NEUTRINO INTERACTION MEASUREMENTS ON ARGON

Kirsty Duffy, Fermi National Accelerator Laboratory
on behalf of the MicroBooNE Collaboration

XXIX International Conference on Neutrino Physics

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Cross-section measurements **on argon** are vital to reduce systematic uncertainties for the **SBN** program and **DUNE**

With **low thresholds** and **4π acceptance**, Liquid Argon Time Projection Chambers (LArTPCs) are powerful detectors to **study detailed final state topologies** and **quantitatively inform theoretical models**

Expanded statistics, better detector understanding since Neutrino 2018

Are models able to describe ν-Ar data?

ArgoNeuT
pathfinder, low statistics

↓

MicroBooNE
high statistics, but initial measurements had large systematic uncertainties

↓

Precision MicroBooNE
improved detector understanding → high statistics, low uncertainties

↓

Future experiments: higher statistics (**SBND**, **ICARUS**, **DUNE-ND**) and lower systematics due to measurements by **LArIAT**, **ProtoDUNEs**

Many measurements of ν-Ar scattering

- ν_μ CC inclusive cross section

  - ArgoNeuT: Single-differential cross section
    Phys. Rev. Lett. 108 161802 (2012)
  - ArgoNeuT: Updated single-differential cross section
    Phys. Rev. D 89, 112003 (2014)
  - μBooNE: Double-differential cross section
    Phys. Rev. Lett. 123, 131801 (2019)
  - μBooNE: Single-differential cross section with updated detector and interaction models
    MICROBOONE-NOTE-1069-PUB

- ν_μ exclusive channels

  - μBooNE: Charged-particle multiplicity
    Eur. Phys. J. C79, 248 (2019)
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    MICROBOONE-NOTE-1071-PUB
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- Other measurements

  - ArgoNeuT: ν_e and $\bar{\nu}_e$ scattering (inclusive)
    arXiv:2004.01956[hep-ex]
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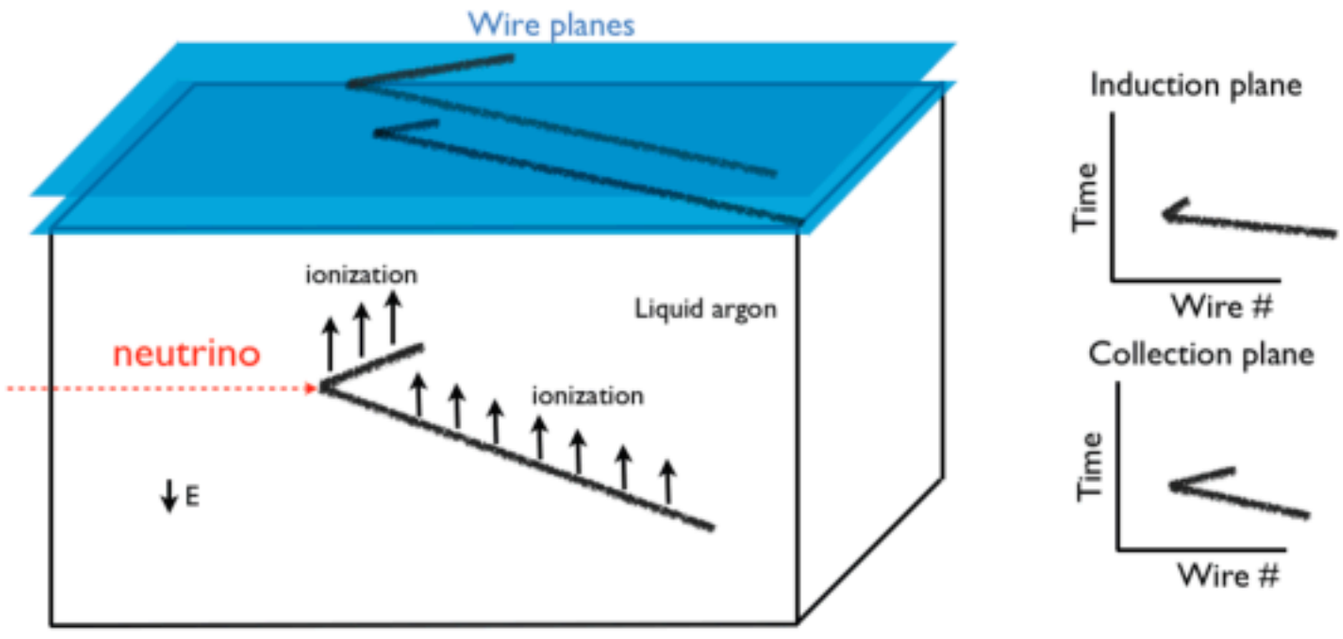
ArgoNeuT is a 40x47x90cm³ LArTPC

JINST 7 P10019 (2012)



- **2 planes** of wires with 4mm spacing collect charge from drifting electrons following secondary particle tracks
- **1.35×10^{20} POT** data in NuMI beamline at Fermilab 2009-2010: $\langle E_{\nu e} \rangle$ = 4.3 GeV, $\langle E_{\bar{\nu} e} \rangle$ = 10.5 GeV
- Placed in front of MINOS near detector at Fermilab: use as **tracking spectrometer**

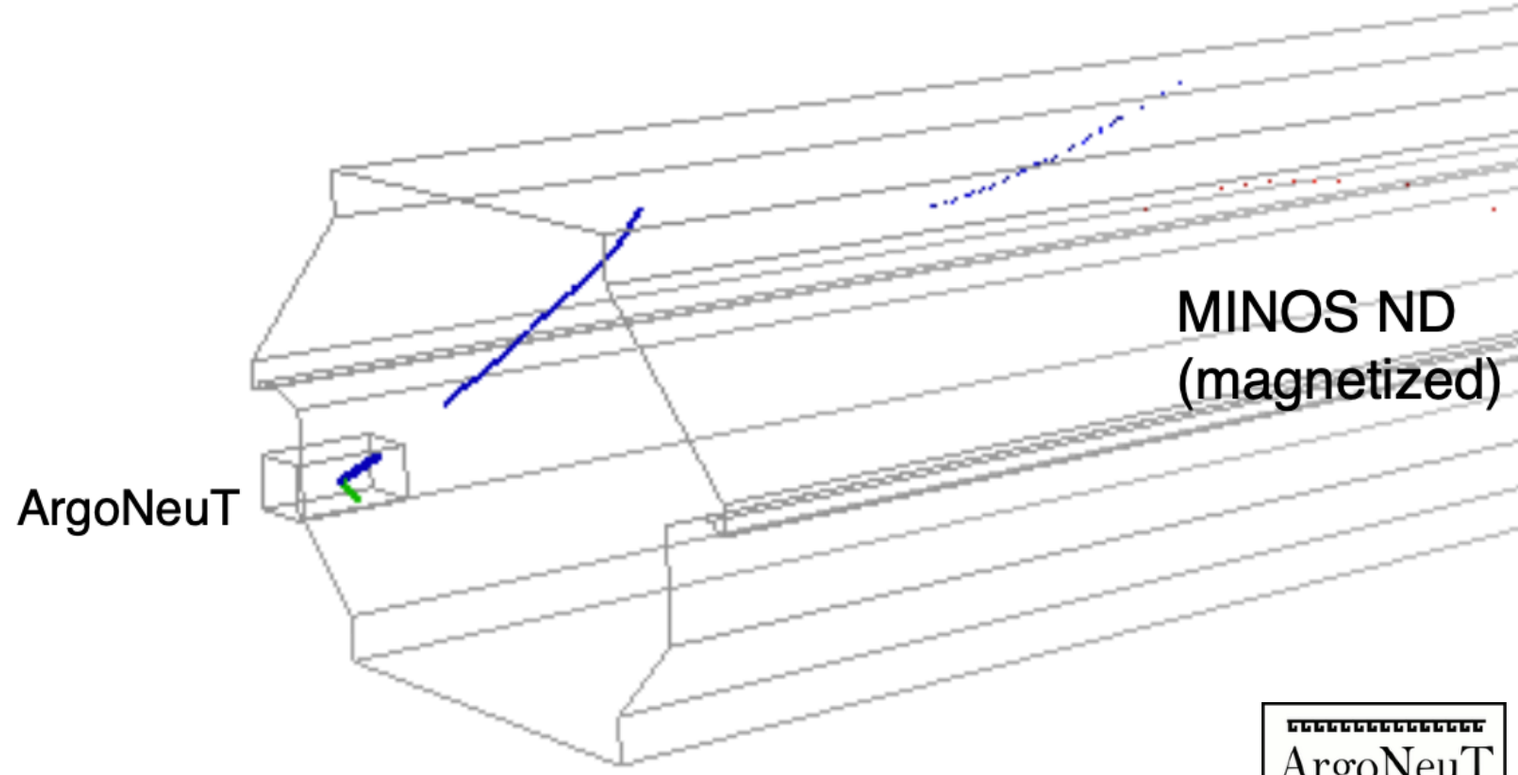


Figure from T.Yang, NuINT 2017

See also: "Searches for New Physics with MicroBooNE" by G. Karagiorgi, 2nd July

Thank you to Fermilab Accelerator Division, Cryogenics team, and Operations team!

MicroBooNE: 170 ton LArTPC

JINST 12 P02017 (2017)

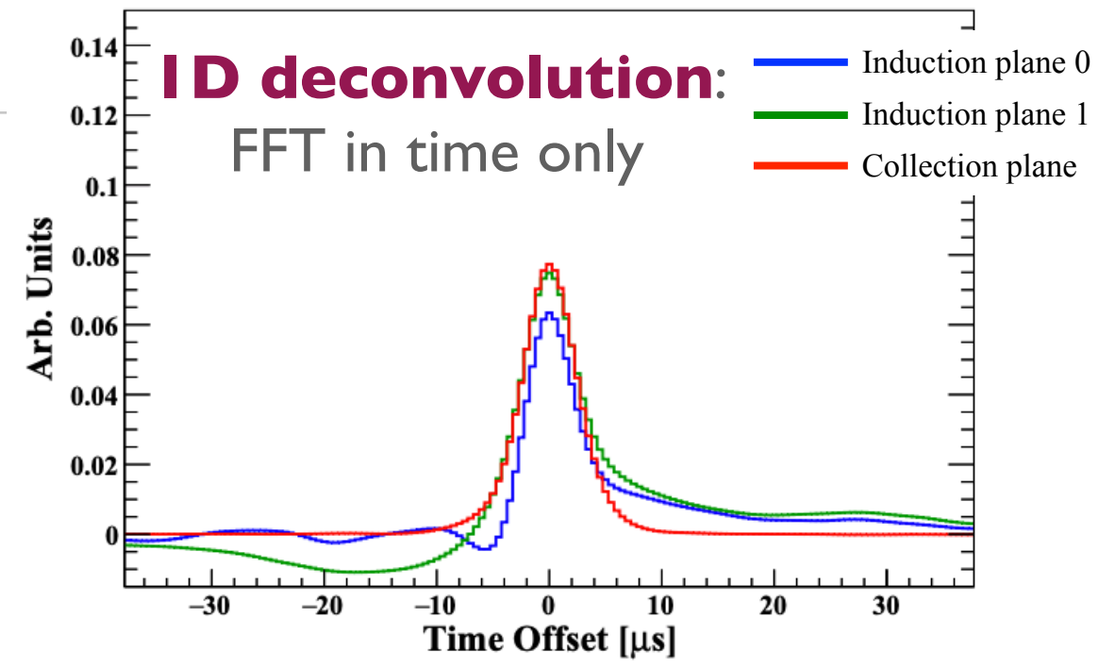
- **3 planes** of wires (vertical, +60°, -60°) with **3mm spacing**
- **32 PMTs** collect light from flash at time of interaction
- Sits in **two neutrino beams** at Fermilab: BNB (on-axis, $\langle E_{\nu\mu}\rangle$=800 MeV) and NuMI (off-axis, $\langle E_{\nu e}\rangle$=650 MeV)
- Stable detector operation since 2015: **longest-running LArTPC to date**
  - >95% DAQ uptime
  - 1.52×10^{21} POT collected in total (analyses shown here use subsets, not full POT)
  - From December 2017: data with **Cosmic Ray Tagger (CRT)**

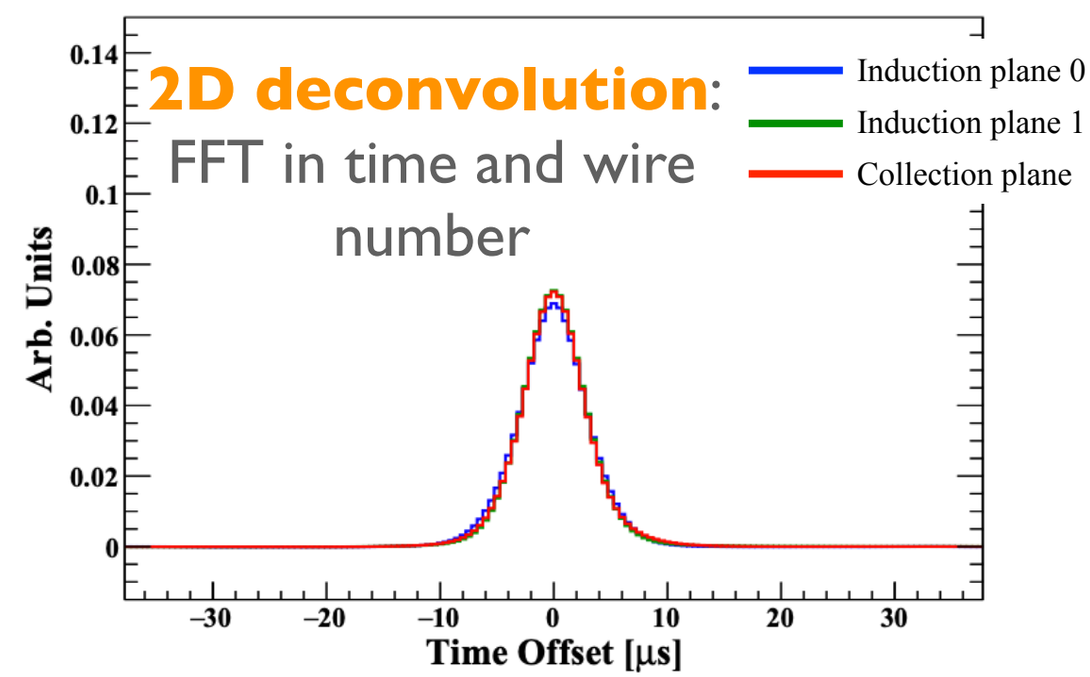
GETTING THE MOST OUT OF LArTPCs

JINST 13 P07006 (2018)

JINST 13 P07007 (2018)

- MicroBooNE Collaboration has made **huge improvements** in our understanding of the detector since Neutrino 2018
- Detailed understanding of detector is **key to our R&D mission** for future LArTPCs
- **Improved signal processing** (2D deconvolution) accounts for interfering wire signals on all three planes
- Tracking is hard when particles go parallel to wires. Precise calorimetry on all planes → 3D tracking → **4π particle identification**



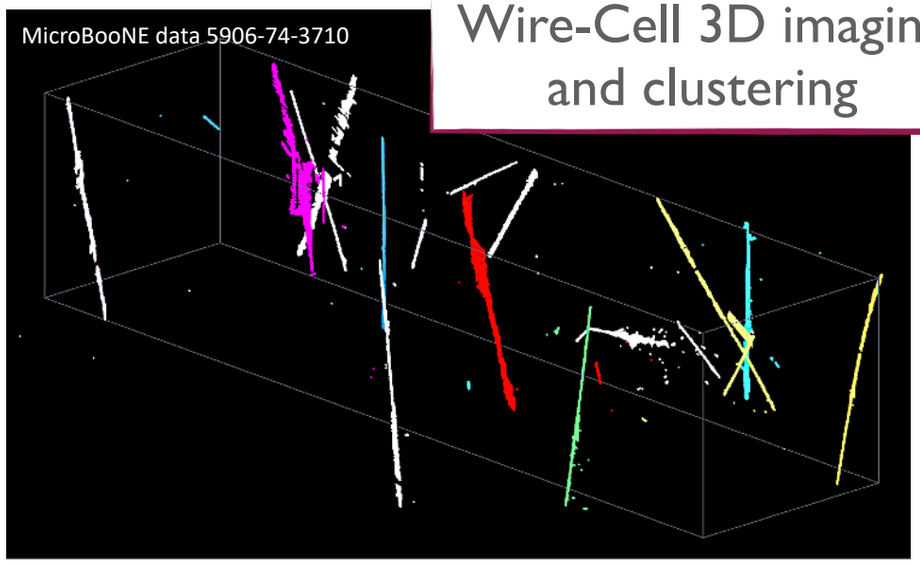


L. Cooper-Troendle, poster 147, poster session 4

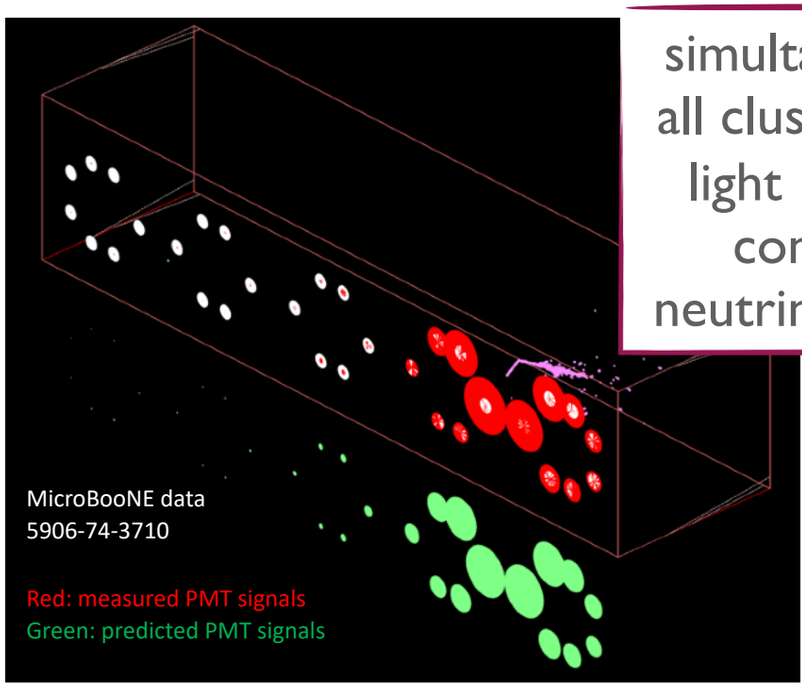
H. Wei, poster 264, poster session 4

IMPROVED DETECTOR UNDERSTANDING ENABLES BETTER MEASUREMENTS

MICROBOONE-NOTE-1084-PUB

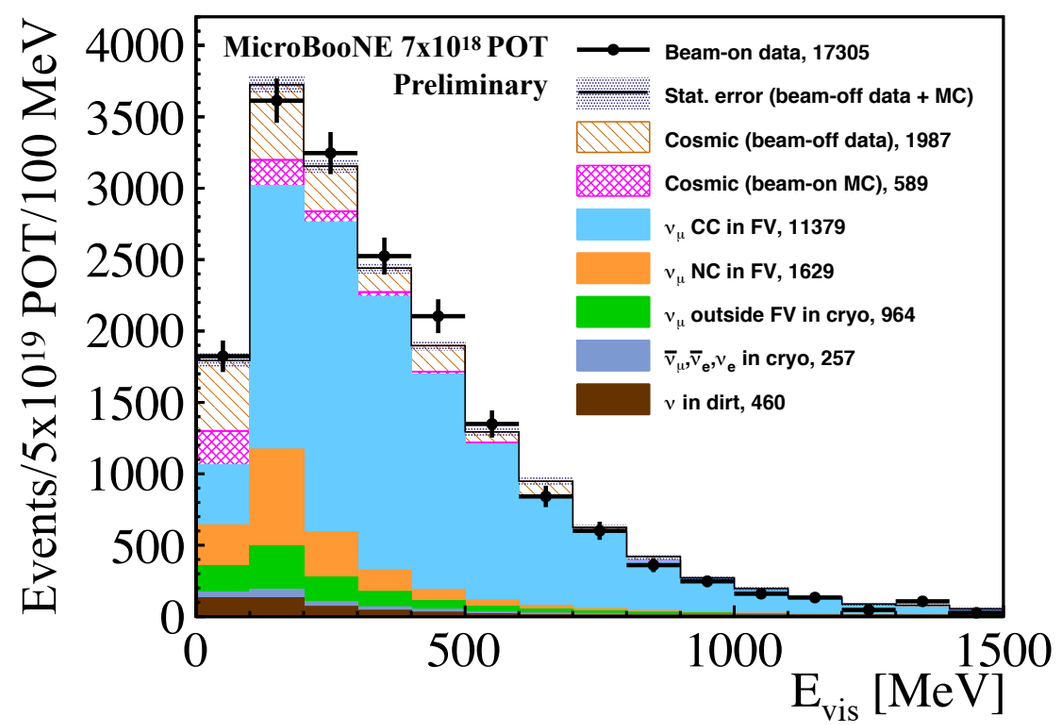


Wire-Cell 3D imaging and clustering



simultaneously match all clusters in event to light → find cluster consistent with neutrino-induced flash

- Cosmic rejection power (without kinematic requirements) **increased by factor of 8** compared to previous publications
- **High efficiency**: 80.4% for ν_μCC (87.6% for ν_eCC)
- **Increased statistics**: 11.3k events,compared to 4.3k events in same data set for 2019 CC inclusive measurement



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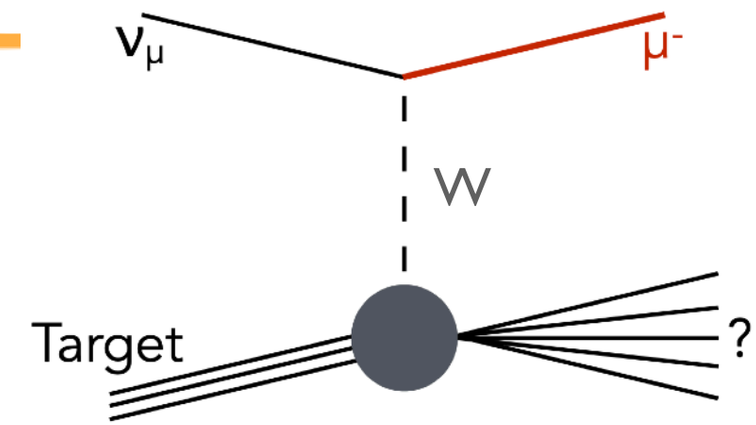
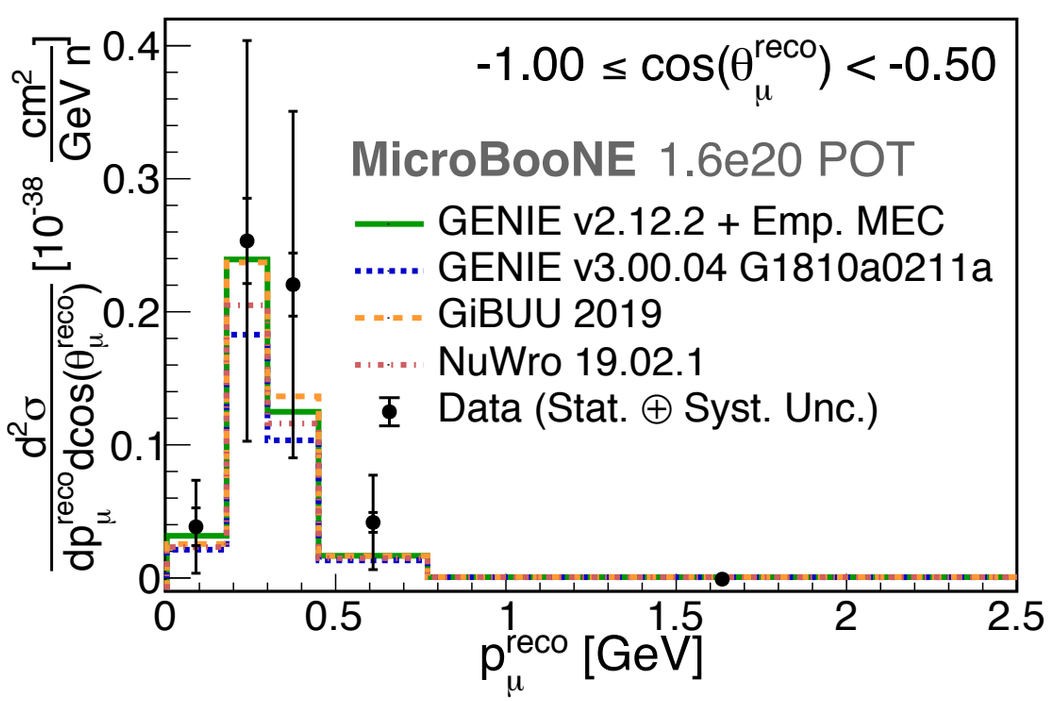
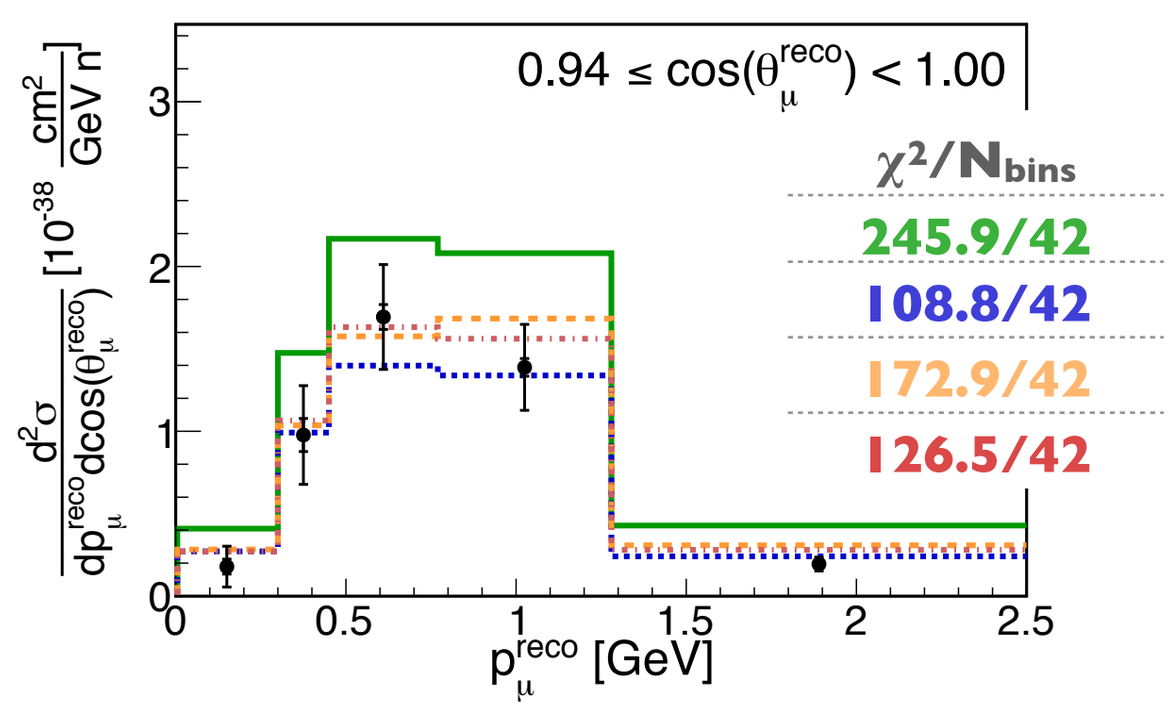
CC INCLUSIVE CROSS SECTION MEASUREMENT



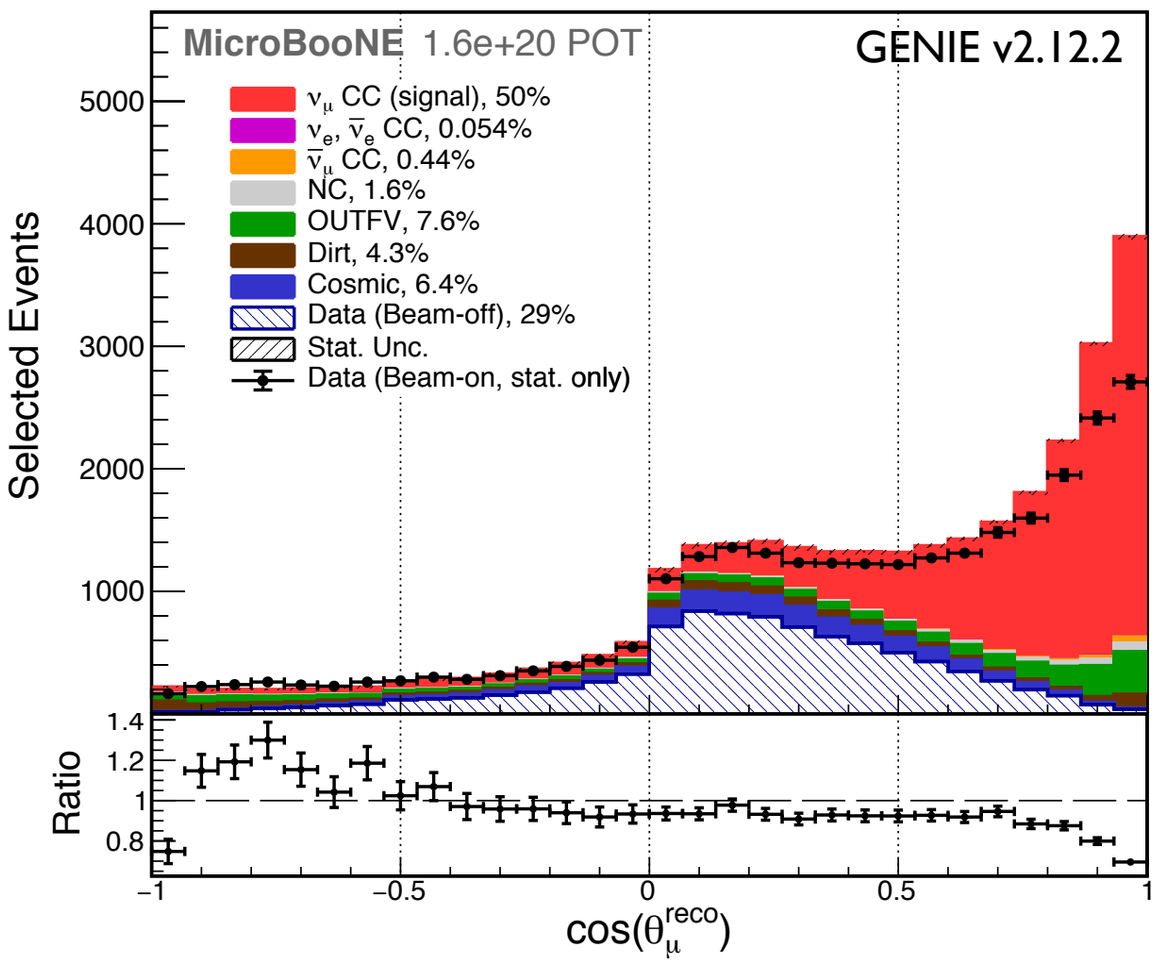
PRL 123, 131801 (2019)

- Selection presented at Neutrino 2018 → new since then: **double-differential** cross section measurement
- **First time** double-differential cross section has been measured on argon: compared to worldwide interaction generators
- All models **overpredict in high-momentum, forward going bins**: interesting physics in this region!





IMPROVED DETECTOR UNDERSTANDING ENABLES BETTER MEASUREMENTS



Previous Measurement

PRL 123, 131801 (2019)

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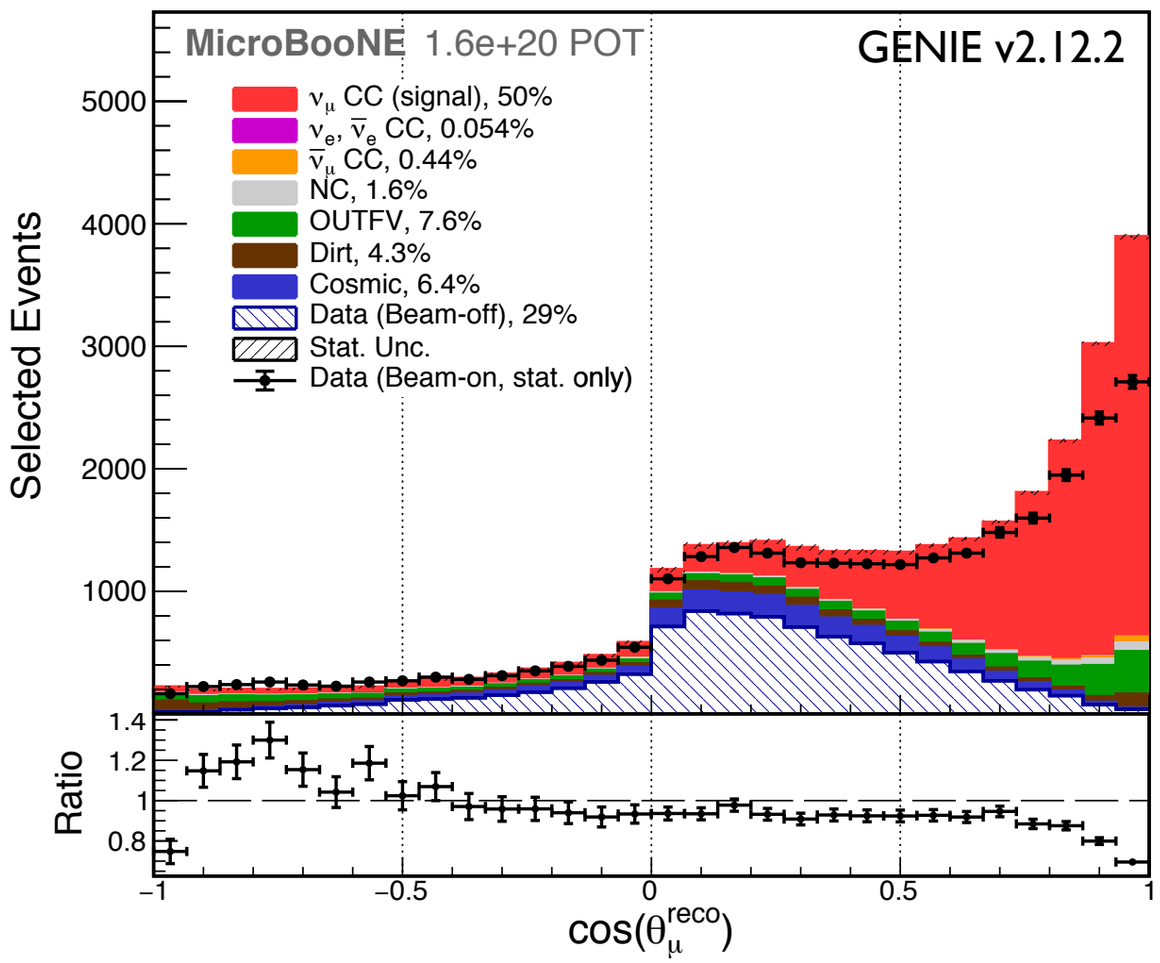

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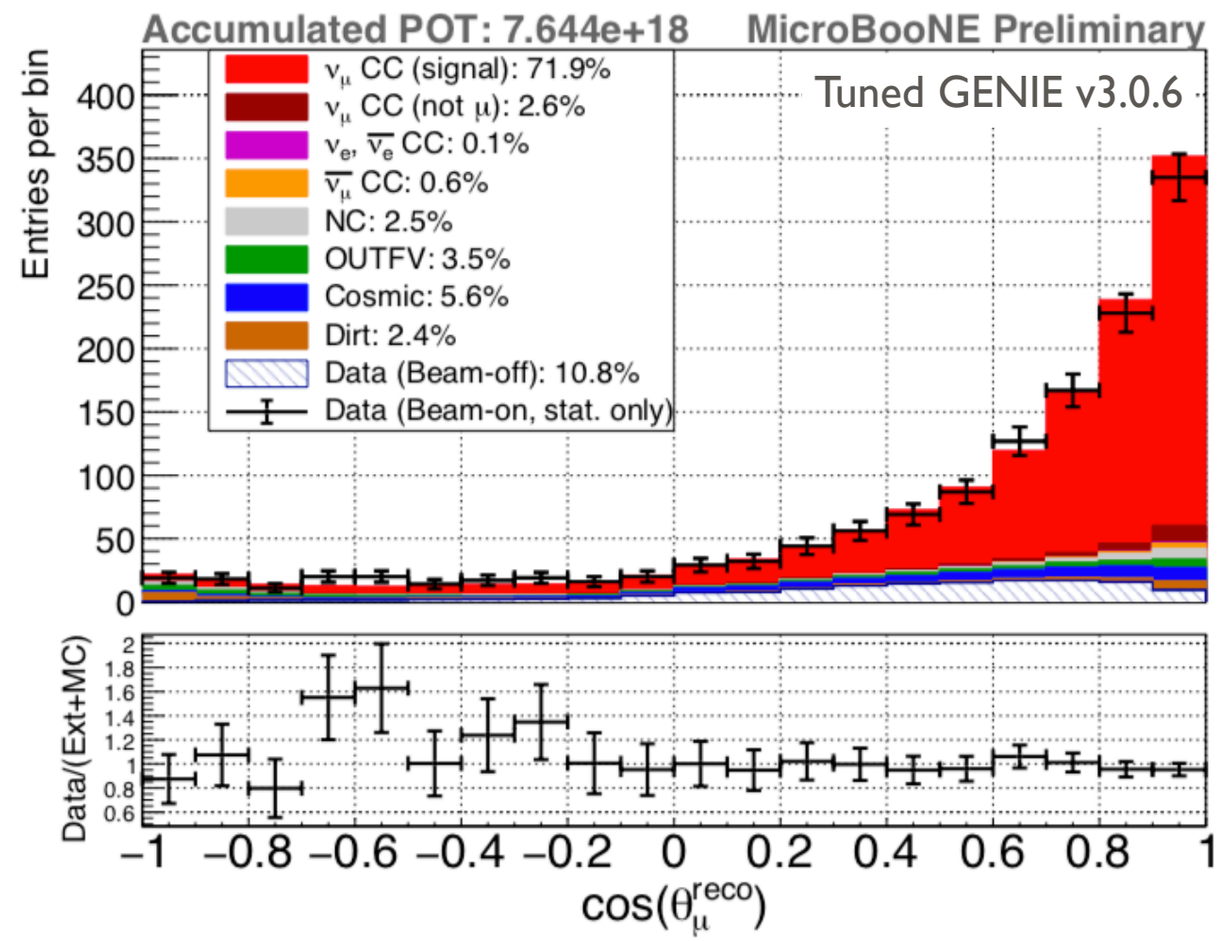

Current Measurement

MICROBOONE-NOTE-1069-PUB

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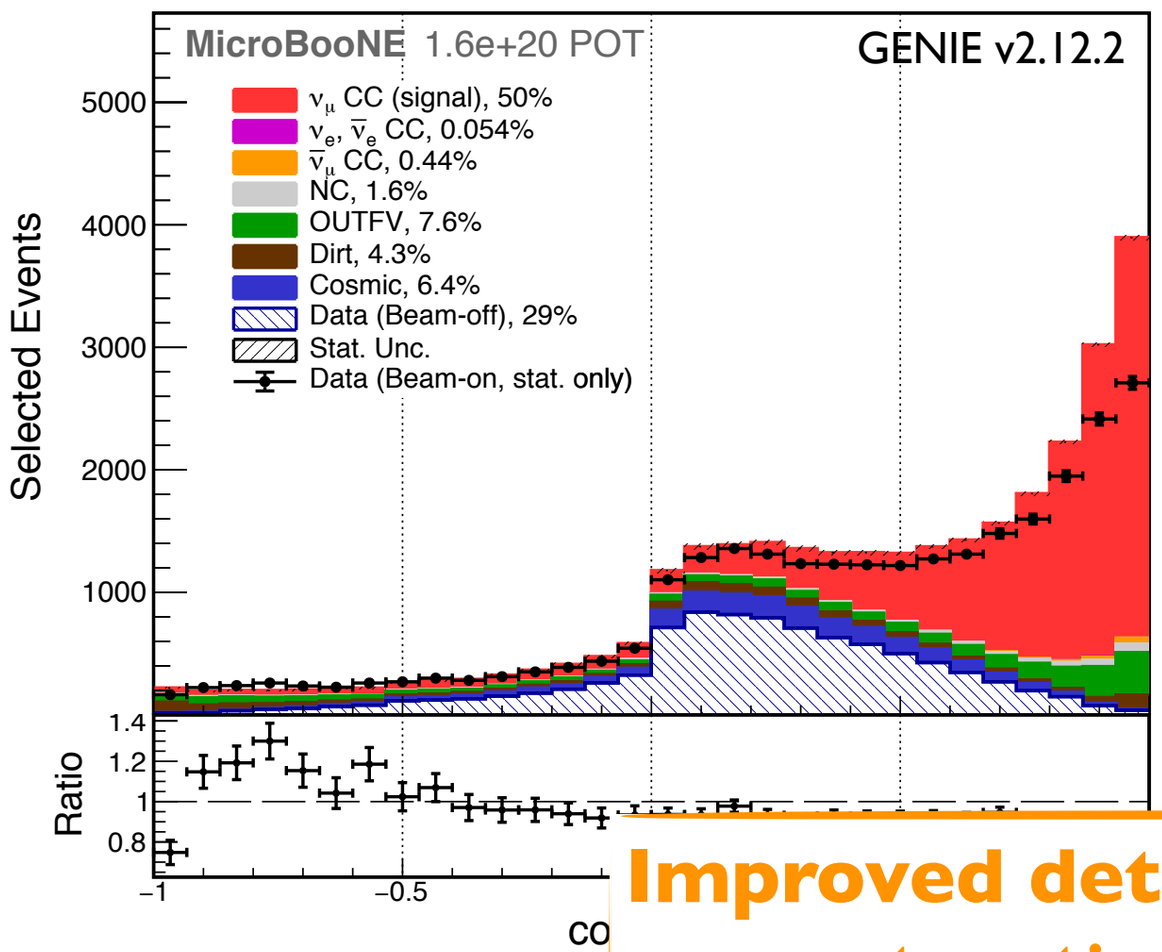
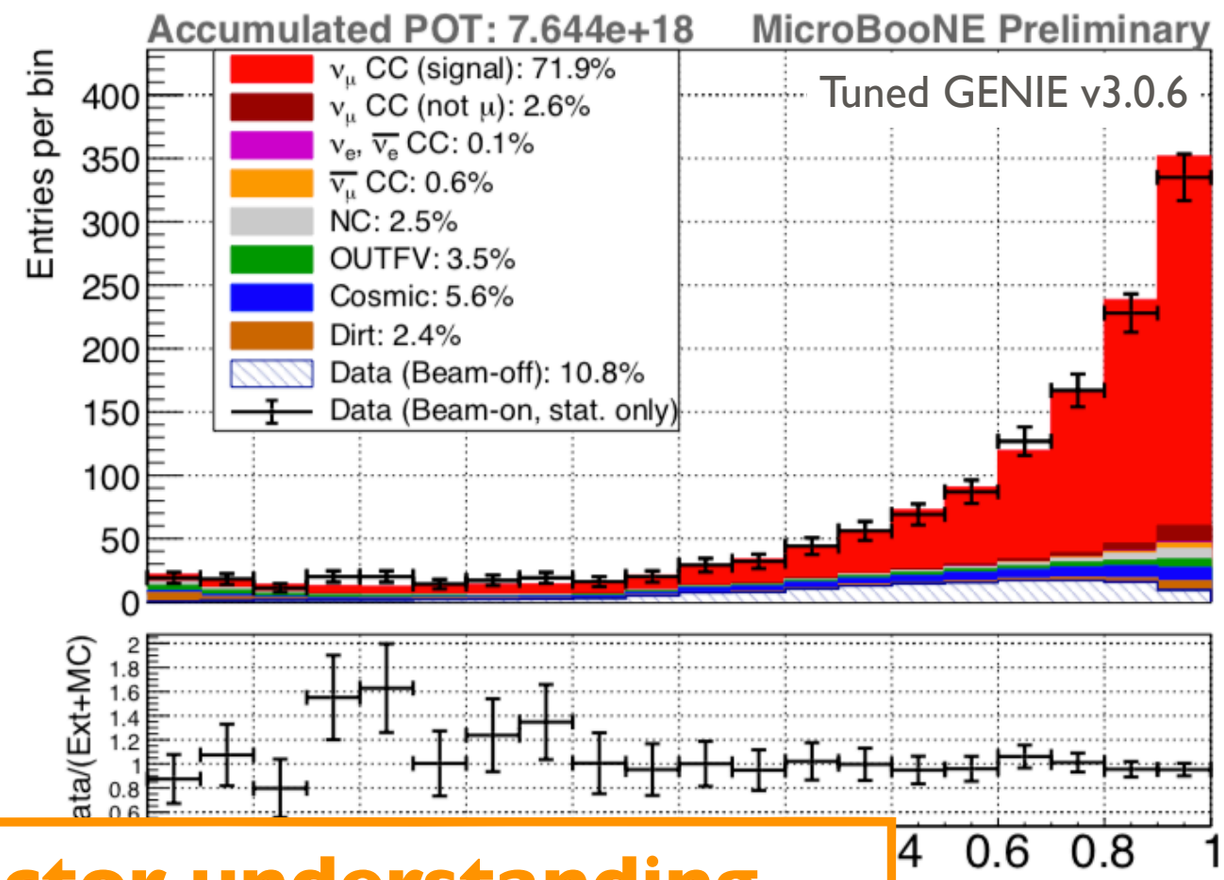




Previous M ... ment

PRL 123, ...

Improved detector understanding, reconstruction, CRT → higher purity

ν_μCC (signal) purity: 50% → 71.9%

Entering backgrounds: 33.3% → 13.2%

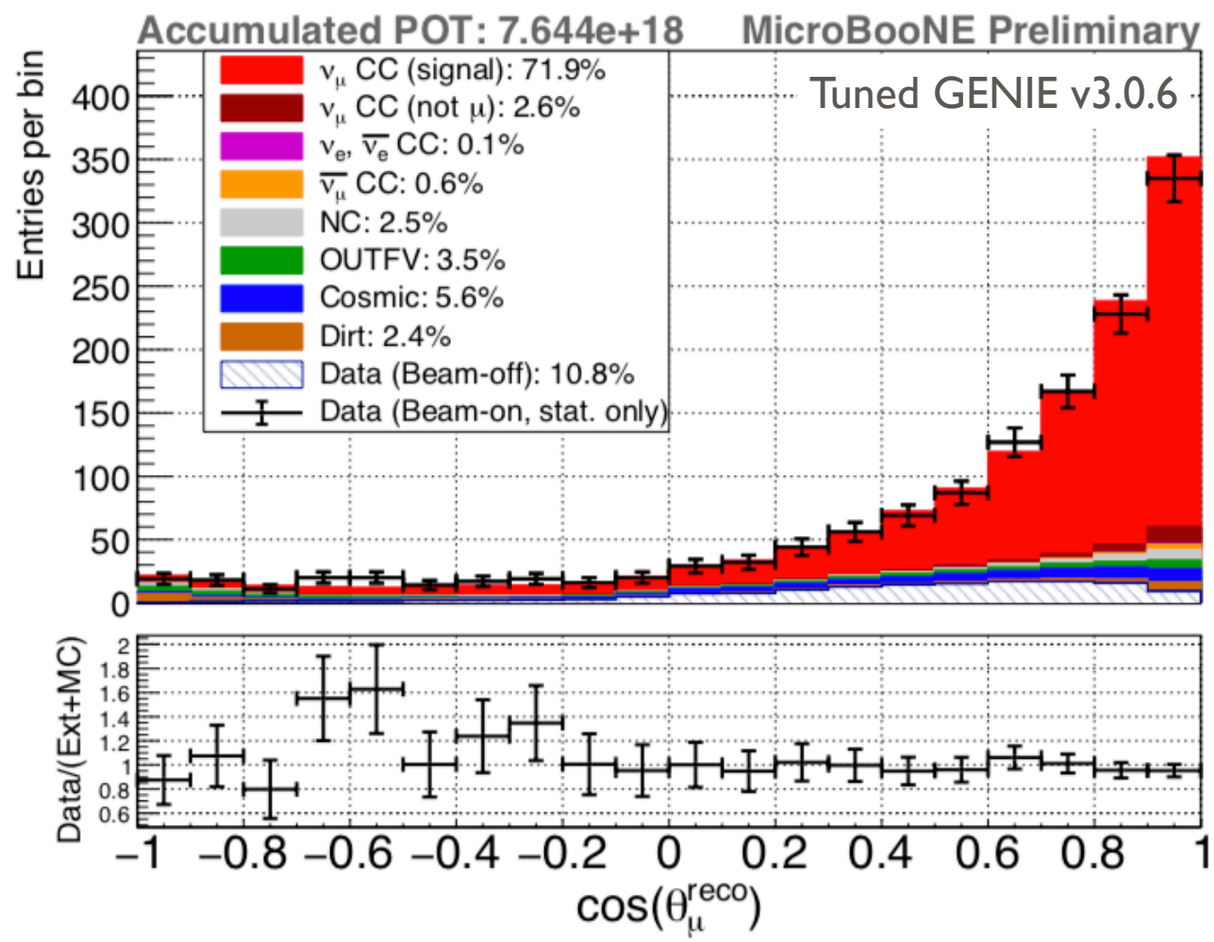
IMPROVED INTERACTION MODELING ENABLES BETTER MEASUREMENTS

Better data-simulation agreement from improved neutrino interaction 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**

MICROBOONE-NOTE-1074-PUB

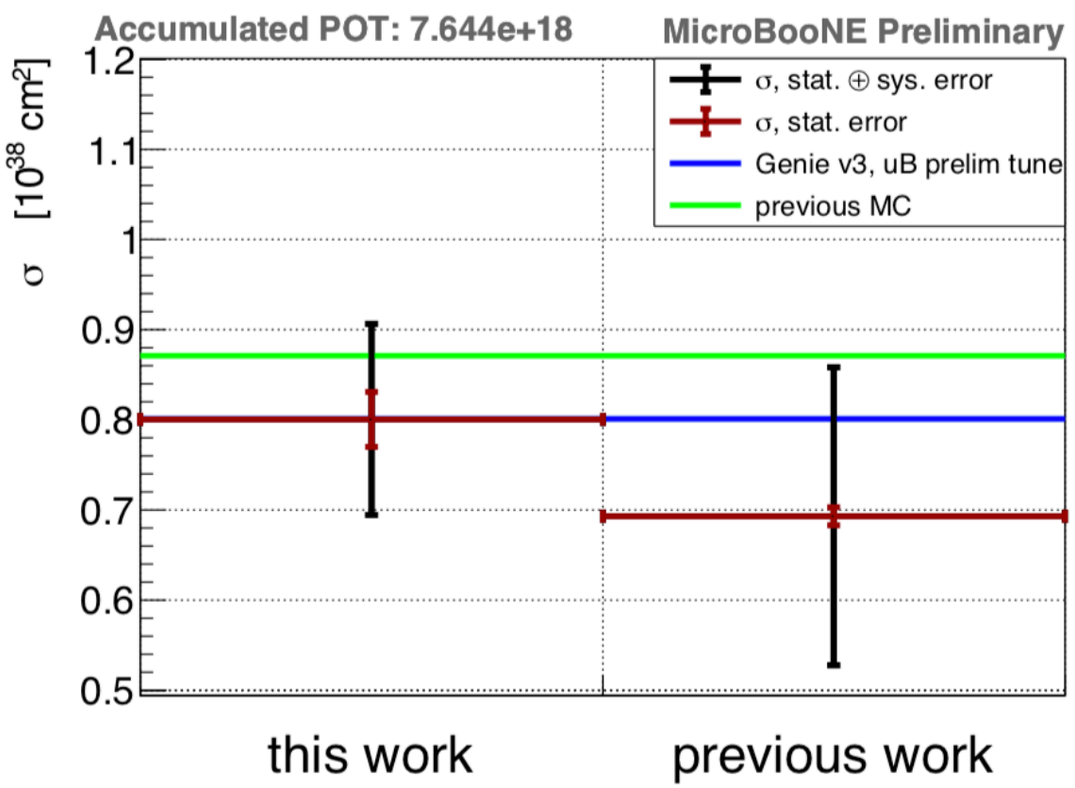
PRL 123, 131801 (201



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)

DRASTICALLY REDUCED SYSTEMATIC UNCERTAINTIES

MICROBOONE-NOTE-1075-PUB . MICROBOONE-NOTE-1069-PUB



Flux-integrated cross section **consistent with previous measurement**

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%**

PRL 123, 131801 (2019)

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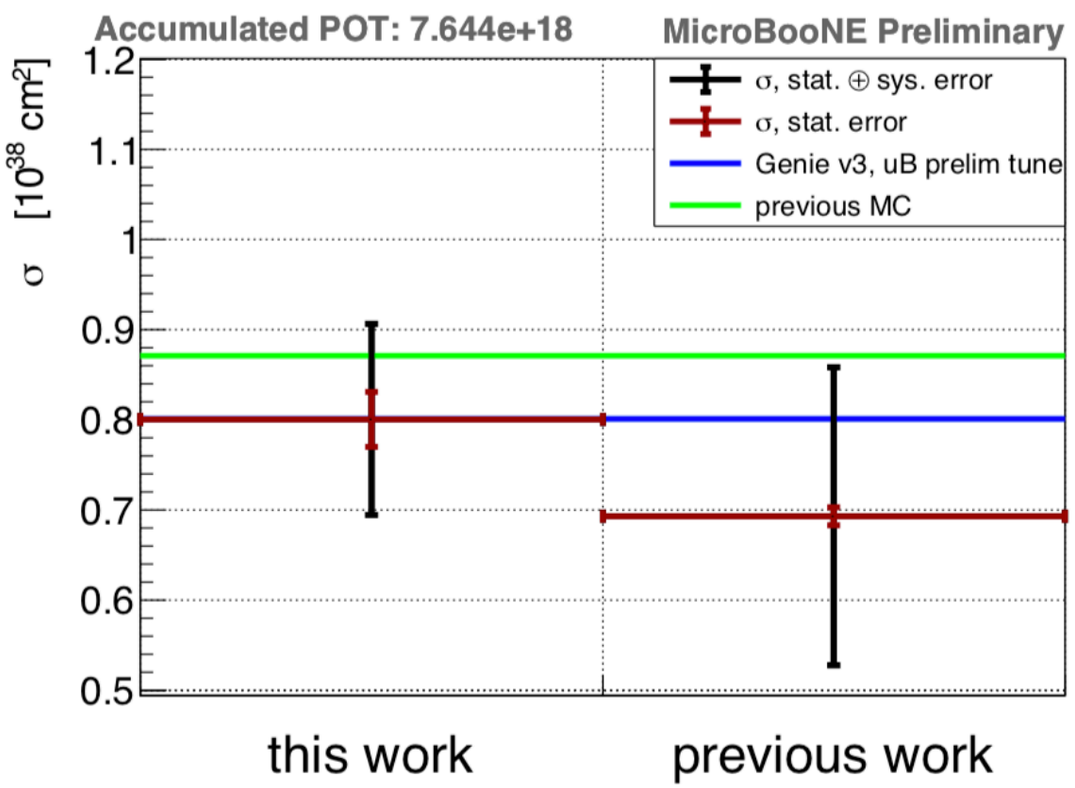

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Largest reduction in uncertainties comes from improved detector understanding

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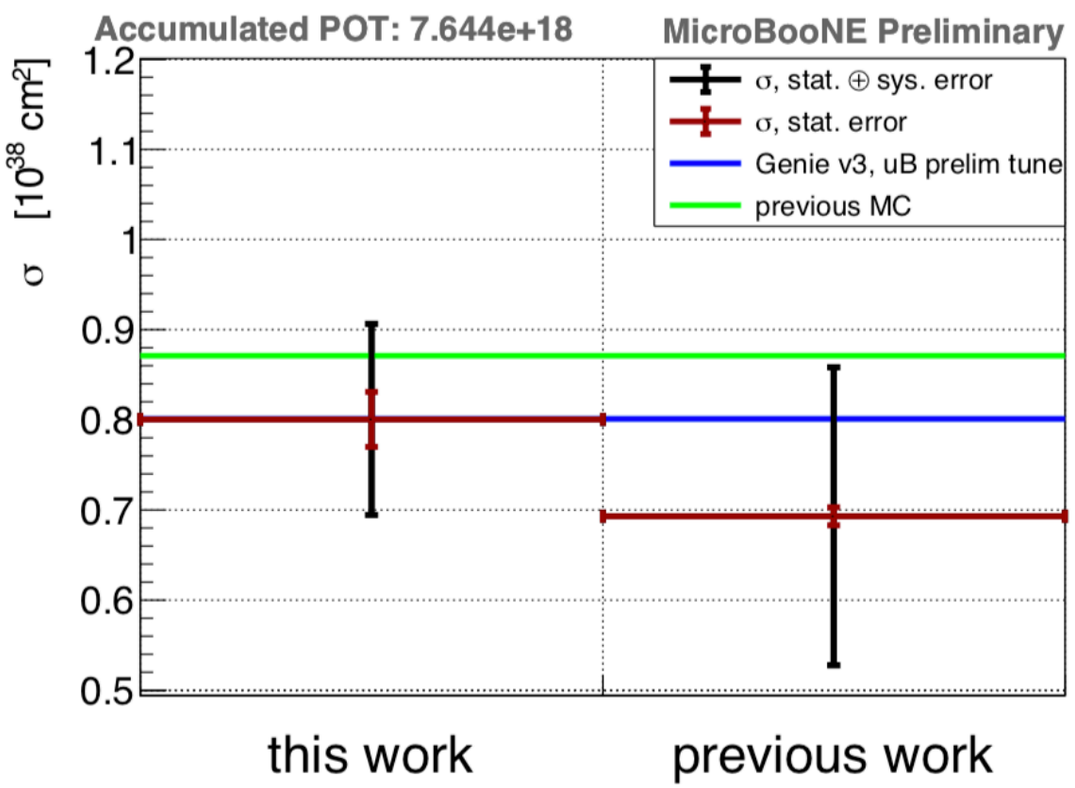

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Instead of cosmic ray simulation, now use overlay: simulated neutrino interactions overlaid on real cosmic data → no uncertainty in cosmic ray model

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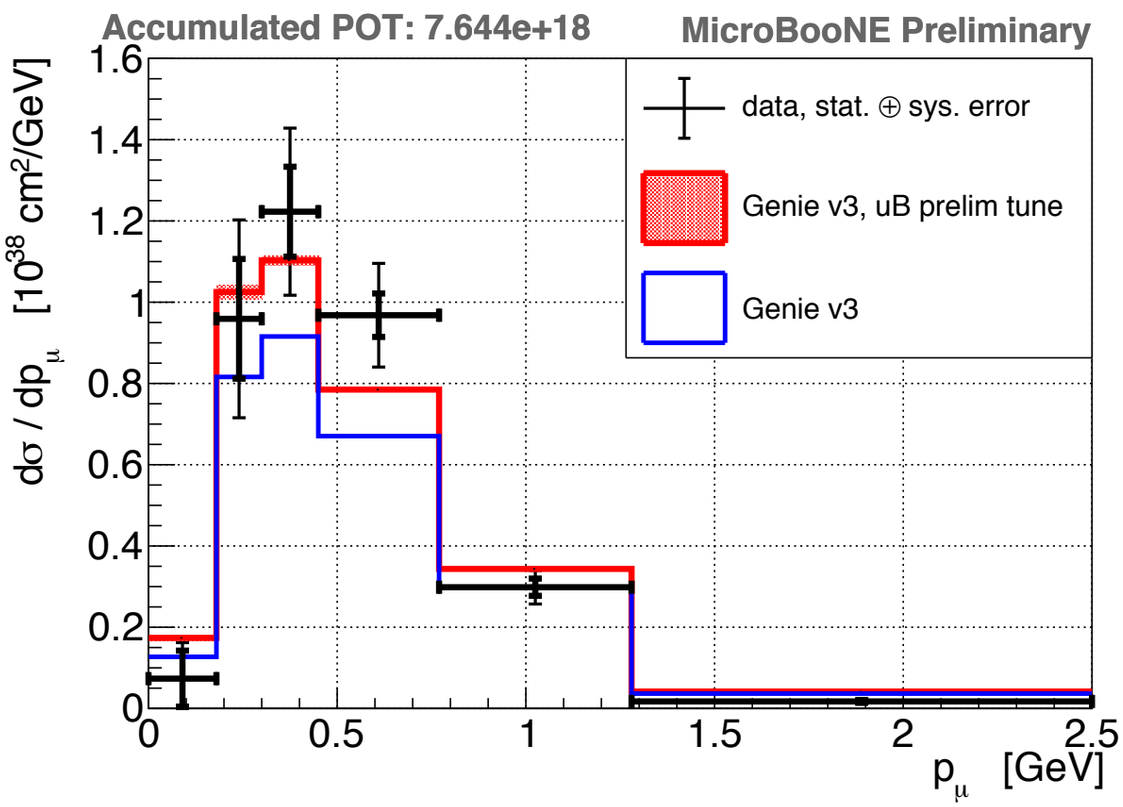

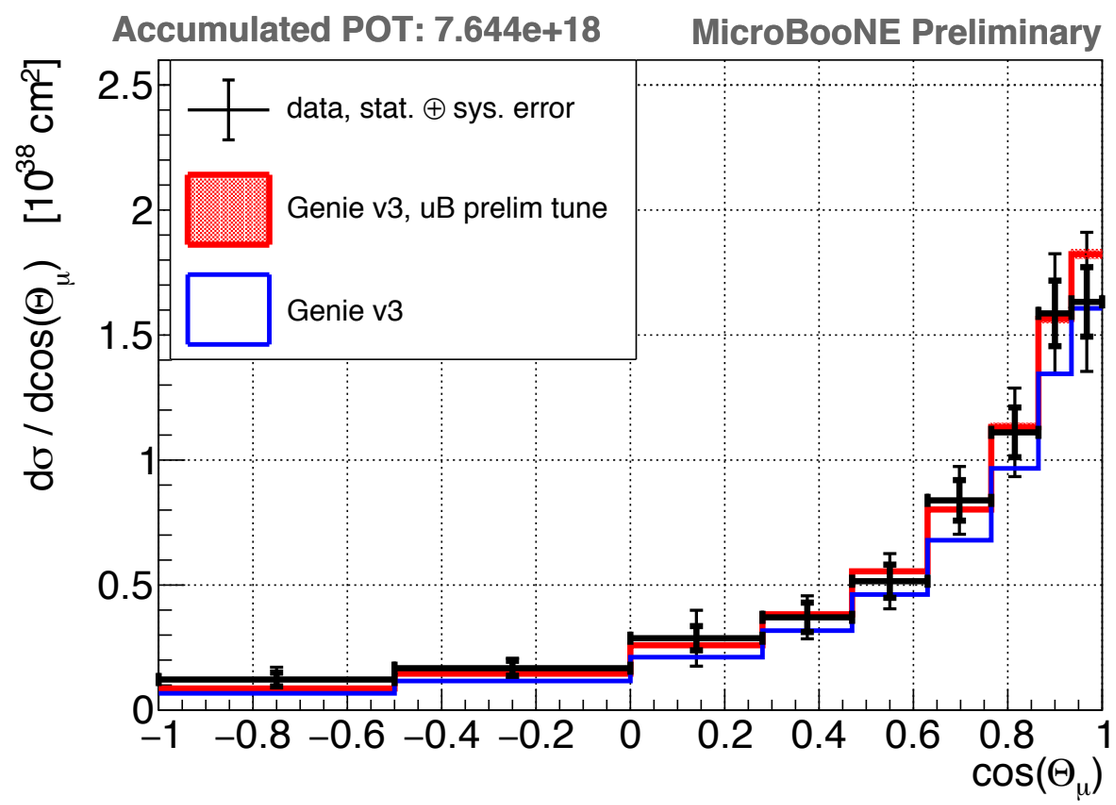

Single-differential cross section as a function of reconstructed muon momentum and angle → **very good agreement with previous measurement,** but **reduced uncertainties**

Future development towards **double-differential** cross-section measurement

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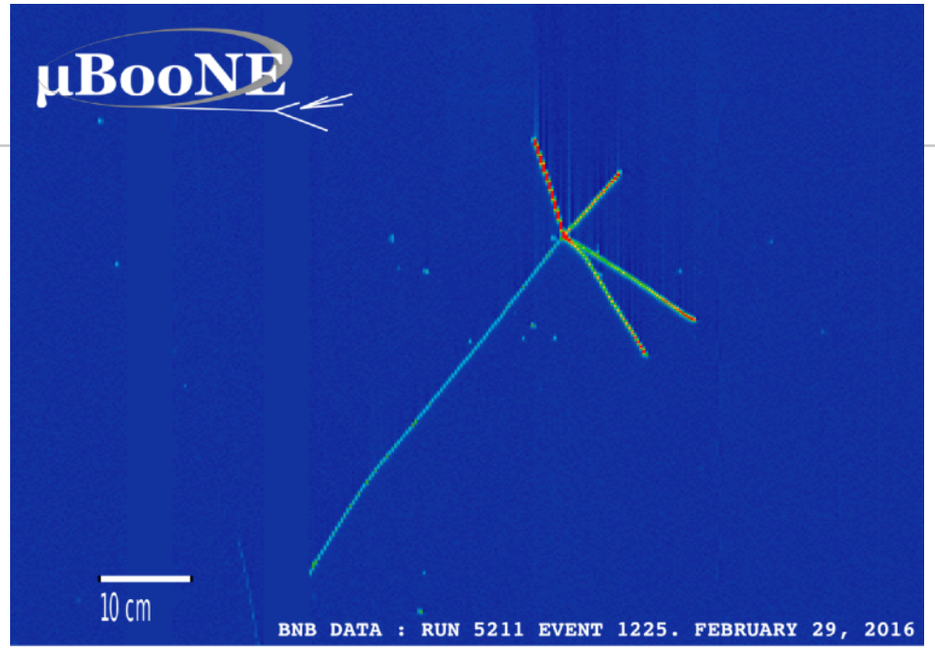
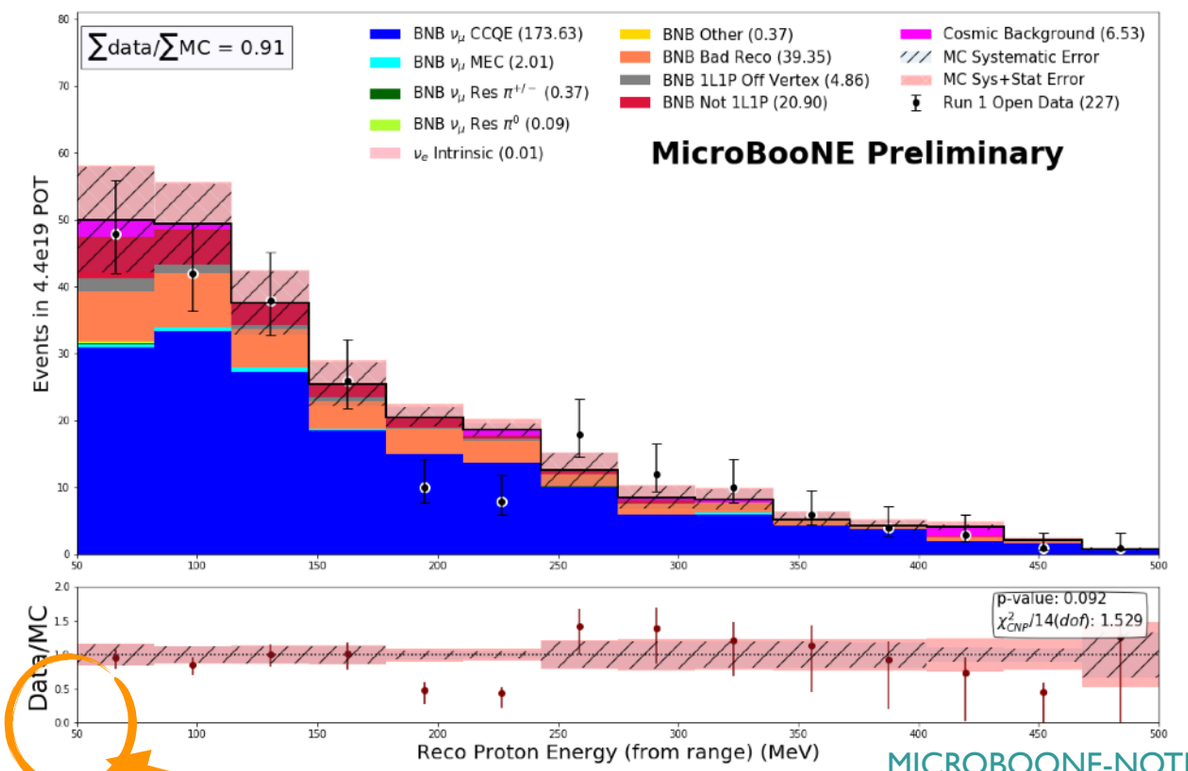
D. Cianci, poster 283, poster session 3

LArTPC STRENGTH: LOW PROTON THRESHOLDS

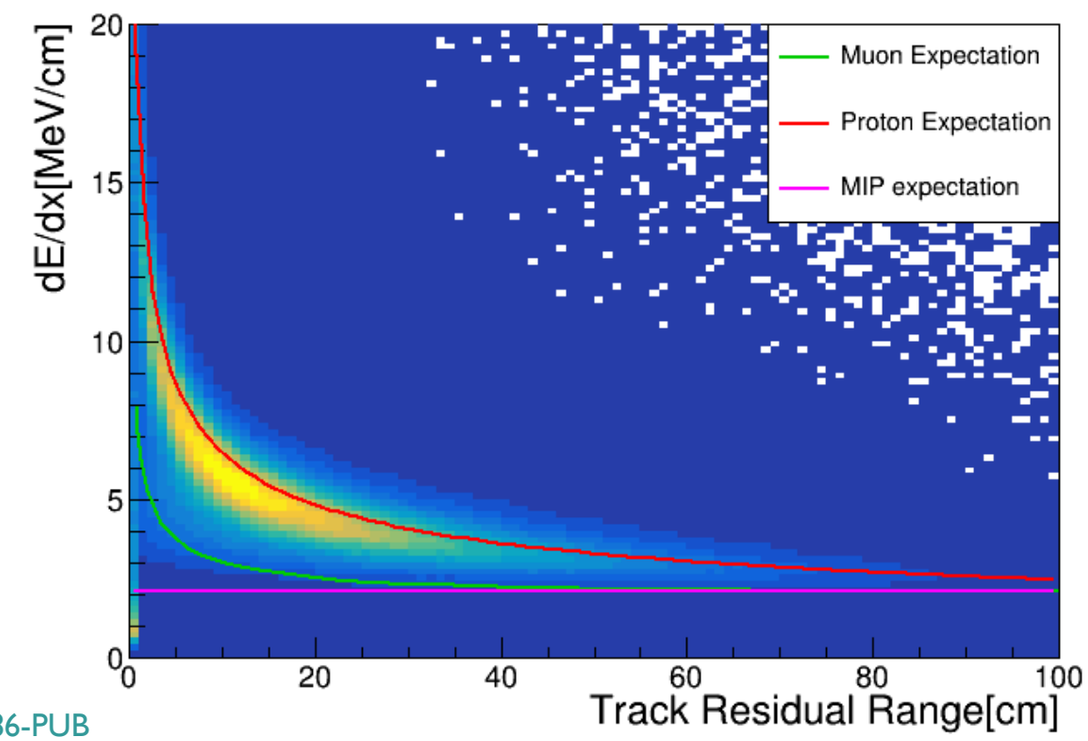
MICROBOONE-NOTE-1056-PUB
JINST 15, P03022 (2020)



- **Low thresholds** → probe 2p2h scattering and nuclear processes
  - MicroBooNE: **300 MeV/c**
  - ArgoNeuT: **200 MeV/c** Phys. Rev. D 90, 012008 (2014)
  - T2K: 500 MeV/c Phys. Rev. D 98, 032003 (2018)
  - MINERvA: 450 MeV/c Phys. Rev. D 99, 012004 (2019)
- Protons **identified by Bragg peak** in last 30 cm of track



MICROBOONE-NOTE-1086-PUB

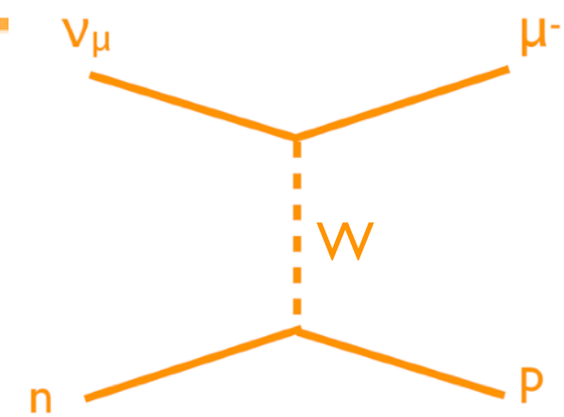


300 MeV/c → 47 MeV KE

A. Papadopoulou, poster 145, poster session 2

CCQE-LIKE CROSS SECTION

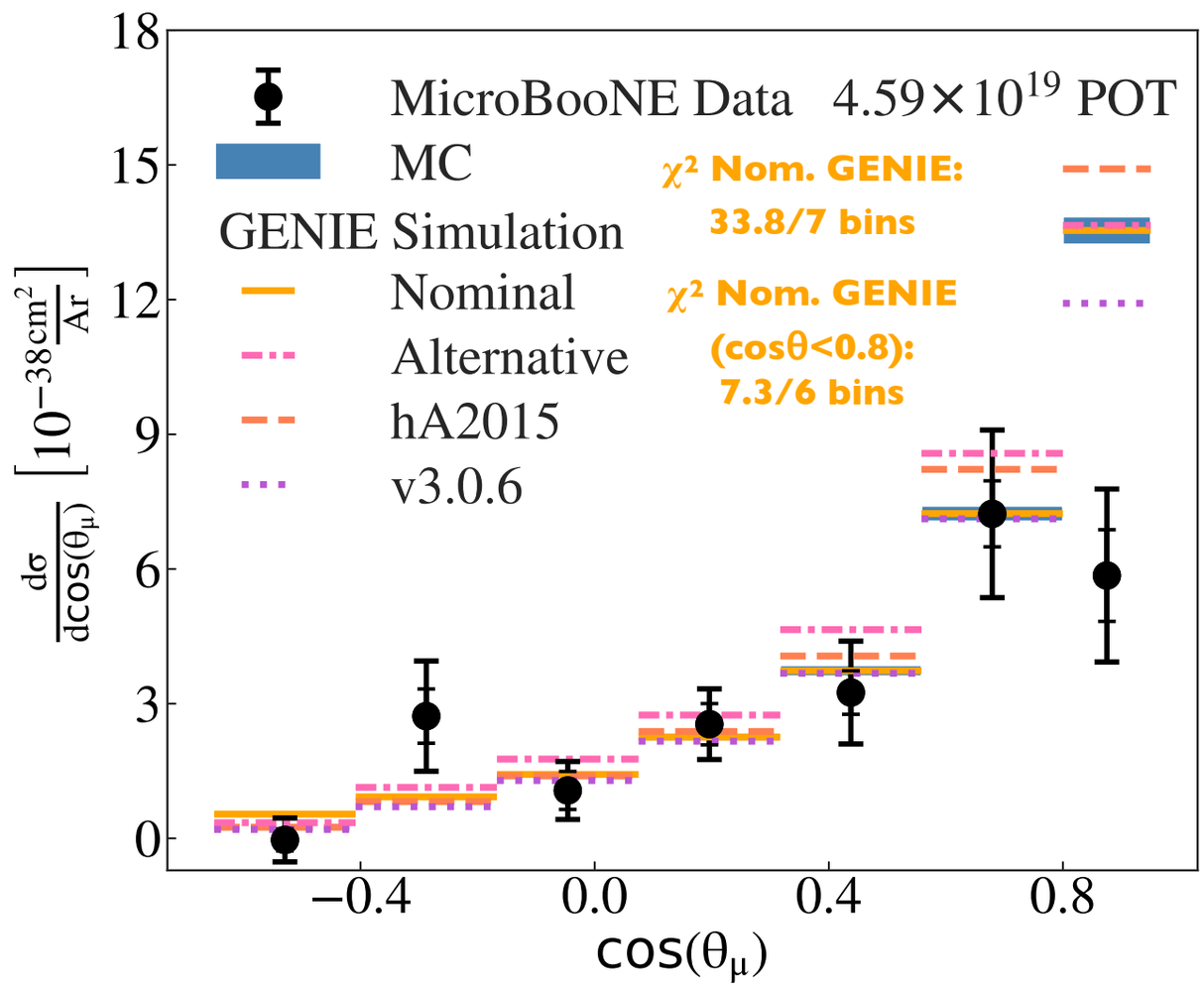
Eur. Phys. J. C 79 673 (2019) arXiv:2006.00108 [hep-ex] (2020)



First extraction of ν_μ-^{40}Ar CCQE-like cross section using a surface LArTPC

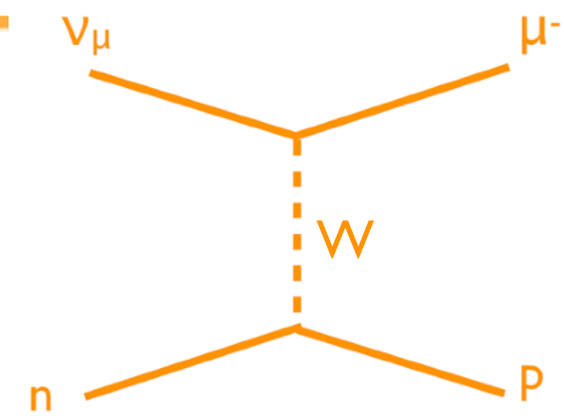
Signal: 1 muon (p_μ>100 MeV/c), 1 proton (p_p>300 MeV/c) with extra cuts on coplanarity and transverse imbalance to enhance CCQE contribution
→ ~84% CC1p0π (~81% CCQE) purity, ~20% efficiency

Good agreement with models, except at very **forward muon scattering** angles
→ low momentum transfer (similar effects previously seen in carbon scattering)

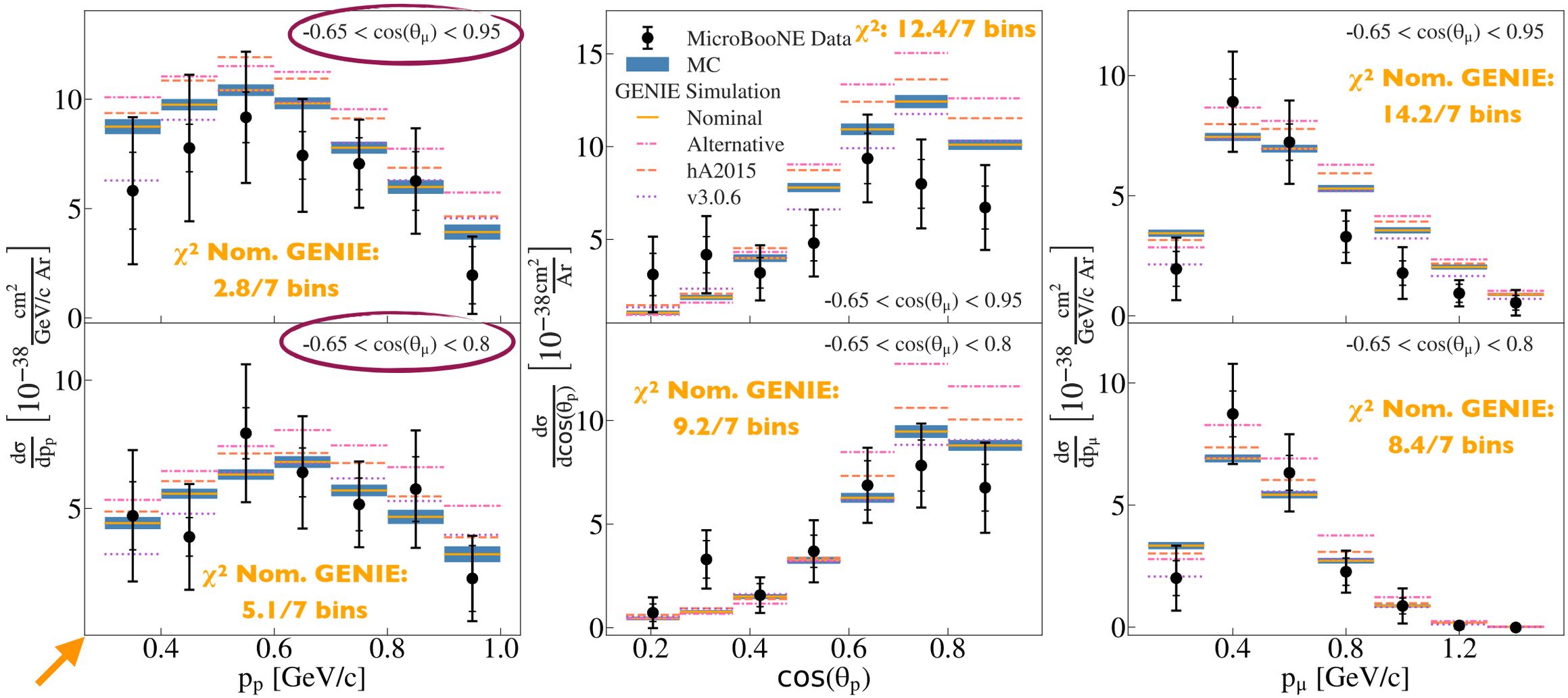


A. Papadopoulou, poster 145, poster session 2

CCQE-LIKE CROSS SECTION



Eur. Phys. J. C 79 673 (2019) arXiv:2006.00108 [hep-ex] (2020)

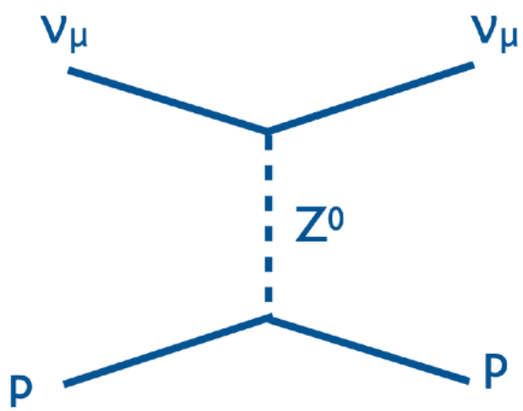


Proton momentum threshold 300 MeV/c

Across all kinematic variables, agreement is improved if forward muon angles are excluded

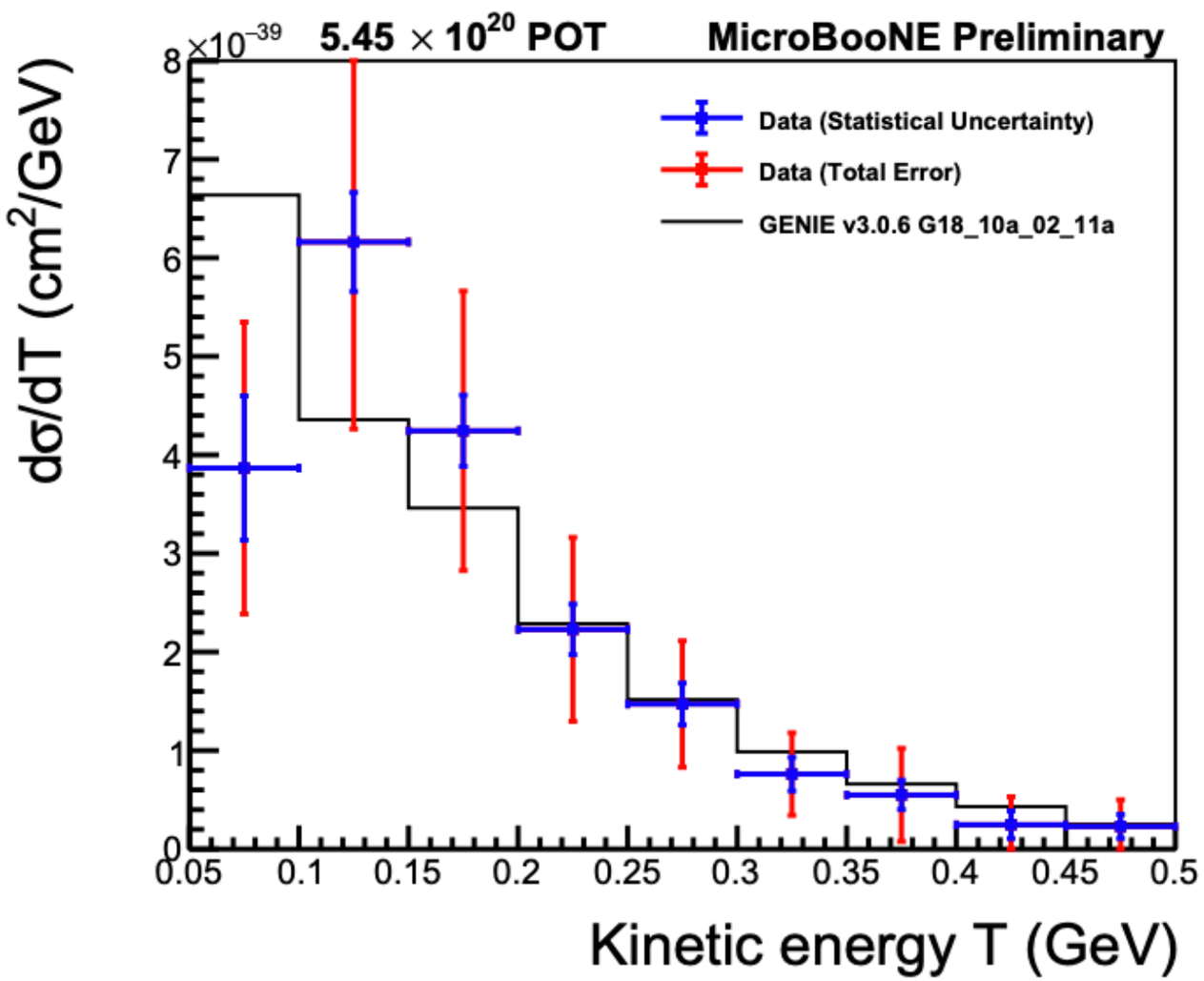
L. Ren, poster 292, poster session 4

NC1P CROSS SECTION

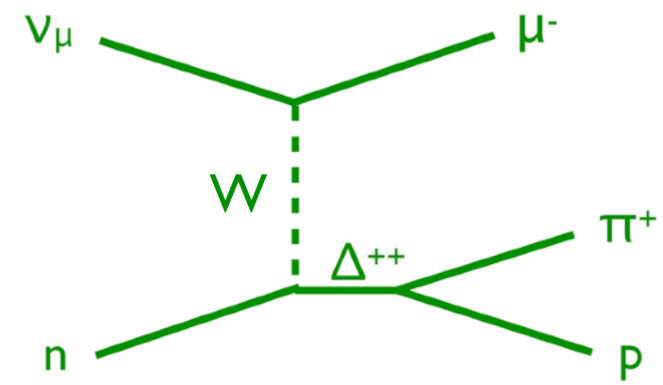


MICROBOONE-NOTE-1067-PUB

- Measure cross section for neutral-current single proton production
- Measurement includes events with $Q^2 \sim 2m_pT_p = 0.1$ GeV^2, **significantly lower** than previous measurements
- Future development towards a measurement of **NC elastic scattering** cross section → measure strange component of neutral-current axial form factor



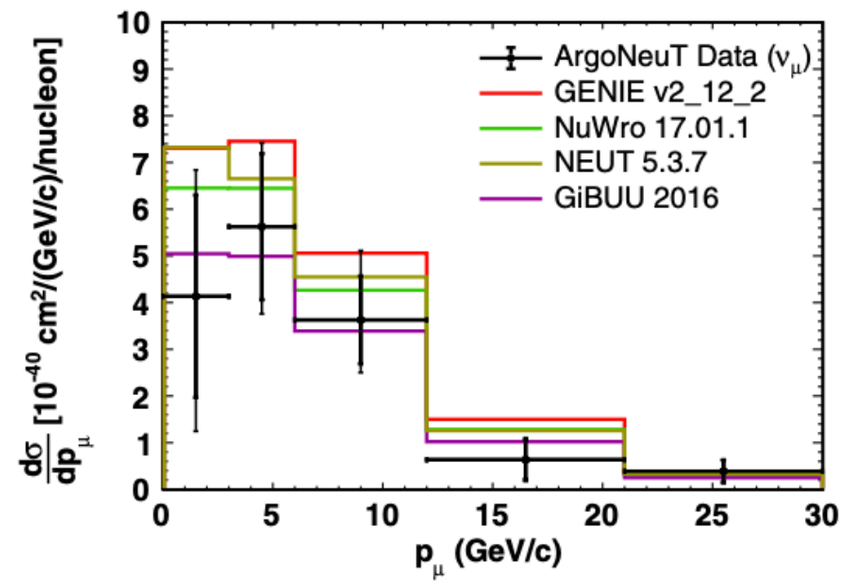
CC $\pi^{\pm}$ PRODUCTION

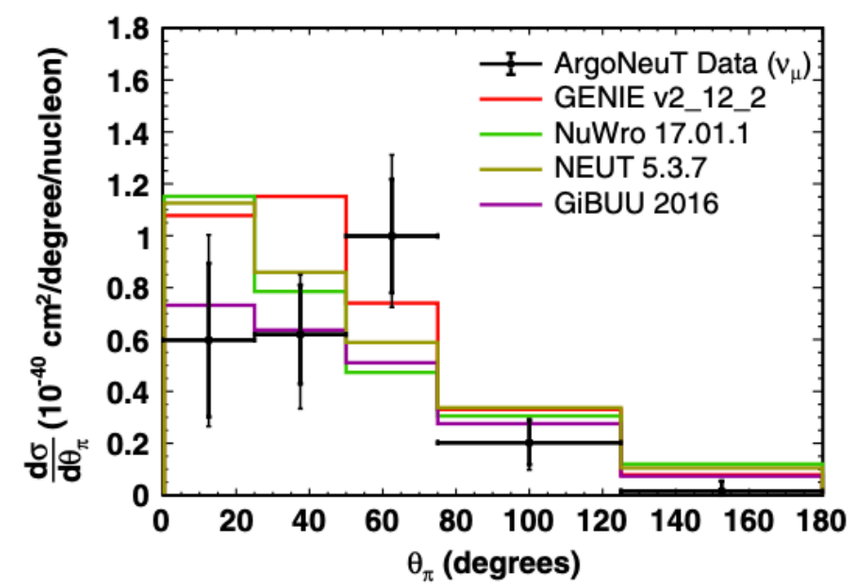


Phys. Rev. D 98, 052002 (2018)

- **Highly relevant for DUNE**: dominant interaction mode at DUNE energies and less well-understood than CCQE-like scattering
- ArgoNeuT ν_μ and $\bar{\nu}_\mu$ CC1$\pi^{\pm}$ measurement:
  - Select **two-track events**: one matched to a track in MINOS (muon candidate)
  - **Select CC1$\pi^{\pm}$ events** using dE/dx of pion candidate, event topology
- MicroBooNE measurement in progress: development work focused on **muon/pion separation** and **pion reinteractions**

ArgoNeuT ν_μ





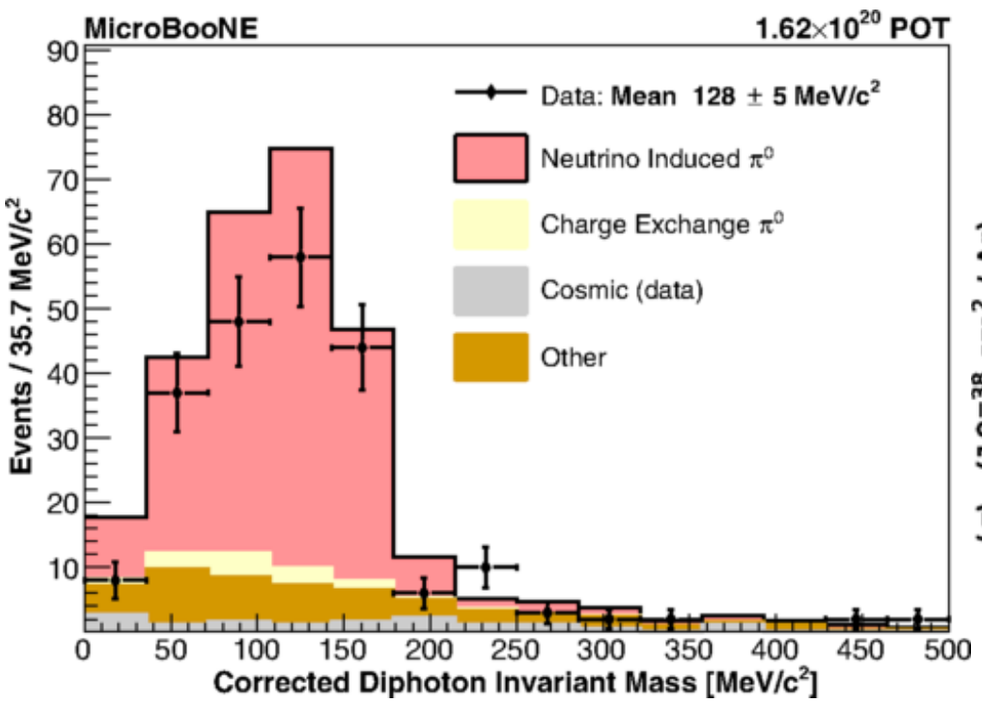
LArIAT, ProtoDUNEs

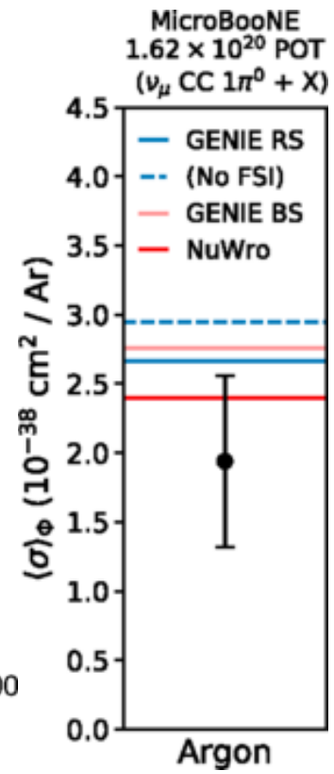
More information: "Searches for New Physics with MicroBooNE", 2nd July

LArTPC STRENGTH: ELECTRONS AND PHOTONS

S. Berkman, Poster 410, Poster Session 2

- **Electrons and photons produce showers in LArTPCs** → important to understand for ν_e appearance searches in SBN and DUNE
- π^0 interactions are a background (although often can be distinguished by energy deposition) — can also be used to **verify shower reconstruction** by reconstructing π^0 mass peak



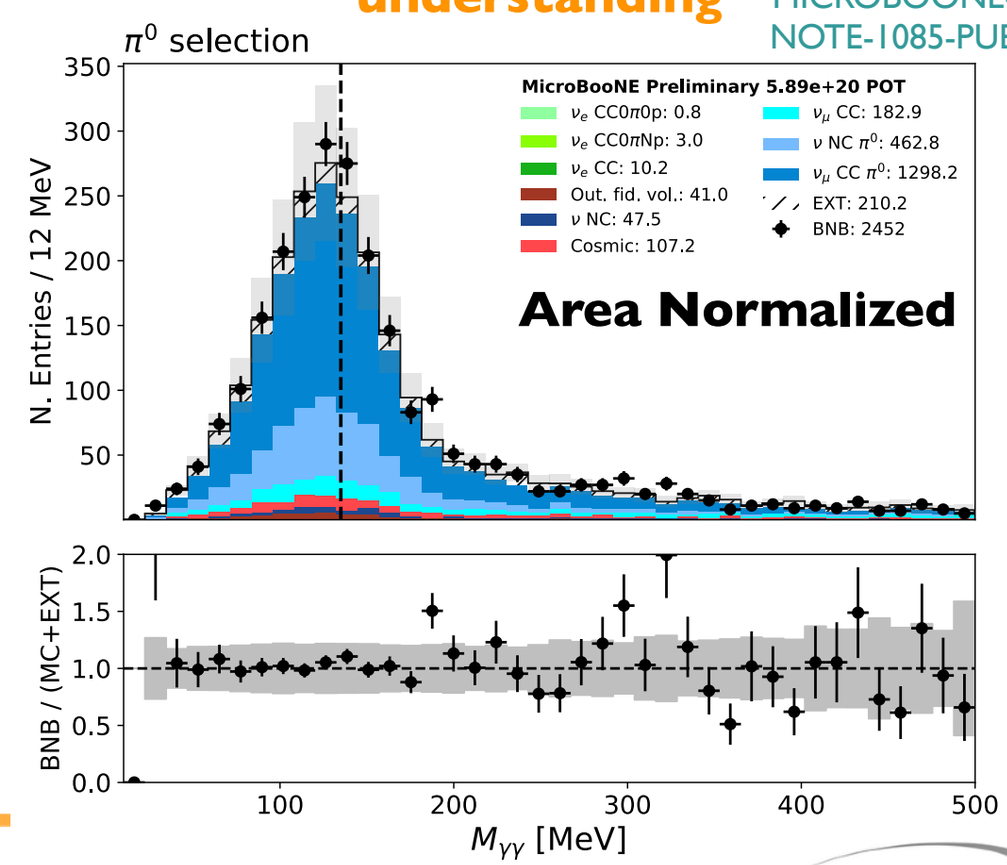


MicroBooNE CCπ⁰ Measurement: presented at Neutrino 2018

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

Current: with improved detector understanding

MICROBOONE-NOTE-1085-PUB

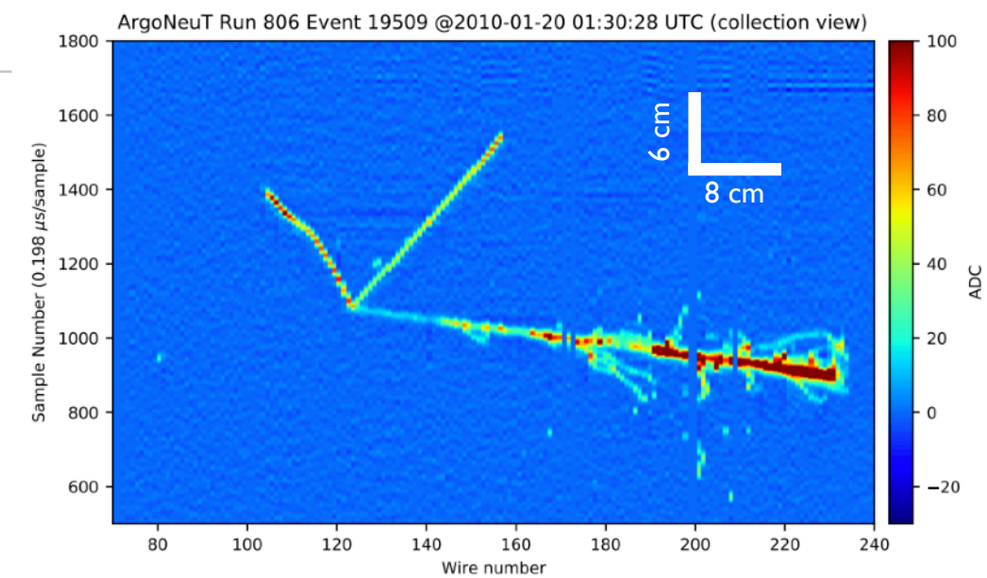


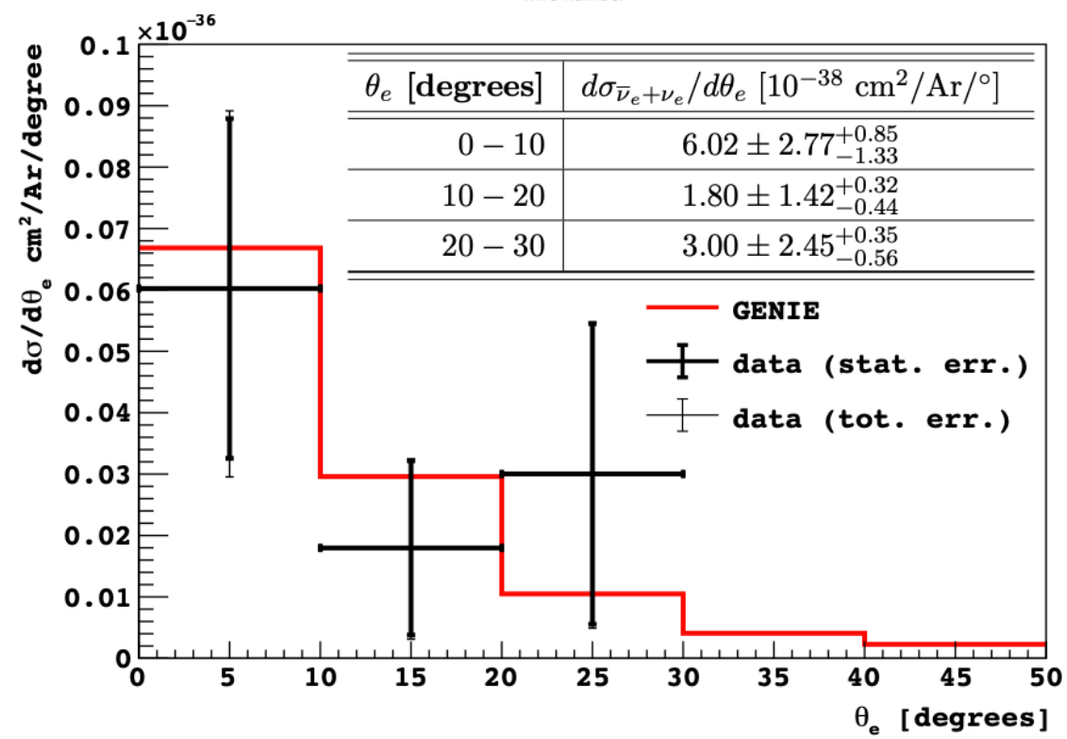
R. Fitzpatrick, Poster 139, Poster Session 4

FIRST MEASUREMENT OF ELECTRON NEUTRINO CROSS SECTION

arXiv:2004.01956 [hep-ex]

- Flux-averaged **$\nu_e+\bar{\nu}_e$ cross section measured by ArgoNeuT**
- Purity 78.9%, efficiency 10.5% → 13 events selected
- **First measurement of its kind** in an energy regime highly relevant for DUNE, demonstration of fully-automated reconstruction and analysis
- MicroBooNE ν_e measurements in BNB - see **"Searches for New Physics with MicroBooNE", 2nd July**
- $\nu_e+\bar{\nu}_e$ cross-section measurements in progress with NuMI beam: purity 40%, efficiency 9% →**~100 events** in 5×10^{19} POT





θ_e [degrees]	$d\sigma_{\bar{\nu}_e+\nu_e}/d\theta_e$ [10^{-38} cm^2/Ar/°]
0 – 10	$6.02 \pm 2.77^{+0.85}_{-1.33}$
10 – 20	$1.80 \pm 1.42^{+0.32}_{-0.44}$
20 – 30	$3.00 \pm 2.45^{+0.35}_{-0.56}$

A. Fiorentini, poster 369, poster session 3

I. Lepetic, Poster 88, Poster Session 1

I. Lepetic, Poster 89, Poster Session 2

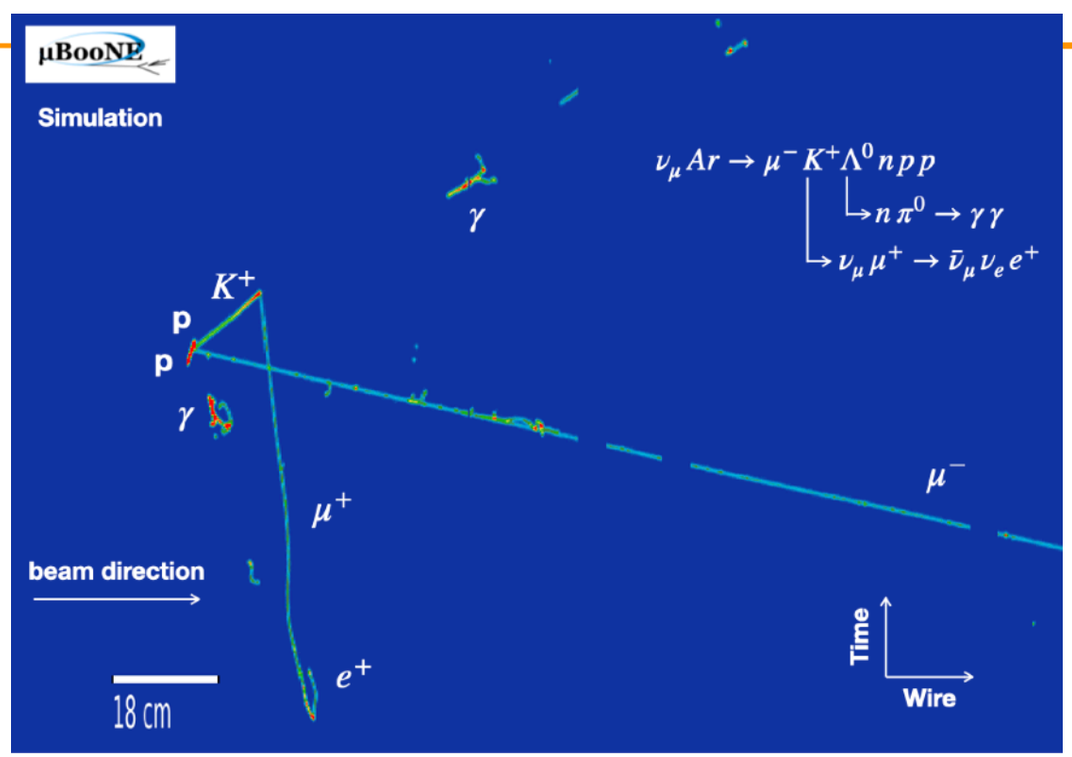
A. Bhat, Poster 4, Poster Session 4

PUSHING THE LIMITS

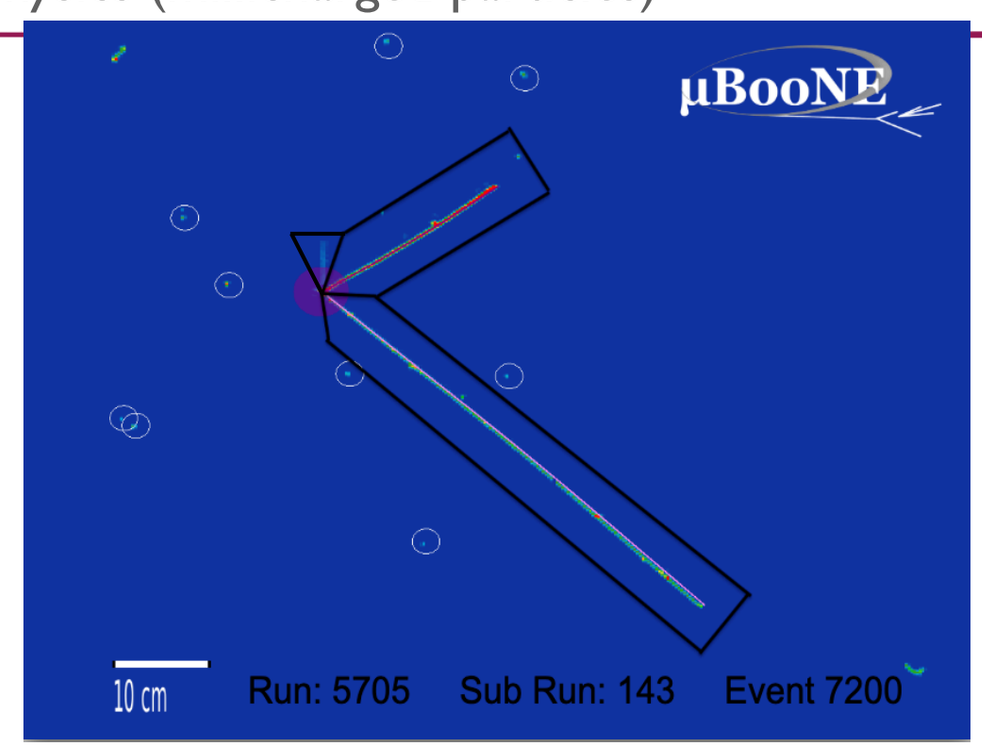
MICROBOONE-NOTE-1050-PUB
Phys. Rev. Lett. 124, 131801 (2020)
Phys. Rev. D 99, 012002 (2019)
MICROBOONE-NOTE-1076-PUB

- **CC kaon production**: rare process, few existing measurements, background for **proton decay** $p \rightarrow K^+\nu$ searches in DUNE
- Selection developed with 68% purity and 7% efficiency → expect 12 candidate interactions in 1.3×10^{21} POT

MICROBOONE-NOTE-1071-PUB



- **Reconstruct sub-MeV particles**: photons from nucleus de-excitation or neutron re-interactions
- Demonstration of low-threshold LArTPC capabilities
- Used in ArgoNeuT to place constraints on BSM physics (millicharged particles)



Many measurements of ν-Ar scattering

- ν_μ CC inclusive cross section

  - ArgoNeuT: Single-differential cross section
    Phys. Rev. Lett. 108 161802 (2012)
  - ArgoNeuT: Updated single-differential cross section
    Phys. Rev. D 89, 112003 (2014)
  - μBooNE: Double-differential cross section
    Phys. Rev. Lett. 123, 131801 (2019)
  - μBooNE: Single-differential cross section with updated detector and interaction models
    MICROBOONE-NOTE-1069-PUB

- ν_μ exclusive channels

  - μBooNE: Charged-particle multiplicity
    Eur. Phys. J. C79, 248 (2019)
  - μBooNE: ν_μ CCQE-like scattering Eur. Phys. J. C 79 673 (2019)
    arXiv:2006.00108 (submitted to PRL)
  - ArgoNeuT: ν_μ and $\bar{\nu}_\mu$ CC2p production
    Phys. Rev. D 90, 012008 (2014)
  - μBooNE: ν_μ CCπ^0 production
    Phys. Rev. D99, 091102(R) (2019)
  - ArgoNeuT: ν_μ and $\bar{\nu}_\mu$ NCπ^0 production
    Phys. Rev. D 96, 012006 (2017)
  - ArgoNeuT: ν_μ and $\bar{\nu}_\mu$ CCπ^+ production
    Phys. Rev. D 98, 052002 (2018)
  - ArgoNeuT: ν_μ and $\bar{\nu}_\mu$ Coherent CCπ^+ production
    Phys. Rev. Lett. 113, 261801 (2014)
  - μBooNE: ν_μ CC kaon production
    MICROBOONE-NOTE-1071-PUB
  - μBooNE: ν_μ NC 1p production
    MICROBOONE-NOTE-1067-PUB

- Other measurements

  - ArgoNeuT: ν_e and $\bar{\nu}_e$ scattering (inclusive)
    arXiv:2004.01956[hep-ex]
  - ArgoNeuT: MeV-scale physics
    Phys. Rev. D 99, 012002 (2019)
  - μBooNE: MeV-scale physics
    MICROBOONE-NOTE-1076-PUB
  - ArgoNeuT: Limits on millicharged particles
    Phys. Rev. Lett. 124, 131801 (2020)

FUTURE PROSPECTS

- This talk has focused on current results from **MicroBooNE** and recent results from **ArgoNeuT**

FUTURE PROSPECTS

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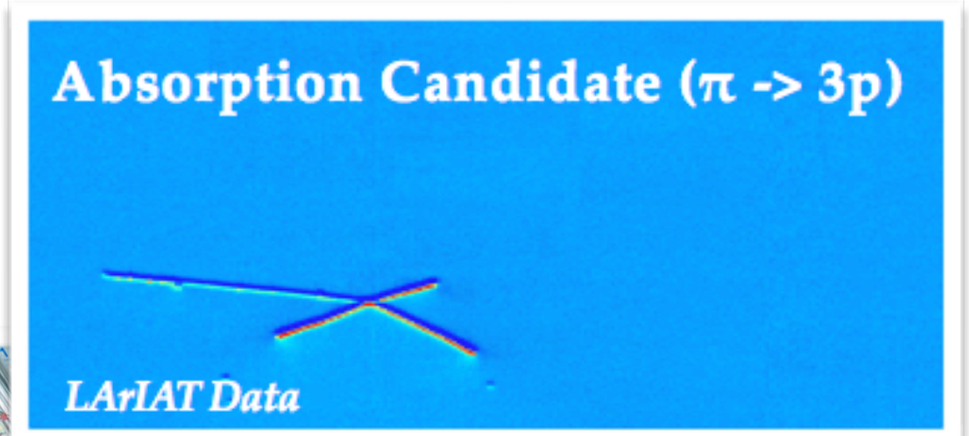
MicroBooNE recent improvements in detector understanding directly results in **reduced systematic uncertainties** on CC inclusive measurement
→ will form the basis of new, **more precise measurements** of neutrino interactions on argon in the near future

Additional measurements in progress: ν_μ CCπ^0, ν_μ CC1π^+, ν_μ CC-Coherent π^+, ν_μ CC0πNp, ν_μ CC0π2p, ν_μ CC0π STV, ν_μ KDAR CC0π, ν_μ CC0π0p, ν_e CC inclusive, ν_e CC0π1p

FUTURE PROSPECTS

- This talk has focused on current results from **MicroBooNE** and recent results from **ArgoNeuT**



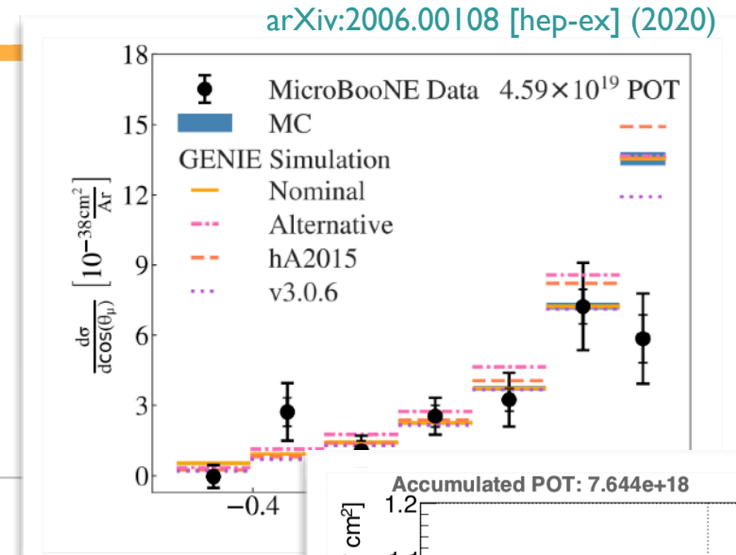
- Exclusive measurements will be informed by test-beam measurements of charged particles in LArTPCs (e.g. interactions of pions, protons) by **LArIAT** and **ProtoDUNEs**

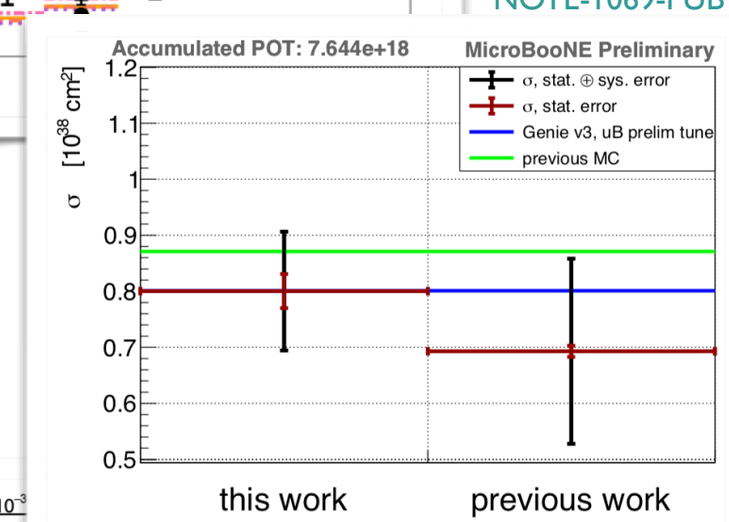
- In the future, look out for more measurements from upcoming experiments: **SBND**, **ICARUS**, and eventually **DUNE-ND**

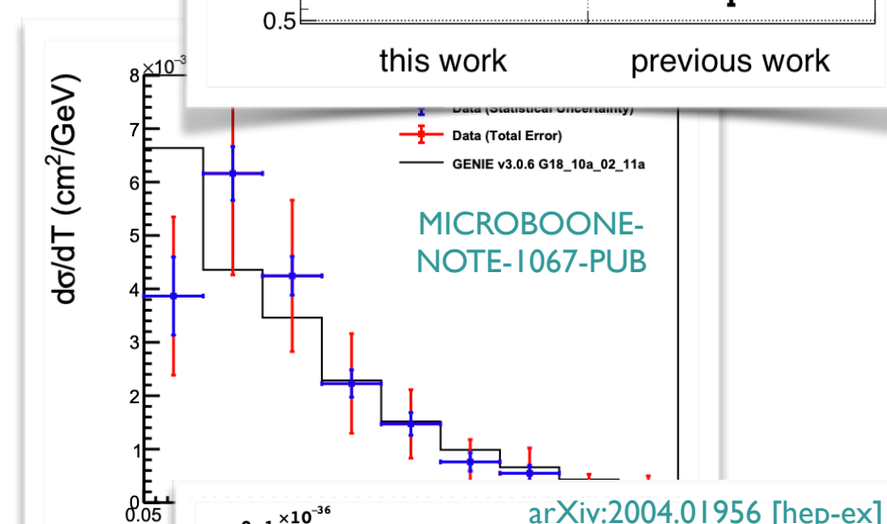
ICARUS will start taking data very soon
SBND will collect **7m ν-Ar interactions in 3 years**
See talk: "ICARUS and the Fermilab Short-Baseline Neutrino Program" on 2nd July

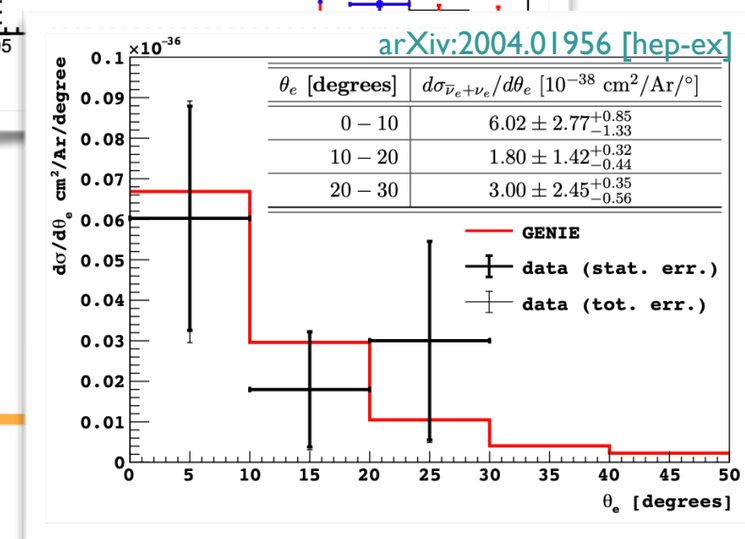
SUMMARY

- Cross-section measurements on argon are **vital** for the success of the SBN program and eventually DUNE
- **Huge progress** over the past two years since Neutrino 2018 → measurements with low-energy protons, π^0s, ν_es and more are **extremely valuable**
- LArTPC technology has demonstrated 4π acceptance and ability to measure sub-MeV energies — we are already able to make **precise, accurate measurements of exclusive final states**
- First time we can confront **models tuned to carbon** with high-statistics argon data: seem to do well with the data now available
- More (and more precise) measurements expected in the future → **stronger tests** of our models









Cross-section Posters and Supporting Documents

- **MicroBooNE**
  - ν_μ CCQE-like measurement: **A. Papadopoulou, Poster 145, Poster Session 2**
    Cosmic rejection: Eur. Phys. J. C 79 673 (2019) , Cross-section measurement: arXiv:2006.00108 [hep-ex] (2020)
  - Updated ν_μ CC-inclusive measurement: MICROBOONE-NOTE-1069-PUB
  - ν_μ NC1p measurement: **L. Ren, Poster 292, Poster Session 4** MICROBOONE-NOTE-1067-PUB
  - ν_μ CCKaon selection: **A. Fiorentini, Poster 369, Poster Session 3** MICROBOONE-NOTE-1071-PUB
  - MeV-scale Physics: **A. Bhat, Poster 4, Poster Session 4** MICROBOONE-NOTE-1076-PUB
  - Interaction model and uncertainties: MICROBOONE-NOTE-1074-PUB
  - Detector uncertainties: **L. Yates, Poster 176, Poster Session 1** MICROBOONE-NOTE-1075-PUB
- **ArgoNeuT**
  - $\nu_e+\bar{\nu}_e$ CC inclusive measurement: **R. Fitzpatrick, Poster 139, Poster Session 4**
    arXiv:2004.01956 [hep-ex]
  - Improved limits on millicharged particles: **I. Lepetic, Poster 89, Poster Session 2**
    Phys. Rev. Lett. 124, 131801 (2020)

MICROBOONE PUBLICATIONS

*** cross-section specific**

- MicroBooNE collaboration, "First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with the MicroBooNE Detector", arXiv:2006.00108, submitted to PRL
- MicroBooNE collaboration, "Vertex-Finding and Reconstruction of Contained Two-track Neutrino Events in the MicroBooNE Detector", arXiv: 2002.09375, submitted to JINST
- MicroBooNE collaboration, "Search for heavy neutral leptons decaying into muon-pion pairs in the MicroBooNE detector", arXiv:1911.10545, Phys. Rev. D101, 052001 (2020), Fermilab News article (02/13/20)
- MicroBooNE collaboration, "Reconstruction and Measurement of O(100) MeV Electromagnetic Activity from $\pi_0 \rightarrow \gamma\,\gamma$ Decays in the MicroBooNE LAr TPC", arXiv:1910.02166, JINST 15, P02007 (2020)
- MicroBooNE collaboration, "A Method to Determine the Electric Field of Liquid Argon Time Projection Chambers Using a UV Laser System and its Application in MicroBooNE", arXiv:1910.01430, submitted to JINST
- MicroBooNE collaboration, "Calibration of the Charge and Energy Response of the MicroBooNE Liquid Argon Time Projection Chamber Using Muons and Protons", arXiv:1907.11736, JINST 15, P03022 (2020)
- MicroBooNE collaboration, "First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at Enu ~0.8 GeV with the MicroBooNE Detector", arXiv:1905.09694, Phys. Rev. Lett. 123, 131801 (2019), Fermilab News article (12/13/19)
- MicroBooNE collaboration, "Design and Construction of the MicroBooNE Cosmic Ray Tagger System", arXiv:1901.02862, JINST 14, P04004 (2019)
- MicroBooNE collaboration, "Rejecting Cosmic Background for Exclusive Neutrino Interaction Studies with Liquid Argon TPCs: A Case Study with the MicroBooNE Detector", arXiv:1812.05679, accepted by Eur. J. Phys. C.
- MicroBooNE collaboration, "First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE LAr TPC", arXiv:1811.02700, Phys. Rev. D99, 091102(R) (2019)
- MicroBooNE collaboration, "A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber", arXiv:1808.07269, Phys. Rev. D99, 092001 (2019), Fermilab News article (09/12/18), DOE HEP Science Highlight (01/30/19)
- MicroBooNE collaboration, "Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions", arXiv:1805.06887, Eur. Phys. J. C79, 248 (2019), Fermilab News article (05/31/18)
- MicroBooNE collaboration, "Ionization Electron Signal Processing in Single Phase LAr TPCs II: Data/Simulation Comparison and Performance in MicroBooNE", arXiv:1804.02583, JINST 13, P07007 (2018), Fermilab News article (07/09/18), DOE HEP Science Highlight (05/21/19)
- MicroBooNE collaboration, "Ionization Electron Signal Processing in Single Phase LAr TPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation", arXiv:1802.08709, JINST 13, P07006 (2018), Fermilab News article (07/09/18), DOE HEP Science Highlight (05/21/19)
- MicroBooNE collaboration, "The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector", arXiv:1708.03135, Eur. Phys. J. C78, 1, 82 (2018)
- MicroBooNE collaboration, "Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter", arXiv:1707.09903, JINST 12, P12030 (2017)
- MicroBooNE collaboration, "Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC", arXiv:1705.07341, JINST 12, P08003 (2017), Fermilab News article (07/05/17), DOE HEP Science Highlight (05/16/18)
- MicroBooNE collaboration, "Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC", arXiv:1704.02927, JINST 12, P09014 (2017)
- MicroBooNE collaboration, "Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering", arXiv:1703.06187, JINST 12 P10010 (2017)
- MicroBooNE collaboration, "Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber", arXiv: 1611.05531, JINST 12, P03011 (2017)
- MicroBooNE collaboration, "Design and Construction of the MicroBooNE Detector", arXiv:1612.05824, JINST 12, P02017 (2017)

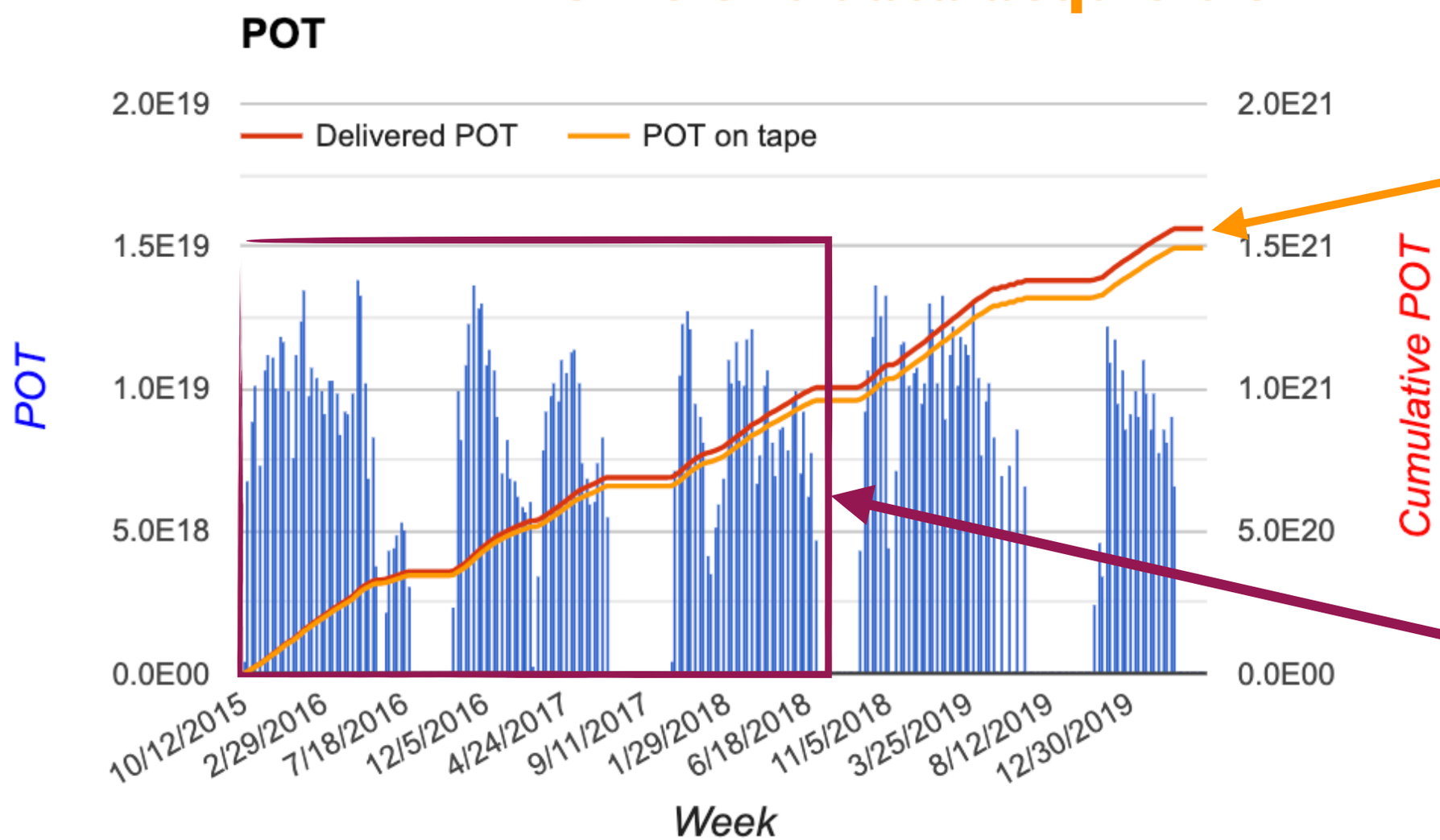
ARGONEUT PUBLICATIONS

*** cross-section specific**

- ArgoNeuT collaboration, "First Measurement of Electron Neutrino Scattering Cross Section on Argon", arXiv:2004.01956[hep-ex]
- ArgoNeuT collaboration, "Improved Limits on Millicharged Particles Using the ArgoNeuT Experiment at Fermilab", arXiv:1911.07996[hep-ex], Phys. Rev. Lett. 124, 131801 (2020)
- ArgoNeuT collaboration, "Demonstration of MeV-Scale Physics in Liquid Argon Time Projection Chambers Using ArgoNeuT", arXiv: 1810.06502[hep-ex], Phys. Rev. D 99, 012002 (2019)
- ArgoNeuT collaboration, "First measurement of the cross section for ν_μ and $\bar{\nu}_\mu$ induced single charged pion production on argon using ArgoNeuT", arXiv:1804.10294[hep-ex], Phys. Rev. D 98, 052002 (2018)
- ArgoNeuT collaboration, "First Observation of Low Energy Electron Neutrinos in a Liquid Argon Time Projection Chamber", arXiv: 1610.04102[hep-ex], Phys. Rev. D 95, 072005 (2017)
- ArgoNeuT collaboration, "Measurement of ν_μ and $\bar{\nu}_\mu$ neutral current $\pi^0 \rightarrow \gamma\gamma$ production in the ArgoNeuT detector", arXiv:1511.00941[hep-ex], Phys. Rev. D 96, 012006 (2017)
- ArgoNeuT collaboration, "First Measurement of Neutrino and Antineutrino Coherent Charged Pion Production on Argon", arXiv:1408.0598[hep-ex], Phys. Rev. Lett. 113, 261801 (2014), Phys. Rev. Lett. 114, 039901 (erratum) (2015)
- ArgoNeuT collaboration, "Detection of Back-to-Back Proton Pairs in Charged-Current Neutrino Interactions with the ArgoNeuT Detector in the NuMI Low Energy Beam Line", arXiv:1405.4261[nucl-ex], Phys. Rev. D 90, 012008 (2014)
- ArgoNeuT collaboration, "Measurements of Inclusive Muon Neutrino and Antineutrino Charged Current Differential Cross Sections on Argon in the NuMI Antineutrino Beam", arXiv:1404.4809[hep-ex], Phys. Rev. D 89, 112003 (2014)
- ArgoNeuT collaboration, "A Study of Electron Recombination Using Highly Ionizing Particles in the ArgoNeuT Liquid Argon TPC", arXiv: 1306.1712[physics.ins-det], JINST 8 P08005 (2013)
- ArgoNeuT collaboration, "Analysis of a Large Sample of Neutrino-Induced Muons with the ArgoNeuT Detector", arXiv:1205.6702[physics.ins-det], JINST 7 P10020 (2012)
- ArgoNeuT collaboration, "First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon", arXiv: 1111.0103[hep-ex], Phys. Rev. Lett. 108 161802 (2012)
- ArgoNeuT collaboration, "The ArgoNeuT Detector in the NuMI Low-Energy beam line at Fermilab", arxiv:1205.6747[physics.ins-det], JINST 7 P10019 (2012)

MICROBOONE DATA COLLECTION

Very **stable detector operation**, smooth and **steady data taking**, **efficient data acquisition**



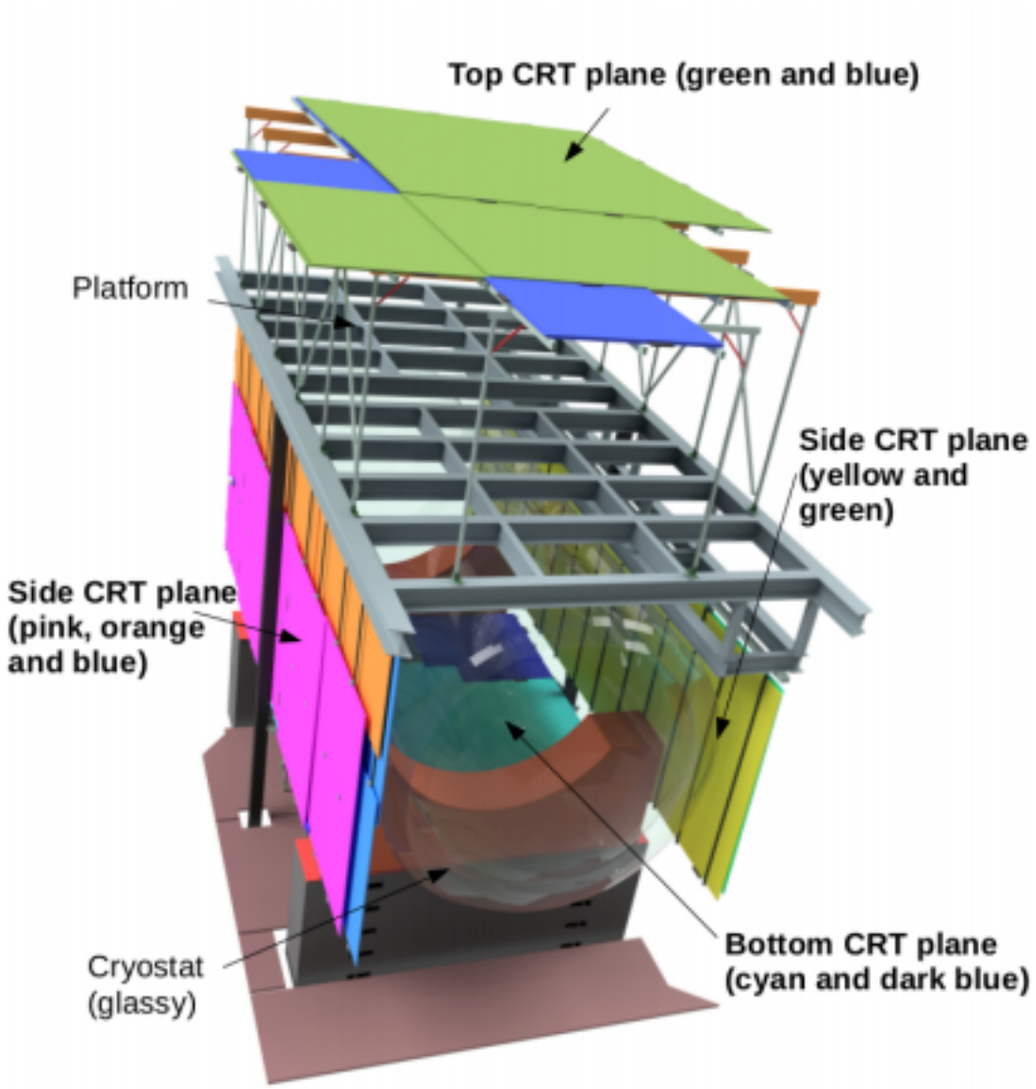
Total data collected: 1.56×10^{21} POT (protons on target)

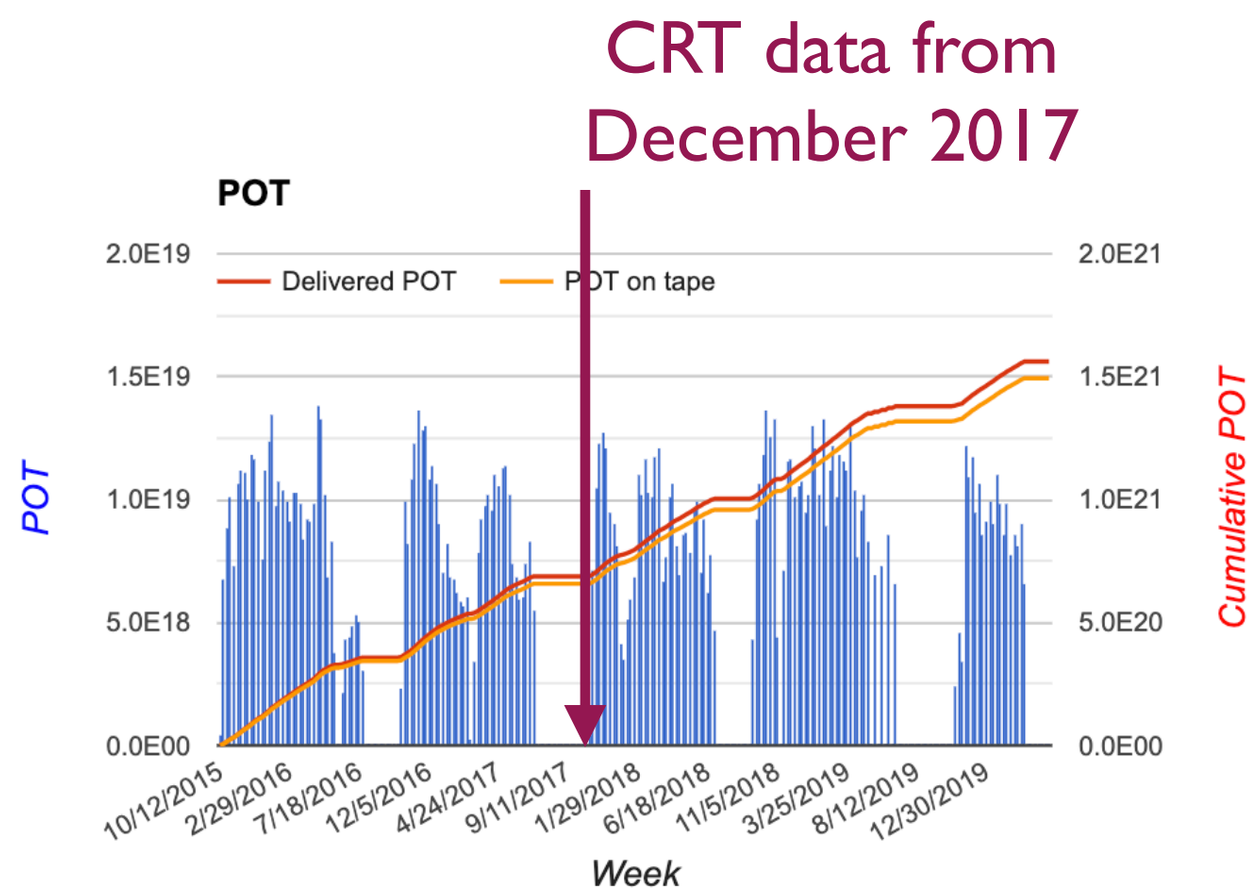
Analyses shown today use subsets of data collected between December 2015 and June 2018

COSMIC RAY TAGGER (CRT)

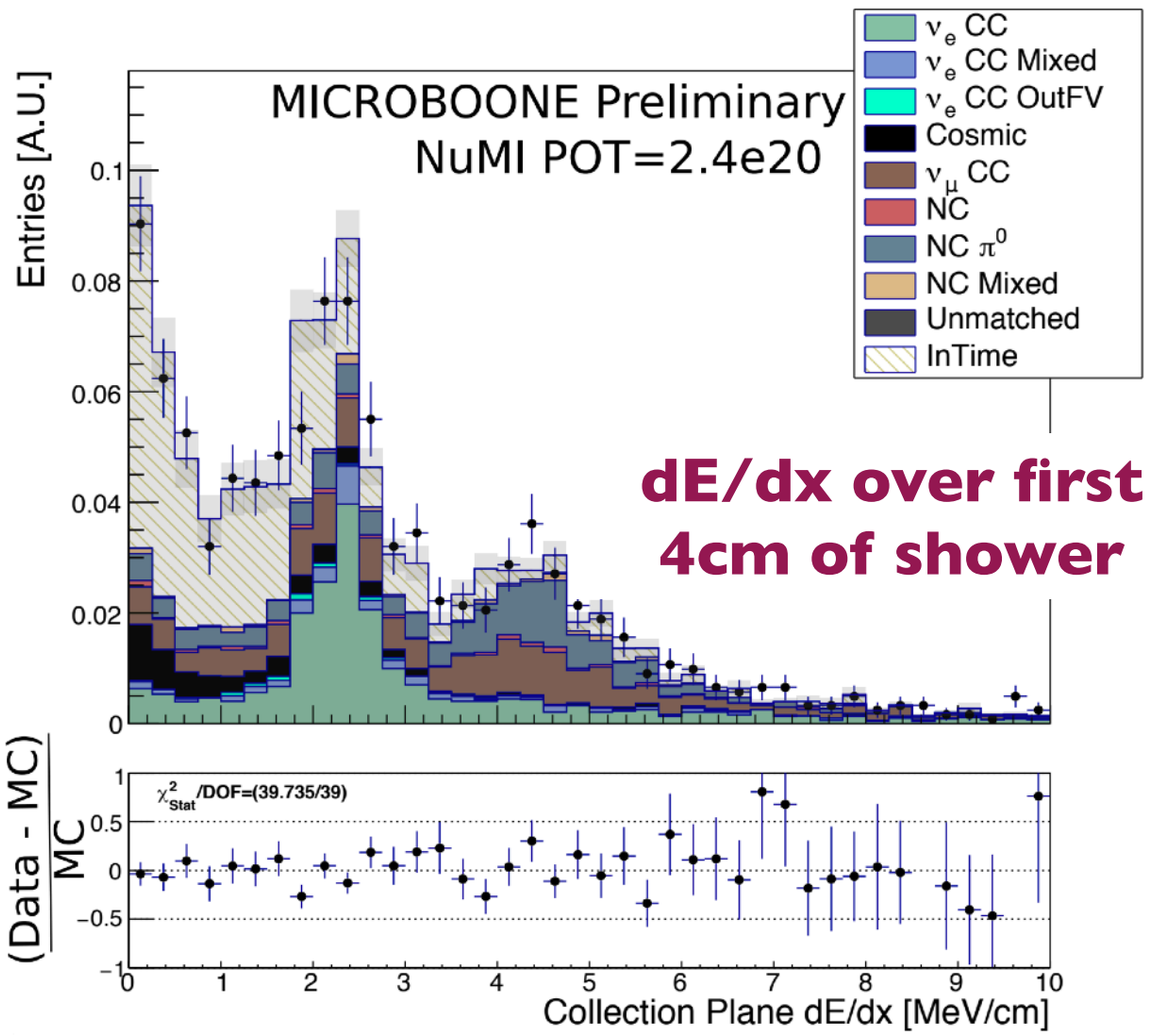
JINST 14 P04004 (2019)

MICROBOONE-NOTE-1069-PUB





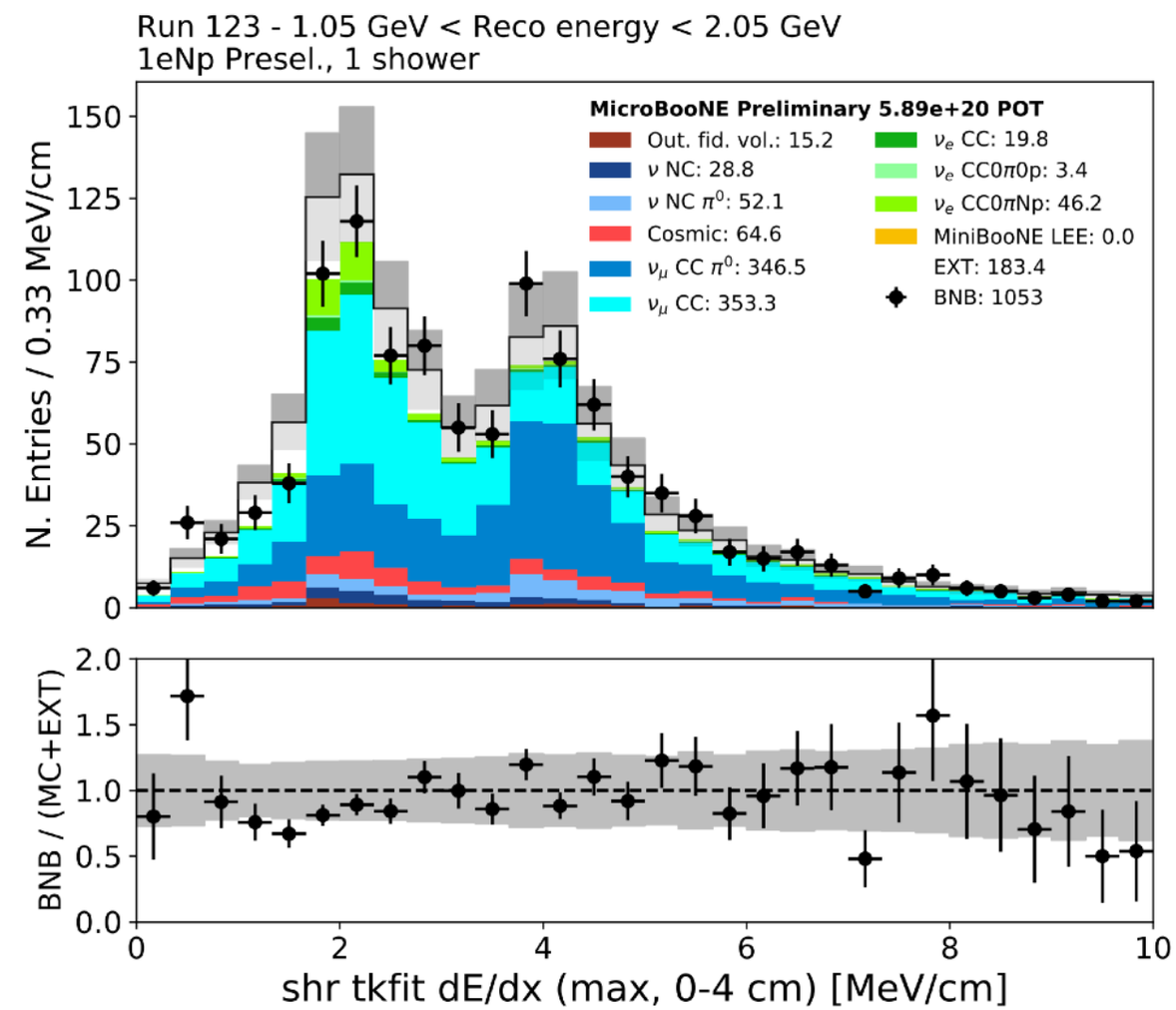
ELECTRON-PHOTON DISCRIMINATION



dE/dx over first 4cm of shower

MicroBooNE ν_e Selection: presented at NuInt 2018

MICROBOONE-NOTE-1054-PUB



Current: with improved detector understanding

MICROBOONE-NOTE-1085-PUB

CC INCLUSIVE CROSS SECTION MEASUREMENT

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

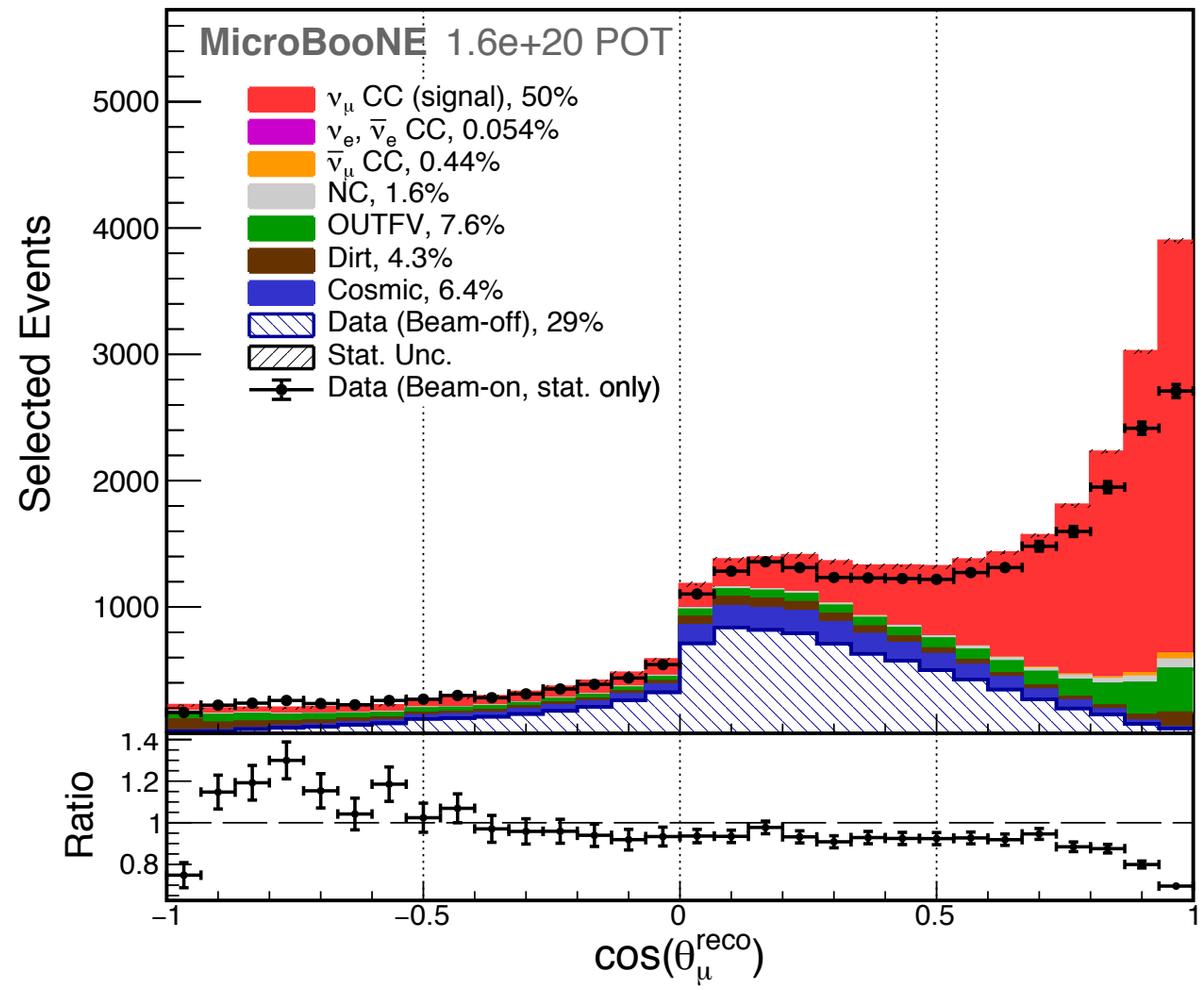
Selection presented at Neutrino 2018

- Topological and optical information → reject background events from cosmic rays
- Energy deposition profile: select candidate muon

Largest ever sample of neutrino interactions on argon

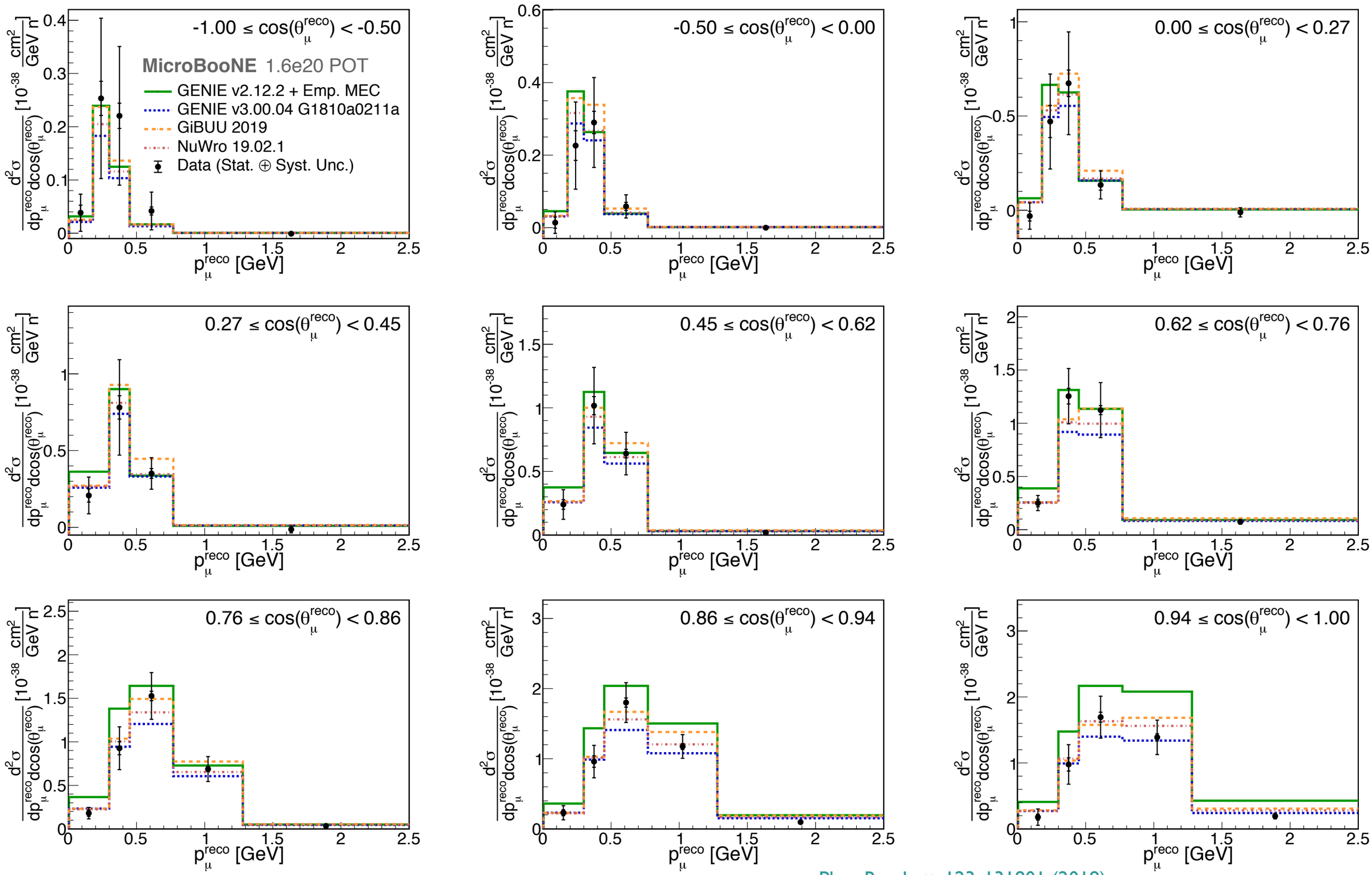
Signal (CC-inclusive) events: 50.4%

Largest background: **cosmic rays** (29%)
→ directly measured with beam-off data



New since Neutrino 2018: **double-differential** cross section measurement

CC Inclusive double-differential measurement



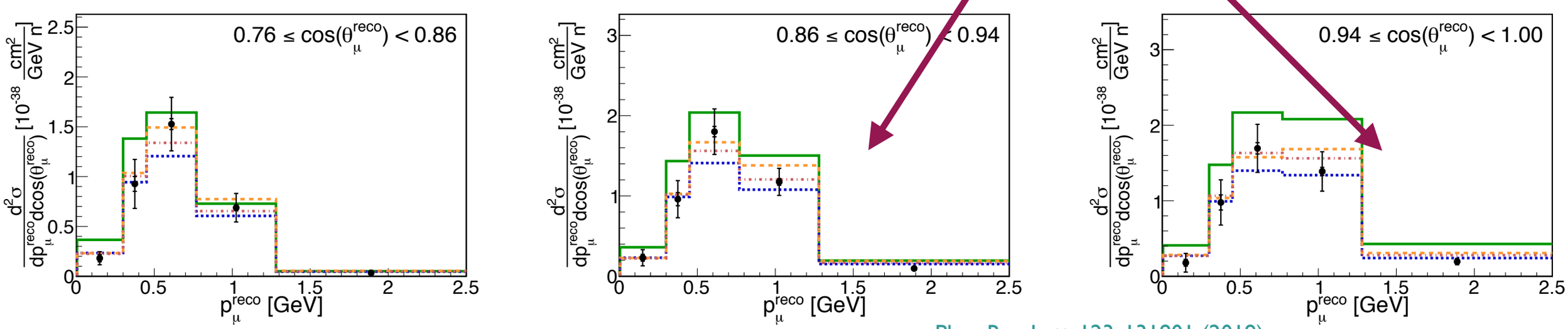
Phys. Rev. Lett. 123, 131801 (2019)

CC Inclusive double-differential measurement

Model	χ^2/N_{bins}
GENIE v2+MEC	245.9/42
GENIE v3	108.8/42
GiBUU	172.9/42
NuWro	126.5/42

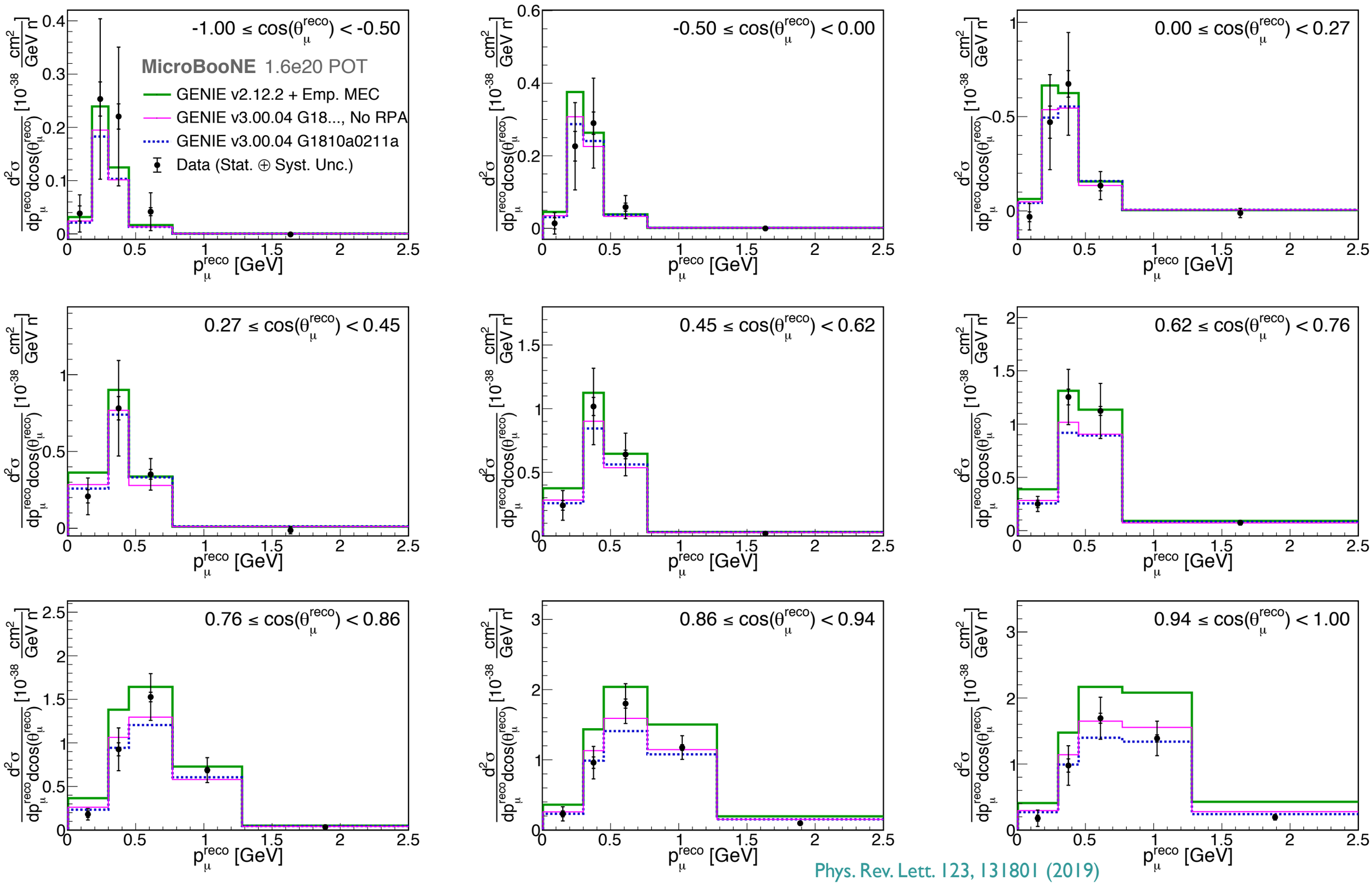
Tension reduced (smaller $\chi 2$) for **GENIE v3**, **NuWro**, and **GiBUU** compared to **GENIE v2**

Large $\chi 2$ driven by high-momentum, forward-going bins



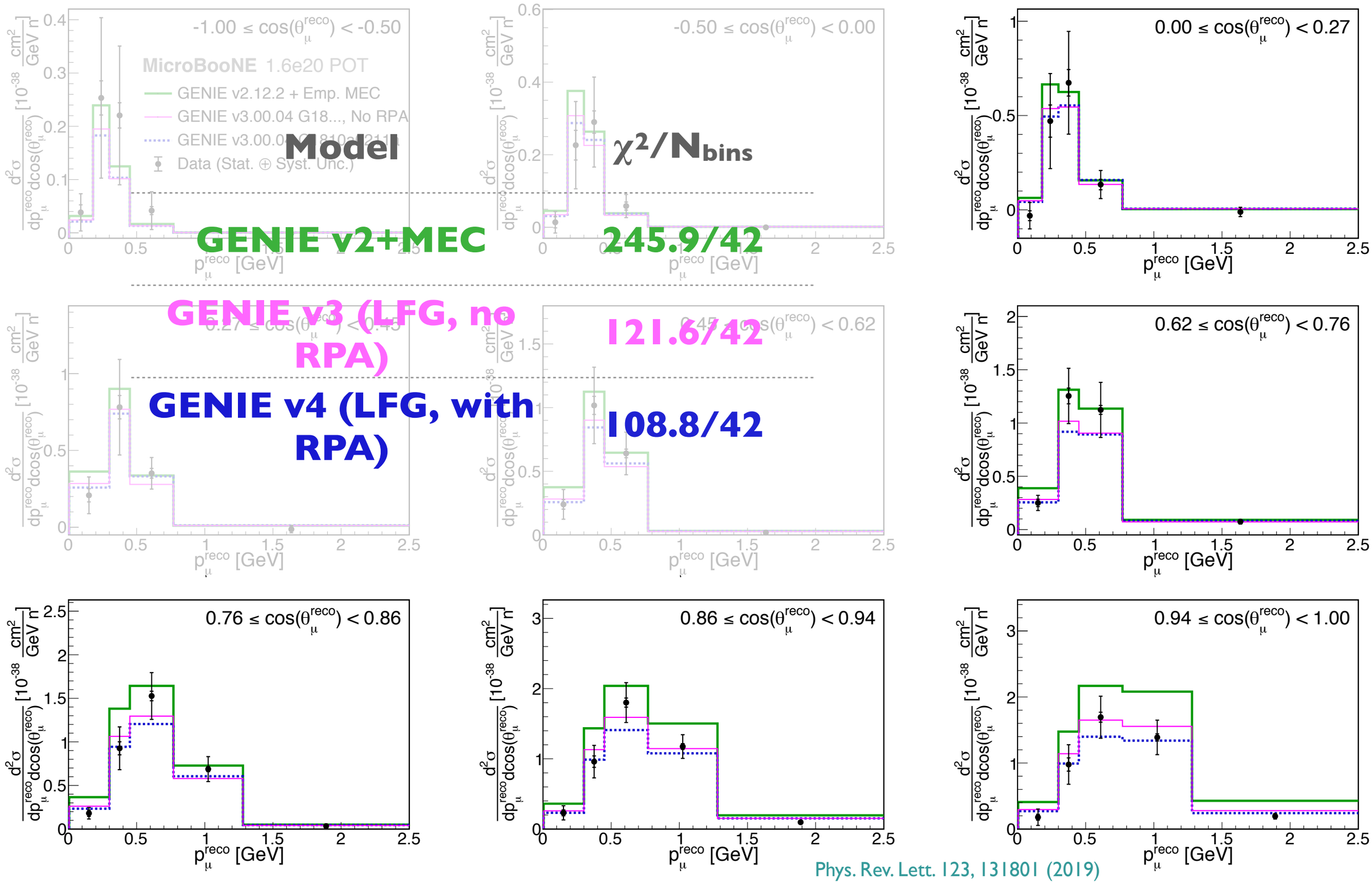
Phys. Rev. Lett. 123, 131801 (2019)

CC Inclusive double-differential measurement



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

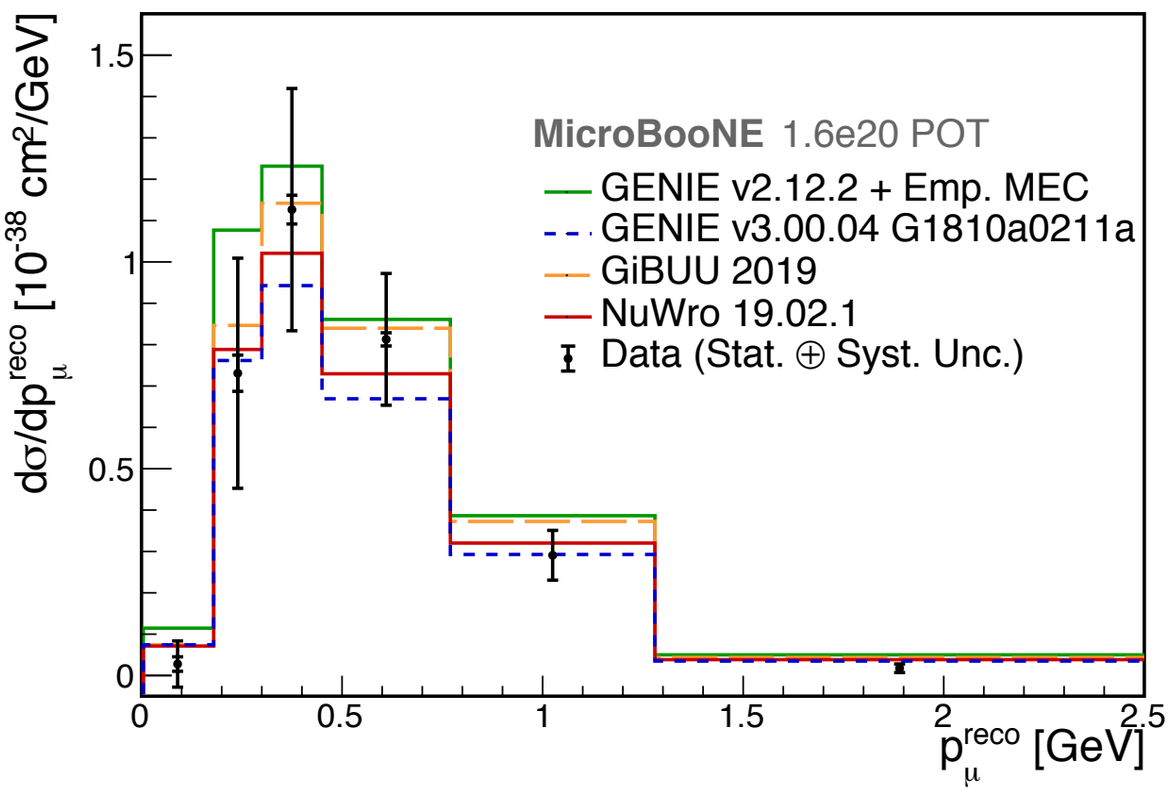
CC Inclusive double-differential measurement

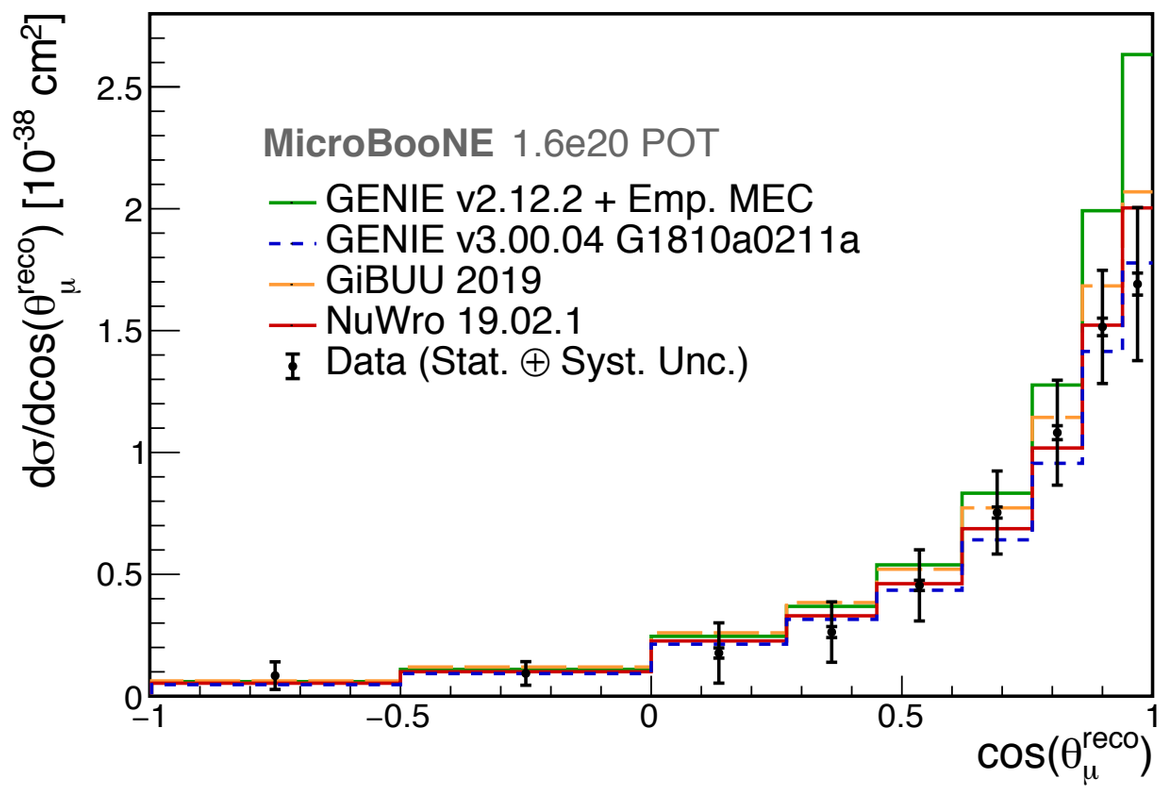


Phys. Rev. Lett. 123, 131801 (2019)

PREVIOUS CC-INCLUSIVE CROSS SECTION: 1D MEASUREMENT

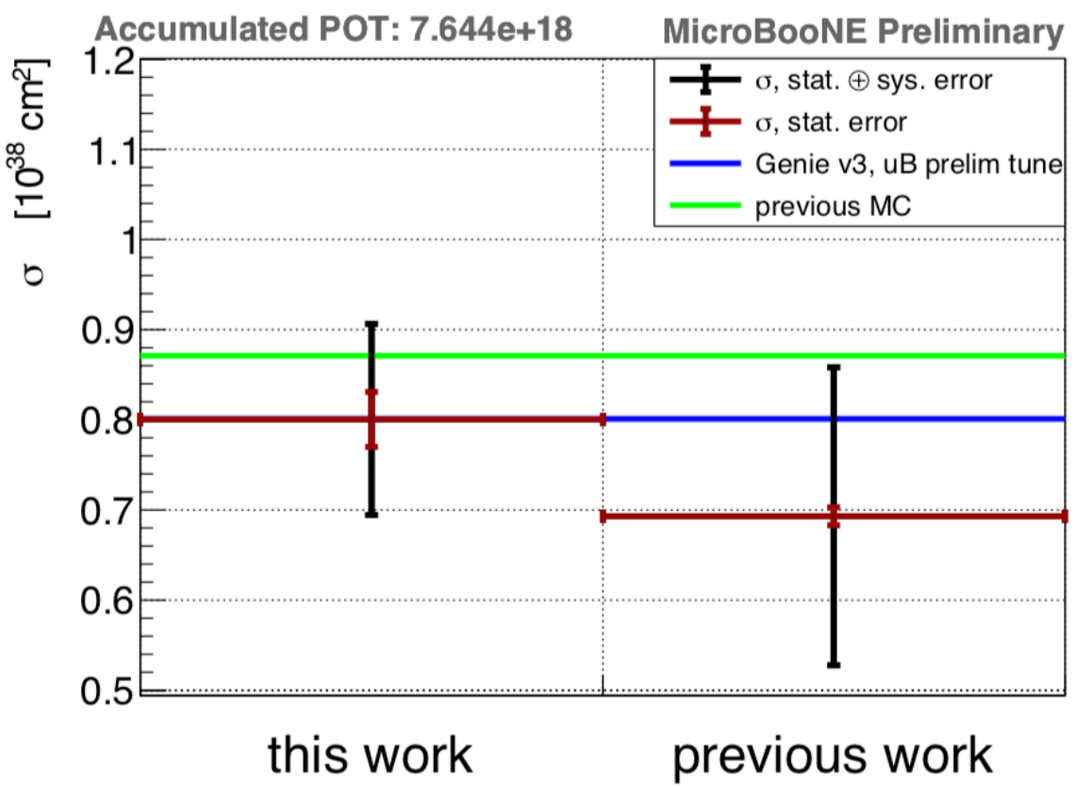
Single-differential cross section measurement presented at Neutrino 2018: PRL 123, 131801 (2019)





UPDATED CC-INCLUSIVE SELECTION: SYSTEMATIC UNCERTAINTIES

MICROBOONE-NOTE-1075-PUB . MICROBOONE-NOTE-1069-PUB



Flux-integrated cross section **consistent with previous measurement**

Drastically reduced systematic uncertainties

CRT better able to reject interactions in surrounding material ("dirt") → reduced systematic uncertainty

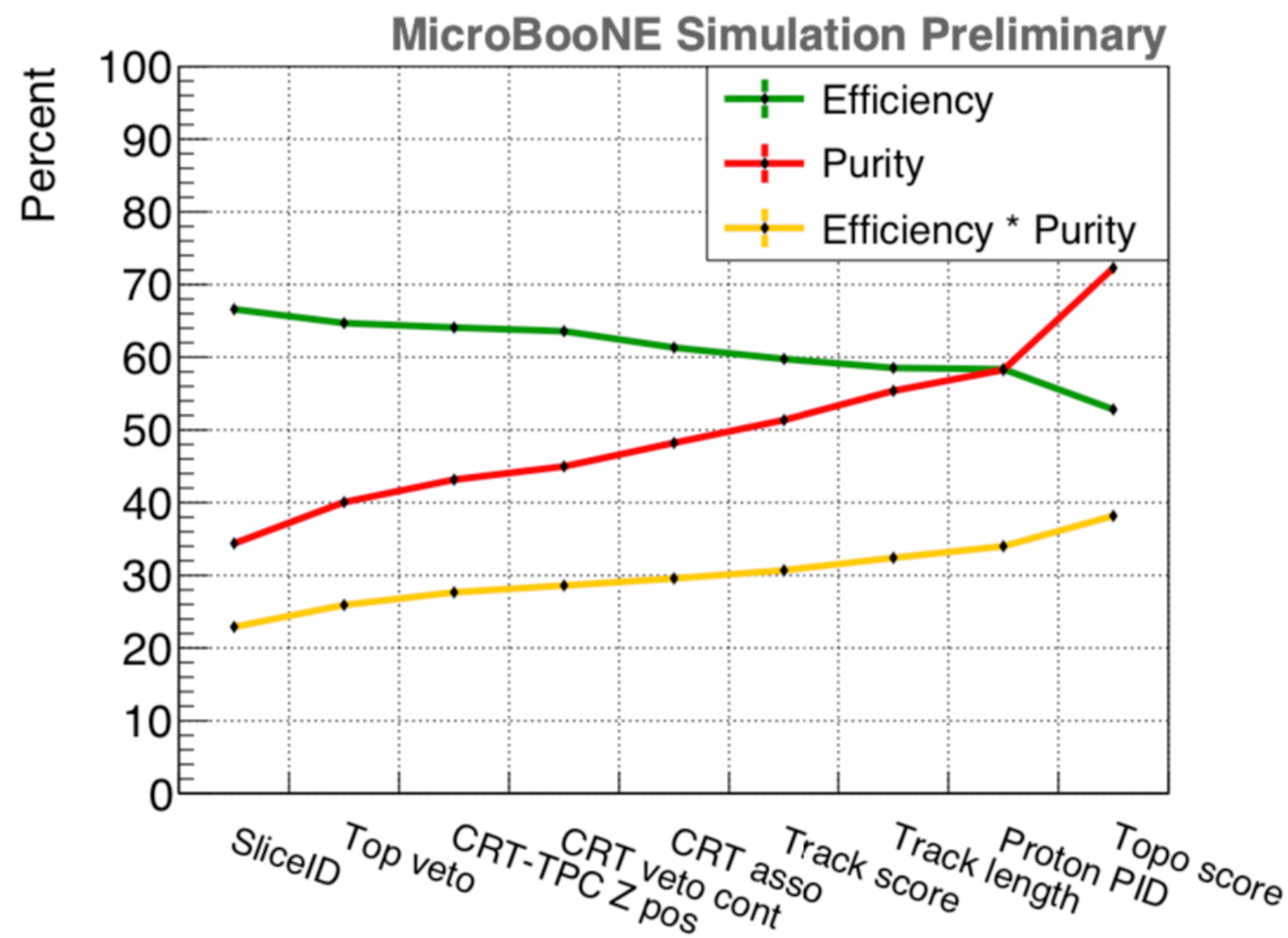
Source	Uncertainty	
	Previous Analysis	This Analysis
Detector response	16.2%	3.3%
Cross section	3.9%	2.7%
Flux	12.4%	10.5%
Dirt background	10.9%	3.3%
Cosmic ray background	4.2%	N/A
POT counting	2.0%	2.0%
CRT	N/A	1.7%
Total Sys. Error	23.8%	12.1%
Statistics	1.4%	3.8%
Total (Quadratic Sum)	**23.8%**	**12.7%**

PRL 123, 131801 (2019)

UPDATED CC-INCLUSIVE SELECTION

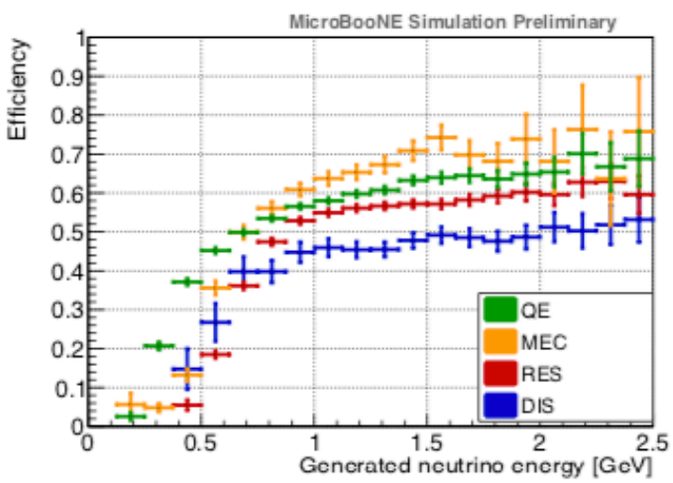
MICROBOONE-NOTE-1069-PUB

- **Cosmic rejection:**
  - Topological and optical information
  - Veto events with CRT hits when all tracks are contained
  - Cut on CRT hit-reconstructed vertex z position if tracks are uncontained
- **Muon selection**
  - Longest track > 20 cm is muon candidate
  - Topology must be track-like
  - Energy deposition must be inconsistent with a proton

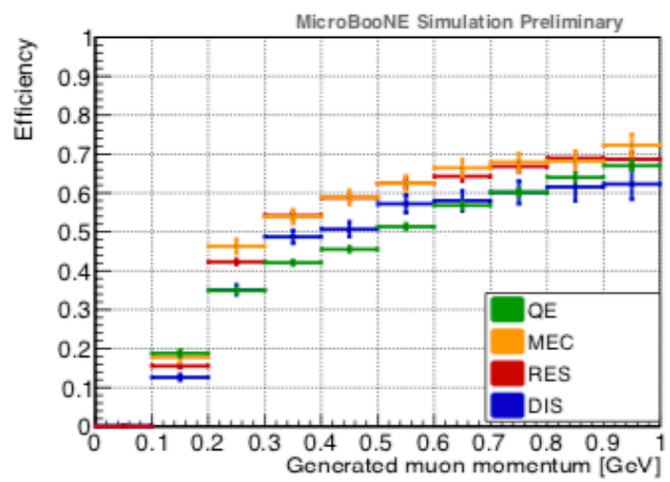


UPDATED CC-INCLUSIVE SELECTION EFFICIENCY

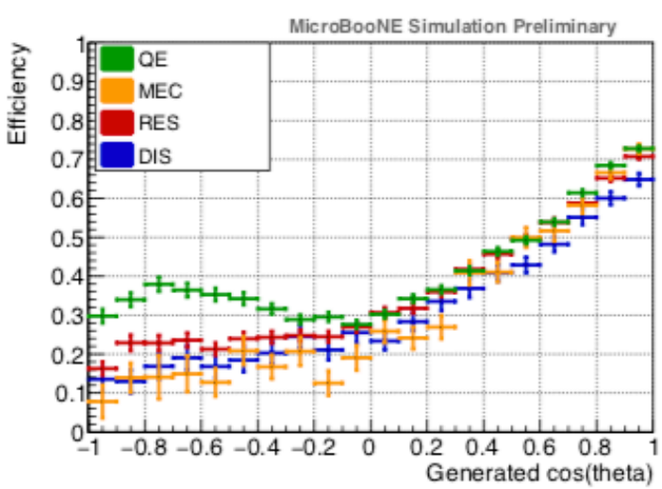
MICROBOONE-NOTE-1069-PUB



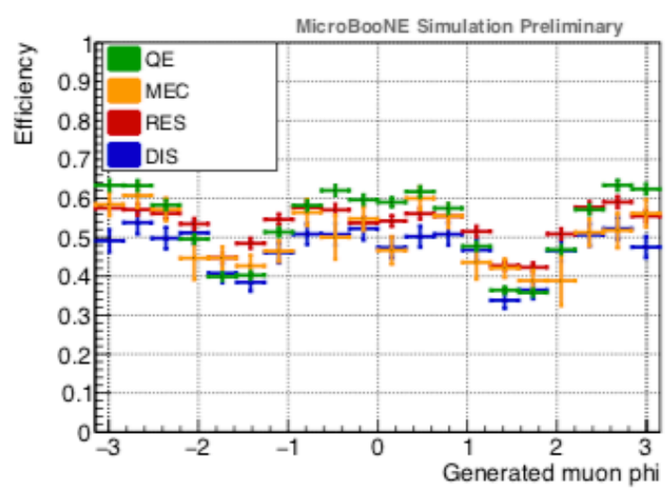
(a) True neutrino energy



(b) True muon momentum



(c) True muon $cos(\theta)$

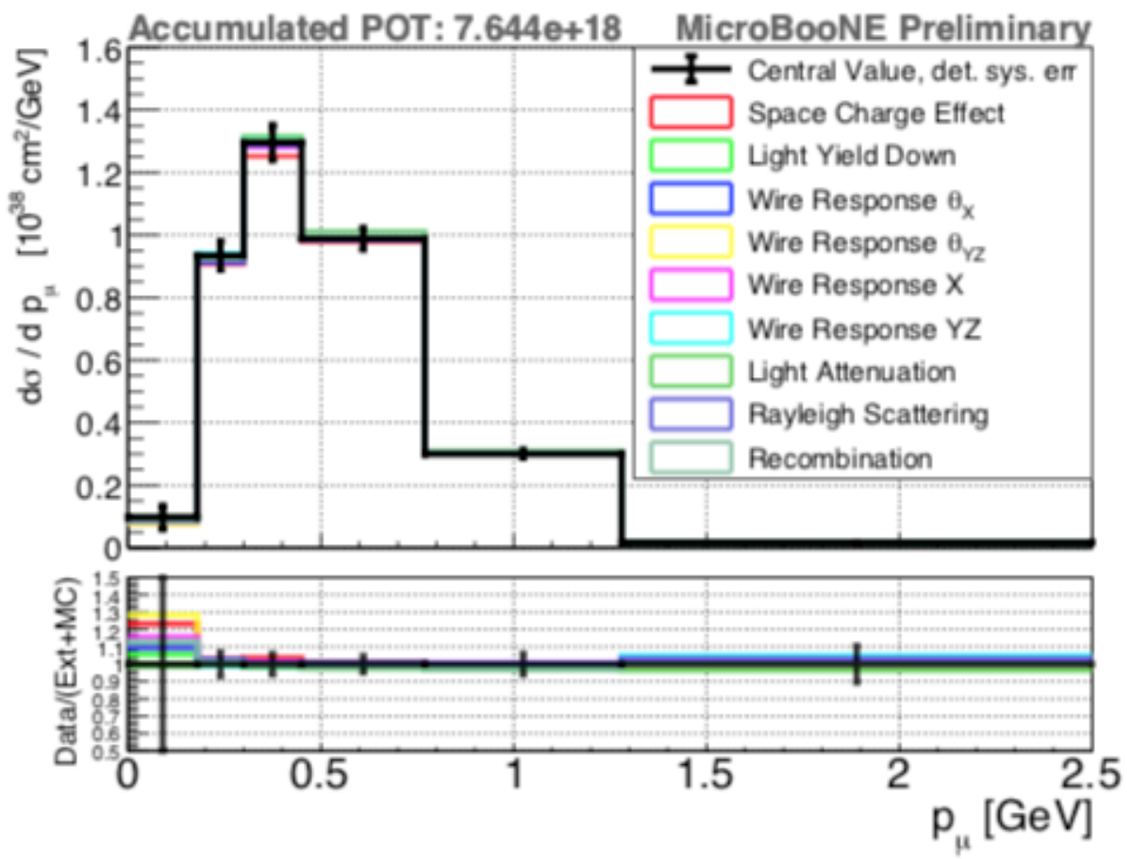


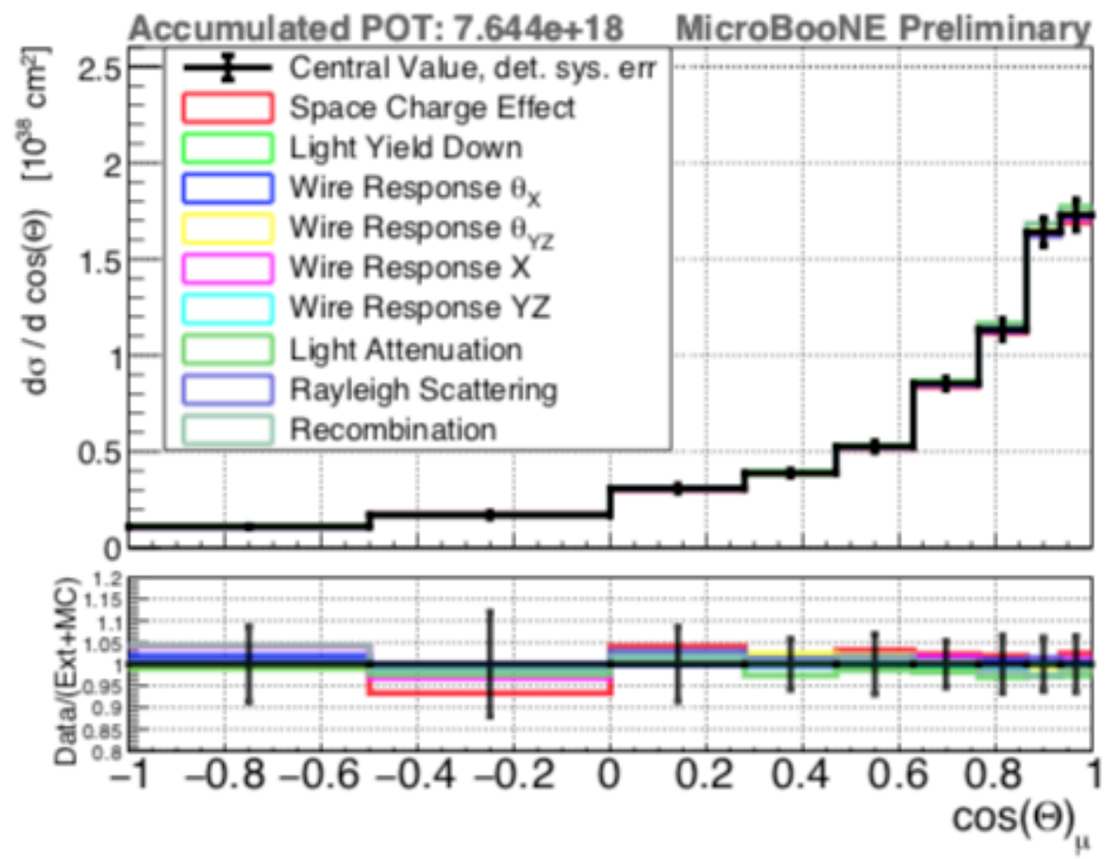
(d) True muon ϕ

- Good efficiency to select **Q**uasi**E**lastic, **M**eson **E**xchange **C**urrent, **RES**onant pion production, and **D**eep **I**nelastic **S**cattering interaction channels
- → truly **inclusive** selection
- Efficiency limited at low neutrino energy/muon momentum due to muon candidate track length > 20 cm requirement

UPDATED CC-INCLUSIVE CROSS SECTION: SYSTEMATIC UNCERTAINTIES

MICROBOONE-NOTE-1069-PUB



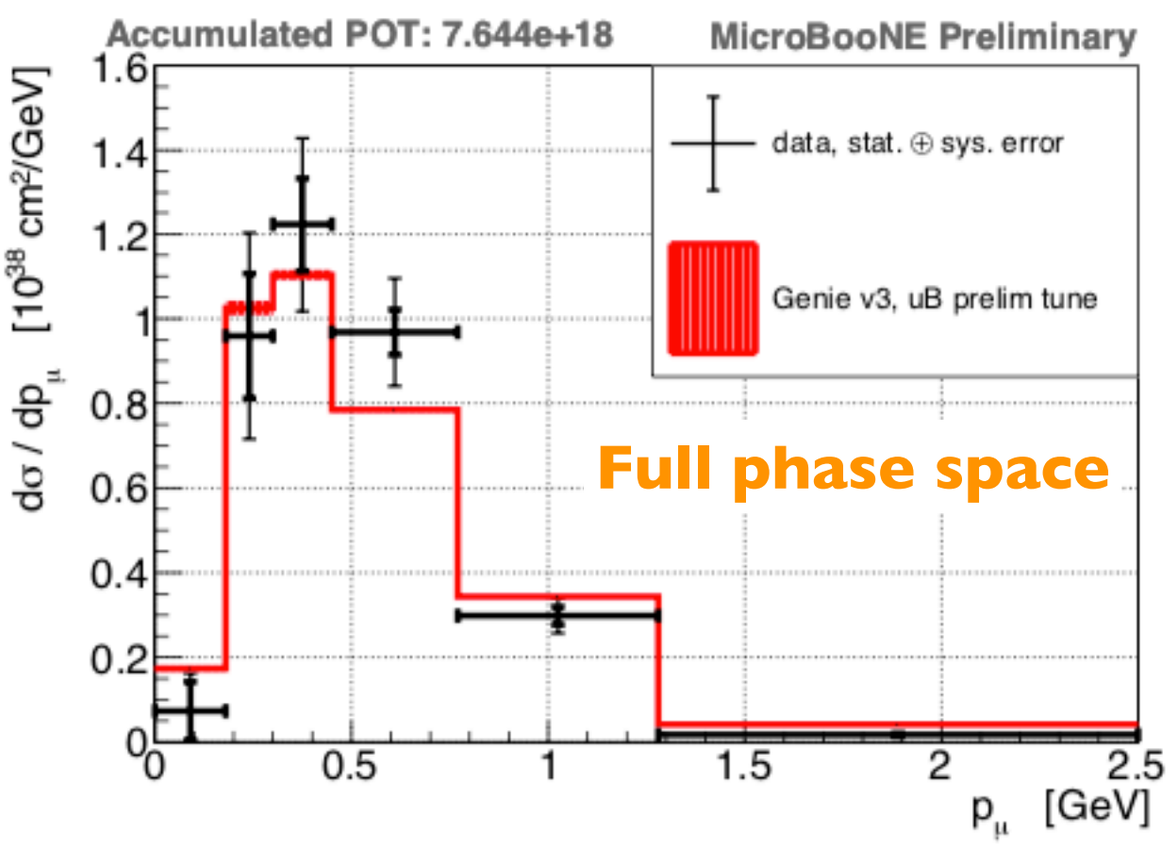


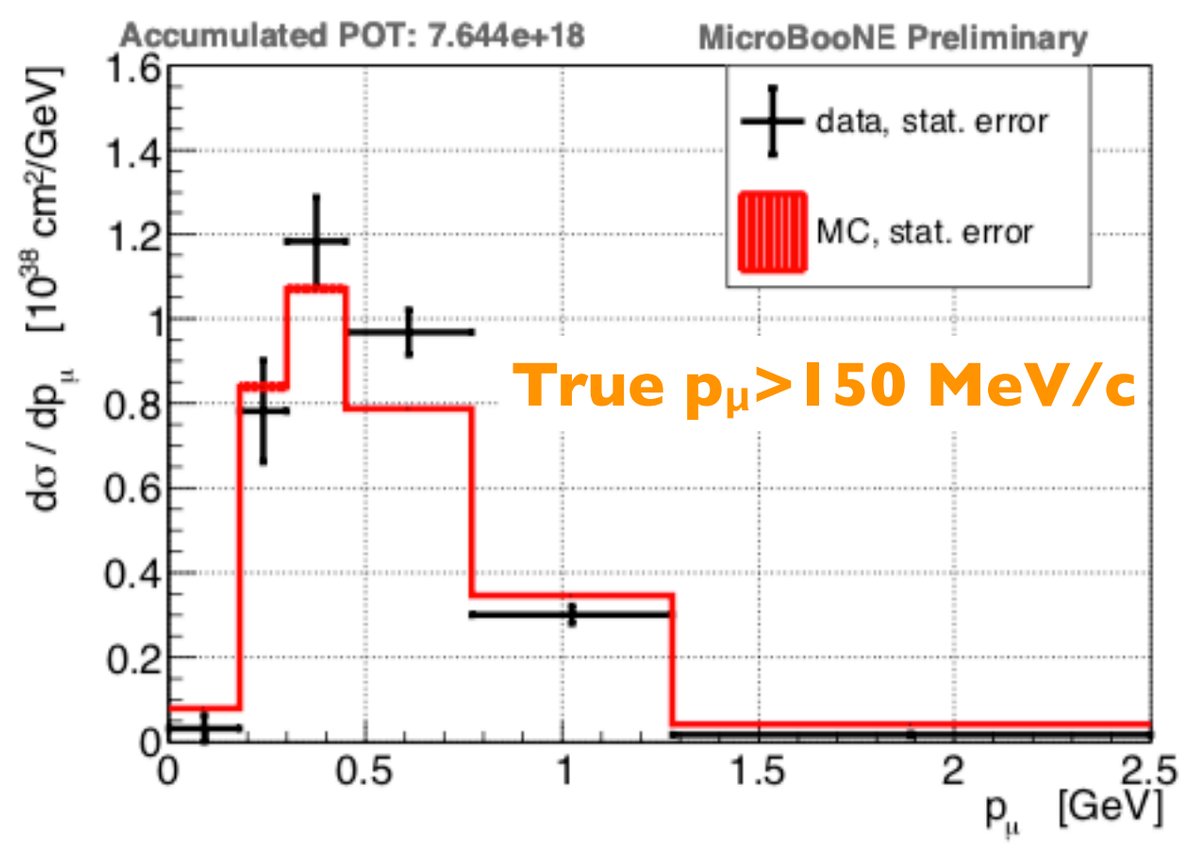
Improved detector understanding → **drastically reduced** systematic uncertainties from detector modeling

UPDATED CC-INCLUSIVE CROSS SECTION: REDUCED PHASE SPACE

MICROBOONE-NOTE-1069-PUB

- Efficiency is low for p_μ<150 MeV due to >20 cm track length requirement
- Main result includes all CC interactions in signal definition (no requirement on muon momentum)
- As a check: re-extract cross section with signal requirement p_μ>150 MeV/c (note: statistical uncertainties only)





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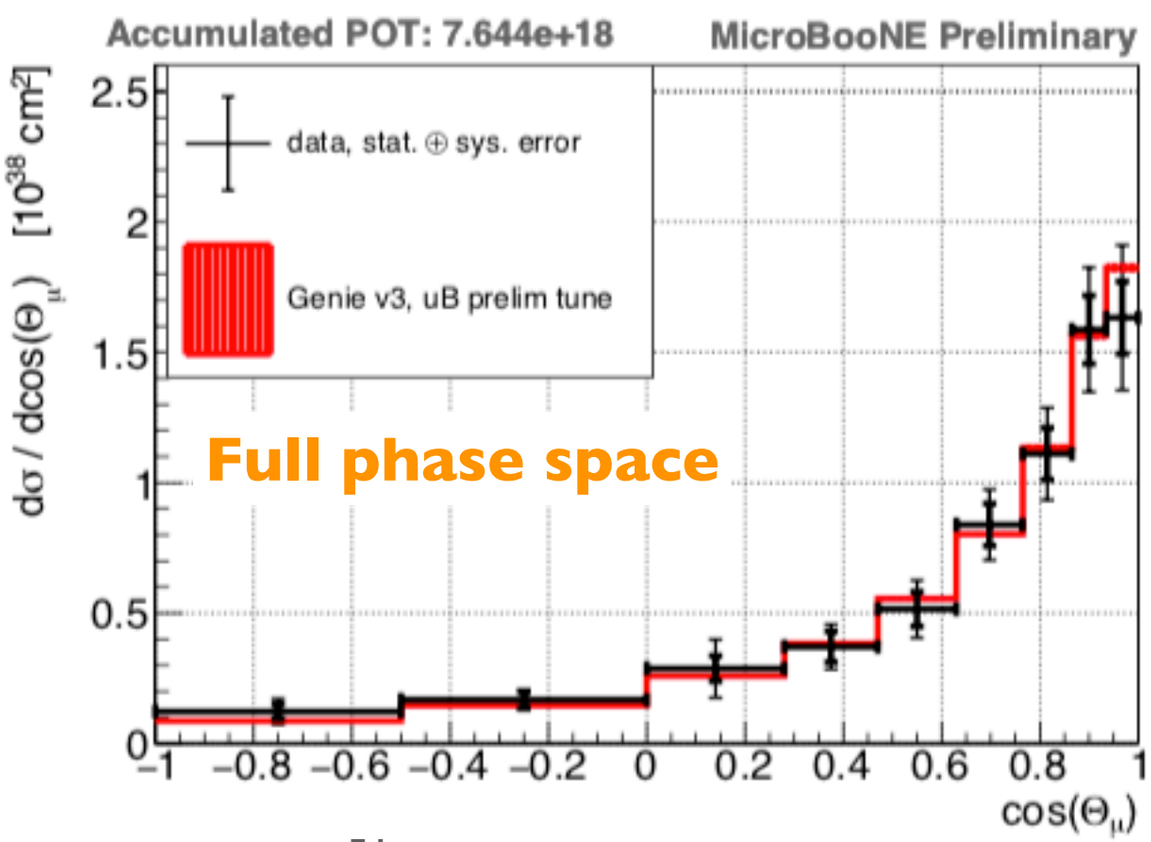
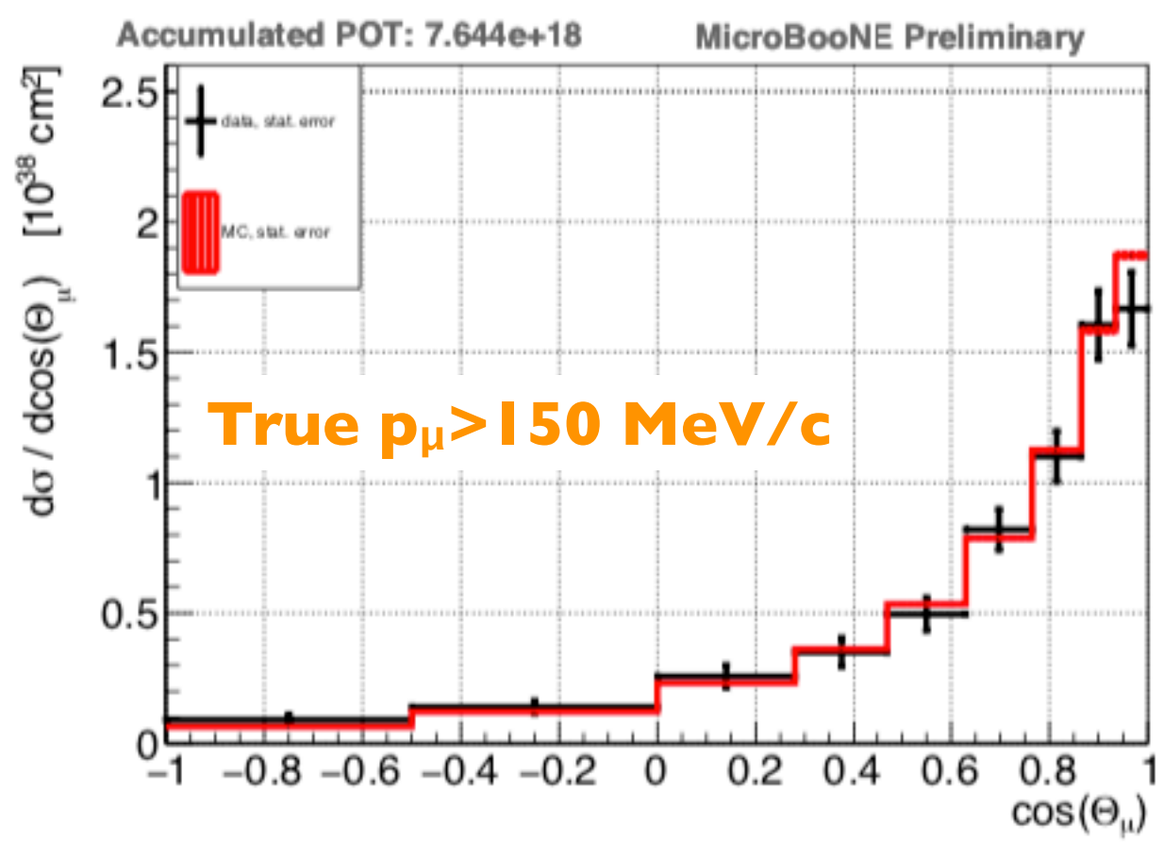




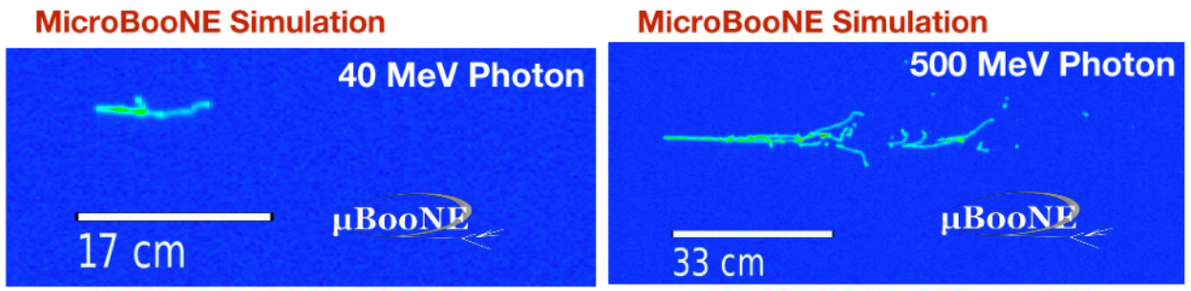
CCPI0 SELECTIONS

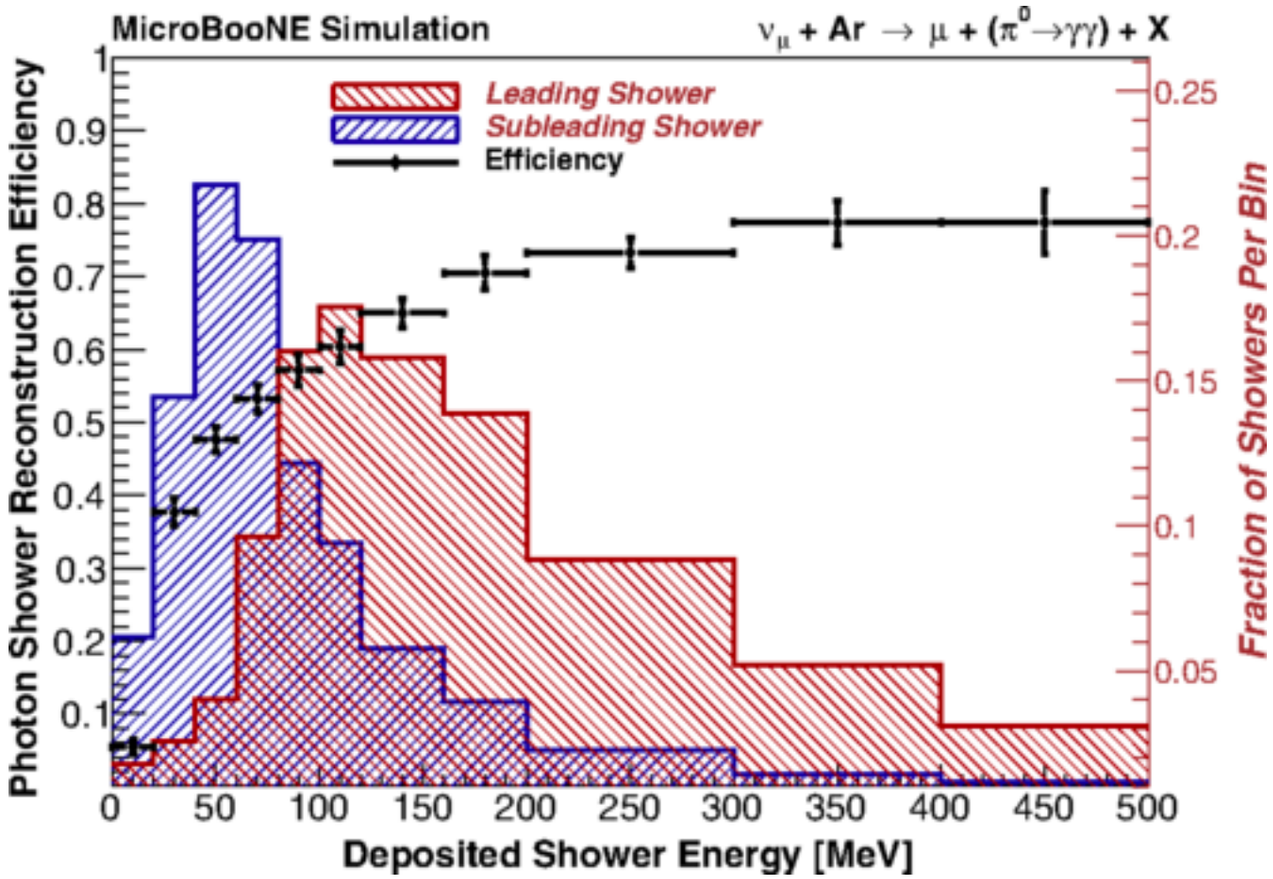
Phys. Rev. D 99, 091102(R) (2019)

Low-energy photons appear more track like
→ low reconstruction efficiency
→ requiring that we reconstruct both π^0 photons limits statistics

Two-shower selection
→ validate π^0 hypothesis by invariant diphoton mass

Single shower selection
→ validate photon hypothesis
→ maximize statistics for cross section measurement

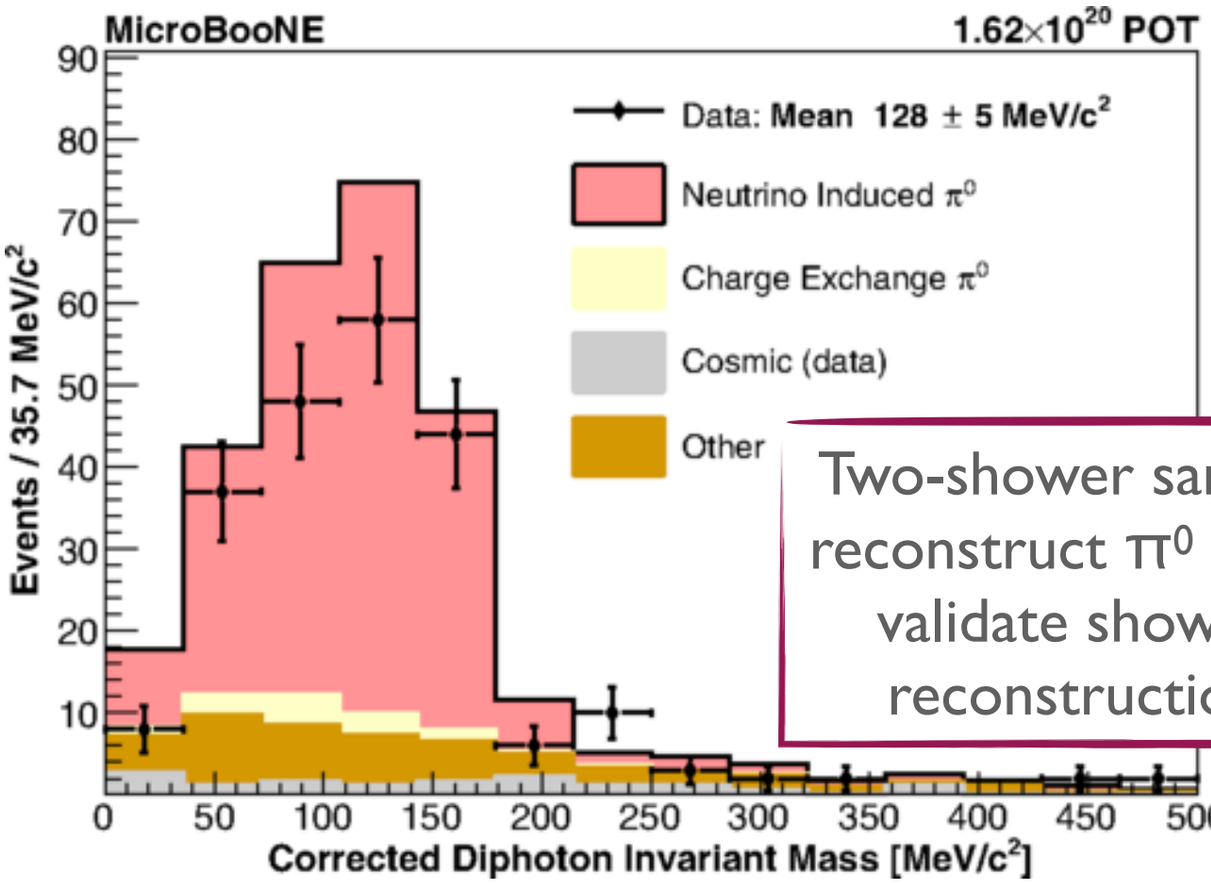




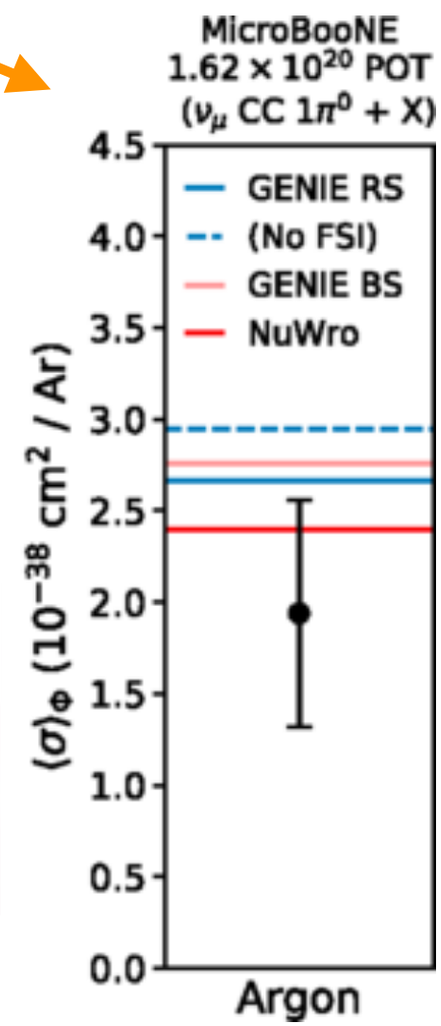
CC π^0 PRODUCTION

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

Select π^0 events by looking for **one** or **two** showers in addition to a candidate muon track



Two-shower sample: reconstruct π^0 mass, validate shower reconstruction



One-shower sample (higher statistics): total π^0 cross-section measurement → agreement with model predictions

A. Papadopolou, poster 145, poster session 2

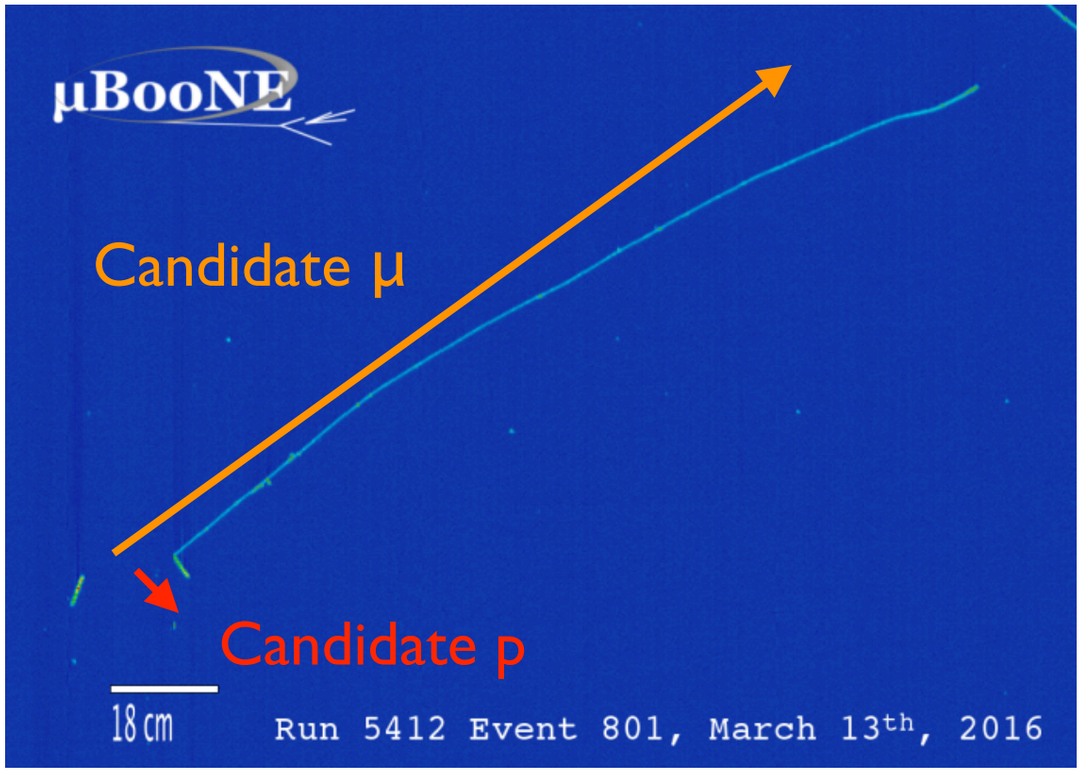
CCQE-LIKE CROSS SECTION

Eur. Phys. J. C 79 673 (2019) arXiv:2006.00108 [hep-ex] (2020)

- **First extraction of ν_μ-^{40}Ar CCQE-like cross section using a surface LArTPC**
- Important channel for low-energy excess search (and other LArTPC oscillation analyses)
- Signal: 1 muon (>100 MeV/c), 1 proton (300 MeV/c)

Selection:

- Two tracks
- Energy deposition consistent with one muon and one proton
- Tracks are not collinear
- Tracks are coplanar
- Low vertex activity
- Low transverse momentum

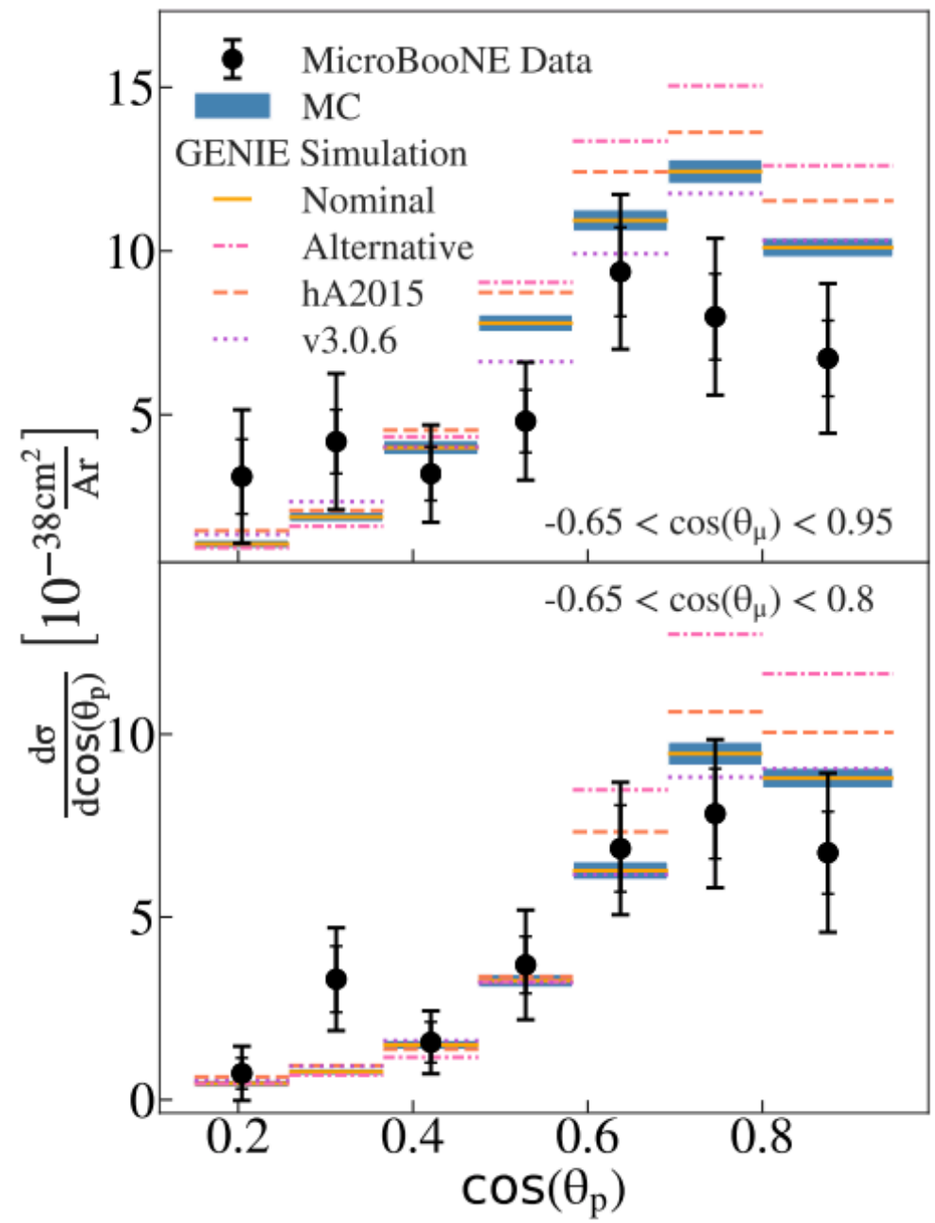


CCQE CROSS SECTION: MODEL COMPARISONS

A. Papadopolou, poster 145, poster session 2

Eur. Phys. J. C 79 673 (2019) arXiv:2006.00108 [hep-ex] (2020)

- **Nominal**: GENIE v2.12.2. Bodek-Ritchie Fermi Gas, Llewellyn-Smith CCQE model, empirical MEC model, Rein-Sehgal resonant and coherent scattering model, "hA" FSI model
- **hA2015**: GENIE v2.12.2 with a more recent "hA2015" FSI model
- **Alternative**: GENIE v2.12.10. Local Fermi Gas, Nieves CCQE model, Nieves MEC model, KLN-BS resonant and BS coherent scattering models, and hA2015 FSI model
- **v3.0.6**: GENIE v3.0.6. Same model configuration as Alternative model, with hA2018 FSI model

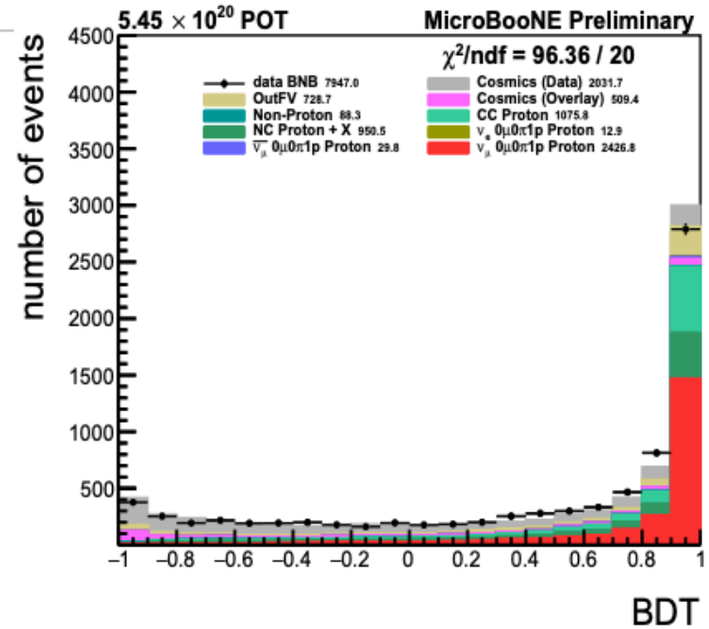


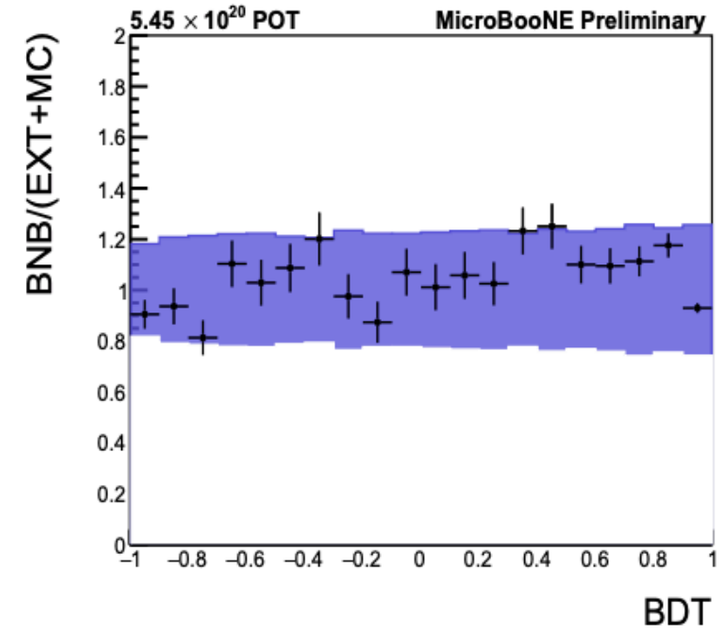
NC1P SELECTION

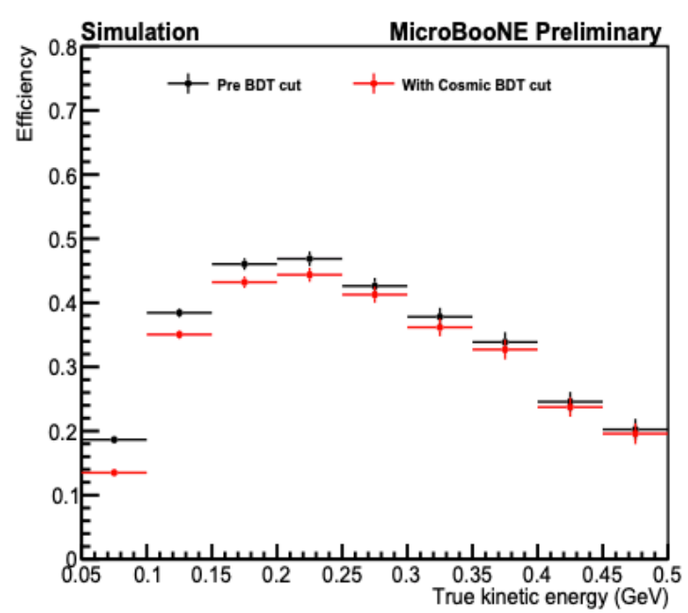
L. Ren, poster 292, poster session 4

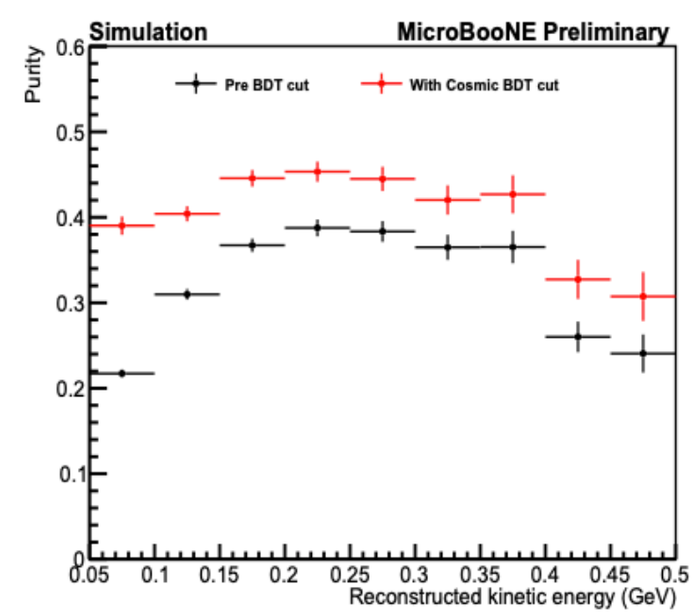
MICROBOONE-NOTE-1067-PUB

- Single **isolated track**
- Must be contained within fiducial volume
- Length 1.2 - 200 cm
- Must be **forward-going** ($\cos\theta > 0$ w.r.t neutrino beam direction)
- **Deposited energy profile** consistent with a proton
- Multi-class gradient-boosted decision tree used to **further reduce background from cosmic interactions**









NC1P CROSS SECTION MEASUREMENT

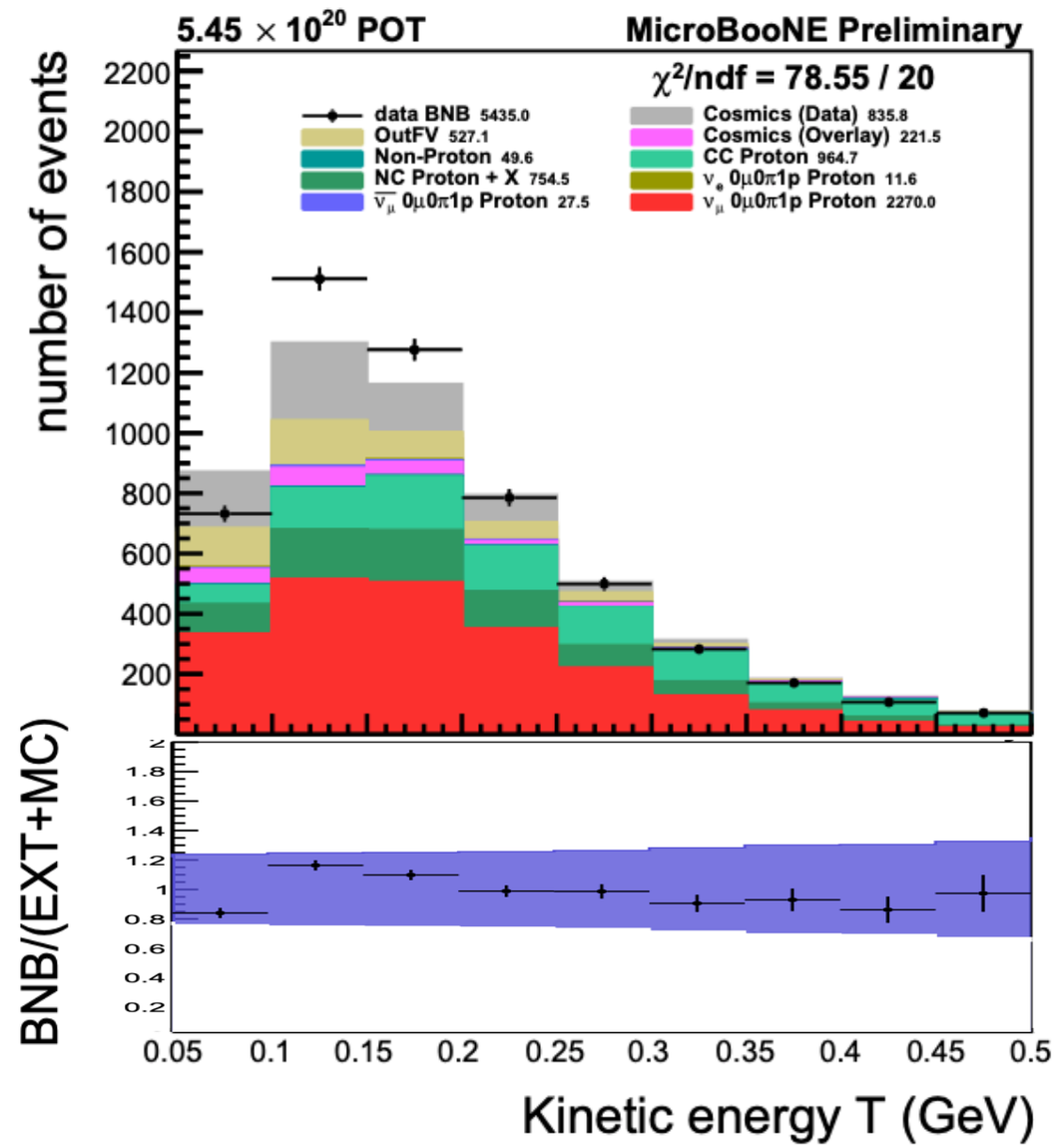
L. Ren, poster 292, poster session 4

MICROBOONE-NOTE-1067-PUB

- Measure cross section for neutral-current single proton production
- Signal: 1 isolated proton

Selection:
42.1% efficiency, 29.8% purity

Largest backgrounds :
- Proton from charged-current interaction (other particles missed by reconstruction)
- Proton from non-1p neutral-current interaction (other particles missed by reconstruction)

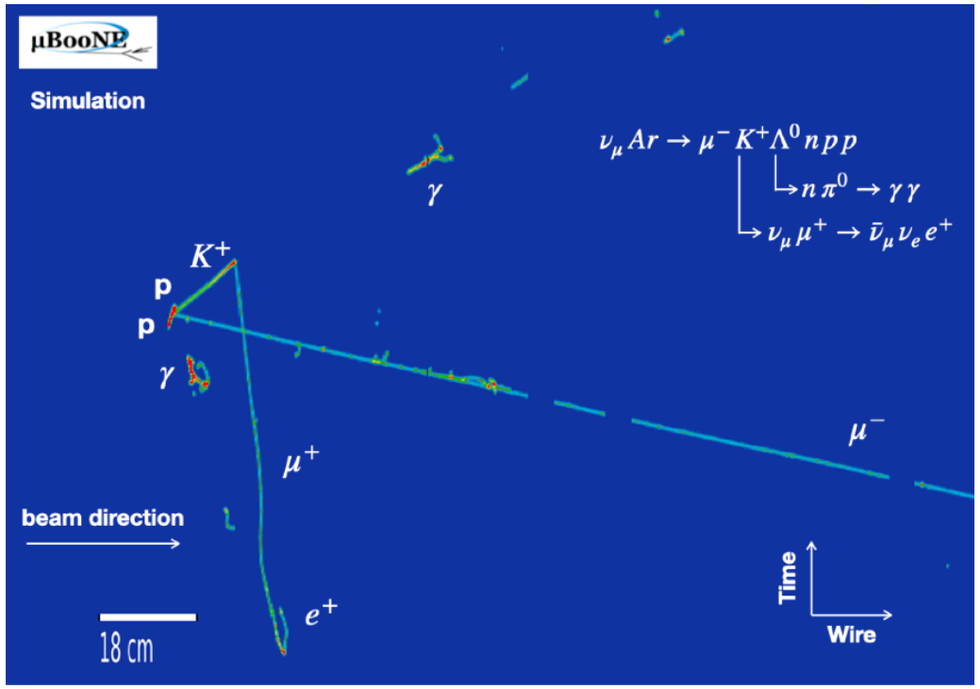


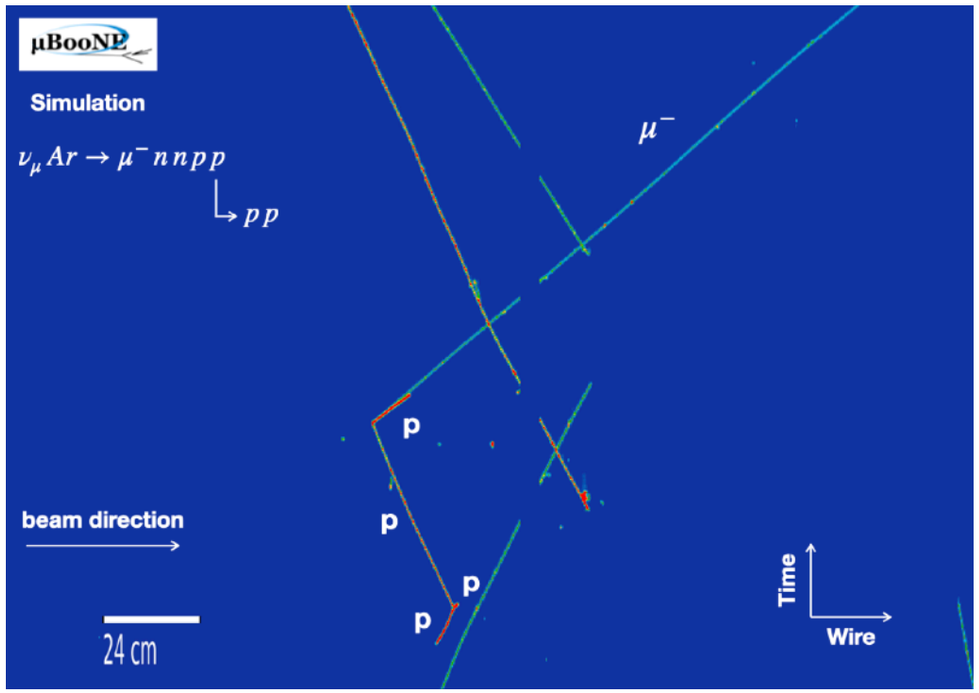
CC KAON PRODUCTION SELECTION

A. Fiorentini, poster 369, poster session 3

MICROBOONE-NOTE-1071-PUB

- **CC kaon production**: rare process, few existing measurements, background for **proton decay** $p \rightarrow K^+\nu$ searches in DUNE
- Selection developed on simulation: look for K^+ track from neutrino interaction and μ^+ from K^+ decay
- 67.7% purity and 7% efficiency → expect to select 12 candidate interactions in 1.3×10^{21} POT MicroBooNE data set
- Aim: cross section measurement and study of K^+ in LArTPC



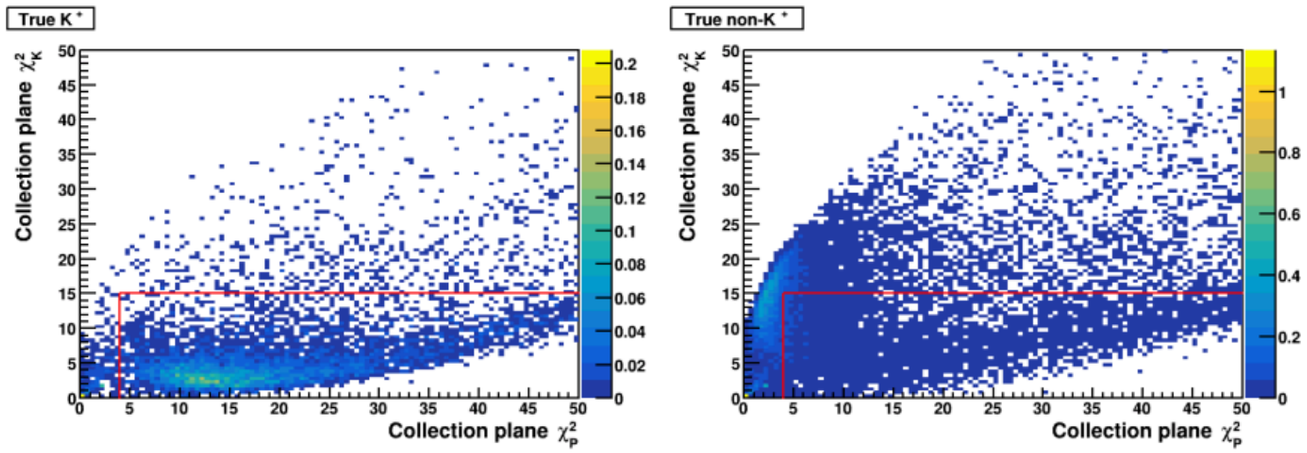


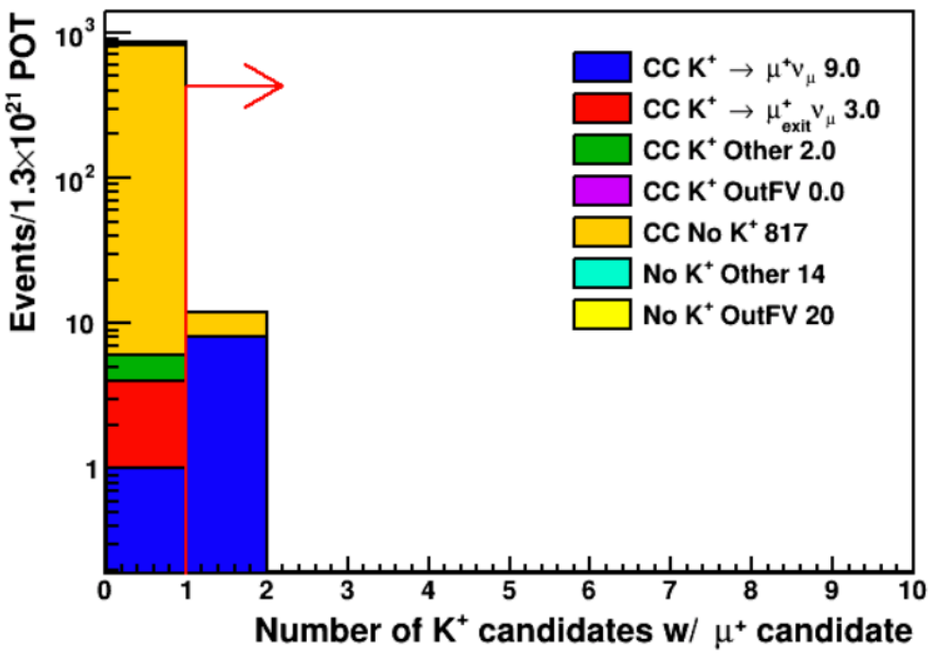
CC KAON SELECTION

A. Fiorentini, poster 369, poster session 3

MICROBOONE-NOTE-1071-PUB

- Reject cosmic rays based on topology and optical information
- Must have one track with energy deposition consistent with a muon
- K^+ candidate selected based on energy deposition: consistent with a kaon and inconsistent with a proton
- Must have exactly one μ^+ candidate: must start within 5cm of end of kaon track, track length >30cm, energy deposition inconsistent with a proton



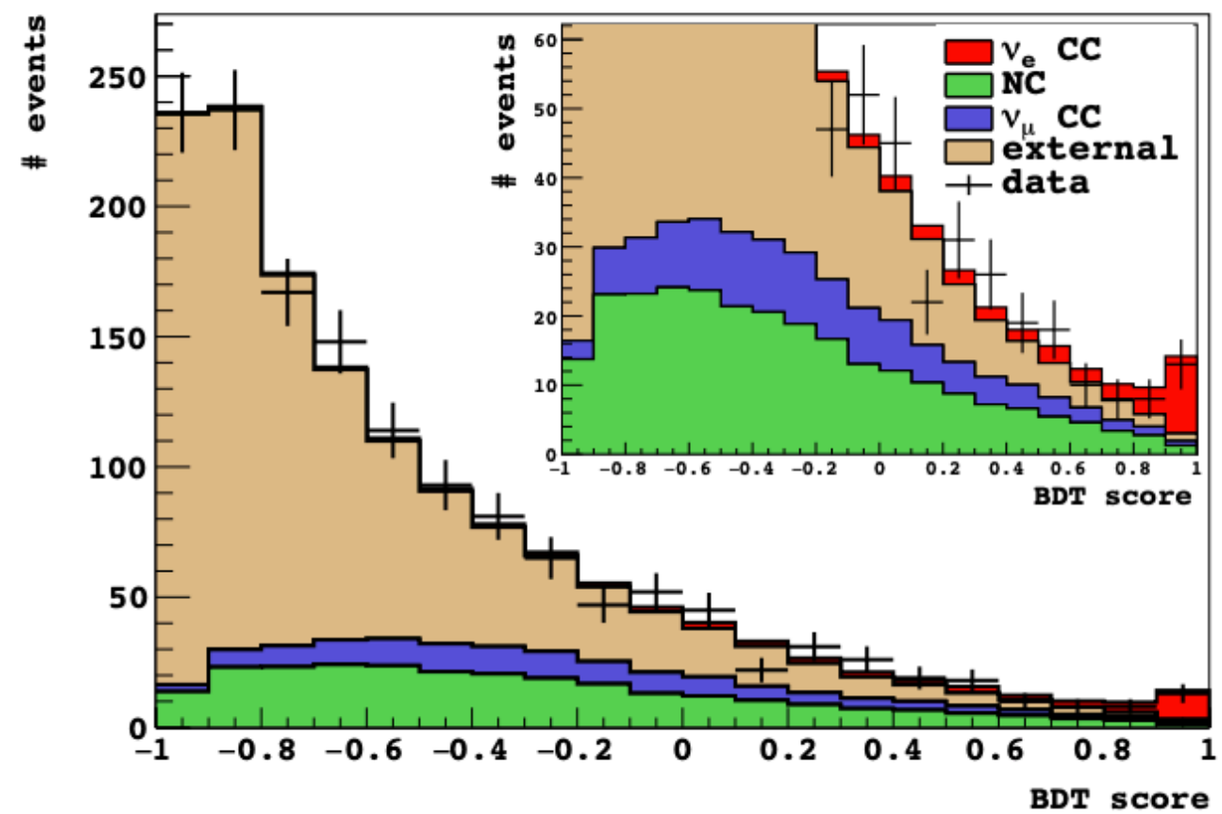


ARGONEUT ELECTRON NEUTRINO SELECTION

R. Fitzpatrick, Poster 139, Poster Session 4

arXiv:2004.01956 [hep-ex]

- Focus on reconstructing leading shower in neutrino interaction
- Reject events with a muon reconstructed in downstream MINOS detector
- Reject events with through-going muons
- Reconstructed shower must be forward-going: cos(θ) >0.05 w.r.t. beam direction
- Shower must start within 2cm of reconstructed vertex
- Electron candidate selected based on topology and charge of entire candidate shower using a BDT: BDT score >0.9



ARGONEUT CHARGED PION PRODUCTION MEASUREMENT

- ArgoNEUT: CC1$\pi^{\pm}$ production Phys. Rev. D 98, 052002 (2018)
- Select two-track events: one matched to a track in MINOS (muon candidate)
- Select CC1$\pi^{\pm}$ events using dE/dx of pion candidate, event topology
- Overall purity 35.8% (ν), 55.7% ($\bar{\nu}$)
- 337 selected ν events (285 $\bar{\nu}$)

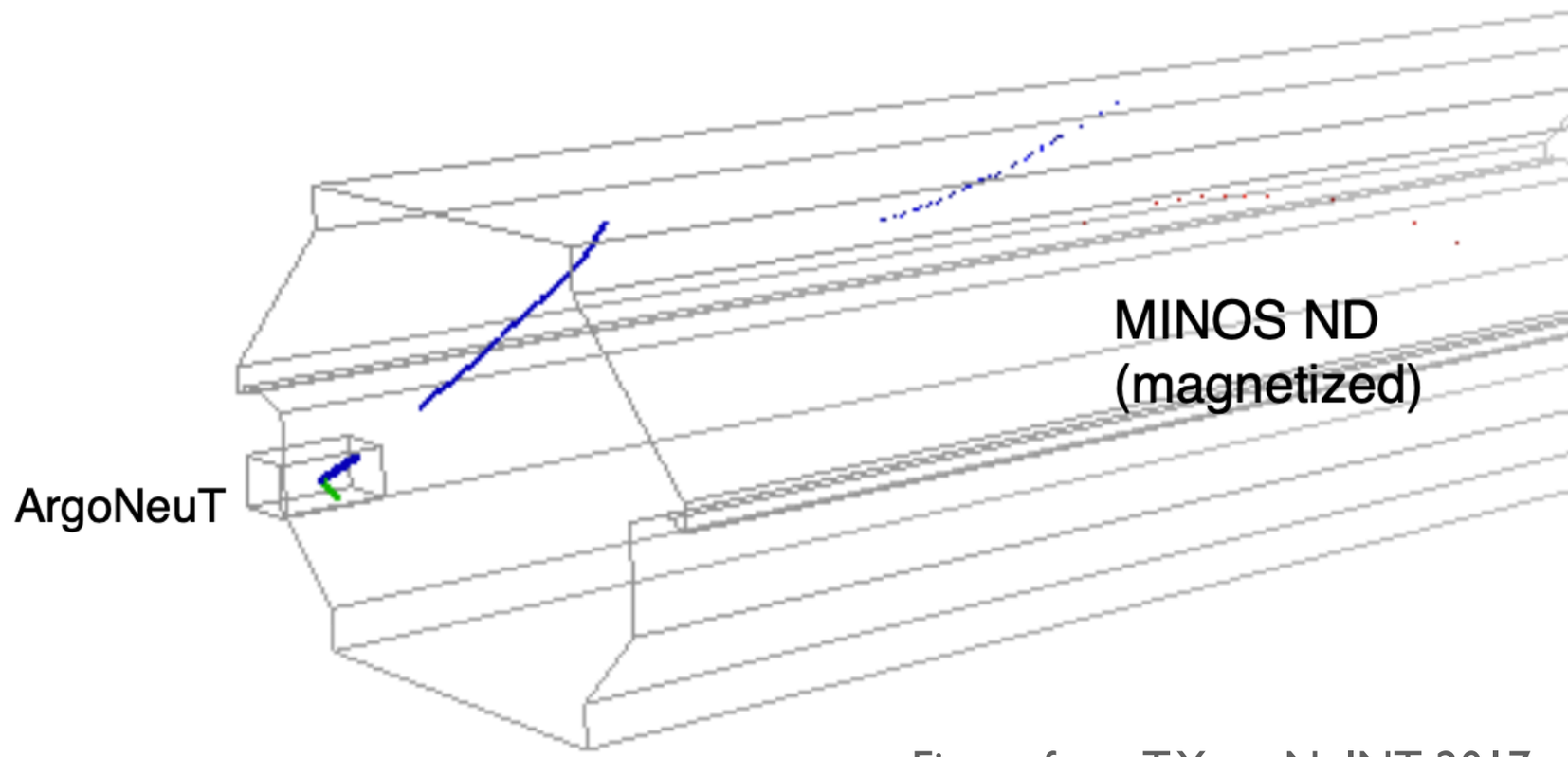
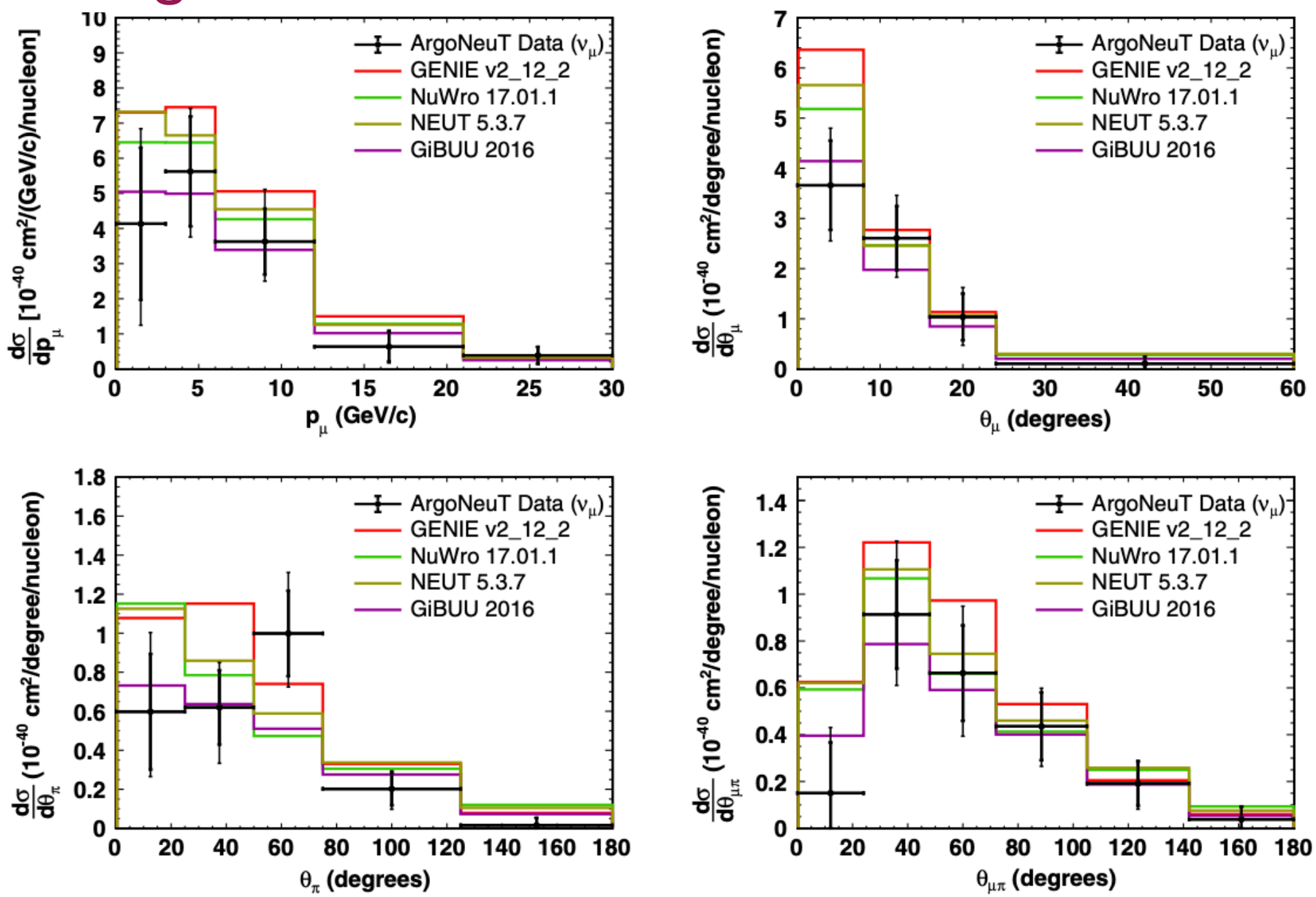


Figure from T. Yang, NuINT 2017

ARGONEUT CHARGED PION PRODUCTION MEASUREMENT

ν_μ CC1$\pi^\pm$ ArgoNeuT measurement

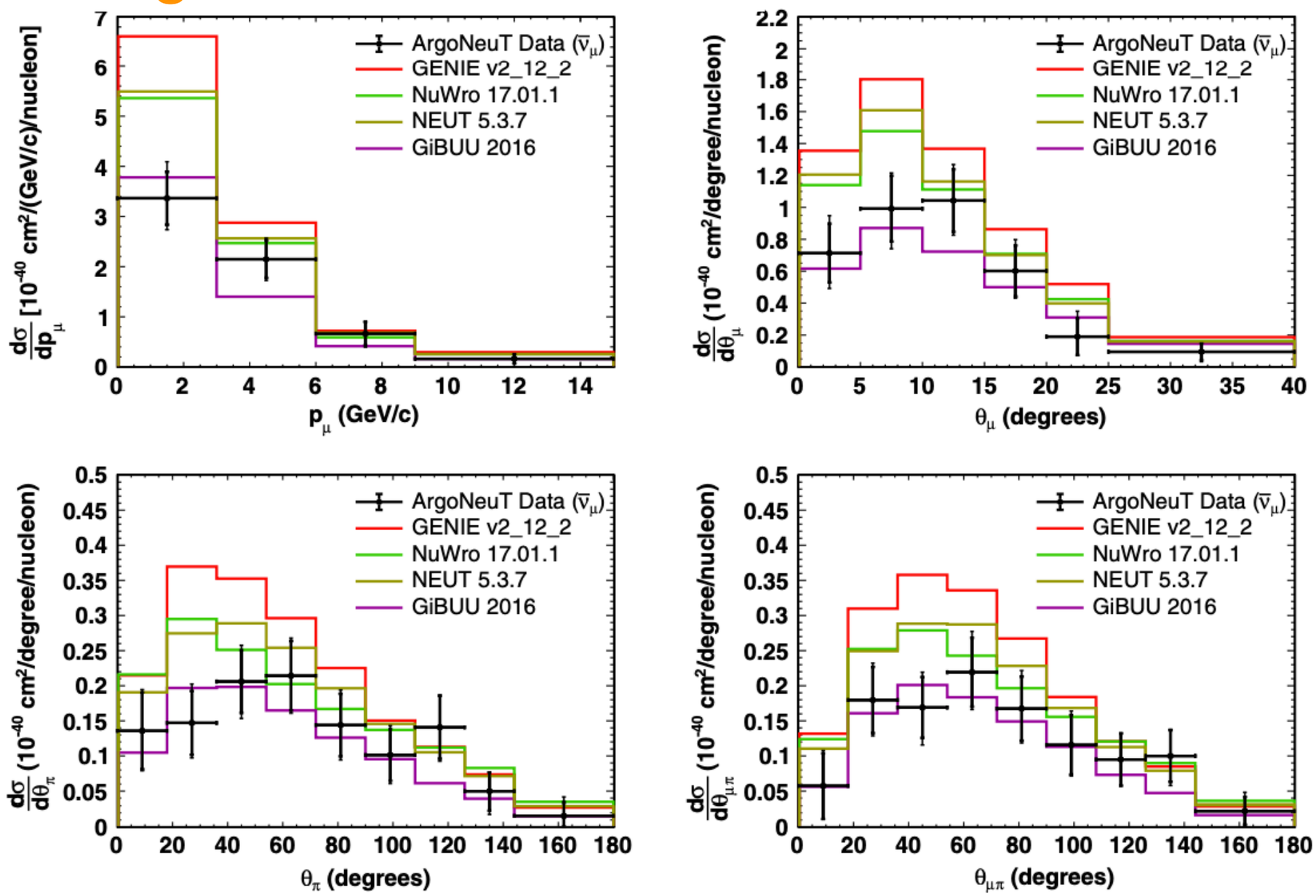
Phys. Rev. D 98, 052002 (2018)



ARGONEUT CHARGED PION PRODUCTION MEASUREMENT

$\bar{\nu}_\mu$ CC1$\pi^\pm$ ArgoNeuT measurement

Phys. Rev. D 98, 052002 (2018)



HARGED PION MEASUREMENT

rement

Phys. Rev. D 98, 052002 (2018)

Resonant pion production model

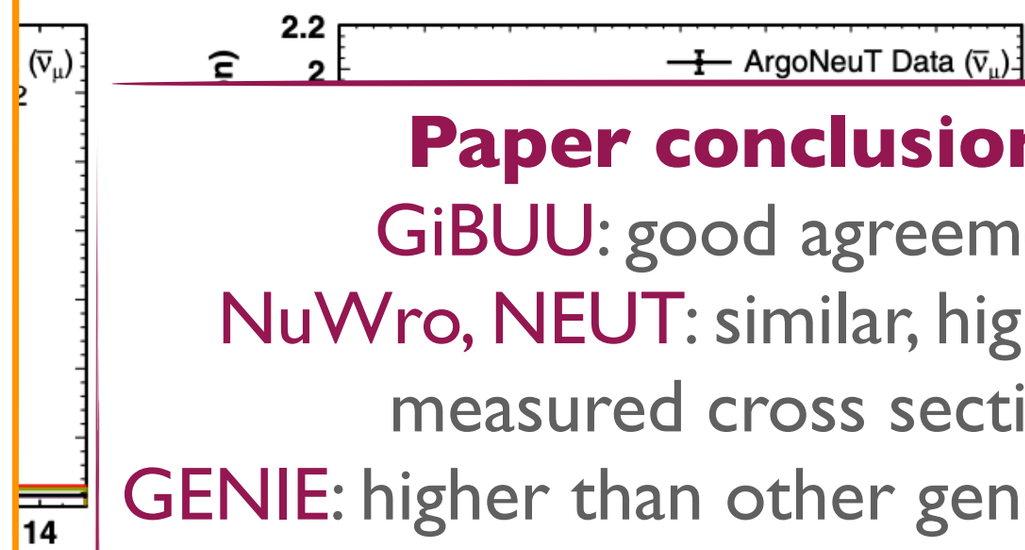
- GENIE, NEUT: Rein-Sehgal
- NuWro: Δ(1232) resonance only

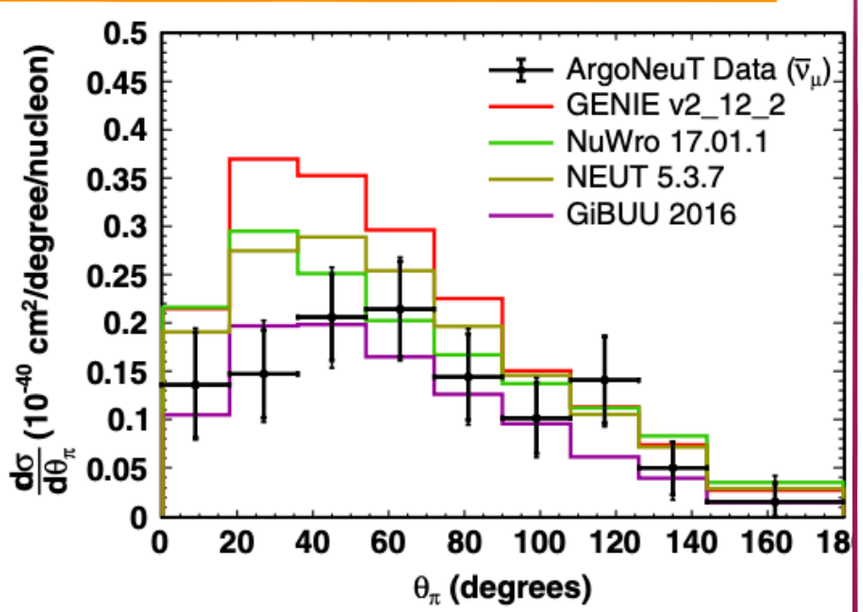
Nonresonant model

- NEUT: Rein-Sehgal
- GENIE, NuWro: Bodek-Yang above resonance region, extrapolate smoothly to converge with resonance model at lower W

FSI

- NEUT, NuWro: Salcedo-Oset cascade
- GENIE: effective cascade model
- GiBUU: quantum-kinetic transport theory





Paper conclusions

GiBUU: good agreement

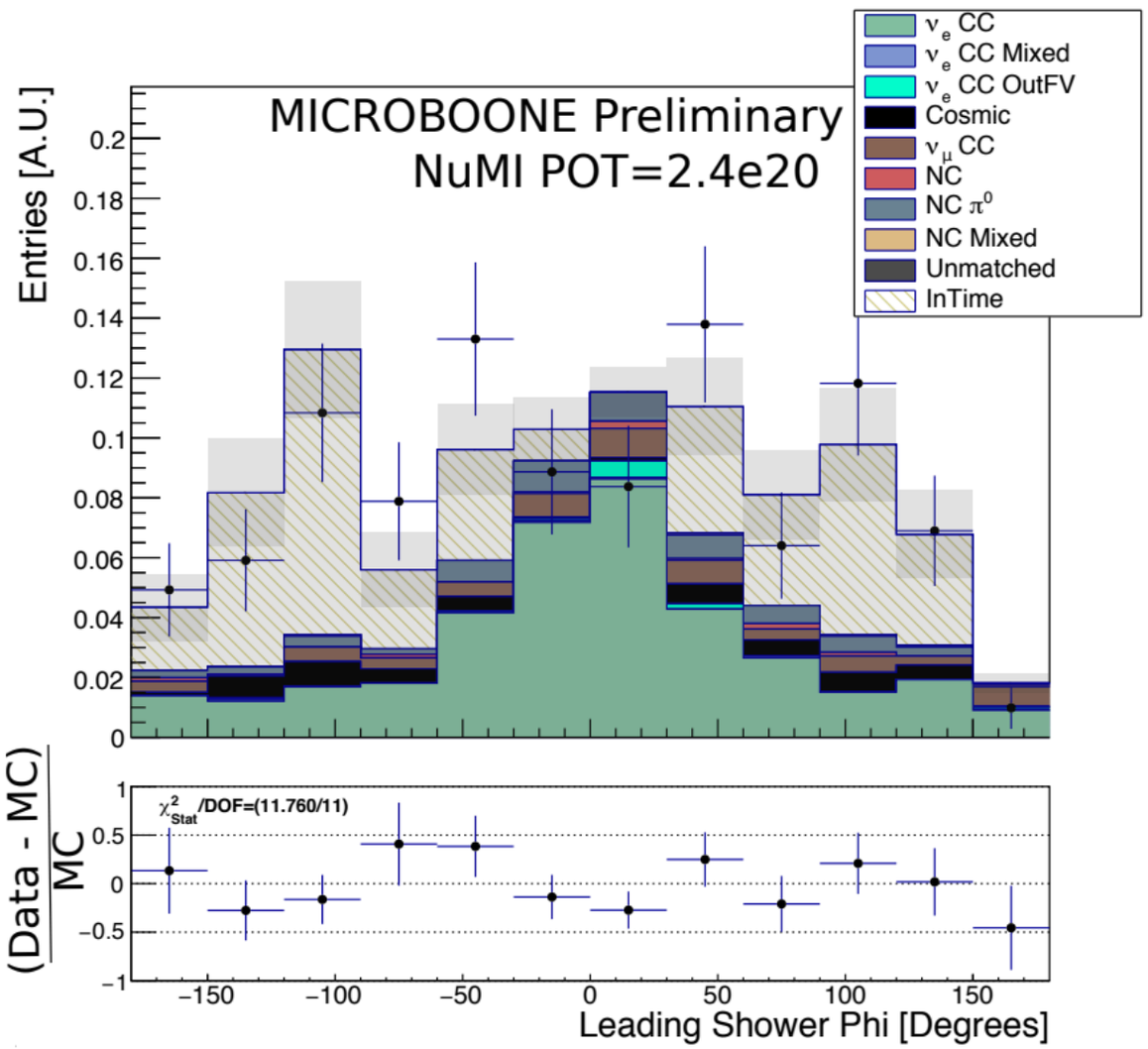
NuWro, NEUT: similar, higher than measured cross section

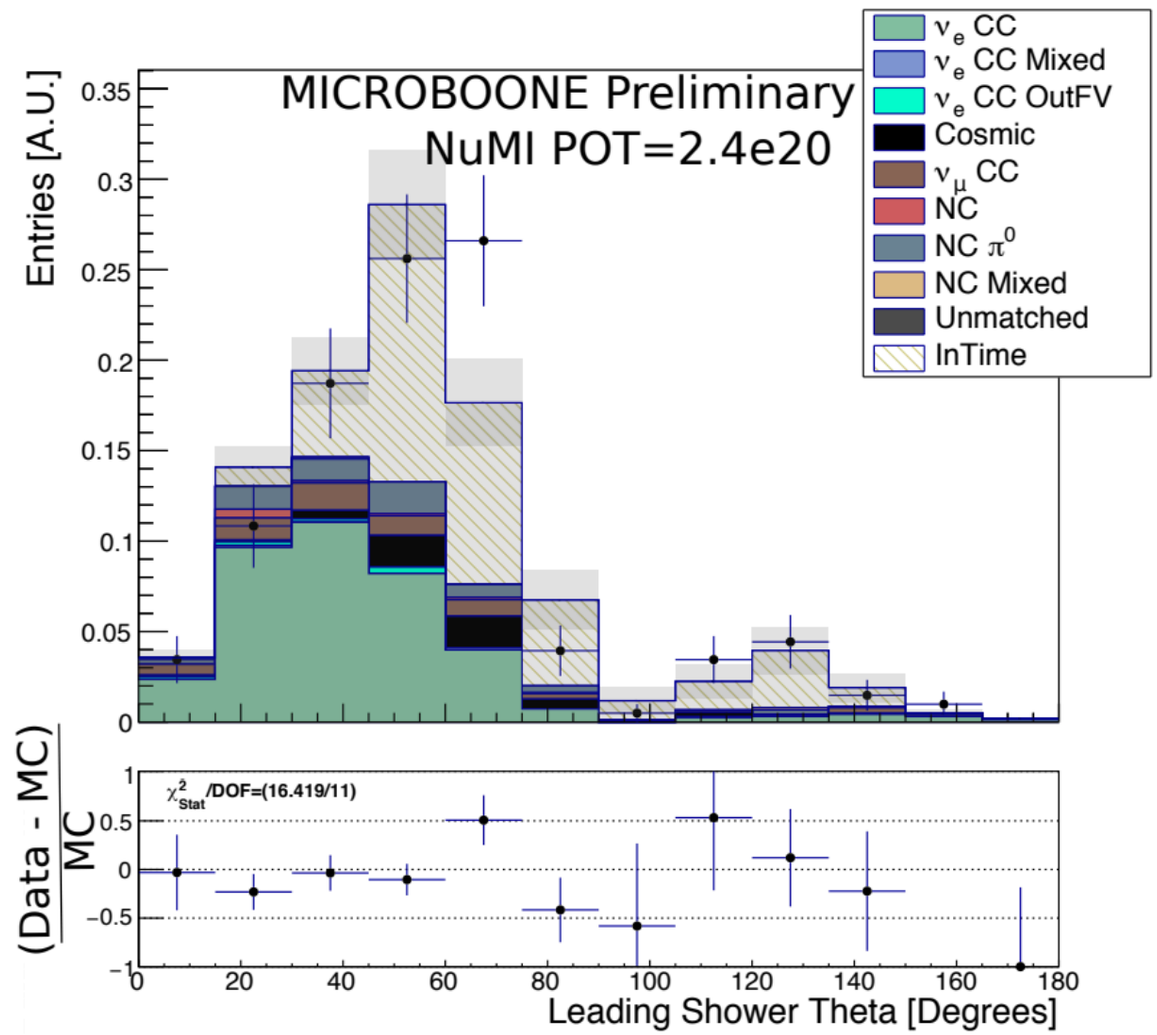
GENIE: higher than other generators and measured cross sections (with reanalysis of bubble chamber data in EPJC (2016) 76: 474 points to GENIE's nonresonant background prediction)

All predictions within 2σ of measurement, except GENIE $\bar{\nu}$ (3.3σ)

MICROBOONE ν_e CC INCLUSIVE SELECTION

MICROBOONE-NOTE-1054-PUB



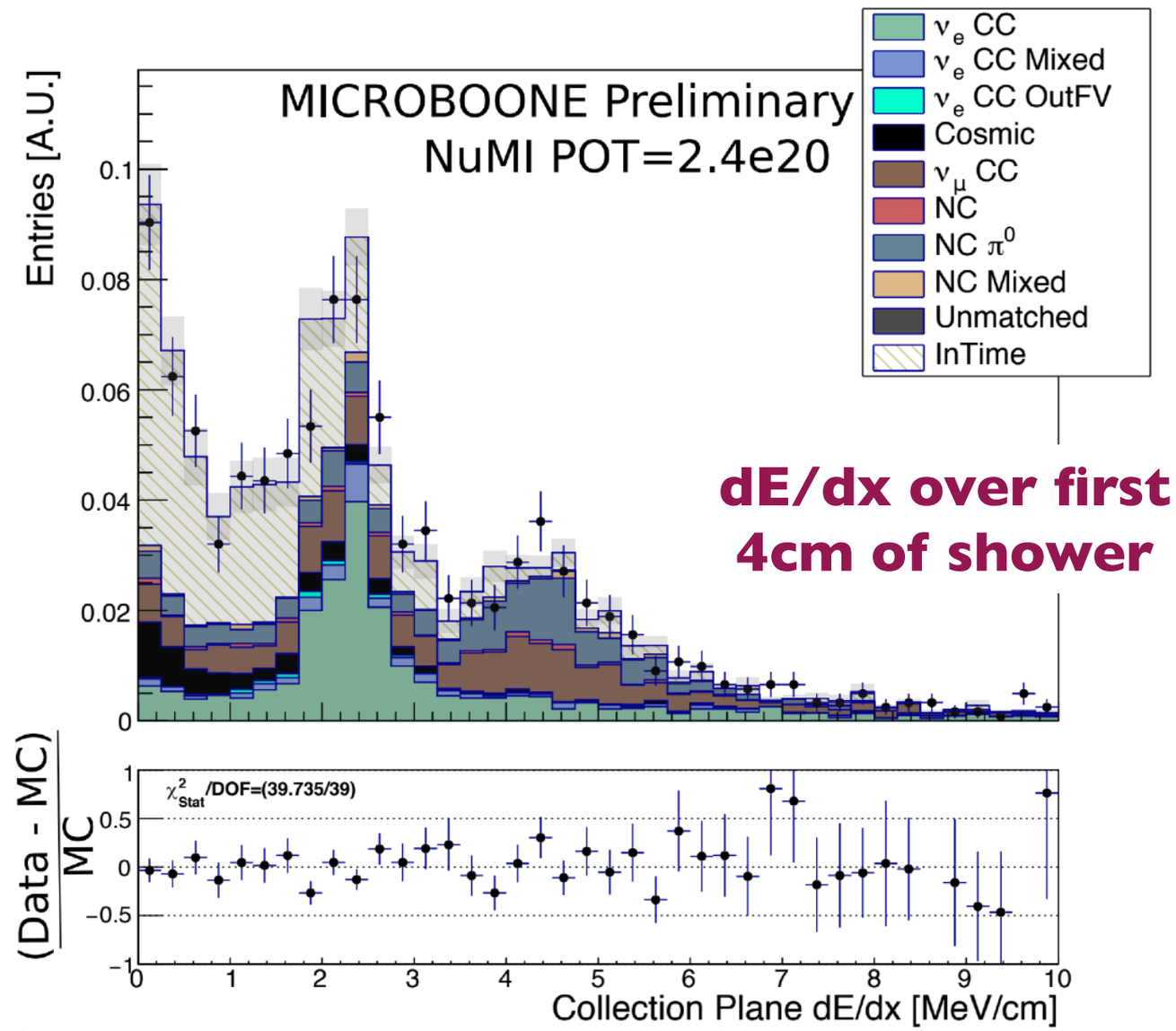


ν_e selection efficiency: 9%, purity: 40%

MICROBOONE $\nu_e+\bar{\nu}_e$ MEASUREMENTS

MICROBOONE-NOTE-1054-PUB

- Select **$\nu_e+\bar{\nu}_e$ CC inclusive** interactions by looking for single shower
- Purity 40%, efficiency 9% → **~100 events** in 5×10^{19} POT
- Future plans:
  - **$\nu_e+\bar{\nu}_e$ CC inclusive** flux integrated cross section measurement
  - **$\nu_e+\bar{\nu}_e$ CC inclusive** differential cross-section measurement
  - Exclusive **$\nu_e+\bar{\nu}_e$ CC1e1p** differential cross-section measurement

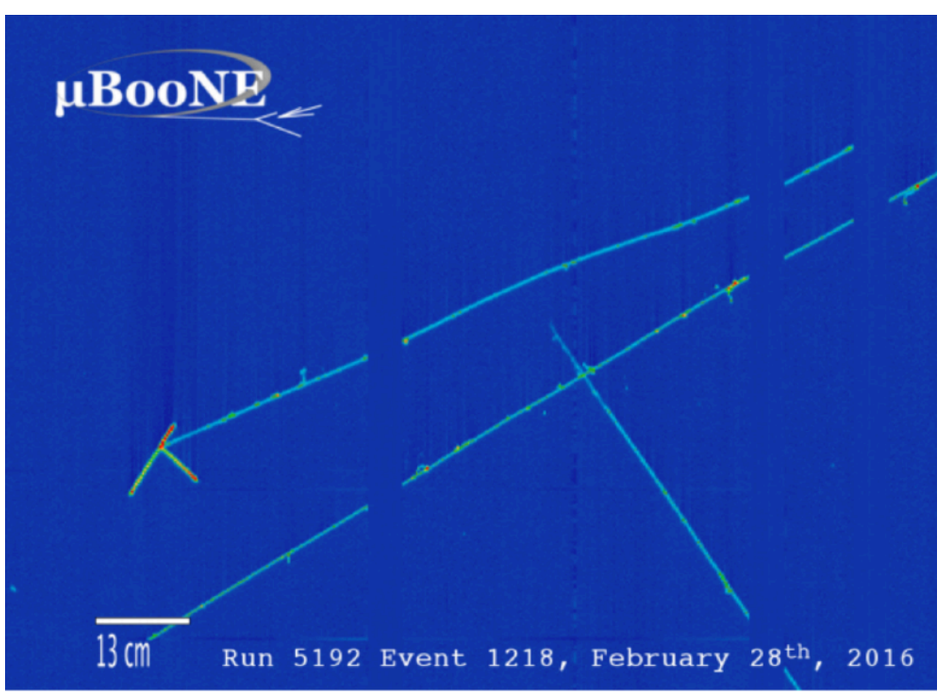


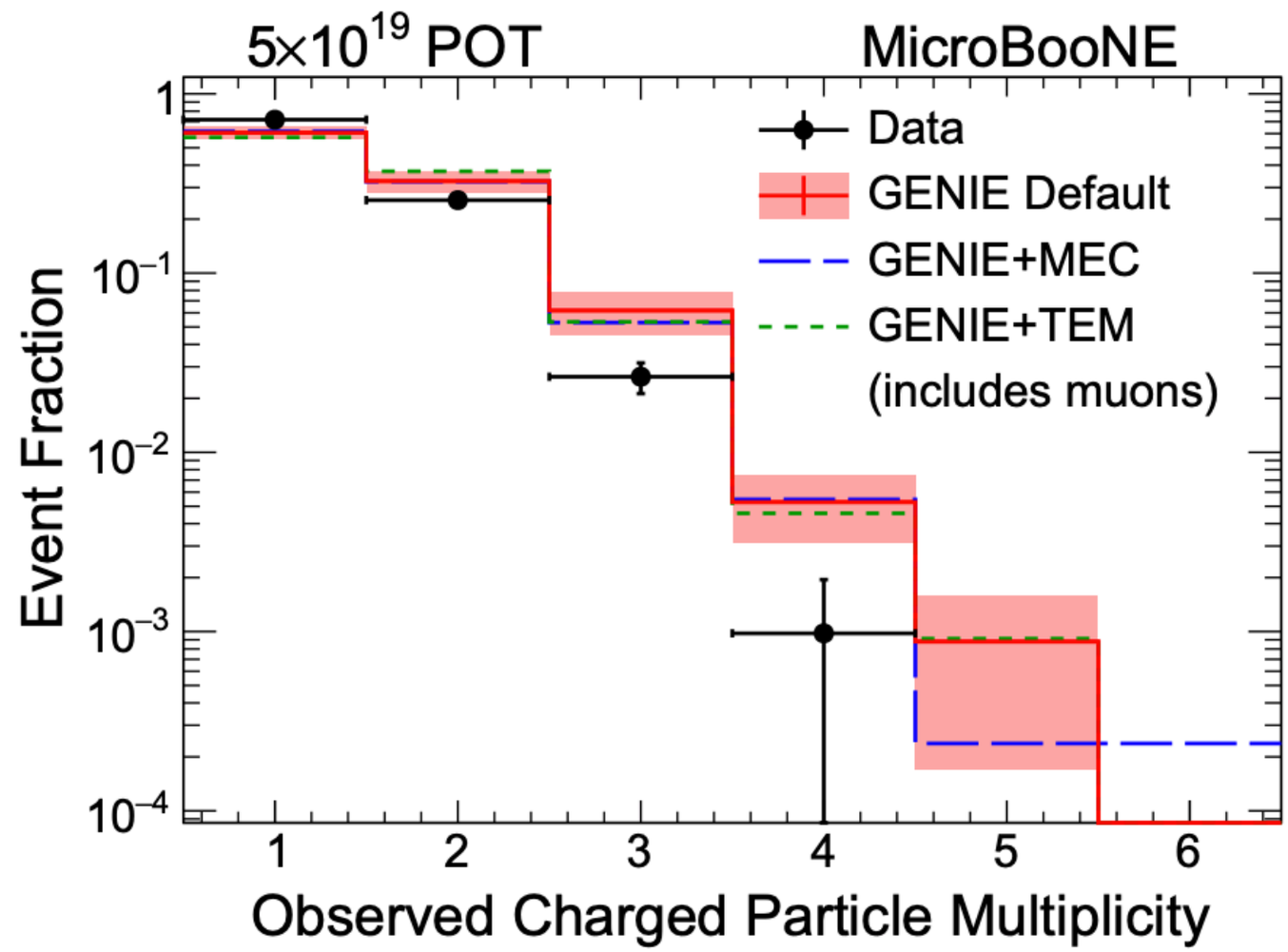
dE/dx over first 4cm of shower

CHARGED PARTICLE MULTIPLICITY

Eur. Phys. J. C79, 248 (2019)

Precise resolution of a LArTPC allows us to look in detail at particles produced in a neutrino interaction → measure **number** and **kinematic distributions** of charged tracks produced





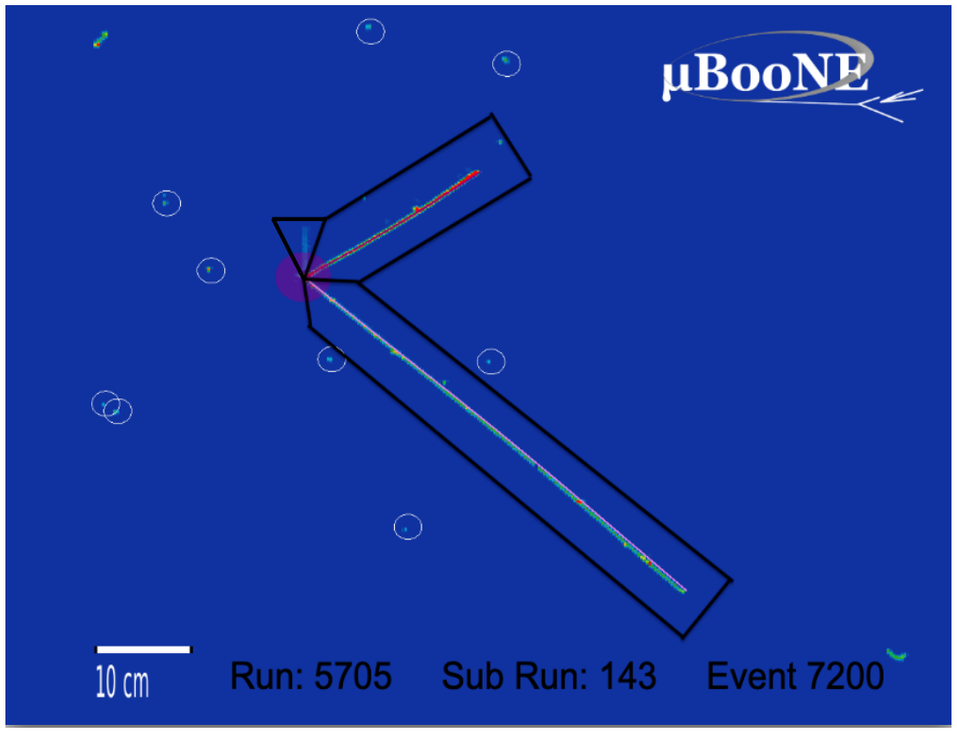
A. Bhat, Poster 4, Poster Session 4

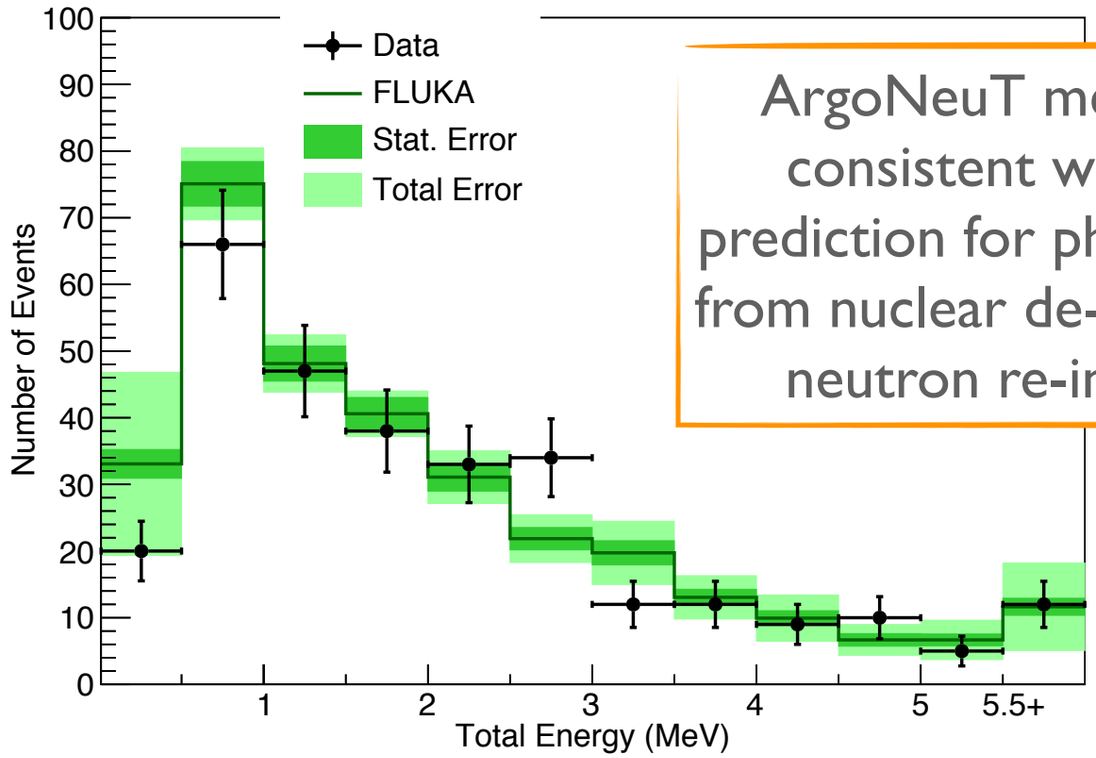
I. Lepetic, Poster 89, Poster Session 2

MEV-SCALE PHYSICS

MICROBOONE-NOTE-1050-PUB Phys. Rev. Lett. 124, 131801 (2020) Phys. Rev. D 99, 012002 (2019) MICROBOONE-NOTE-1076-PUB

- Both ArgoNeuT and MicroBooNE have demonstrated ability to reconstruct **energy depositions from sub-MeV particles** (ArgoNeuT: 300 keV, MicroBooNE: 100 keV)
- Demonstration of **low-threshold LArTPC capabilities**: important for measurements of cross sections, especially solar neutrinos, supernova neutrinos, and neutrinos from μDAR
- Measurement of **Ar-39 decays** in MicroBooNE
- BSM physics **search for millicharged particles** in ArgoNeuT set leading limits (poster by I. Lepetic)





ArgoNeuT measurement: consistent with FLUKA prediction for photons coming from nuclear de-excitation and neutron re-interactions