First Results from MicroBooNE's Low Energy Excess Search and Constraints on eV-Scale Sterile Neutrino Oscillations

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on behalf of the MicroBooNE collaboration

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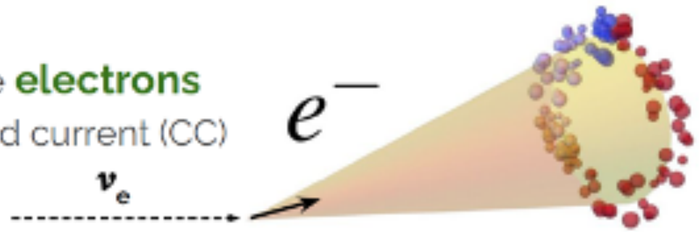
Wright Laboratory

Yale

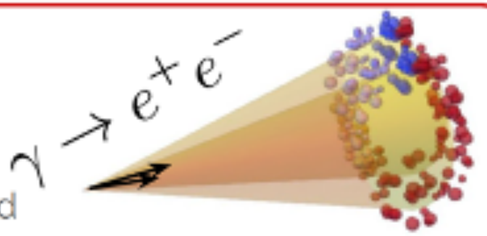
MiniBooNE anomaly

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

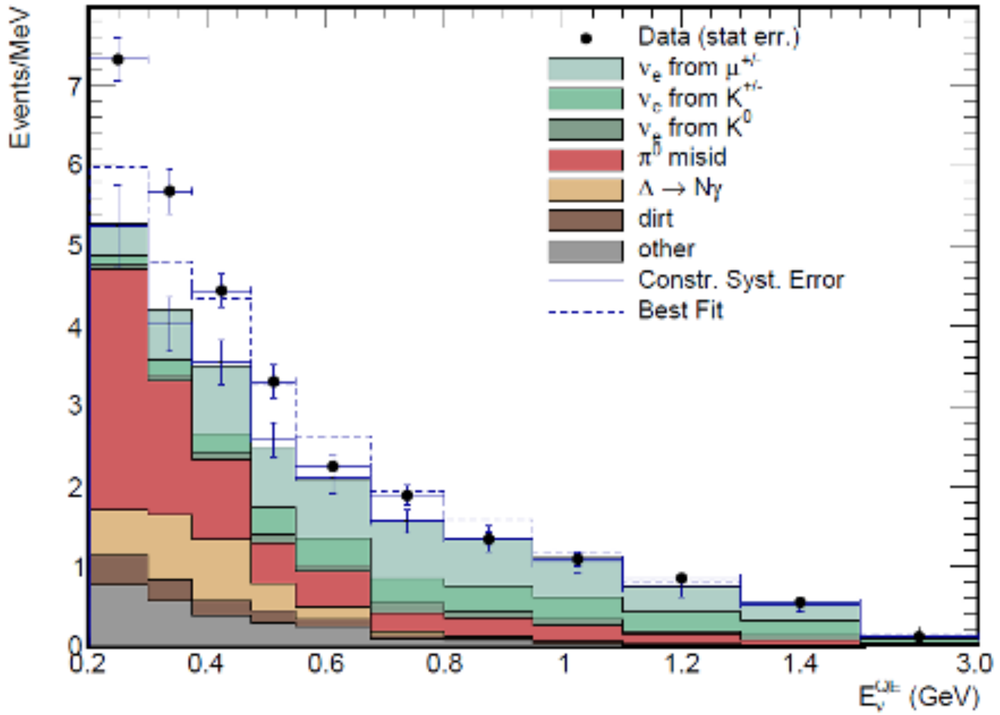
It detected ν_e by the **electrons** produced in charged current (CC) interactions.



However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring



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



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

Liquid Argon Time Projection Chamber (LArTPC)

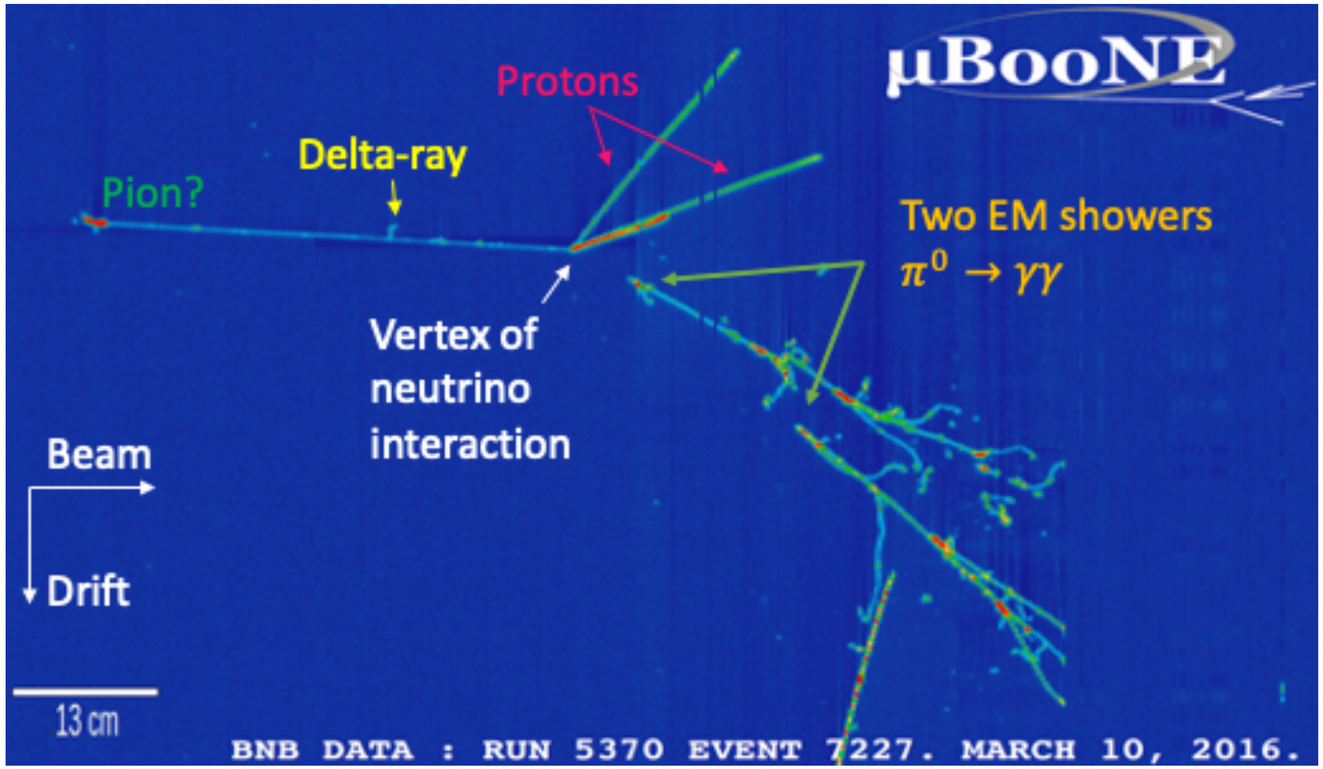
- LArTPC is capable of identifying different species of particles and reconstructing 3D images with fine-grained information

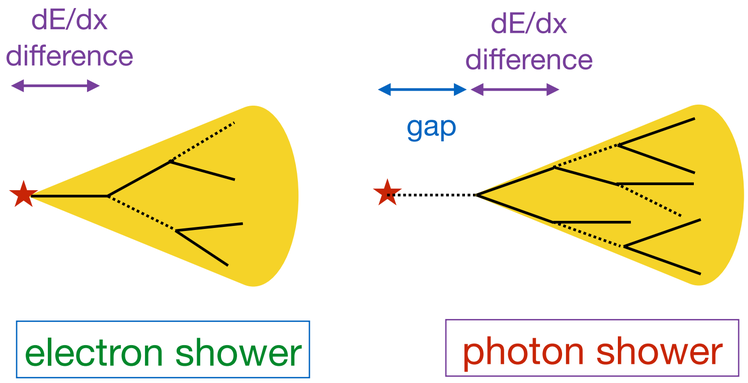
  - neutrino vertex

  - particle flow (mother-daughter particle relationship)

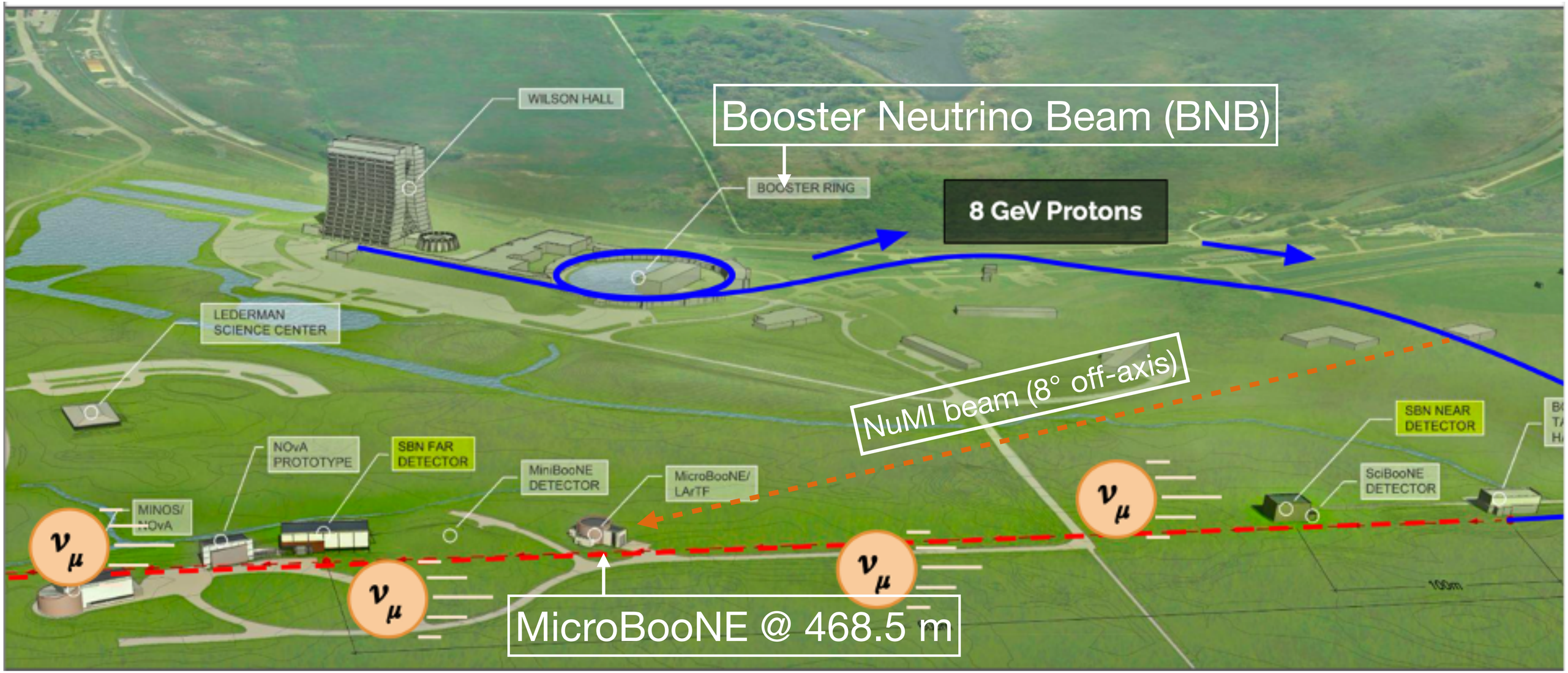
  - track vs. shower separation

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





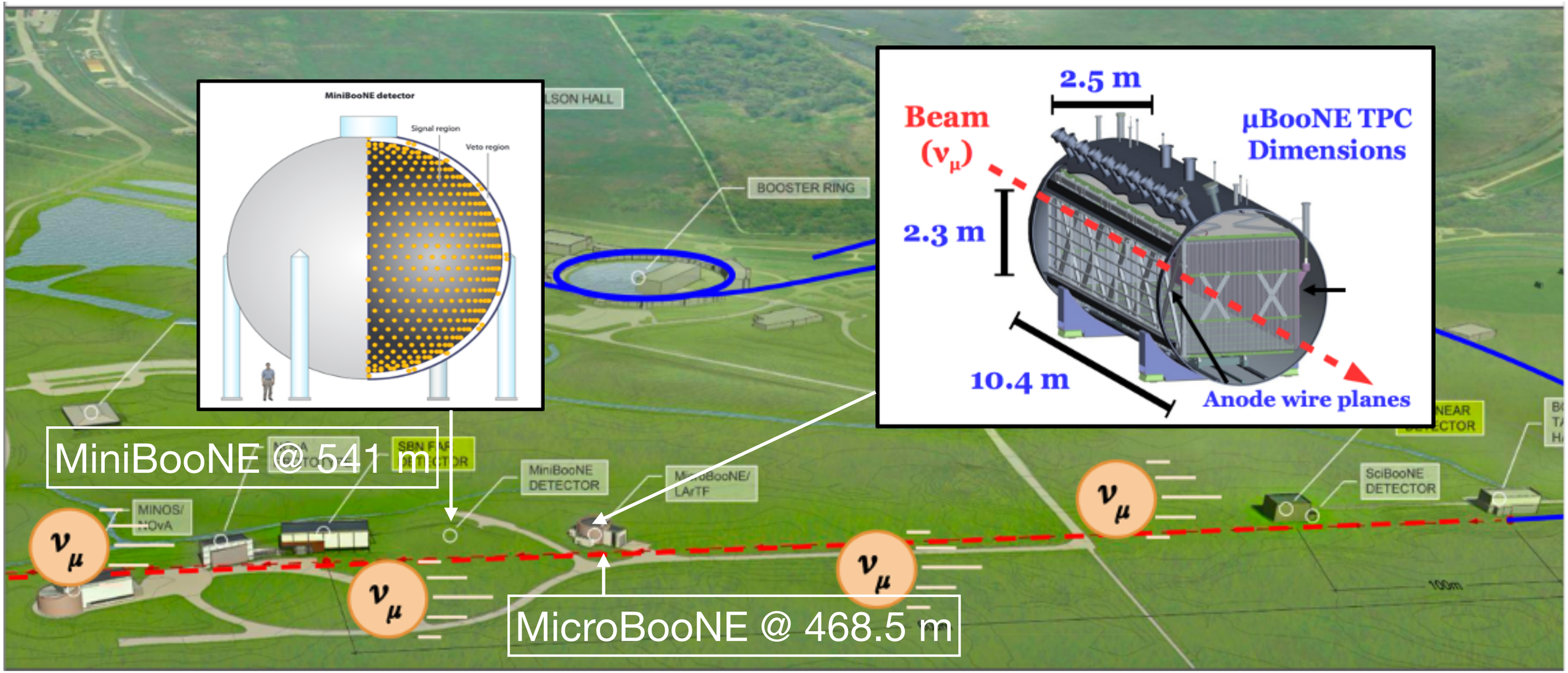
MicroBooNE @ Fermilab



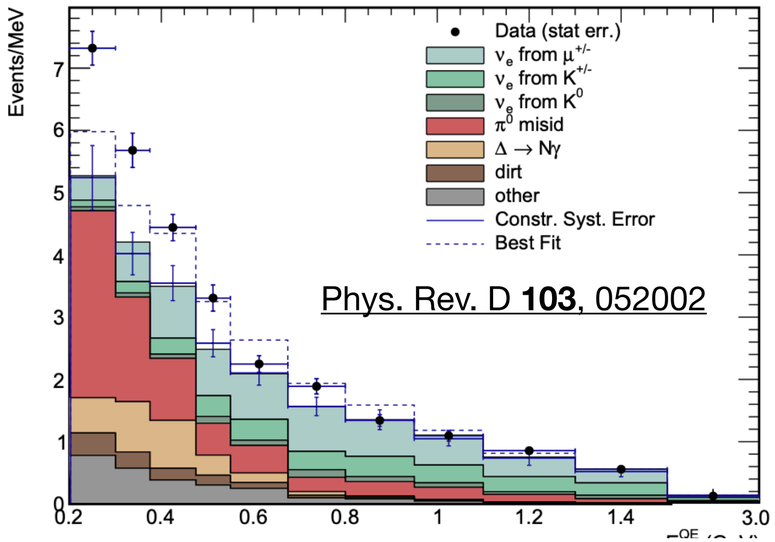
MicroBooNE @ Fermilab

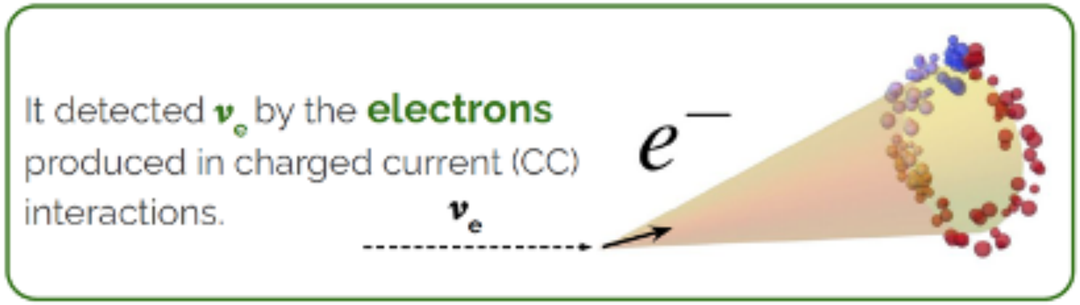
Cherenkov detector with 820 tonne mineral oil

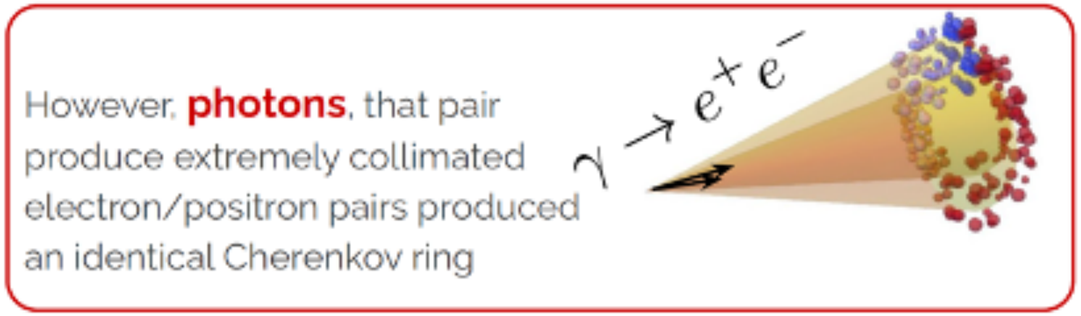
170 (85) tonne liquid argon in cryostat (TPC)



Photon excess or electron excess?



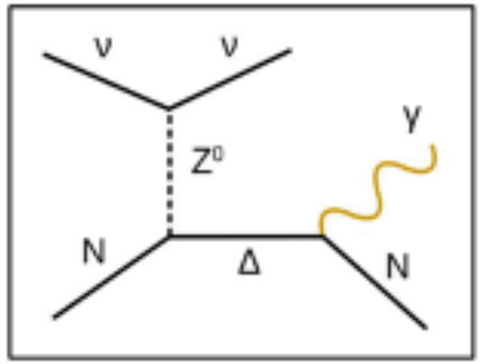


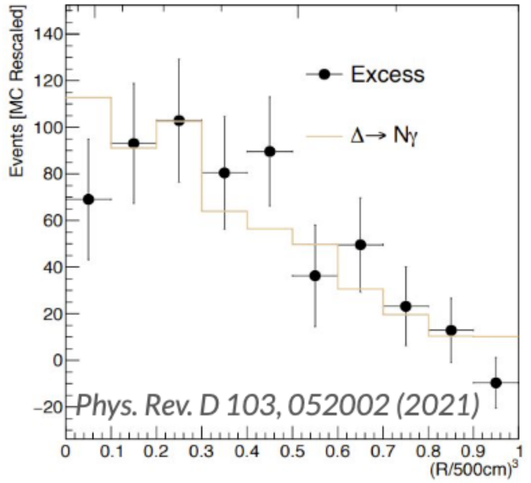


- electron-like excess
  - due to mis-modeled/unknown process?
  - oscillation-driven excess?
- photon-like excess
  - due to mis-modeled/unknown process producing photons, *such as Neural-Current (NC) Δ resonance radiative decay?*

Single-photon low energy excess (gLEE) search

- targeting NC Δ resonance radiative decay ($\Delta \rightarrow N\gamma$)
  - standard model process
  - never been directly observed in neutrino scattering
- an enhancement in NC $\Delta \rightarrow N\gamma$ by a factor of **3.18** would give good agreement with the observed MiniBooNE LEE





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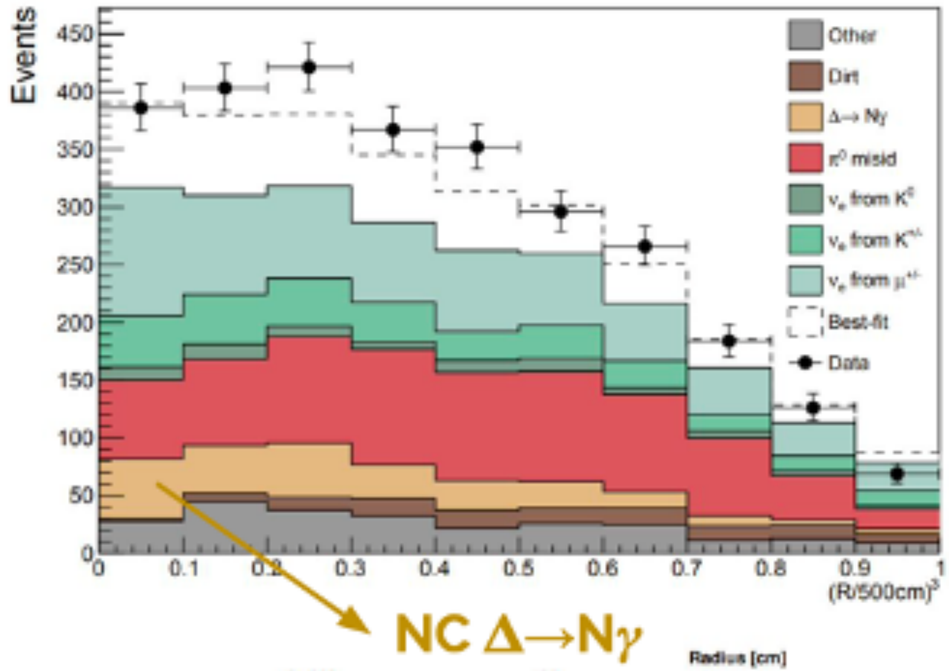


gLEE result

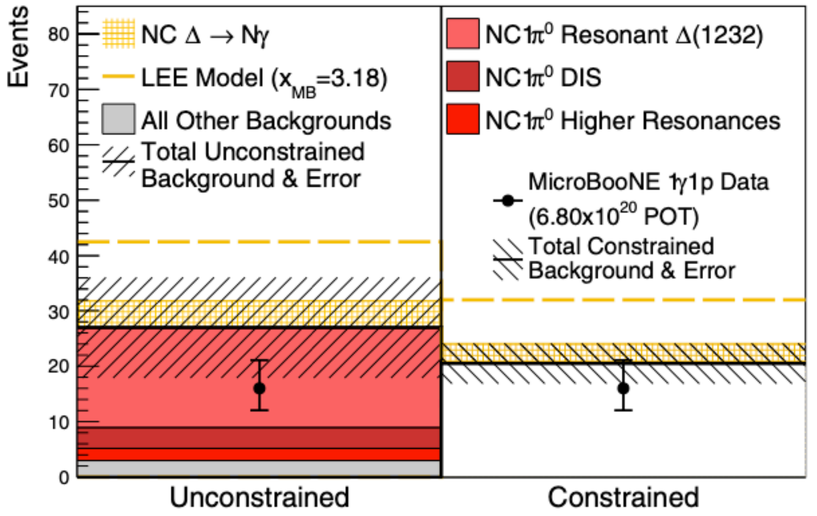
- the analysis selects two NC Δ rich single-photon channels: 1γ1p & 1γ0p

- **the result disfavors the most suspected single-photon background as a sole source of the MiniBooNE excess at 94.8% C.L.**

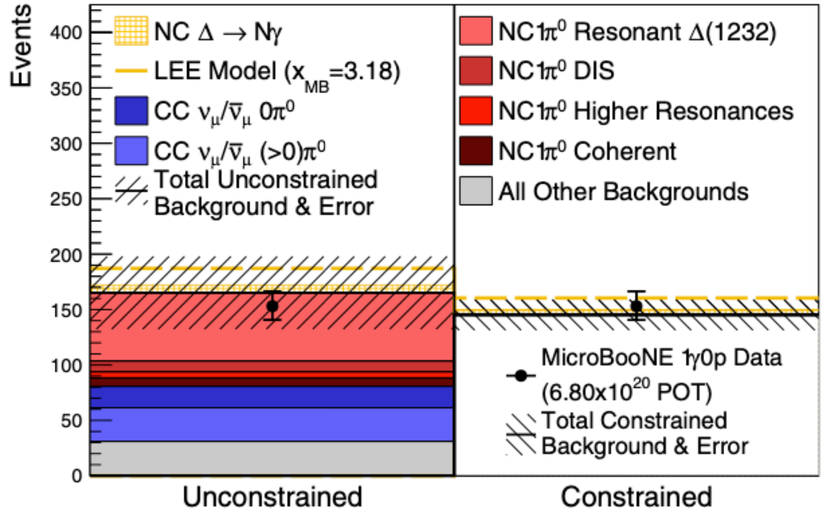
- bound on the normalization of $\Delta \rightarrow N\gamma$ was determined to be 2.3 at 90% C.L.

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

1γ1p



1γ0p



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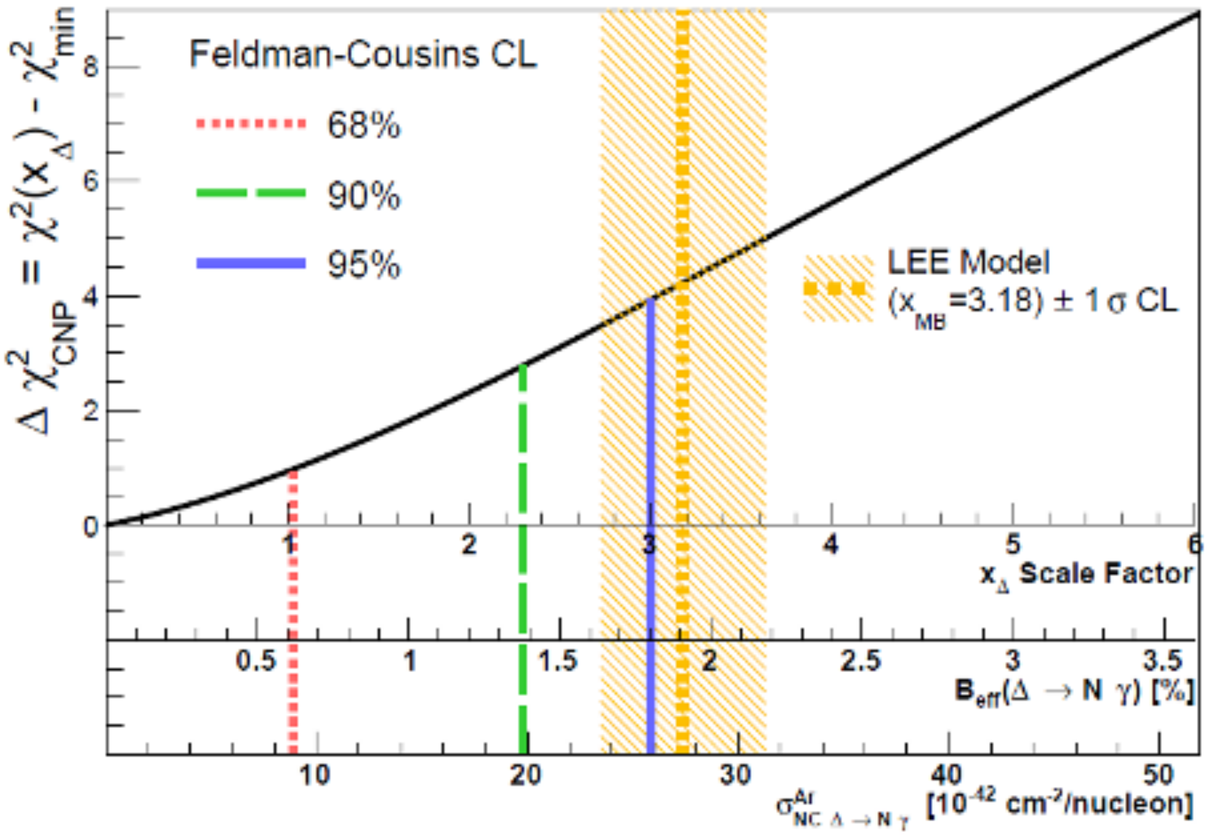
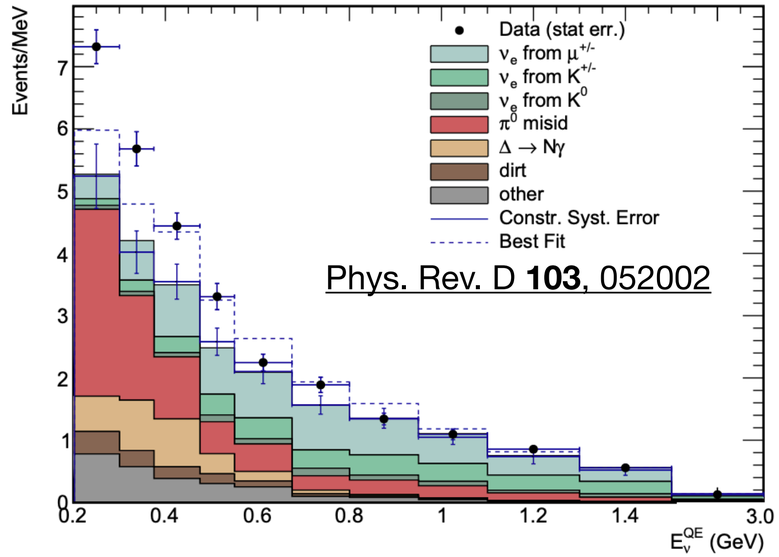


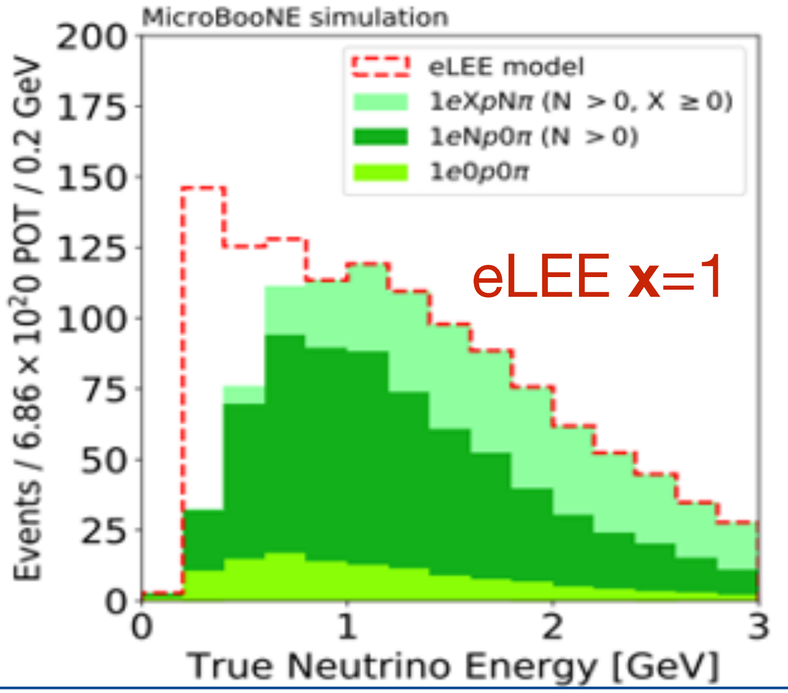
ν_e low energy excess (eLEE) search

- assumption about the excess:
  an energy-dependent enhancement of intrinsic ν_e events in the beam at low energy

- empirical eLEE model is derived from MiniBooNE, by unfolding detector response, acceptance, efficiency

unfolding





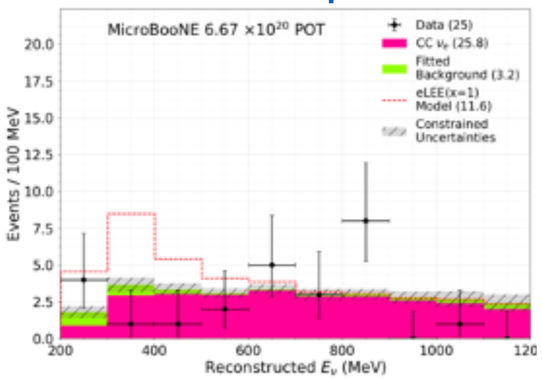
MiniBooNE **x**:
1±0.08 (stat.)
1±0.21 (full)

eLEE results

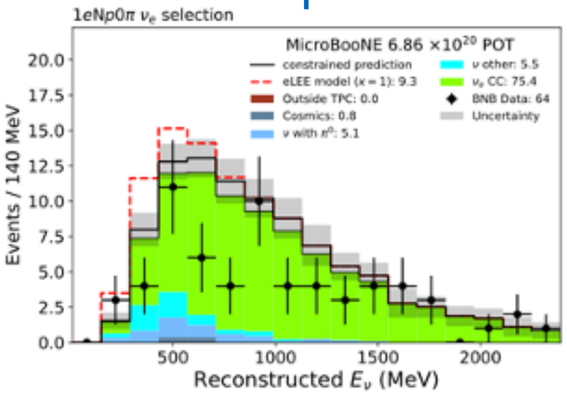
Phys. Rev. Lett. 128, 241801

- three independent eLEE searches, targeting four different final states: 1e1p, 1eNp0π, 1e0p0π, 1eX
- 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, **the existence of sterile neutrinos cannot be ruled out** by the MicroBooNE eLEE result, which is a generic low-energy ν_e excess search

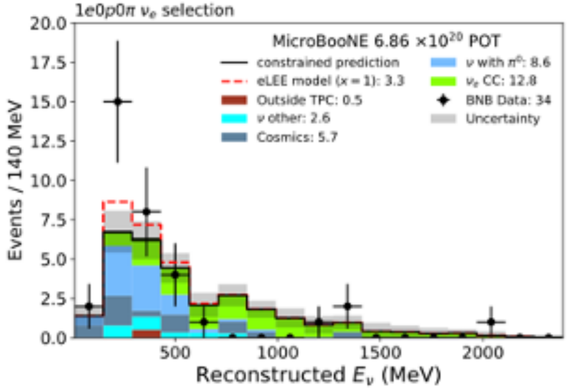
1e1p



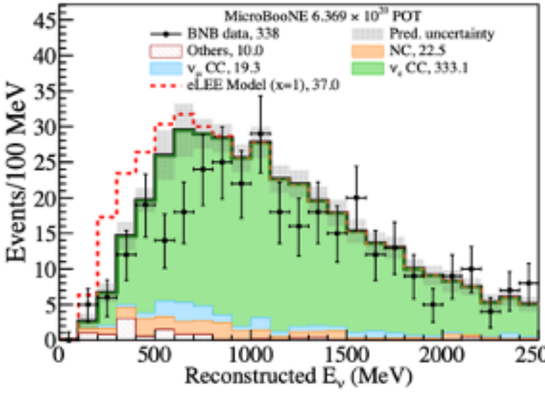
1eNp0π



1e0p0π



1eX



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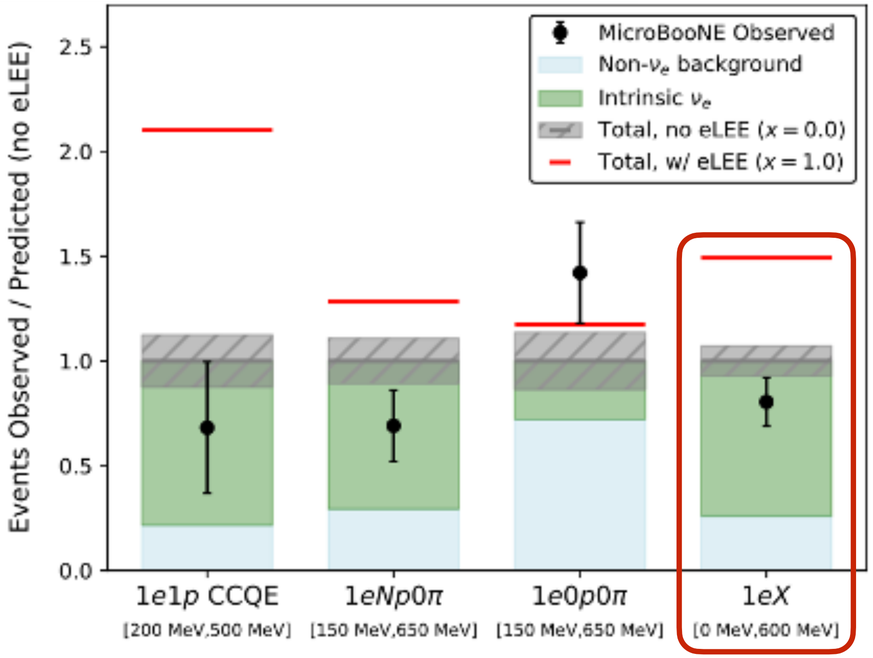
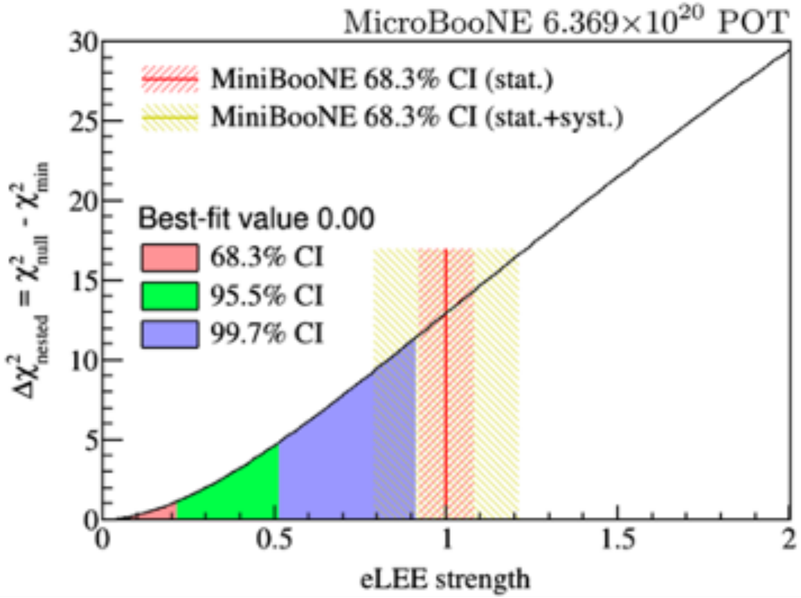


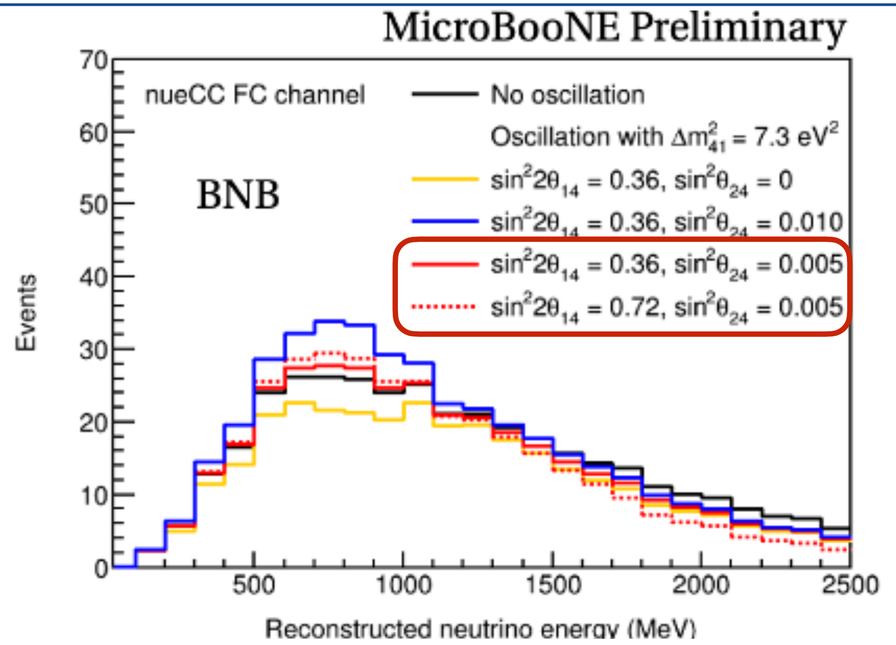


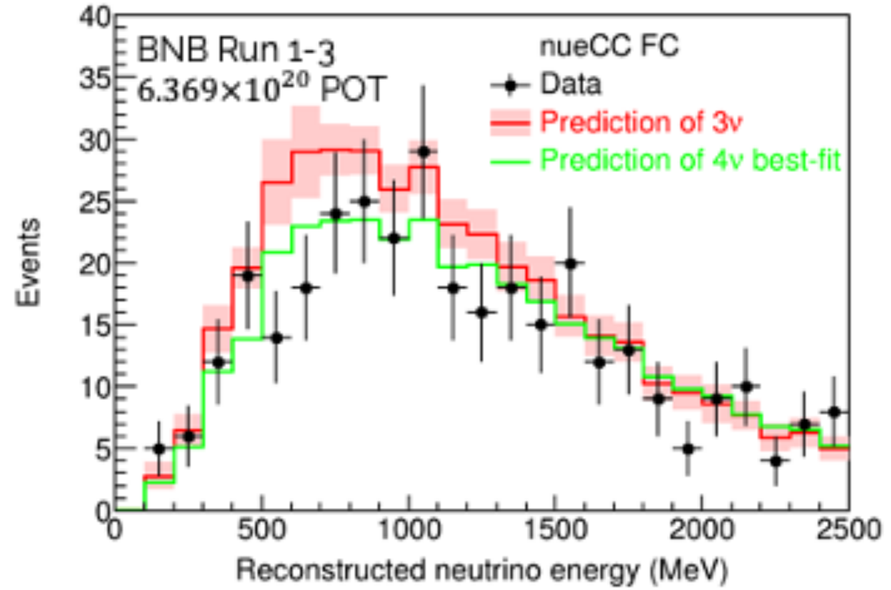
3+1 neutrino oscillation analysis

- 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

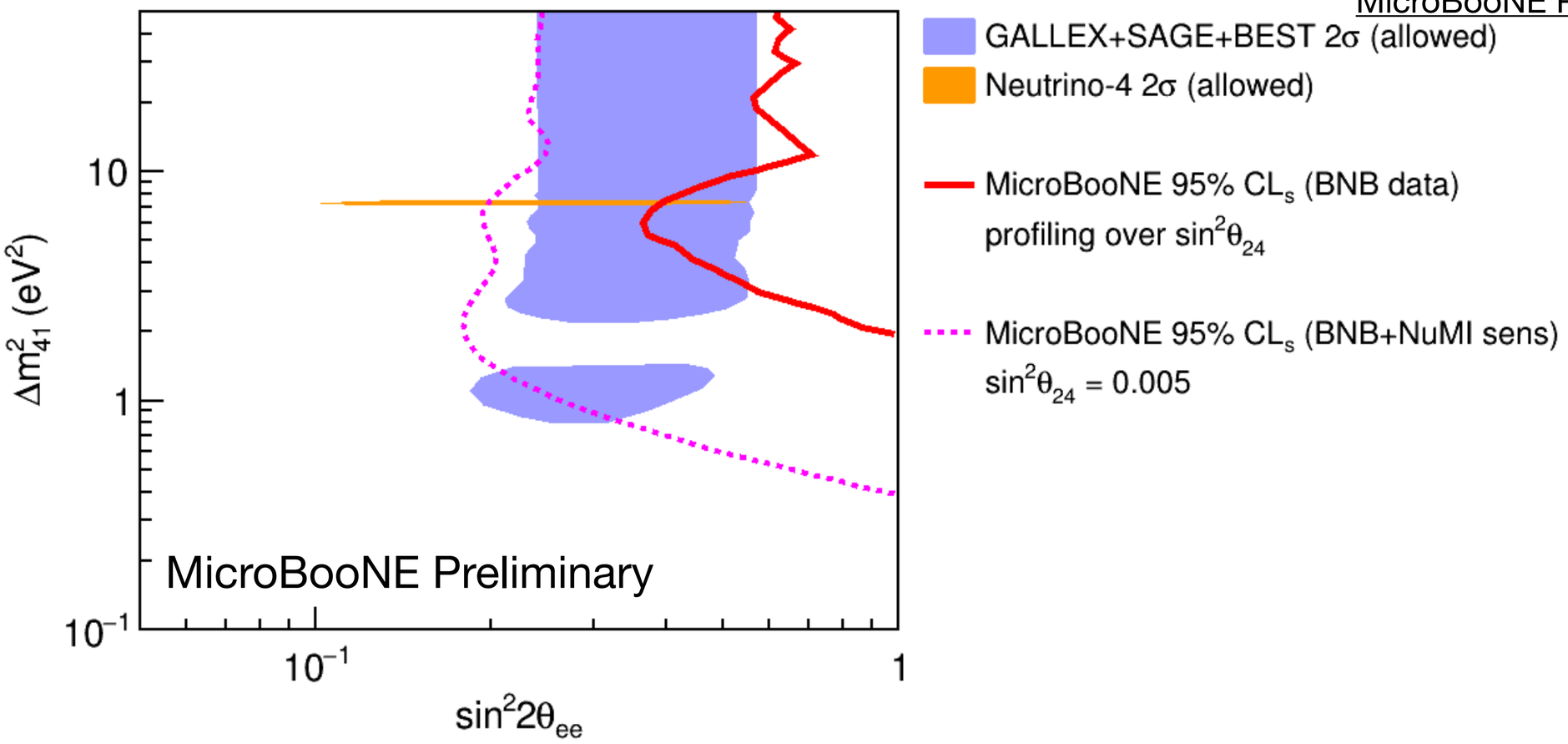
- considering full 3+1 oscillation, BNB Run1-3 data was found to be **consistent with the 3ν hypothesis within 1σ** following the Feldman-Cousins approach





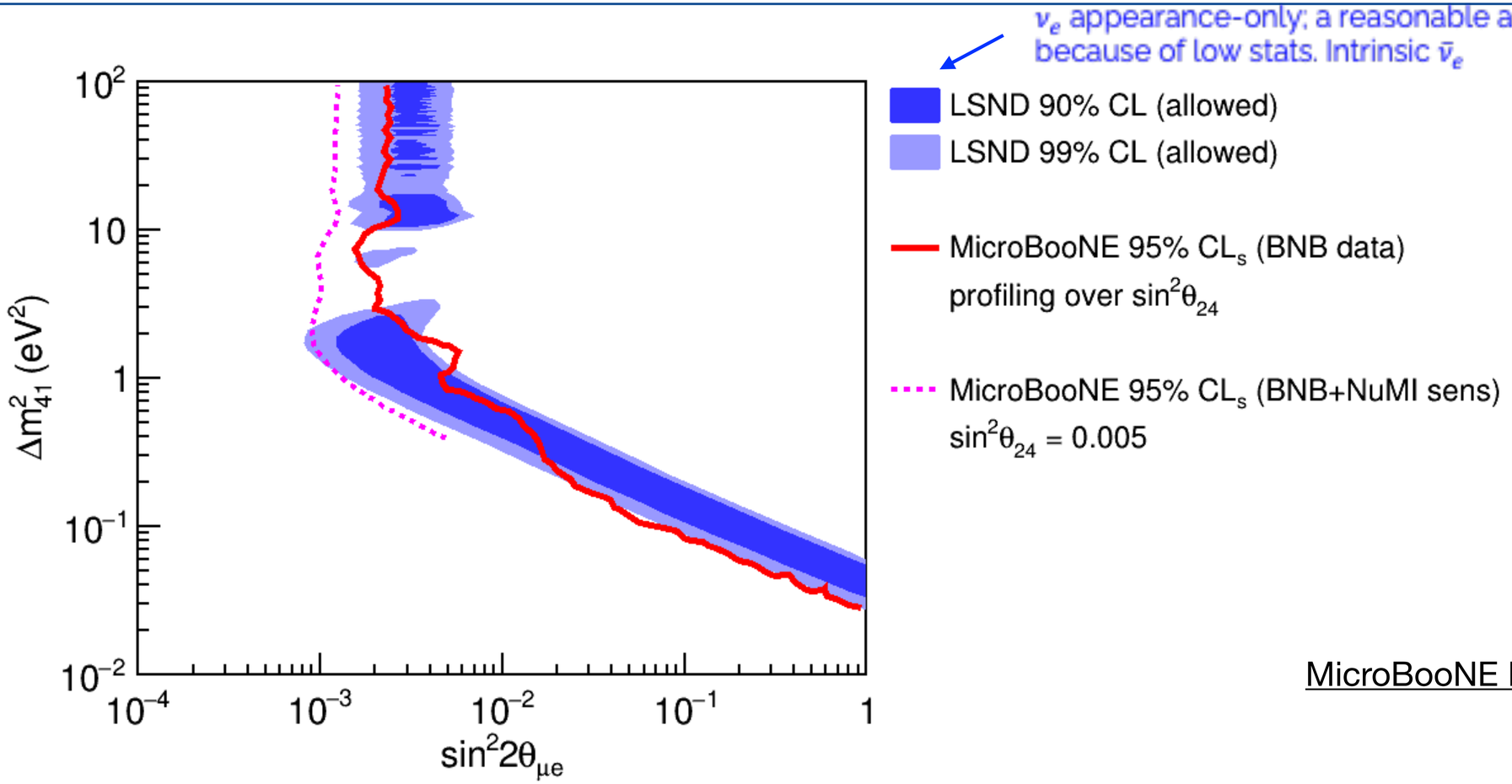
3+1 oscillation analysis result: ν_e disappearance

MicroBooNE Public Note #1116



- competitive limit on the eV-scale ν_e disappearance, first ν-*Ar* scattering data limit
- sensitivity significantly improved when combining both BNB and NuMI, mainly due to ν_e appearance-disappearance degeneracy mitigation

3+1 oscillation analysis result: ν_e appearance



MicroBooNE Public Note #1116

- 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

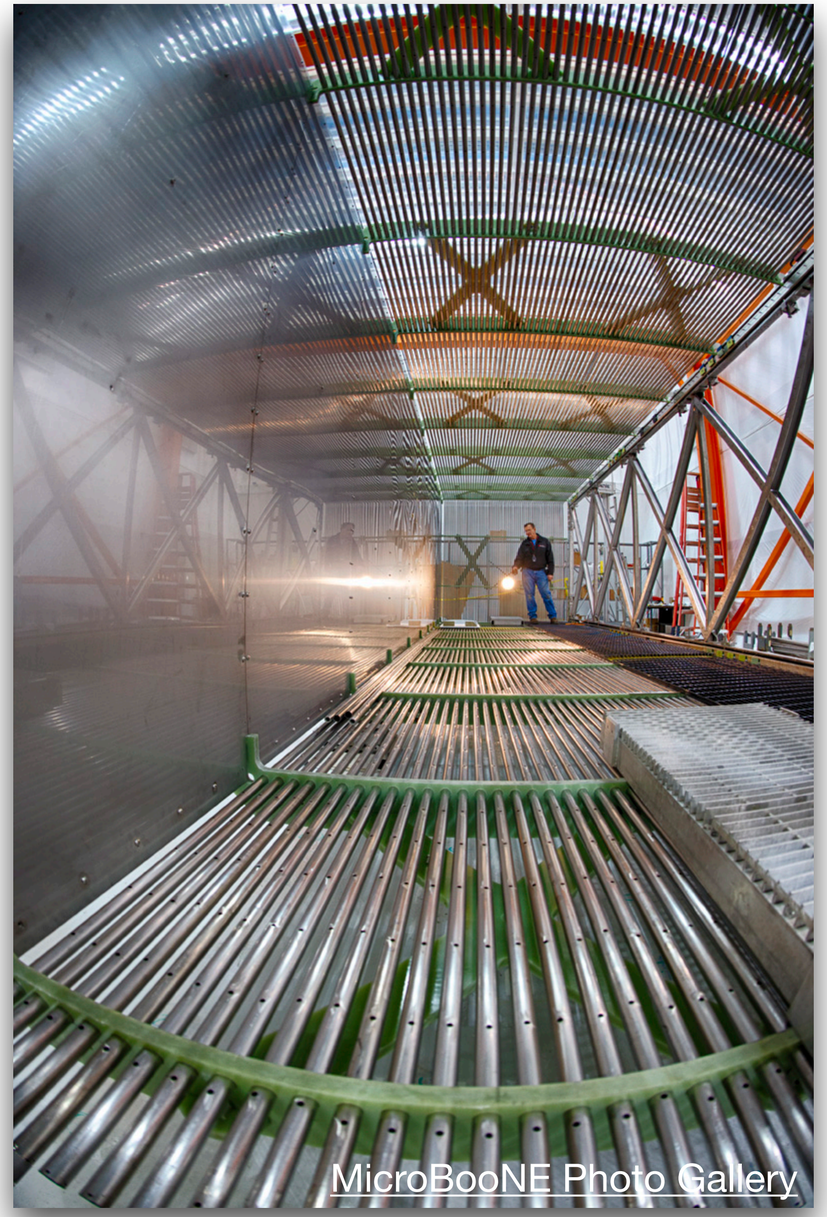
Summary

- MicroBooNE's first searches for low energy excess **found no evidence of excessive ν_e or NC Δ radiative decay to explain the MiniBooNE excess**

- 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**

- further investigation on MiniBooNE excess, searches for other BSM particles/processes (e.g. e^+e^-), and oscillation analysis with BNB & NuMI data are underway



μBooNE

Thank You!

Fermilab

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THE ROYAL SOCIETY

Backup

LArTPC: Liquid Argon Time Projection Chamber

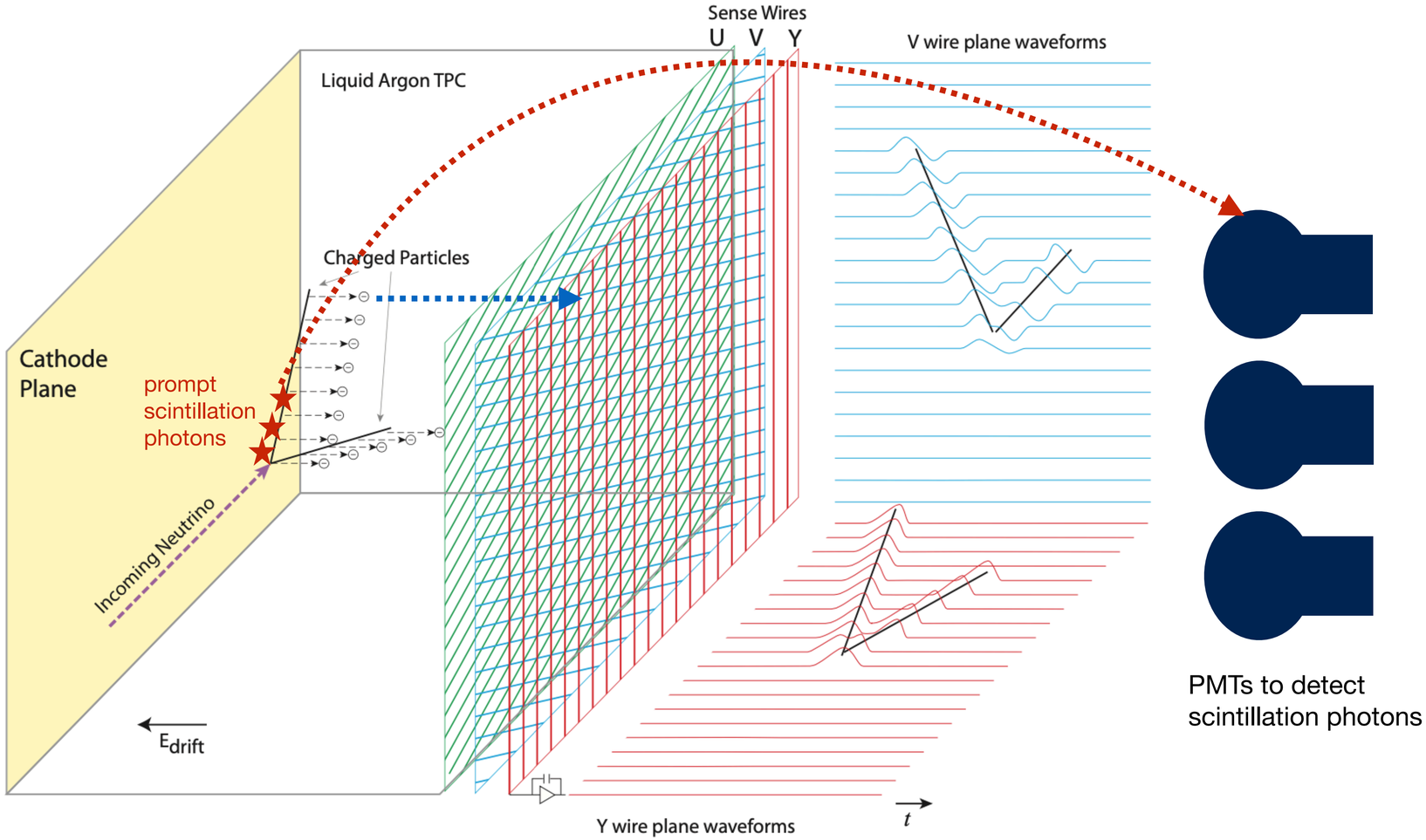
charged particle enters detector

⬇

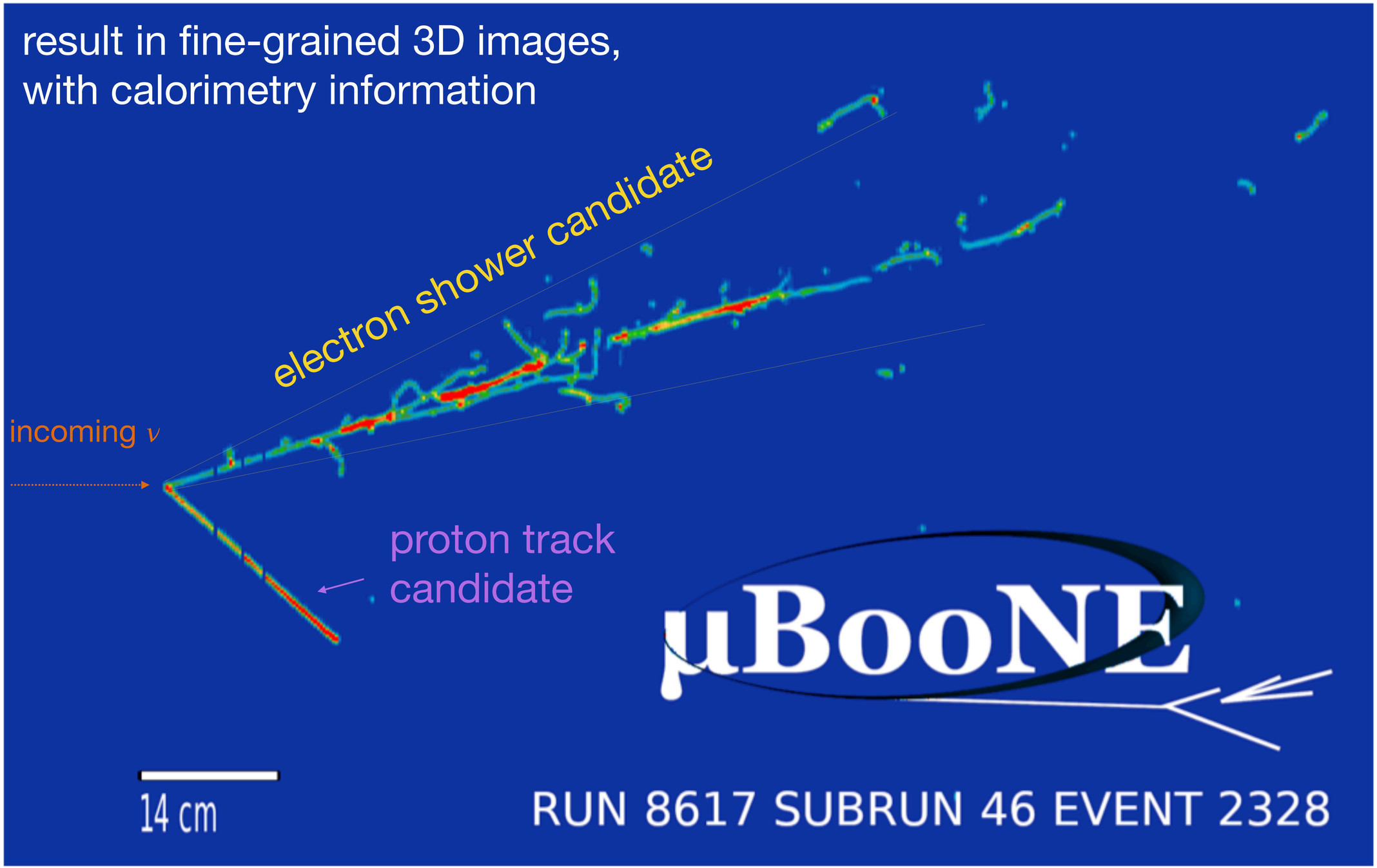
scintillation light emitted by excited Ar, detected by PMTs

⬇

ionization electrons drift to anode plane, detected by sense wires

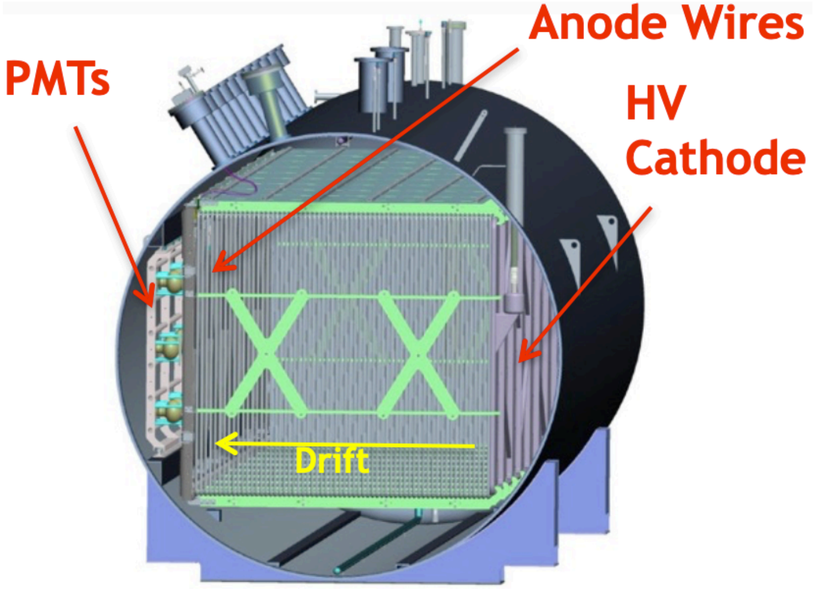


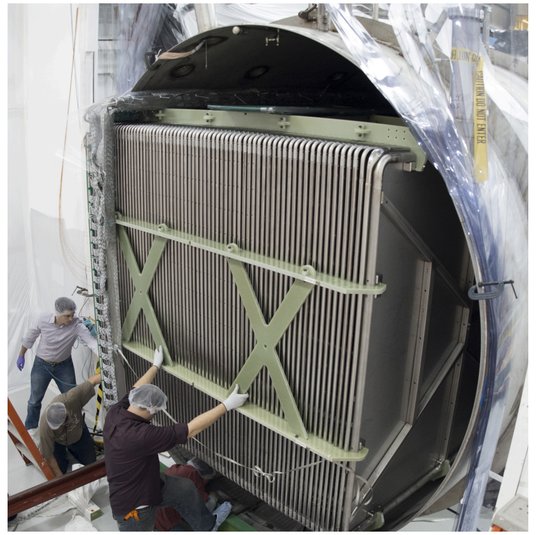
result in fine-grained 3D images,
with calorimetry information



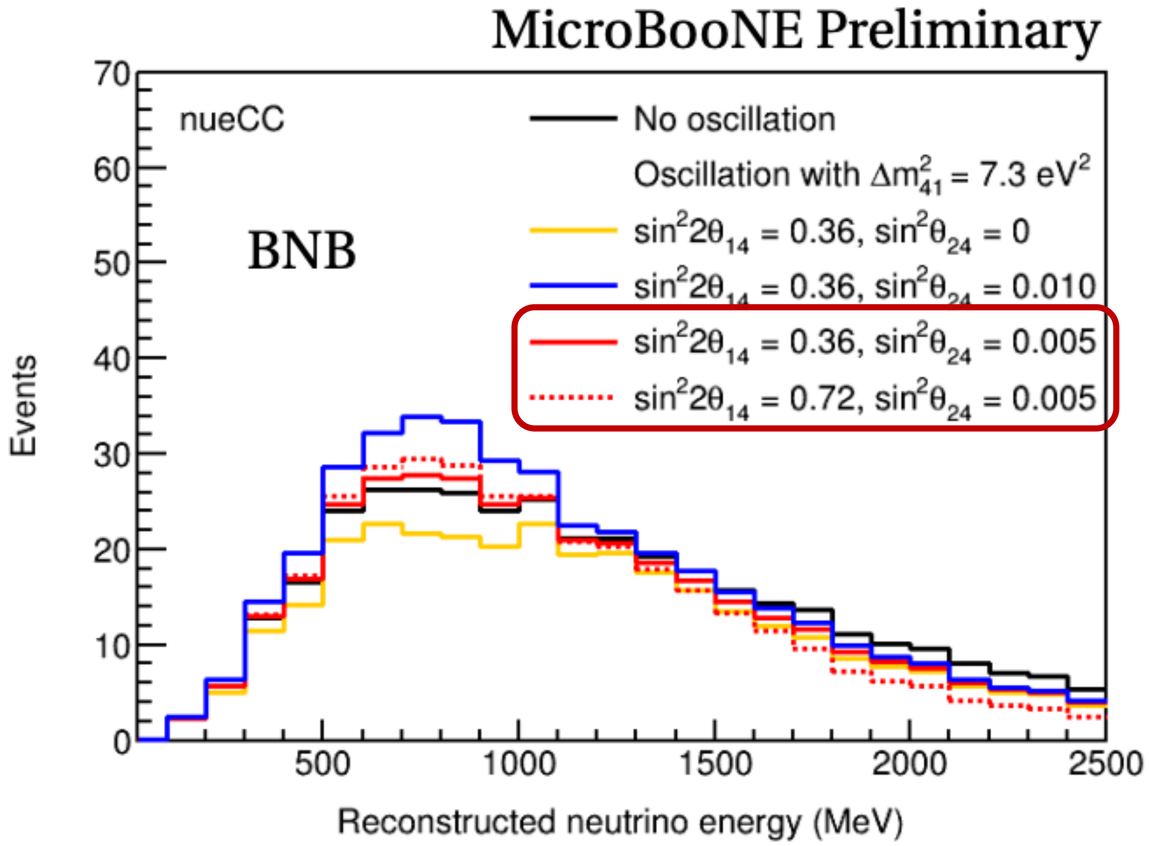
MicroBooNE experiment

- 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





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

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

- **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)

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

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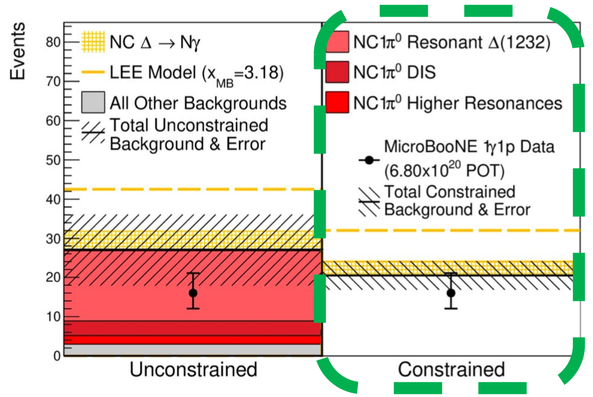
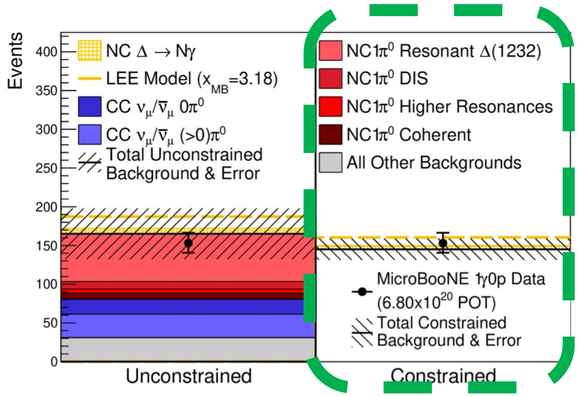
1γ1p



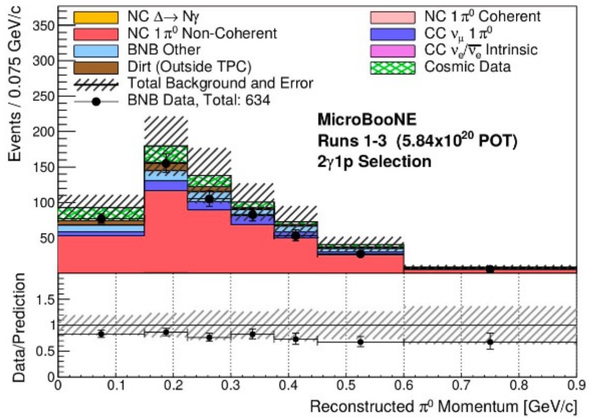
One-bin, Shower Energy from 0-0.6 GeV

1γ0p



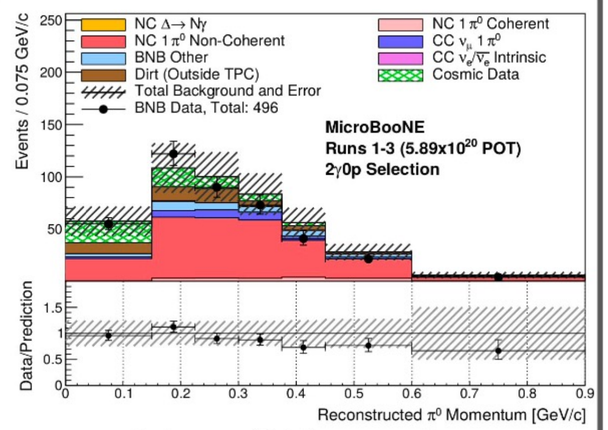
One-bin, Shower Energy from 0.1-0.7 GeV

2γ1p



7-bins, π^0 Momentum from 0-0.9 GeV/c

2γ0p

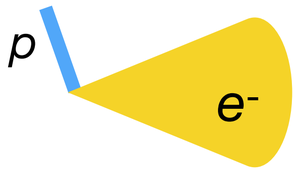


7-bins, π^0 Momentum from 0-0.9 GeV/c

MicroBooNE's search for an excess of electron neutrino interactions

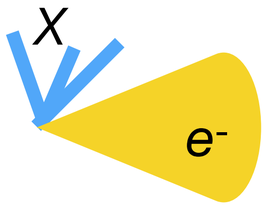
three independent searches across multiple single electron final states

- 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