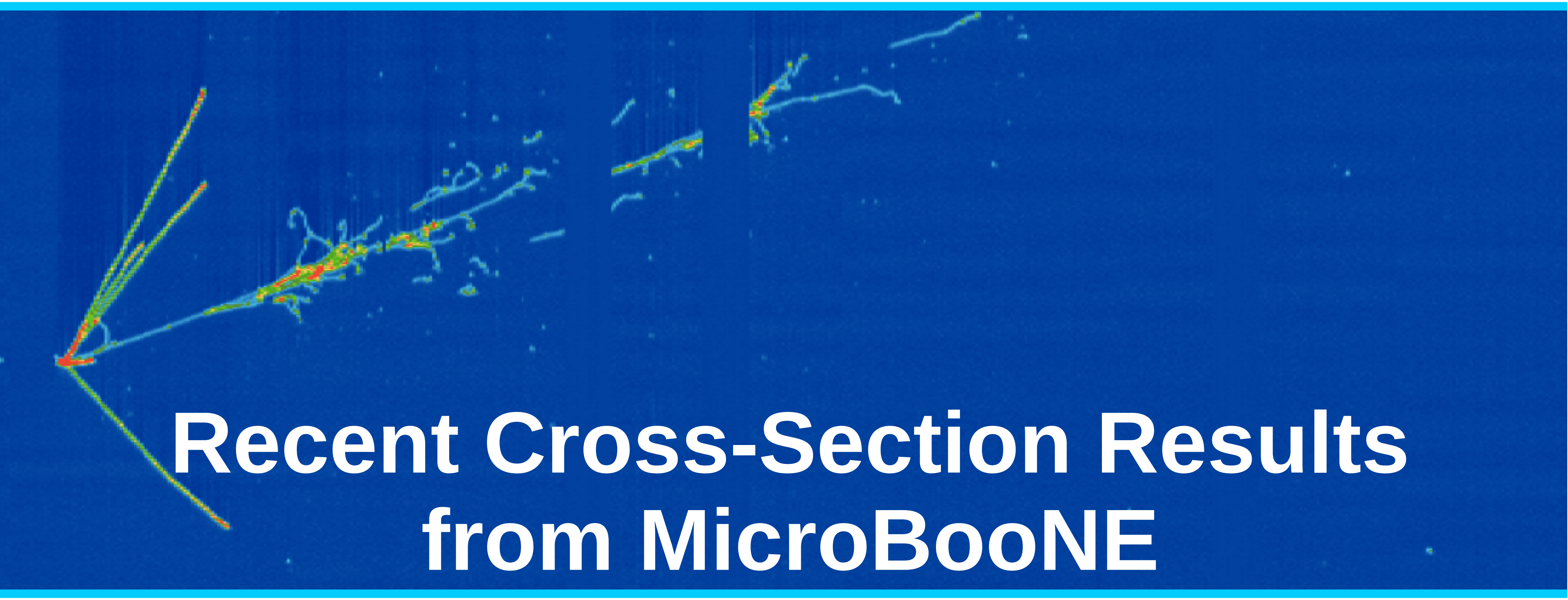


Recent Cross-Section Results from MicroBooNE

Pip Hamilton
on behalf of the MicroBooNE collaboration

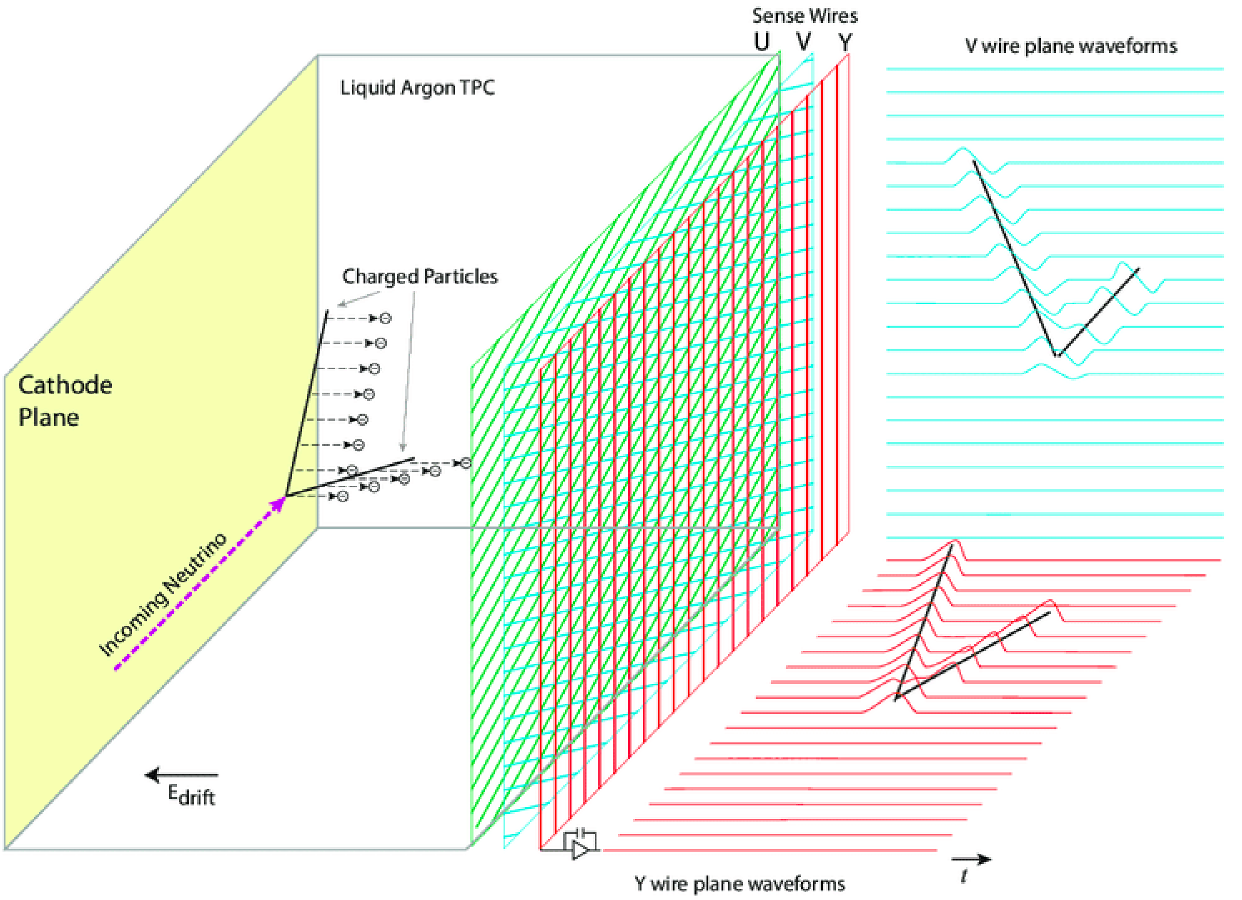
Overview

- **Neutrino Cross-Sections in LArTPCs**
- **The MicroBooNE Experiment**
- **MicroBooNE Cross-Section Results**
  - Charged Current Inclusive Cross-Section
  - Charged Current π^0 Cross-Section
  - Charged Particle Multiplicity Measurement
  - Charged Current N-Proton Kinematic Measurements
  - NuMI ν_e Charged Current Selection
- **Conclusions**

Neutrino Cross-Sections in LArTPCs

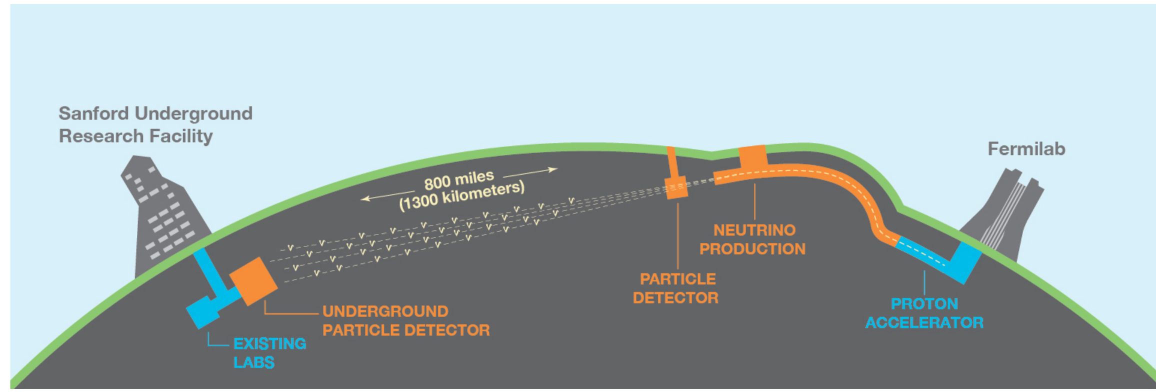
What is a LArTPC?

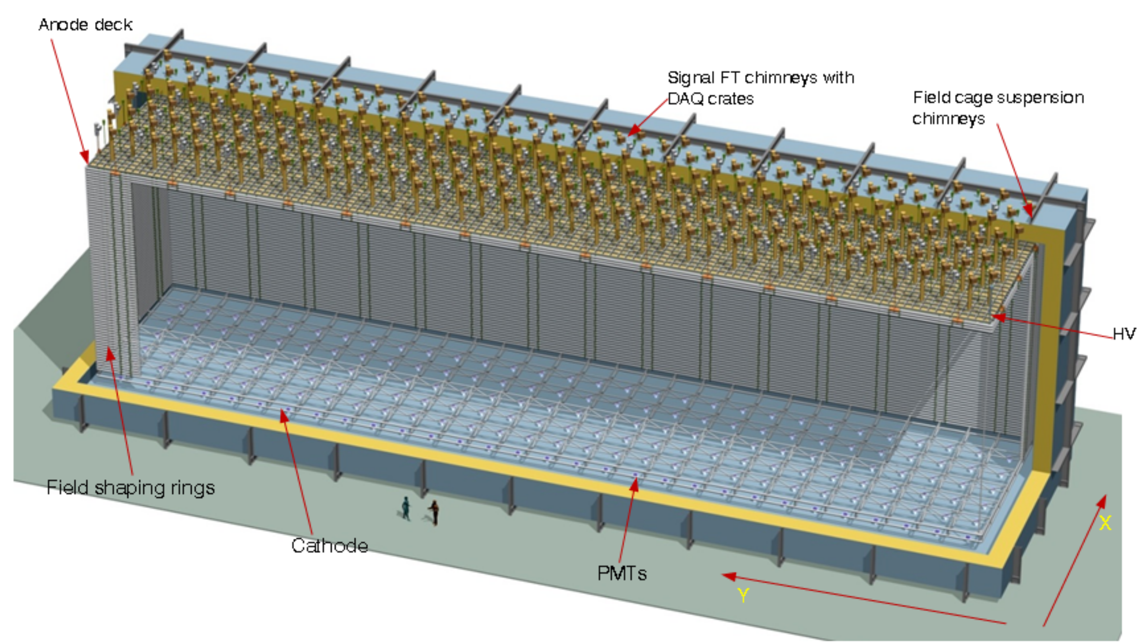
- **Liquid Argon Time Projection Chamber**
- Volume of liquid argon held under a uniform electric field.
- Charged particles produced by neutrino interactions ionise Ar atoms along their path.
- Electric field drifts ionisation electron to planes of sense wires where they are collected and read out.
- Ar scintillation light gives a timestamp for the interaction, allowing reconstruction in 3D.



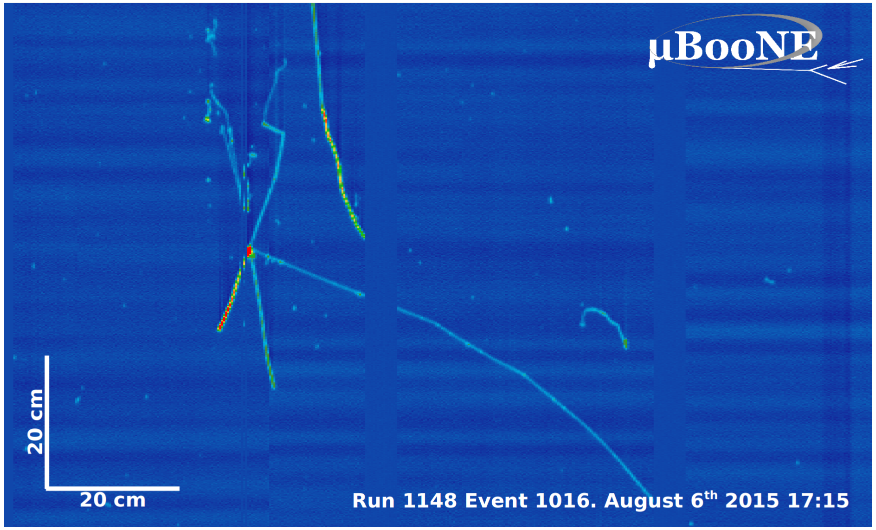
Past, Present & Future LArTPCs

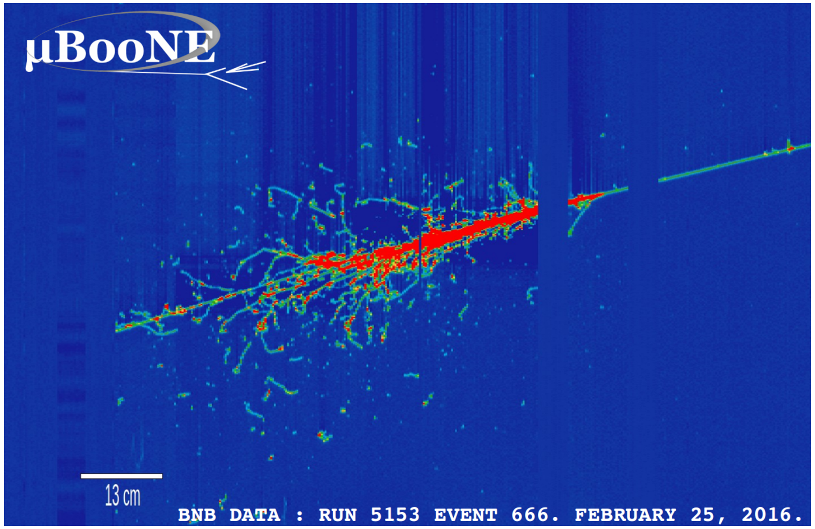
- **Past:** ICARUS, ArgoNeuT
- **Present:** MicroBooNE, ProtoDUNE
- **Future:** SBN, DUNE



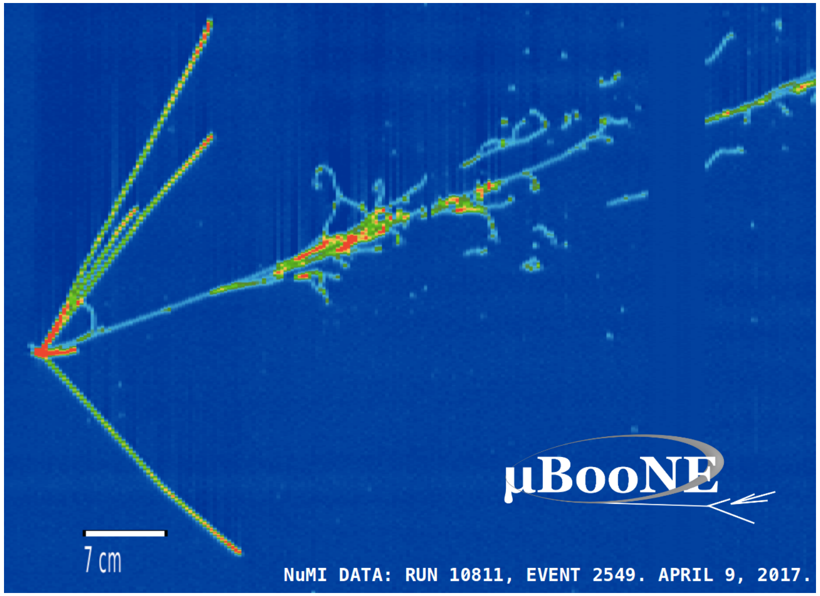


LArTPC Advantages





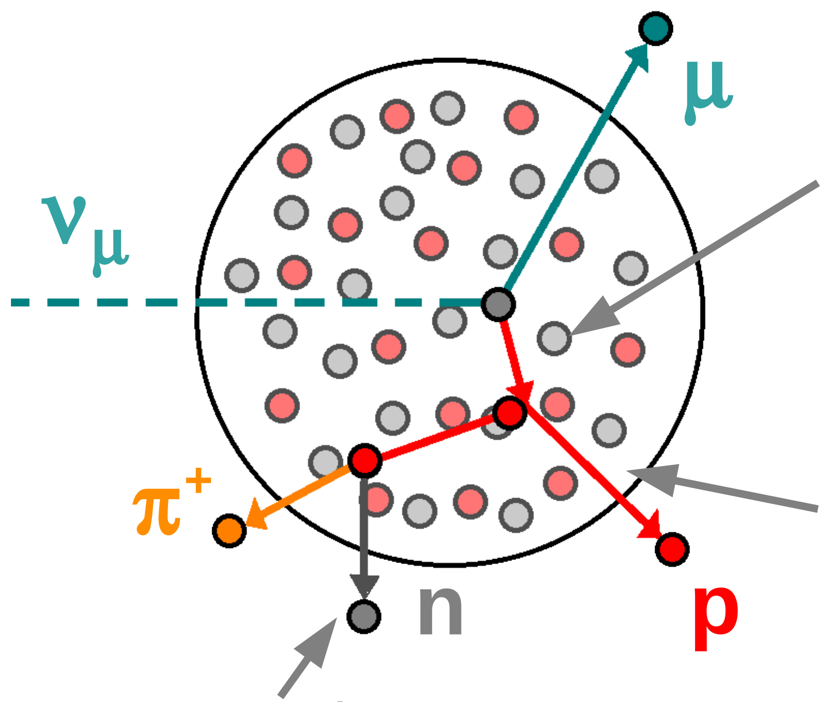
- Millimetre-scale resolution.
- Built-in calorimetry from charge deposition.
- Excellent particle identification capabilities.



Neutrino Cross-Sections

To achieve the potential of next-generation oscillation experiments, we must control the systematic uncertainties from our knowledge of neutrino cross-sections.

- Accurately reconstructing the neutrino energy requires a detailed understanding of neutrino-nucleus interactions.
- Comparative lack of data on Ar, which is a large, complex nucleus!



What was the momentum of the target nucleon?

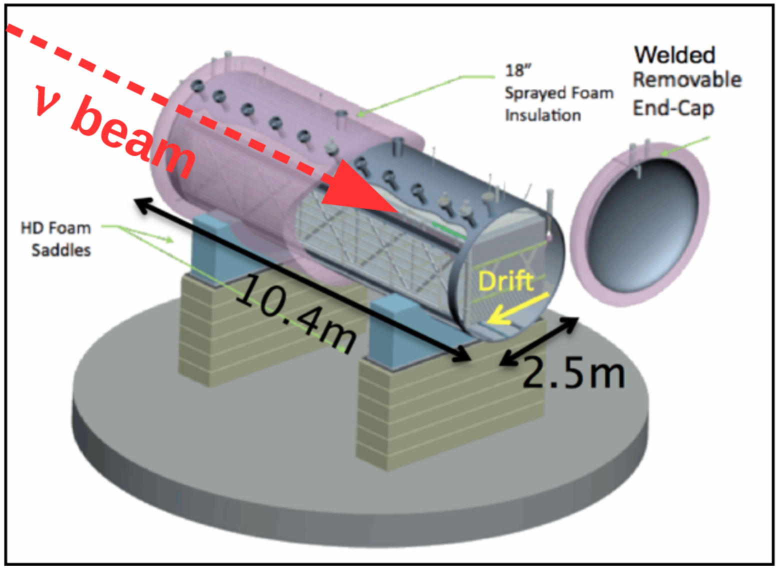
Does Σ *p* at the ν vertex = Σ *p* of the particles escaping the nucleus?

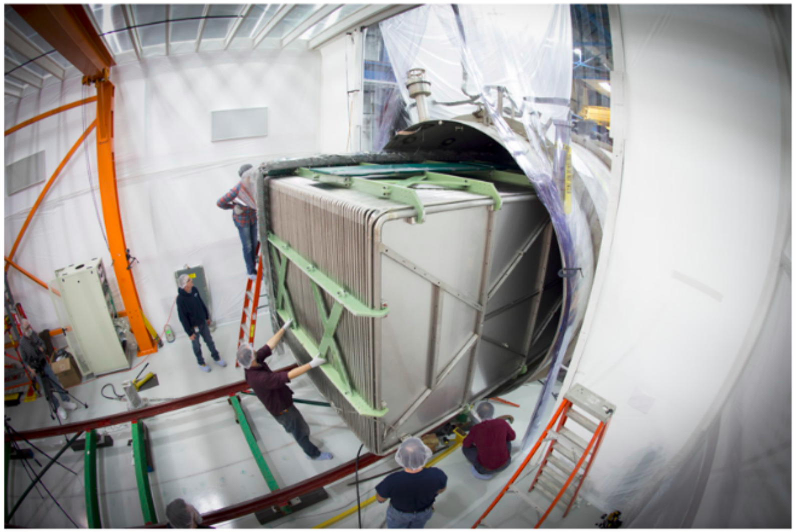
How many neutral particles carry energy away unseen?

- LArTPCs are a detector technology whose time has come.
- Exploiting the advantages of LArTPC imaging, MicroBooNE can measure neutrino cross-sections in fine detail and with high statistics.
- Understanding ν-Ar cross-sections will be necessary for the success of DUNE and the SBN programme as oscillation experiments.

The MicroBooNE Experiment

The MicroBooNE Detector

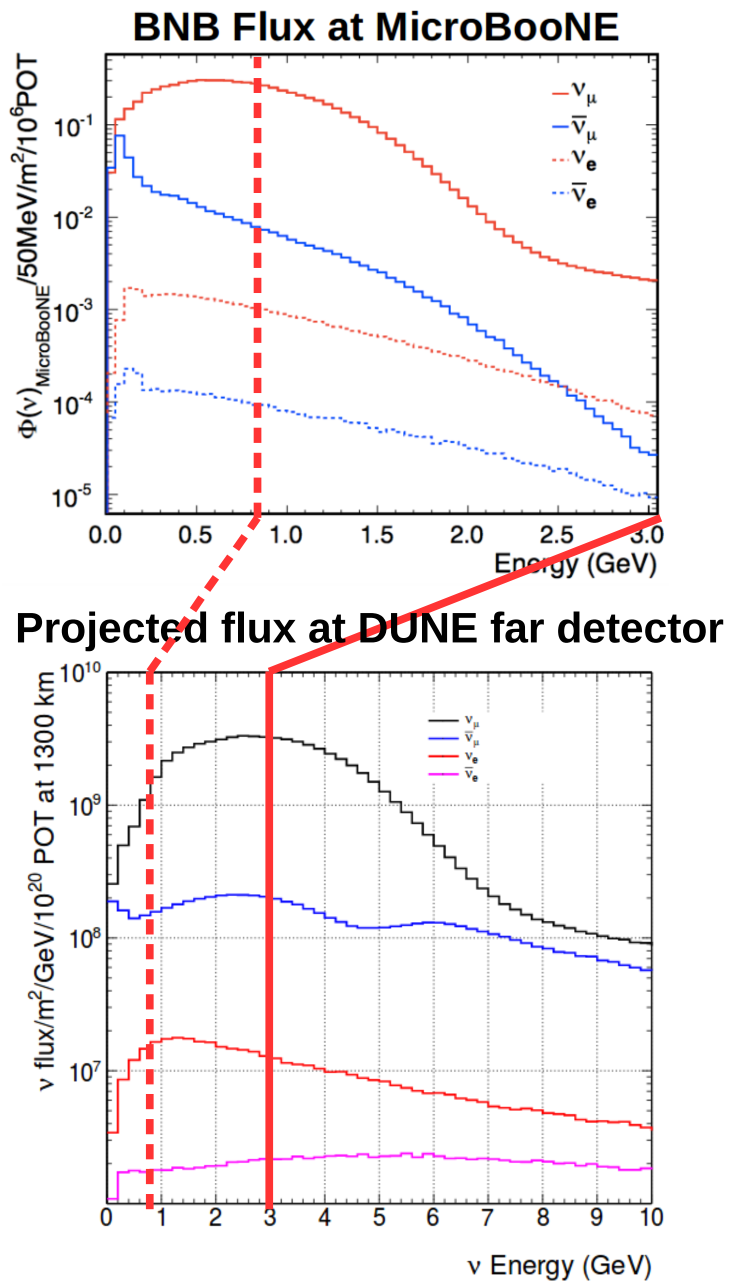




- 170 tons of LAr (active volume 90 tons).
- Over 8,000 wires, spaced 3mm apart.
  - 1 vertical collection plane
  - 2 induction planes at ±60°
- 32 8" PMTs behind wire planes.

The MicroBooNE Beam

- 470m downstream from BNB beam dump.
- Also samples NuMI beam at an off-axis angle of 135 mrad.
- Collecting data since October 2015.
- 1.32×10^{21} POT collected in the BNB to date.



MicroBooNE Cross-Section Results

MicroBooNE Cross-Sections

- **Charged Current Inclusive**

  First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at E_ν~0.8 GeV with the MicroBooNE Detector

  Accepted to PRL, arXiv:1905.09694

- **Charged Current π^0**

  First Measurement of ν_μ Charged-Current π^0 Production on Argon with a LArTPC

  Phys.Rev. D99 (2019) no.9, 091102, arXiv:1811.02700

- **Charged Particle Multiplicity**

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

  Eur. Phys. J. C79 (2019) no.3, 248, arXiv:1805.06887

- **Charged Current N Protons**

  Selection of ν_μ charged–current induced interactions with N>0 protons and performance of events with N=2 protons in the final state in the MicroBooNE detector from the BNB

  MicroBooNE public note 1056

- **NuMI ν_e Selection**

  Automated Selection of Electron Neutrinos from the NuMI beam in the MicroBooNE Detector and Prospects for a Measurement of the Charged-Current Inclusive Cross Section

  MicroBooNE public note 1054

Charged Current Inclusive

Signal definition: ν_μ + Ar → μ + (other particles)

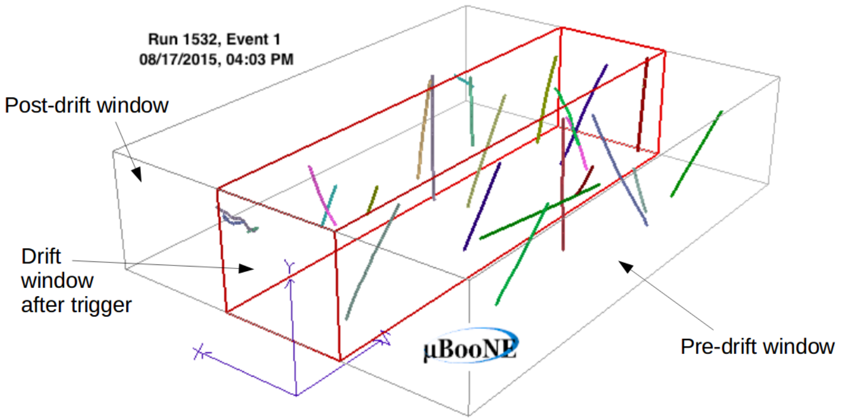
- Simplest and highest-statistics cross-section channel to measure, with a robustly defined final state.
- Global test of neutrino interaction models: sum of all CC channels.
- Proves our understanding of MicroBooNE simulation and reconstruction.
- Direct bearing on ν_μ disappearance for DUNE.

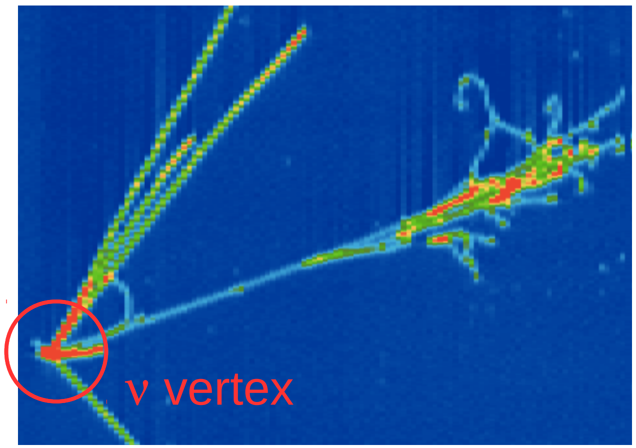
CC Inclusive Selection

Data Sample: 1.6×10^{20} POT

To measure charged-current ν_μ interactions in MicroBooNE, we face 3 main challenges:

- **Cosmic rejection:** MicroBooNE is a surface-level detector, experiences a flux of cosmic muons much higher than the rate of neutrino interactions.
- **Vertex identification:** Busy, detailed images make it non-trivial to distinguish true neutrino interaction point.
- **Energy reconstruction:** Detector is only 2.5m wide ⇒ not all neutrino-induced muons are contained.



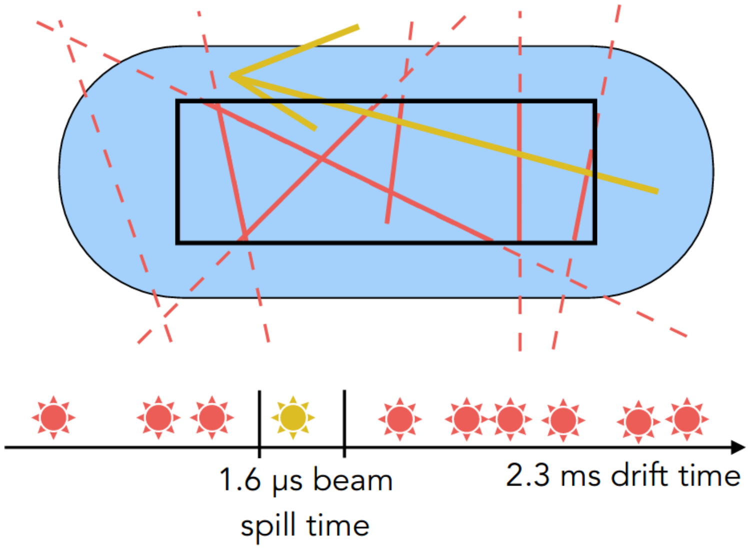


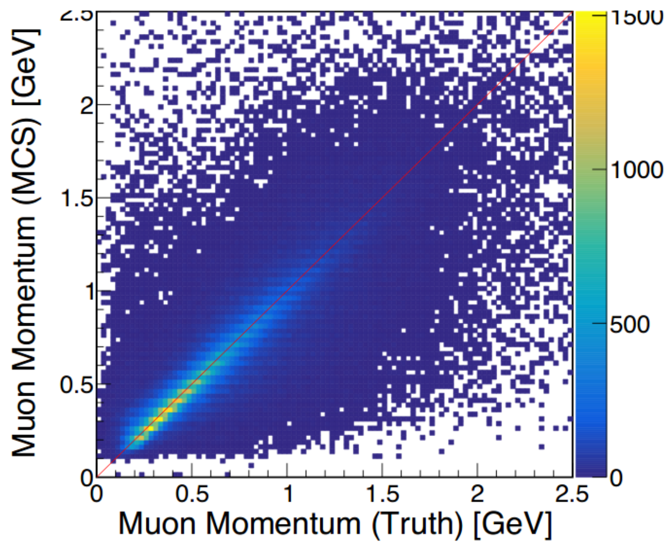
CC Inclusive Selection

- **Cosmic mitigation**
  - Use scintillation light to identify tracks originating in the beam window.
  - Reject through-going muons
  - Reject stopping muons by looking for Michel decay.
- **Vertex identification**
  - Pandora reconstruction software
- **Energy reconstruction**
  - Use multiple Coulomb scattering to assess muon momentum by fitting scattering angle along trajectory.

Using these tools, selection achieves

Efficiency = 57%, **Purity** = 50%

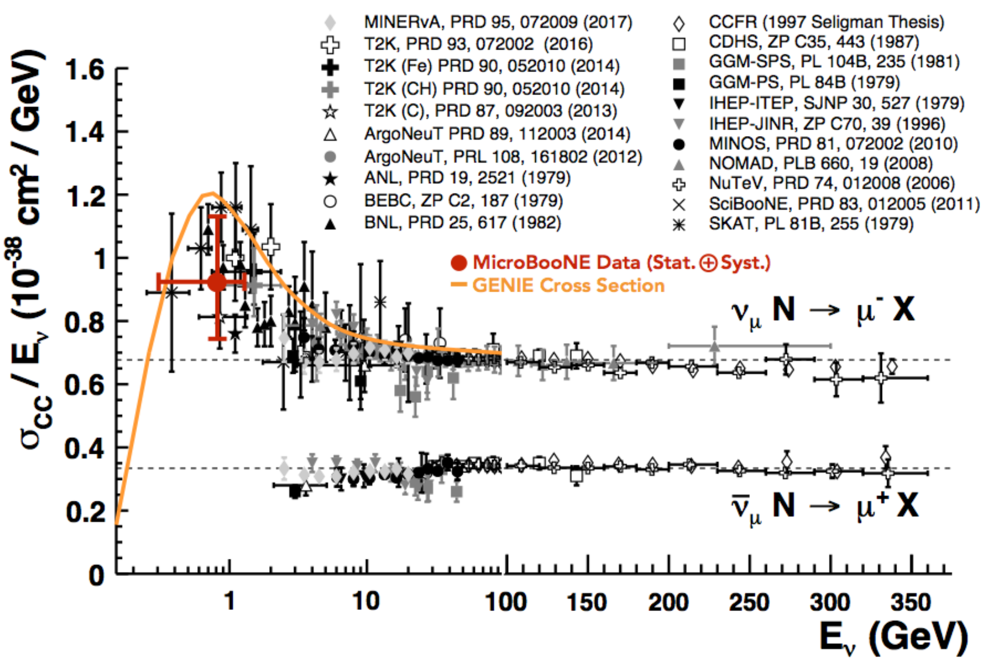




CC Inclusive Results

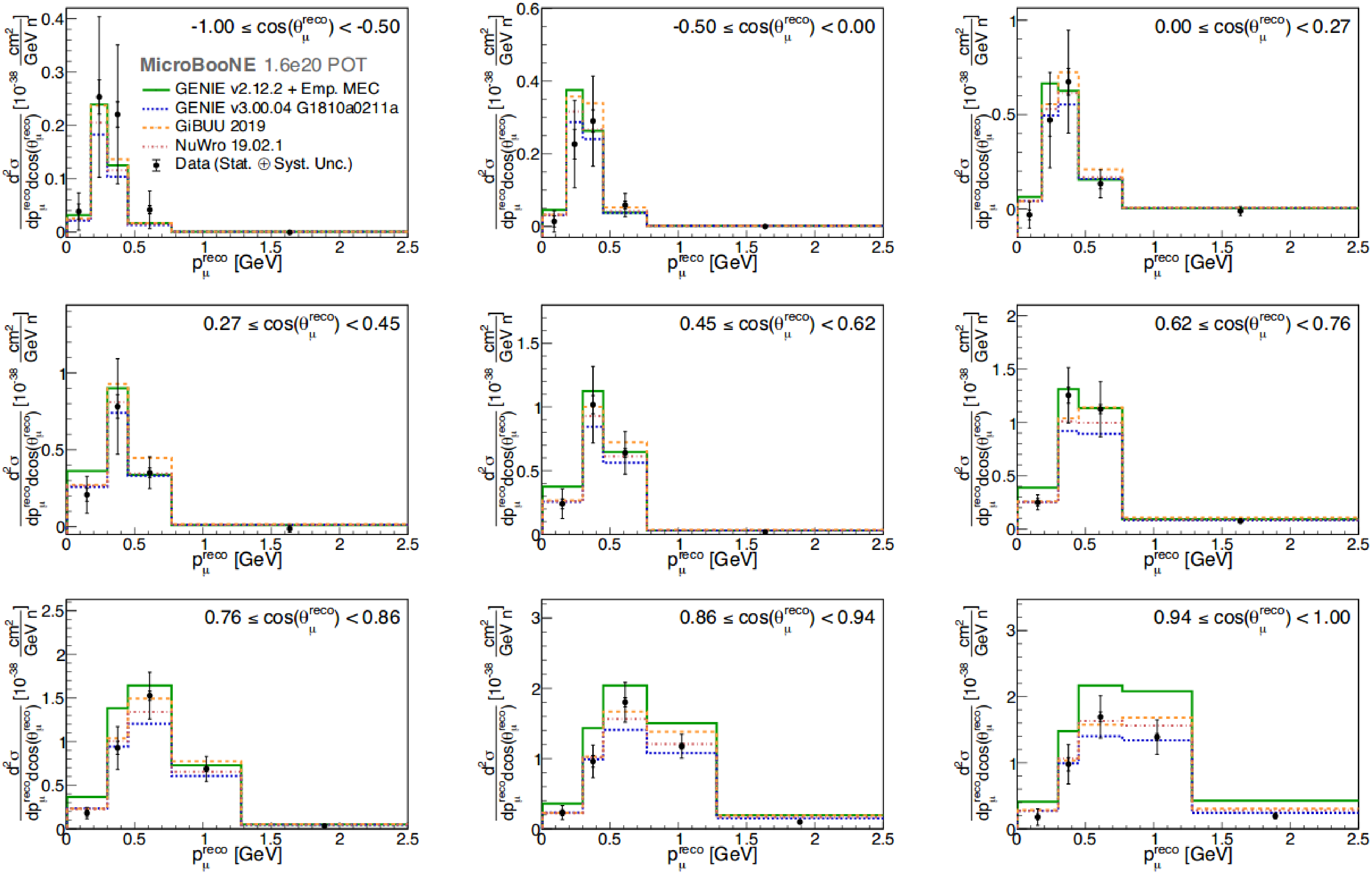
Flux-integrated cross-section:

$$\sigma = 0.693 \pm 0.010\,(\mathrm{stat.}) \pm 0.165\,(\mathrm{syst.}) \times 10^{-38}\,\mathrm{cm}^2$$



Systematic	Relative uncertainty
Beam flux	12.4%
Cross-section modelling	3.9%
Detector response	16.2%
Dirt background	10.9%
Cosmic background	4.2%
TOTAL	23.8%

CC Inclusive Results



μBooNE

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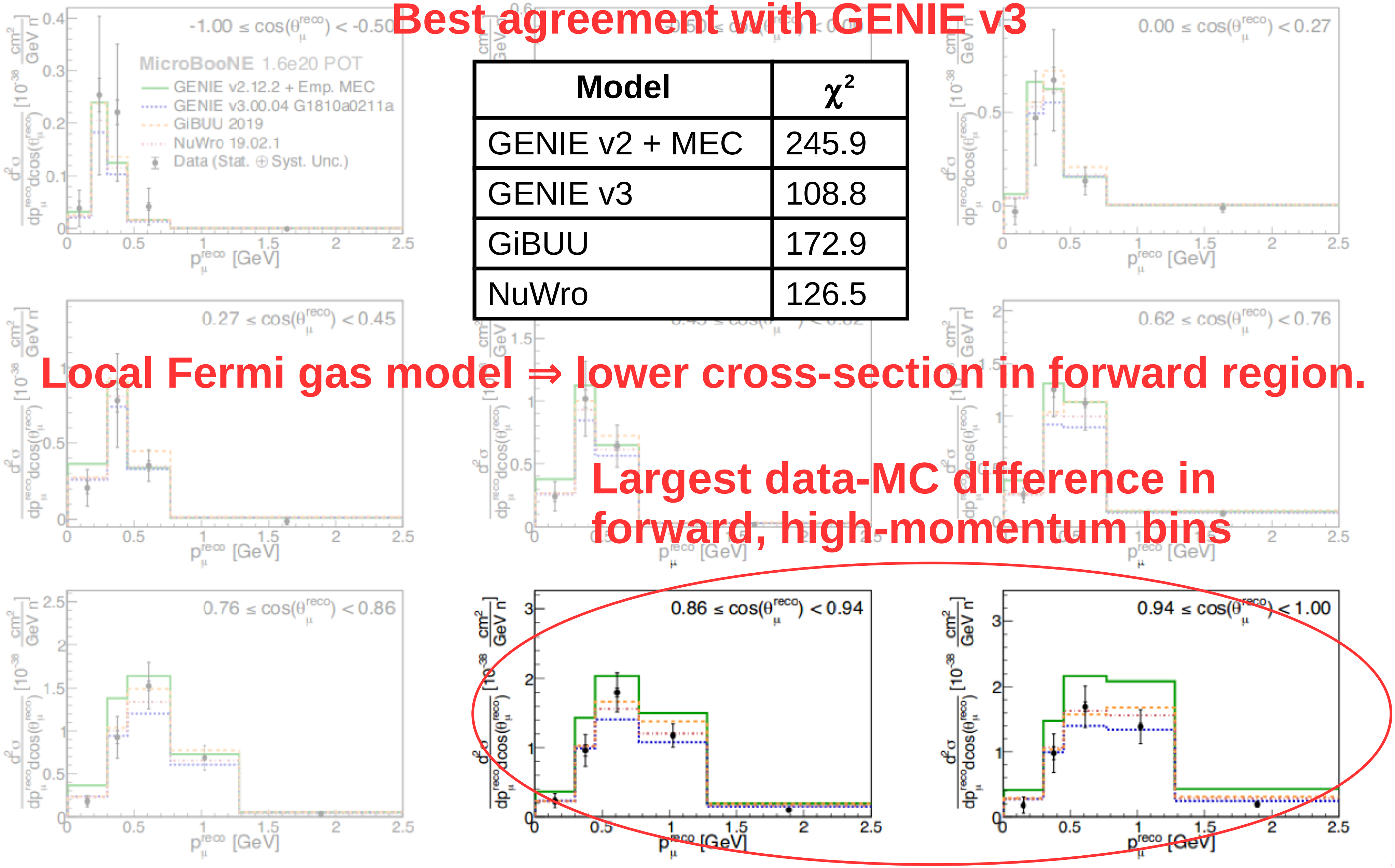
CC Inclusive Results

Best agreement with GENIE v3

Model	χ^2
GENIE v2 + MEC	245.9
GENIE v3	108.8
GiBUU	172.9
NuWro	126.5

Local Fermi gas model ⇒ lower cross-section in forward region.

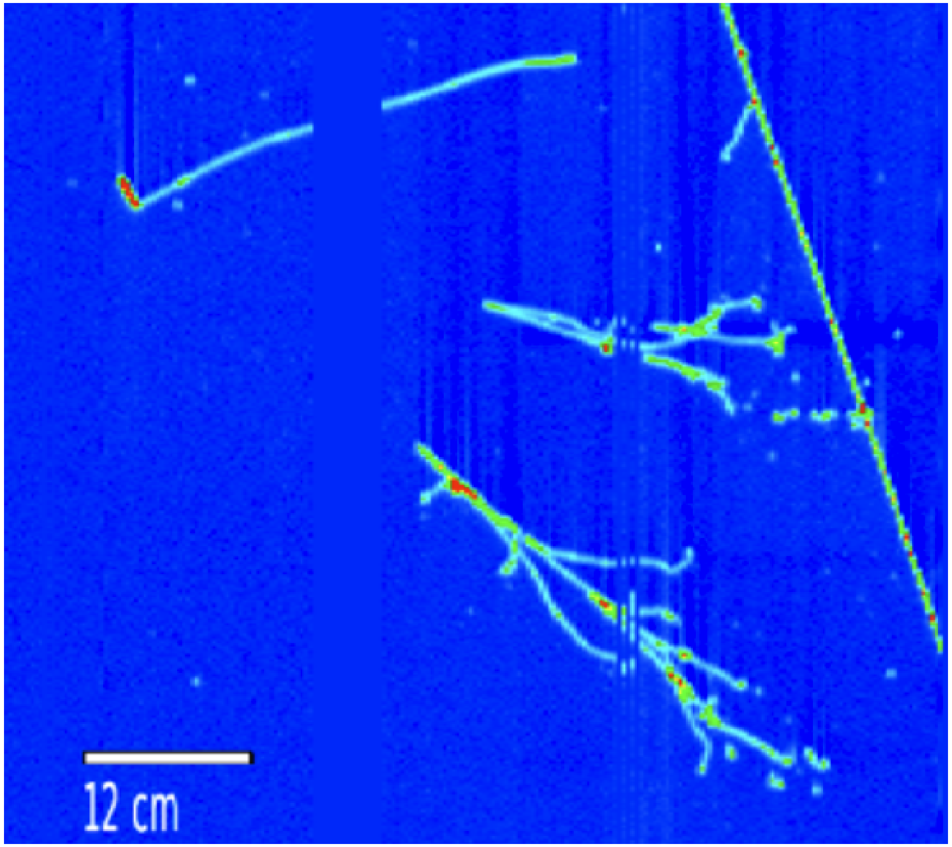
Largest data-MC difference in forward, high-momentum bins



Charged Current π^0

Signal definition: ν_μ + Ar → μ + π^0 + (other particles)

- π^0 decay to $\gamma\gamma$ is a major background for ν_e appearance searches.
- CCπ^0 is easier to measure than NCπ^0 and helps constrain some of the same processes.
- Demonstrates LArTPC shower reconstruction.
- Never before studied on argon.

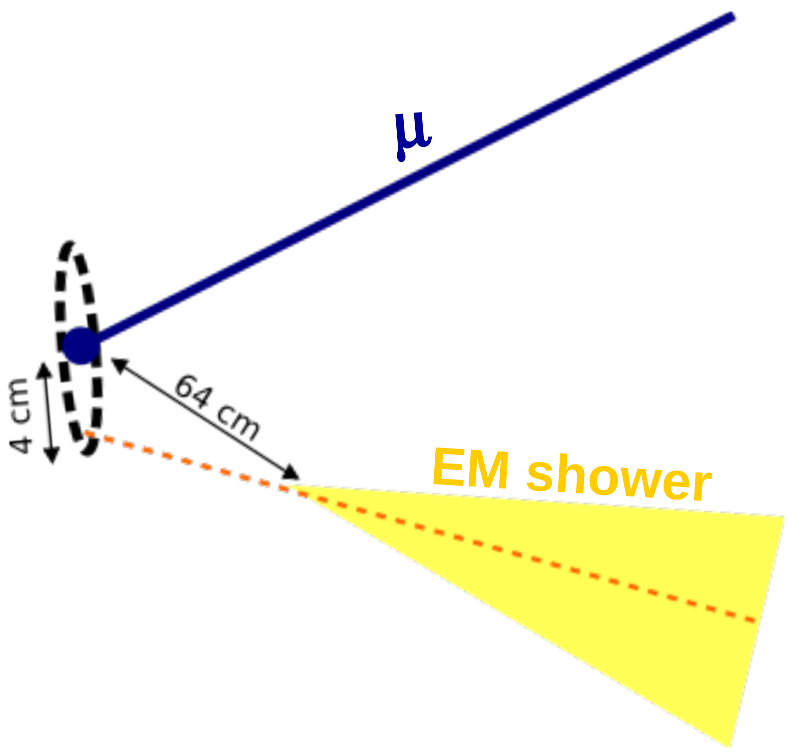


CCπ^0 Selection

Data sample: 1.6×10^{20} POT

In addition to cosmic rejection, vertex finding etc., look for a vertex with a muon track and one or more associated EM showers.

An EM shower is deemed 'associated' if its extrapolated vector comes within 4cm, and its point of origin lies within 64cm of the vertex.



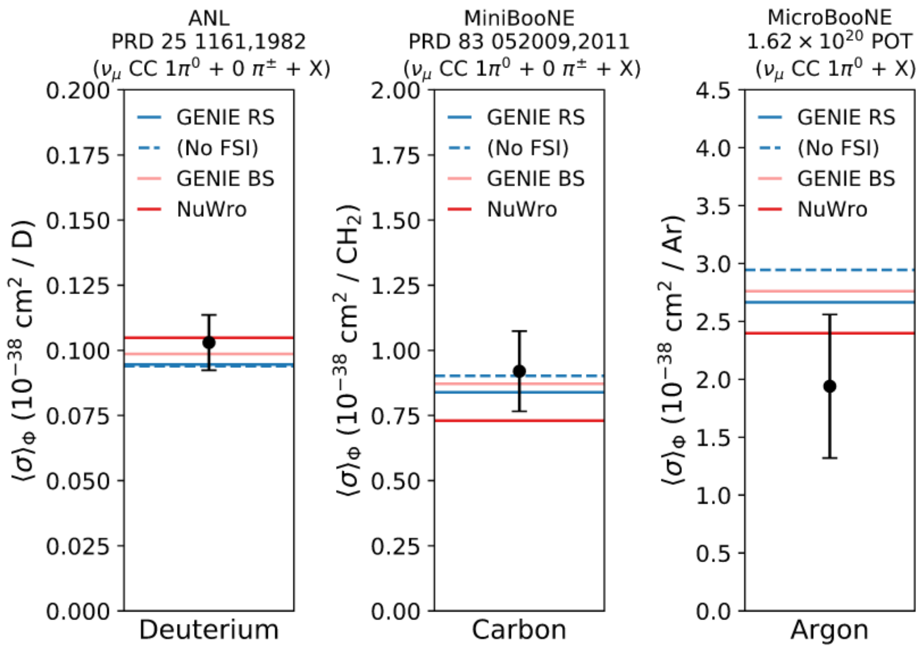
This selection achieves

Efficiency = 16%, **Purity =** 56%

Charged Current π^0

Flux-integrated cross-section:

$$\langle\sigma\rangle_\Phi = 1.9 \pm 0.2\ (\text{stat}) \pm 0.6\ (\text{syst}) \times 10^{-38}\ \frac{\text{cm}^2}{\text{Ar}}$$



Systematic	Relative uncertainty
Beam flux	16%
Interaction model	17%
Detector simulation	21%
TOTAL	31%

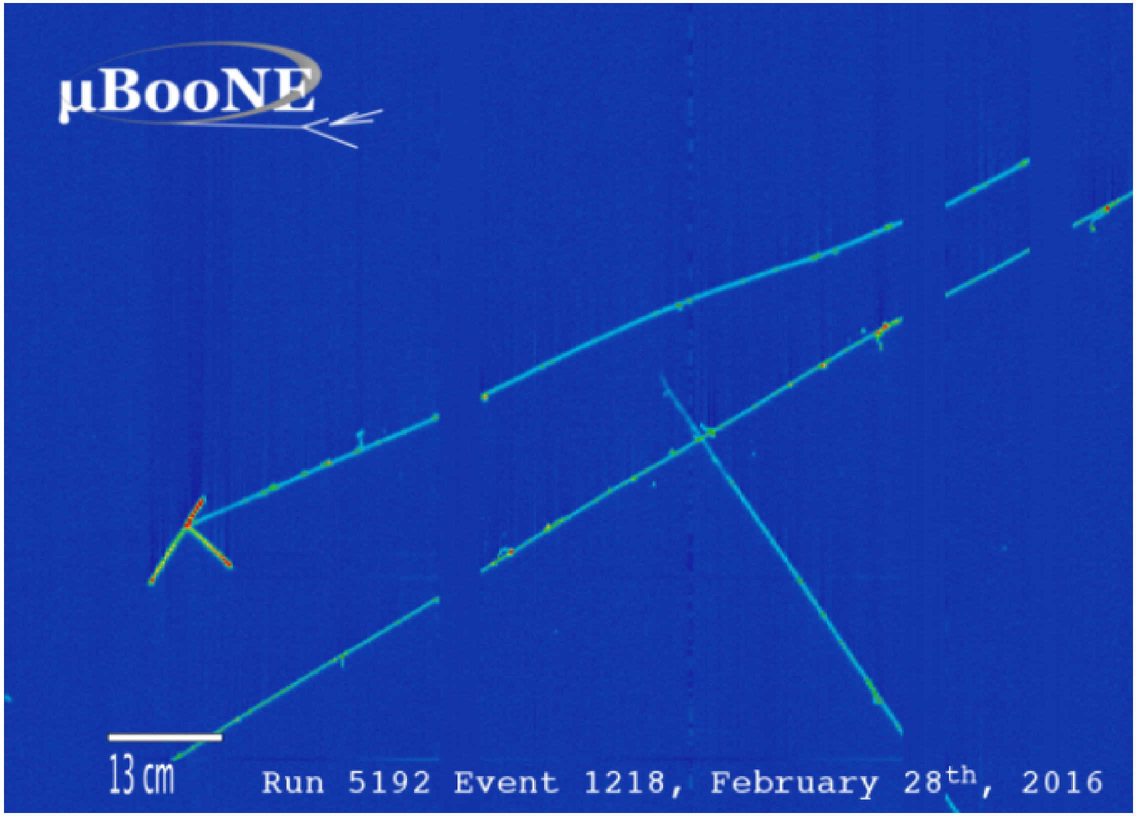
Expect detector systematics to be reduced by ongoing calibration.

ANL & BNL measurements exclude additional charged mesons in final state.

Charged Particle Multiplicity

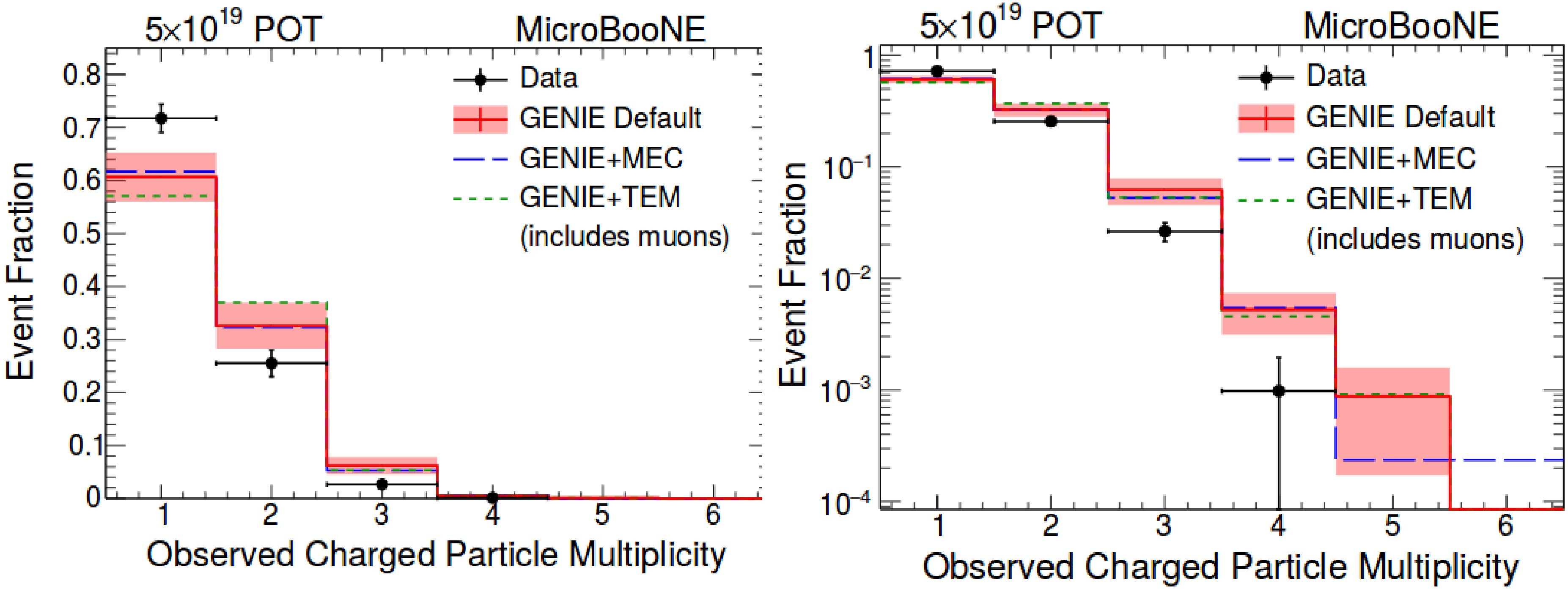
Signal: ν_μ + Ar → μ + (N charged particles) + (other particles)

- Empirical test of scattering models used in neutrino generators.
- Few measurements on argon.
- Measure relative event fraction in each multiplicity bin, not cross-section.



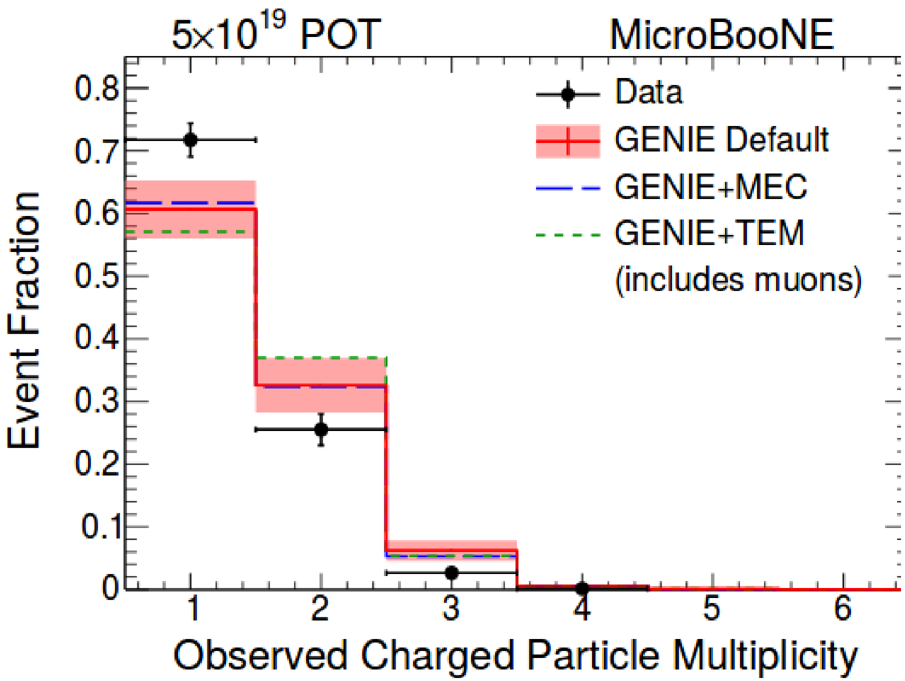
Data sample: 5×10^{19} POT **Selection:** similar to CC inclusive

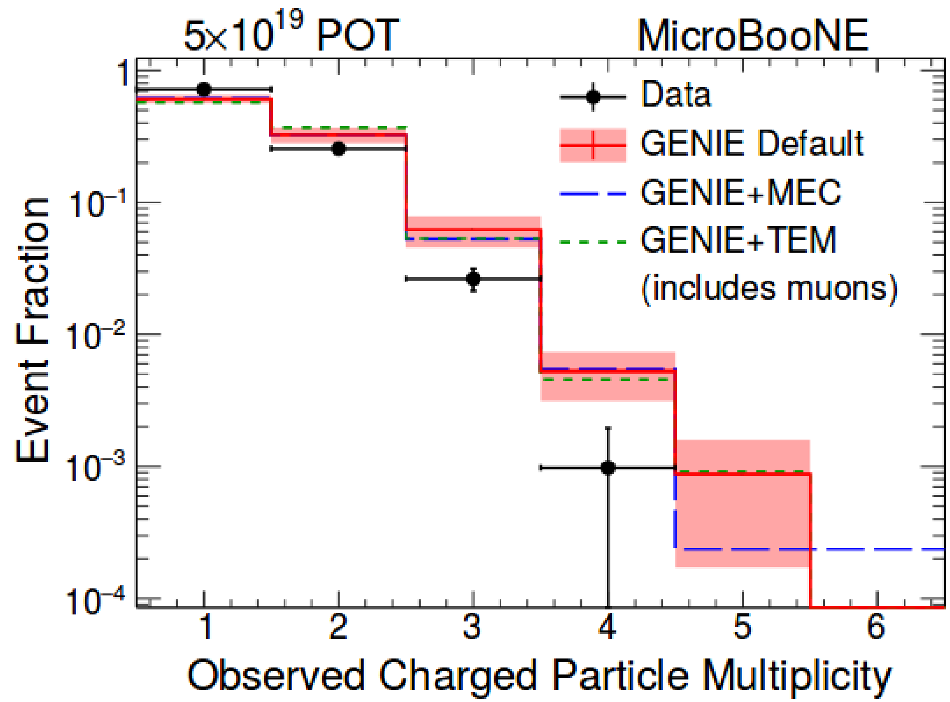
Charged Particle Multiplicity



Systematic	Relative uncertainty			
	M=1	**M=2**	**M=3**	**M=4**
MC statistics	2%	3%	7%	22%
Track efficiency	7%	11%	25%	34%
Background model	2%	2%	0%	0%
Flux shape	0%	0.4%	0.2%	0.5%
Electron lifetime	0.5%	0.1%	6%	5%

Charged Particle Multiplicity





- Observe fewer M=3 events than GENIE prediction: consistent with MINERνA and T2K.
- Observe more M=1 events than GENIE prediction: consistent with ArgoNeuT.

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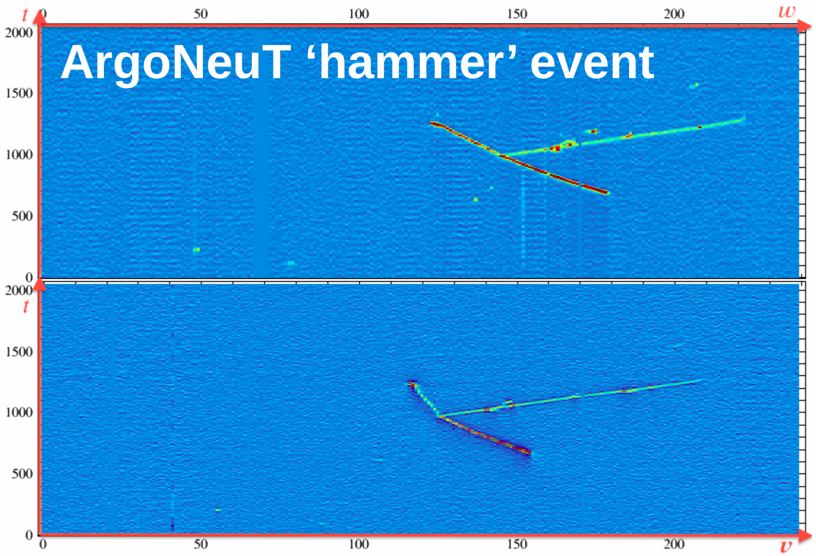
Charged Current N Protons

Signal: $\nu_\mu + Ar \rightarrow \mu$ + (1 or more protons)

- Direct measurement of 2p2h process
- Lower momentum threshold for proton reconstruction than other experiments.
- 4π angular acceptance.

Data sample: 4.4×10^{19} POT



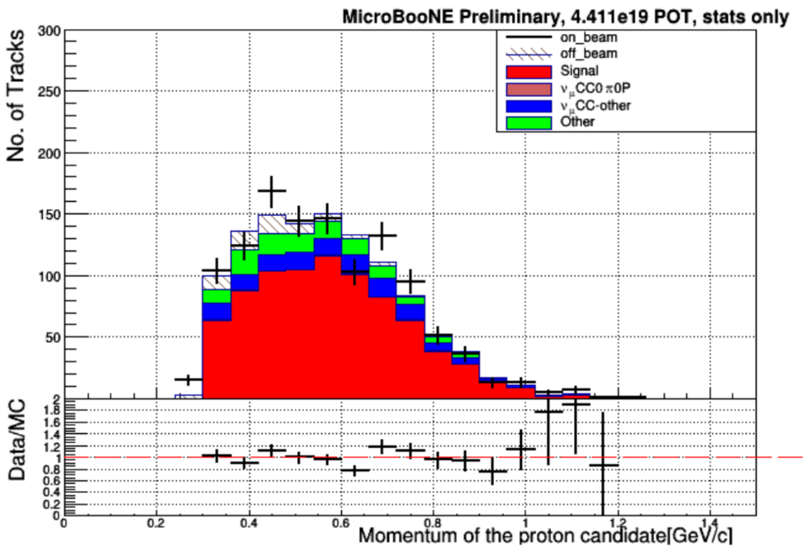
Selection: Similar to CC inclusive, exploiting LArTPC PID capabilities (93% accurate for protons).

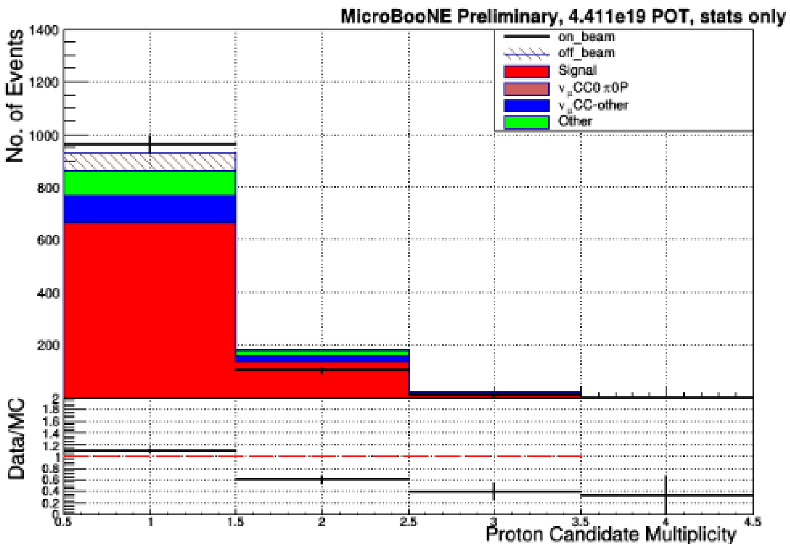
Efficiency = 29%, **Purity** = 77%

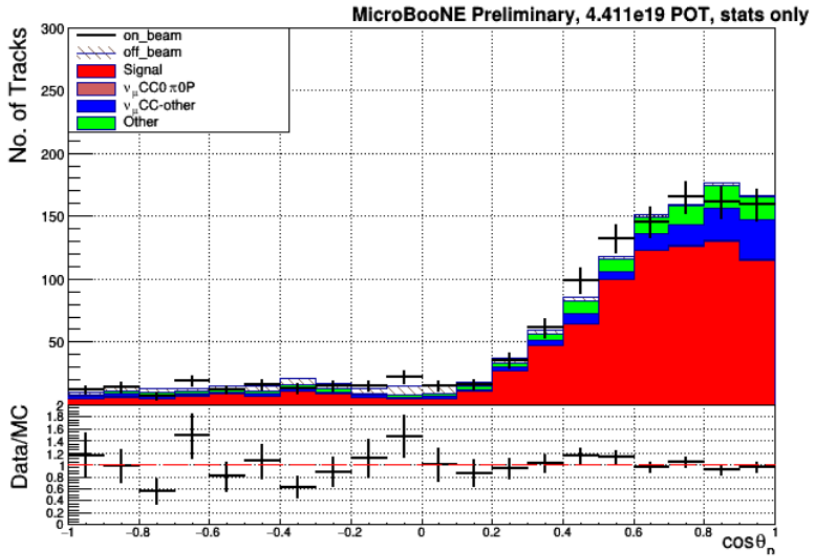
Experiment	Momentum Threshold	Kinetic Energy Threshold
MicroBooNE	300 MeV/c	47 MeV
MINERνA	450 MeV/c	102 MeV
T2K	500 MeV/c	126 MeV

Charged Current N Protons

- Good initial agreement between data and simulation (GENIE).
- Work ongoing on detector systematics.



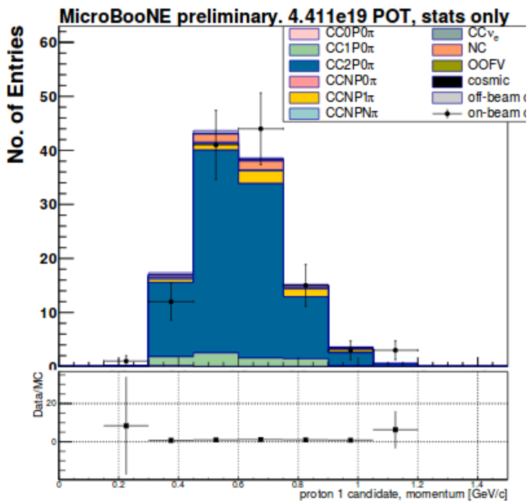


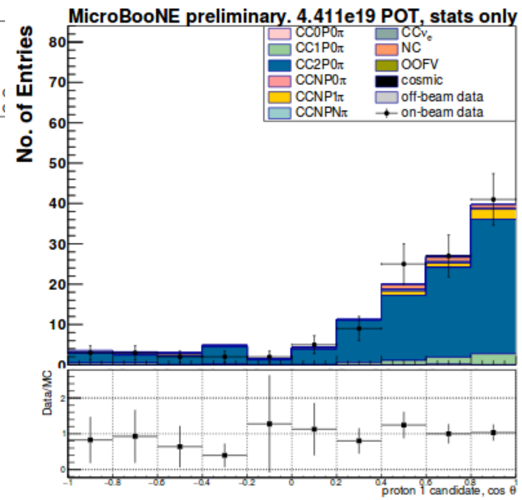


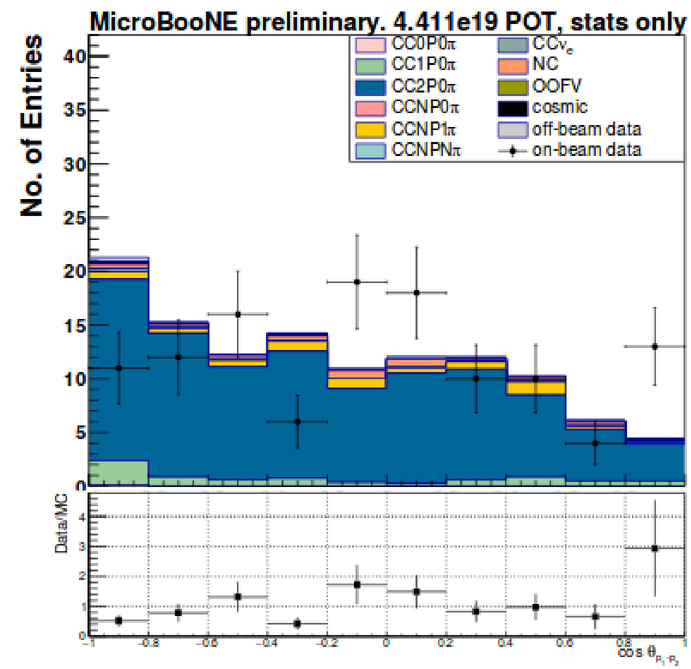
Charged Current 2 Protons

Momentum | **θ w.r.t. beam** | **Proton-to-proton θ**

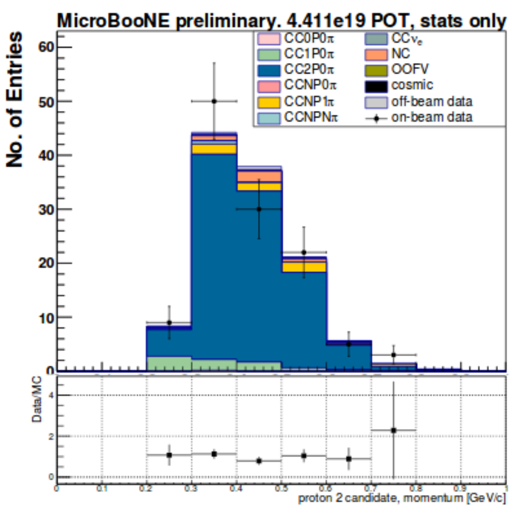
Leading proton

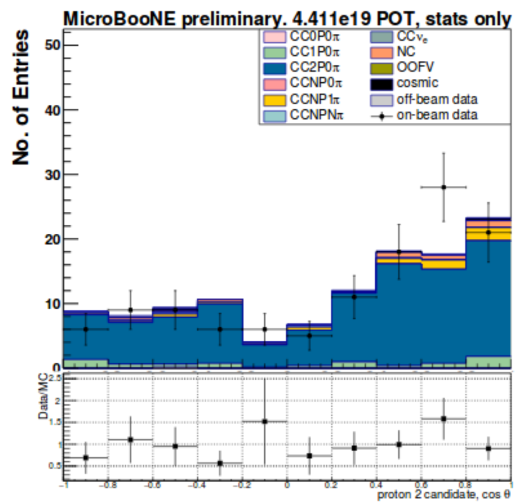






Sub-leading proton





119 selected events; expect ~430 in full data sample.

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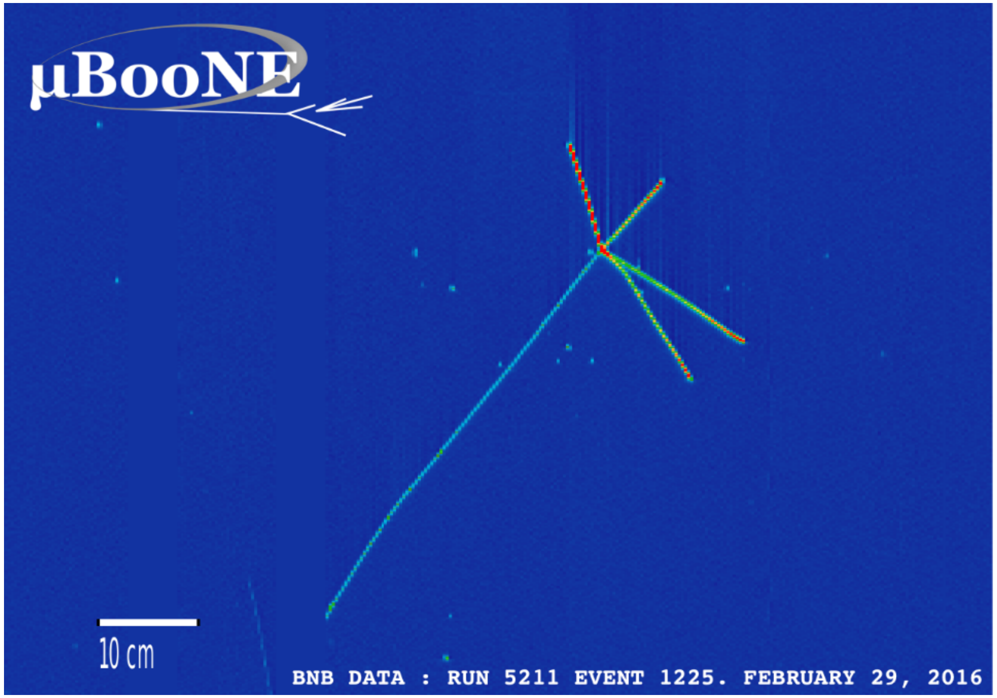
Selected CC N-Proton Events



NuMI ν_e CC Selection

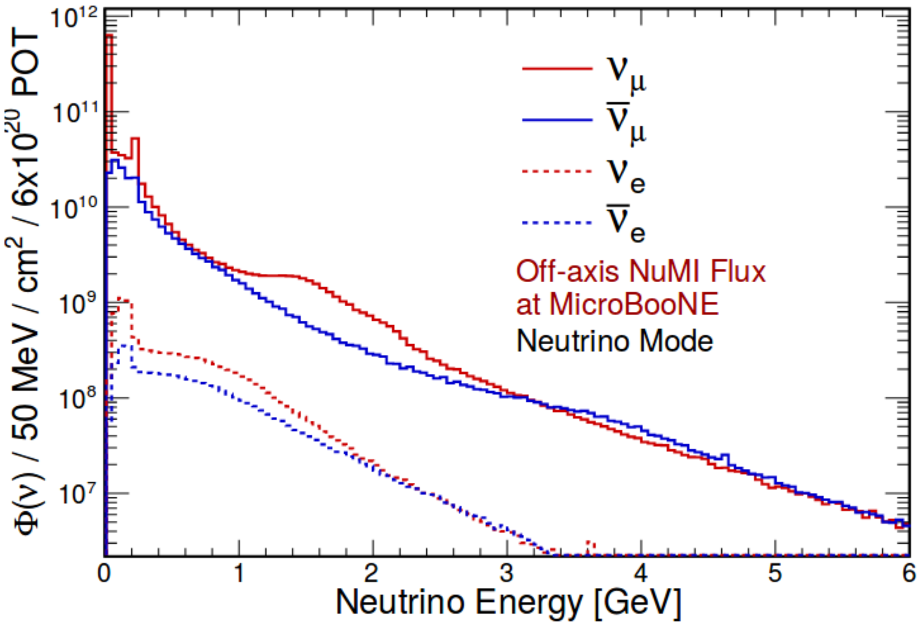
Signal: $\nu_e/\bar{\nu}_e + Ar \rightarrow e^{\pm}$ + (other particles)

- ν_e appearance is golden channel for SBN sterile search and DUNE; need to understand the cross-section on Ar.
- NuMI flux covers a larger range of the projected DUNE spectrum than BNB.

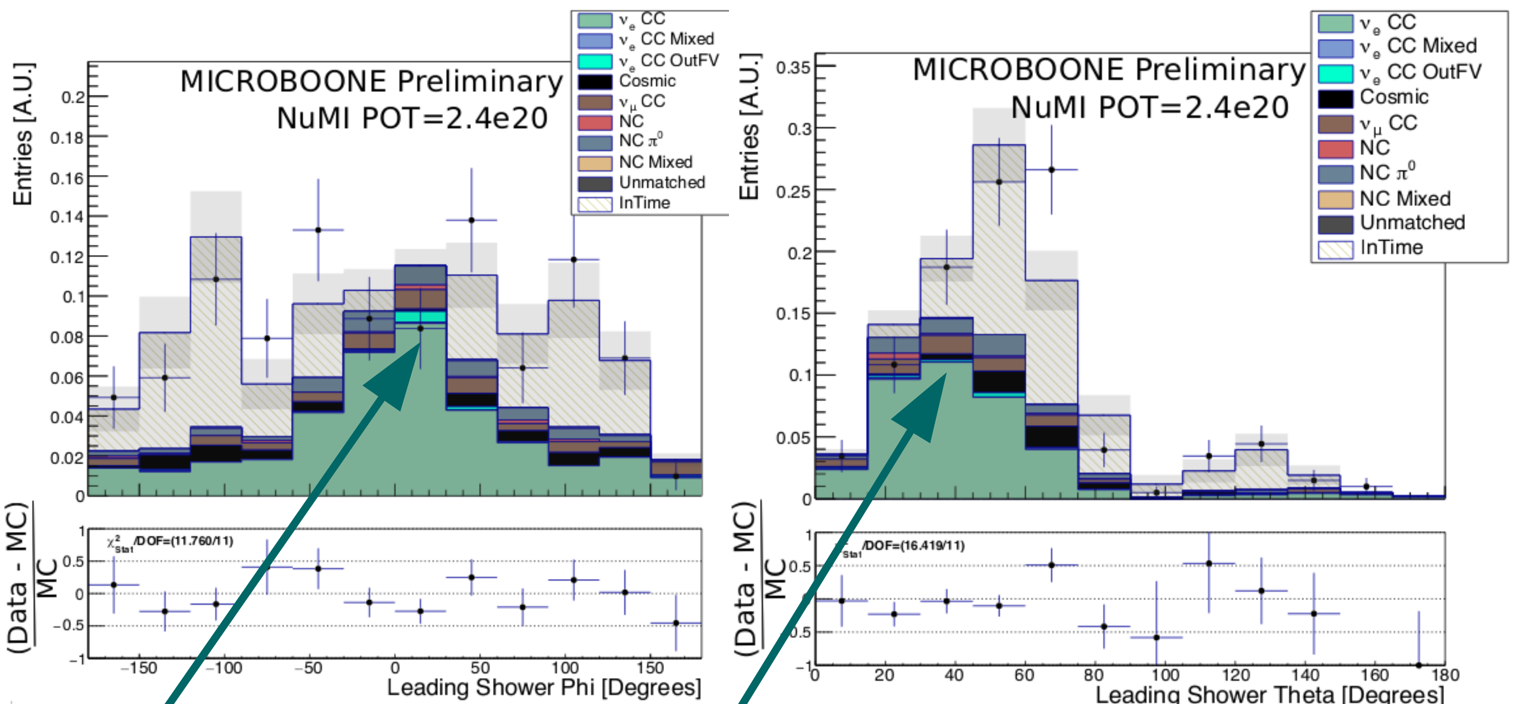
Data sample: 2.4×10^{20} POT

Selection: Based on Pandora EM shower tagging, achieves

Efficiency = 9%,
Purity = 40%



NuMI ν_e CC Selection - Kinematic Measurements

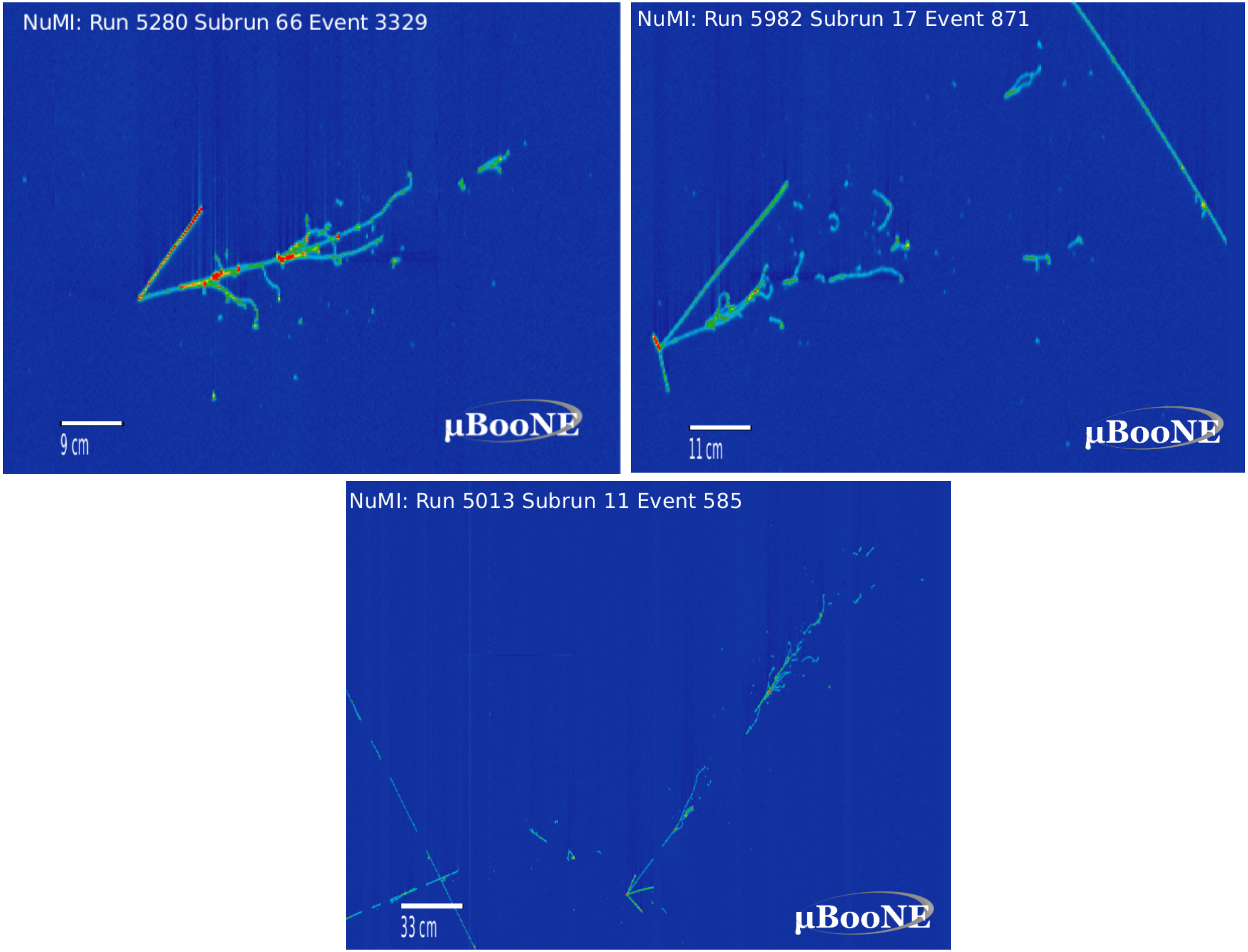


NuMI off-axis angle

~100 selected events – largest ν_e sample on Ar to date!

Aim to bring this forward to full $\nu_e + \bar{\nu}_e$ CC inclusive cross-section measurement; anticipate 14% (stat) + 30% (sys) sensitivity.

Selected NuMI ν_e CC Events



Conclusions

Conclusions

- MicroBooNE has published three neutrino interaction results, each providing an empirical test of our interaction models.
  - **CC inclusive**
  - **CCπ^0**
  - **Charged particle multiplicity**
- Many other measurements underway.
  - **CC N protons**
  - **NuMI ν_e CC**
  - CCπ0 differential, CC 0 hadrons, exclusive ν_e channels…
- Our automated event reconstruction and simulation is now tested and mature (and still growing more sophisticated).
- Higher-statistics samples will be available after we unblind our full dataset (1.32×10^{21} POT), allowing measurements of rare and highly specific channels.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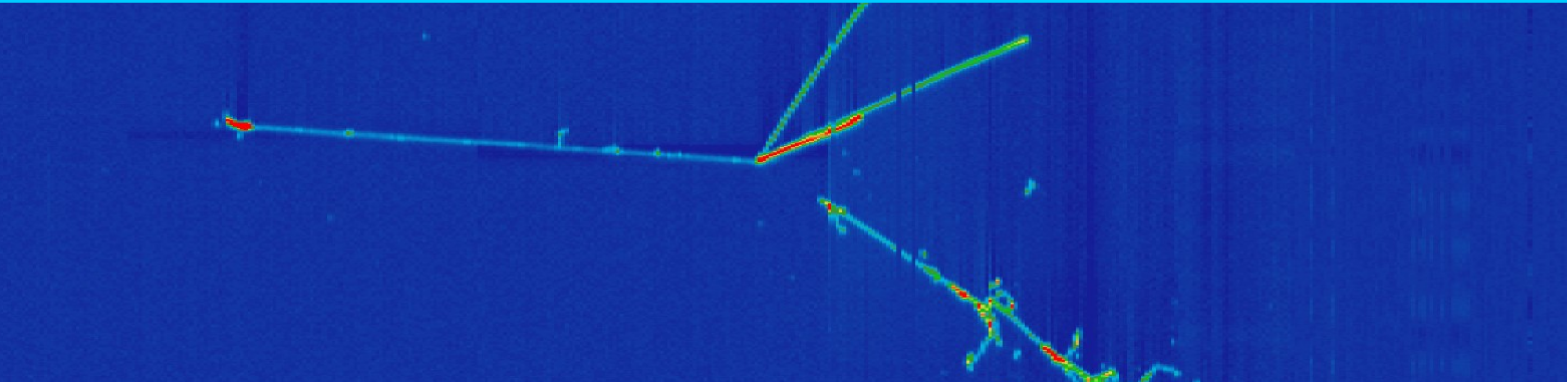
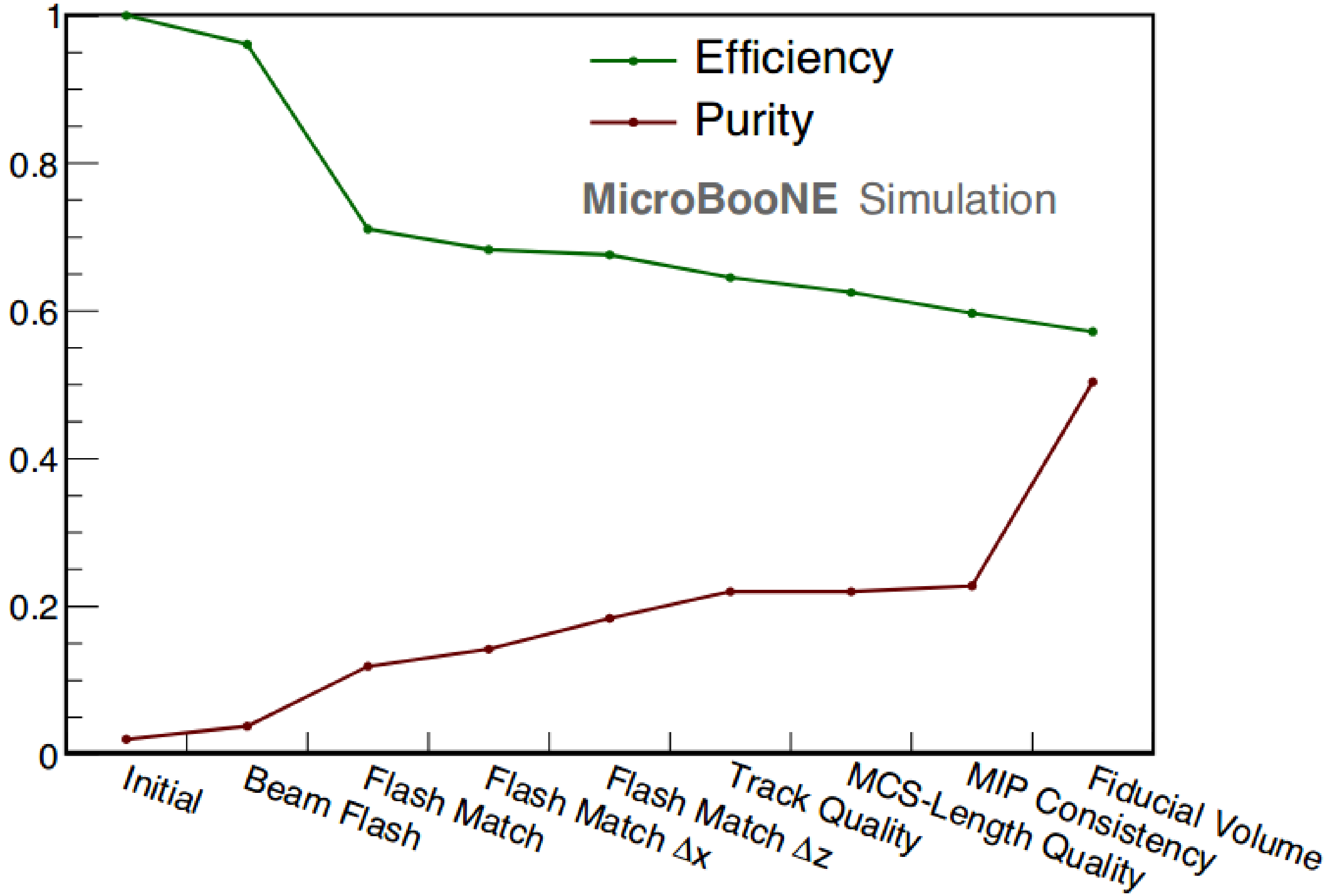
Thank You!

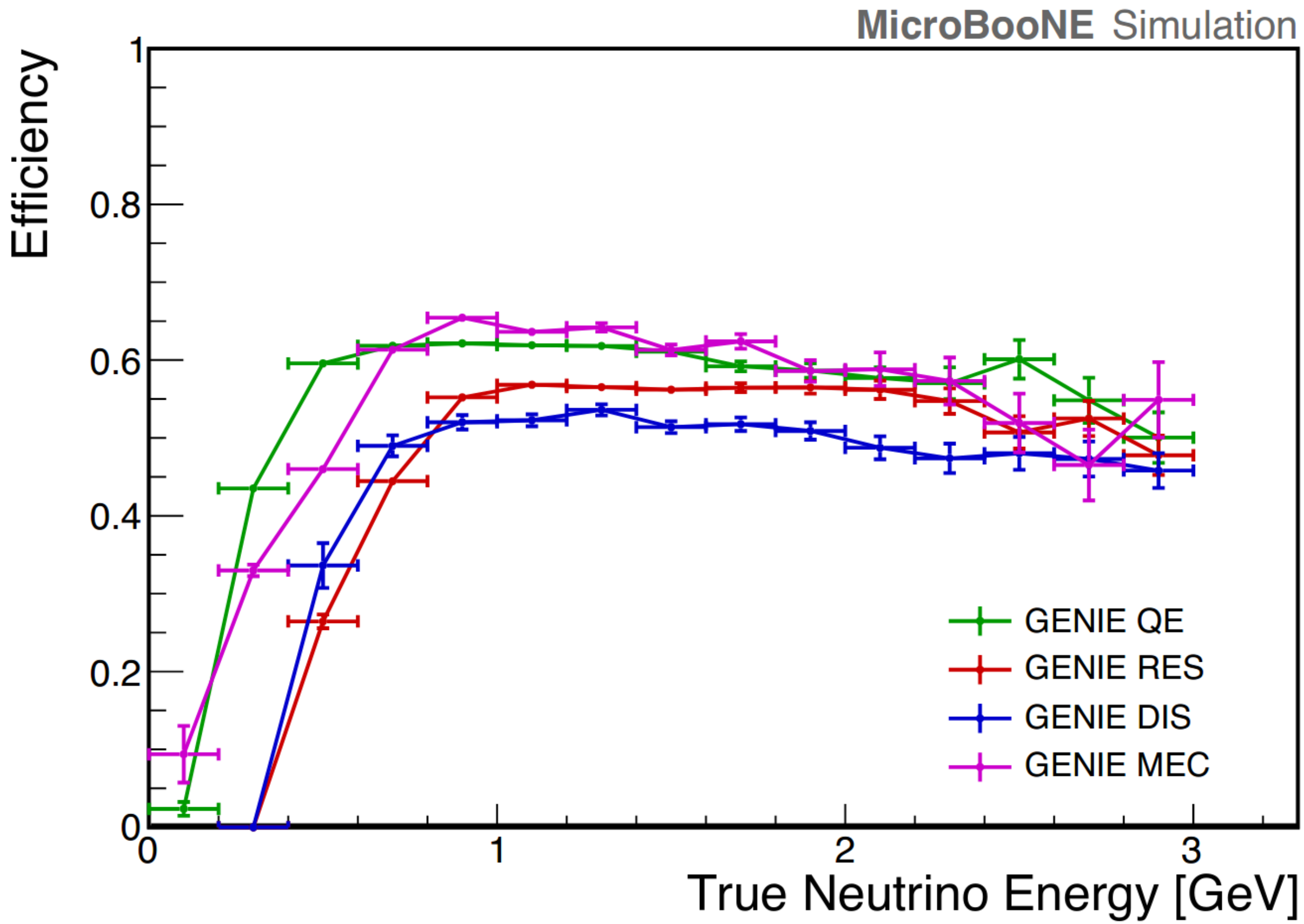


Backups

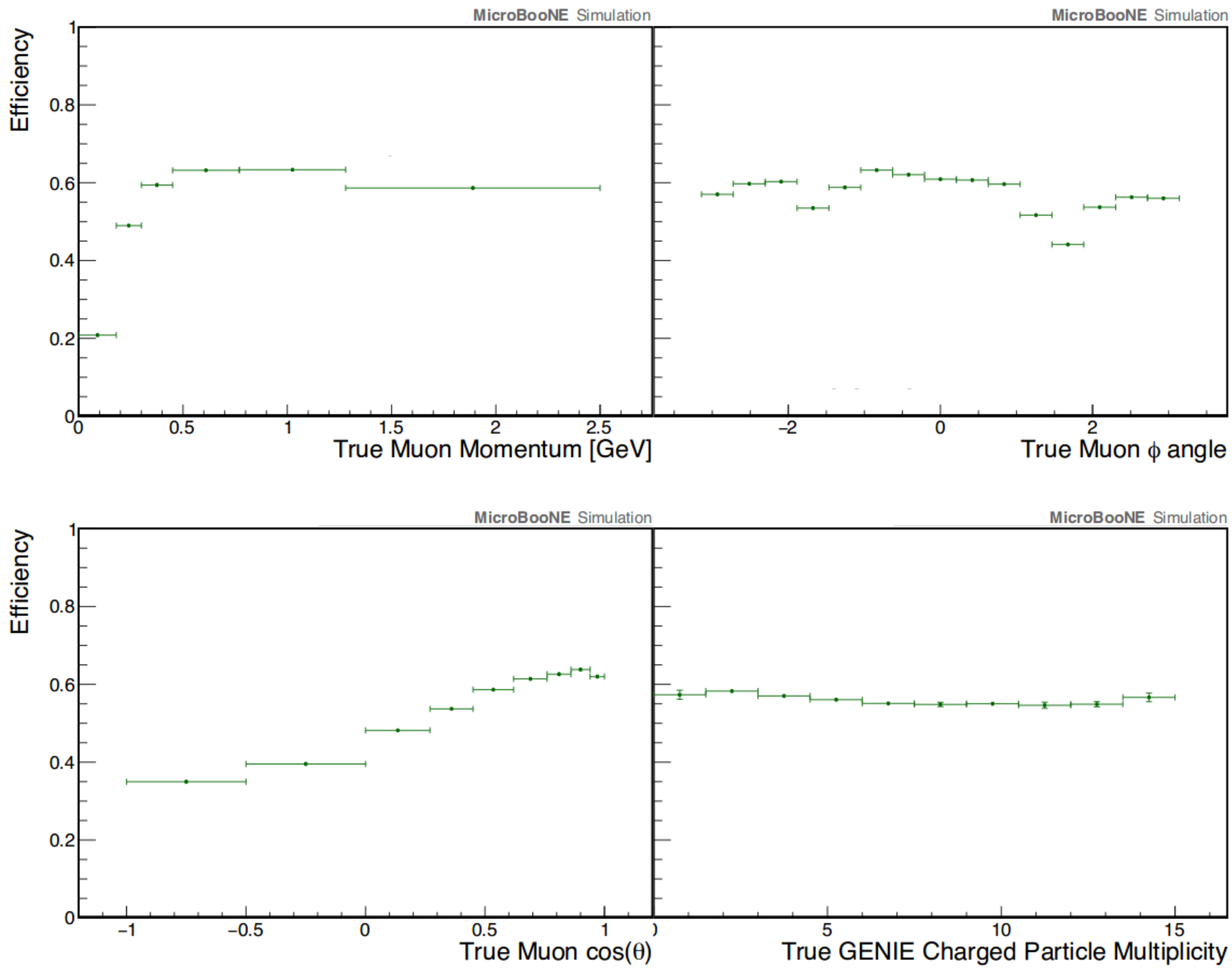
CCIncl Selection Performance



CCIncl Selection Efficiency



CCIncl Selection Efficiency



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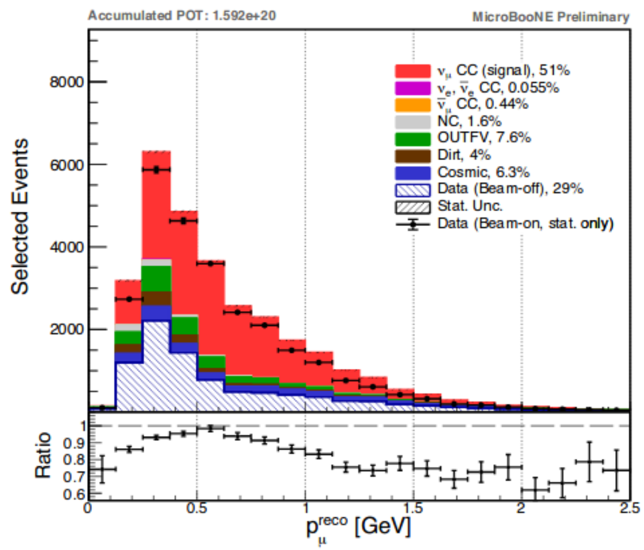
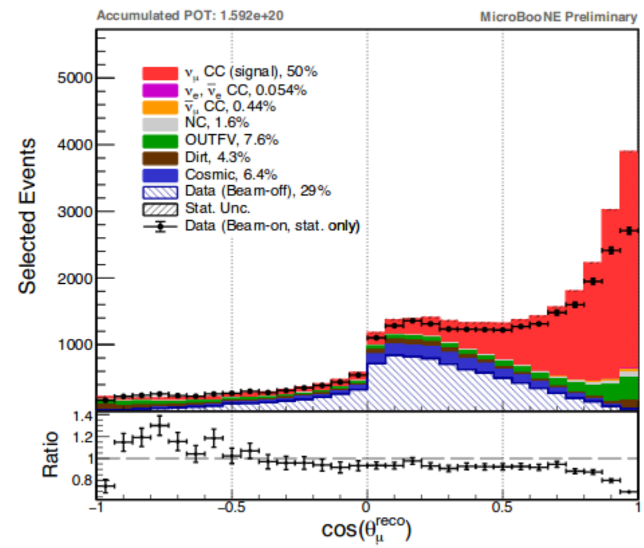
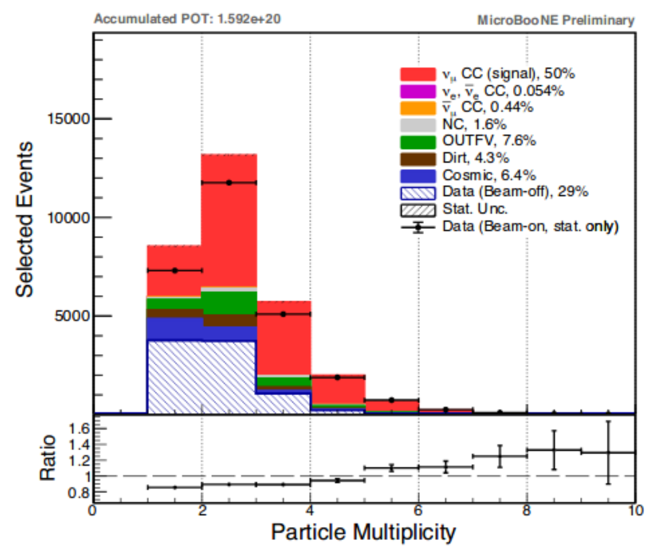
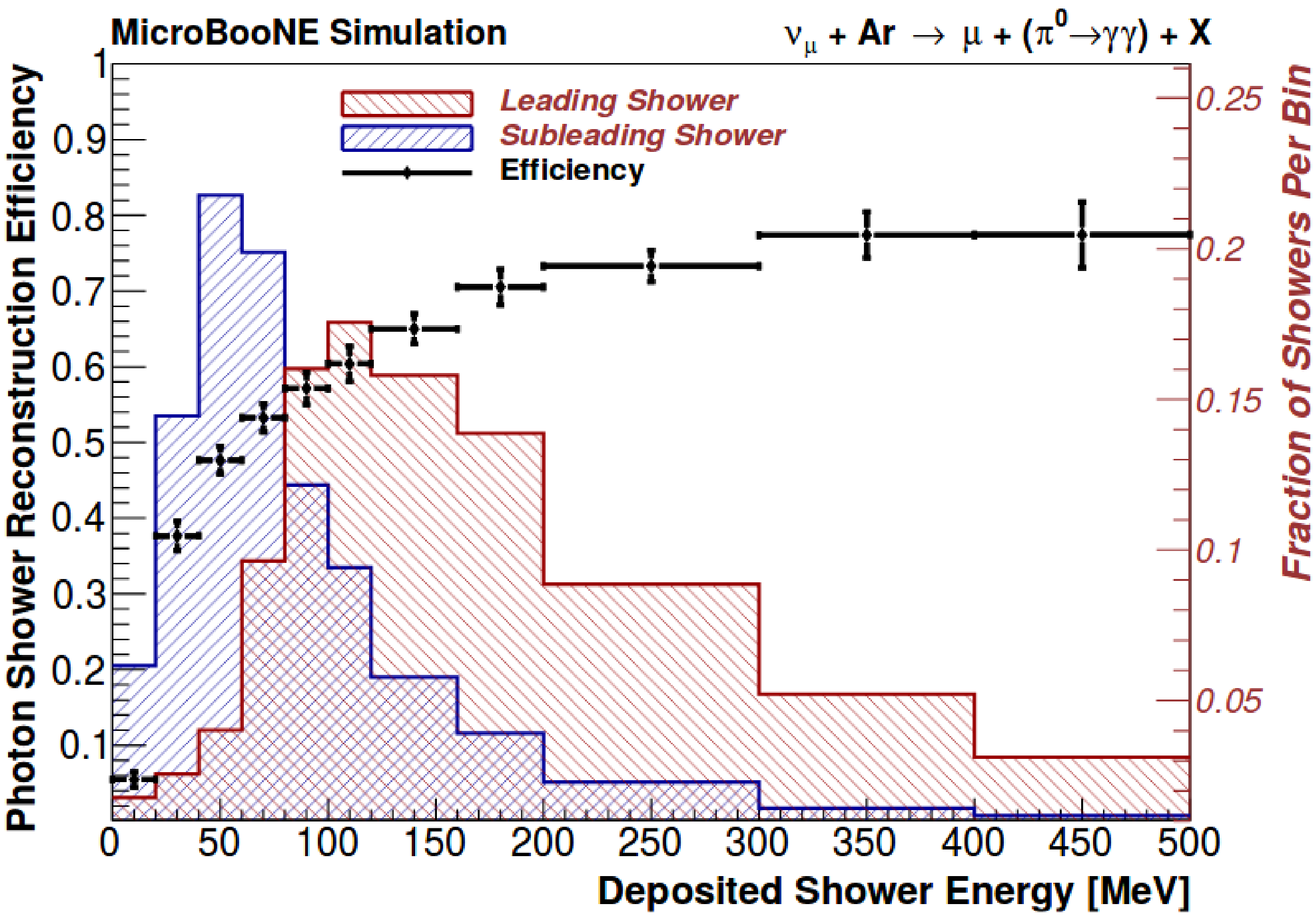
CCIncl Selected Events





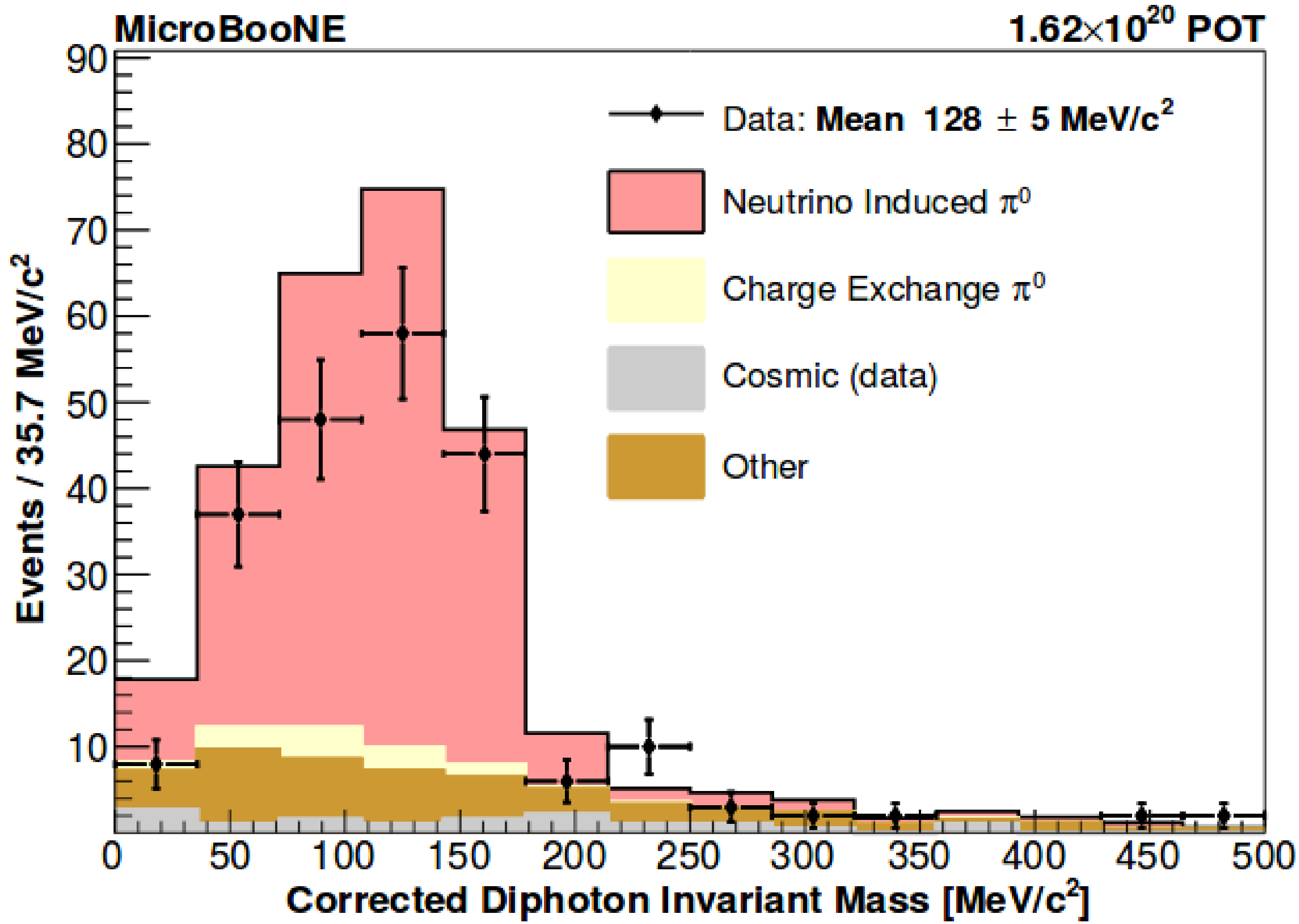


CCπ^0
Shower Reconstruction Efficiency



$CC\pi^0$

Diphoton Invariant Mass



CPM Selection Cuts

Selection cuts	On-beam data Events	On-beam data Passing rates	Off-beam data Events	Off-beam data Passing rates	MC default Events	MC default Passing rates
Total events	547616		2954586		188880	
ν_μ events passing pre-cuts	4049	(0.74%/0.74%)	14213	(0.48%/0.48%)	7106	(3.8%/3.8%)
Events passing dead region cut	3080	(76%/0.56%)	10507	(74%/0.36%)	5632	(79%/2.9%)
Long track starting 46 cm below the TPC top surface	2438	(79%/0.44%)	7883	(75%/0.27%)	4795	(85%/2.6%)
Long track to vertex distance < 3 cm	2435	(99%/0.44%)	7862	(99%/0.27%)	4781	(99%/2.5%)
Events with ≥ 80 collection plane hits	1930	(79%/0.35%)	5279	(67%/0.17%)	4387	(92%/2.3%)
Events passing wire gap cuts	1795	(93%/0.33%)	4954	(94%/0.16%)	4016	(92%/2.1%)

Multiplicities	On-beam data Events	On-beam data Event rate	Off-beam data Events	Off-beam data Event rate	MC default Events	MC default Event rate
Total events	1795		4954		4016	
mult = 1	1379	77%	4113	83%	2599	65%
mult = 2	389	22%	828	17%	1186	30%
mult = 3	26	1.4%	12	0.2%	210	5%
mult = 4	1	0.06%	1	0.2%	18	0.4%
mult = 5	0	0%	0	0%	3	0.07%

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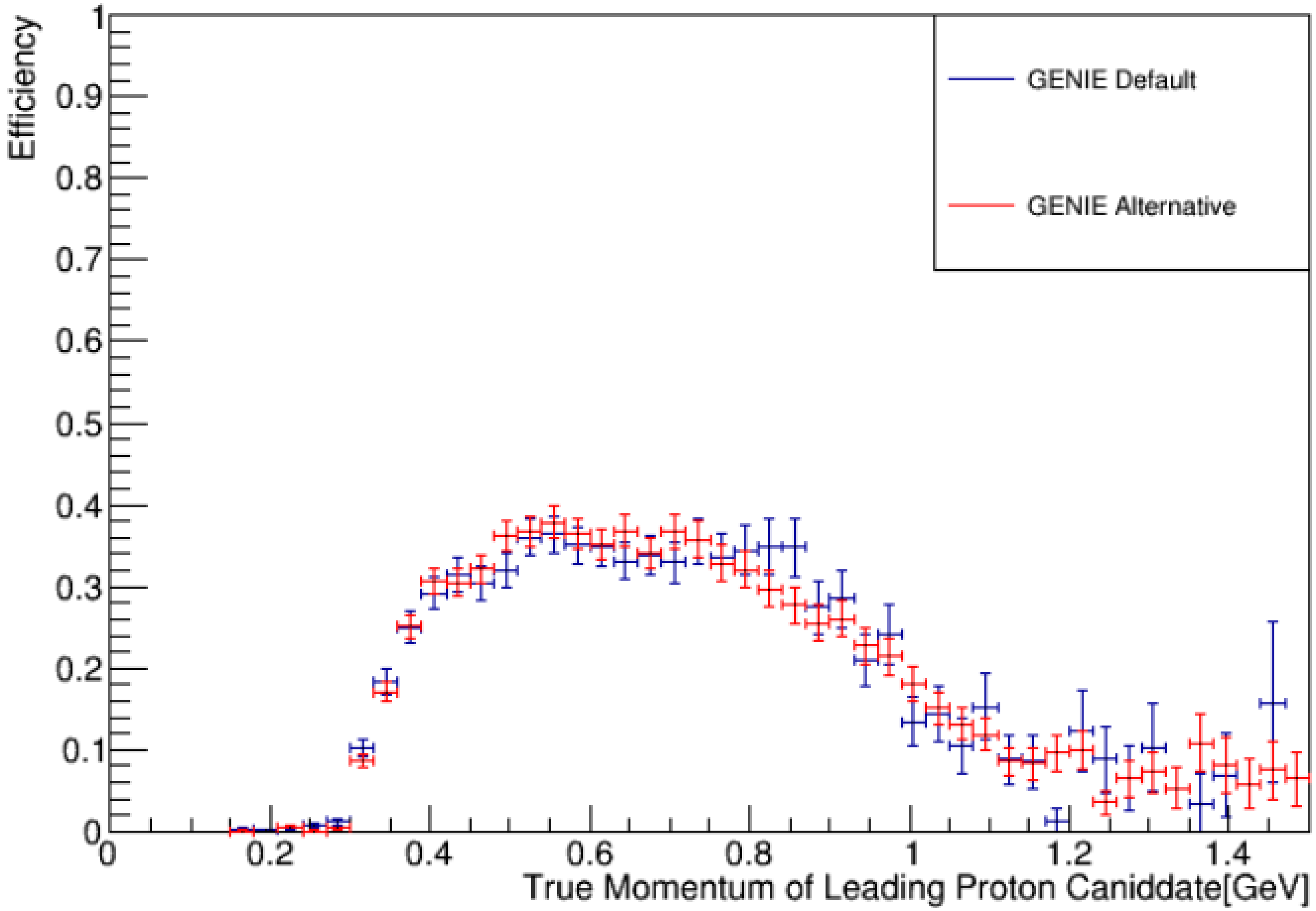
CC N Proton
Proton Tracking Efficiency



CC N Proton Selection Model Dependence

Topology	Composition (GENIE Default)	Composition (GENIE Alternative)
$CC0\pi0Proton$	0.1%	0.3%
$CC0\pi1Proton$	6.3%	6.9%
$CC0\pi2Proton$	83.%	77.9%
$CC0\pi NProton$	0.%	0%
$CC1\pi NProton$	5.5%	9.3 %
$CCN\pi NProton$	1.%	0.65%
$CC\nu_e$	0.%	0%
NC	3.35%	4.3%
$OOFV$	0.2%	0.3%
cosmic	0.7%	0.4%
Efficiency $CC0\pi2Proton$	14.7%	15.2%

Model element	GENIE Default	GENIE Alternative
Nuclear Model	Bodek-Ritchie Fermi Gas	Local Fermi Gas
Quasi-elastic	Llewellyn-Smith	Nieves
Meson-Exchange Current	Empirical	Nieves
Resonant	Rein-Seghal	Berger-Seghal
Coherent	Rein-Seghal	Berger-Seghal
FSI	hA	hA2014

NuMI ν_e Selection Efficiency