Recent Cross-section Measurements from MicroBooNE

Lake Louise Winter Institute
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On behalf of the MicroBooNE collaboration

The Need for Neutrino Scattering Measurements

What we can measure:

$$R(\vec{\mathbf{x}}) = \sum_{i}^{\text{process}} \sum_{j}^{\text{target}} \int_{E_{\min}}^{E_{\max}} \Phi(E_\nu) \times \sigma_i(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times N_j \times P(\nu_A \rightarrow \nu_B)$$

Neutrino oscillation analysis for three flavours or more:

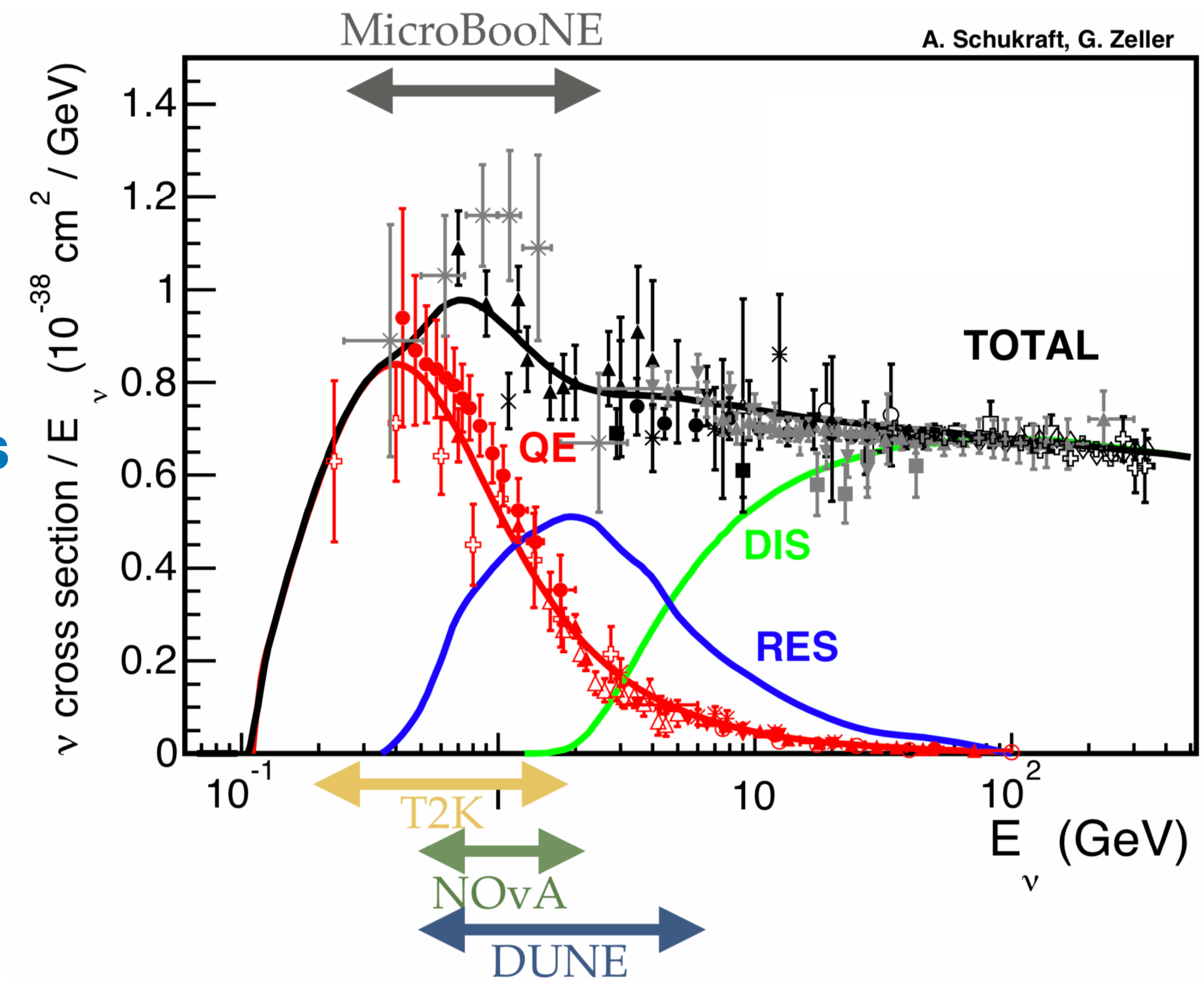
- Extract oscillation probability
- Constrain systematics
- Develop neutrino interaction generators

Background for beyond standard model physics (BSM):

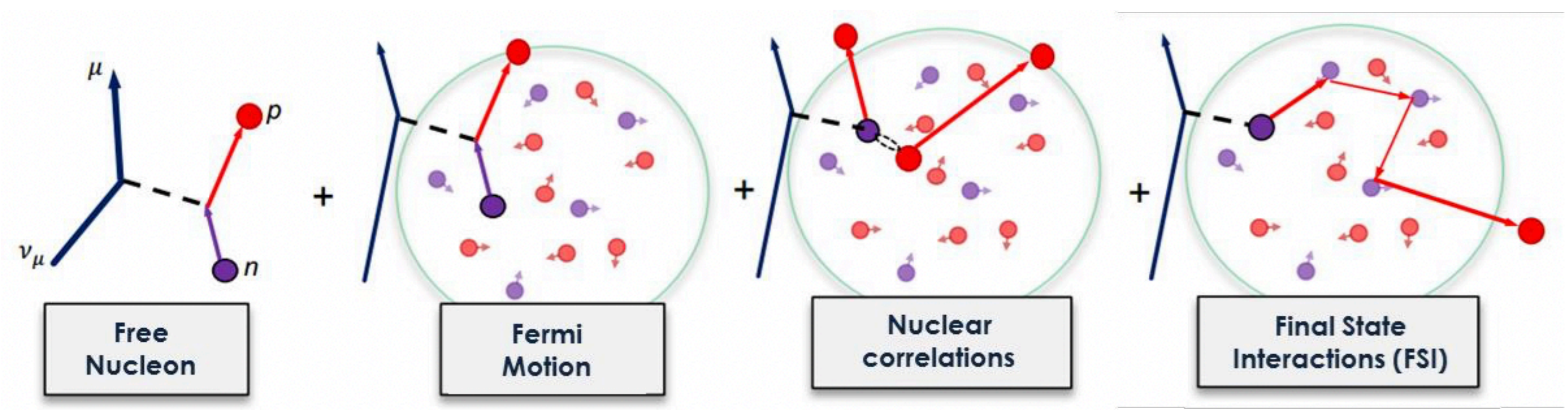
- Milli-charged particles
- Neutrino trident
- Proton decay
- Direct dark matter search

Not an Easy Task

Mix of interaction modes



Nuclear effect



Plot by Patrick Stowell

MicroBooNE's Cross-section Service

Modern accelerator-based neutrino experiments studying neutrino scattering

Experiment	beam	$\langle E_\nu \rangle$, $\langle E_{\overline{\nu}} \rangle$ GeV	neutrino target(s)	run period
ArgoNeuT	$\nu, \overline{\nu}$	4.3, 3.6	Ar	2009 – 2010
ICARUS (at CNGS)	ν	20.0	Ar	2010 – 2012
K2K	ν	1.3	CH, H_2O	2003 – 2004
* MicroBooNE	ν	0.8	Ar	2015 –
MINERvA	$\nu, \overline{\nu}$	3.5 (LE), 5.5 (ME)	He, C, CH, H_2O, Fe, Pb	2009 – 2019
MiniBooNE	$\nu, \overline{\nu}$	0.8, 0.7	CH_2	2002 – 2019
MINOS	$\nu, \overline{\nu}$	3.5, 6.1	Fe	2004 – 2016
NOMAD	$\nu, \overline{\nu}$	23.4, 19.7	C–based	1995 – 1998
NOvA	$\nu, \overline{\nu}$	2.0, 2.0	CH_2	2010 –
SciBooNE	$\nu, \overline{\nu}$	0.8, 0.7	CH	2007 – 2008
T2K	$\nu, \overline{\nu}$	0.6, 0.6	CH, H_2O, Fe	2010 –

PDG (Neutrino Cross Section Measurements Review)

MicroBooNE has the advantage of
High-precision event reconstruction
High-statistics ν-Ar data

* See Sophie's MicroBooNE overview talk

- **Constrain model systematics for future oscillation studies**
  SBN and DUNE have the same target material: argon
- **Probe for nuclear effects**
  Argon is a big nucleus. Our studies are sensitive to final states.
- **Contribute ν-Ar scattering measurements for the development of various generators**
  Data on neutrino interaction with argon nucleus is rare!

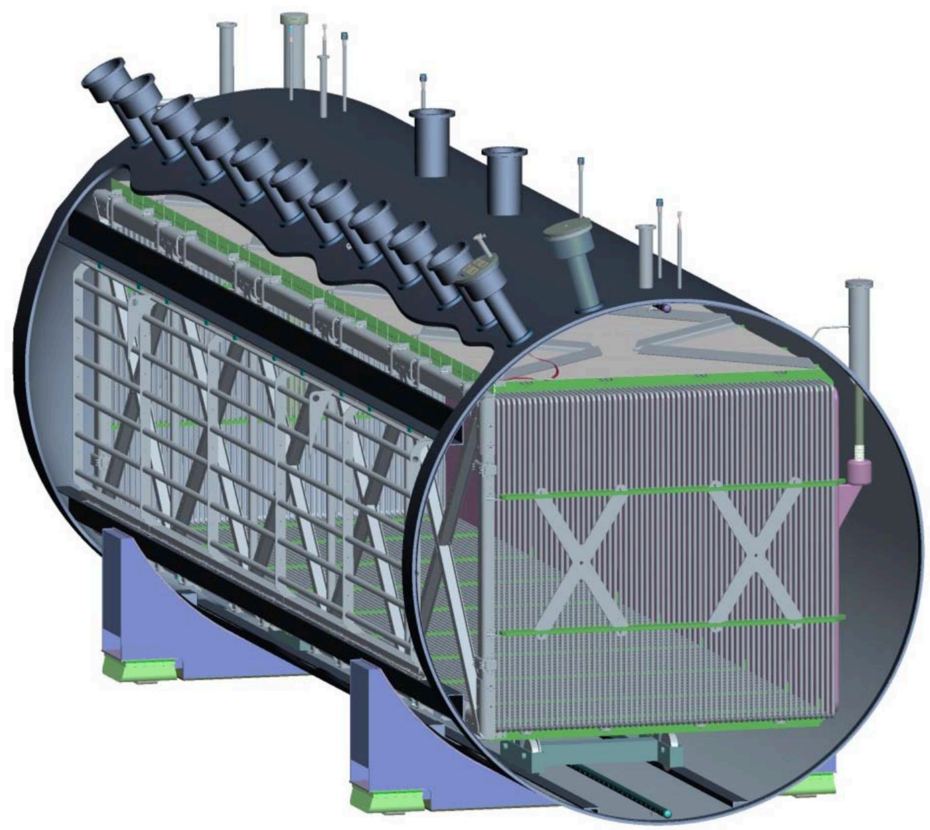
Topology-based Cross-section Analyses

BNB
Booster Neutrino Beam

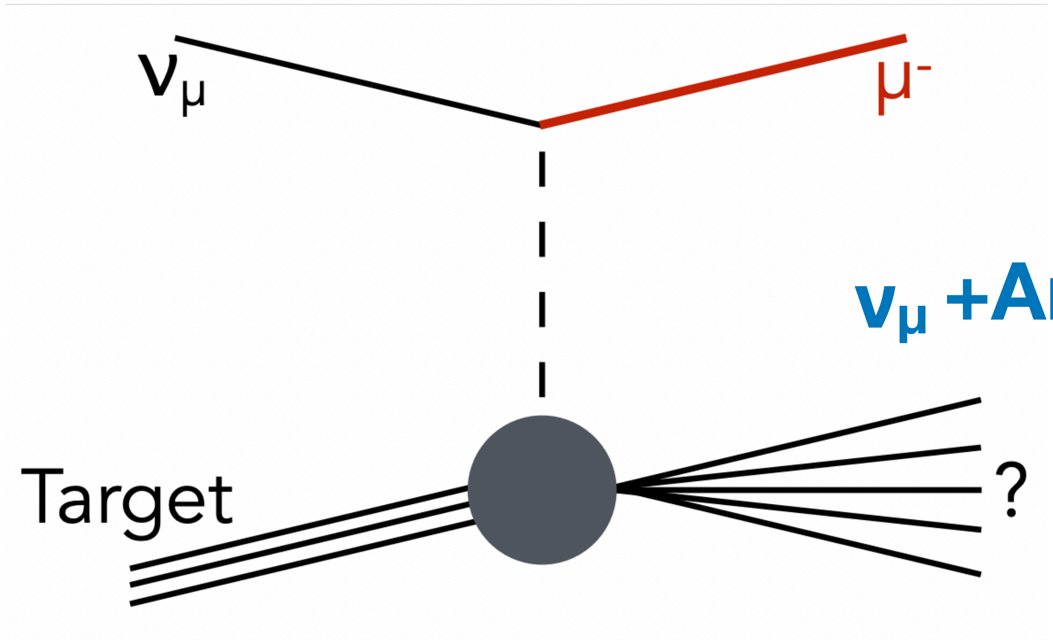
- ν_μ CC inclusive
  - → ν_μ CC π^0
  - → ν_μ CC 0π
    - → ν_μ CC 0π 2p
    - → ν_μ CC 0π Np
- NC elastic

NuMI
The Neutrinos at the Main Injector beam

- ν_e CC inclusive



ν_μ Charge Current Inclusive



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

$\nu_\mu + Ar \rightarrow \mu^- + X$

- **First double differential cross-section on argon** muon kinematics: p_μ and $\cos\theta_\mu$
- **First inclusive measurement on argon at low O(1GeV) neutrino energies**
- **Full angular coverage**
- **Full momentum coverage**
  Multiple Coulomb Scattering (MCS)* is used to reconstruct muon momentum, which allows muon to be either contained or exiting

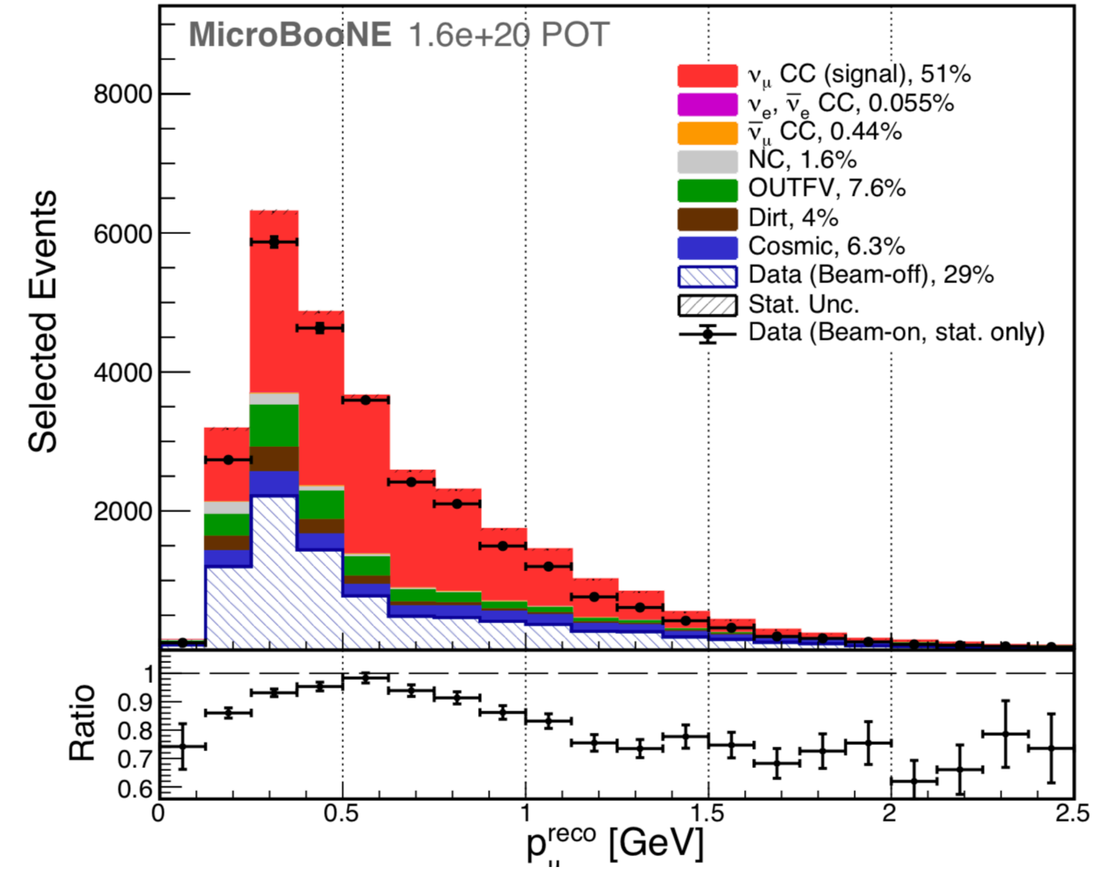
* JINST 12 P10010 (2017)

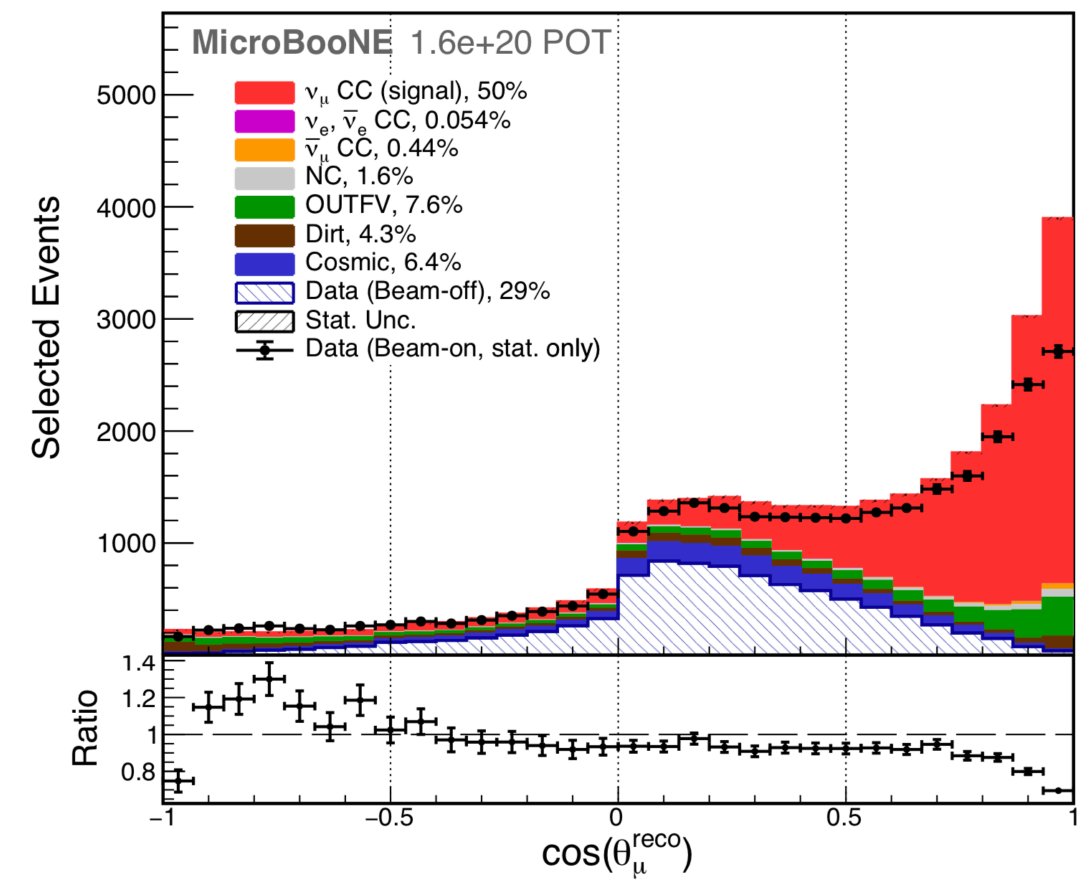
ν_μ Charge Current Inclusive: Selection

Selected Events: 27,200
Signal purity: 50.4%

- **Cosmic rejection:**
  - Through-going tacks
  - Tracks outside of the TPC time window with the trigger t0
  - Stopping muons (by Bragg peak and/or Michel electron tagging)
  - Flash Match:

    Check the consistency of reconstructed light signals from the PMTs and the modelled light signal corresponding to a cluster of charge deposition
- **Reconstruction quality**
- **M.I.P consistency (by calorimetry)**
- **Fiducial volume**





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

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ν_μ Charge Current Inclusive: Systematics

$$E^{\text{syst}} = E^{\text{flux}} + E^{\text{xsec}} + E^{\text{detector}} + \ldots$$

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

Source of uncertainty	Relative uncertainty [%]
Beam flux	12.4
Cross section modeling	3.9
Detector response	16.2
Dirt background	10.9
Cosmic ray background	4.2
MC statistics	0.2
Statistics	1.4
Total	23.8

Various detector aspects, such as dynamic induced charge, light yield, space charge effect and electron lifetime**, are considered in the simulation and/or are calibrated in the latest analyses.**

ν_μ Charge Current Inclusive: Results

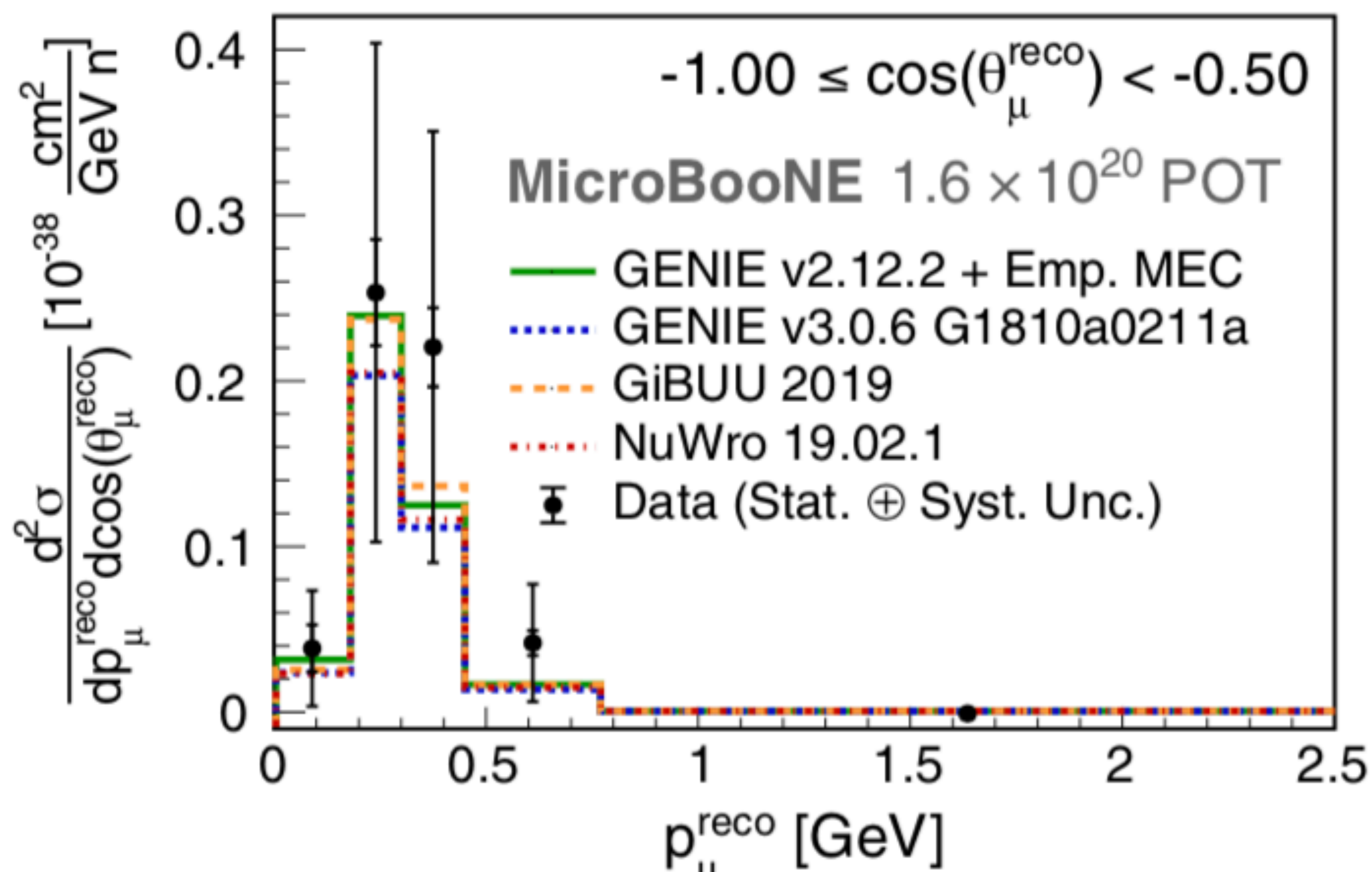
$$\left\langle \frac{d^2\sigma}{dp_\mu^{reco} d\cos\theta_\mu^{reco}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{target} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu \cdot \Delta \cos\theta_\mu)_i}$$

i identifies a bin in the $p_\mu \cos\theta_\mu$ space

Forward folding with detector smearing and efficiency published

Model	χ^2/ Nbins
GENIE v2 + MEC	245.9/42
GENIE v3	108.8/42
GiBUU	172.9/42
NuWro	126.5/42

Test against different models:
High χ^2 is mostly driven by high momentum bins in forward direction



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

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ν_μ CC π^0

From ν_μ CC pre-selection

Single-shower selection:

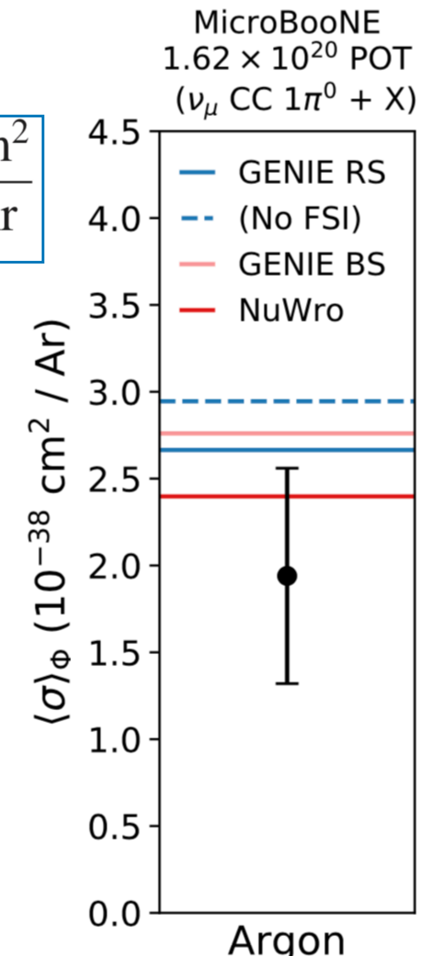
- Able to reconstruct and distinguish photon shower
- Able to identify vertex
- Verified with conversion distance

Two-shower verification:

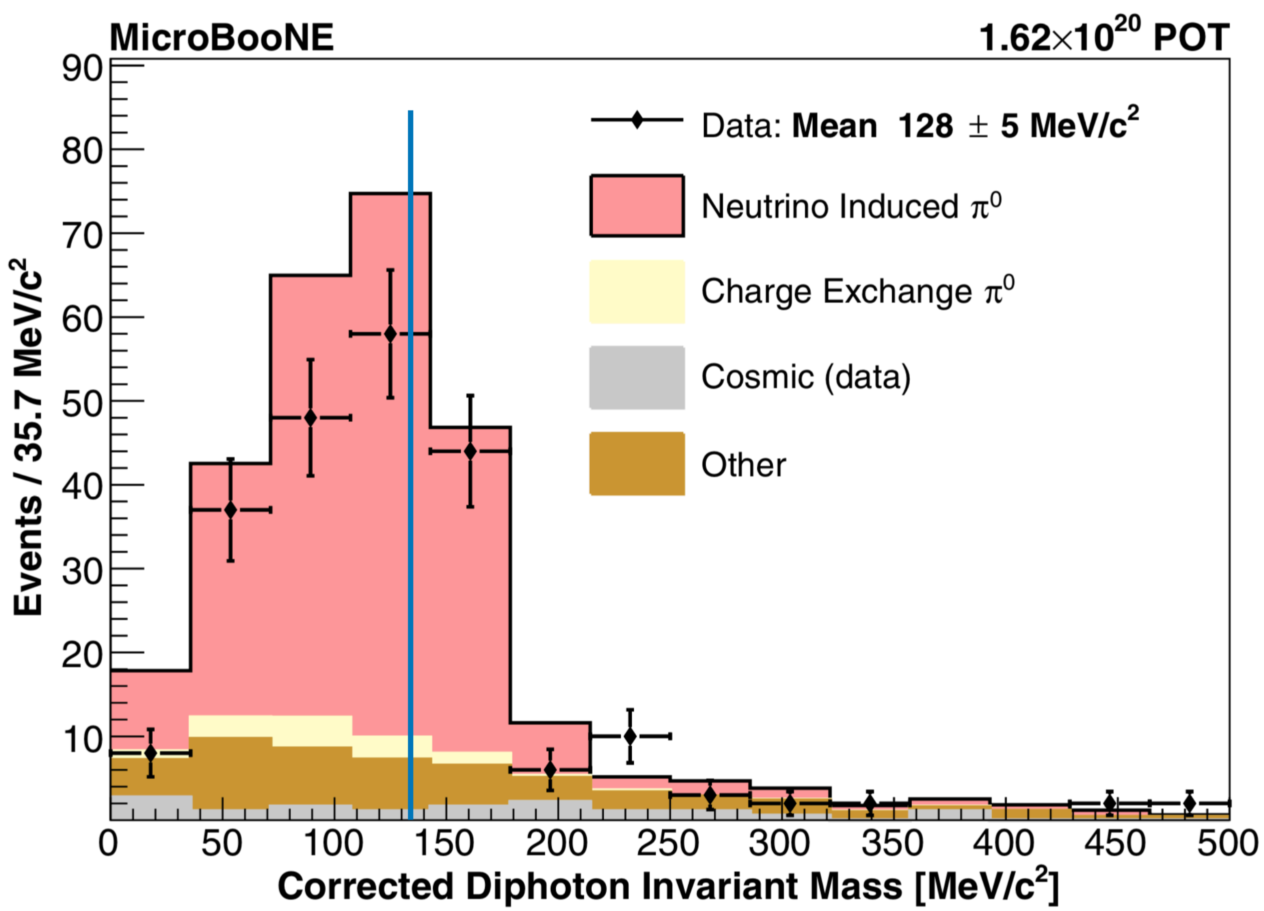
- Test with π^0 mass

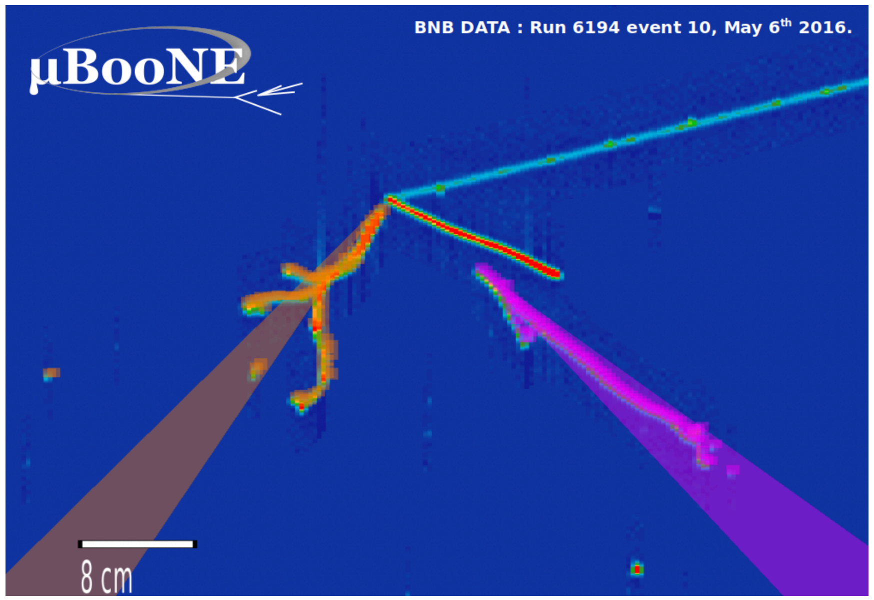
Phys. Rev. D 99, 091102(R) (2019)

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



First on argon
Flux integrated cross-section measurement of ν_μ CC π^0





C. Adams et al 2020 JINST15 P02007

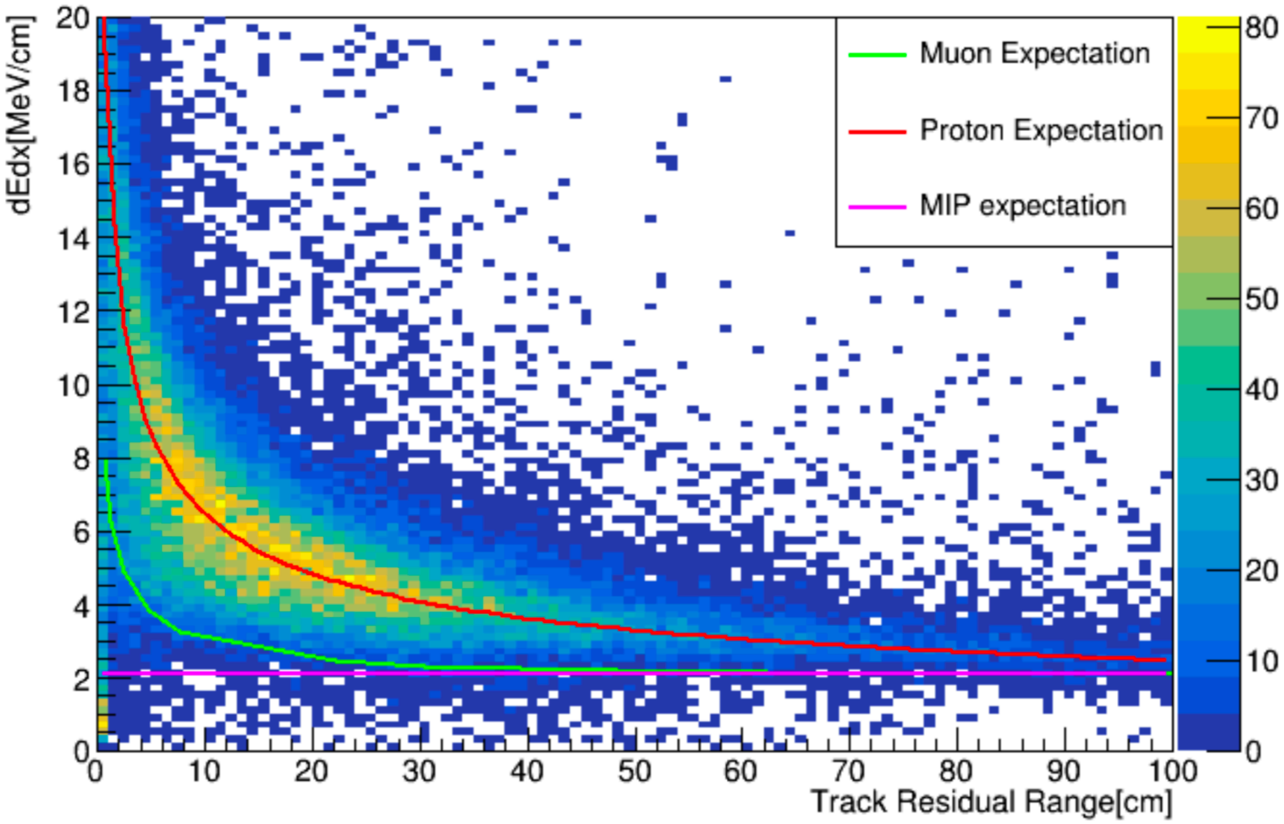
ν_μ CC 0π with Protons

From ν_μ CC inclusive selection

Proton identification

Using χ^2 test statistics
to compare dE/dx profile to the theoretic
profile from Bethe-Bloch

Protons are required to be contained



Proton purity > 92%

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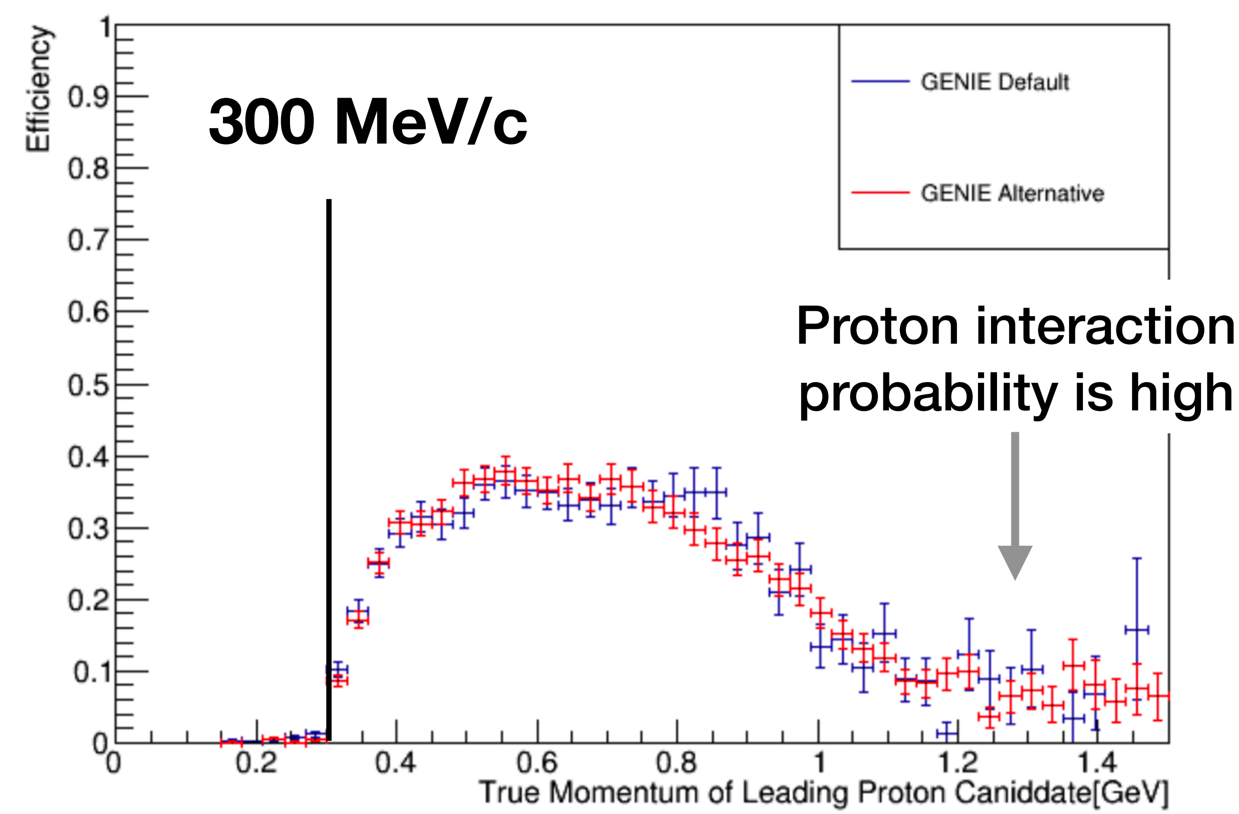
Proton threshold

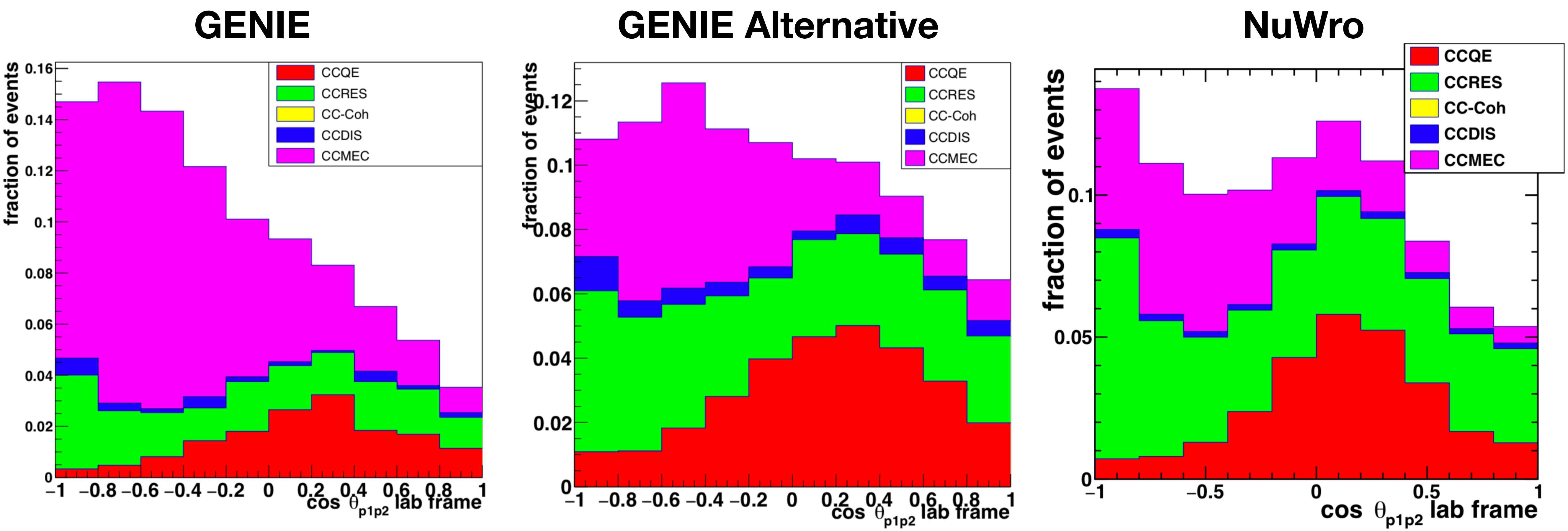
- Kinematic energy: **47 MeV**
- Track length: **1.5 cm**



The lowest energy threshold in current running accelerator-based neutrino experiments.

ν_μ CC 0π 2p

Same selection in different models



- **Probe nuclear dynamics**
- **Support the development of generators**

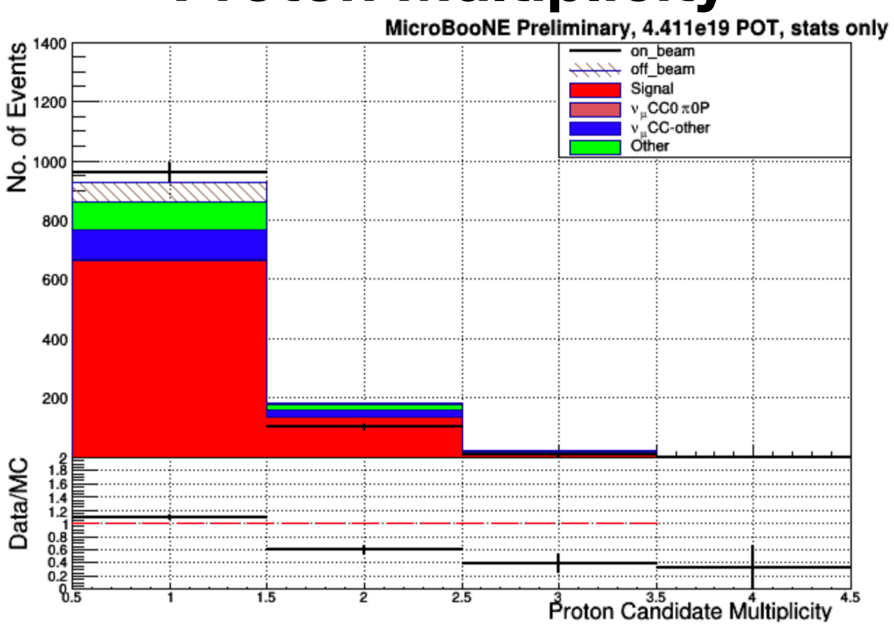
MICROBOONE-NOTE-1056-PUB PRL in preparation

ν_μ CC 0π Np (N>0)

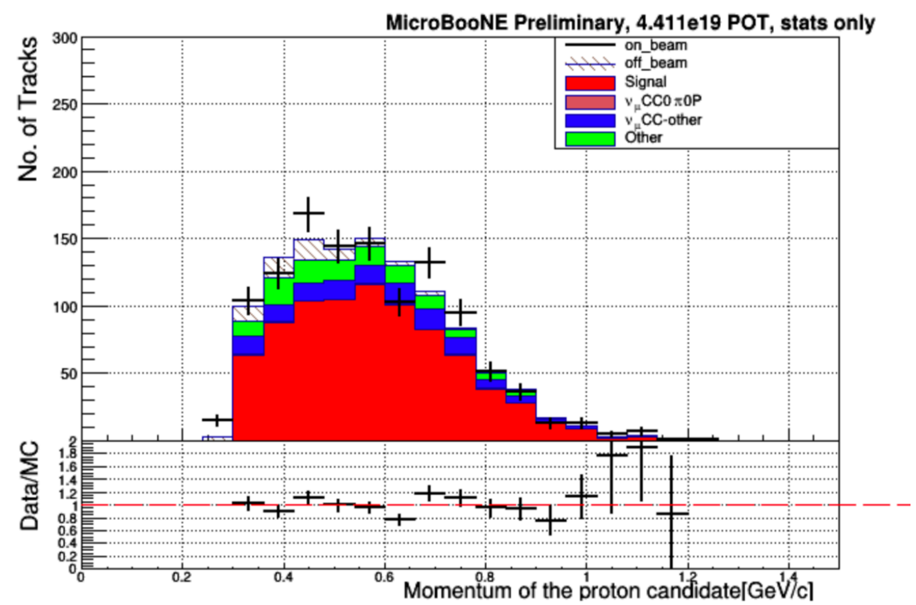
Proton multiplicity

	Nreco=1	Nreco=2	Nreco=3	Nreco=4	Nreco=5
Ntrue=1	4404	128	4	0	0
Ntrue=2	663	621	9	0	0
Ntrue=3	113	115	49	1	1
Ntrue=4	18	36	23	5	0
Ntrue=5	7	17	10	2	0

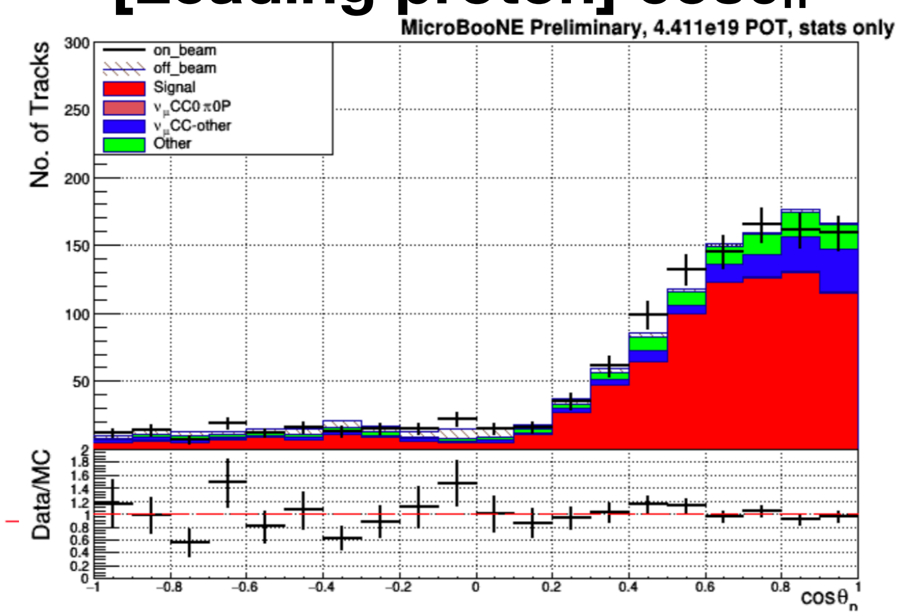
Proton Multiplicity



[Leading proton] Momentum



[Leading proton] cosθ$_n$



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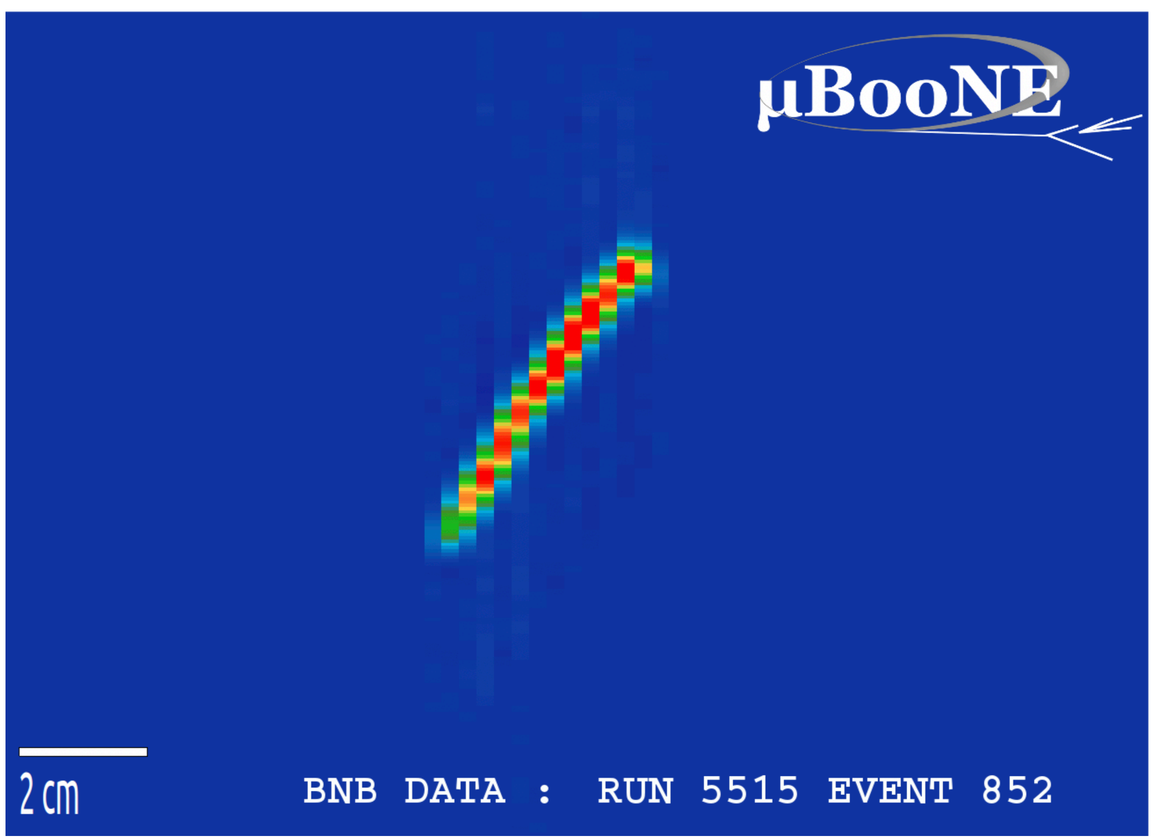
PRD in preparation (differential cross-section measurement)

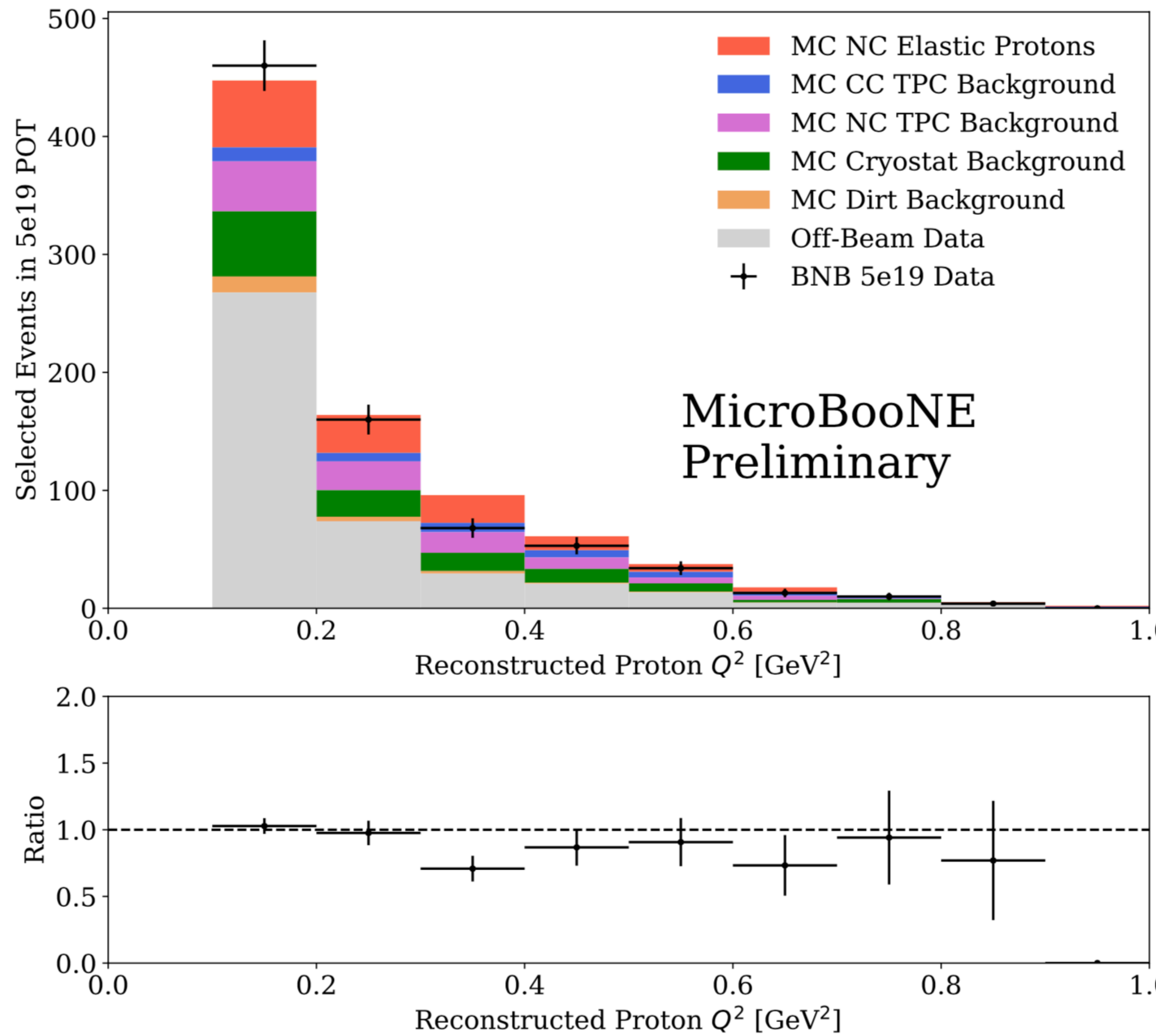
NC Elastic

$\nu_\mu + Ar \rightarrow \nu_\mu + p + N^*$

- The topology is a single proton
- Decent efficiency (expect ~1000 NC elastic events in the collected data)
- Goal: cross-section and axial mass measurement



$$Q_p^2 = 2T_pM_p$$



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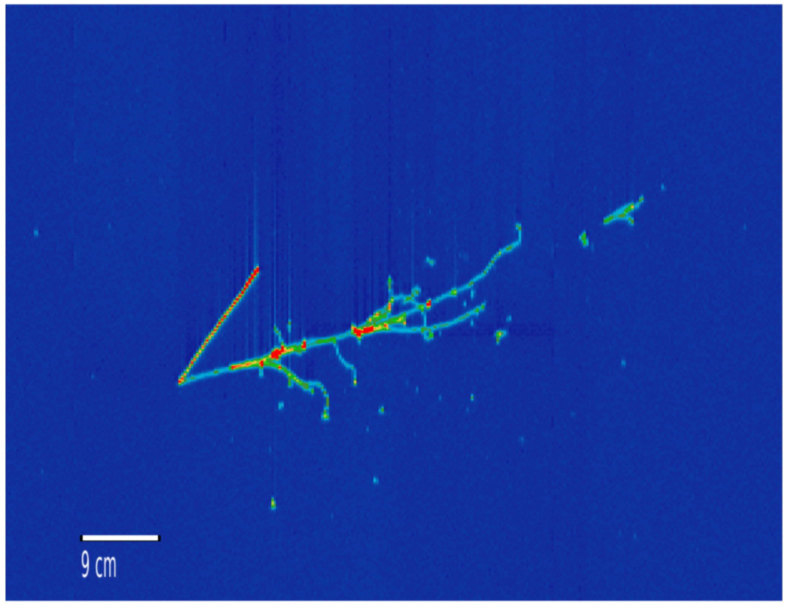
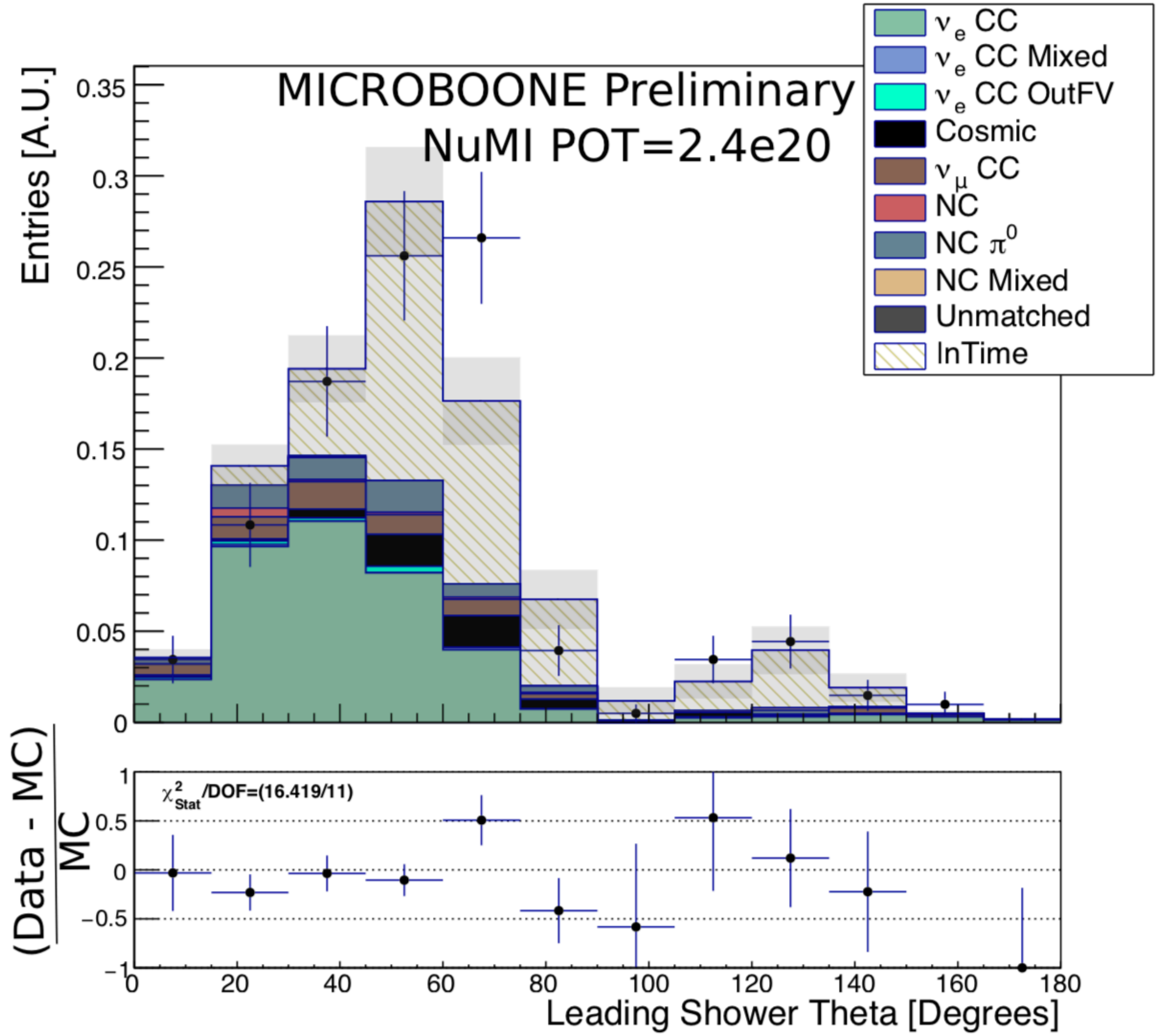
ν_e CC inclusive

$\nu_e / \overline{\nu}_e + Ar \rightarrow e^{\pm} + X$



- **Using NuMI** (5% ν_e in NuMI flux comparing <1% ν_e in BNB flux) **to measure ν_e inclusive cross-section**
- **Automated selection**
  - Identify electron shower
  - ~100 signal events
- **Verified with closure test in measuring cross-section**

$\sigma_{MC} = 4.83 \pm 0.69\ (stat) \pm 1.20\ (sys) \times 10^{-39}\ cm^2$



MICROBOONE-NOTE-1054-PUB

Paper in preparation

Work in Progress - Near Future Measurements

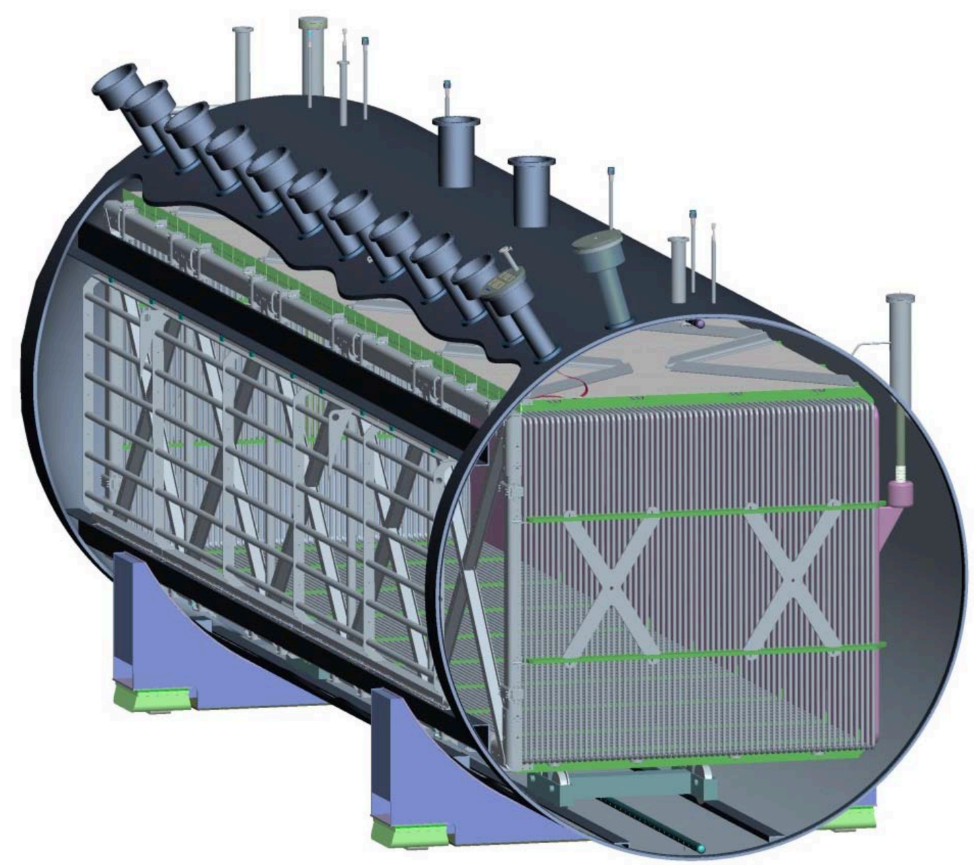
Mostly topology-based measurement

BNB

- **ν_μ CC inclusive** (with updated simulation, detector calibration and cosmic ray tagger)
- **ν_μ CC π+**
- **ν_μ CC π^0** (differential cross-section measurement)
- **ν_μ CC 0π 0p**
- **ν_μ CC 0π 1p**
- **Transverse variables in ν_μ CC0π**
- **ν_μ CC kaon production**
- **NC elastic scattering**

NuMI

- **ν_e CC inclusive**
- **ν_e CC Np**
- **Kaon decay at rest**



Summary

MicroBooNE ν-Argon cross-section measurements are important for:

- Constraining model systematics for future oscillation experiments (SBN/DUNE)
- The development of neutrino interaction generators
- Understanding backgrounds for beyond standard model physics

MicroBooNE published cross-section measurements:

- ν_μ CC inclusive (first double differential measurement on argon, first inclusive measurement in O(1 GeV) neutrino energy on argon)
  Phys. Rev. Lett. 123, 131801 (2019)
- ν_μ CC π^0 (first π^0 cross-section measurement on argon)
  Phys. Rev. D 99, 091102(R) (2019)

Preliminary results (public)

- ν_μ CC 0π 2p
- ν_μ CC 0π Np
- NC elastic
- ν_e NC inclusive (NuMI)

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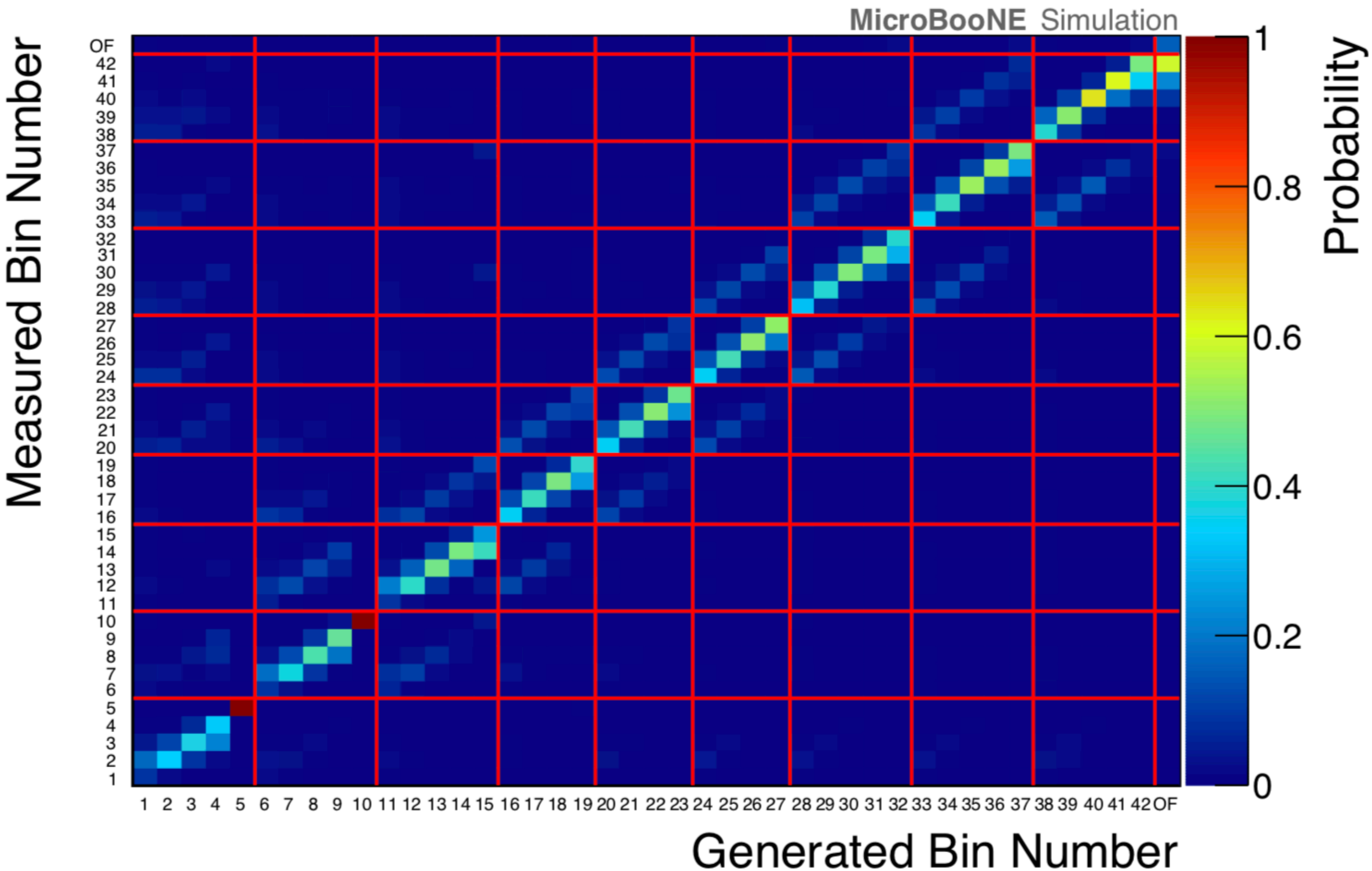
More results coming soon!

Back Up

ν_μ Charge Current Inclusive: Migration Matrix



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ν_μ Charge Current Inclusive: Systematics

$$E^{\text{syst}} = E^{\text{flux}} + E^{\text{xsec}} + E^{\text{detector}}$$

$$E_{ij} = \frac{1}{N_s}\sum_{s=0}^{N_s}(\sigma_i^s - \sigma_i^{cv})(\sigma_j^s - \sigma_j^{cv})$$

$$E_{ij}^{det} = \sum_{m=1}^{u}(\sigma_i^{cv} - \sigma_i^m)(\sigma_j^{cv} - \sigma_j^m)$$

Source of uncertainty	Relative uncertainty [%]
Beam flux	12.4
Cross section modeling	3.9
Detector response	16.2
Dirt background	10.9
Cosmic ray background	4.2
MC statistics	0.2
Statistics	1.4
Total	23.8

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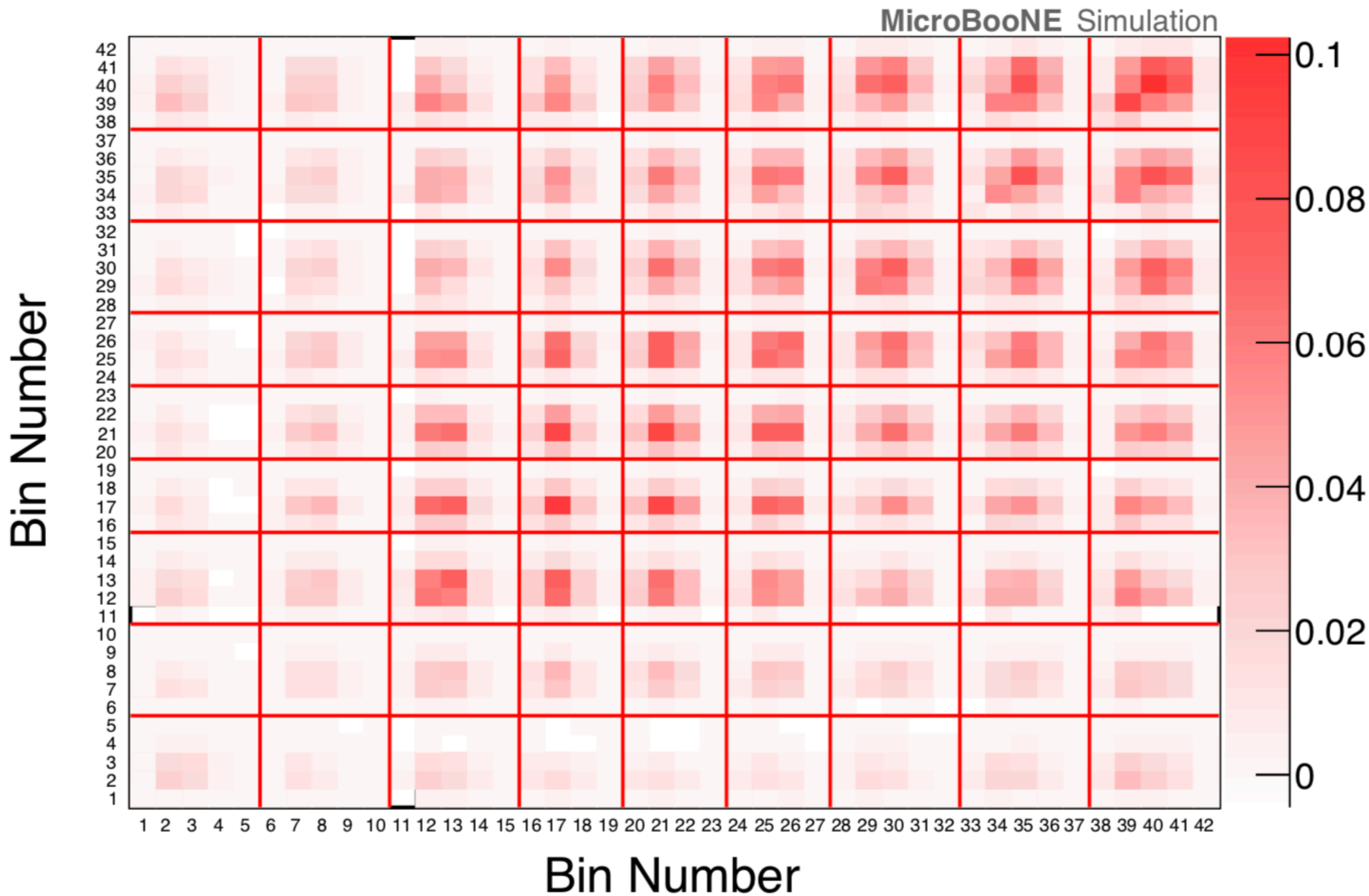
Systematic Sample	Relative Uncertainty [%]
Induced Charge Effect	13.0
Light Yield Model	4.7
Channel Saturation	4.3
Space Charge Effect	3.7
TPC Visibility	3.7
Electron Lifetime	2.9
Misconfigured Channels	1.8
Longitudinal Diffusion	1.7
Transverse Diffusion	1.6
PE Noise	0.4
Wire Response	0.2
Wire Noise	0.1
Electron Recombination	0.1

ν_μ Charge Current Inclusive: Covariance Matrix



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ν_μ Charge Current Inclusive

$$\left\langle \frac{d^2\sigma}{dp_\mu^{\text{reco}} d\cos\theta_\mu^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{target} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu \cdot \Delta \cos\theta_\mu)_i}$$

i identifies a bin in the $p_\mu \cos\theta_\mu$ space

Forward folding with detector smearing and efficiency published

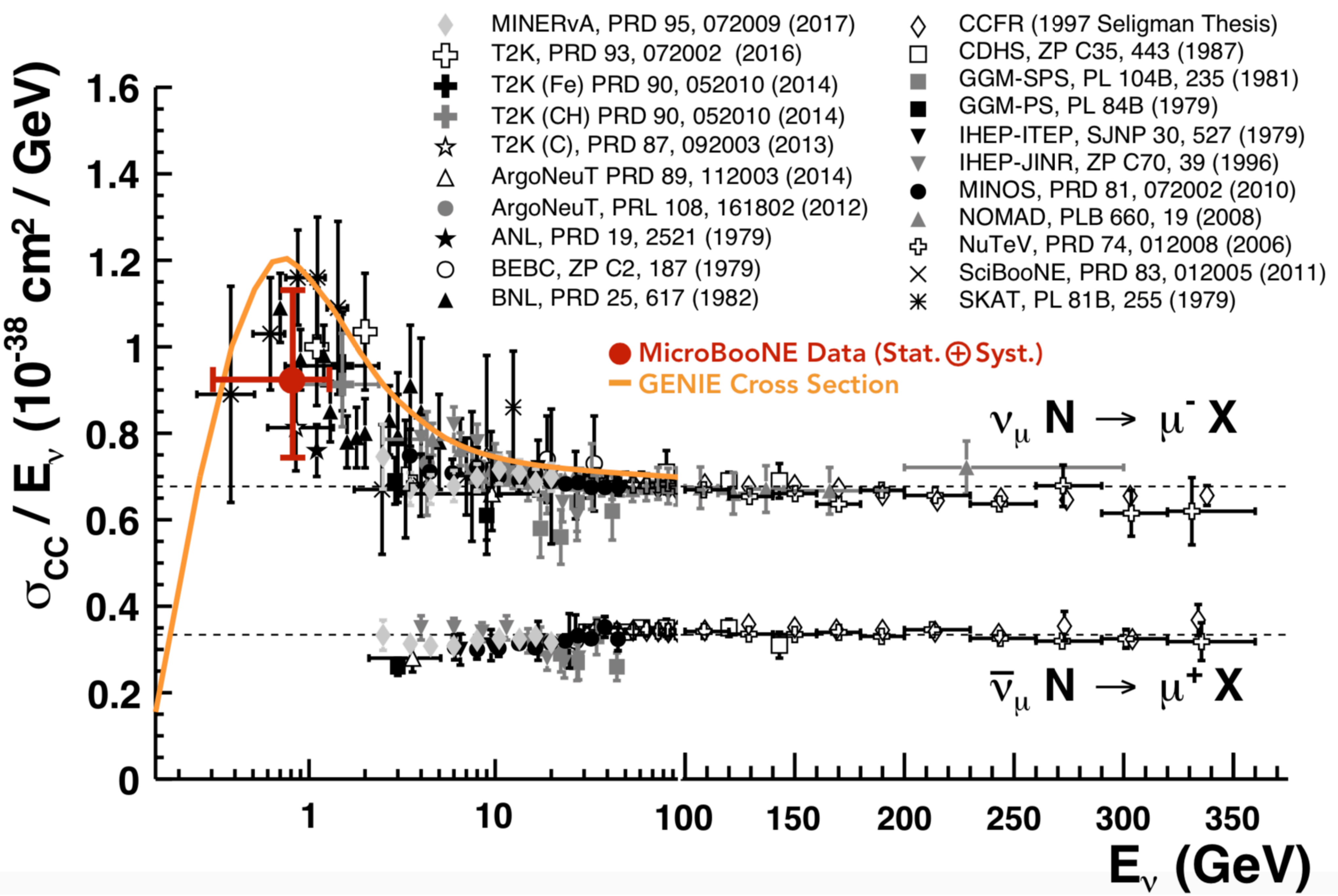
$$\tilde{\epsilon}_i = \frac{\sum_{j=1}^{M} S_{ij} N_j^{\text{sel}}}{\sum_{j=1}^{M} S_{ij} N_j^{\text{gen}}},$$

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

ν_μ Charge Current Inclusive: Results

Flux integrated cross-section per nucleon

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



ν_μ Charge Curent Inclusive: Model Comparison

Model Element	GENIE v2 + MEC (v2.12.2)	GENIE v3 (v3.00.04 G1810a0211a)	NuWro (19.02.1)	GiBUU (2019)
Nuclear Model	Bodek-Ritchie Fermi Gas [1]	Local Fermi Gas [2, 3]	Local Fermi Gas [2, 3]	Consistent nuclear medium corrections throughout. Also uses a LFG model for nucleon momenta, a separate MEC model [11], and propagates final state particles according to the Boltzmann-Uehling-Uhlenbeck equations [11]
Quasi-elastic	Llewellyn-Smith [4]	Nieves [2, 3]	Nieves [2, 3]	
MEC	Empirical [5]	Nieves [2, 3]	Nieves [2, 3]	
Resonant	Rein-Seghal [6]	Berger-Seghal [7]	Berger-Seghal [7] (pion production from [9])	
Coherent	Rein-Seghal [6]	Berger-Seghal [7]	Berger-Seghal [7]	
FSI	hA [8]	hA2018 [8]	Oset [10]	

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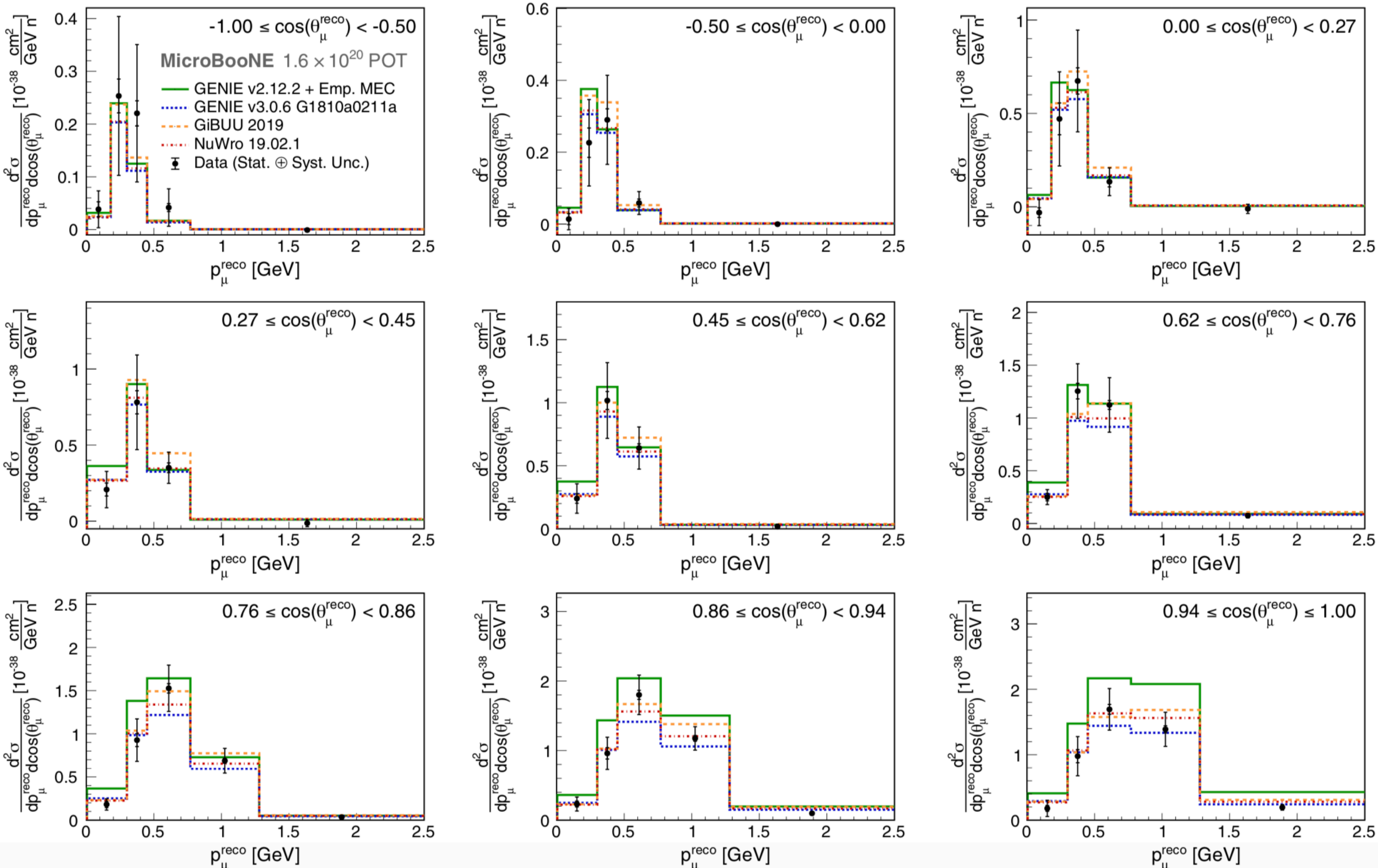
ν_μ Charge Curent Inclusive: Results



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

ν_μ CC 0π 2p: Model Comparison

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

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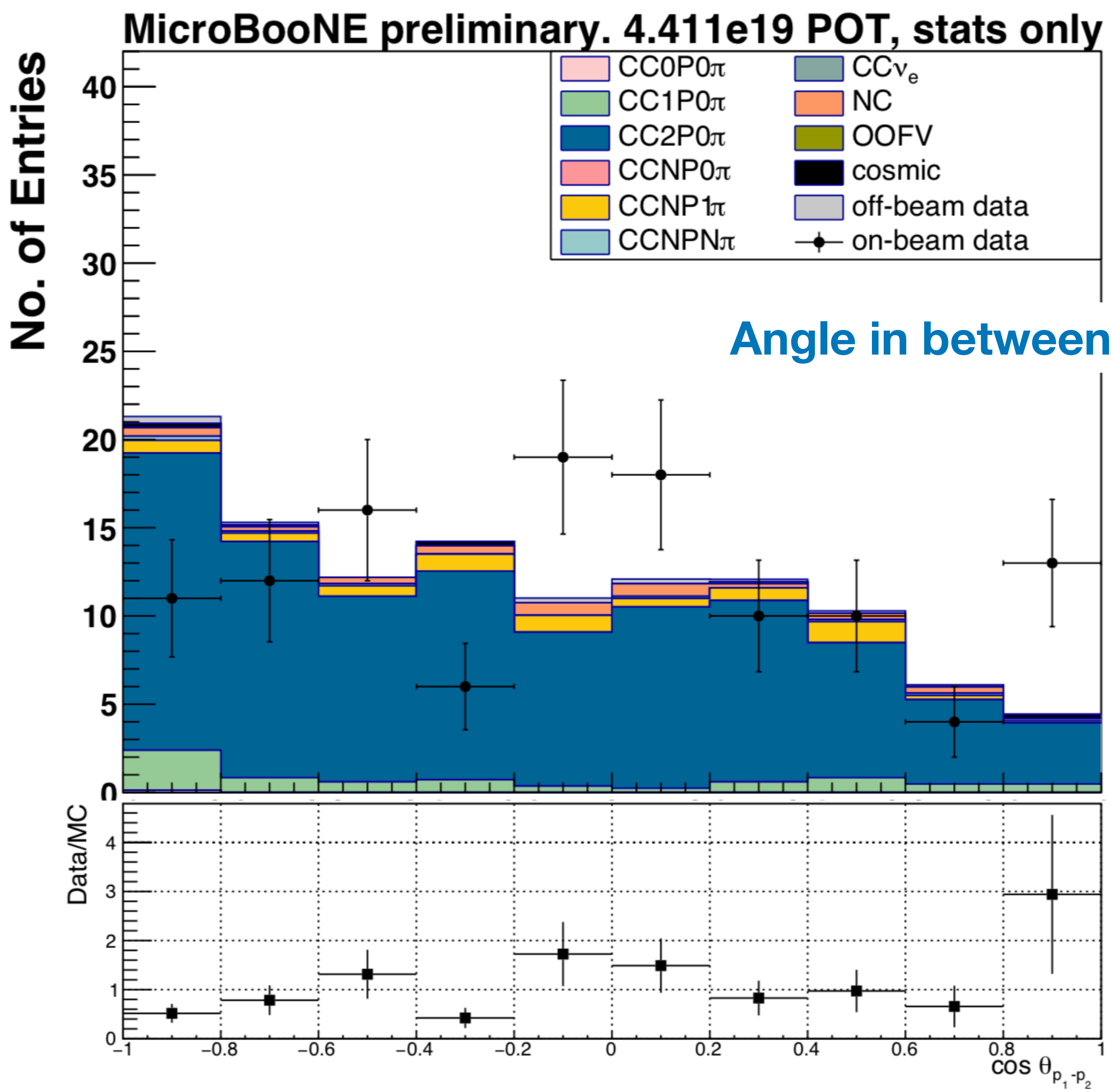
ν_μ CC 0π 2p



Angle in between the two protons

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