First ν+Ar Interaction Measurements From MicroBooNE

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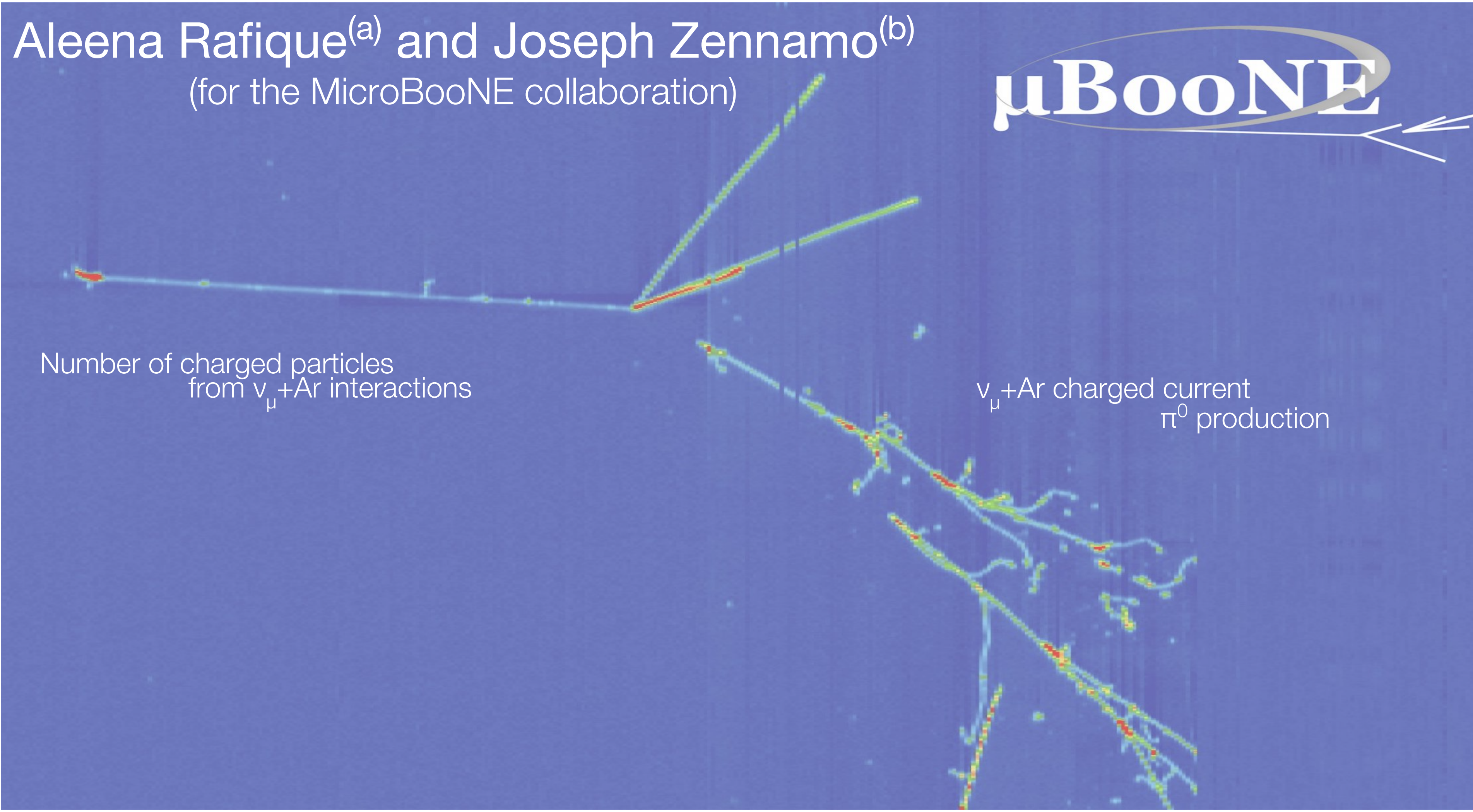
(for the MicroBooNE collaboration)



Kansas State University (a)
Fermilab (b)

In This Talk

Today we'll present the first MicroBooNE ν+Ar interaction measurement results

- First measurements of
  1. Multiplicity of charged particles from ν_μ-Ar scattering
  2. ν_μ-Ar cross section of charged current single π^0 production

- Measurements span a range of physics and techniques
  - 1st requires efficient tracking to perform an inclusive analysis
  - 2nd requires low energy shower reconstruction to study an exclusive channel

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Why Study ν_μ-Ar Interactions

- We need to understand ν-Ar interactions for MicroBooNE physics analyses and future LArTPC experiments (like DUNE and SBN)

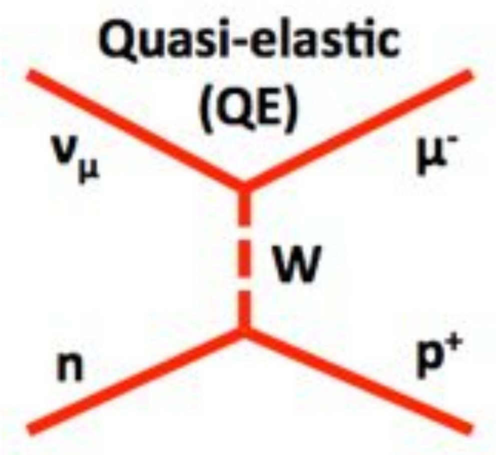
- GENIE[*] is the most commonly used neutrino event generator for experiments to use
  - We present the most comprehensive tests of GENIE with ν_μ-Ar data

- Limited data is available on ν-Ar scattering
  - ArgoNeuT is the only other LArTPC to produce cross section results with higher E_ν

*GENIE: Neutrino event generator: https://genie.hepforge.org/

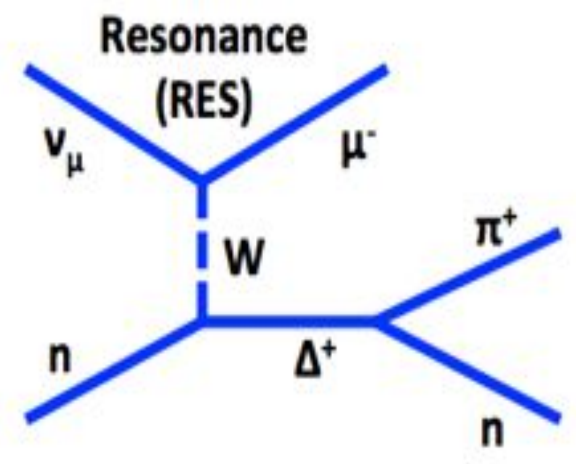
Charged Current Interactions

Two charged particles



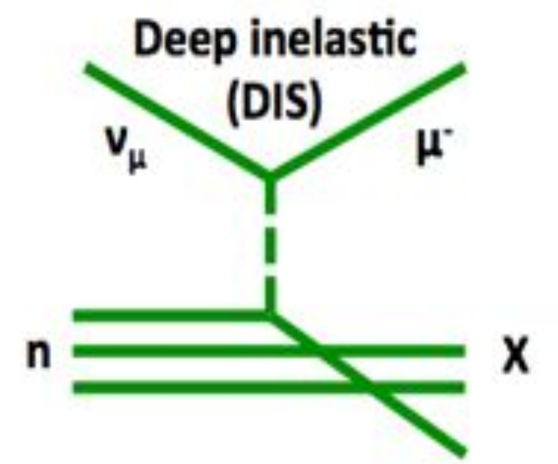
Scattering from Independent nucleon

Two/three charged particles



Inelastic scattering: Excites the nucleon

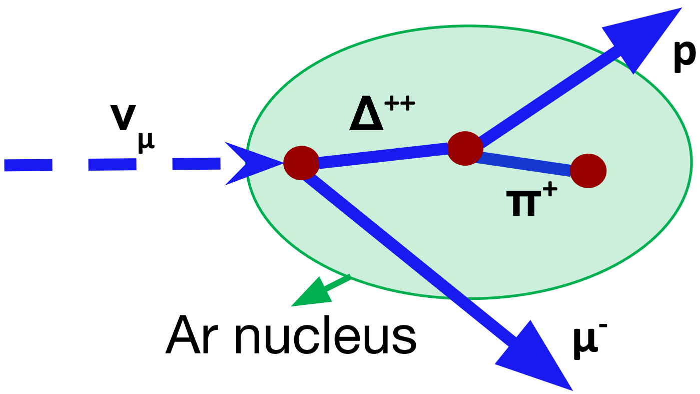
Many charged particles



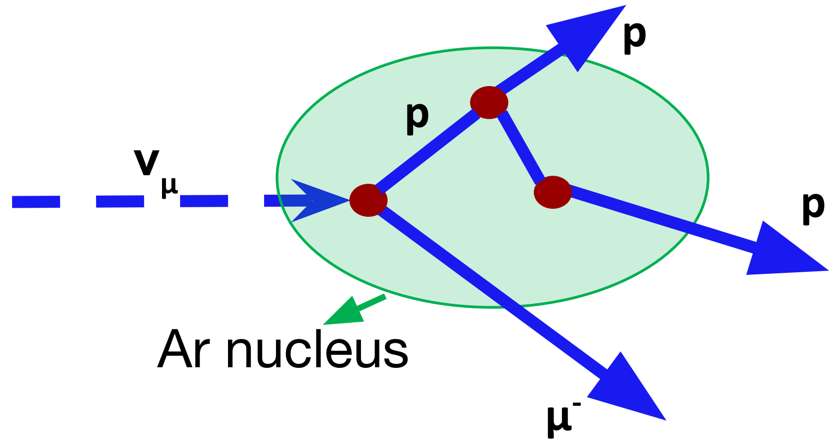
Scattering through quarks: Nucleon breaks up

Nuclear Effects

Three particle topology → Two particle topology



Two particle topology → Three particle topology

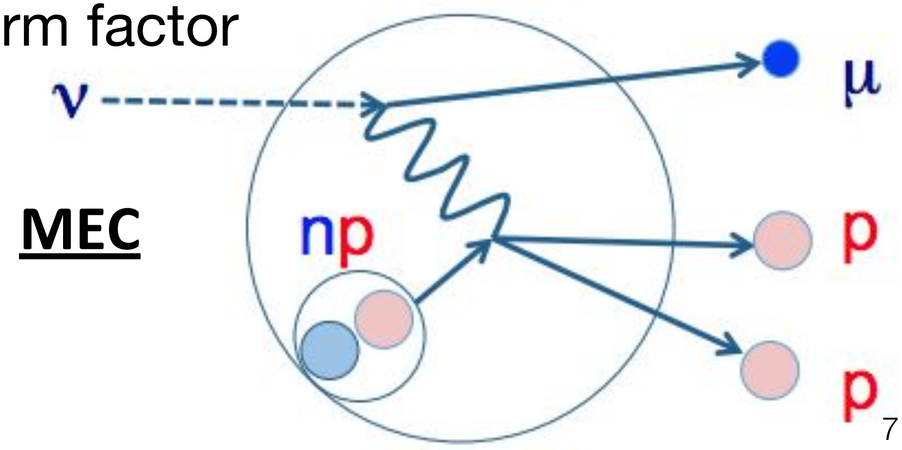


Argon is a complex nucleus in which final state interactions can change the final state topology of the interaction

Testing Nuclear Models

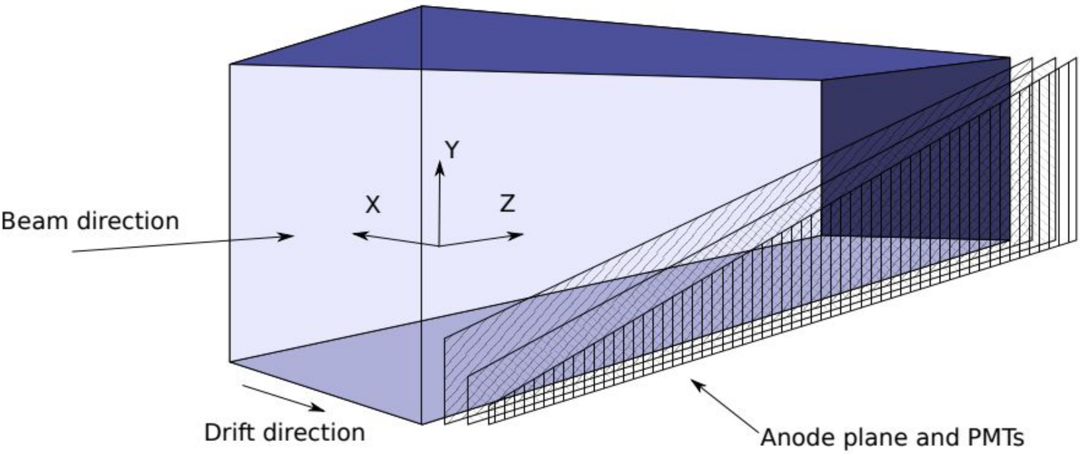
- Models for these nuclear effects are largely based on electron scattering data
  - Need to test if these hold up in neutrino scattering

- Two such models will be put to the test today using the MicroBooNE LArTPC
  - <u>Meson Exchange Current (MEC):</u> Populates multi-nucleon final states
  - <u>Transverse Enhancement Model (TEM):</u> Enhancement of the transverse quasi-elastic form factor



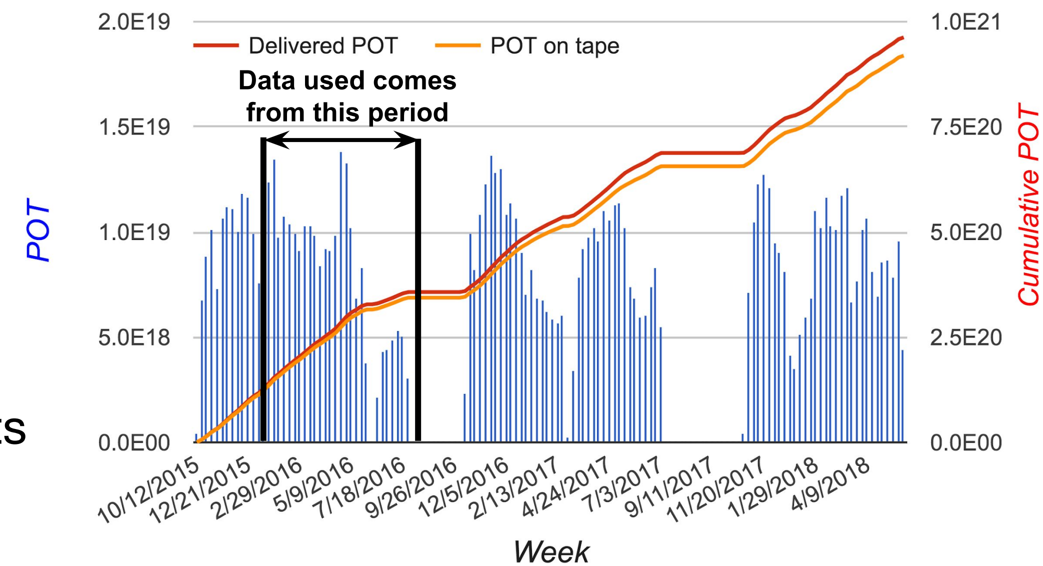
MicroBooNE

JINST 12, P02017 (2017)



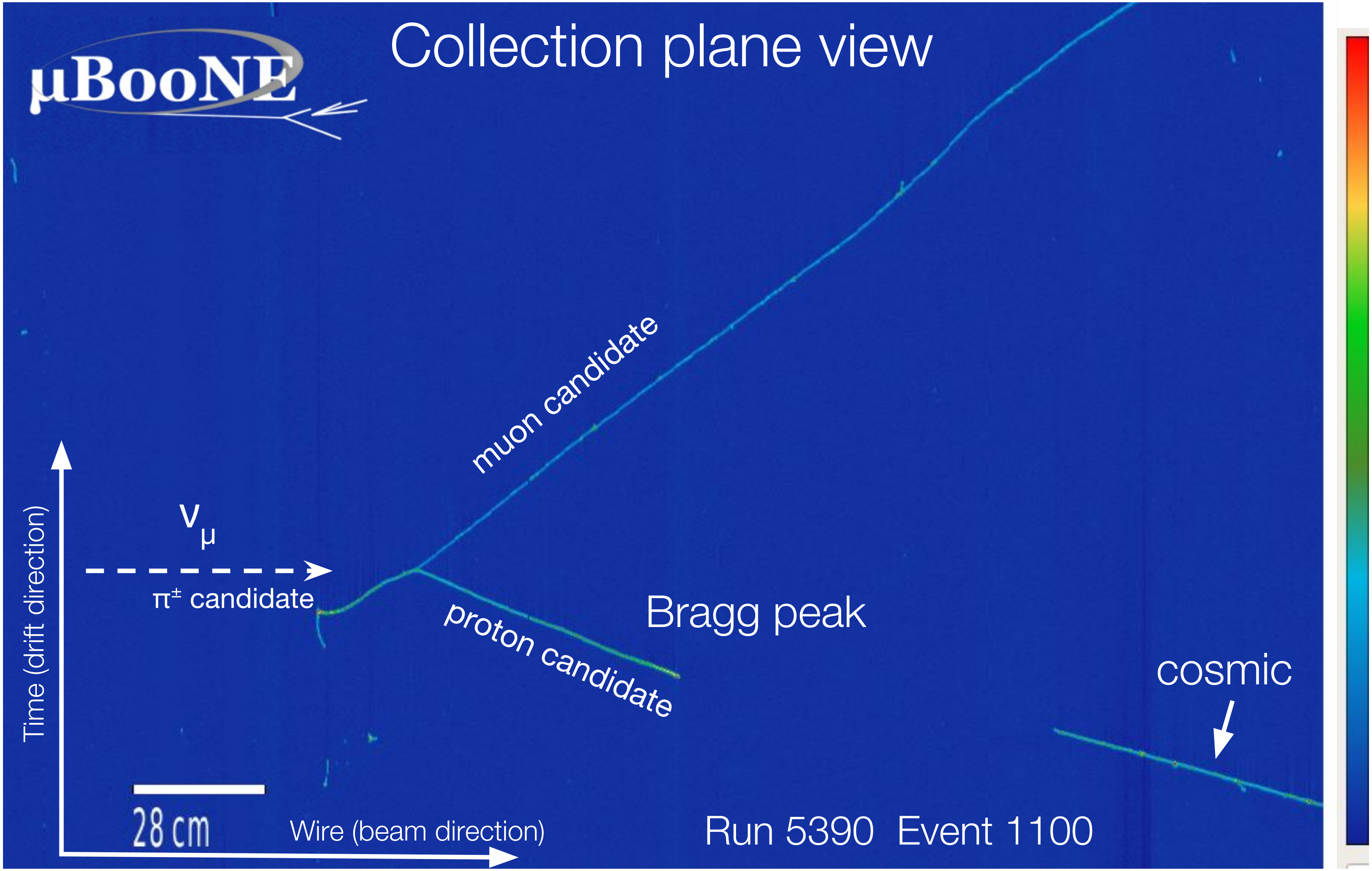
- Sits in BNB[1]
  - Pure source of ν_μ
  - Average $E_\nu < 1$ GeV
  - Benefits from 10+ years validation from MiniBooNE

- 85 tonne active mass
- Has three wire planes:
  - 3mm wire spacing gives us impeccable spatial resolution
  - Final plane collects charge to give calorimetric measurements
- Triggered by an array of PMTs
- Collecting beam data since October 2015



[1]PRD 79, 072002 (2009)

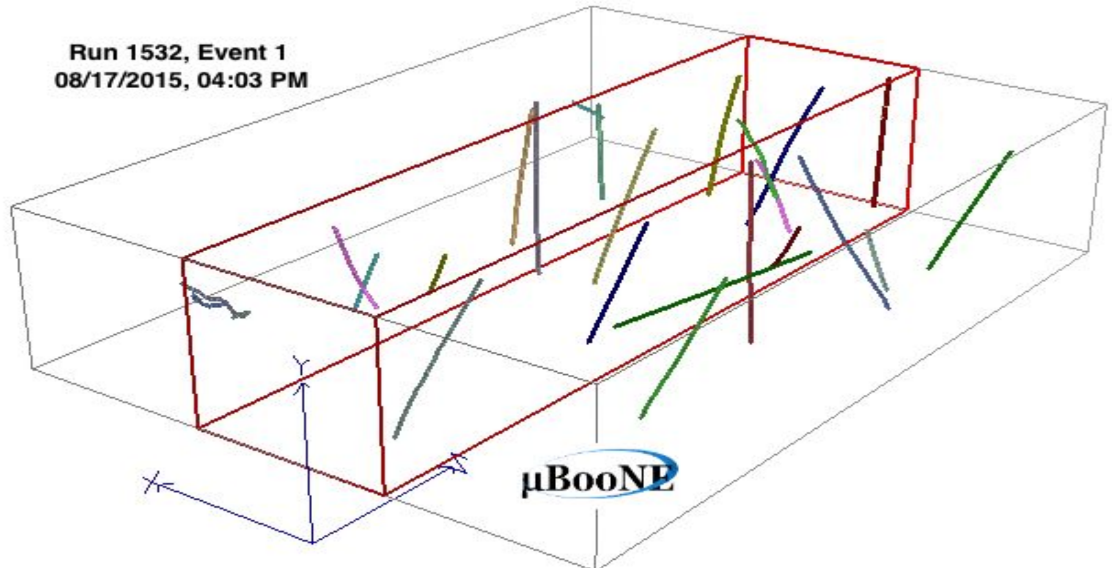
Candidate Neutrino Event Display



JINST 12, P08003 (2017), arXiv:1802.08709, arXiv:1804.02583, Eur. Phys. J. C78, 1, 82 (2018)

Cosmics in MicroBooNE

- Cosmic backgrounds come from:
  - Near surface location
  - 2.3 ms drift time



- On-beam data: Data taken after PMT and beam triggers
- Off-beam data: Same trigger conditions except for the coincidence requirements with the beam

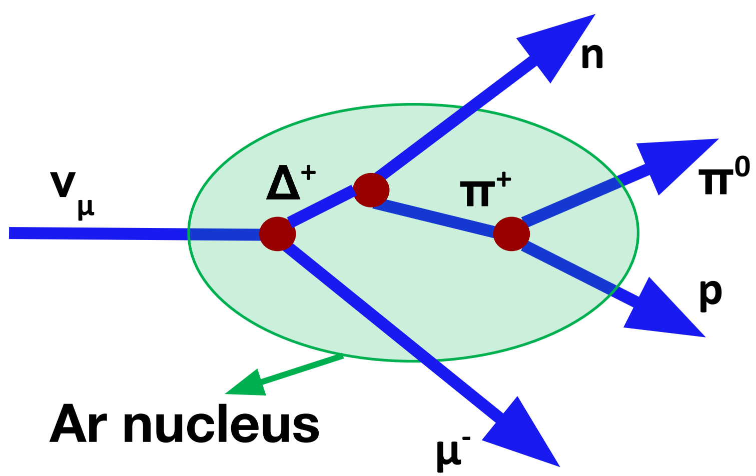
<u>Challenge for MicroBooNE analyses:</u>

1. 97% of the triggered events have cosmic-only data events
2. Remaining 3% events have both cosmics and neutrinos are in same event (~20 cosmics and 1 neutrino)

Charged Particle Multiplicity (CPM)

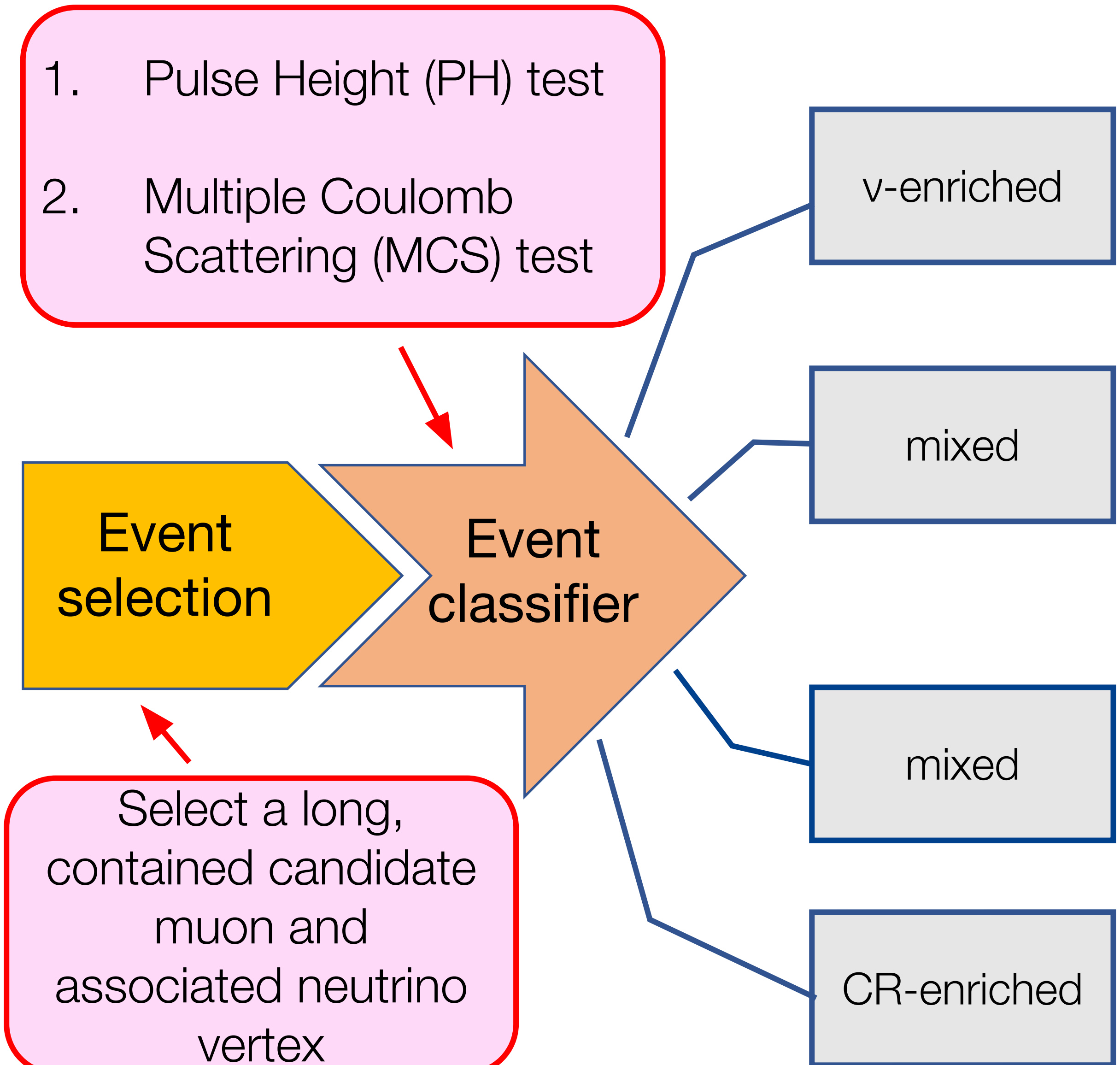
- **<u>Analysis Goal:</u>** Count the number of reconstructed charged particles exiting the target nuclei at the interaction point
  - We tag $\mu^{\pm}$, $\pi^{\pm}$, and *p*; but π^{0} and *n* are not included
  - Kinetic energy thresholds: 69 MeV for *p* and 31 MeV for $\mu^{\pm}/\pi^{\pm}$
- Gives knowledge of ν_{μ}-Ar interactions in form of directly observable quantity
- First measurement of charged track multiplicity in ν_{μ} CC interactions in argon

Resonance Interaction



CPM = 2

Analysis Method

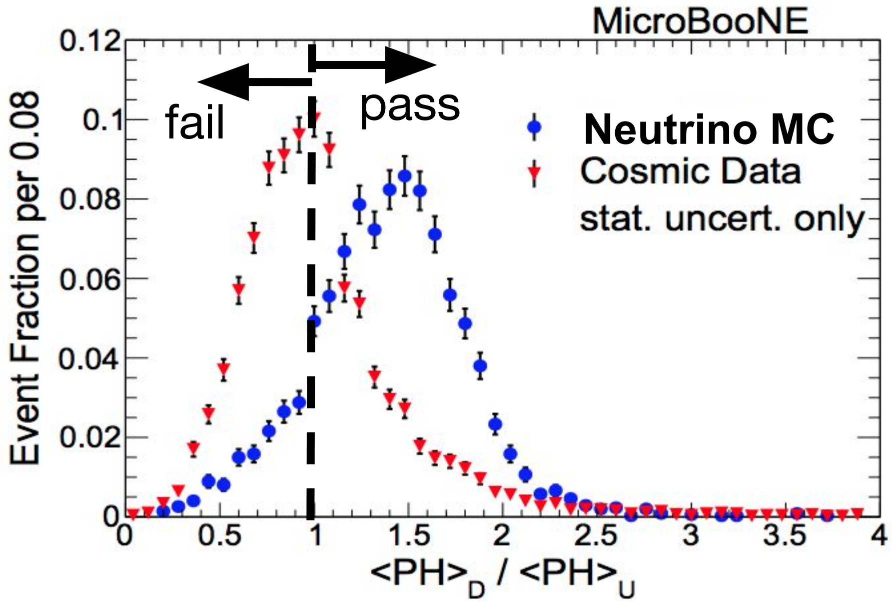


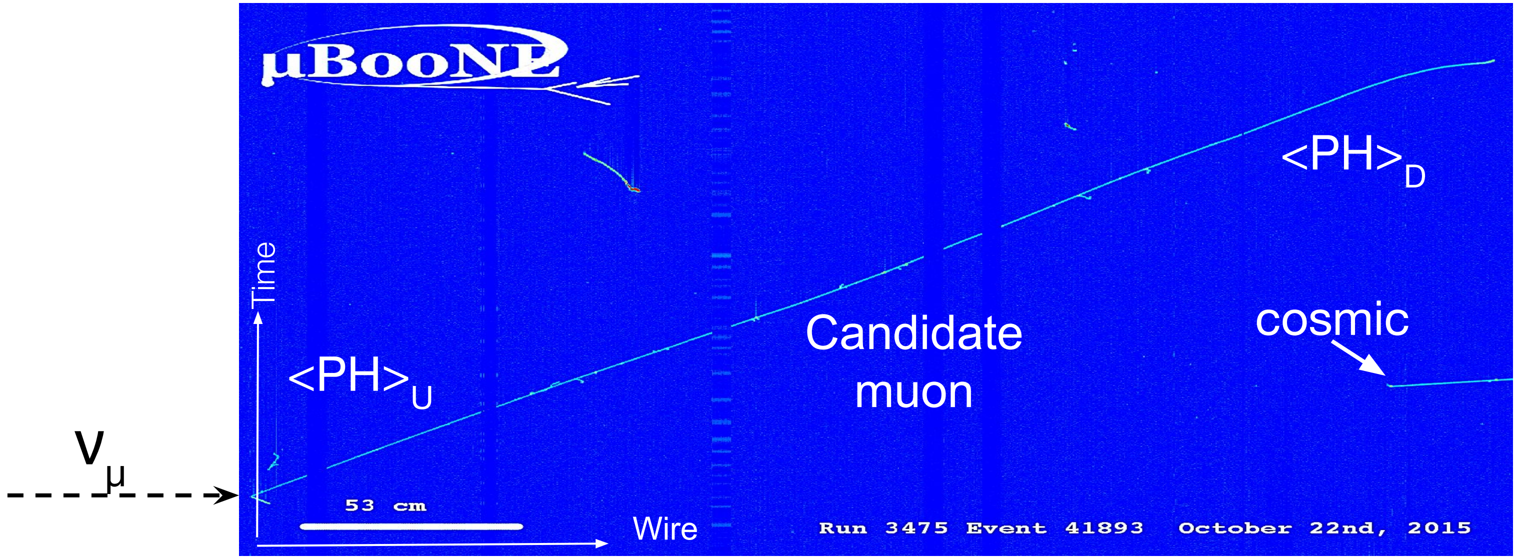
<u>Goal:</u> Extract the number of on-beam neutrinos for CPM distribution

- Perform a likelihood fit using the number of events in each of the these four categories

Pulse Height (PH) Test

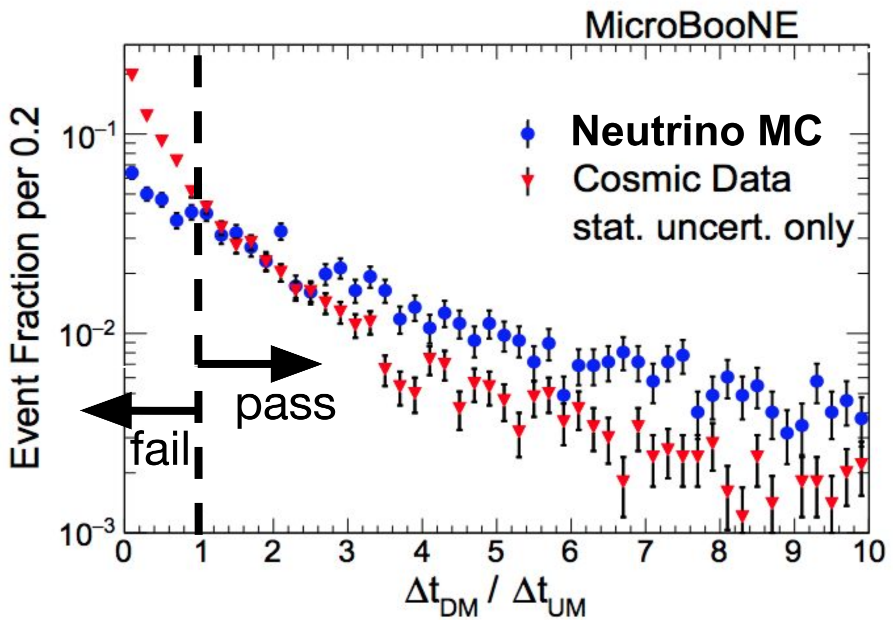
Rate of energy loss increases along the track from upstream to downstream end

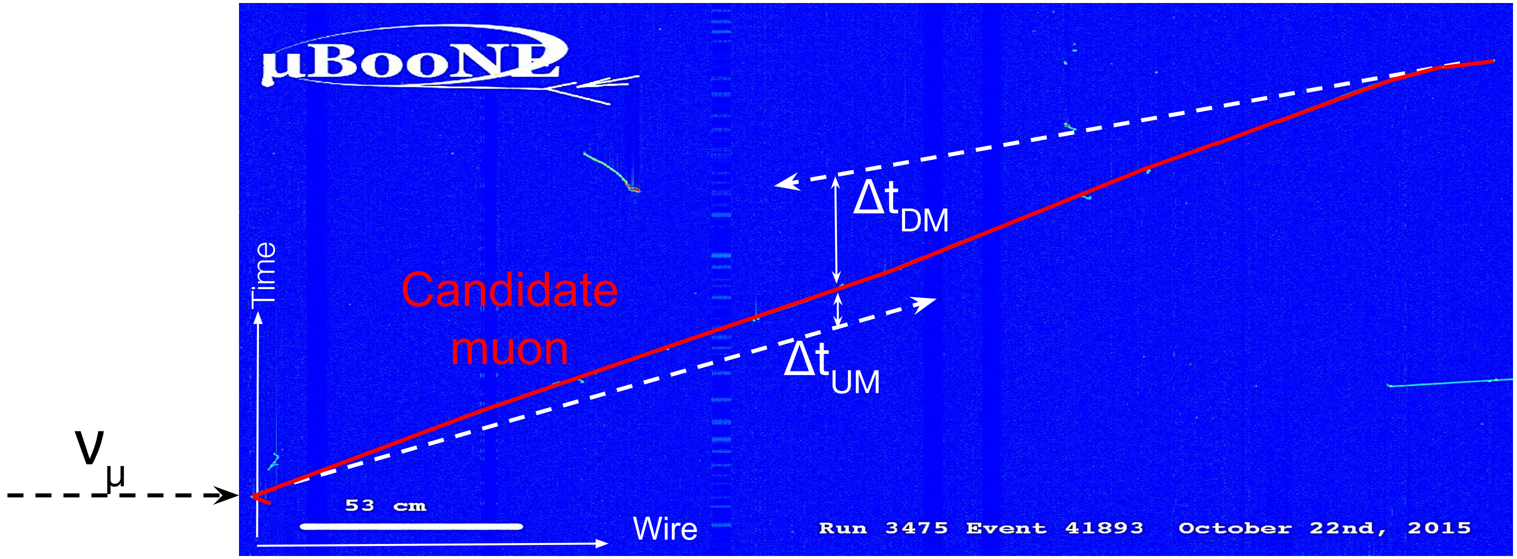




Multiple Coulomb Scattering (MCS) Test

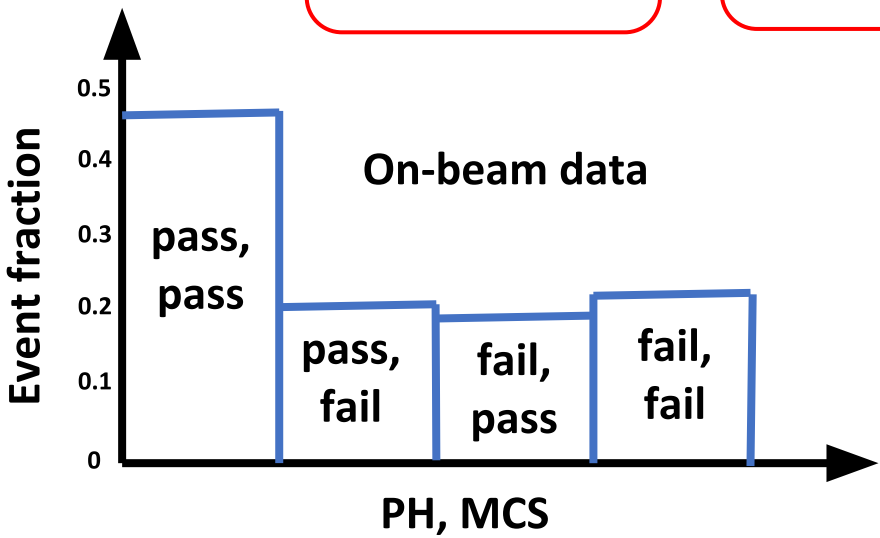
Scattering is more pronounced along the downstream end of the track as the momentum decreases.

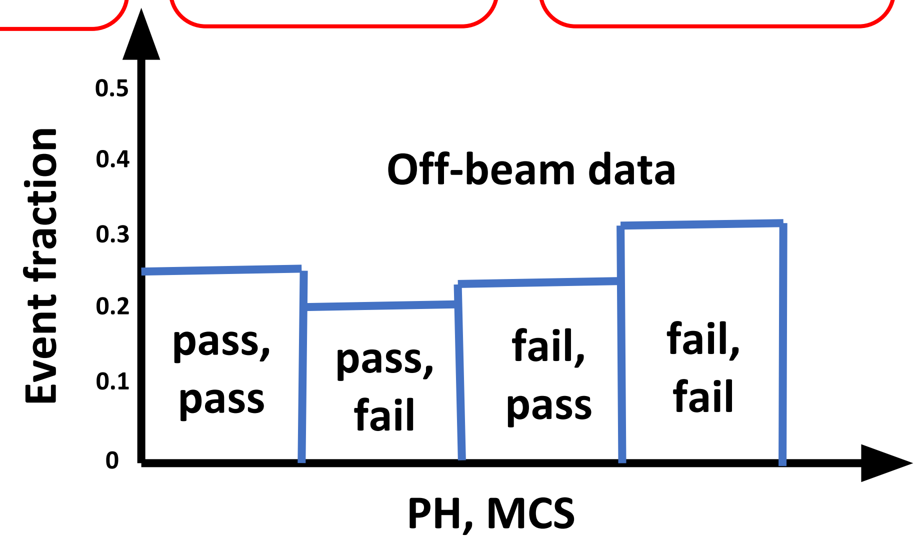




Signal Extraction Method

PH, MCS= (pass, pass) v-enriched | (pass, fail) mixed | (fail, pass) mixed | (fail, fail) CR-enriched



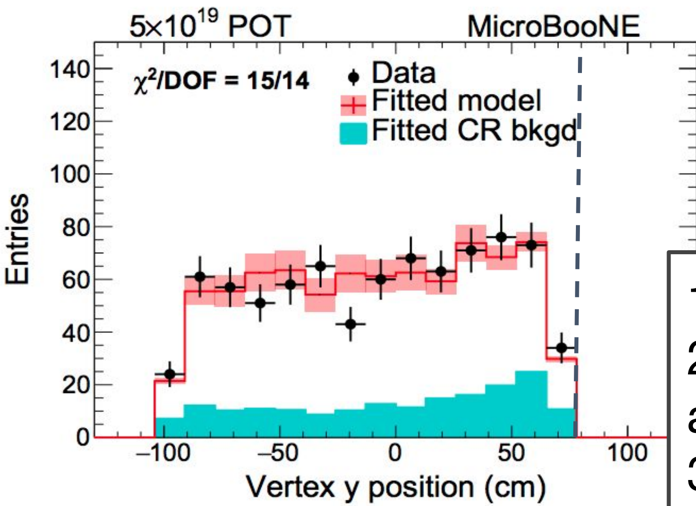


- To get to CPM, we perform likelihood fit multiplicity bin by bin to extract the number of on-beam neutrinos

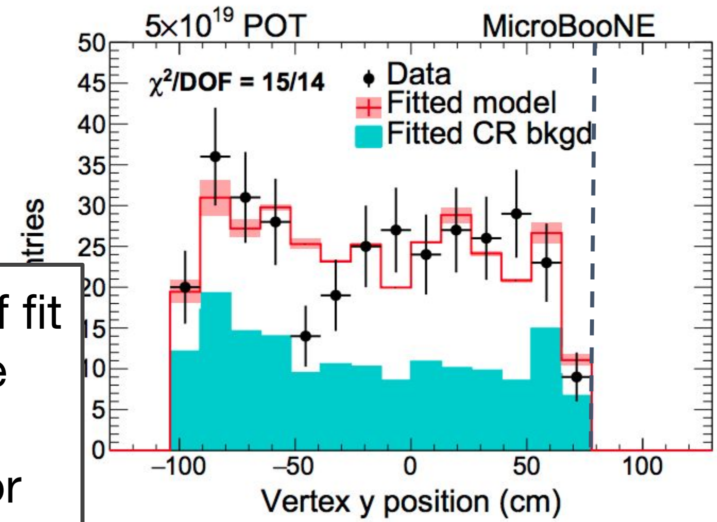
Nearly model independent method

Post-Fit Vertex y Distributions

ν-enriched sample

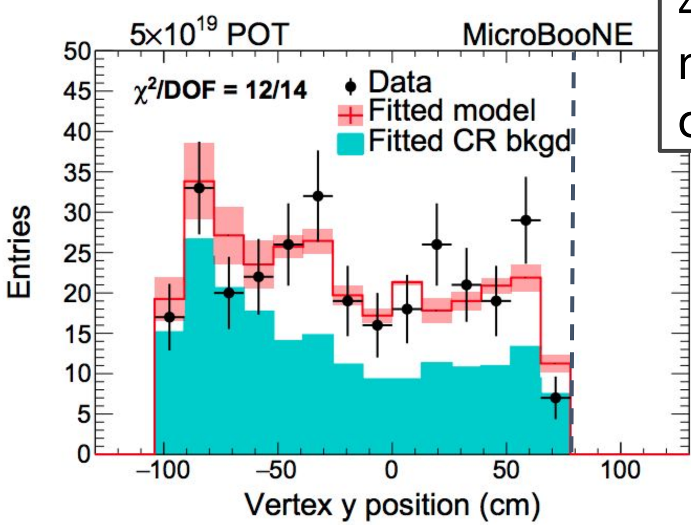


Mixed sample

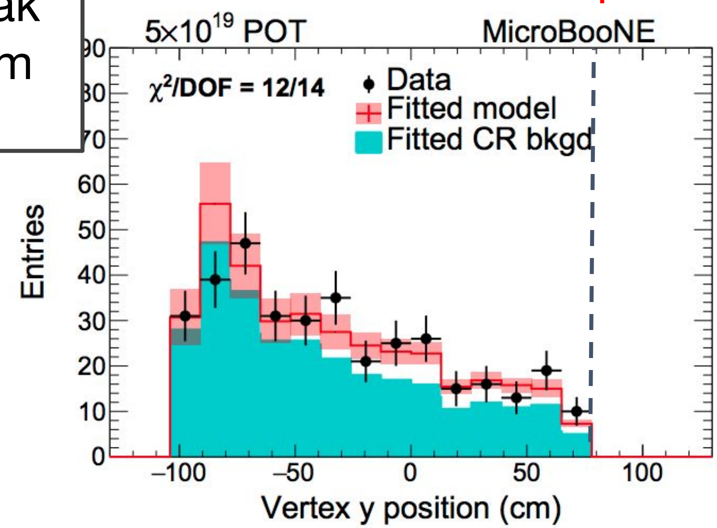


1. Validation of fit
2. Good shape agreement
3. Efficiency for selecting ν is flat
4. cosmics peak near the bottom of TPC

Mixed sample

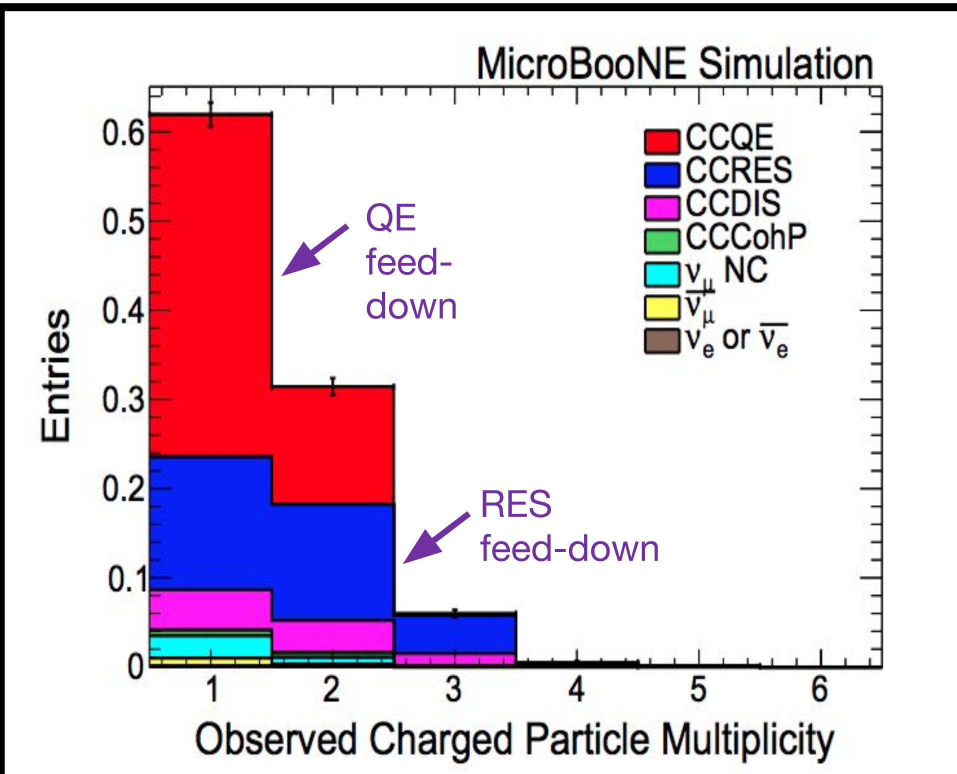


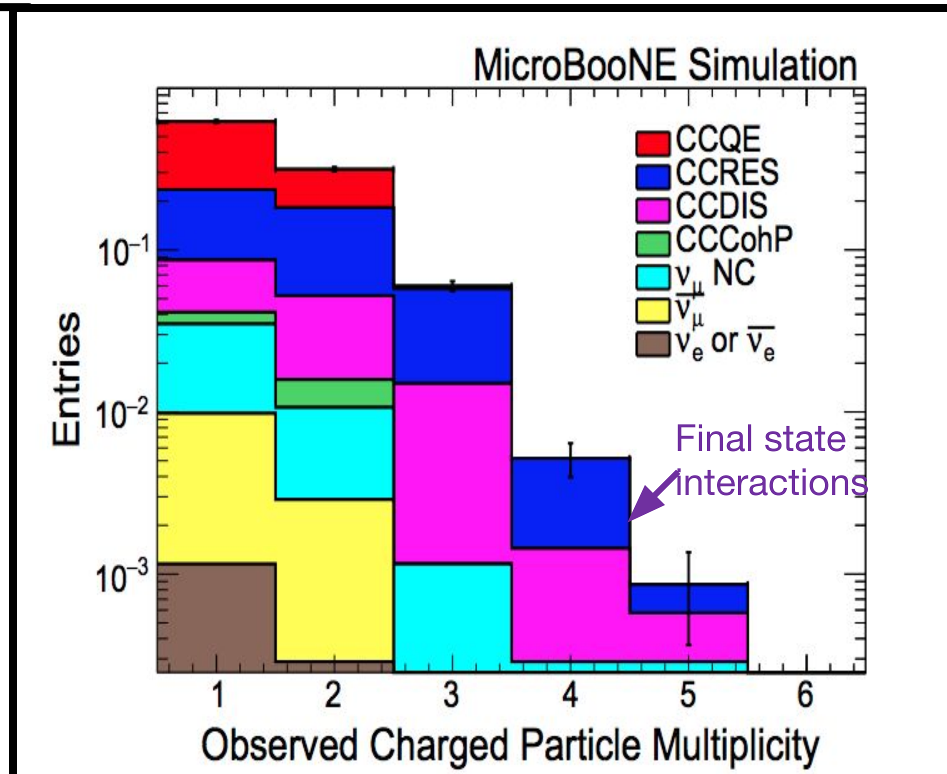
CR-enriched sample



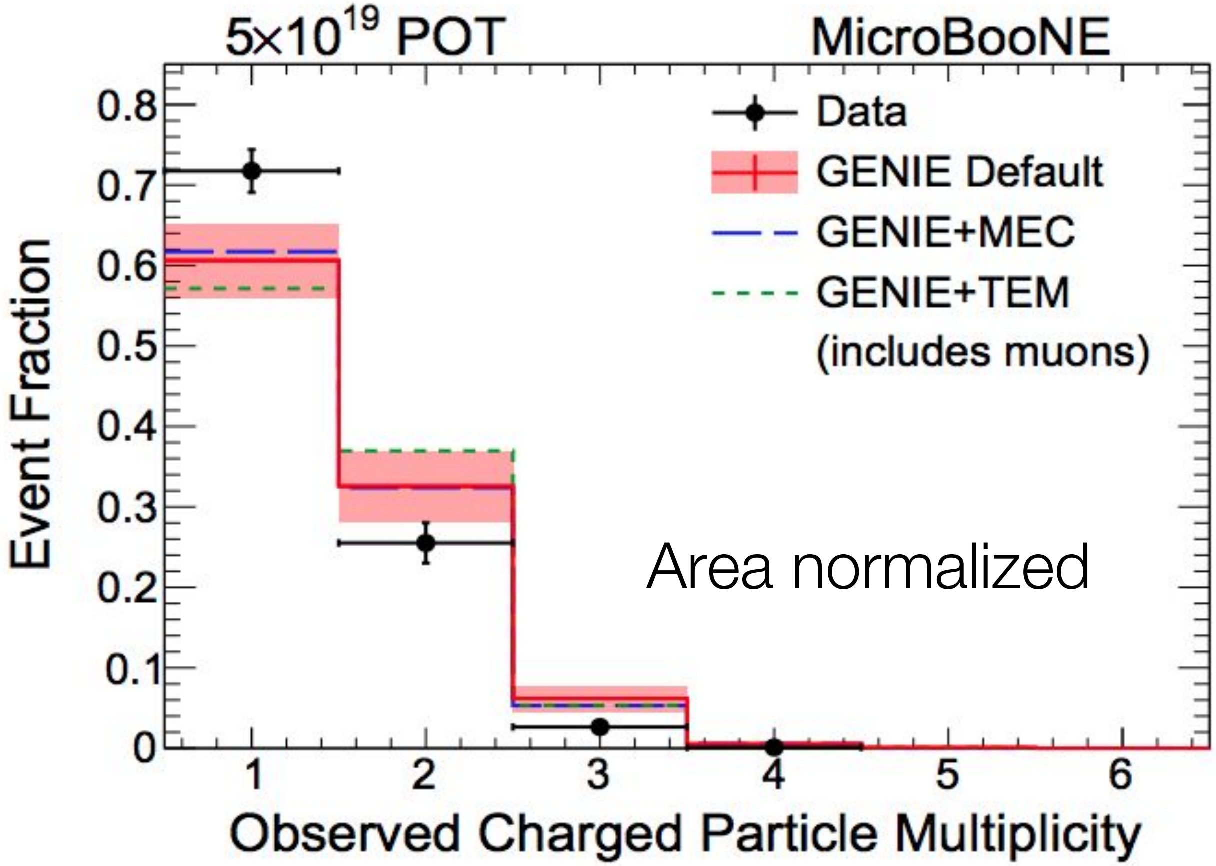
Expected CPM From GENIE

Leading source of feed-down comes from efficiency and acceptance effects





First CPM Distribution From ν+Ar Data



- Data favors lower multiplicity compared to all three simulations
- Simulation agrees with data at the 2σ level

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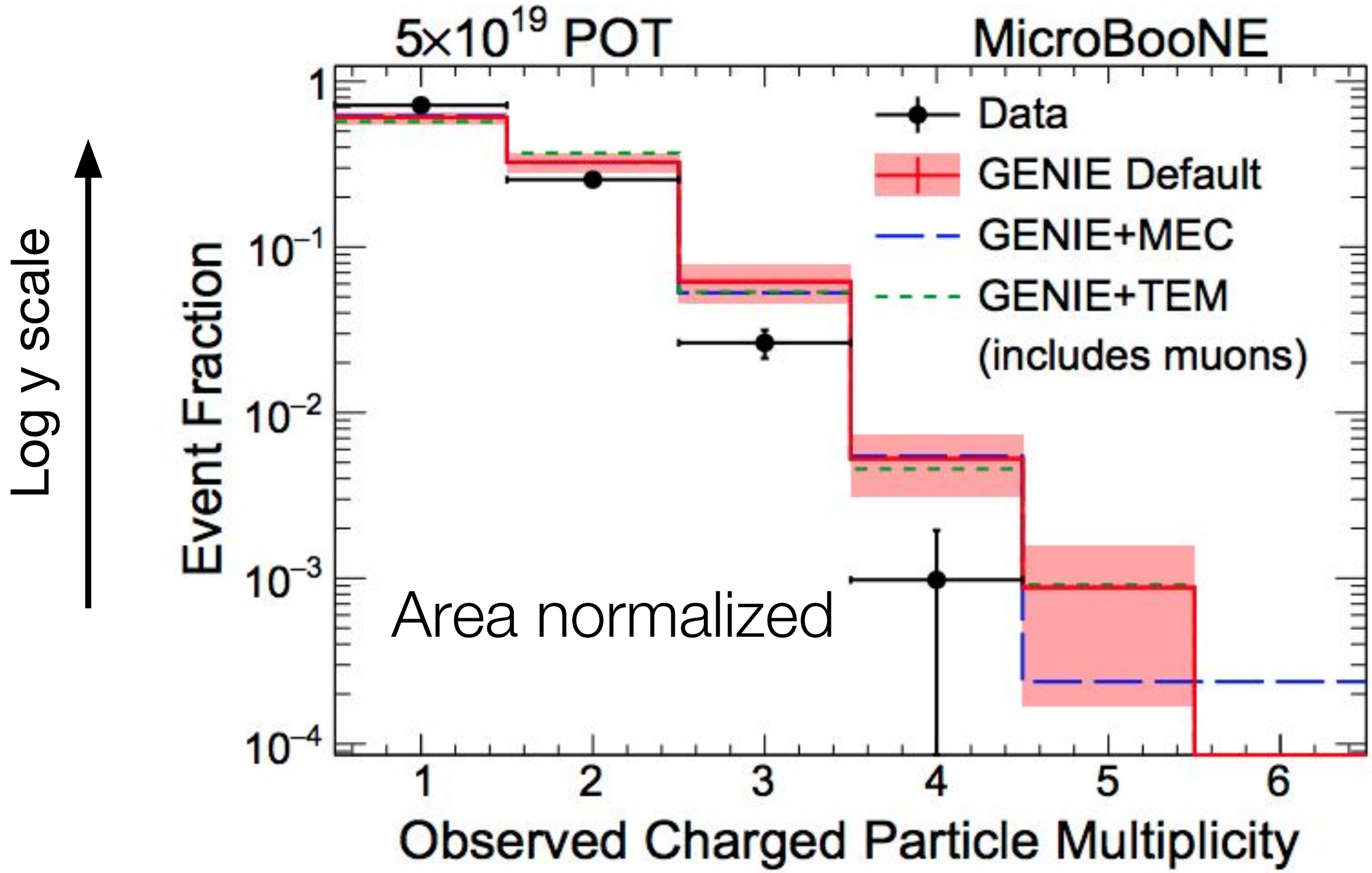

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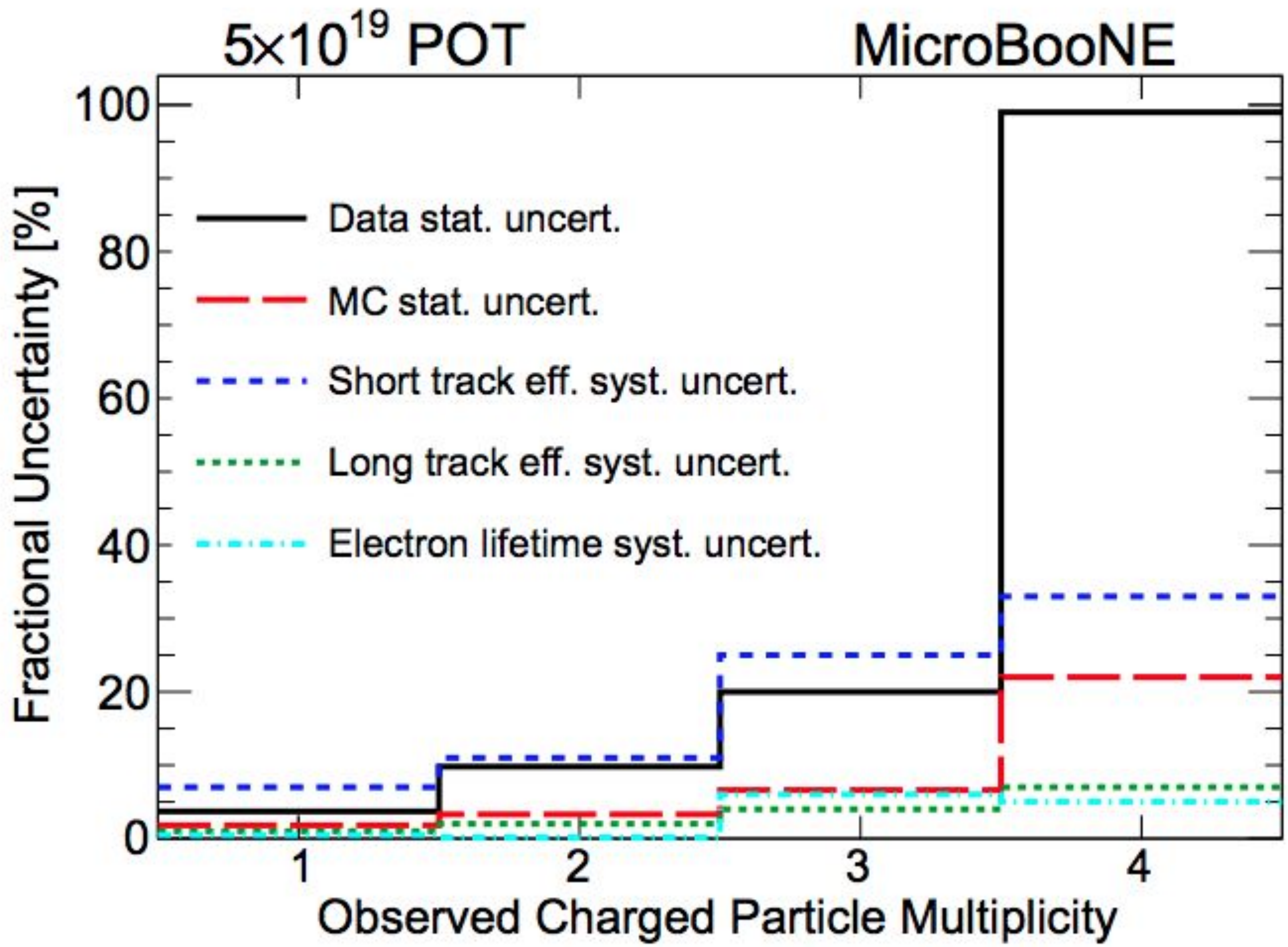
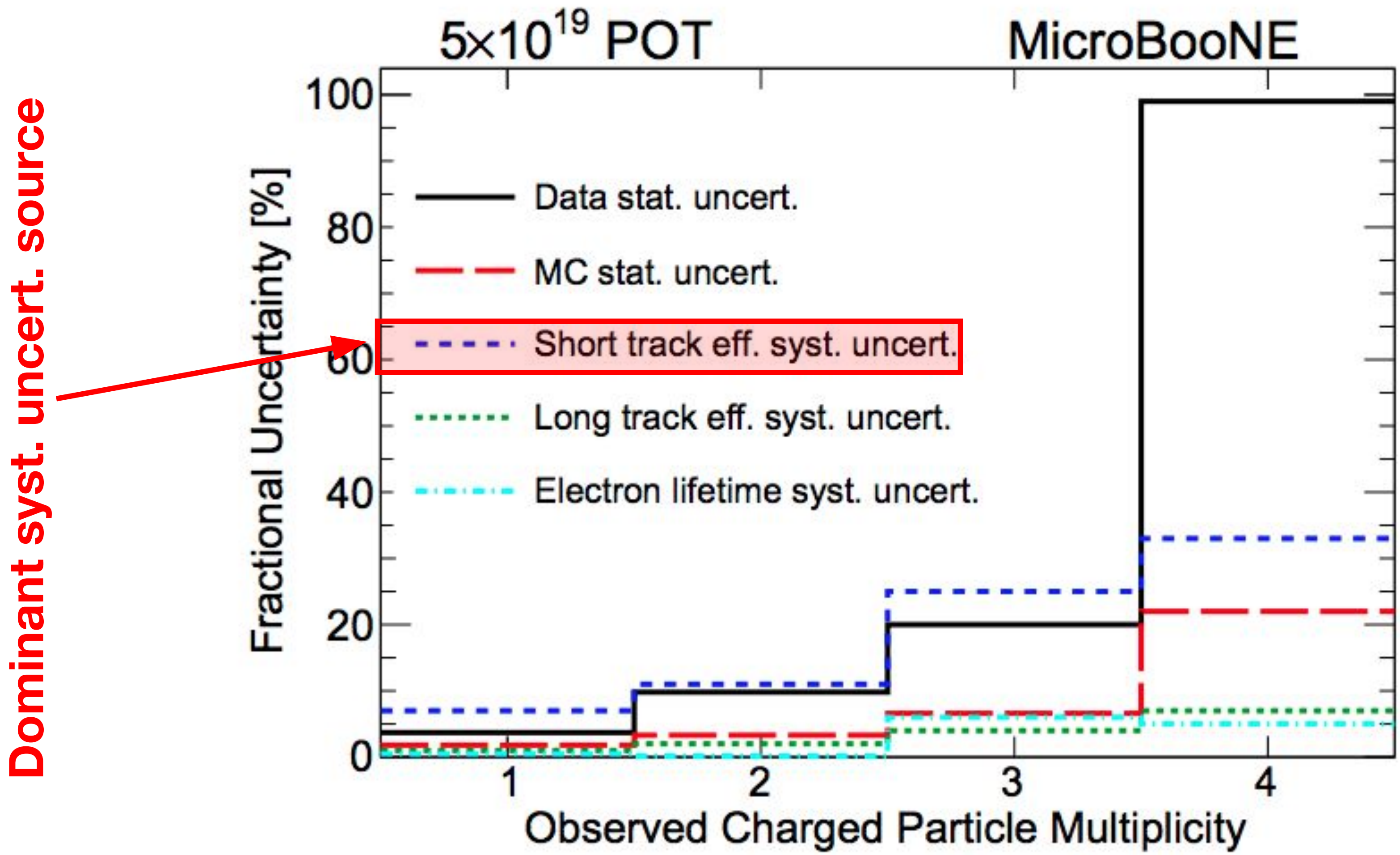
Uncertainty Estimates



Uncertainty Estimates



Kinematic Distributions

- The most comprehensive test of GENIE
  - 40 distributions in the paper
- Quantities
  - track/vertex positions (in x,y,z coordinates)
  - track length and angles (polar, azimuthal)
- All categories
  - ν-enriched distributions
  - Mixed distributions
  - CR-enriched distributions
- Multiplicities
  - All multiplicities
  - Multiplicity 1, 2, and 3 distributions
- Models
  - GENIE default
  - GENIE+MEC
  - GENIE+TEM

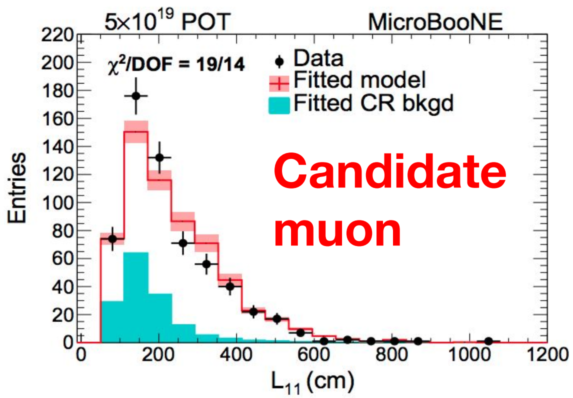
Some ν-enriched distributions are on the next slides

- **Good shape agreement in all distributions**
- **Can't distinguish GENIE models at this stage**

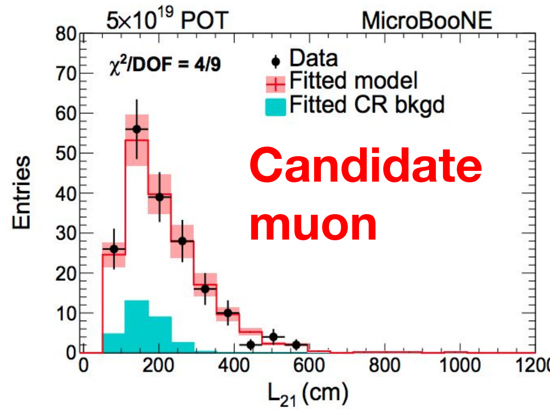
CPM paper:
https://arxiv.org/abs/1805.06887
Submitted to PRD

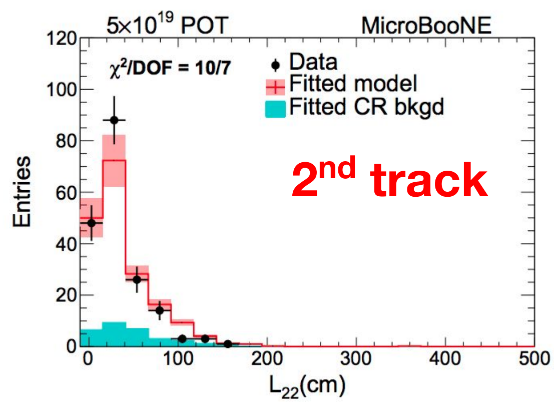
Track Length Distributions

Mult =1

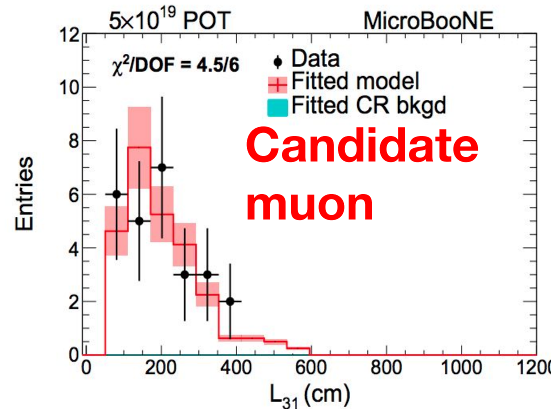


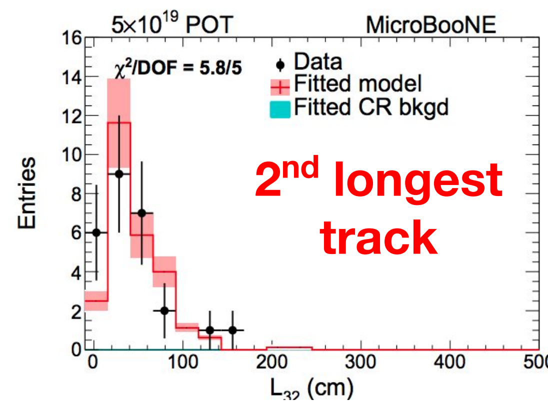
Mult =2

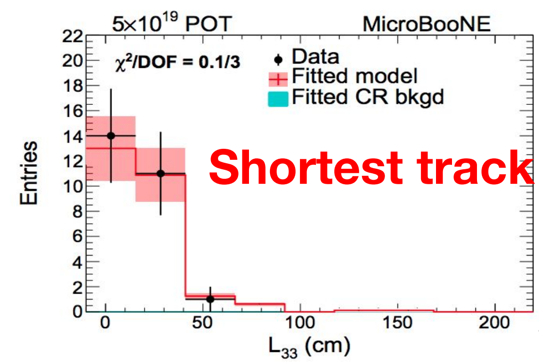




Mult =3



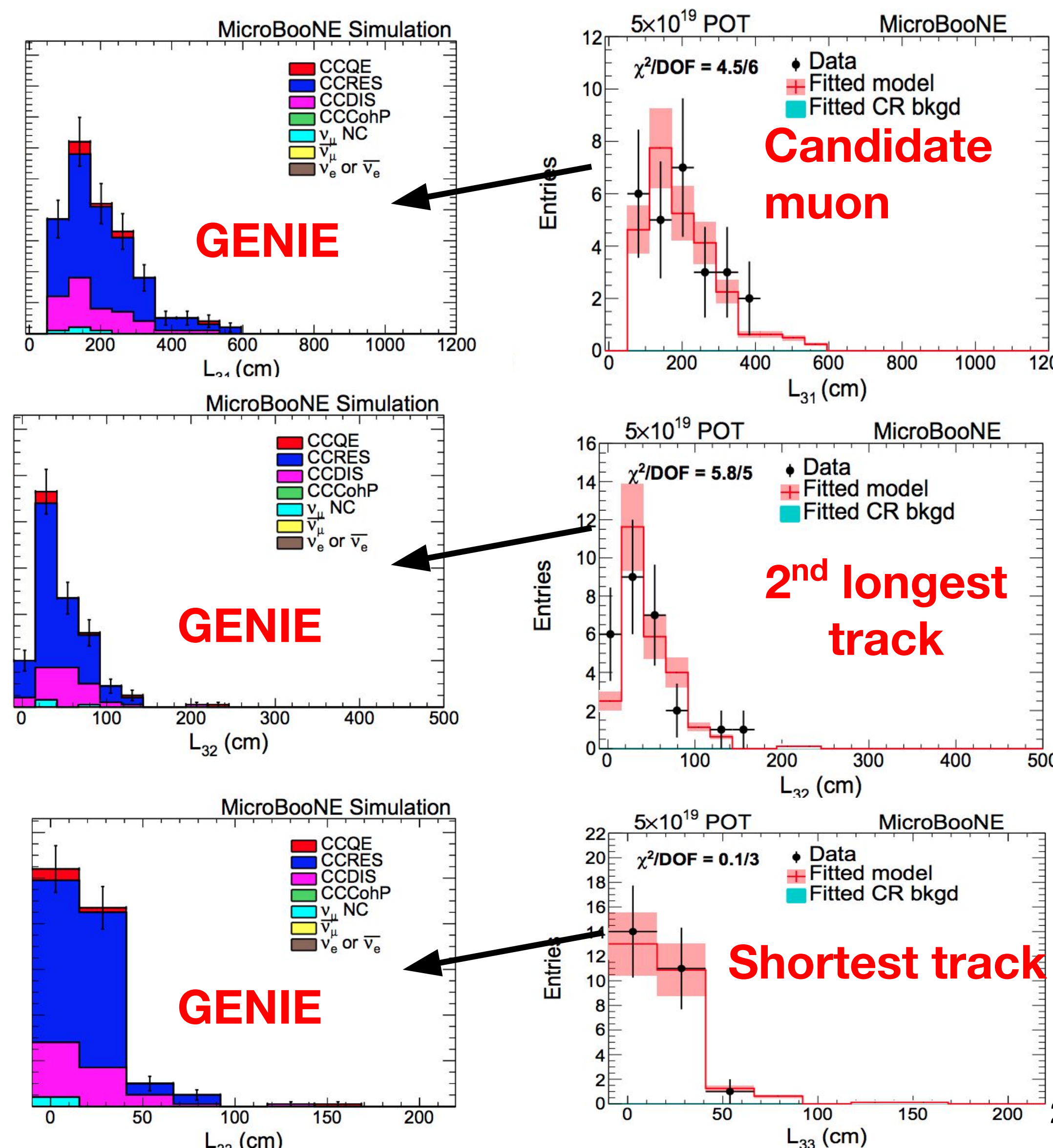




- Good shape agreement in data and simulation
- Sample becomes pure as we go to higher multiplicities

Track Length Distributions in GENIE

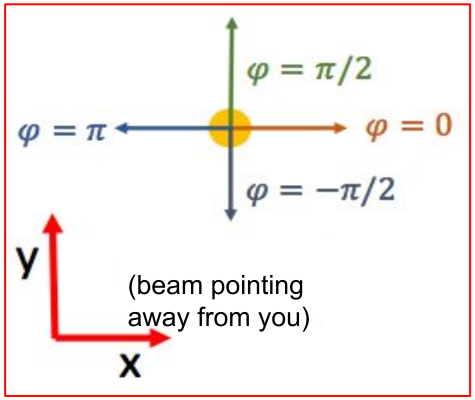
Mult =3 **Mult =3**

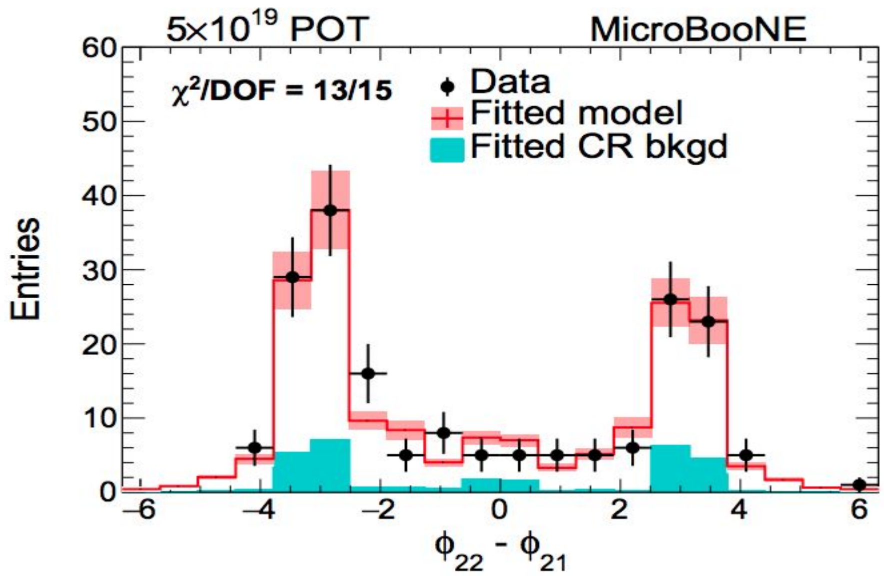


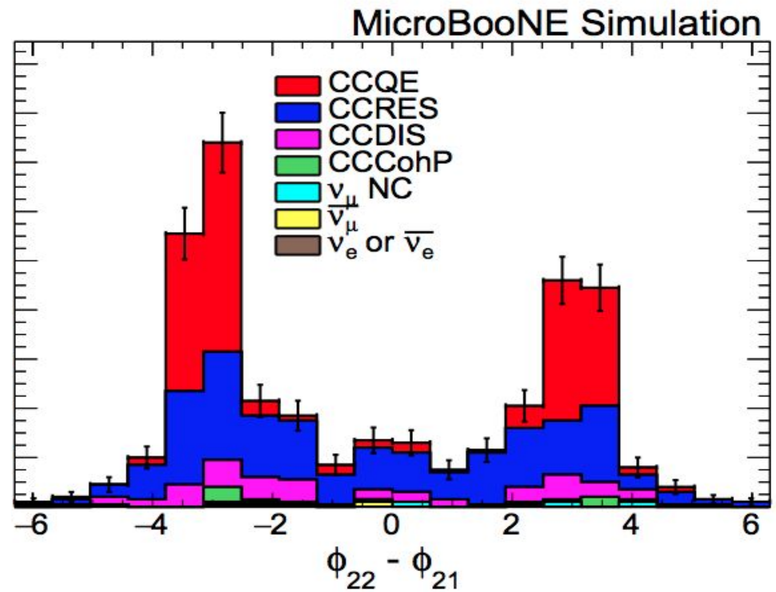
Good shape agreement even for the enhanced resonance events

Difference in Azimuthal Angle

$\Phi_{short} - \Phi_{long}$ (multiplicity = 2)







Here an inclusive analysis gives a sense of exclusive final states

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  1. Multiplicity of charged particles from ν_μ-Ar scattering
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- Measurements span a range of physics and techniques
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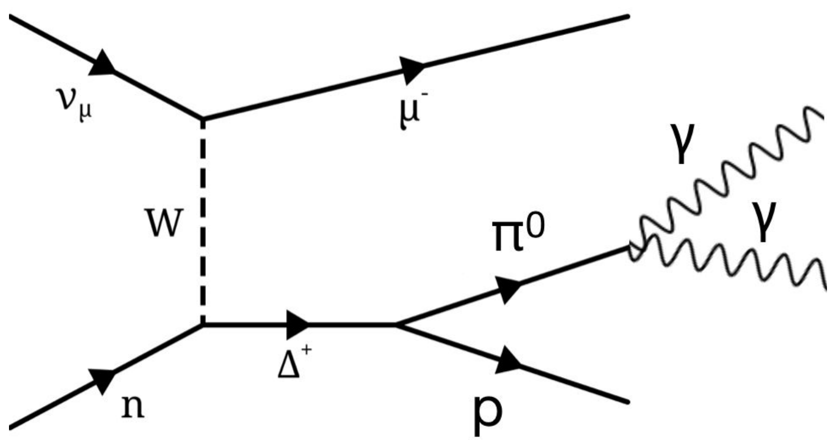
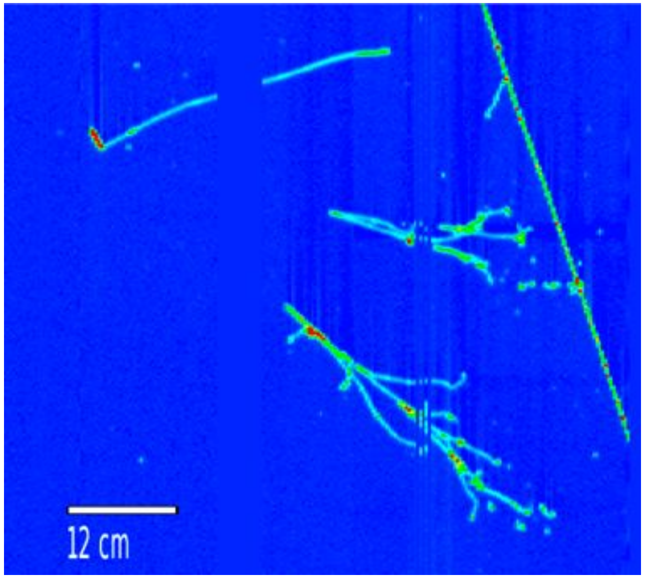
Exclusive Channels

- Measuring exclusive channels enable us to bring final state interactions and nuclear effects into finer focus
- This is the first absolute cross section from MicroBooNE
- We performed a measurement of the total flux-integrated cross section for charged current single π^0 production
  - This topology offers us an excellent testing ground to vet our shower energy and angular resolution
  - Also gives insight into π^0 production which is a background to searches for $\nu_\mu \rightarrow \nu_e$ oscillations





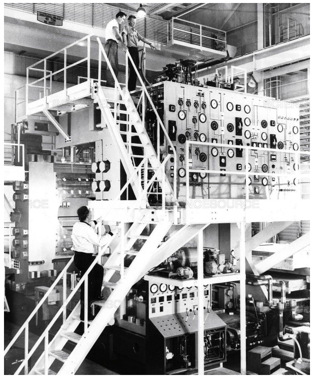
Published ν_μ CC 1 π^0 Measurements

(A = 1,2)

Hydrogen

BNL 7'

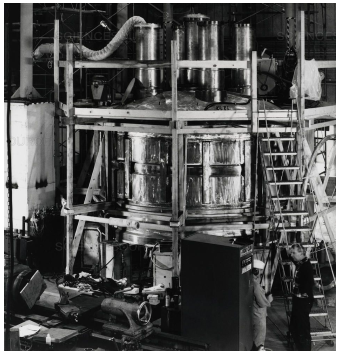
Phys. Rev. D 19, 2521 (1979)



ANL 12'

Phys. Rev. D 25, 1161 (1982)

Phys. Rev. D 34, 2554 (1986)



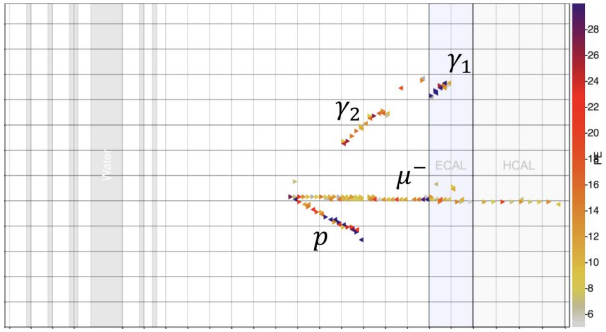
(A = 12)

Carbon

Minerva

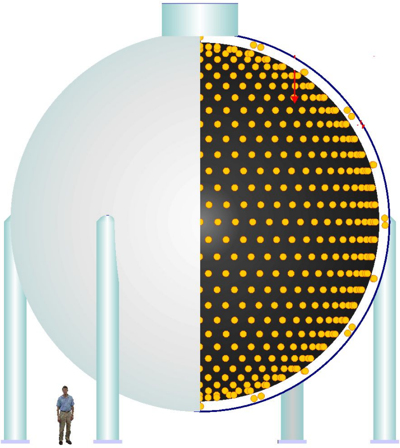
Physics Letters B 749, 130 (2015)

Phys. Rev. D96, 072003 (2017)



MiniBooNE

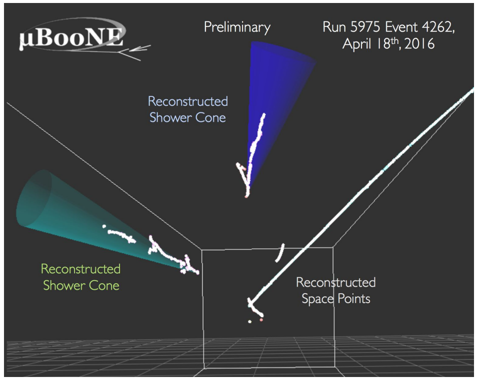
Phys. Rev. D 83, 052009 (2011)



(A = 40)

Argon

MicroBooNE

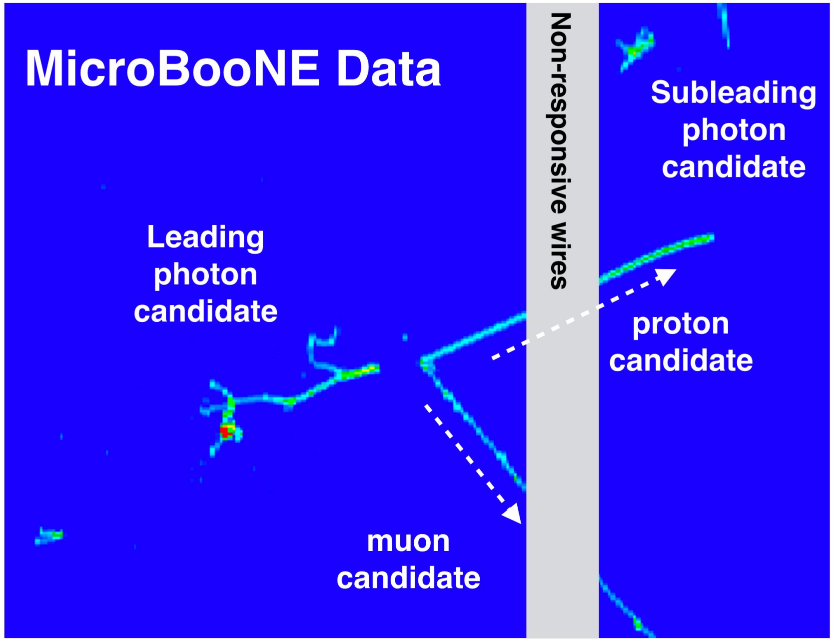


The final state we will be analyzing is
ν_μ + Ar → μ + 1 π^0 + X

Scaling from carbon to argon we expect pion absorption effects ~2x strong (default GENIE scales as $A^{2/3}$)

Challenge of Analysis

- Challenging topology: Requires both track and low energy shower reconstruction
  - **First demonstration of shower reconstruction being used to analyze LArTPC data**
  - The exquisite detail of the LArTPC enables us to resolve very low energy showers



- Charged current topology can be used to enable a second pass reconstruction
  - **Use neutrino vertex to seed our shower reconstruction**

Preselection Purity:

ν_μ CC - 81%

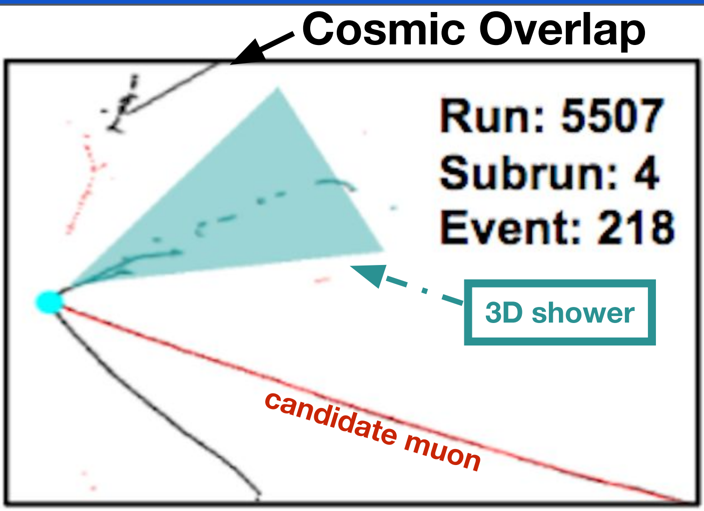
(ν_μ CC π^0 - 6%)

Preselection Efficiency:

ν_μ CC π^0 - 32%

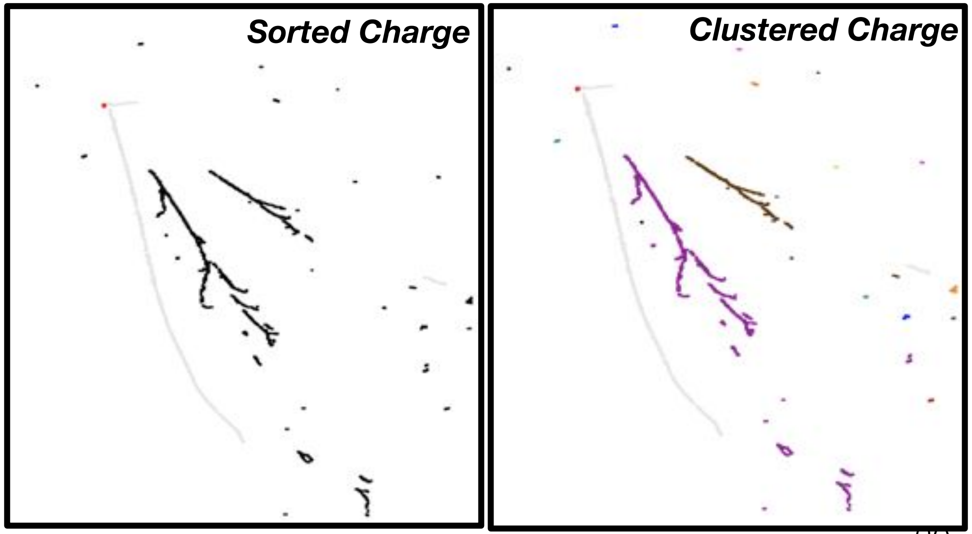
Shower Reconstruction

- Need guards against cosmic charge being added to our showers
  - **Conservative approach sacrifices charge completeness to allow for charge purity**
- Remove clusters from neutrino-induced tracks leveraging our spatial resolution
  - Linearity and transverse distribution of charge
- Remaining charge is clustered using OpenCV[1]



A. Hackenburg, Yale U., Ph.D. Thesis

OpenCV

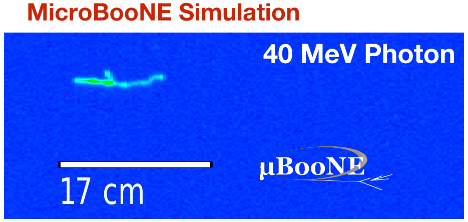


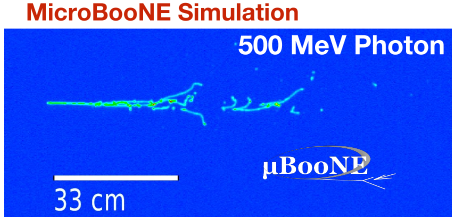
D. Caratelli, Columbia U., Ph.D. Thesis

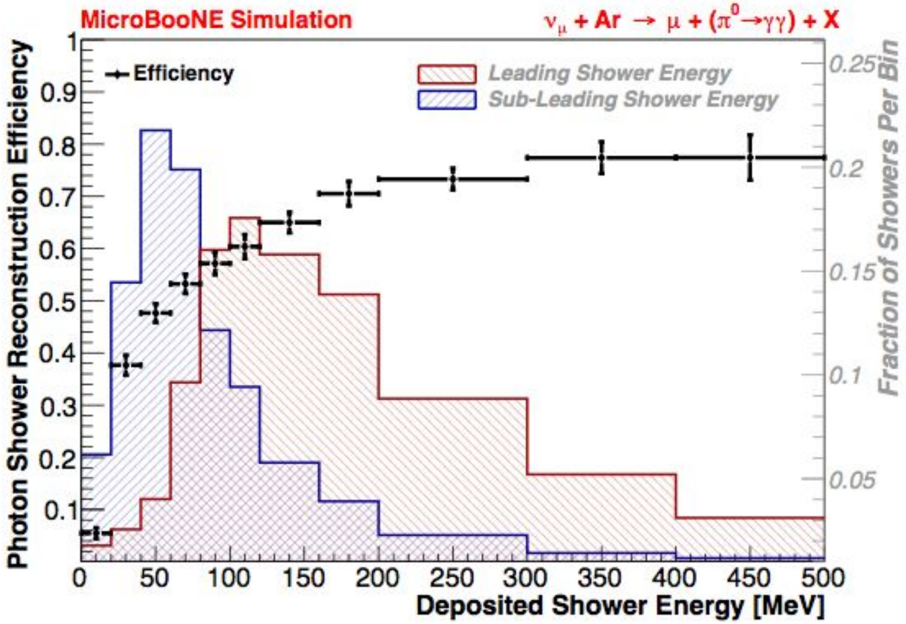
[1]*G. Bradski, Dr. Dobb's Journal of Software Tools, (2000).*

Shower Reconstruction Performance

- Shower reconstruction has an average efficiency of:
  - 62% for leading shower
  - 50% for subleading shower
- Low energy photons appear more track-like
  - Leads to lower efficiency







Single Shower Selection

For cross section, maximize statistics by requiring at least one shower reconstructed

Validate Photon Hypothesis:

Study the conversion distance of showers

Two Shower Selection

Cross checked with events with at least two showers be reconstructed

Validate π^0 Hypothesis:

Study the invariant diphoton mass

Single Shower Selection

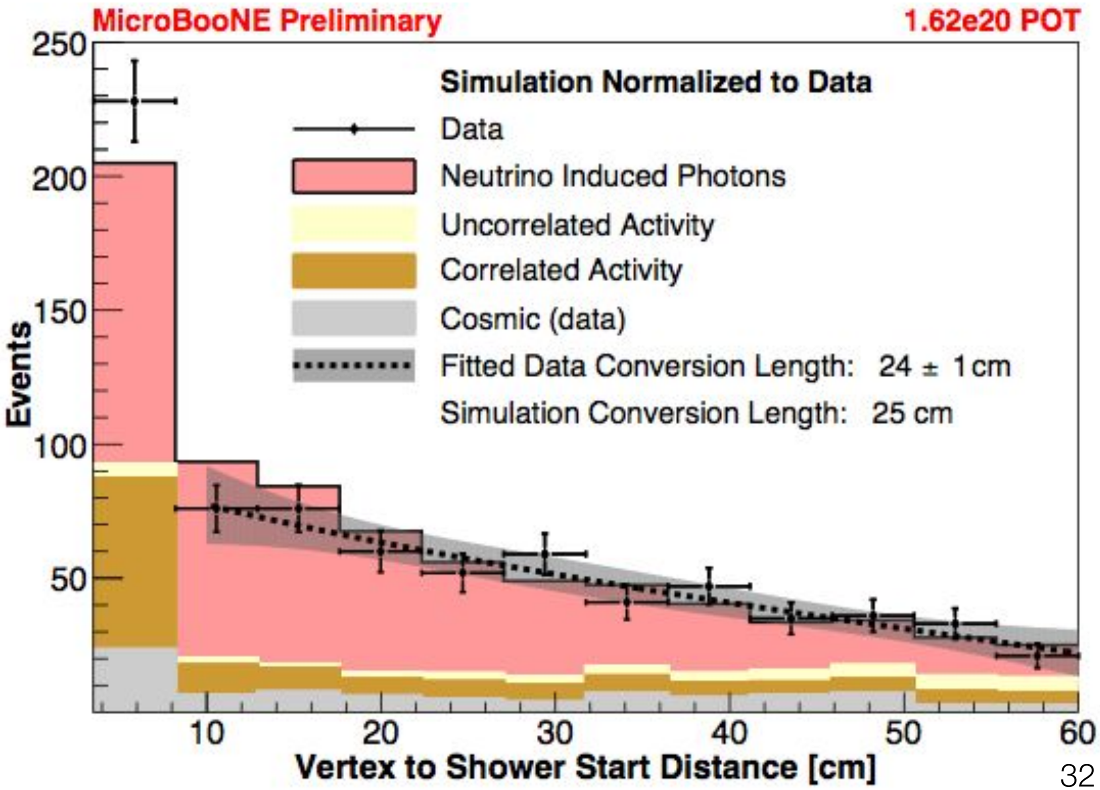
- Attempt to match reconstructed showers back to our interaction vertex:
  - Convert near the vertex
  - Backward projection has a small distance of closest approach to the vertex
- Use the mean free path length to validate our photon hypothesis
  - **Measured length in data and simulation agree within uncertainties**

One Shower Selection

Efficiency: 17%
Purity: 53%

771 Events

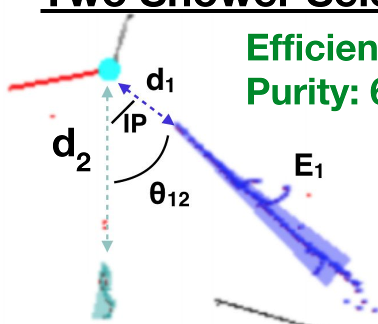
A. Hackenburg, Yale U., Ph.D. Thesis



Cross Check with Two Showers

- A subsample of our events will have two reconstructed showers
  - Select events taking into account the allowed kinematics of π^0 decays
- With two showers we can study the diphoton invariant mass
  - Correct individual shower energies for known sources of energy loss based on simulation[1]
  - **Measured mass in data and simulation consistent with $M_{\pi 0}$ (135 MeV)**

Two Shower Selection



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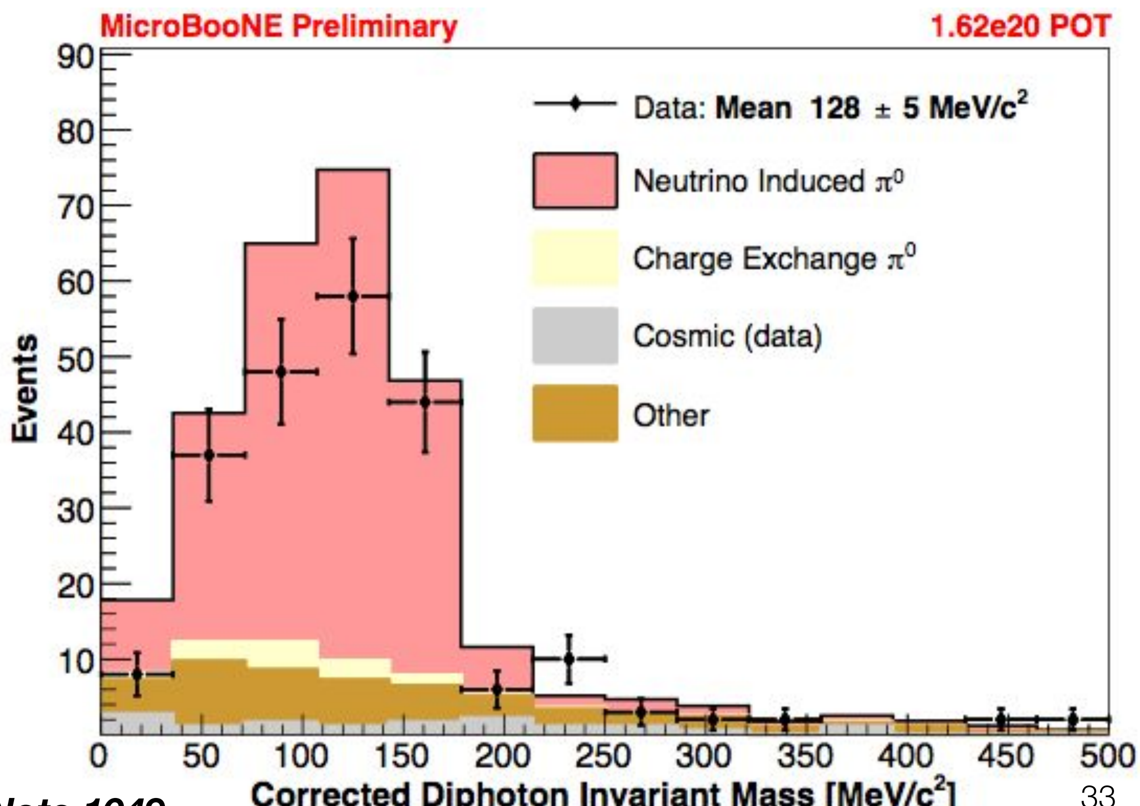

 [1]MicroBooNE Public Note 1049

Cross Check with Two Showers

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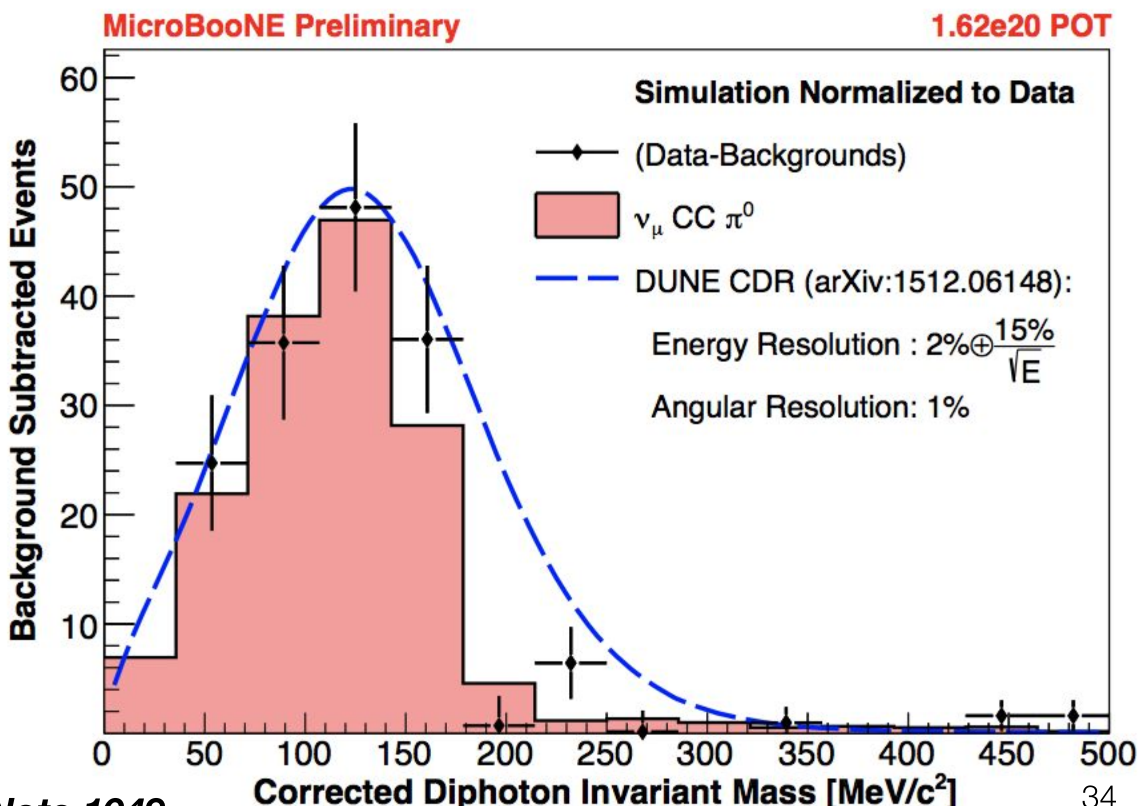
  - Select events taking into account the allowed kinematics of π^0 decays
- With two showers we can study the diphoton invariant mass
  - Correct individual shower energies for known sources of energy loss based on simulation[1]
  - **Measured mass in data and simulation consistent with $M_{\pi 0}$ (135 MeV)**

This tests the assumptions made in the DUNE CDR and SBN Proposal

We are achieving a better energy resolution in data than expected



[1]*MicroBooNE Public Note 1049*

Flux-Integrated Total Cross Section

With our validated single shower selection...

Data Events
Selected single shower events from on-beam data
N = 771 events

Cosmic Backgrounds
Background taken from off-beam data
B^c = 87 events

Neutrino Backgrounds
Backgrounds modeled by GENIE simulation
B^{sim} = 347 events

$$\langle\sigma^{\nu_\mu CC\pi^0}\rangle_\Phi = \frac{N - B^C - B^{sim}}{\epsilon T \Phi}$$

Signal Efficiency
Efficiency is estimated from simulation
ε = 17%

Number of Targets
We have measured contaminants to be <1ppm,

Treat full volume as pure argon

Integrated Flux
Integrate ν_μ flux over full range

ν_μ Interaction Model Uncertainties

- GENIE provides a set of uncertainties that go with their default models
  - These uncertainties are tuned to cover differences between the models and neutrino and pion scattering data
  - Over 35 parameters within the models are independently varied $\pm 1\sigma$ and the cross section is remeasured

$$\langle \sigma^{\nu_\mu CC\pi^0} \rangle_\Phi = \frac{N - B^C - B^{sim}}{\epsilon T \Phi}$$

Backgrounds are modeled directly from GENIE simulation

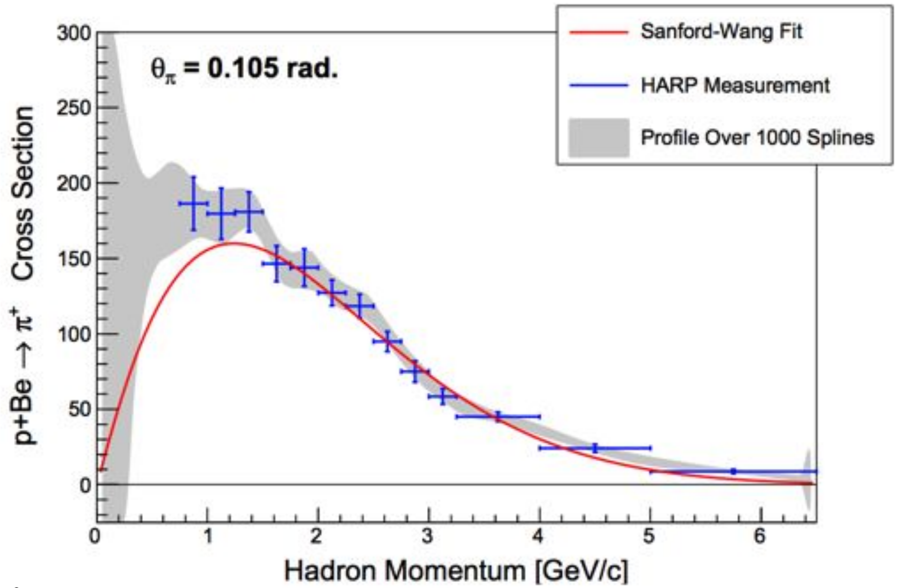
Backgrounds are dominated by resonant events that GENIE assigns large uncertainties

Even though the efficiency is derived from the simulation it is less sensitive to these uncertainties

Together these are a 17% overall uncertainty

Neutrino Flux Uncertainties

Leverage the 10+ years of MiniBooNE work by using the flux uncertainties derived for their final analyses[1,2]



$$\langle \sigma^{\nu_\mu CC\pi^0} \rangle_\Phi = \frac{N - B^C - B^{sim}}{\epsilon T \Phi}$$

Normalization shifts impact background estimates which tend to come from higher energy neutrinos

Integrate over full flux range at the lowest energies the flux becomes very uncertain

Together these are a 16% overall uncertainty

[1]PRD 79, 072002 (2009)

[2]MicroBooNE Public Note 1031

Detector Simulation Uncertainties

- Pursued a conservative estimate of many effects by creating separate MC sets with modified detector simulation
  - Microphysics of charge/light production and transport to readout
  - Simulated detector response
- Contribution from simulated cosmics also assigned an uncertainty

Future analyses will benefit from ongoing efforts to measure these in-situ and correct them via calibrations

$$\langle \sigma^{\nu_\mu \mathrm{CC}\pi^0} \rangle_\Phi = \frac{N - B^C - B^{sim}}{\epsilon T \Phi}$$

Leads to more/fewer real photon backgrounds or mistakenly reconstructing tracks as showers

Certain variations impact track reconstruction modifying preselection efficiency

These tend to be second order

Together these are a 21% overall uncertainty

Final Cross Section

First Measurement of $\nu_\mu + Ar \rightarrow \mu + 1\ \pi^0 + X$

$$\left\langle \sigma^{\nu_\mu \mathbf{CC}\pi^0} \right\rangle_\Phi = (1.94 \pm 0.16\ [\text{stat.}] \pm 0.60\ [\text{syst.}]) \times 10^{-38}\ \frac{\text{cm}^2}{\text{Ar}}$$

Compare our measurement with two sets of GENIE models

<u>Nuclear Models</u>

Default
Bodek-Ritchie Fermi Gas
Alt.
Local Fermi Gas

<u>Resonant Models</u>

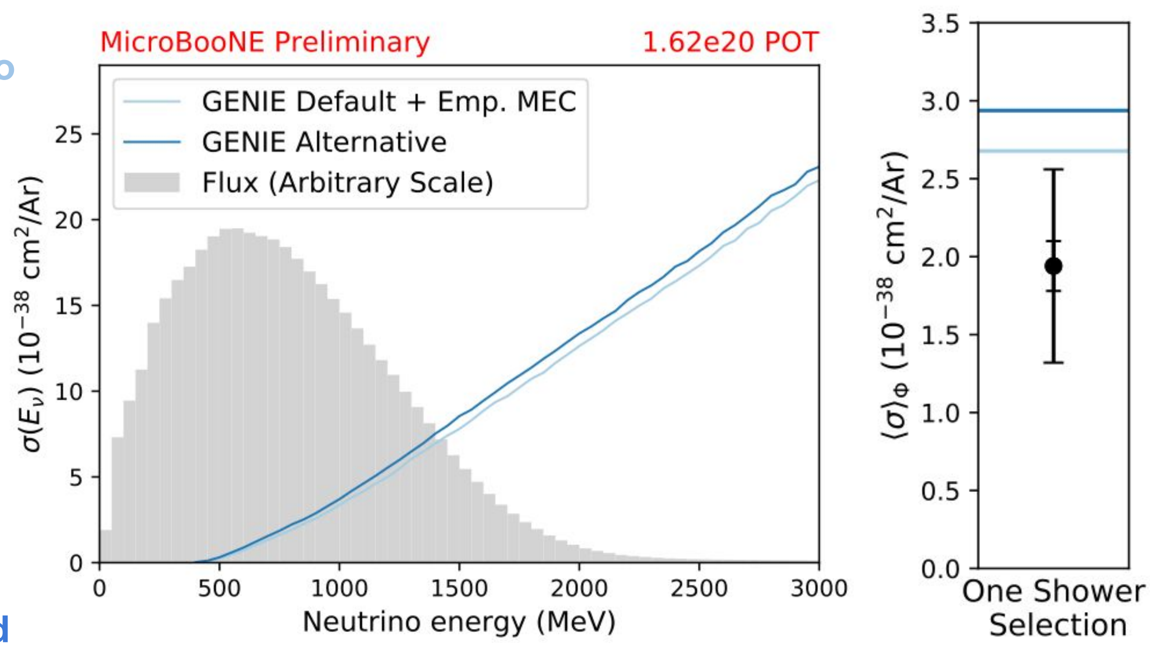
Default
Rein-Seghal
Alt.
Berger-Seghal

<u>FSI Models</u>

Default
hA
Alt.
hA2014

Based on tune to MINOS

Theory models tuned to MiniBooNE



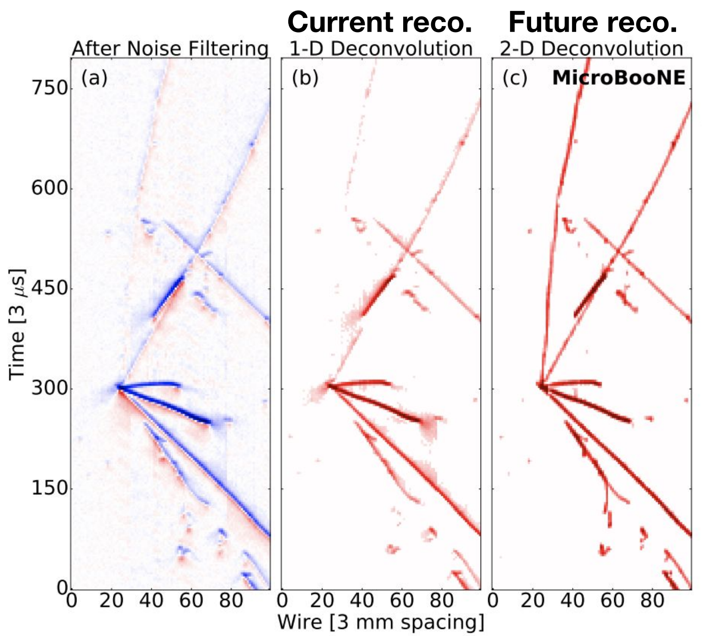
Our measurement is consistent, within 1.6σ, with predictions from both model sets

Future Prospects

- To further vet these models we'll need to extract differential cross sections in pion kinematics and reduce sensitivity to our simulation
- Working on many efforts that will enable this

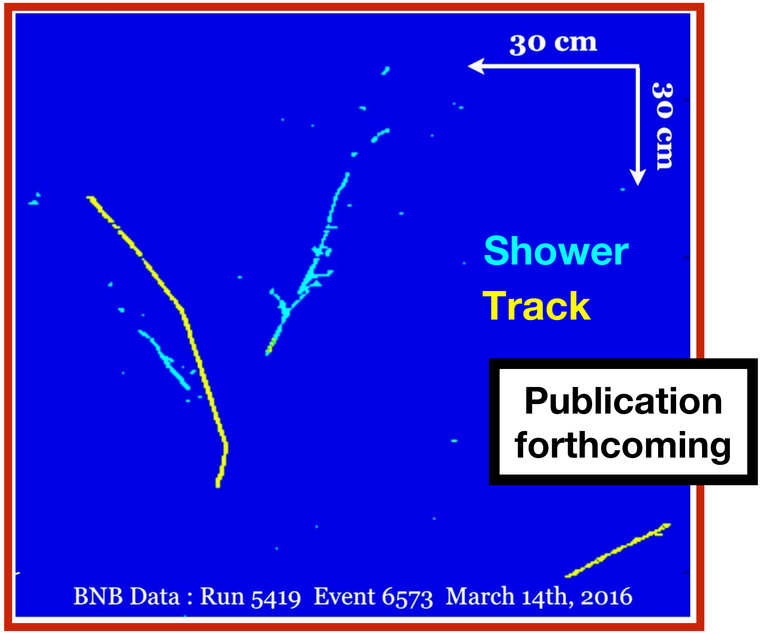
Detector Understanding

arXiv:1804.02583[*] and arXiv:1802.08709



Studies of signal processing to build a more robust reconstruction

Image Classification Techniques

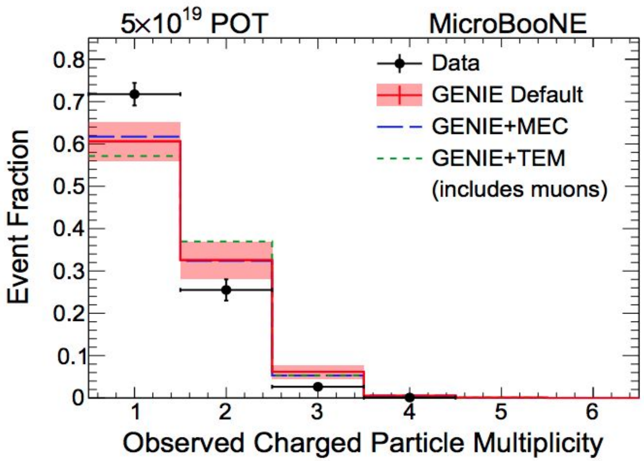


We have pioneered the application of CNNs to LArTPCs

[*] Accepted by JINST

Conclusions

MicroBooNE has begun to utilize the full promise of the LArTPC to test our neutrino interaction models in GENIE

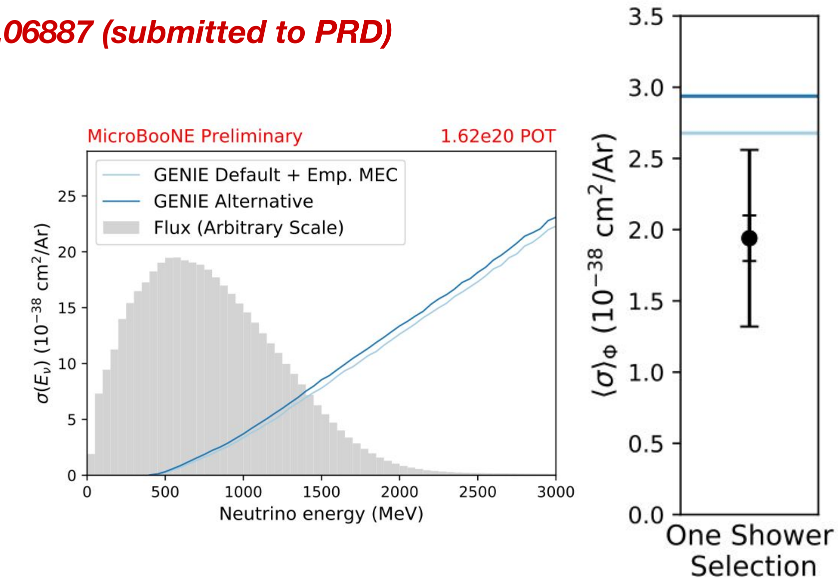


Performed the first measurement of fully inclusive charged particle production in ν_μ+Ar interactions

Read more at arXiv:1805.06887 (submitted to PRD)

Measured the first charged current single π^0 cross section in ν_μ+Ar interactions

Read more in MicroBooNE Public Note 1032



Future measurements will benefit from our continued effort to constrain our systematic uncertainties and new more robust reconstruction algorithms

Stay tuned….until next week...

Neutrino 2018

NEUTRINO 2018 Heidelberg 4–9 June

First Charged-Current Muon-Neutrino Inclusive Cross Section Measurement with the MicroBooNE Detector

Marco Del Tutto[1] and Anne Schukraft[2] representing the MicroBooNE collaboration

Electron-neutrino reconstruction and selection in the µBooNE LArTPC using the Pandora pattern recognition

STEFANO ROBERTO SOLETI on behalf of the MicroBooNE collaboration

First Deep Learning based Event Reconstruction for Low-Energy Excess Searches with MicroBooNE

A. Hourlier (MIT), V. Genty (Columbia), R. An (IIT) hourlier@mit.edu on behalf of the MicroBooNE Collaboration

Recent Progress on Wire-Cell Tomographic Event Reconstruction for LArTPCs

Hanyu Wei for the MicroBooNE collaboration
Physics Department, Brookhaven National Lab, Upton, New York, 11973, USA

The MicroBooNE Search for Single Photon Events

Robert Murrells - University of Manchester on behalf of the MicroBooNE Collaboration

Comparison of ν_μ-Ar multiplicity distributions observed by MicroBooNE to GENIE model predictions

Kansas State University — Aleena Rafique

Next week is Neutrino 2018 and MicroBooNE will be highlighting many new results beyond what was discussed here today!

13 posters of new work will be shown along with a presentation of our latest results by Roxanne Guenette (Harvard)

Over 300 pages of public notes complement these presentations

These are all publicly available here:
http://microboone.fnal.gov/public-notes

Identification of CC0π events with final state protons in MicroBooNE

Libo Jiang[1], Steve Dytman[1], Andy Furmanski[2]

Towards Automated Neutrino Selection at MicroBooNE using Tomographic Event Reconstruction

Brooke Russell for the MicroBooNE collaboration

Hunting Muon Neutrinos in MicroBooNE with Deep Learning Techniques

Jarrett Moon (MIT), representing the MicroBooNE Collaboration

MicroBooNE Low-Energy Excess Signal prediction through Unfolding MiniBooNE Monte-Carlo and Data

Mark Ross-Lonergan on behalf of the MicroBooNE Collaboration

Applying Deep Neural Network Techniques for LArTPC Data Reconstruction

Laura Domine[1] and Kazuhiro Terao[2], on behalf of MicroBooNE
[1]Stanford University, [2]SLAC National Accelerator Laboratory

Thank you from MicroBooNE

See you in Heidelberg!