Latest Results from MicroBooNE

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on behalf of the MicroBooNE collaboration

February 22, 2023
Lake Louise Winter Institute

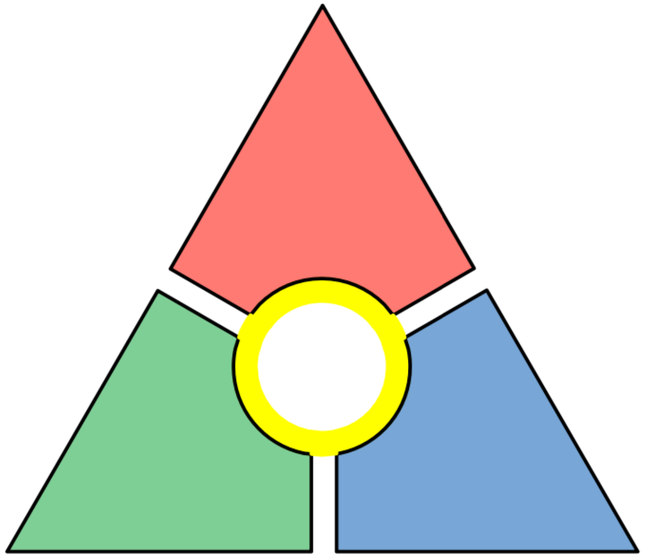
MicroBooNE science goals

address MiniBooNE LEE and BSM

- same neutrino beamline & roughly same location as MiniBooNE
- unique electron/photon separation capability
- search for BSM physics

LArTPC hardware & software R&D

- LArTPC design, cryostat, cold electronics
- noise filtering, TPC signal processing, detector physics,
- event reconstruction



study ν-Ar interactions

- one of the largest uncertainties in neutrino oscillation experiments
- provide important input for LArTPC experiments

MicroBooNE science output

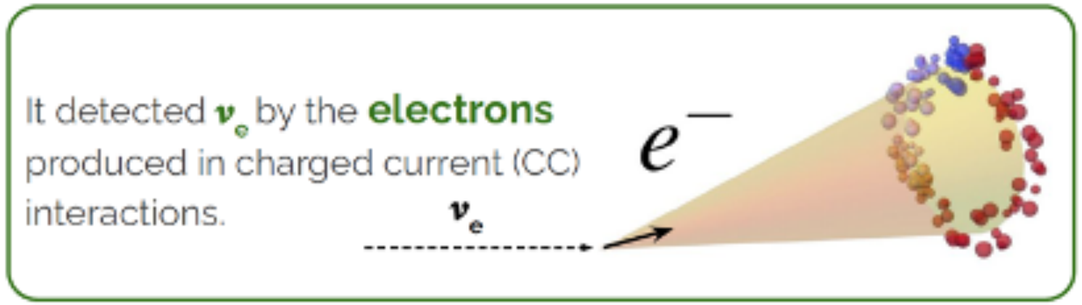
2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023

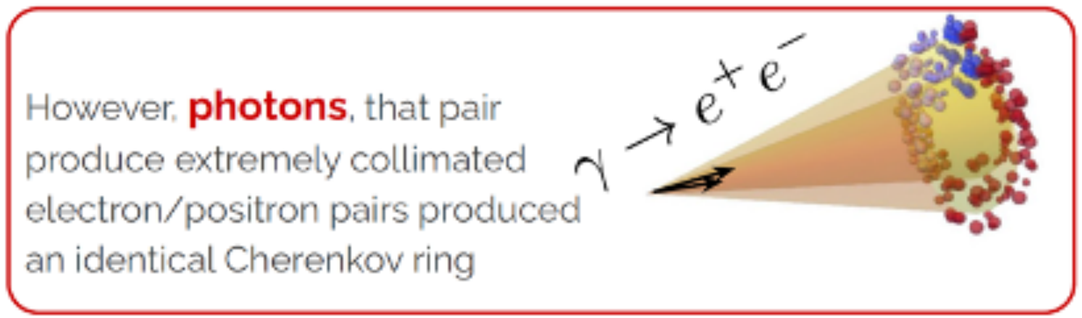
55 papers:
~1/2 detector R&D
~1/2 physics

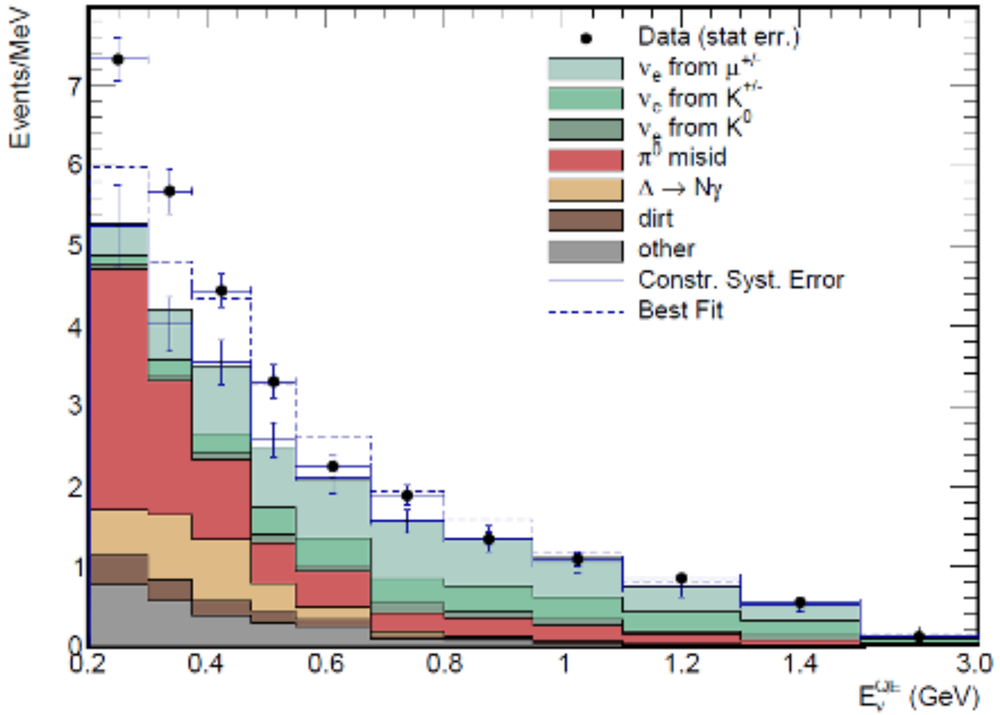
MiniBooNE anomaly

Phys. Rev. D **103**, 052002

- MiniBooNE (2002-2019) observed a low energy excess (LEE) of electromagnetic events with 4.8σ significance







- MiniBooNE Cherenkov detector unable to distinguish between electrons and photons
- MiniBooNE also unable to detect hadronic final-state particles below Cherenkov threshold

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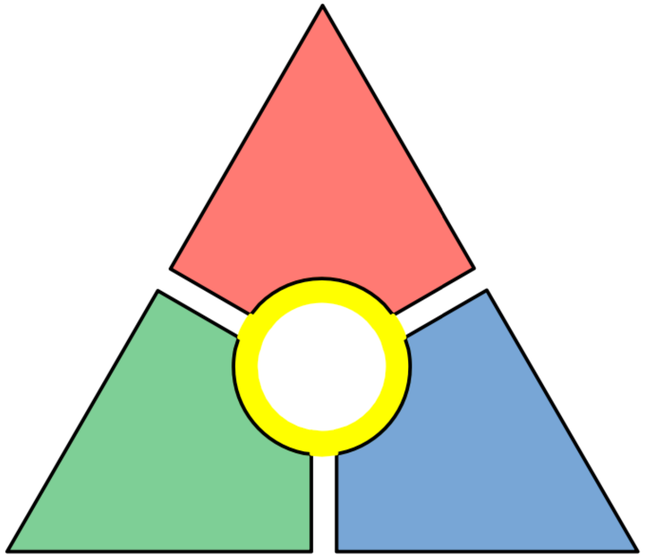


study ν-Ar interactions

- one of the largest uncertainties in neutrino oscillation experiments
- provide important input for LArTPC experiments

Liquid Argon Time Projection Chamber

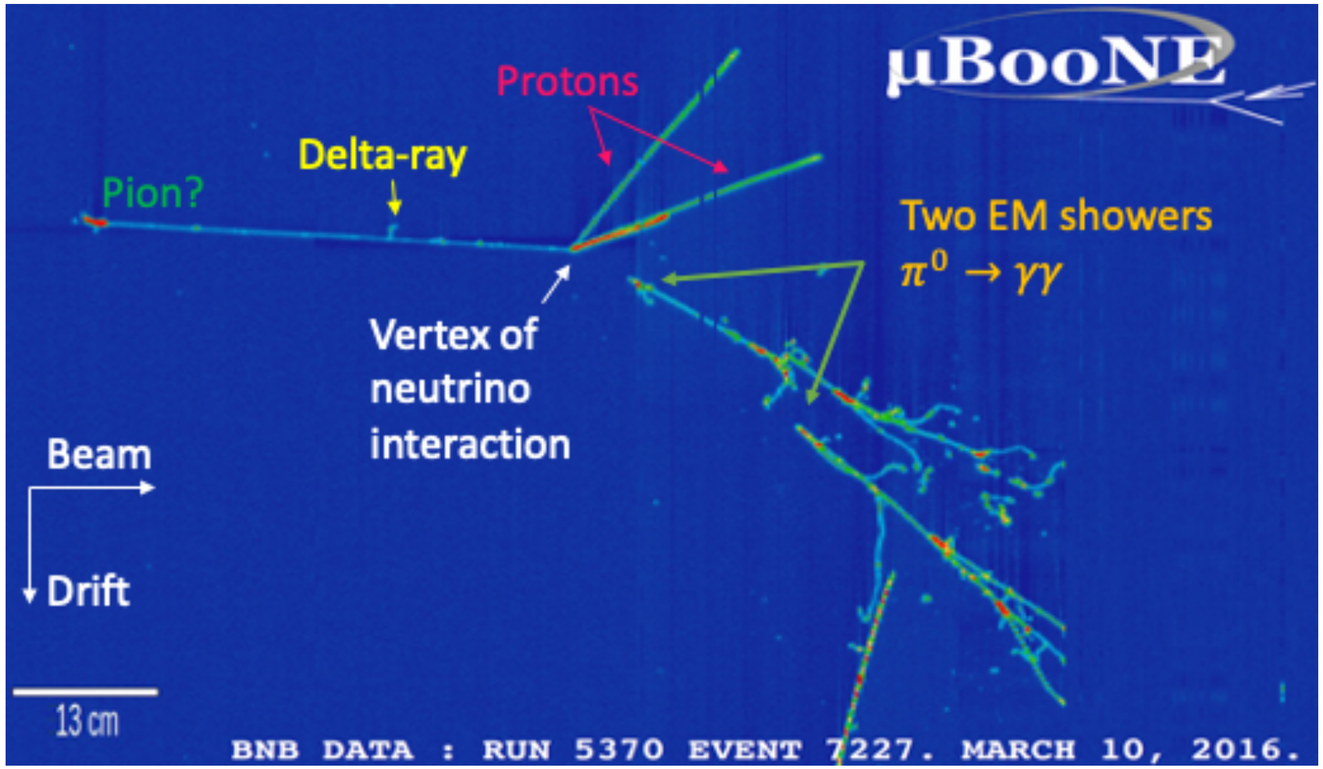
- LArTPC is capable of identifying different species of particles and reconstructing 3D images with fine-grained information

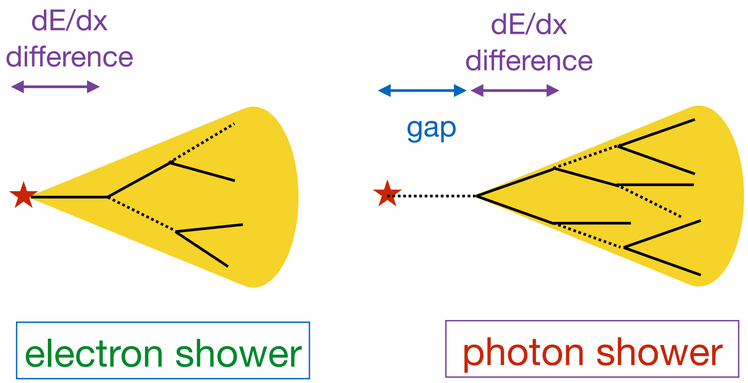
  - neutrino vertex

  - particle flow (mother-daughter particle relationship)

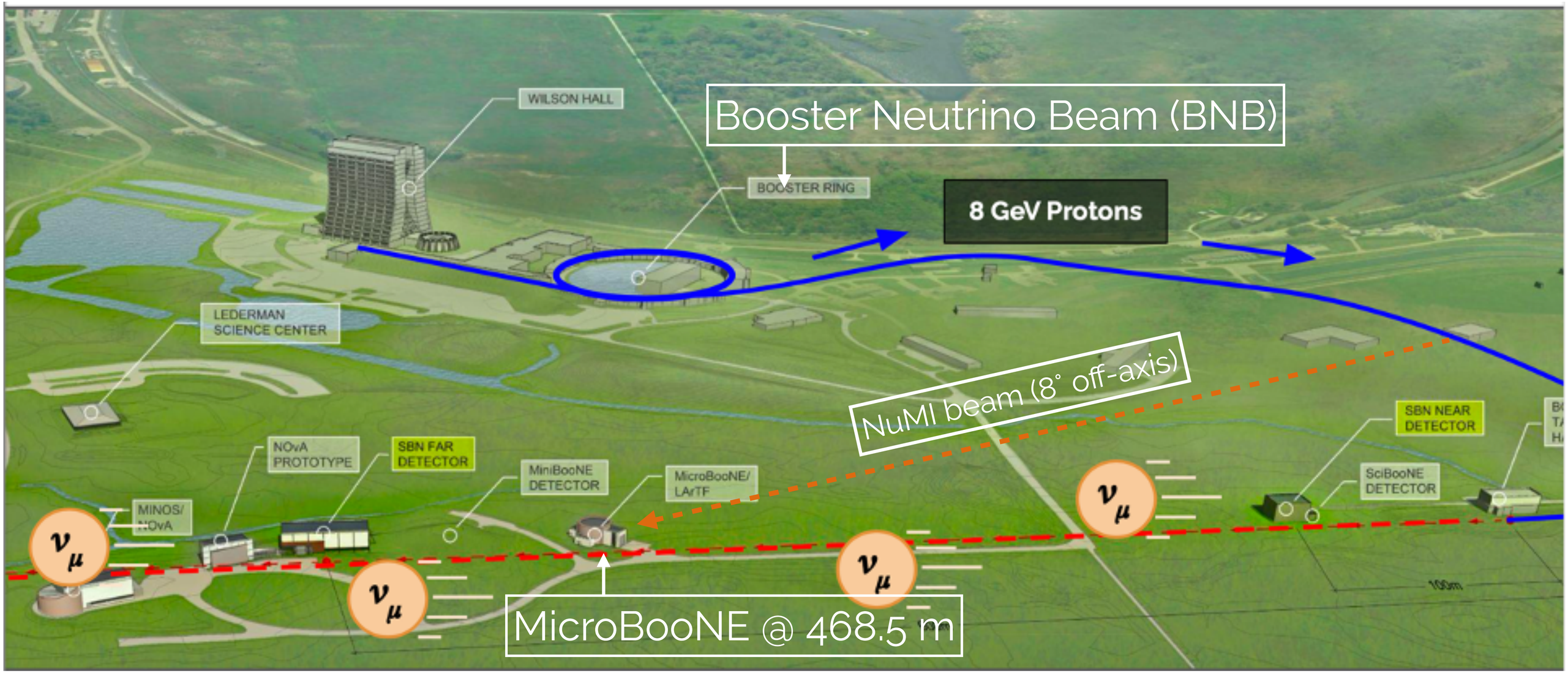
  - track vs. shower separation

  - electron vs. photon (e+e- pair production) separation



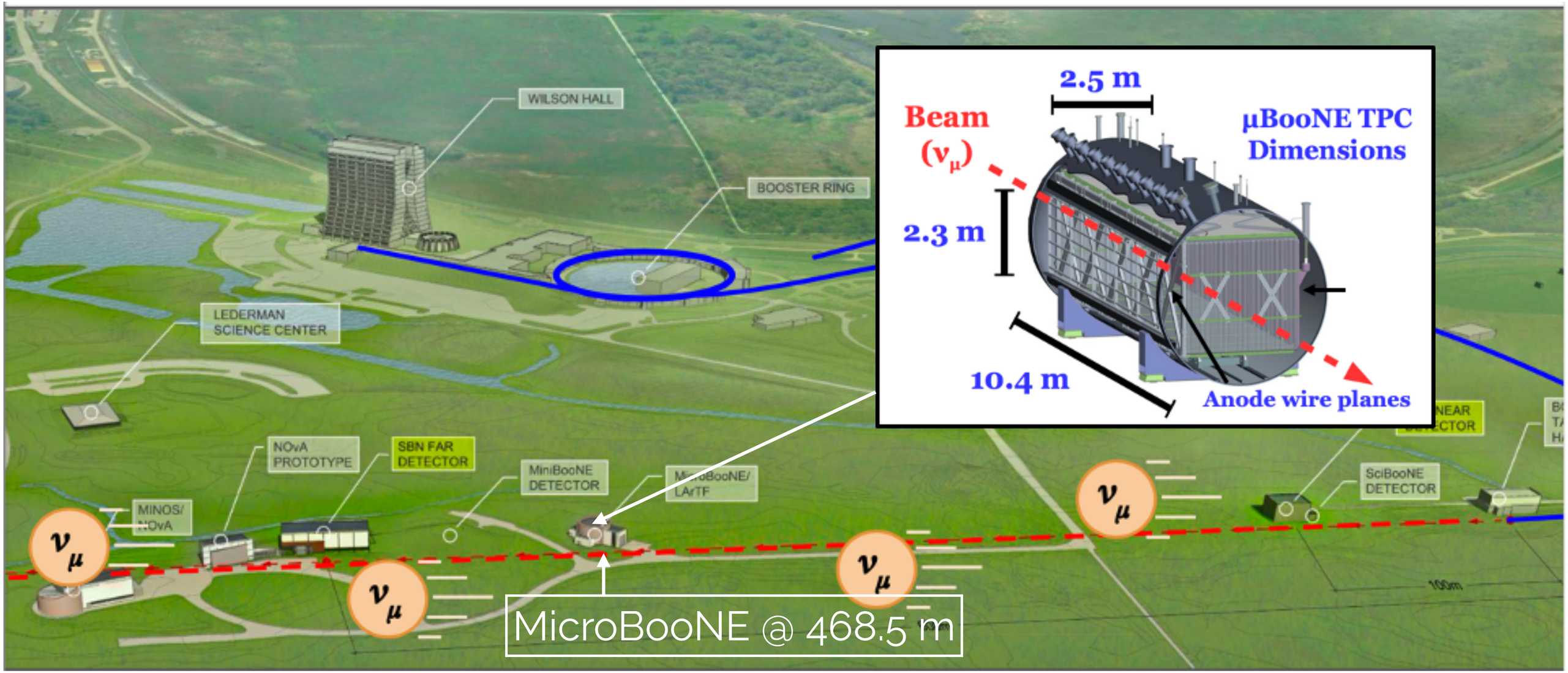


MicroBooNE @ Fermilab



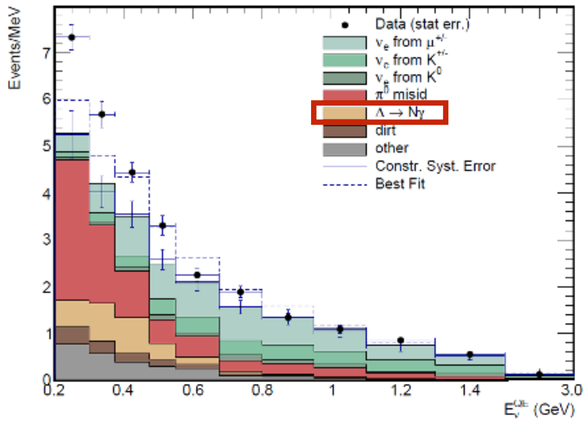
MicroBooNE @ Fermilab

170 (85) tonne liquid argon in cryostat (TPC)

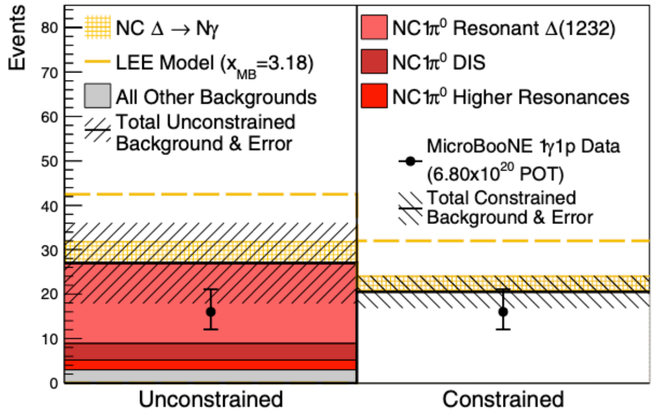


First LEE results 2021

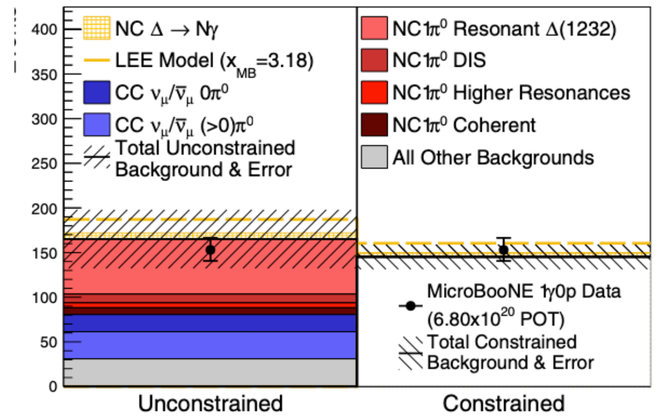
"Q: is LEE coming from underestimated NCΔ background?"



$1\gamma 1p$

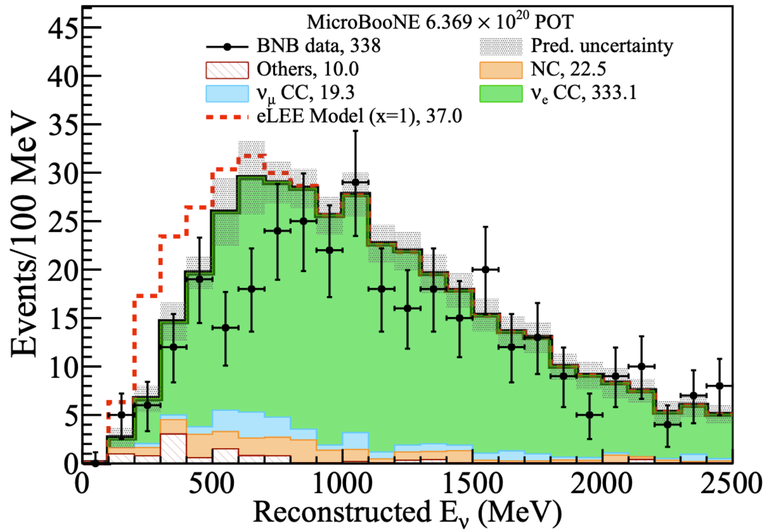


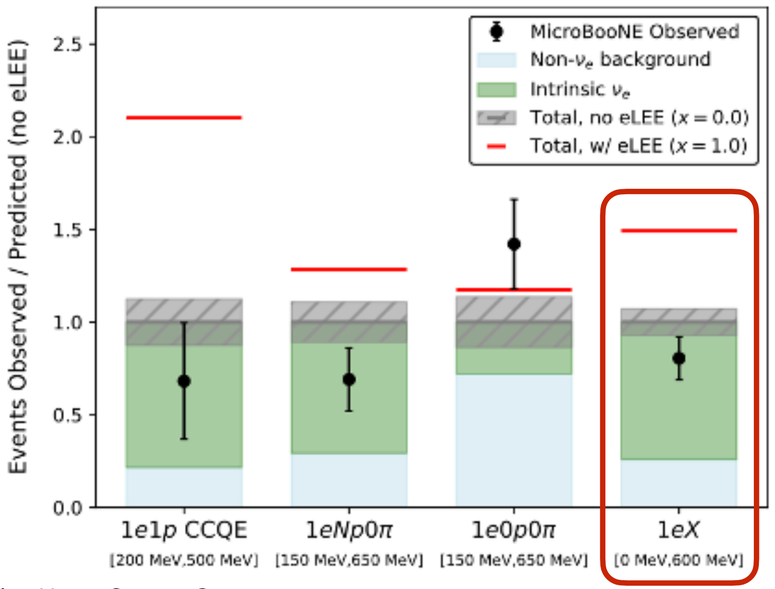
$1\gamma 0p$



Phys. Rev. Lett. **128**, 111801

"Q: is LEE coming from electron neutrinos?"





Phys. Rev. Lett. 128, 241801
Phys. Rev. D 105, 112005

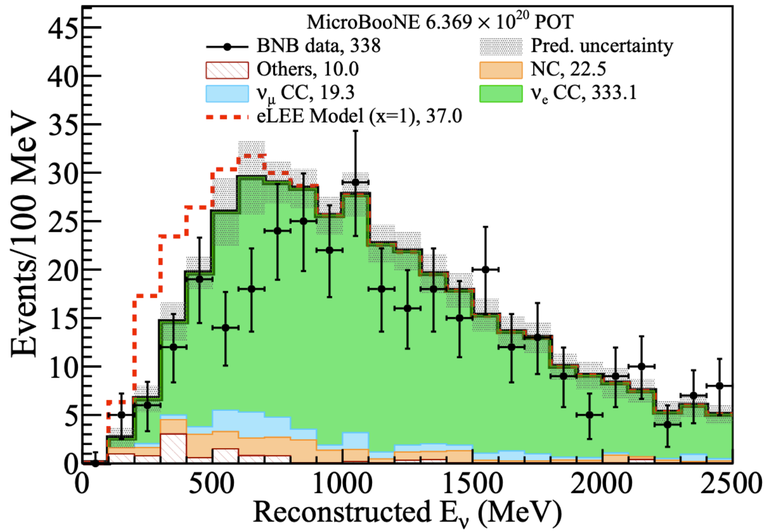
What did we learn from the LEE result?

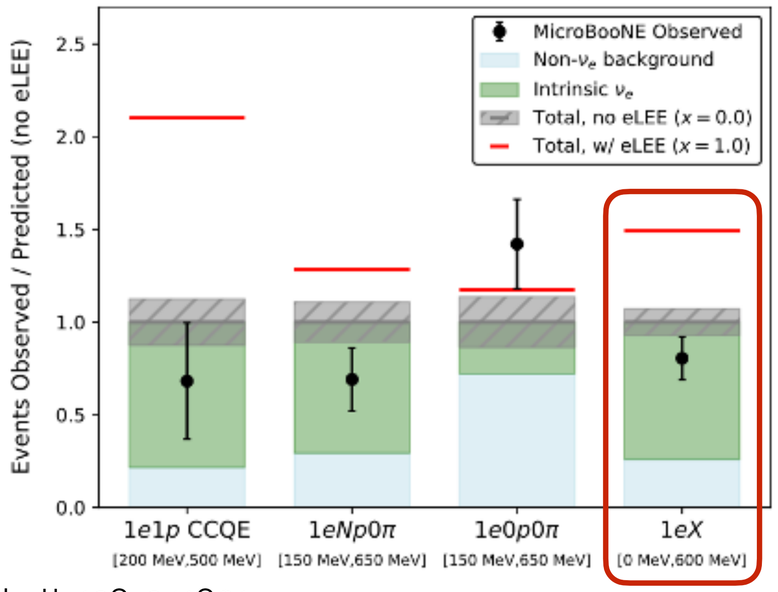
- observed ν_e candidate rates are statistically consistent with the predicted background rates in the LEE region

- with exception of the low ν_e purity channel 1e0p0π, the hypothesis that ν_e events are ***fully responsible*** for the median MiniBooNE LEE is rejected at 97% C.L. and >3σ in the inclusive channel

  - however, **this analysis does not address specifically the sterile neutrino hypothesis**, which is a generic low-energy ν_e excess search

"Q: is LEE coming from electron neutrinos?"

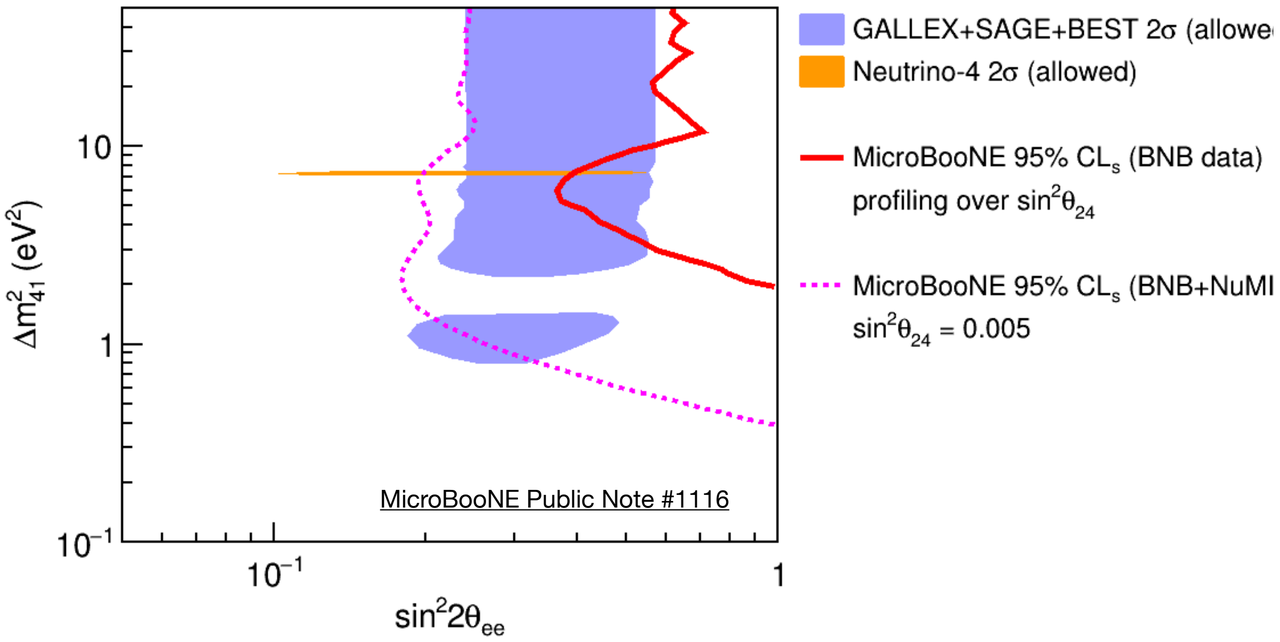




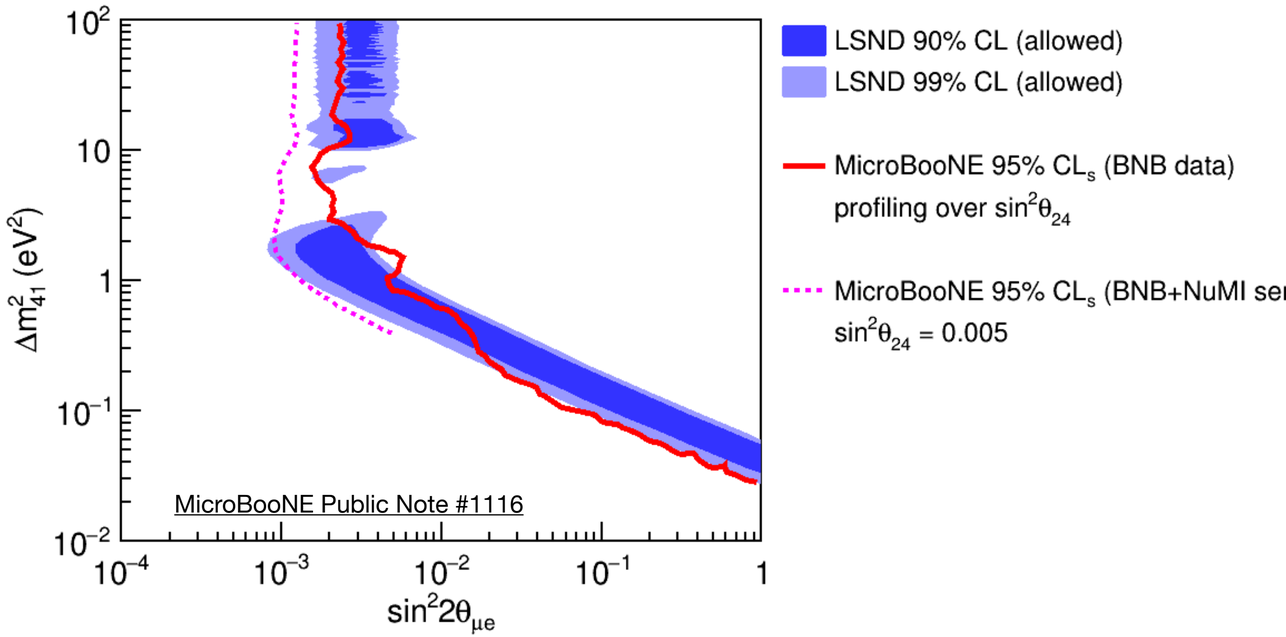
Phys. Rev. Lett. 128, 241801
Phys. Rev. D 105, 112005

3+1 neutrino oscillation analysis

ν_e disappearance



ν_e appearance



- **competitive limit** on the eV-scale ν_e disappearance, first ν-*Ar* scattering data limit
- **part of the LSND allowed region is excluded** by the MicroBooNE 95% C.L.

sensitivity significantly improved when combining both BNB and NuMI, mainly due to ν_e appearance-disappearance degeneracy mitigation

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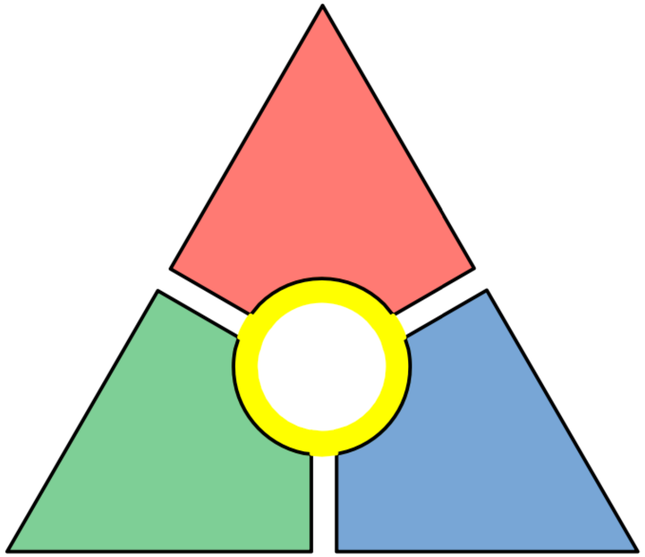


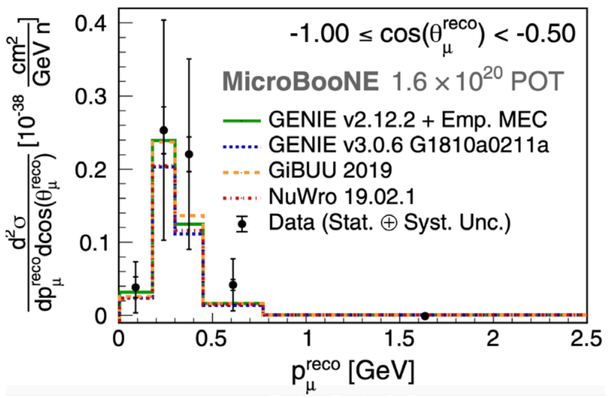
study ν-Ar interactions

- one of the largest uncertainties in neutrino oscillation experiments
- provide important input for LArTPC experiments

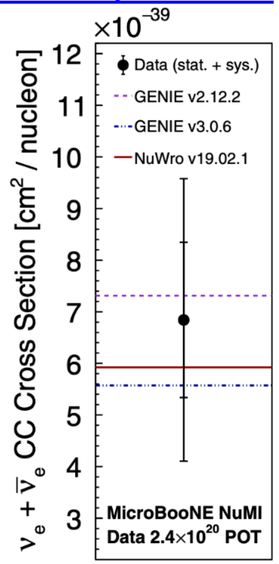
Studying ν-Ar cross sections @ MicroBooNE

- leveraging LArTPC's excellent capability of tracking calorimetry
  - understanding of charged-current (CC) inclusive and neutral-current (NC) π^0 cross section is desired for oscillation measurements
  - exclusive cross sections further guide event generators to pin down underlying reaction mechanism
  - "1st generation" results covered wide range of channels, providing foundation for next set of results

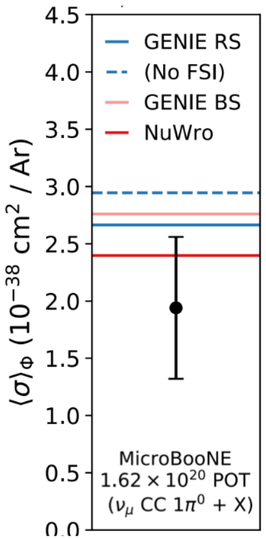
PRL **123**, 131801



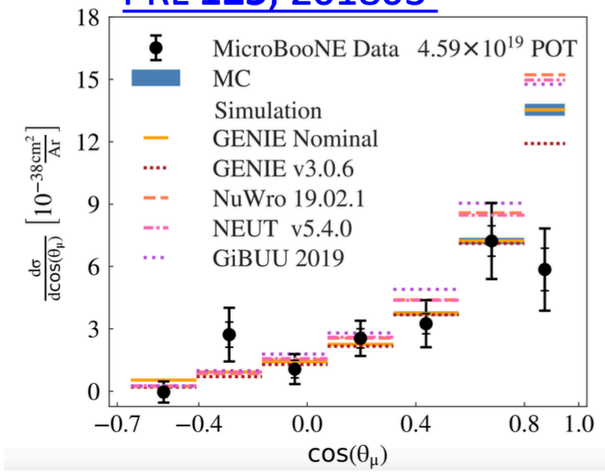
PRD **104**, 052002



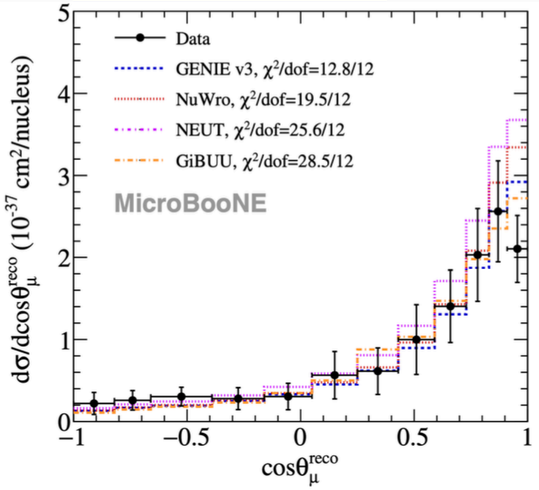
PRD **99**, 091102



PRL **125**, 201803



PRD **102**, 112013

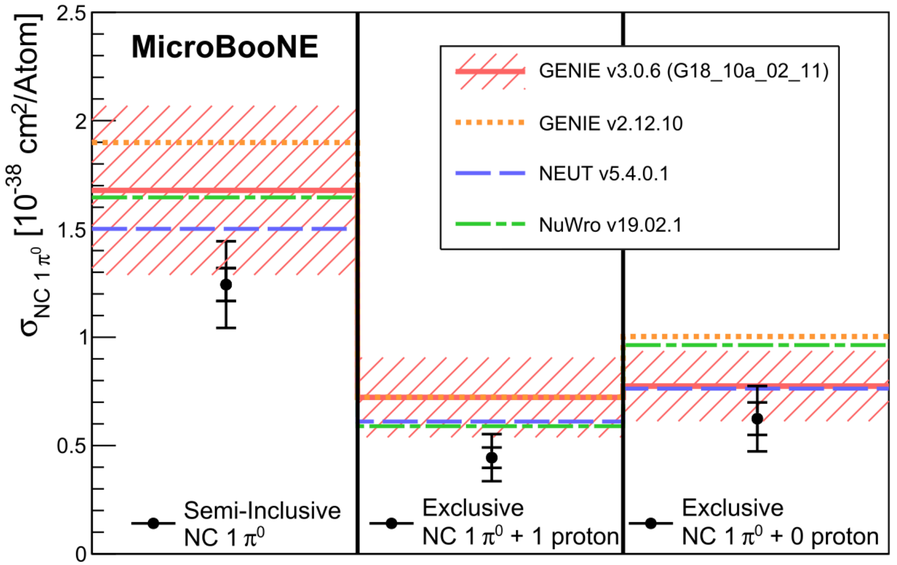


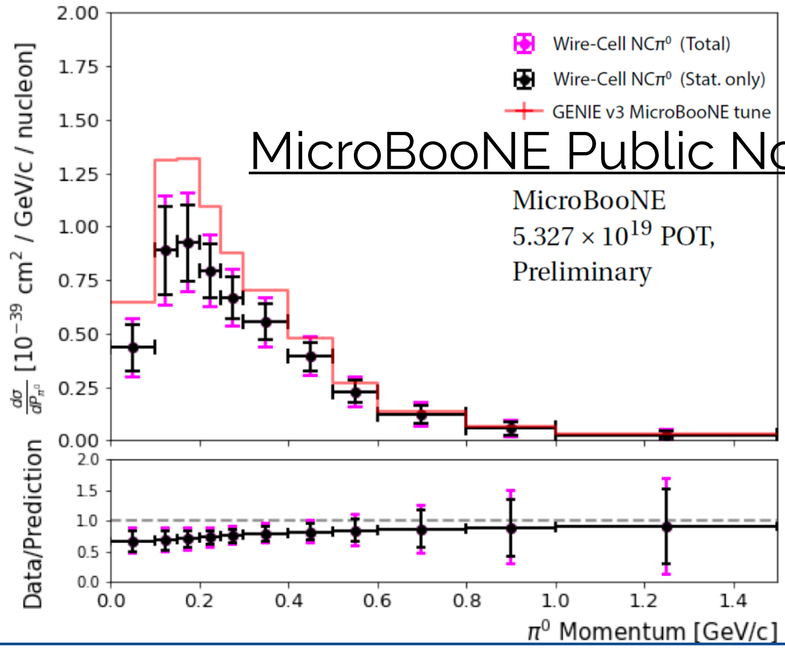
X. Qian, NuINT 2022

NCπ⁰ cross section analyses

Phys. Rev. D 107, 012004 (2023)

- inclusive NC 1π⁰ measurement on argon
  - first exclusive measurement in the 0p and 1p channels
- deficit seen compared to all model studied
- ongoing analysis to extract differential cross sections
- ~1σ deficit over much of the phase space in π⁰ momentum with an interesting slope

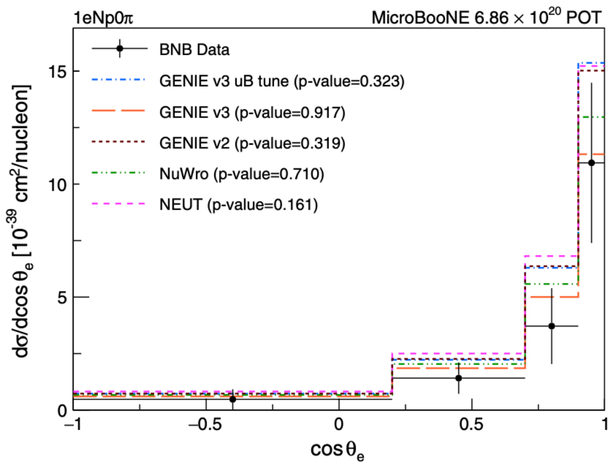


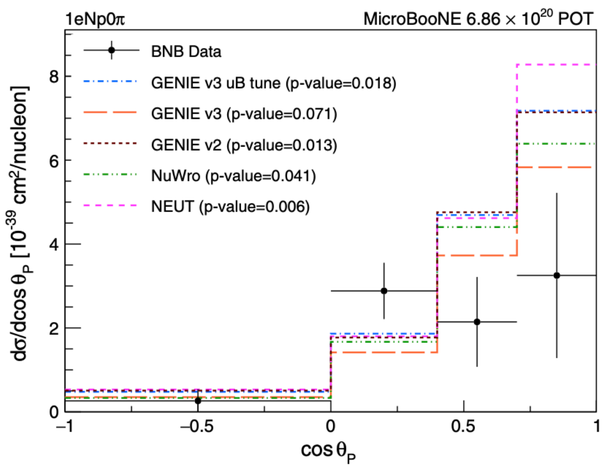


MicroBooNE Public Note 111

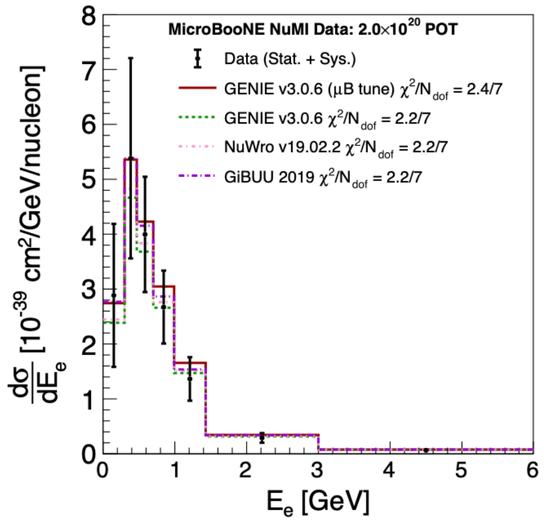
ν_eCC cross section analyses (BNB vs. NuMI)

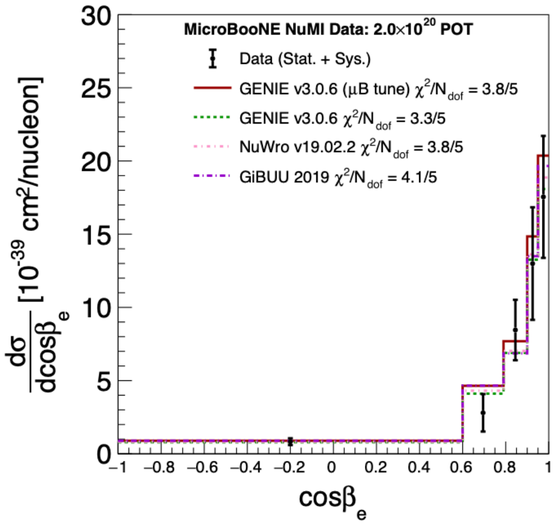
Phys. Rev. D 106, L051102





Phys. Rev. D 105, L051102





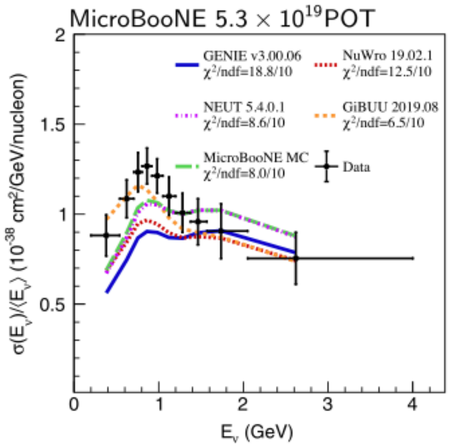
- first differential exclusive ν_μCC cross section without pions
  - categorize the proton final state with low energy threshold
  - **consistent result with model predictions within uncertainties**, slightly favor predictions of a lower overall cross section

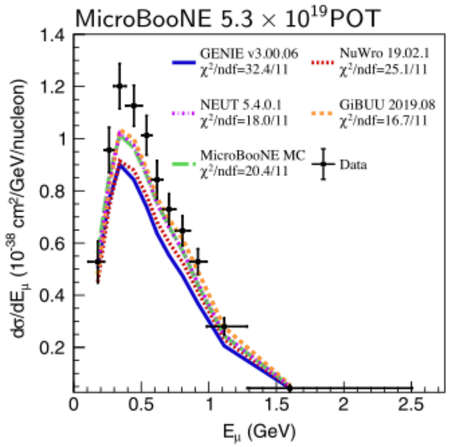
- differential inclusive $\nu_e + \bar{\nu}_e$ cross section
  - enhanced event selection efficiency and purity
  - **consistent results with model predictions within uncertainties**

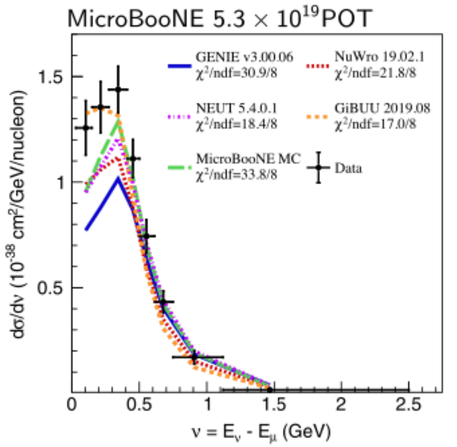
Inclusive ν_μCC cross section analyses

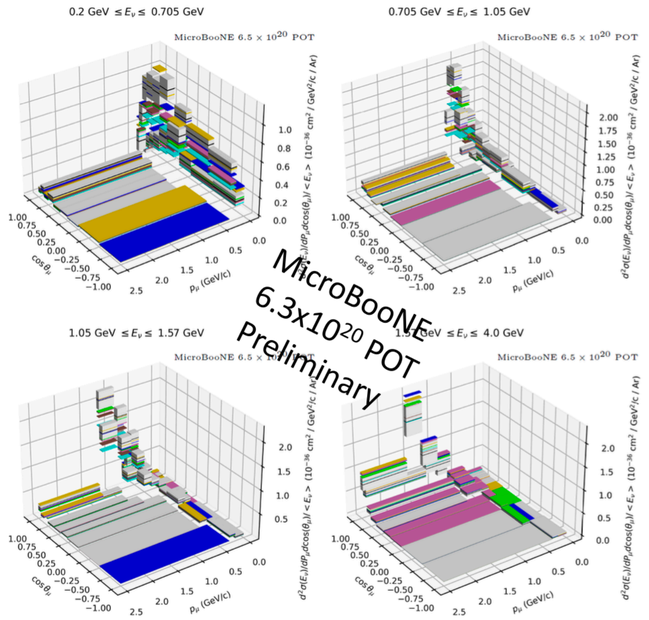
Phys. Rev. Lett. 128, 151801 (2022)

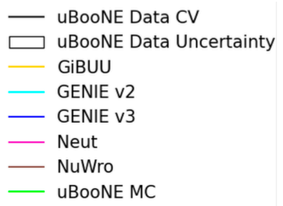
- energy-dependent cross section has been performed
  - using new model validation procedure based on the conditional covariance matrix formalism
- extended to triple differential cross sections for inclusive ν_μCC in {E_ν, P_μ, cosθ_μ}, rich information can be extracted











Model Generator	χ^2/ndf
Genie v2	740.8/138
Genie v3 (MicroBooNE Tune)	313.9/138
Genie v3 (Default Tune)	309.7/138
GIBUU	265.6/138
NEUT	233.1/138
NuWro	200.9/138

MicroBooNE Public Note 1122

And much more XS measurements coming

CC inclusive

- ν_e CC inclusive @ NuMI
- ν_μ CC inclusive @ NuMI
- ν_e/ν_μ ratios @ NuMI
- E_ν, E_μ, hadronic energy @ NuMI & BNB

Much more coming from 30+ active analyses

Pion production

- ν_μ CC$1\pi^+$ @ BNB
- ν_μ CC-Coherent @ BNB
- ν_μ CCπ^0 @ BNB
- ν_μ NCπ^0 @ BNB
- ν_μ CC/NC π^0 @ BNB

CC0π

- ν_μ Single Transverse Variables @ BNB
- ν_μ CC2p topologies @ BNB
- ν_μ CC0π inclusive @ BNB
- ν_μ CC0π0p @ BNB
- ν_e CC0πNp @ NuMI

Rare channels

- ν_μ CC Kaon @ BNB
- ν_μ CC Kaon @ NuMI
- η production @ BNB
- Hyperon (Λ,Σ) production @ NuMI
- MeV-scale Physics in MicroBooNE

X. Qian, NuINT 2022

Summary

- MicroBooNE is the first neutrino experiment to fully realize and exploit the power of LArTPC
- MicroBooNE found no evidence of excessive of ν_e and NC Δ radiative decay as a sole source of the MiniBooNE anomaly
- a full 3+1 oscillation analyses were carried out to interpret the MicroBooNE eLEE results under a sterile neutrino oscillation hypothesis
  - the data (~50% BNB dataset) was found to be consistent with 3-flavor hypothesis
- with well-understood LArTPC detector, simulation, and dataset, wealth of cross section measurements are being carried out, including NCπ^0, inclusive & exclusive ν_e CC/ν_μCC, and many others
  - already benefiting the community with better understanding of ν-Ar interactions, providing inputs for current/future LArTPC experiments

μBooNE

Thank You!

Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

SNF SWISS NATIONAL SCIENCE FOUNDATION

Science & Technology Facilities Council

THE ROYAL SOCIETY

Backup slides

LArTPC: Liquid Argon Time Projection Chamber

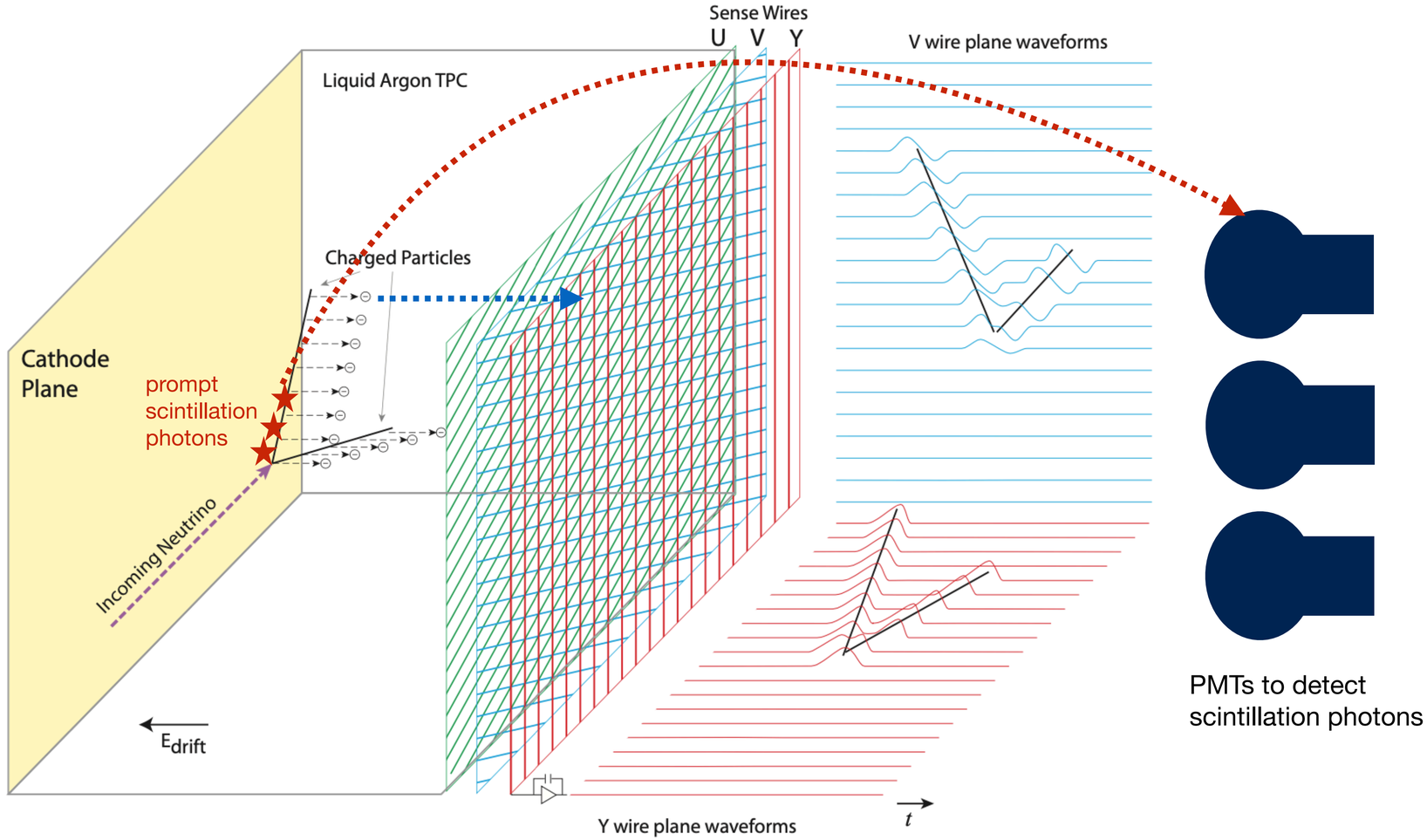
charged particle enters detector

⬇

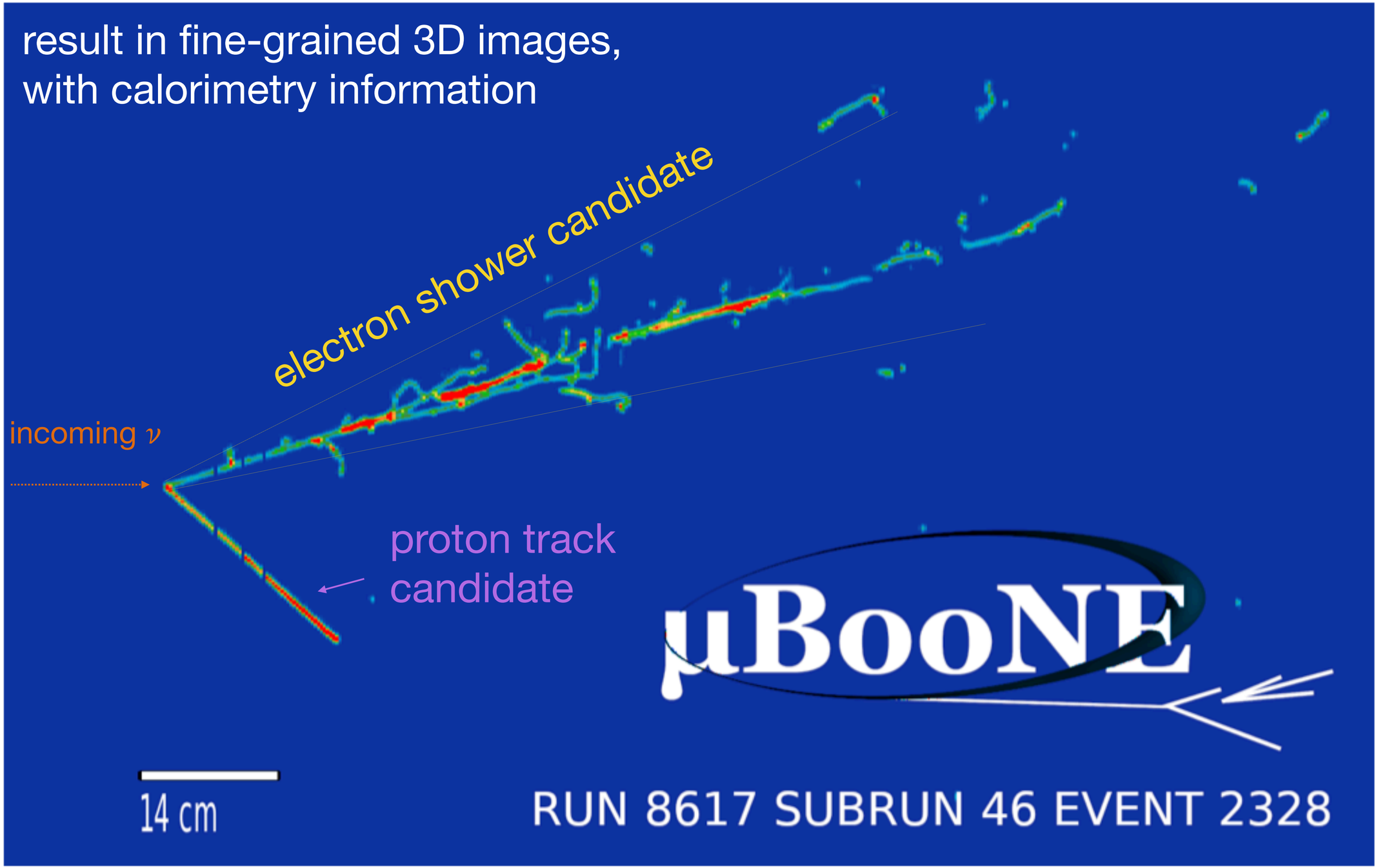
scintillation light emitted by excited Ar, detected by PMTs

⬇

ionization electrons drift to anode plane, detected by sense wires

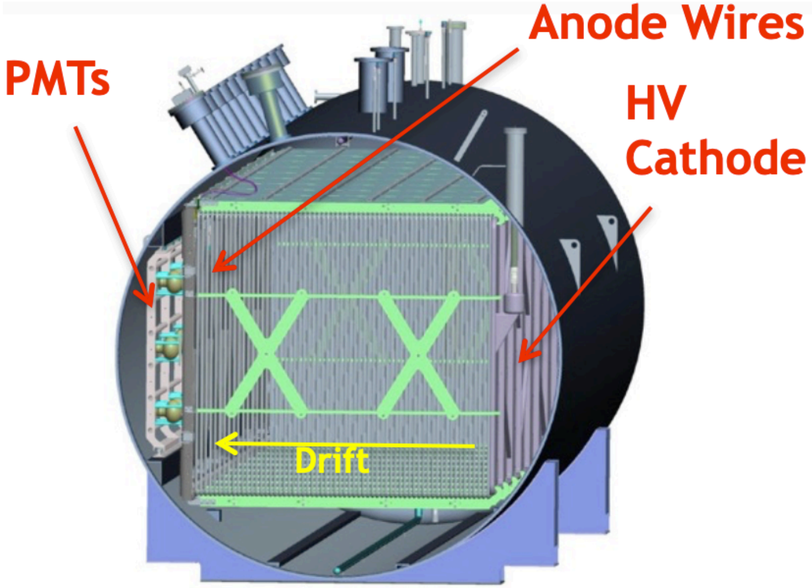


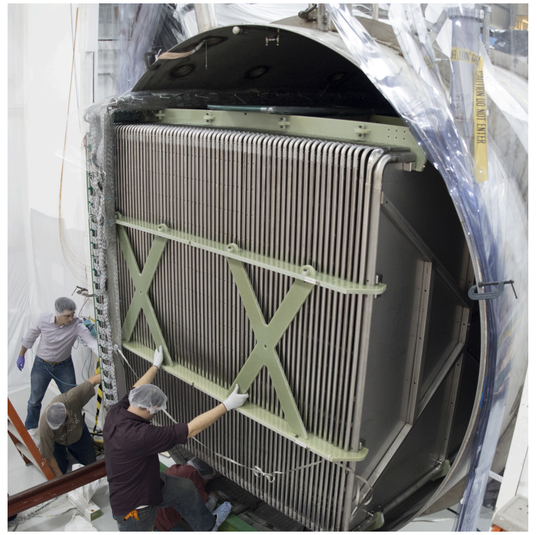
result in fine-grained 3D images,
with calorimetry information



MicroBooNE experiment

- LArTPC Detector
  - 85 tons of LAr active volume
  - TPC: 8192 anode sense wires in 3 planes
    PMT: 32 8-inch PMTs
  - CRT (cosmic ray tagger) is installed around TPC
  - located at BNB beamline in Fermilab, started taking data since Oct. 2015
- physics goal
  - strong understanding of the detector and highly developed event reconstruction, paving the way to future LAr detectors (SBN & DUNE)
  - neutrino interaction measurements
  - towards low-energy excess: definitively address the MiniBooNE anomaly





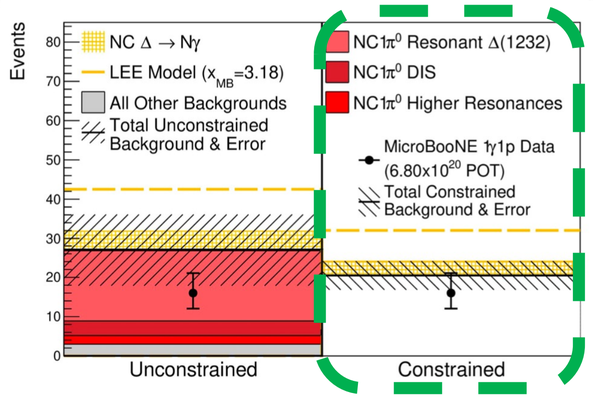
This LEE search proceeds with a simultaneous side-by-side fit of four topologically distinct samples

Two **NC Δ→Nγ** rich **single-photon** selections

Two high-statistics **NC π^0 rich** **two-photon** selections

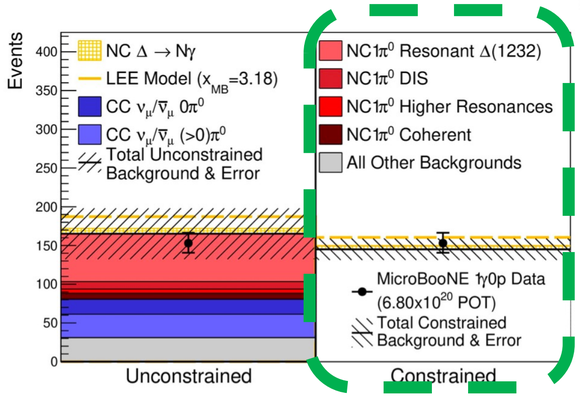
Phys. Rev. Lett. **128**, 111801

1γ1p



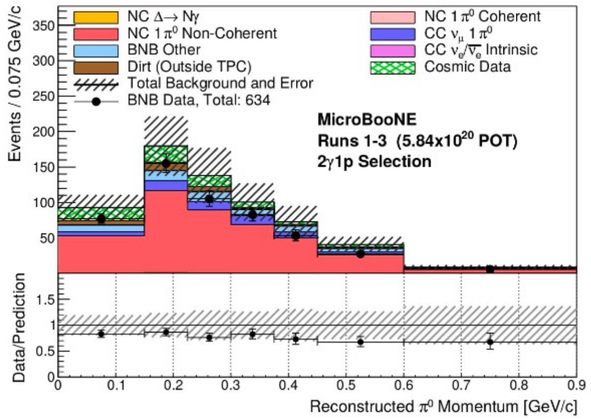
One-bin, Shower Energy from 0-0.6 GeV

1γ0p



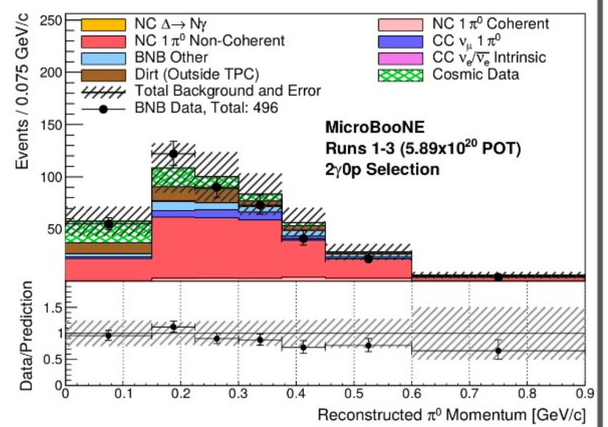
One-bin, Shower Energy from 0.1-0.7 GeV

2γ1p



7-bins, π^0 Momentum from 0-0.9 GeV/c

2γ0p

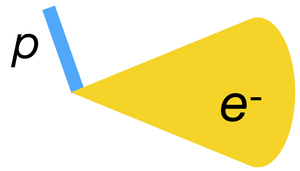


7-bins, π^0 Momentum from 0-0.9 GeV/c

MicroBooNE's search for an excess of electron neutrino interactions

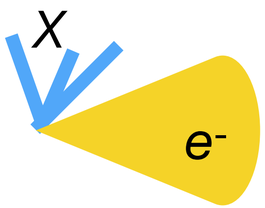
three independent searches across multiple single electron final states

- exclusive two-body charged-current quasi-elastic (CCQE) ν_e scattering [1e1p]



- semi-inclusive ν_e scattering without final state pions [1eNp0π (N≥1) + 1e0p0π]

- inclusive ν_e scattering [1eX]

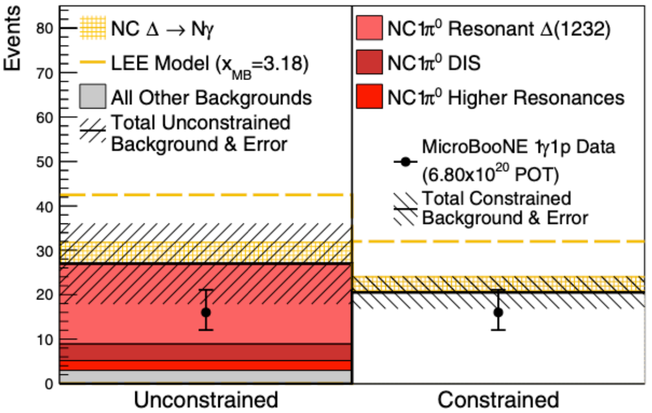


MB excess and sterile neutrinos

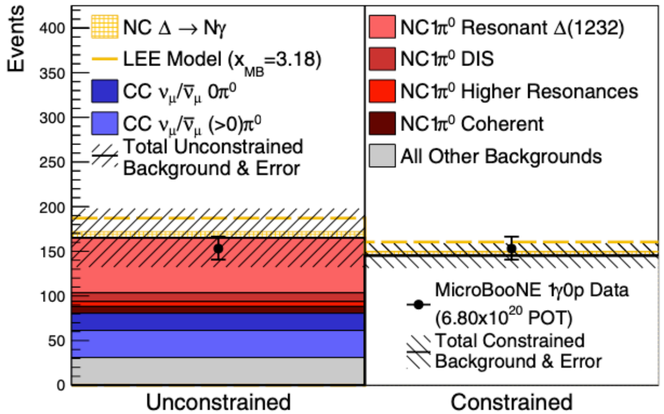
- the MicroBooNE eLEE result disfavors the MB excess originating from a pure ν_e excess
- the existence of sterile neutrinos cannot be ruled out by the MicroBooNE eLEE result, which is a generic low-energy ν_e excess search
- the MicroBooNE eLEE results can be re-interpreted under a sterile neutrino oscillation hypothesis: a combination of short-baseline ν_e appearance and ν_e disappearance
- 3+1 oscillation searches using the selections in the MicroBooNE eLEE searches are performed

First LEE results 2021

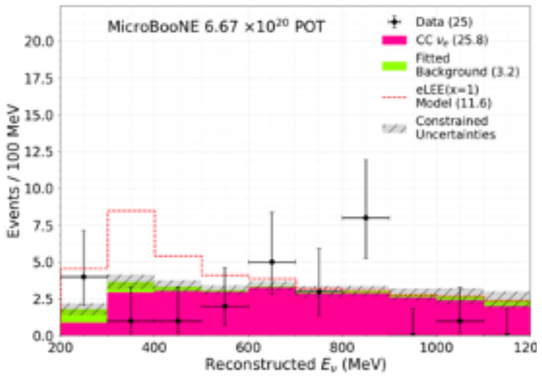
1γ1p



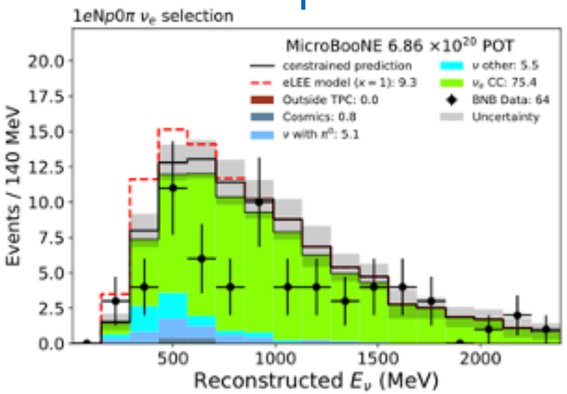
1γ0p

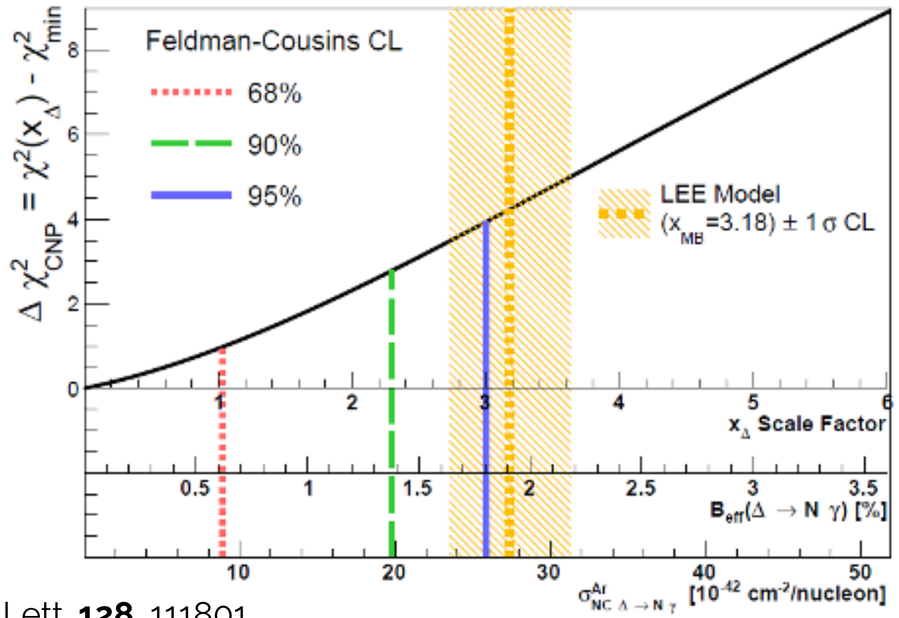


1e1p



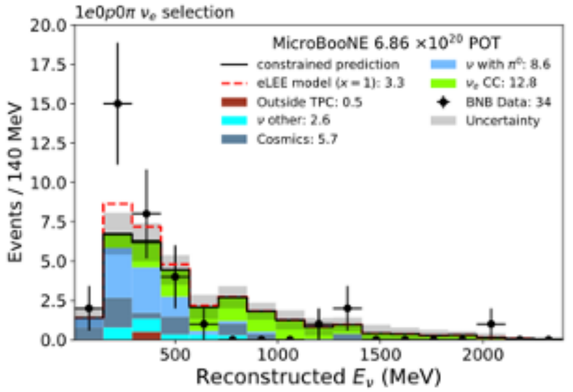
1eNp0π



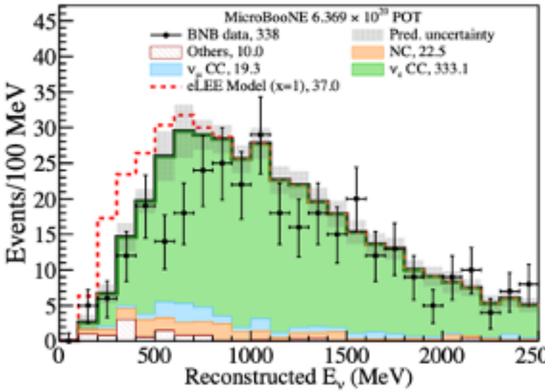


Phys. Rev. Lett. **128**, 111801

1e0p0π



1eX



Phys. Rev. D 105, 112005

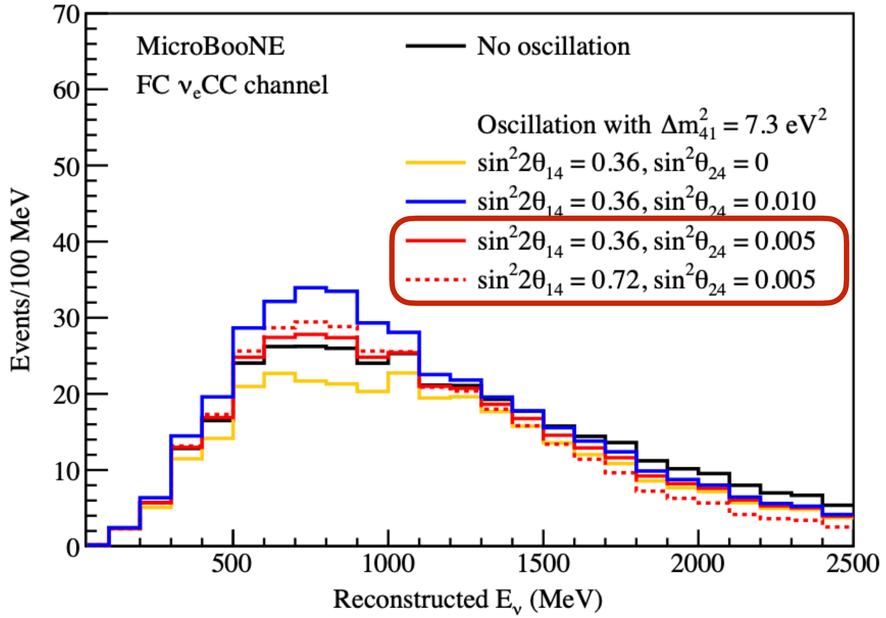
3+1 neutrino oscillation analysis

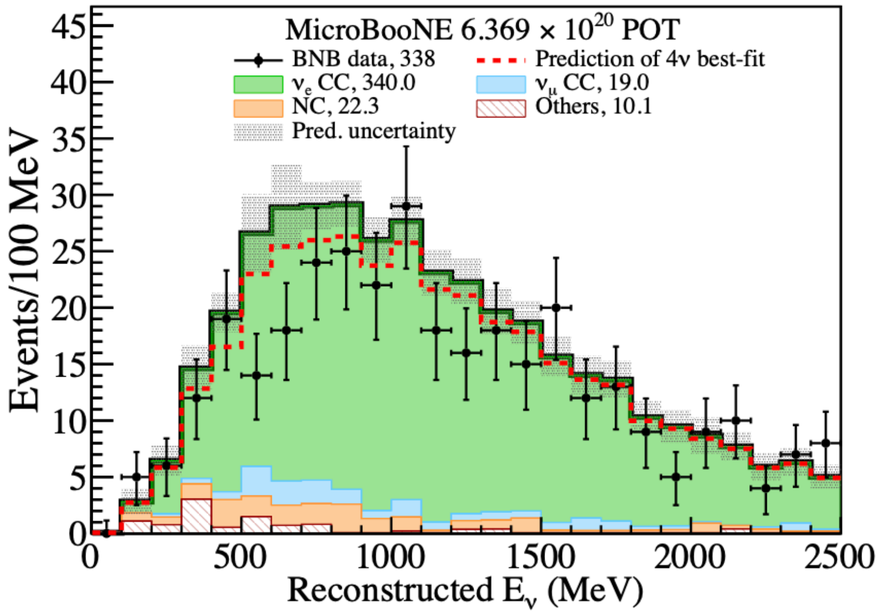
Phys. Rev. Lett. 130, 011801 (2023)

- eLEE results are re-interpreted under a sterile neutrino oscillation hypothesis: a combination of short-baseline ν_e appearance, ν_e disappearance, and ν_μ disappearance

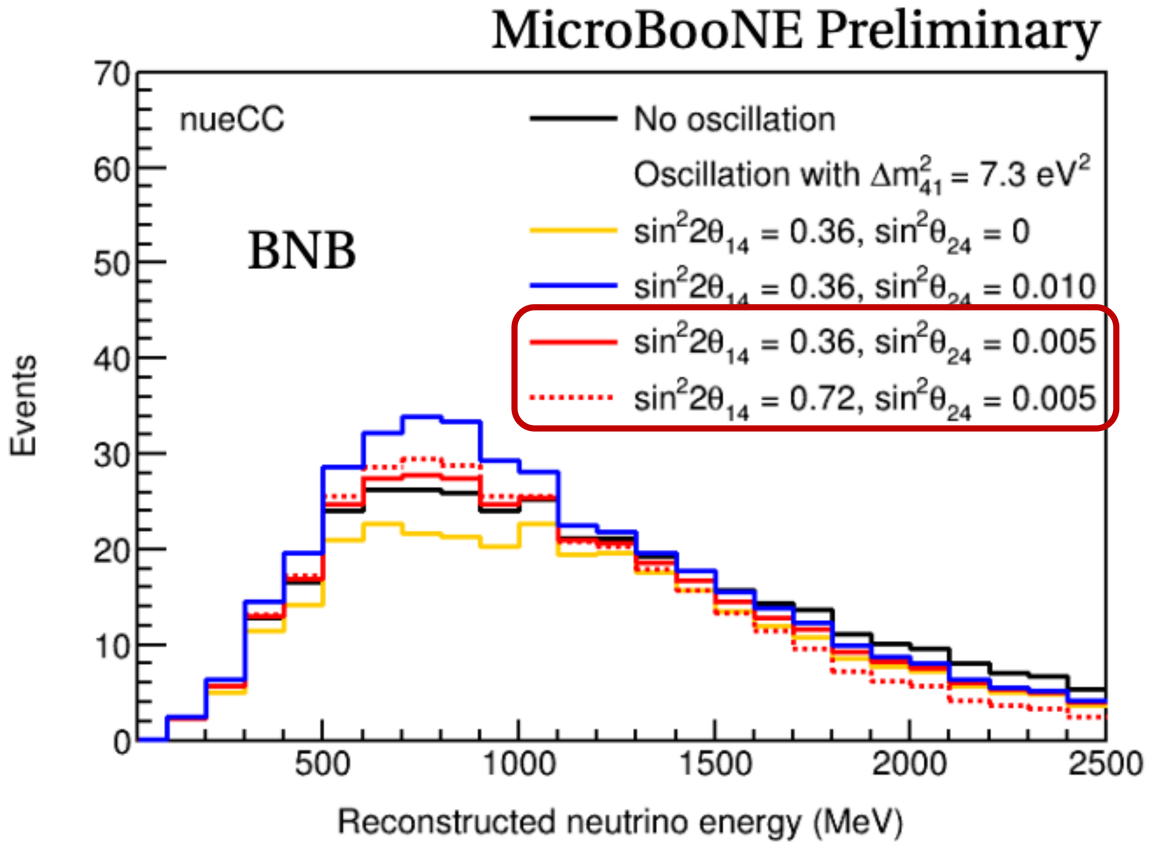
  - ν_e disappearance can cancel the appearance of ν_e events: *degeneracy of oscillation parameters*

- considering full 3+1 oscillation, BNB Run1-3 data was found to be **consistent with the 3ν hypothesis within 1σ** following the Feldman-Cousins approach





Cancellation of ν_e appearance and ν_e disappearance -- degeneracy of oscillation parameters



Different degeneracy points:
degeneracy mitigation utilizing both

ν_e disappearance ν_e appearance

$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \to \nu_e} + N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \to \nu_e}$$
$$= N_{\text{intrinsic } \nu_e} \cdot \left[1 + \left(R_{\nu_\mu/\nu_e} \cdot \sin^2\theta_{24} - 1\right) \cdot \sin^2 2\theta_{14} \cdot \sin^2 \Delta_{41}\right]$$

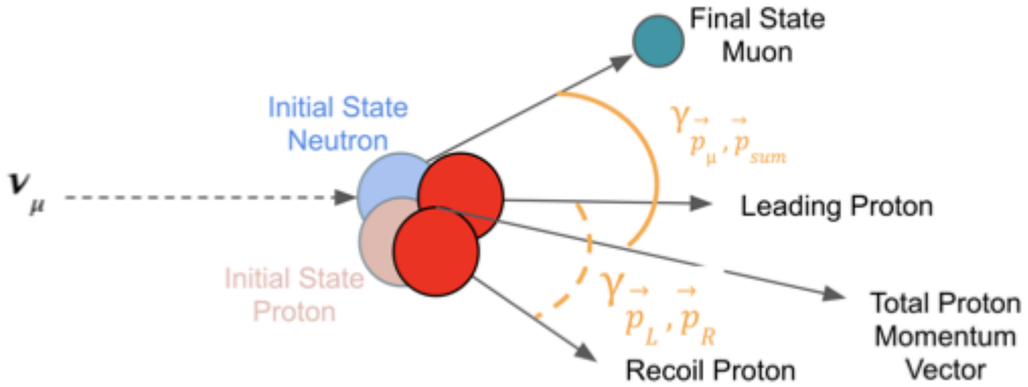
- **Degeneracy** when $\sin^2 \theta_{24}$ approaches R_{ν_e/ν_μ} which is the ratio of intrinsic ν_e and ν_μ in the neutrino flux
- **Sensitivity/exclusion limits gets much worse around the degeneracy point**

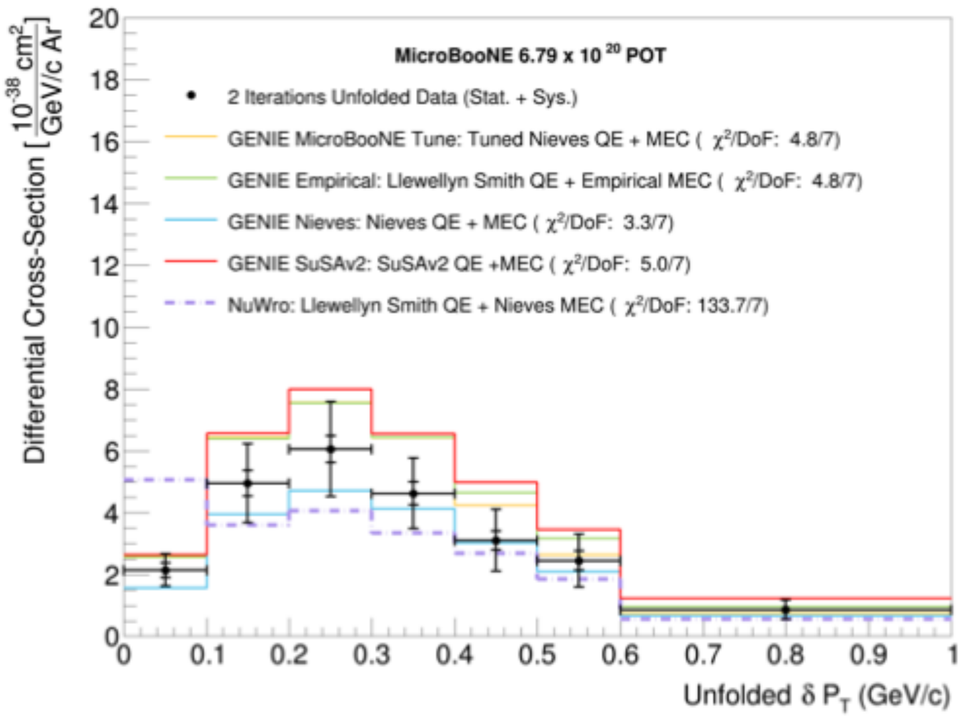
	R_{ν_e/ν_μ} (degeneracy $\sin^2 \theta_{24}$ value)
MicroBooNE w. BNB	~0.005 (average)
MicroBooNE w. NuMI	~0.04 (average)

Differential cross section of ν_μCC 2p

arXiv:2211.03734

- first time differential cross section measurement in this topology
  - sensitive to the Meson Exchange Current (MEC) interactions
- results w.r.t. transverse momentum strongly disfavor NuWro's treatment of correlated P-N pari (back-to-back





CCQE-like ν_μCC with transverse kinematic imbalance (TKI)

arXiv:2301.03706

- first -Ar differential Xs on TKI variables
  - sensitive to details of proton FSI modeling and the initial-stνate Fermi motion
- extension to double differential Xs $\{\delta\alpha_T, \delta P_T\}$ for the first time
  - probe region with greatest model discrimination power