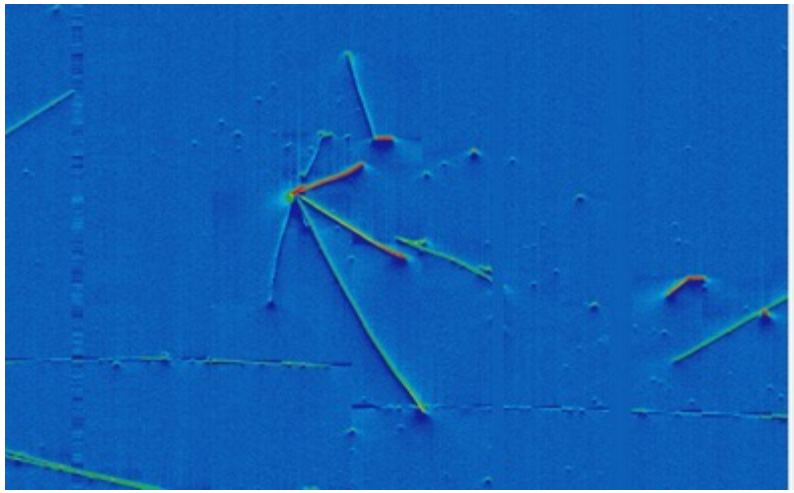
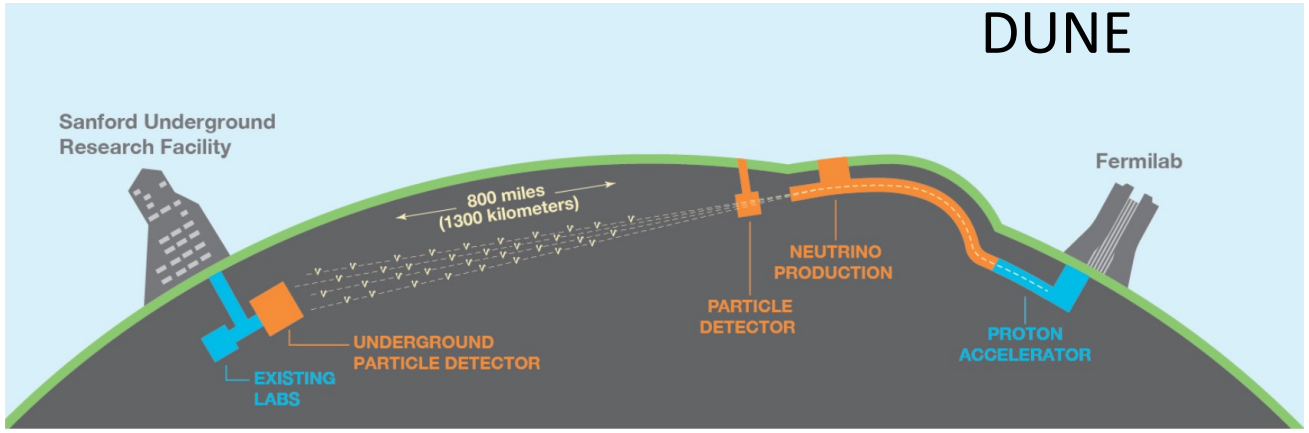
Overview of Cross Section Results: Argon Targets



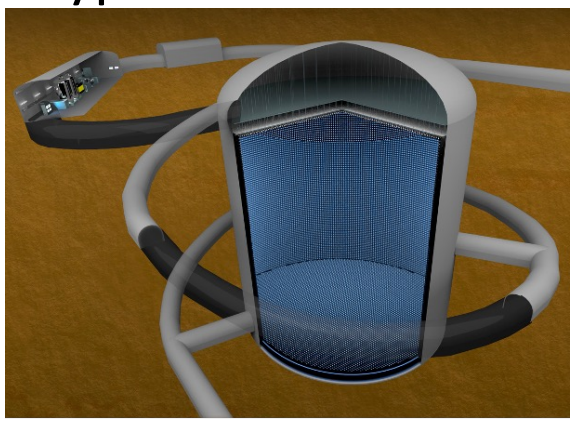
Sophie Berkman
Michigan State University
NuFact
August 22, 2023

Future Neutrino Oscillation Experiments

DUNE



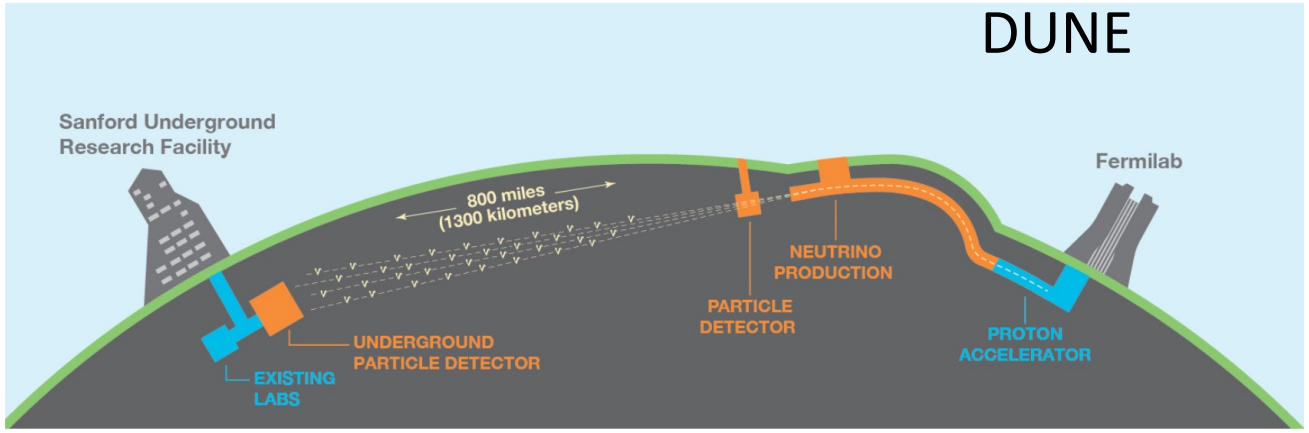
Hyper-Kamiokande



- Future long baseline oscillation experiments will make precision measurements of neutrino oscillation parameters, including mass hierarchy and CP violation

Future Neutrino Oscillation Experiments

DUNE



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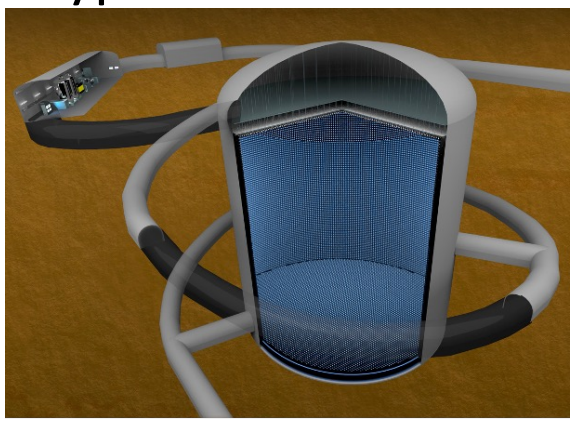


We measure the neutrino rate:

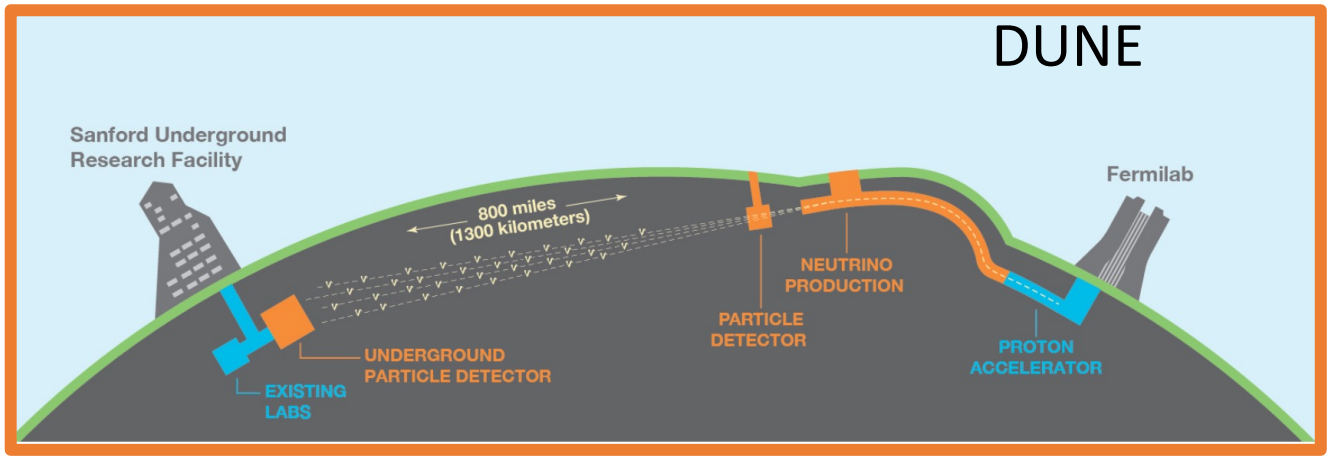
And want to extract neutrino oscillation parameters:

$$R(\vec{x}) = \Phi(E_\nu) \times \sigma(E_\nu, \vec{x}) \times \epsilon(\vec{x}) \times P(\nu_\mu \to \nu_e)$$

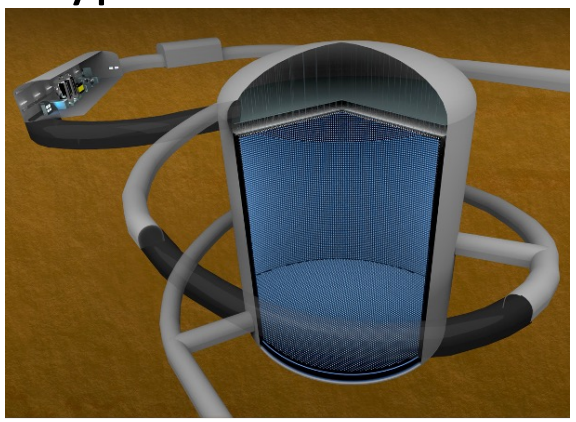
Requires very good understanding of:

1. Neutrino flux: $\Phi(E_\nu)$
2. Detector efficiency: $\epsilon(\vec{x})$
3. Cross section: $\sigma(E_\nu)$

Future Neutrino Oscillation Experiments



Hyper-Kamiokande



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1. Neutrino flux: $\Phi(E_\nu)$
2. Detector efficiency: $\epsilon(\vec{x})$
3. Cross section: $\sigma(E_\nu)$

More in presentations yesterday: [1], [2]

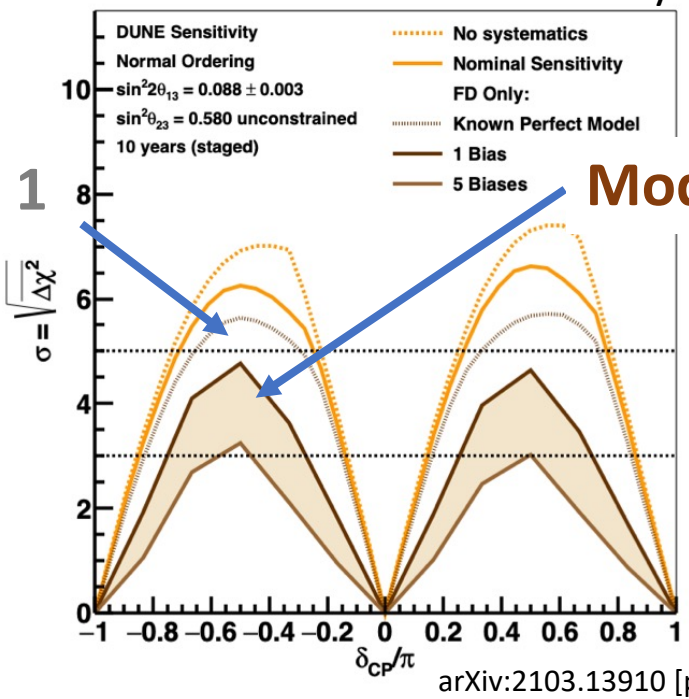
This talk:
Neutrino-argon cross sections

Next talk:
Other nuclear targets by Raquel Castillo Fernandez

Importance of Argon Measurements

- Neutrino-nucleus interaction measurements required for precision oscillation measurements
  - Significant impact on discovery sensitivity and often a limiting systematic uncertainty
- Most generator models have been developed based on measurements on lighter nuclei like carbon and oxygen
  - Argon is a heavier nucleus and therefore may be more impacted by nuclear effects like FSI

DUNE CP Violation Sensitivity



Model 1

Model 2

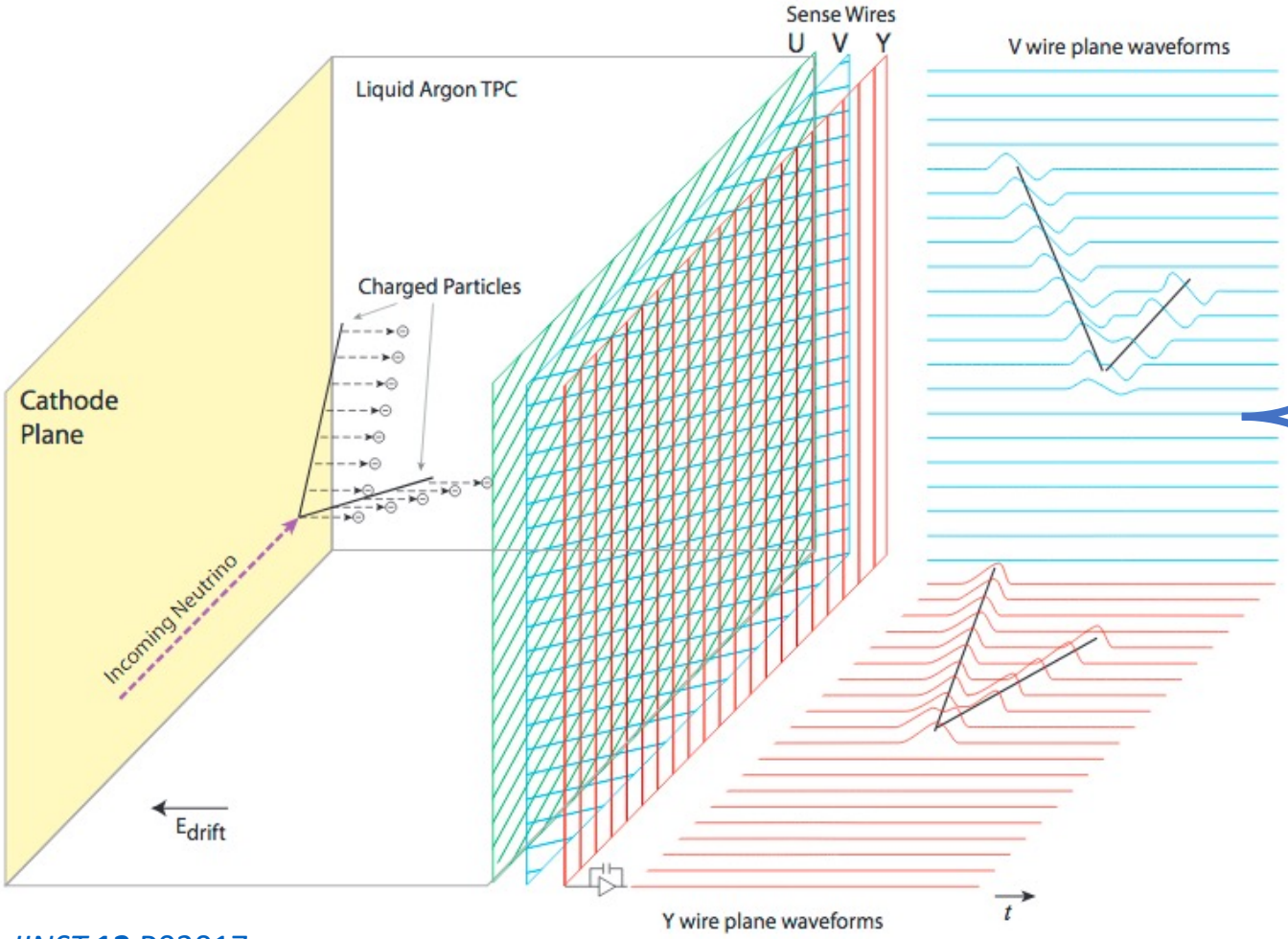
arXiv:2103.13910 [physics.ins-det]

2022 PDG

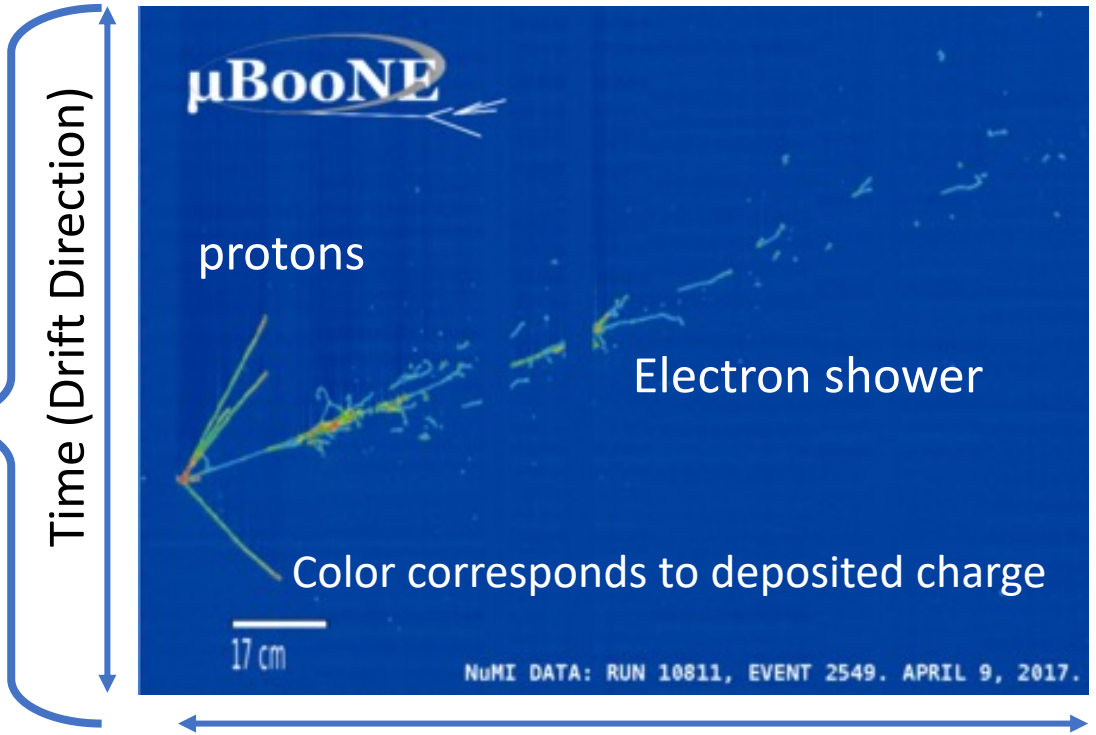
Experiment	beam	$\langle E_\nu \rangle$, $\langle E_{\overline{\nu}} \rangle$ GeV	neutrino target(s)	run period
ArgoNeuT	$\nu, \overline{\nu}$	4.3, 3.6	Ar	2009 – 2010
ICARUS (at CNGS)	ν	20.0	Ar	2010 – 2012
ICARUS (at FNAL)	ν	0.8	Ar	2021 –
K2K	ν	1.3	CH, H_2O	2003 – 2004
MicroBooNE	ν	0.8	Ar	2015 – 2020
MINERvA	$\nu, \overline{\nu}$	3.5 (LE), 5.5 (ME)	He, C, CH, H_2O, Fe, Pb	2009 – 2019
MiniBooNE	$\nu, \overline{\nu}$	0.8, 0.7	CH_2	2002 – 2019
MINOS	$\nu, \overline{\nu}$	3.5, 6.1	Fe	2004 – 2016
NOMAD	$\nu, \overline{\nu}$	23.4, 19.7	C–based	1995 – 1998
NOvA	$\nu, \overline{\nu}$	2.0, 2.0	CH_2	2010 –
SciBooNE	$\nu, \overline{\nu}$	0.8, 0.7	CH	2007 – 2008
T2K	ν, $\overline{\nu}$	0.6, 0.6	CH, H_2O, Fe	2010 –

More measurements → creation of more accurate models → better understanding of prediction

Liquid Argon Time Projection Chambers



JINST **12** P02017



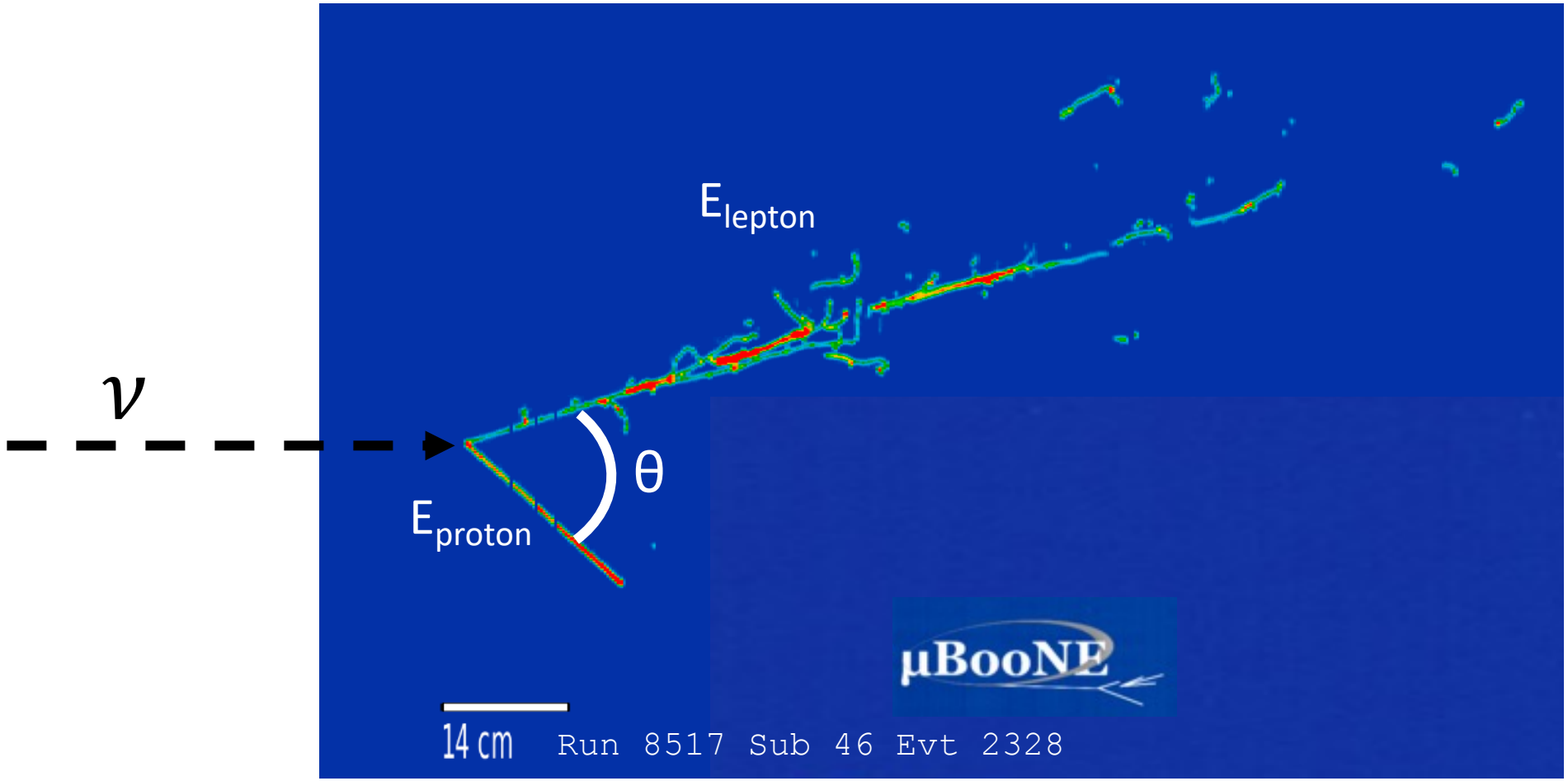
Showers (e, π^0):

Tracks (μ, p, π^+):

- Protons are charged so they always ionize the argon
  - Visible down to tens of MeV, depending on wire spacing -> access to lepton and hadronic parts of interactions

What Can We Measure?

1. Lepton properties: energy, angle relative to hadrons

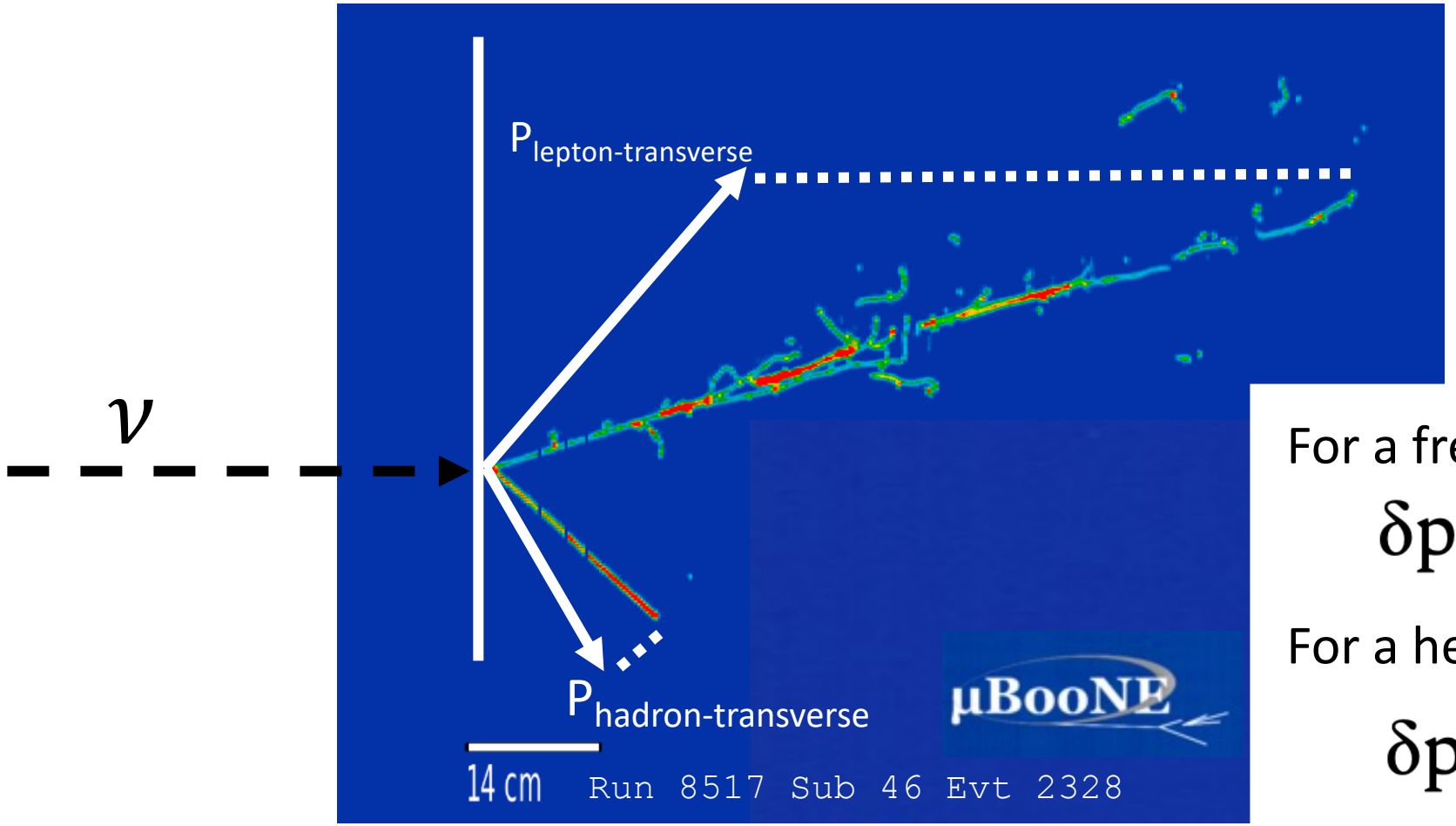


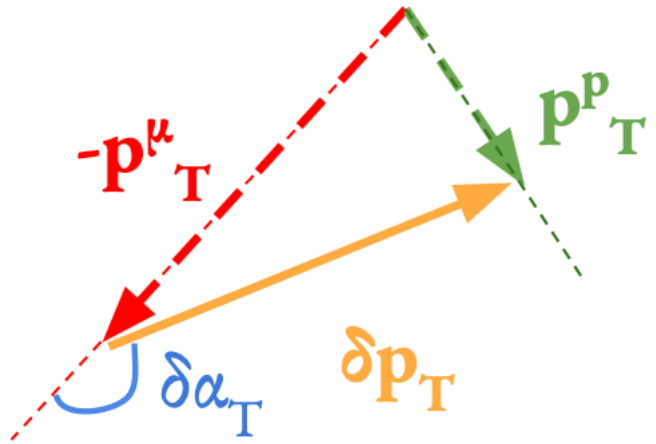
2. Hadronic System: energy and number of protons/pions

These kinematics are inputs to calculate neutrino energy

What Can We Measure?

3. Transverse kinematic imbalance: sensitivity to final state interactions and nuclear model





For a free nucleon target:

$$\delta p_T = \left| \mathbf{p}_T^{\mu} + \mathbf{p}_T^{p} \right| = 0$$

For a heavier target (like argon):

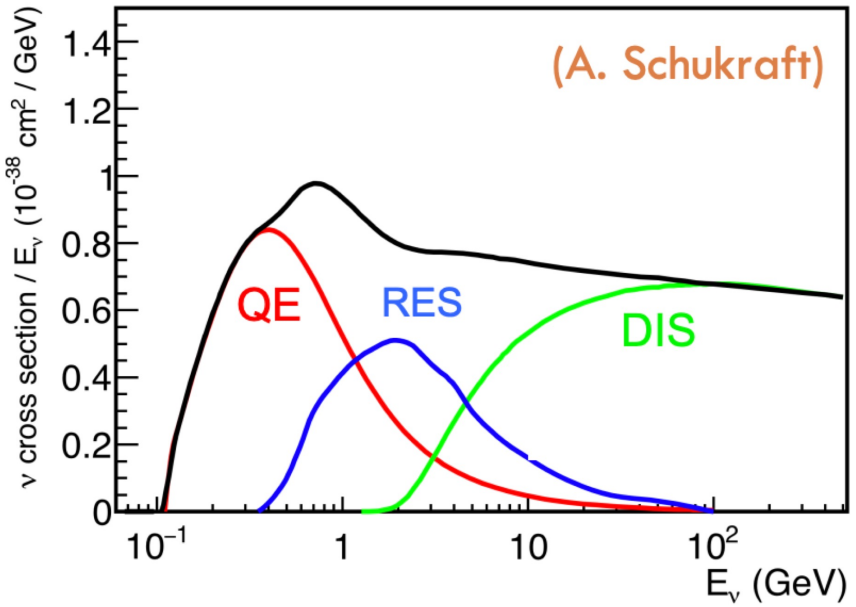
$$\delta p_T = \left| \mathbf{p}_T^{\mu} + \mathbf{p}_T^{p} \right| > 0$$

More in upcoming talks and poster:
[1], [2], [3]

Orientation of imbalance: $\delta\alpha_T$

What measurements do we need?

- **Charged current measurements:**



Inclusive:

$\nu_\mu + X \rightarrow \mu + X$

Quasi-Elastic:

$\nu_\mu + n \rightarrow \mu^- + p$

Resonant pion production:

$\nu_\mu + p/n \rightarrow \mu + \pi + p/n$

Multi-proton:

$\nu_\mu + \mathrm{Ar} \rightarrow \mu + 2p$

Coherent scattering:

$\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + \pi^+ + \mathrm{Ar};$

- **Neutral current measurements**
- **Anti-neutrino measurements**
- **Electron neutrino measurements:**

In all the same channels, to the extent statistics allow
Small component of neutrino beam(0.5-5%)

… And any others!

The more we have to build models the better our predictions will be for oscillation measurements

ArgoNeuT and MicroBooNE

- Liquid argon time projection chamber detectors
- To date most neutrino-argon cross section measurements are from these experiments

	ArgoNeuT [JINST 7 (2012) P10019]	MicroBooNE [JINST 12 (2017) 02, P02017]
Operation:	2009-2010	2015-2020
Active Volume:	0.25 Ton	85 Ton
Beam Energy:	NuMI (on-axis): neutrino = <4.6 GeV> anti-neutrino = <3.6 GeV>	BNB: neutrino = <0.8 GeV> NuMI (8˚ off axis): neutrino = ~<0.9 GeV> anti-neutrino = ~<0.9 GeV>

Overview of selected results from these experiments

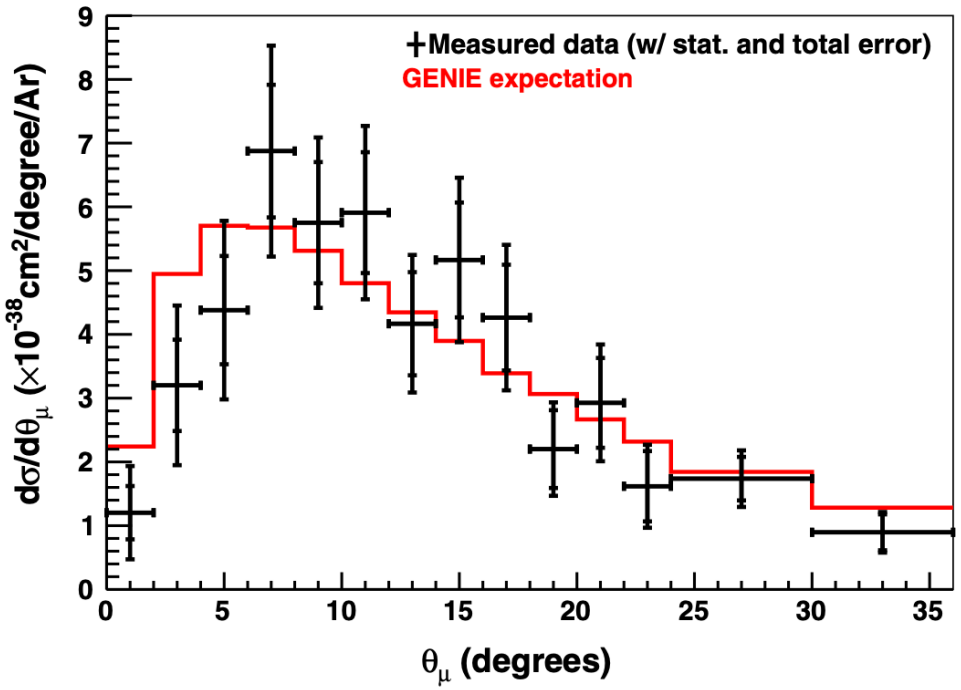
Inclusive Muon Neutrino Measurements

- Dominant component of the beam (95%+)
- Requires only identifying the charged lepton: do not separate between hadronic final states
- Test overall cross section model

$$\nu_\mu + X \rightarrow \mu + X$$

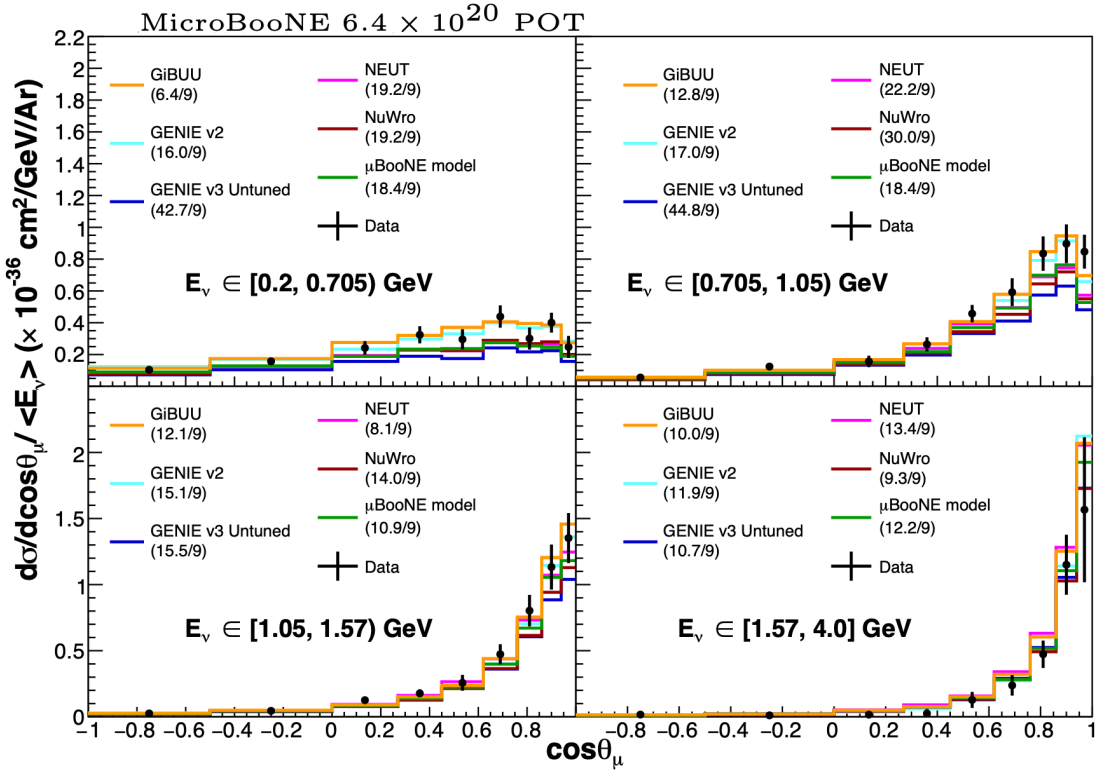
2012: First measurement

ArgoNeuT: Phys. Rev. Lett. **108**, 161802



2023: First triple differential measurement

MicroBooNE: arXiv:2307.06413



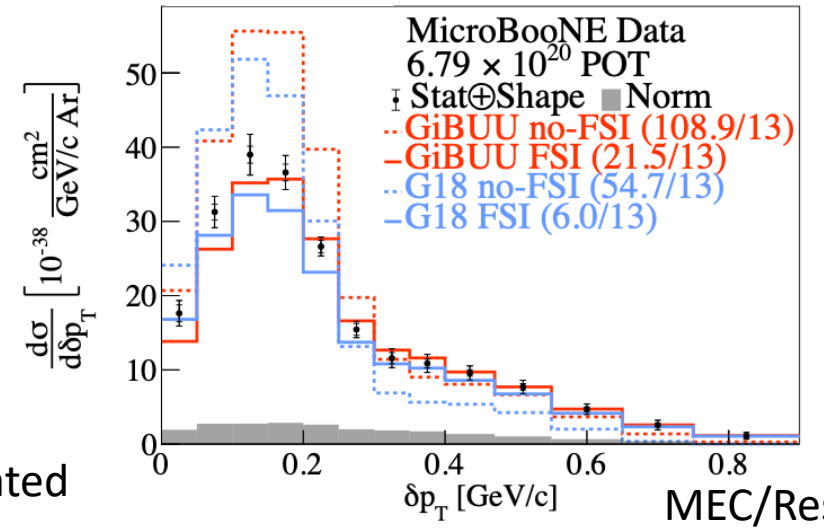
More in upcoming talks: [1], [2]

CCQE-like Topology: 1μ1p0π

- First transverse kinematic imbalance measurement on argon target

Compare with and without FSI: data favors including FSI

All Events



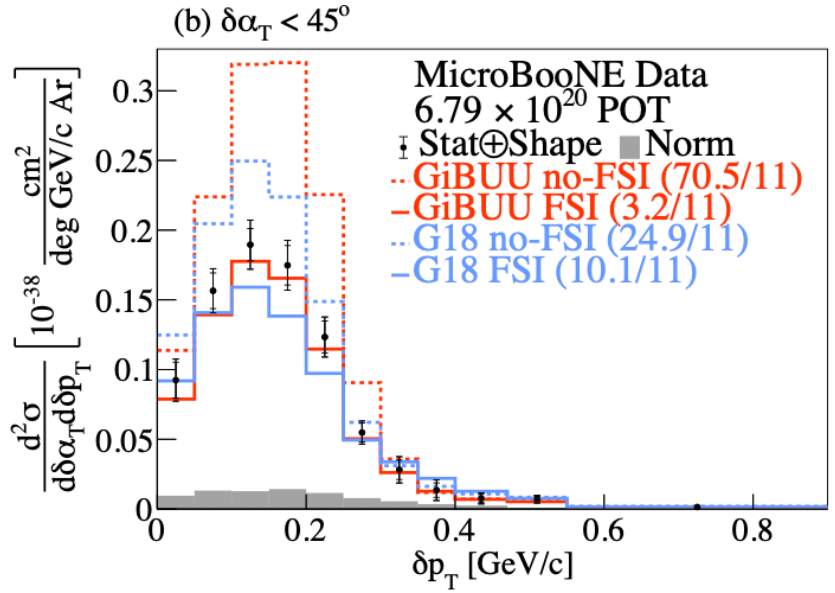
$$\nu_\mu + n \rightarrow \mu^- + p$$

arXiv:2301.03700, accepted by PRL

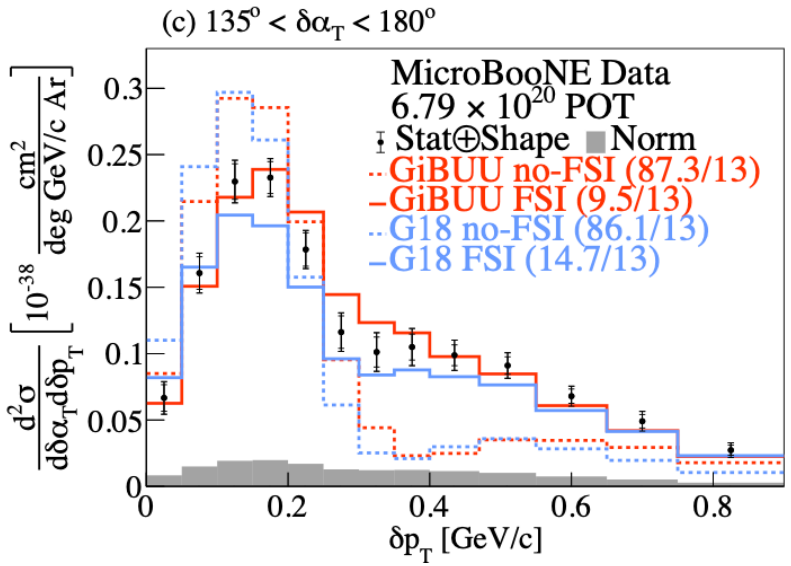
arXiv:2301.03706, accepted by PRD

More in upcoming talks and poster: [1], [2], [3]

Quasi-Elastic Dominated



MEC/Resonant/FSI Dominated



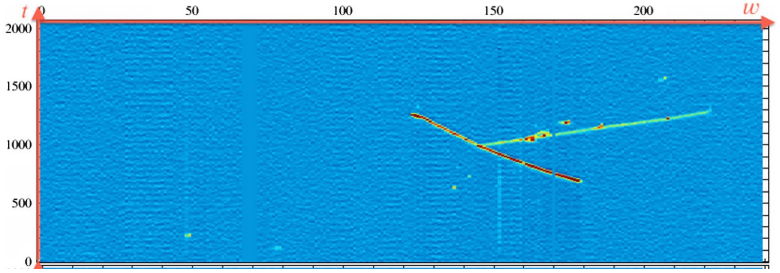
Consistent with local Fermi gas models in generators

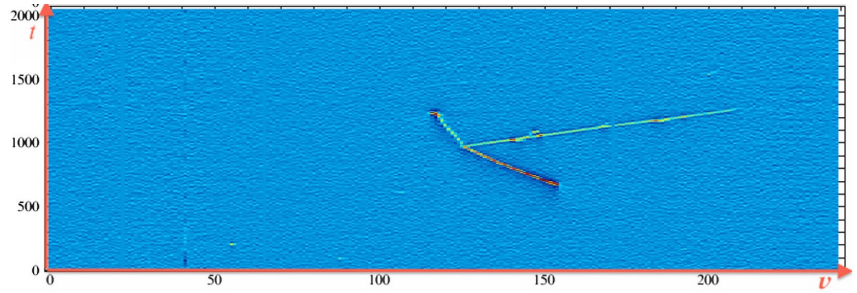
FSI models have good agreement with data

Multi-Proton Measurement: 1μ2p0π

$$\nu_\mu + \mathrm{Ar} \rightarrow \mu + 2p$$

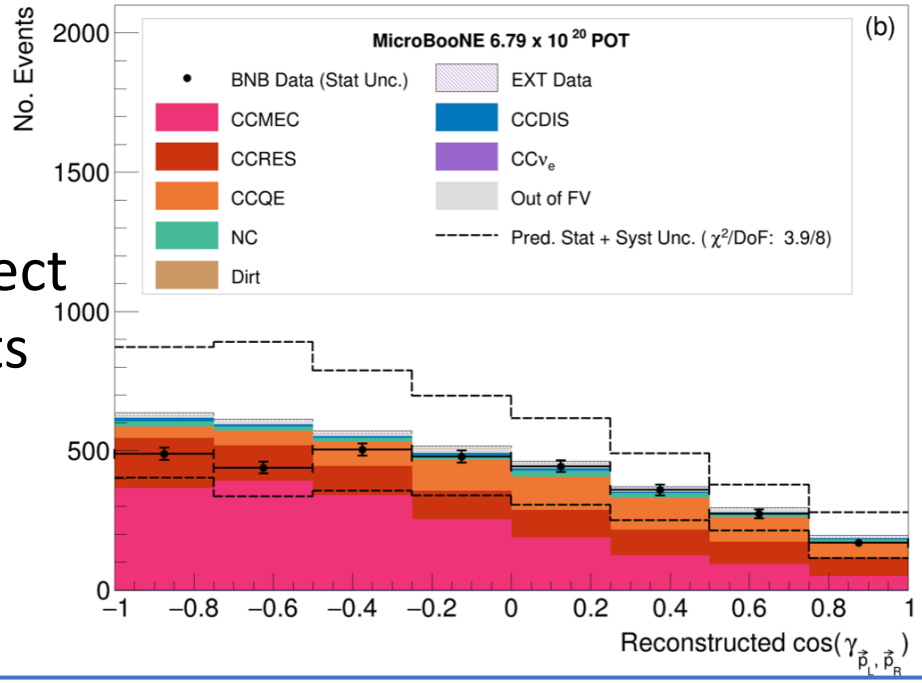
ArgoNeuT: First observation in argon [Phys. Rev. D **90**, 012008]



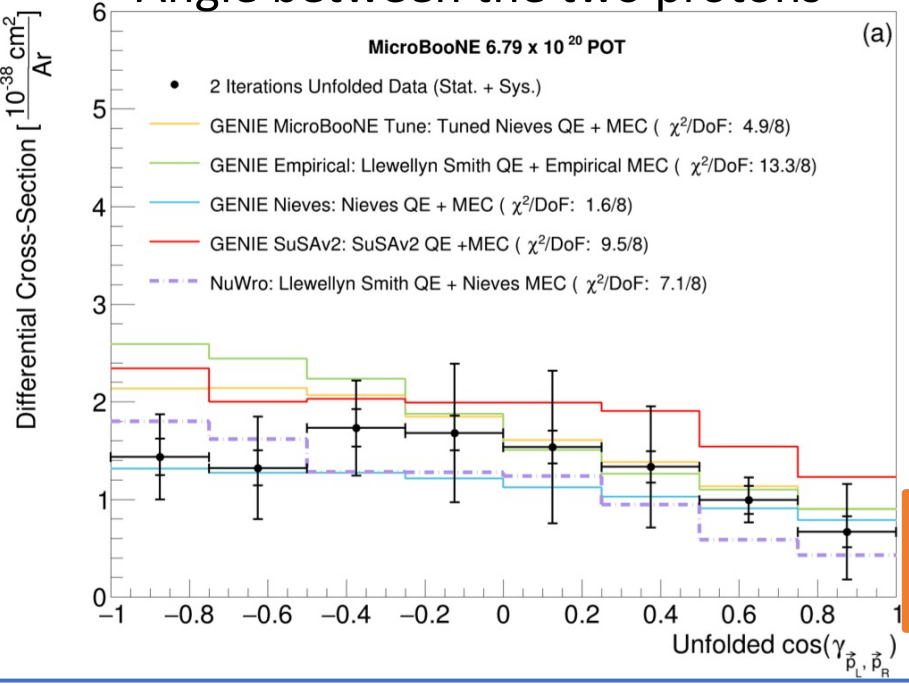


MicroBooNE: First cross section measurement [arXiv:2211.03734]

Mostly select MEC events



Angle between the two protons



Model tension at low cos(γ)

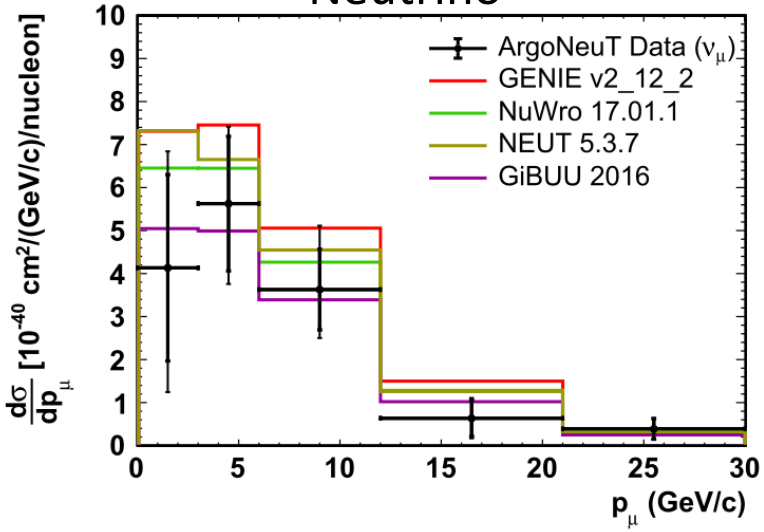
More in upcoming talks: [1], [2]

CC1π⁺ and CC Coherent: ArgoNeuT First Measurements

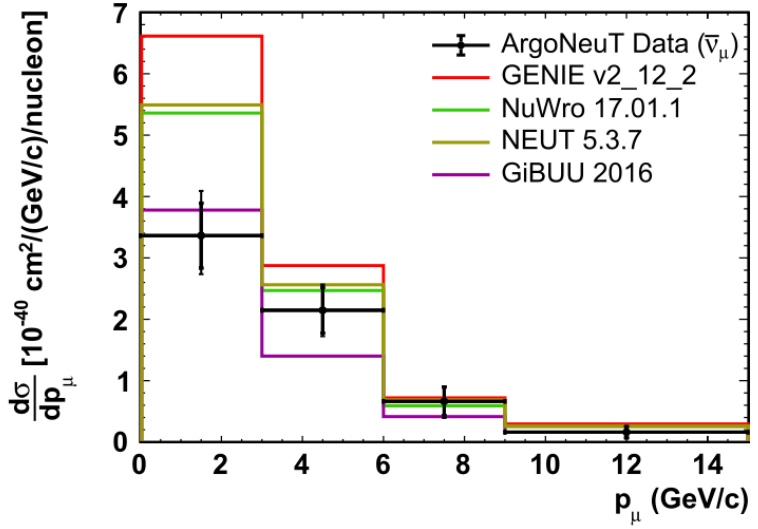
- CC1π⁺: [Phys. Rev. D **98**, 052002]

$$\nu_\mu + p/n \rightarrow \mu + \pi + p/n$$

Neutrino

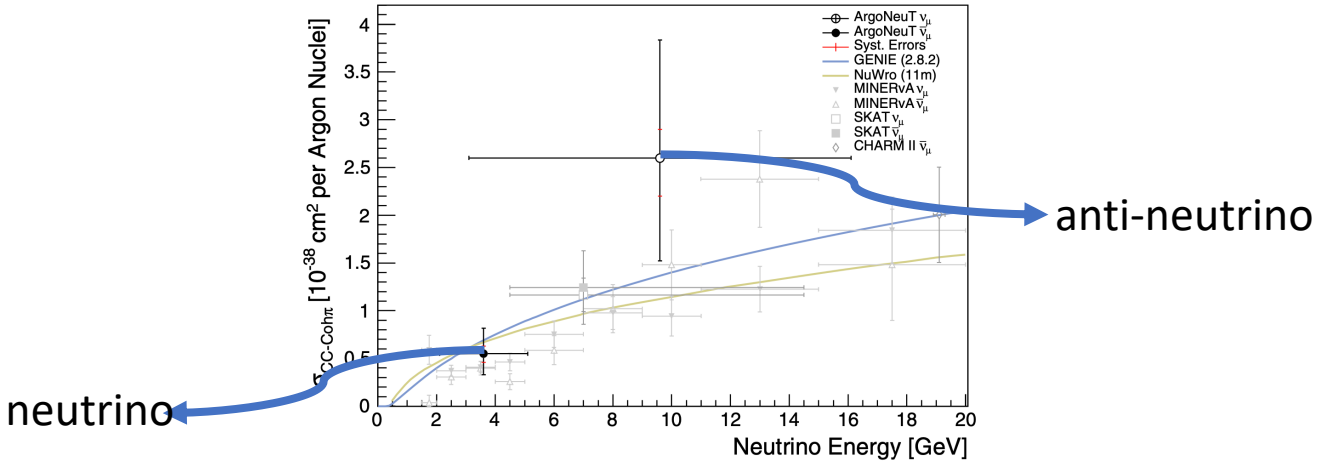


Anti-neutrino



- Resonance interactions will be some of the dominant at DUNE energies
- Reasonable agreement with GiBUU, overprediction in other generators.
- Similar story in θ_μ

- Coherent scattering off argon nucleus: [Phys. Rev. Lett. **113**, 261801]



$$\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + \pi^+ + \mathrm{Ar};$$
$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \pi^- + \mathrm{Ar};$$

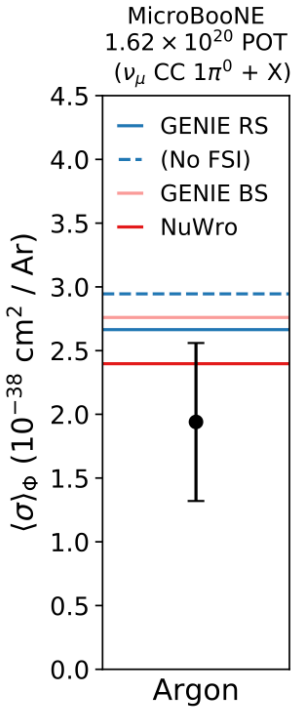
Low statistics at this point; dominated by statistical uncertainties

Interactions with π^0s

- Resonance interactions are in the peak of the DUNE neutrino energy spectrum
- Important background for electron neutrino searches: π^0 -> γ γ

Charged Current:

MicroBooNE [Phys. Rev. D **99**, 091102(R)]

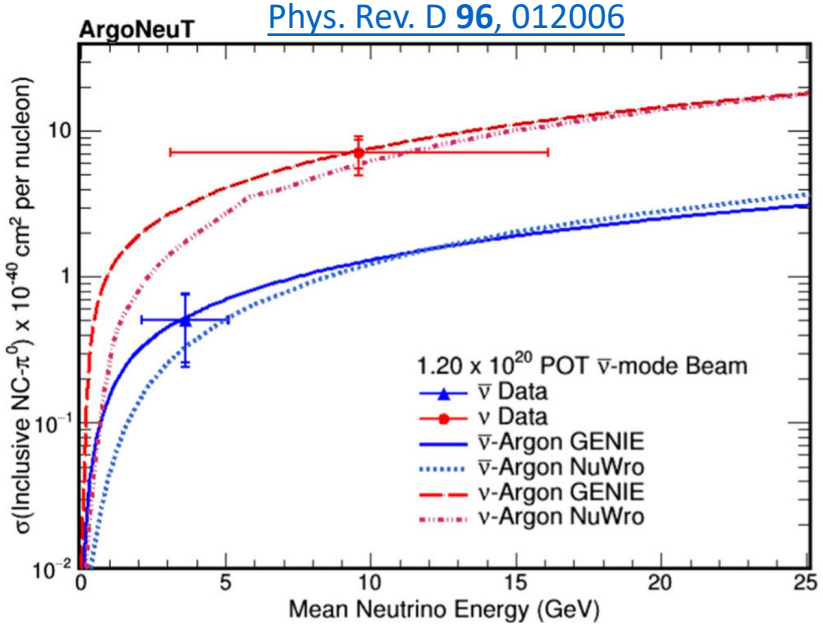


First inclusive cross section

Best agreement with NuWro

Neutral Current:

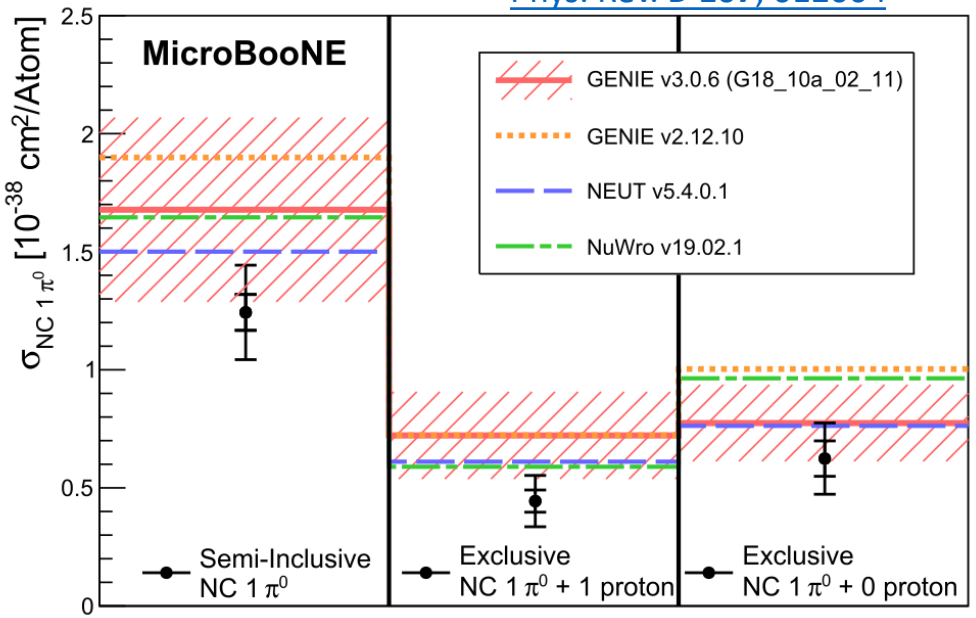
ArgoNeuT inclusive cross section [Phys. Rev. D **96**, 012006]



$$\nu_\mu + \mathrm{Ar} \rightarrow \nu_\mu + \pi^0 + \mathrm{X},$$

$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \bar{\nu}_\mu + \pi^0 + \mathrm{X}$$

MicroBooNE exclusive hadronic final states [Phys. Rev. D **107**, 012004]



More in upcoming talks: [1], [2]

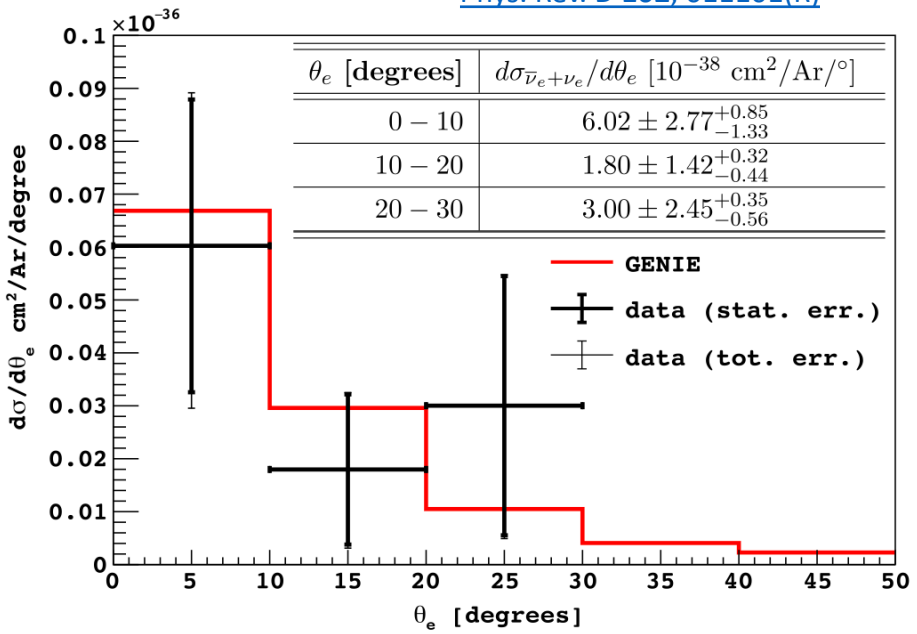
Electron Neutrino Inclusive

$$\nu_e + Ar \rightarrow e + X$$

- Important for electron neutrino appearance searches and CP measurements
- Combined neutrino and anti-neutrino data from NuMI beamline
- General model agreement, though statistically limited as electron neutrinos are a small fraction of the beam

ArgoNeuT: First measurement

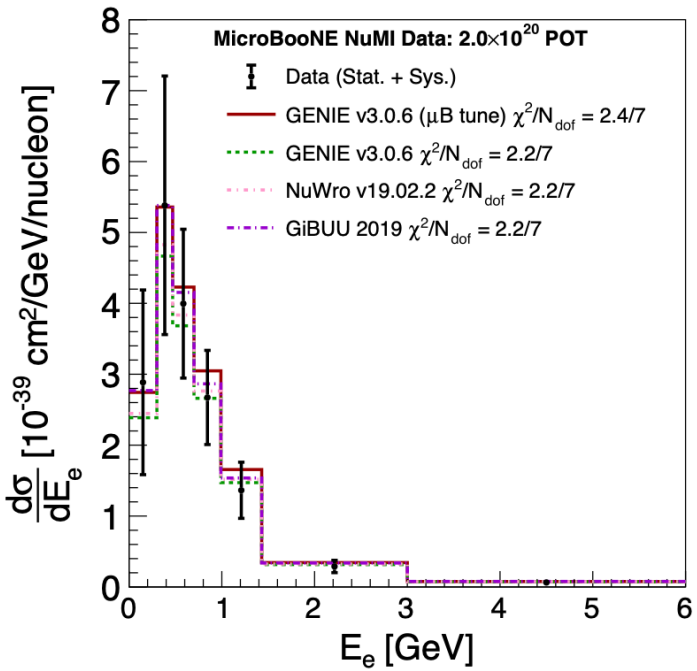
Phys. Rev. D **102**, 011101(R)

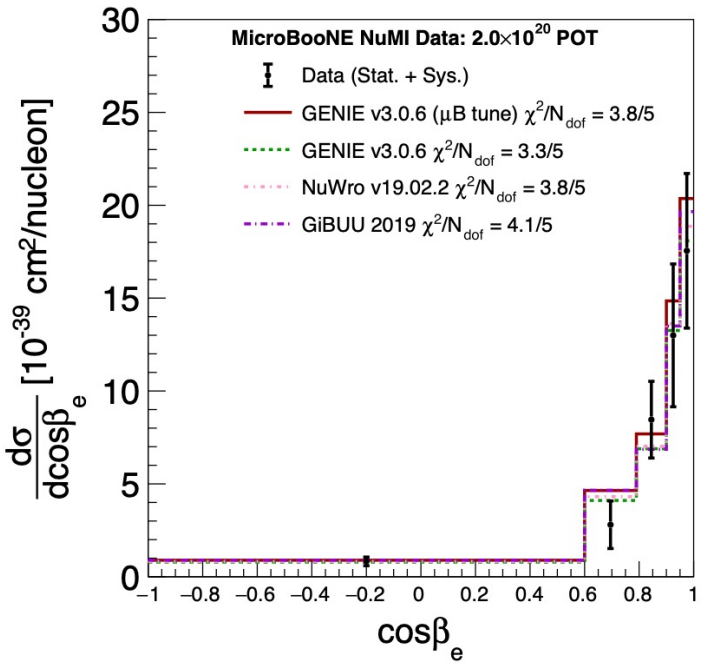


θ_e [degrees]	$d\sigma_{\overline{\nu}_e+\nu_e}/d\theta_e$ [10^{-38} cm^2/Ar/°]
$0-10$	$6.02 \pm 2.77^{+0.85}_{-1.33}$
$10-20$	$1.80 \pm 1.42^{+0.32}_{-0.44}$
$20-30$	$3.00 \pm 2.45^{+0.35}_{-0.56}$

MicroBooNE: Differential in lepton energy and angle

Phys. Rev. D **105**, L051102



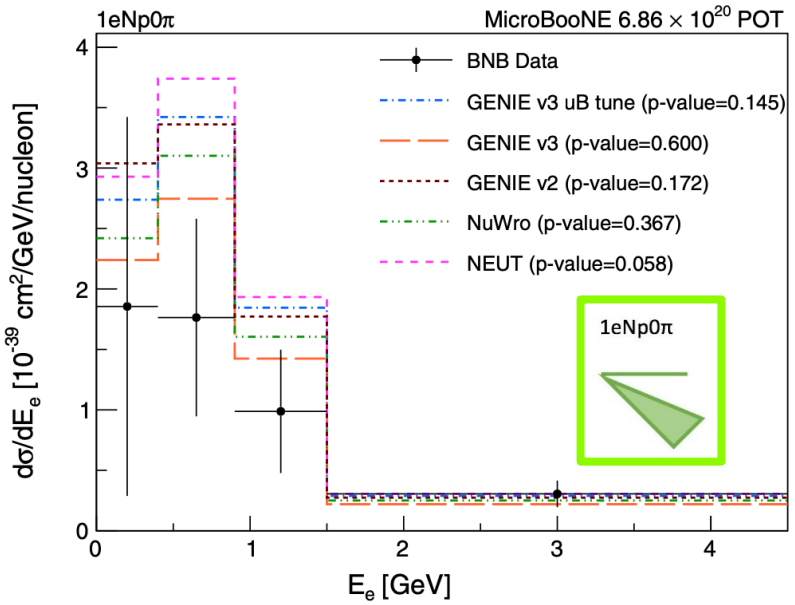


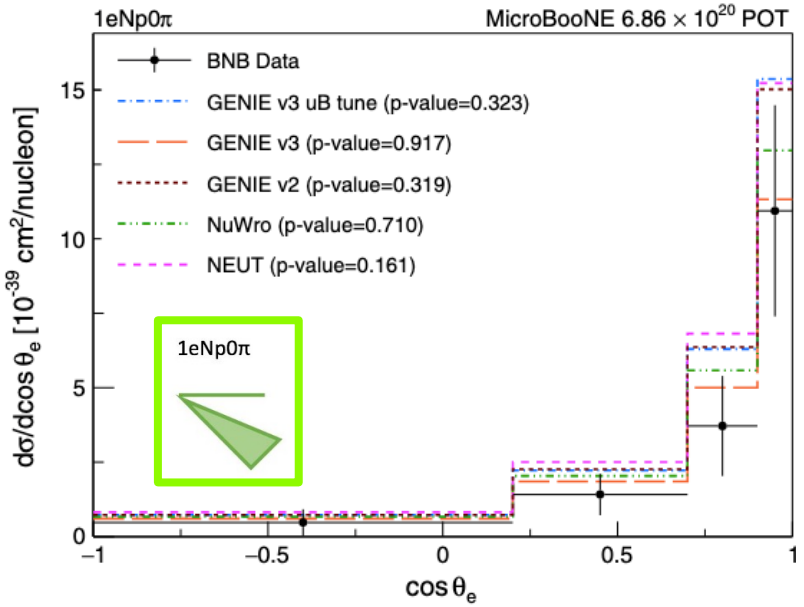
Electron Neutrino Exclusive: CC0π

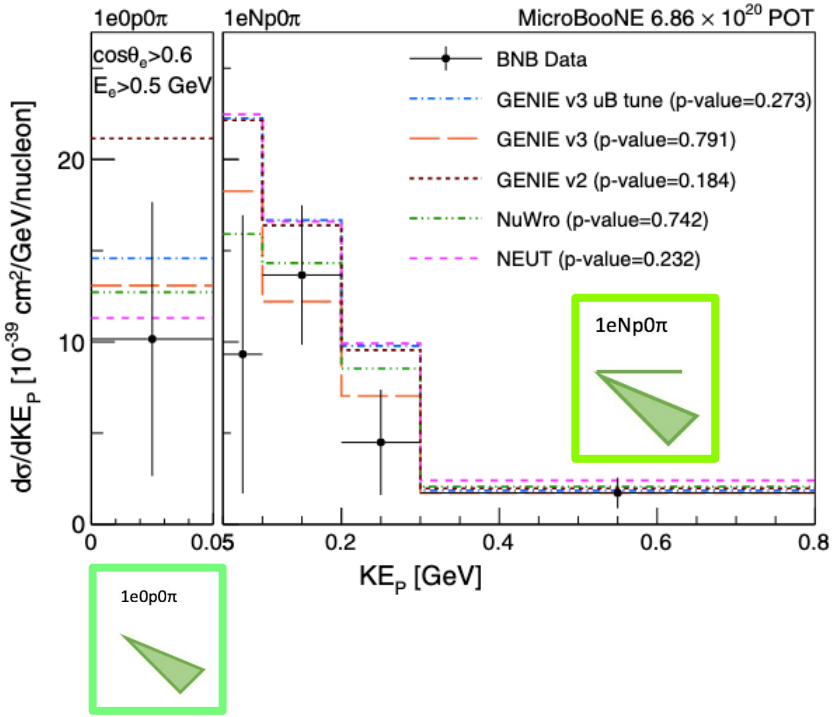
- First exclusive electron neutrino measurement on argon with MicroBooNE
- BNB data: 0.5% of beam is electron neutrinos
- Best agreement with models with overall lower predictions

$$\nu_e + Ar \rightarrow e + Np + 0\pi$$

Phys. Rev. D Letter, 106, L051102 (2022)







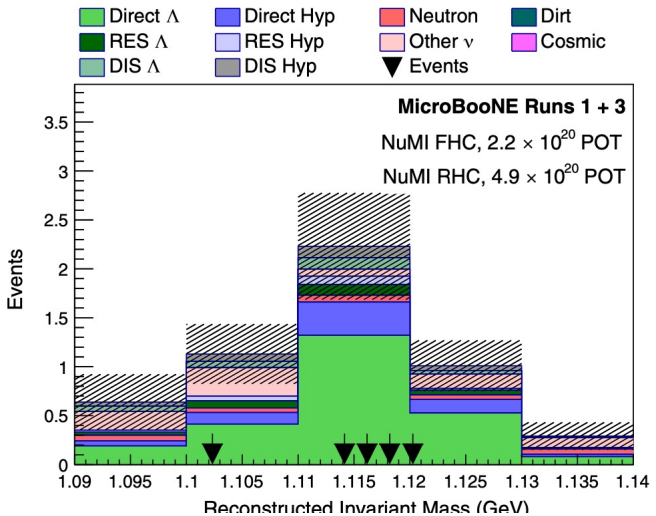
Rare Channels: Λ and η Production

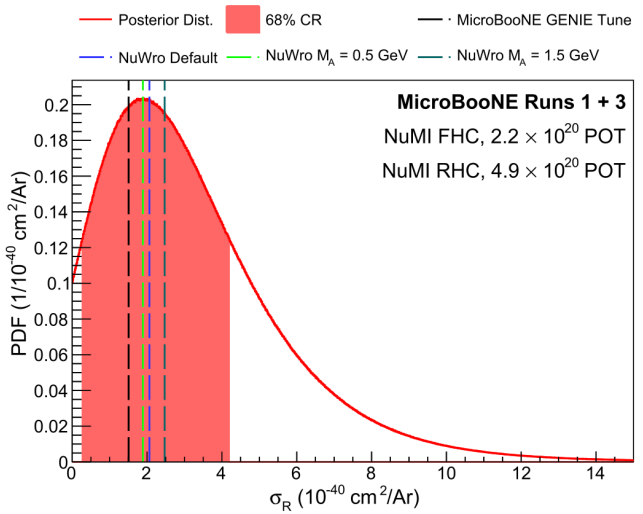
- First searches for rare channels with the higher statistics argon interactions in MicroBooNE

$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \Lambda + X$$

- Background to proton decay searches: mimics $p \rightarrow K\nu$
- Strictly anti-neutrinos: may provide constraint

Phys. Rev. Lett. **130**, 231802

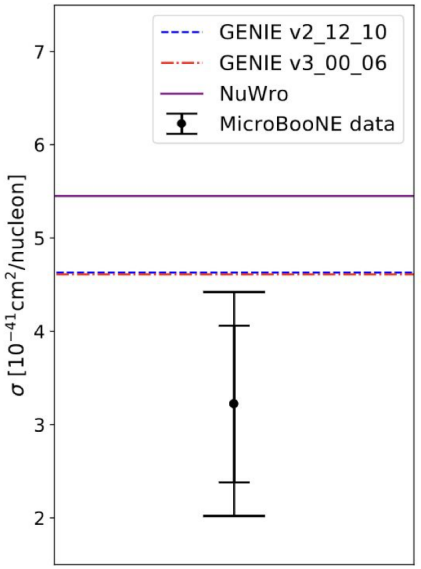




More in upcoming talks: [1], [2]

$$\nu_\mu + N \rightarrow \mu + \eta + N$$

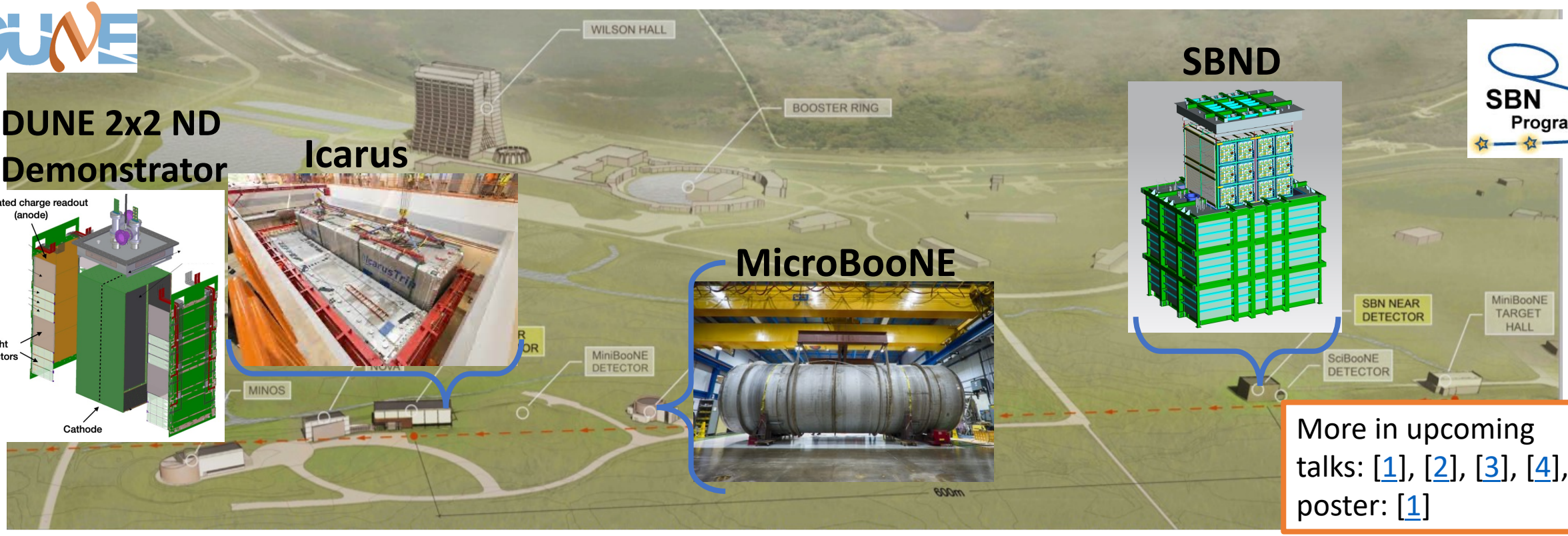
- Handle on higher order resonance modeling: N(1535) and N(1650) both have significant branching ratios to η
- Proton decay channels that produce η



arXiv:2305.16249

More in upcoming talk: [3]

Wealth of New Data Ahead



DUNE 2x2 ND Demonstrator

Icarus

MicroBooNE

SBND

SBN Program

More in upcoming talks: [1], [2], [3], [4], [5]
poster: [1]

More statistics: better isolation of various final state topologies [1]

SBND expects 20-30 times more data in the BNB than current data sets, average neutrino energy 0.8 GeV
SBND NuInt '22

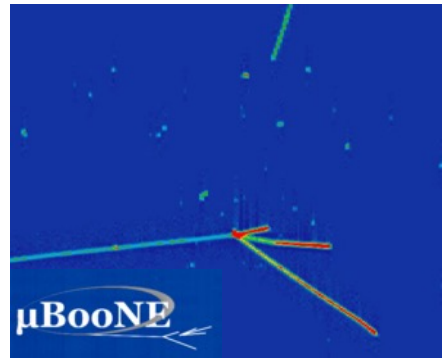
Icarus will measure NuMI neutrinos at ~5 degrees off axis (up to ~2 GeV) in addition to BNB neutrinos
Icarus NuINT '22

DUNE 2x2 ND Demonstrator will collect NuMI data on-axis over a range of energies (~2-8 GeV) 2x2 NuINT 2022

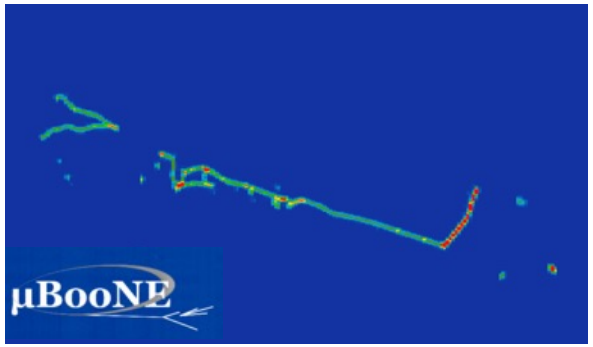
Opportunity for high statistics measurements, possibility of NuMI anti-neutrinos in Icarus and DUNE 2x2

Conclusions

- Neutrino-argon cross section measurements will provide critical input to models and future oscillation measurements



- Exciting time for neutrino-argon cross sections:
  - Refining experimental techniques to identify new exclusive states and rare channels for the first time



- Looking ahead to significantly more data with upcoming experiments
  - Many presentations with more details on neutrino-argon cross section measurements this week: MicroBooNE, Icarus, DUNE 2x2 demonstrator