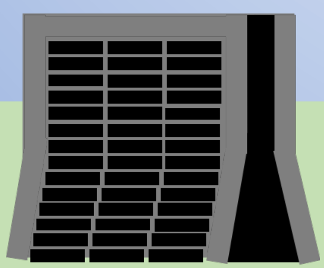
The University of Manchester

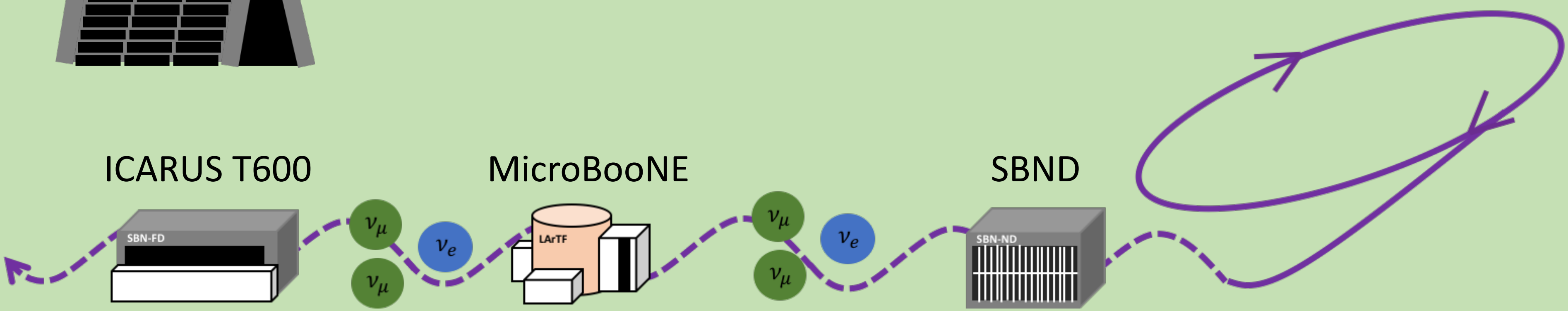
# Recent Neutrino Cross Section Results from MicroBooNE

**Krishan Mistry,** on behalf of the MicroBooNE Collaboration

19 Feb 2021



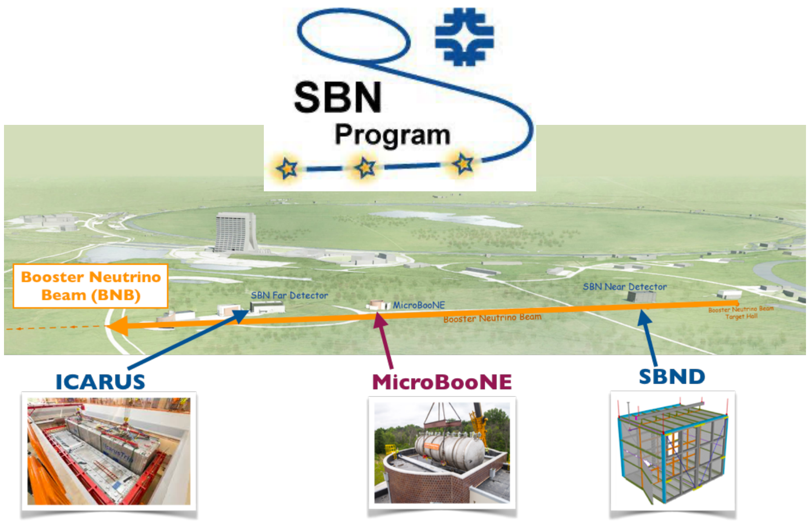
XIX International Workshop on Neutrino Telescopes



# Growing Interest in $\nu$–Ar Cross Sections

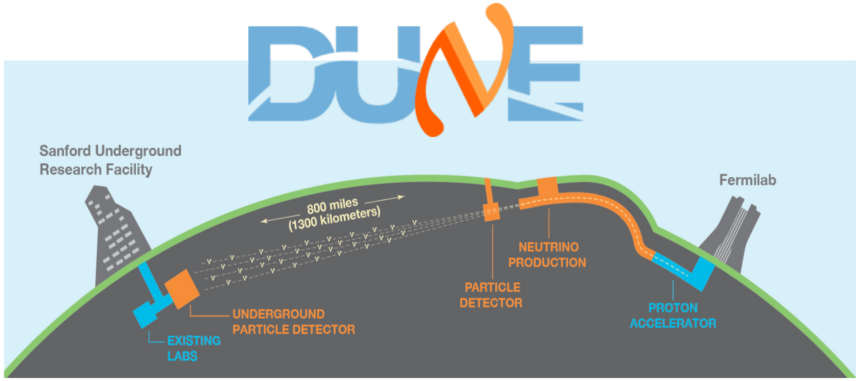
µBooNE

- A number of current and future neutrino oscillation experiments are employing Liquid Argon Time Projection Chambers (**LArTPCs**)
  - Short Baseline Neutrino (**SBN**) Program
  - Deep Underground Neutrino Experiment (**DUNE**)




arXiv:1503.01520 [physics.ins-det]

- Measurements of the $\nu$–Ar cross section directly feed into these experiments:
  - Allow us to develop models that are capable of describing neutrino interaction data on argon




arXiv:2002.03005 [hep-ex]

# Testing Models

- We can test models of neutrino interactions on argon by studying the outgoing particles and their kinematics
- Targeted channels can probe different physics

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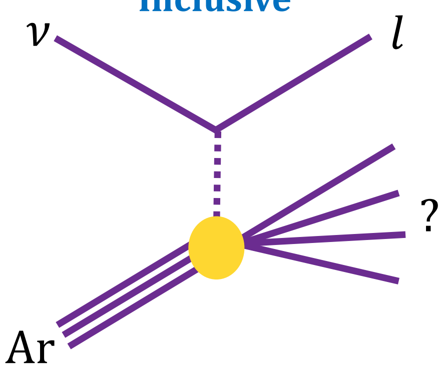
**Charged Current (CC) Inclusive**




- No requirements on the additional particles reconstructed with the outgoing lepton

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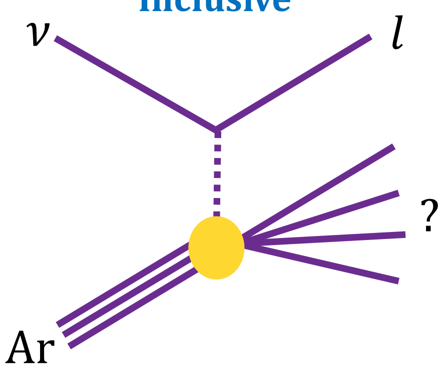


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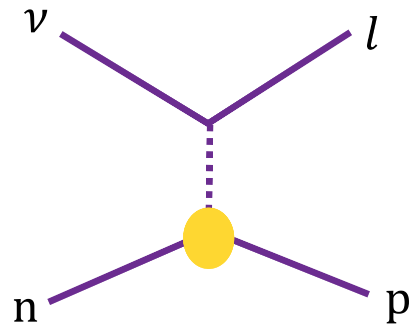
**CC Quasi-Elastic (QE)-Like**




- 1 proton and 1 lepton in the final state

# Testing Models

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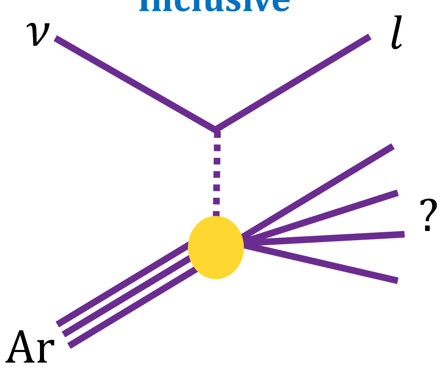


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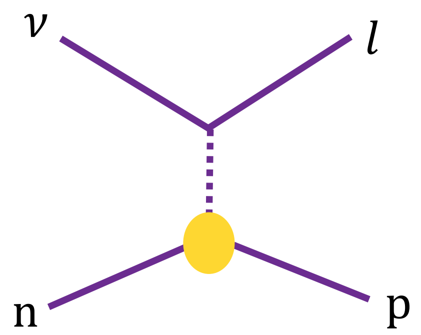
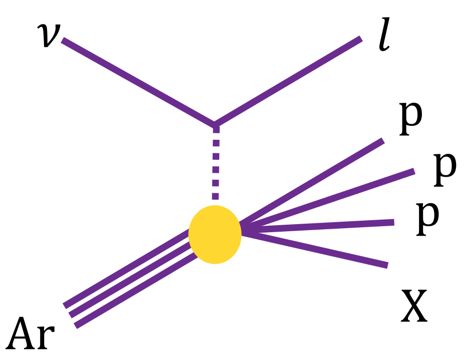



- 1 proton and 1 lepton in the final state

**CC 0π Np**

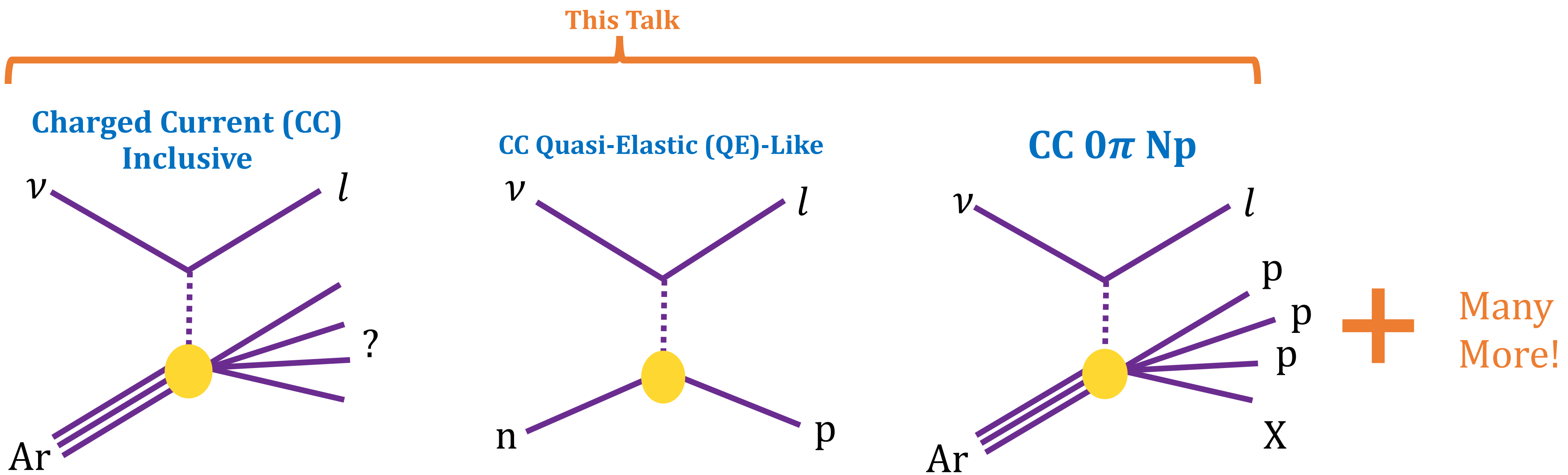



- N protons and 1 lepton in the final state

# Testing Models

µBooNE

- We can test models of neutrino interactions on argon by studying the outgoing particles and their kinematics
- Targeted channels can probe different physics

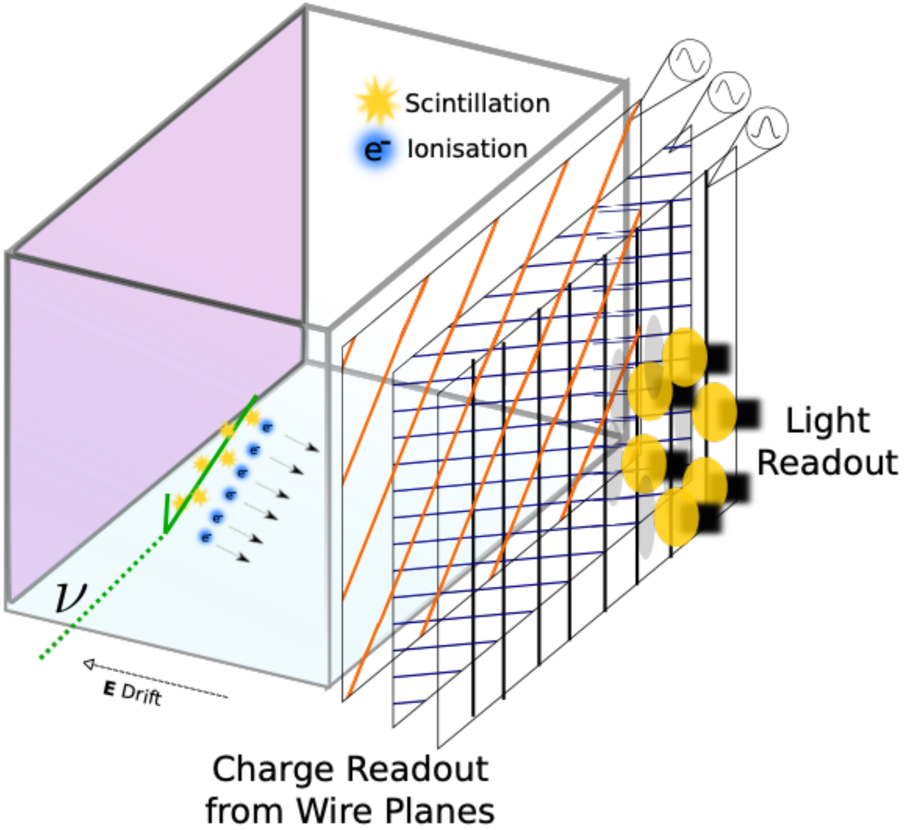



- No requirements on the additional particles reconstructed with the outgoing lepton
- 1 proton and 1 lepton in the final state
- N protons and 1 lepton in the final state

# Our Physics Probe: LArTPC

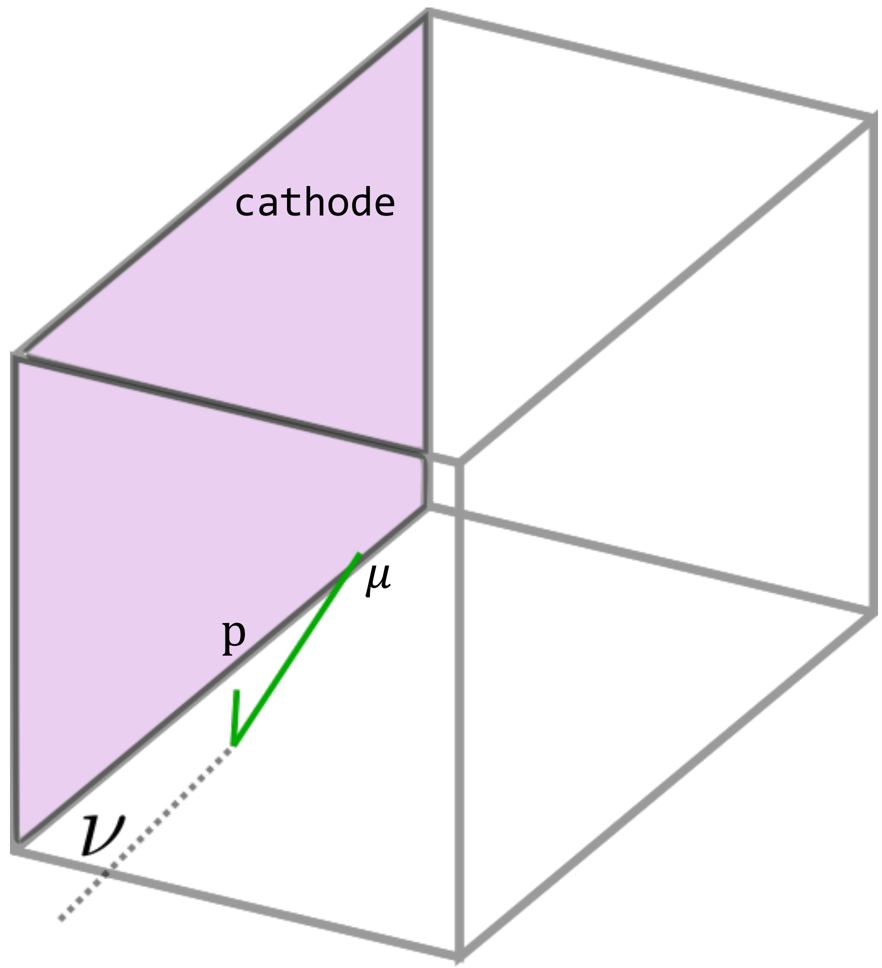


- LArTPCs are well equipped to do cross section physics and study the particles from a neutrino interaction
  - Low detection thresholds
  - $4\pi$ acceptance
  - Precise calorimetric information
- Lets see how they work…



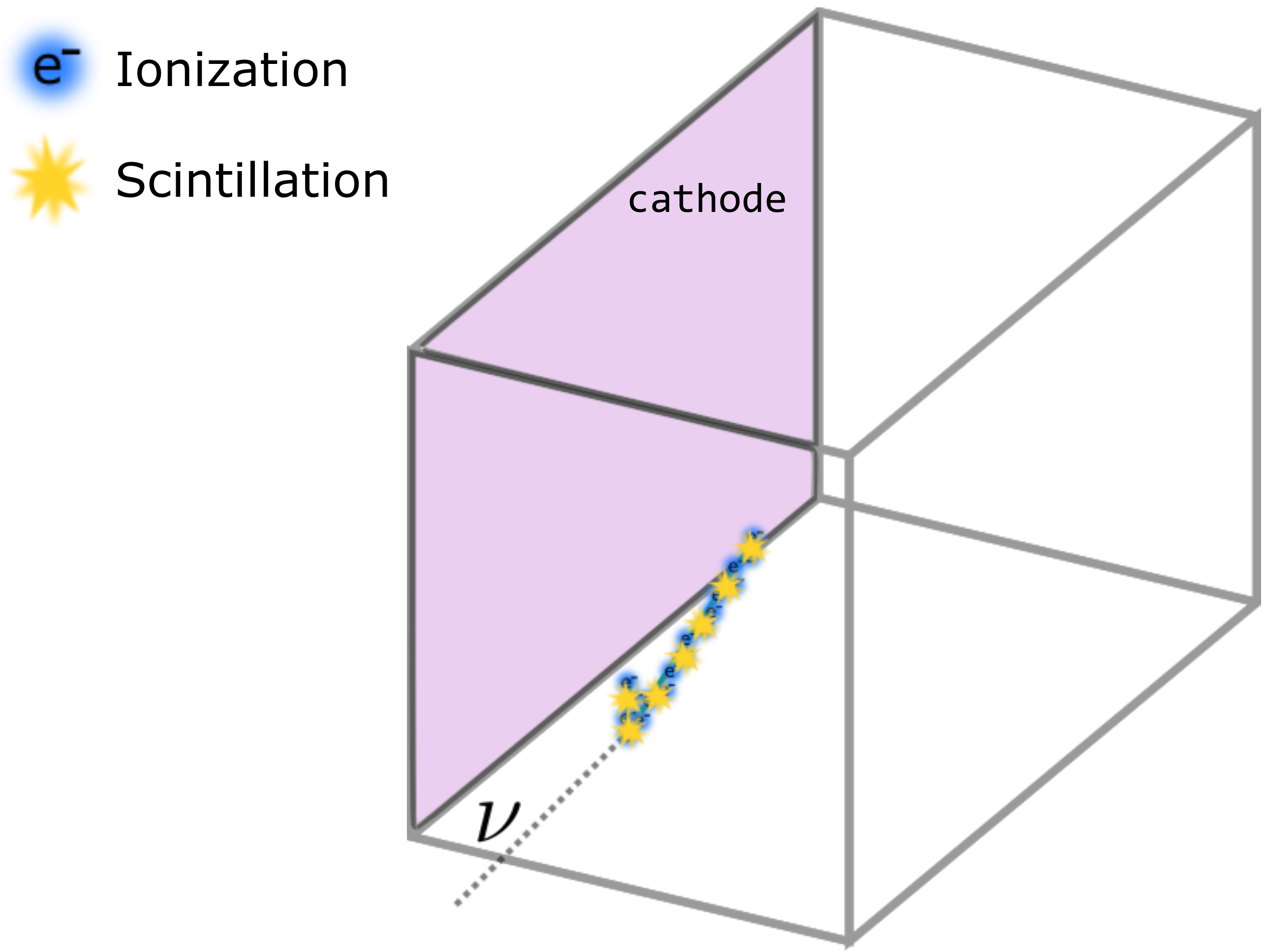
# LArTPC Operation

$\nu$ Interaction



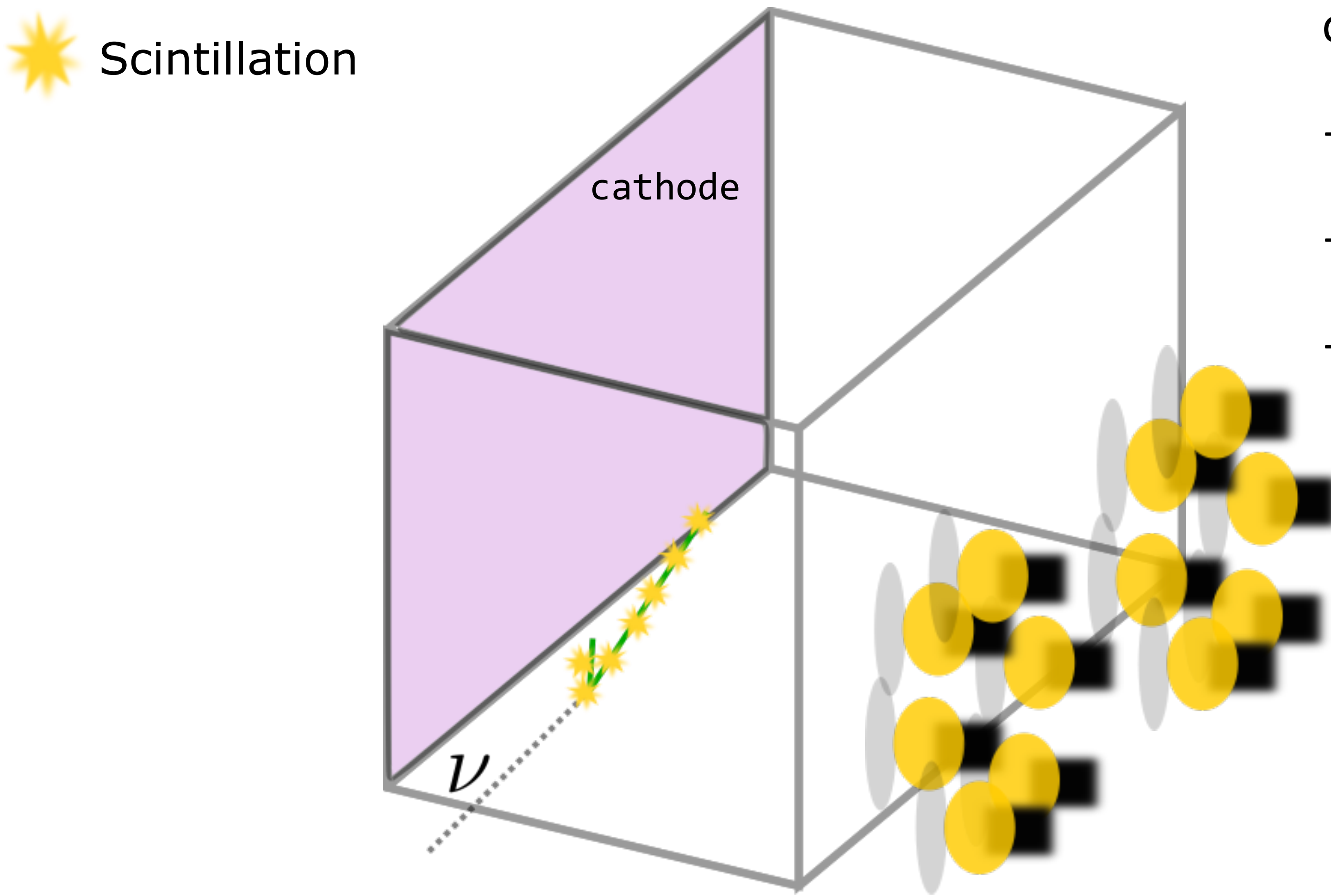

Neutrino interacts with the argon inside the TPC volume and produces daughter particles

# LArTPC Operation




Charged daughter particles ionize and excite the argon

# LArTPC Operation



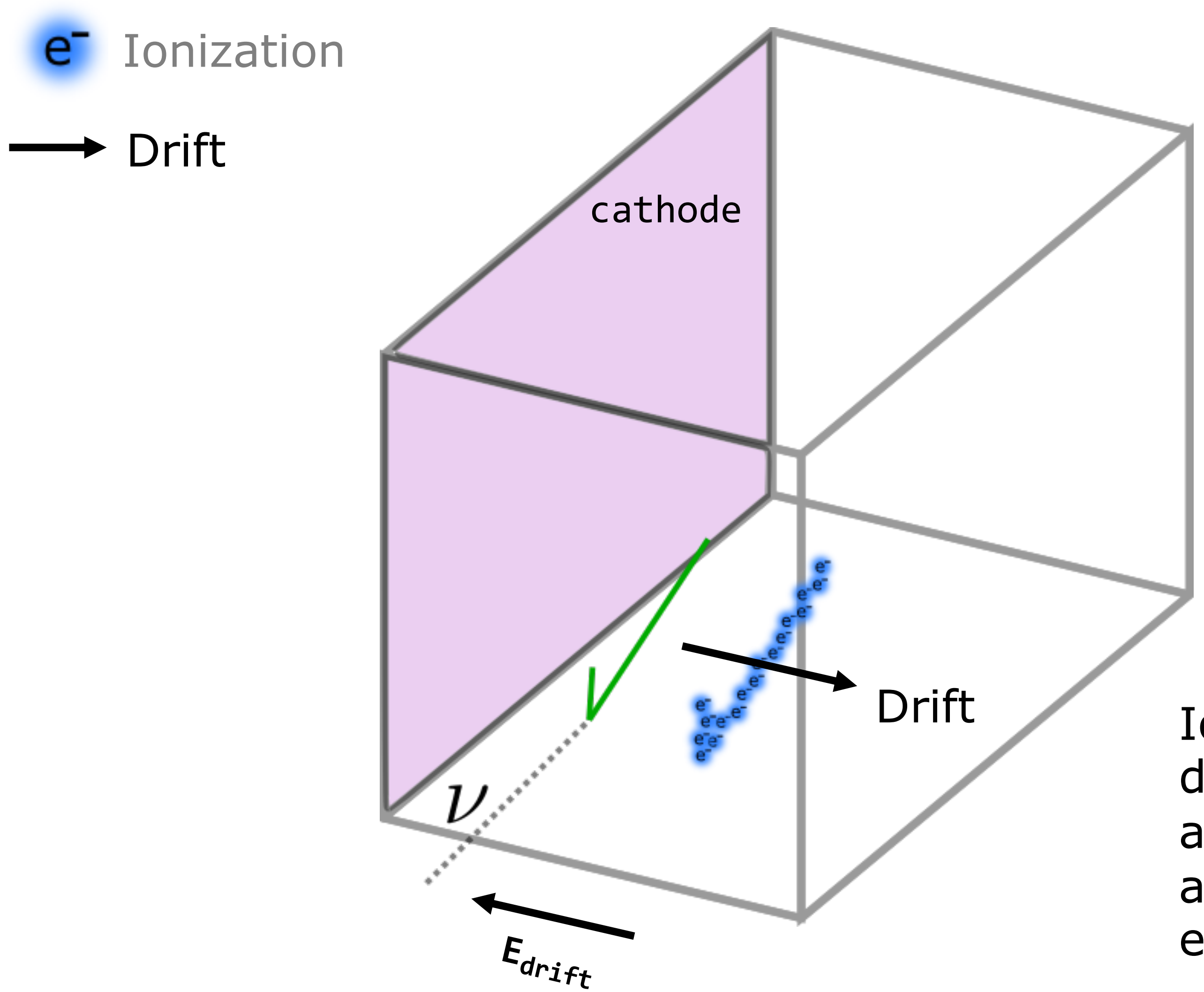

Scintillation light detected by PMTs

→ $t_0$

→ Reconstruction

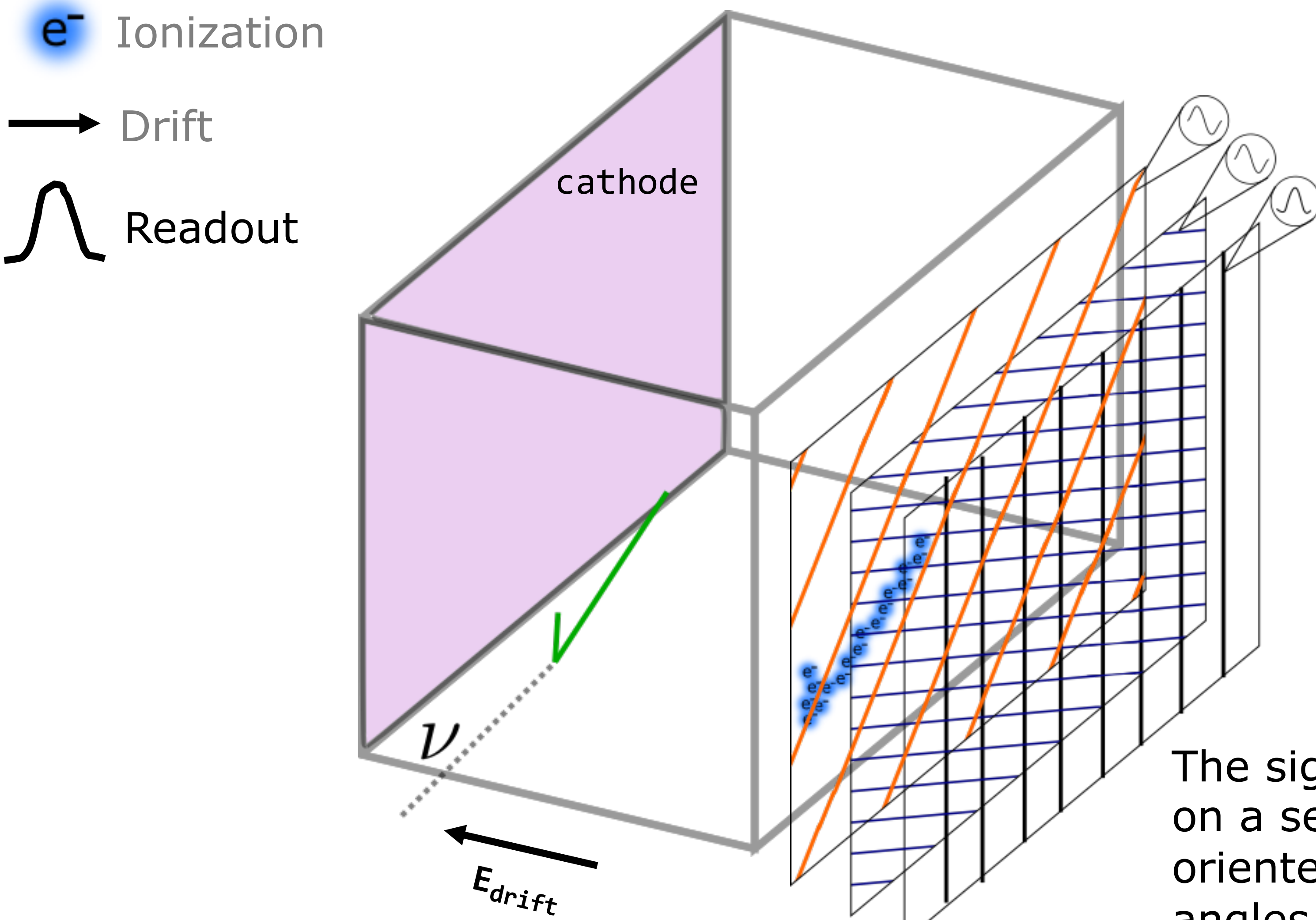
→ Trigger

# LArTPC Operation




Ionisation electrons drift towards the anode with the application of an electric field

# LArTPC Operation



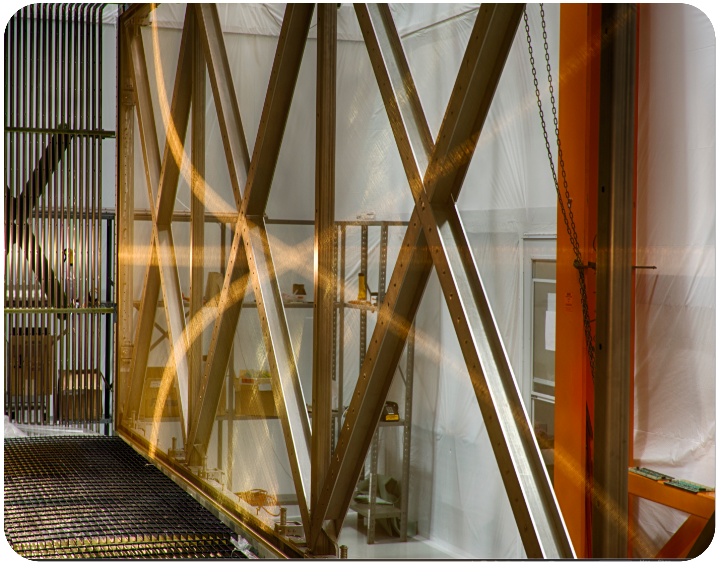

The signal is recorded on a set of wire planes oriented at different angles

# MicroBooNE

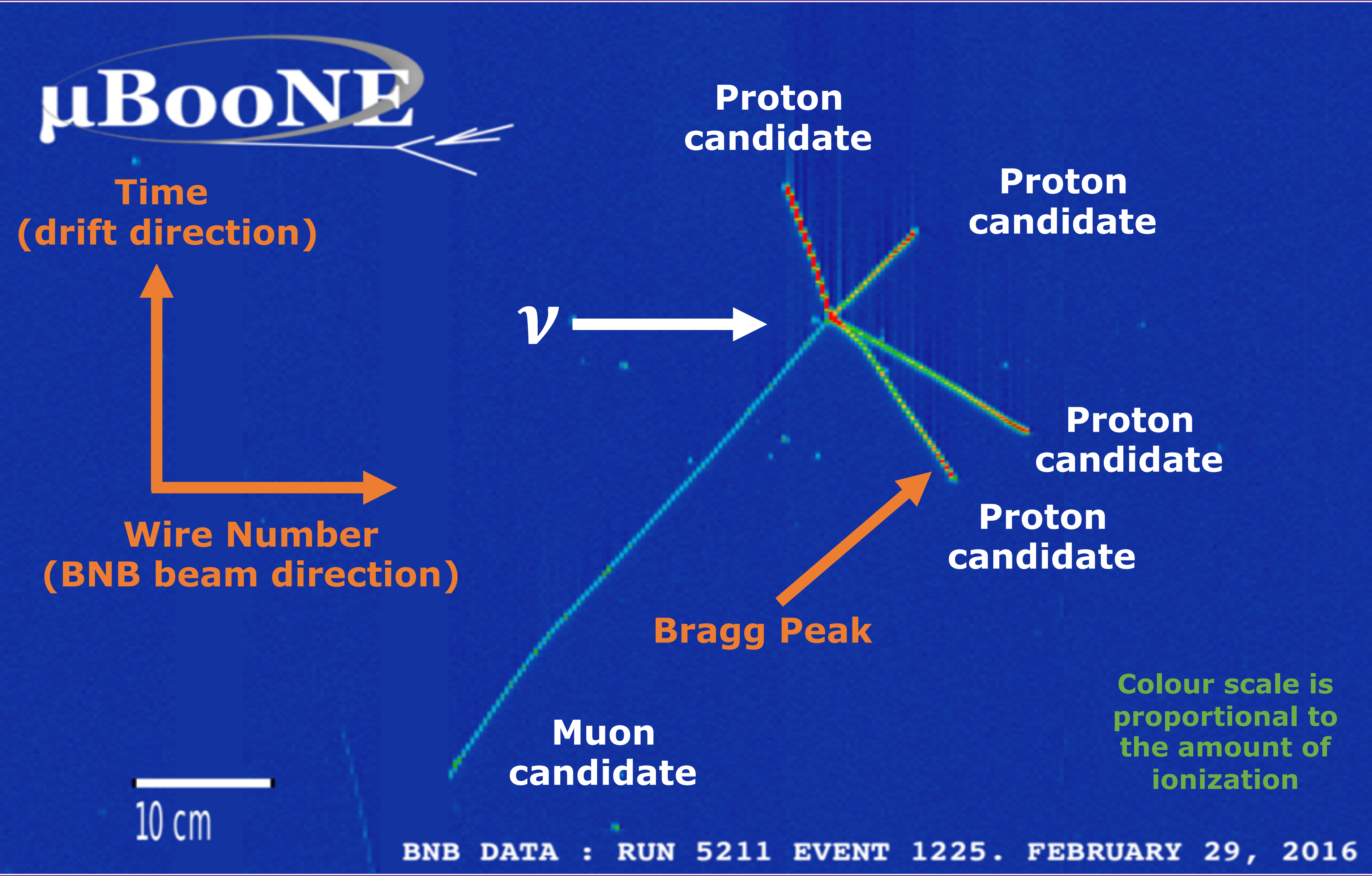
μBooNE

- 85 tonne active volume LArTPC at Fermilab
  - Stable operation since 2015
- 3 planes of wires (vertical, +60$^o$, -60$^o$)
  - 3 mm wire spacing
- 32 PMTs
- Sits in two neutrino beams:
  - **BNB (on-axis)** $<E\nu_\mu> = 800$ MeV
  - **NuMI (off-axis)** $<E\nu_e> = 650$ MeV

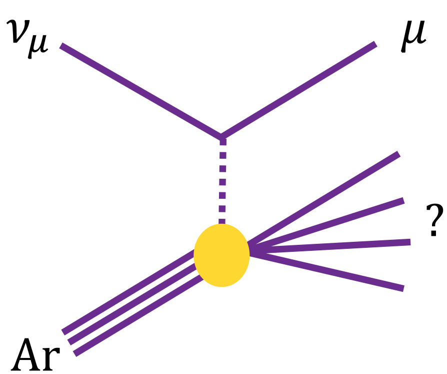
JINST 12 P02017 (2017)



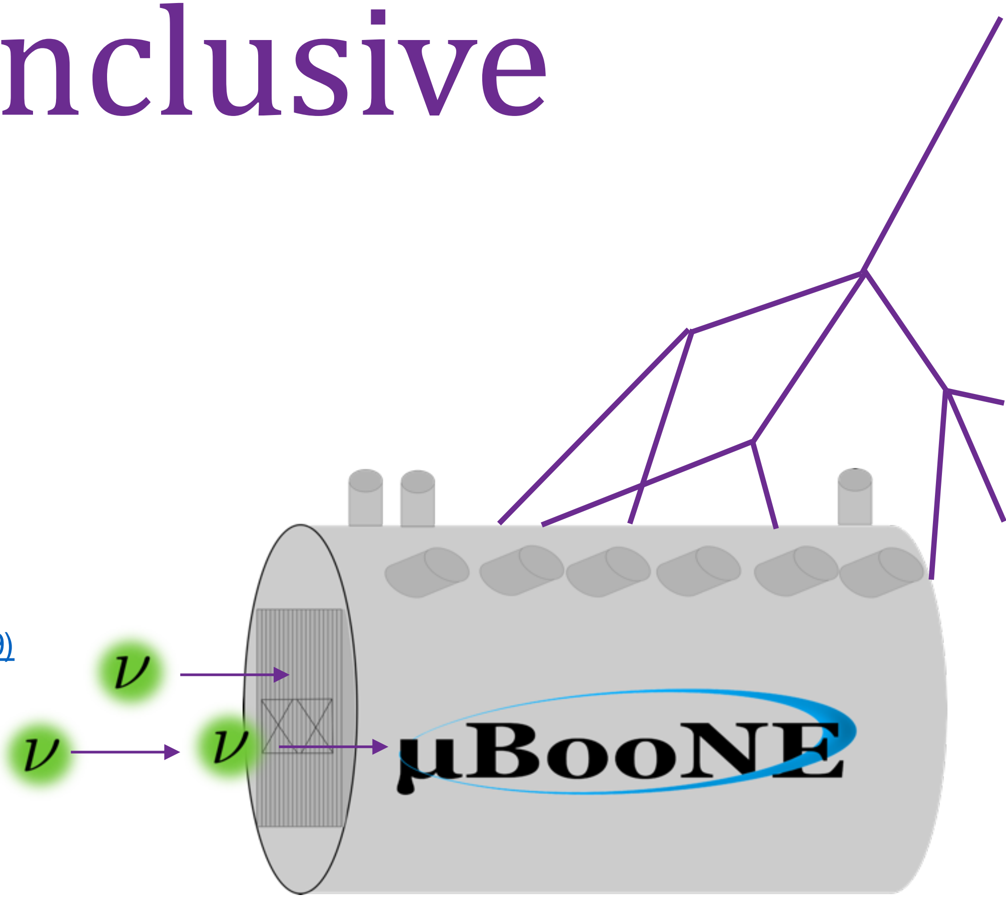
# MicroBooNE Event Display



# $\nu_\mu$ CC Inclusive

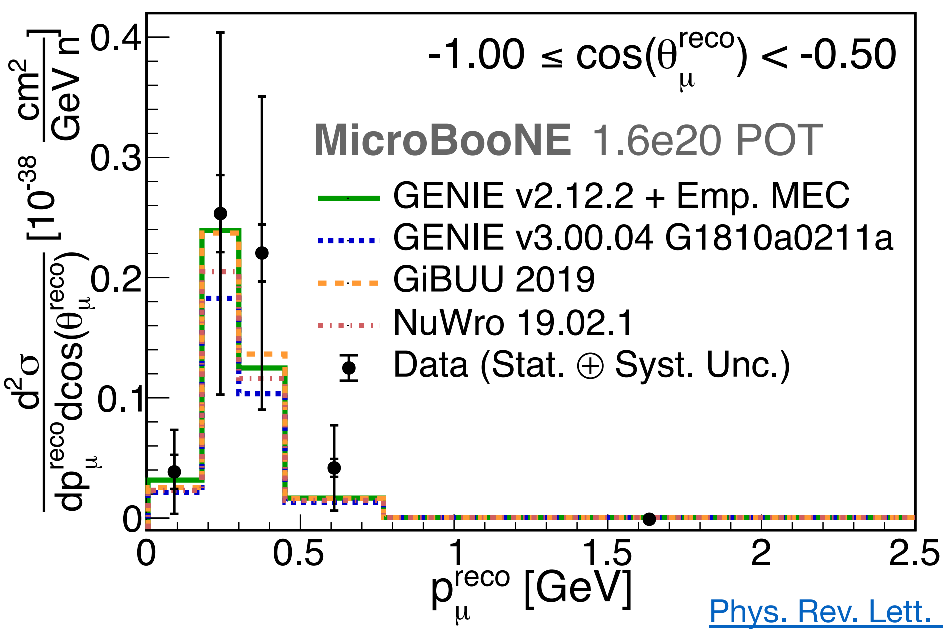


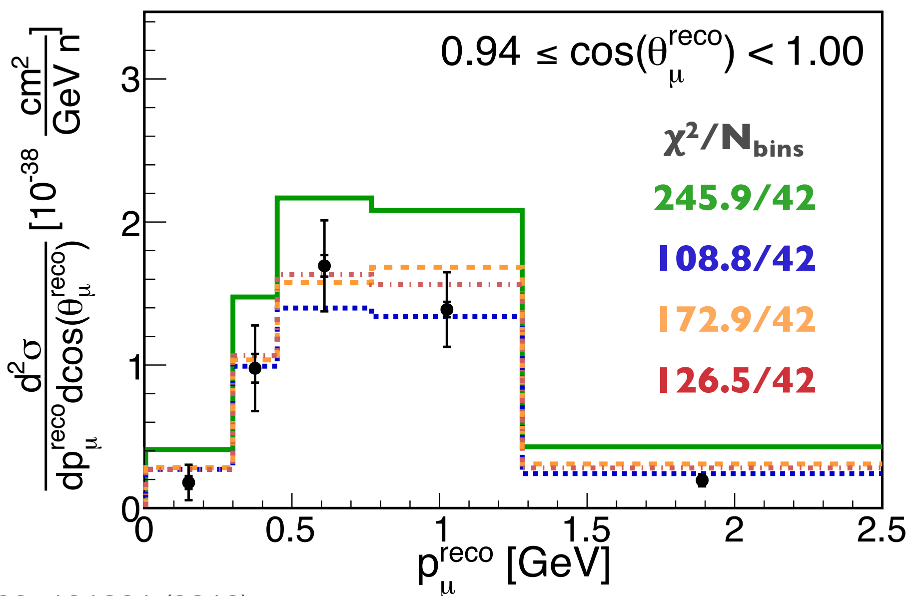

[Phys. Rev. Lett. 123, 131801 (2019)](https://doi.org/10.1103/PhysRevLett.123.131801)



# $\nu_\mu$ CC Inclusive Cross Section

- First **double differential** cross section measurement on argon
  - 50% purity, 57% efficiency
  - Compared to many interaction generators
    - GENIE v2, GENIE v3, GiBUU, NuWro
- All models overpredict in high-momentum, forward going angular bins
  - Drives the large $\chi^2/N_{d.o.f.}$



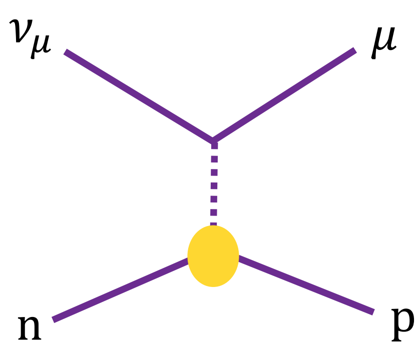




Phys. Rev. Lett. 123, 131801 (2019)

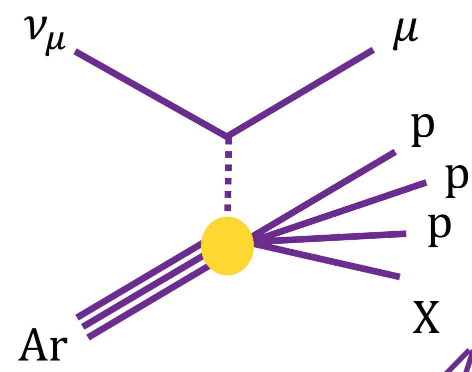
# $\nu_\mu$ CC QE-Like and $\nu_\mu$ CC $0\pi$ Np

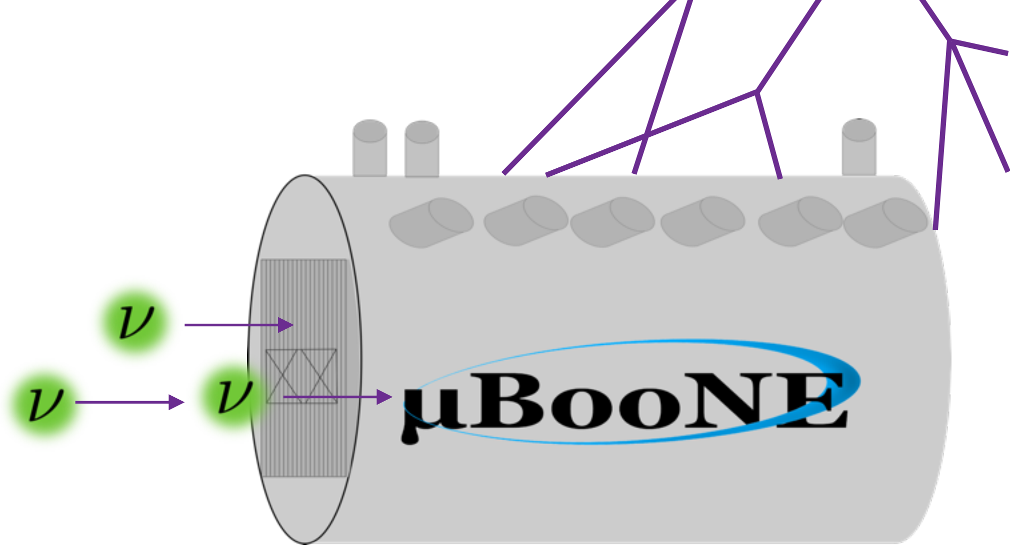
Eur. Phys. J. C 79 673 (2019)

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




Phys. Rev. D 102, 112013 (2020)



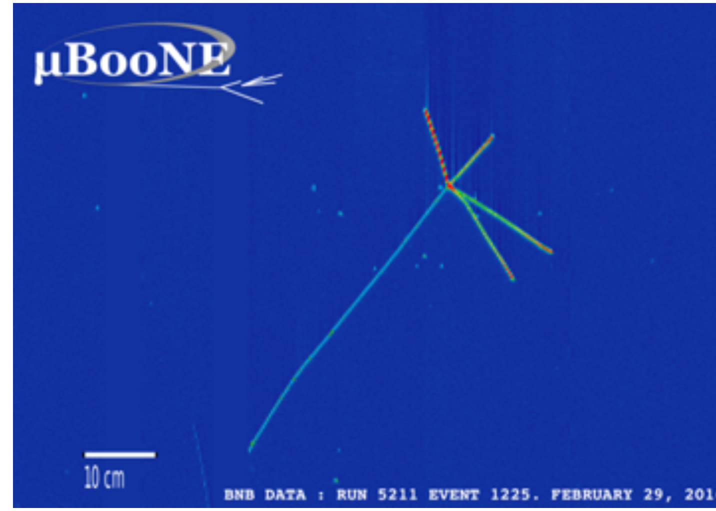



# What physics can we study with low proton thresholds?

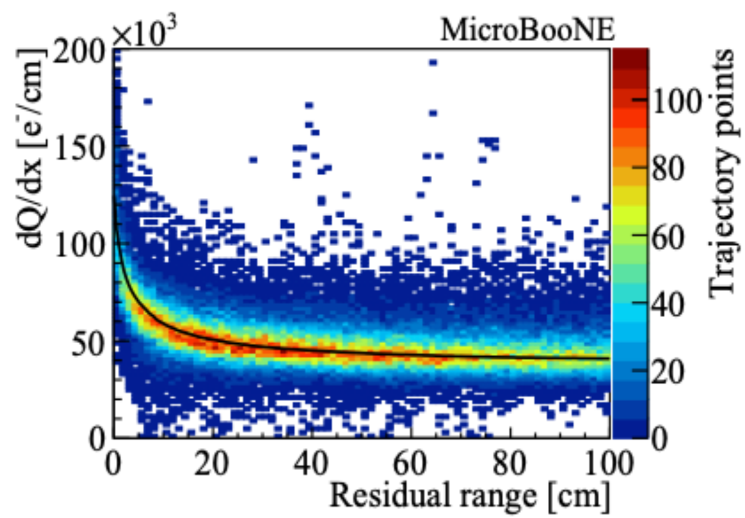
- Protons at low momenta give us access to new information about nuclear effects:
  - Nucleon-nucleon correlations e.g. 2 particle 2 hole (2p2h)
  - Final State Interactions (FSI)
- LArTPCs are able to push these thresholds down and explore new regions of phase space
- Protons are identified by a Bragg peak in last 30 cm of a track

| LArTPCs | Other Detector Types |
|---|---|
| **MicroBooNE**: 300 MeV/c | **T2K**: 500 MeV/c<br>Phys. Rev. D 98, 032003 (2018) |
| **ArgoNeuT**: 200 MeV/c<br>Phys. Rev. D 90, 012008 (2014) | **MINER$\nu$A**: 450 MeV/c<br>Phys. Rev. D 99, 012004 (2019) |

MICROBOONE-NOTE-1056-PUB




JINST 15, P03022 (2020)



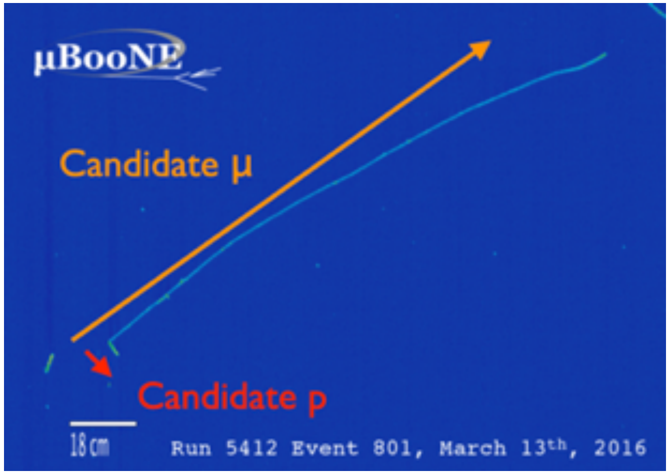

**dQ/dx** = charge deposited per distance
**Residual range** = distance from end of track

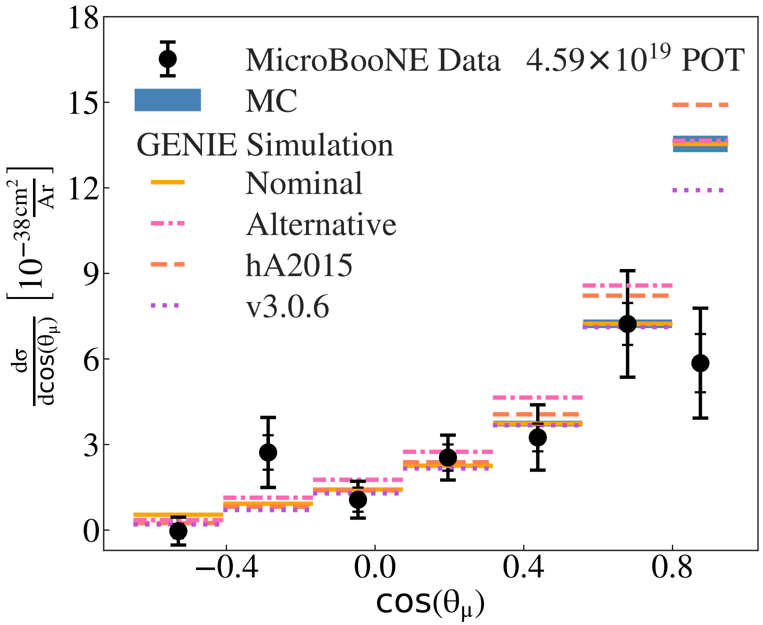
# $\nu_\mu$ CCQE-Like Cross Section

- First extraction of $\nu_\mu$-Ar CCQE-like cross section using a surface LArTPC
  - Proton momentum and angle
  - Muon momentum and angle
  - Calorimetric measured energy and $Q^2$
- $\approx$ 84% purity CC 1p 0$\pi$
- $\approx$ 20% efficiency
- Good agreement with the models except at very forward muon scattering angles

$\chi^2/N_{d.o.f.}$ Nom. GENIE: **33.8/7**

$\chi^2/N_{d.o.f.}$ Nom. GENIE ($\cos\theta<0.8$): **7.3/6**



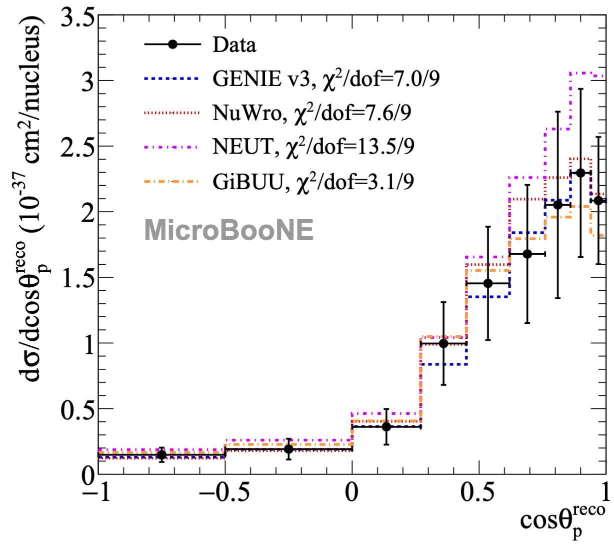

Eur. Phys. J. C 79 673 (2019)

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

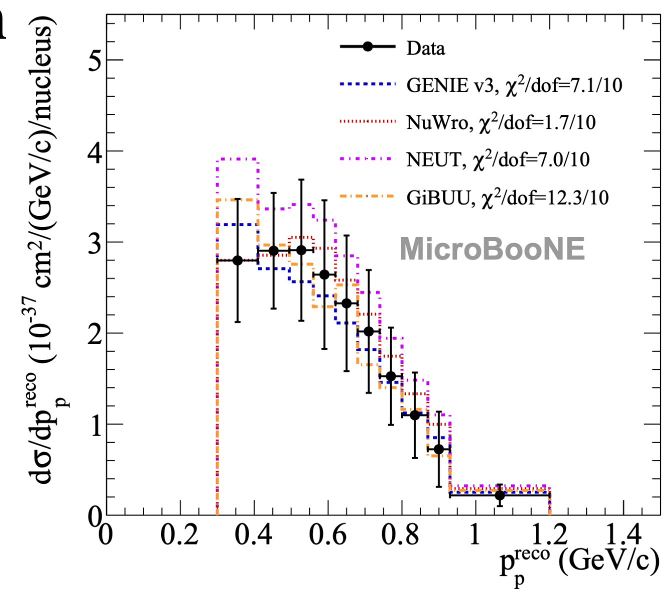
# $\nu_\mu$ CC $0\pi$ Np (N≥1)

µBooNE

- Measurement of the cross section as a function of :
  - Proton momentum and angle
  - Muon momentum and angle
  - Muon-proton opening angle
- 71% purity, 29% efficiency
- Generators show reasonable agreement in proton momentum and angle
- Lowest bin in proton momentum has never been seen before
  - Region where FSI and 2p2h are dominant
  - Test modelling of nuclear effects in generators



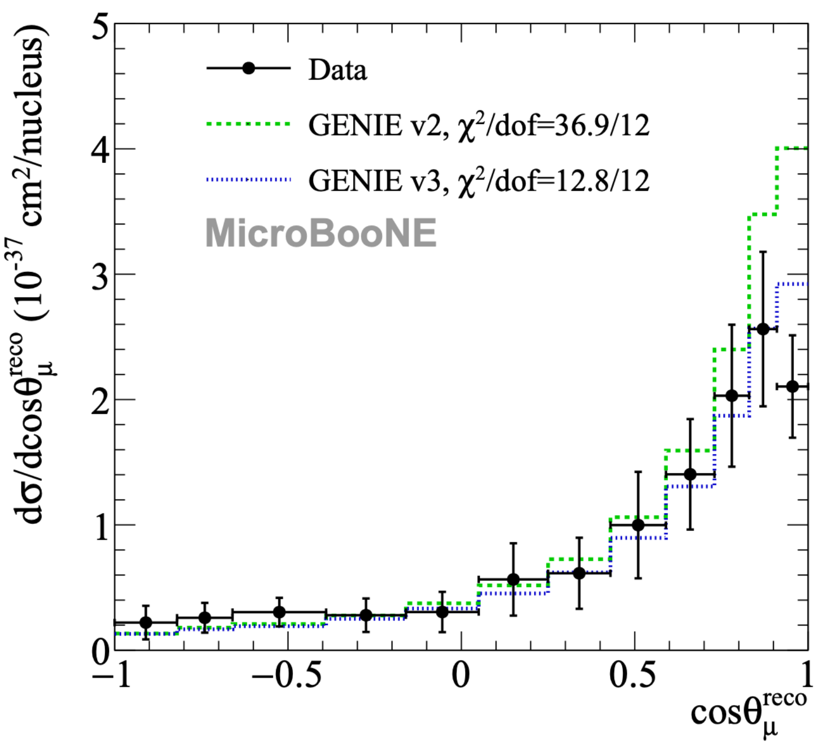

Phys. Rev. D 102, 112013 (2020)

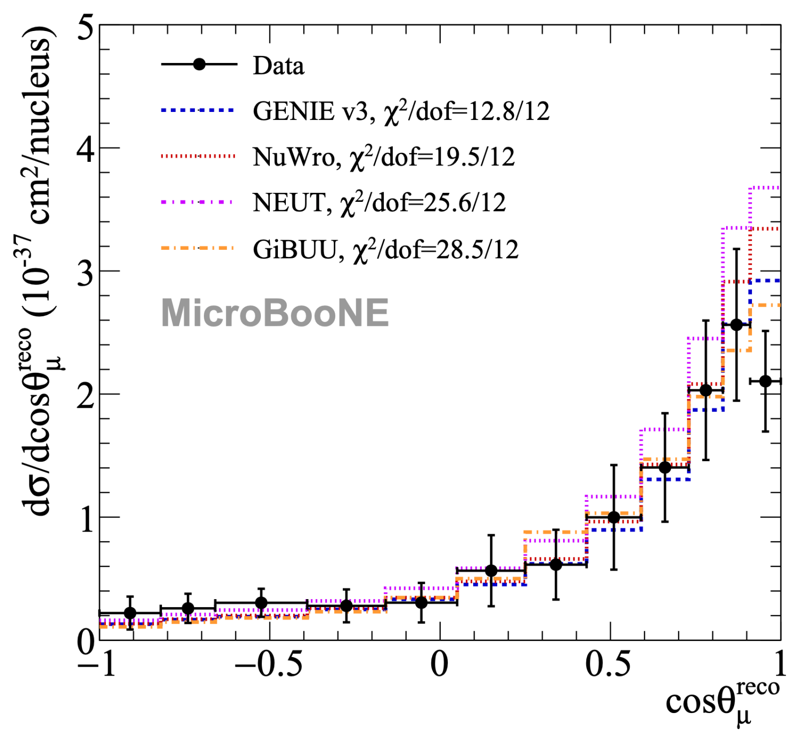


# $\nu_\mu$ CC 0$\pi$ Np (N≥1)

- Large over-prediction at forward-going angles for the muon
  - Consistent with CC inclusive and CCQE-like measurements

- New models improve the agreement, but not completely

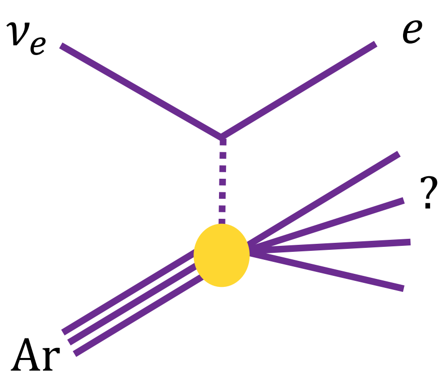


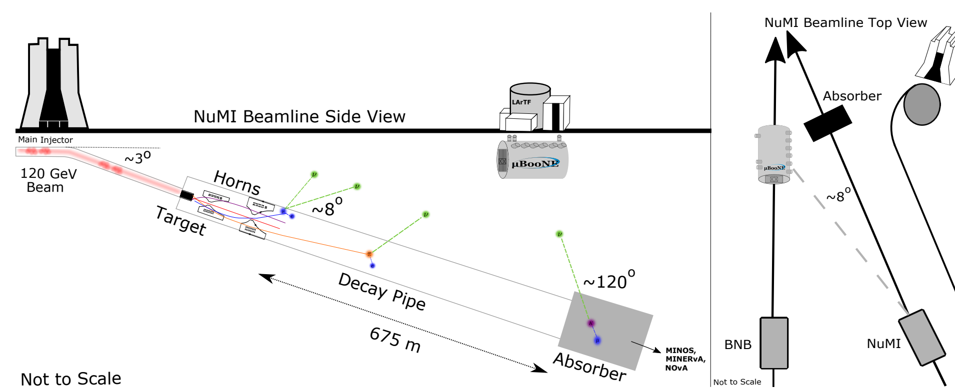

Phys. Rev. D 102, 112013 (2020)

# $\nu_e + \bar{\nu}_e$ CC Inclusive

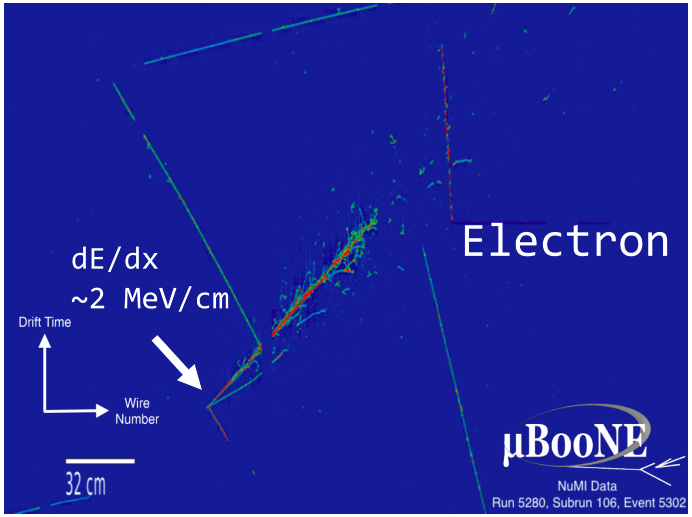
**using the NuMI beam**

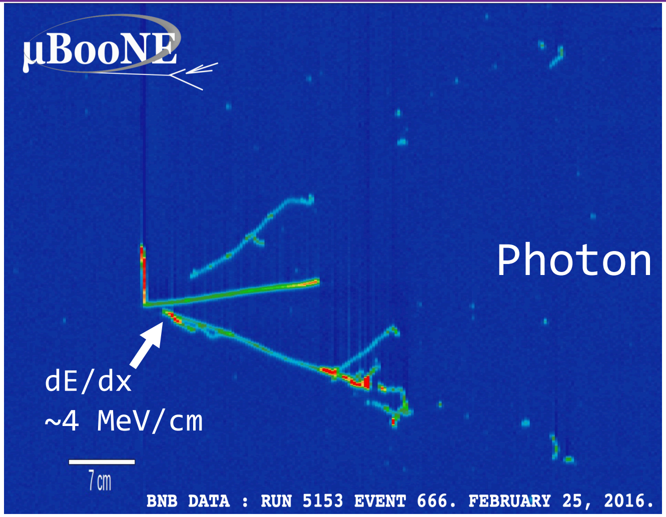



[arXiv:2101.04228 [hep-ex]](https://arxiv.org/abs/2101.04228)



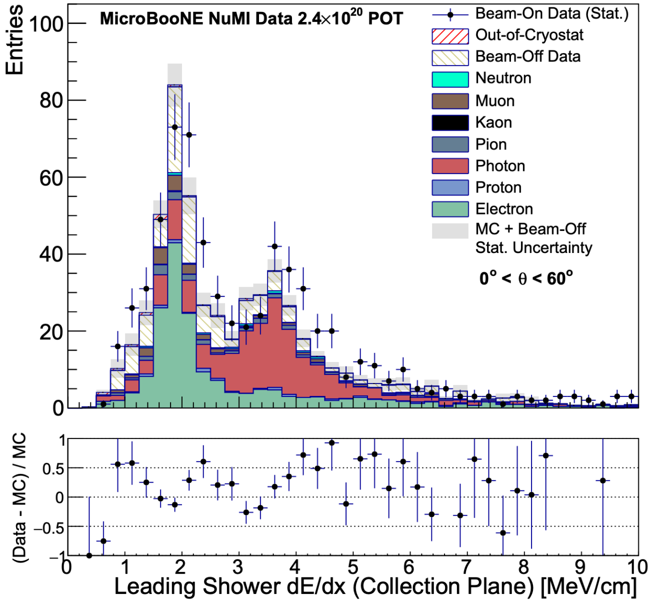
# Electron-Photon Separation



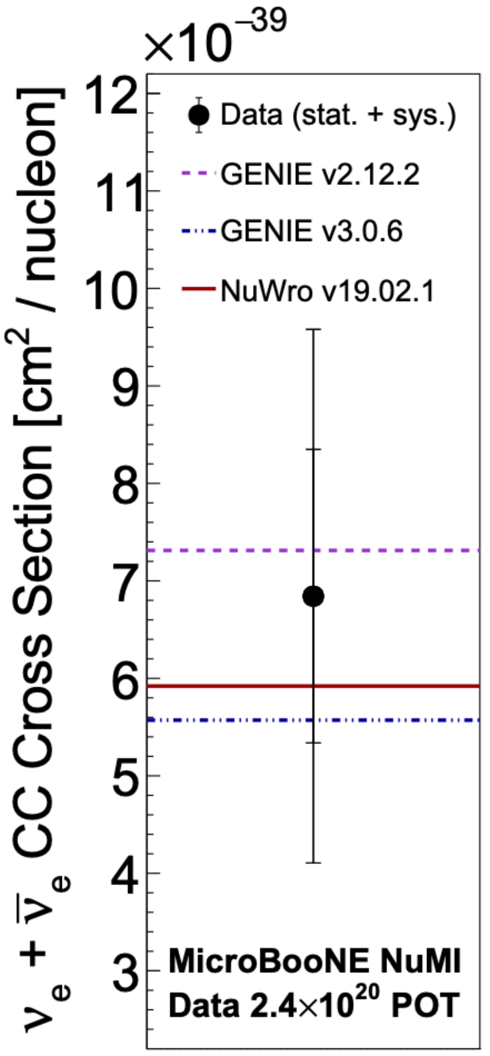

- Able to demonstrate the first fully automated discrimination of electron and photon induced electromagnetic (EM) showers in a LArTPC

- Utilize the energy loss per cm (dE/dx):
  - **Electrons**: dE/dx near the start of a EM-shower is a minimum ionizing particle (MIP) ~ 2 MeV/cm
  - **Photons**: dE/dx near the start of a EM-shower is twice a MIP from the $e^-/e^+$ pair produced ~ 4 MeV/cm



# Cross Section Measurement

- First $\nu_e + \bar{\nu}_e$ measurement using the NuMI beam from MicroBooNE
  - 214 selected events
- Final selection purity of 39% and efficiency 9%
- Total cross section is in agreement with the GENIE v2, GENIE v3 and NuWro generators
- Next generation of analyses in progress using improvements to simulation
  - Significantly reduced cosmic backgrounds (largest contribution in this analysis)
  - Reduced uncertainties, improved purity and efficiency
  - Coming soon: differential cross section in variables such as the outgoing lepton energy!




arXiv:2101.04228 [hep-ex]

**For more details Marina's flash talk on this measurement earlier today!**

# Many more measurements coming!

µBooNE

- MicroBooNE is starting to ramp up its cross section program
  - **Six cross section publications to date** and many more in the works!
- New analyses use a tuned version of `GENIE v3`
  - Tuned CCQE and CCMEC models to T2K $\nu_\mu$ CC $0\pi$ data MICROBOONE-NOTE-1074-PUB
- Good progress on measurements include:

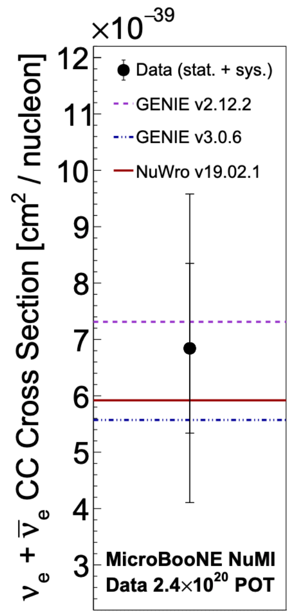
- $\nu_\mu$ CC inclusive MICROBOONE-NOTE-1069-PUB **See Wenqiang's flash talk today**
- $\nu_\mu$ CC $\pi^0$
- $\nu_\mu$ CC $1\pi^\pm$
- $\nu_\mu$ CC coherent $\pi^+$
- $\nu_\mu$ CC $0\pi$ 2p
- $\nu_\mu$ CC $0\pi$ 1p Single Transverse Variables (STV)
- $\nu_\mu$ CC $0\pi$ Np STV
- $\nu_\mu$ CC kaon production MICROBOONE-NOTE-1071-PUB
- $\nu_\mu$ CC $0\pi$ 0,1p
- $\nu_\mu$ CC $\eta$ production
- $\nu_\mu$ NC $\pi^0$ / $\nu_\mu$ CC $\pi^0$ ratio
- $\nu_\mu$ NC 1p MICROBOONE-NOTE-1067-PUB
- $\nu_\mu$ CC hyperon production (NuMI)
- $\nu_\mu$ CC inclusive (NuMI)
- $\nu_e$ CC inclusive (NuMI)
- $\nu_e$ CC $0\pi$ Np (NuMI)
- …

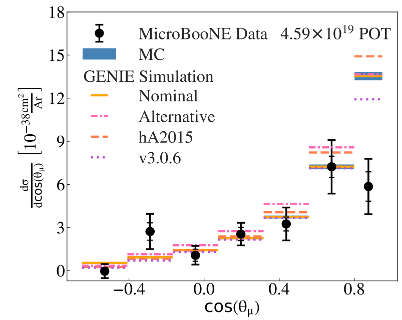
# Summary

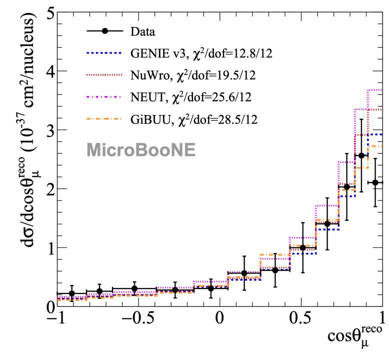
- Cross section measurements of $\nu$-Ar interactions will allow us to develop models that describe $\nu$-Ar interaction data

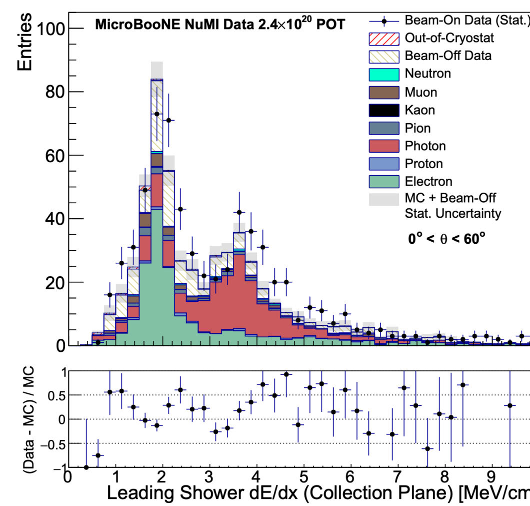
- Recent results from MicroBooNE
  - Hints of mis-modelling in the prediction of high momentum, forward going muons
  - Able to study protons at low momenta, 300 MeV/c
  - First measurement of the $\nu_e$-Ar cross section using the NuMI beam at MicroBooNE
  - Demonstrate a fully automated electron photon separation using the dE/dx of an EM-shower

- Many new measurements coming soon!



# Thank You

Interested in more from MicroBooNE?

MiniBooNE anomalous excess:

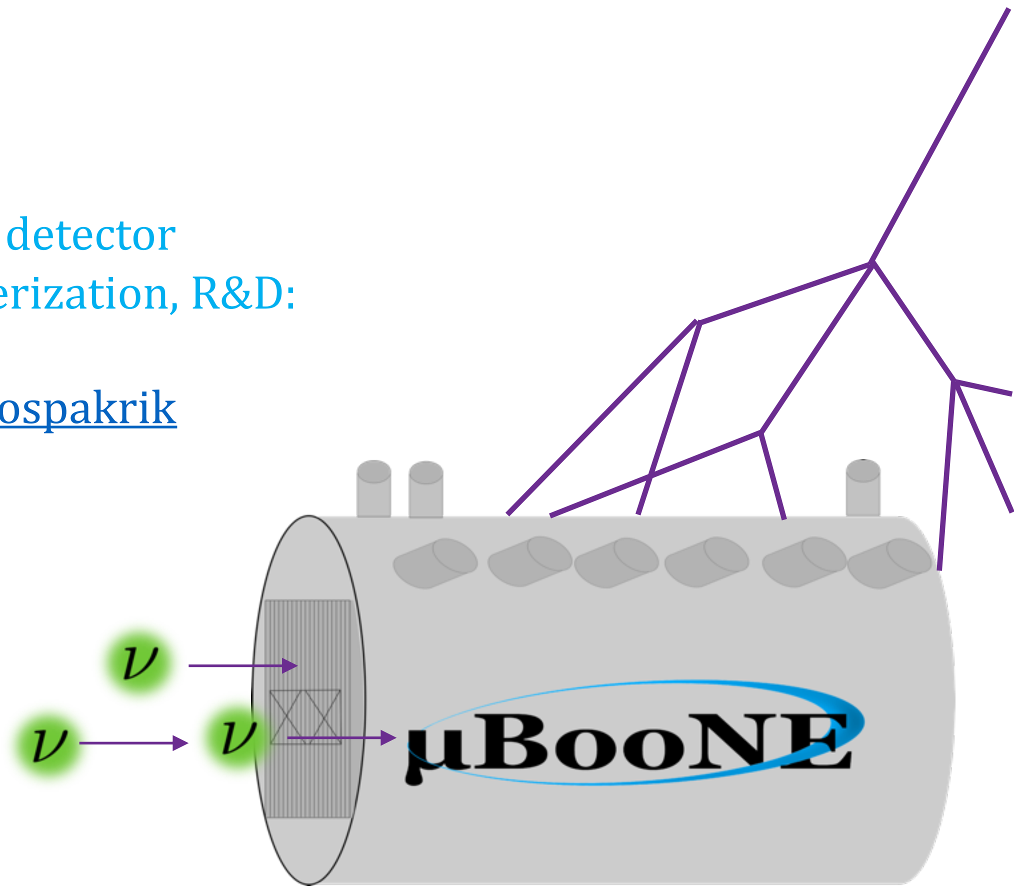
- [Mark Ross-Lonergan]
- [Hanyu Wei]
- [Andrew Mogan]

Astrophysics and BSM Capabilities in MicroBooNE:

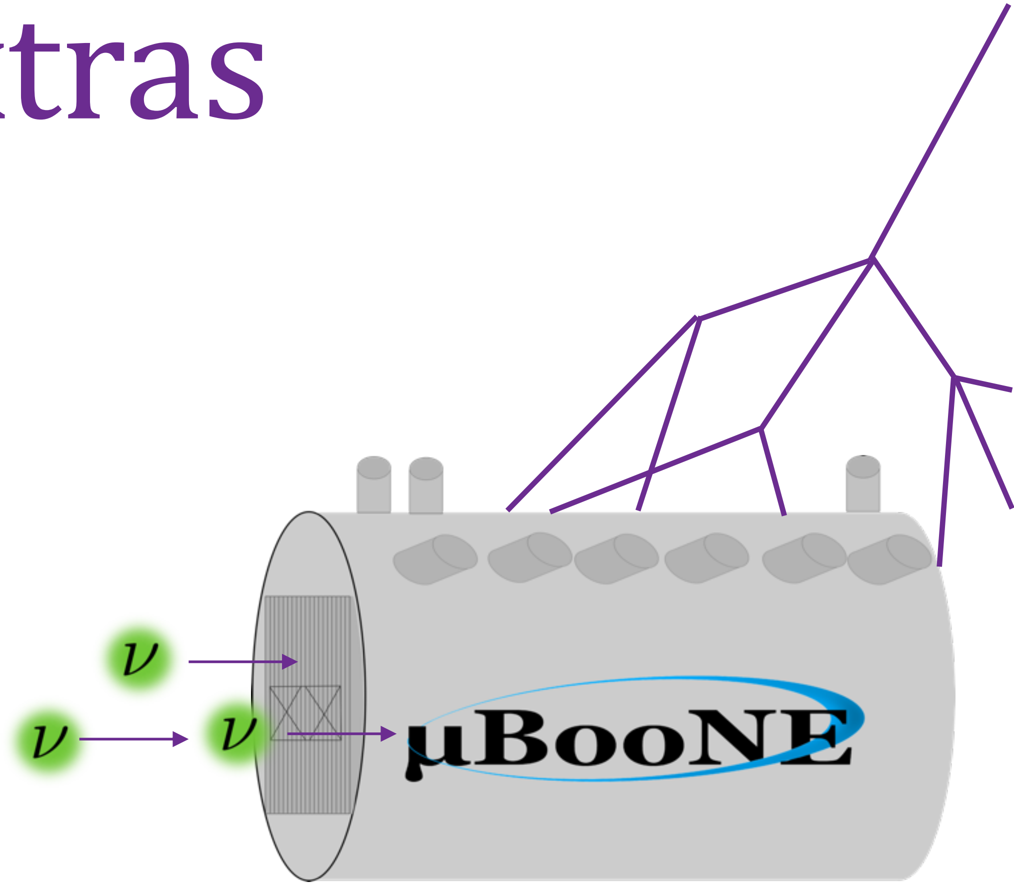
- [Pawel Guzowski]

LArTPC detector characterization, R&D:

- [Maya Wospakrik]



# Extras



# Signal Definitions

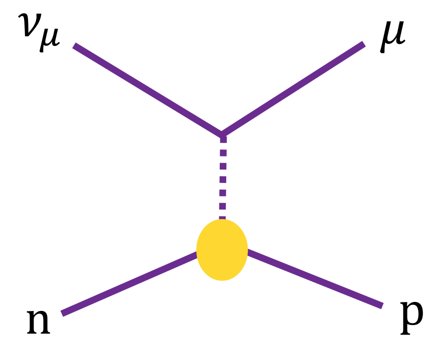
μBooNE

## $\nu_\mu$ CC QE-Like

Eur. Phys. J. C 79 673 (2019)

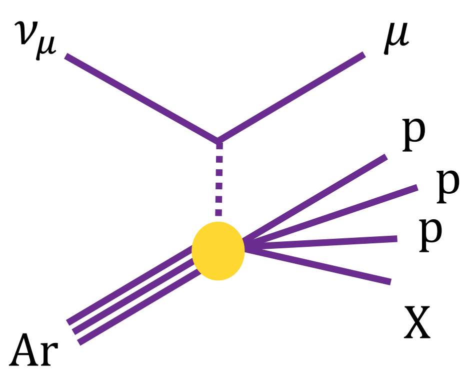
Phys. Rev. Lett. 125, 201803 (2020)

- 1 muon
  - $p_\mu > 100$ MeV/c
- 1 proton
  - $> 300$ MeV/c



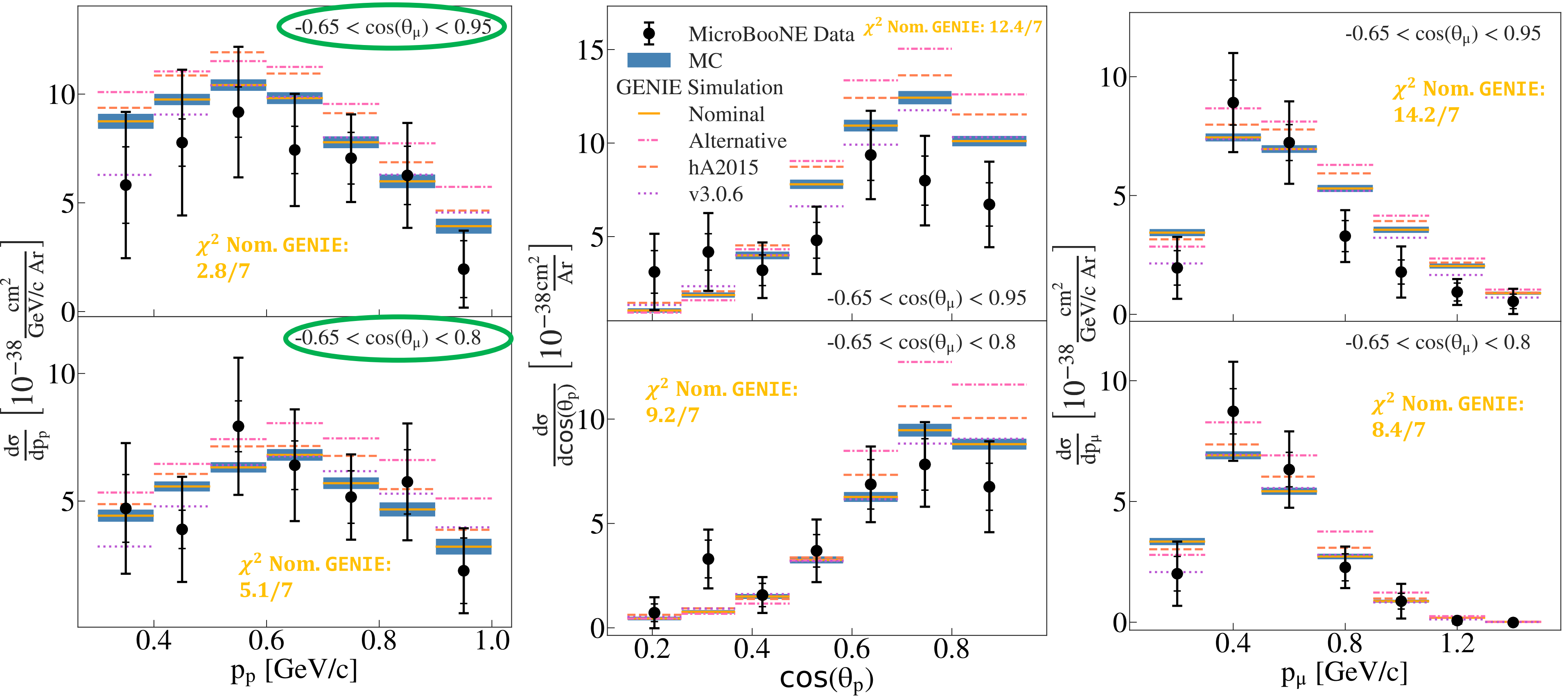

## $\nu_\mu$ CC $0\pi$ Np (N≥1)

- 1 muon
  - $p_\mu > 100$ MeV/c
- At least 1 proton
  - $300 < p_p < 1200$ MeV/c
- No pions



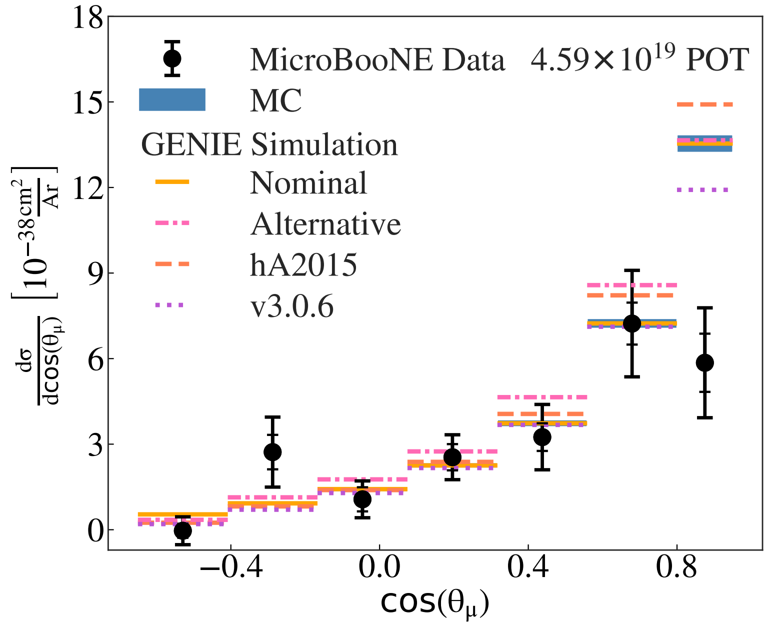

Phys. Rev. D 102, 112013 (2020)

# CCQE-Like Cross Section




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

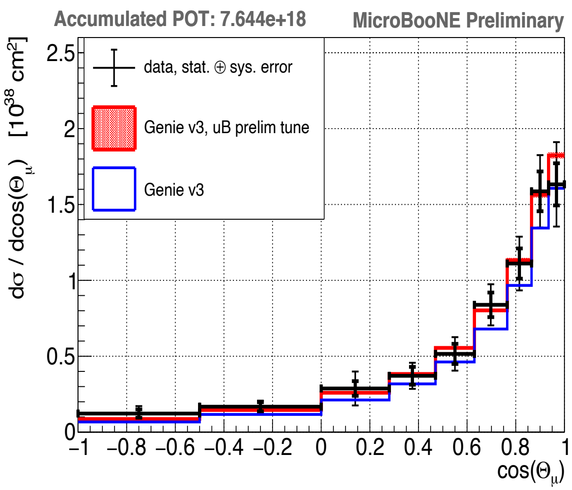
- Nominal: GENIE v2.12.2. Bodek-Ritchie Fermi Gas, Llewellyn-Smith CCQE model, empirical MEC model, Rein-Sehgal resonant and coherent scattering model, "hA" FSI model
- hA2015: GENIE v2.12.2 with a more recent "hA2015" FSI model
- Alternative: GENIE v2.12.10. Local Fermi Gas, Nieves CCQE model, Nieves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



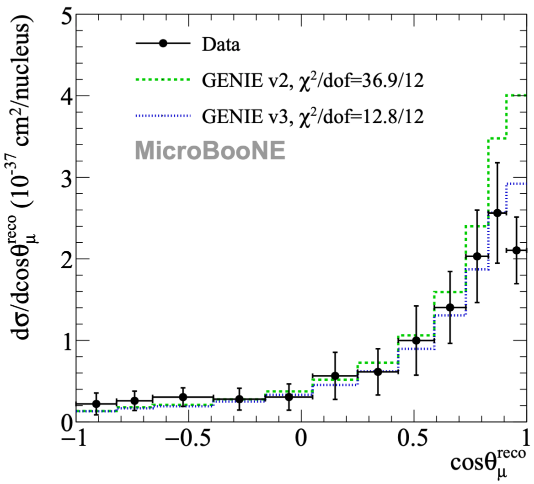
µBooNE

- All three compare to the same GENIE models
  - Cross comparison

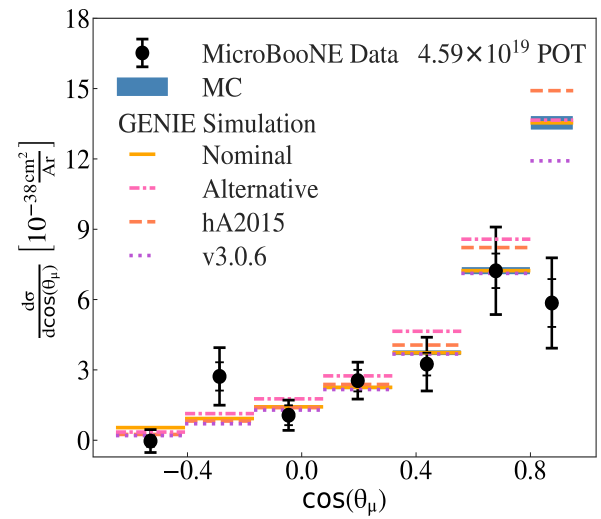
GENIE v3




GENIE v2 GENIE v3




GENIE v2 GENIE v3




$\nu_\mu$ CC Inclusive
Inclusive
Some deficit

$\nu_\mu$ CC $0\pi$ Np
More exclusive
Turnover in data

$\nu_\mu$ CC QE-Like
Even more exclusive
Even more deficit

MICROBOONE-NOTE-1069-PUB

Phys. Rev. D 102, 112013 (2020)

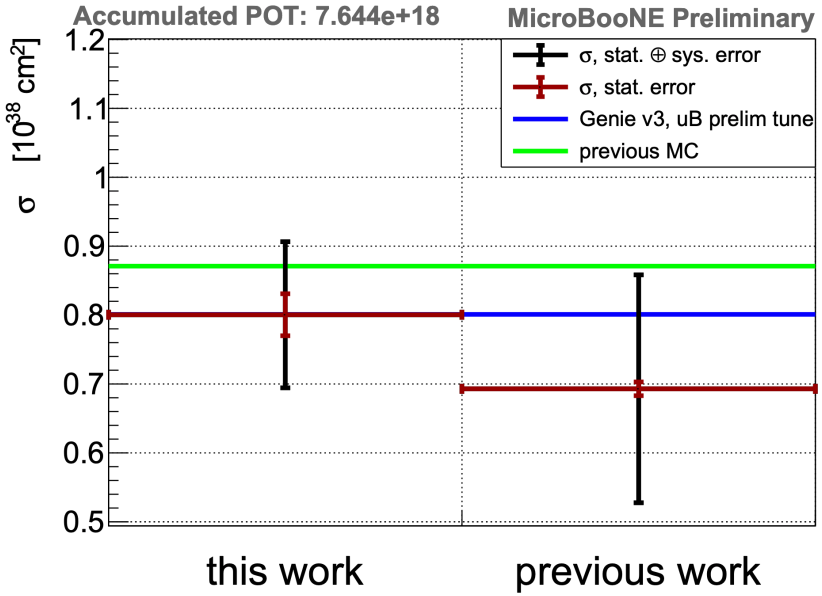
Eur. Phys. J. C 79 673 (2019)

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

# Improvements to Simulation

- Major improvements to the detector simulation in upcoming analyses
  - Includes the simulation of induced charge effects on neighbouring wires
  - Expect drastically reduced detector systematics for future analyses

- Example here shows the improvement for the $\nu_\mu$ CC inclusive

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| 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%** |

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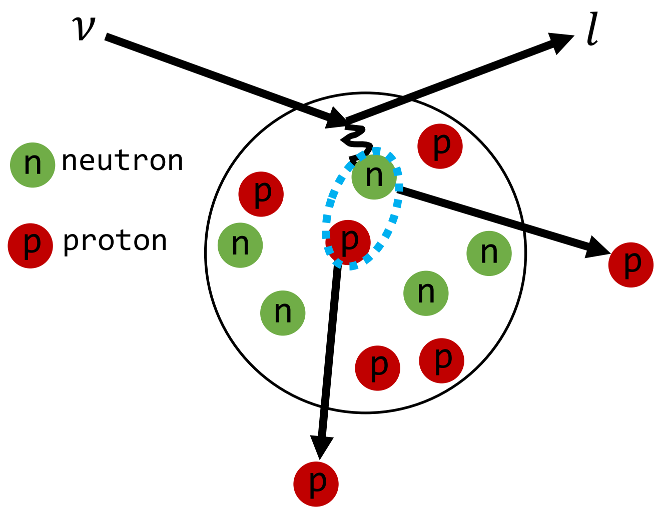
JINST 13 P07006 (2018)

JINST 13 P07007 (2018)

# Nucleon-Nucleon Correlations

µBooNE

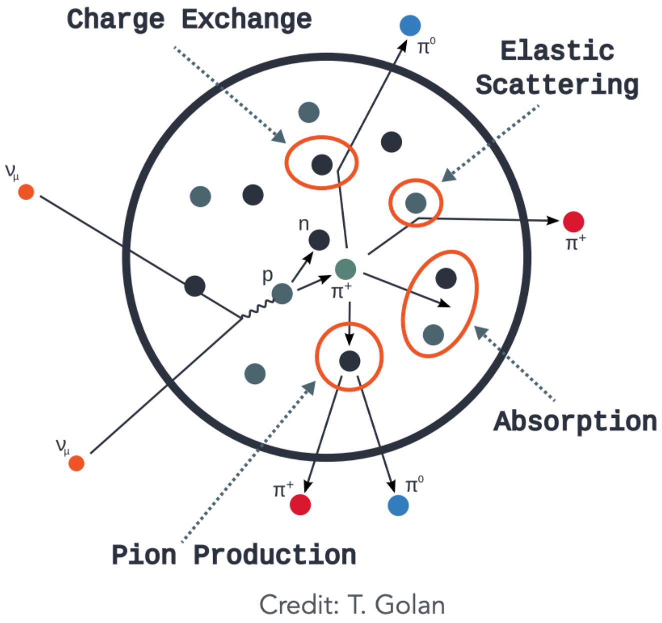



- Neutrino can interact with a correlated pair of nucleons inside the nucleus
  - Meson Exchange Current (MEC)
  - Short Range Nucleon-Nucleon Correlations (SRC)

- As a result, we get two proton emission (or more!)
  - "2 particle 2 hole" or 2p2h
  - Final state is different from the traditional QE interaction, $1l$ 1p, state

# Final State Interactions (FSI)

µBooNE



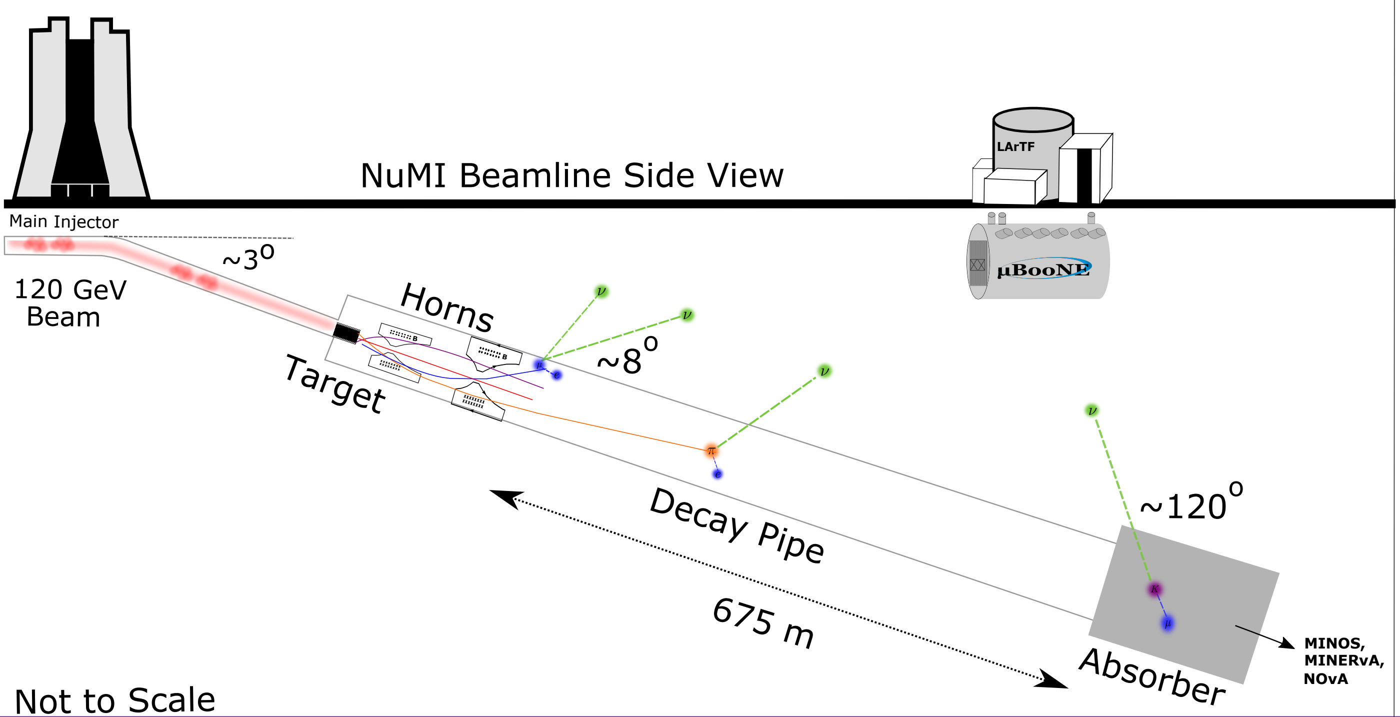

- Nucleons from the $\nu$-Ar interaction can re-scatter while propagating through the nucleus
  - Charge exchange
  - Elastic scattering
  - Absorption
  - Pion Production

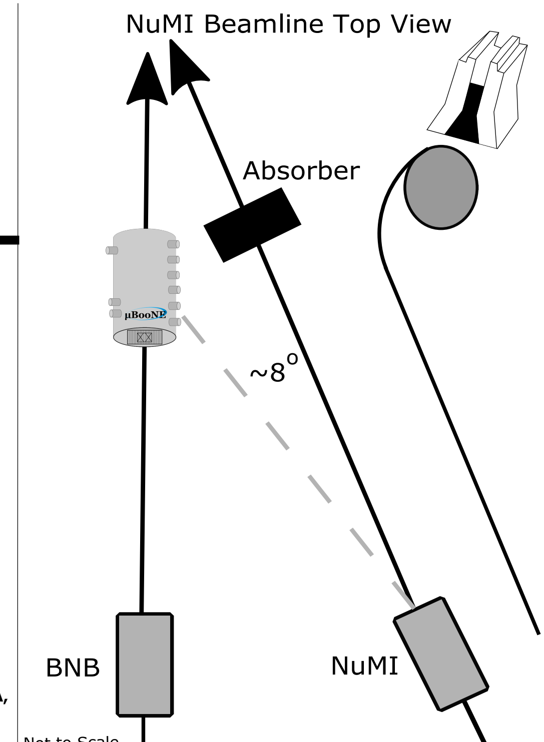
- The resulting particles seen in the detector are different to the initial interaction
  - Scales with nucleus size
  - Impacts final particle momenta and particle multiplicities

# NuMI Flux at MicroBooNE

- NuMI is off axis to MicroBooNE (side and top view)
  - Neutrinos can reach MicroBooNE with angles ranging from 8 – 120 deg
  - Majority of selected neutrinos come from target ~8 deg in the $\nu_e + \bar{\nu}_e$ measurement presented in this talk

[arXiv:2101.04228 [hep-ex]]

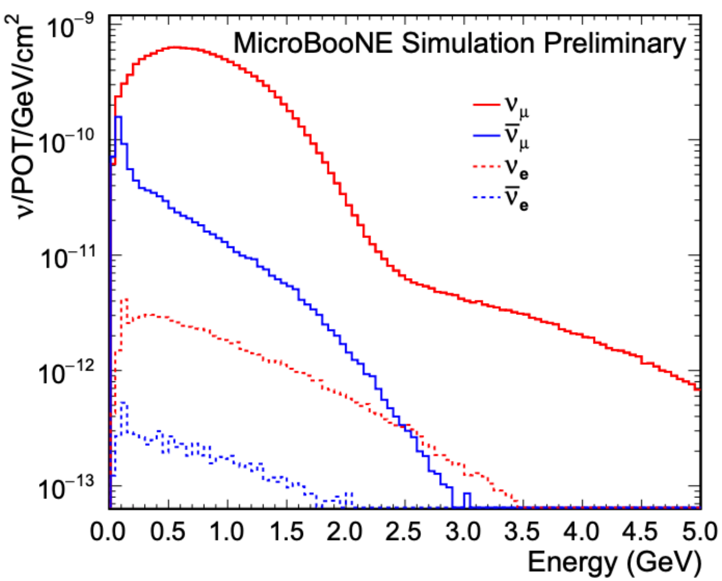


# BNB and NuMI Flux at MicroBooNE

- BNB Flux at MicroBooNE peaked around 1 GeV (on-axis)
- NuMI flux at MicroBooNE covers a wide range of energies (off-axis)

**BNB Flux**

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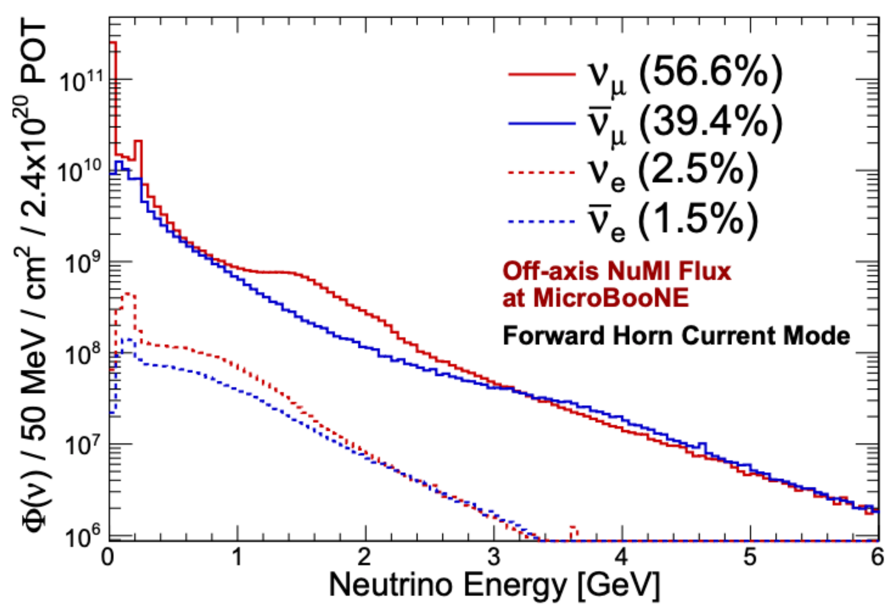
**NuMI Flux**




arXiv:2101.04228 [hep-ex]