraction

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

$$\sigma_* = \frac{N_{\text{Obs}} - B}{T\Phi\Gamma\epsilon} \quad (2)$$

T = number of targets.

$\Phi = \bar{\nu}_\mu$ flux.

$\Gamma = 0.64 = \Lambda \rightarrow p + \pi^-$ branching fraction.

ϵ = 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]:

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

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

- Posterior distribution on data event rate:

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

- 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_* .

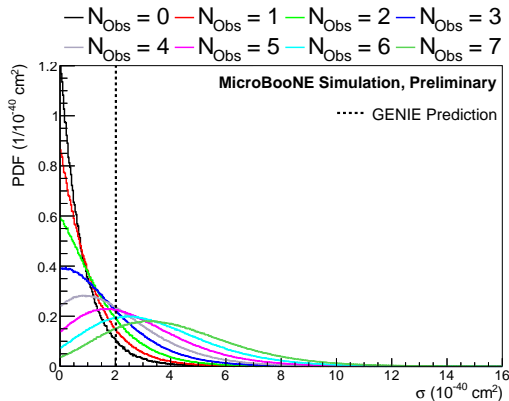


Figure: Bayesian posterior distributions on extracted cross section for a given number of data events.

Summary

- Analysis of Λ production in $\bar{\nu}_\mu$ interactions is ready for application to MicroBooNE data.
- Early stages of preparing publication.

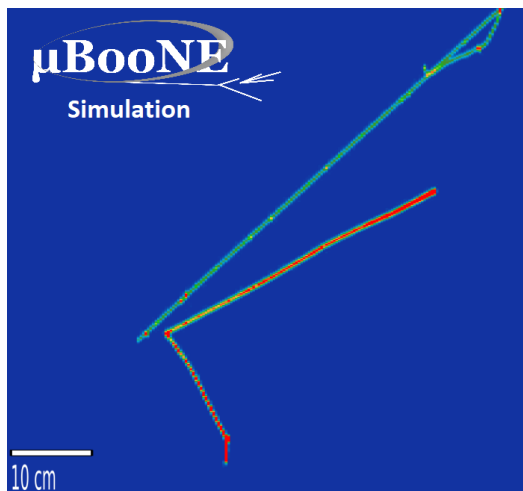


Figure: Selected signal event.

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.

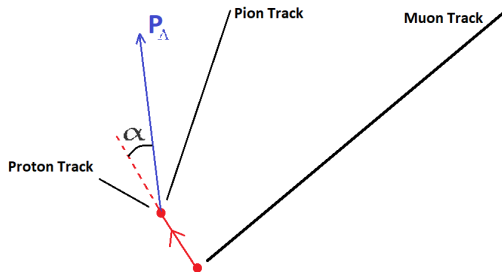


Figure: α angle calculation.

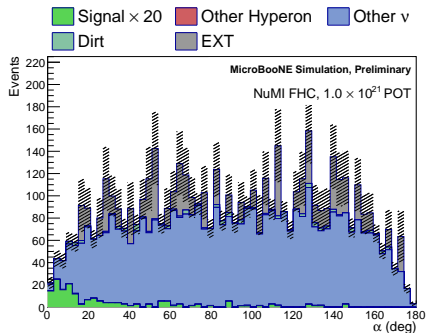


Figure: Values for signal and BG.