NEUTRINO INTERACTION MEASUREMENTS ON ARGON

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

IPPP topical meeting on physics with high-brightness stored muon beams

10th February 2021

55 cm

Run 3469 Event 53223, Oct

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**

Are models able to describe ν-Ar data?

ArgoNeuT
pathfinder, low statistics

↓

MicroBooNE
high statistics, but initial measurements had large systematic uncertainties

↓

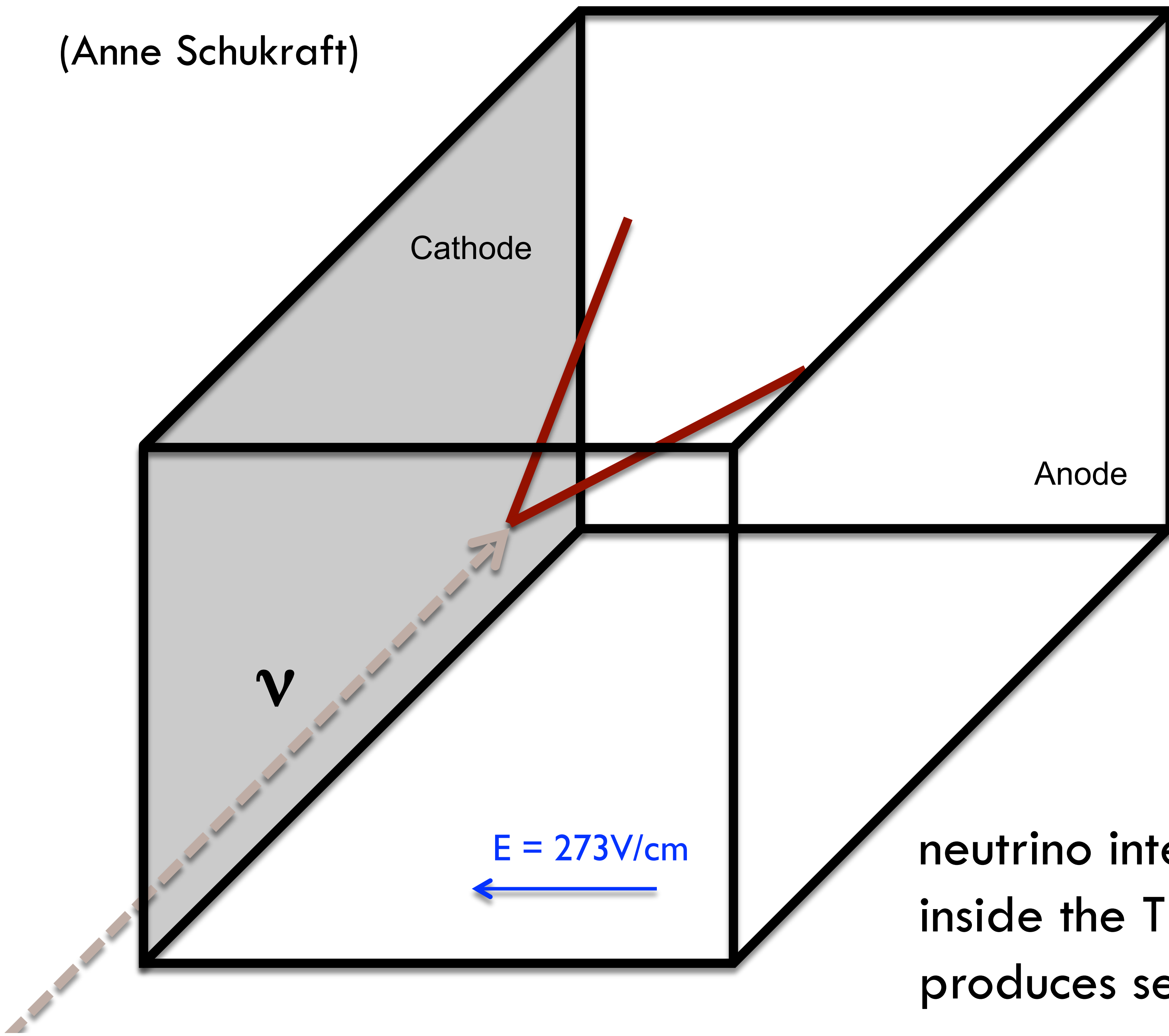
Precision MicroBooNE
improved detector understanding → high statistics, low uncertainties

↓

Future experiments: higher statistics (**SBN**, **DUNE**) and lower systematics due to measurements by **LArIAT**, **ProtoDUNEs**

LIQUID ARGON TPC

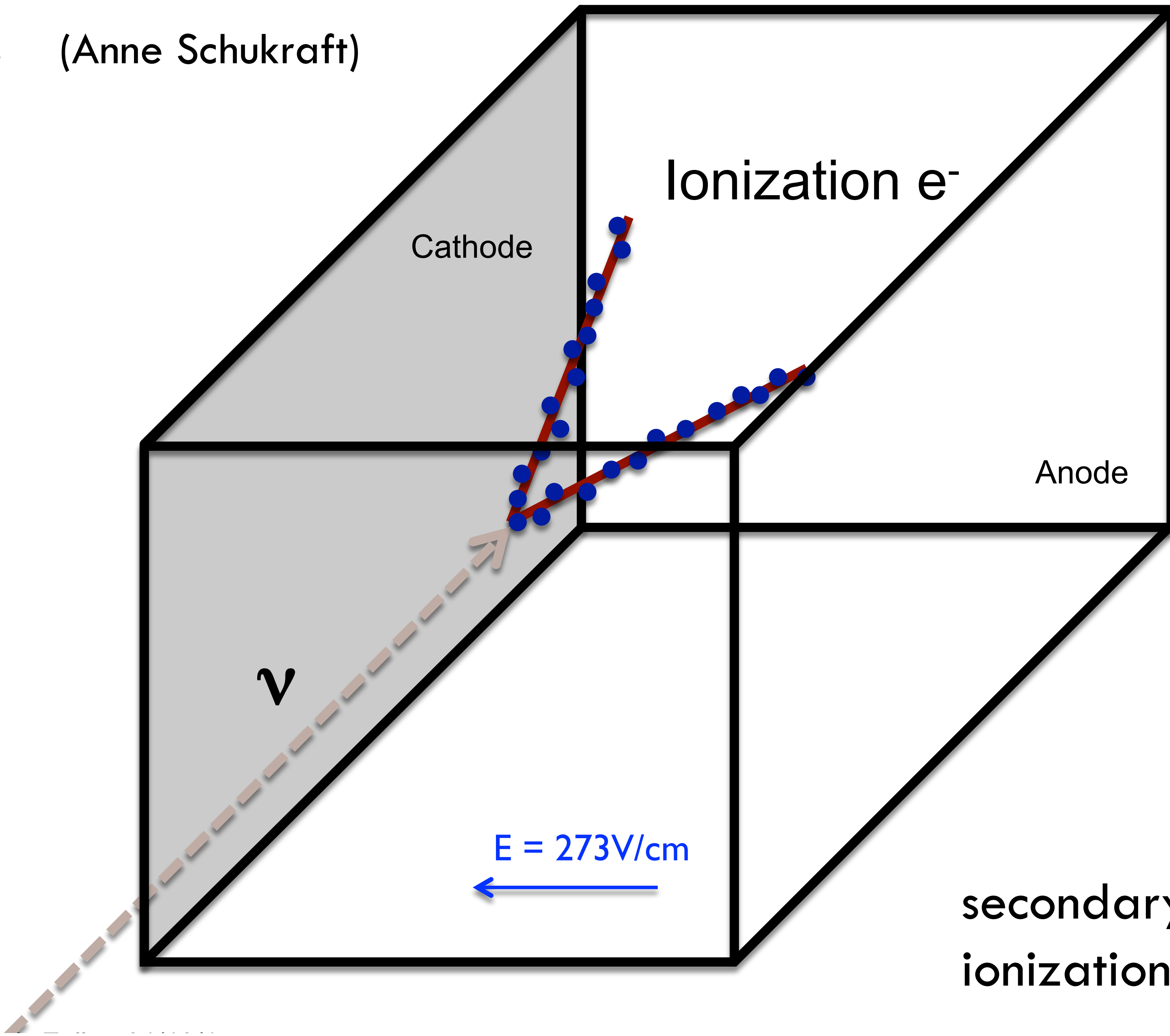
(Anne Schukraft)



neutrino interacts with the argon inside the TPC volume and produces secondary particles

LIQUID ARGON TPC

(Anne Schukraft)



secondary particles produce ionization electrons

LIQUID ARGON TPC

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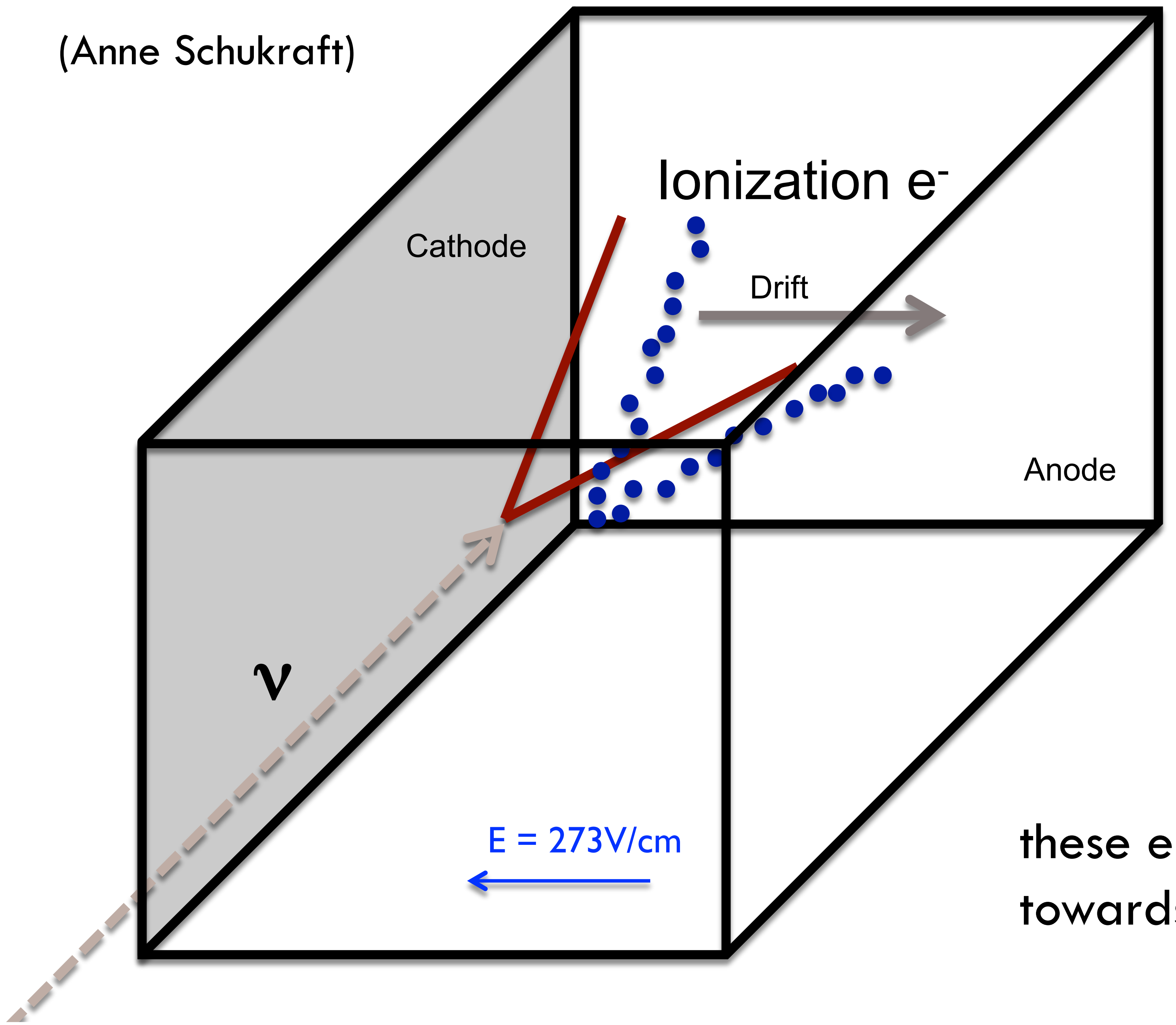
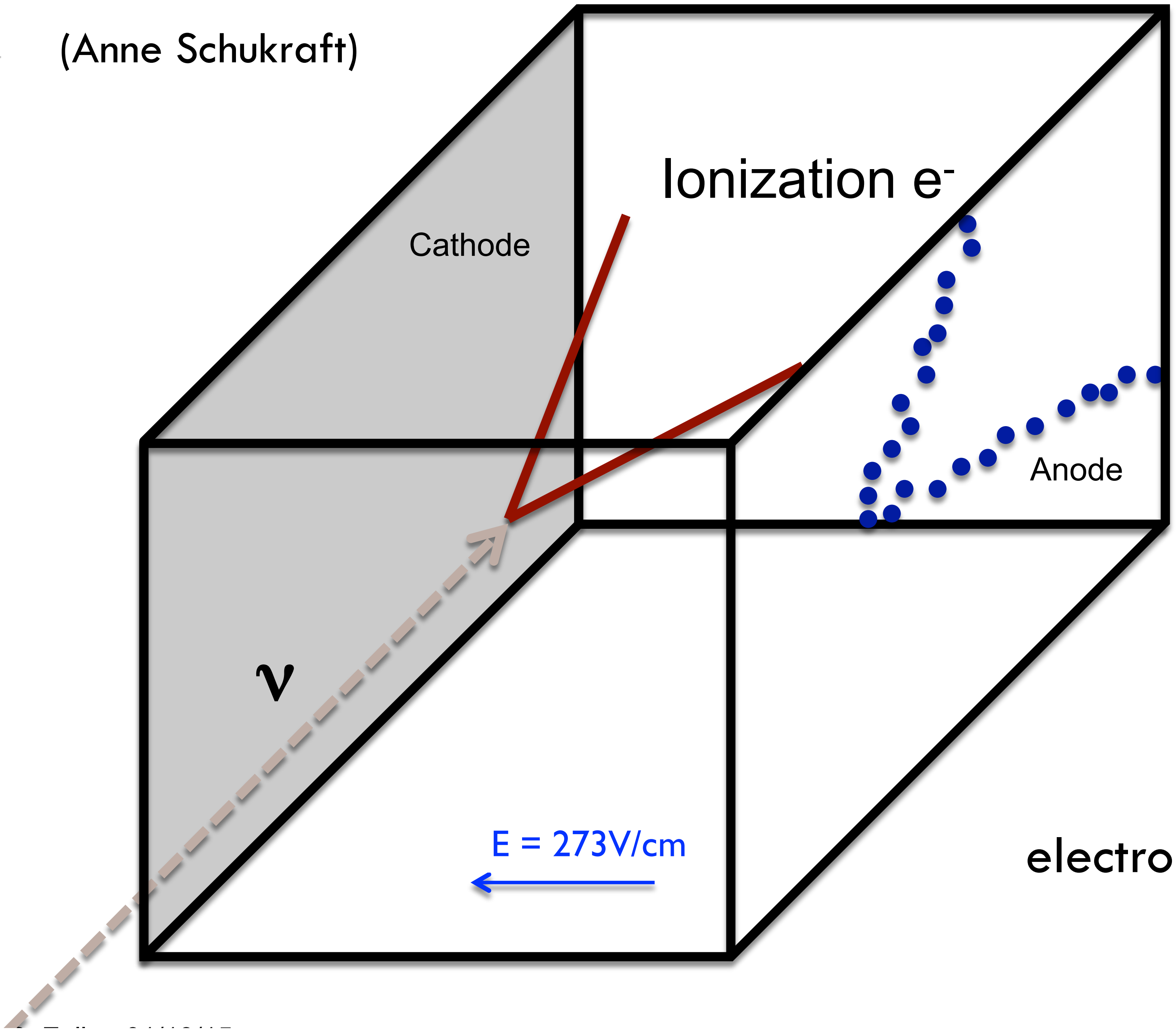


these electrons drift towards the anode

LIQUID ARGON TPC

(Anne Schukraft)

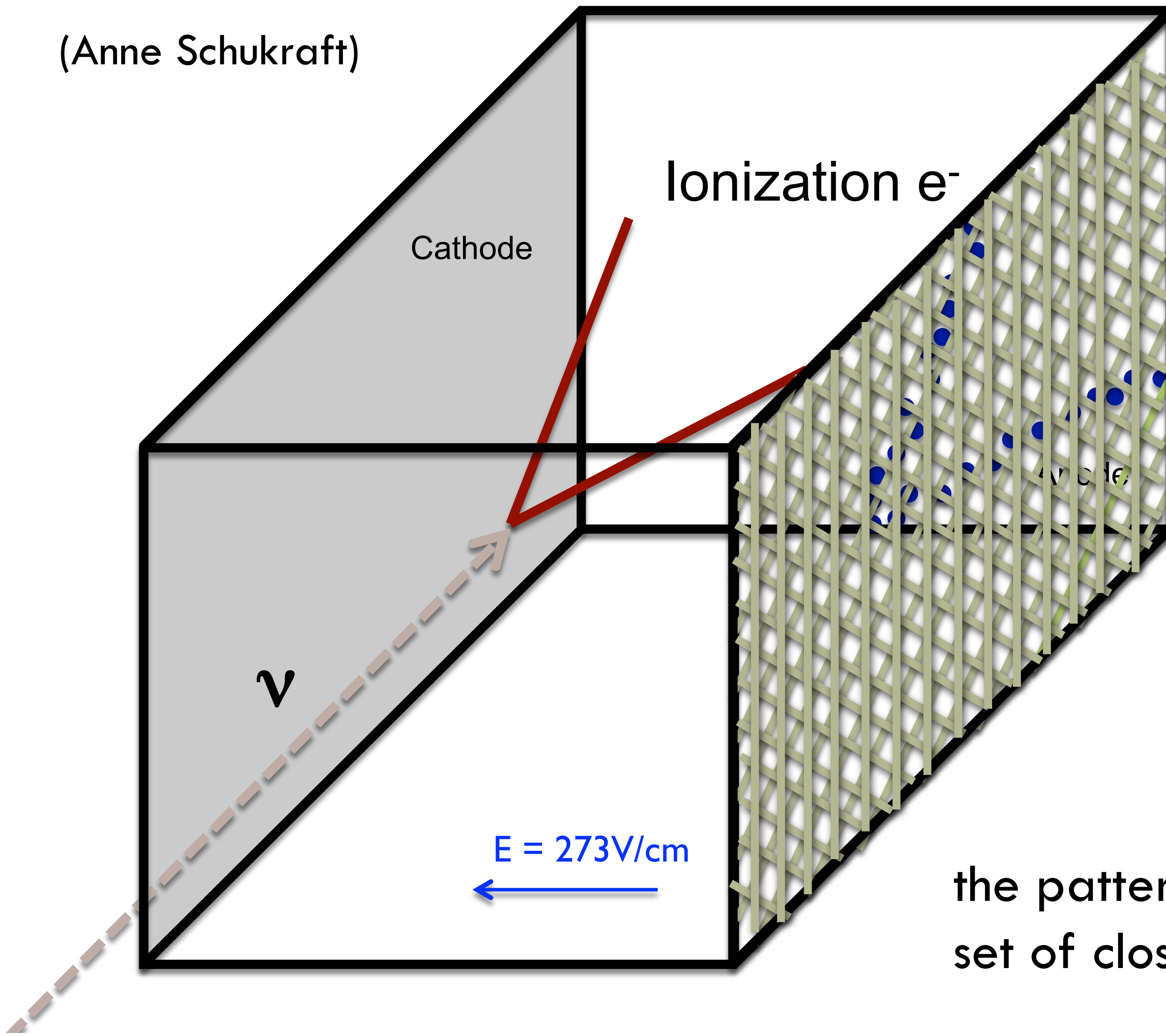


electrons arrive at anode

LIQUID ARGON TPC

(Anne Schukraft)

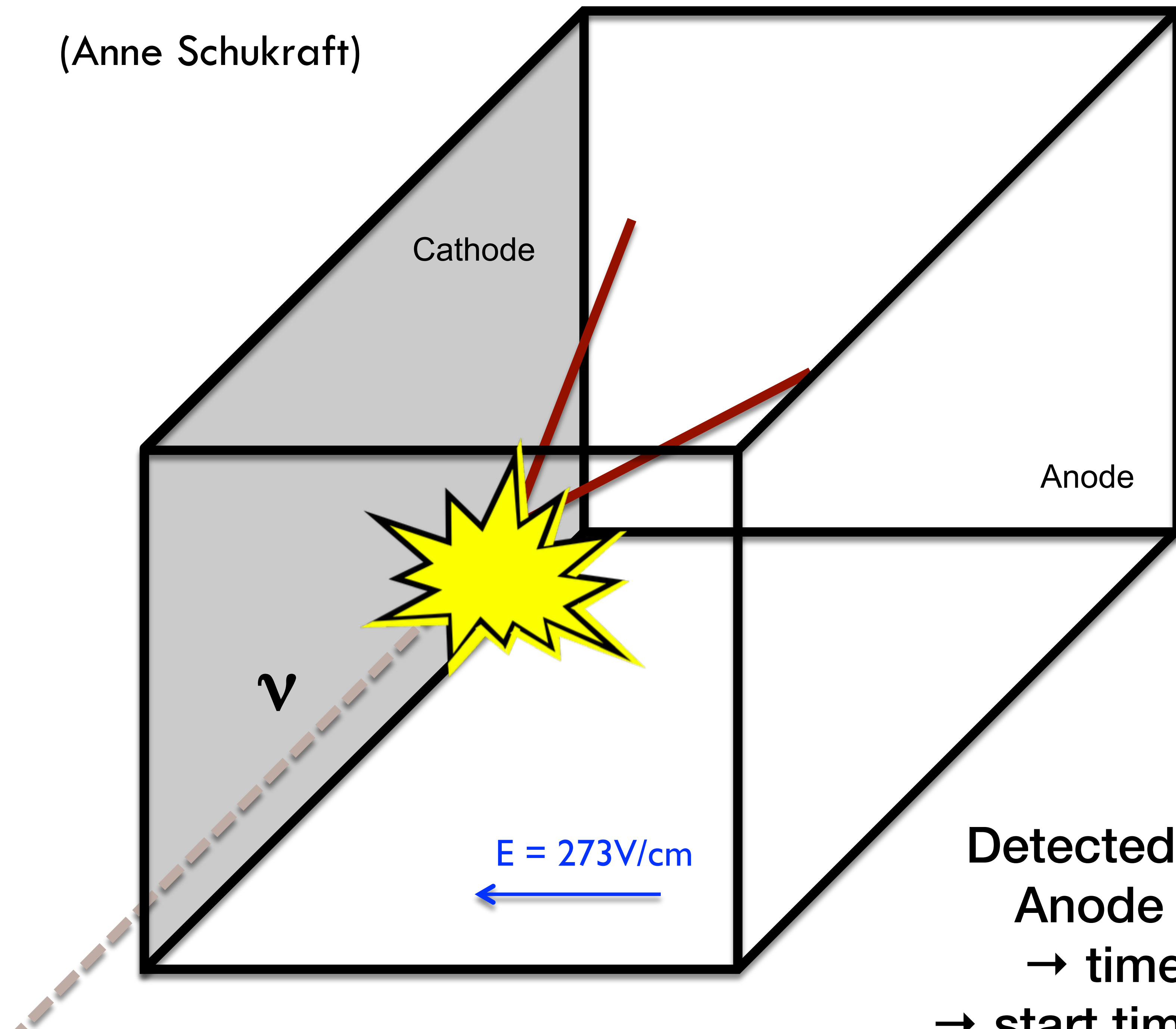
wire planes



the pattern is recorded on a set of closely spaced wires

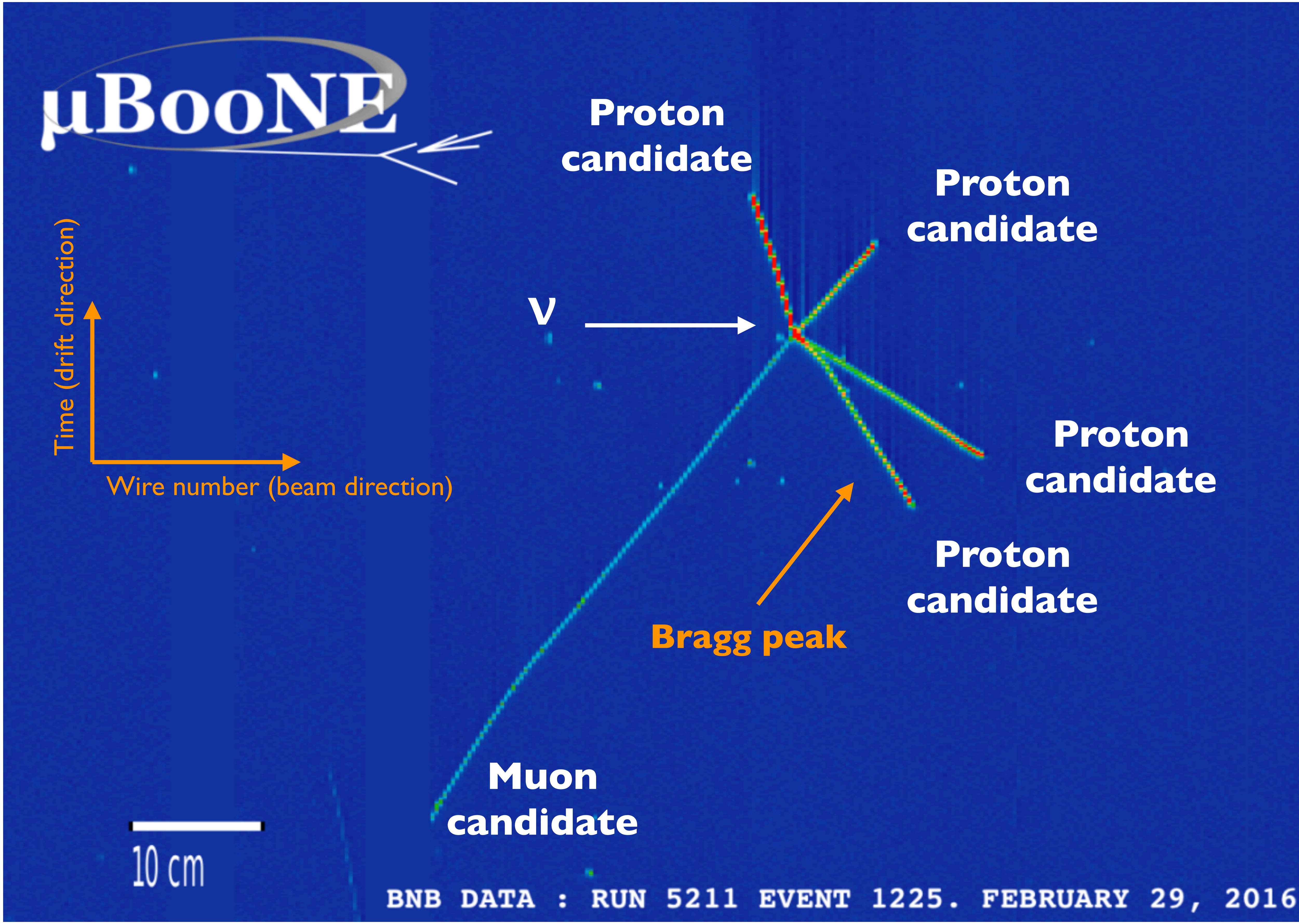
LIQUID ARGON TPC

(Anne Schukraft)



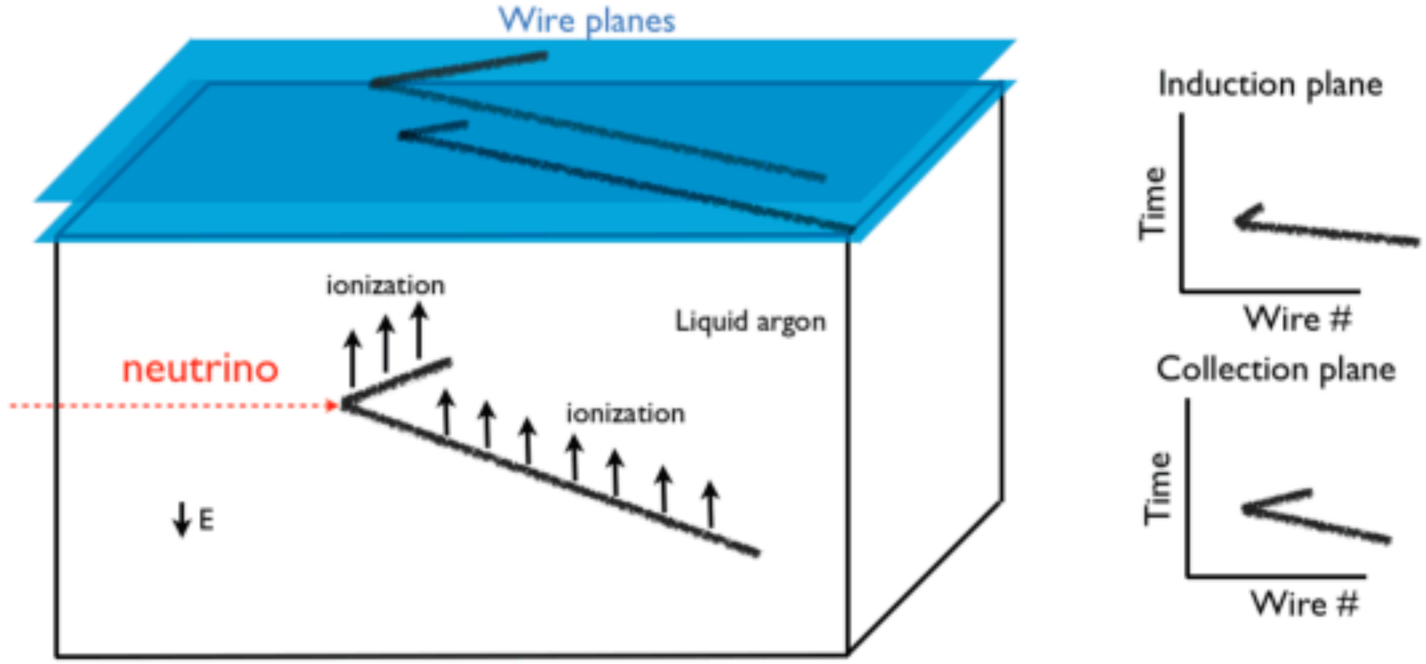
Flash of scintillation light at time of neutrino interaction

Detected by PMTs behind Anode plane to get t0
→ time of interaction
→ start time for electron drift


μBooNE
Proton candidate
Proton candidate
ν
Proton candidate
Proton candidate
Bragg peak
Muon candidate
Time (drift direction)
Wire number (beam direction)
10 cm
BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

ArgoNeuT is a 40x47x90cm^3 LArTPC

JINST 7 P10019 (2012)



- **2 planes** of wires with 4mm spacing collect charge from drifting electrons following secondary particle tracks
- **1.35x10^{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**

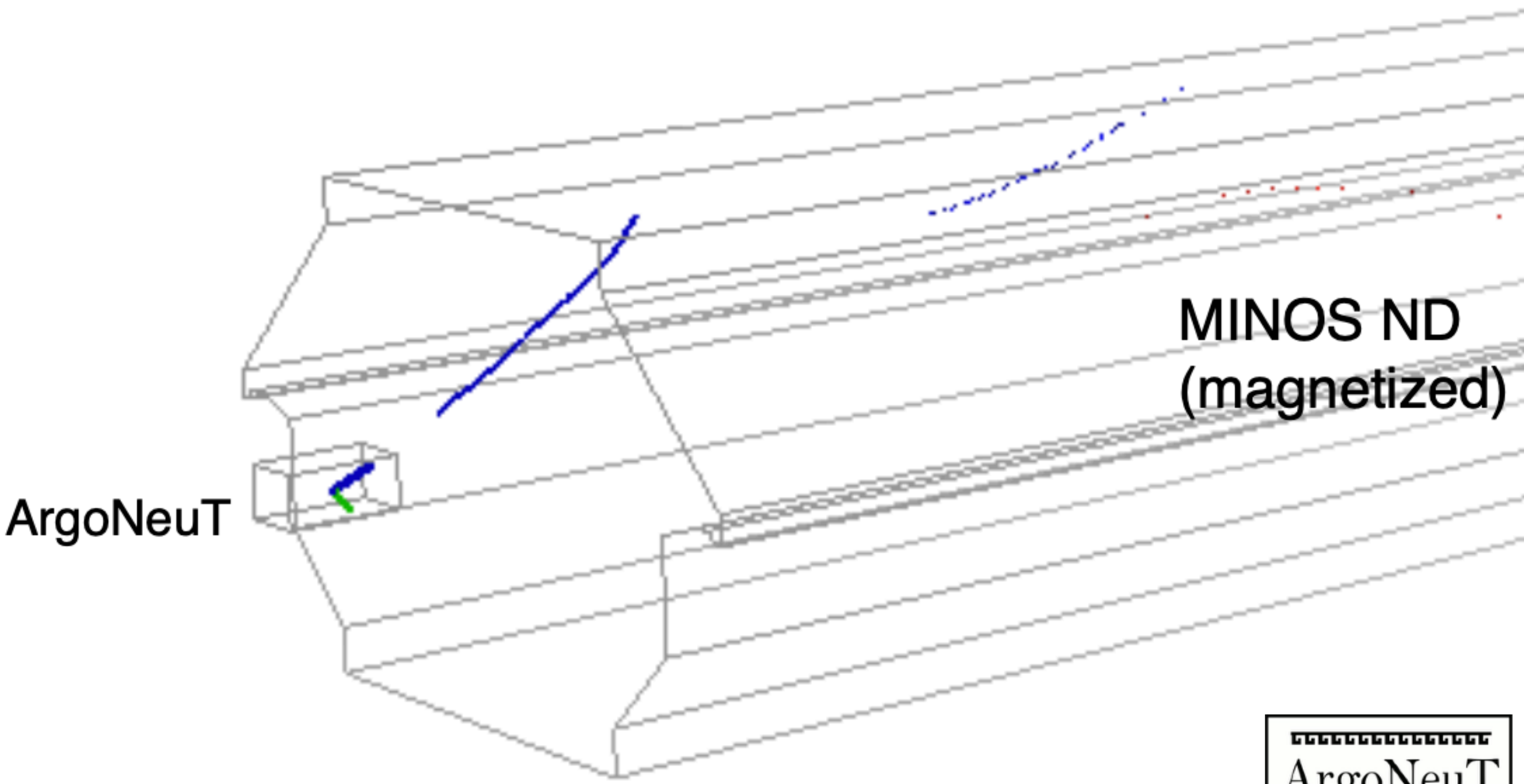
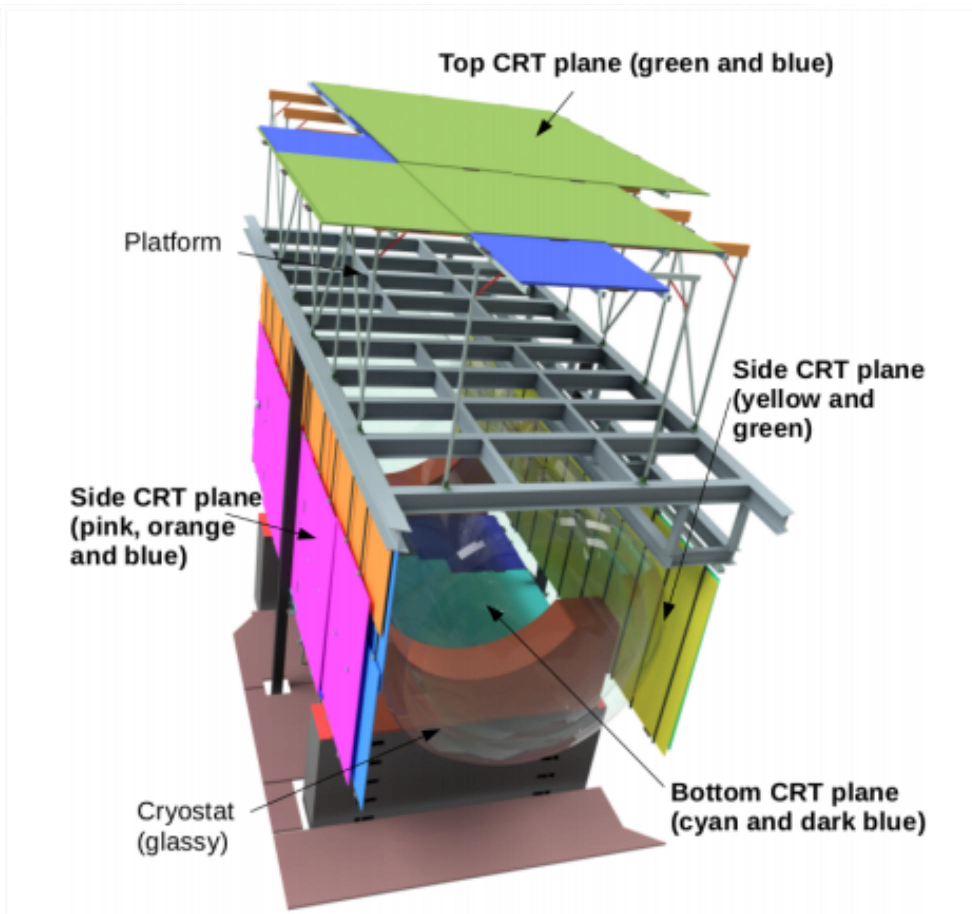


Figure from T.Yang, NuINT 2017

ArgoNeuT

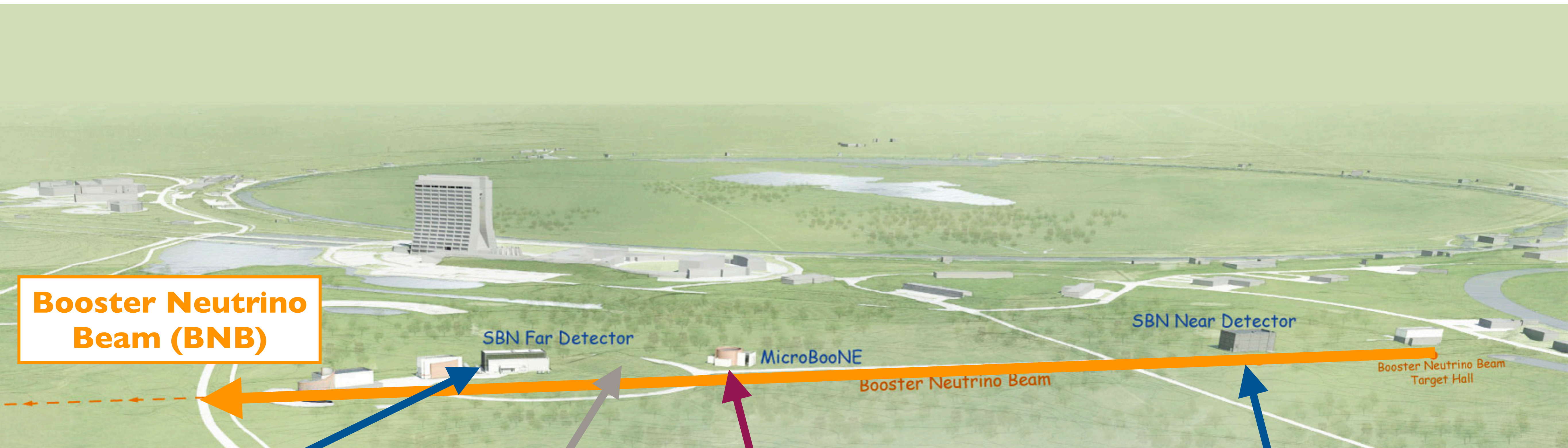


MicroBooNE: 170 ton LArTPC

JINST 12 P02017 (2017)

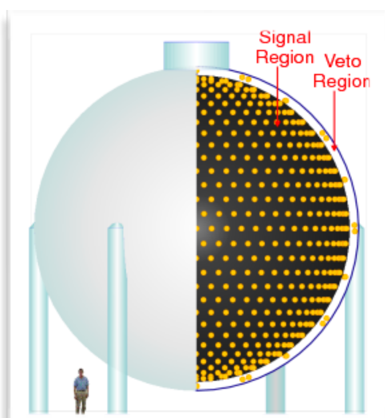
- **3 planes** of wires (vertical, +60°, -60°) with **3mm spacing**
- **32 PMTs** collect light from flash at time of interaction
- Sits in **two neutrino beams** at Fermilab: BNB (on-axis, $\langle E_{\nu\mu} \rangle$=800 MeV) and NuMI (off-axis, $\langle E_{\nu e} \rangle$=650 MeV)
- Stable detector 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)**

SHORT-BASELINE NEUTRINOS AT FERMILAB (SBN)



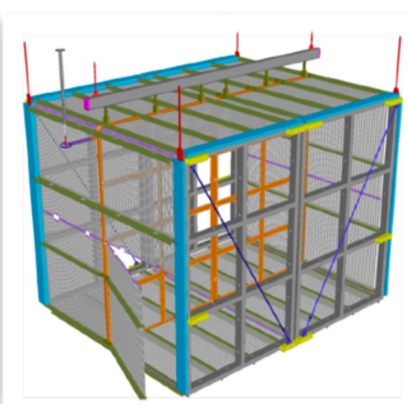
ICARUS

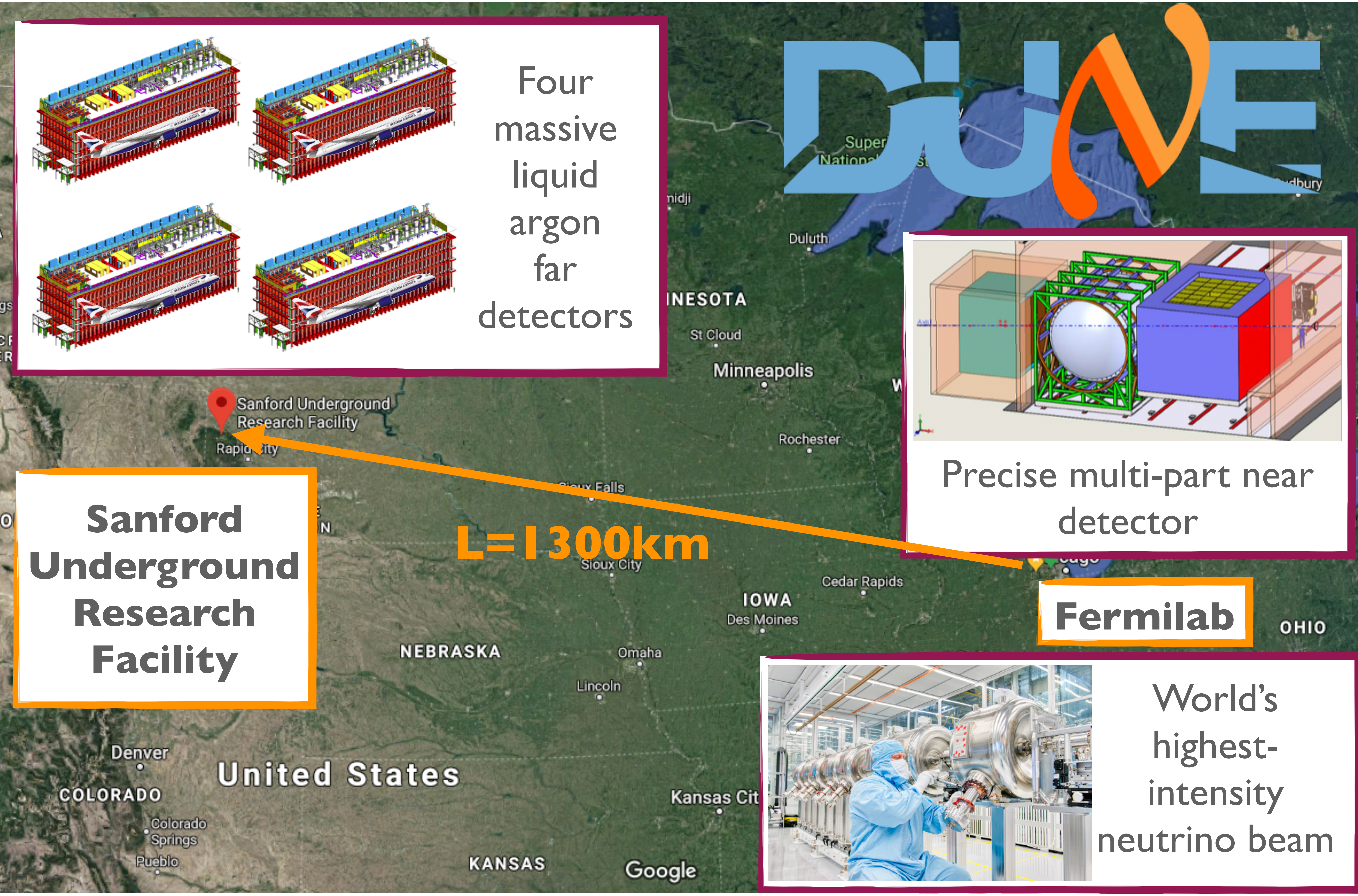
MiniBooNE



MicroBooNE

SBND





Four massive liquid argon far detectors

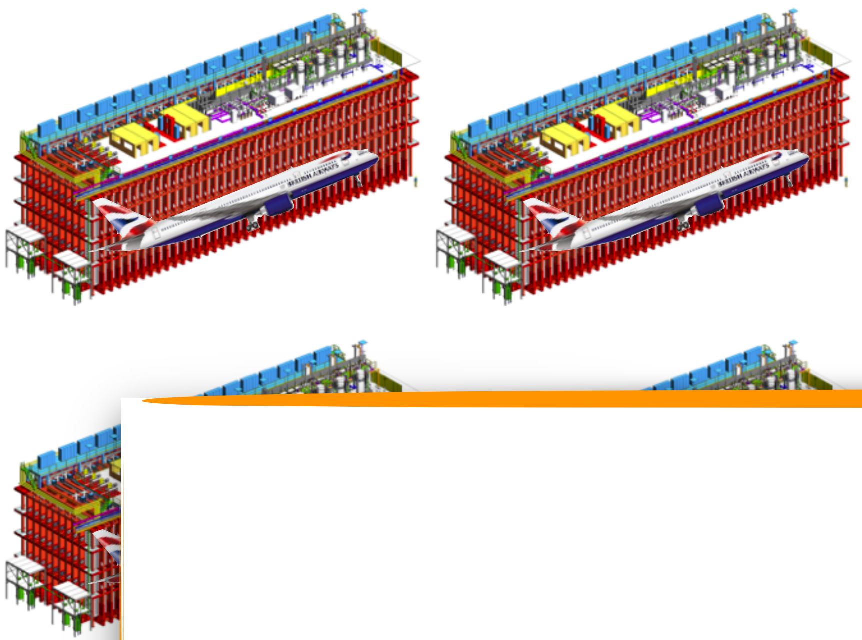
Precise multi-part near detector

Sanford Underground Research Facility

L=1300km

Fermilab

World's highest-intensity neutrino beam



Four
massive
liquid
argon

Motivation:

Improve understanding of neutrino interactions
→ improve **flavour and energy reconstruction** for DUNE

Develop models that are **capable of fitting** high-statistics data from DUNE near detectors

neutrino beam

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)

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

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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)
Phys. Rev. D 102, 011101(R) (2020)

μBooNE: ν_e and $\bar{\nu}_e$ total cross section (inclusive)
arXiv:2101.04228[hep-ex]

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MICROBOONE-NOTE-1076-PUB

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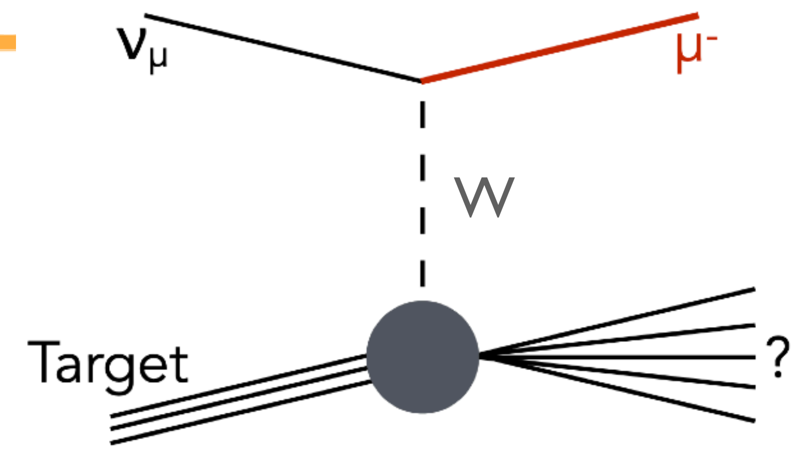
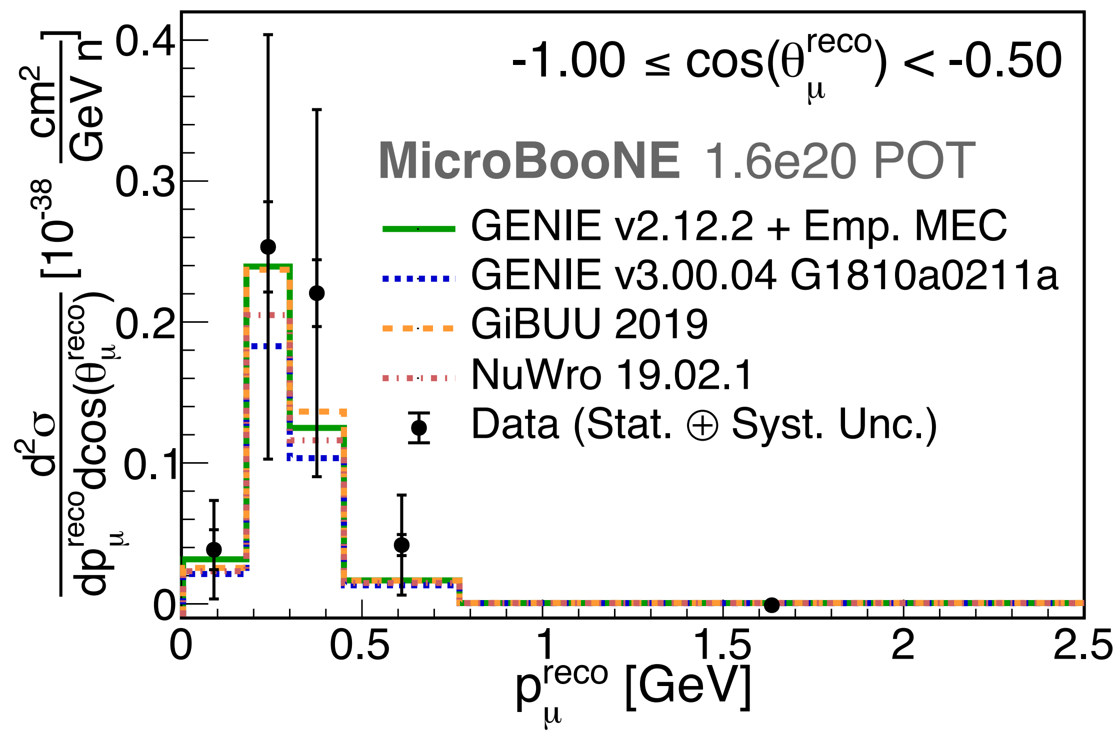
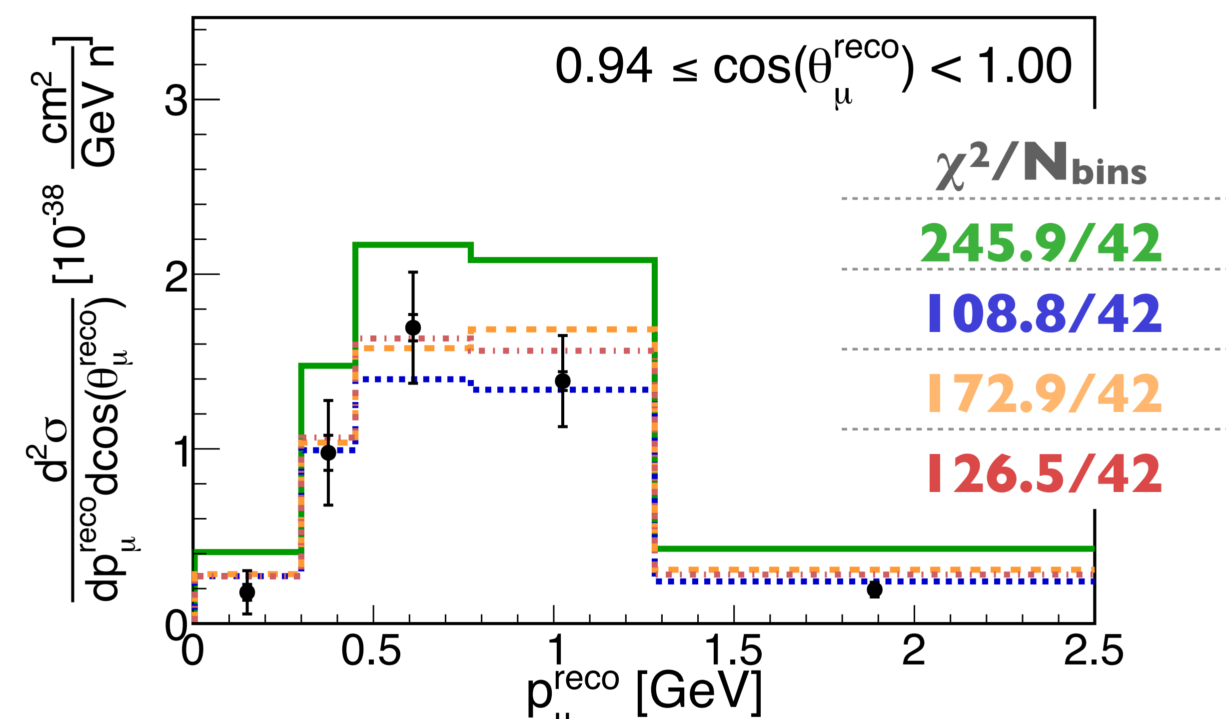
CC INCLUSIVE CROSS SECTION MEASUREMENT



PRL 123, 131801 (2019)

- **First ever double-differential cross section measurement** on argon: compared to worldwide interaction generators
- All models **overpredict in high-momentum, forward going bins**: interesting physics in this region!



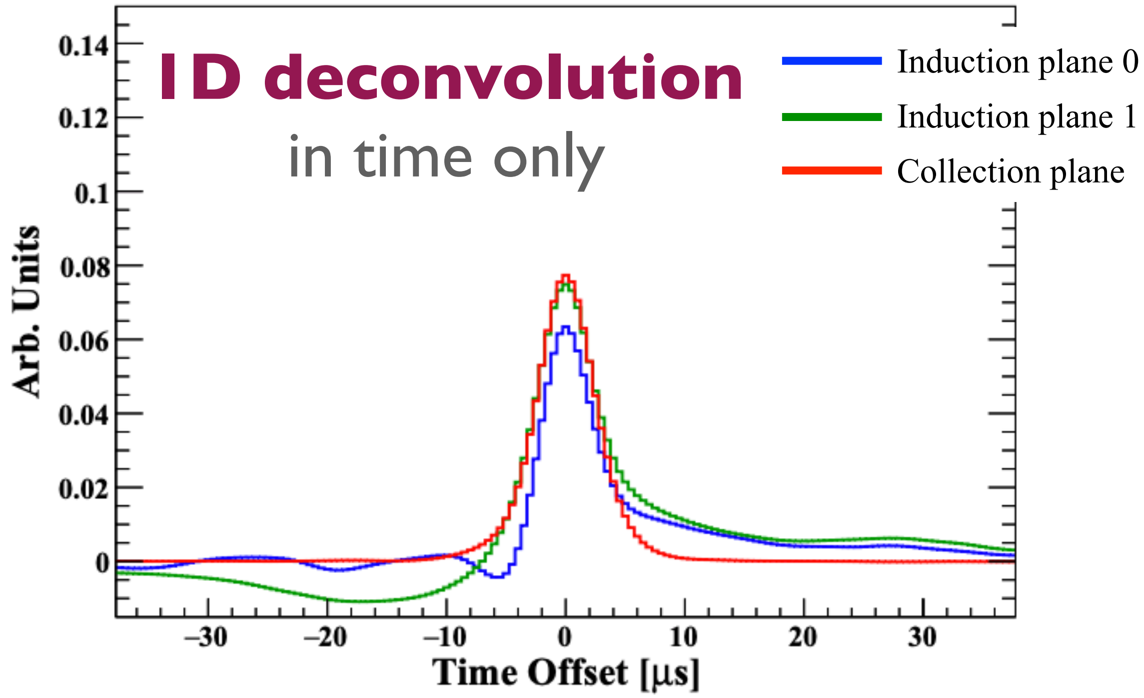


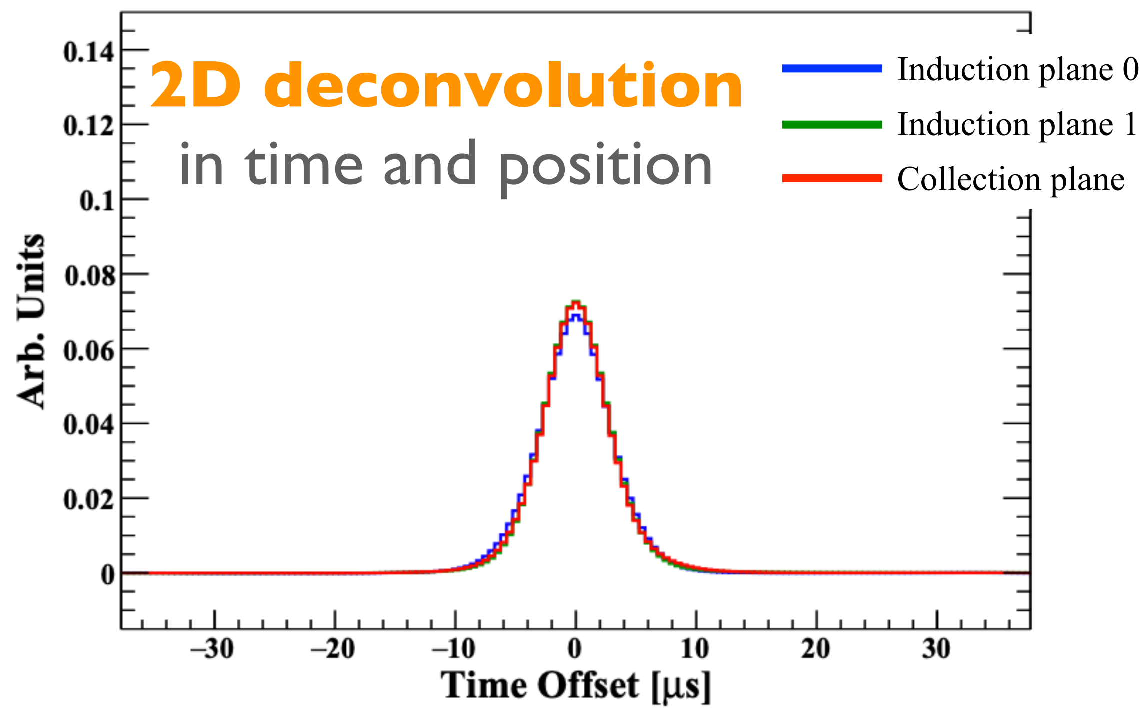
GETTING THE MOST OUT OF LArTPCs

JINST 13 P07006 (2018)

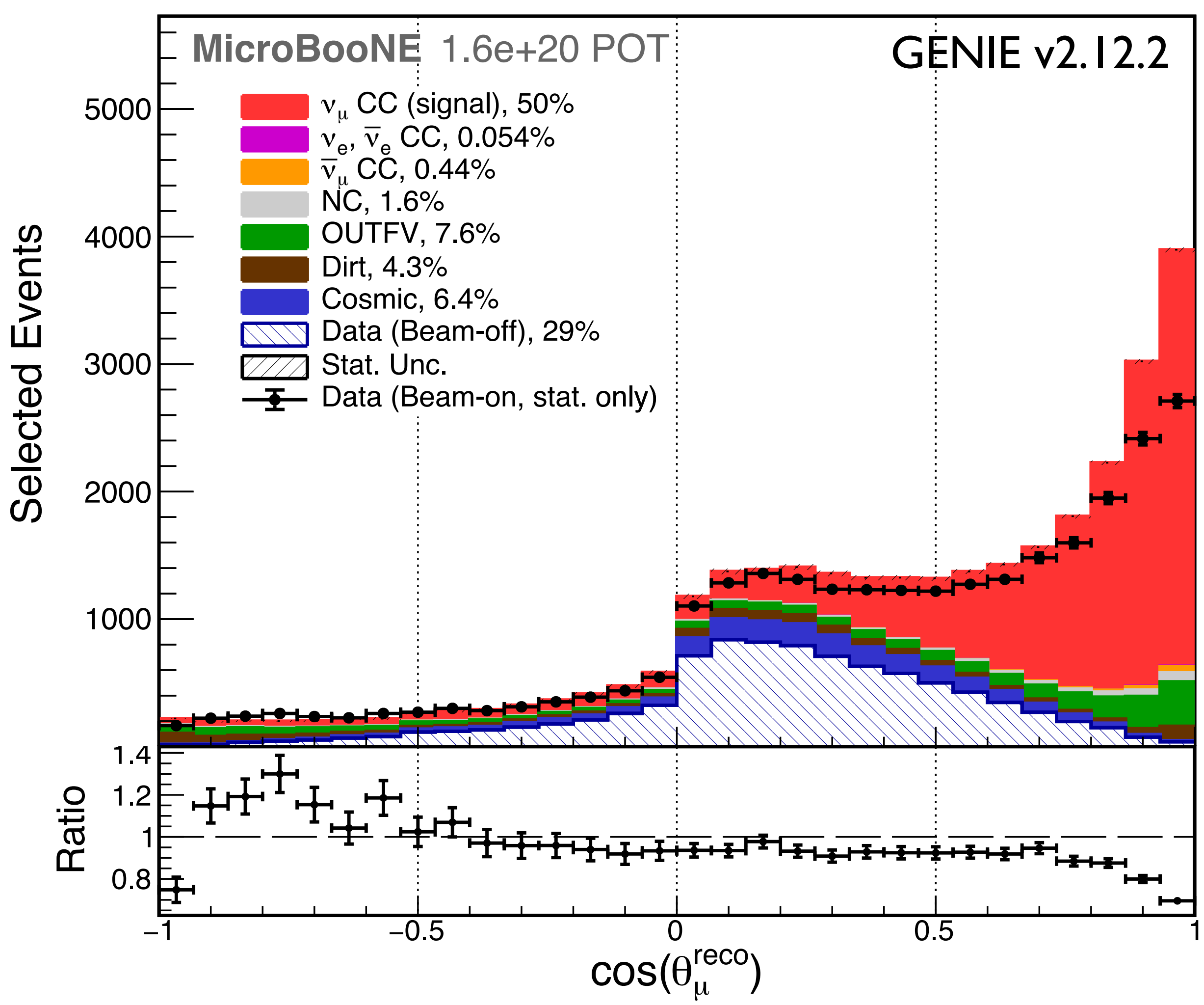
JINST 13 P07007 (2018)

- MicroBooNE Collaboration has made **huge improvements** in our understanding of the detector in the past few years
- 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**





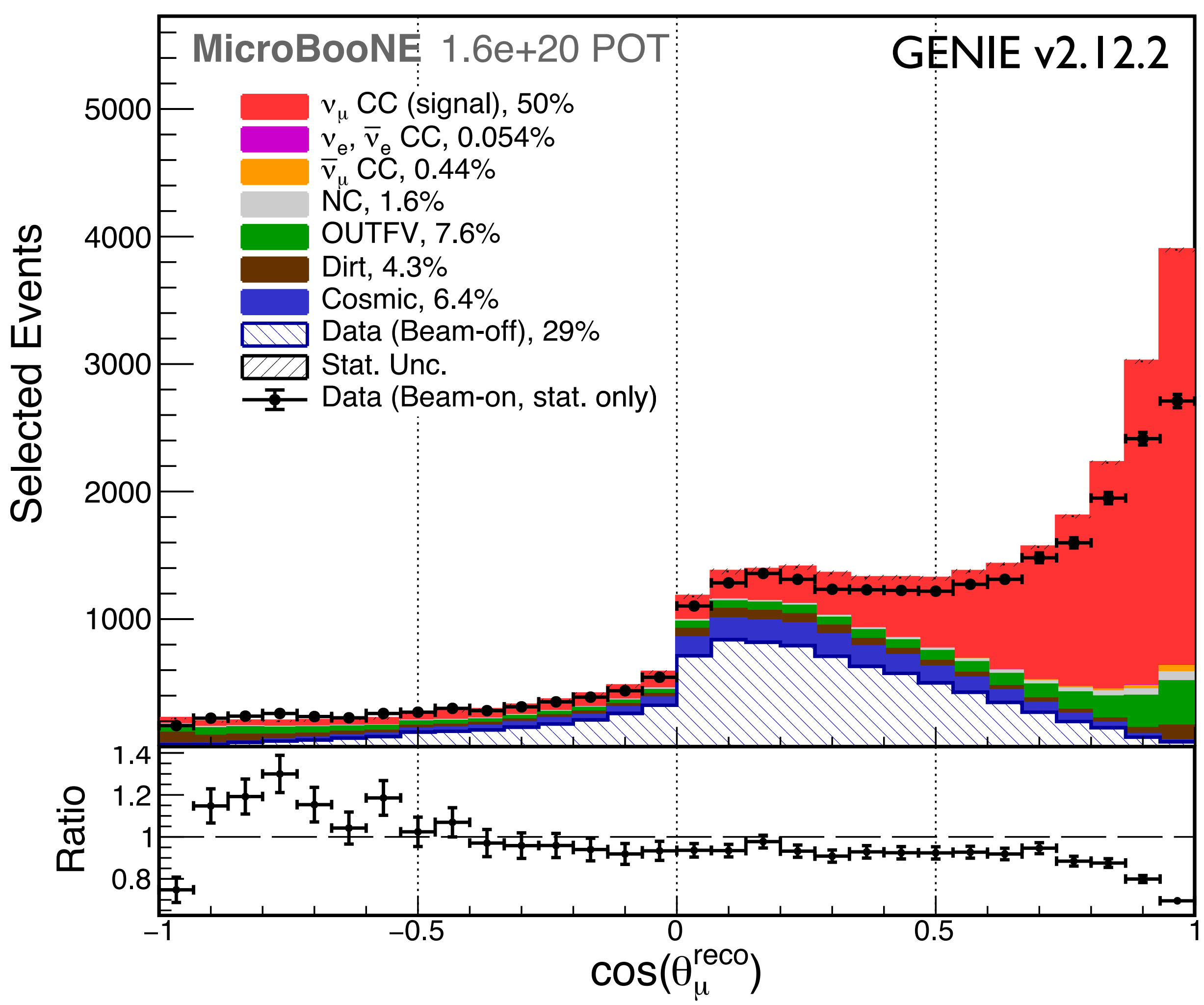
IMPROVED DETECTOR UNDERSTANDING ENABLES BETTER MEASUREMENTS

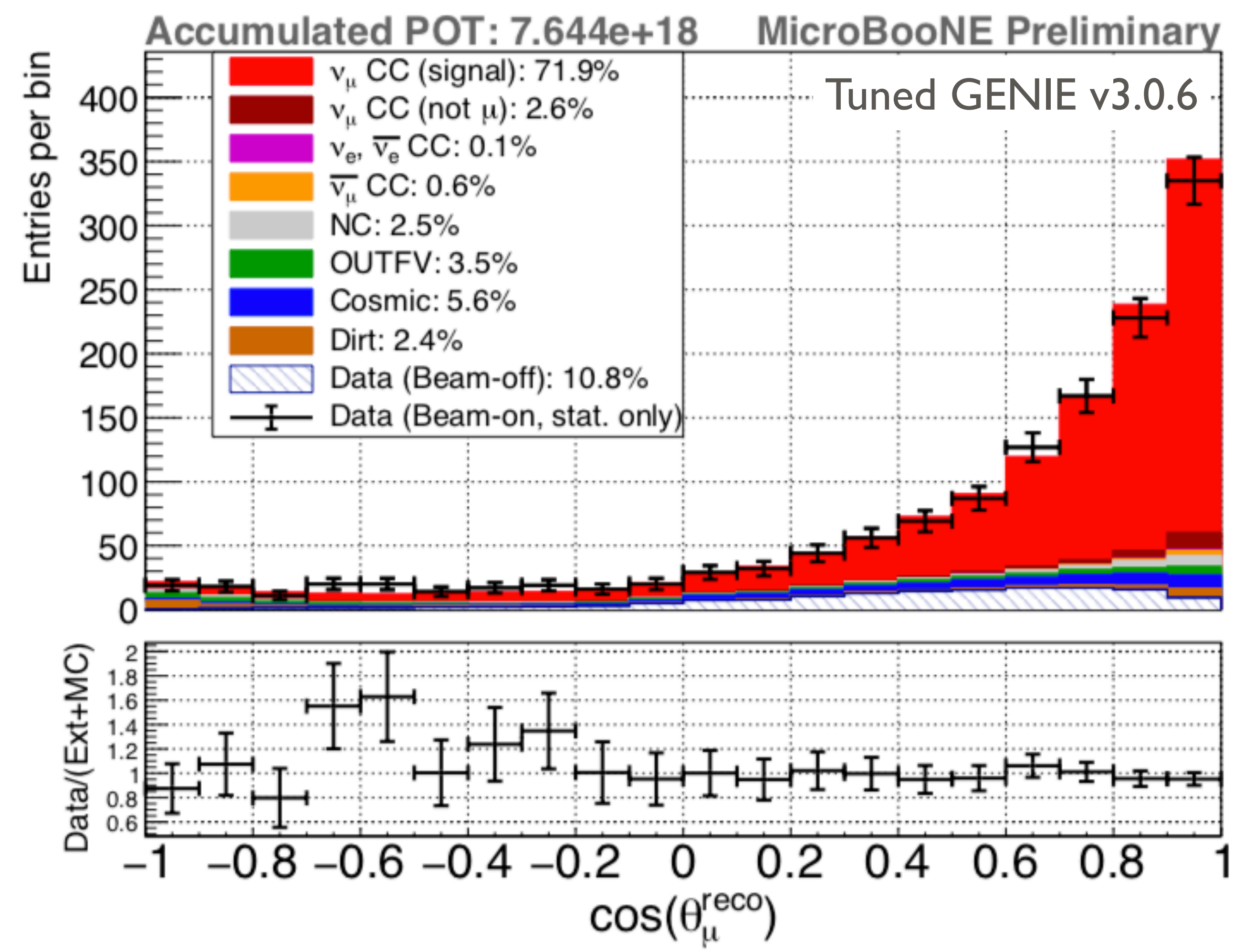


Previous Measurement

PRL 123, 131801 (2019)

IMPROVED DETECTOR UNDERSTANDING ENABLES BETTER MEASUREMENTS





Previous Measurement

PRL 123, 131801 (2019)

Current Measurement

MICROBOONE-NOTE-1069-PUB

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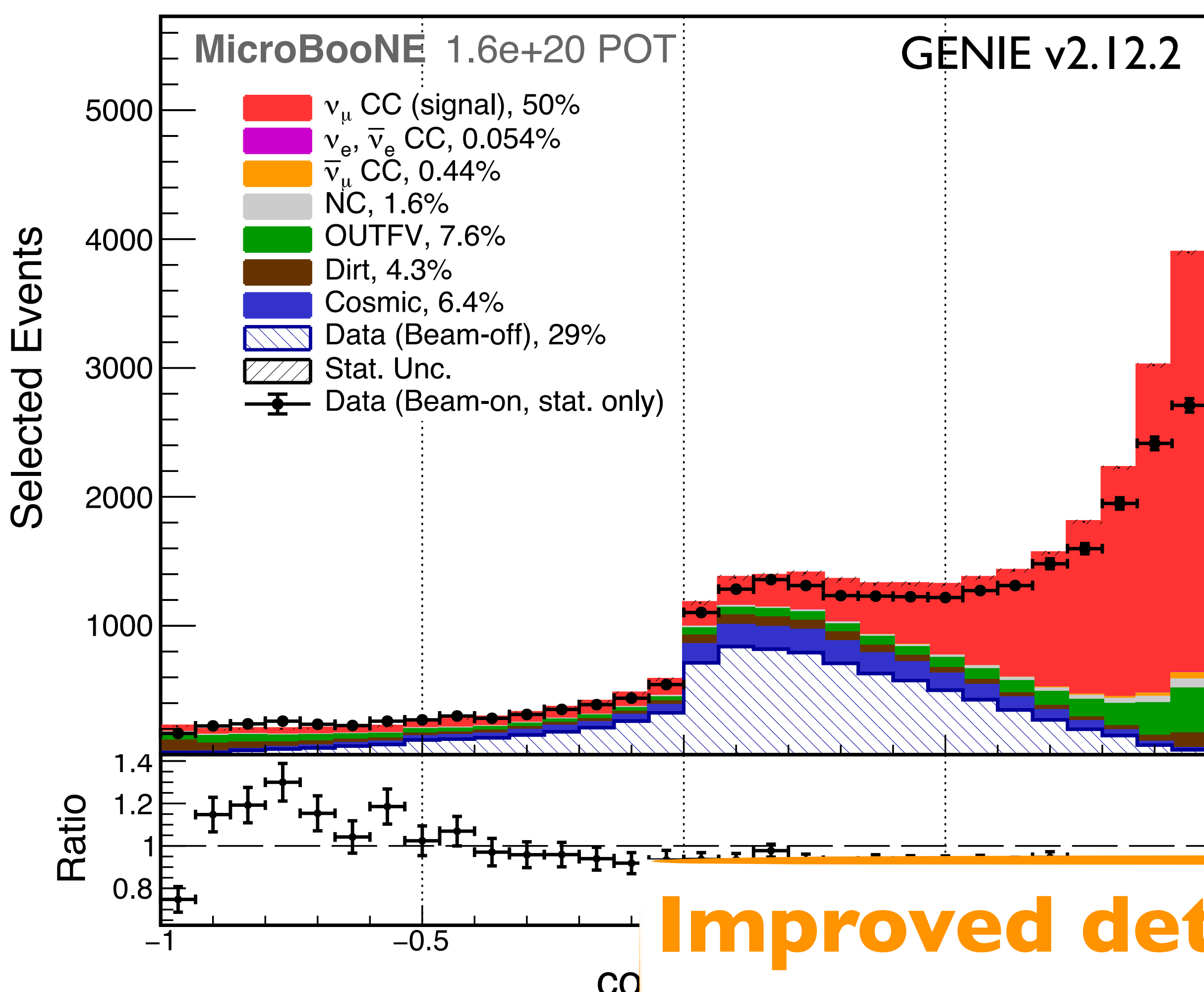
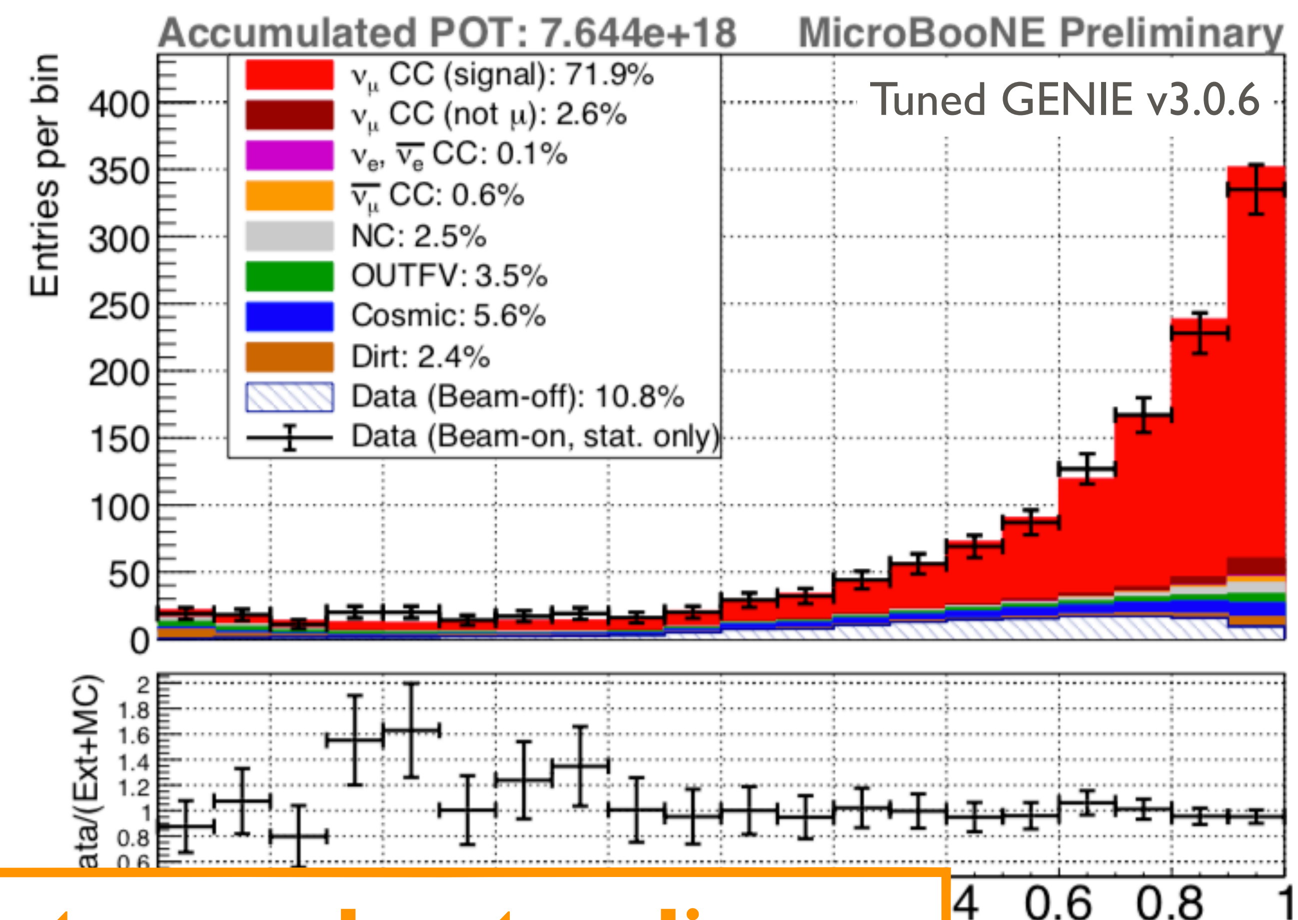




Previous M… …ment

PRL 123,

Improved detector understanding, reconstruction, CRT → higher purity

ν_μCC (signal) purity: 50% → 71.9%

Entering backgrounds: 33.3% → 13.2%

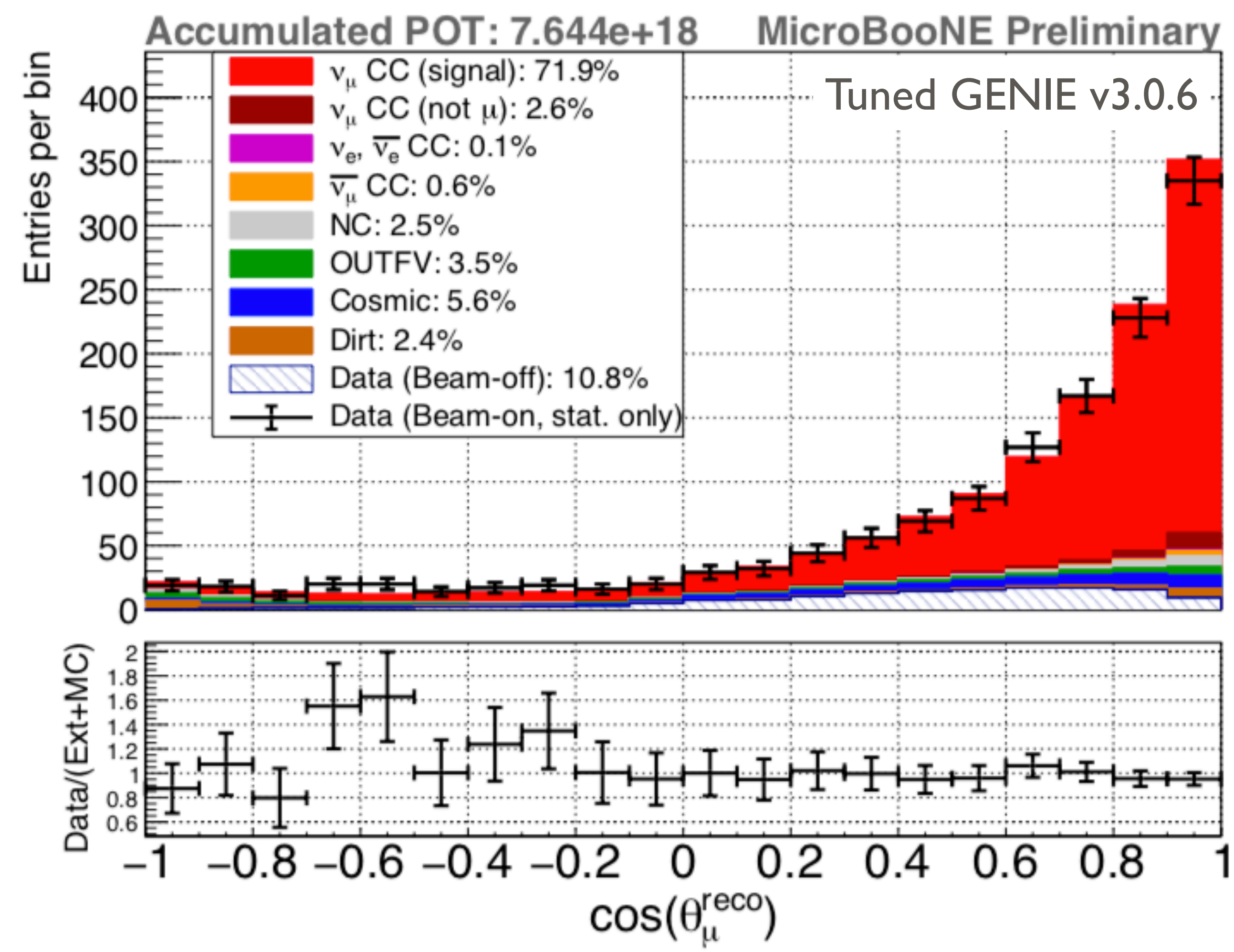
IMPROVED INTERACTION MODELING ENABLES BETTER MEASUREMENTS

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**

PRL 123, 131801 (201

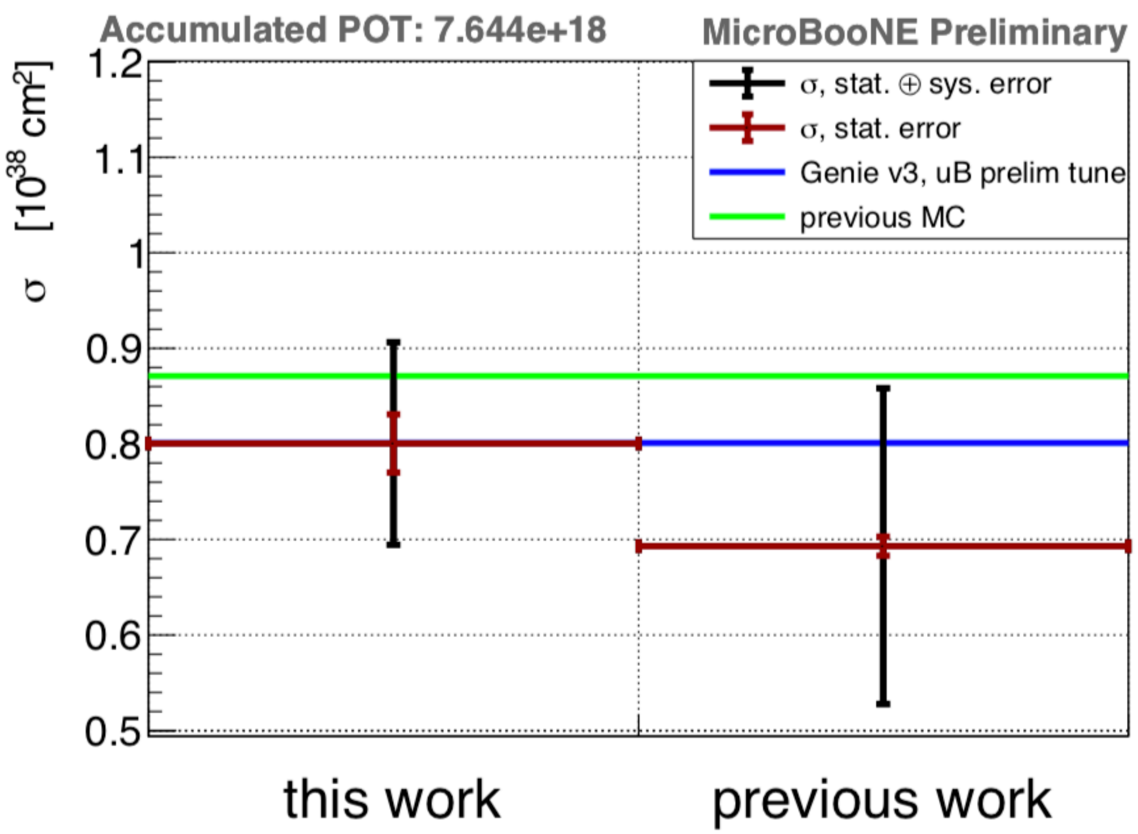
MICROBOONE-NOTE-1074-PUB



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%	-
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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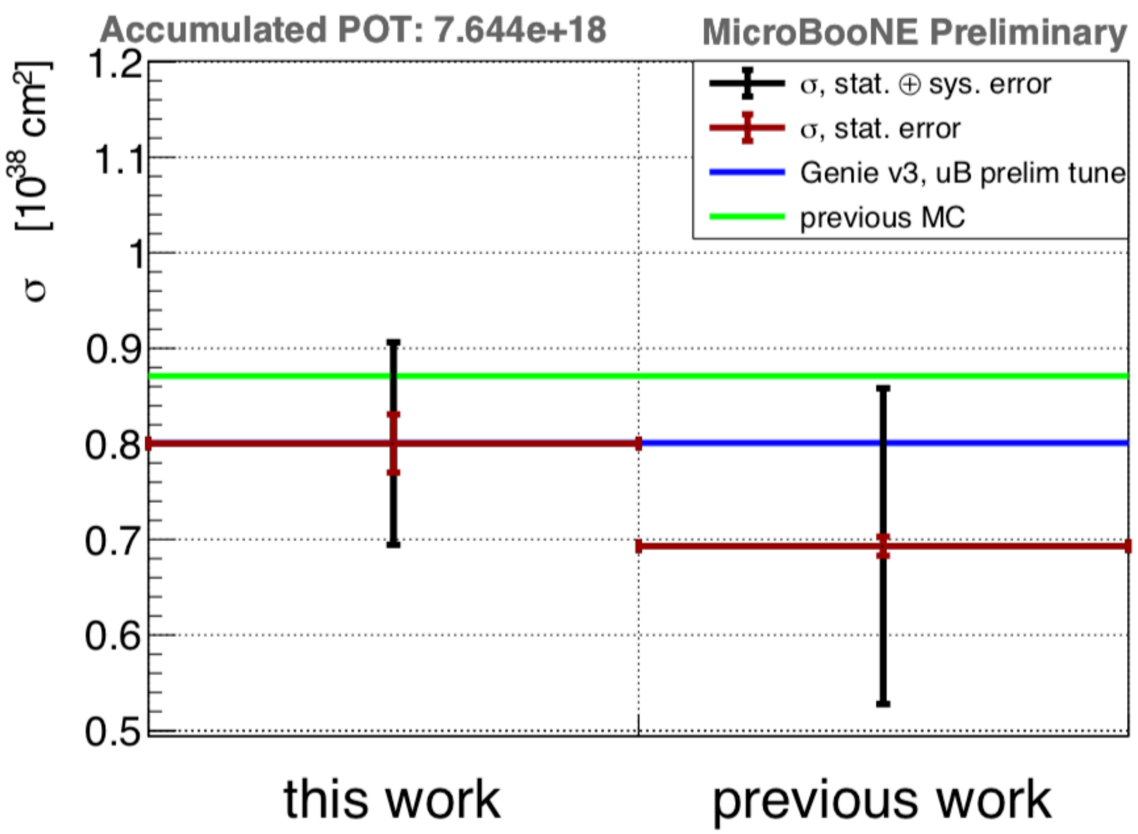
MICROBOONE-NOTE-1075-PUB MICROBOONE-NOTE-1069-PUB



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Largest reduction in uncertainties comes from improved detector understanding

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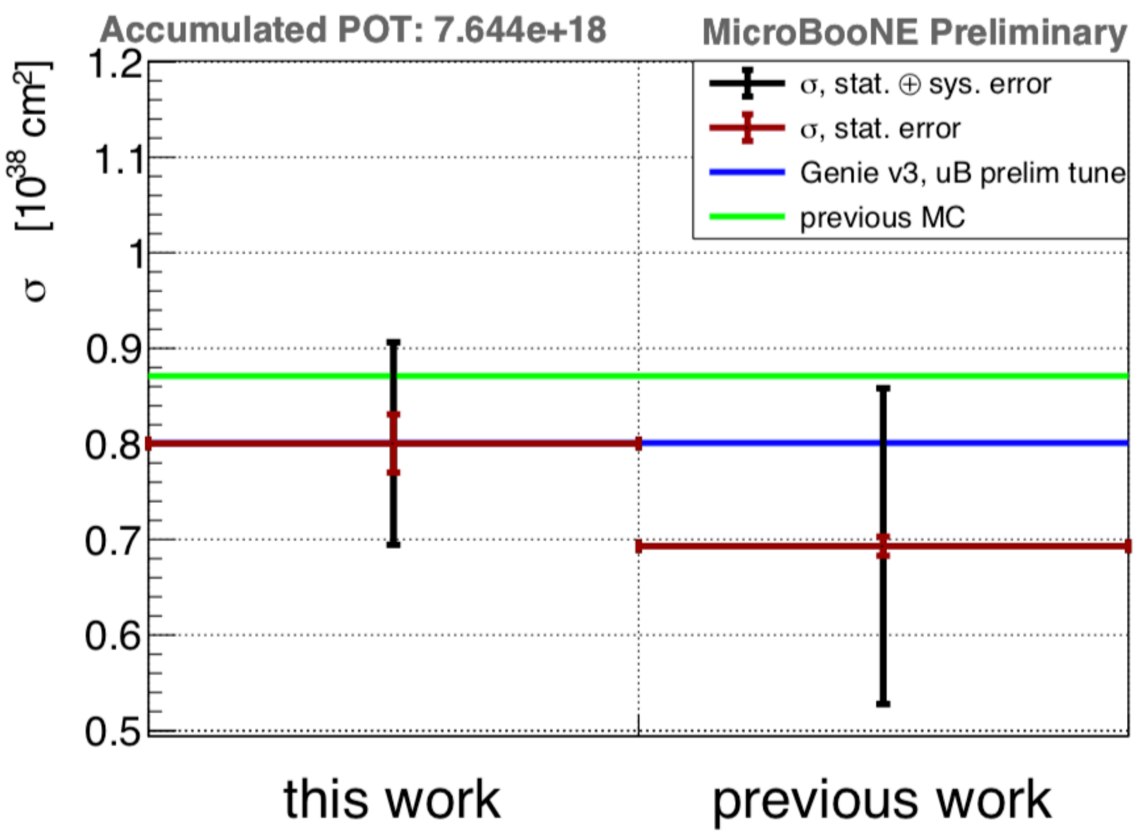

Flux-integrated cross section **consistent with previous measurement**

Drastically reduced systematic uncertainties

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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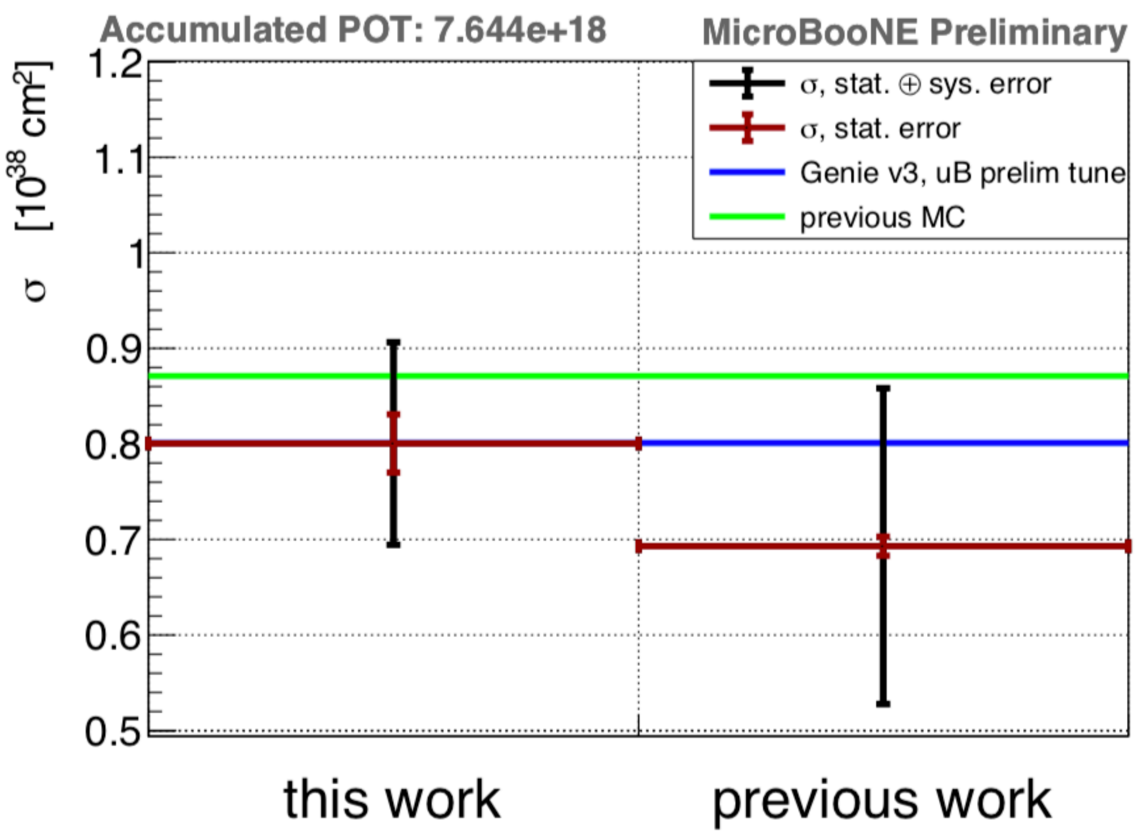
PRL 123, 131801 (2019)

µBooNE

DRASTICALLY REDUCED SYSTEMATIC UNCERTAINTIES

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



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

Drastically reduced systematic uncertainties

Dominant uncertainty on inclusive cross-section is now from flux model

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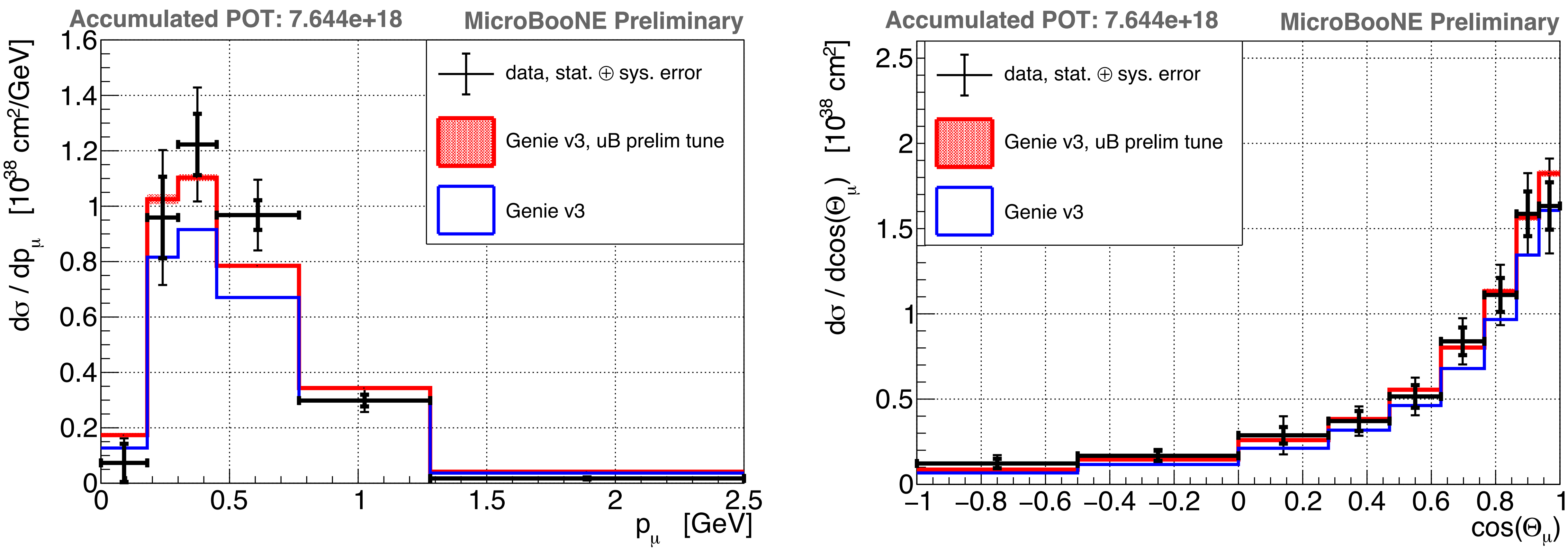
IMPROVED CROSS SECTION MEASUREMENT

MICROBOONE-NOTE-1074-PUB MICROBOONE-NOTE-1075-PUB MICROBOONE-NOTE-1069-PUB

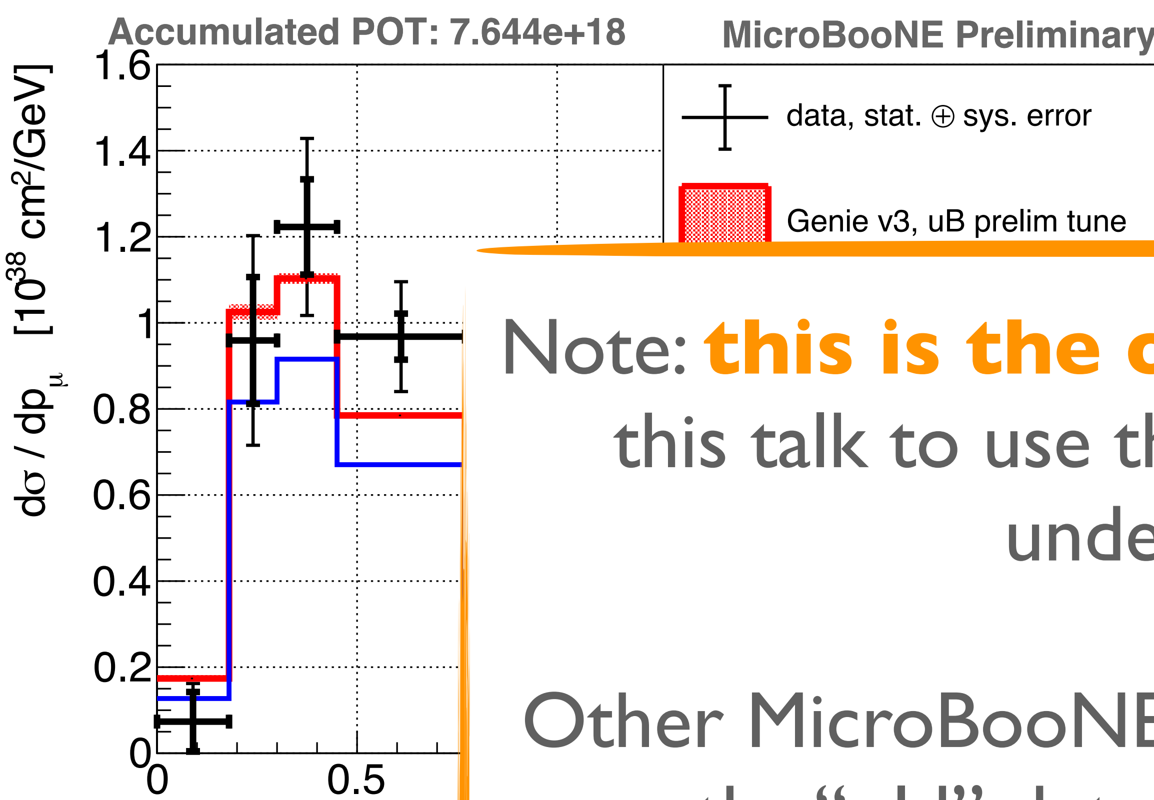


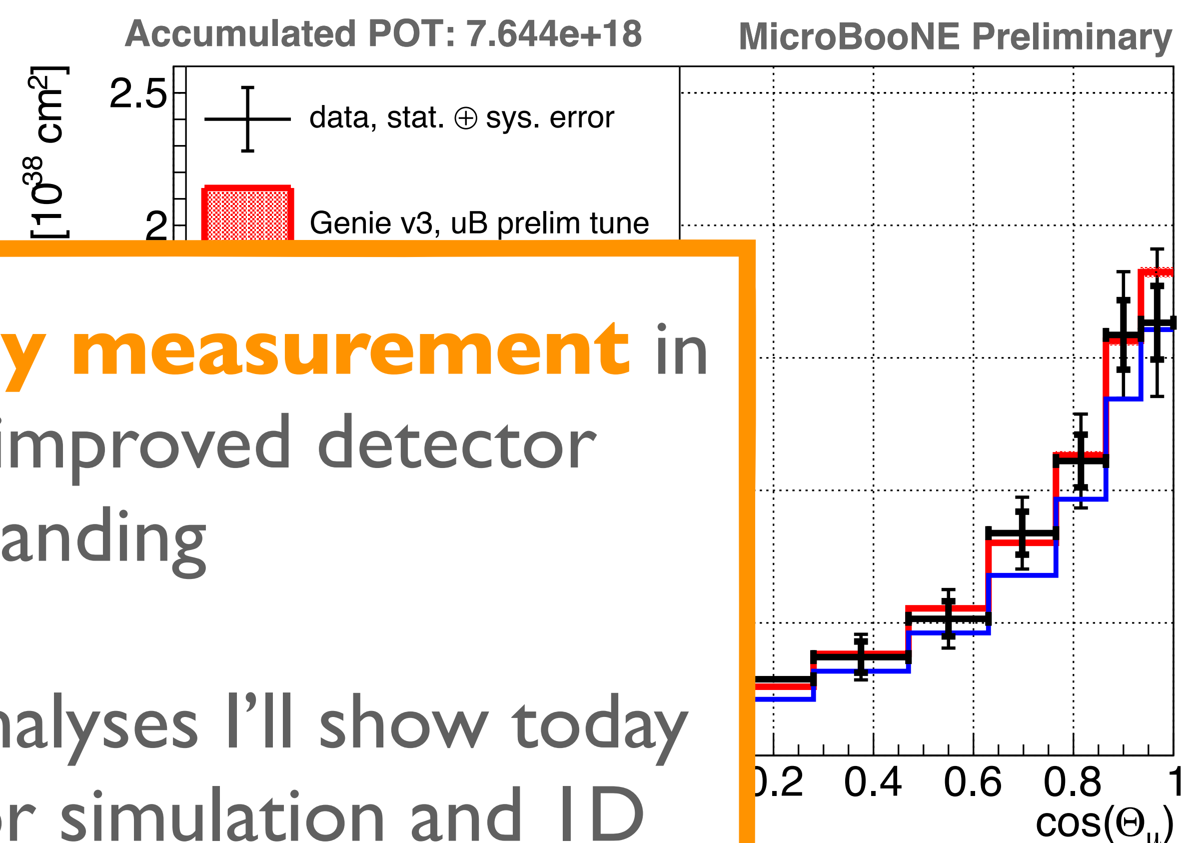
Single-differential cross section as a function of reconstructed muon momentum and angle → **very good agreement with previous measurement,** but **reduced uncertainties**

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

IMPROVED CROSS SECTION MEASUREMENT

MICROBOONE-NOTE-1074-PUB MICROBOONE-NOTE-1075-PUB MICROBOONE-NOTE-1069-PUB





Note: **this is the only measurement** in this talk to use the improved detector understanding

Other MicroBooNE analyses I'll show today use the "old" detector simulation and 1D deconvolution

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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)

MicroBooNE: ν_μ CC kaon production
MICROBOONE-NOTE-1071-PUB

MicroBooNE: ν_μ NC 1p production
MICROBOONE-NOTE-1067-PUB

- Other measurements

ArgoNeuT: ν_e and $\bar{\nu}_e$ scattering (inclusive)
Phys. Rev. D 102, 011101(R) (2020)

MicroBooNE: ν_e and $\bar{\nu}_e$ total cross section (inclusive)
arXiv:2101.04228[hep-ex]

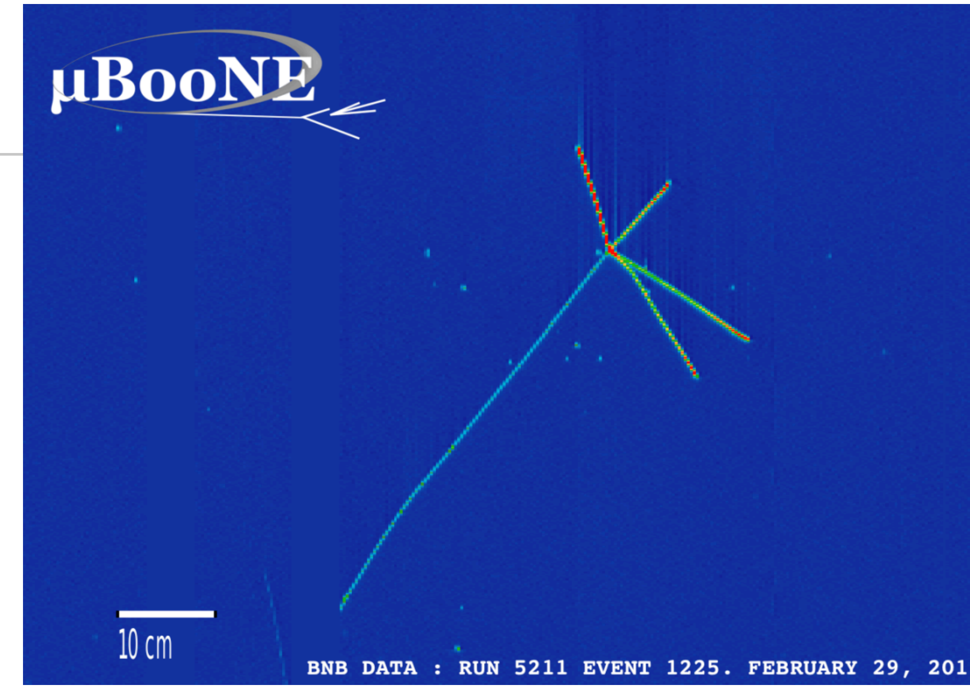
ArgoNeuT: MeV-scale physics Phys. Rev. D 99, 012002 (2019)

MicroBooNE: MeV-scale physics
MICROBOONE-NOTE-1076-PUB

ArgoNeuT: Limits on millicharged particles
Phys. Rev. Lett. 124, 131801 (2020)

LArTPC STRENGTH: LOW PROTON THRESHOLDS

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

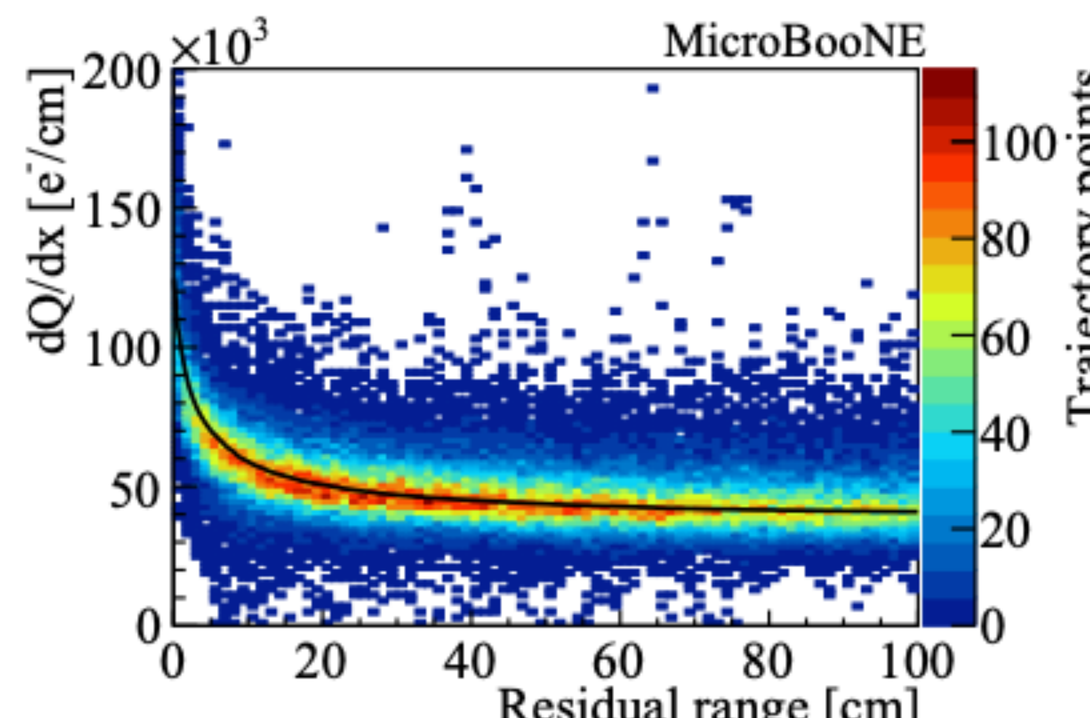


- Measuring proton kinematics gives us more information about the interaction
- **Low thresholds** → access to new information about nuclear effects, probe e.g. 2p2h scattering

Phys. Rev. D 98, 032003 (2018)

- MicroBooNE: **300 MeV/c**
- ArgoNeuT: **200 MeV/c**
  Phys. Rev. D 90, 012008 (2014)
- T2K: 500 MeV/c
- MINERvA: 450 MeV/c
  Phys. Rev. D 99, 012004 (2019)

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

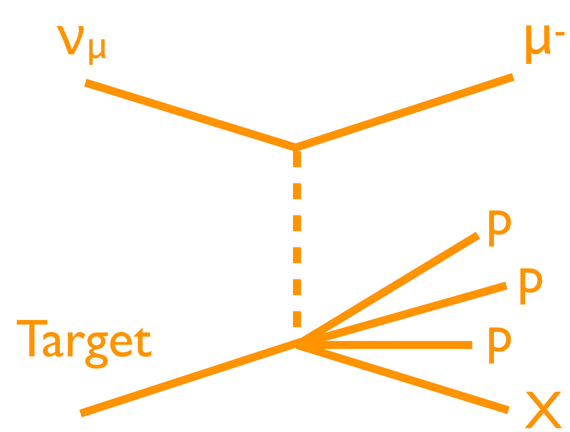


CC0πNp (N≥1) CROSS SECTION

Phys. Rev. D 102, 112013 (2020)

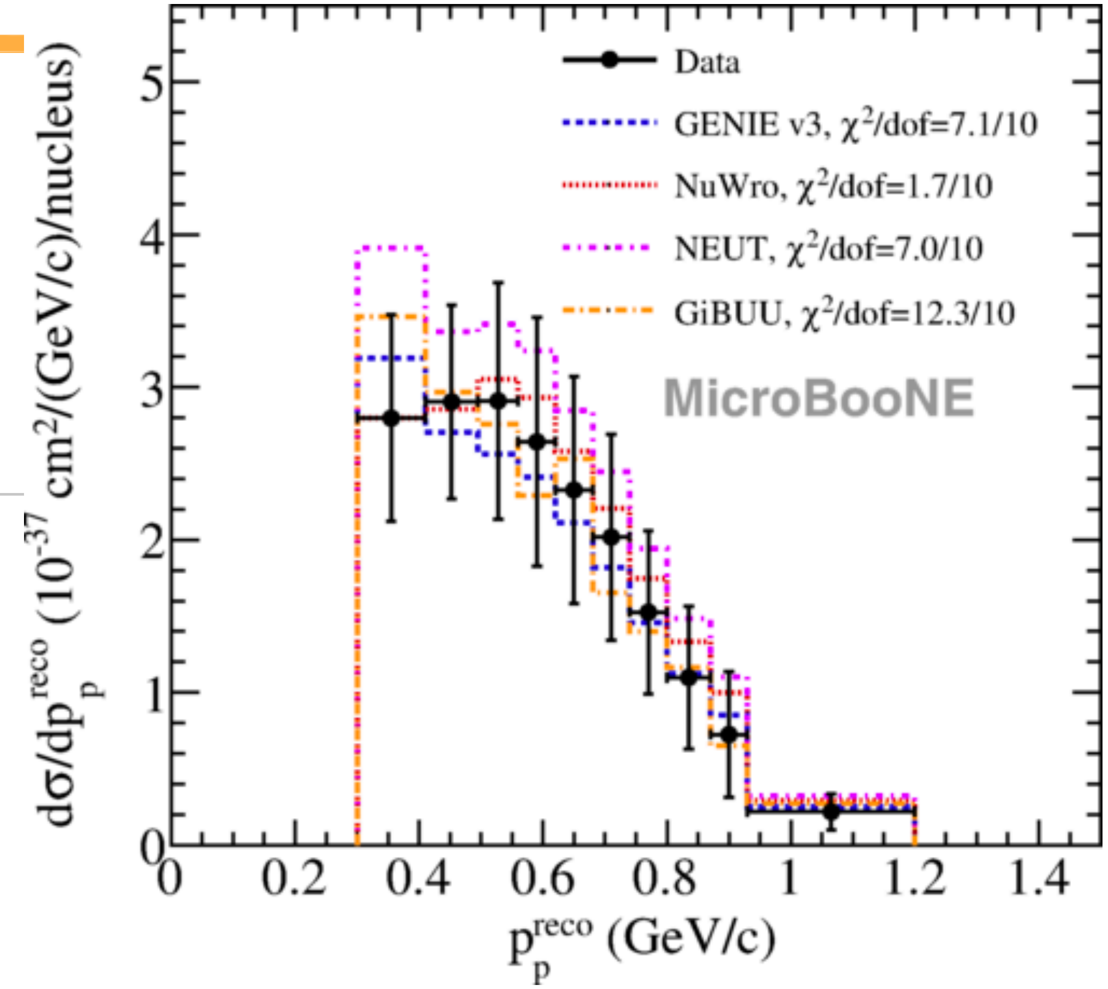
Signal:

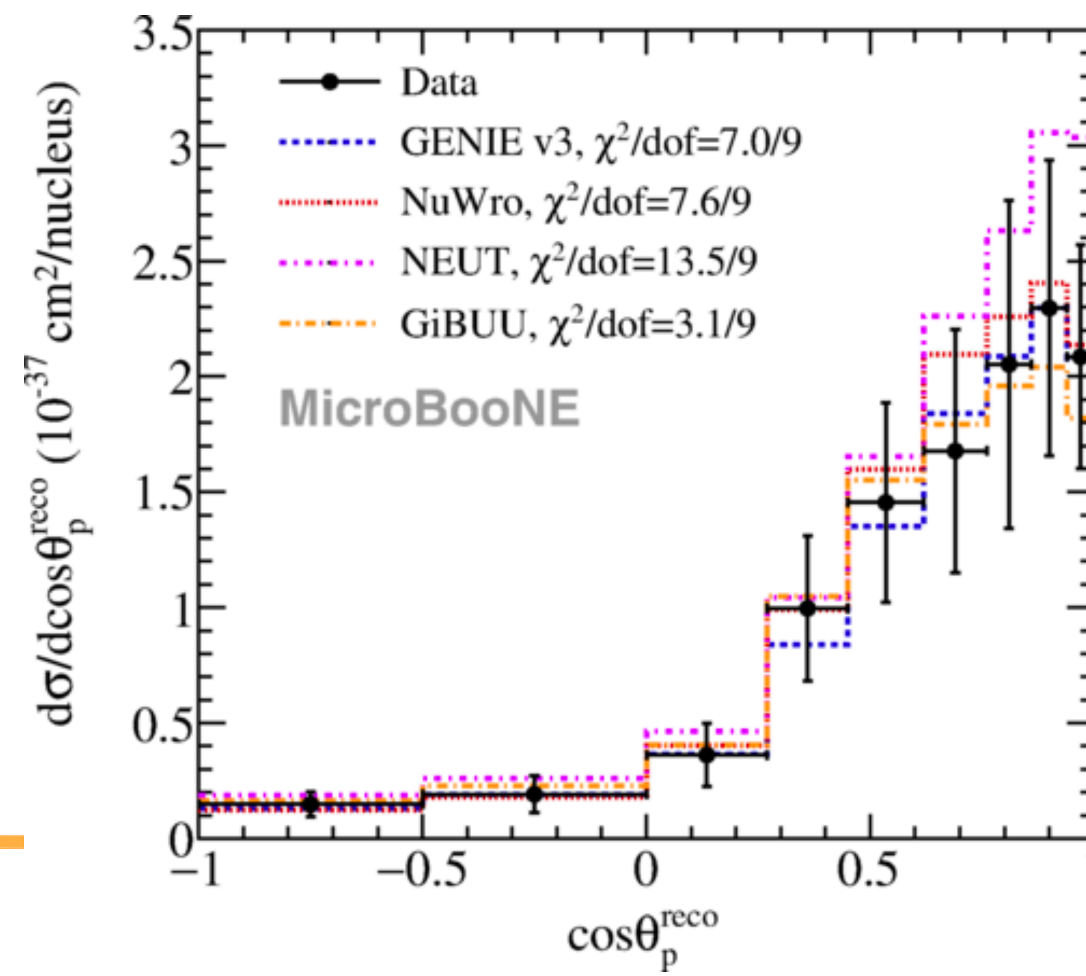
- 1 muon (p_μ>100 MeV/c)
- At least 1 proton ($300<p_p<1200$ MeV/c)
- No pions



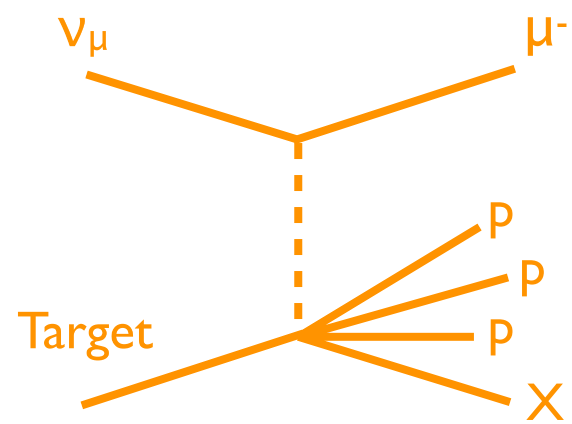
→ **71% purity, 29% efficiency**

- Proton momentum and angle show **reasonable agreement** with generators
- Lowest bin in proton momentum has not been seen before — **Low thresholds = new information** about proton kinematics

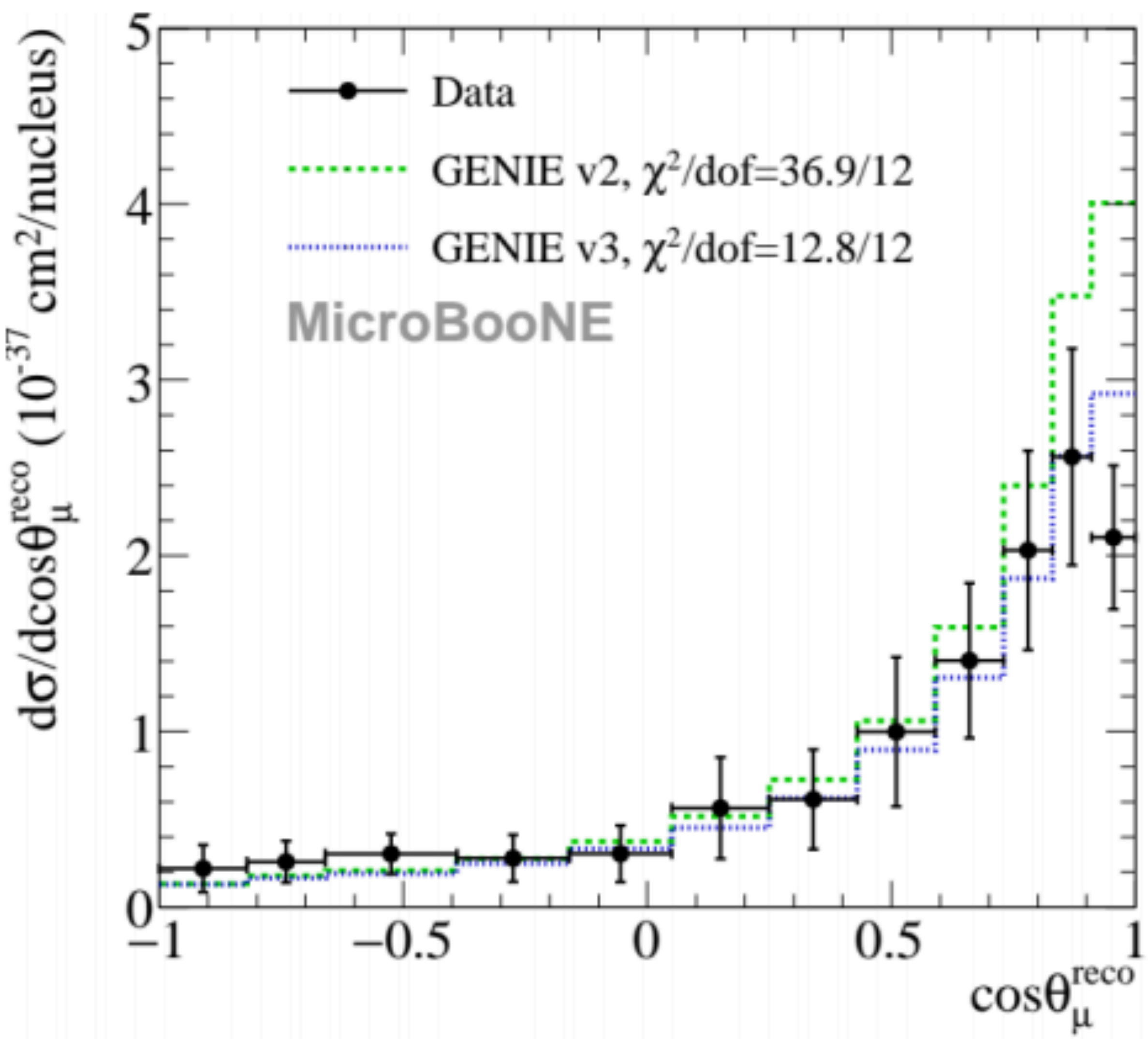


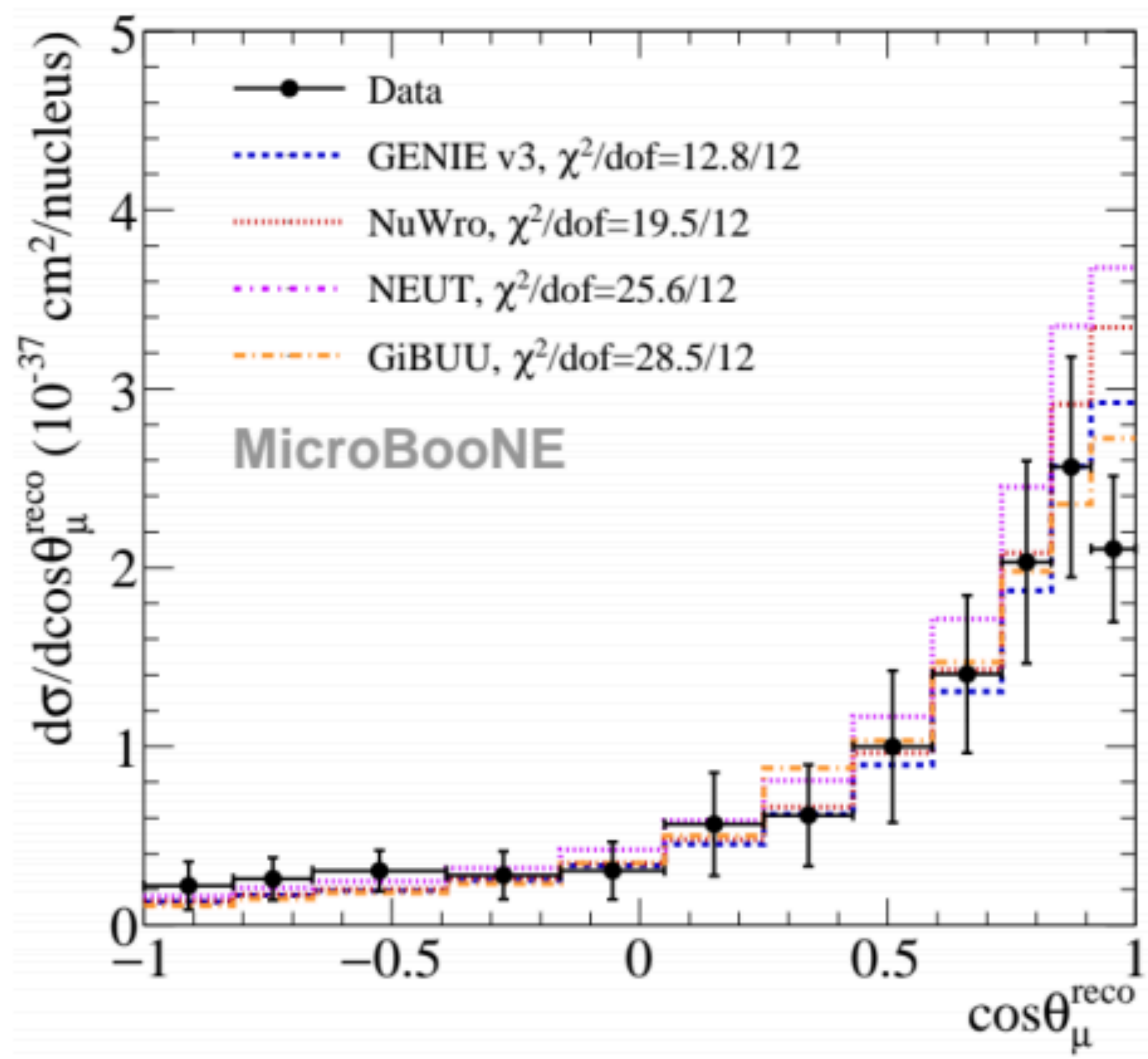


CC0πNp (N≥1) CROSS SECTION



Phys. Rev. D 102, 112013 (2020) also includes measurement as a function of muon momentum, muon-proton opening angle

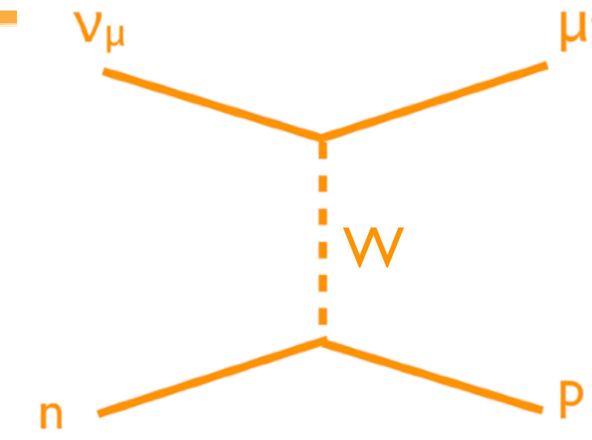




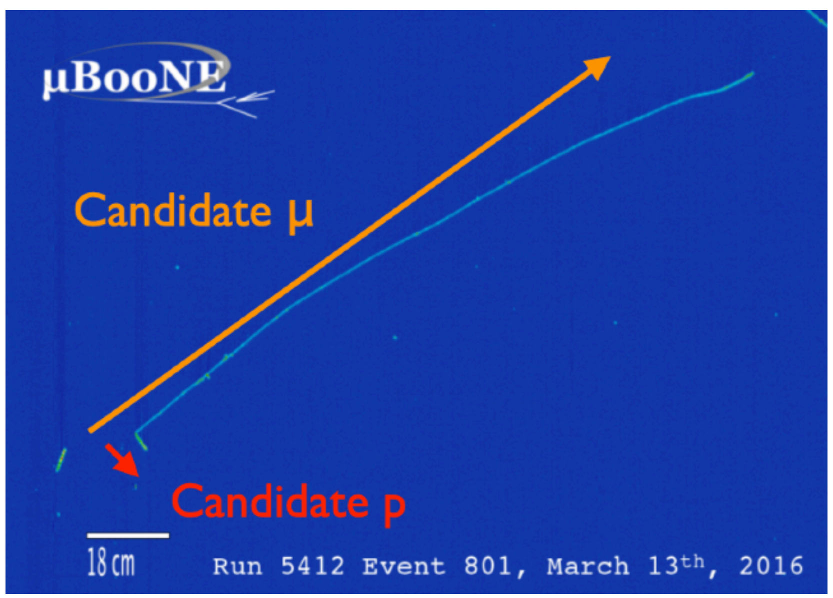
- Big over-prediction at forward-going angles
- Models with RPA do much better, but not quite enough

CCQE-LIKE CROSS SECTION

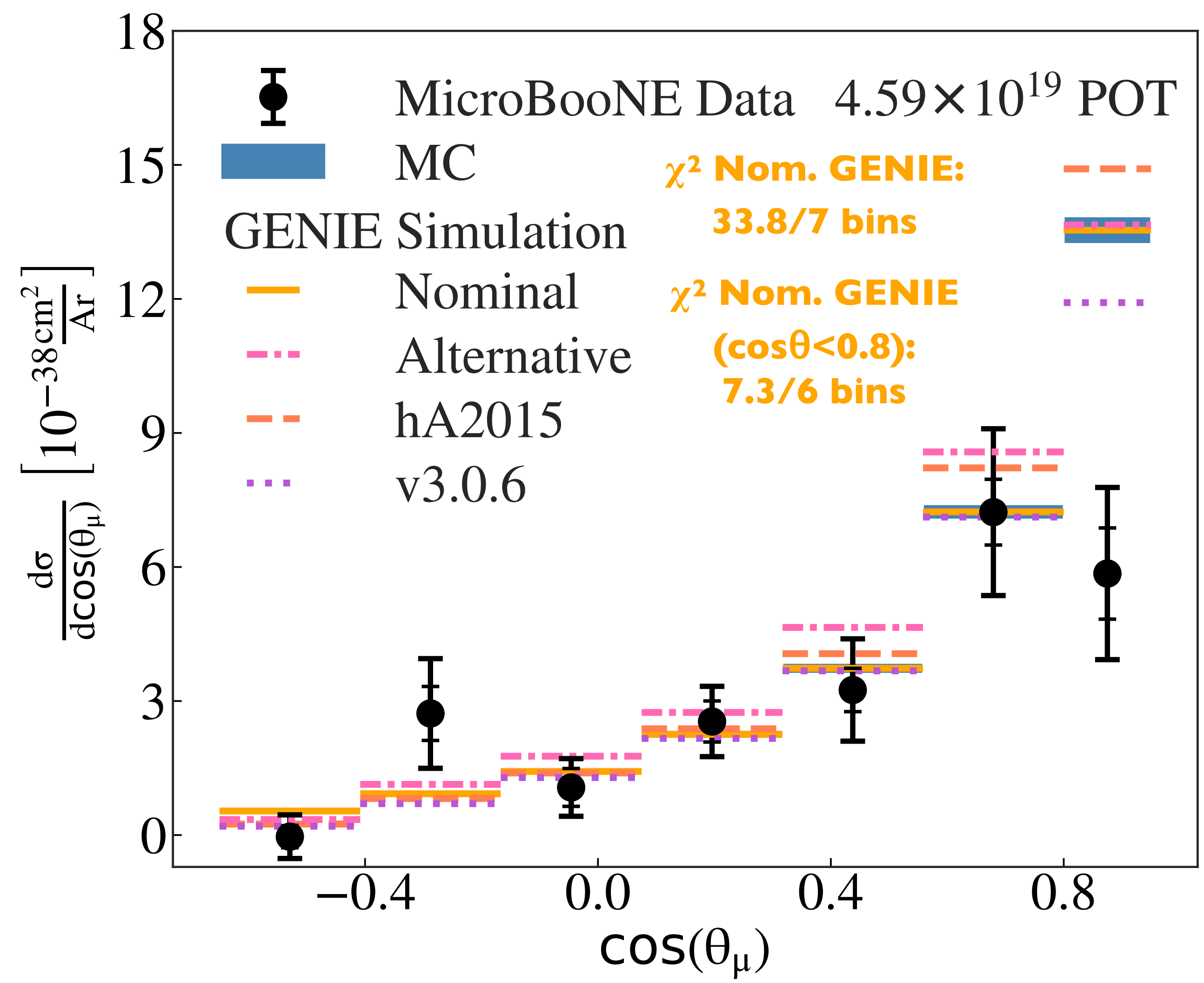
Eur. Phys. J. C 79 673 (2019)   Phys. Rev. Lett. 125, 201803 (2020)



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



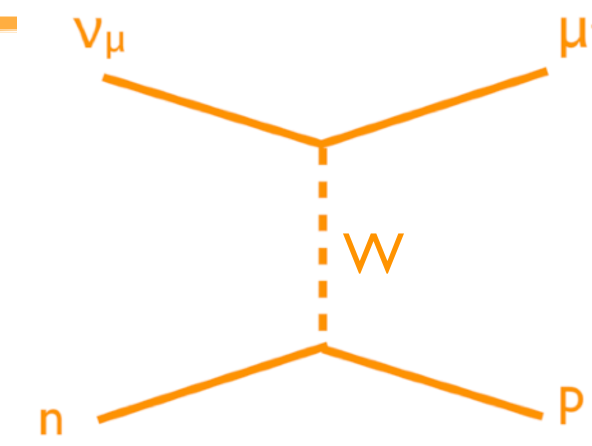
→ ~84% CC1p0π (~81% CCQE) purity, ~20% efficiency

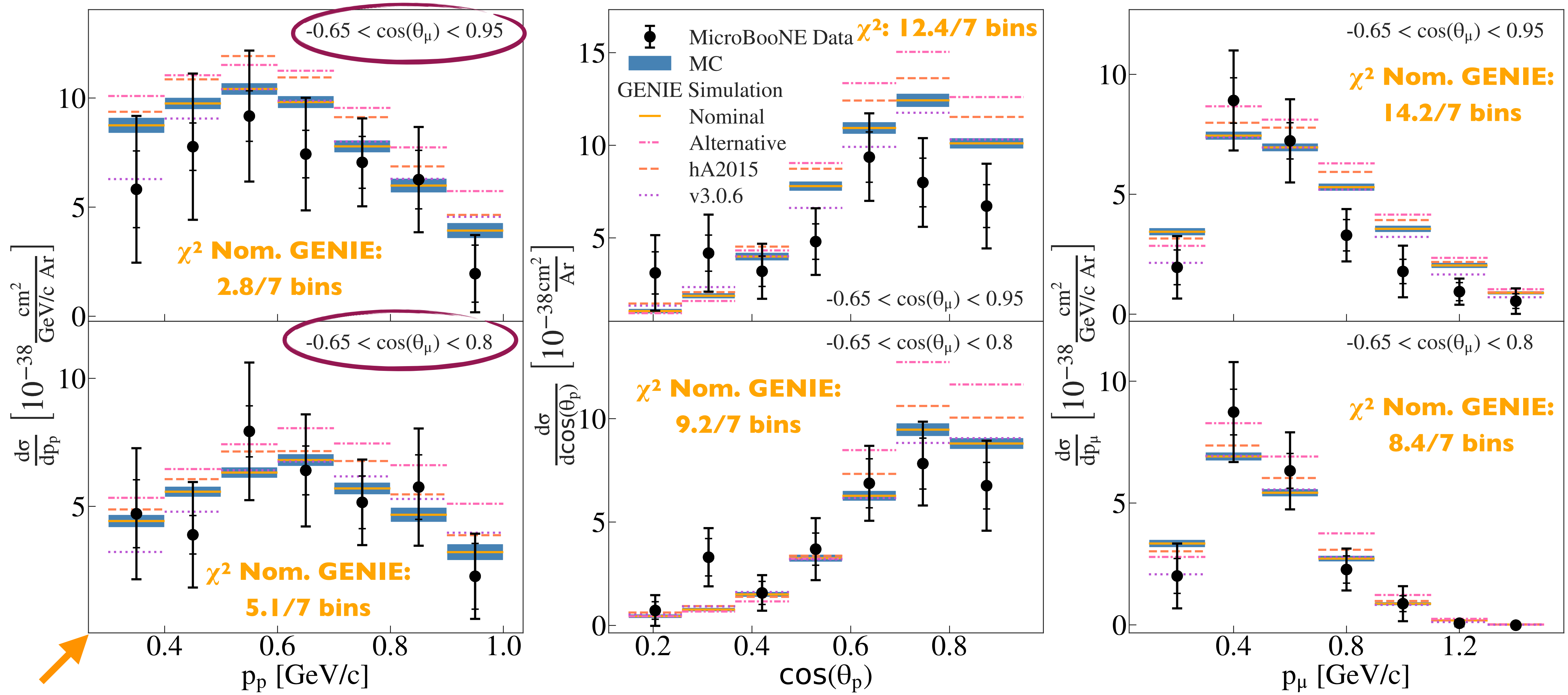


Good agreement with models, except at very **forward muon scattering** angles

CCQE-LIKE CROSS SECTION

Eur. Phys. J. C 79 673 (2019)   Phys. Rev. Lett. 125, 201803 (2020)





Proton momentum threshold 300 MeV/c

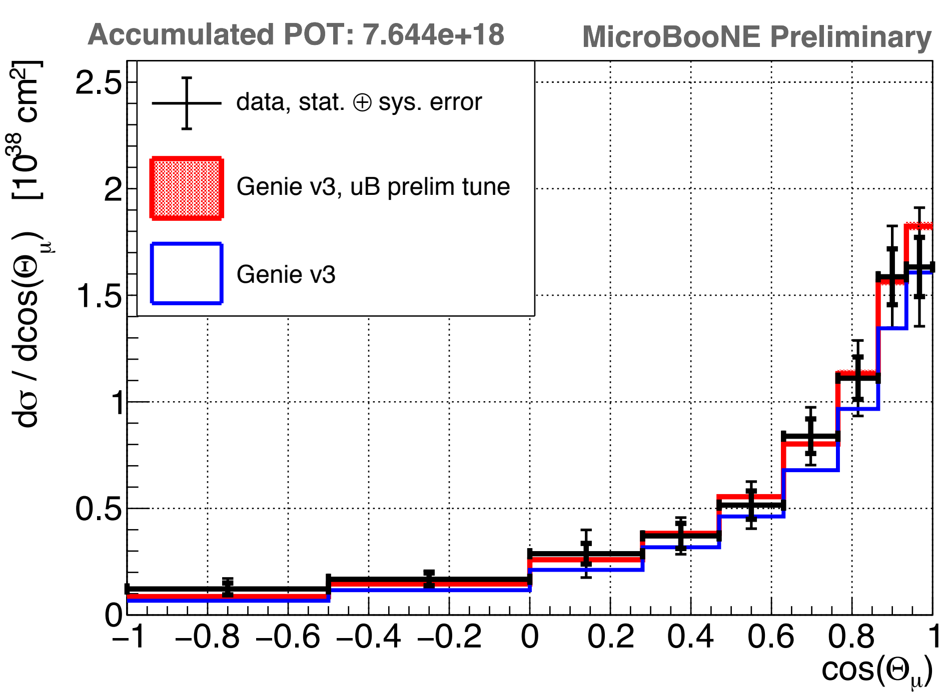
Across all kinematic variables, agreement is improved if forward muon angles are excluded

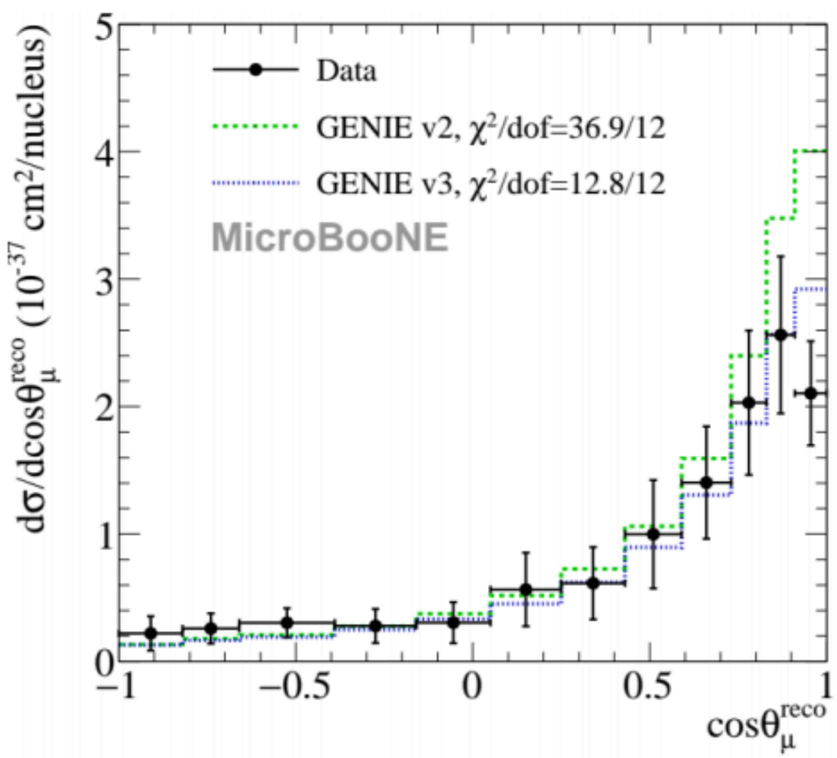
THAT FORWARD-ANGLE BIN: A CONSISTENT STORY

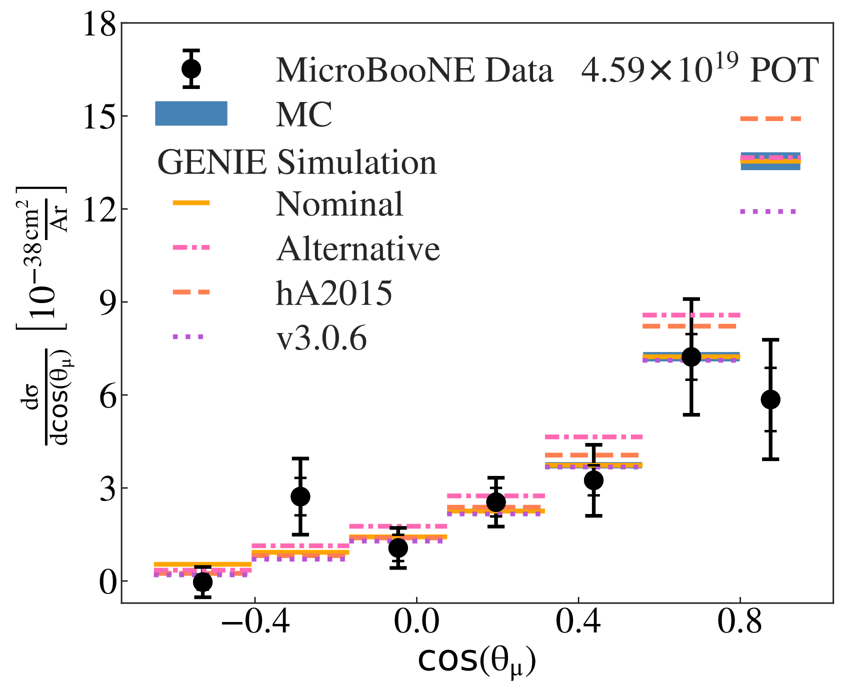
Phys. Rev. Lett. 123, 131801 (2019)   Phys. Rev. D 102, 112013 (2020)   Eur. Phys. J. C 79 673 (2019)   Phys. Rev. Lett. 125, 201803 (2020)

All three compare to the same GENIE models → cross-comparison

GENIE v3	GENIE v2 GENIE v3	GENIE v2 GENIE v3

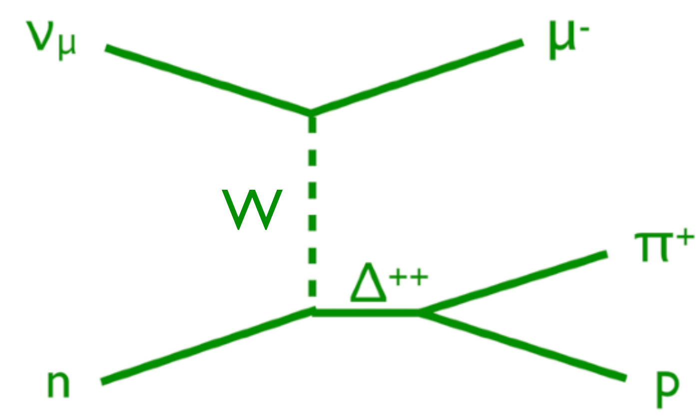






CC Inclusive	**CC0πNp**	**CCQE-like**
Inclusive	More exclusive	Even more exclusive
Some deficit	Turnover in data	Even more deficit

CC $\pi^{\pm}$ PRODUCTION

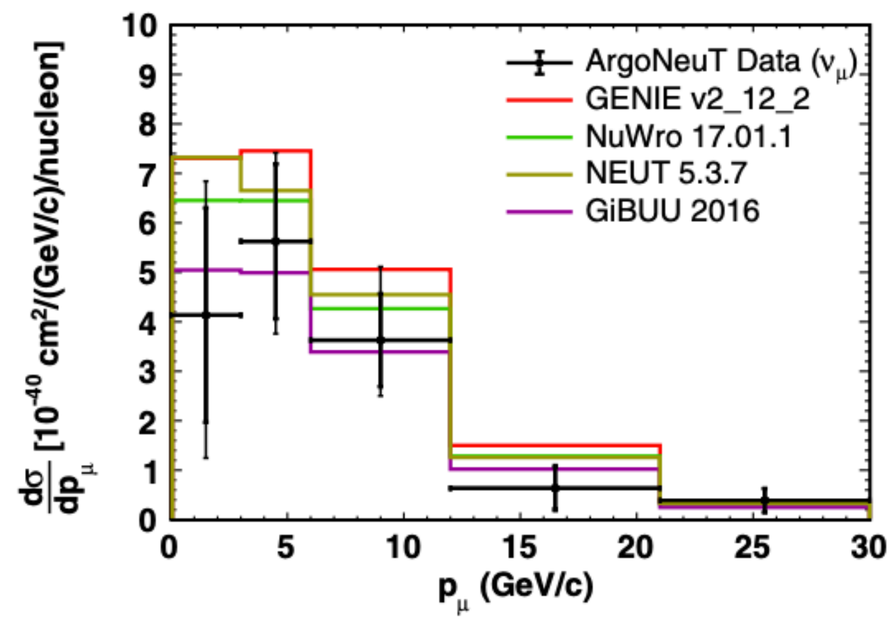


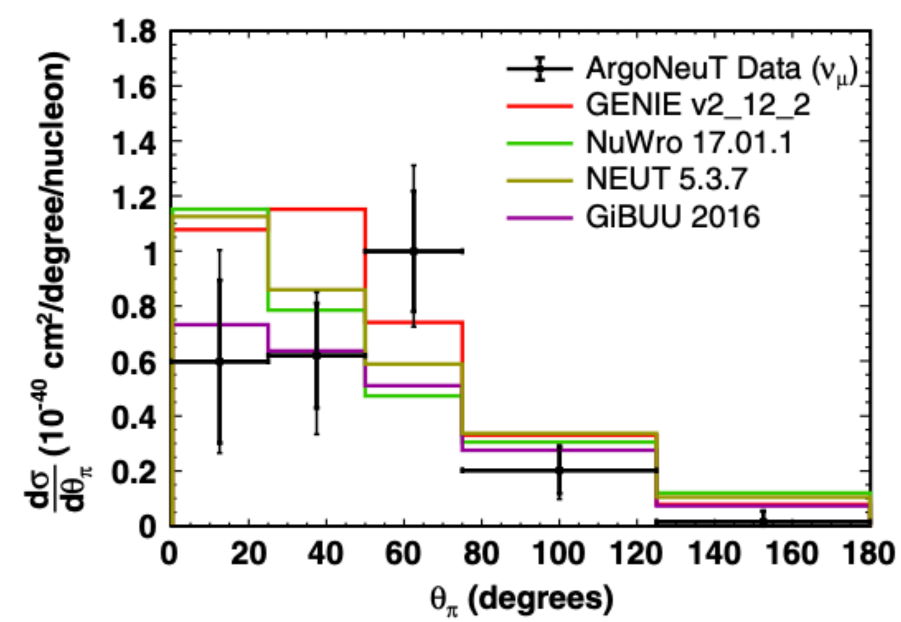
Phys. Rev. D 98, 052002 (2018)

- **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**

LArIAT, ProtoDUNEs

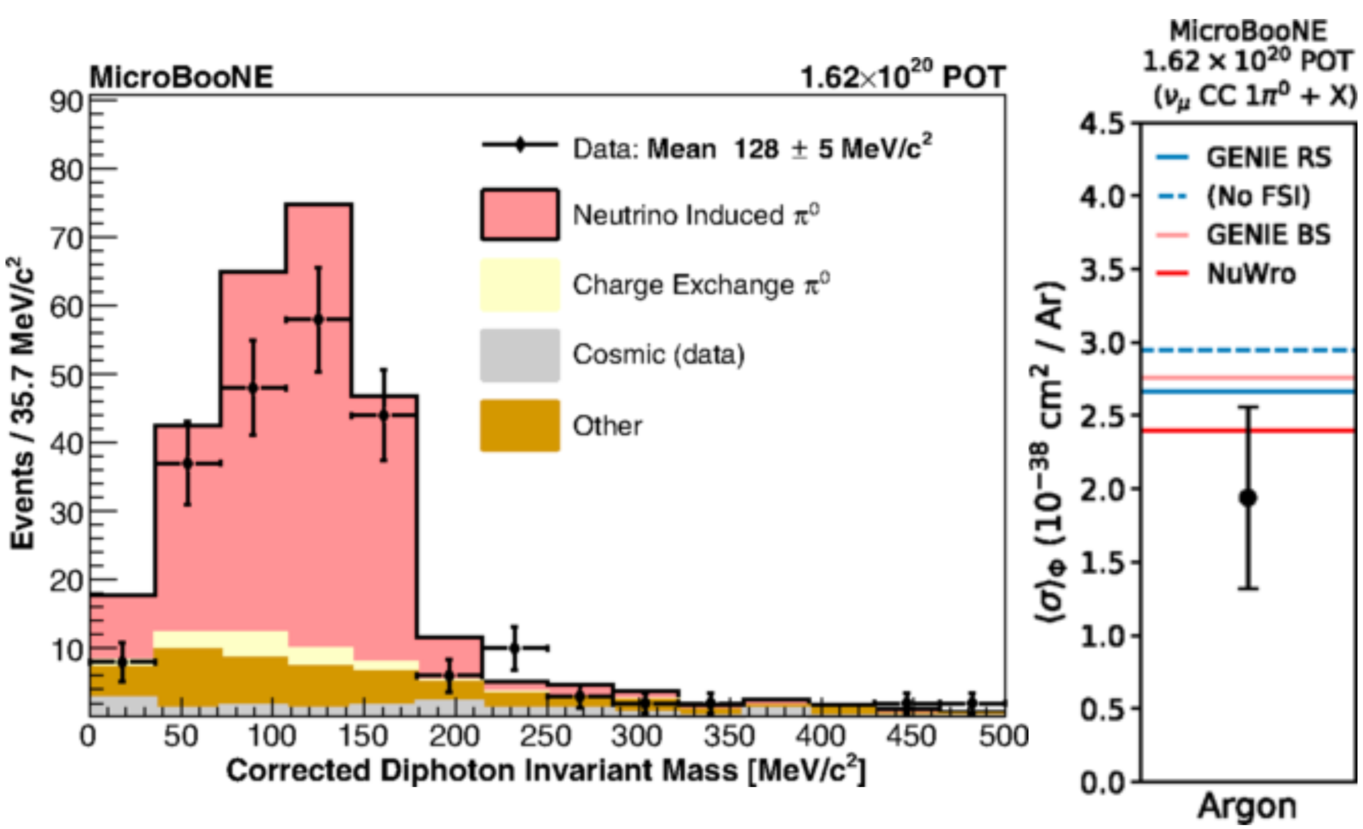
ArgoNeuT ν_μ





LArTPC STRENGTH: ELECTRONS AND PHOTONS

- **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

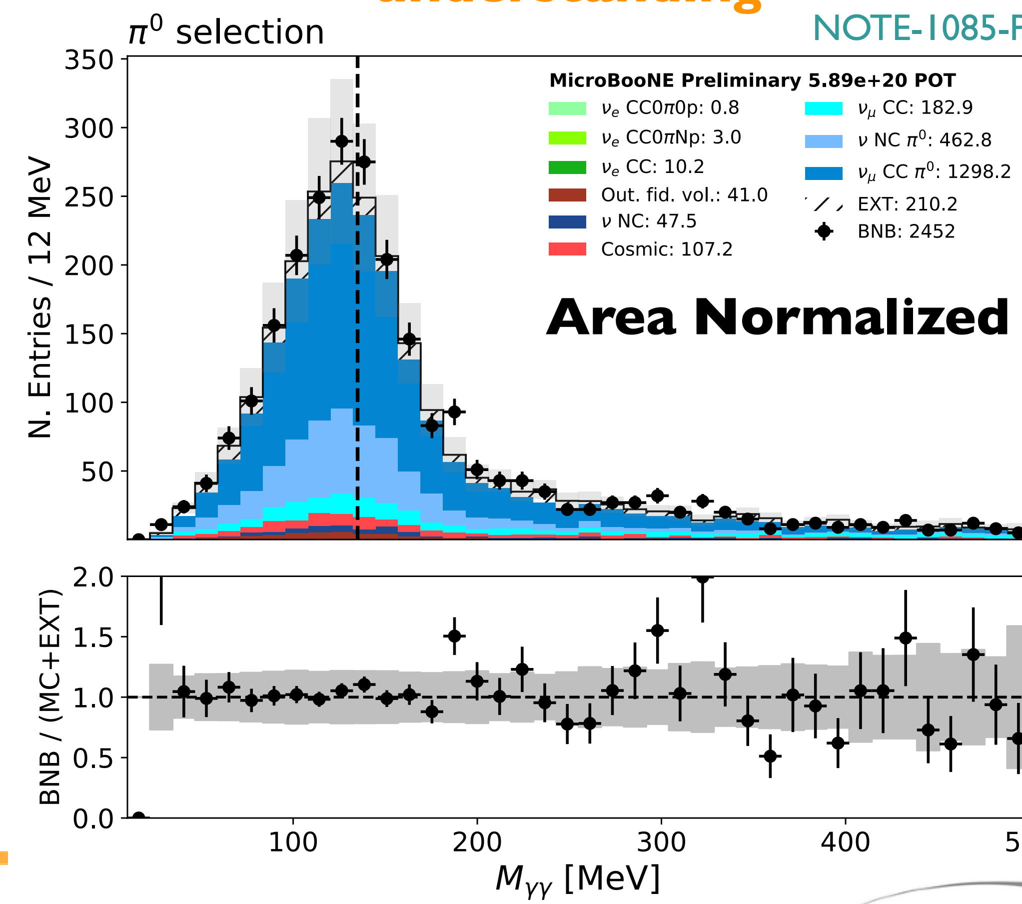


MicroBooNE CCπ^0 Measurement (2019)

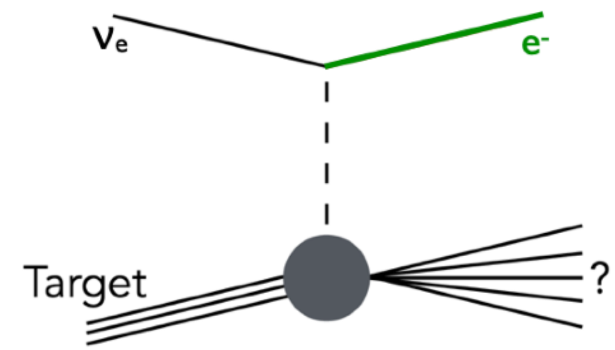
Phys. Rev. D 99, 091102(R) (2019)

Current: with improved detector understanding

MICROBOONE-NOTE-1085-PUB

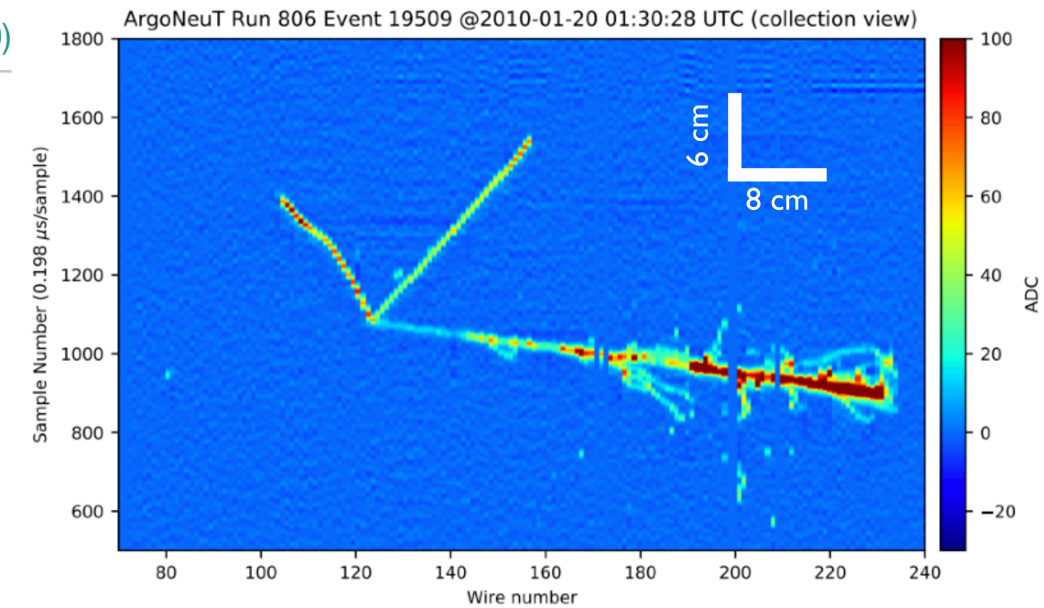


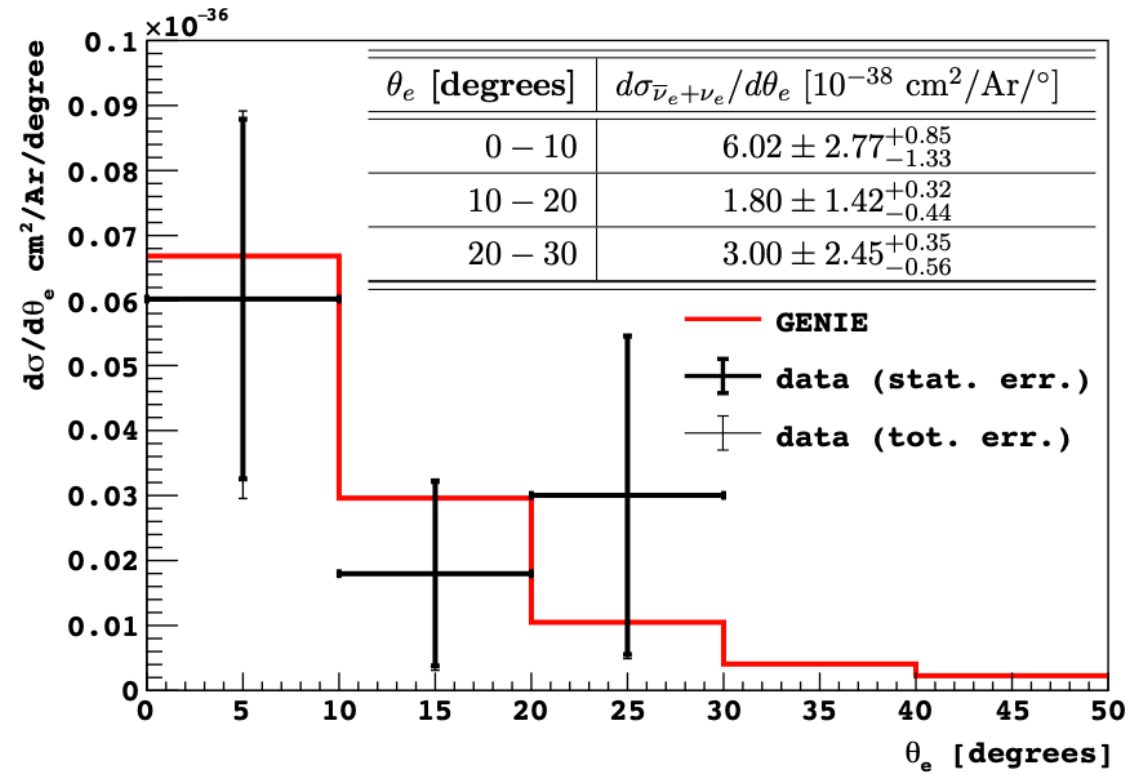
FIRST MEASUREMENT OF ELECTRON NEUTRINO CROSS SECTION



Phys. Rev. D 102, 011101(R) (2020)

- Flux-averaged **ν_e+$\bar{\nu}_e$ cross section measured by ArgoNeuT**
- **First measurement of its kind** in an energy regime highly relevant for DUNE, demonstration of fully-automated reconstruction and analysis
- Purity 78.9%, efficiency 10.5% → 13 events selected



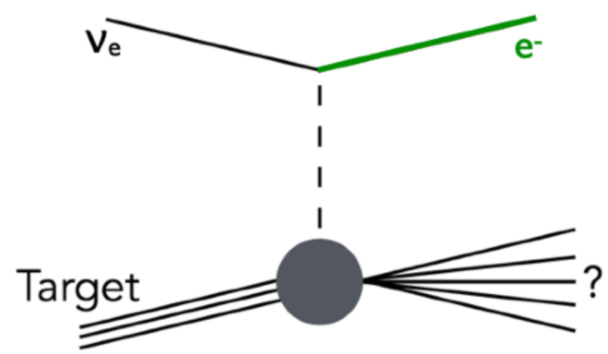


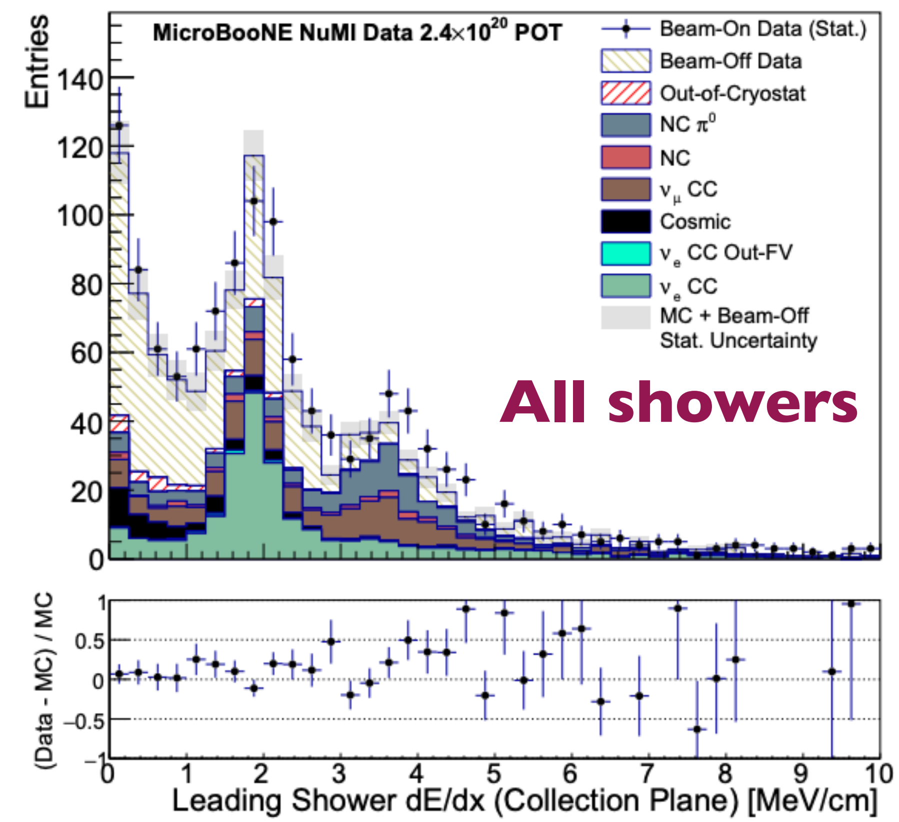
θ_e [degrees]	$d\sigma_{\bar{\nu}_e+\nu_e}/d\theta_e$ [10^{-38} cm^2/Ar/°]
0 – 10	$6.02 \pm 2.77^{+0.85}_{-1.33}$
10 – 20	$1.80 \pm 1.42^{+0.32}_{-0.44}$
20 – 30	$3.00 \pm 2.45^{+0.35}_{-0.56}$

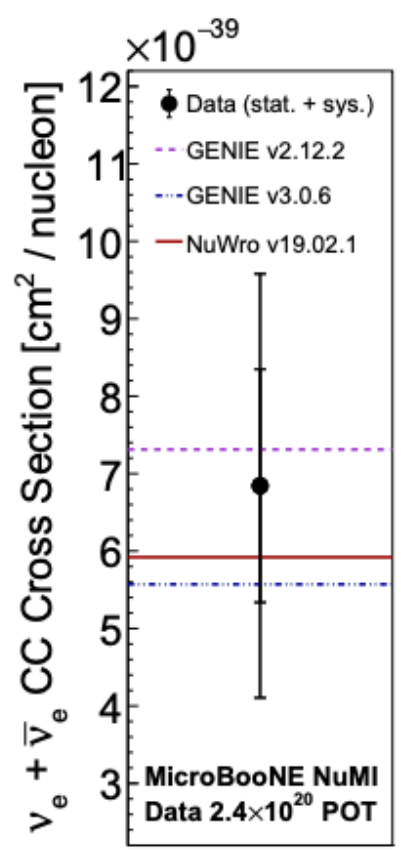
MICROBOONE: ELECTRON NEUTRINO CROSS SECTION

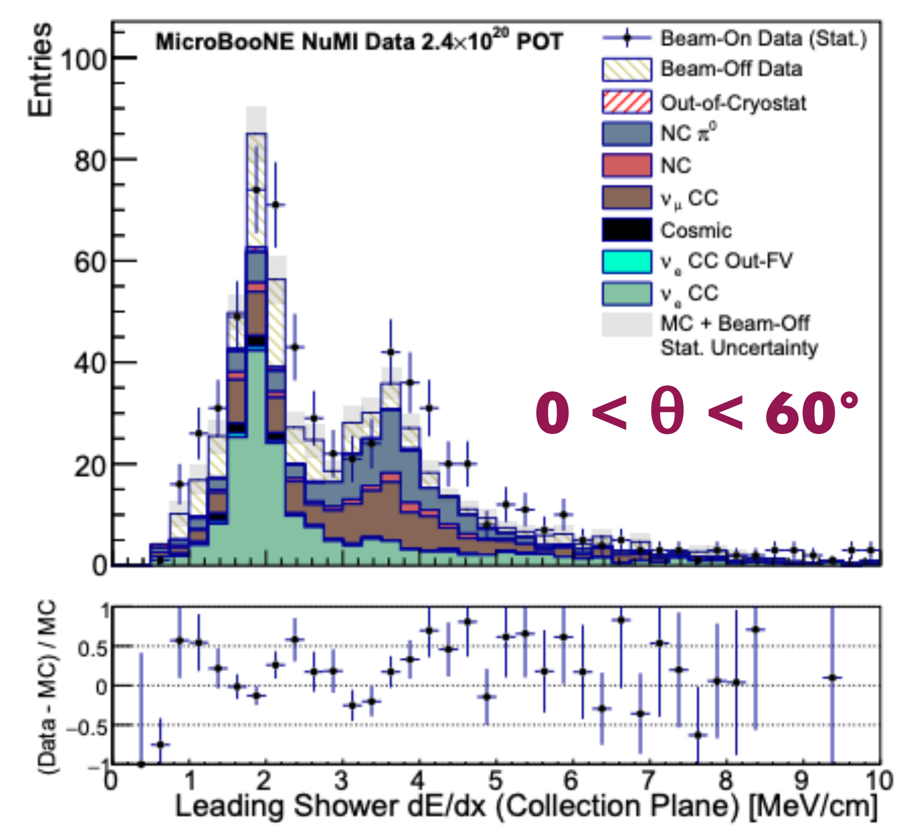
arXiv:2101.04228[hep-ex]

- MicroBooNE ν_e search for low-energy excess in BNB
- $\nu_e+\overline{\nu}_e$ total cross-section measurement with NuMI beam:
  - Off-axis beam: **~5% ν_e content**
  - Purity 40%, efficiency 9%
  - Purity excluding cosmics > 65%
  - → **~100 events** in 2.4x10[20] POT
- Expect large improvements in next-generation analyses with 4π particle identification









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)

MicroBooNE: Double-differential cross section
Phys. Rev. Lett. 123, 131801 (2019)

MicroBooNE: Single-differential cross section with updated detector and interaction models
MICROBOONE-NOTE-1069-PUB

- ν_μ exclusive channels

MicroBooNE: Charged-particle multiplicity
Eur. Phys. J. C79, 248 (2019)

MicroBooNE: ν_μ CCQE-like scattering Eur. Phys. J. C 79 673 (2019)
Phys. Rev. Lett. 125, 201803 (2020)

MicroBooNE: ν_μ CC0πNp (N≥1) scattering
Phys. Rev. D 102, 112013 (2020)

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Phys. Rev. D 98, 052002 (2018)

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MICROBOONE-NOTE-1071-PUB

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MICROBOONE-NOTE-1067-PUB

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arXiv:2101.04228[hep-ex]

ArgoNeuT: MeV-scale physics Phys. Rev. D 99, 012002 (2019)

MicroBooNE: 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

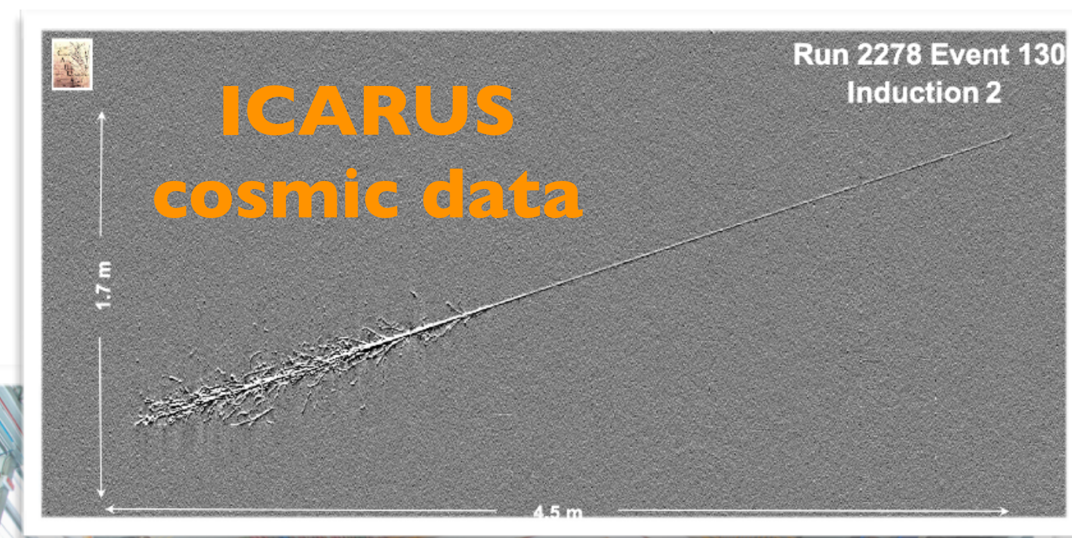
- This talk has focused on current results from **MicroBooNE** and recent results from **ArgoNeuT**

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 include: ν_μ CC inclusive hadronic energy, ν_μ CCπ^0, ν_μ NCπ^0, ν_μ CC1π^+, ν_μ CC-Coherent π^+, ν_μ CC0π2p, ν_μ CC0π STV, ν_μ KDAR CC0π, ν_μ CC0π0p, ν_μ hyperon production, ν_μ CC eta production, 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**

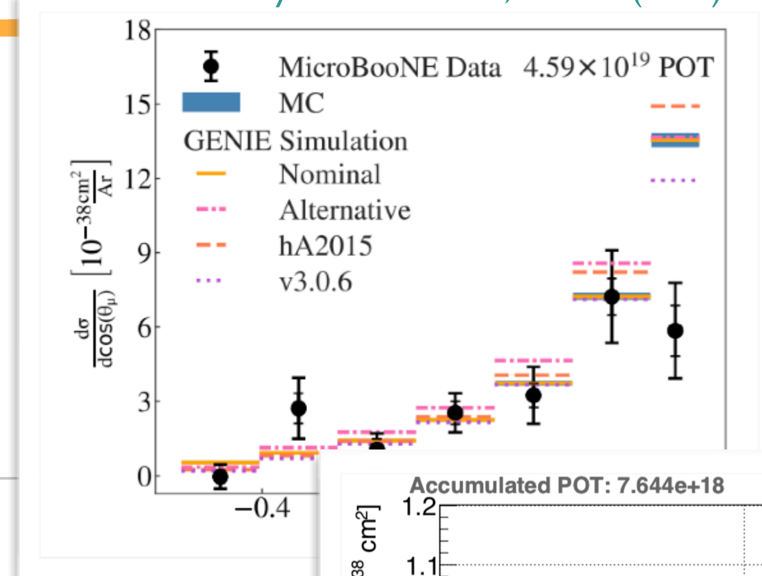
- In the future, expect more measurements from upcoming experiments: **SBND**, **ICARUS**, and eventually **DUNE-ND**

ICARUS will start taking data very soon
SBND will collect **7m ν-Ar interactions in 3 years**

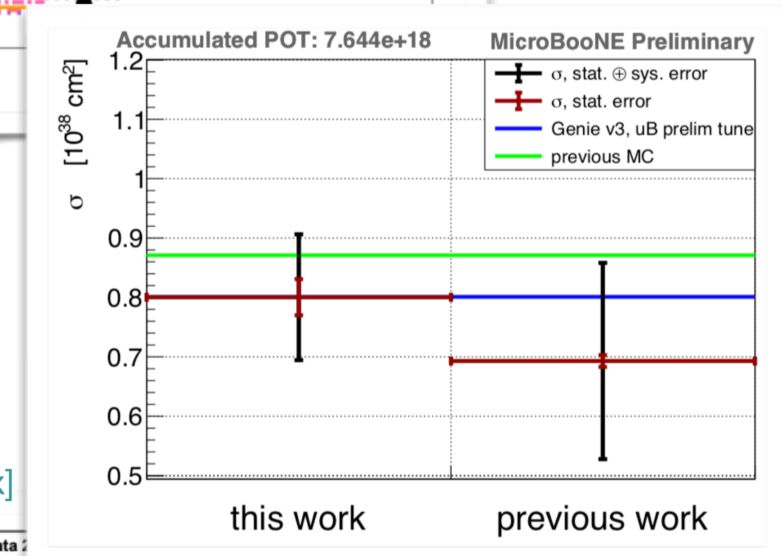
SUMMARY

- Cross-section measurements on argon are **vital** for the success of the SBN program and eventually DUNE
- 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**
- **Huge progress** over the past few years: first time we can confront **models tuned to carbon** with high-statistics argon data
- More (and more precise) measurements expected in the future → **stronger tests** of our models

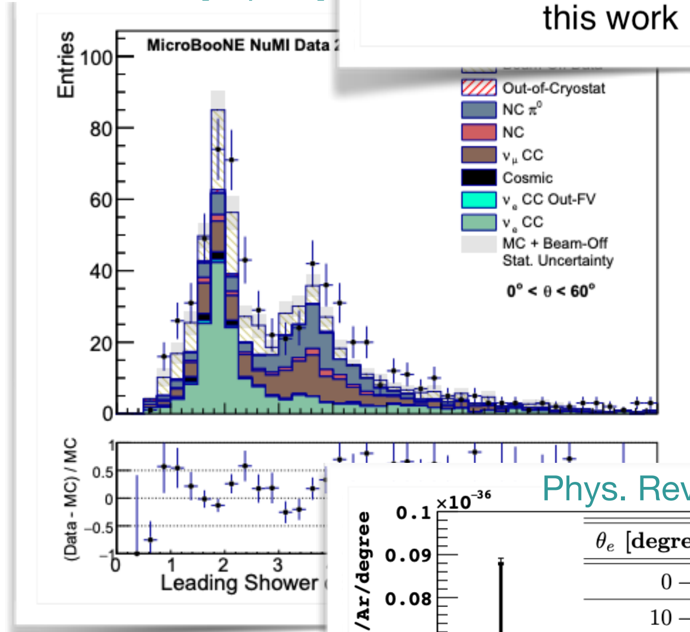
Phys. Rev. Lett. 125, 201803 (2020)



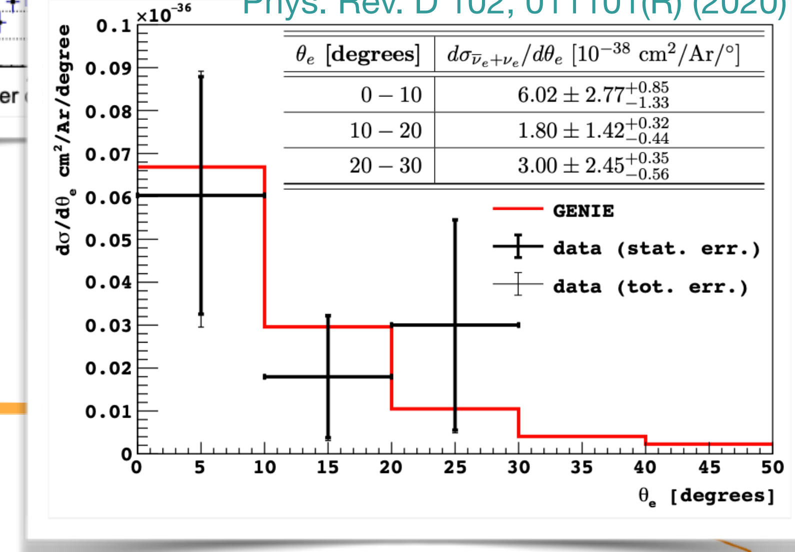
MICROBOONE-NOTE-1069-PUB



arXiv:2101.04228[hep-ex]



Phys. Rev. D 102, 011101(R) (2020)



THANK YOU

MICROBOONE PUBLICATIONS

*** cross-section specific**

- MicroBooNE collaboration, "Cosmic Ray Background Rejection with Wire-Cell LAr TPC Event Reconstruction in the MicroBooNE Detector", arXiv:2101.05076, submitted to PRD
- MicroBooNE collaboration, "Measurement of the Flux-Averaged Inclusive Charged Current Electron Neutrino and Antineutrino Cross Section on Argon using the NuMI Beam and the MicroBooNE Detector", arXiv:2101.04228, submitted to PRD
- MicroBooNE collaboration, "Measurement of the Atmospheric Muon Rate with the MicroBooNE Liquid Argon TPC", arXiv:2012.14324, submitted to JINST
- MicroBooNE collaboration, "Semantic Segmentation with a Sparse Convolutional Neural Network for Event Reconstruction in MicroBooNE", arXiv:2012.08513, submitted to PRD
- MicroBooNE collaboration, "High Performance Generic Neutrino Detection in a LAr TPC Near the Earth's Surface with the MicroBooNE Detector", arXiv:2012.07928, submitted to PRL
- MicroBooNE collaboration, "Neutrino Event Selection in the MicroBooNE Liquid Argon Time Projection Chamber using Wire-Cell 3D Imaging, Clustering, and Charge-Light Matching", arXiv:2011.01375, submitted to JINST
- MicroBooNE collaboration,"A Convolutional Neural Network for Multiple Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber", arXiv:2010.08653, submitted to PRD
- MicroBooNE collaboration,"Measurement of Differential Cross Sections for Muon Neutrino Charged Current Interactions on Argon with Protons and No Pions in the Final State with the MicroBooNE Detector", arXiv:2010.02390, Phys. Rev. D102, 112013 (2020)
- MicroBooNE collaboration, "Measurement of Space Charge Effects in the MicroBooNE LAr TPC Using Cosmic Muons", arXiv:2008.09765, JINST 15, P12037 (2020)
- MicroBooNE collaboration, "The Continuous Readout Stream of the MicroBooNE Liquid Argon Time Projection Chamber for Detection of Supernova Burst Neutrinos", arXiv:2008.13761, submitted to JINST
- MicroBooNE collaboration, "First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with the MicroBooNE Detector", arXiv:2006.00108, Phys. Rev. Lett. 125, 201803 (2020), Fermilab News article (12/16/2020)
- 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 $\pi^0 \to \gamma\gamma$ 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**

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- 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 $\pi^0 \to \gamma\gamma$ 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)
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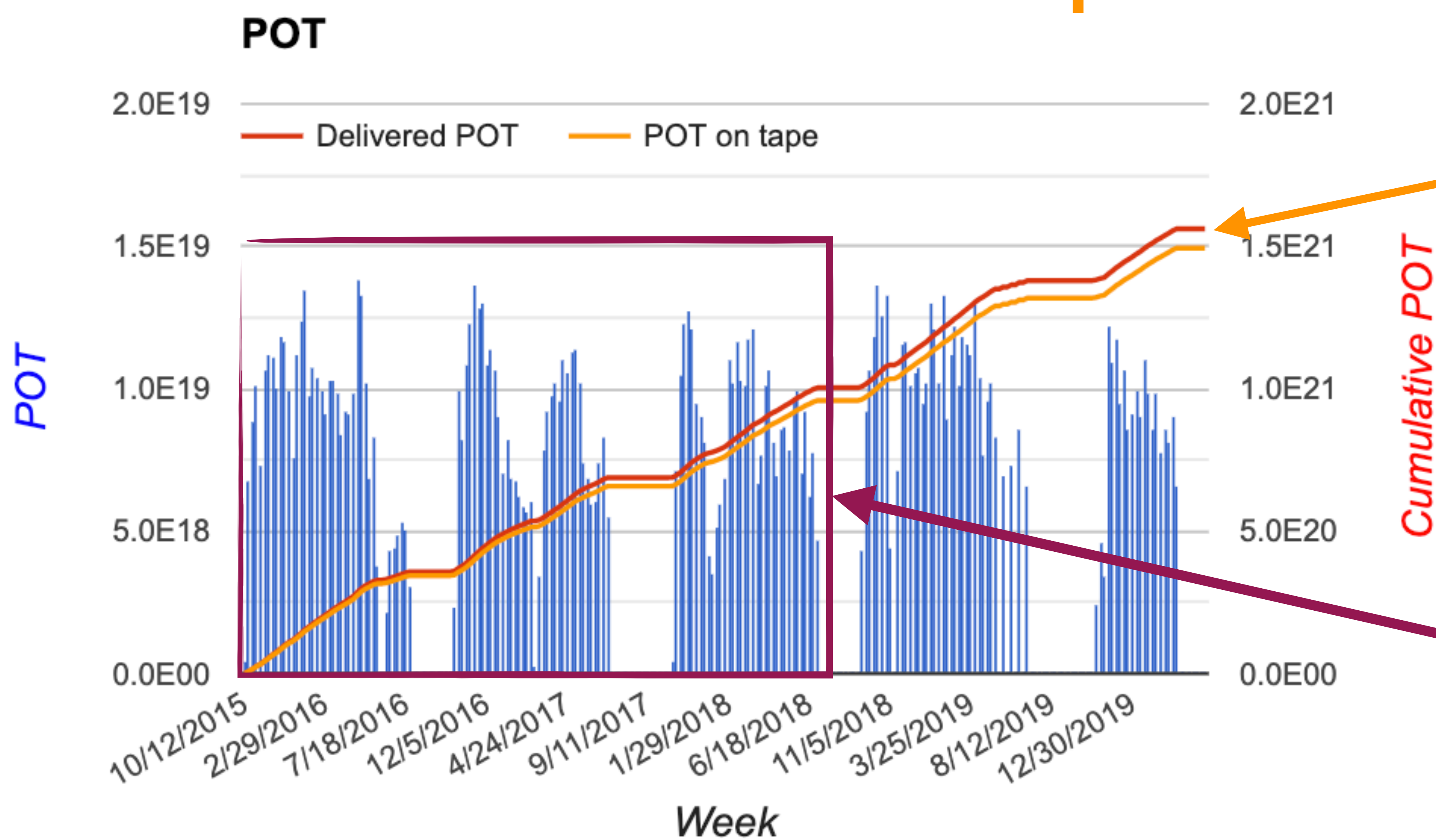
- ArgoNeuT collaboration, “A Study of Electron Recombination Using Highly Ionizing Particles in the ArgoNeuT Liquid Argon TPC”, arXiv:1306.1712[physics.ins-det], JINST 8 P08005 (2013)
- ArgoNeuT collaboration, “Analysis of a Large Sample of Neutrino-Induced Muons with the ArgoNeuT Detector”, arXiv:1205.6702[physics.ins-det], 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)

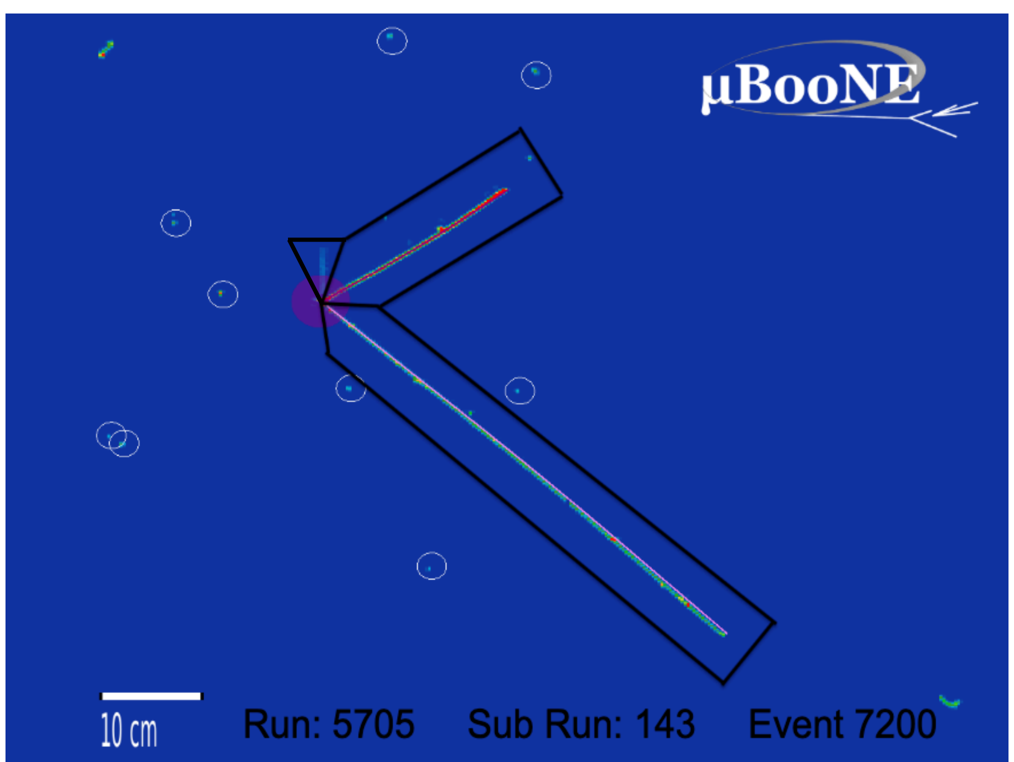
Analyses shown today use subsets of data collected between December 2015 and June 2018

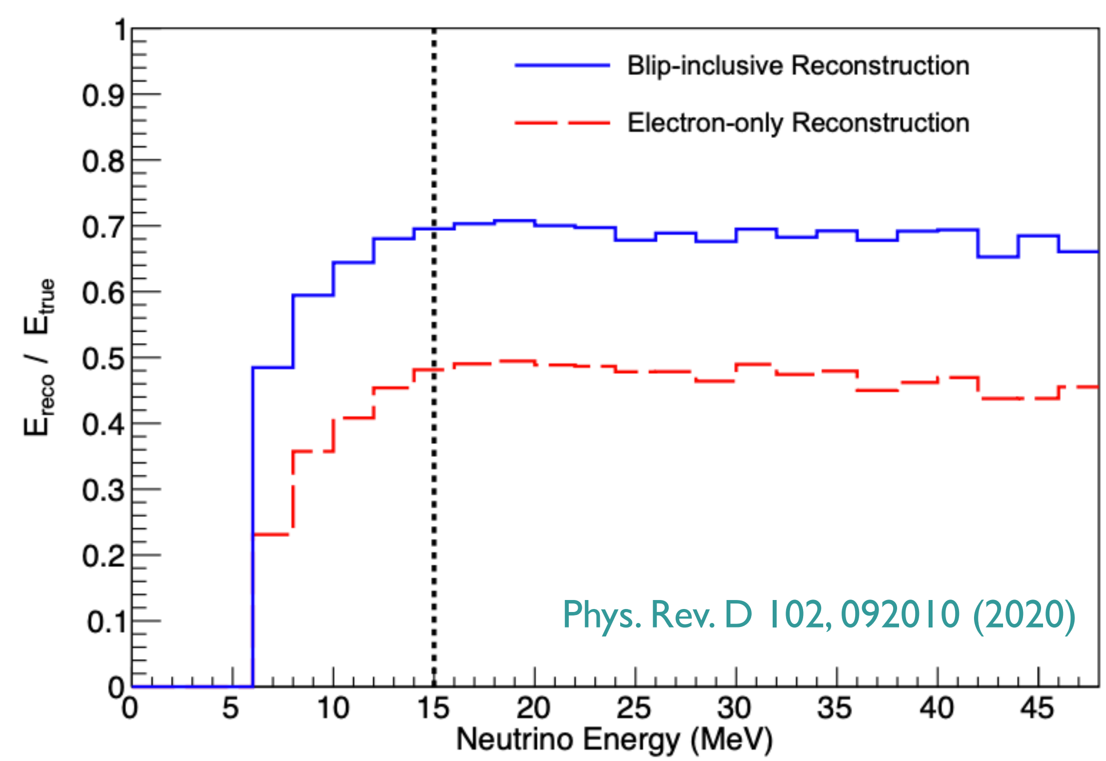
μBooNE

PUSHING THE LIMITS

Phys. Rev. D 102, 092010 (2020)
Phys. Rev. Lett. 124, 131801 (2020)
Phys. Rev. D 99, 012002 (2019)
MICROBOONE-NOTE-1076-PUB

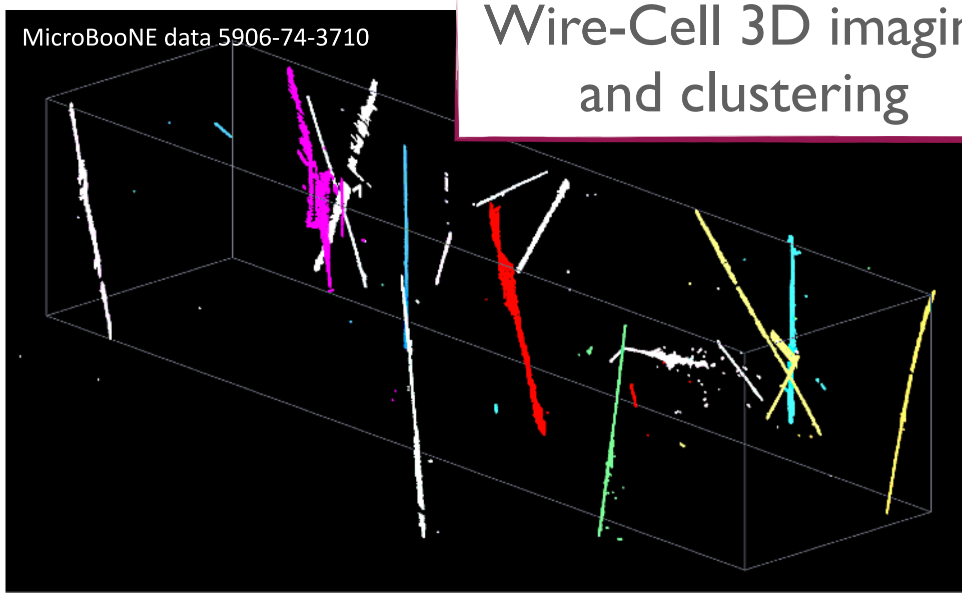
- Both ArgoNeuT and MicroBooNE have demonstrated ability to reconstruct **energy depositions from sub-MeV particles** (ArgoNeuT: 300 keV, MicroBooNE: 100 keV)
- Generally **photons** from nucleus de-excitation or **neutron** re-interactions → can give **substantial improvements** in calorimetry and energy reconstruction
- Used in ArgoNeuT to place constraints on BSM physics search for millicharged particles



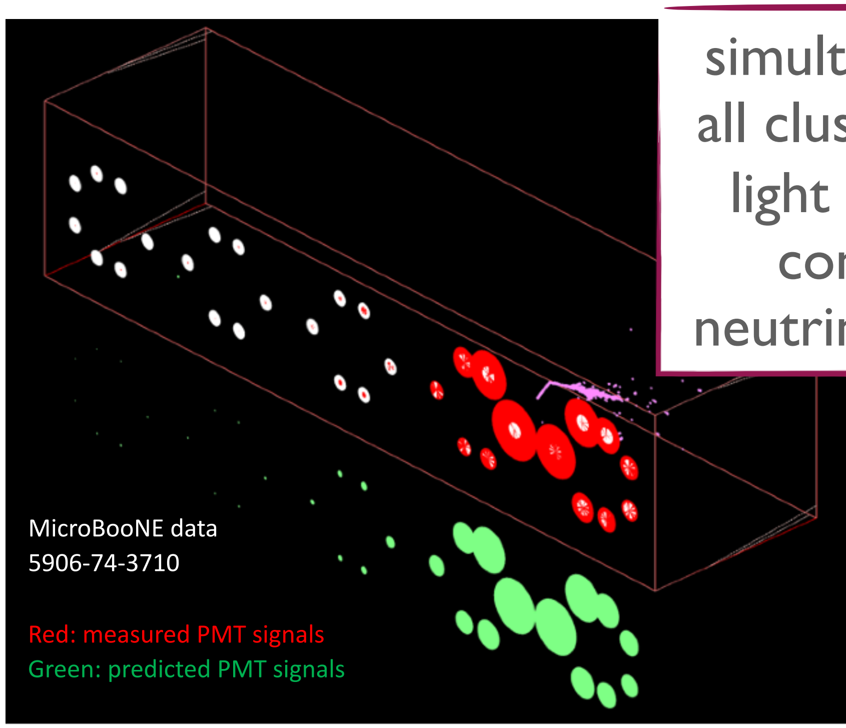


IMPROVED DETECTOR UNDERSTANDING ENABLES BETTER MEASUREMENTS

arXiv:2011.01375[physics.ins-det] arXiv:2012.07928[hep-ex]

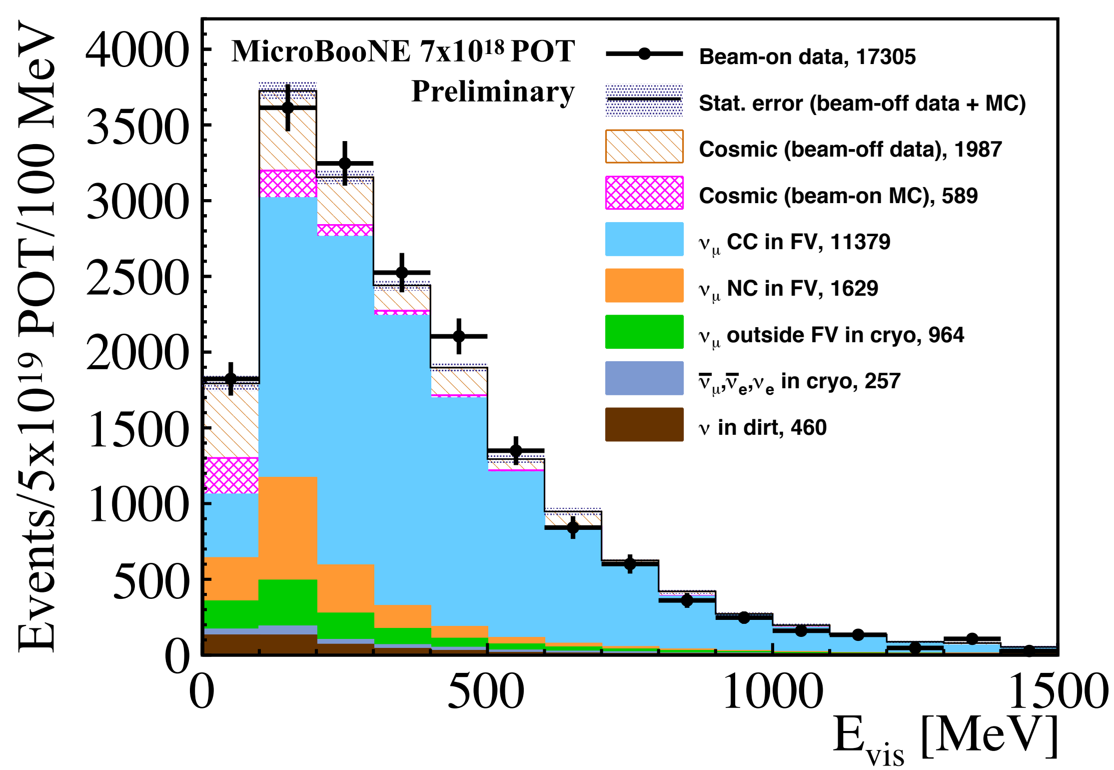


Wire-Cell 3D imaging and clustering

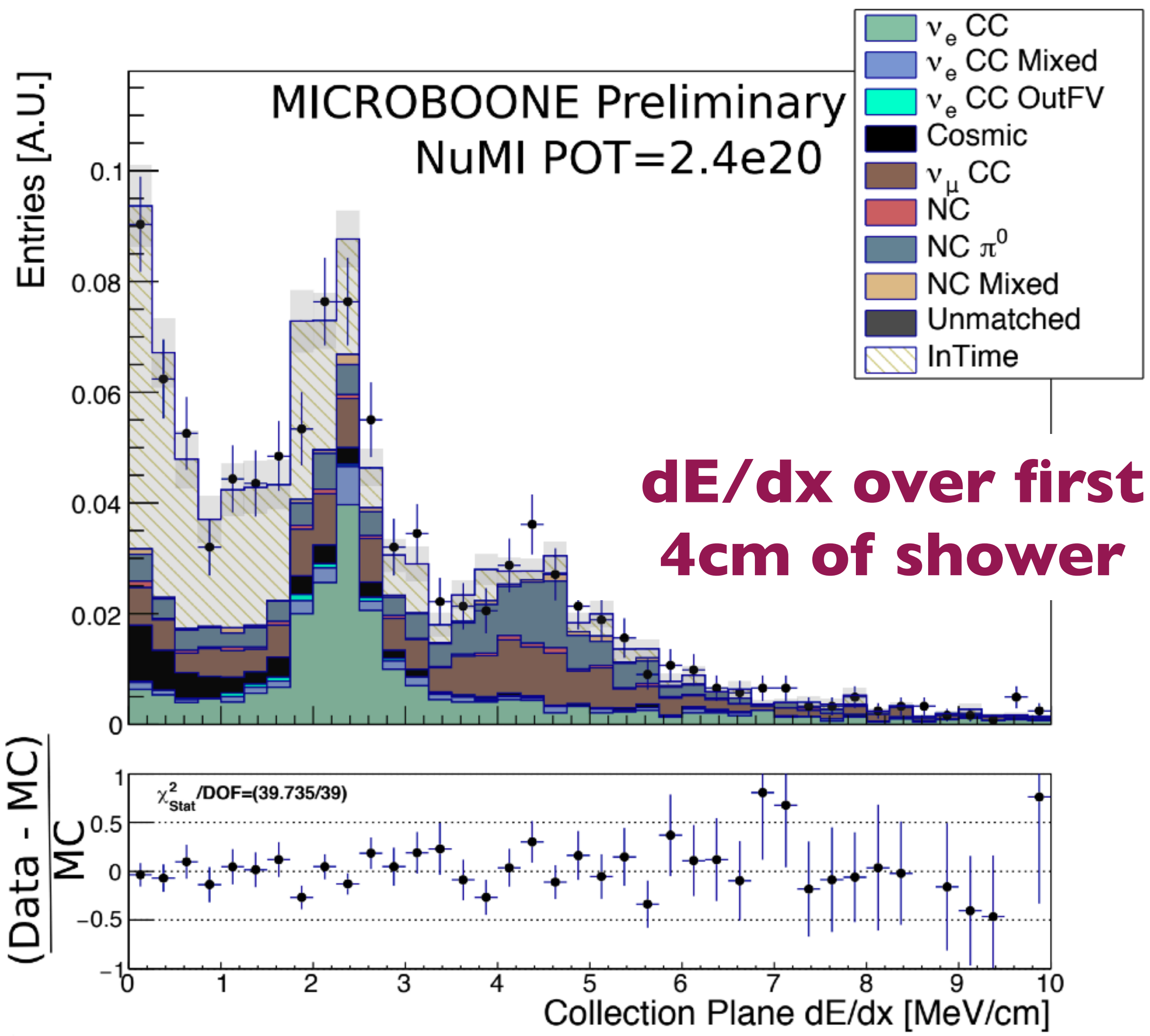


simultaneously match all clusters in event to light → find cluster consistent with neutrino-induced flash

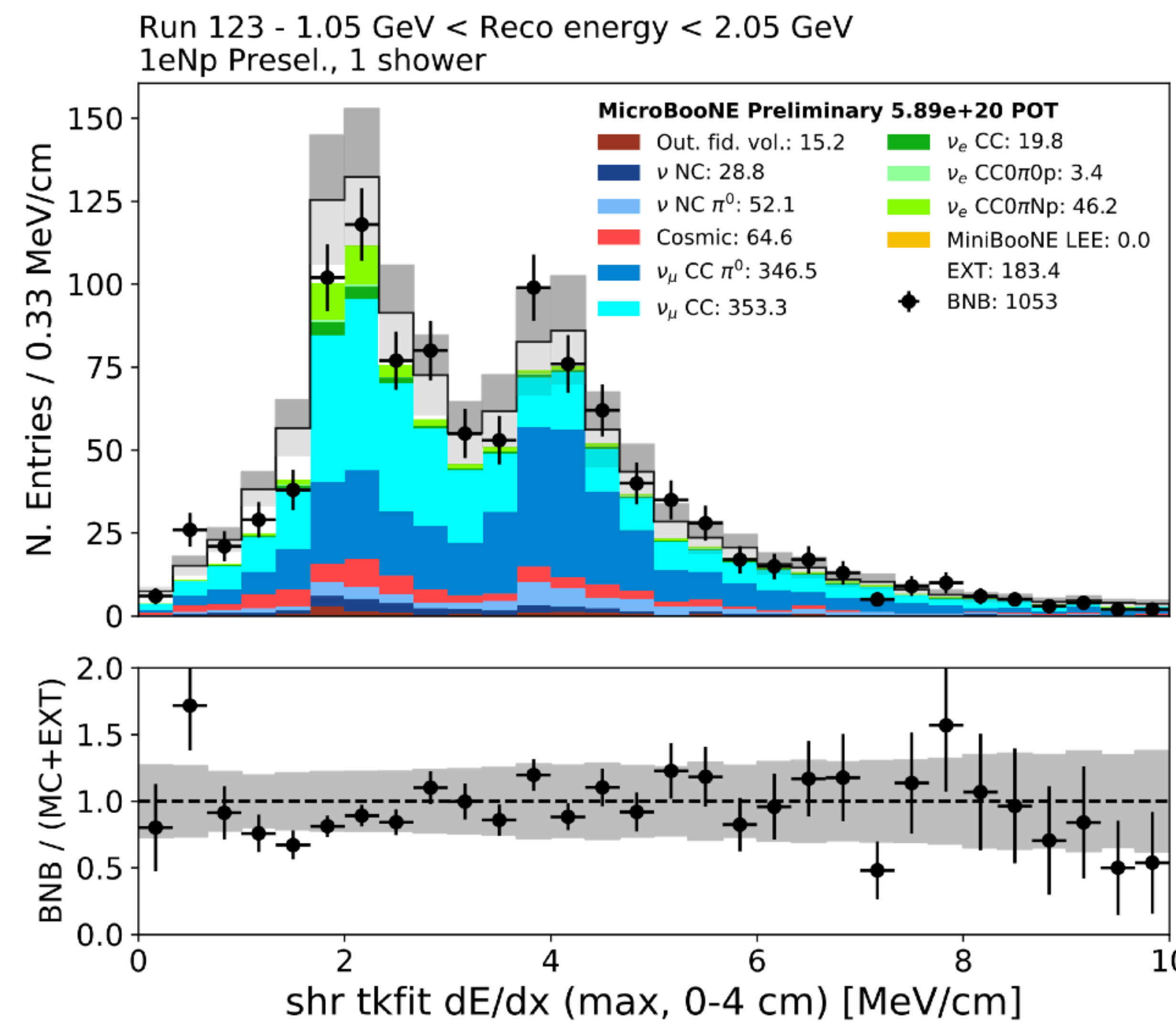
- Cosmic rejection power (without kinematic requirements) **increased by factor of 8** compared to previous publications
- **High efficiency**: 80.4% for ν_μCC (87.6% for ν_eCC)
- **Increased statistics**: 11.3k events,compared to 4.3k events in same data set for 2019 CC inclusive measurement



ELECTRON-PHOTON DISCRIMINATION



dE/dx over first 4cm of shower



MicroBooNE ν_e Selection

Current: with improved detector understanding

MICROBOONE-NOTE-1054-PUB

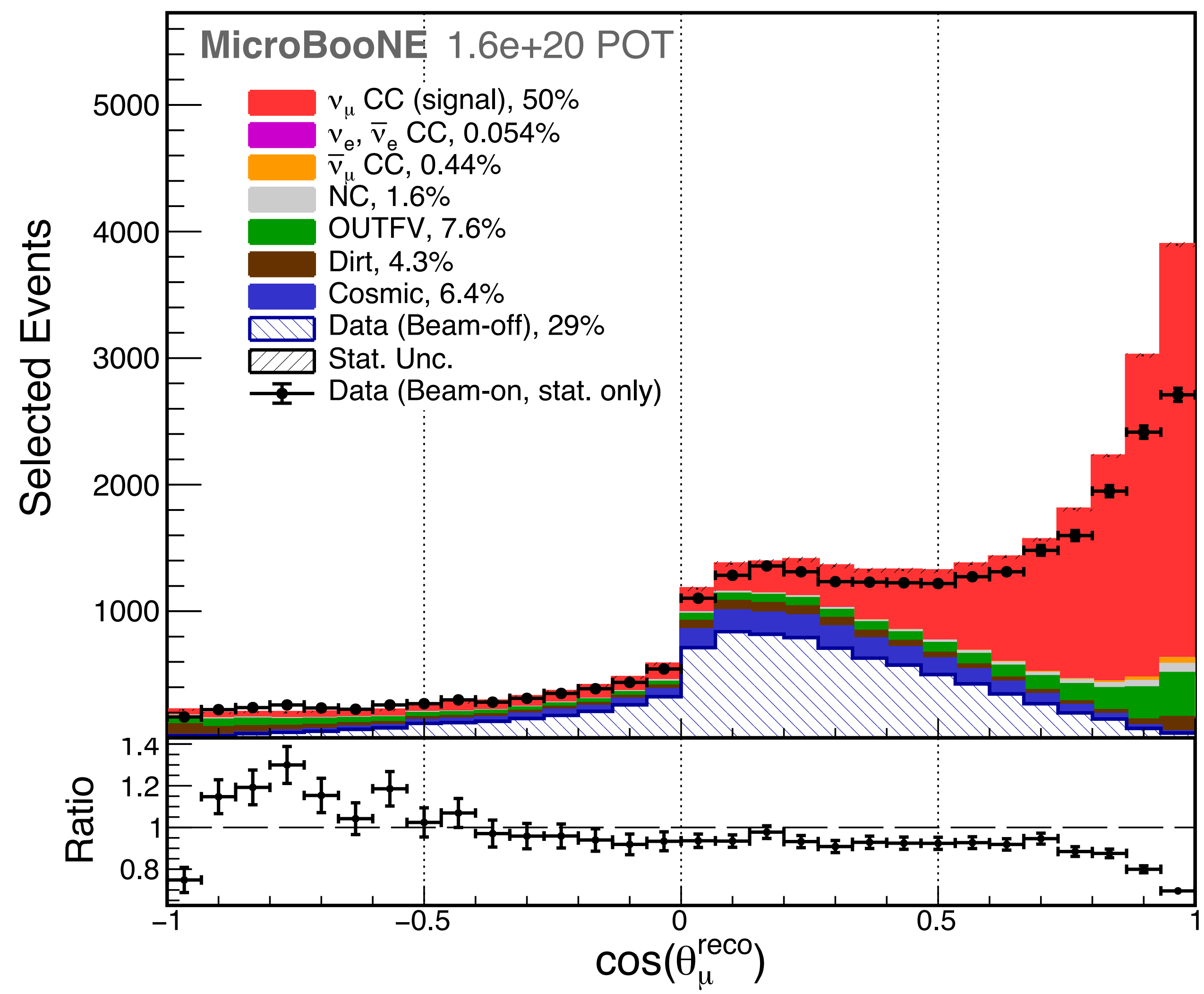
MICROBOONE-NOTE-1085-PUB

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%

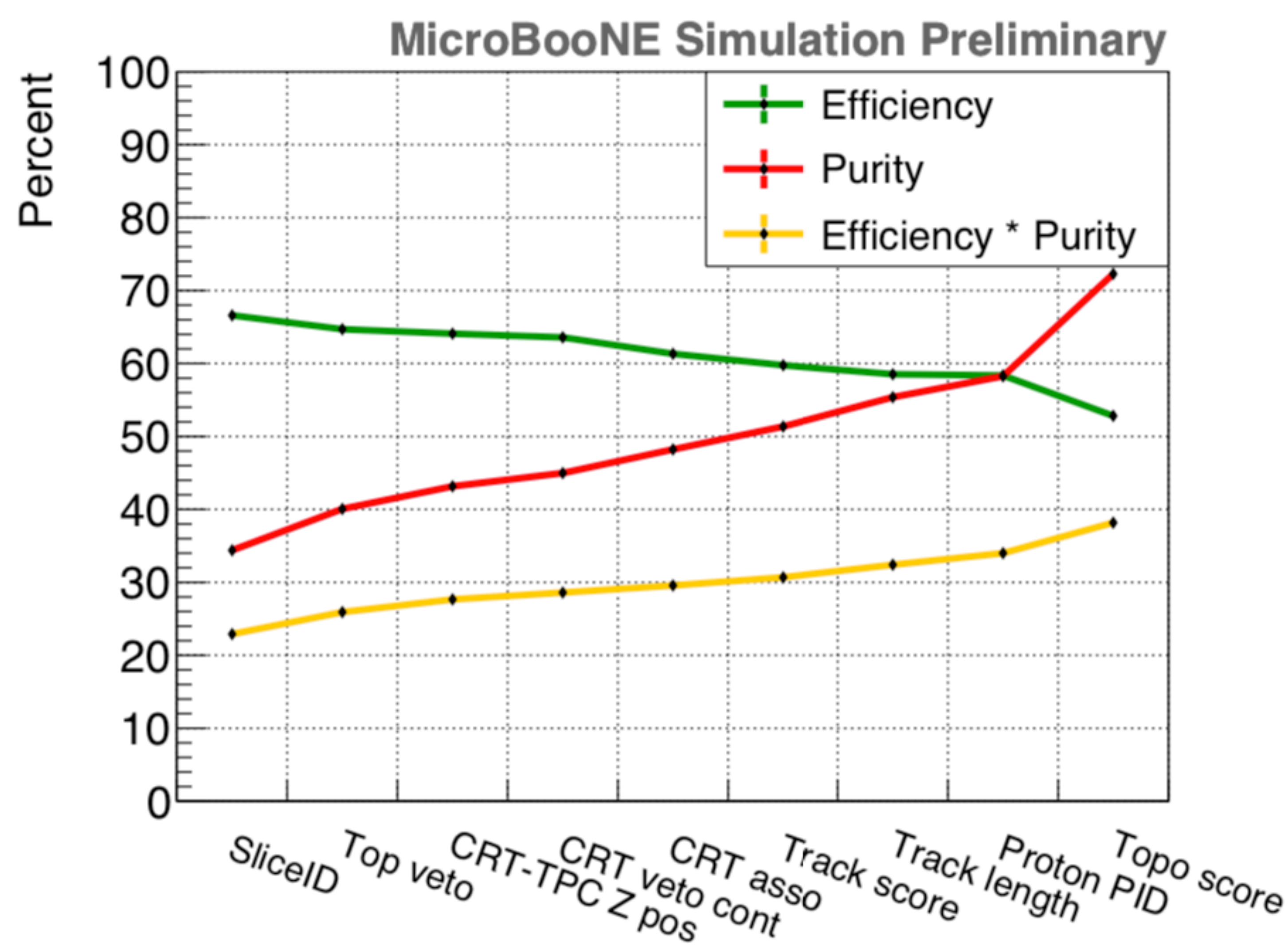
Largest background: **cosmic rays** (29%)
→ directly measured with beam-off data

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

UPDATED CC-INCLUSIVE SELECTION

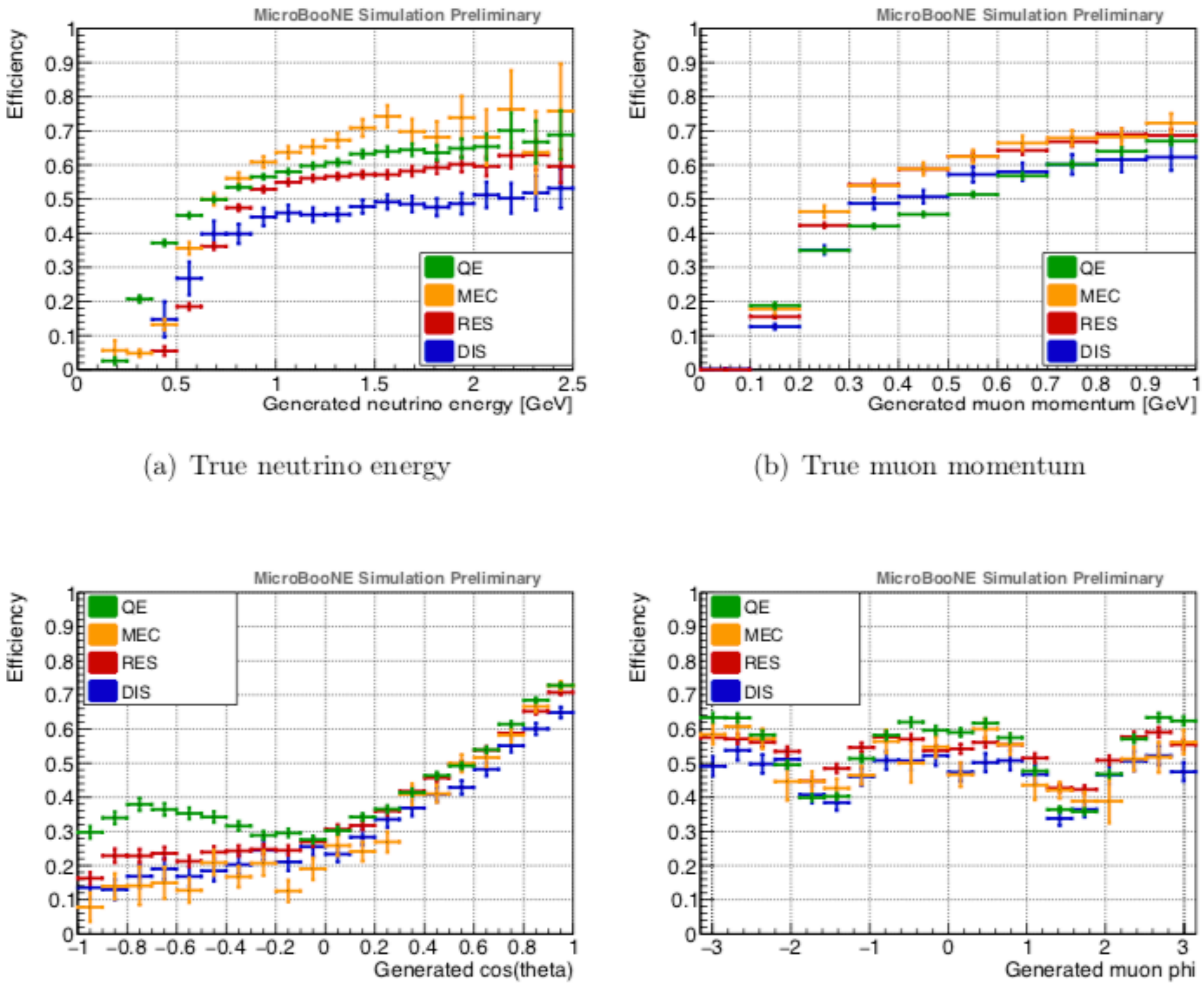
MICROBOONE-NOTE-1069-PUB

- **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 $cos(\theta)$

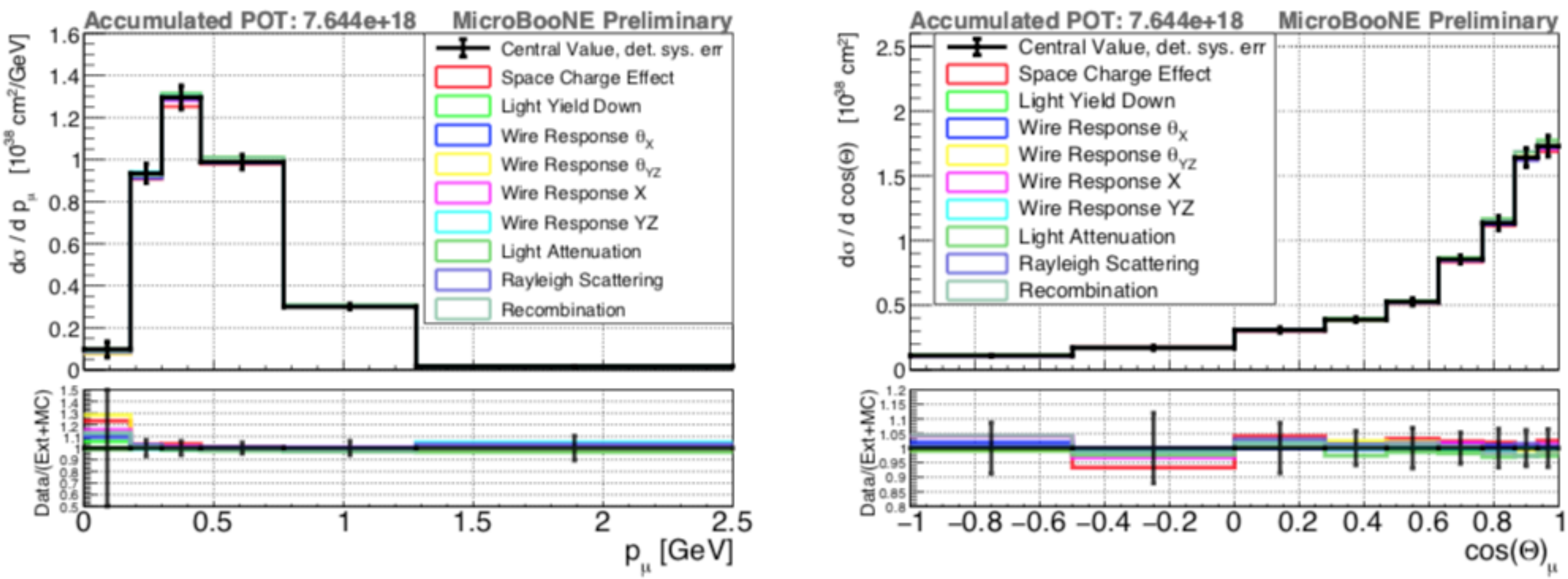
(d) True muon ϕ

- 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

μBooNE

UPDATED CC-INCLUSIVE CROSS SECTION: SYSTEMATIC UNCERTAINTIES

MICROBOONE-NOTE-1069-PUB



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

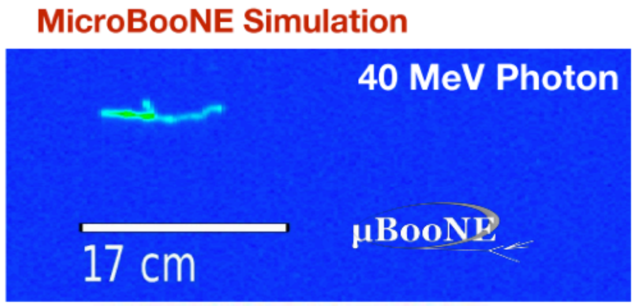
CCPI0 SELECTIONS

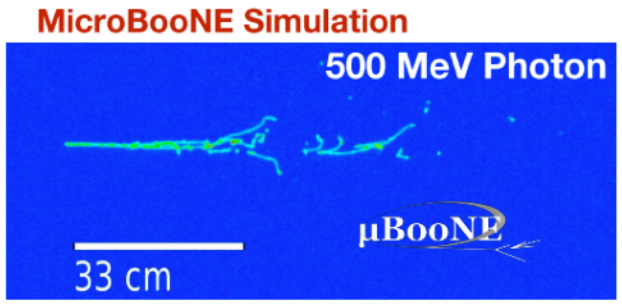
Phys. Rev. D 99, 091102(R) (2019)

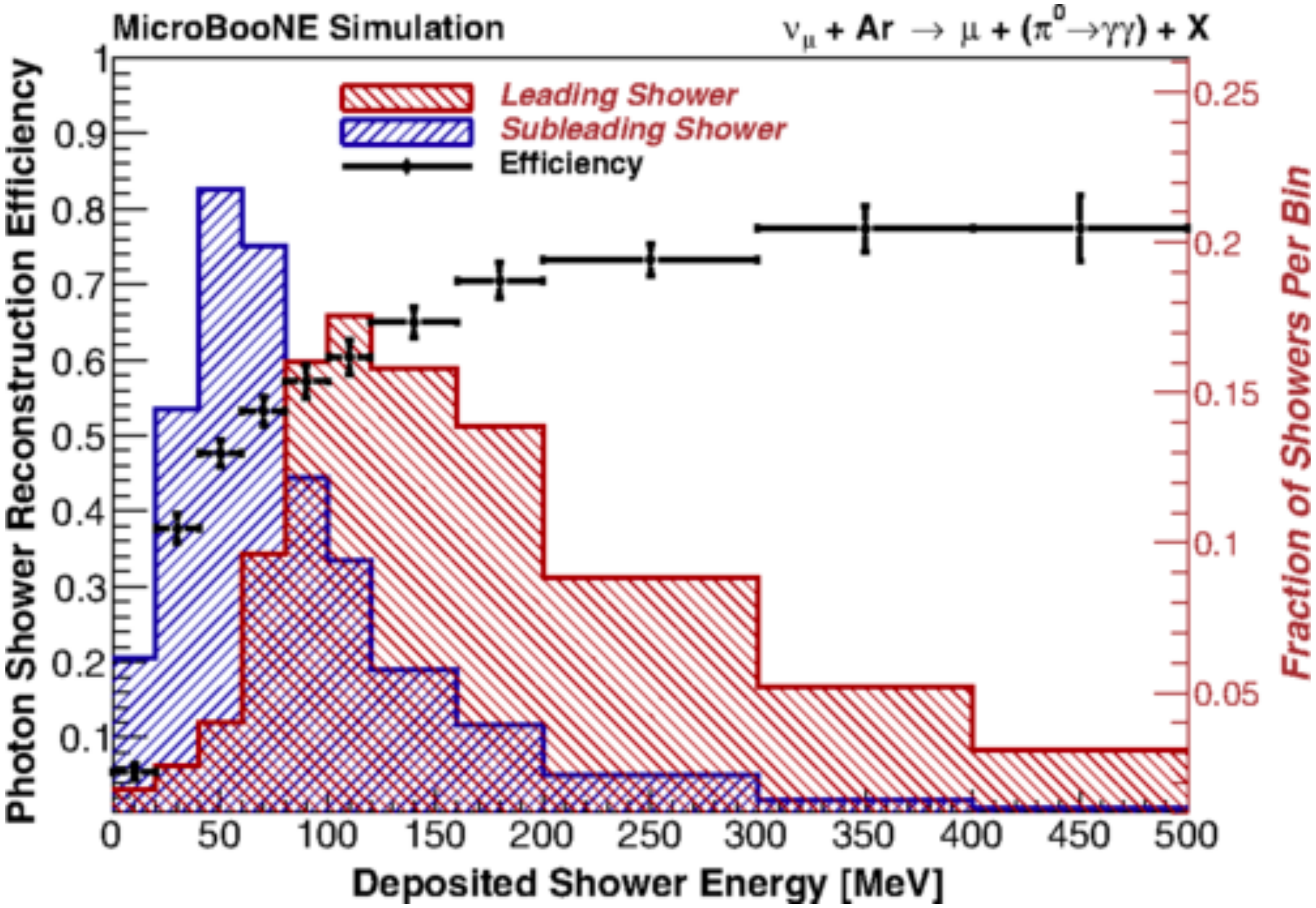
Low-energy photons appear more track like
→ low reconstruction efficiency
→ requiring that we reconstruct both π^0 photons limits statistics

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

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



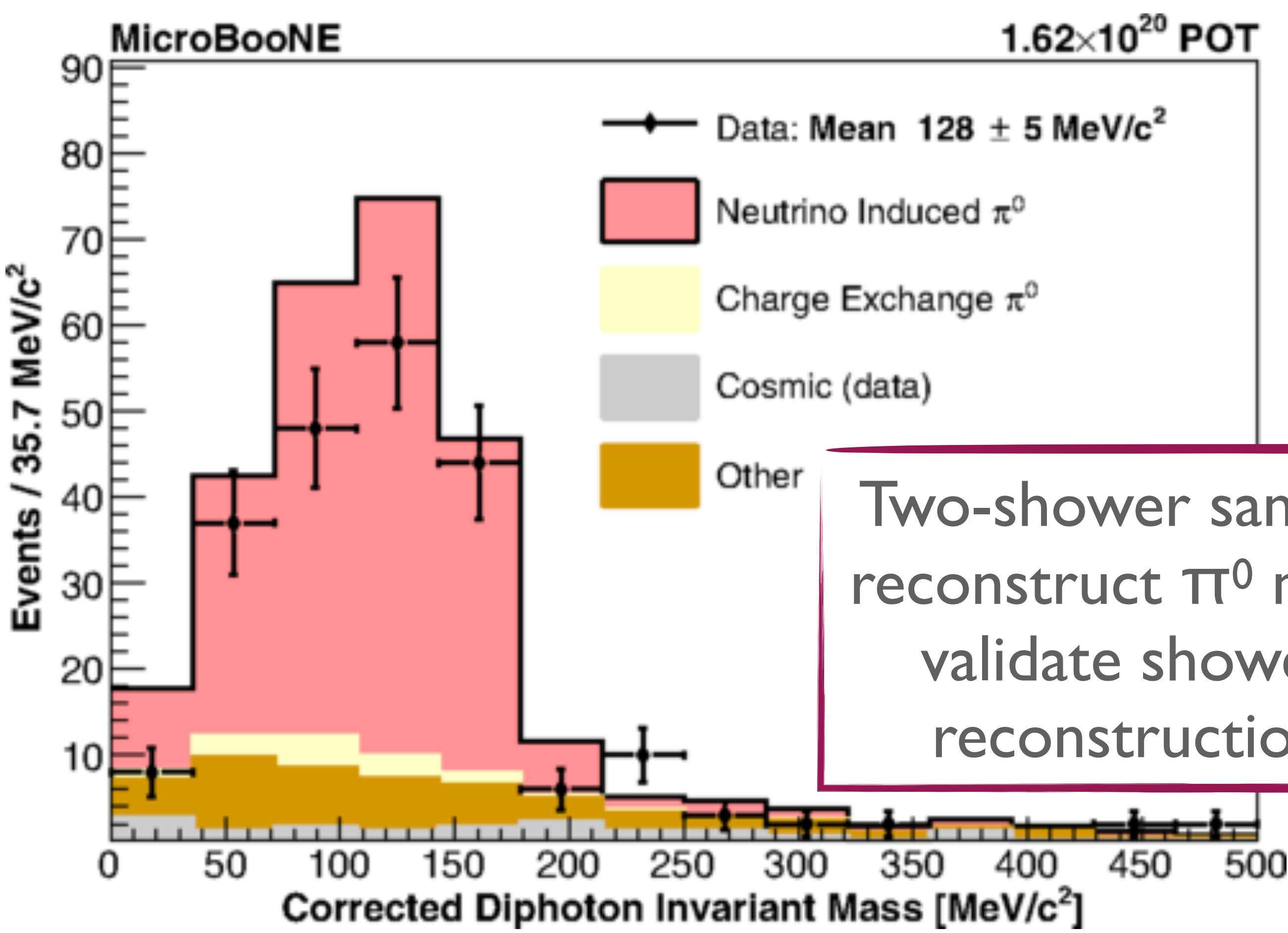




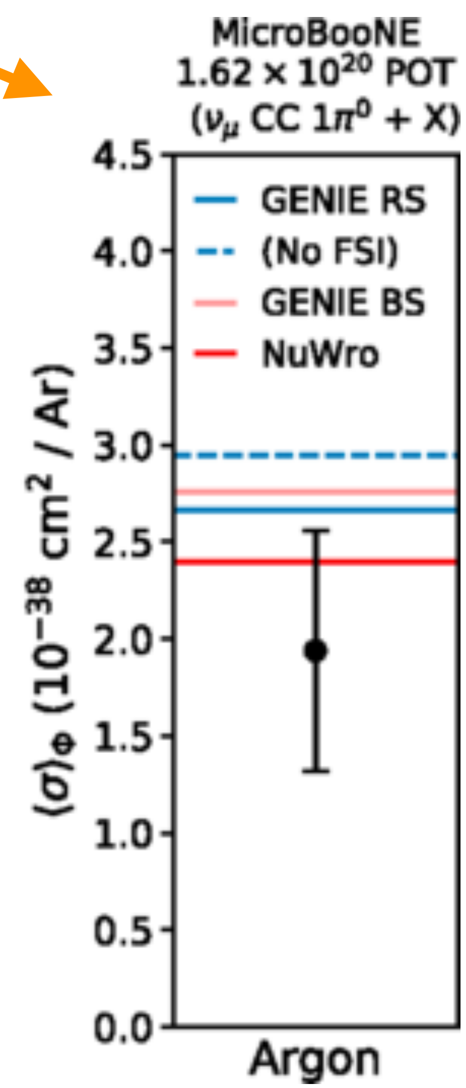
CC π^0 PRODUCTION

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

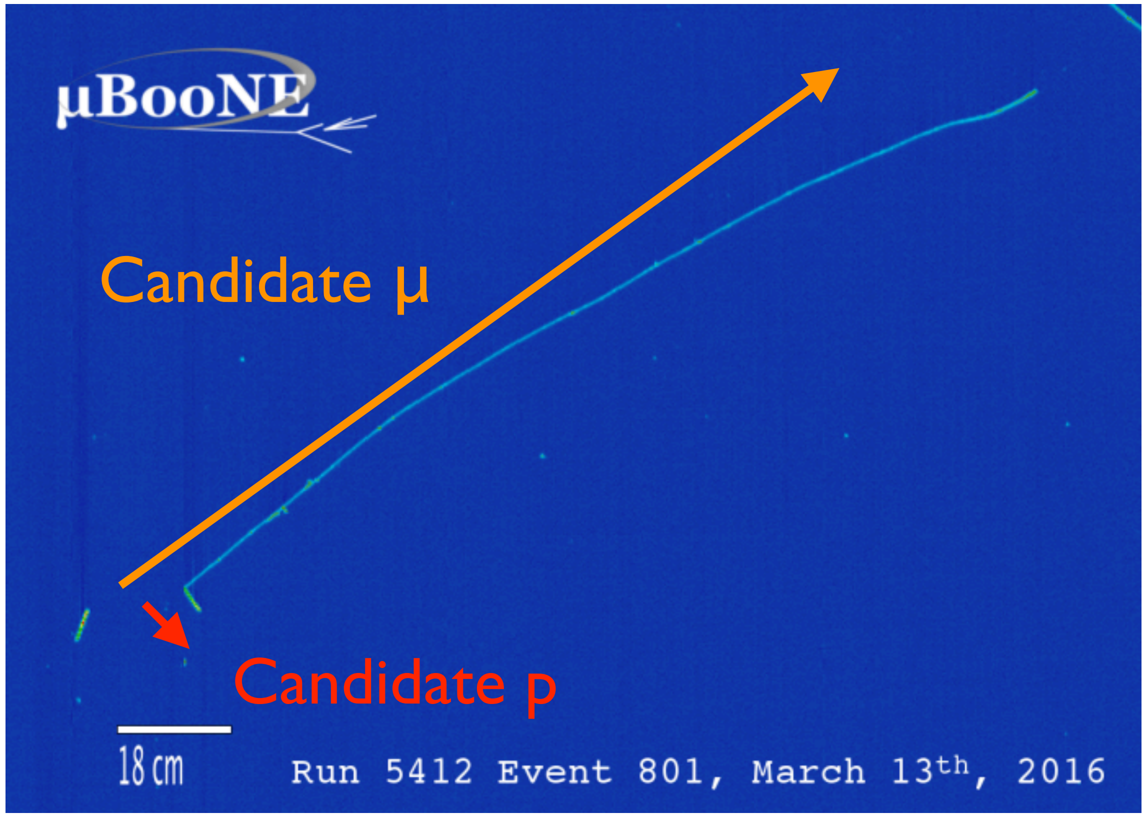
CCQE-LIKE CROSS SECTION

Eur. Phys. J. C 79 673 (2019)   Phys. Rev. Lett. 125, 201803 (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:

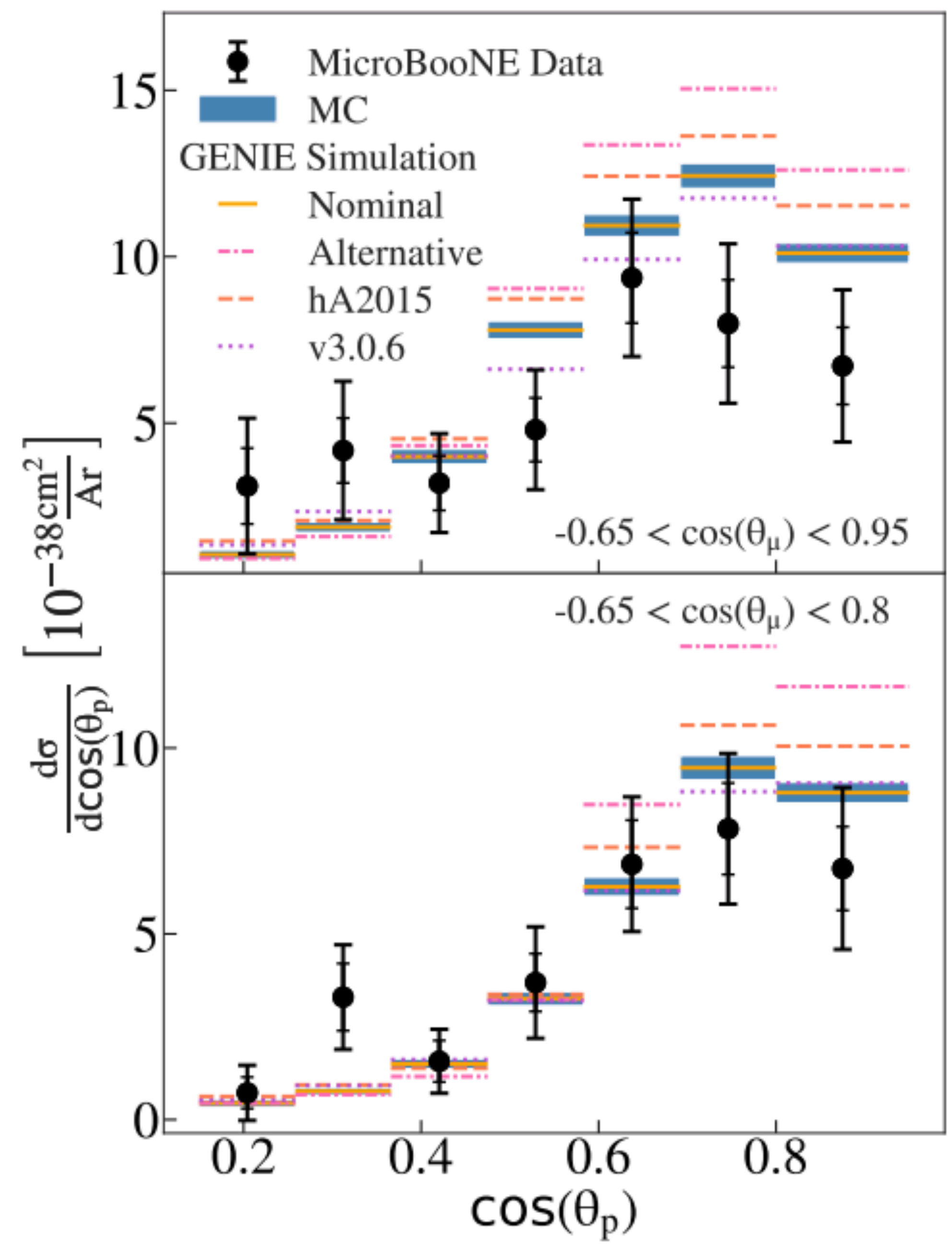
- Two tracks
- Energy deposition consistent with one muon and one proton
- Tracks are not collinear
- Tracks are coplanar
- Low vertex activity
- Low transverse momentum



CCQE CROSS SECTION: MODEL COMPARISONS

Eur. Phys. J. C 79 673 (2019) Phys. Rev. Lett. 125, 201803 (2020)

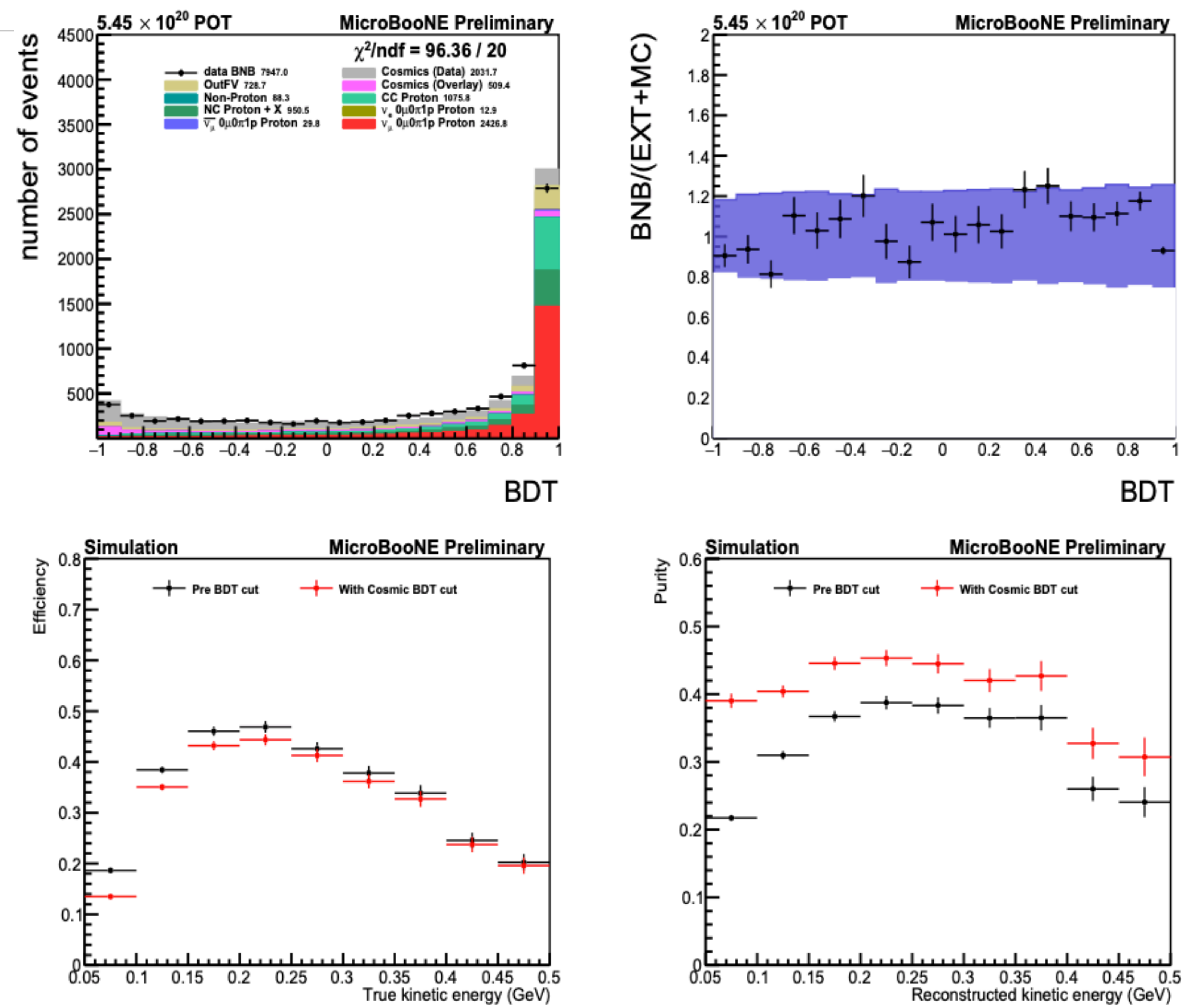
- **Nominal**: GENIE v2.12.2. Bodek-Ritchie Fermi Gas, Llewellyn-Smith CCQE model, empirical MEC model, Rein-Sehgal resonant and coherent scattering model, "hA" FSI model
- **hA2015**: GENIE v2.12.2 with a more recent "hA2015" FSI model
- **Alternative**: GENIE v2.12.10. Local Fermi Gas, Nieves CCQE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

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**



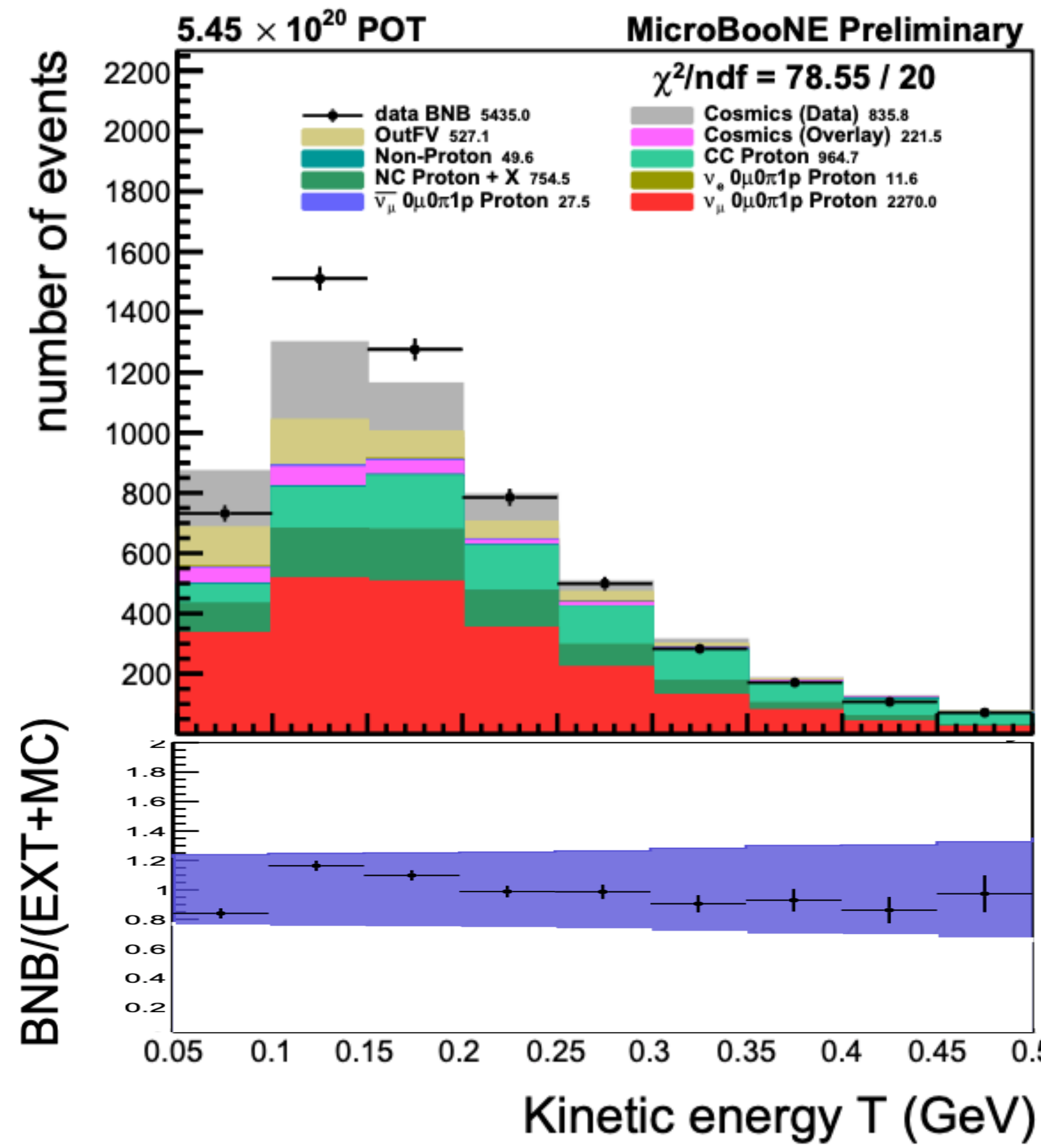
NC1P CROSS SECTION MEASUREMENT

MICROBOONE-NOTE-1067-PUB

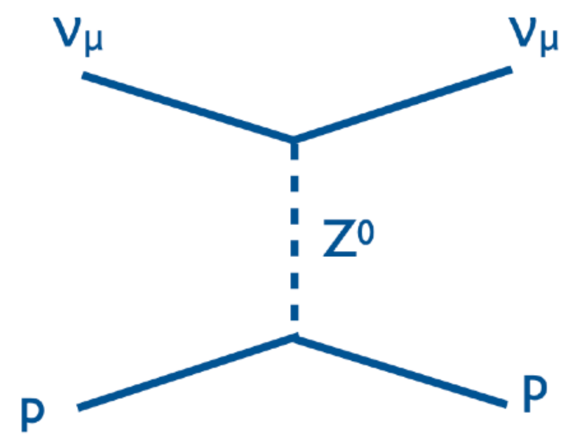
- Measure cross section for neutral-current single proton production
- Signal: 1 isolated proton

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)

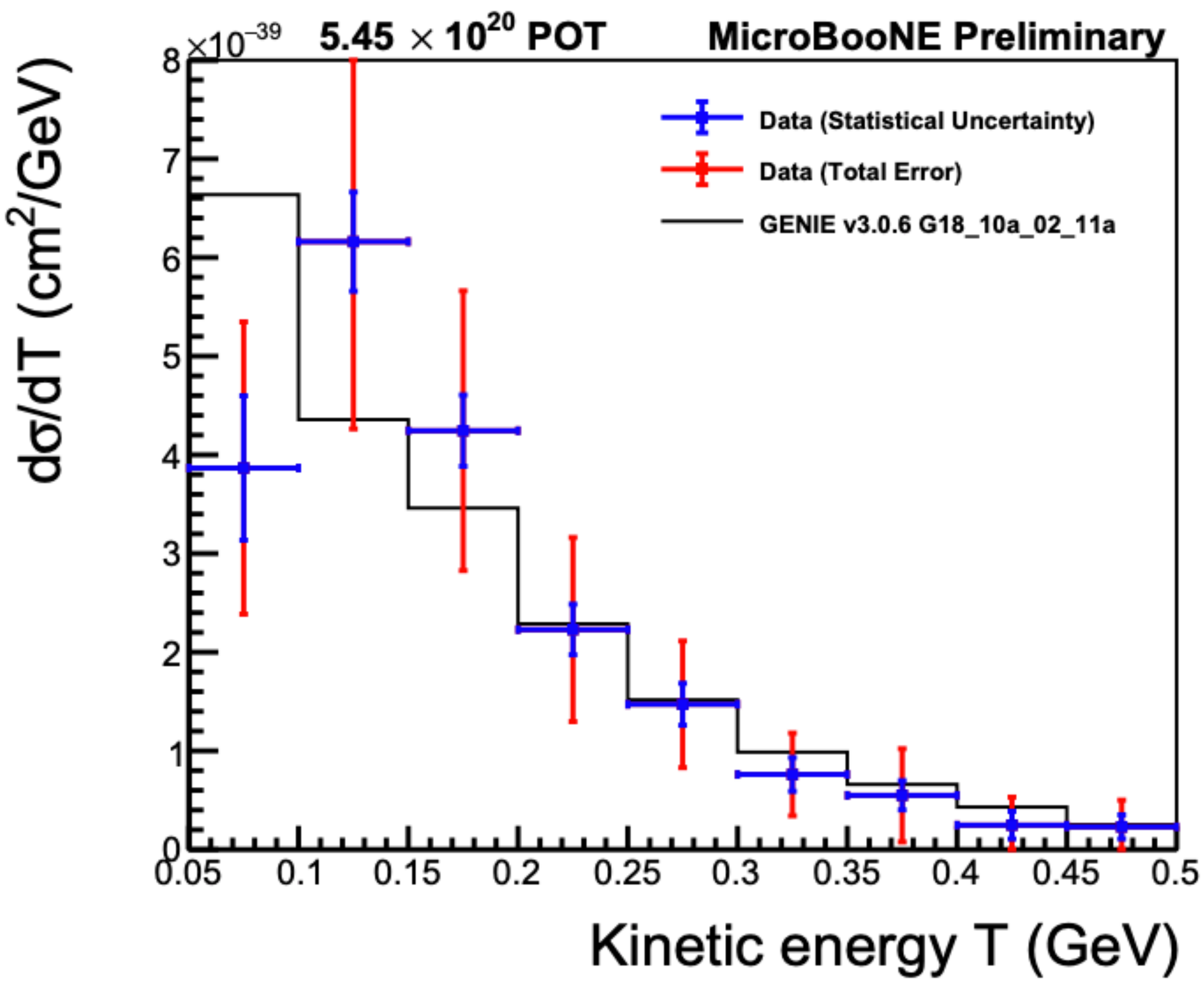


NC1P CROSS SECTION



MICROBOONE-NOTE-1067-PUB

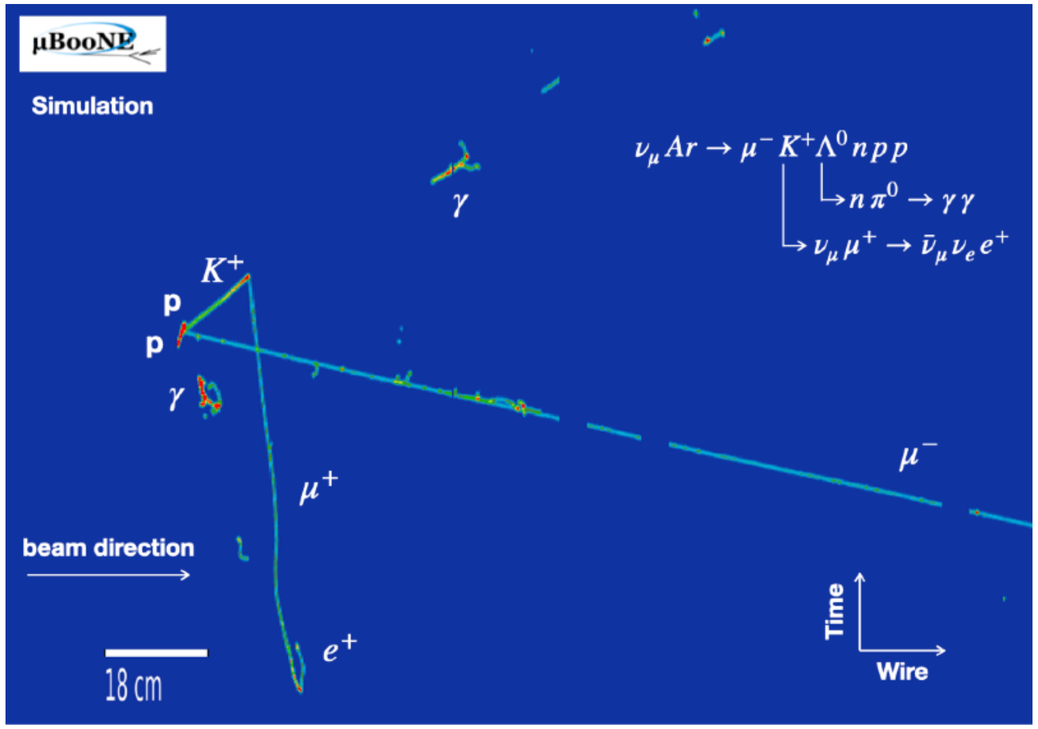
- Measure cross section for neutral-current single proton production
- Measurement includes events with $Q^2 \sim 2m_pT_p = 0.1$ GeV^2, **significantly lower** than previous measurements
- Future development towards a measurement of **NC elastic scattering** cross section → measure strange component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

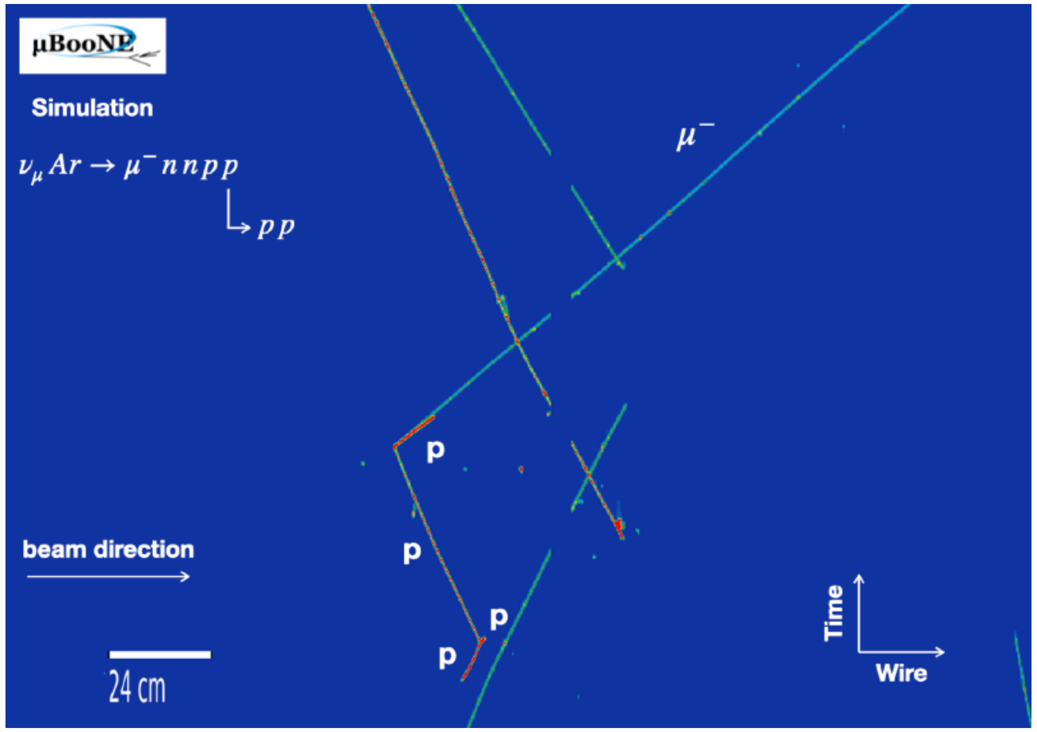


CC KAON PRODUCTION SELECTION

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

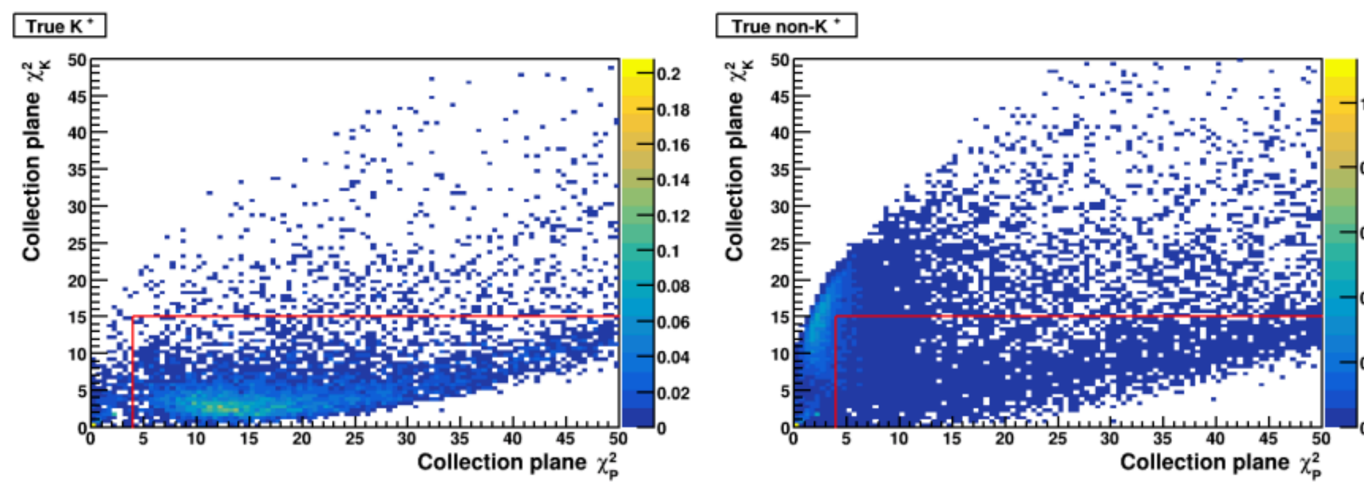


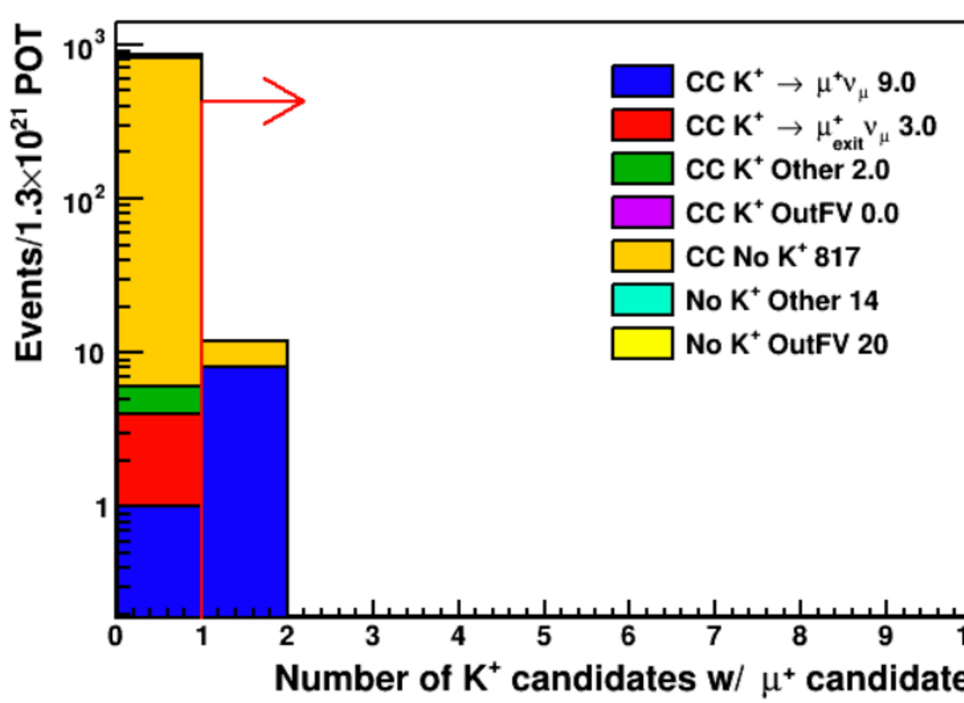


CC KAON SELECTION

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

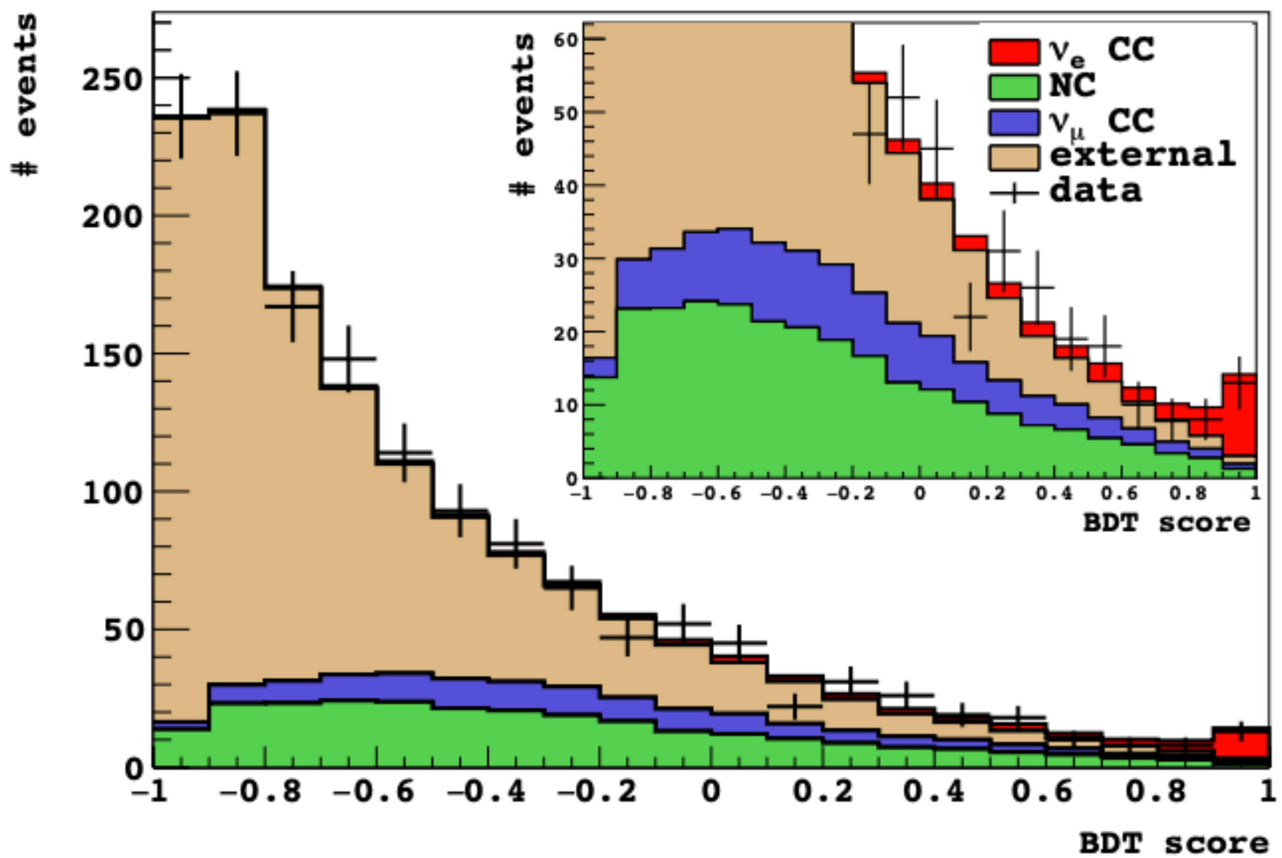




ARGONEUT ELECTRON NEUTRINO SELECTION

Phys. Rev. D 102, 011101(R) (2020)

- 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 $\bar{\nu}$)

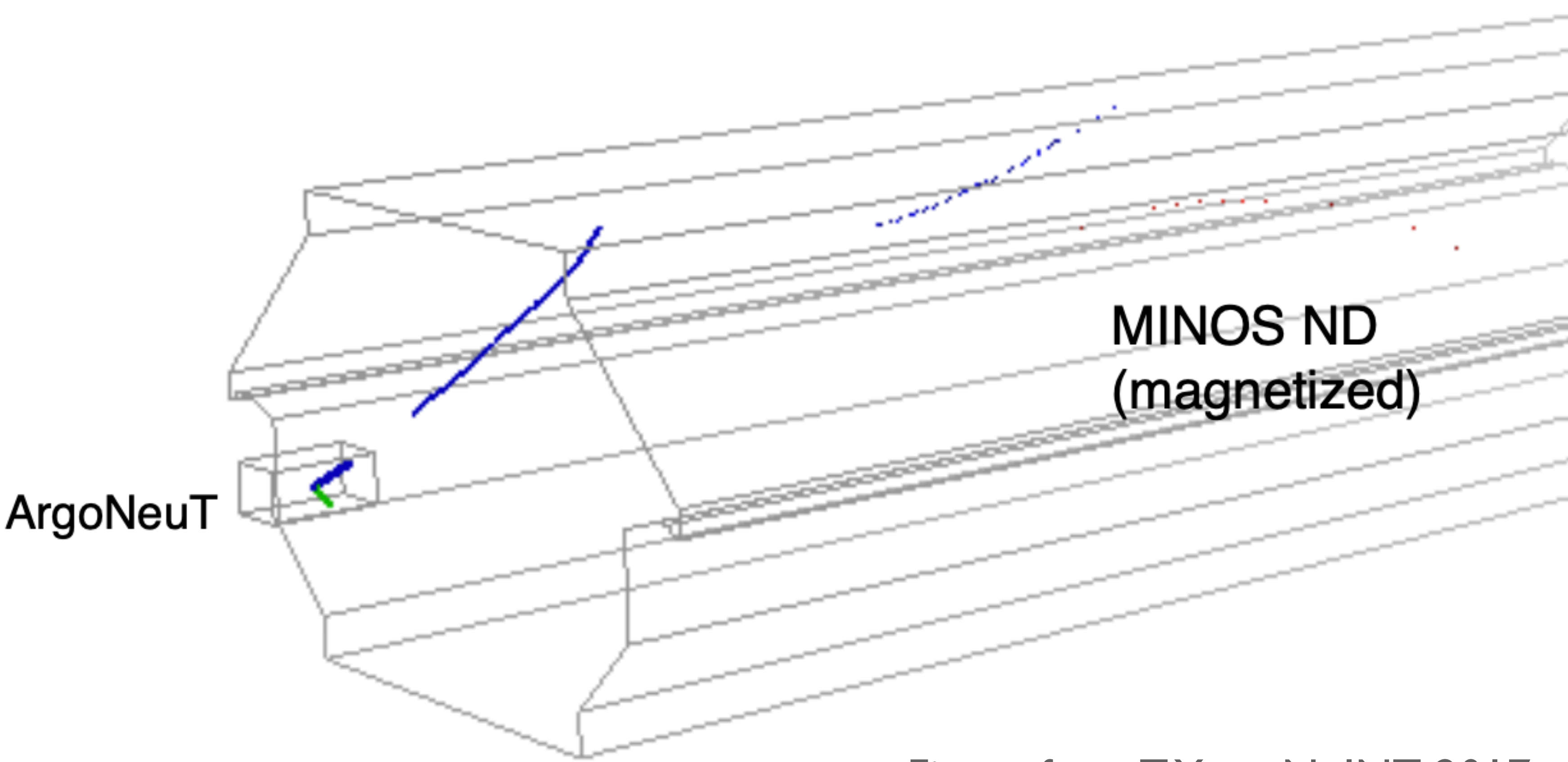
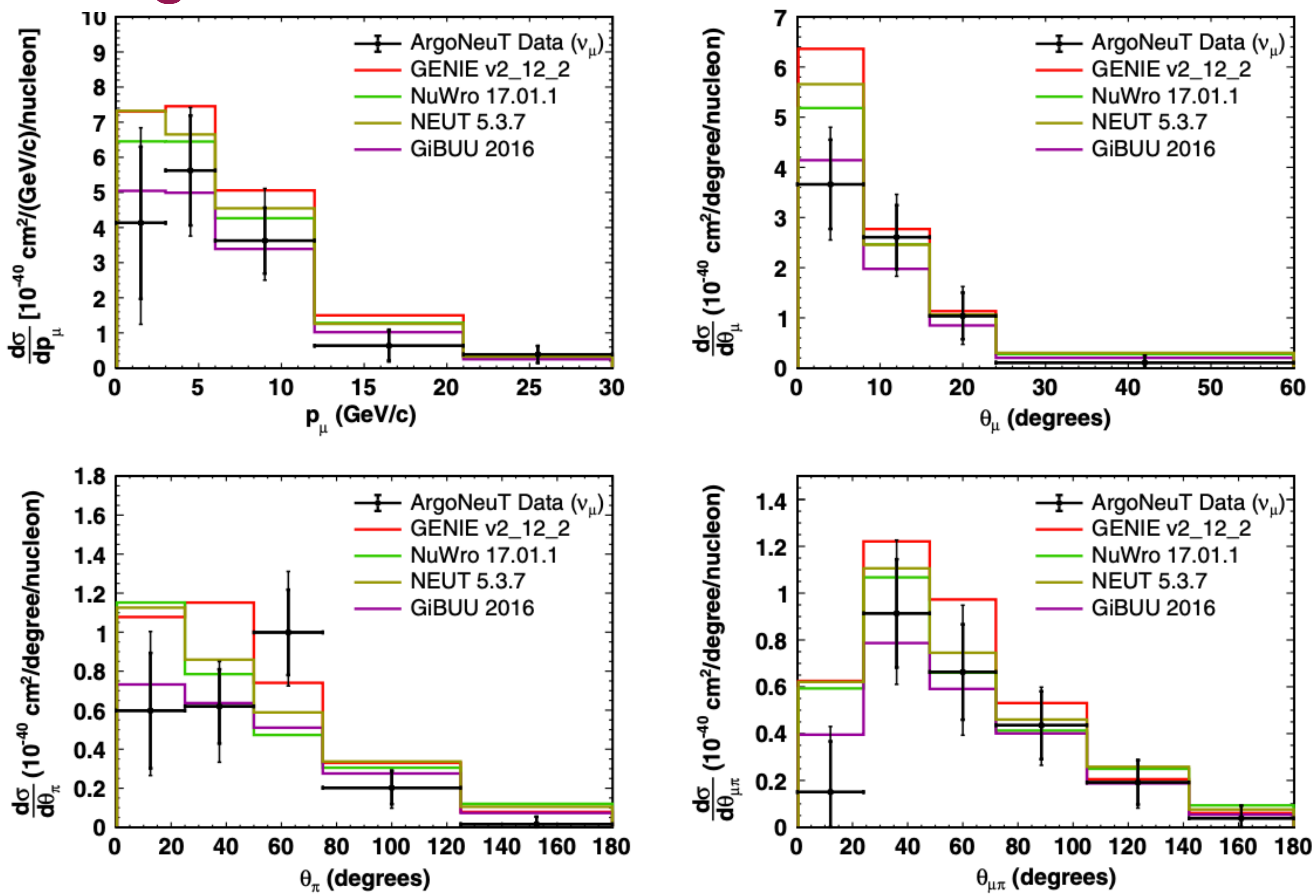


Figure from T.Yang, NuINT 2017

ARGONEUT CHARGED PION PRODUCTION MEASUREMENT

ν_μ CC1$\pi^\pm$ ArgoNeuT measurement

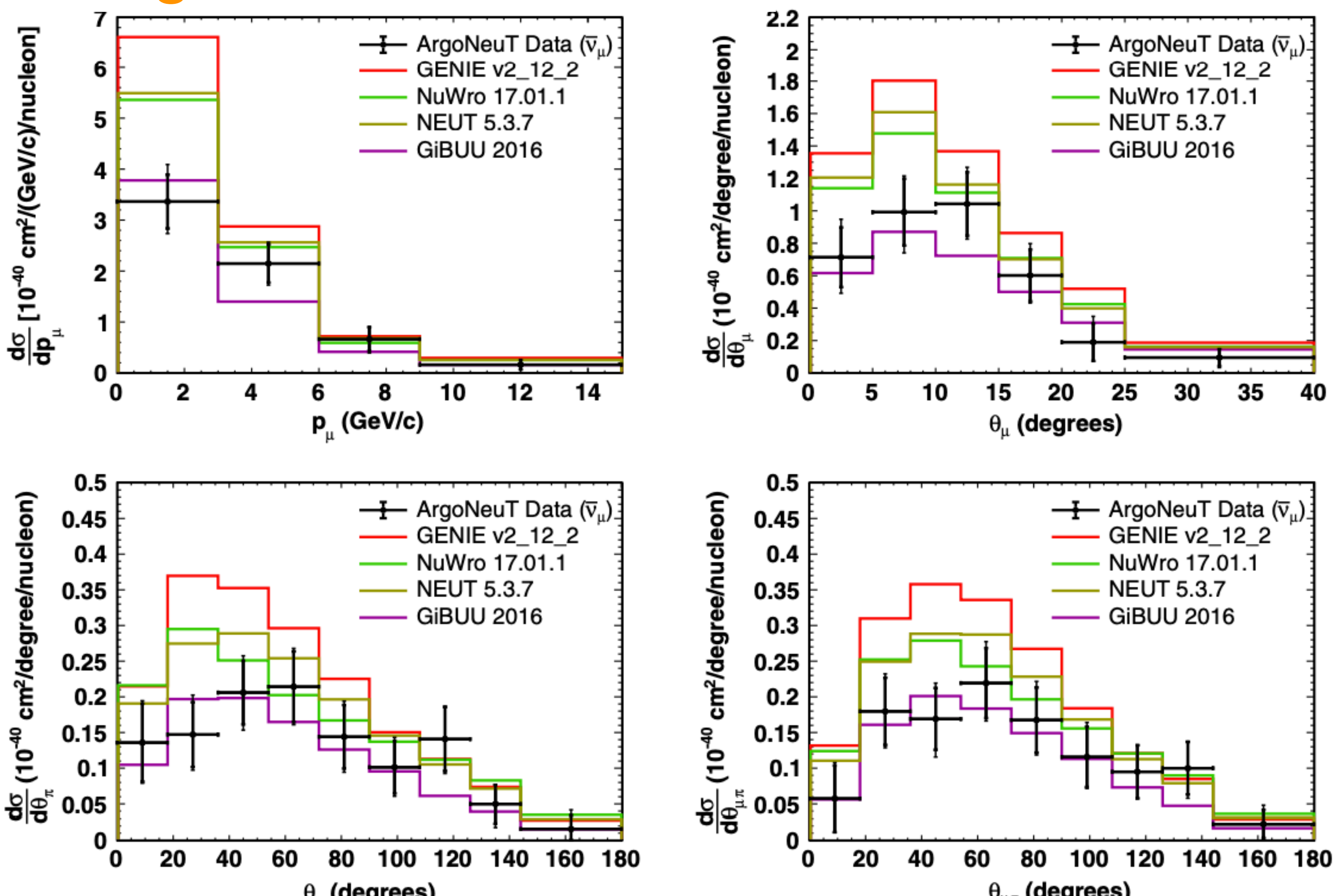
Phys. Rev. D 98, 052002 (2018)



ARGONEUT CHARGED PION PRODUCTION MEASUREMENT

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

Phys. Rev. D 98, 052002 (2018)



HARGED PION MEASUREMENT

ement

Phys. Rev. D 98, 052002 (2018)

Resonant pion production model

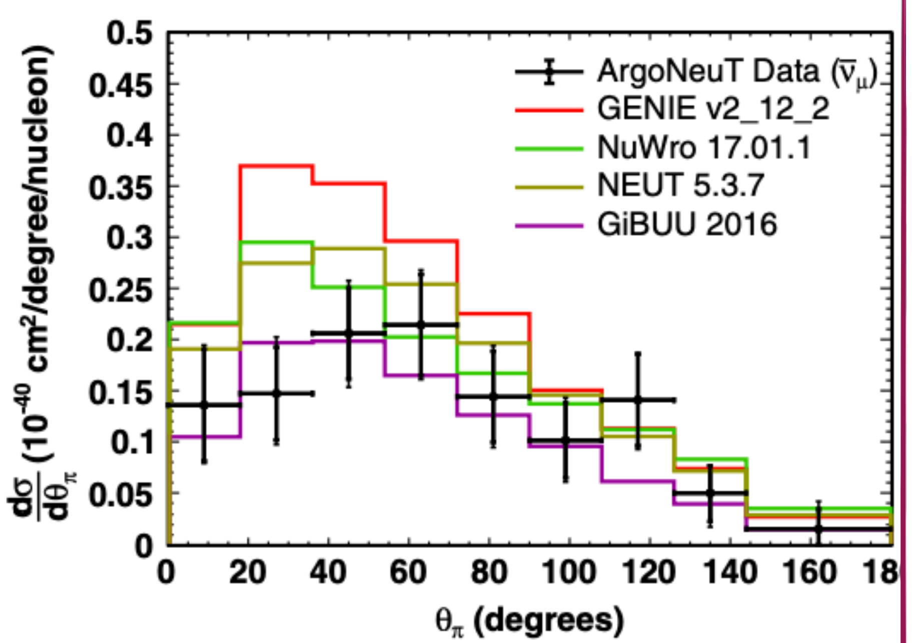
- GENIE, NEUT: Rein-Sehgal
- NuWro: Δ(1232) resonance only

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



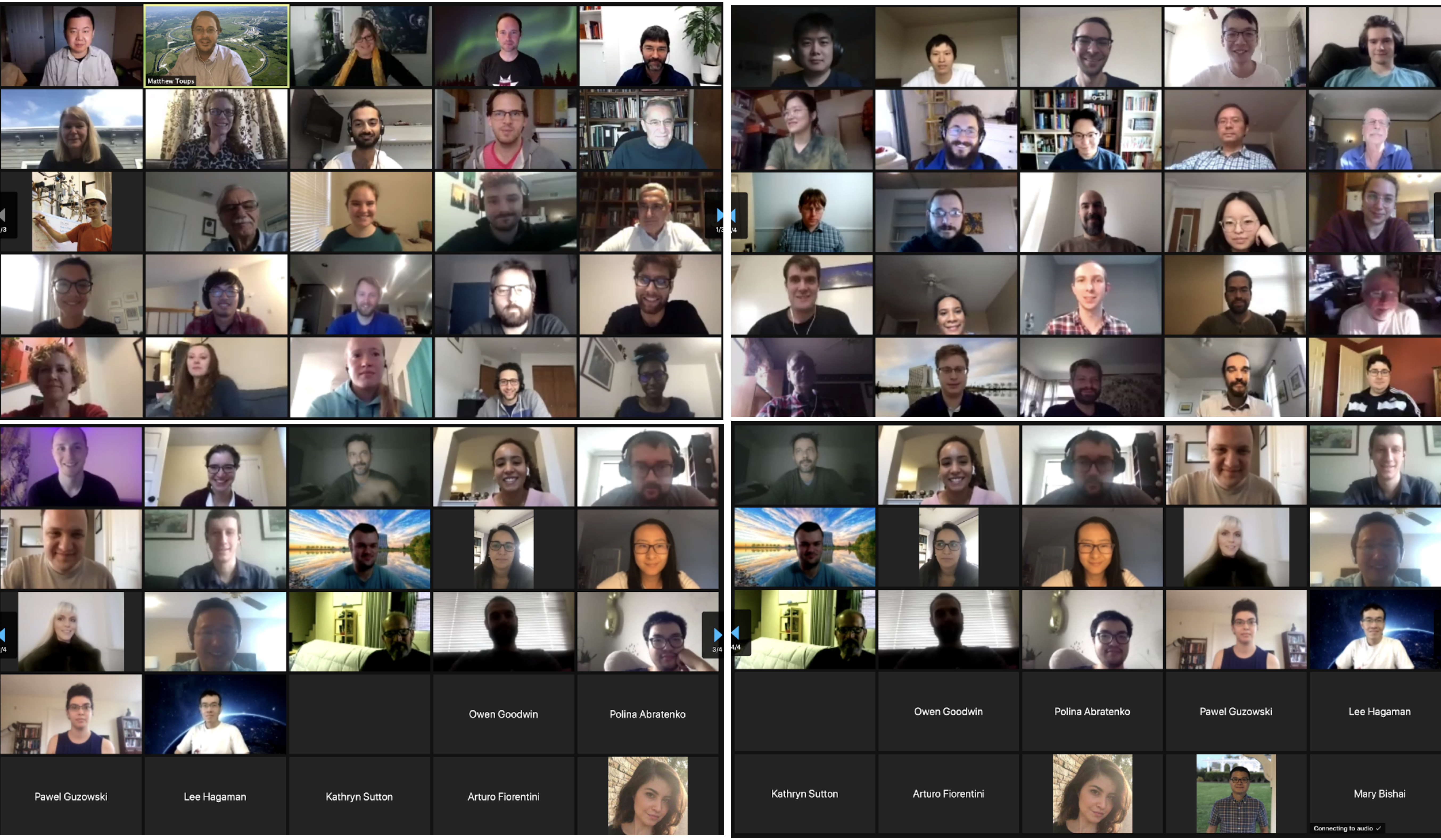
Paper conclusions

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)


Matthew Toups
Owen Goodwin
Polina Abratenko
Pawel Guzowski
Lee Hagaman
Kathryn Sutton
Arturo Fiorentini
Owen Goodwin
Polina Abratenko
Pawel Guzowski
Lee Hagaman
Kathryn Sutton
Arturo Fiorentini
Mary Bishai
Connecting to audio