Rare Processes in MicroBooNE

Christopher Thorpe

On Behalf of the MicroBooNE Collaboration

Rare Processes

- MicroBooNE has collected the largest dataset of $\nu/\bar{\nu}$ interactions with argon to date.
- This enables studies of rare final states, we have several analyses in development:

1. CCQE-like Λ production.
2. Single kaons.
3. $K + \Lambda$.
4. η mesons.

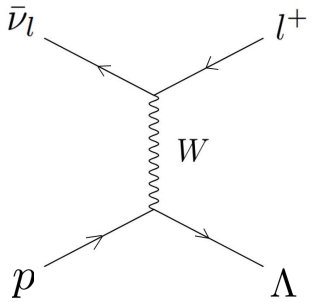
Rare Processes

- MicroBooNE has collected the largest dataset of $\nu/\bar{\nu}$ interactions with argon to date.
- This enables studies of rare final states, we have several analyses in development:

1. **CCQE-like Λ production. $\leftarrow$ The focus of this talk. More on the other analyses later.**
2. Single kaons.
3. $K + \Lambda$.
4. η mesons.

CCQE-like Hyperon Production

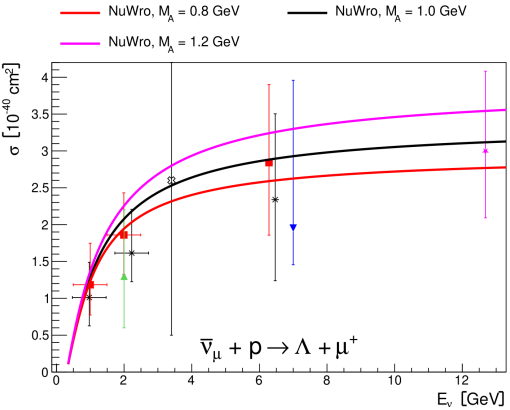
- W boson converts an up quark into a strange quark inside a nucleon:



- Other production mechanisms are resonance excitation/decay and deep inelastic scattering.

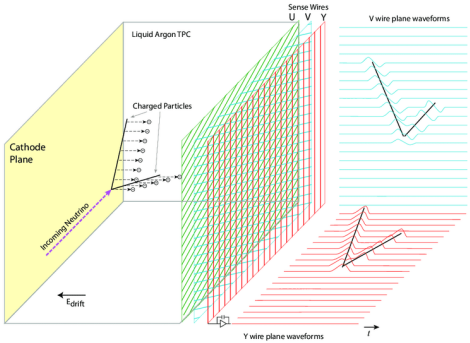
CCQE-like Hyperon Production

- This process is very poorly constrained by existing measurements.
- Measuring multiple channels can help separate $\bar{\nu} - N$ cross section physics from nuclear effects.
- **Only generated by anti-neutrinos.**
- Expect $\mathcal{O}(100)$ hyperons in MicroBooNE's data, with millions of background interactions.

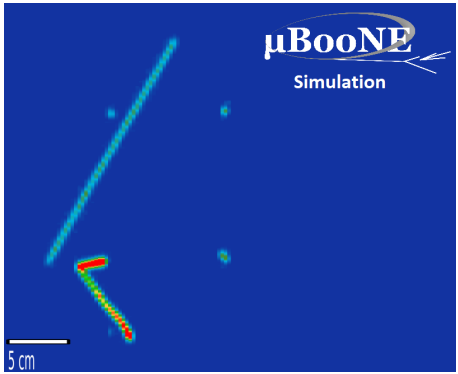


Predictions from NuWro compared with entire Λ production dataset [1].

LArTPCs



Operational principle of the MicroBooNE LArTPC.

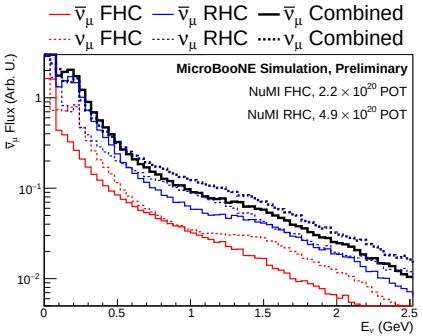


A simulated $\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu + \Lambda$ event.

See Xin Qian's talk for more details!

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**.



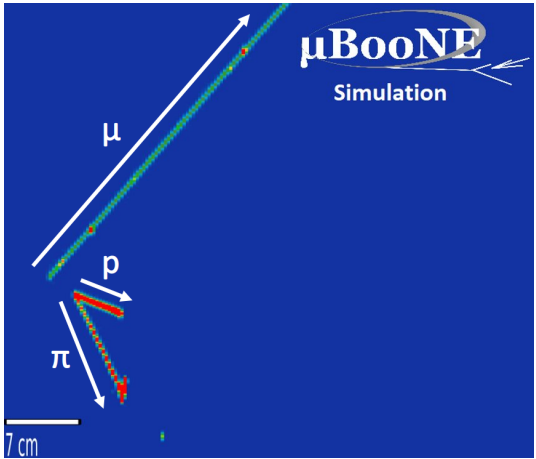
The flux used.

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 37 interactions among 1.9M triggers before applying any selection to data from two periods in 2015/16 and 2017/18.
- Challenging selection!

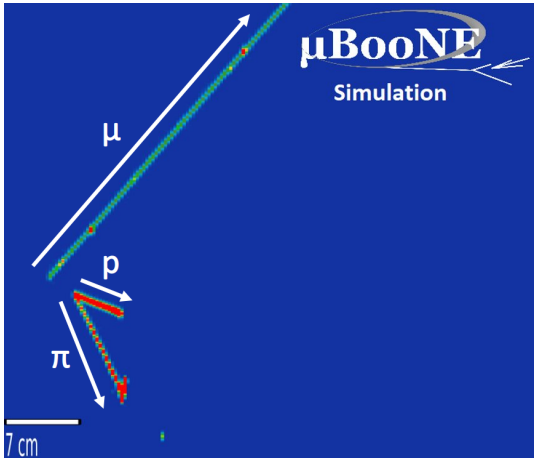


Selected signal event from MicroBooNE simulation.

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.

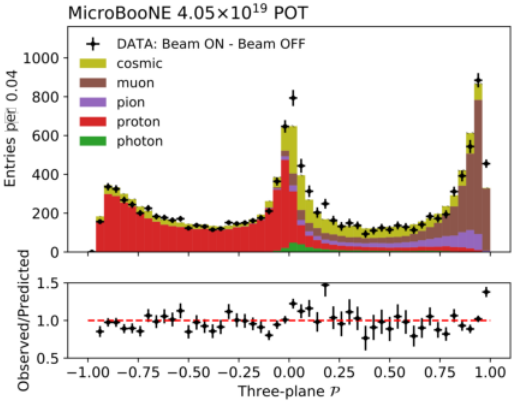
No selection:
Signal/Background $\sim 10^{-5}$.



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.

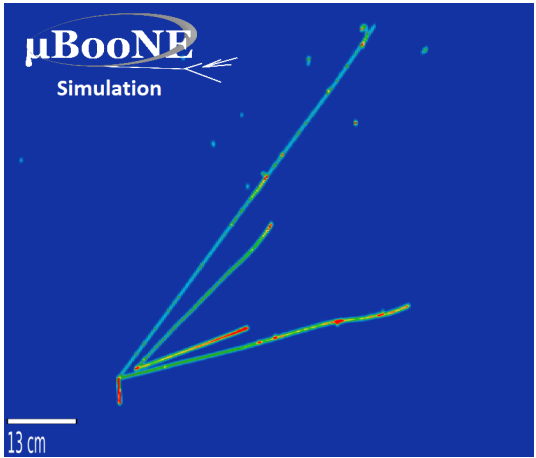


PID: Log ratio of muon and proton likelihoods [2].

After preselection + Muon ID:
Signal/Background $\sim 10^{-3}$.

Decay Track Selection

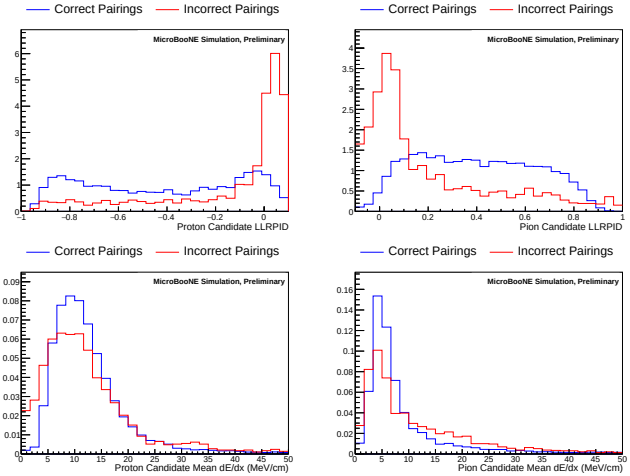
- Want to calculate useful quantities like invariant mass.
- Need the pair of tracks belonging to the $\Lambda \rightarrow p + \pi^-$.
- It is crucial the p and π^- labels are *in the right order.*



Selected Λ event from MicroBooNE simulation.

Decay Track Selection

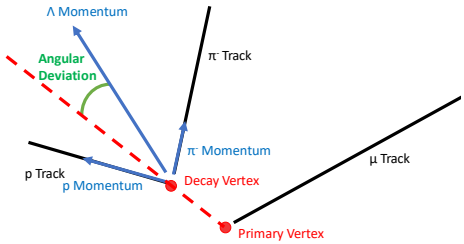
- Employ an array of BDTs that utilises 7 variables to produce a response score for each combination.
- Variables used include PIDs, track/shower classification scores.
- Select correct pair of tracks in $\approx 95\%$ of signal events.

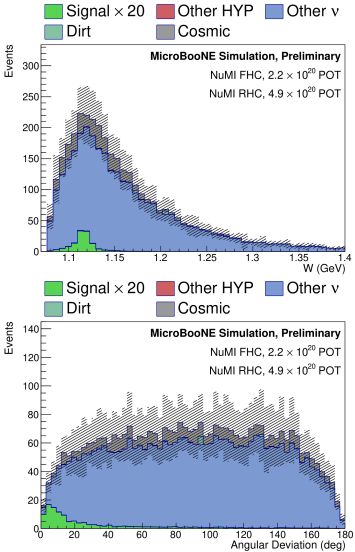


Some variables used in the decay track selection.

Decay Analysis

- Two variables to check consistency of kinematics and geometry with that of a real Λ decay: Invariant mass *W* and angular deviation.





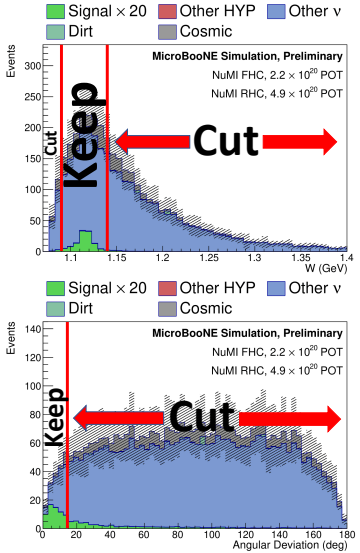
Variables used to analyse decay kinematics.

Decay Analysis

- Two variables to check consistency of kinematics and geometry with that of a real Λ decay: Invariant mass W and angular deviation.

- Keep events with $1.09 < W < 1.14$ GeV^2 and angular deviation $< 14^\circ$.

After decay analysis:
Signal/Background $\sim 10^{-1}$.

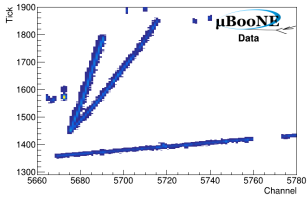


Variables used to analyse decay kinematics.

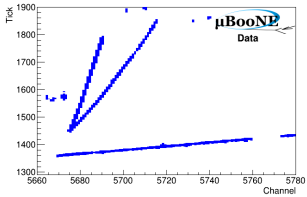
“Island” Finding

- Gap between muon and V distinguishes Λ from background.
- Analyse event display, check if activity from decay forms a separate region of activity to muon.
- Test each plane separately.

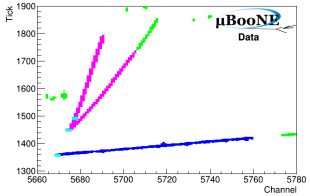
After island finding:
Signal/Background $\sim$ 1.
Improved from 10^{-5}.



Raw wire activity.



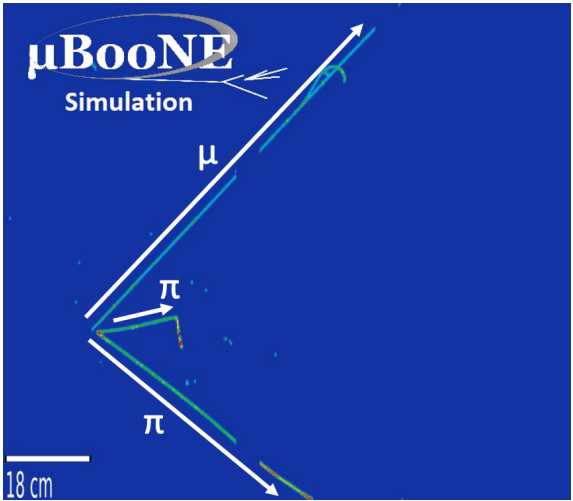
After filtering.



With islands, Muon, and Λ.

Background

- Main remaining background consists of other hyperon production channels.
- Some background from neutron interactions.
- Event with reconstruction failures.



Separated V is produced by $n + \mathrm{Ar} \rightarrow 2\pi$.

Cross Section Extraction

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

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

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

- Systematics (in backup): 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 [3]:

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

$$\varphi_{B}(B) = P(B|B_{\mathrm{MC}}) \tag{4}$$

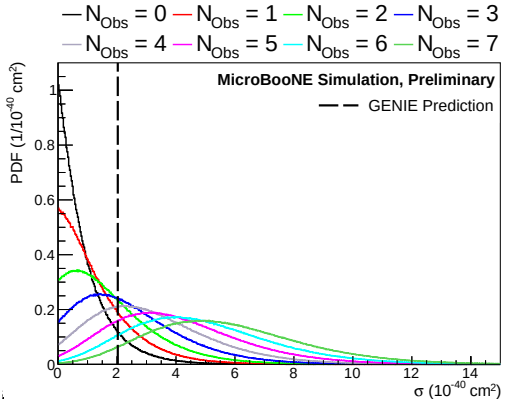
- Posterior distribution on data event rate:

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

- Use uniform priors.

Cross Section Extraction - Complete

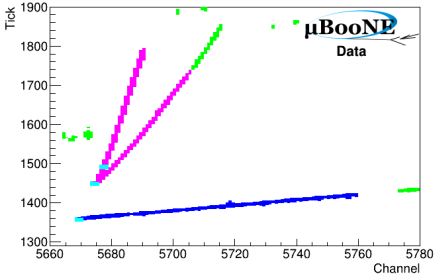
- Throw many values of ϵ, B and N from their respective posterior distributions.
- Systematic uncertainties are included by throwing fluctuations on these, using the covariance matrix of B, ϵ, and Φ.
- Build the posterior distribution on σ_*.



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

Hand Scanning

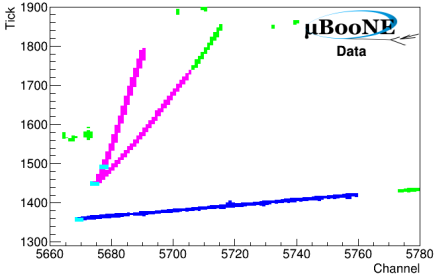
- Bad reconstruction BG has very low MC statistics.
- Can't calculate uncertainties properly by reweighting MC.
- Solution is to remove it with hand scanning, then uncertainties no longer matter.



Island finding event display.

Hand Scanning

- Performed a blinded study on event displays of MC simulation.
- Use the result to model the effect on efficiency and BG.
- Five people performed the scanning. Spread in their results is a new uncertainty.

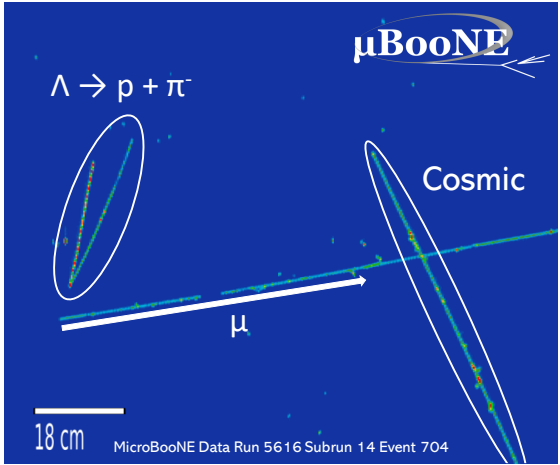


Island finding event display.

Unblinding

- Run the automated selection over the data.
- Mix the selected data with MC to conceal the number of data events from the scanners to avoid bias.

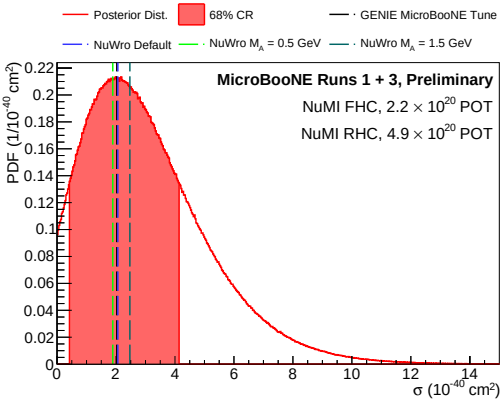
- The automated selection identified **five** Λ candidates in the data.
- The scanners selected between 3 and 5 of those.



One of the five selected data events.

The Result!

- We obtain a cross section of $2.0^{+2.1}_{-1.6} \times 10^{-40}$ cm^2.
- This is consistent with predictions from GENIE and NuWro.
- See MicroBooNE Public Note 1121 for more information!



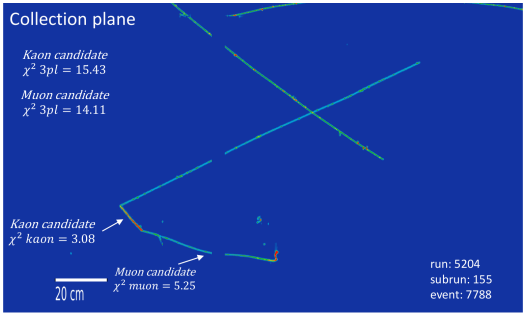
The extracted cross section.

Kaons!

- We're exploring several signals with kaons in the final state:

1. Exclusive single K.
2. Inclusive K.
3. Exclusive $\Lambda + K^+$.

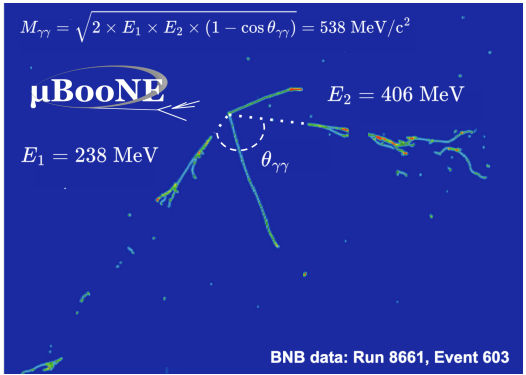
- Background for proton decay experiments.
- K decay at rest is a calibration tool.



A possible $\nu_\mu + \mathrm{Ar} \rightarrow \mu + K$ event observed in MicroBooNE data.

η Production!

- Tool for studying the $N(1535)$ resonance.
- Identify through its decay $\eta \to \gamma\gamma$, $W = 548$ MeV.
- Another signal for shower energy calibration.



A candidate $\eta \to \gamma\gamma$ event identified in MicroBooNE data.

Summary

- **We have completed the first Λ production analysis in a LArTPC.**
- Documented in MicroBooNE public notes 1097, 1112 and 1121.
- **Official publication coming soon!**
- Several other final states are being looked into, including kaons and η mesons.

Thank you for listening!

References I

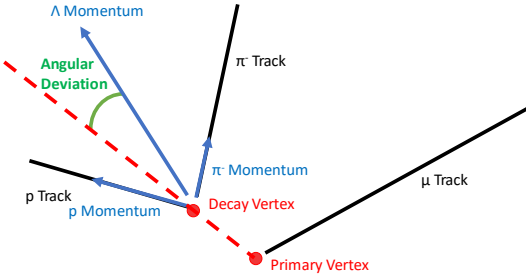
[1] C. Thorpe, J. Nowak, K. Niewczas, J. T. Sobczyk and C. Juszczak, Phys. Rev. C **104** (2021) no.3, 035502

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

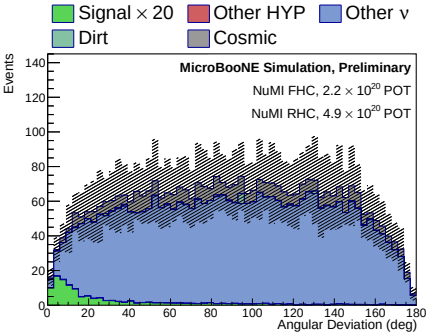
[3] https://root.cern.ch/doc/master/classTEfficiency.html. Accessed August 2021. Root version 6.16 used.

α Parameter

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



α angle calculation.



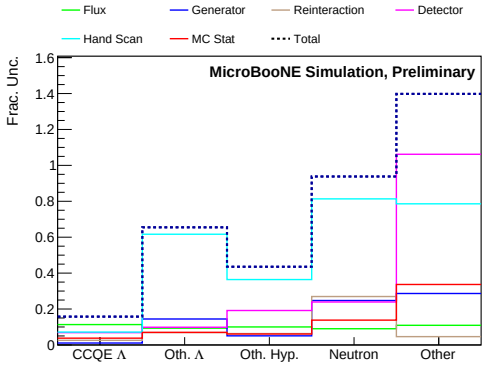
Values for signal and BG.

Systematics

- Consider five sources of systematic uncertainty:

1. Flux simulation.
2. Event generator modelling.
3. Secondary interactions.
4. Detector effects.
5. Hand scanning efficiency.

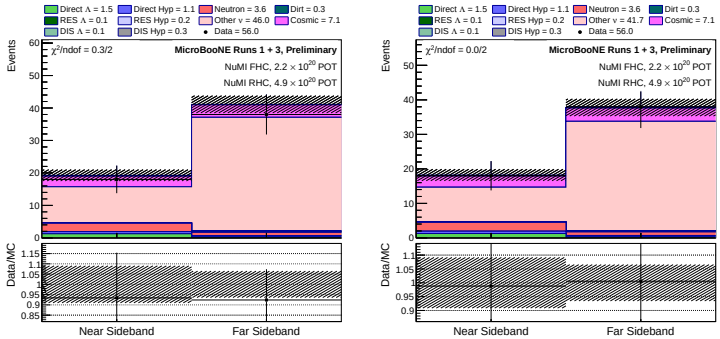
- See MicroBooNE Public Note 1112 for a description of the systematics calculations.



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

Sideband Constraint

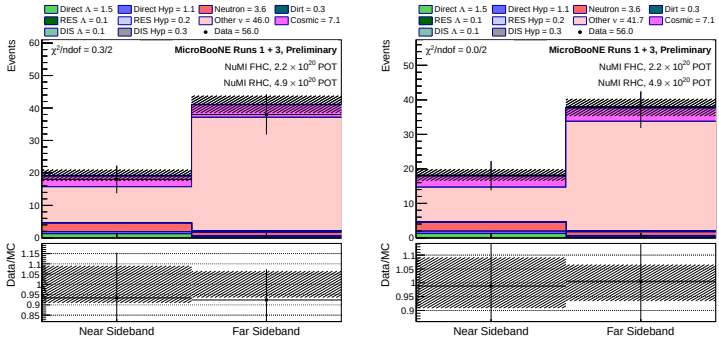
- Alternative method to the hand scanning for dealing with the bad reconstruction background.



The sideband data before and after fitting.

Sideband Constraint

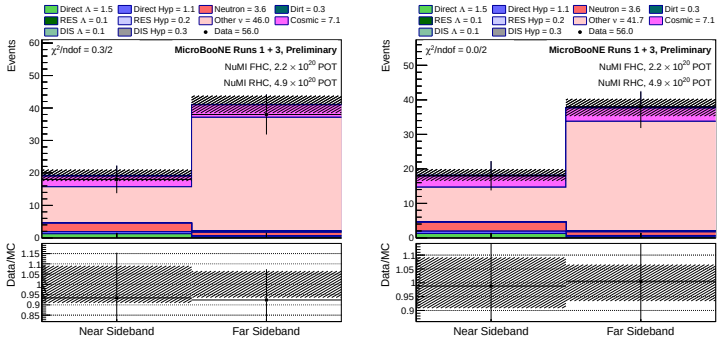
- Invert the cuts applied to the angular deviation and invariant mass to produce the sideband dataset.
- Use this to estimate the “bad reconstruction” background by performing a fit.



The sideband data before and after fitting.

Sideband Constraint

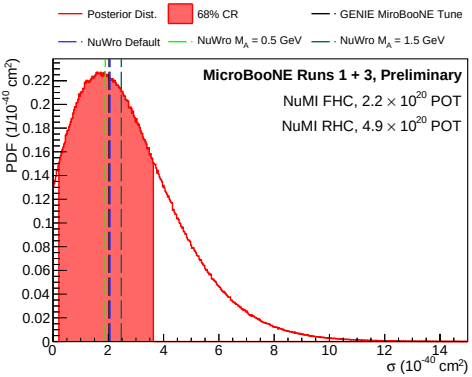
- Fit each systematic variation separately, use these fits to build the final ϵ, Φ, B covariance matrix.



The sideband data before and after fitting.

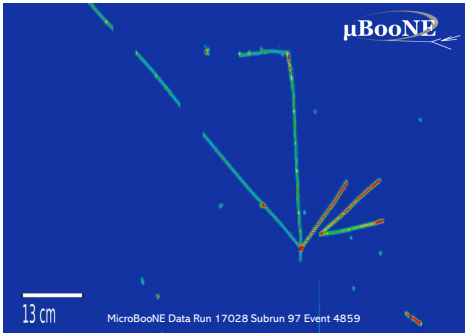
Sideband Constraint

- Obtain final cross section of $1.6^{+2.0}_{-1.4} \times 10^{-40}$ cm^2.
- Consistent with the hand scanning result, with slightly worse sensitivity.

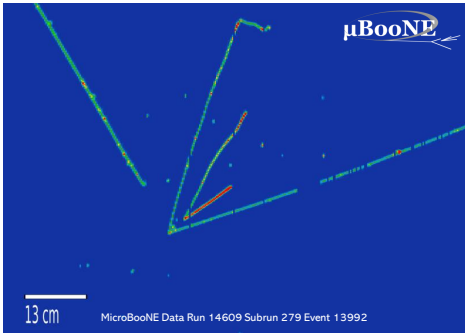


The extracted cross section probability distribution.

Selected Data

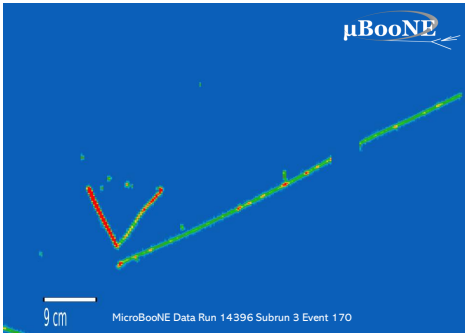


Selected data 1/5.

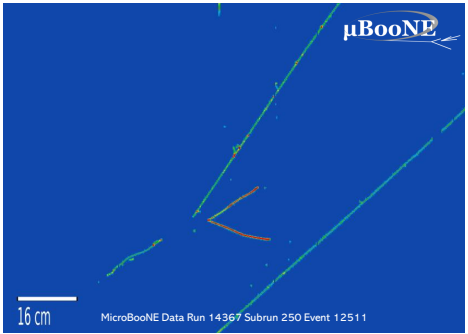


Selected data 2/5.

Selected Data

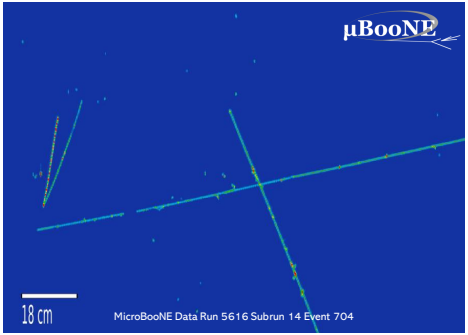


Selected data 3/5.



Selected data 4/5.

Selected Data



Selected data 5/5.