First Results from MicroBooNE's LEE Search

Andrew J. Mogan
On behalf of the MicroBooNE Collaboration

SUSY 2022

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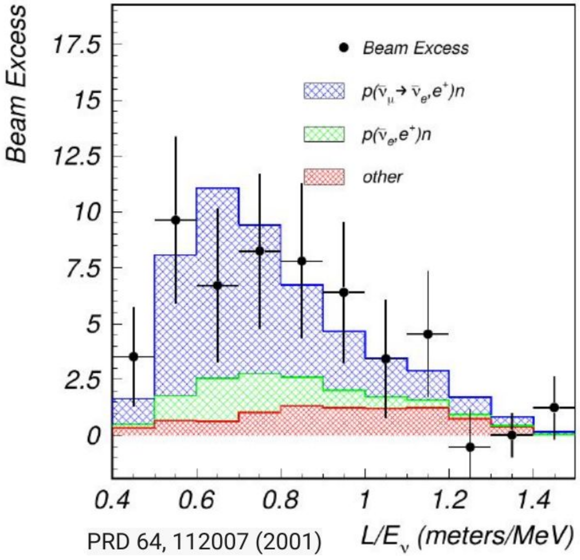
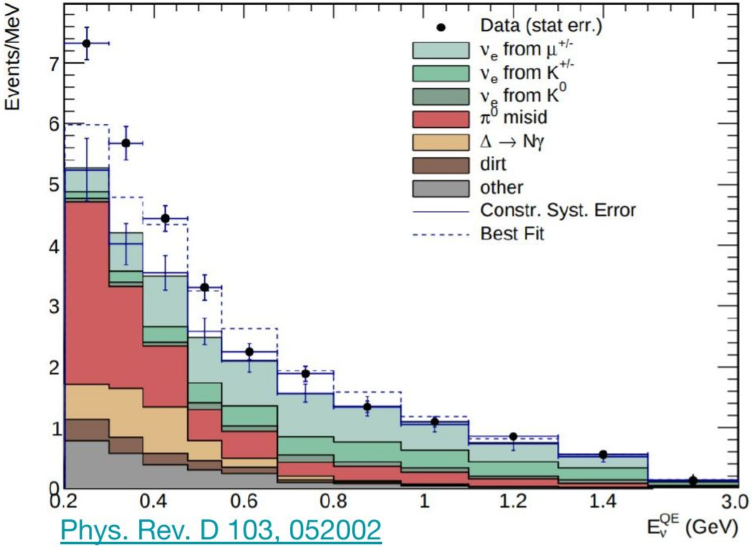
Short-Baseline Anomalies

- LSND (left) and MiniBooNE (right) both observed an excess of neutrino-like events
- Flavor oscillations not expected at short baseline (L/E ~ 1 km/GeV)
- Can be interpreted as evidence for sterile neutrino oscillations



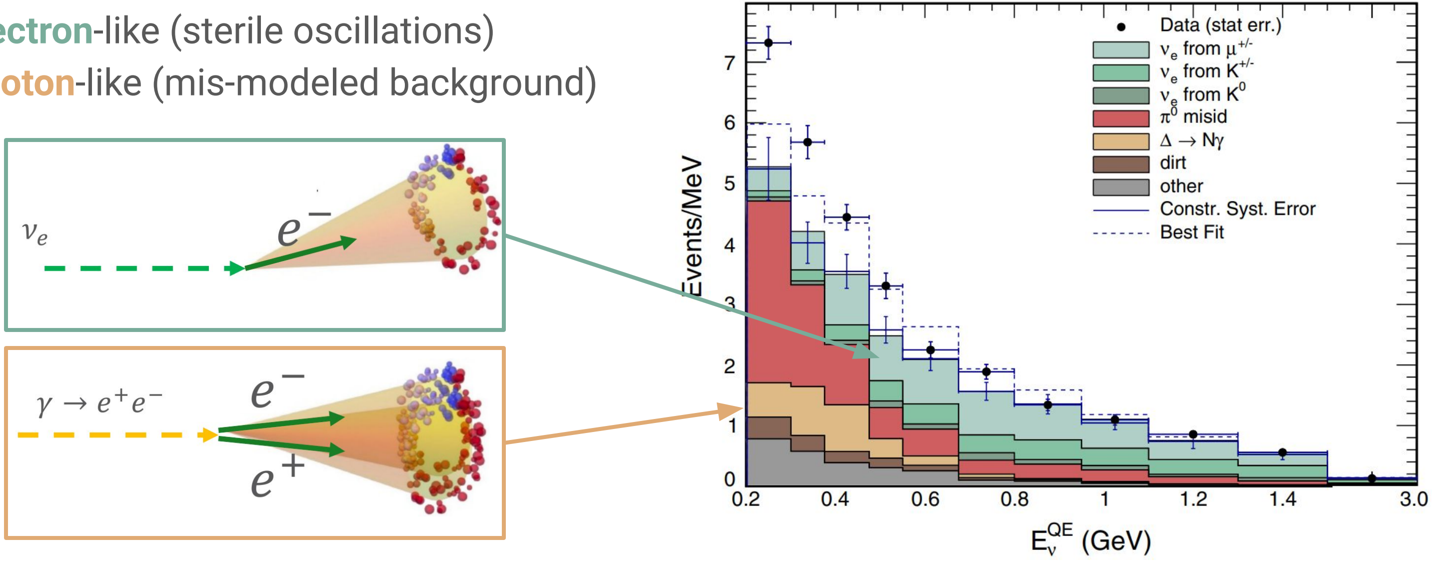
PRD 64, 112007 (2001)



Phys. Rev. D 103, 052002

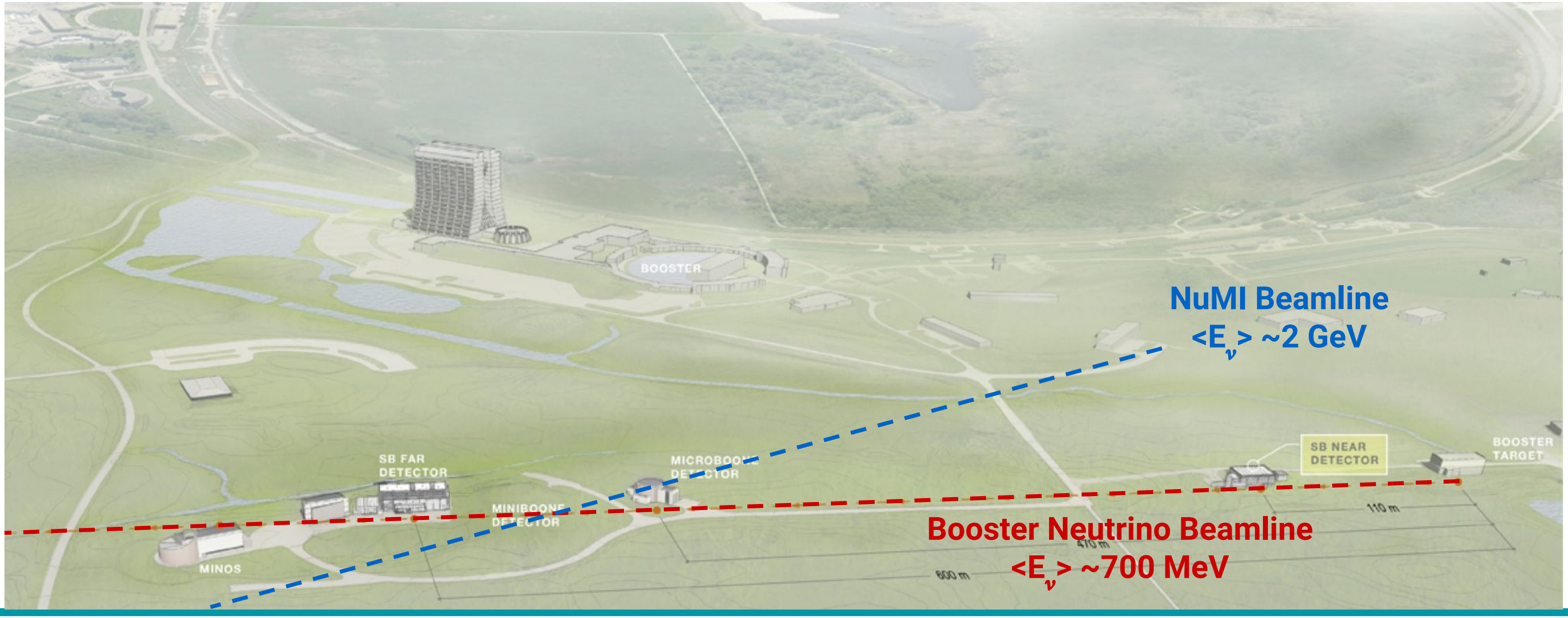
MiniBooNE Low-Energy Excess (LEE)

- Mineral oil Cherenkov detector whose signal is a single electromagnetic (EM) shower
  - Difficulty distinguishing electron showers from photon showers
  - Only sensitive to particles above Cherenkov threshold (not protons)
- Excess could be either
  - **Electron**-like (sterile oscillations)
  - **Photon**-like (mis-modeled background)



MicroBooNE

- 170-ton (89-ton active volume) Liquid argon time projection chamber (LArTPC)
- Collected ~half a million neutrino events from 2015 to 2021
- Located on same beamline as MiniBooNE (Booster Neutrino Beam)



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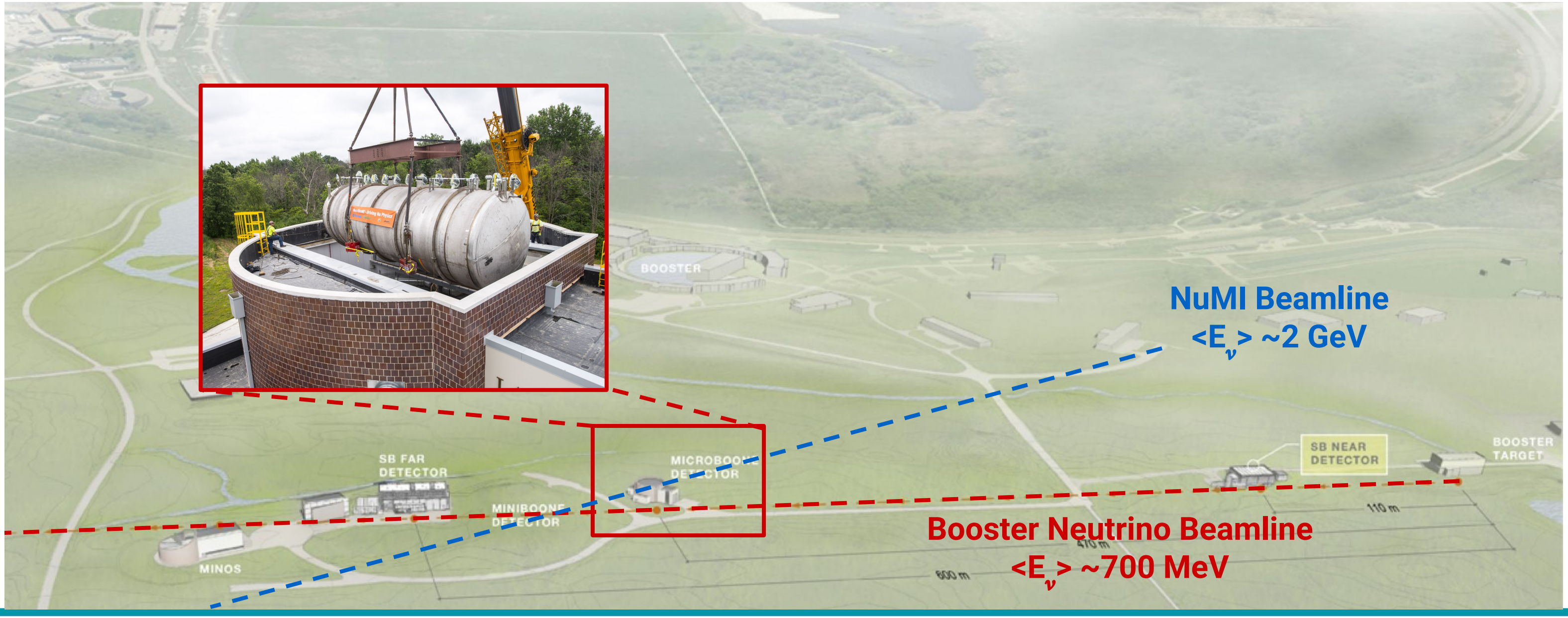
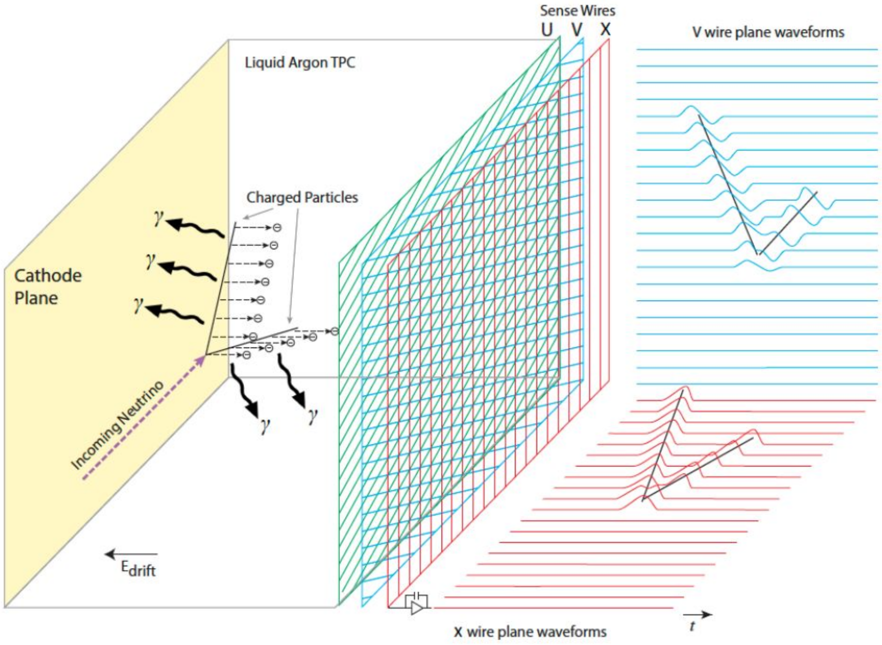
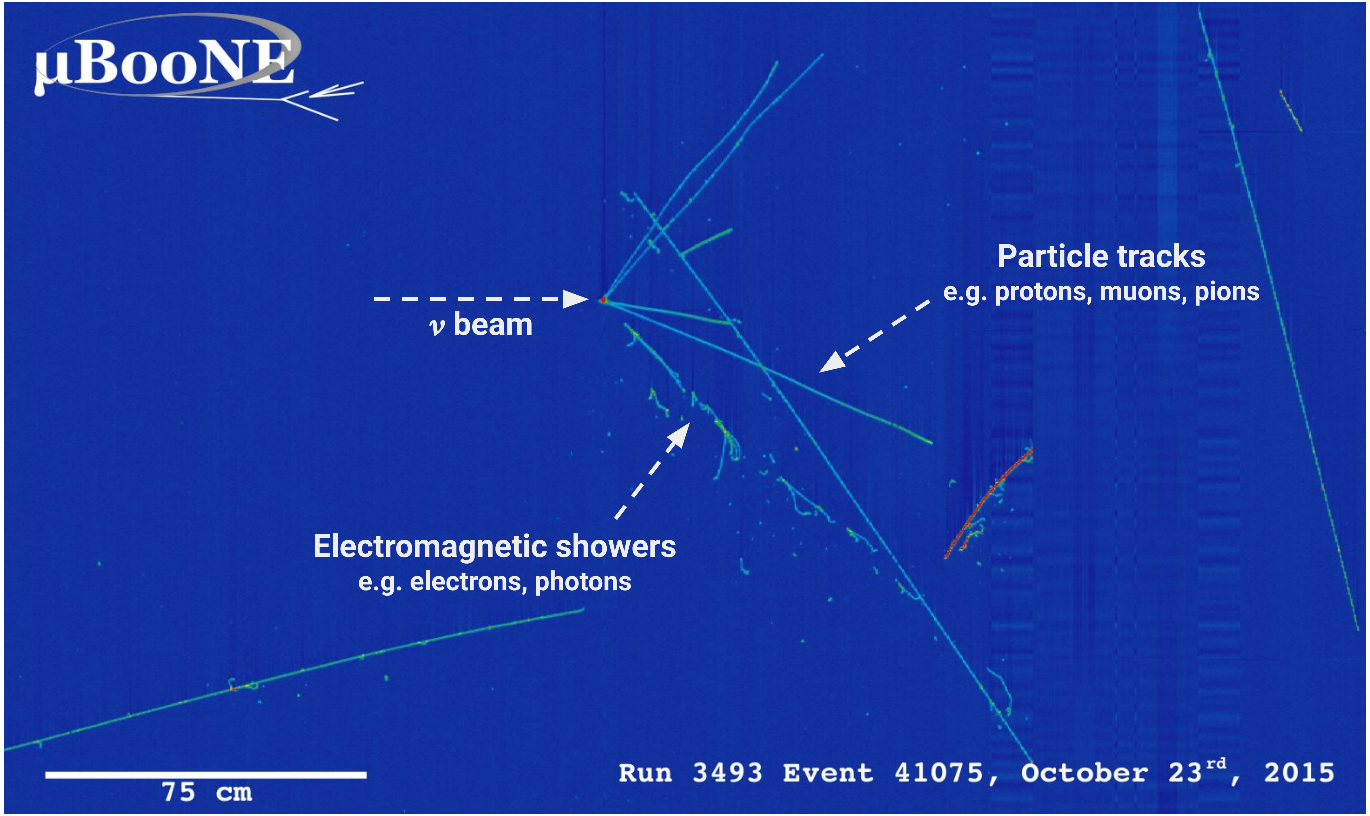


Liquid Argon Time Projection Chambers

- Signals from ionization electrons and scintillation photons
  - Photons captured by photomultiplier tubes (not pictured)
  - Electrons drifted toward readout wires via electric field
- Three readout wire planes at different orientations
  - Individual plane images combined into 3D reconstruction of neutrino interactions
- High resolution allows for electron/photon separation

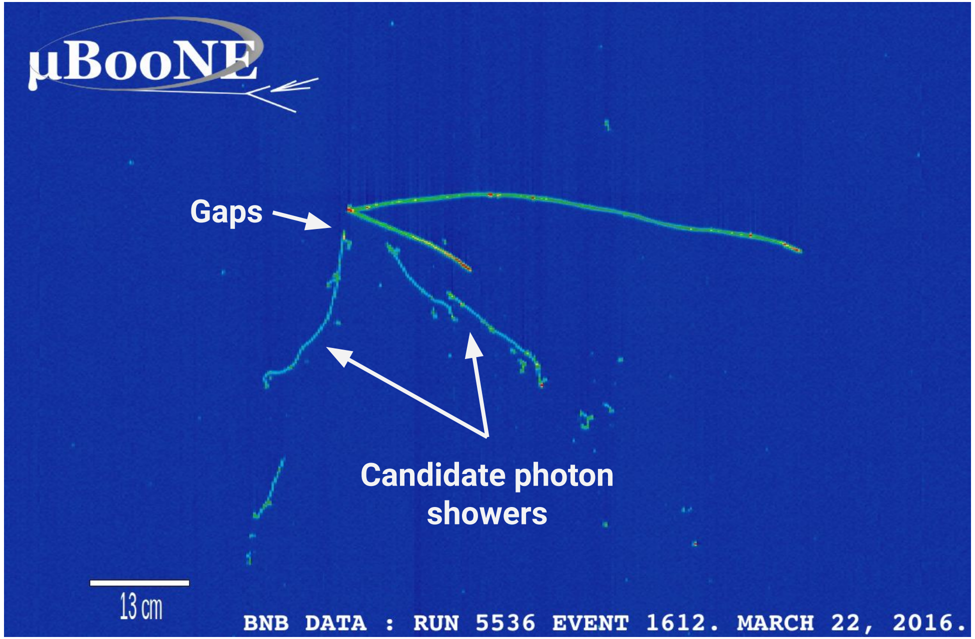


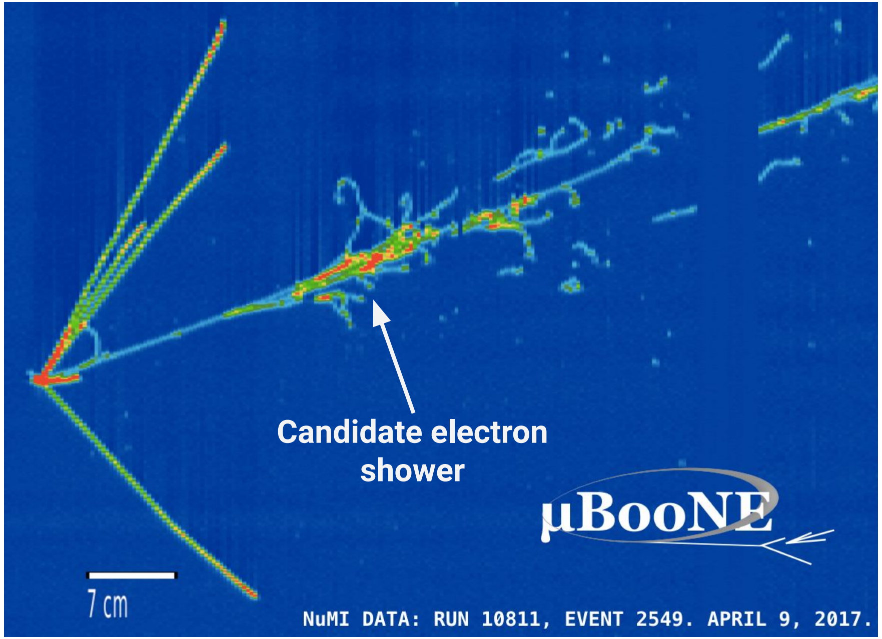
LArTPC Event Display



e/γ Separation: Conversion Distance

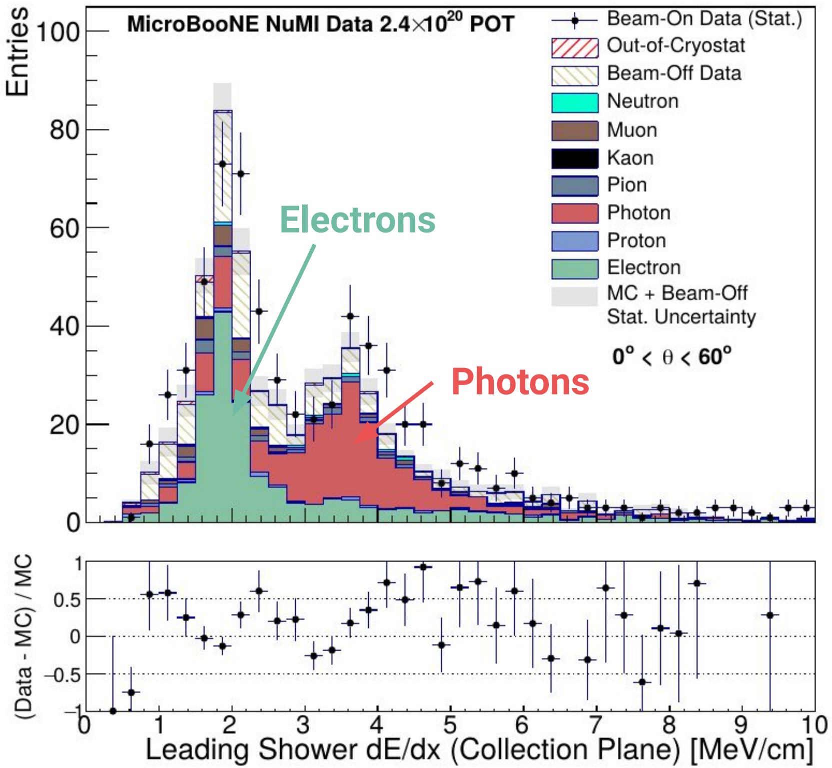
- Photon propagate invisibly before pair converting; electrons attached to vertex





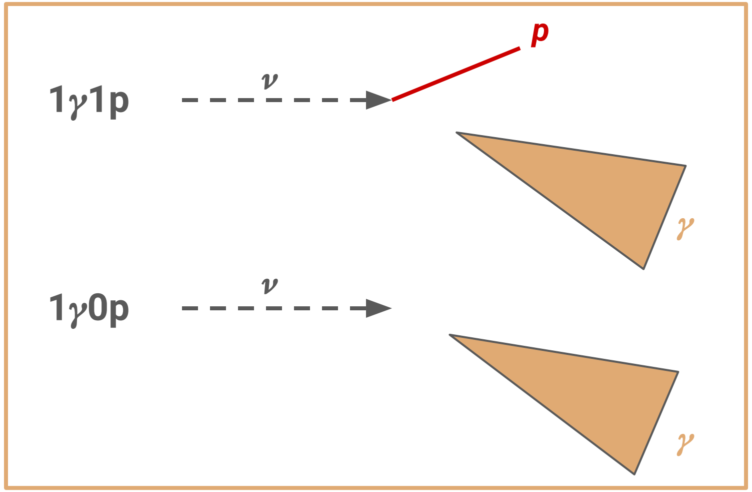
e/γ Separation: Shower dE/dx

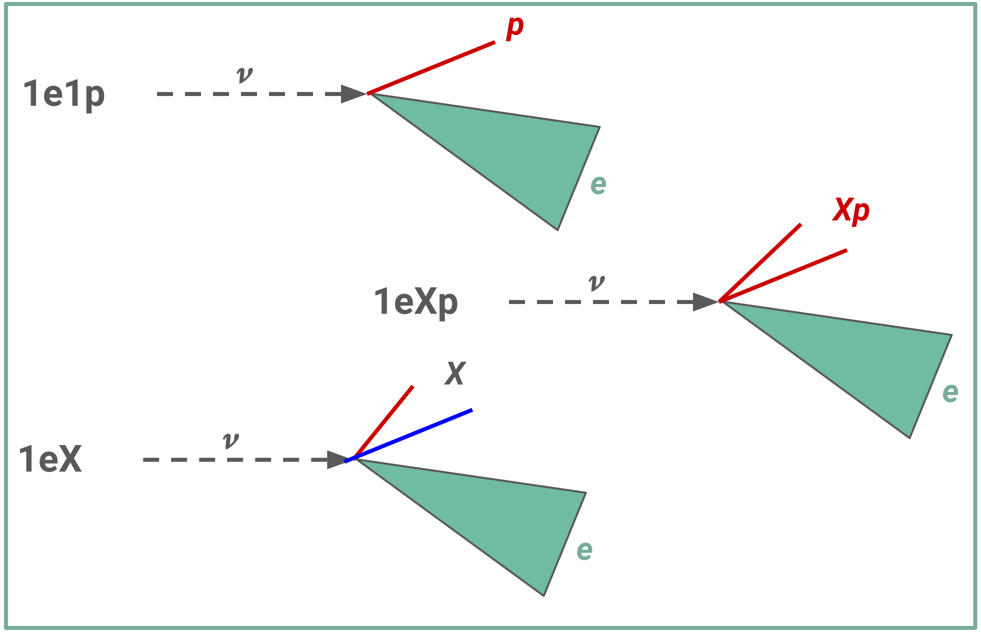
Phys. Rev. D **104**, 052002



- dE/dx: energy deposition per unit length
- Left: leading shower dE/dx from the NuMI inclusive CC ν_e analysis
- Photons pair convert ⇒ expect peak at 2x electron peak

LEE Searches

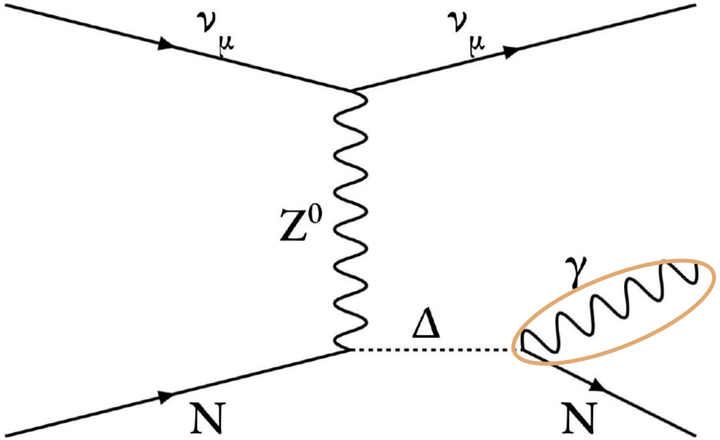




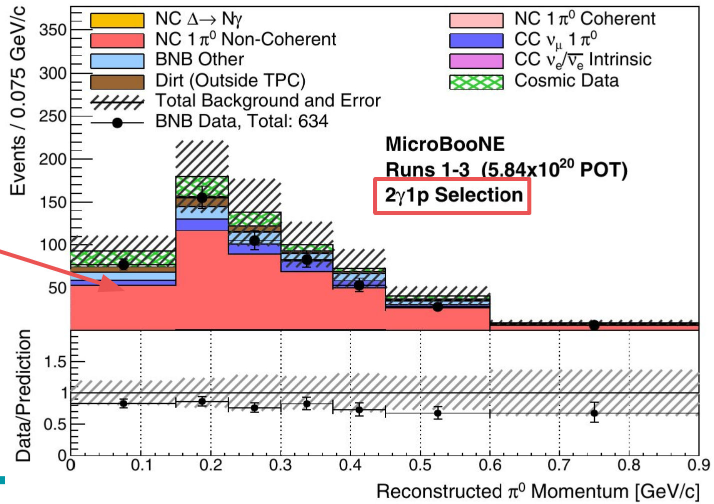
- NC Δ radiative decay search
  - Δ→Nγ
  - Standard model process
  - Branching ratio ~0.6%
    - Δ→Nπ^0 ~99%
- Three complementary ν_e searches
  - Different topology and reconstruction algorithms for each
  - Single electron in final state

Single-Photon Search

- Pandora[1] pattern recognition framework for reconstruction
- Boosted decision tree (BDT) selection
  - Inputs include shower energies and directions, track length and energy, etc.
- Five BDTs trained on separate backgrounds:
  - Cosmic background, CC ν_e, two trained on NC π^0, and other beam-related backgrounds
- NC π^0 background constrained with high-purity 2γ samples
- Enhancement of $\Delta \rightarrow N\gamma$ x3.18 standard model rate would explain MiniBooNE LEE



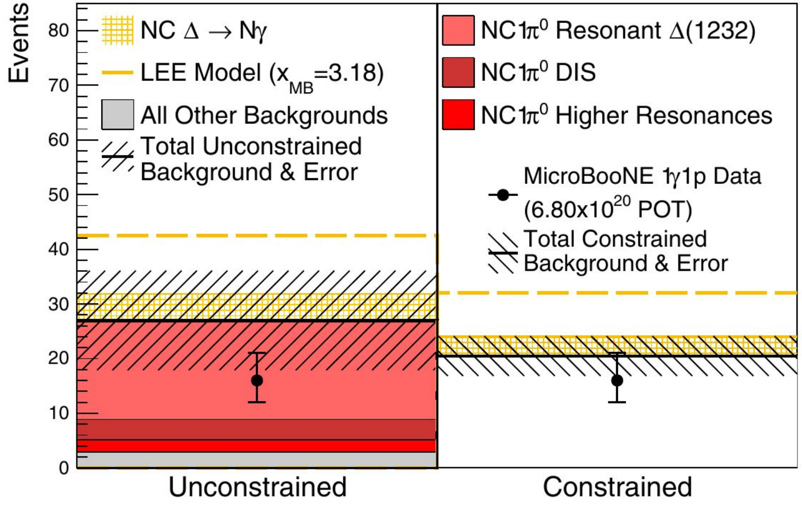
Phys.Rev.Lett. 128 (2022) 111801

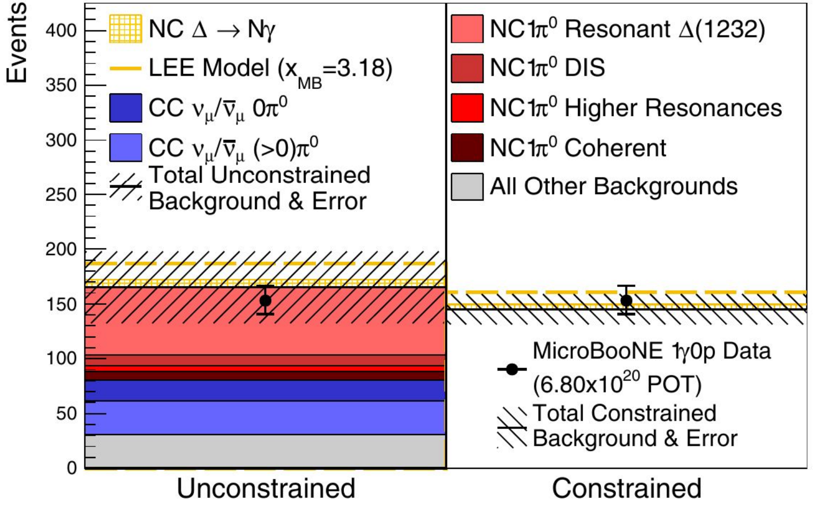


1. EPJC 78, 182 (2018)

Results

- Enhancement of NC Δ radiative decay as sole explanation for the MiniBooNE LEE disfavored at 94.8% CL
- Upper bound on enhancement factor of x2.3 SM rate at 90% CL
  - Most stringent limit to date on neutrino-induced $\Delta \rightarrow N\gamma$



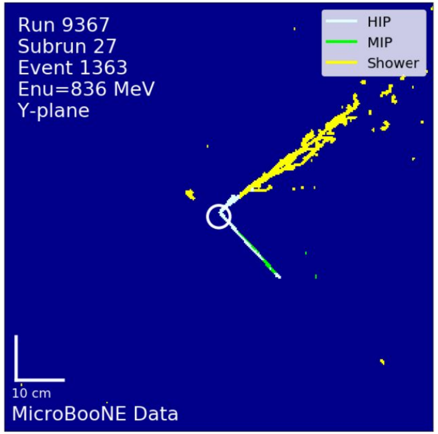


Phys.Rev.Lett. 128 (2022) 111801

Electron Searches

ν_e + Ar → 1e1p0π

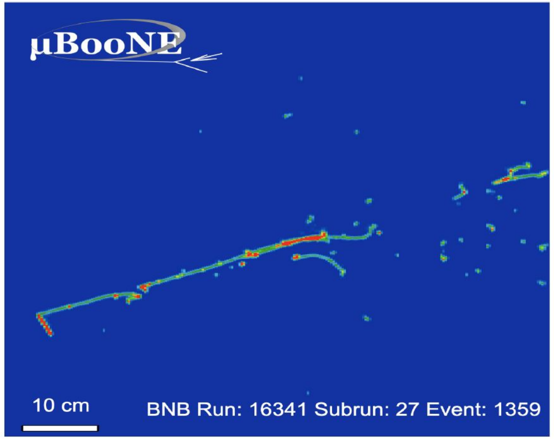
- Exclusive selection
- Deep learning reconstruction[1]
- Targets CCQE interactions



1. Phys. Rev. D **103**, 052012

ν_e + Ar → 1eXp0π

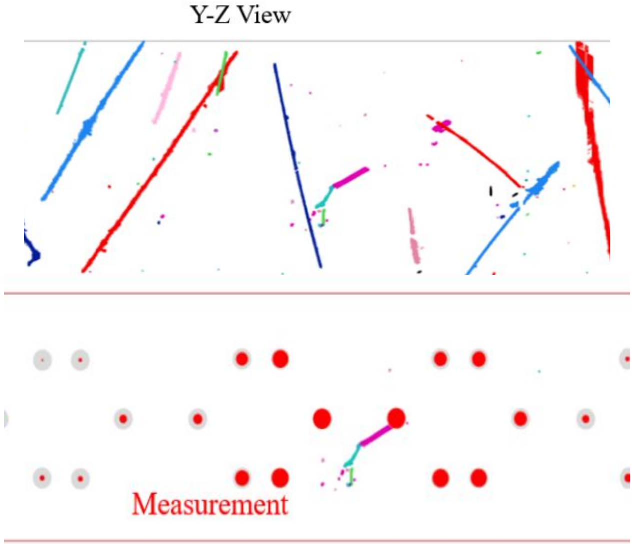
- Semi-inclusive selection
- Pandora reconstruction[2]
- 0p and Np (N > 0) channels treated separately



2. EPJC 78, 182 (2018)

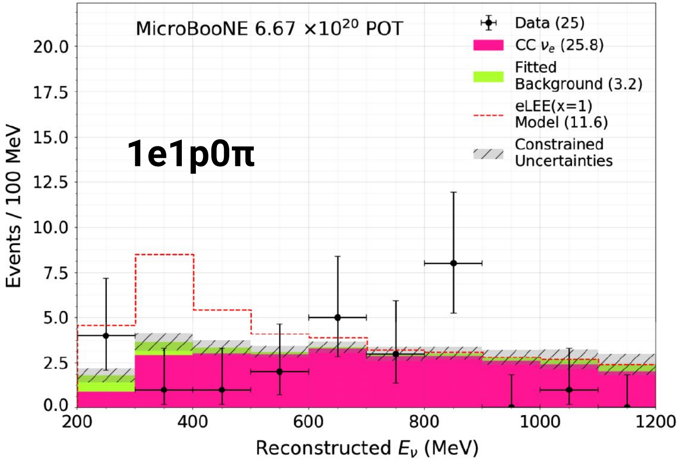
ν_e + Ar → 1eX

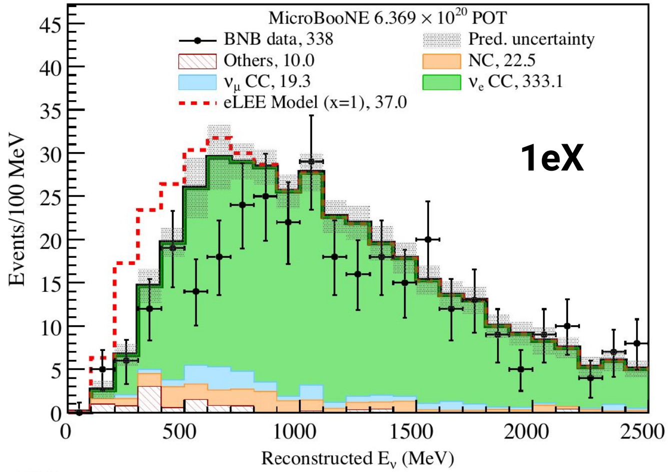
- Inclusive selection
- Wirecell reconstruction[3]

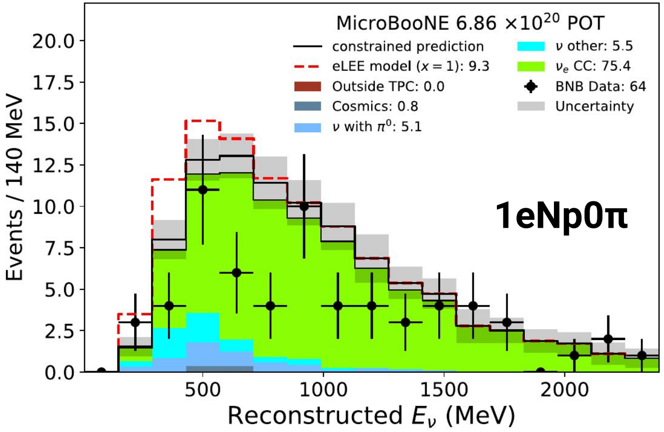


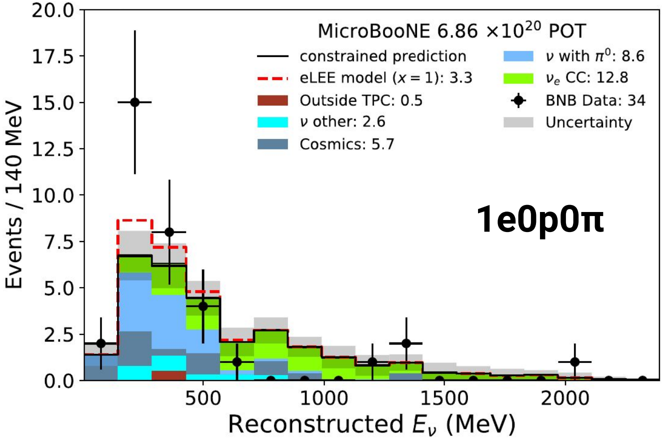
3. JINST 17 P01037

Selected ν_e Energy Spectra



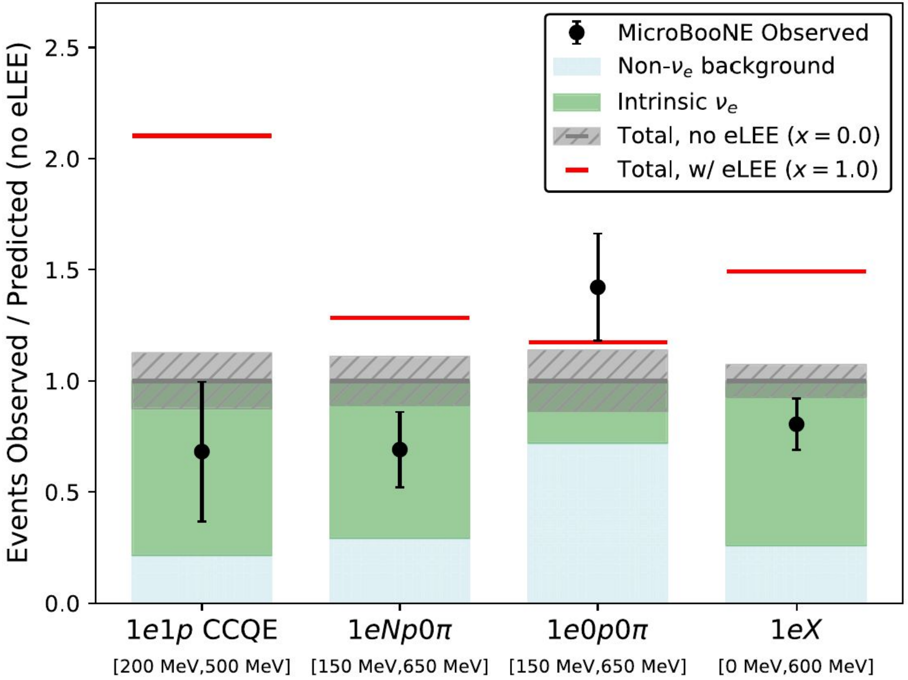






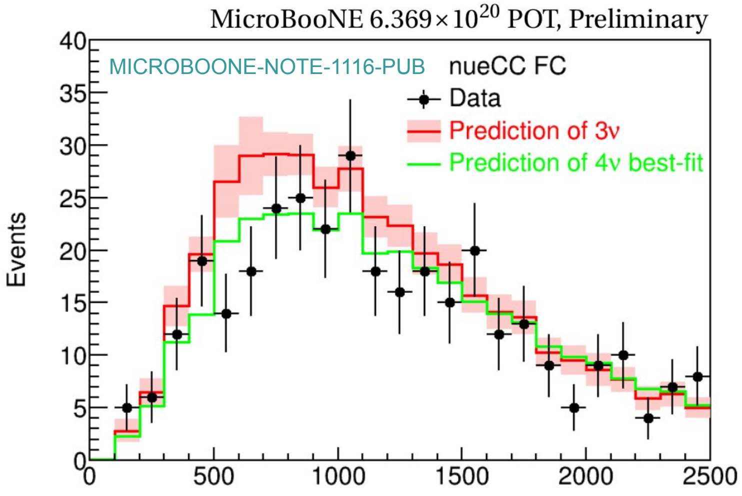
ν_e Search Results

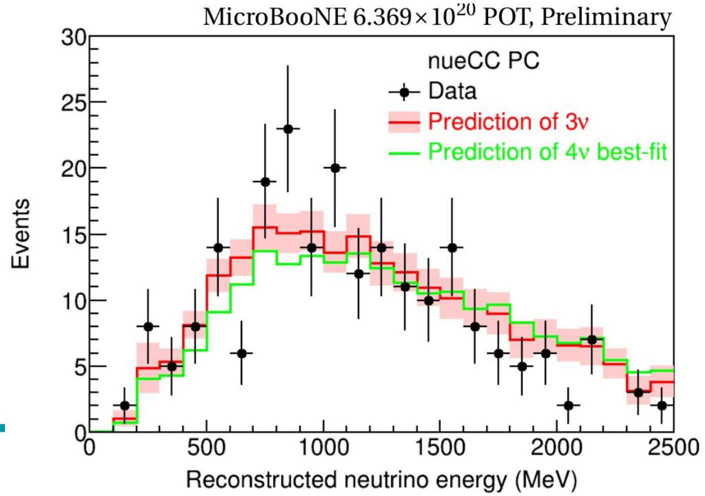
- No excess of ν_e events observed
- All channels consistent with or slightly below expectation
- Slight excess in 1e0p0π
  - Low sensitivity, background dominated
- Reject the hypothesis that the LEE is solely due to CC ν_e interactions at 97% CL
- Disfavor low-energy ν_e interactions as the primary contributor to the excess



3+1 Search

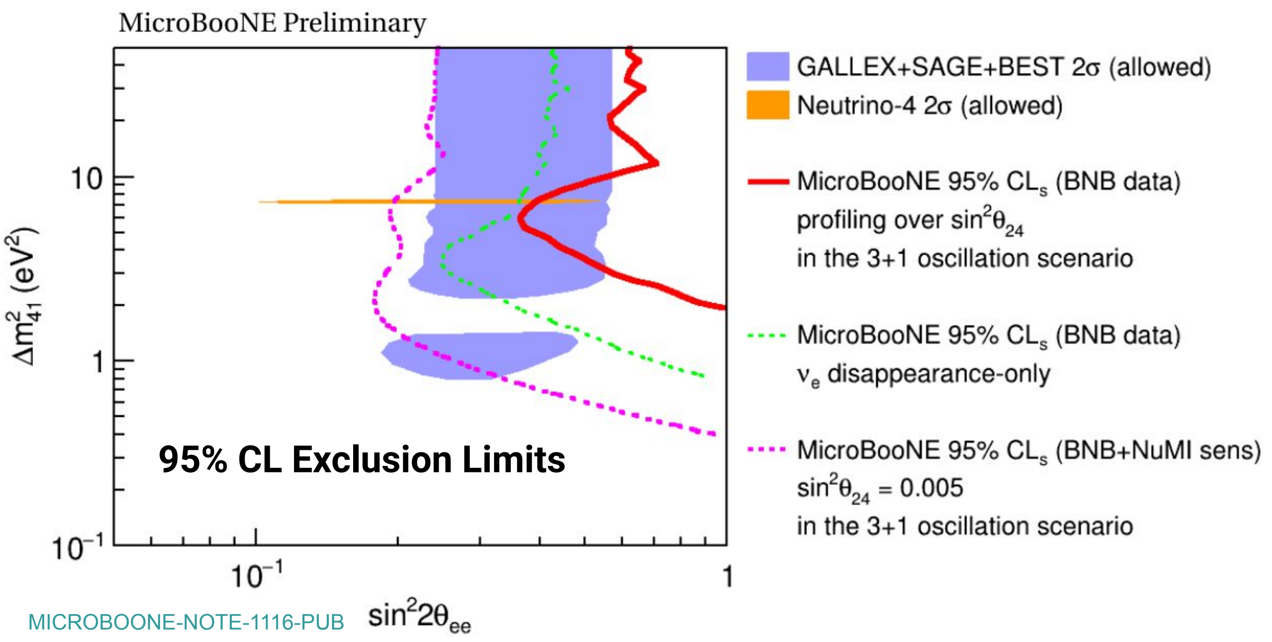
- Currently using data from 1eX selection
  - 3+1 fit with deep learning 1e1p data in progress
- Fit in 7 channels using fully contained (FC) and partially contained (PC) events:
  - FC and PC CC ν_e
  - FC and PC CC ν_μ
  - FC and PC CC π^0
  - NC π^0
- Neutrino energy spectra across all channels agrees with three-flavor oscillation within 1σ
  - Using Feldman-Cousins approach
- 95% exclusion limits calculated using frequentist CLs method





Results: ν_e Disappearance

- Including NuMI data significantly improves sensitivity
  - Mitigates degeneracy in $\sin^2(\theta_{24})$



MICROBOONE-NOTE-1116-PUB

Results: ν_e Appearance

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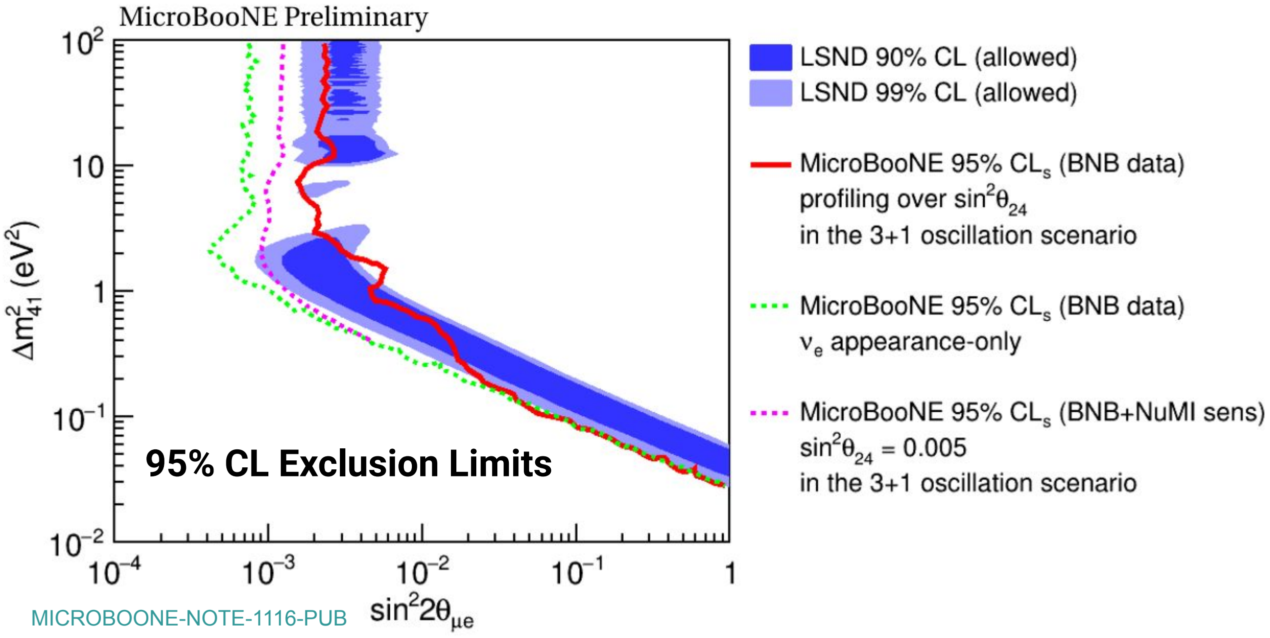


MICROBOONE-NOTE-1116-PUB

Summary

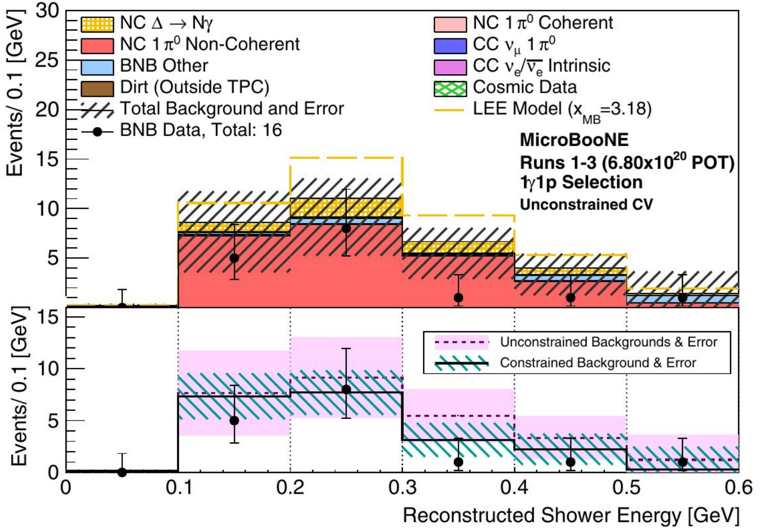
- MicroBooNE has analyzed single-photon and CC ν_e channels to investigate the MiniBooNE LEE
- No excess observed in any investigated channels
- 3+1 sterile oscillation fit using BNB data shows no evidence for sterile oscillations
  - Updated fits with NuMI data in the future
- More data processing; look forward to higher-statistics analysis
- For more:
  - See Pawel Guzowski's talk next
  - See Xiao Luo's plenary talk Thursday at noon

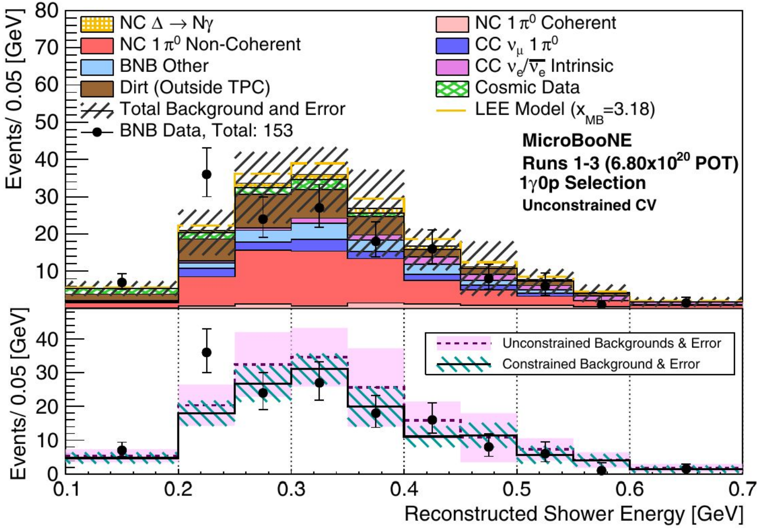
Backup

Single-Photon Constraint using 2γ Samples

- High-statistics 2γ samples used to constrain uncertainties and large NC π^0 background
- Total background prediction reduced by 24% (1γ1p) and 12% (1γ0p)
- Primary topic of my PhD thesis!

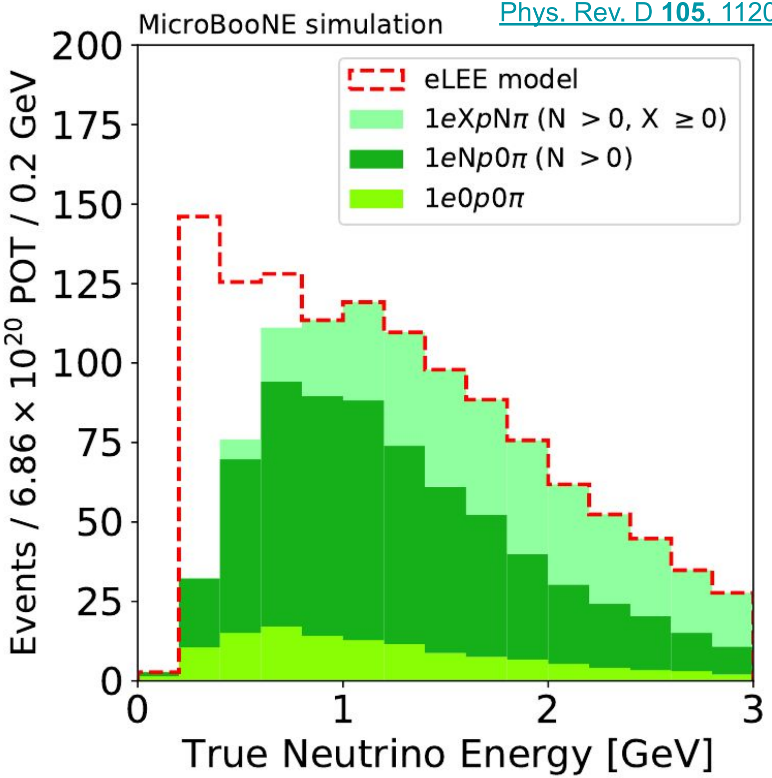
	$1\gamma 1p$	$1\gamma 0p$
Unconstr. bkgd.	27.0 ± 8.1	165.4 ± 31.7
Constr. bkgd.	20.5 ± 3.6	145.1 ± 13.8
NC $\Delta \to N\gamma$	4.88	6.55
LEE ($x_{MB} = 3.18$)	15.5	20.1
Data	16	153





eLEE Model

Phys. Rev. D **105**, 112004



- Excess event unfolded from MiniBooNE data
- Treated as an energy-dependent flux scaling factor
  - Peaked at low energy

3+1 Degeneracy in BNB-Only

- Degeneracy as $\sin^2(\theta_{24})$ approaches 1/R

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

- Different ν_μ to ν_e ratio in NuMI
  - Higher ν_e content in NuMI beam
  - ⇒ Degeneracy mitigated when including NuMI data