Recent neutrino cross-section results from MicroBooNE

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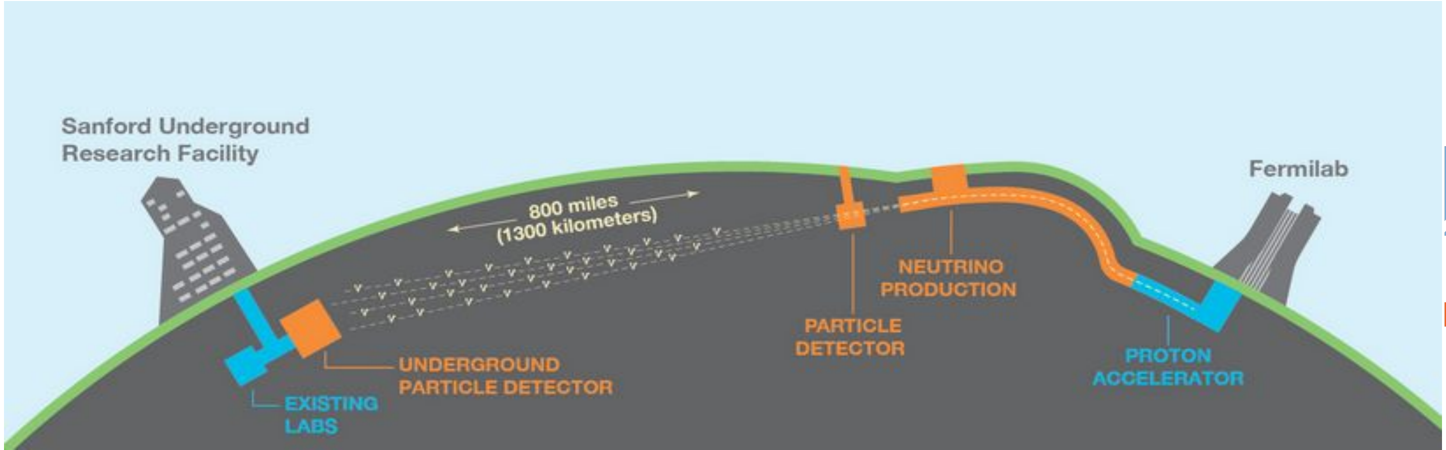
Overview

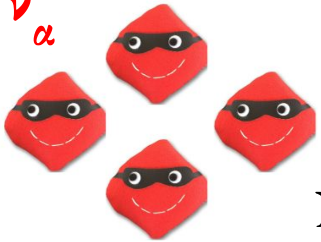
- Era of high precision neutrino oscillation measurements aiming to extract the oscillation parameters and to determine the mass hierarchy
- Liquid Argon Time Projection Chambers (LArTPCs) are state-of-the-art detectors in neutrino physics
- Demand for precise ν cross section measurements on a complex nucleus

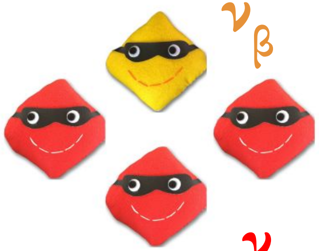


DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Importance of Cross Section Measurements

ν_α





ν_β

ν_α

Source → **Near Detector**: Detect ν_α - - - Distance L - - → **Far Detector**: Detect ν_β

Event Rate, Flux, Efficiency, Oscillation probability

$$N(E_{rec}) \sim \Phi(L,E_{\nu,true})\ \sigma(E_{\nu,true})\ \varepsilon(E_{\nu,true})\ \mathbf{P}(\nu_\alpha \rightarrow \nu_\beta)$$

Precision <u>cross section</u> measurements are a prerequisite for accurate oscillation probability measurements

LArTPC Experiments

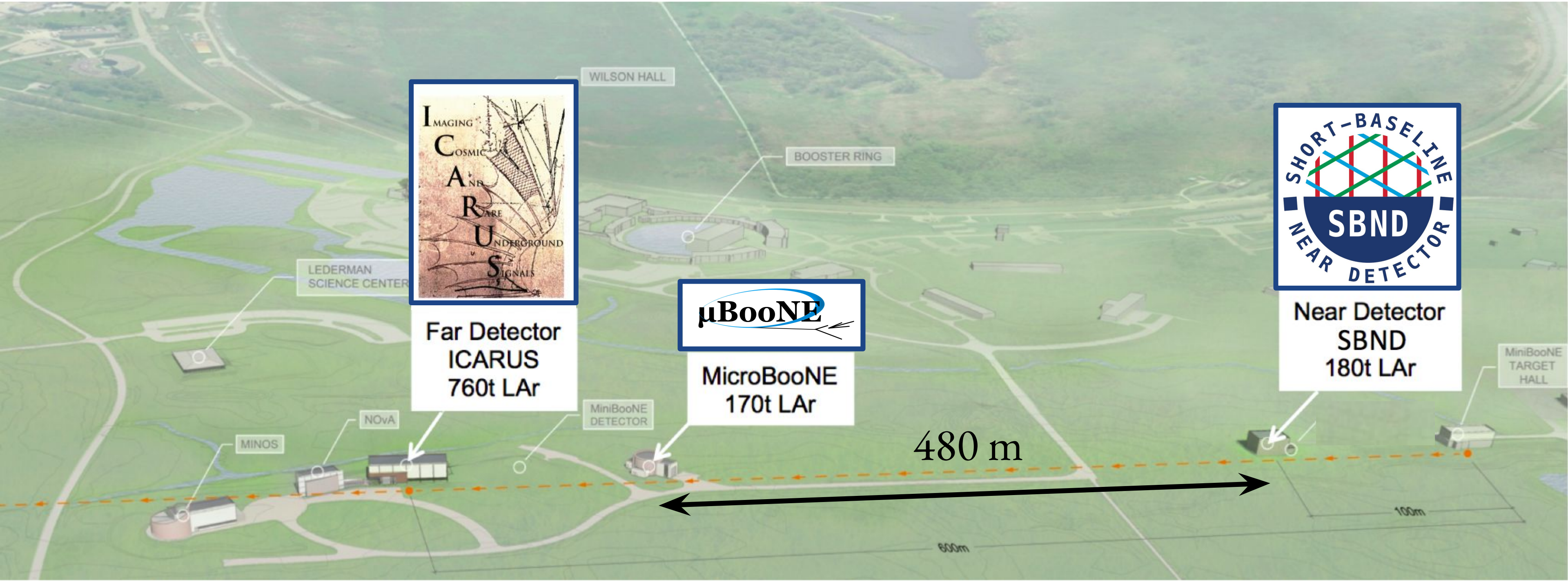
Short Baseline

Long Baseline

- Head start for DUNE with Short-Baseline Neutrino (SBN) Program
- LArTPCs are ideal for detailed measurements of complex topologies
- MicroBooNE has already recorded ~500k ν scattering events over the past 5 years

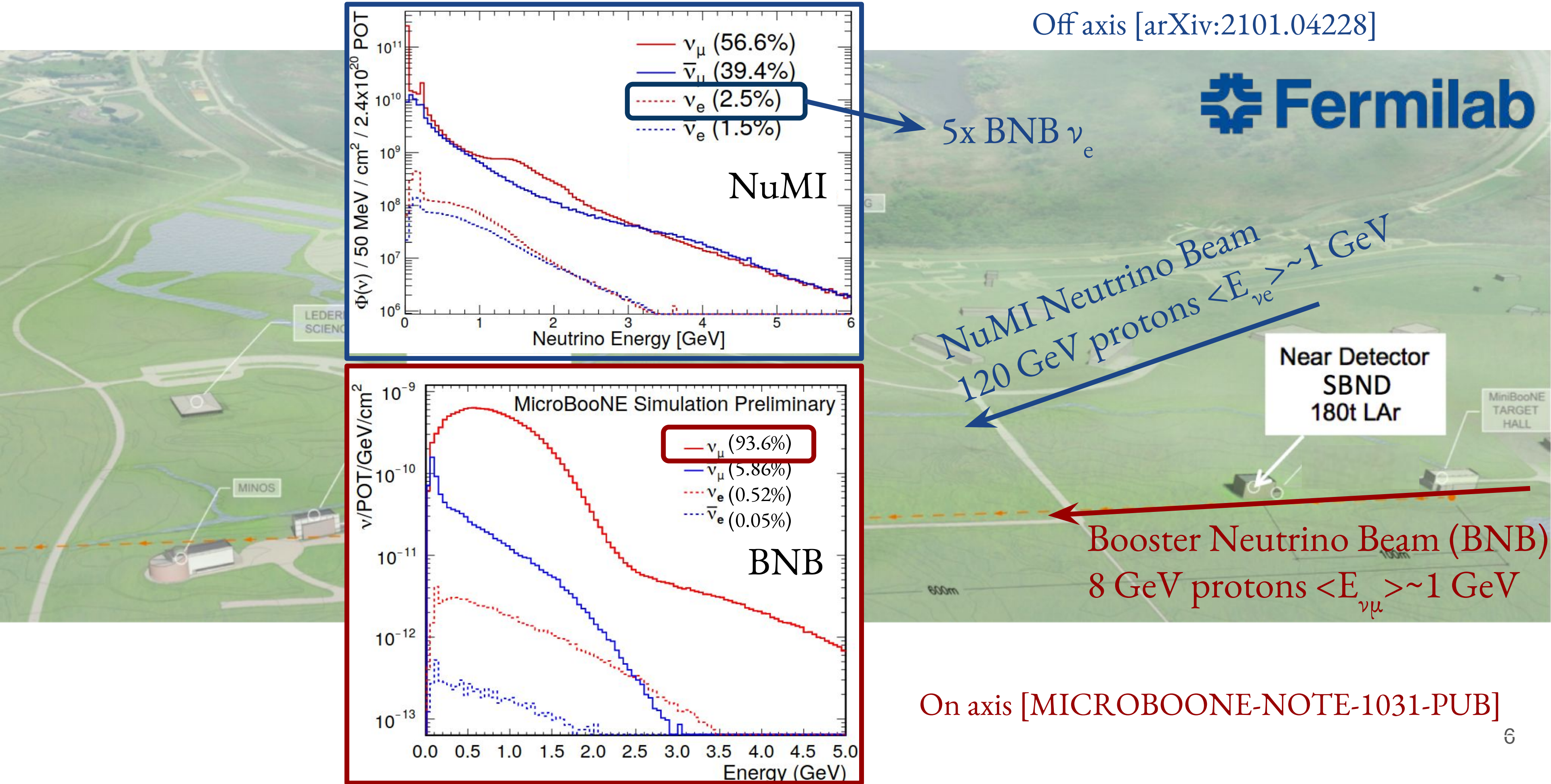
  → Largest available ν-Argon scattering dataset

MicroBooNE @ Fermilab

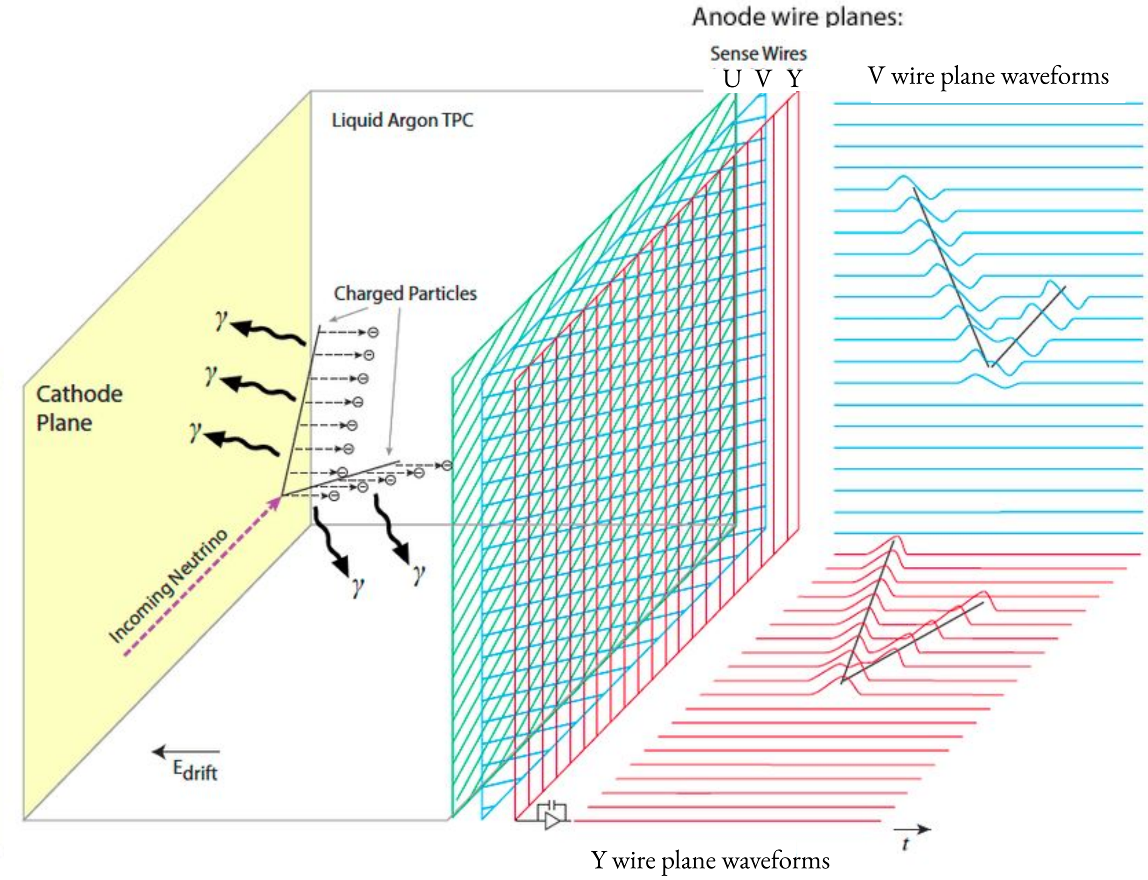


JINST 12, P02017 (2017)

MicroBooNE Beams

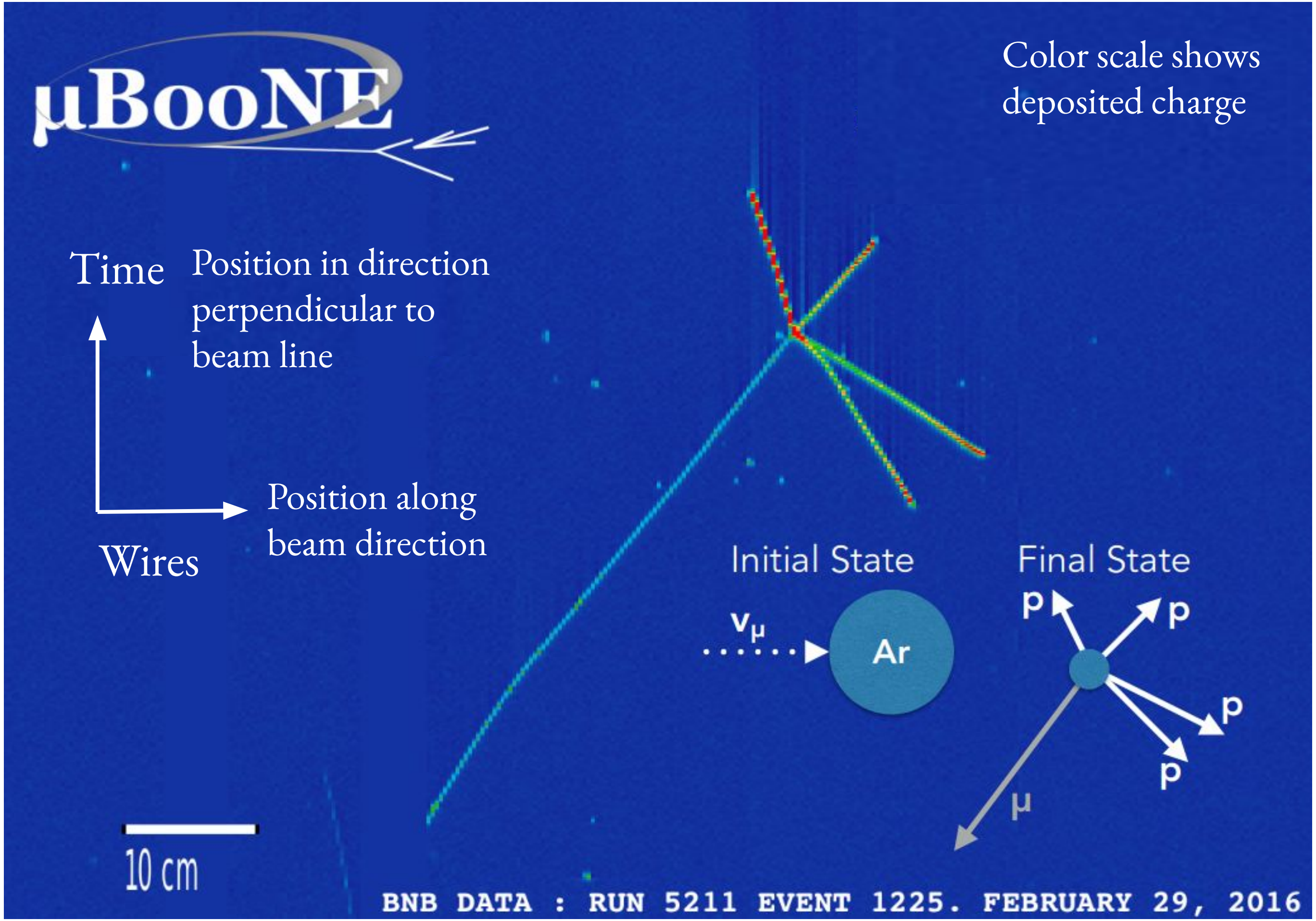


Time Projection Chambers



MicroBooNE detector

- 3 wire planes
- 8192 gold coated wires
- 3 mm wire spacing
- 32 PMTs



MicroBooNE event display

- Low detection thresholds
- Precise calorimetric information
- 4π coverage & high statistics

Wealth Of ν-Argon Scattering Results

- $\nu_e+\bar{\nu}_e$ Charged Current (CC) inclusive cross section
  → Flux averaged total cross section — arXiv:2101.04228

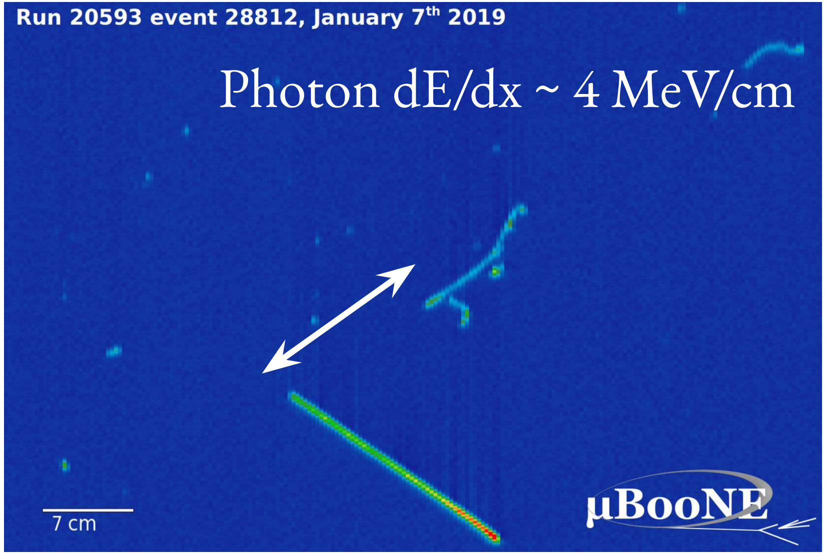
- ν_μ CC inclusive cross section
  → Double differential cross section — **Phys. Rev. Lett. 123, 131801 (2019)**
  → Single differential cross section with updated detector and interaction models
  MICROBOONE-NOTE-1069-PUB

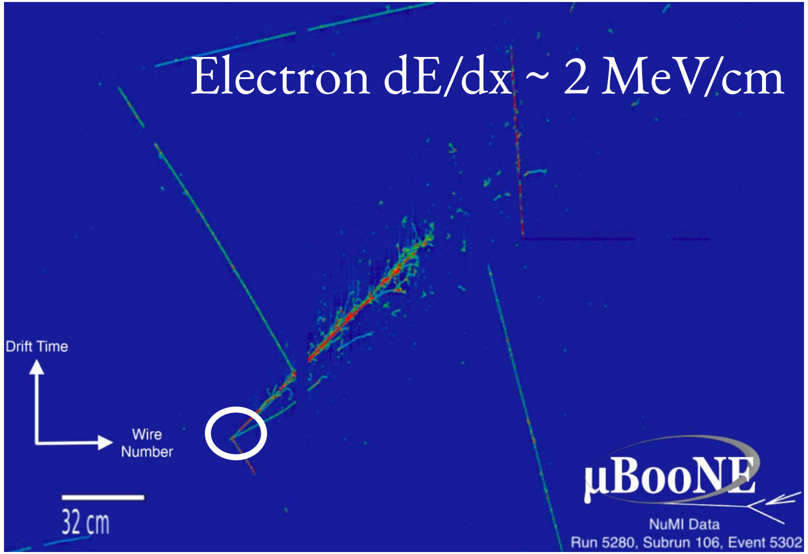
- ν_μ exclusive channels
  → ν_μ CCπ^0 flux averaged total cross section — Phys. Rev. D99, 091102(R) (2019)
  → ν_μ CC with protons and no pions — Phys. Rev. D102, 112013 (2020)
  → ν_μ CCQE-like scattering — Eur. J. Phys. C79, 673 (2019)
  Phys. Rev. Lett. 125, 201803 (2020)
  → ν_μ NC1p production — MICROBOONE-NOTE-1067-PUB

Let's take a closer look at them !

LArTPC Strength: Electrons And Photons

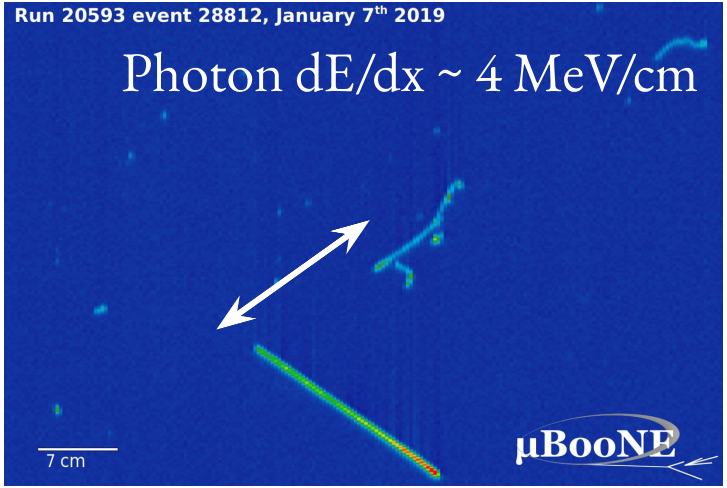
- Both electrons and photons produce showers in LArTPCs
  → Important to understand for ν_e appearance searches in SBN and DUNE
- Photons from π^0 decays are the dominant background
- LArTPC discrimination power using **deposited energy** and **vertex/shower-start distance**

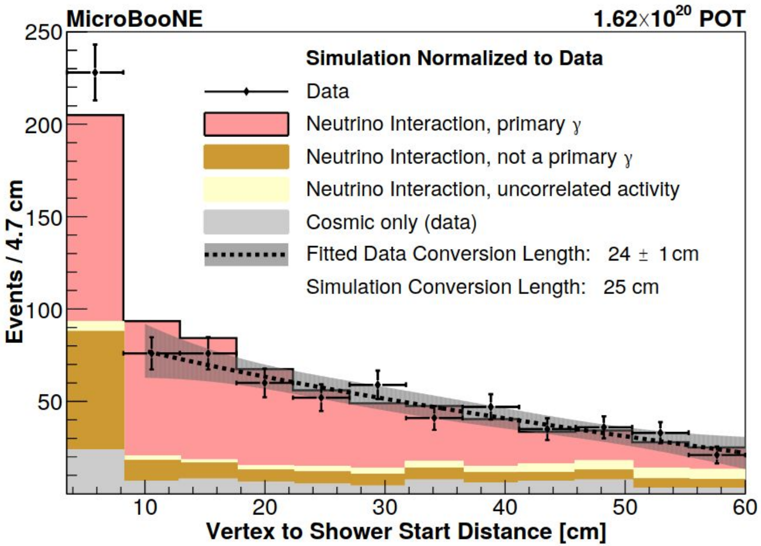


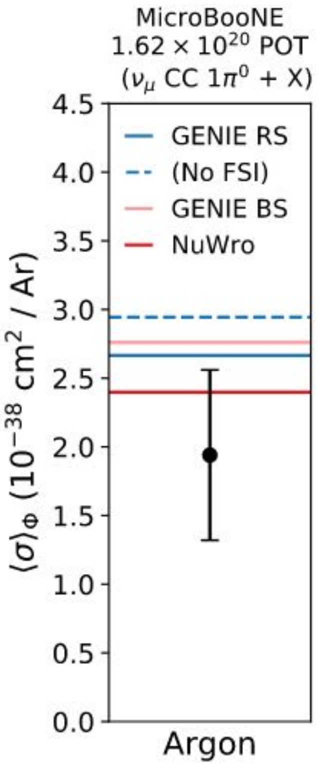


LArTPC Strength: Photons

- Deposited energy of ~ 4 MeV/cm
- Clear separation between interaction vertex and shower start point
- First measurement of flux averaged ν_μ-Ar CCπ^0 cross section



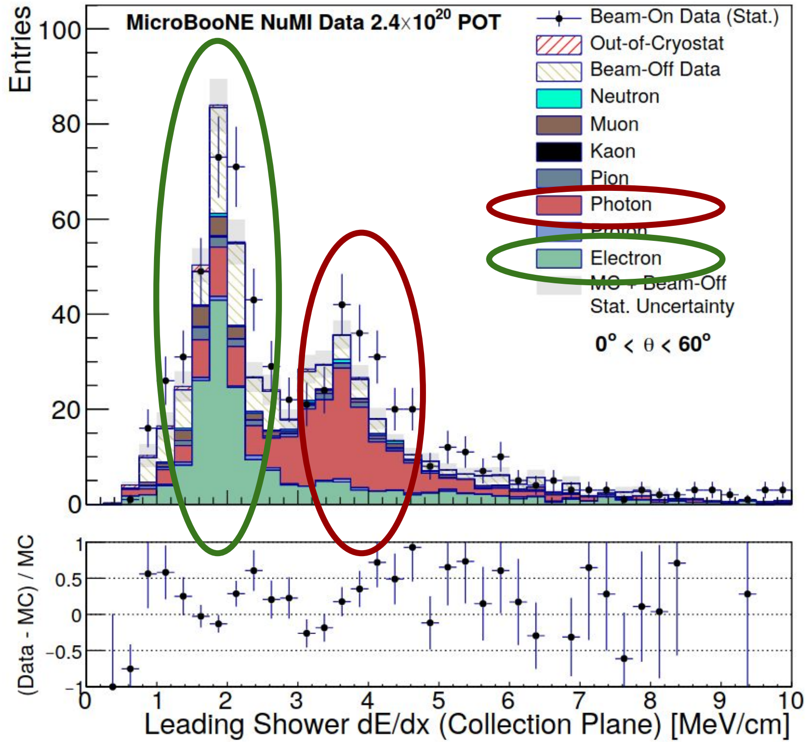


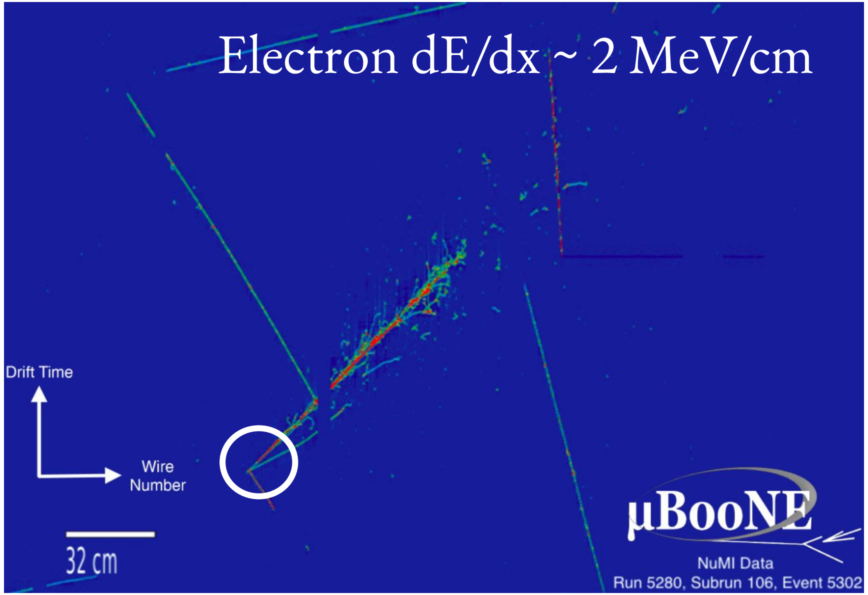


Phys. Rev. D99, 091102(R) (2019)

LArTPC Strength: Electrons

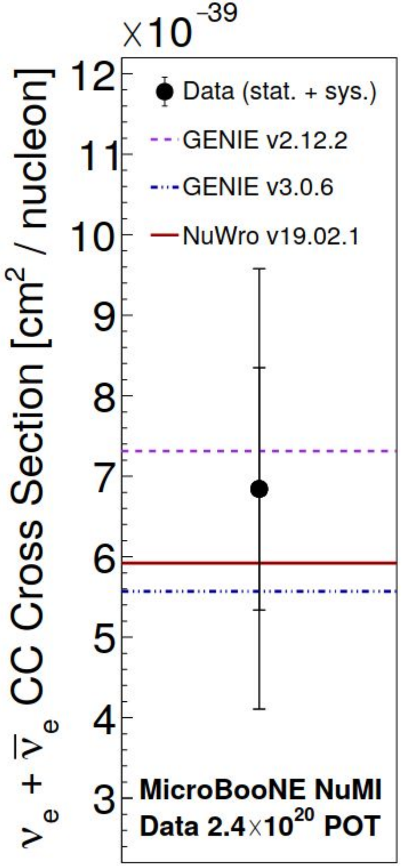
- Electrons deposit half the energy compared to photons
- Shower start attached to interaction vertex





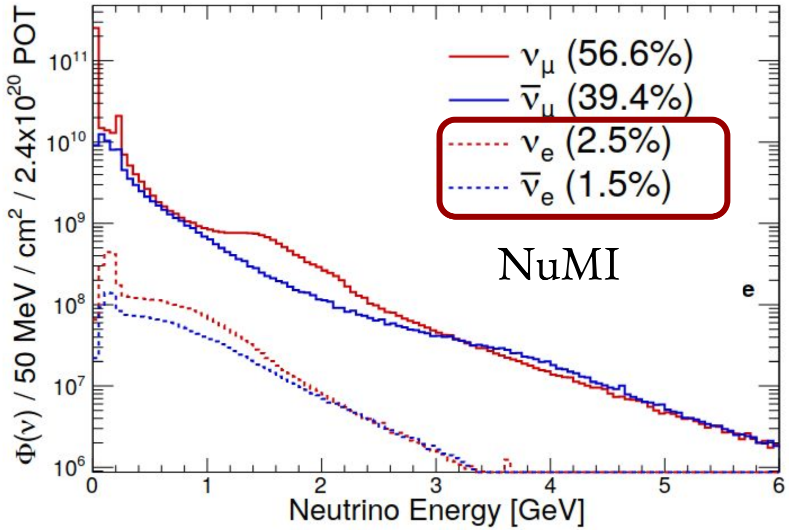
arXiv:2101.04228

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

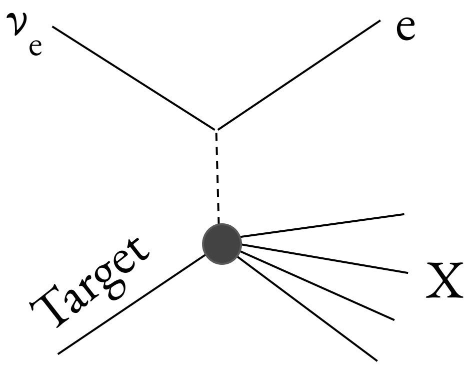


arXiv:2101.04228

- Largest ever sample of ν_e-Ar interactions with > 200 events
- Purity ~40%
- Efficiency ~10%
- In good agreement with models

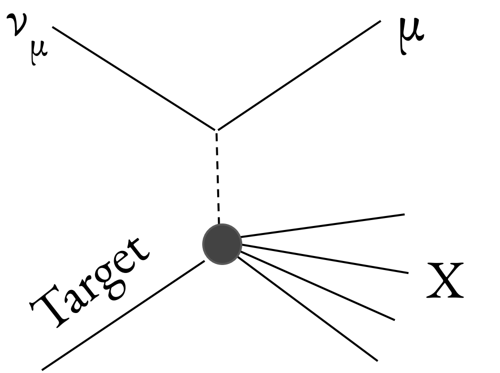


arXiv:2101.04228

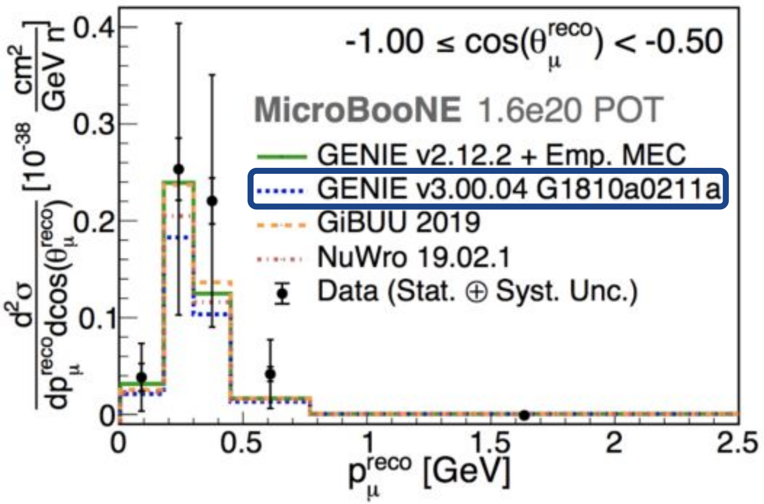


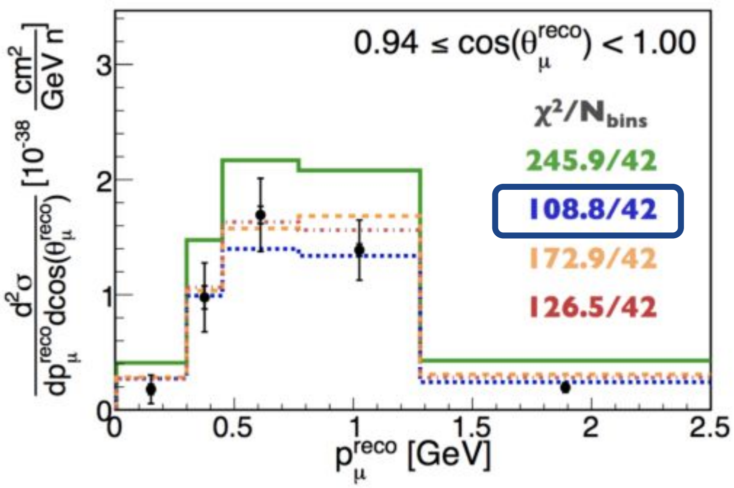
Boosting the ν_e statistics (<1% ν_e in BNB)

ν_μ CC Inclusive @ BNB



- First double differential measurement on Argon
- Overall good agreement with theory
- More recent models achieve better agreement at forward scattering angles





Need more detailed topologies to investigate differences

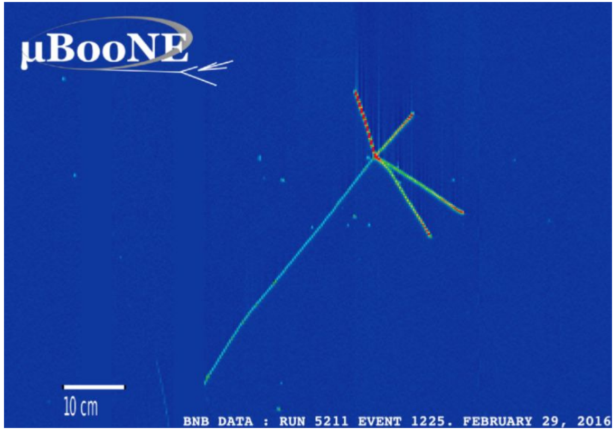
Phys. Rev. Lett. 123, 131801 (2019)

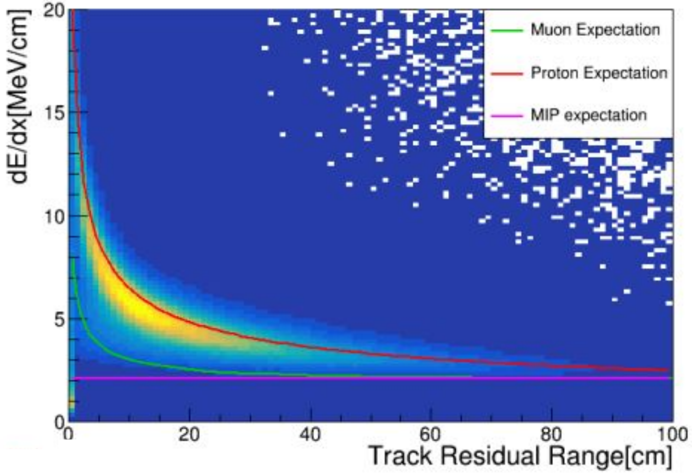
LArTPC Strength: Low Proton Thresholds

- Low thresholds probe more detailed interaction channels and nuclear effects
  → MicroBooNE: **300 MeV/c**
  → ArgoNeuT: 200 MeV/c
  Phys. Rev. D 90, 012008
  → T2K: 500 MeV/c
  Phys. Rev. D 98, 032003
  → MINERvA: 450 MeV/c
  Phys. Rev. D 99, 012004

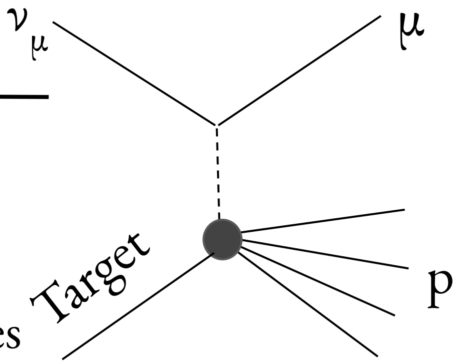
- Protons identified by Bragg peak in last 30 cm of track

JINST 15, P03022 (2020)

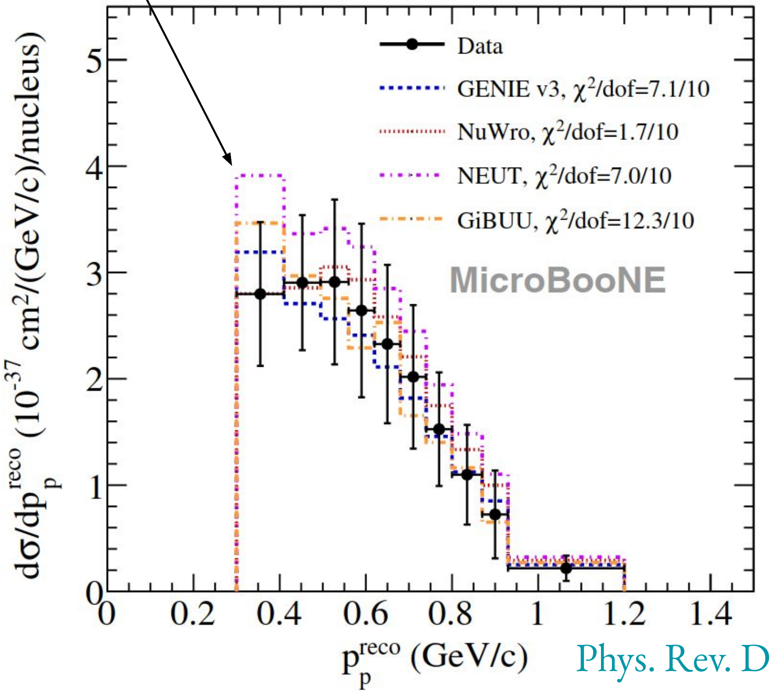


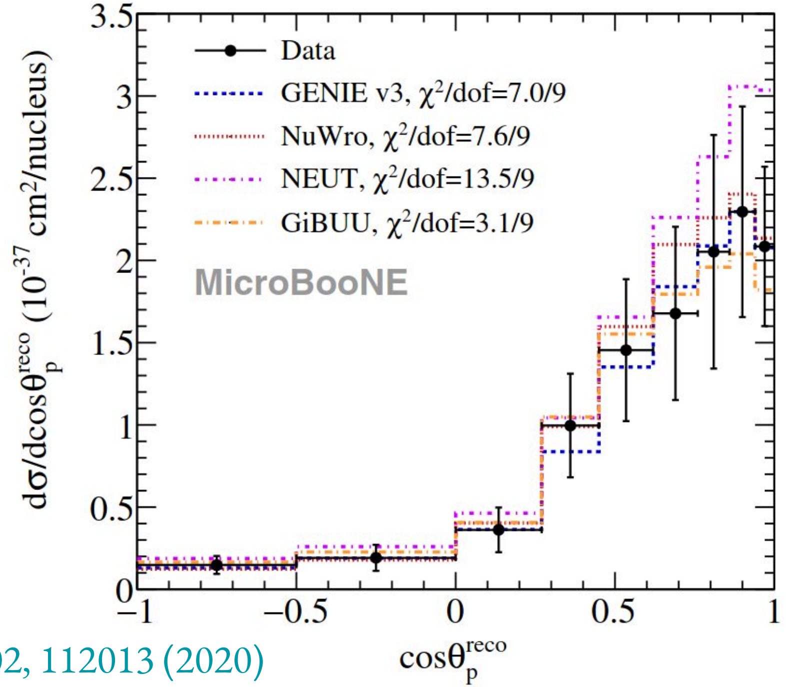


CC0πNp with N≥1



- Event selection: P_μ > 100 MeV/c, 300 < P_p < 1200 MeV/c , 0π
- Purity ~70% & efficiency ~30%
- Overall agreement in proton kinematics
- Bin close to detection threshold most sensitive to model differences

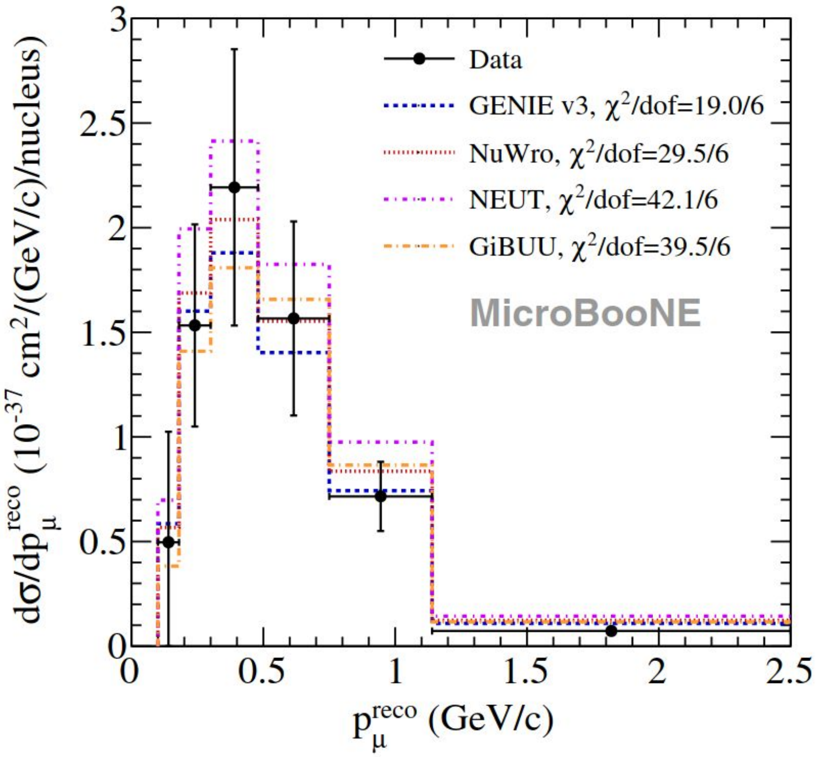


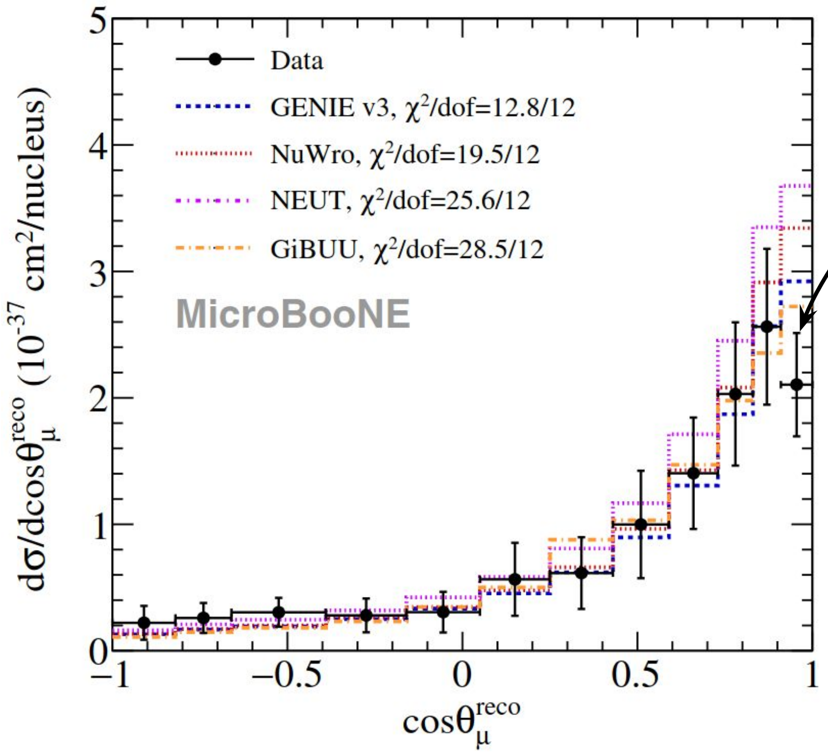


Phys. Rev. D102, 112013 (2020)

CC0πNp with N≥1

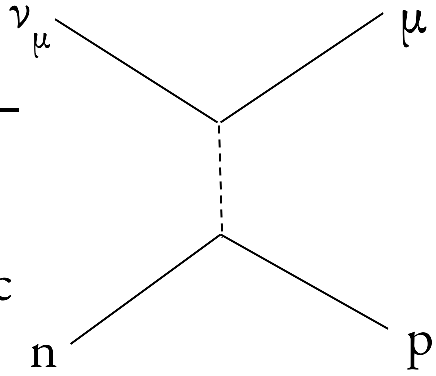
Disagreement in muon kinematics at forward scattering angles





Phys. Rev. D102, 112013 (2020)

CCQE-like



- Simple topology dominant at energies relevant for SBN
- Event selection: P_μ > 100 MeV/c, single proton P_p > 300 MeV/c
- Cosmic contamination reduction

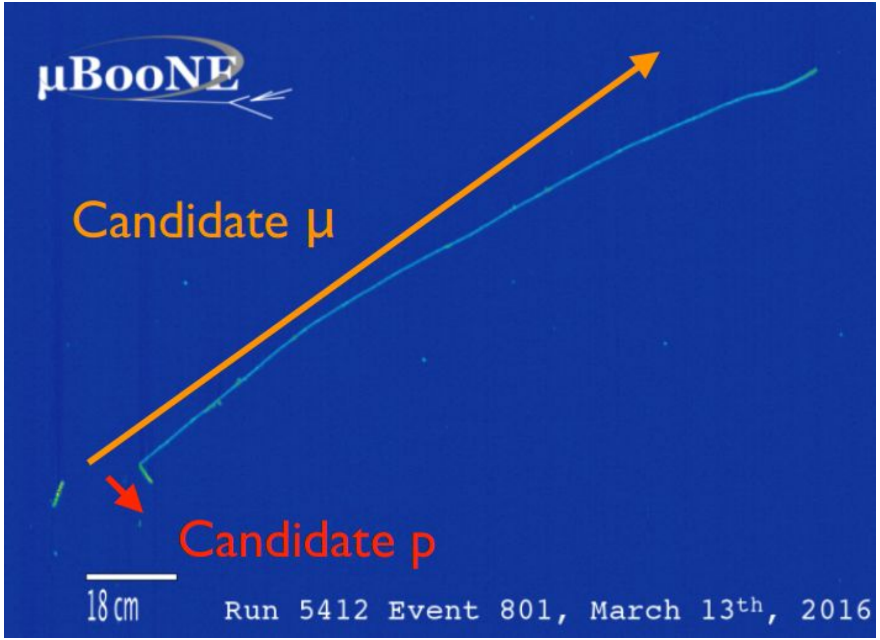
$$|\Delta\theta_{\mu p} - 90^o| < 55^o$$

- QE contribution enhancement

$$|\Delta\phi_{\mu p} - 180^o| < 35^o$$

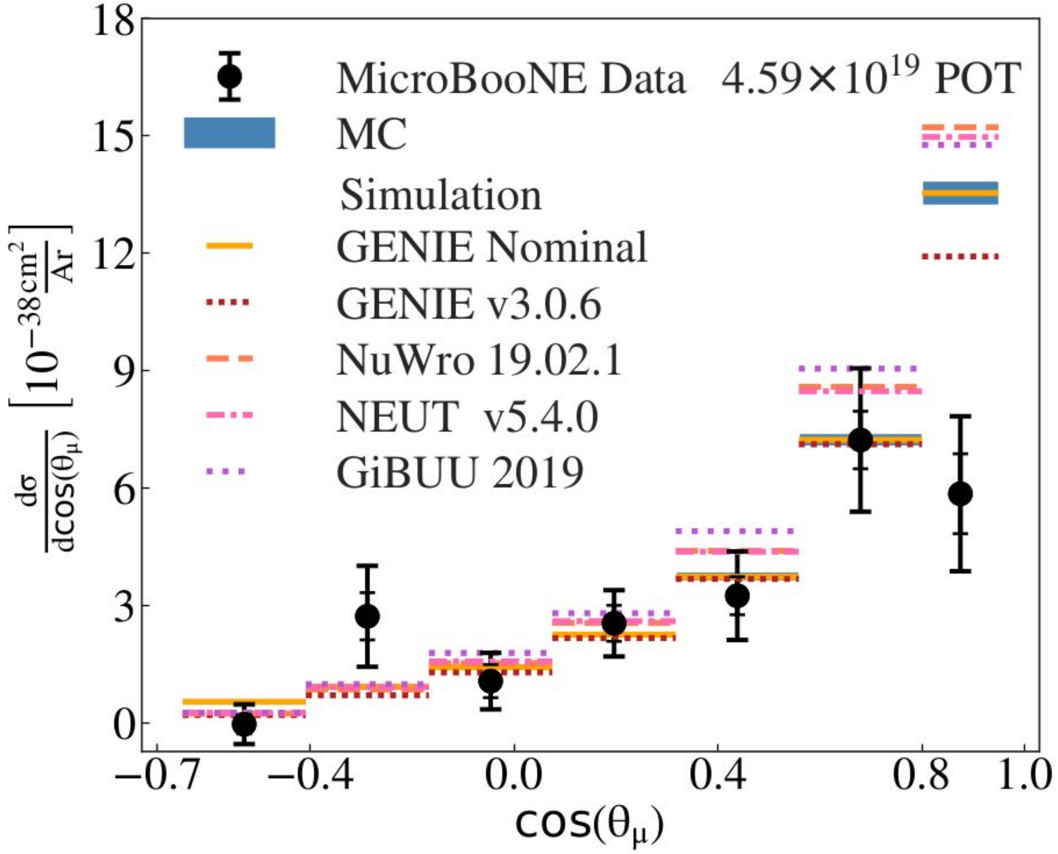
$$P_T = |\vec{P}_\mu + \vec{P}_p|_T < 0.35\, GeV/c$$

- CCQE purity ~80%



Phys. Rev. Lett. 125, 201803 (2020)

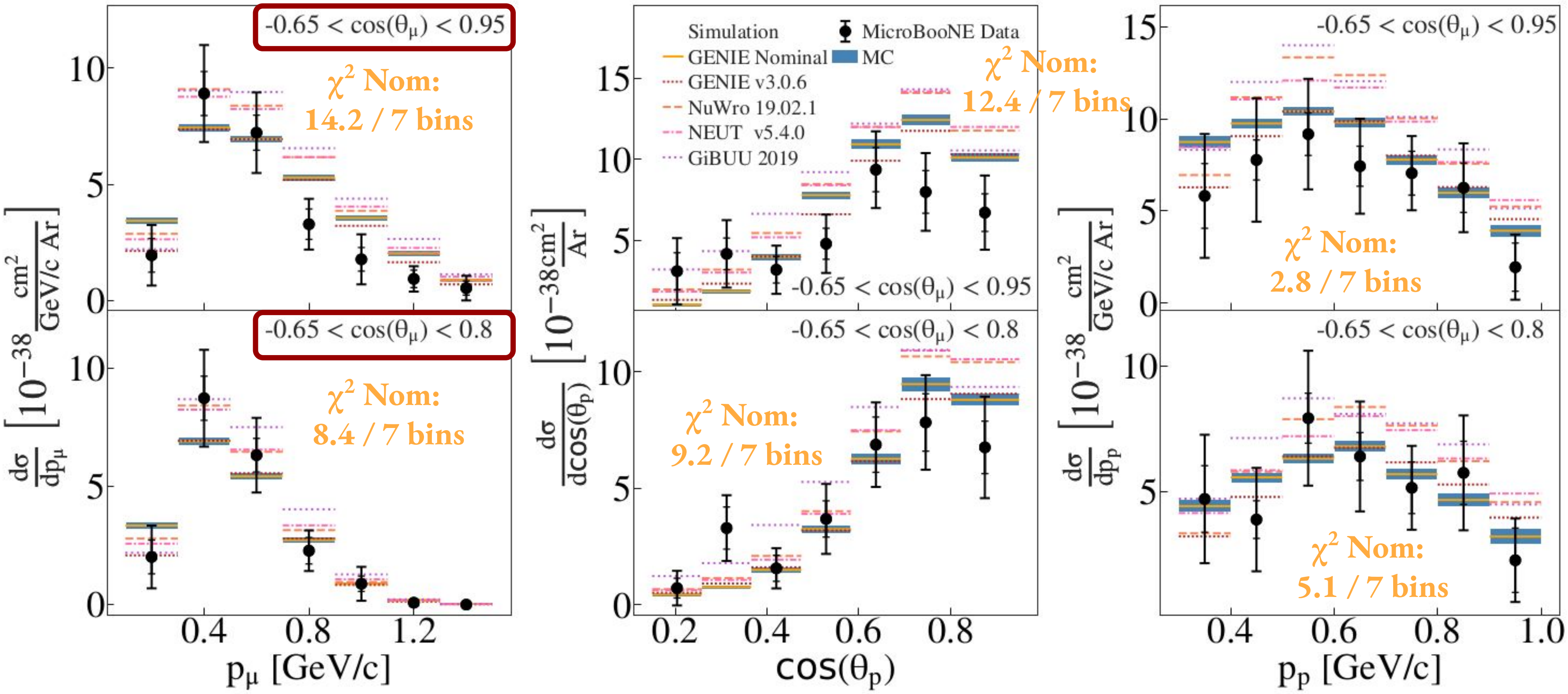
CCQE-like



Good agreement with models, except at very forward muon scattering angles

Phys. Rev. Lett. 125, 201803 (2020)

CCQE-like

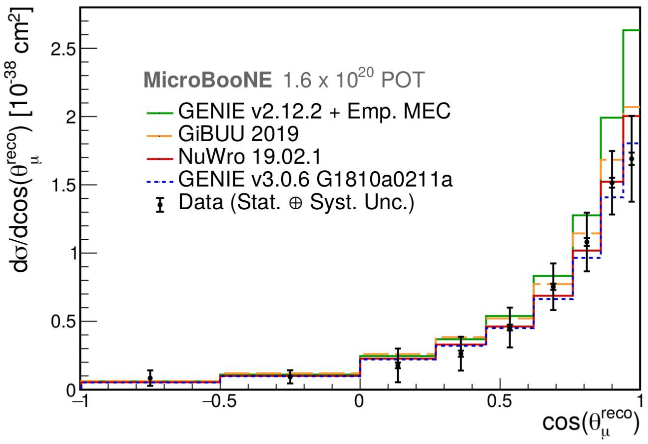


Improved agreement if forward muon angles are excluded

Phys. Rev. Lett. 125, 201803 (2020)

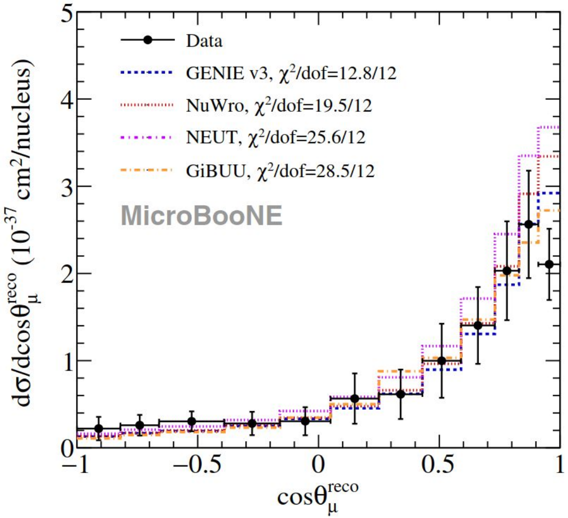
Consistent Picture

ν_μ CC Inclusive
MC excess in forward bin



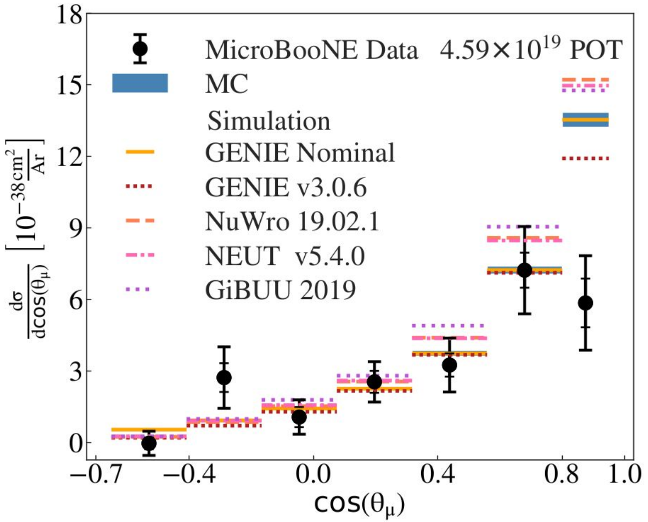
Phys. Rev. Lett. 123, 131801 (2019)

ν_μ CCNp
Data turnover in forward bin



Phys. Rev. D102, 112013 (2020)

ν_μ CCQE-like
Biggest deficit in forward bin



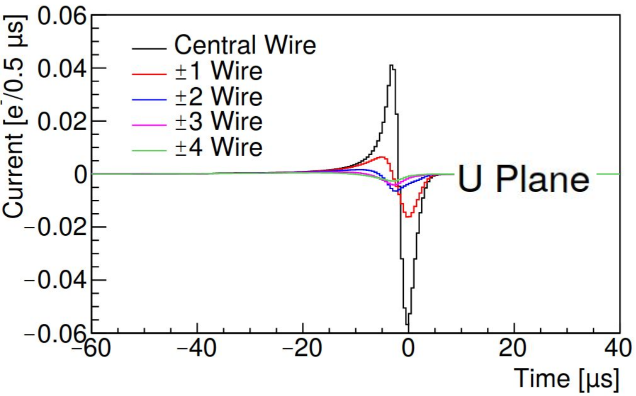
Phys. Rev. Lett. 125, 201803 (2020)

But far from the end of our cross section story!

Getting Even More Out Of LArTPCs

Better detector understanding
- Signal processing from all planes
- Improved calorimetry
- Better reconstruction efficiency

JINST 13, P07006 (2018)
JINST 13, P07007 (2018)



Reduced systematic uncertainties
- Data driven method for vastly improved detector uncertainties

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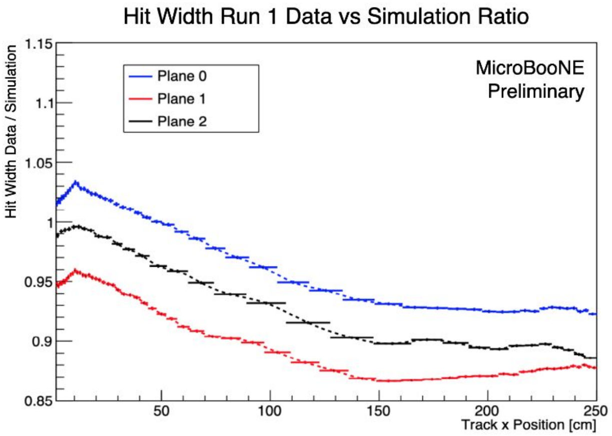
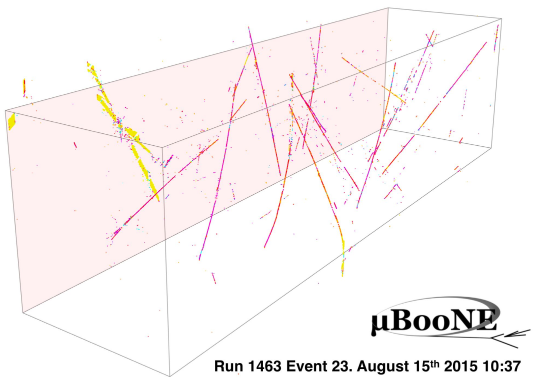


Reduced cosmic contamination uncertainty
- Cosmic Ray Tagger installed in 2018
- Cosmic data as background to simulation

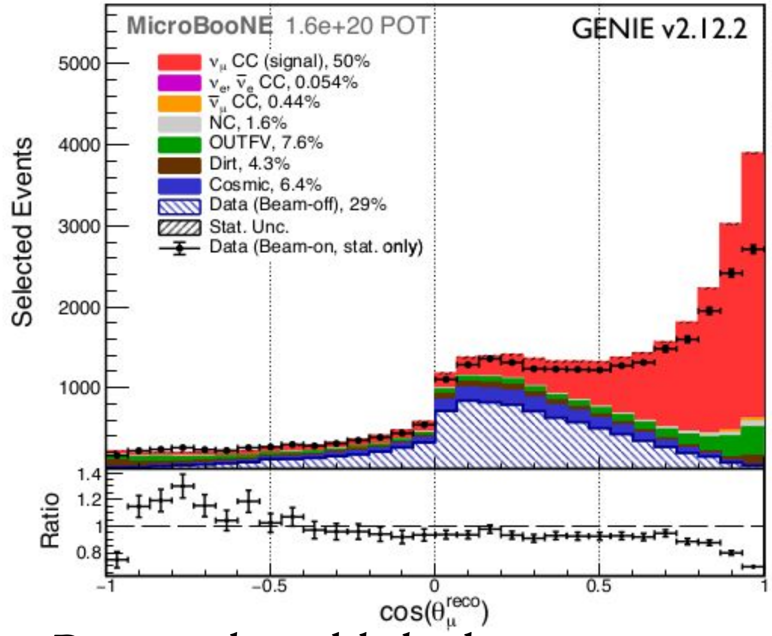
JINST 14, P04004 (2019)



Improved Detector Understanding Enables Precision Measurements

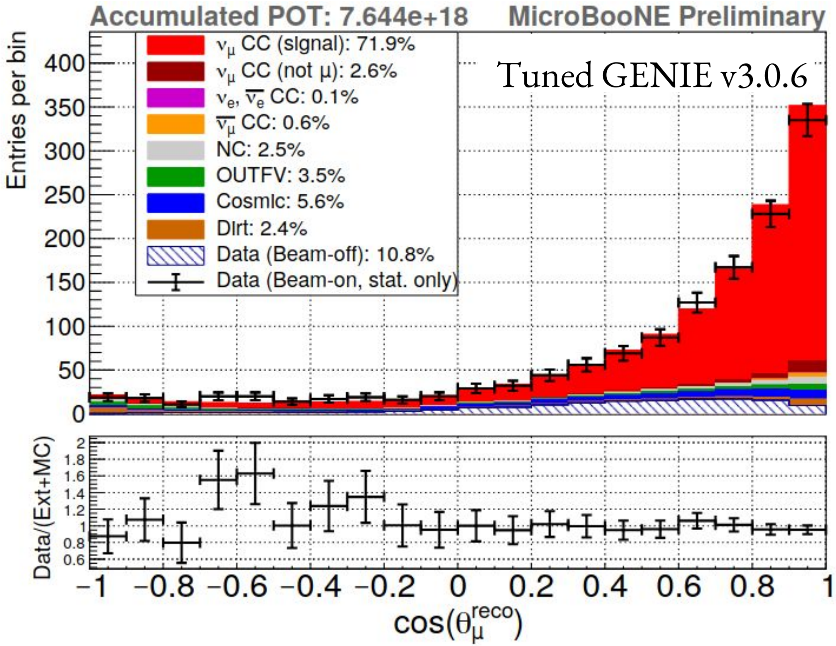
- Improved ν_μ CC inclusive purity from 50% to 71.9%
- Reduction of cosmic contamination by a factor of ~3
- Reduced detector uncertainties from 16.2 % to 3.3 %

See backup slide 33



Previously published measurement

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



Current measurement

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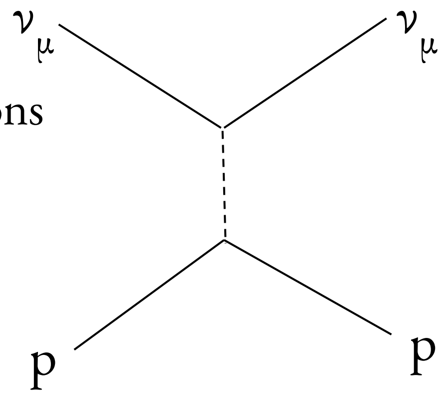
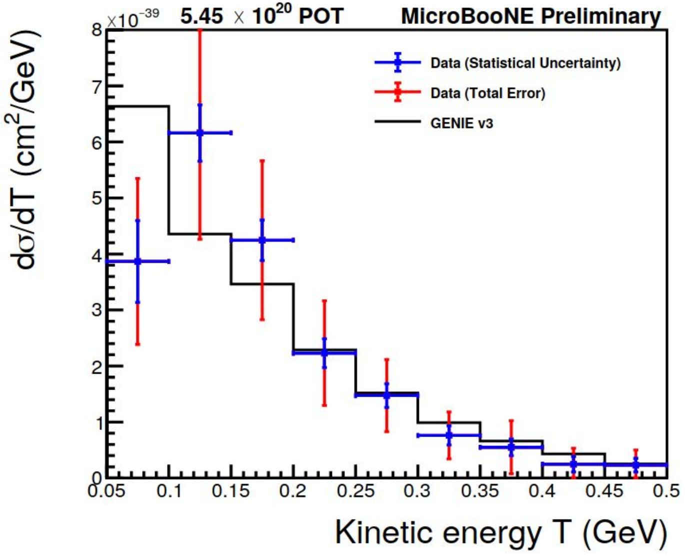
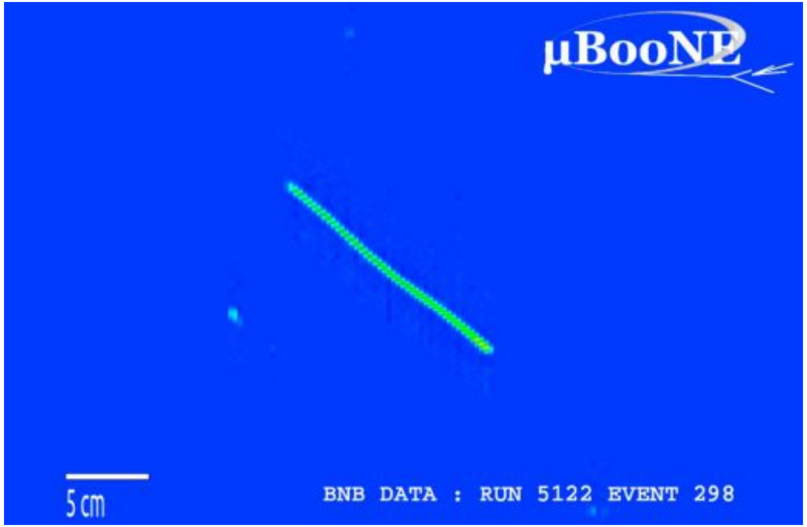
NC1p



- Improvements allow for rare final states, e.g. neutral current interactions
- 1 proton track with 1.2 < length < 200 cm
- Lowest Q^2 NC1p analysis to date (0.1 GeV^2)
- Purity ~40% & efficiency ~30%
- Can measure strange component of neutral-current axial form factor





MICROBOONE-NOTE-1067-PUB

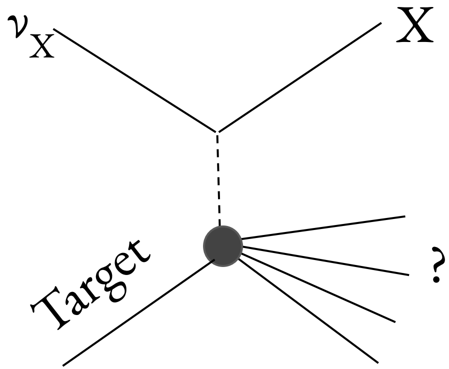
Summary

- Cross-section measurements on Argon are vital for the success of the SBN program and eventually DUNE

- Huge progress over the past two years
  → Measurements with low-energy protons, π^0s, ν_es and more are extremely valuable

- LArTPC technology has demonstrated 4π acceptance
  → We are already able to make accurate measurements of exclusive final states

- More (and more precise) measurements expected in the future
  → Benchmark the performance of our models



Wealth Of Results To Follow

CC inclusive

- ν_e CC inclusive @ NuMI
- ν_μ CC inclusive @ NuMI
- ν_e/ν_μ ratios @ NuMI
- E_ν, E_μ, hadronic energy @ NuMI & BNB

CC0π

- ν_μ Single Transverse Variables @ BNB
- ν_μ CC2p topologies @ BNB
- ν_μ CC0π inclusive @ BNB
- ν_μ CC0π0p @ BNB
- ν_e CC0πNp @ NuMI

Pion production

- ν_μ CC1π^+ @ BNB
- ν_μ CC-Coherent @ BNB
- ν_μ CCπ^0 @ BNB
- ν_μ NCπ^0 @ BNB
- ν_μ CC/NC π^0 @ BNB

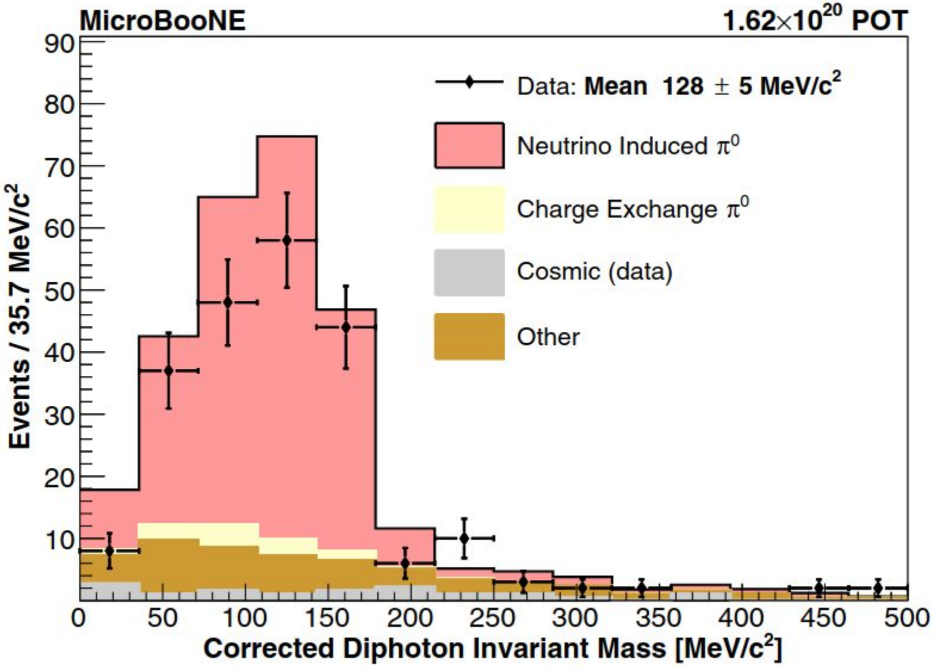
Rare channels

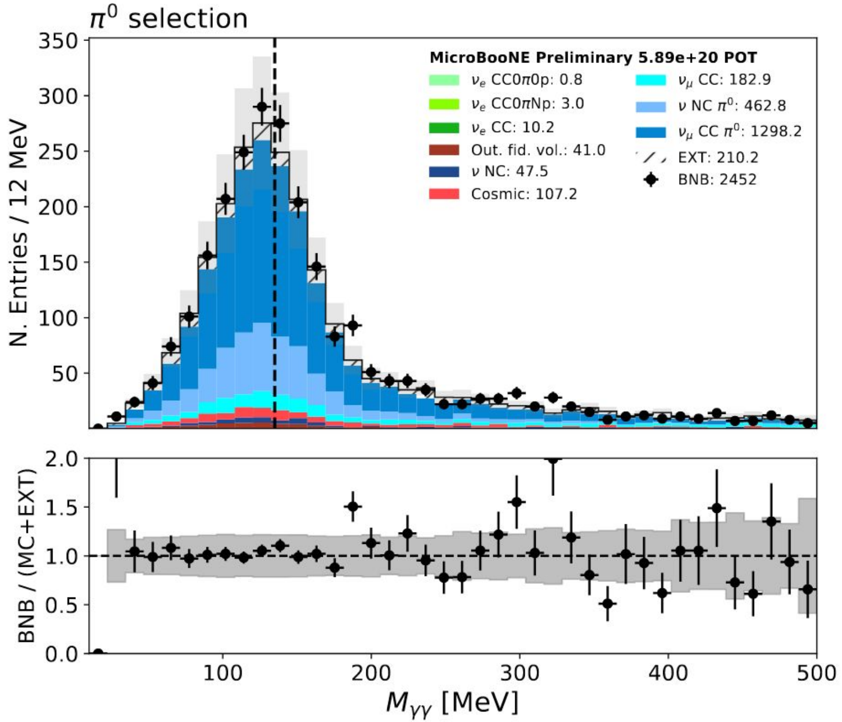
- ν_μ CC Kaon @ BNB
- ν_μ CC Kaon @ NuMI
- η production @ BNB
- Hyperon (Λ,Σ) production @ NuMI
- MeV-scale Physics in MicroBooNE


μBooNE
10 cm
BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016
Thank you!

Backup Slides

π^0 Invariant Mass





Phys. Rev. D99, 091102(R) (2019)

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NuMI Beam

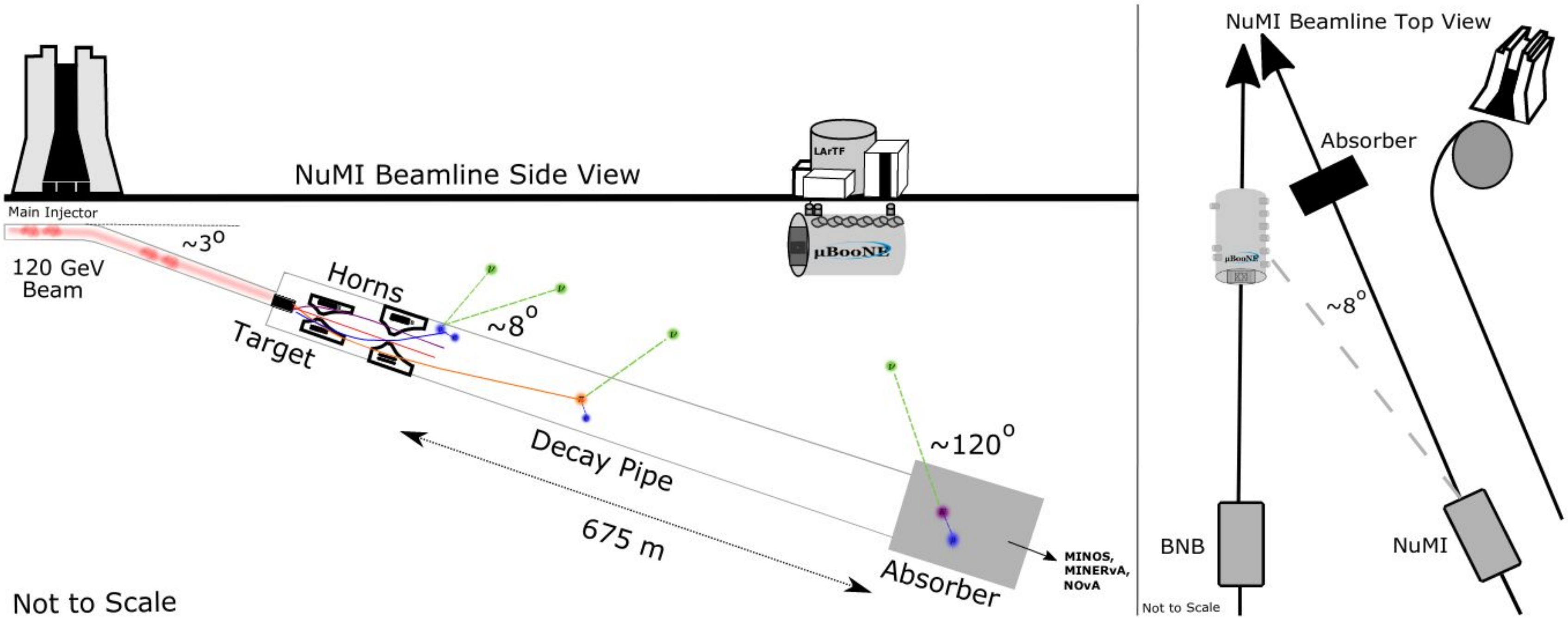


FIG. 3. The position of the MicroBooNE detector relative to the NuMI neutrino beam target with views projected to the side and above. The NuMI beamline is angled 3° downwards and the distance of the NuMI target to MicroBooNE is approximately 679 m. The flux of neutrinos at MicroBooNE covers angles ranging from 8° to 120° relative to the NuMI beamline direction.

arXiv:2101.04228

BNB Beam Neutrino Mode

	ν_μ		$\overline{\nu}_\mu$	
Flux (ν/cm^2/POT)		5.19×10^{-10}		3.26×10^{-11}
Frac. of Total		93.6%		5.86%
Composition	π^+:	96.72%	π^-:	89.74%
	K^+:	2.65%	$\pi^+ \to \mu^+$:	4.54%
	$K^+ \to \pi^+$:	0.26%	K^-:	0.51%
	$K^0 \to \pi^+$:	0.04%	K^0:	0.44%
	K^0:	0.03%	$K^0 \to \pi^-$:	0.24%
	$\pi^- \to \mu^-$:	0.01%	$K^+ \to \mu^+$:	0.06%
	Other:	0.30%	$K^- \to \pi^-$:	0.03%
			Other:	4.43%

	ν_e		$\overline{\nu}_e$	
Flux (ν/cm^2/POT)		2.87×10^{-12}		3.00×10^{-13}
Frac. of Total		0.52%		0.05%
Composition	$\pi^+ \to \mu^+$:	51.64%	K^0_L:	70.65%
	K^+:	37.28%	$\pi^- \to \mu^-$	19.33%
	K^0_L:	7.39%	K^-:	4.07%
	π^+:	2.16%	π^-:	1.26%
	$K^+ \to \mu^+$:	0.69%	$K^- \to \mu^-$:	0.07%
	Other:	0.84%	Other:	4.62%

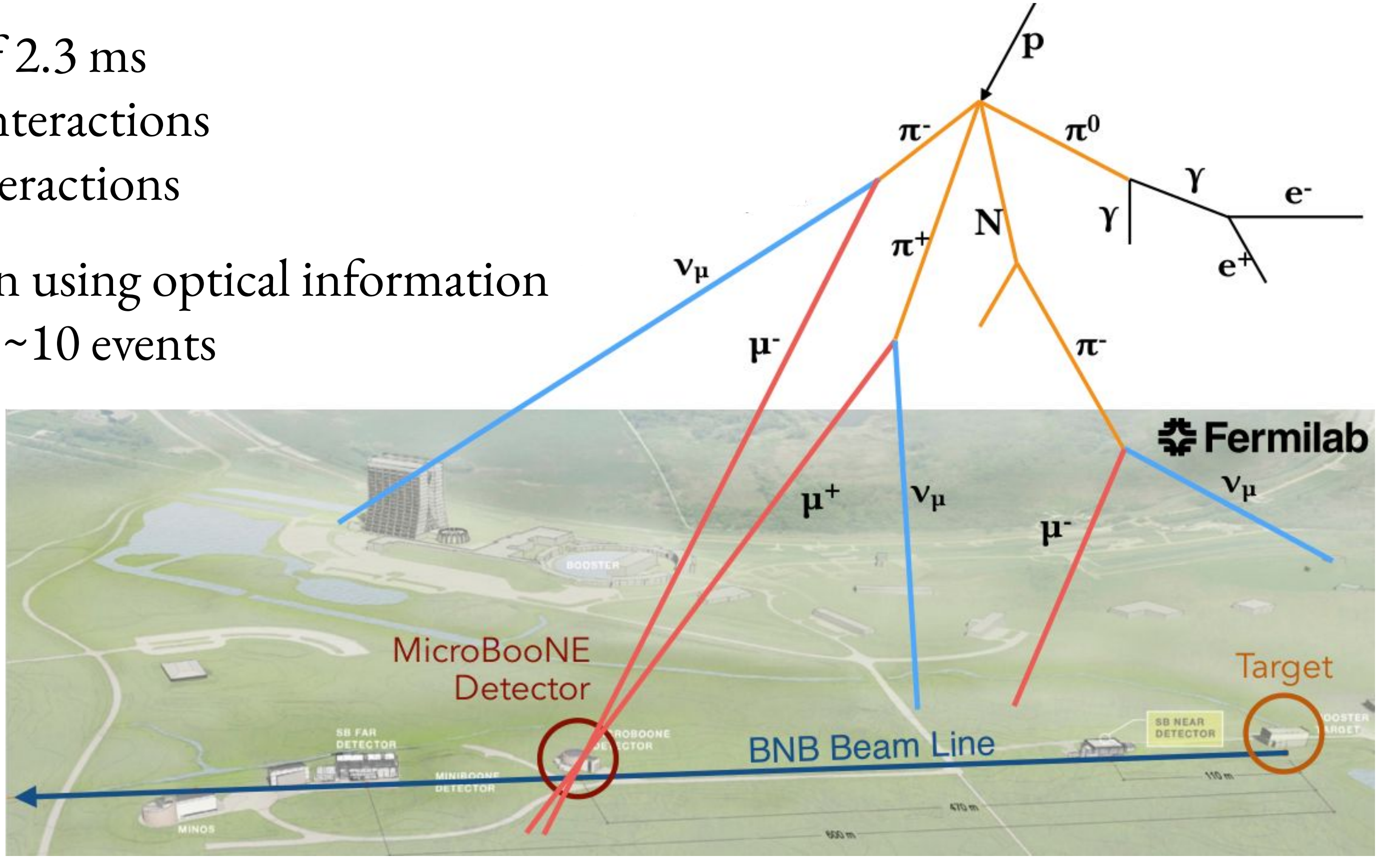
MICROBOONE-NOTE-1031-PUB

Cosmic Background Dominance

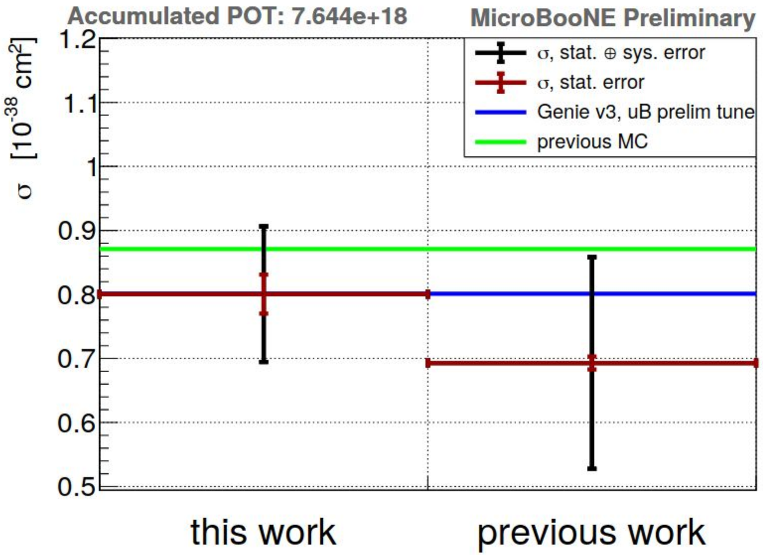
Readout window of 2.3 ms

- ~20 cosmic interactions
- ~0.0017 ν interactions

Significant reduction using optical information to 1 ν interaction in ~10 events



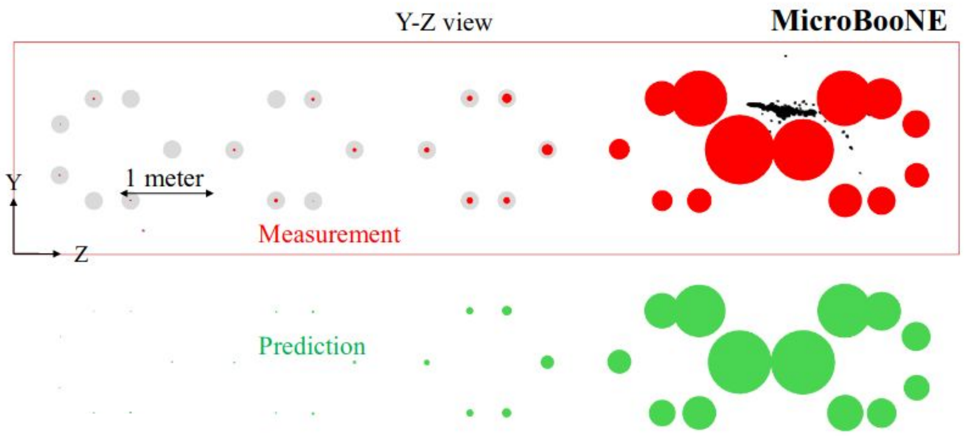
Drastically Reduced Systematic Uncertainties



Source	Uncertainty	
	Previous Analysis	This Analysis
Detector response	16.2%	3.3%
Cross section	3.9%	2.7%
Flux	12.4%	10.5%
Dirt background	10.9%	3.3%
Cosmic ray background	4.2%	N/A
POT counting	2.0%	2.0%
CRT	N/A	1.7%
Total Sys. Error	23.8%	12.1%
Statistics	1.4%	3.8%
Total (Quadratic Sum)	**23.8%**	**12.7%**

Flux-integrated $\nu\mu$ CC inclusive cross section consistent with previous measurement with significantly reduced systematics

Advanced TPC/PMT Matching



arXiv:2012.07928

- ❑ High neutrino selection efficiency
- ❑ Improved cosmic-ray background rejection

GENIE v3.0.6

GENIE v3.0.6 models used:
QE/MEC → **J. Nieves, J.E. Amaro, M. Valverde** Phys. Rev. C 70, 055503 (2004) and
R. Gran, J. Nieves, F. Sanchez. M. Vicente-Vacas Phys. Rev. D 88, 113007 (2013)
RES/COH → **C. Berger, L. Sehgal** Phys. Rev. D 76, 113004 (2007), Phys. Rev. D 79, 053003 (2009)
FSI → work by **L. Salcedo, E. Oset, M. Vicente-Vacas, C. Garcia-Recio**
Nucl. Phys. A 484, 557-592 (1988) and **V. Pandharipande, S.C. Pieper** Phys. Rev. C 45, 791-798 (1992)

Better Data/Simulation Agreement From Improved Modeling

- GENIE v2.12.2 → GENIE v3.0.6
- Tuned CCQE and CCMEC models to T2K ν_μ CC0π data
- T2K data is on a carbon target
  → Tuning seems to give good agreement with MicroBooNE's argon-target data

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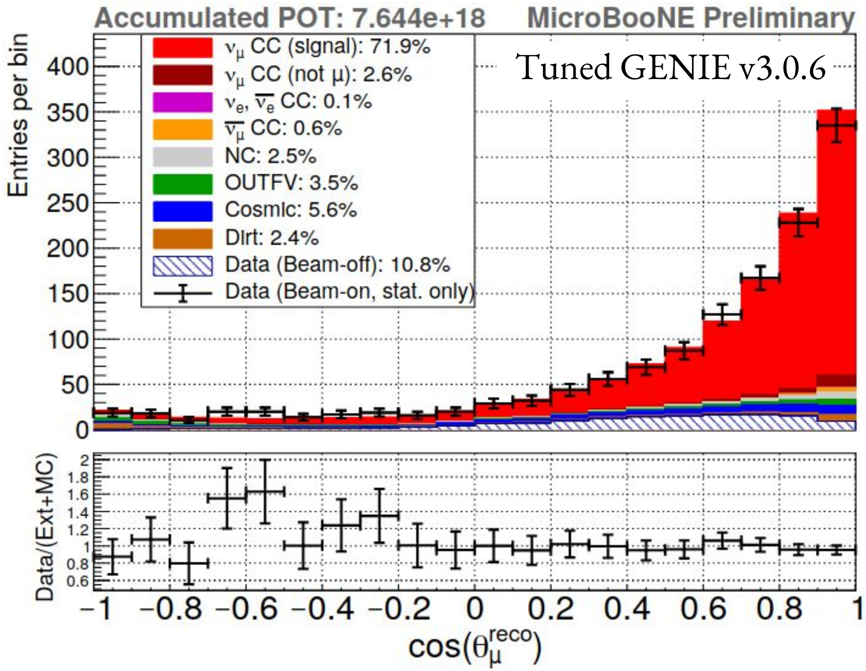

Current measurement

MICROBOONE-NOTE-1069-PUB