Recent neutrino cross-section results from MicroBooNE

Elena Gramellini,
Lederman Fellow

Sept 8th, 2021, NuFact

MicroBooNE at NuFact

This talk:

→ Standard candles:

ν_μ Inclusive CC Cross Sections

ν_e Inclusive CC Cross Sections

→ Rate Events:

Analysis of Λ^0 Production

Samantha Sword-Fehlberg's talk:

→ An exploration of the Ar nucleus through the lens of protons

Steven Gardiner's talk:

→ A description of our model tuning, and how it compares to Argon data

Kathryn Sutton's talk on Monday:

→ Progress in photon-Like Low Energy Excess Search

MicroBooNE at NuFact

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→ Progress in photon-li...

En...

Plus many posters!!

[CCQE, NC Elastic, Lambda, CC Inclusive]

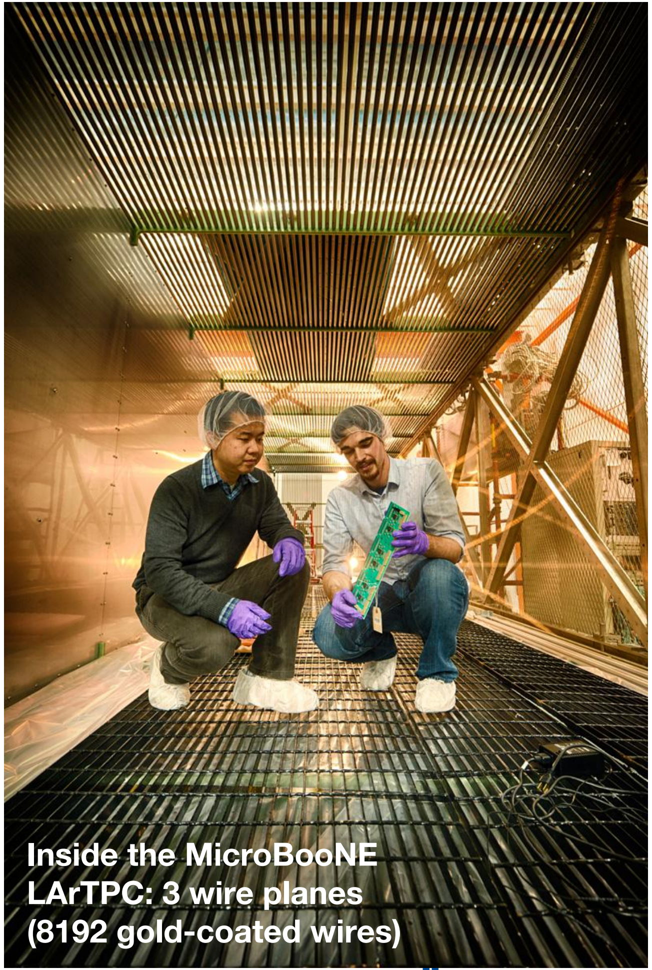
Fermilab

MicroBooNE at a glance

MicroBooNE is the longest running **Liquid Argon Time Projection Chamber** at FNAL. With 85 ton active volume, MicroBooNE collects neutrinos on-axis from the BNB and highly off-axis from NuMI.

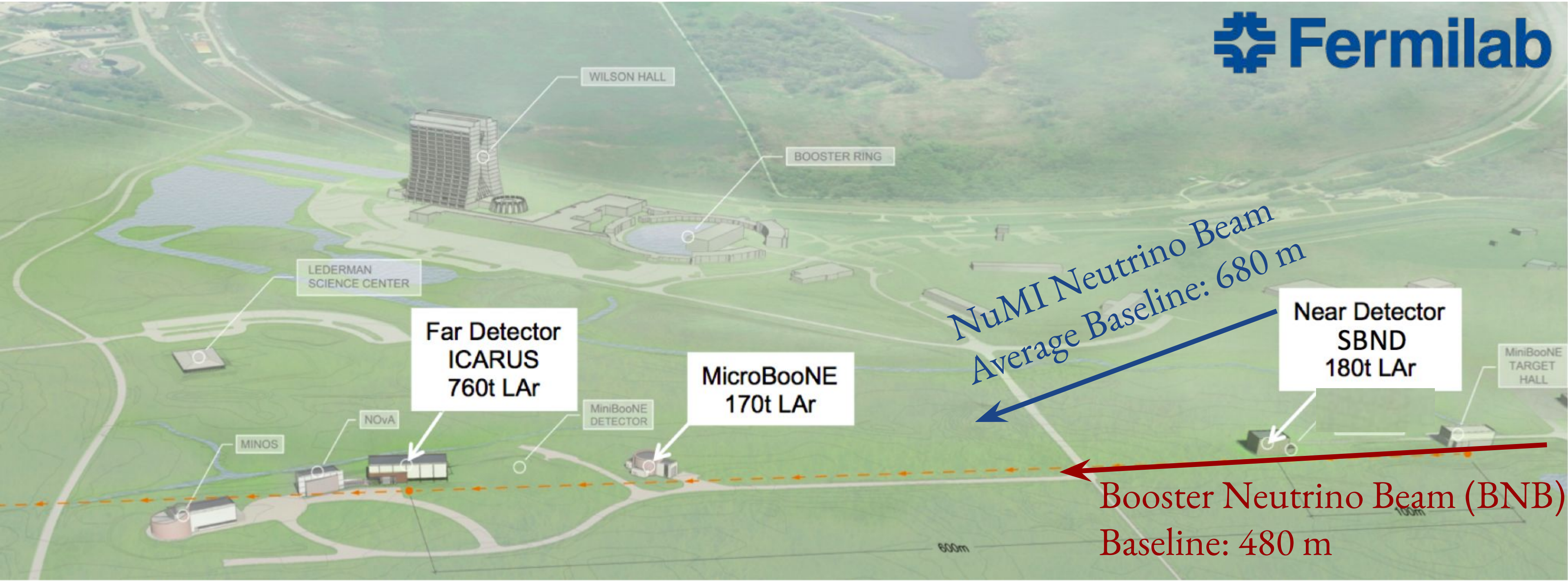
Completed 5 years physics runs: 2015-2021.
Largest neutrino-argon dataset available to date.

Just started exciting R&D program!



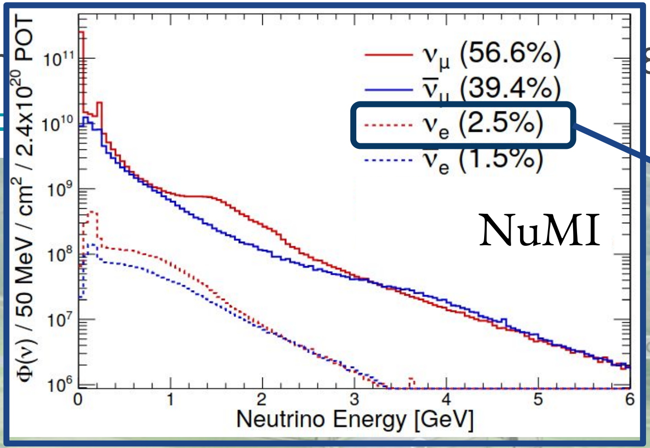
Beams at MicroBooNE

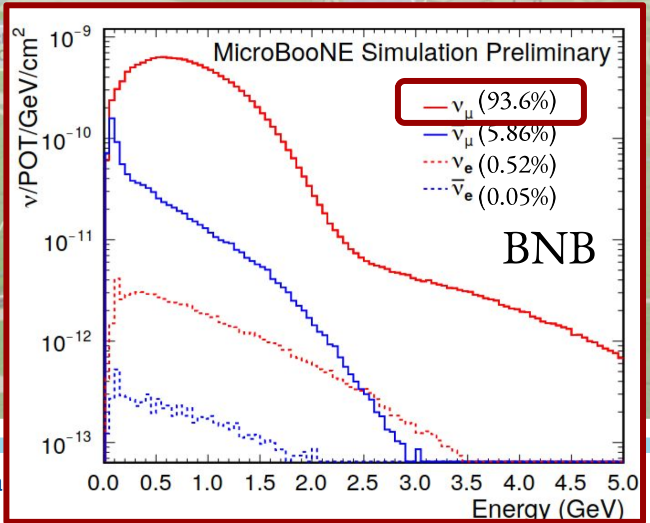
MicroBooNE collects neutrinos on-axis from the BNB and 108 mrad off-axis from NuMI, MICROBOONE-NOTE-1031-PUB, arXiv:2101.04228

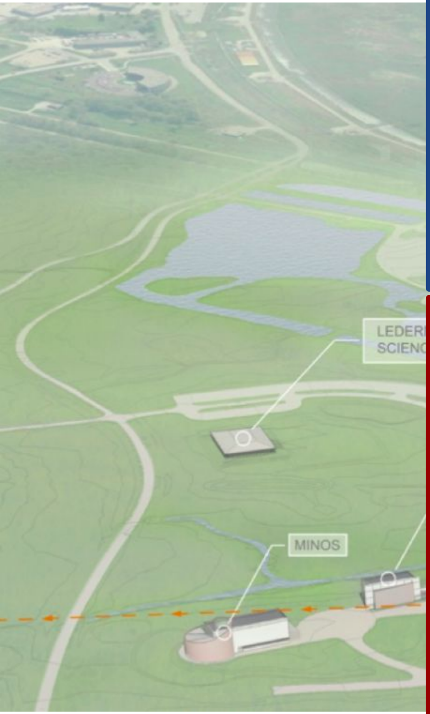


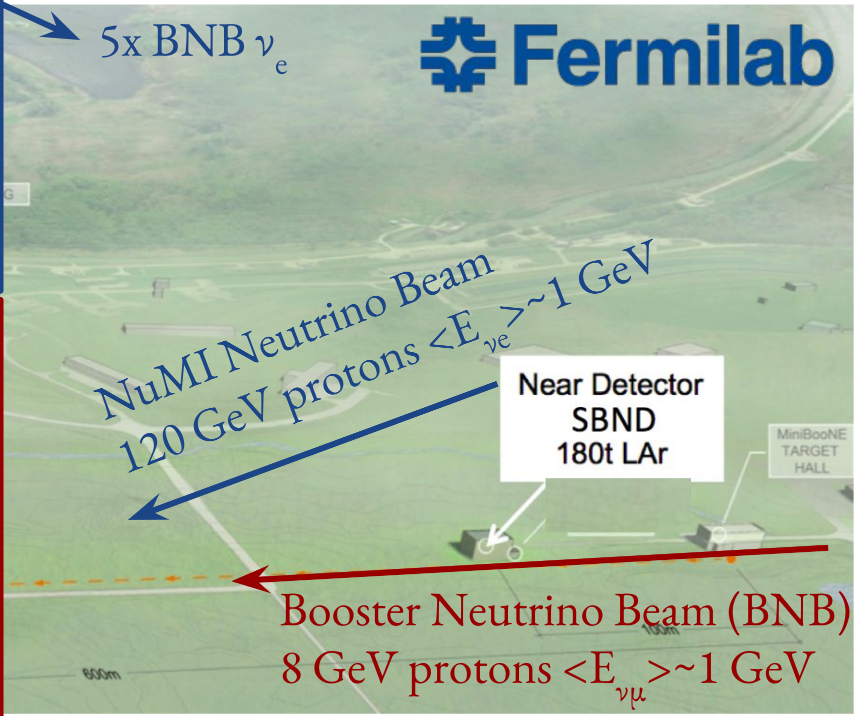
Beams at MicroBooNE

MicroBooNE collects n… 8 mrad off-axis from NuMI,
MICROBOONE-NOTE-…









MicroBooNE Publications

MicroBooNE has a large body of published work:
33 papers,
56 public notes

Sharing findings with LAr community…

Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector
Measurement of the Longitudinal Diffusion of Ionization Electrons in the Detector
Cosmic Ray Background Rejection with Wire-Cell LAr TPC Event Reconstruction in the MicroBooNE Detector
Measurement of the Flux-Averaged Inclusive CC ve and Anti-ve Cross Section on Argon using the NuMI Beam in MicroBooNE
Measurement of the Atmospheric Muon Rate with the MicroBooNE Liquid Argon TPC
Semantic Segmentation with a Sparse Convolutional Neural Network for Event Reconstruction in MicroBooNE
High-performance Generic Neutrino Detection in a LAr TPC near the Earth's Surface with the MicroBooNE Detector
Neutrino Event Selection in the MicroBooNE LAr TPC using Wire-Cell 3D Imaging, Clustering, and Charge-Light Matching
A Convolutional Neural Network for Multiple Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
The Continuous Readout Stream of the MicroBooNE Liquid Argon Time Projection Chamber for Detection of Supernova Burst Neutrinos
2021 Vertex-Finding and Reconstruction of Contained Two-track Neutrino Events in the MicroBooNE Detector
Measurement of Differential Cross Sections for Muon Neutrino CC Interactions on Argon with Protons and No Pions in the Final State
Measurement of Space Charge Effects in the MicroBooNE LAr TPC Using Cosmic Muons
First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with the MicroBooNE Detector
Search for heavy neutral leptons decaying into muon-pion pairs in the MicroBooNE detector
Reconstruction and Measurement of O(100) MeV Electromagnetic Activity from Neutral Pion to Gamma Gamma Decays in the MicroBooNE LArTPC
A Method to Determine the Electric Field of Liquid Argon Time Projection Chambers Using a UV Laser System and its Application in MicroBooNE
2020 Calibration of the Charge and Energy Response of the MicroBooNE Liquid Argon Time Projection Chamber Using Muons and Protons
First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at Enu ~0.8 GeV with the MicroBooNE Detector
Design and Construction of the MicroBooNE Cosmic Ray Tagger System
Rejecting Cosmic Background for Exclusive Neutrino Interaction Studies with Liquid Argon TPCs: A Case Study with the MicroBooNE Detector
First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE detector
A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
2019 Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions
Ionization Electron Signal Processing in Single Phase LArTPCs II: Data/Simulation Comparison and Performance in MicroBooNE
Ionization Electron Signal Processing in Single Phase LArTPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation
2018 The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector
Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter
Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC
Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC
Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering
Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber
2017 Design and Construction of the MicroBooNE Detector

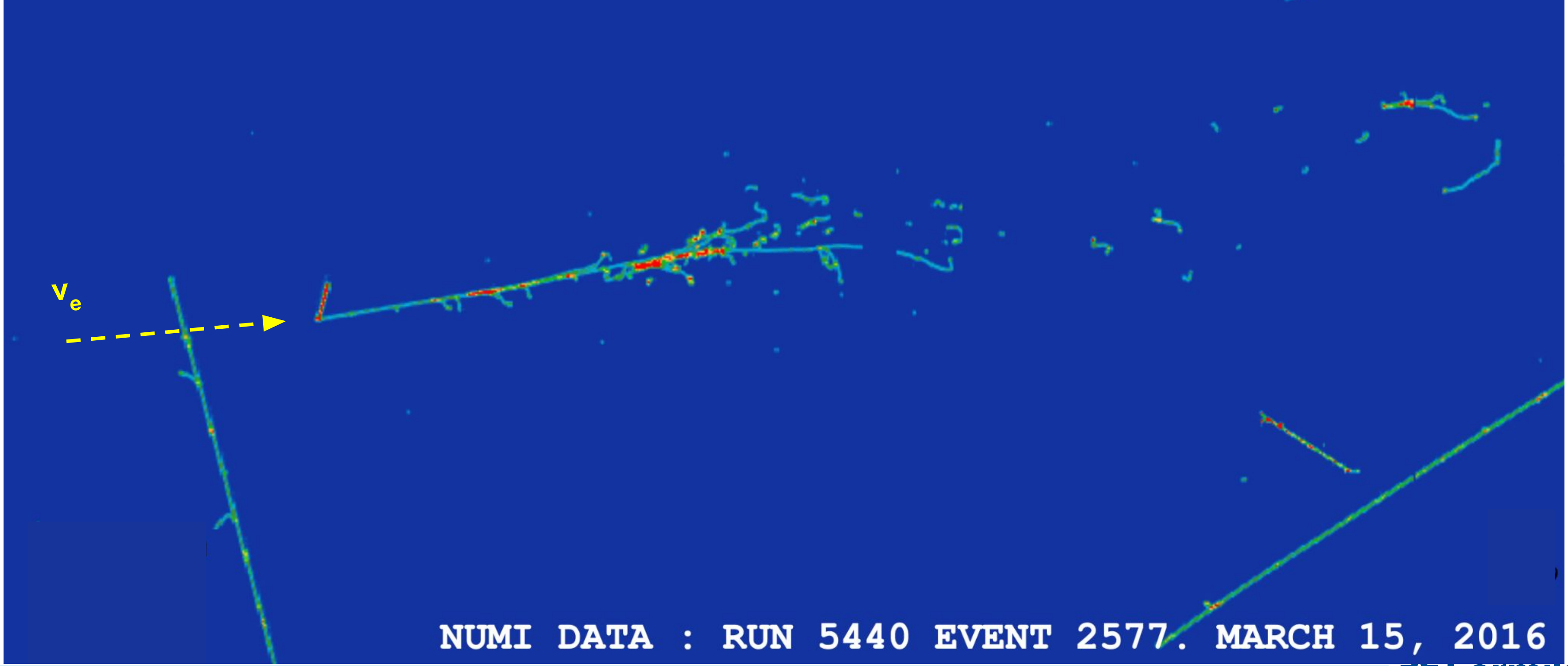
…to boost SBN and DUNE's success
See Maurizio Bonesini's talk

Fermilab

LArTPC in action

Extremely detailed 3D images + calorimetry + PID

unprecedented tool for neutrino interaction & BSM physics



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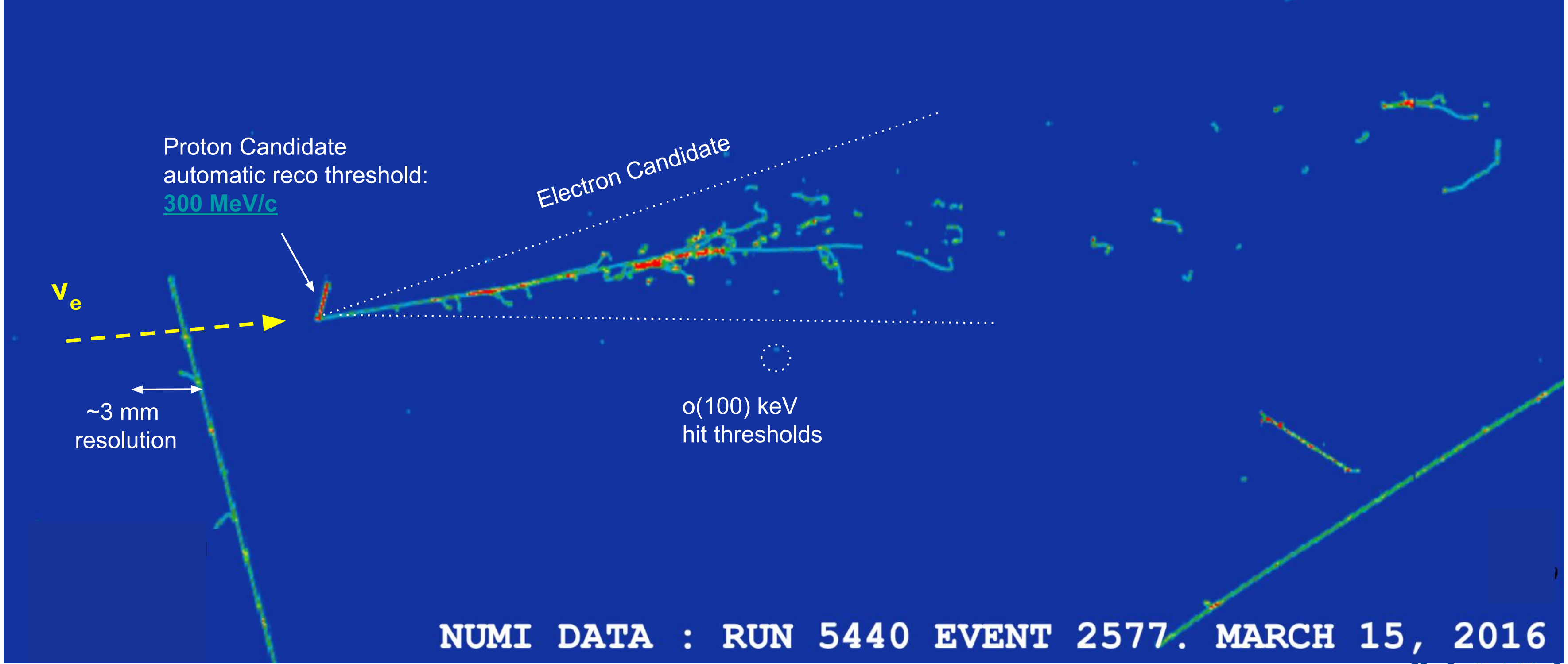

µBooNE

LArTPC in action

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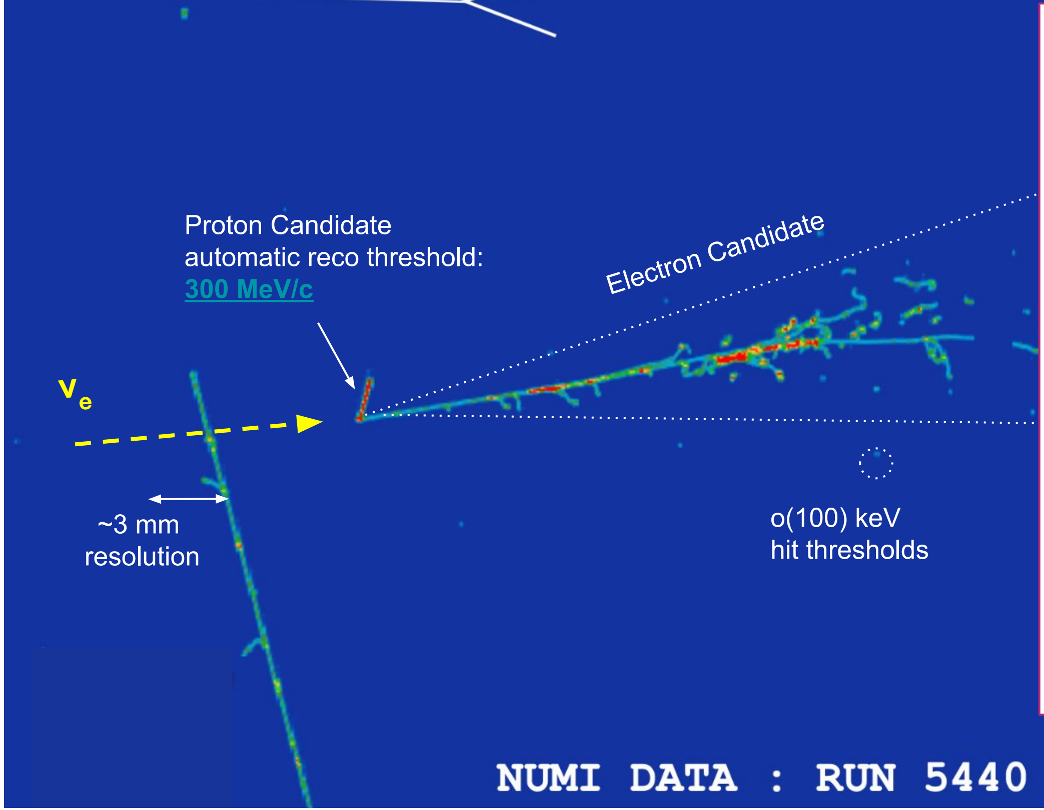
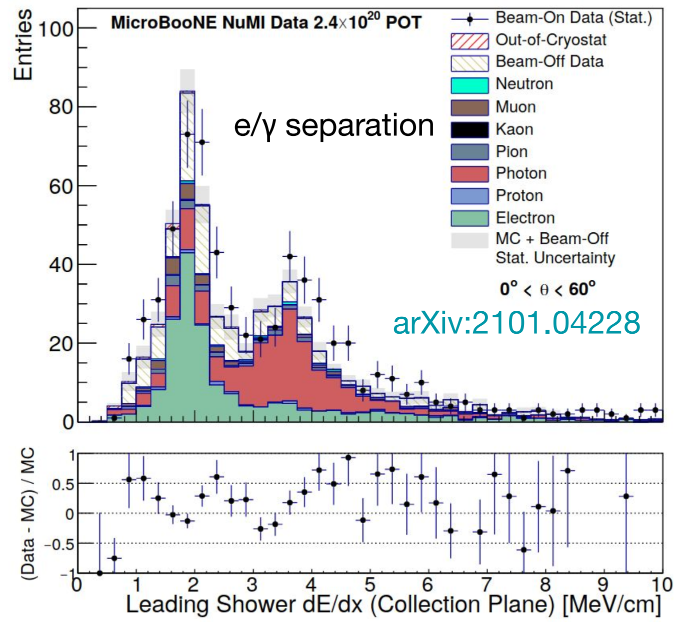


Particle ID: e/γ

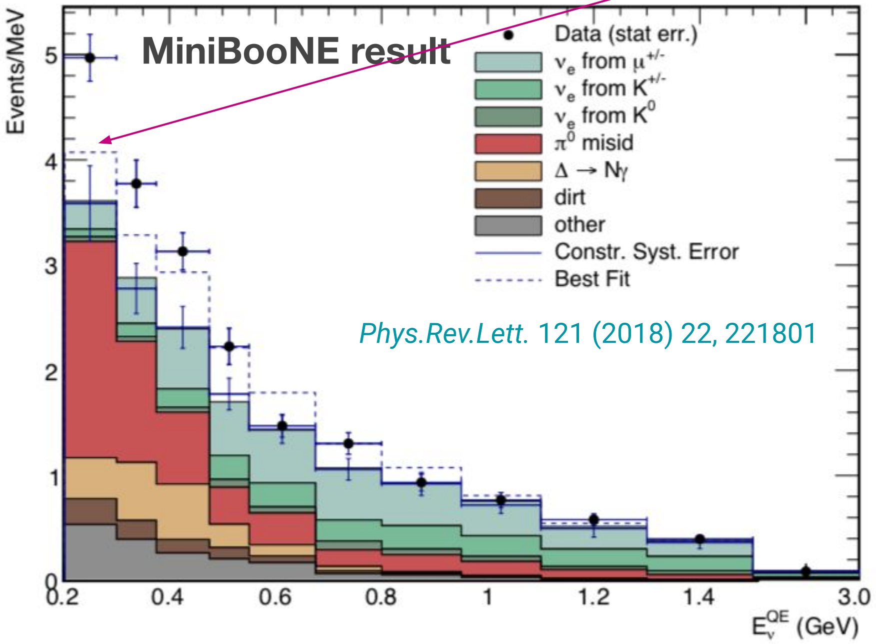


Fermilab

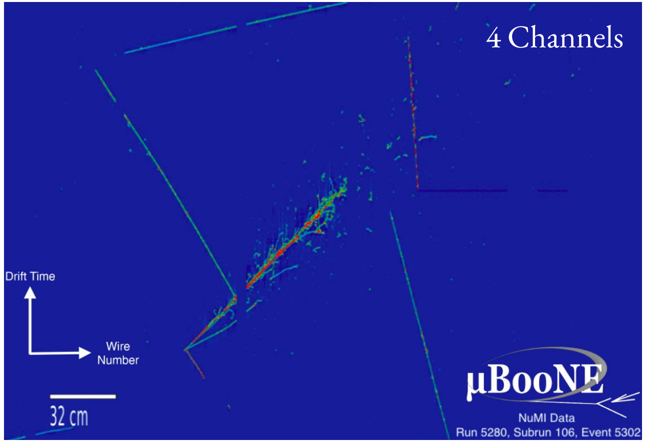
To e⁻ or not to e⁻? Why is e/γ separation a big deal?

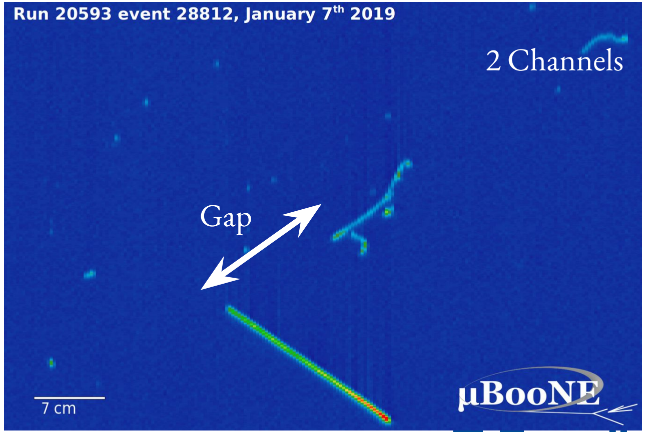
Primary physics goal:

Investigate the nature of the MiniBooNE excess of low energy electromagnetic events. **Is it electrons? Is it photons?**



Phys.Rev.Lett. 121 (2018) 22, 221801





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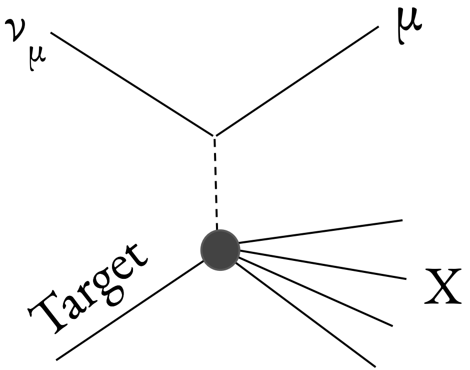
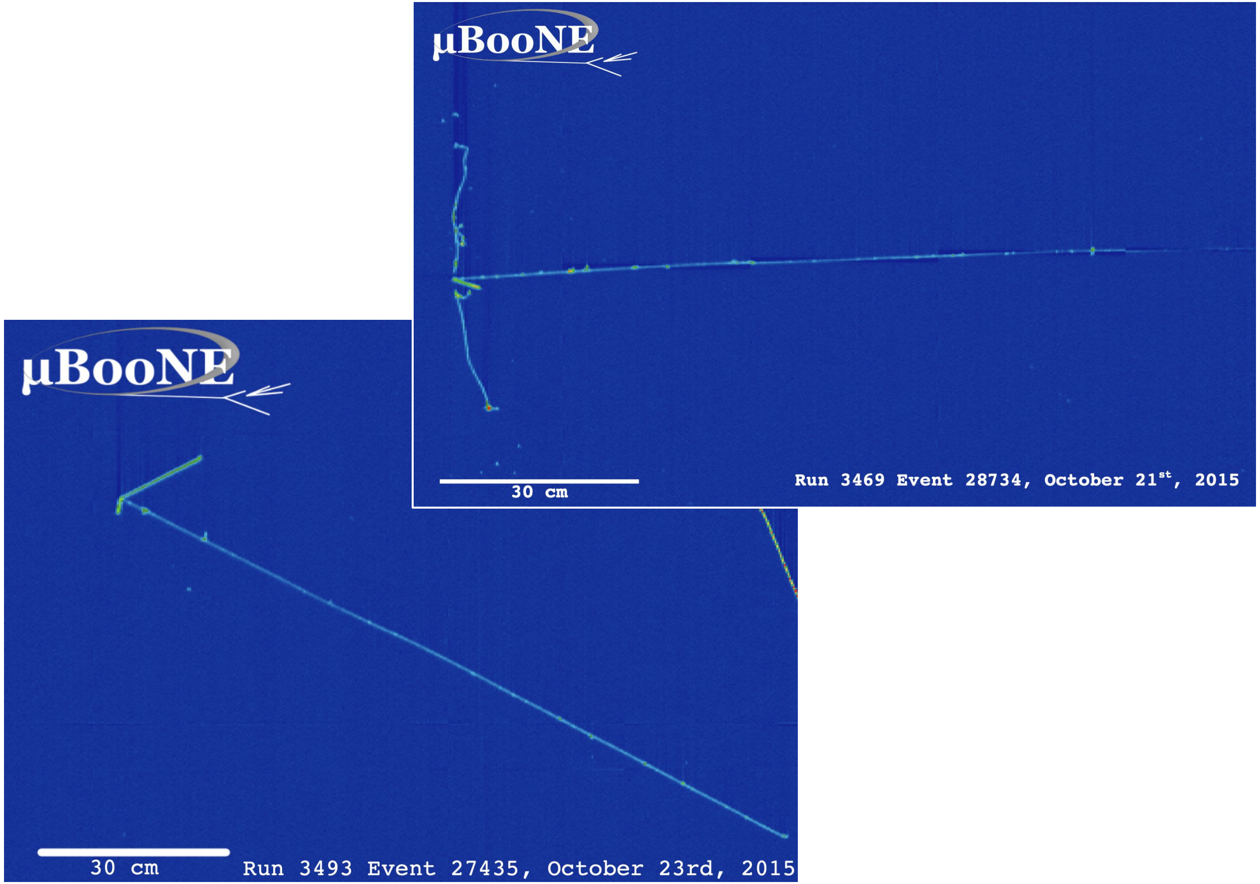
ν_μ CC Inclusive @ BNB



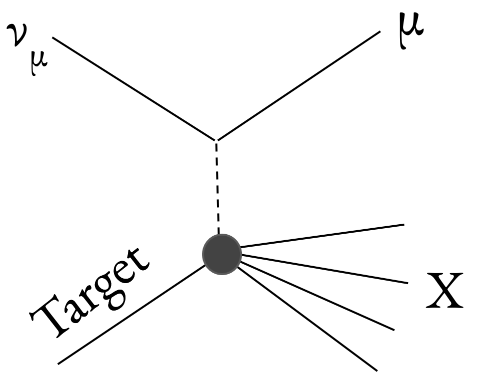


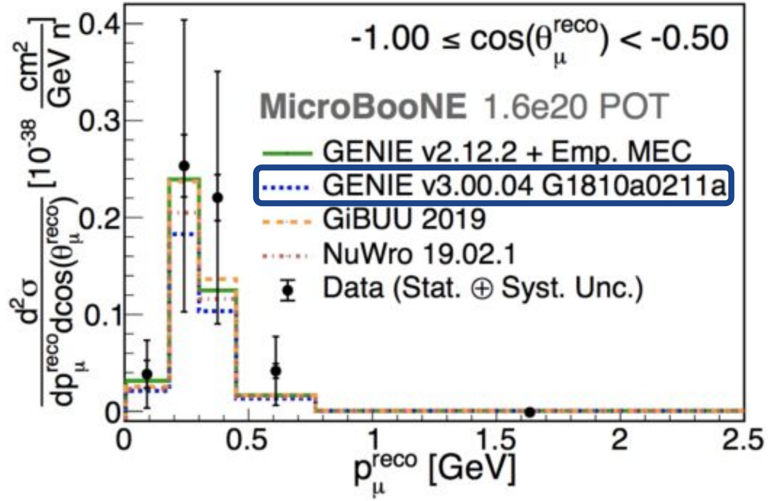
Fermilab

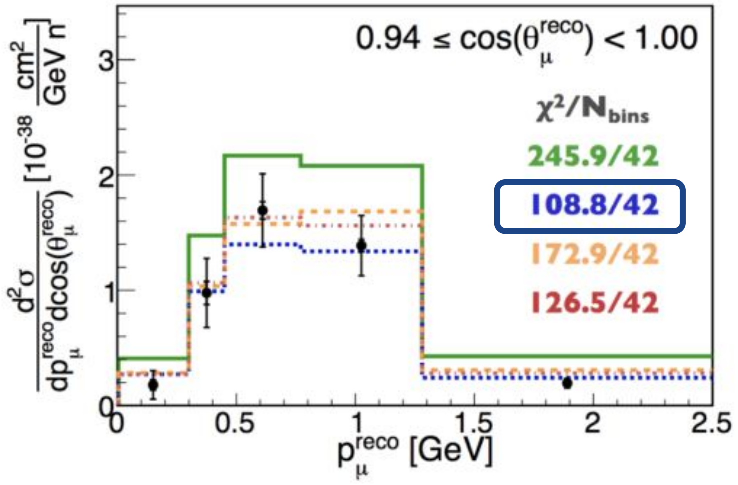
ν_μ CC Inclusive @ BNB

In single detector measurements, muon neutrinos are used to constrain uncertainties on electron neutrinos flux and interaction model.

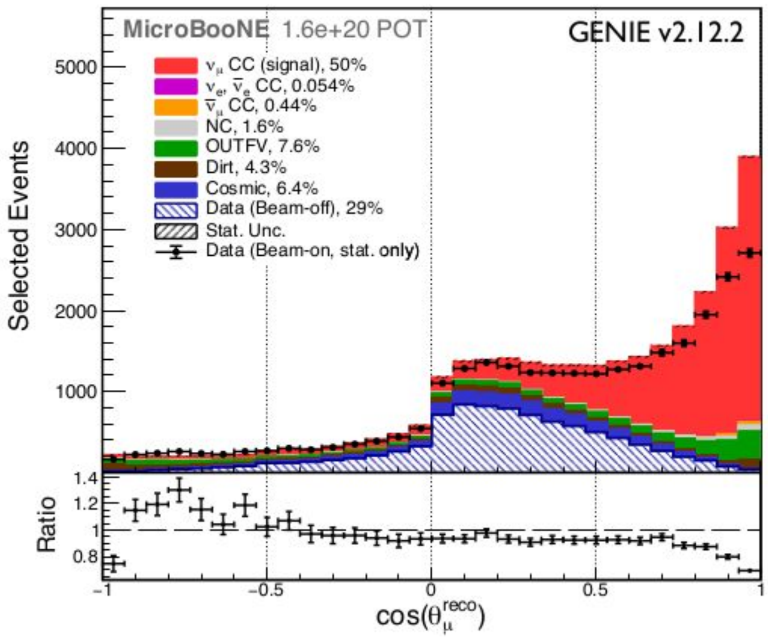
First double differential measurement on Argon
→ Overall good agreement with theory (Phys. Rev. Lett. 123, 131801 (2019)).
More recent models achieve better agreement at forward scattering angles.
Forward folding cross section extraction technique.





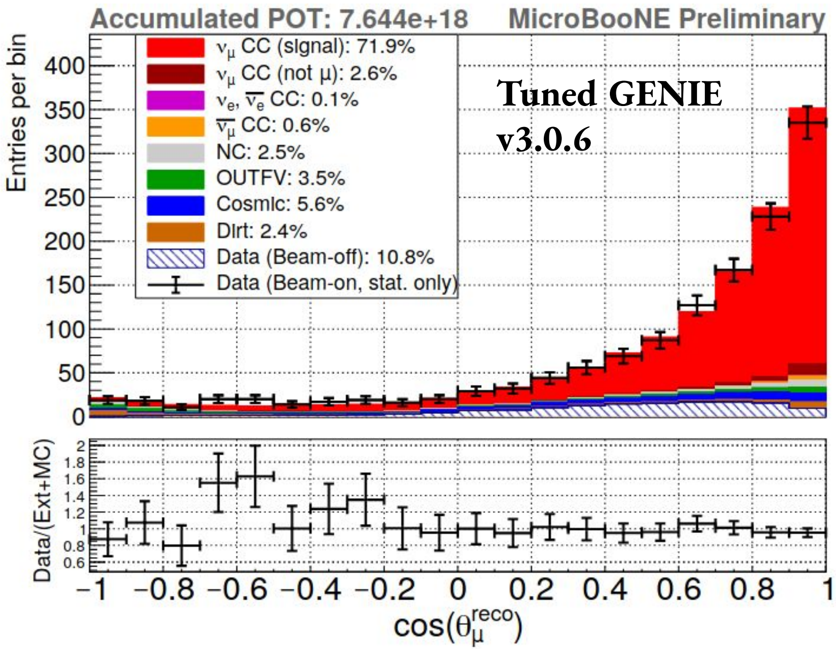


ν_μ CC Inclusive @ BNB: a Sneak Peek at Next Gen Analyses



Previously published measurement

Phys. Rev. Lett. 123, 131801 (2019)



Update measurement

MICROBOONE-NOTE-1069-PUB

ν_μ CC Inclusive @ BNB: a Sneak Peek at Next Gen Analyses

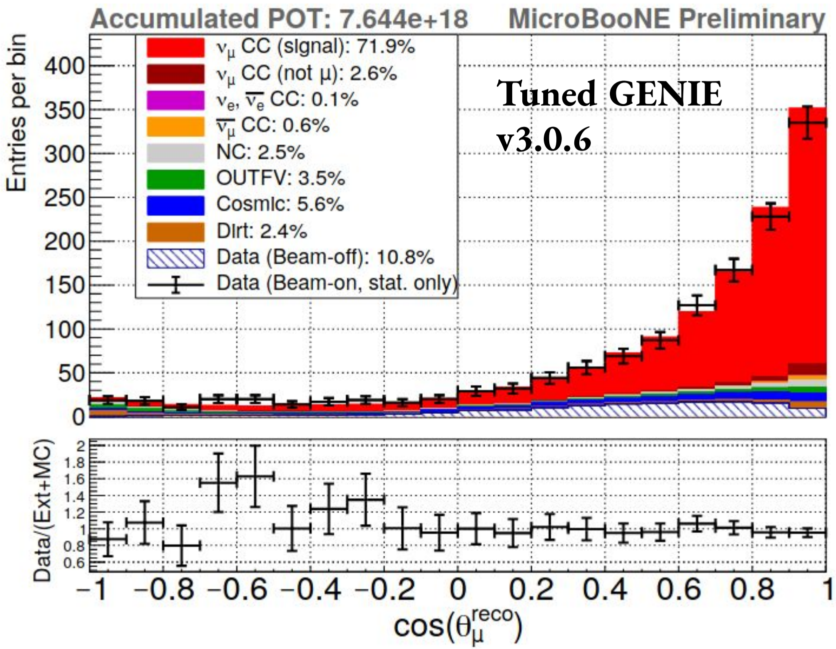
Updates included:

Better detector understanding:
signal processing from all planes & improved calorimetry
JINST 13, P07006 (2018), JINST 13, P07007 (2018)

Reduced systematic uncertainties via a data driven method for detector systematics and cosmics modelling
MICROBOONE-NOTE-1075-PUB

Improved neutrino interaction model
→ See Steven's talk

Use of the Cosmic Ray Tagger



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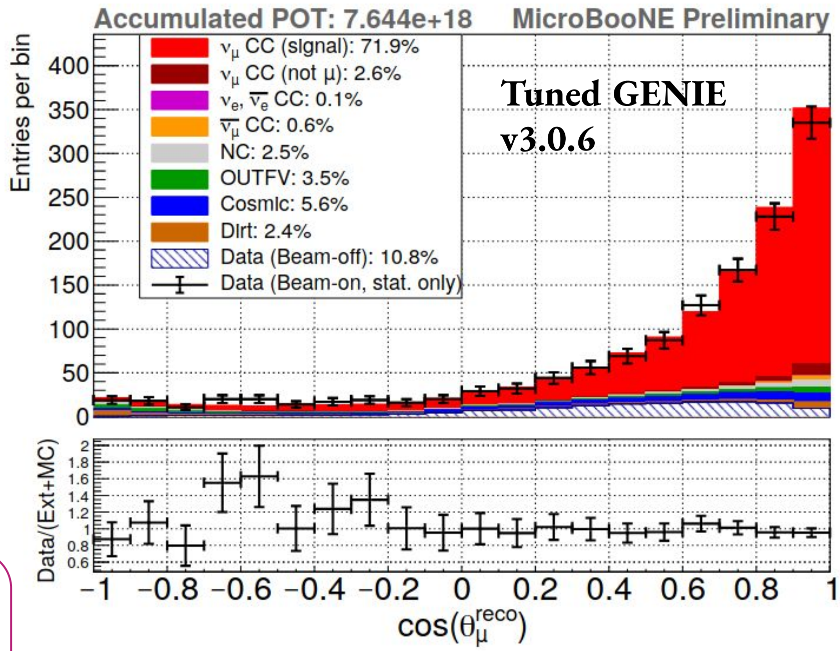
Improved neutrino interaction model

Results:
→ Purity: from 50% to 71.9%
→ 3x Reduction of cosmic contamination
→ Detector uncertainties from 16.2% to 3.3 %



Update measurement
MICROBOONE-NOTE-1069-PUB

Energy dependent ν_μ CC Inclusive @ BNB

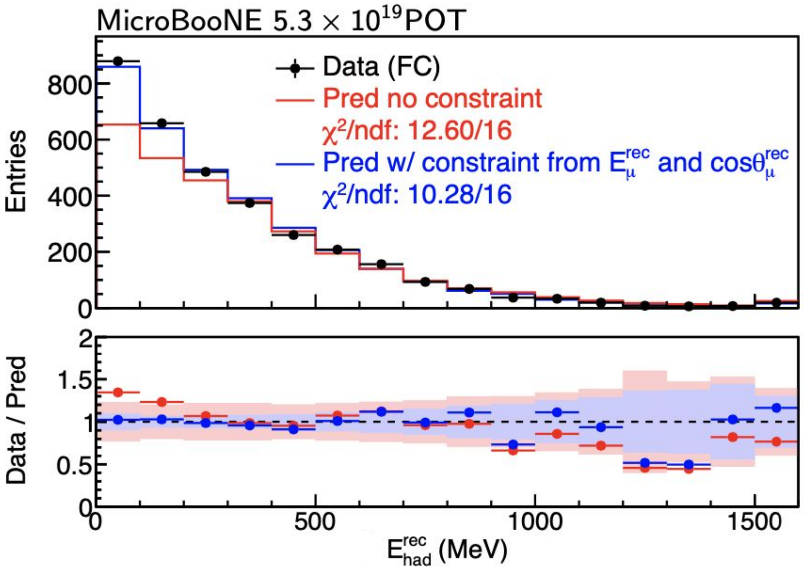
NuFact Premiere!

New energy-dependent measurement of inclusive ν_μ CC interactions: total and differential in muon energy and energy transfer

Biggest sample of selected ν_μ CC interactions on Argon to date: 11528 events.

Improved Purity ~92% & Efficiency ~68% thanks to new tomographic event reconstruction paradigm.

JINST 16, P06043 (2021)



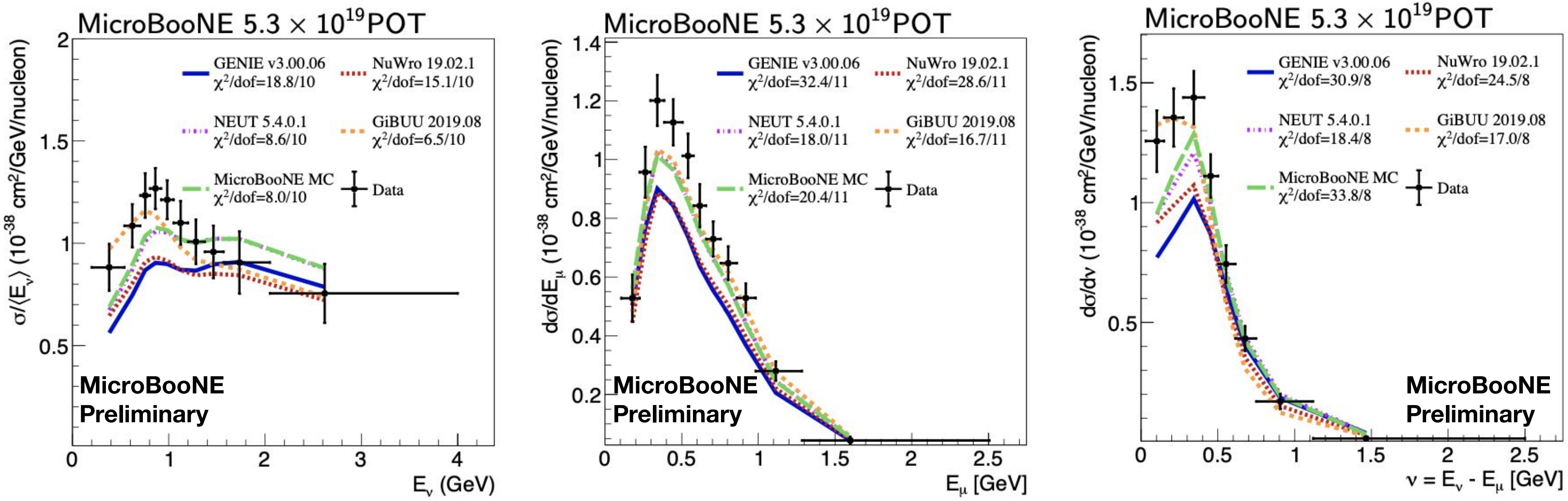
The analysis uses the subset of the data where the muon is fully contained to characterize the muon kinematics and constrain the prediction for missing hadronic energy.

More at CC Inclusive

Energy dependent ν_μ CC Inclusive @ BNB

NuFact Premiere!

Extracted cross section with Wiener SVD spearheaded for this measurement 2017 *JINST* 12 P10002.
The central predictions of GENIE v3 and NuWro are slightly disfavored compared to the other three predictions.



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Energy dependent ν_μ CC Inclusive @ BNB

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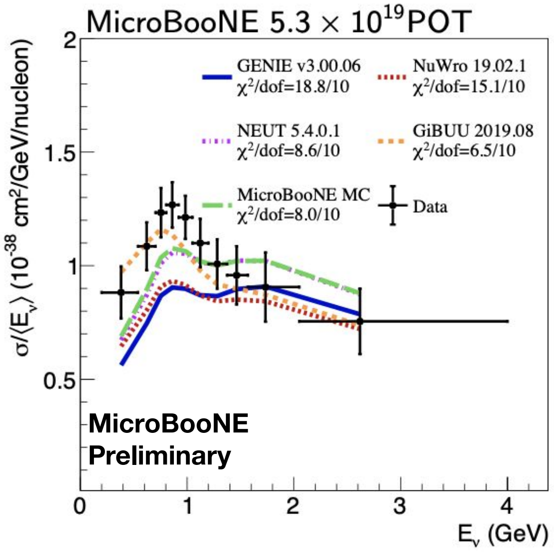
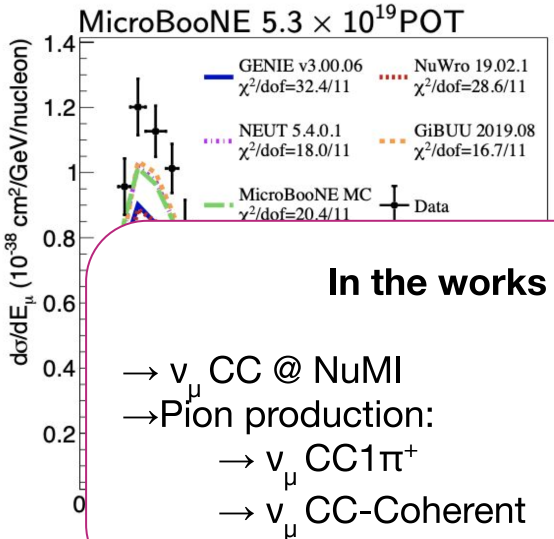
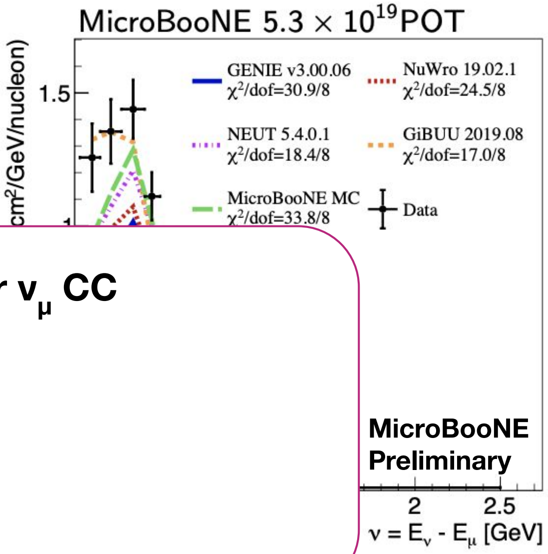


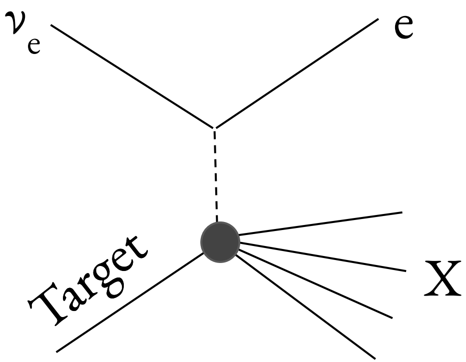


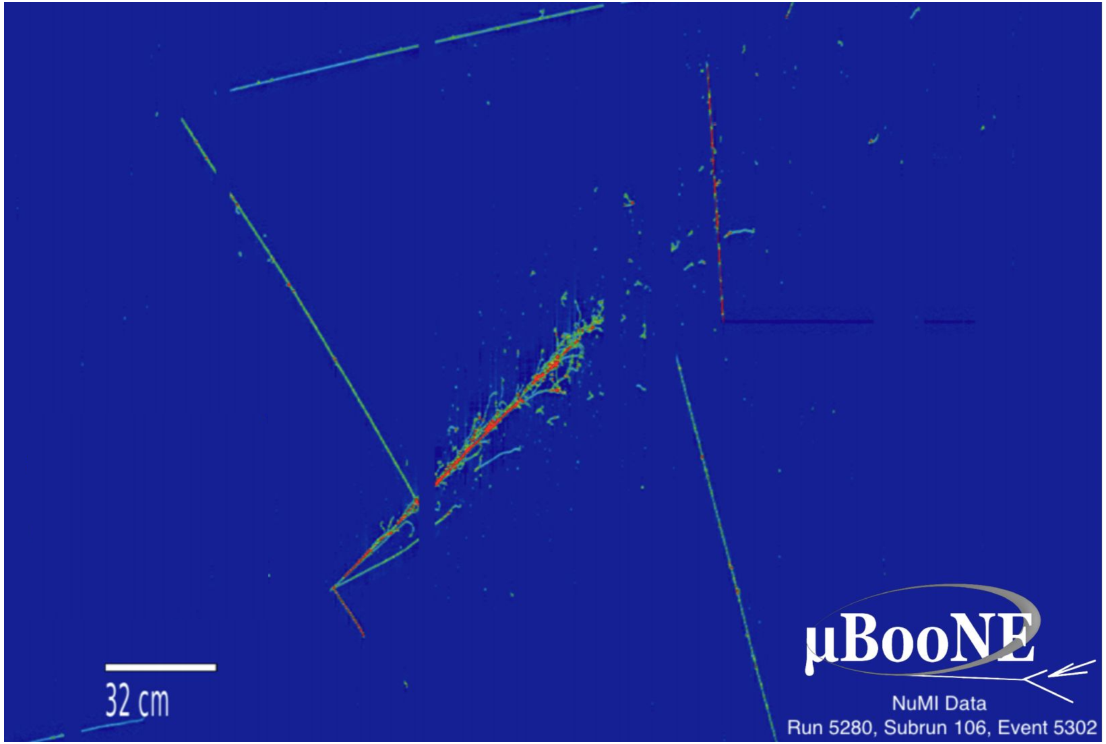


In the works for ν_μ CC

→ ν_μ CC @ NuMI
→ Pion production:
  → ν_μ CC1π^+
  → ν_μ CC-Coherent

$\nu_e + \bar{\nu}_e$ CC Inclusive @ NuMI

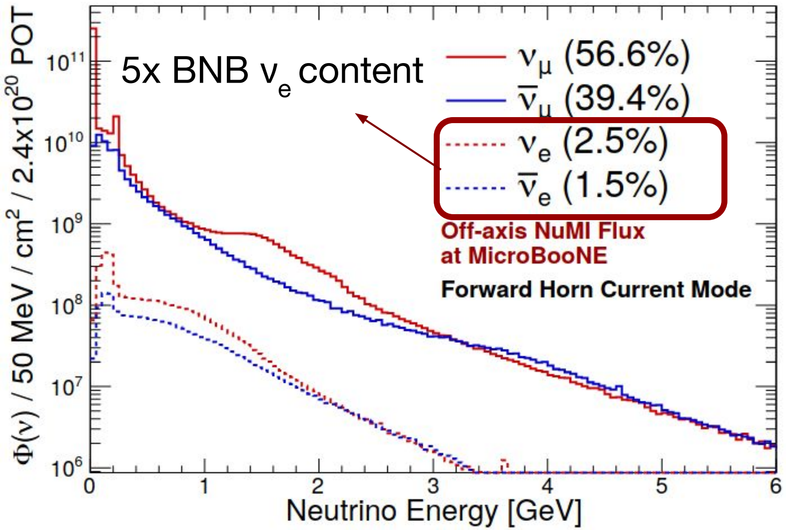




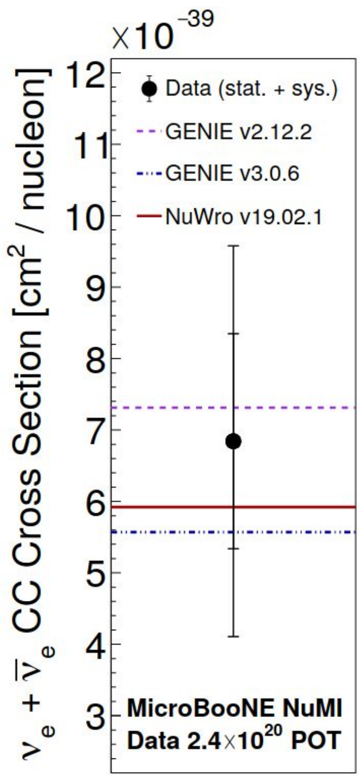
$\nu_e + \bar{\nu}_e$ CC Inclusive @ NuMI

Flux averaged total cross section. 214 selected events
Selection main requirement: at least one shower compatible with electron hypothesis: Purity ~40%, Efficiency ~10%.

In good agreement with models



Systematic Source	Relative Uncertainty [%]
Interaction	10
Detector Response	23
Beam Flux	22
POT Counting	2
Cosmic Simulation	4
Out-of-Cryostat Simulation	6
Total	34



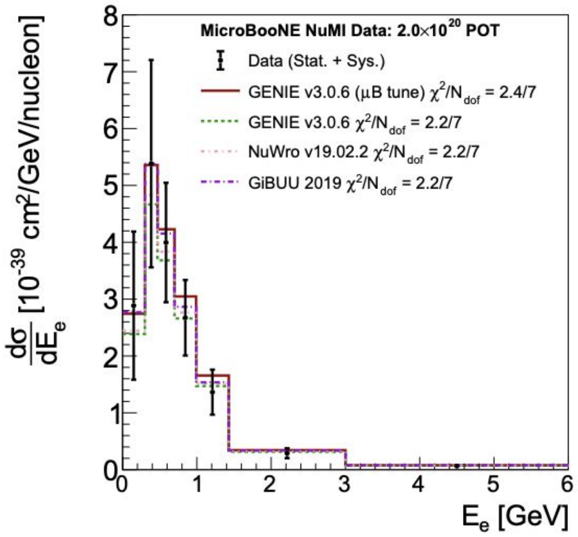
arXiv:2101.04228 (PRD accepted)

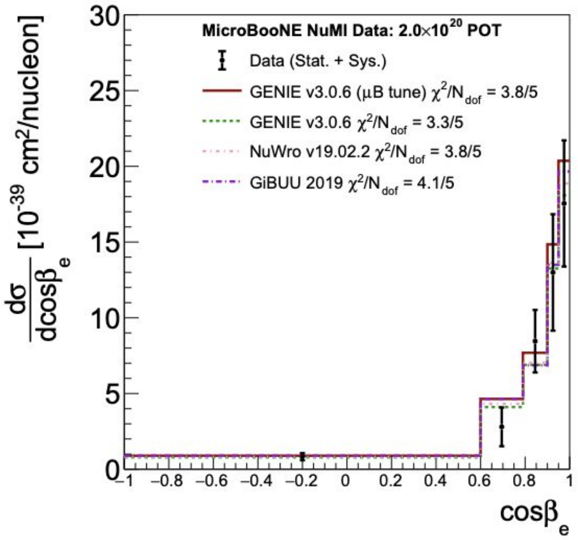
Differential $\nu_e + \bar{\nu}_e$ CC Inclusive @ NuMI

NuFact Premiere!

First Measurement of Inclusive ν_e and $\bar{\nu}_e$ CC differential in Lepton Energy on Argon.

Selection main requirement: at least one shower compatible with electron hypothesis.
Biggest sample of selected ν_e CC interaction on Argon to date: 243 events.
Purity ~70%, Efficiency ~20%. Extracted cross section in good agreement with models.





Total cross section compatible with previous measurement, a factor of 2 reduction in uncertainties

Source of Uncertainty	Relative Uncertainty [%]
Beam Flux	17.4
Detector	6.8
Cross Section	5.8
POT Counting	2.0
Out-of-Cryostat	1.8
Proton/Pion Reinteractions	1.2
Beam-off Normalization	0.1
Total Systematic Uncertainty	19.8
MC Statistics	0.8
Data Statistics	10.0
Total Uncertainty	22.2

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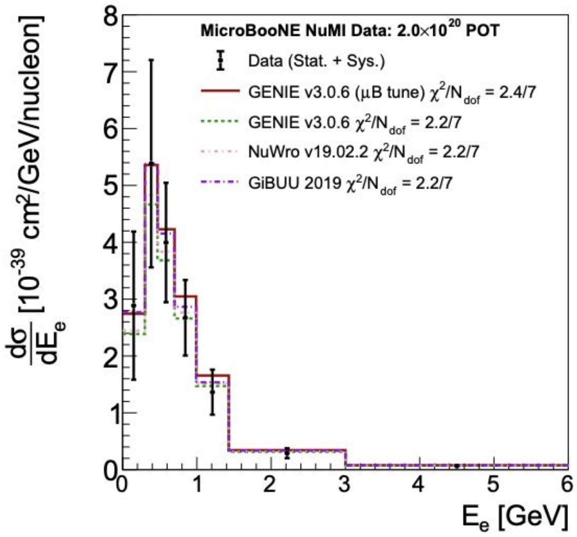

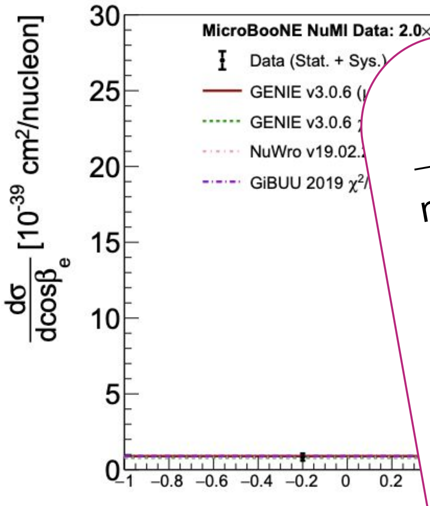

In the works from NuMI ν_e:

→ ν_e CC inclusive differential in neutrino energy

→ ν_e CC 1eNp exclusive

→ ν_e/ν_μ ratios

→ Anti ν_e inclusive

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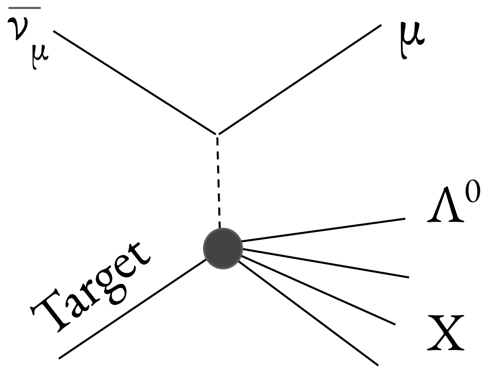
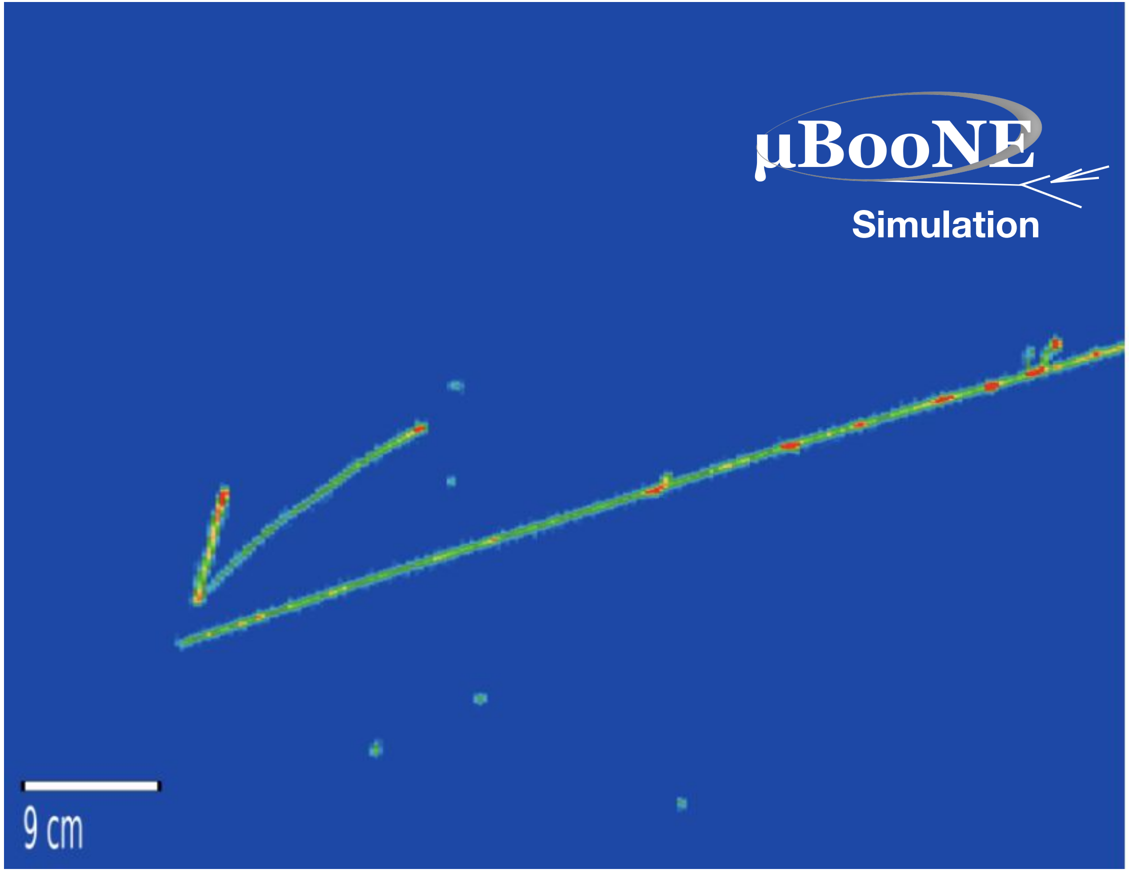
Lambda Production @NuMI





Lambda Production @NuMI

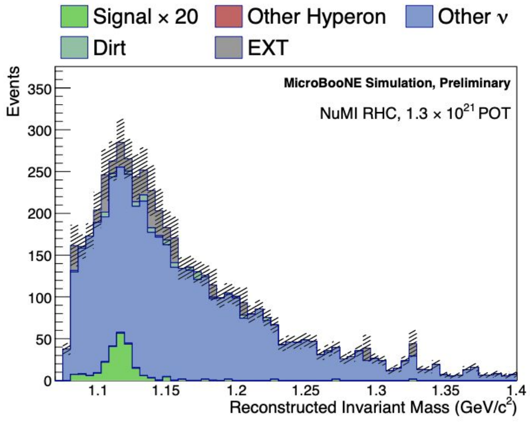
NuFact Premiere!

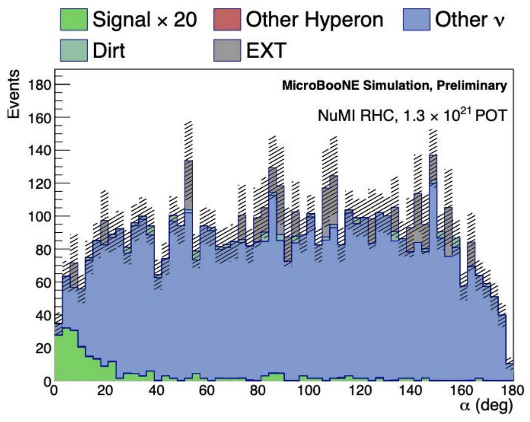
Production of baryons containing strange quark → similar to CCQE, different FSI: unique probe of nucleus [arxiv.org:2010.12361].

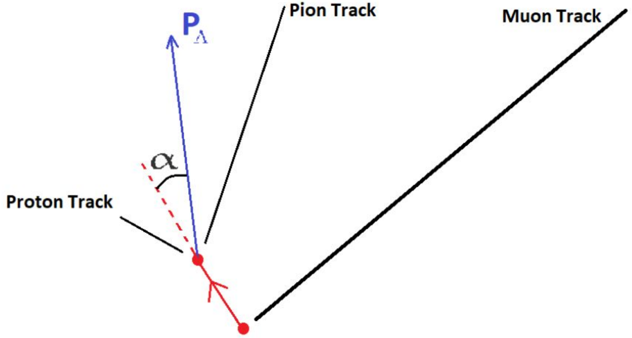
Selection targets Cabibbo suppressed Λ production events with $\Lambda \rightarrow p + \pi^-$ decay (BR 64%), p_p > 300 MeV/c and p_π > 300 MeV/c.

$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \Lambda^0 + X$$

AntiNeutrinos needed! NuMI data is the richest place in MicroBooNE. Still, hard search because of rarity of the process. NuWro will be the gen of choice for this analysis since it employs a dedicate hyperon production







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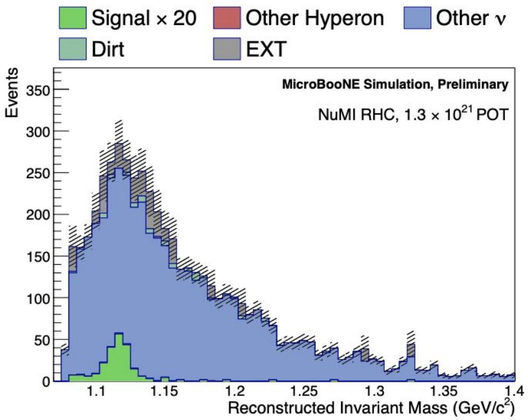

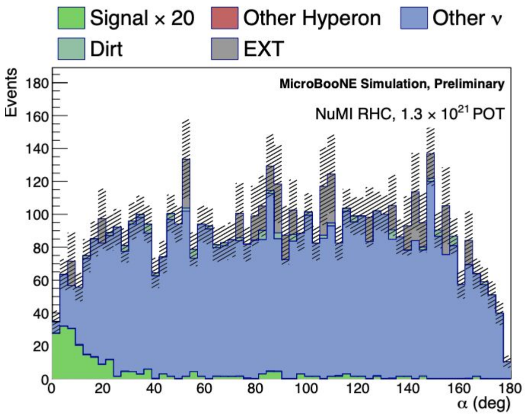

Current Predicted Performance

on full NuMI dataset (5 years) :

Efficiency: 7%, Signal: 9 ± 0.8 (MC stat.)

Background: 3.1 ± 1.4 events

[from initial 6.7 M events]

All details in [3]

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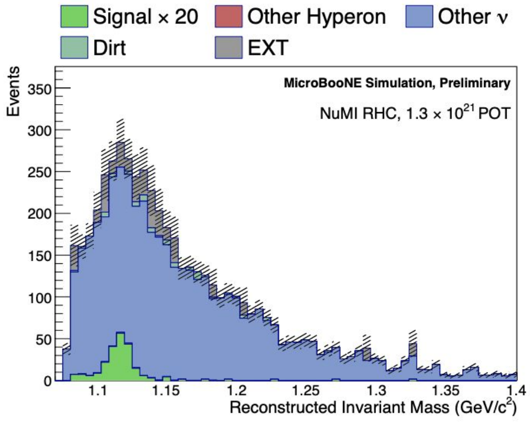
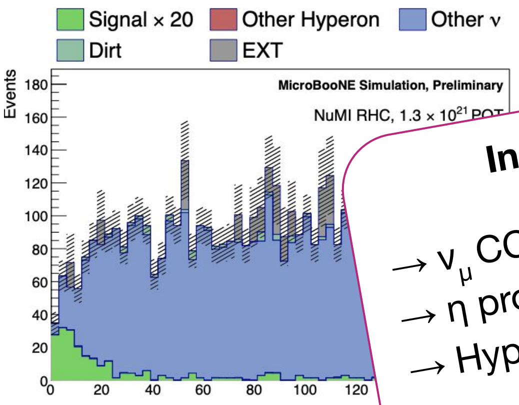
$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \Lambda^0 + X$$

AntiNeutrinos needed! NuMI data is the richest place in MicroBooNE. Still, hard search because of rarity of the process. NuWro will be the gen of choice for this analysis since it employs a dedicate hyperon production





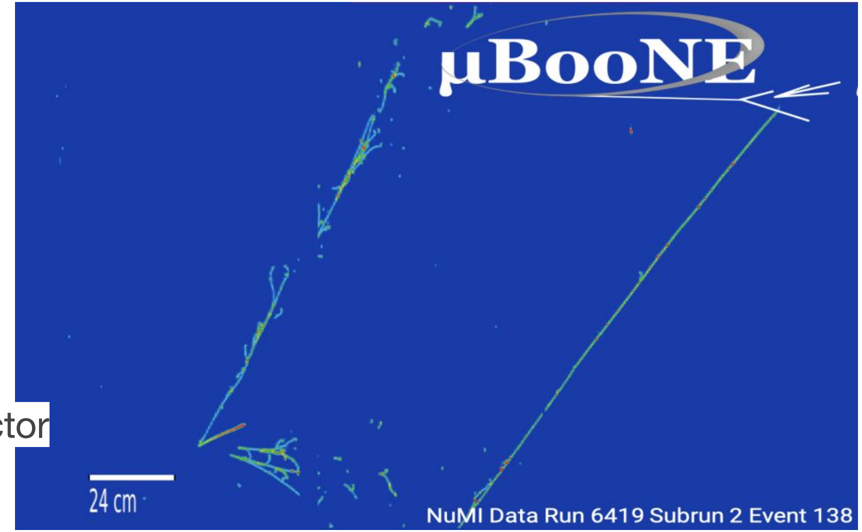
In the works for rare channels:

- → ν_μ CC Kaon @ BNB & NuMI
- → η production
- → Hyperon (Λ,Σ) production @ NuMI

Takeaways

MicroBooNE has collected the **largest sample** of **neutrino-argon** interactions available to date and has **completed our first era of cross section analyses:**
→ Stepping stones for many more!

Next-gen wave of results has started (more in next talk!), with **notable improvements** concerning the interaction model employed, the reconstruction paradigms, the detector simulation and modeling of the cosmics.



Measuring neutrino cross sections on argon with high precision **opens a new window in the exploration of the nucleus** and it is **foundational for BSM work** in LArTPCs: we are setting solid basis for **a series of first results** on the MiniBooNE low energy excess (coming soon).

Exciting times ahead!!! Stay tuned!

Backup

Wiener SVD in a nutshell

The Wiener-SVD **unfolding** technique corrects a measured differential event rate for inefficiency and finite resolution.

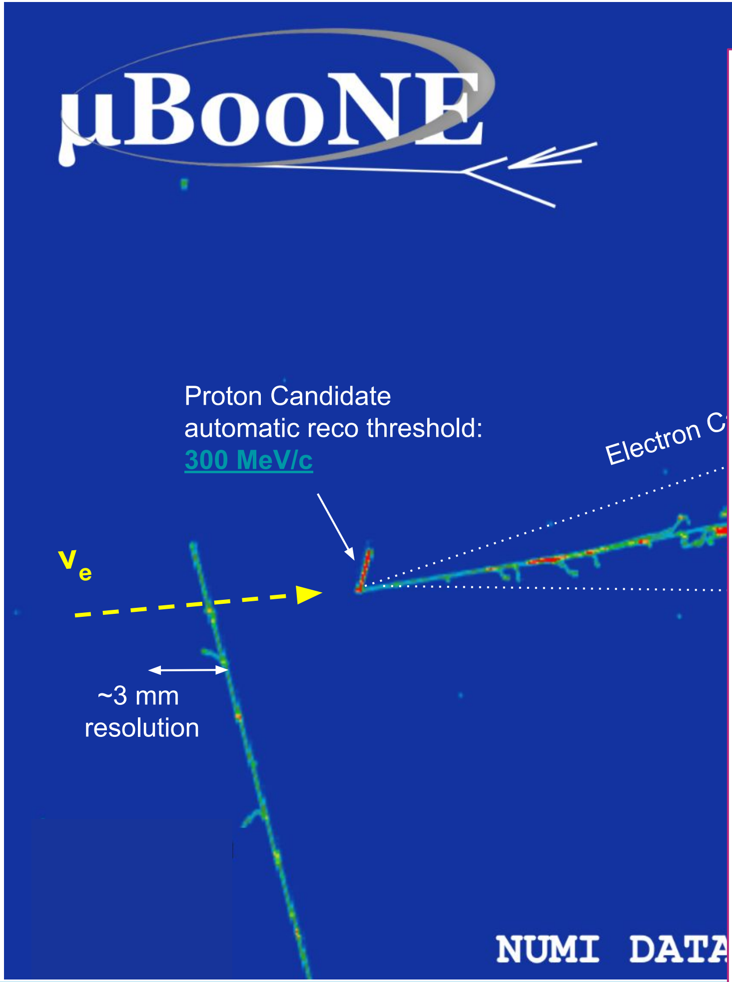
$$\left(\frac{dR}{dx}\right)_i = \frac{N_i - B_i}{T \times \Phi \times \Delta x_i},$$

The correction is performed by minimizing a X^2 score comparing data to a prediction and includes a regularization term. The regularization is determined from a Wiener filter by **minimizing** the mean square error between the **variance** and **bias** of the result.

In addition to the measured event rate, the inputs to the method are a **covariance matrix** calculated from simulation (which approximately describes the statistical and systematic uncertainties on the measurement), and a **response matrix** that describes the detector smearing and efficiency.

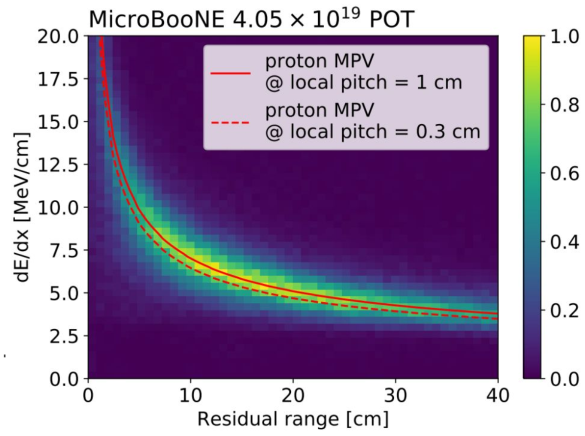
Treat all uncertainties using a multivariate normal distribution. Unfolded result is a linear transformation of the measurement. Simple recipes for assessing uncertainties & bias

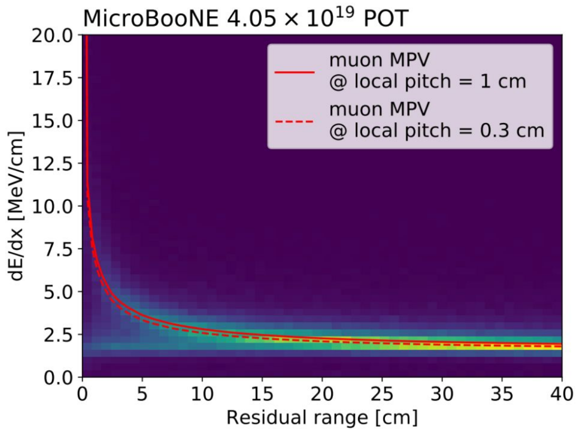
The Wiener-SVD method produces an *unfolded* cross section in true kinematics, a covariance matrix describing the total uncertainty on this cross section, and an additional smearing matrix, A_c, which contains information about the regularization and bias of the measurement. The matrix A_c is applied to a true cross section prediction when comparing to the unfolded data.



Particle ID: p/µ

Pioneering new techniques
muon/proton separation
based on established
methodology in the field
arXiv:2109.02460





Exploring the MiniBooNE LEE

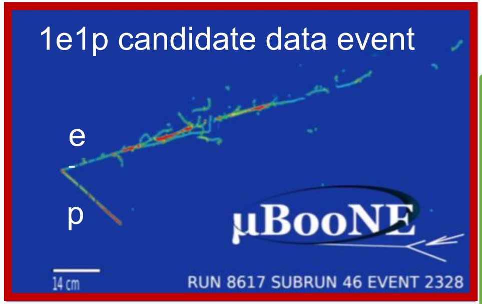
ν_e analyses:

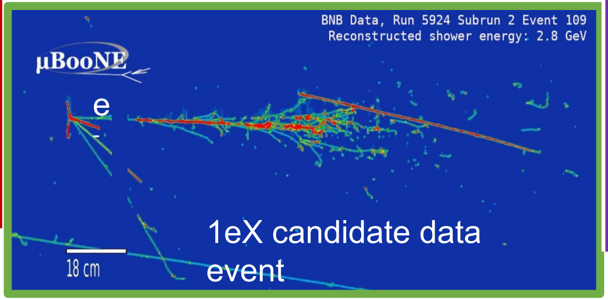
→ MiniBooNE-like final state (Pandora, 1eNp, 1e0p)
→ restricting to quasi-elastic kinematics (Deep Learning , 1e1p)
→ all ν_e final states (Wire-Cell, 1eX)

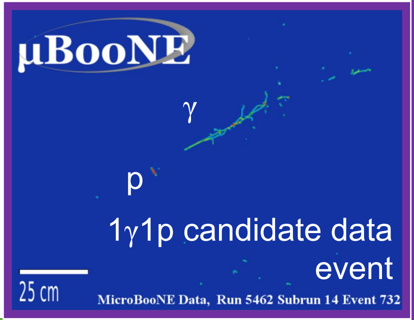
single photon analysis:

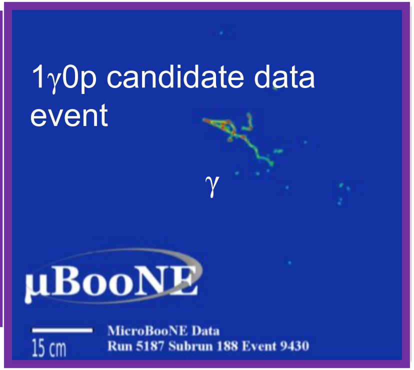
→ targeting Delta radiative decay hypothesis
(Pandora, $1\gamma1p$, $1\gamma0p$)

3 reconstruction paradigms, 6 complementary channels

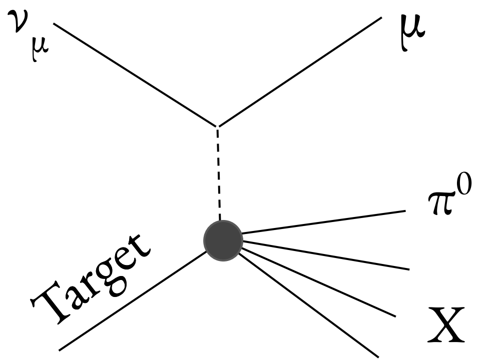


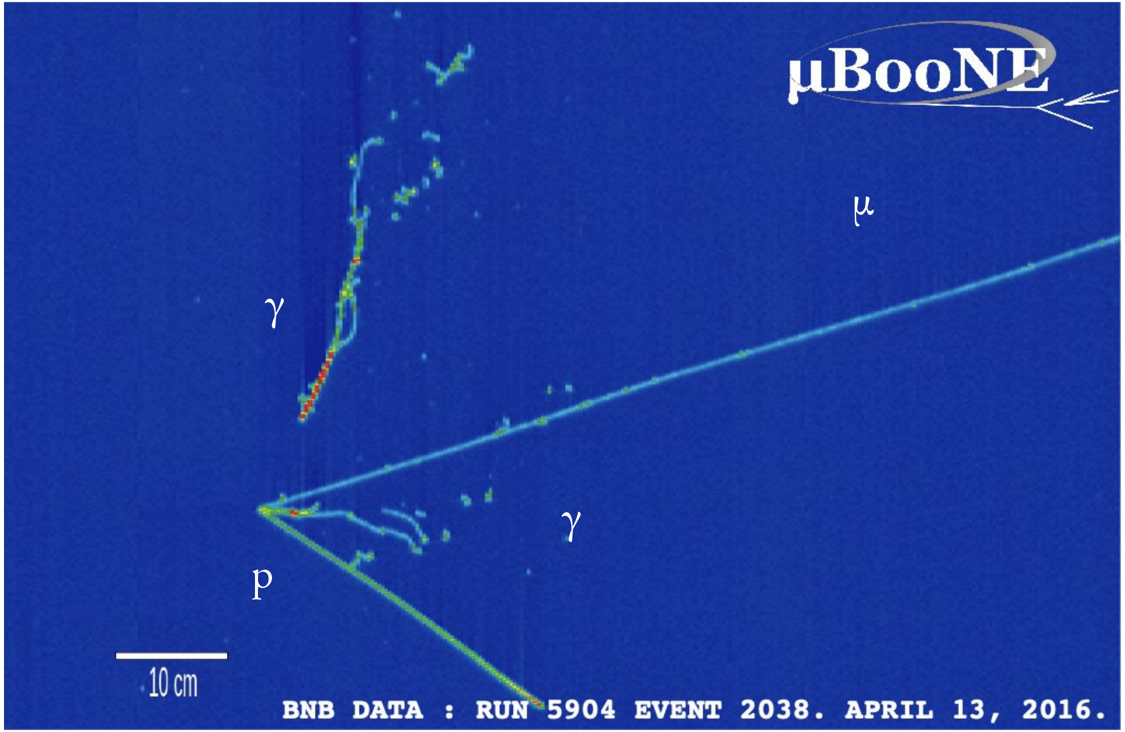






Production of neutral pions





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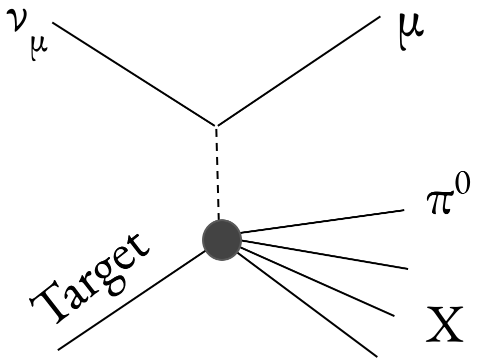
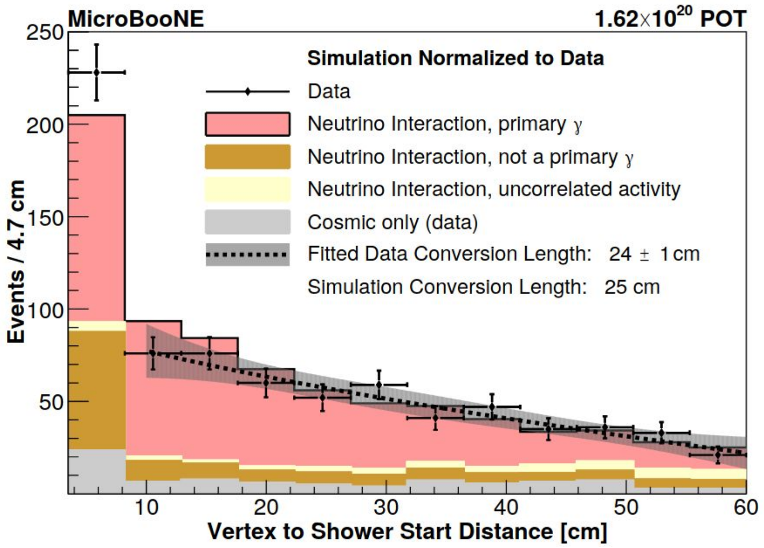
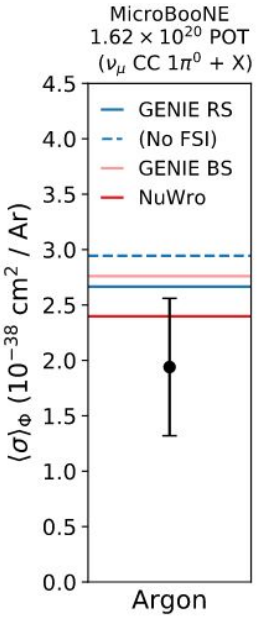
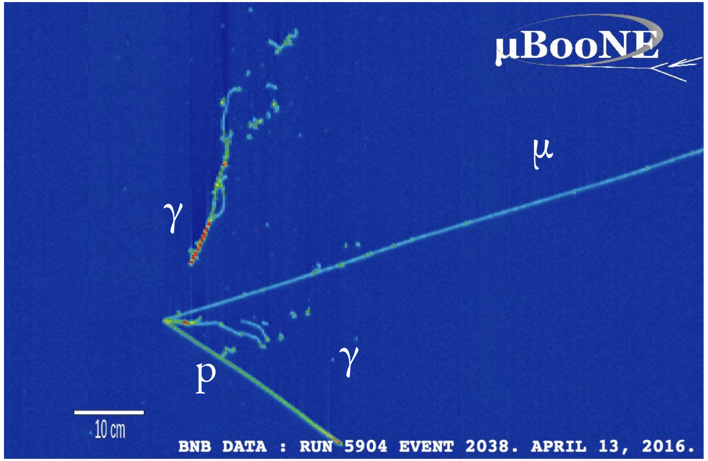


Fundamental background to the LEE search
First measurement of flux averaged ν_μ-Ar CCπ^0 cross section
Phys. Rev. D99, 091102(R) (2019)



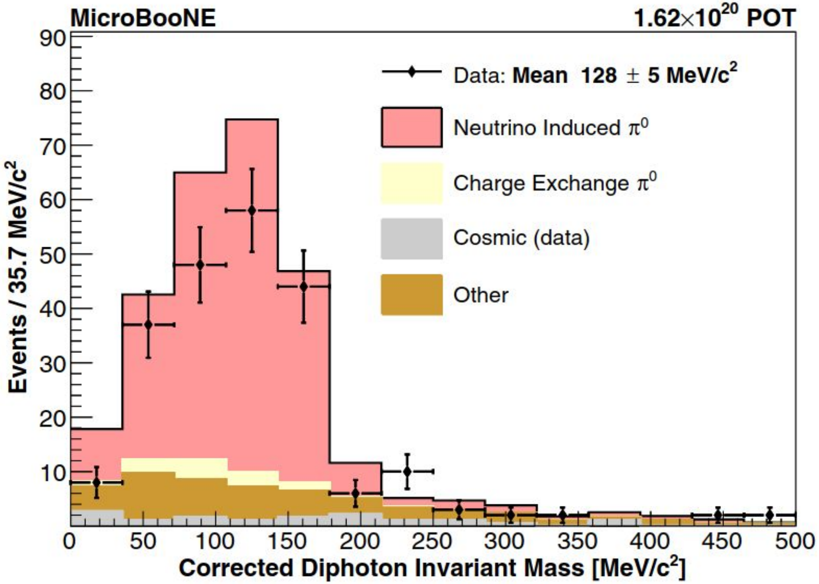




Fermilab

More on Neutral Pions: updates!

With the update described, more analyses studying neutral pions will be released soon.



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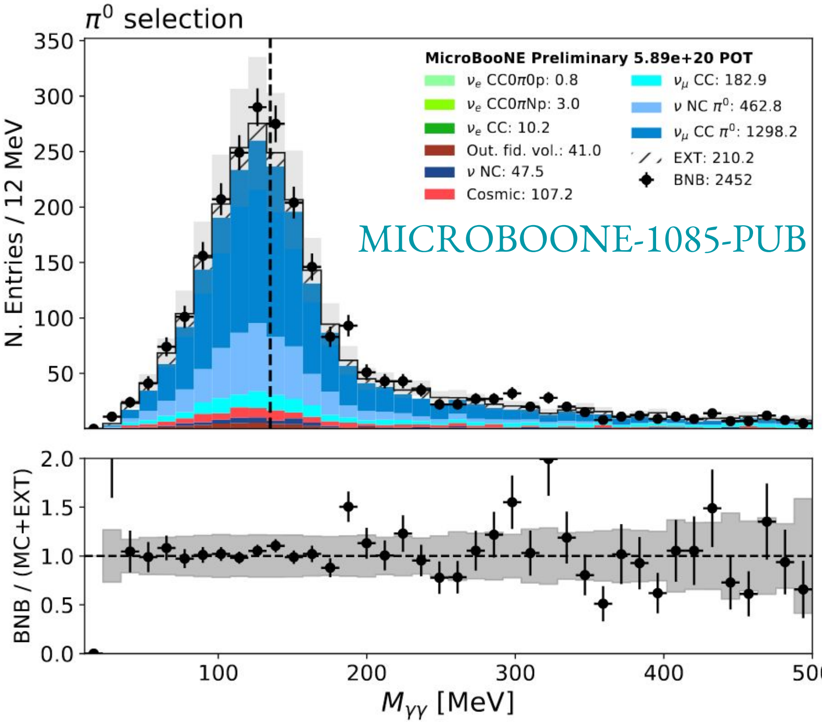

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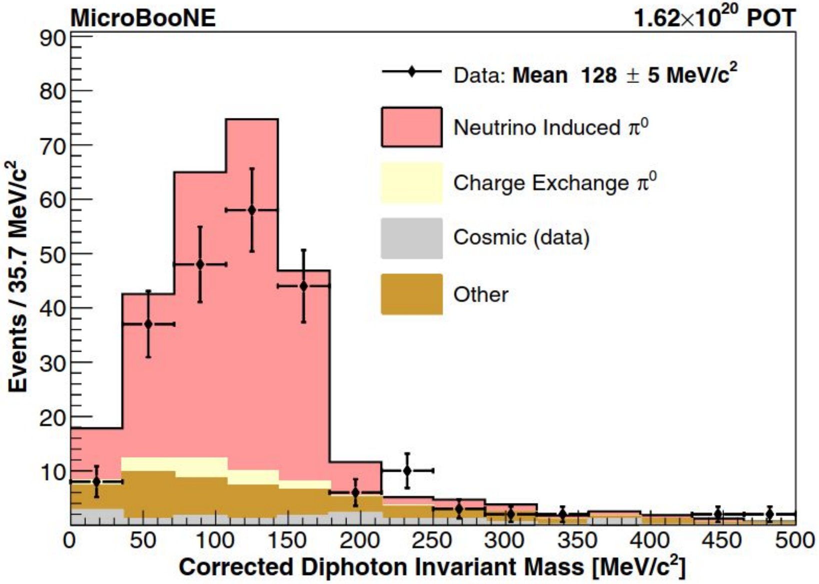

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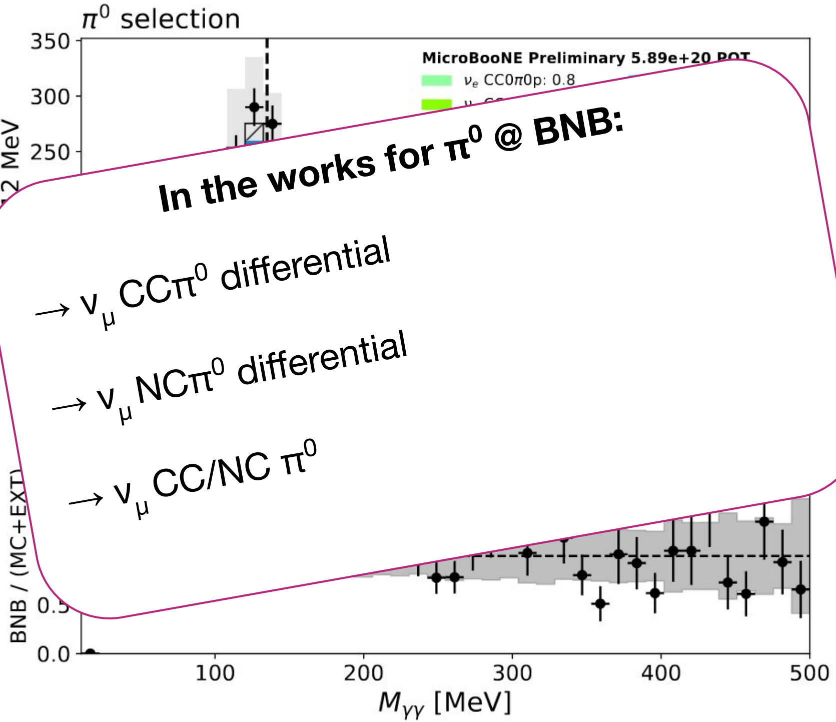

In the works for π^0 @ BNB:

→ ν_μ CCπ^0 differential

→ ν_μ NCπ^0 differential

→ ν_μ CC/NC π^0

Fermilab