INTENSE: particle physics experiments at the intensity frontier. A cooperative Europe – United States effort.

WP3
MicroBooNE Results

MidTerm Review Meeting, Dec 2, 2022

Melissa Uchida

UNIVERSITY OF CAMBRIDGE

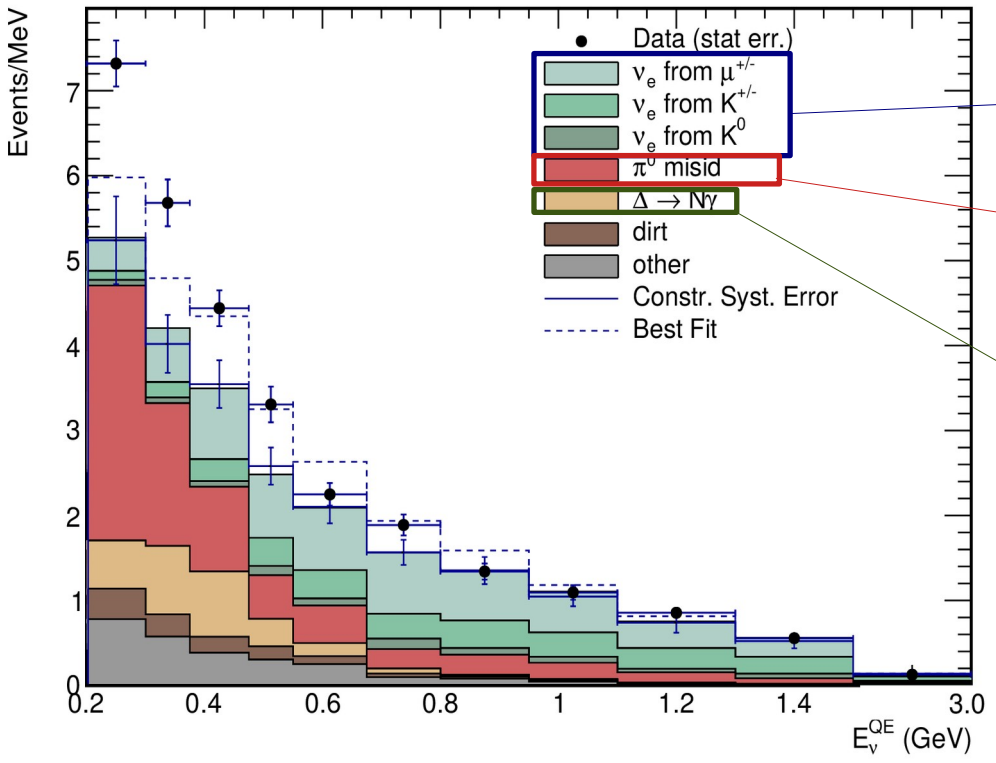
European Commission

Intense
H2020 MSCA ITN
G.A. 858199

µBooNE

The MiniBooNE Low Energy Excess

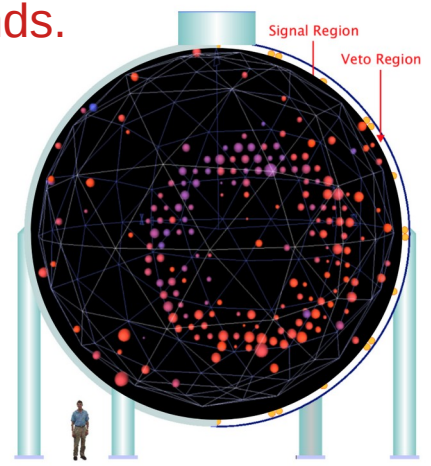
MiniBooNE Electron-like selection has a lot of photon backgrounds.



Flux?

Mis-ID'd pi-zero background (measured in-situ).

Mis-ID'd photon background?



Event display: MiniBooNE collaboration

Or real electron neutrino appearance?

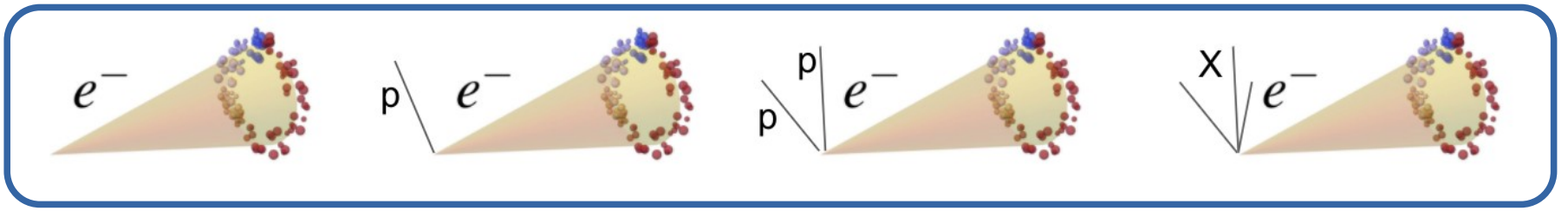
Sees 4.5σ excess in neutrino mode, 4.7σ in antineutrino mode.

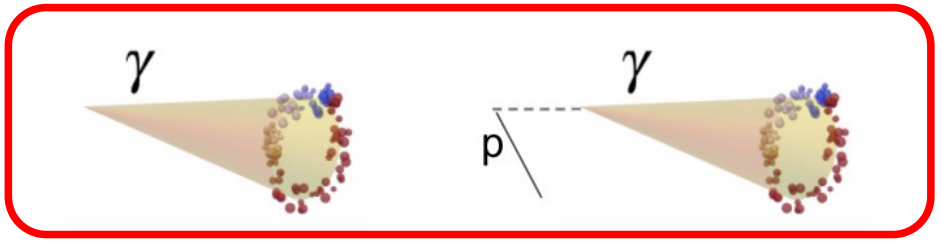
The MicroBooNE LEE Analyses

We can **characterise any LEE excess beyond** simply whether it is **electrons or photons** but **also in terms of particle content and kinematics** (on both the leptonic and hadronic side).

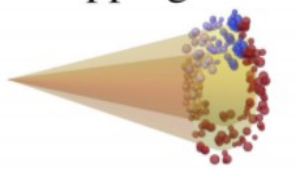
Remaining **agnostic to specific new-physics hypotheses.**

MicroBooNE's First LEE Exploration



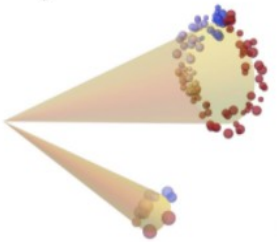


Overlapping e^+e^-

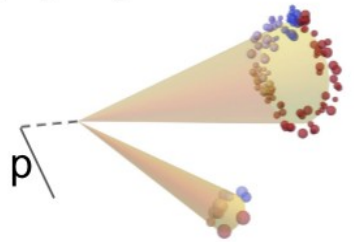


Overlapping e^+e^-

Highly Asymmetric e^+e^-



Highly Asymmetric e^+e^-



Credit: Mark R-L

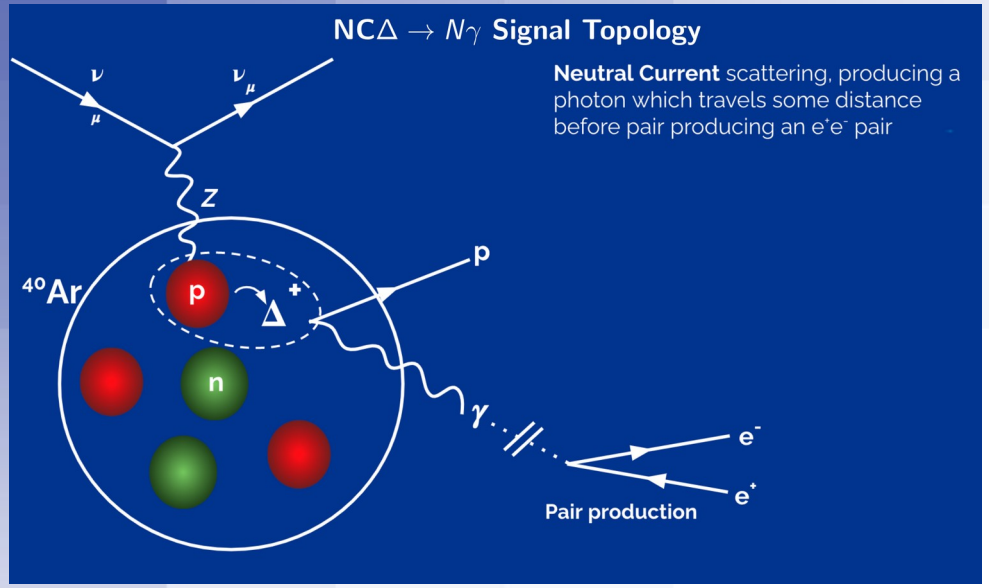
MicroBooNE LEE Exploration so far..

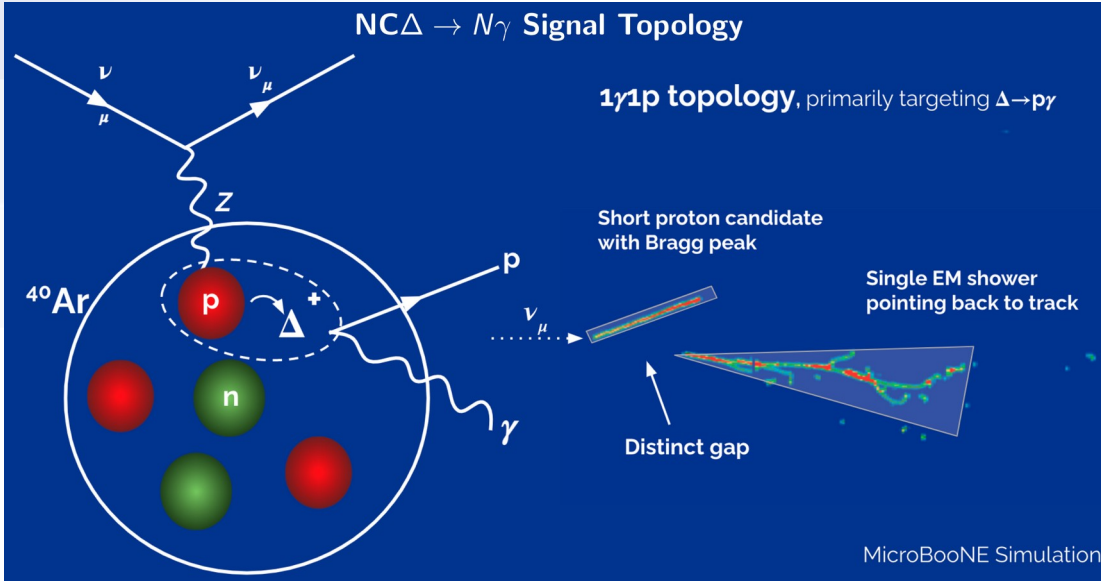
First series of results (1/2 the MicroBooNE data set)

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔ [7]	✔ [7]	✔ [7]	✔ [7]			✔ [7]		
Sterile ν Decay	✔ [13,14]	✔ [13,14]	✔ [13.14]	✔ [13,14]			✔ [4,11,12,15]	✔ [4]	✔ [4]
Dark Sector & Z' *	✔ [2,3]				✔ [2,3]	✔ [2,3]	✔ [1,2,3]	✔ [1,2,3]	✔ [1,2,3]
More complex higgs *					✔ [10]	✔ [10]	✔ [6,10]	✔ [6,10]	✔ [6,10]
Axion-like particle *					✔ [8]		✔ [8]		
Res matter effects	✔ [5]	✔ [5]	✔ [5]	✔ [5]					
SM γ production							✔	✔	✔

*Requires heavy sterile/other new particles also

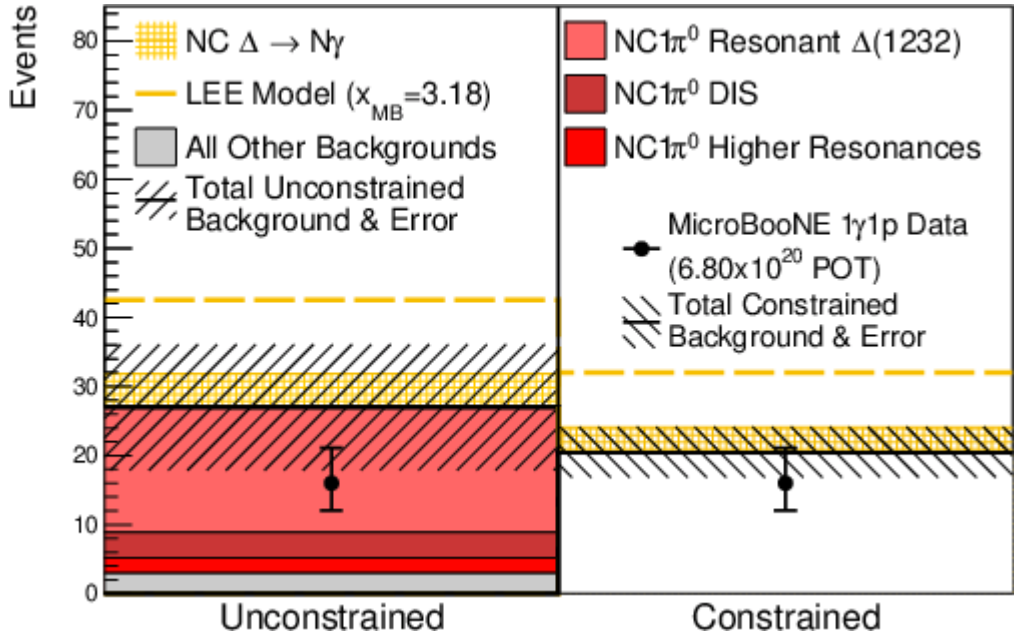
MicroBooNE's Photon Analysis

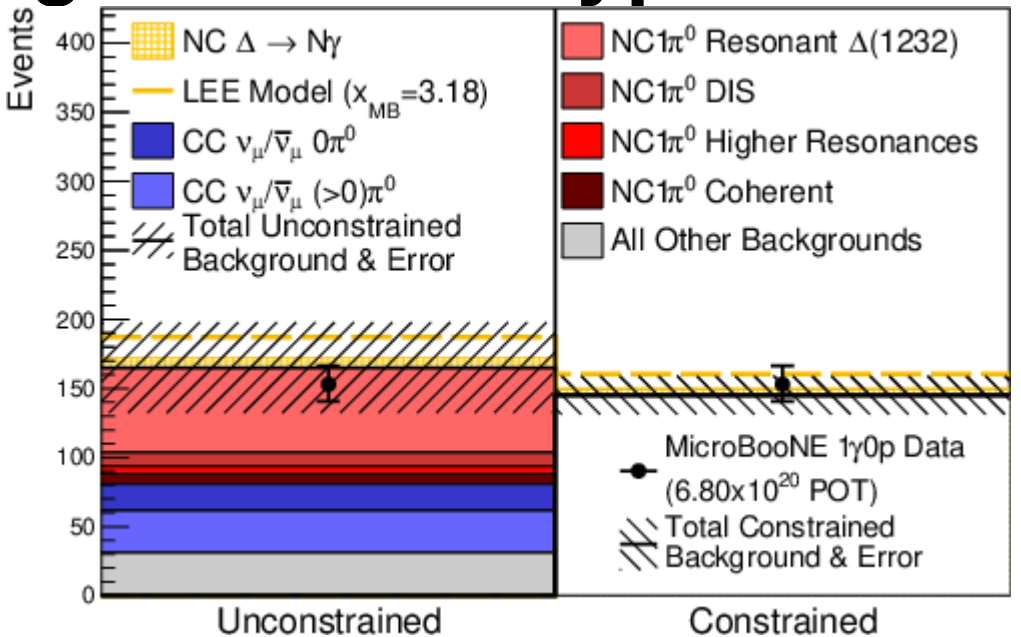




- Uses two two-photon selections to constrain NCπ^0 background.
- Signal samples are single photon.
- Physics modelled with GENIE v3.0.6→ Berger-Sehgal resonance model.

1st Test of the LEE: Single-Photon Hypothesis





	$1\gamma 1p$
Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \to N\gamma$	4.88
LEE ($x_{\mathrm{MB}} = 3.18$)	15.5
Data	16

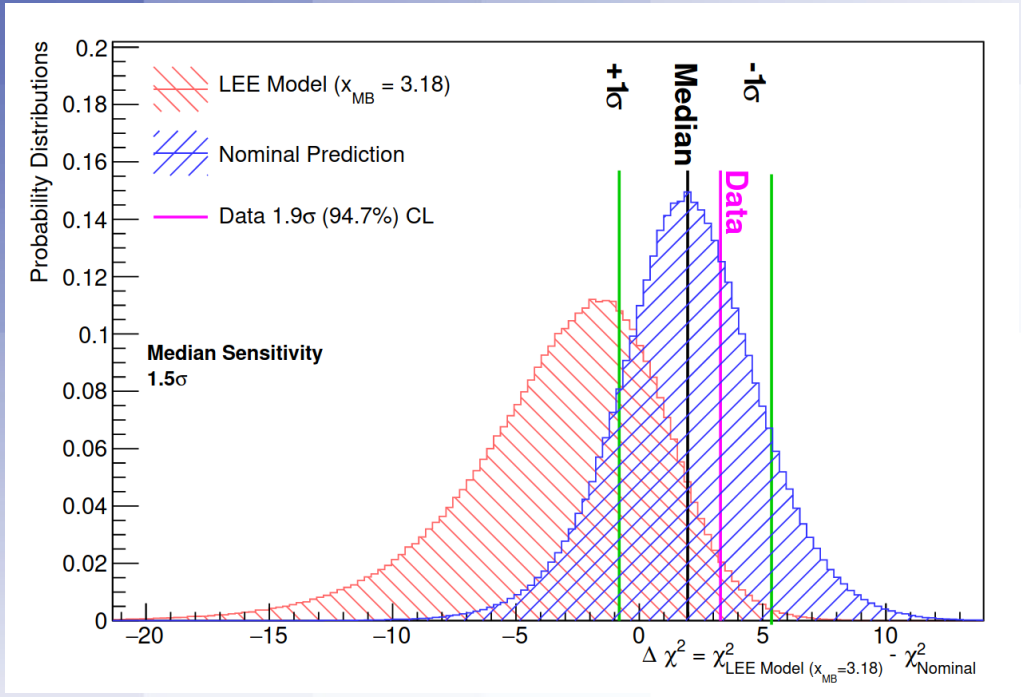
16 data events observed

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

153 data events observed

* Bckgrd is constrained via an in-situ high-purity measurement of NC π0 evts, poss. via dedicated 2γ1p & 2γ0p selections.

Well then...



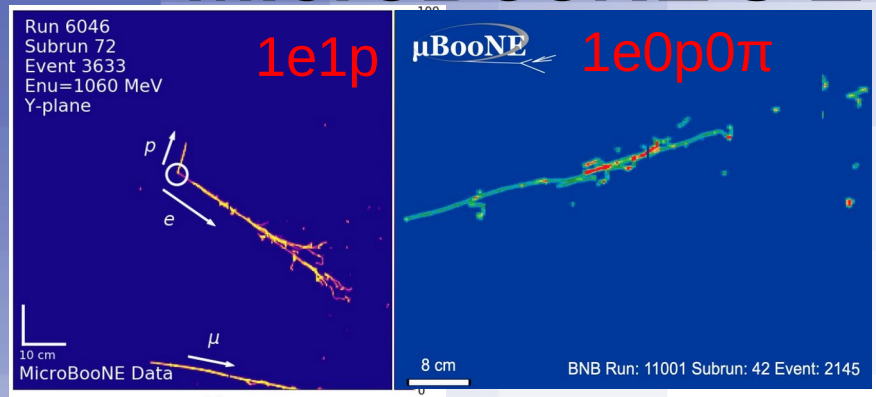
50-fold improvement over prior limit on rate of this interaction.

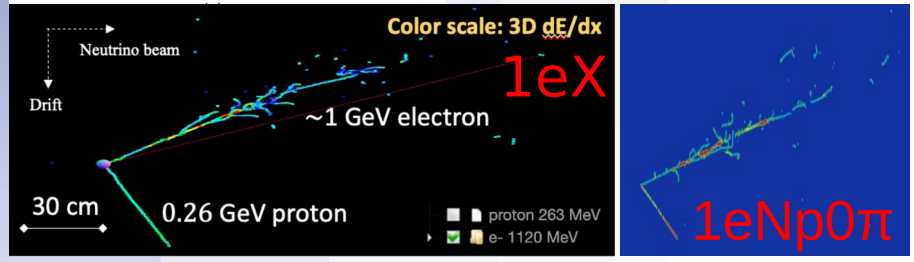
Phys.Rev.Lett. 128 (2022) 11, 111801

Disfavours the NCΔ→Nγ explanation of **LEE** at **94.8%** confidence level.

	$1\gamma 1p$	$1\gamma 0p$
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 ($x_{\text{MB}} = 3.18$)	15.5	20.1
Data	16	153

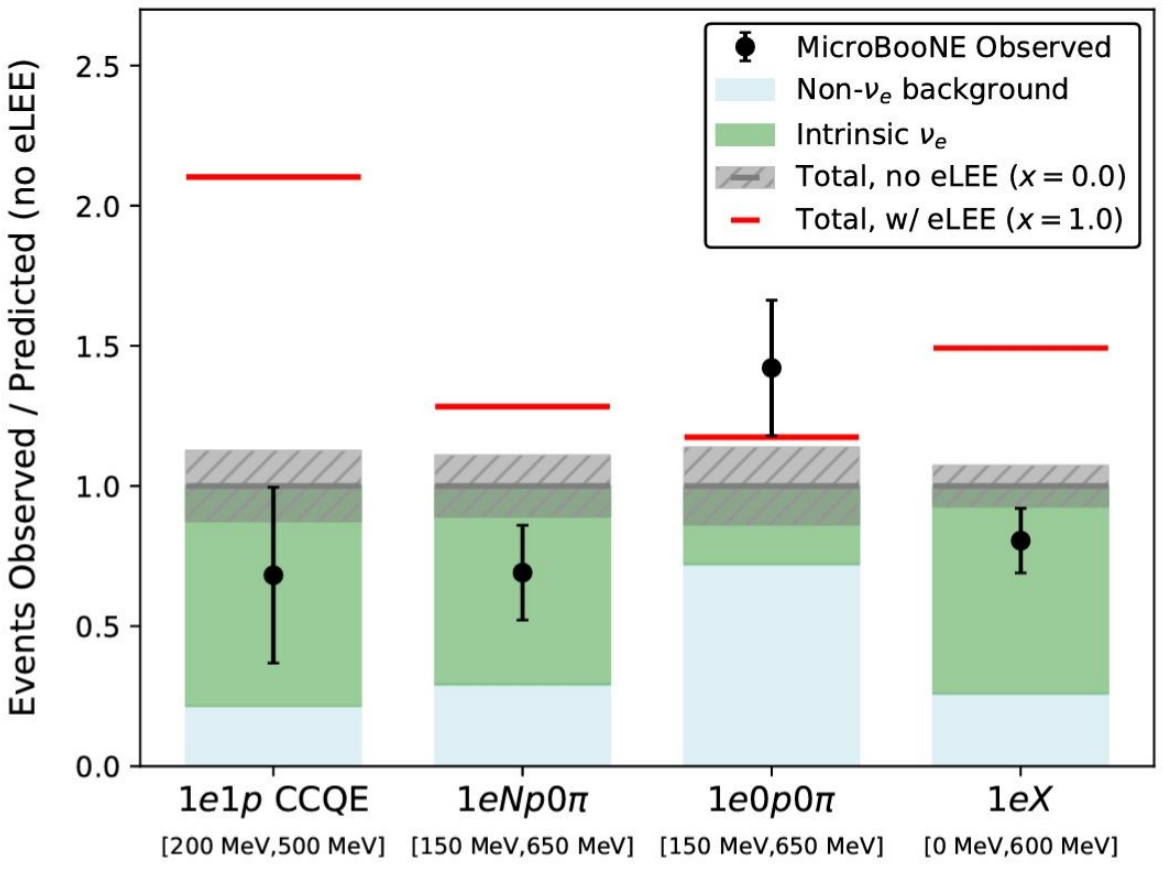
MicroBooNE's Electron-Like Analysis





- 3 distinct e-like LEE search analyses:
  - CCQE 1e1p. PRD arXiv:2110.14080
  - Pionless: 1eNp0π and 1e0p0π PRD arXiv:2110.14065
  - 1eX. PRD arXiv:2110.13978
- Start with high-statistics muon-like samples to make data-driven electron-like prediction.
  - Heavily reduces uncertainties on e-like spectrum.
- Excellent rejection of cosmic-ray and photon shower backgrounds.
- High-statistics auxiliary measurements of π^0 and ν_μ CC events to produce data-driven ν_e estimates with constrained uncertainties.
- **Use unfolded MiniBooNE-like excess to test hypothesis → Not a sterile model!**

MicroBooNE's electron-like LEE Results



All analyses observe ν_e event rates:

- **agree with or are below the predicted rates from 3-flav ν osc,**
- over full analysis energy range and
- in the signal-enhanced low-energy region defined by each analysis prior to unblinding,
- (with the exception of the 1e0p0π, which is background dominated).

Reject the hypothesis that simple charged current ν_e fully explains the MiniBooNE excess at >97% CL in all analyses.

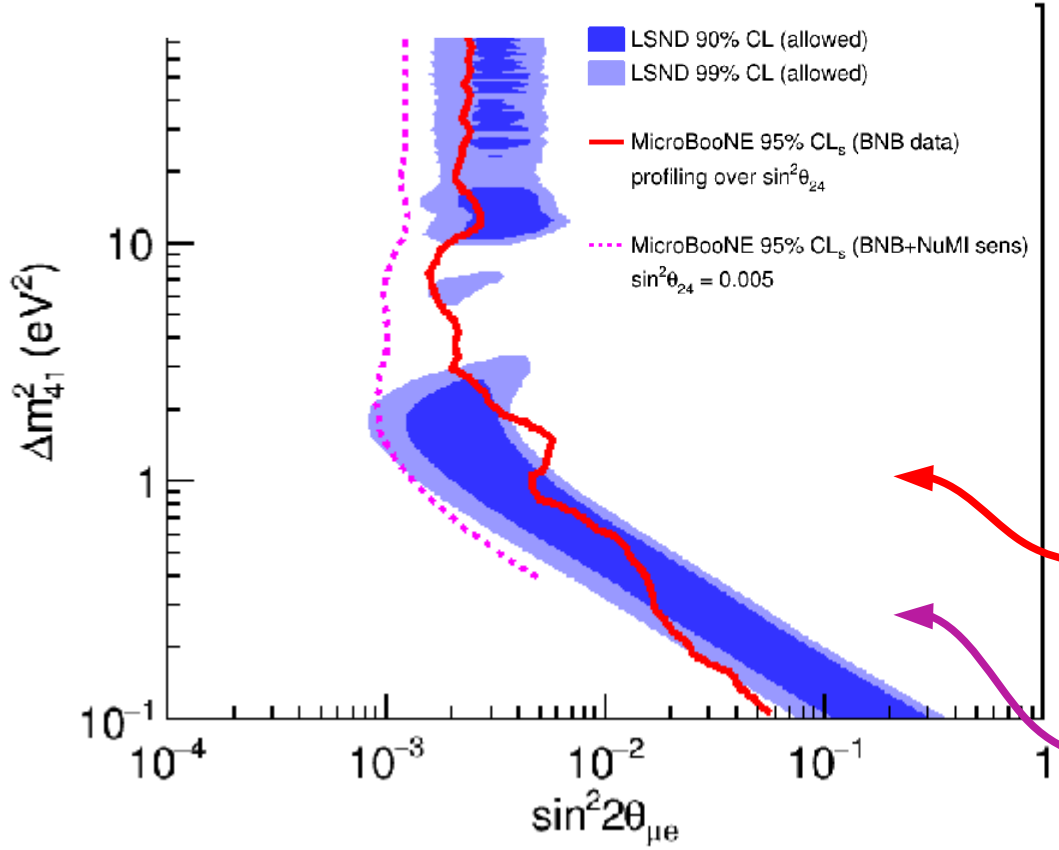
UNIVERSITY OF CAMBRIDGE

eLEE PRL

European Commission
Intense
H2020 MSCA ITN G.A. 858199

New Constraints on eV-Scale Sterile Neutrinos

MICROBOONE-NOTE-1116-PUB

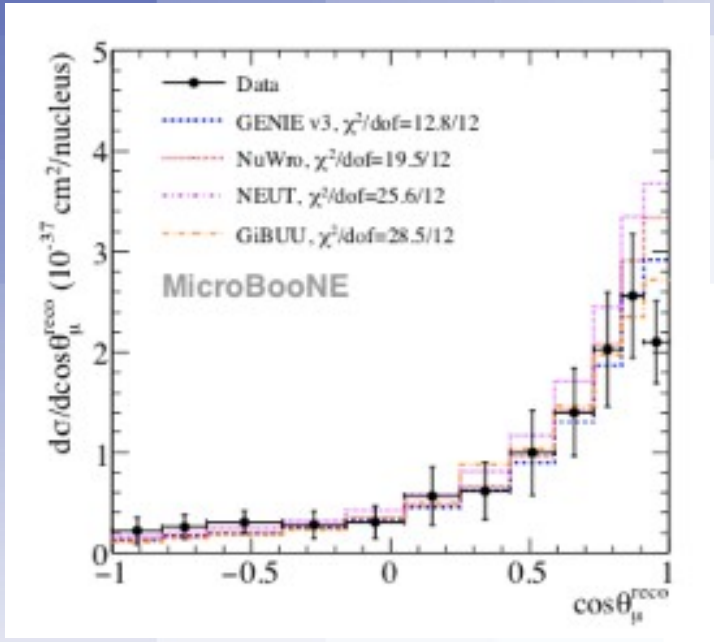


The **inclusive CC ν_e** results have subsequently been turned into a direct bound on eV scale sterile neutrinos.

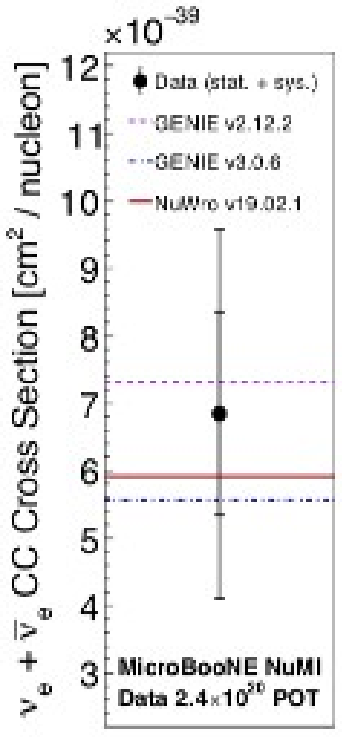
As the inclusive CC ν_e selection utilises high statistics CC ν_μ events to help constrain systematics, **a full 3+1 sterile neutrino fit must be performed** in order to fully take into account all possible flavour transitions.

- With this **full 3+1 analysis**, part of the LSND allowed region is excluded by the MicroBooNE 95% CL limit,
- Combining both data sets significantly improves sensitivity → **Upcoming BNB + NuMI analysis** will be sensitive to full LSND allowed regions.
  BNB R ν_e/ν_μ: 0.005 & NuMI R ν_e/ν_μ: 0.04

Neutrino Cross Sections



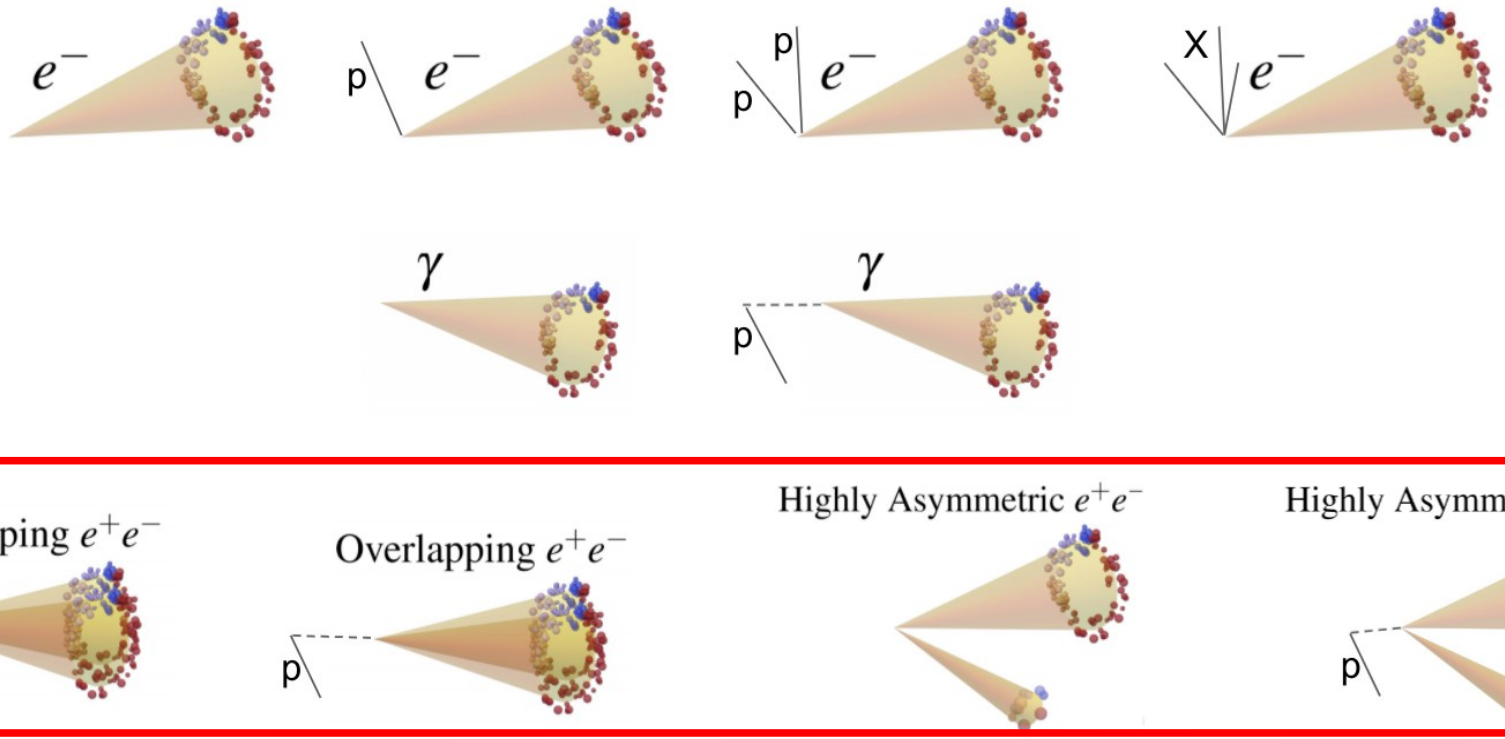
PRD 102, 112013 (2020)



ArXiv:2101.04228 (2021)

- ν_e CC inclusive (ν_e + Ar —> e + X), NuMI beam!
  - ArXiv:2101.04228 (2021)
- CC Np (ν_μ + Ar —> μ + Np,0π):
  - PRD 102, 112013 (2020)
- QE-like (ν_μ + Ar —> μ + p):
  - PRL 125, 201803 (2020)
- ν_μ CC inclusive (ν_μ + Ar —> μ + X):
  - PRL 123, 131801 (2019)
- Charged track multiplicities:
  - Eur. Phys. J. C79, 248 (2019)
- CC π^0 (ν_μ + Ar —> μ + π 0):
  - PRD 99, 091102R (2019)
- More coming inc.: **kaon (NuMi and BNB)**, NC elastic, CC 2p, transverse kinematics, NC π^0, CC/NC π^0, CC π^+, CC coherent π^+, and η production.

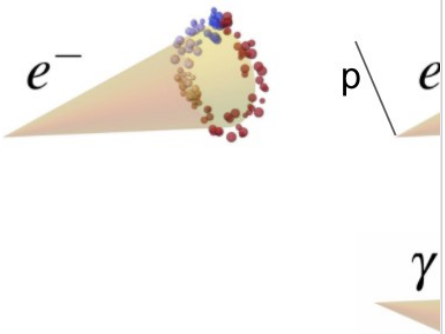
MicroBooNE Next Steps



Credit: Mark R-L

G.A. 858199

MicroBooNE Next Steps



First series of results (1/2 the MicroBooNE data set)

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔[7]	✔[7]	✔[7]	✔[7]			✔[7]		
Sterile ν Decay	✔[13,14]	✔[13,14]	✔[13.14]	✔[13,14]			✔[4,11,12,15]	✔[4]	✔[4]
Dark Sector & Z' *	✔[2,3]				✔[2,3]	✔[2,3]	✔[1,2,3]	✔[1,2,3]	✔[1,2,3]
More complex higgs *					✔[10]	✔[10]	✔[6,10]	✔[6,10]	✔[6,10]
Axion-like particle *					✔[8]		✔[8]		
Res matter effects	✔[5]	✔[5]	✔[5]	✔[5]					
SM γ production							✔	✔	✔

*Requires heavy sterile/other new particles also

Credit: Mark R-L

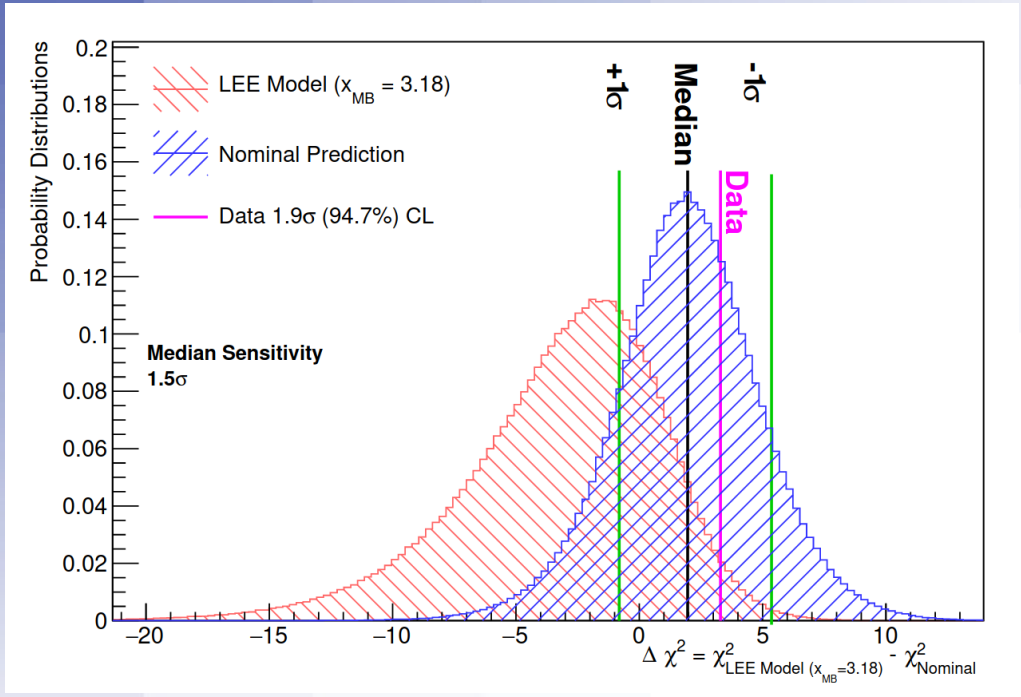
Summary

- **MicroBooNE has performed the first detailed study of the MiniBooNE excess.**
- **Photon-like:**
  - **NCΔ→Nγ explanation of LEE disfavoured at 94.8% CL.**
- **Electron-like:**
  - Results consistent with nominal ν_e rate expectations from BNB → no excess of ν_e events observed.
  - **Simple ν_e CC as full explanation of MiniBooNE LEE disfavoured at >97% CL.**
- **3+1 eV scale Sterile Neutrinos:**
  - **The data are consistent with the 3ν hypothesis and provide no evidence for a sterile neutrino.**
  - **Exclusion limits cover a large fraction of sterile ν parameter space allowed by results from other experiments.**
  - A combined BNB+NuMI oscillation analysis is planned to mitigate the degeneracy of oscillation parameters.
- **The LEE is real→ so it is far more exciting than we thought!**
- Stay tuned—more to come from MicroBooNE!
  - Double the data statistics (all analyses reported here are still statistics-limited).
- Tests of additional LEE models:
  - **Improved analyses:** different interpretations of MiniBooNE LEE with the same final states.
  - Analyses targeting **new final states topologies** also well underway.

Thank you!

Back-up Slides...

Well then...



50-fold improvement over prior limit on rate of this interaction.

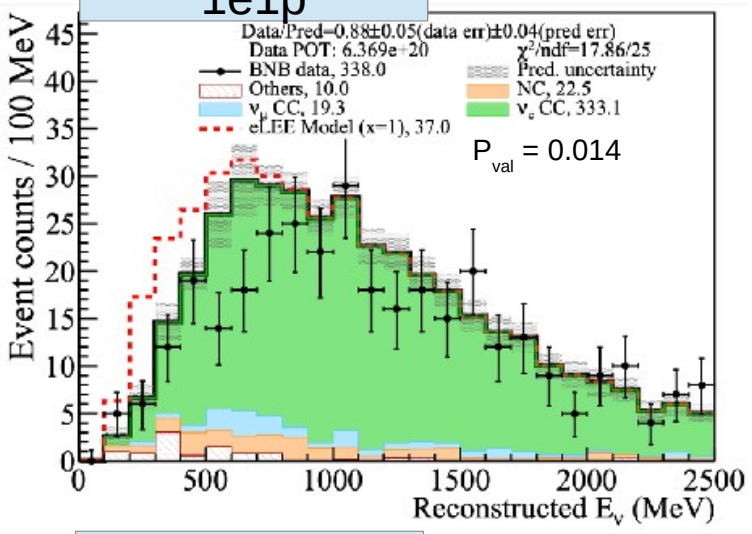
Phys.Rev.Lett. 128 (2022) 11, 111801

Disfavours the NCΔ→Nγ explanation of **LEE** at **94.8%** confidence level.

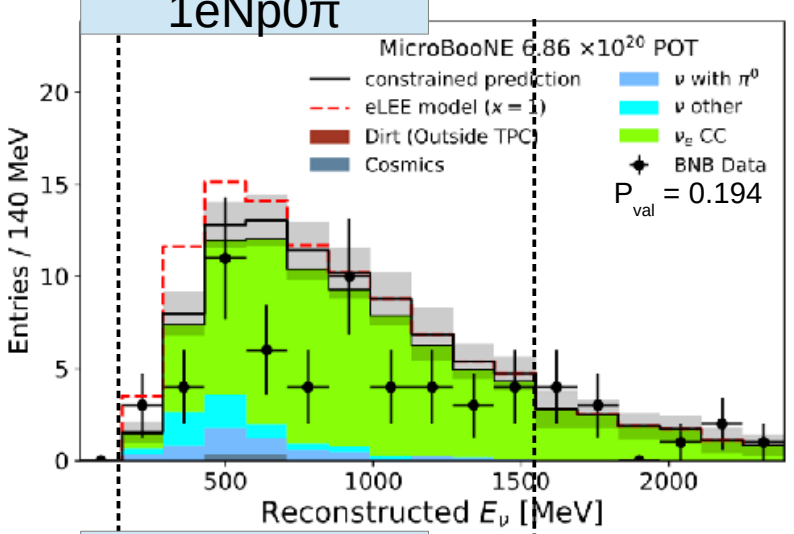
	$1\gamma 1p$	$1\gamma 0p$
Unconstr. bkgd.	27.0 ± 8.1	165.4 ± 31.7
Constr. bkgd.	20.5 ± 3.6	145.1 ± 13.8
NC $\Delta \to N\gamma$	4.88	6.55
LEE ($x_{\text{MB}} = 3.18$)	15.5	20.1
Data	16	153

Electron-LEE Neutrino Energy

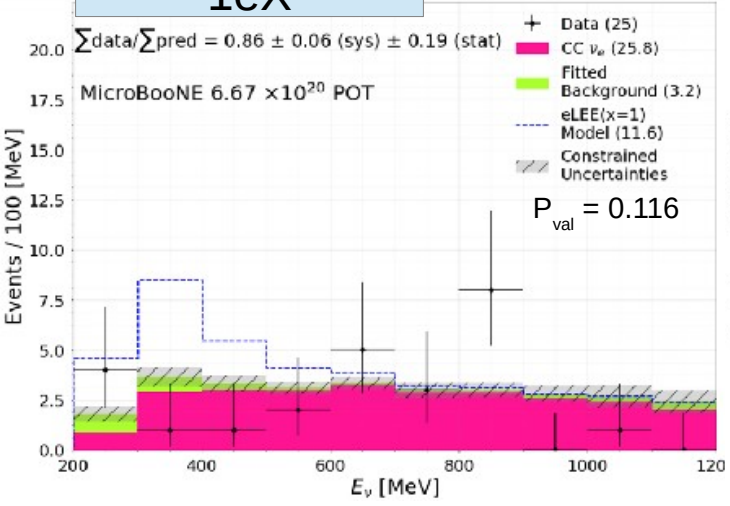
1e1p



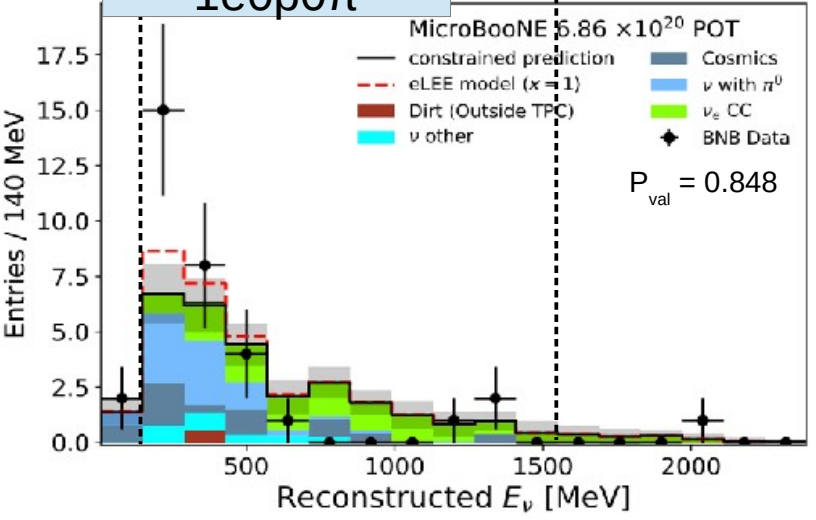
1eNp0π



1eX



1e0p0π



Some tension:

~ 800 MeV in CCQE 1e1p selection, and

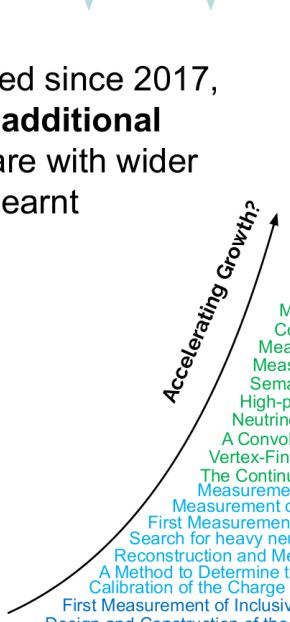
~ 150 MeV (& at forward angles) in 1e0p0π selection (bckg. dom.).

Deficit in 1eNp0π and 1e1p selections at ~400-800 MeV.

MicroBooNE Publications

2017 | 2018 | 2019 | 2020 | 2021 | 2022

49 papers published since 2017, with more than **70 additional** public-notes to share with wider community as we learnt



Search for long-lived heavy neutral leptons and Higgs portal scalars decaying in the MicroBooNE detector
Measurement of neutral current single π^0 production on argon with the MicroBooNE detector
Observation of radon mitigation in MicroBooNE by a liquid argon filtration system
Cosmic ray muon clustering for the MicroBooNE liquid argon time projection chamber using sMask-RCNN
Novel approach for evaluating detector-related uncertainties in a LArTPC using MicroBooNE data
First measurement of energy-dependent inclusive muon neutrino charged-current cross sections on argon with the MicroBooNE detector
Search for an anomalous excess of inclusive charged-current ν_e interactions without pions in the final state with the MicroBooNE experiment
Search for an anomalous excess of charged-current quasi-elastic ν_e interactions with the MicroBooNE experiment using deep-learning-based reconstruction
New theory-driven GENIE tune for MicroBooNE
Search for an anomalous excess of inclusive charged-current ν_e interactions in the MicroBooNE experiment using Wire-Cell reconstruction
Search for an excess of electron neutrino interactions in MicroBooNE using multiple final state topologies
Wire-Cell 3D pattern recognition techniques for neutrino event reconstruction in large LArTPCs
Electromagnetic shower reconstruction and energy validation with Michel electrons and π^0 samples for the deep-learning-based analyses in MicroBooNE
Search for neutrino-induced NC Δ radiative decay in MicroBooNE and a first test of the MiniBooNE low-energy excess under a single-photon hypothesis
First measurement of inclusive electron-neutrino and antineutrino charged current differential cross sections in charged lepton energy on argon in MicroBooNE
Calorimetric classification of track-like signatures in liquid argon TPCs using MicroBooNE data
Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector
Measurement of the Longitudinal Diffusion of Ionization Electrons in the Detector
Cosmic Ray Background Rejection with Wire-Cell LAr TPC Event Reconstruction in the MicroBooNE Detector
Measurement of the Flux-Averaged Inclusive Charged Current Electron Neutrino and Antineutrino Cross Section on Argon using the NuMI Beam in MicroBooNE
Measurement of the Atmospheric Muon Rate with the MicroBooNE Liquid Argon TPC
Semantic Segmentation with a Sparse Convolutional Neural Network for Event Reconstruction in MicroBooNE
High-performance Generic Neutrino Detection in a LAr TPC near the Earth's Surface with the MicroBooNE Detector
Neutrino Event Selection in the MicroBooNE LAr TPC using Wire-Cell 3D Imaging, Clustering, and Charge-Light Matching
A Convolutional Neural Network for Multiple Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
Vertex-Finding and Reconstruction of Contained Two-track Neutrino Events in the MicroBooNE Detector
The Continuous Readout Stream of the MicroBooNE Liquid Argon Time Projection Chamber for Detection of Supernova Burst Neutrinos
Measurement of Differential Cross Sections for Muon Neutrino CC Interactions on Argon with Protons and No Pions in the Final State
Measurement of Space Charge Effects in the MicroBooNE LAr TPC Using Cosmic Muons
First Measurement of Differential Charged Current Quasi-Elastic-Like Muon Neutrino Argon Scattering Cross Sections with the MicroBooNE Detector
Search for heavy neutral leptons decaying into muon-pion pairs in the MicroBooNE detector
Reconstruction and Measurement of O(100) MeV Electromagnetic Activity from Neutral Pion to Gamma Gamma Decays in the MicroBooNE LArTPC
A Method to Determine the Electric Field of Liquid Argon Time Projection Chambers Using a UV Laser System and its Application in MicroBooNE
Calibration of the Charge and Energy Response of the MicroBooNE Liquid Argon Time Projection Chamber Using Muons and Protons
First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at Enu ~0.8 GeV with the MicroBooNE Detector
Design and Construction of the MicroBooNE Cosmic Ray Tagger System
Rejecting Cosmic Background for Exclusive Neutrino Interaction Studies with Liquid Argon TPCs: A Case Study with the MicroBooNE Detector
First Measurement of Muon Neutrino Charged Current Neutral Pion Production on Argon with the MicroBooNE detector
A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber
Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions
Ionization Electron Signal Processing in Single Phase LArTPCs II: Data/Simulation Comparison and Performance in MicroBooNE
Ionization Electron Signal Processing in Single Phase LArTPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation
The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector
Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter
Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC
Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC
Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering
Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber
Design and Construction of the MicroBooNE Detector

MicroBooNE Publications

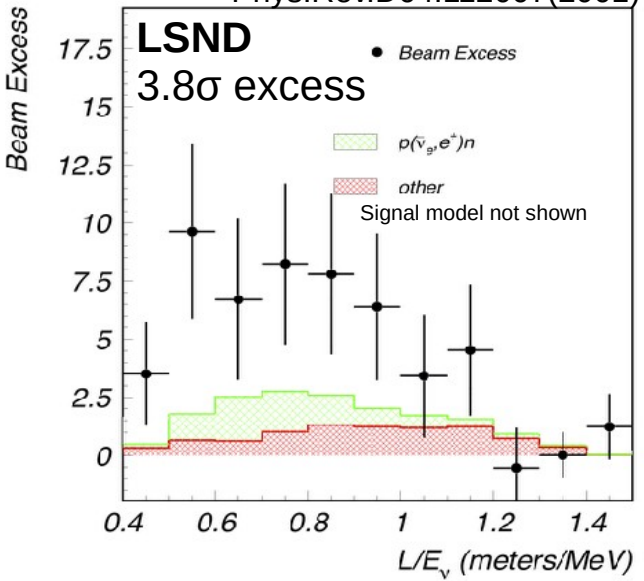
8 papers focused on exotic **BSM** physics and on flagship **Low-Energy Excess searches**

10 papers improving our understanding of neutrino cross-sections on Argon, with ~ 30 more analysis on the way!

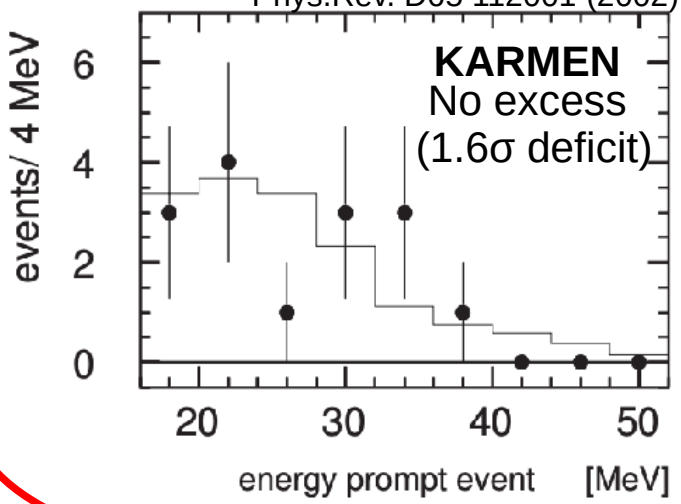
31 on **vital LArTPC hardware and software R&D,** dessiminiting pioneering info for DUNE and SBN program

Short-Baseline Neutrino Experiment Anomalies

Phys.Rev.D64:112007(2001)



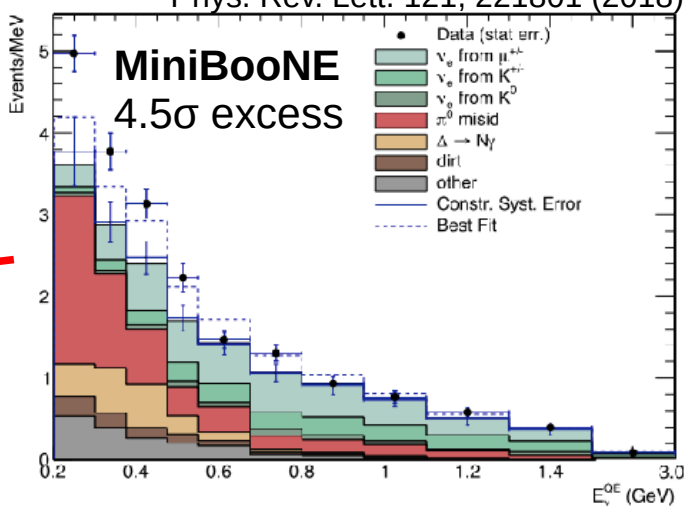
Phys.Rev. D65 112001 (2002)



μ decay-at-rest

π decay-at-rest

Phys. Rev. Lett. 121, 221801 (2018)



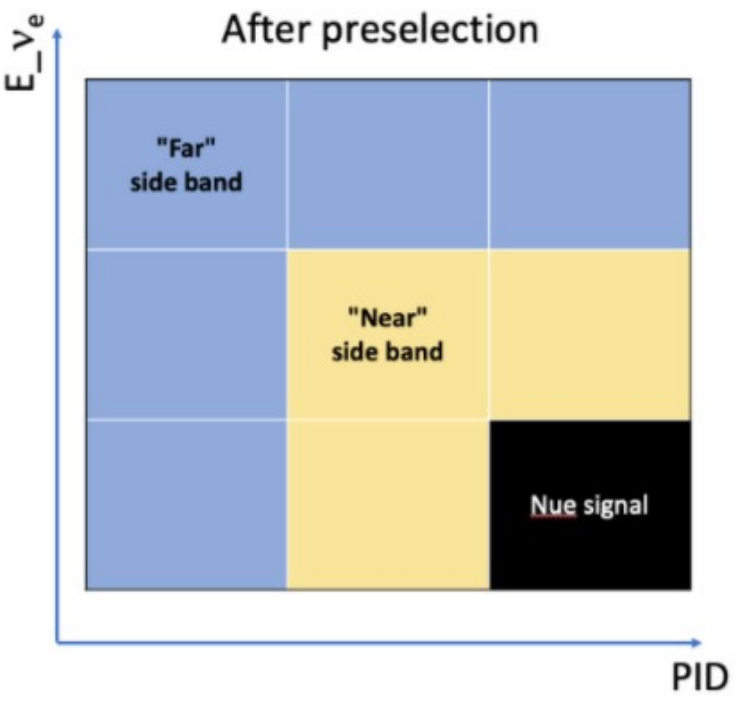
π decay-in-flight

Definitive test of short baseline ν_e appearance requires new experiments and detector technology:

→ enter the **MicroBooNE** Liquid argon time projection chamber (LArTPC).

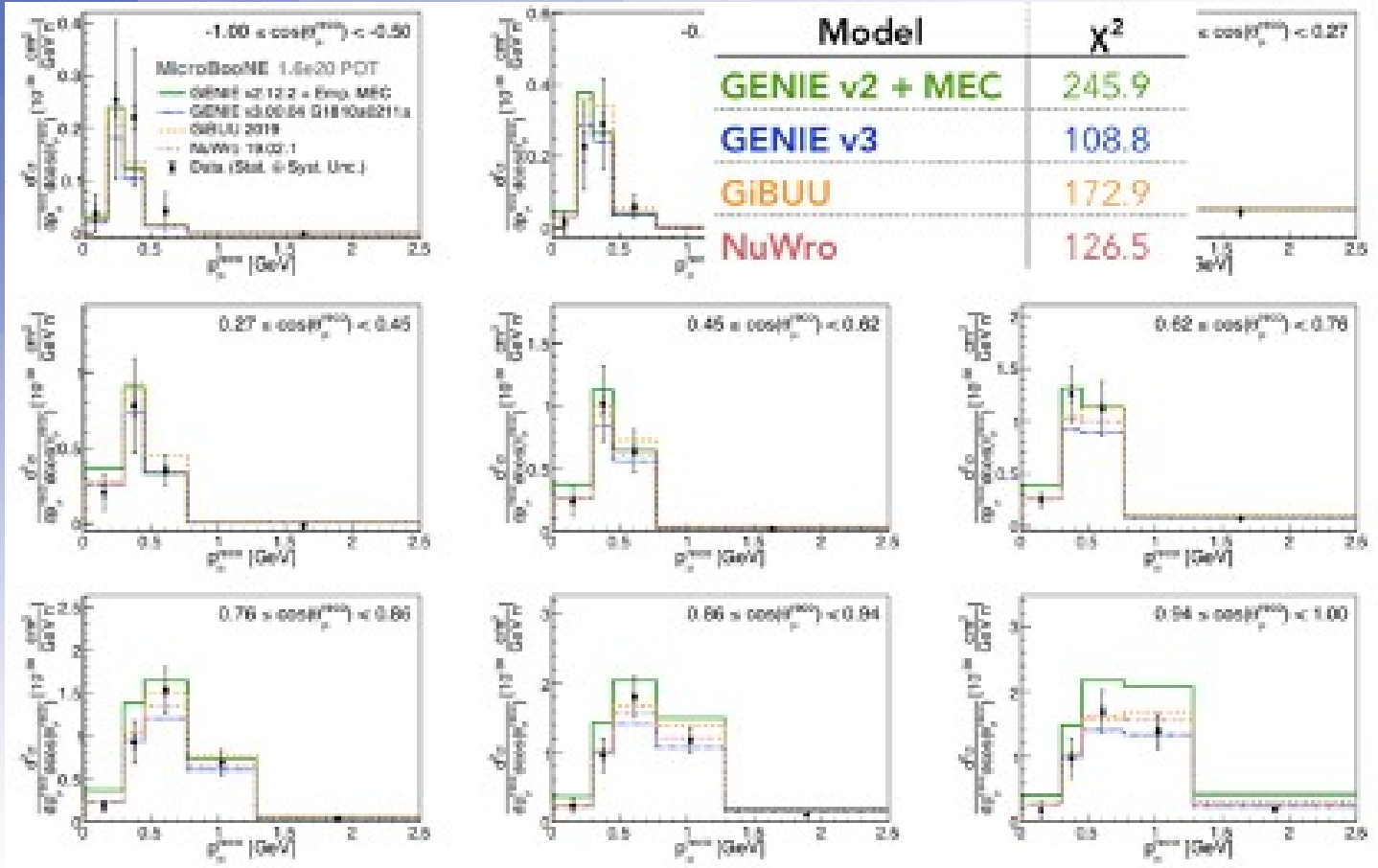
MicroBooNE Blind Analysis

- BNB ν_e data only accessed after:
  - analyses were developed on simulated samples and
  - validated on sideband data samples + a small open subset of data in Runs 1 & 3.
- After the analyses were frozen and before unblinding, LEE analyses defined “far” and “near” ν_e sidebands,
  - used to step progressively closer to LEE-signal-model-enhanced low-energy region.



Results presented today are unchanged since data unblinding.

Neutrino Interaction Modelling



Model	χ^2
GENIE v2 + MEC	245.9
GENIE v3	108.8
GiBUU	172.9
NuWro	126.5

- MicroBooNE drove the development of v3 GENIE; 2 yr effort:
- MicroBooNE GENIE tune
  - includes new nuclear models, new fits to global data,
  - MicroBooNE public note #1074.
- We are the first to examine neutrino scattering in argon at these energies and with such high statistics.