

Recent Results from MicroBooNE

Lu Ren

On behalf of the MicroBooNE Collaboration

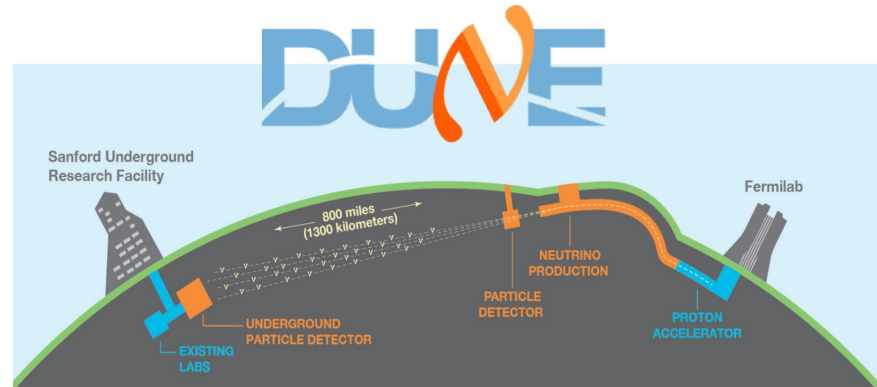


U.S. DEPARTMENT OF
ENERGY

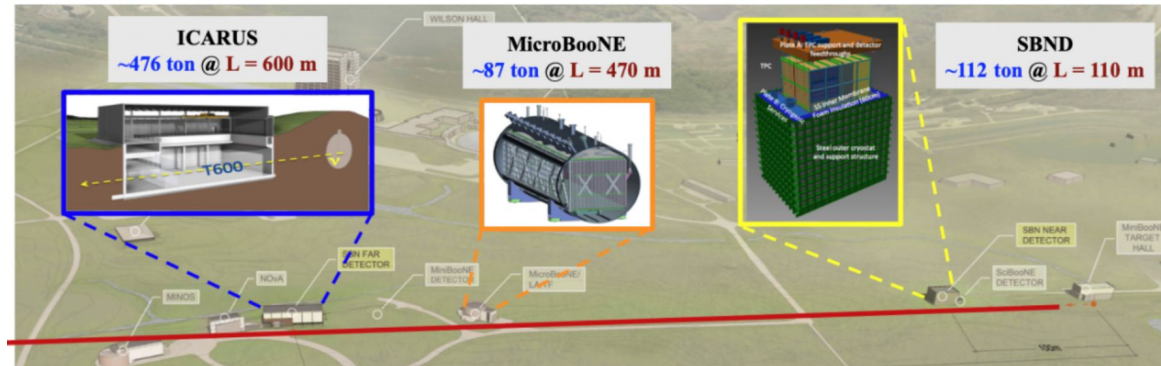
Office of
Science

LAr Neutrino Experiments

- Current and future neutrino oscillation experiments
 - DUNE
 - SBND and ICARUS
- Need to understand neutrino-argon interactions for
 - Neutrino energy reconstruction
 - Systematic uncertainty estimation

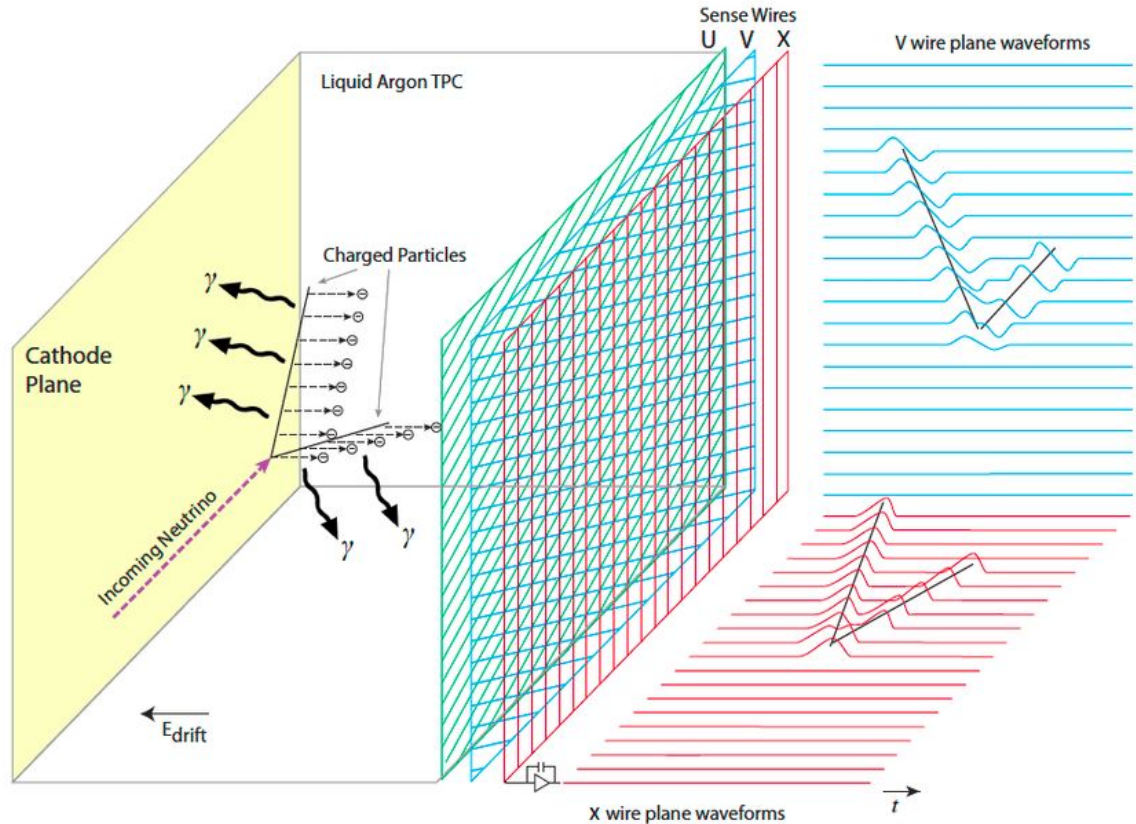


<https://arxiv.org/abs/2002.03005>



<https://sites.slac.stanford.edu/neutrino/experiments/icarus>

LArTPC



- Being used in current and next-generation neutrino oscillation experiments
- Scintillation light collected by the photomultiplier tubes (PMTs) behind the anode
- Low thresholds and high resolution

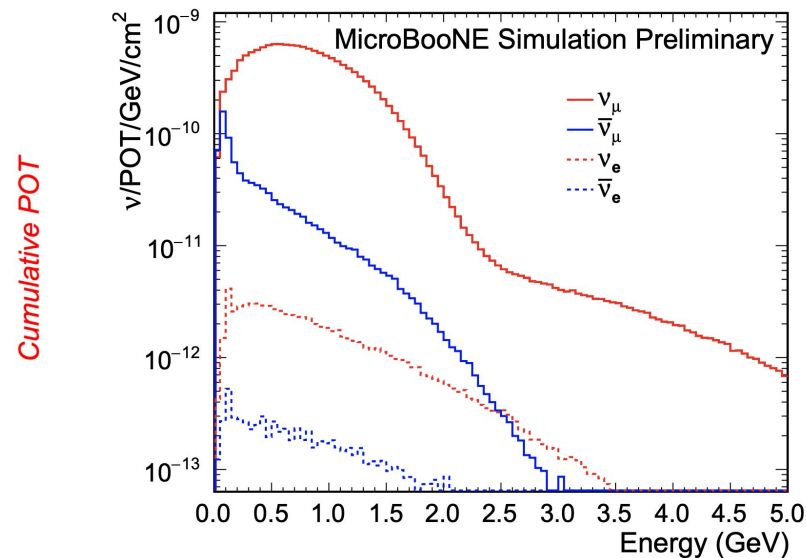
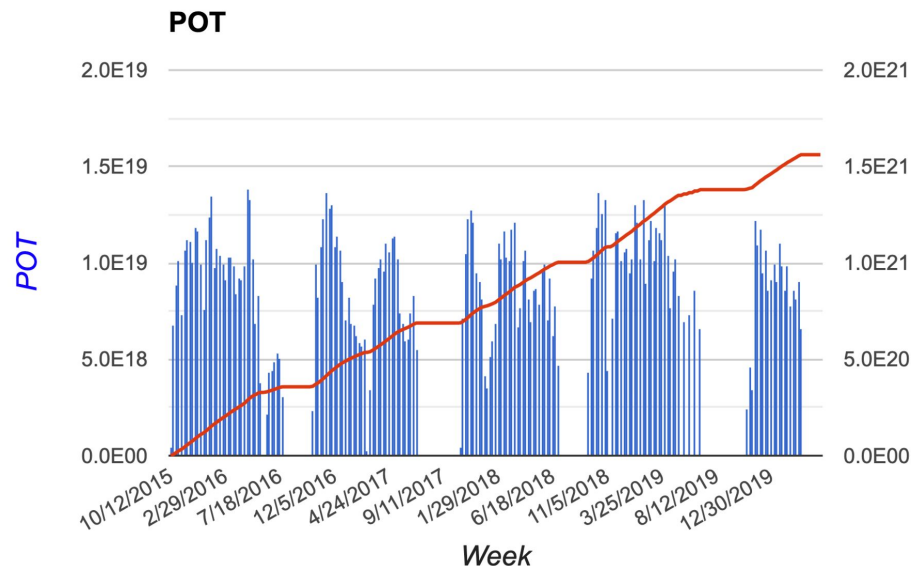
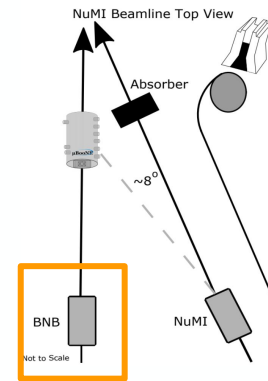
MicroBooNE

- 85 ton active mass, surface-based LArTPC
- 3 planes of wires (vertical, $+60^\circ$, -60°) with 3mm spacing
- 32 PMTs collect light from flash at time of interaction
- Longest running LArTPC to date, completed data taking from 2015-2021
- Receives Booster Neutrino Beam (BNB) and Neutrinos at the Main Injector (NuMI) beam at Fermilab



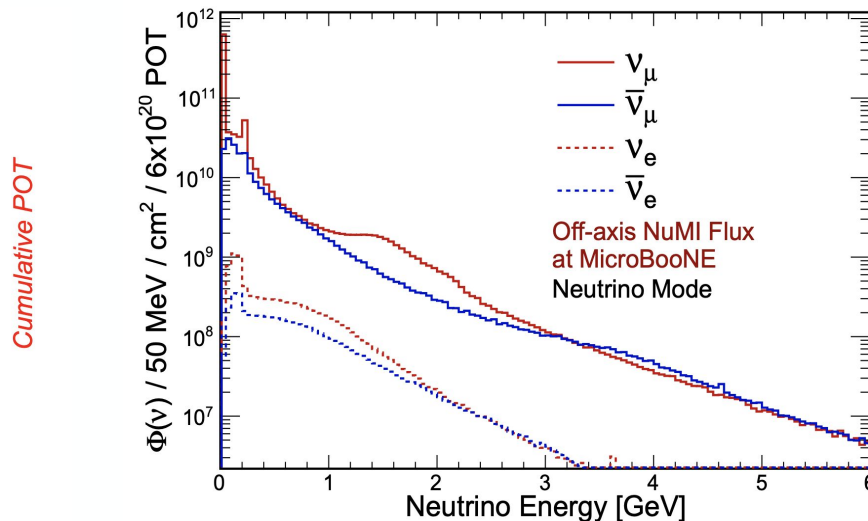
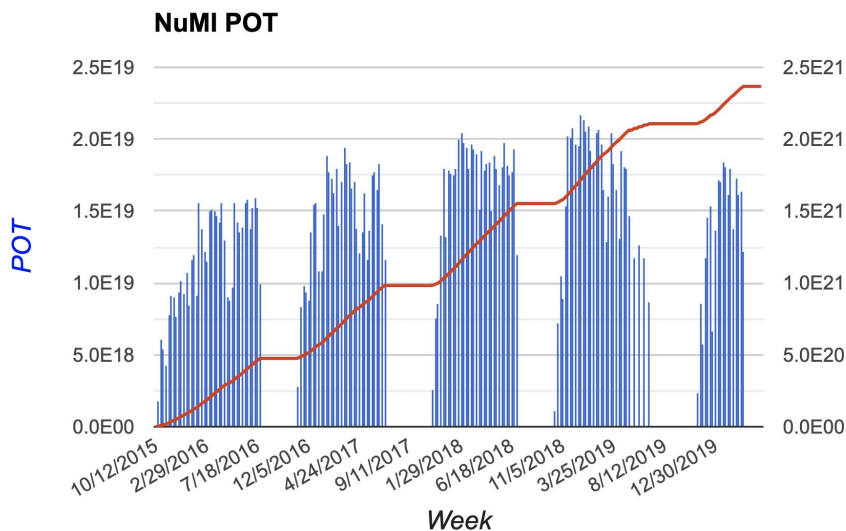
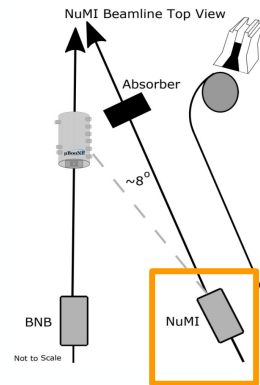
BNB

- MicroBooNE is 470 m from the target
- BNB ν_μ flux peaks at 0.7 GeV
- We have collected 1.56×10^{21} Protons On Target (POT)



NuMI

- MicroBooNE receives off-axis NuMI beam
- About 680 m from the target
- We have collected 2.37×10^{21} POT
- Larger fraction of ν_e than BNB



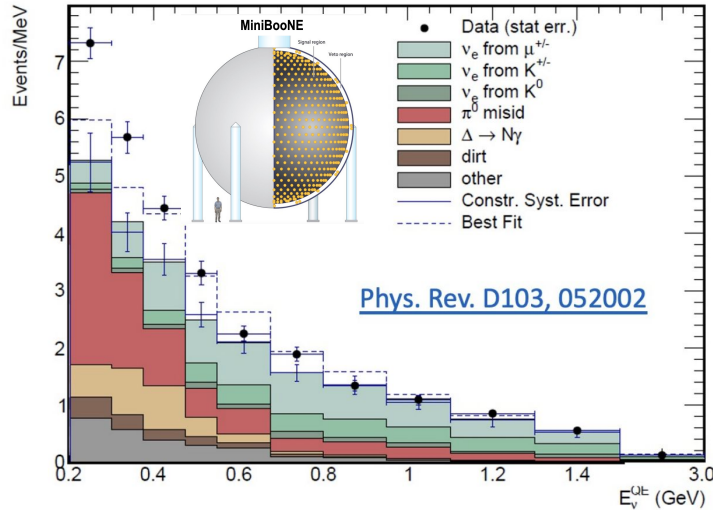
Physics Goals

- MiniBooNE Low Energy Excess (LEE)
- Neutrino-Ar Interactions
- Beyond the Standard Model (BSM) Physics searches

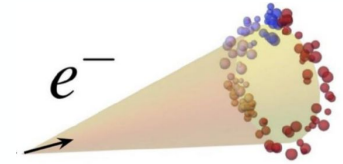
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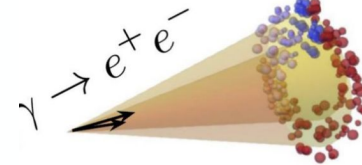
MiniBooNE Low Energy Excess



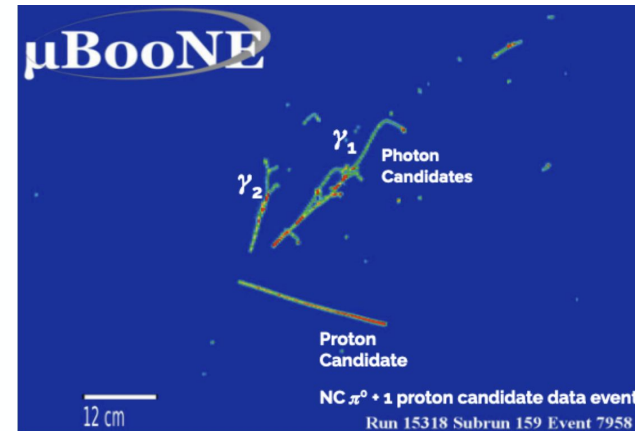
Electron-like excess



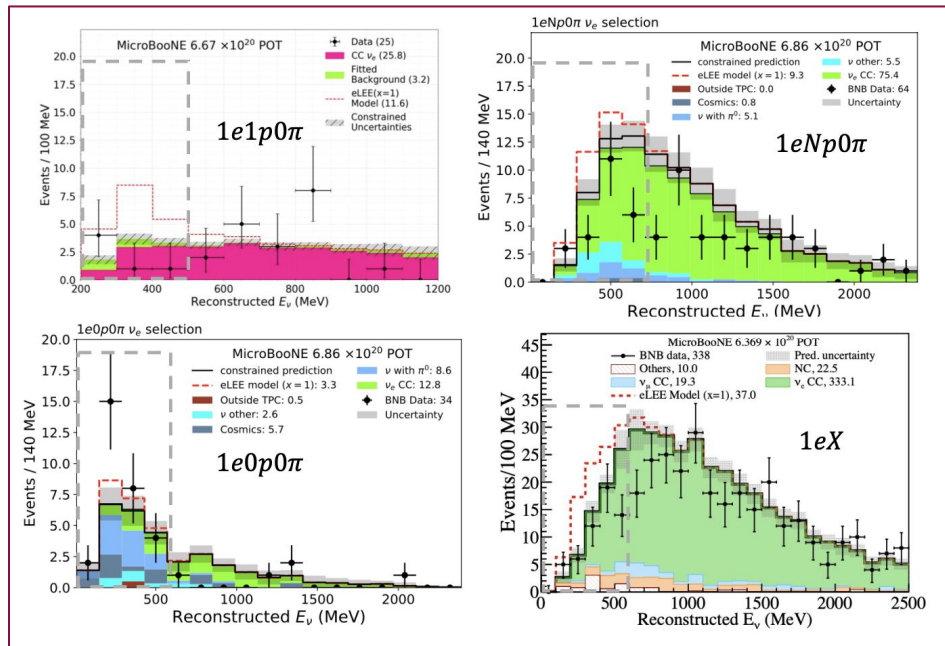
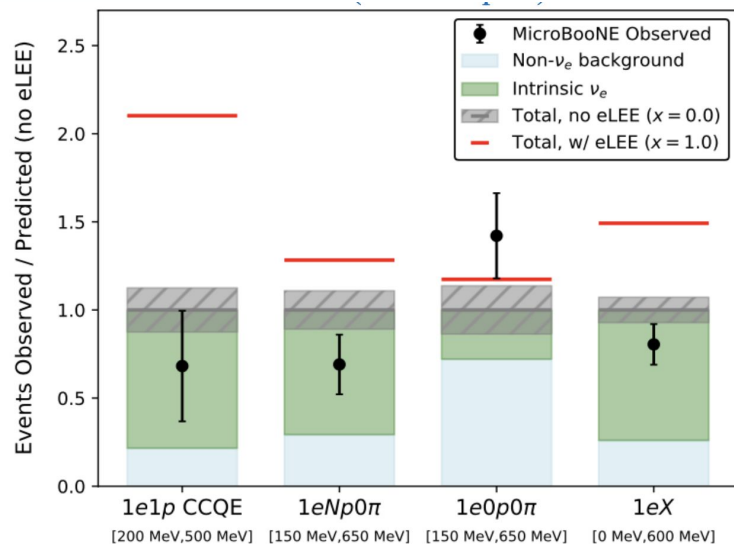
Photon-like excess



- 17 years of data, 4.8σ excess
- BNB data
 - eLEE
 - gLEE



First LEE Results: Electron-like (eLEE)

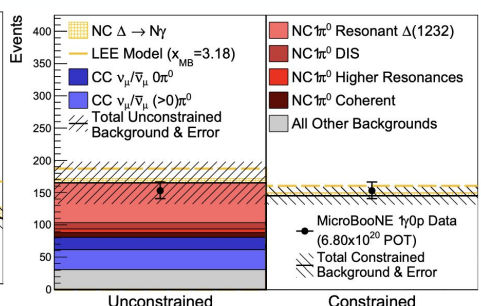
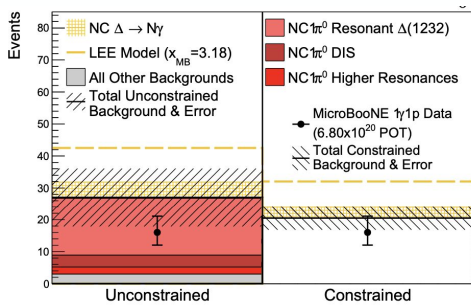
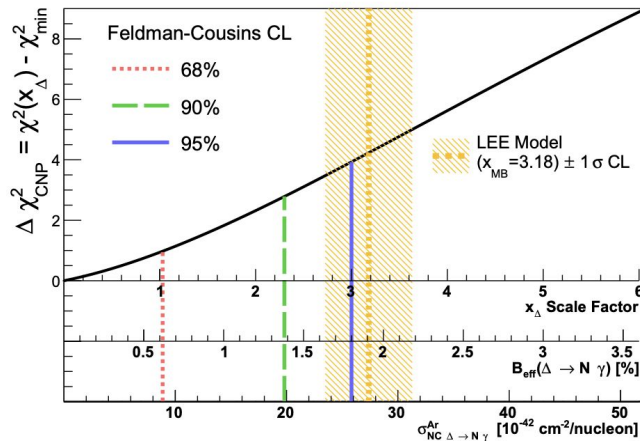


- Three independent searches
 - Final state topology
 - Reconstruction approach
- Observed candidate rates consistent with the predicted background rates

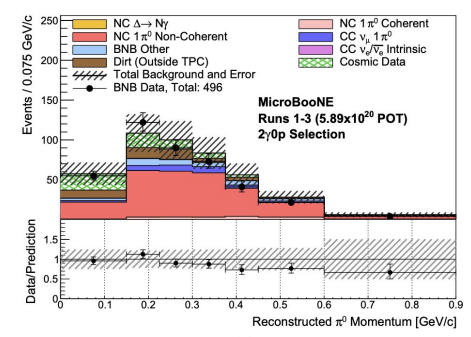
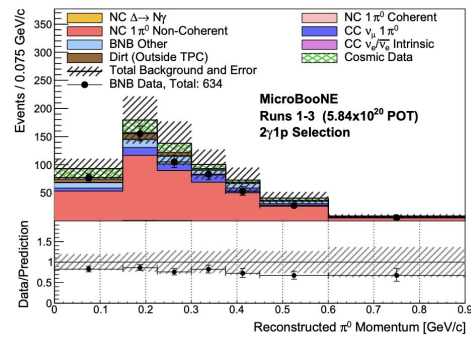
Phys. Rev. D 105, 112003 (2022)
 Phys. Rev. D 105, 112005 (2022)
 Phys. Rev. D 105, 112004 (2022)
 Phys. Rev. Lett. 128, 111801 (2022)

First LEE Results: Photon-like (gLEE)

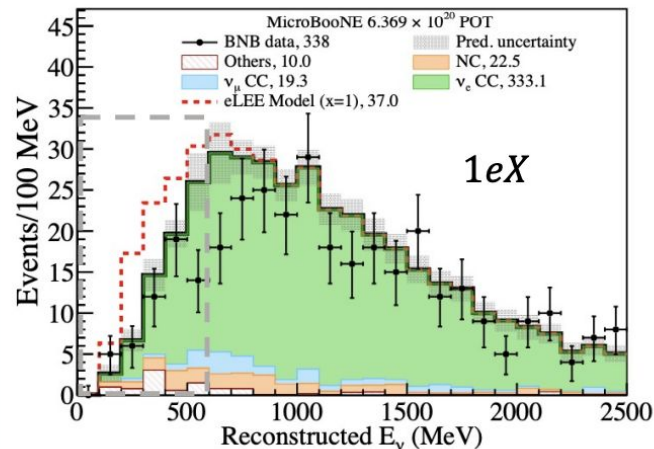
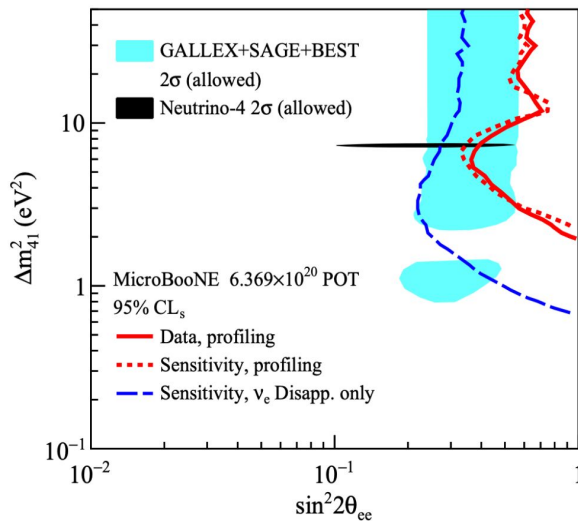
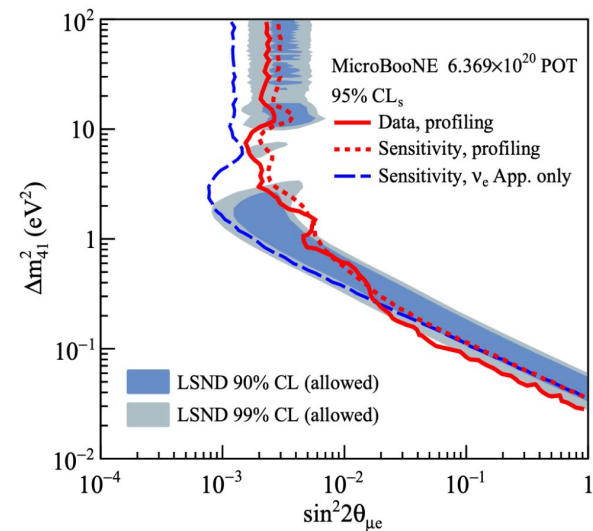
- Targeting NC Δ resonance radiative decay
 - Standard model process
 - Never been directly observed in neutrino scattering
- This LEE search proceeds with a simultaneous side-by-side fit of four topologically distinct samples
- Disfavors NC Δ resonance radiative decay as the only source of the MiniBooNE excess at 94.8% C.L
- NC π^0 cross section measurement



Phys.Rev.Lett. 128 (2022) 111801



3+1 Oscillation Analysis



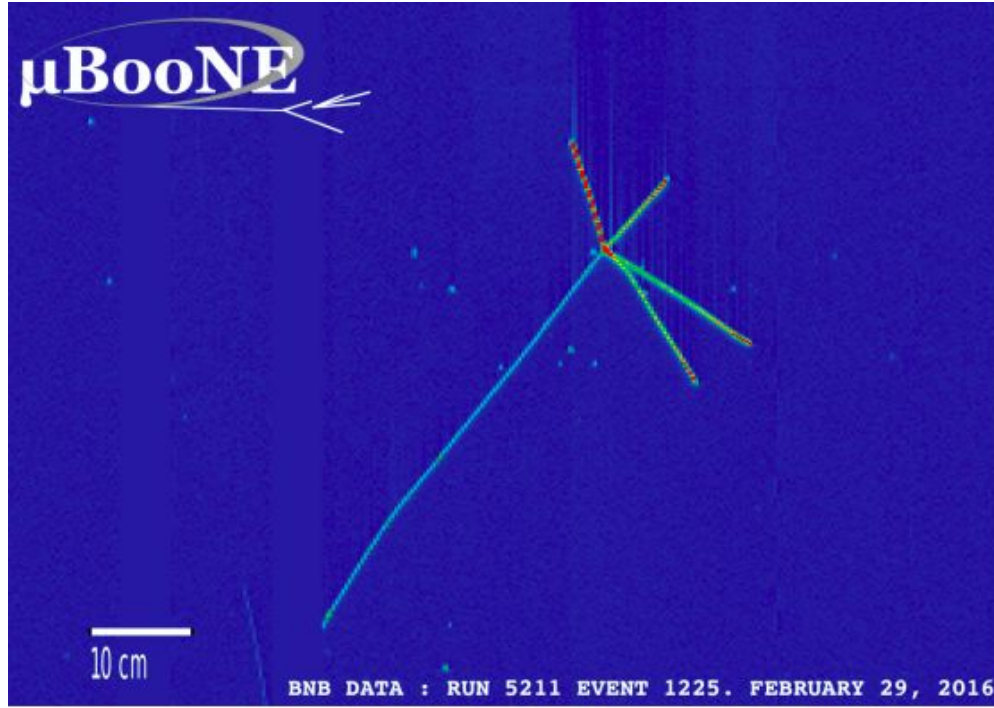
- Some LSND allowed region excluded
- First constraints, competitive in the relatively high Δm^2_{41} region, on the eV-scale sterile neutrino parameter space measured in a LArTPC detector
- Paves the way for future neutrino oscillation searches
- An upcoming search for sterile neutrino oscillations combining the BNB and NuMI data

Phys.Rev.Lett. 130 (2023) 1, 011801

Physics Goals

- MiniBooNE Low Energy Excess (LEE)
- Neutrino-Ar Interactions
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Neutrino-Ar Cross section measurements



- Largest neutrino-Ar interaction data
 - ~ 500 k events
- High resolution allows for investigation of multiple final state topologies
 - Nuclear effects
 - Final state interactions
- Value input for current and future LArTPC experiments
- >10 published cross section papers
- ~ 30 ongoing cross section analyses

Neutrino-Ar Cross section measurements

- 1-D CC1p TKI
- 2-D CC1p TKI
- CC2p
- 3-D CC Inclusive
- NC π^0
- Rare channels

Transverse kinematic imbalance (TKI)

- Nuclear effect indicators

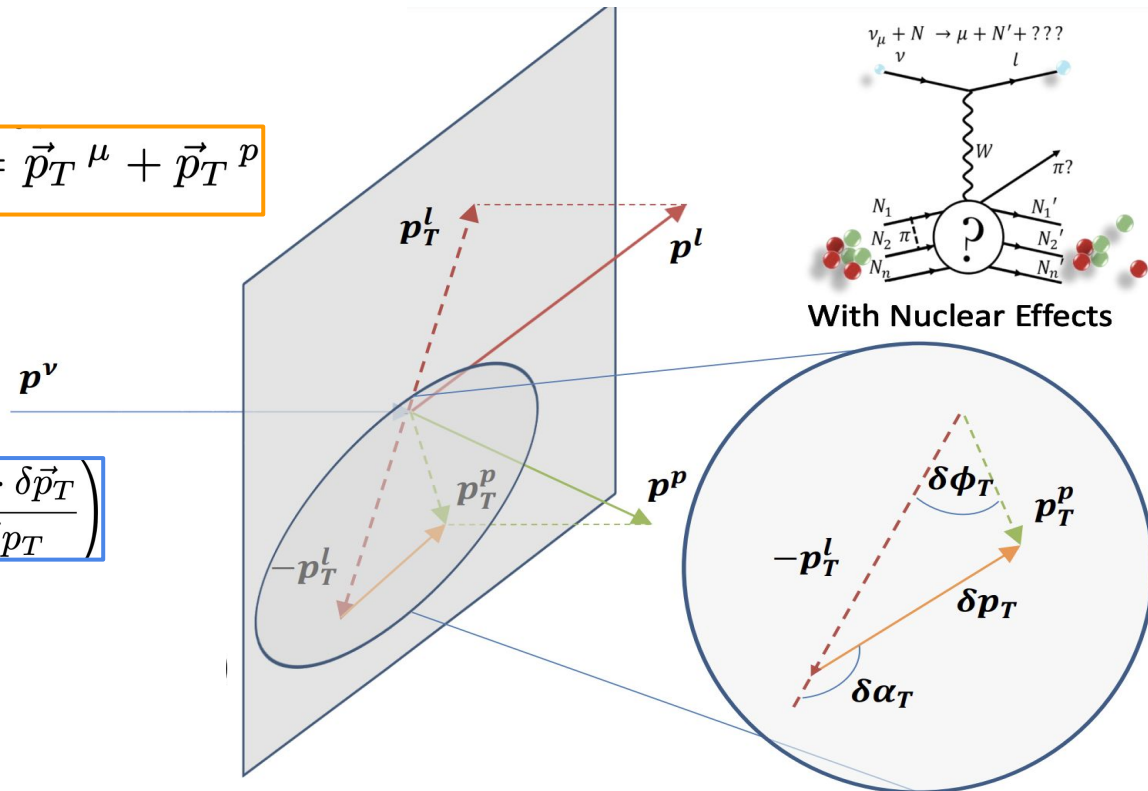
- **Transverse missing momentum**

$$\delta \vec{p}_T = \vec{p}_T^\mu + \vec{p}_T^p$$

- **Orientation of imbalance**

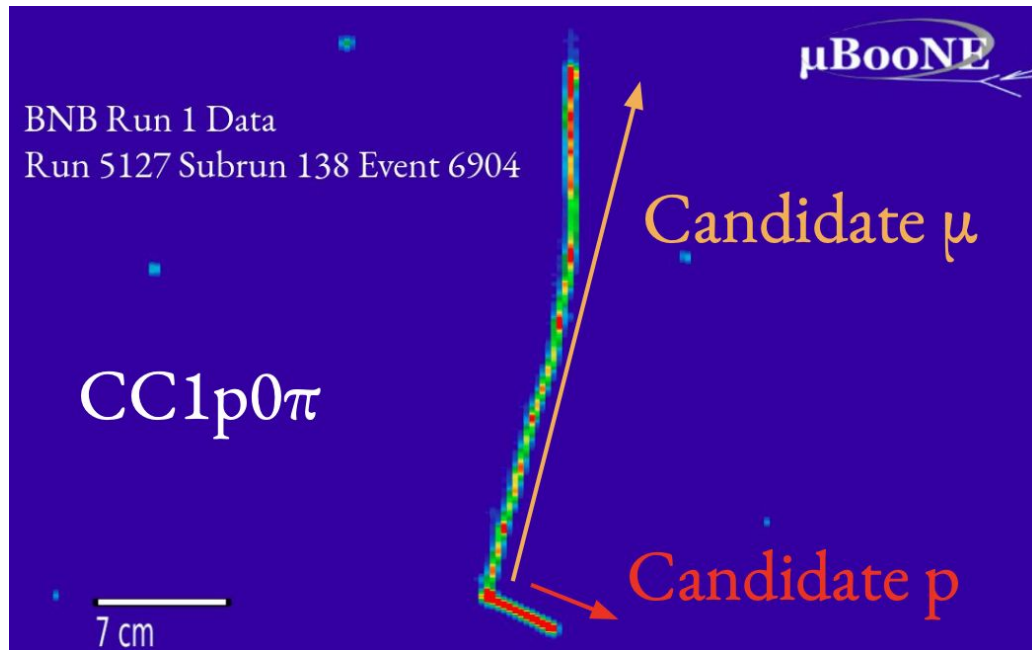
$$\delta \alpha_T = \arccos \left(\frac{-\vec{p}_T^\mu \cdot \delta \vec{p}_T}{p_T^\mu \delta p_T} \right)$$

- Previous measured in T2k and MINERvA



TKI from Charged-current Quasi-elastic-like events

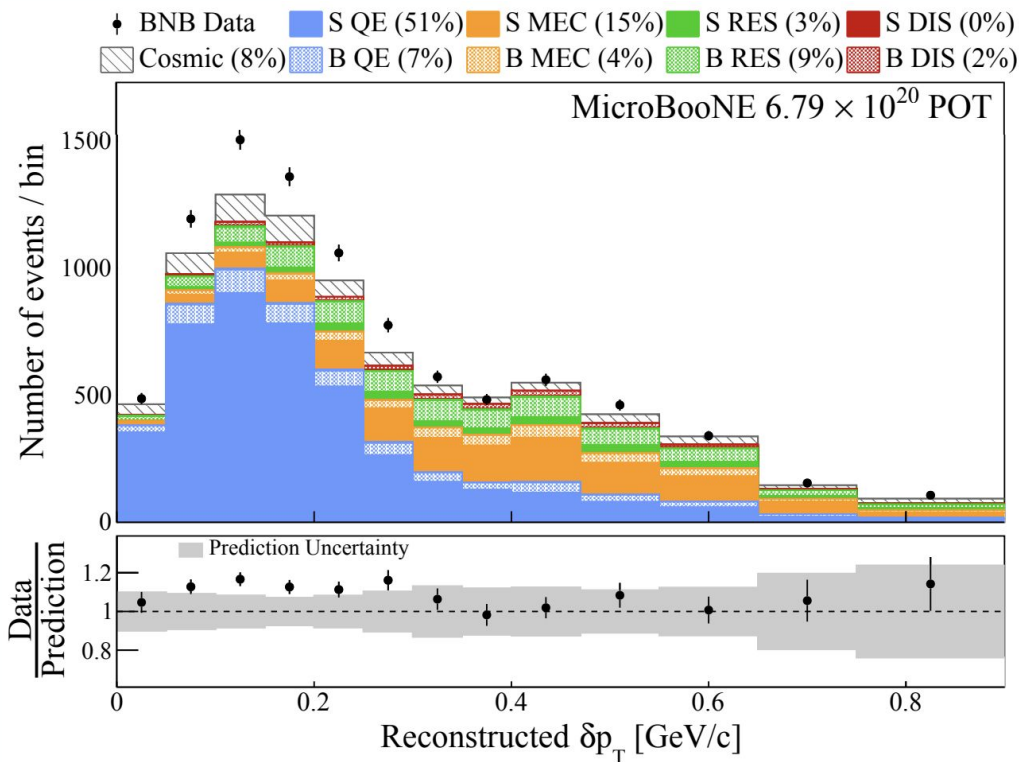
- Final state requirements
 - Muon candidate
 - $100 < P < 1200$ MeV/c
 - Proton candidate
 - $P > 300$ MeV/c
 - No charged pions above 70 MeV/c
 - No neutral pions
 - No requirements on neutrons
- ~ 9 k candidate events



Phys.Rev.D 108 (2023) 5, 053002

TKI from Charged-current Quasi-elastic-like events

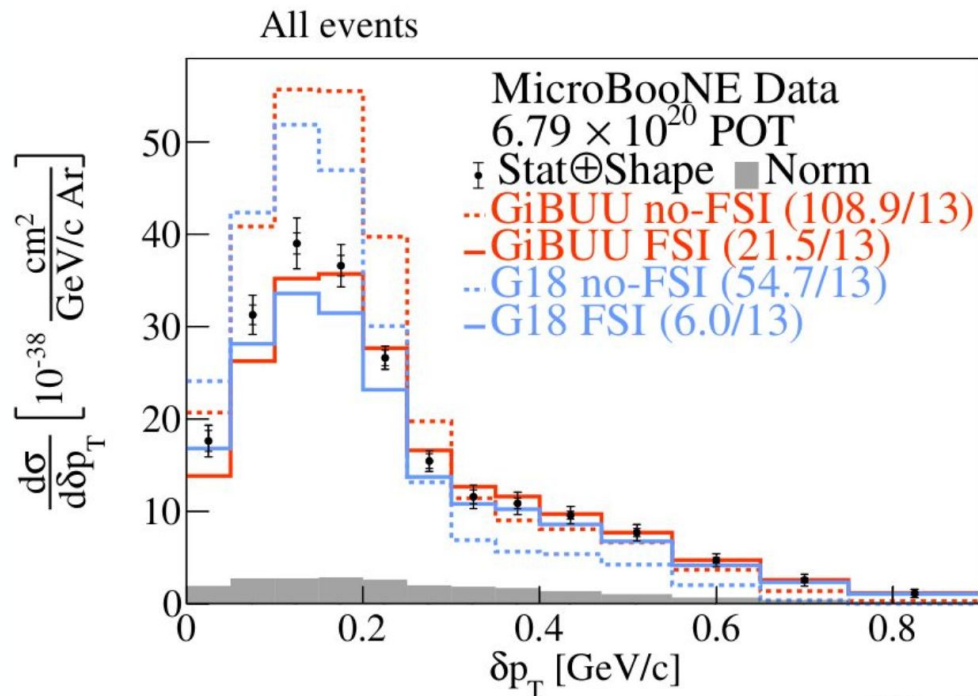
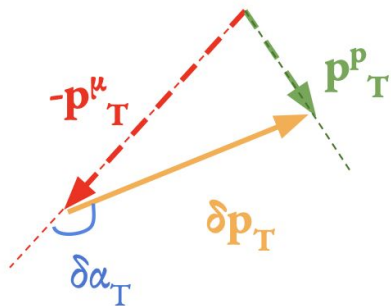
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Phys.Rev.D 108 (2023) 5, 053002

TKI from Charged-current Quasi-elastic-like events

- First measurement from neutrino-argon interactions
- Final state interaction alters the shape

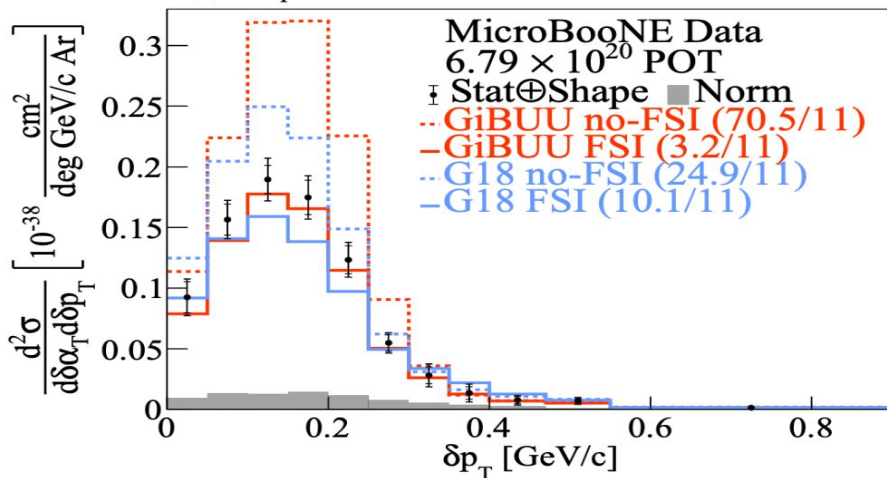


Phys.Rev.D 108 (2023) 5, 053002

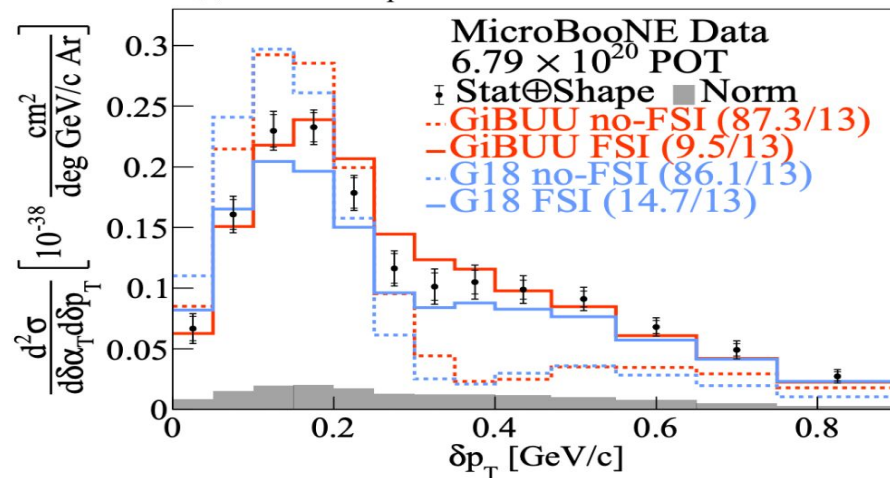
TKI in 2D

- First measurement of muon neutrino double-differential cross sections
- Identified parts of the phase space where the Fermi motion can be largely disentangled from FSI and multi-nucleon effects
 - To benchmark and tune the FSI modeling in event generators

(b) $\delta\alpha_T < 45^\circ$



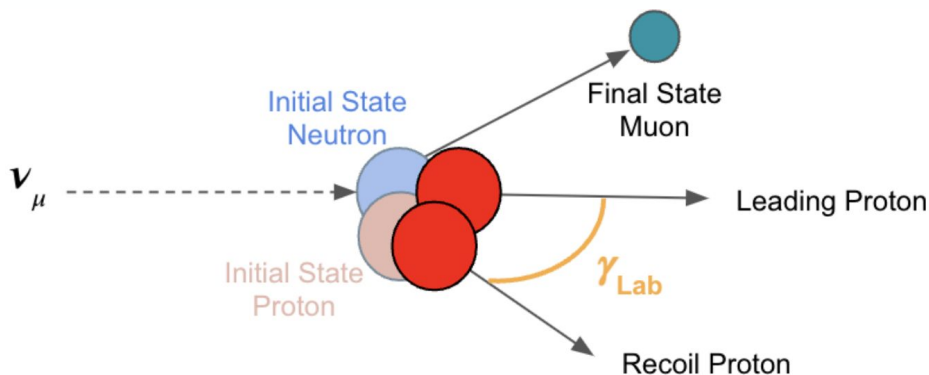
(c) $135^\circ < \delta\alpha_T < 180^\circ$



Phys.Rev.Lett. 131 (2023) 10, 101802

Charged-current Two Proton Knockout

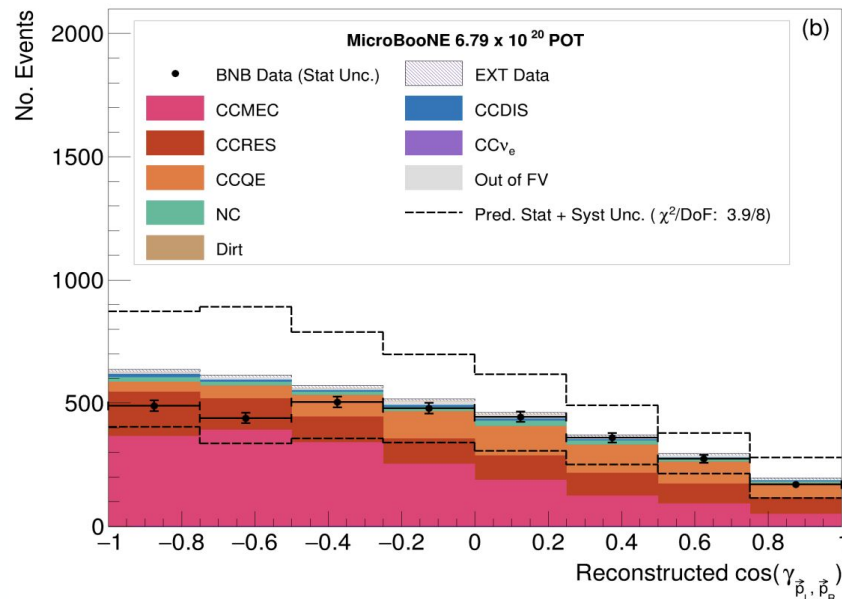
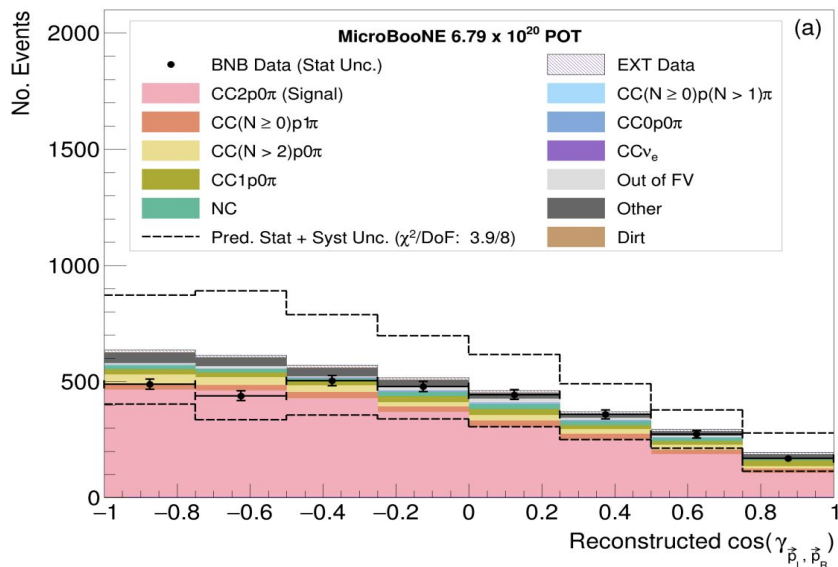
- First neutrino-argon cross sections for an exclusive 2p final state
- γ_{Lab} : angle between the two protons - Sensitive to modeling choices for MEC and QE



arXiv:2211.03734

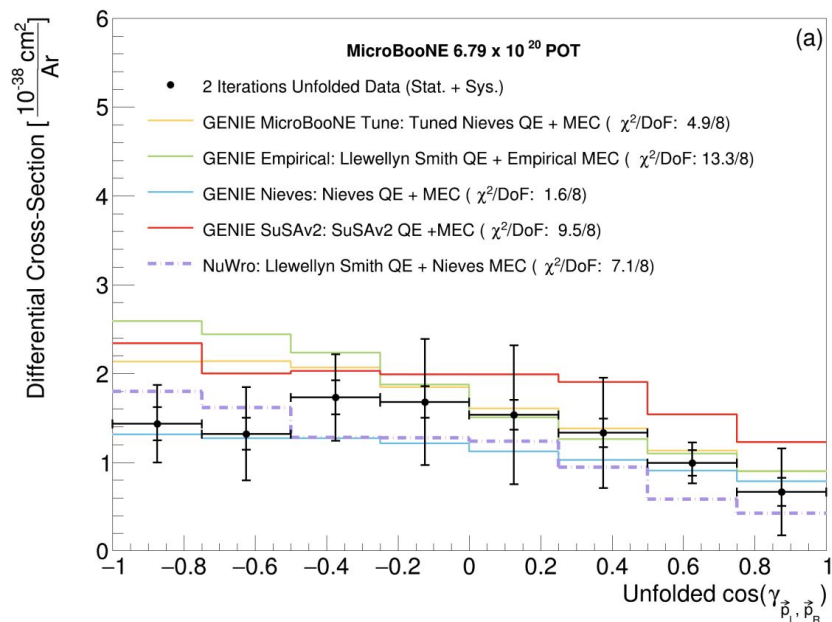
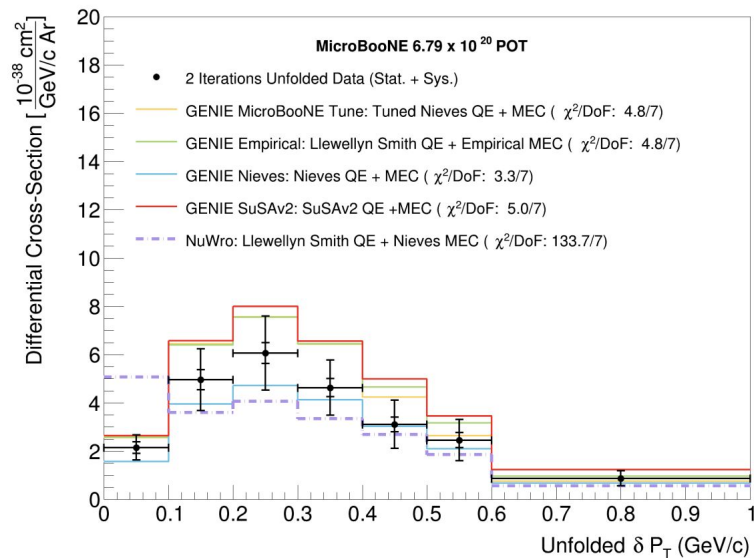
Charged-current Two Proton Knockout

- Efficiency of 13%
- Purity of 65%



arXiv:2211.03734

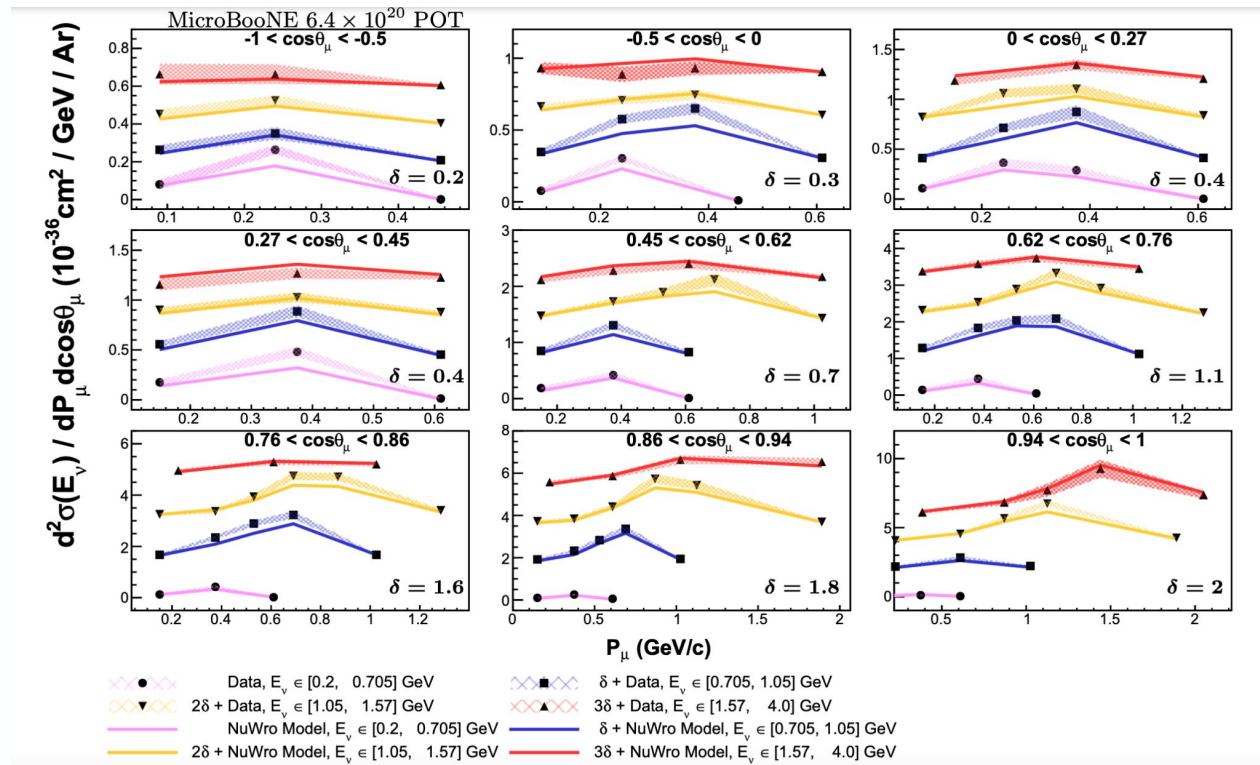
Charged-current Two Proton Knockout



arXiv:2211.03734

Charged-current Inclusive 3D measurement

- First measurement over a complete three dimensional kinematic phase space for inclusive $\nu\mu$ CC scattering
- Allows for better understanding of neutrino event generator performance

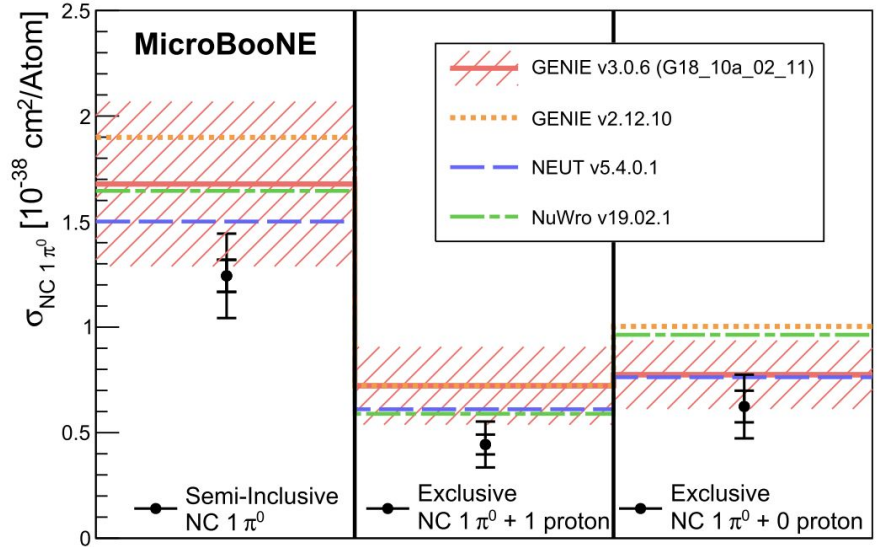


arXiv:2307.06413

NNN 2023, October 13th, 2023

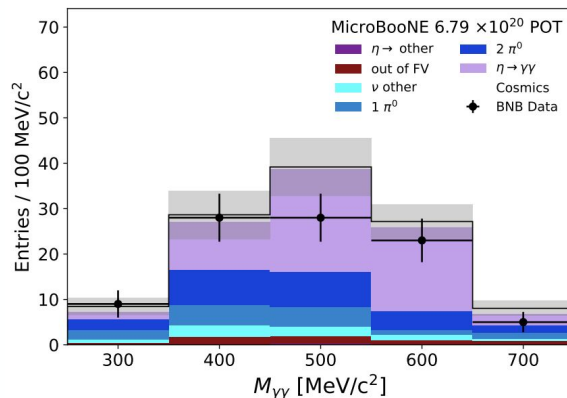
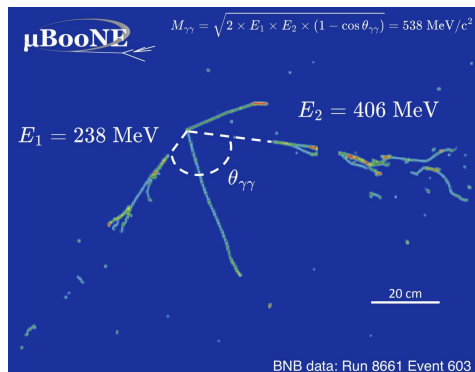
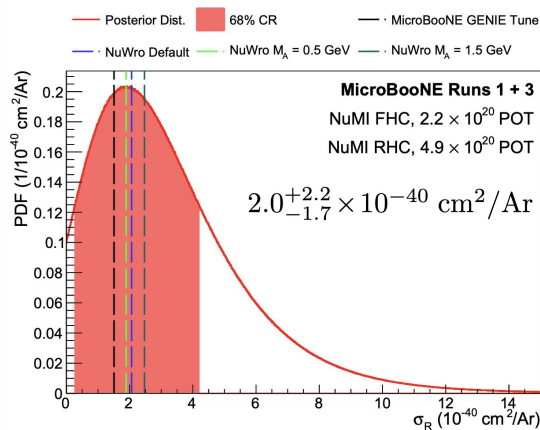
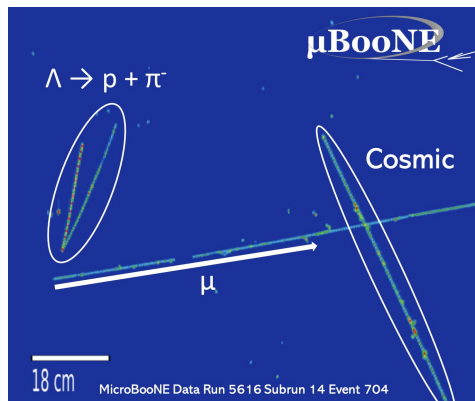
NC π^0

- Highest-statistics measurement to date of neutrino neutral current single pion production on argon
- Constraint for backgrounds to single-photon searches
- NEUT slightly more consistent with our measurement



Phys. Rev. D **107**, 012004

Rare channels: Λ Baryon Production and η production



- First Λ baryon production in a modern detector
- Λ baryons through invariant mass and separated vertex
- Identified 5 candidate from 2.2×10^{20} POT FHC and 4.9×10^{20} POT RHC NuMI data

Phys. Rev. Lett. 130, 231802 (2023)

- First cross section measurement for η production in neutrino Ar interactions

$$\nu_{\text{CC+NC}} \rightarrow \eta + X \rightarrow 2\gamma + 0\pi^0 + X$$

arXiv:2305.16249

Physics Goals

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“Deep Learning techniques to search for rare processes in LArTPC-based neutrino experiments” by Daisy Kalra this afternoon

Summary

- MicroBooNE has completed data taking with 1.56×10^{21} POT BNB data and 2.37×10^{21} POT NuMI data collected
- First low-energy excess results show no evidence of excessive electron- or photon-like excess to explain the MiniBooNE anomaly
- Full 3+1 oscillation analyses were carried out to interpret the MicroBooNE eLEE results under a sterile neutrino oscillation hypothesis
- Progress on precise neutrino-argon cross section measurements in the last few years
- More exciting results from MicroBooNE coming soon

Thank you!

Backup

Overview of MicroBooNE's Cross Section Program

- BNB (ν_μ)
 - CC Inclusive
 - CCQE-like
 - CC0 π Np
 - CC0 π 2p
 - CC0 π 0p
 - CC1 π^+
 - CC π^0
 - CC Coherent
 - CC Kaon
 - NC π^0
 - NC1p
 - NC Elastic
 - η production
 - MeV-scale Physics
 - ...
- NuMI
 - ν_e CC Inclusive
 - ν_μ CC Inclusive
 - ν_e/ν_μ CC ratios
 - ν_e CC0 π Np
 - ν_μ CC Kaon
 - Hyperon production
 - Kaon Decay-At-Rest (KDAR)
 - ...