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

WP3
MicroBooNE Results

MidTerm Review Meeting, Nov 28, 2022

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UNIVERSITY OF CAMBRIDGE

European Commission

Intense
H2020 MSCA ITN
G.A. 858199

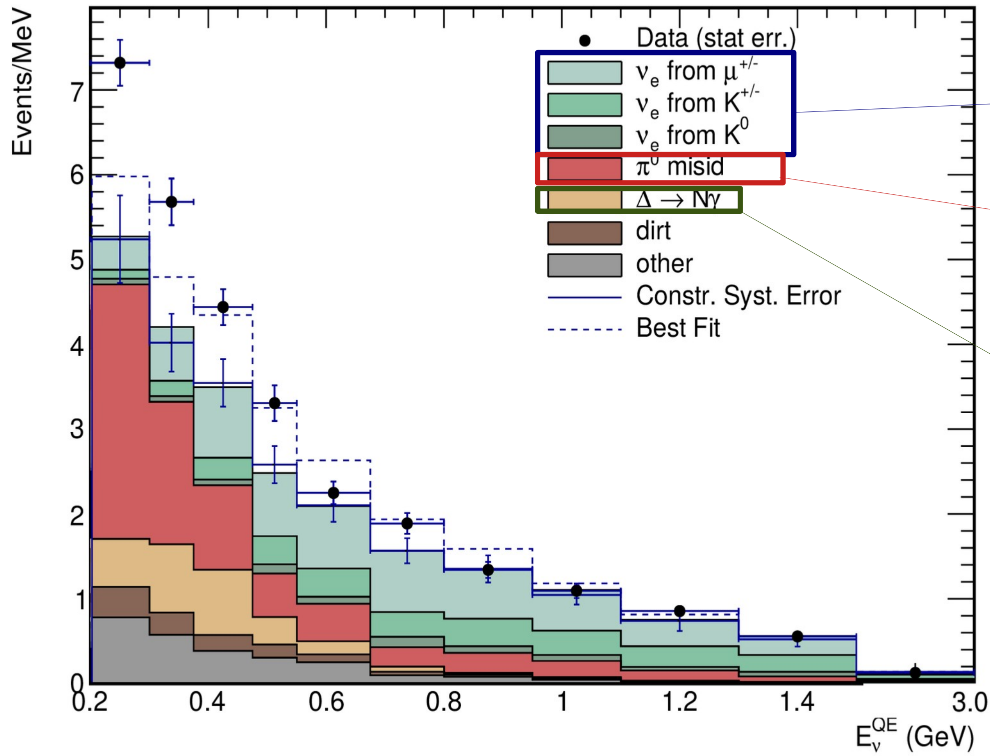
µBooNE

Outline

- Introduction.
- A tour of MicroBooNE.
- MicroBooNE γ results.
- MicroBooNE ν_e results.
- New results!!!
- The future of MicroBooNE.

The MiniBooNE Low Energy Excess

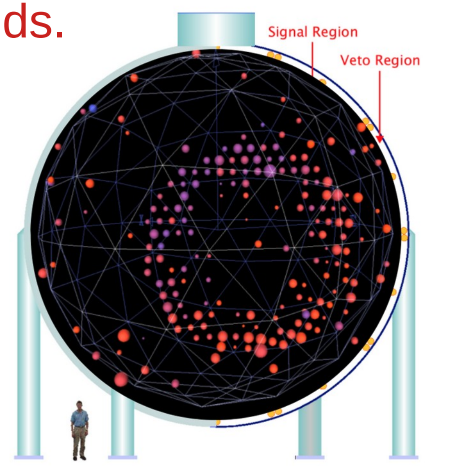
MiniBooNE Electron-like selection has a lot of photon backgrounds.



Flux?

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

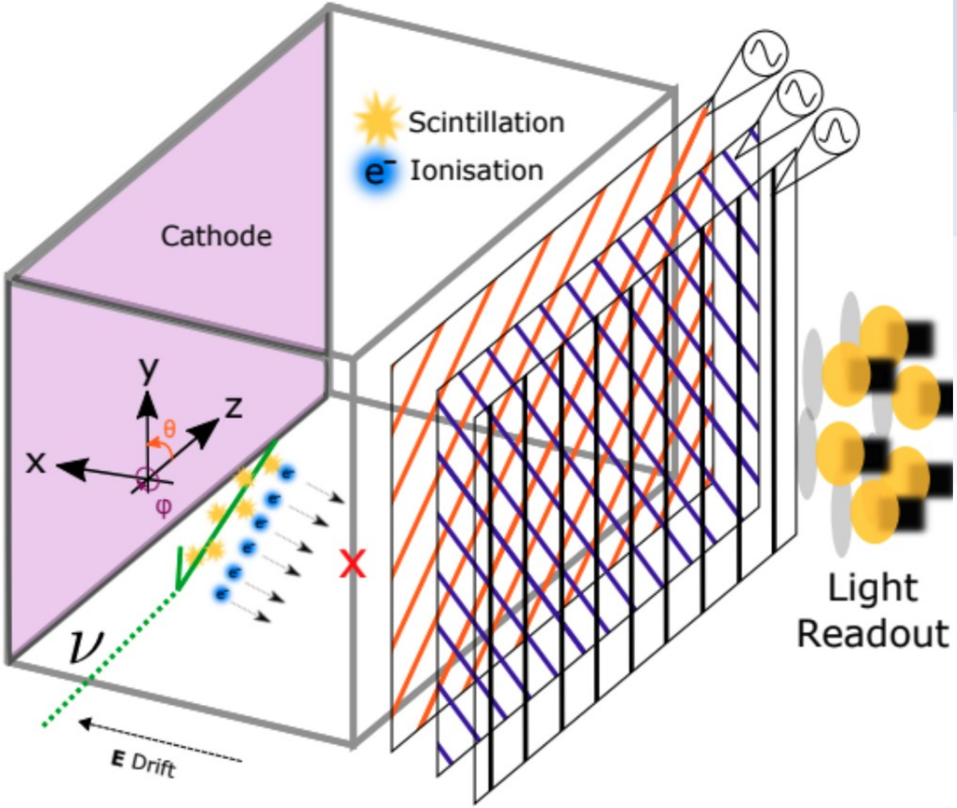
Mis-ID'd photon background?



Event display: MiniBooNE collaboration

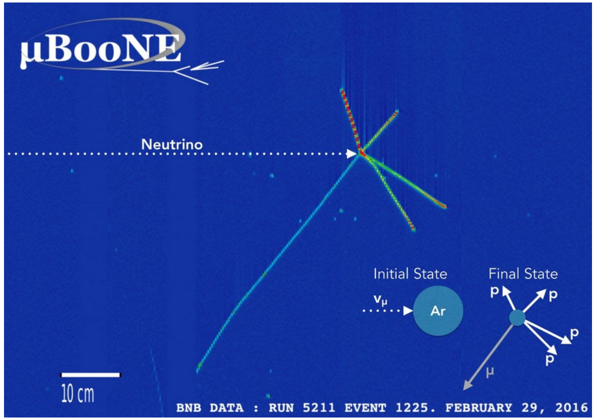
Or real electron neutrino appearance?

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



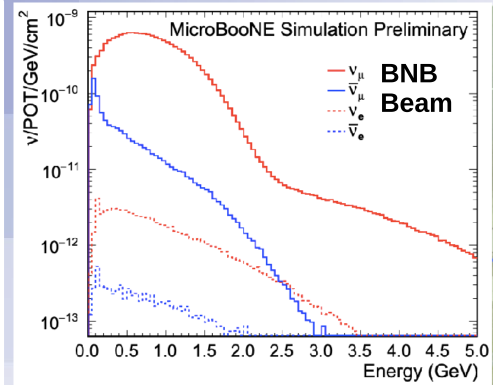
MicroBooNE

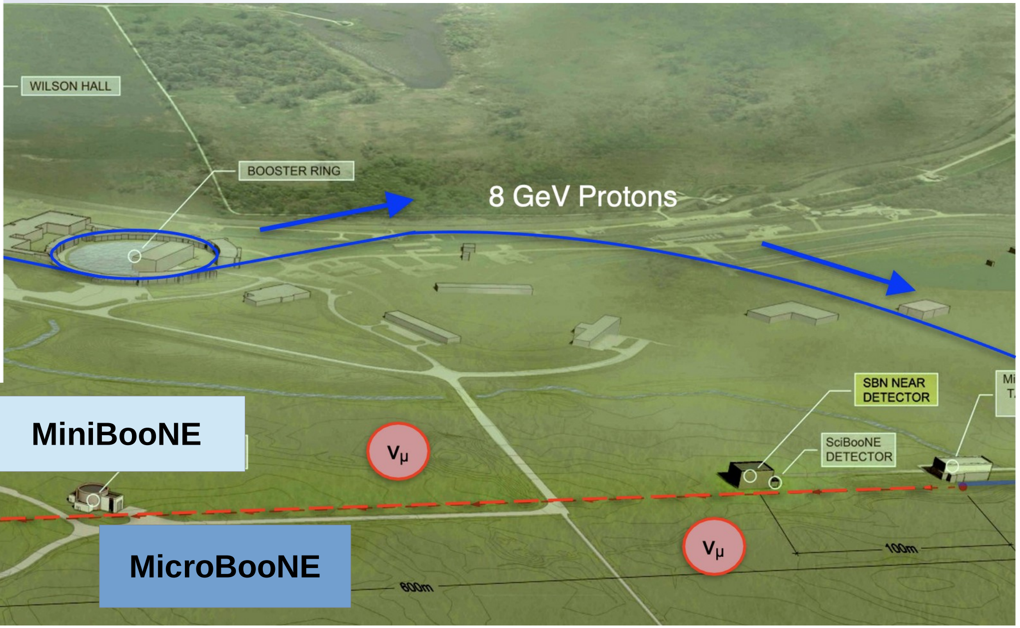
- Large-scale LArTPC:
  - 85 tonnes (active mass),
  - 8192 wires (3 mm pitch) on 3 planes,
  - 32 8” Cryogenic PMTs,
  - UV laser calibration, Cosmic Ray Tagger.
- Crucial for scaling up to DUNE.
  - Cold electronics: 40:1 signal-to-noise ratio.
  - Gas piston purge: >18 ms electron lifetime.



Science goals:

- Resolve the nature of miniBooNE’s low-energy excess (LEE).
- Study GeV-scale ν-Ar interactions.
- LArTPC hardware and software testbed and R&D.





- 470m downstream from the BNB,
- 2 Beams: – BNB (on-axis, <E_{ν_μ}> 800 MeV) and
  – NuMI (off-axis, <E_{ν_e}> 650 MeV).
- Collected data from 2015 to 2020,

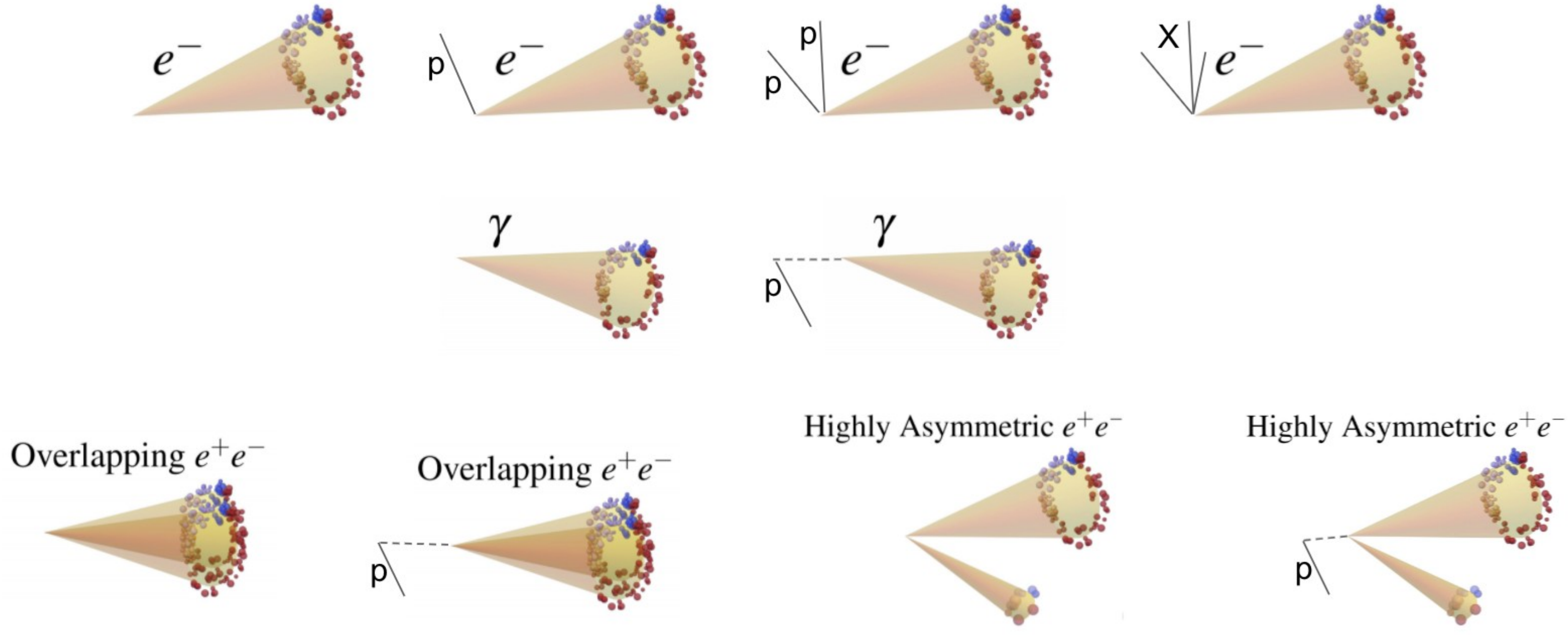
→ largest sample of ν interactions on Ar in the world.

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).

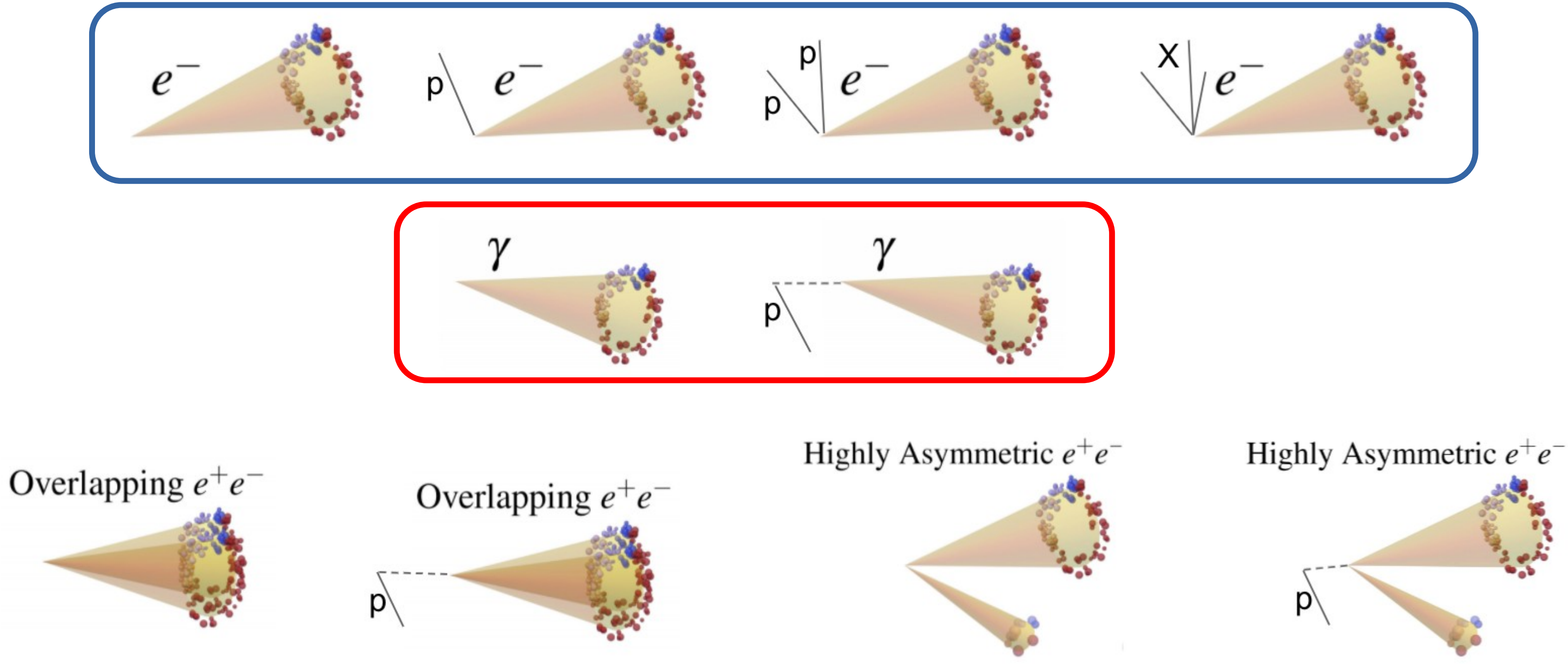
Remaining **agnostic to specific new-physics hypotheses.**

What is the LEE Particle Content?



Credit: Mark R-L

MicroBooNE's First LEE Exploration



Credit: Mark R-L

MicroBooNE LEE Exploration so far..

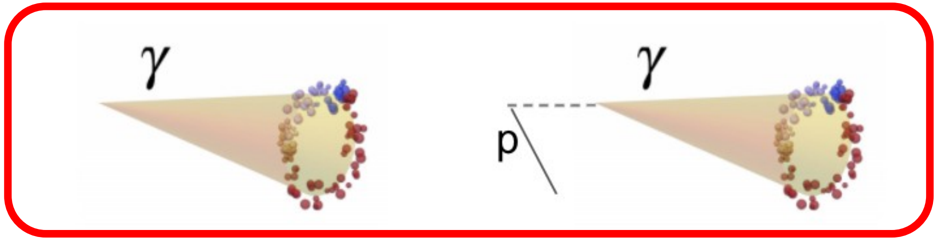
µBooNE

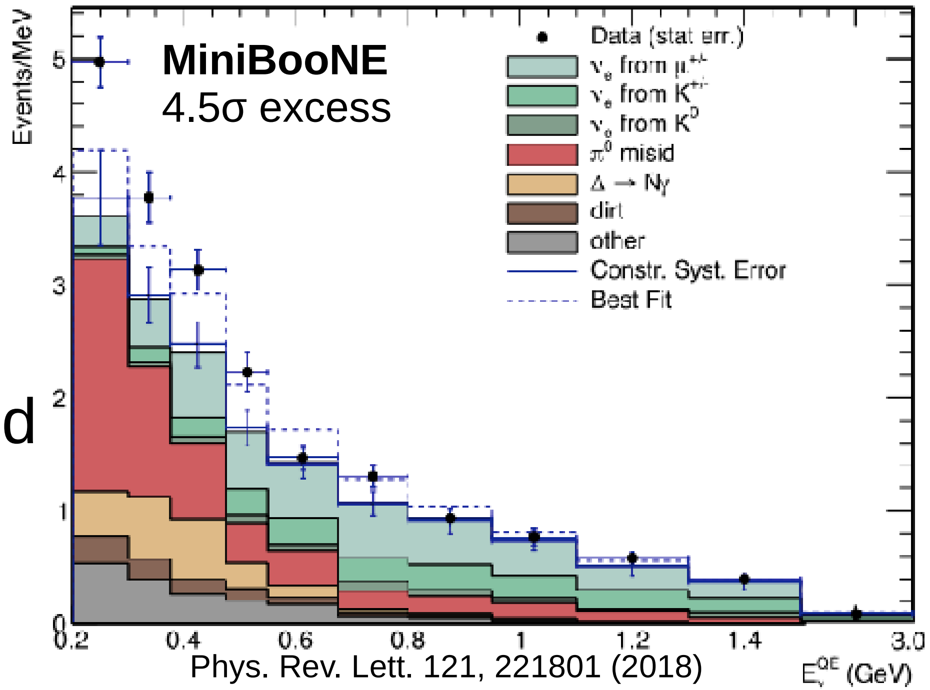
First series of results (1/2 the MicroBooNE data set)

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-Like Analysis

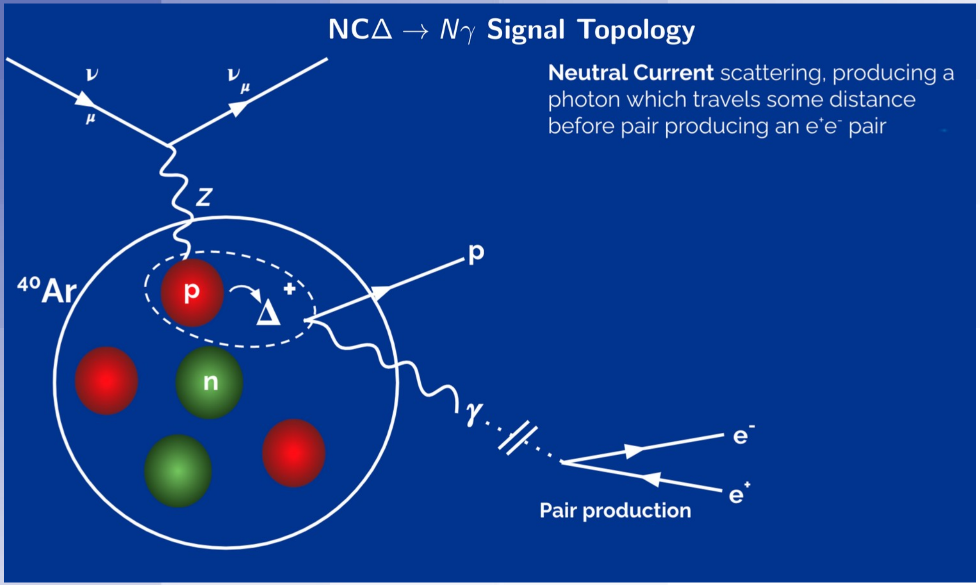


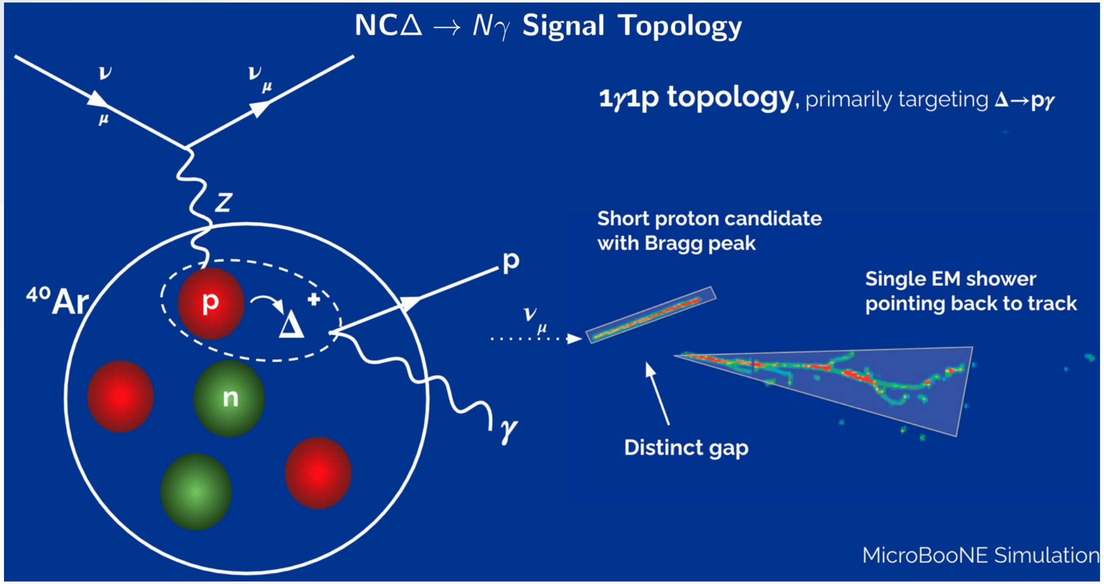


Phys. Rev. Lett. 121, 221801 (2018)

- NCΔ→Nγ is a significant background in the MiniBooNE analysis.
- This process has never been measured in neutrino scattering.
- Multiplying the generator prediction for this by **3.18** resolves the LEE – we can test this alternative model!

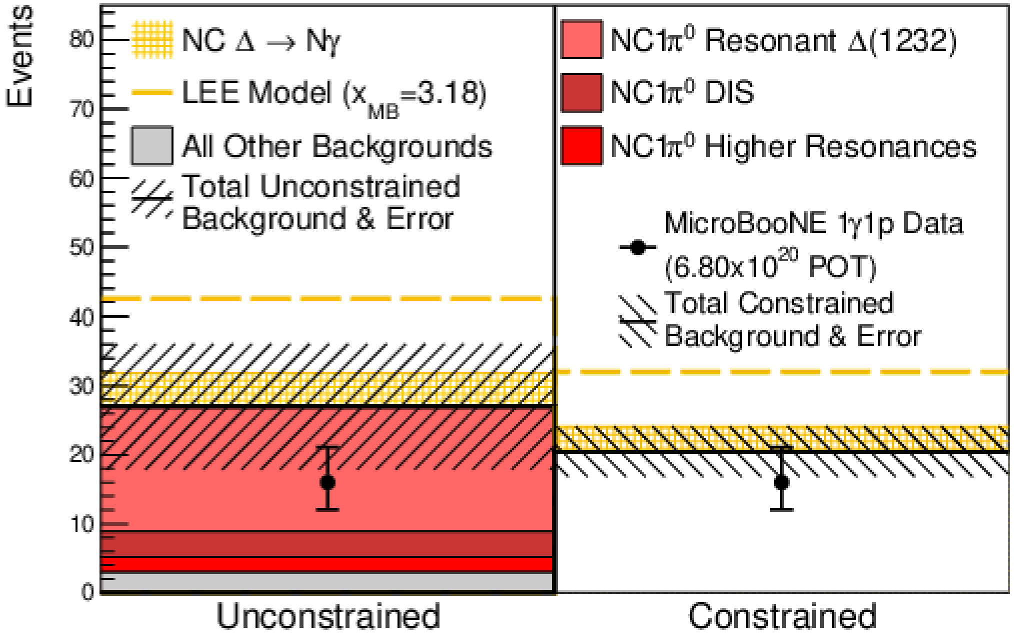
MicroBooNE's Photon Analysis

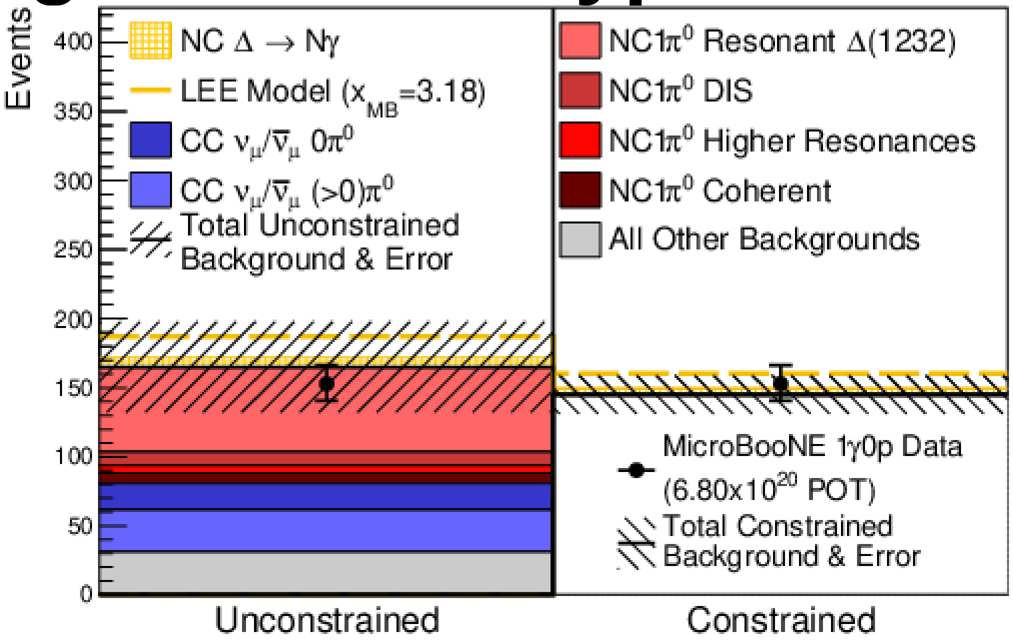




- Uses two two-photon selections to constrain NCπ^0 background.
- Signal samples are single photon.
- Physics modelled with GENIE v3.0.6 → Berger-Sehgal resonance model.

1st Test of the LEE: Single-Photon Hypothesis





	$1\gamma1p$
Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \to N\gamma$	4.88
LEE ($x_{MB} = 3.18$)	15.5
Data	16

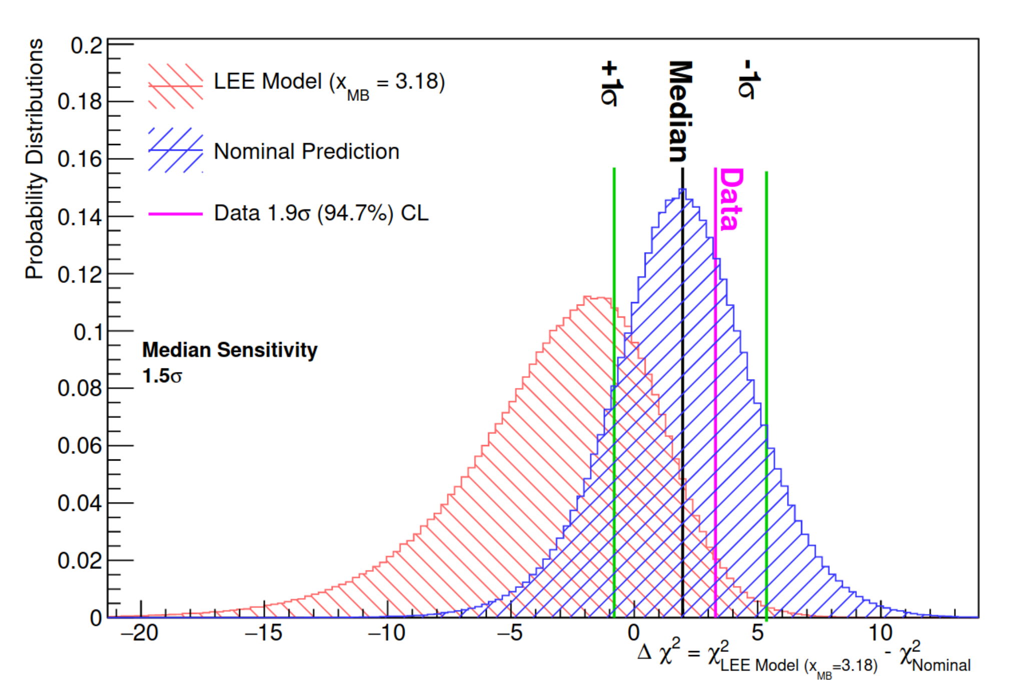
16 data events observed

	$1\gamma0p$
Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
NC $\Delta \to N\gamma$	6.55
LEE ($x_{MB} = 3.18$)	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...



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

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

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

	$1\gamma1p$	$1\gamma0p$
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
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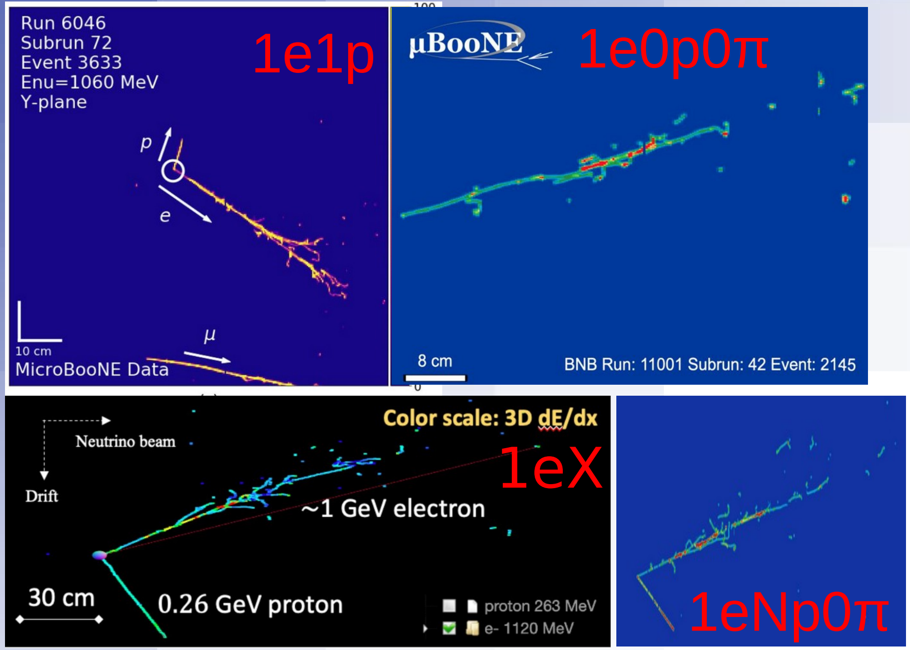
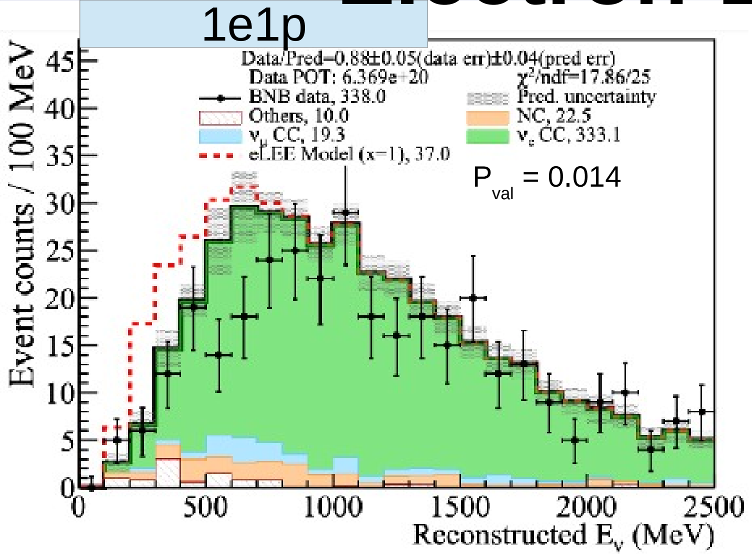
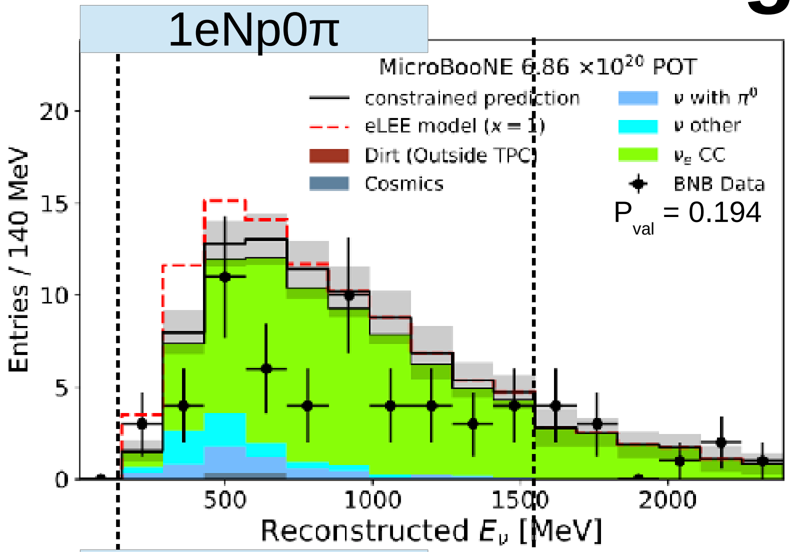
MicroBooNE's Electron-Like Analysis

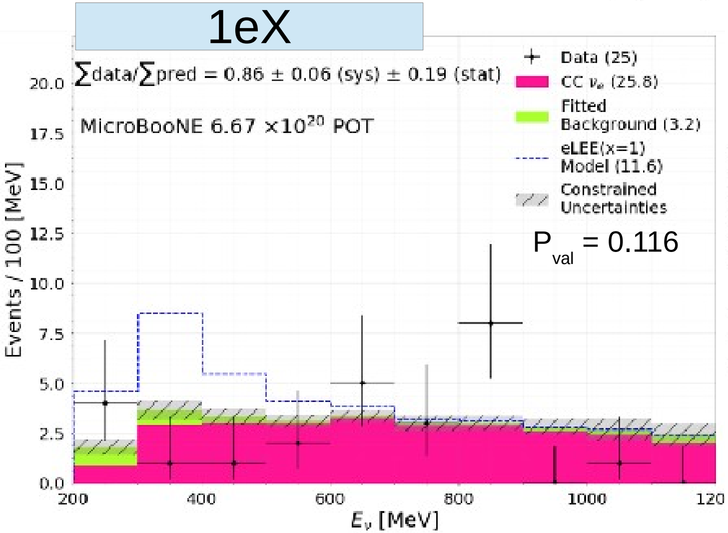


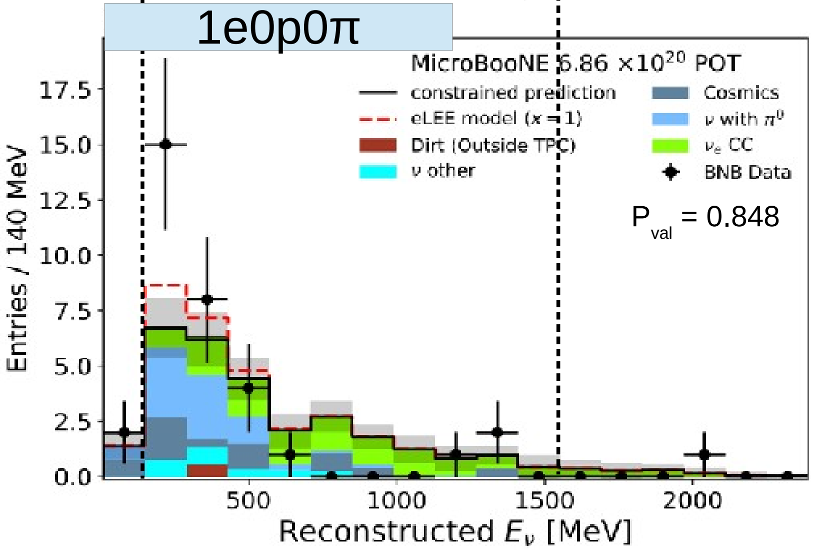
- 3 distinct e-like LEE search analyses:
  - CCQE 1e1p. — PRD arXiv:2110.14080
  - Pionless: 1eNp0π and 1e0p0π — PRD arXiv:2110.14065
  - 1eX. — PRD arXiv:2110.13978
- Start with high-statistics muon-like samples to make data-driven electron-like prediction.
  - Heavily reduces uncertainties on e-like 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!**

Electron-LEE Neutrino Energy









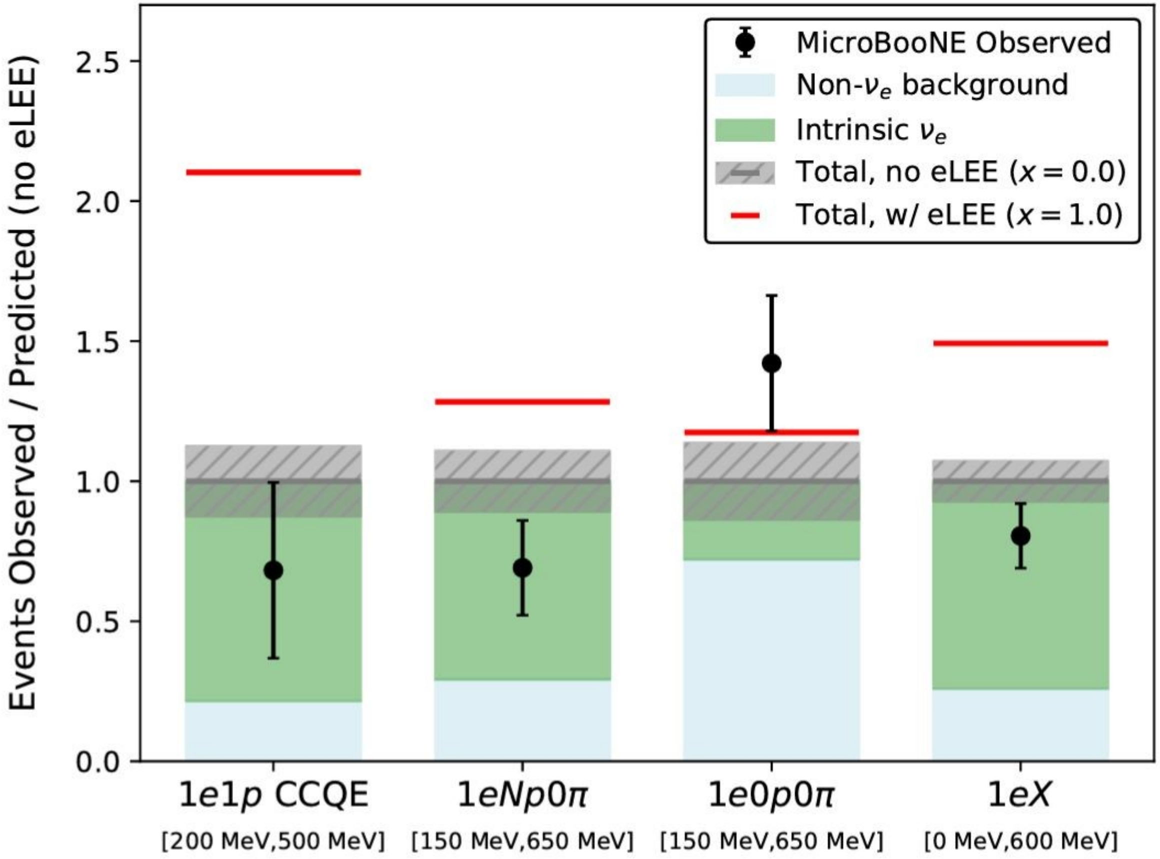
Some tension:

~ 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'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.

eLEE PRL

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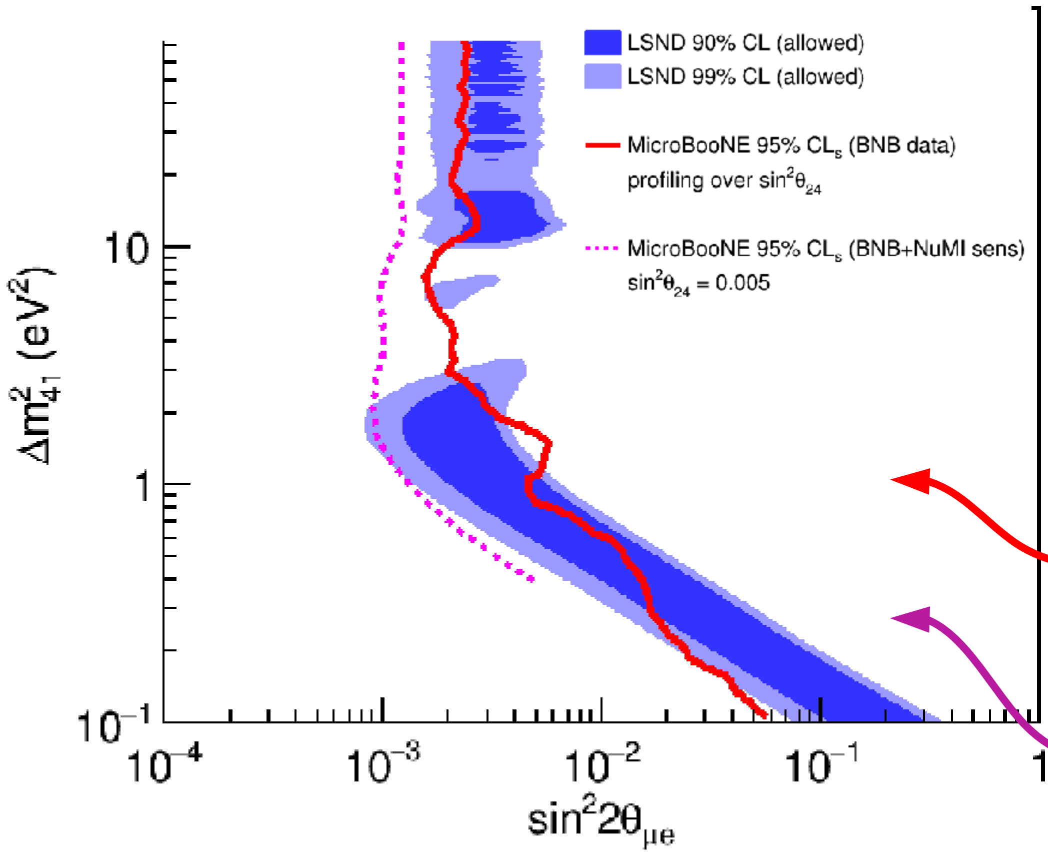
New Constraints on eV-Scale Sterile Neutrinos

MICROBOONE-NOTE-1116-PUB

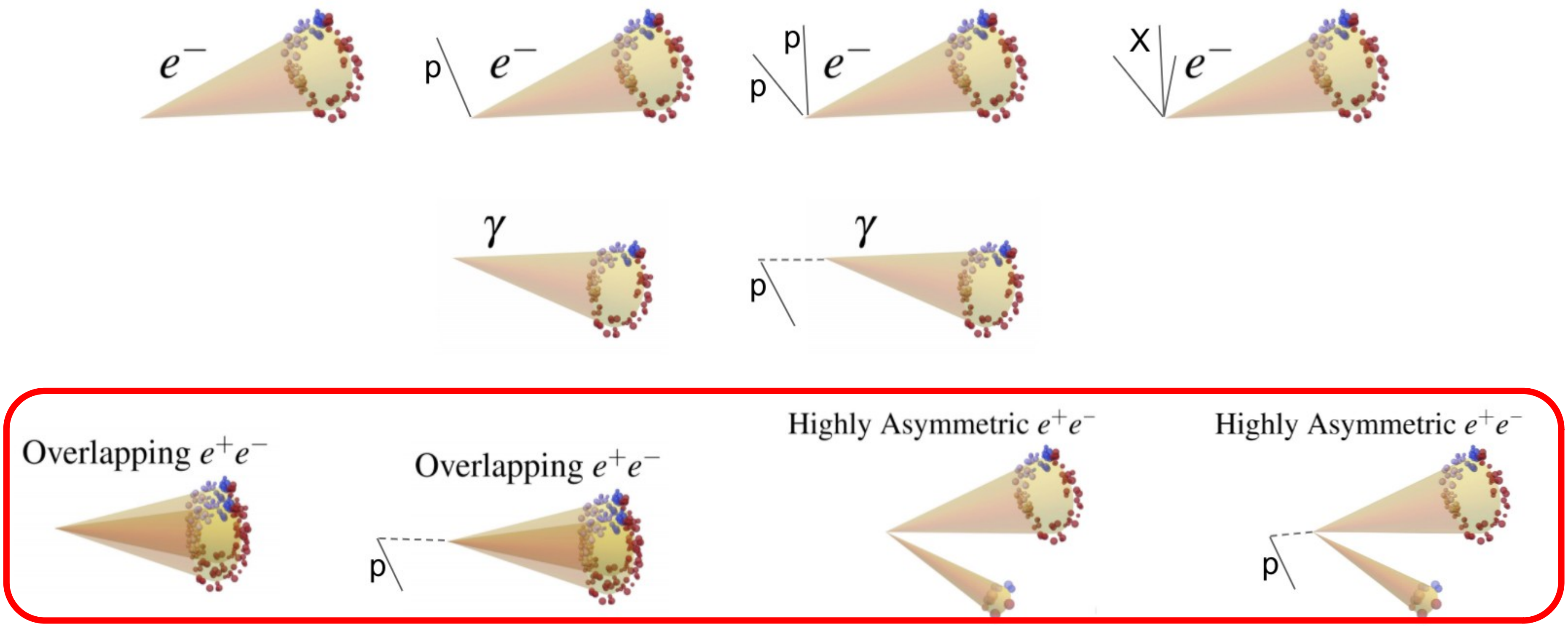


The **inclusive CC ν_e** results have subsequently been turned into a direct bound on eV scale sterile neutrinos.

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

MicroBooNE Next Steps



Credit: Mark R-L

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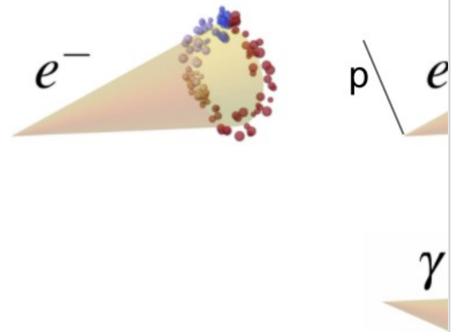
MicroBooNE Next Steps



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

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*Requires heavy sterile/other new particles also

Credit: Mark R-L

G.A. 858199

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

Accelerating Growth?

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
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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

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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...

Neutrinos: What We Know

Can be same flavour (disappearance), or different (appearance)

Just handles the units.

Controls frequency

$$P(\nu_x \rightarrow \nu_y) = \sin^2(2\theta)\sin^2(1.27\Delta m^2(\text{eV}^2)\frac{L(\text{km})}{E(\text{GeV})})$$

Controls the amplitude

- They have mass and "oscillate":
  - Produced in flavour states $\nu_{e\text{-}\mu}$, travel in mass states $\nu_{1\text{-}3}$.
  - Flavour changes as a function of energy and distance travelled.
- Described by 3 mixing angles, 2 mass splittings and 1 phase.

- Measured:

θ_{23}=45.6±2.3°

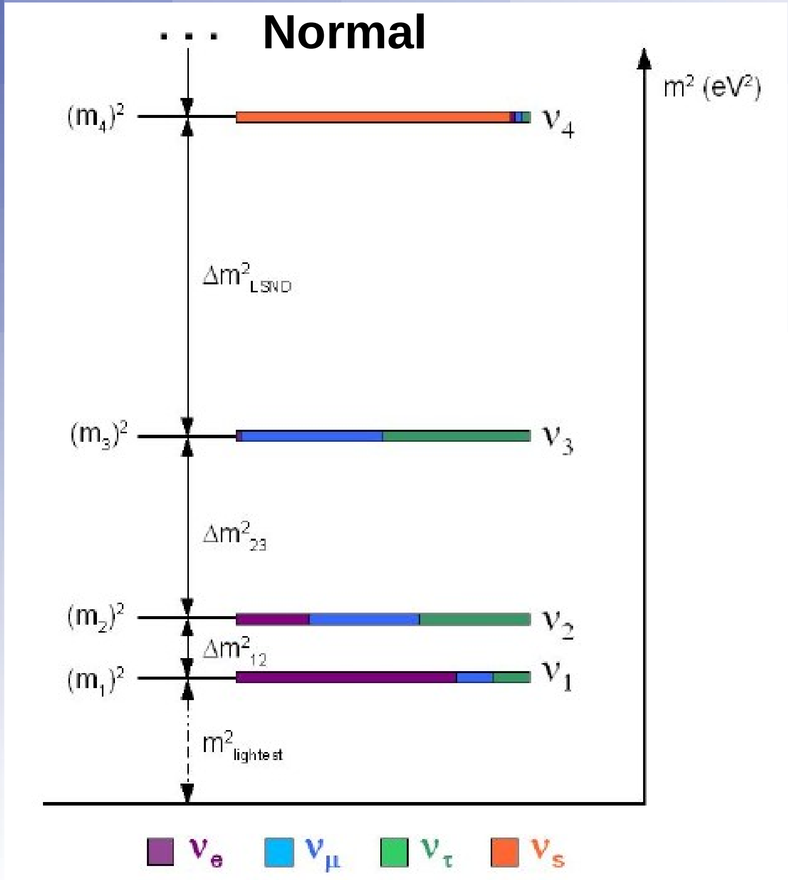
θ_{12}=33.6±0.85°

θ_{13}=8.33±0.22°

Δm^2_{21} = 7.53±0.18x10^{-5} eV^2

$|\Delta m^2_{32}|$ = 2.45±0.05x10^{-3} eV^2

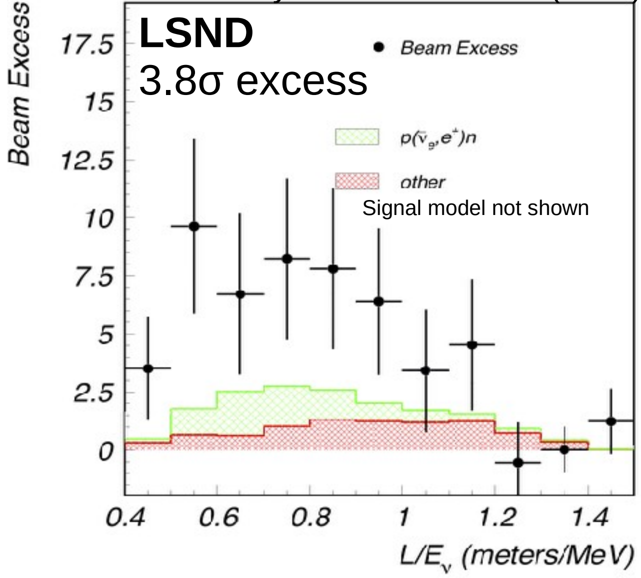
Neutrinos: What We Don't Know



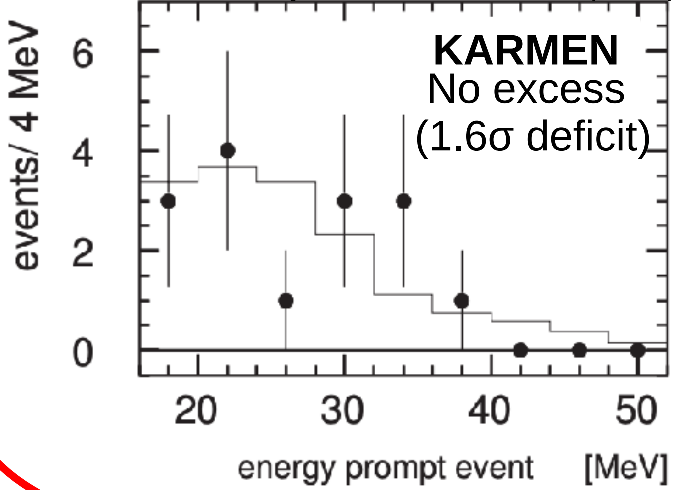
- Do neutrinos violate CP? $\delta^{CP} \neq 0$.
- Are neutrinos their own anti-particle?
- What is the absolute neutrino mass?
- How are neutrino masses ordered?
- What is the origin of neutrino mass?
- **Are there other neutrinos yet to be discovered?**

Short-Baseline Neutrino Experiment Anomalies

Phys.Rev.D64:112007(2001)



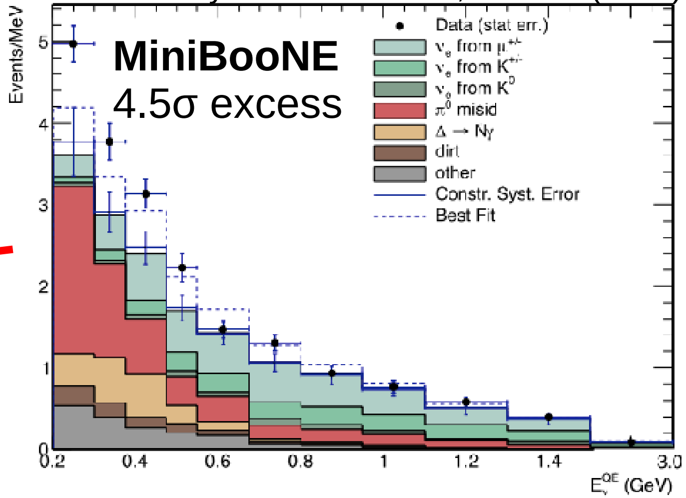
Phys.Rev. D65 112001 (2002)



π decay-at-rest

μ decay-at-rest

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



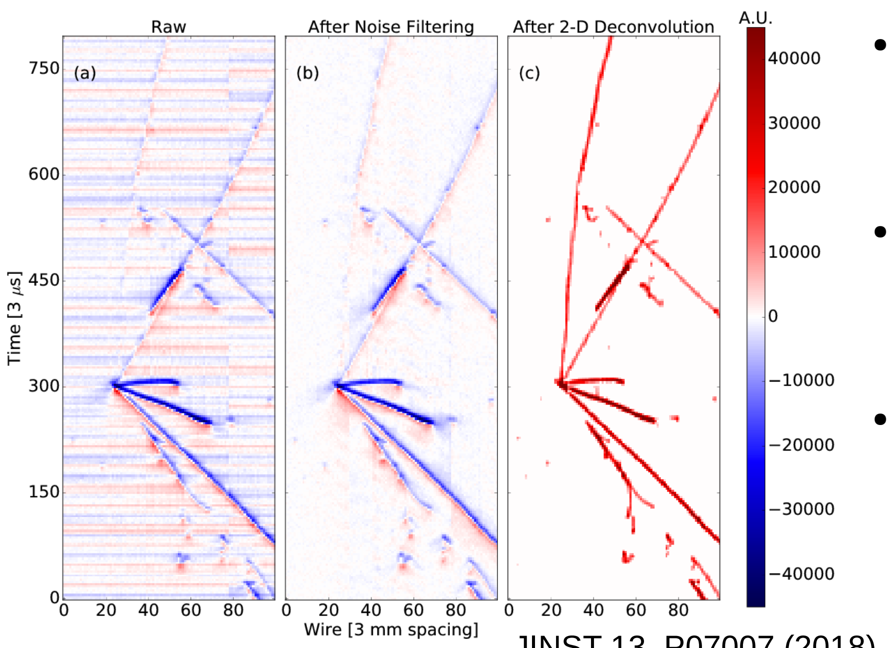
π decay-in-flight

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

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

Detector Performance

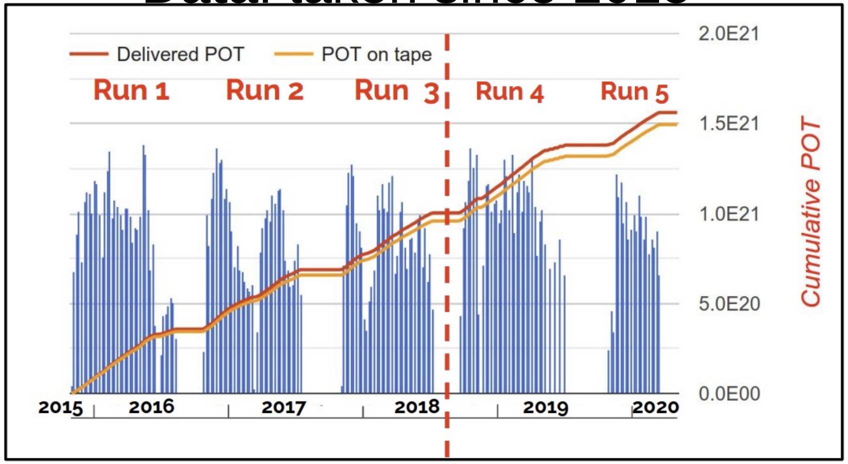
- Data-driven **electric field maps**:
  - UV laser: JINST 15, P07010 (2020),
  - cosmic muons: JINST 15, P12037 (2020).
- **Calorimetric and EM shower calibrations**:
  - JINST 15 P03022 (2020), JINST 15 P02007 (2020),
  - JINST 13 (2018) P07006.
- Longitudinal **diffusion** of ionization e- ’s: arXiv:2104.06551

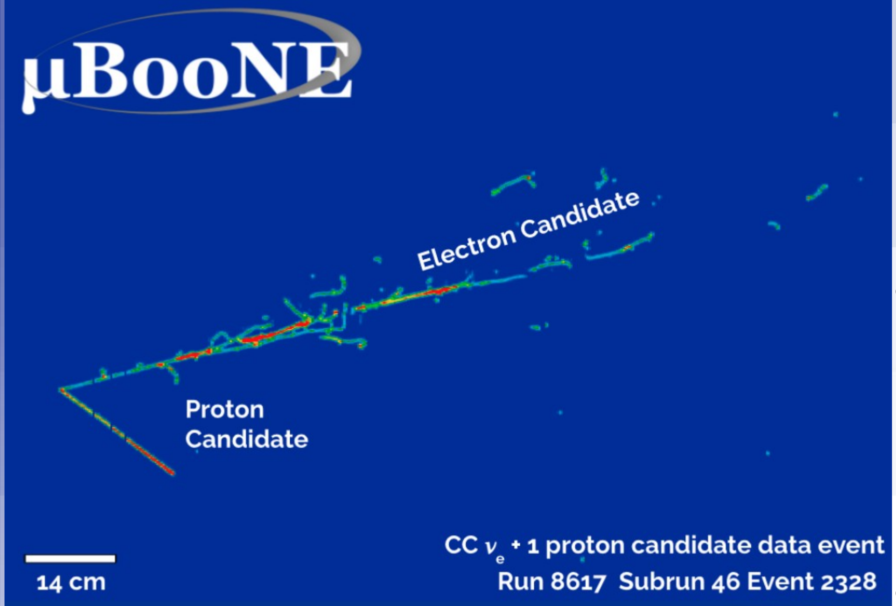


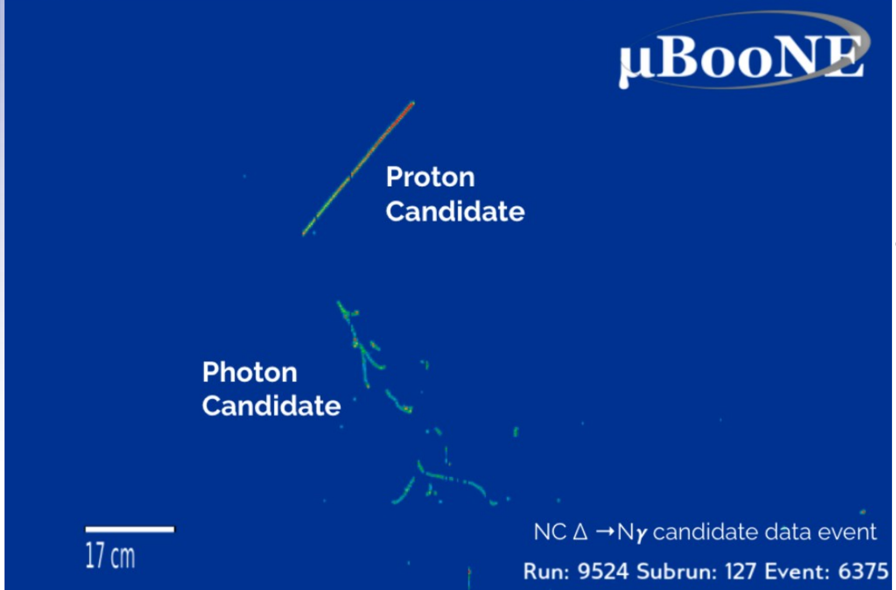
JINST 13, P07007 (2018)

Advanced signal processing: produces 2D de-convolved waveforms, which represent the number of drift electrons that arrive at each wire as a function of time.

Data: taken since 2015







Event Reconstruction

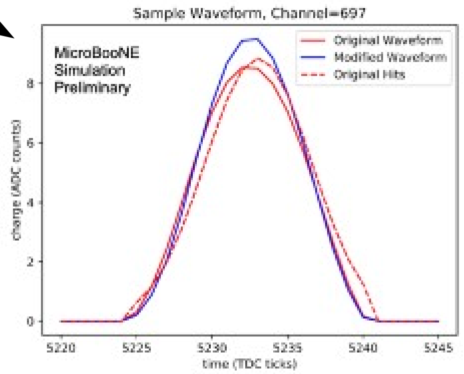
Co-developed 3 fully-automated and independent event reconstruction frameworks - excellent LArTPC resolution:

- **Pandora**
  - Multi Algorithm approach provides robust automated pat-rec.
  - Multiple neutrino cross section results (CC inclusive, CC π^0, CC Np, QE-like, ν_e), BSM searches (HNL, Higgs portal scalar).
  - Eur. Phys. JC78, 82 (2018).
- **Deep Learning (DL)**
  - First of their kind applications in a LAr TPC.
  - PRD 103, 052012 (2021), PRD 103, 092003 (2021),
  - JINST 16, P02017 (2021), PRD 99, 092001 (2019).
- **Wire-Cell**
  - fully 3D, next-generation charge-to-light matching, improved cosmic removal.
  - Phys.Rev.Applied 15 (2021) 6, 064071, JINST 16 (2021) 06, P06043, arXiv:2012.07928 (PRA).

See poster Jingyuan Shi: Comparison Studies

MicroBooNE Systematics

- **Detector uncertainties**
  - Novel data-driven technique using wire responses has significantly reduced our detector systematics.
  - EPJ C arXiv:2111.03556
- **Neutrino cross section uncertainties**
  - Apply best practices from other experiments
    - (MINERvA, NOvA, T2K) etc,
  - and the results from our own GENIE tuning.
  - Vary > 50 different parameters to assess ν interaction uncertainties.
  - PRD arXiV:2111.03556.
- **Neutrino flux uncertainties**
  - Make use of the very well-understood BNB from MiniBooNE.
  - MicroBooNE public note #1031.



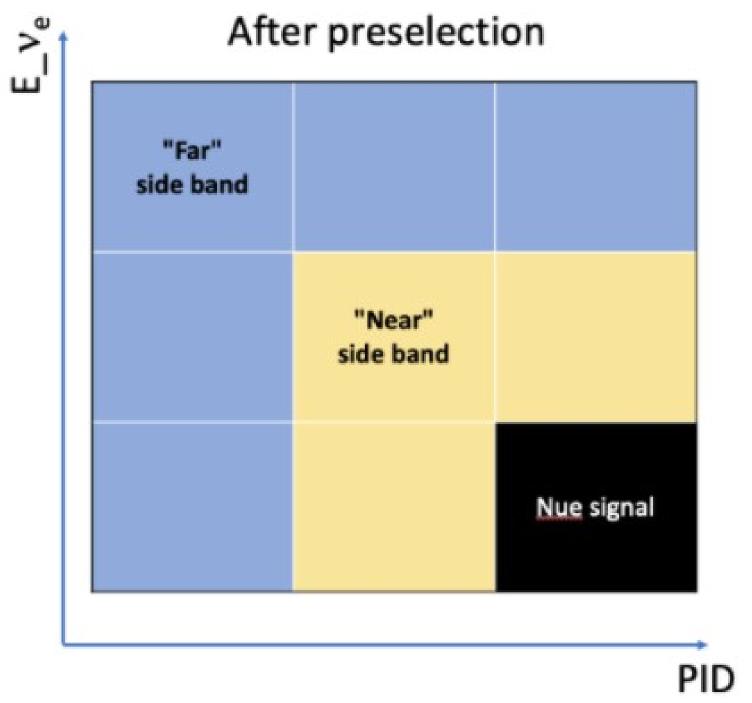
µB GENIE tune params

Variation Name
genie_all
AGKYpT1pi
AGKYxF1pi
AhtBY
BhtBY_UBGenie
CV1uBY
CV2uBY_UBGenie
CoulombCCQE
EtaNCEL
FrAbs_N_UBGenie
FrAbs_pi
FrCEx_N
FrCEx_pi
FrInel_N_UBGenie
FrInel_pi
FracDelta_CCMEC
FracPN_CCMEC
MFP_N
MFP_pi
MaCCQE
MaCCRES
MaNCEL
MaNCRES
MvCCRES
MvNCRES
NonRESBGvbarnCC1pi
NonRESBGvbarnCC2pi
NonRESBGvbarnNC1pi
NonRESBGvbarnNC2pi
NonRESBGvbarpCC1pi
NonRESBGvbarpCC2pi
NonRESBGvbarpNC1pi
NonRESBGvbarpNC2pi
NonRESBGvnCC1pi
NonRESBGvnCC2pi
NonRESBGvnNC1pi_UBGenie
NonRESBGvnNC2pi_UBGenie
NonRESBGvpCC1pi
NonRESBGvpCC2pi
NonRESBGvpNC1pi
NonRESBGvpNC2pi
Min/Max Variations
NormCCCOH
NormNCCOH
RPA_CCQE
Theta_Delta2Npi
VecFFCCQEshape
AxFFCCQEshape
DecayAngMEC

Parallel talk Alex Moor: ν_e/ν_μ Ratio Weds @11

MicroBooNE Blind Analysis

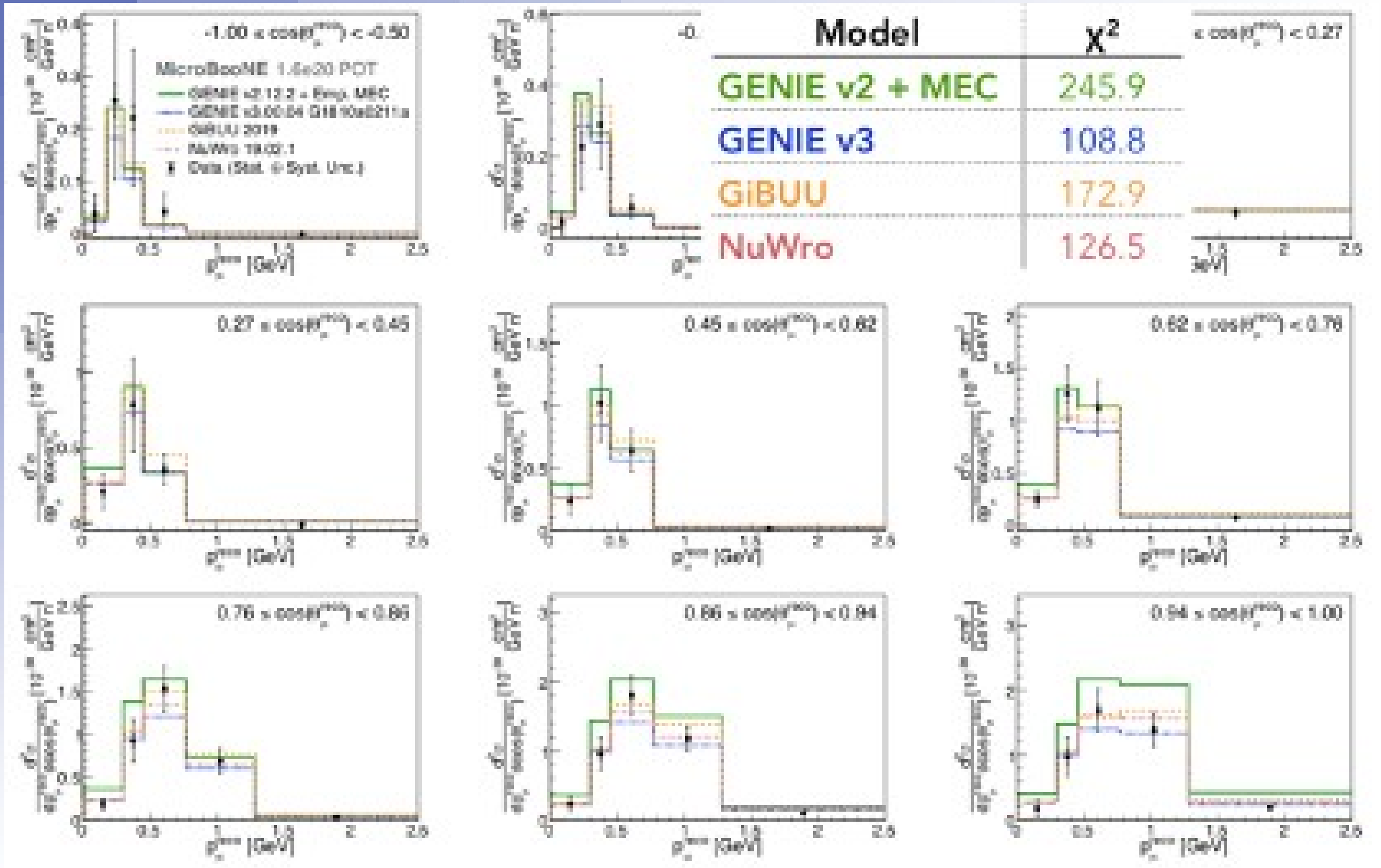
- BNB ν_e data only accessed after:
  - analyses were developed on simulated samples and
  - validated on sideband data samples + a small open subset of data in Runs 1 & 3.
- After the analyses were frozen and before unblinding, LEE analyses defined “far” and “near” ν_e sidebands,
  - used to step progressively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



Results presented today are unchanged since data unblinding.

Neutrino Interaction Modelling

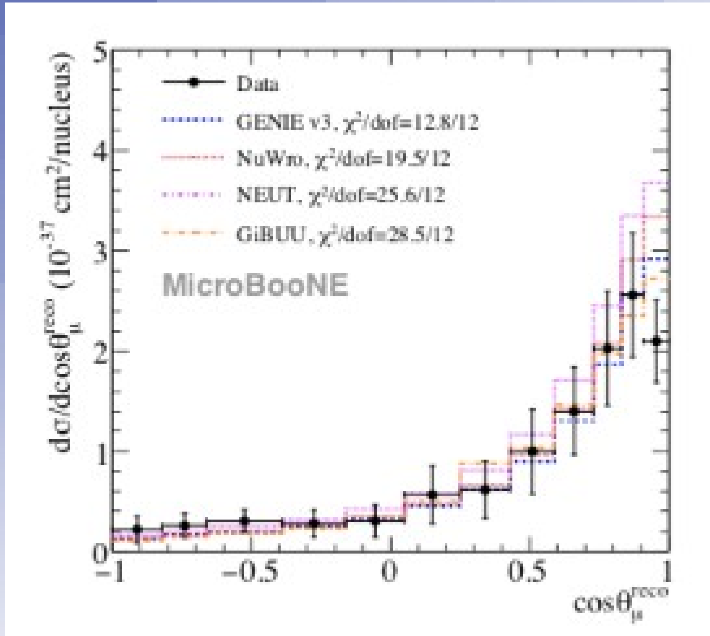
μBooNE



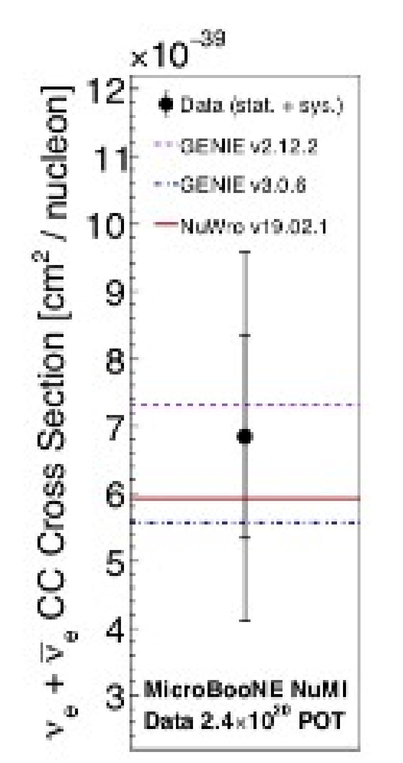
Model	χ^2
GENIE v2 + MEC	245.9
GENIE v3	108.8
GiBUU	172.9
NuWro	126.5

- 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.

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.: NC elastic, CC 2p, transverse kinematics, NC π^0, CC/NC π^0, CC π^+, CC coherent π^+, kaon and η production.

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

Accelerating Growth?

- 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
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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

- Search for long-lived heavy neutral leptons and Higgs portal scalars decaying in the MicroBooNE detector
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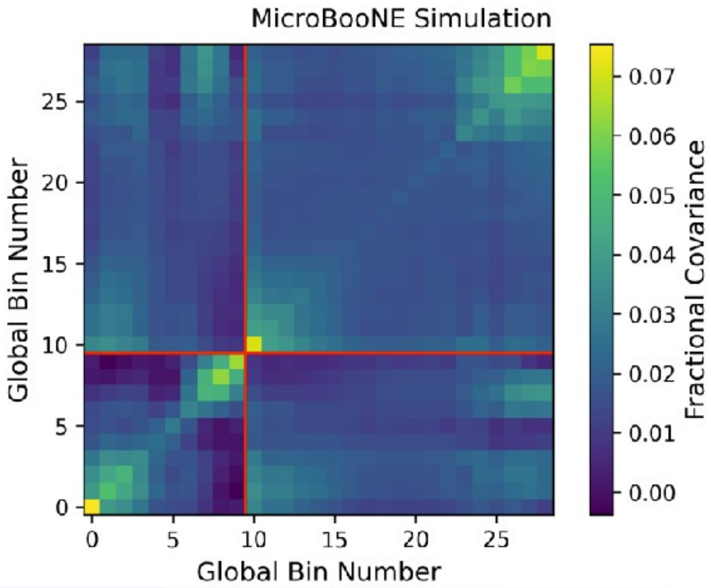

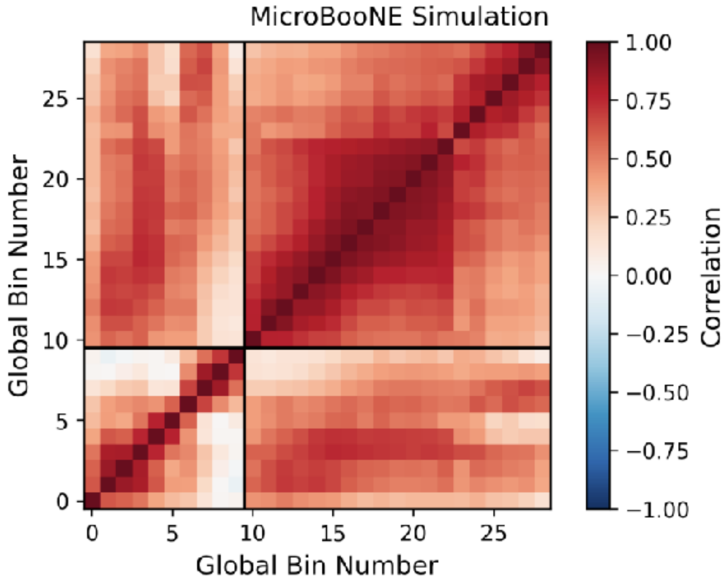

Covariance Matrix Formalism

- To test the compatibility between our prediction m and the measured data n, we construct a χ^2 test statistic using the covariance matrix formalism:

$$\chi^2 = \sum_{i,j=1}^{N} (n_i - m_i)\, C_{ij}^{-1}\, (n_j - m_j)$$

- We construct the full systematic covariance matrix as a sum of individual components, depending on the source of the systematic uncertainty:

$$C^{\mathrm{Syst}} = C^{\mathrm{Flux}} + C^{\mathrm{XSec}} + C^{\mathrm{Detector}} + C^{\mathrm{MCstat}}$$

- Systematic uncertainties are calculated by varying simulation parameters within their uncertainties N times individually (“unisim”) or simultaneously (“multisim”) either through reweighting events or by re-running the simulation and then computing bin shifts with respect to the central value simulation:

$$C_{ij} = \frac{1}{N} \sum_{k=1}^{N} \left(n_i^k - n_i^{\mathrm{CV}} \right) \left(n_j^k - n_j^{\mathrm{CV}} \right)$$

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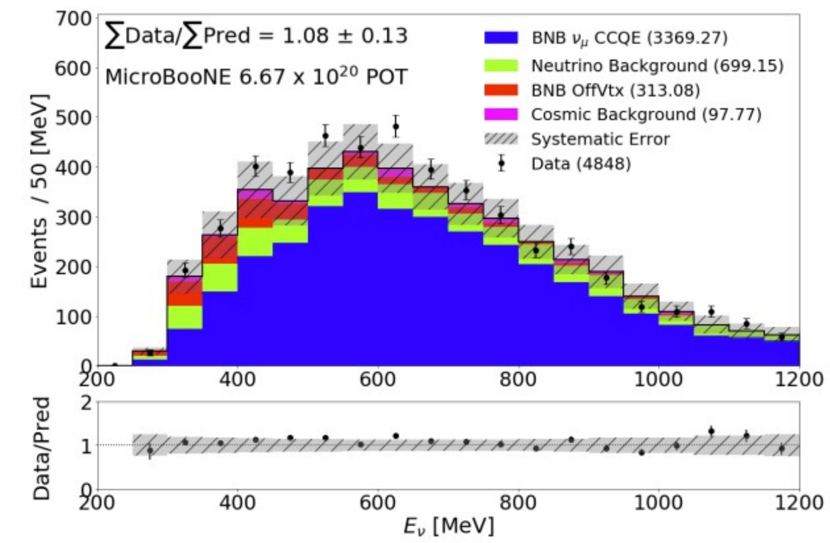
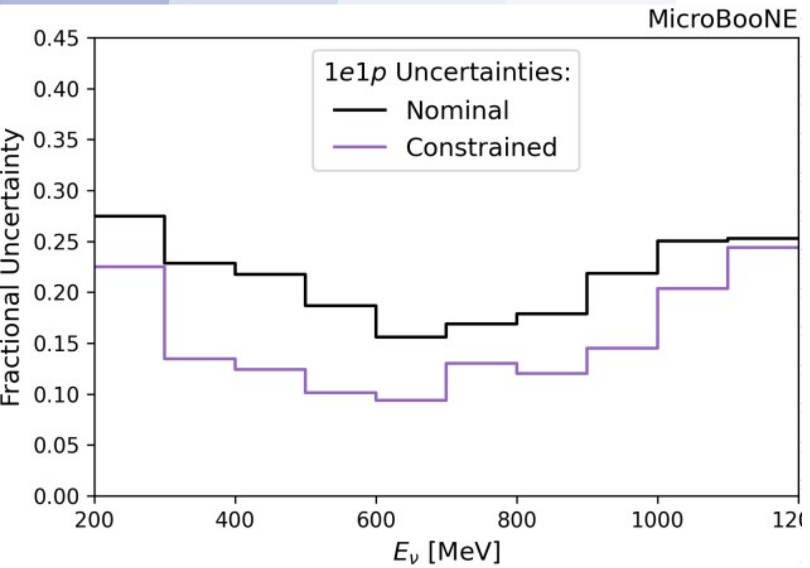
Conditional Constraint





- All analyses: leverage ν_μ and ν_e correlations:
  - Common flux parentage.
  - Lepton universality.
- ν_e samples + high-statistics ν_μ sidebands correlated → shared sources of modelling uncertainty → encoded in joint ν_μ-ν_e cov. matrix.
- Conditional constraint formalism used to update the central value ν_e prediction m^e and its uncertainties given the measured ν_μ data m^μ.

$$m^{e\ \mathrm{constrained}} = m^e + C^{e\mu}\left(C^{\mu\mu}\right)^{-1}\left(n^\mu - m^\mu\right)$$

$$C^{ee\ \mathrm{constrained}} = C^{ee} - C^{e\mu}\left(C^{\mu\mu}\right)^{-1}C^{\mu e}$$

- This reduces uncertainty in ν_e prediction by > factor of 2-3.

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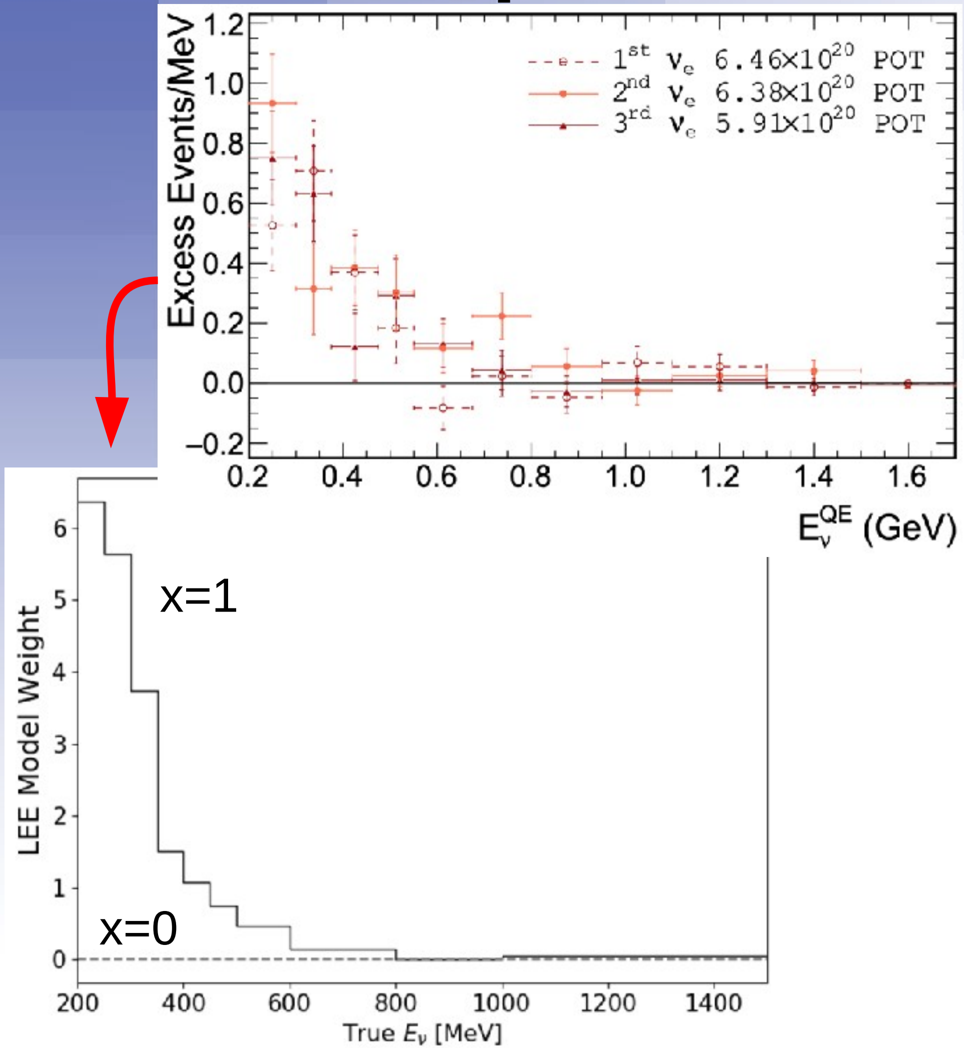
A Simple Model of the MiniBooNE LEE



To simulate the MiniBooNE LEE in MicroBooNE, we construct a simple model:

- Extract an energy-dependent event rate of ν_e interactions by iterative unfolding of the MiniBooNE event excess,
  - considering only statistical uncertainties on the MiniBooNE data and simulated events.
- Derive a scaling template from the increased event rate relative to the MiniBooNE prediction and then apply it to the simulated intrinsic ν_e events in MicroBooNE.
- Define a signal strength x that scales the normalization of this template, with x=1 corresponding to the median unfolded MiniBooNE LEE.

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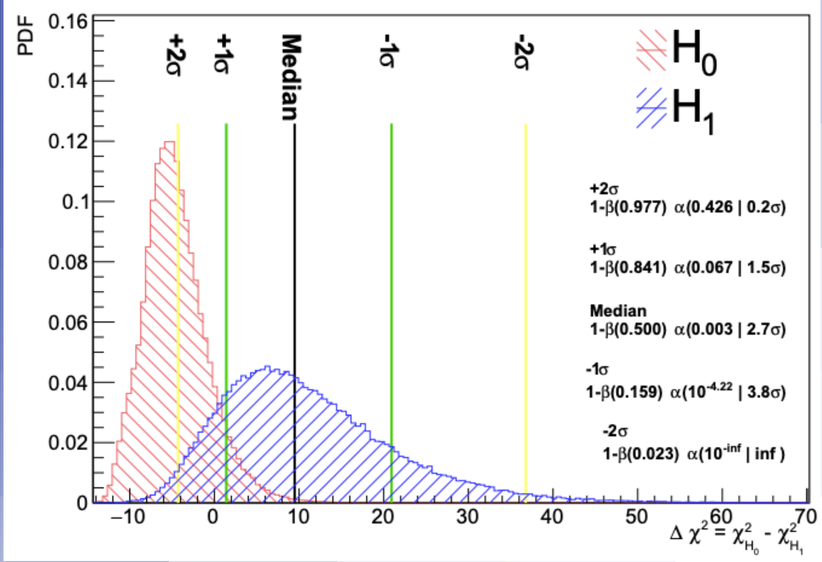
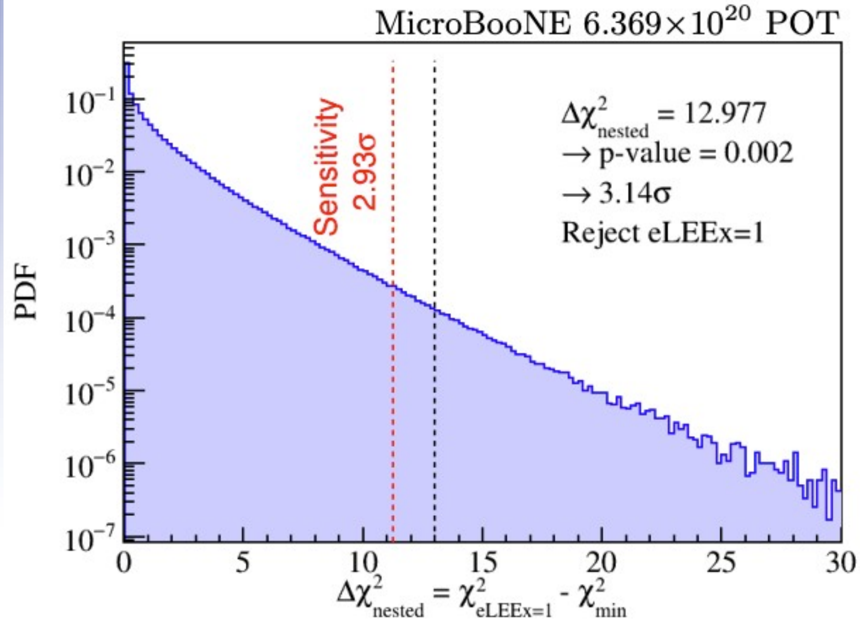




Statistical Tests

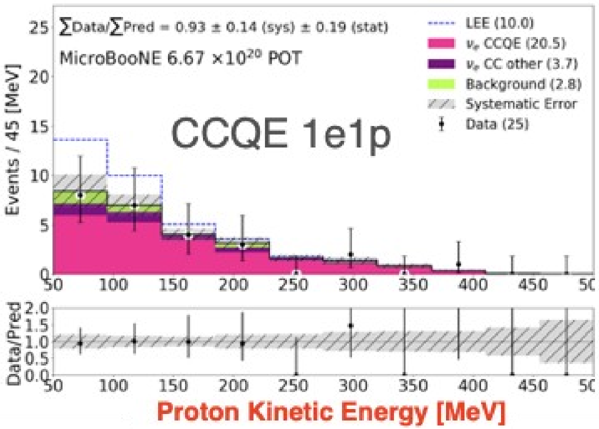
- Is data consistent with constrained expectation?
  - Addressed by χ2 goodness-of-fit test
- W.R.T simple model of the MiniBooNE LEE
  - Do we reject the constrained expectation in favour of our median unfolded MiniBooNE LEE model? Or vice versa?
    - 2-hypothesis log-likelihood ratio test:

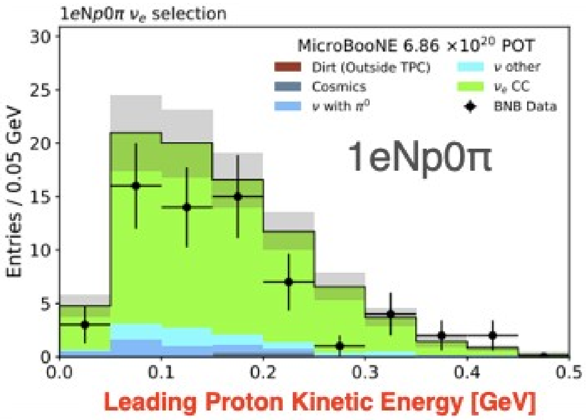
$$\Delta\chi^2_{\text{simple}} = \chi^2|_{\text{eLEEx=1}} - \chi^2|_{\text{eLEEx=0}}$$

  - If we adjust our constrained expectation upwards in a manner similar to the MiniBooNE LEE by scaling our simple model, is the agreement with the data better? What signal strength is preferred by the data?
- Addressed by nested log-likelihood ratio test:

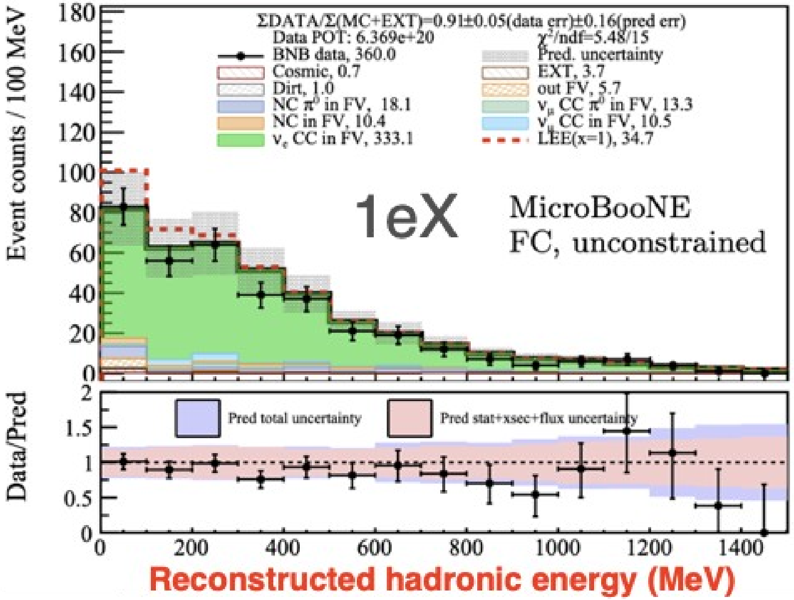
$$\Delta\chi^2_{\text{nested}} = \chi^2|_{\text{eLEEx=x'0}} - \chi^2_{\text{min}}|_{\text{eLEEx=x'min}}, \quad x_{\text{min}} \geq 0$$

Electron-LEE Hadronic Energy

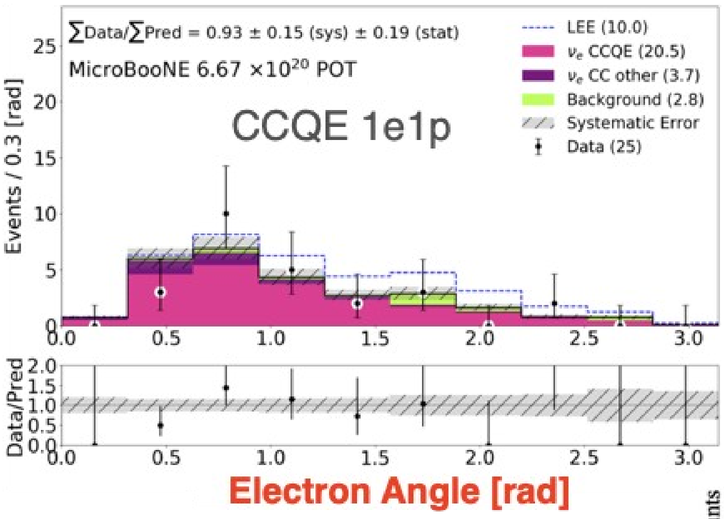


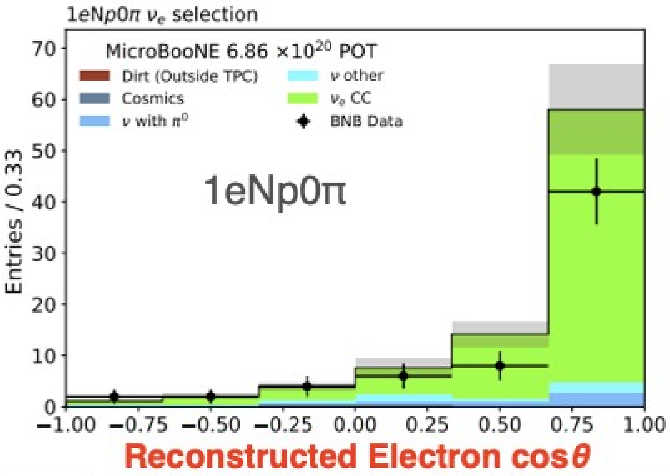


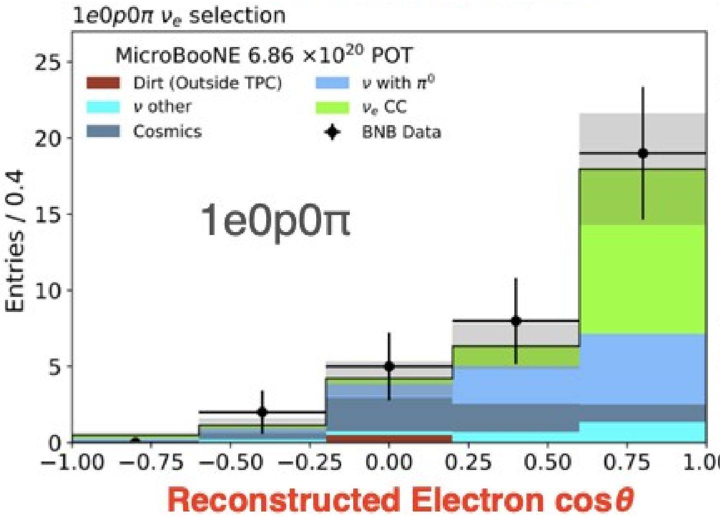
The powerful LArTPC allows us to measure interactions in terms of Hadronic variables – not possible at previous LEE experiments.

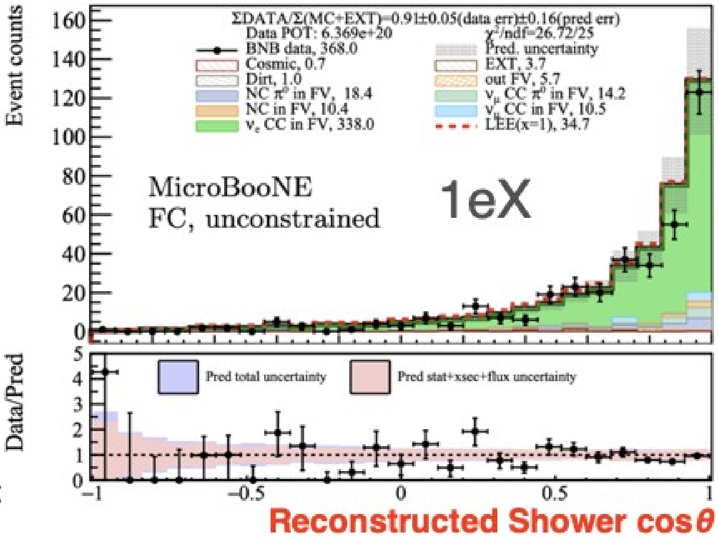


Electron-LEE Lepton Angle







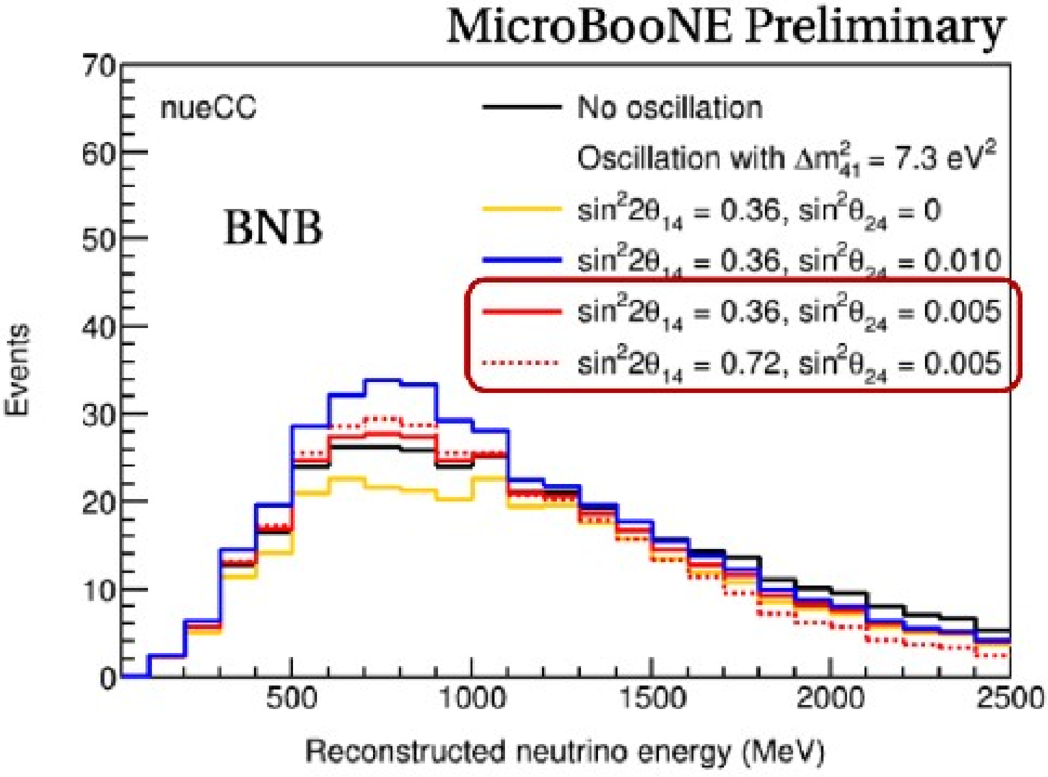


Both the leptonic and hadronic kinematics can be studied in the LArTPC.

1.7σ deficit in medium energy, forward direction.

Within expectation elsewhere.

Oscillation Parameter Degeneracy



ν_e disappearance ν_e appearance

$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} P_{\nu_e \to \nu_e} + N_{\text{intrinsic } \nu_\mu} P_{\nu_\mu \to \nu_e}$$

$$= N_{\text{intrinsic } \nu_e}[1 + (R_{\nu_\mu/\nu_e} \sin^2\theta_{24} - 1)\sin^2 2\theta_{14} \sin^2 \frac{\Delta m^2_{41} L}{4E}]$$

Cancellation if $\sin^2\theta_{24} = R_{\nu e/\nu\mu}$

(ratio of ν_e to ν_μ in beam)

→ about 0.005 in BNB

→ about 0.04 in NuMI

Short Baseline Neutrino Program

All LarTPC detectors → more interaction and detector uncertainties can be cancelled.

Powerful near-detector to drastically reduce systematic uncertainties on baseline-dependent physics.