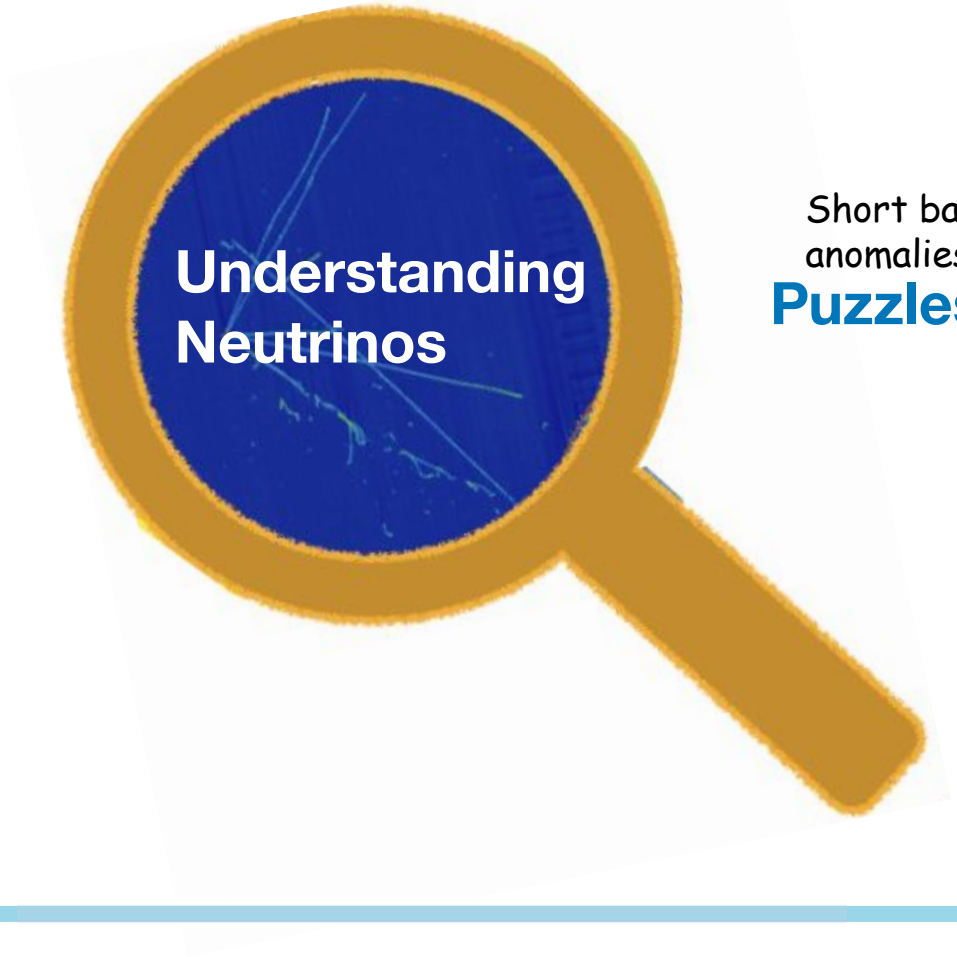
Sterile Neutrino Search at MicroBooNE using both the BNB and NuMI Beams

Puzzles | Physics | Path Forward

Meghna Bhattacharya on behalf of the MicroBooNE Collaboration

August 22nd, 2023

NuFact, Seoul, South Korea

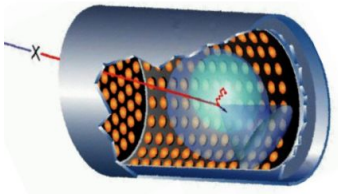


Short baseline
anomalies

Puzzles | Physics | Path Forward

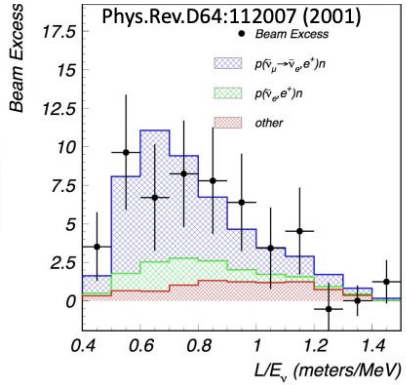
Fermilab

Anomalies in Neutrino Sector

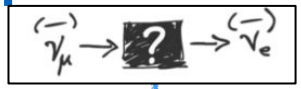


Liquid **S**cintillator
Neutrino **D**etector

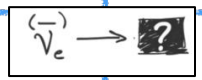
LSND



~3.8 σ excess

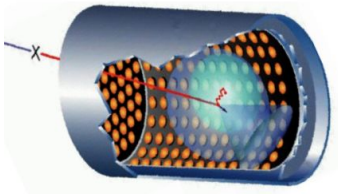


excess $\bar{\nu}_e$



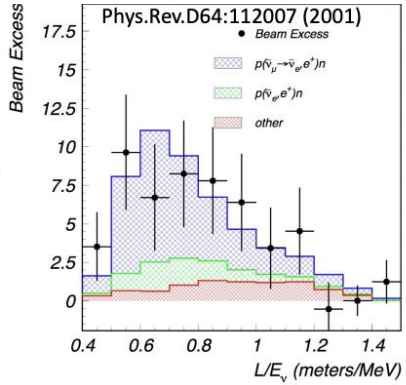
Fermilab

Anomalies in Neutrino Sector



Liquid Scintillator Neutrino Detector

LSND



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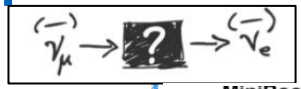
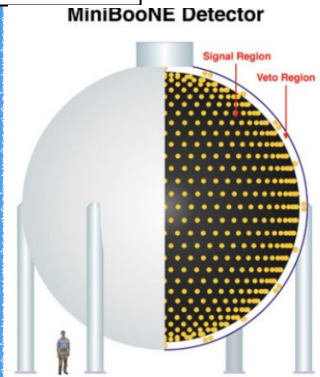
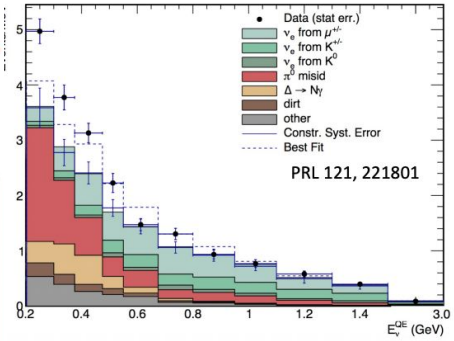


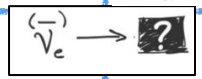
MiniBooNE





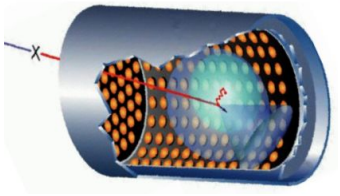
~4.8 σ excess

excess ν_e



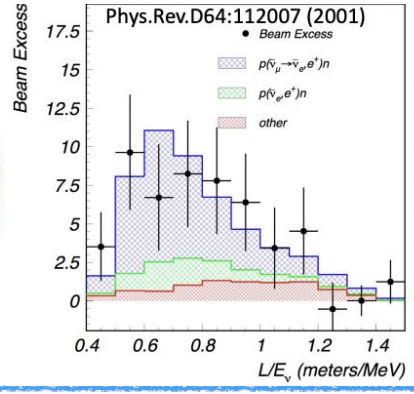
Fermilab

Anomalies in Neutrino Sector



Liquid Scintillator Neutrino Detector

LSND



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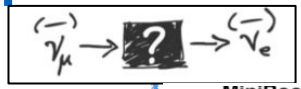
excess $\bar{\nu}_e$



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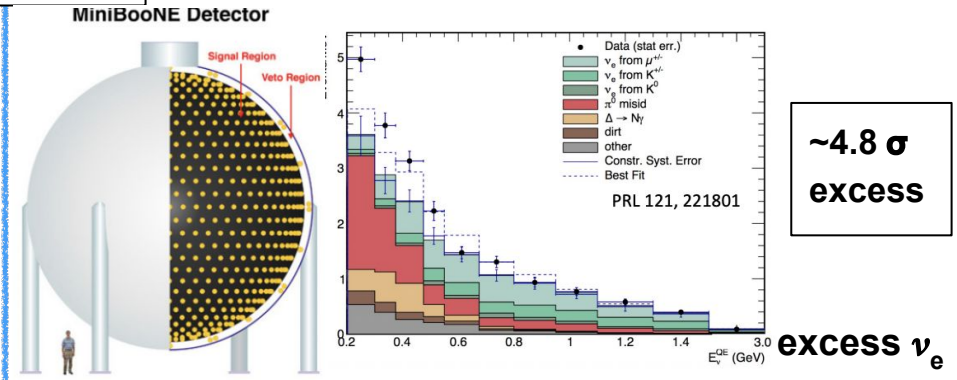
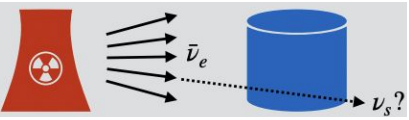
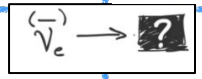


~4.8 σ excess

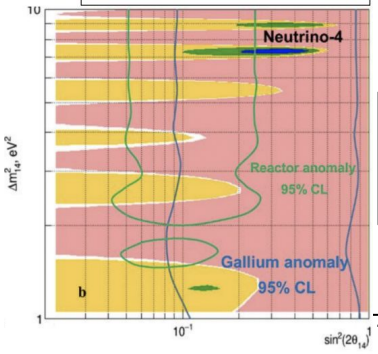
excess ν_e

Reactor Anomaly





PRD 104 (2021) 3, 032003

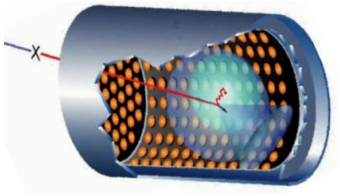


~3 σ deficit

$\bar{\nu}_e$ deficit

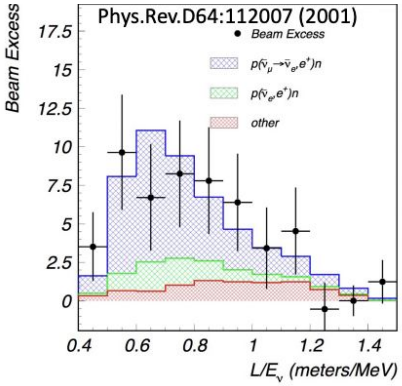
Fermilab

Anomalies in Neutrino Sector



Liquid Scintillator Neutrino Detector

LSND



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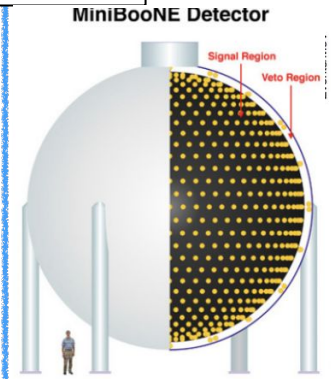
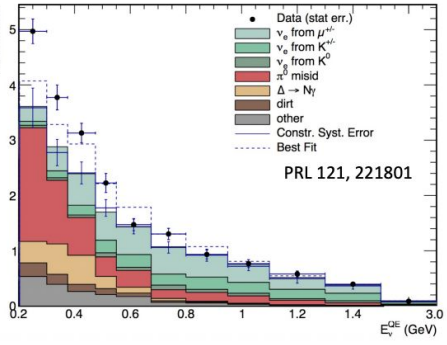
excess $\bar{\nu}_e$

MiniBooNE

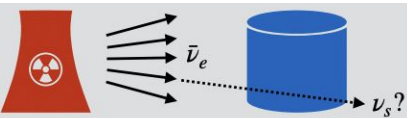


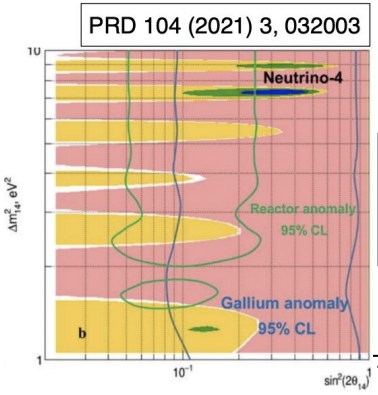


~4.8 σ excess

excess ν_e

Reactor Anomaly

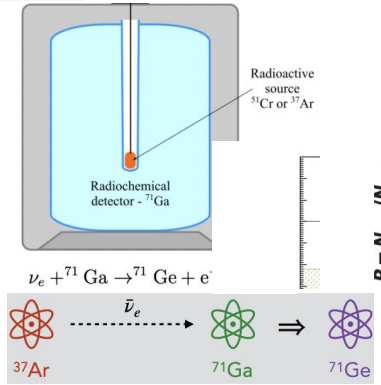


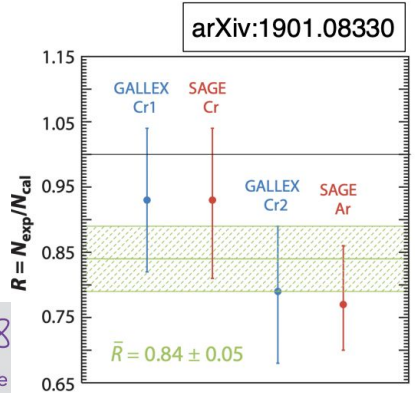


~3 σ deficit

$\bar{\nu}_e$ deficit

Gallium Anomaly



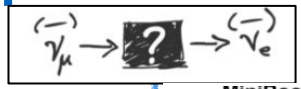


~3 σ deficit

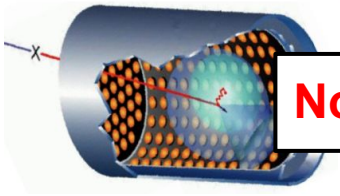
ν_e deficit

Fermilab

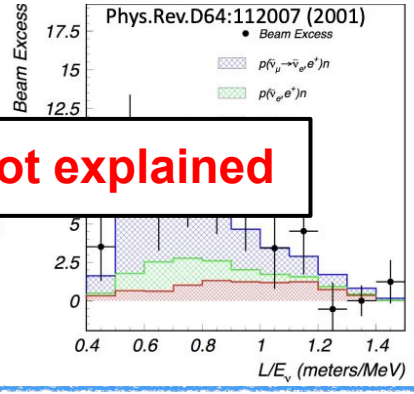
Anomalies in Neutrino Sector



LSND



Liquid Scintillator Neutrino Detector

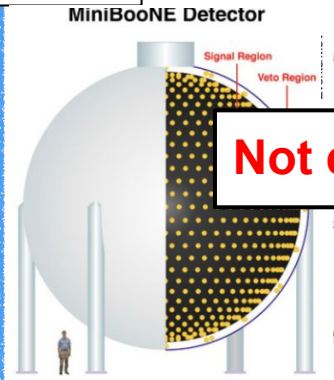


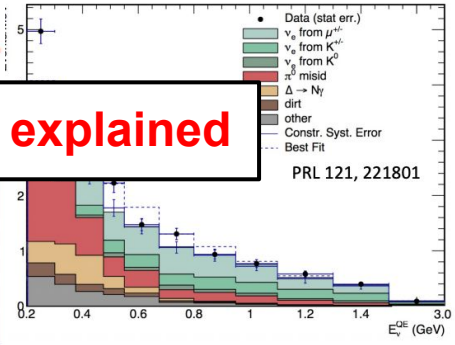
Not explained

~3.8 σ excess

excess $\bar{\nu}_e$

MiniBooNE





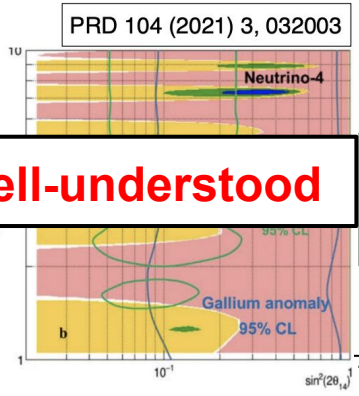
Not explained

~4.8 σ excess

excess ν_e

Reactor Anomaly

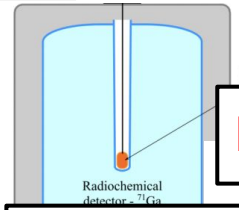
Relatively well-understood

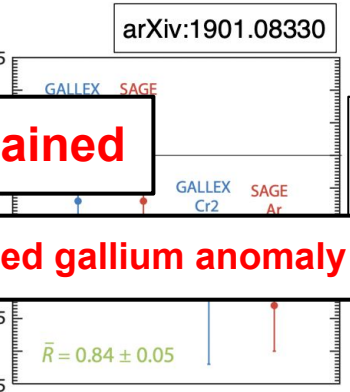


~3 σ deficit

$\bar{\nu}_e$ deficit

Gallium Anomaly

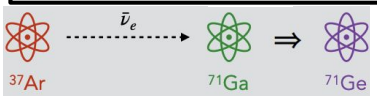




Not explained

~3 σ deficit

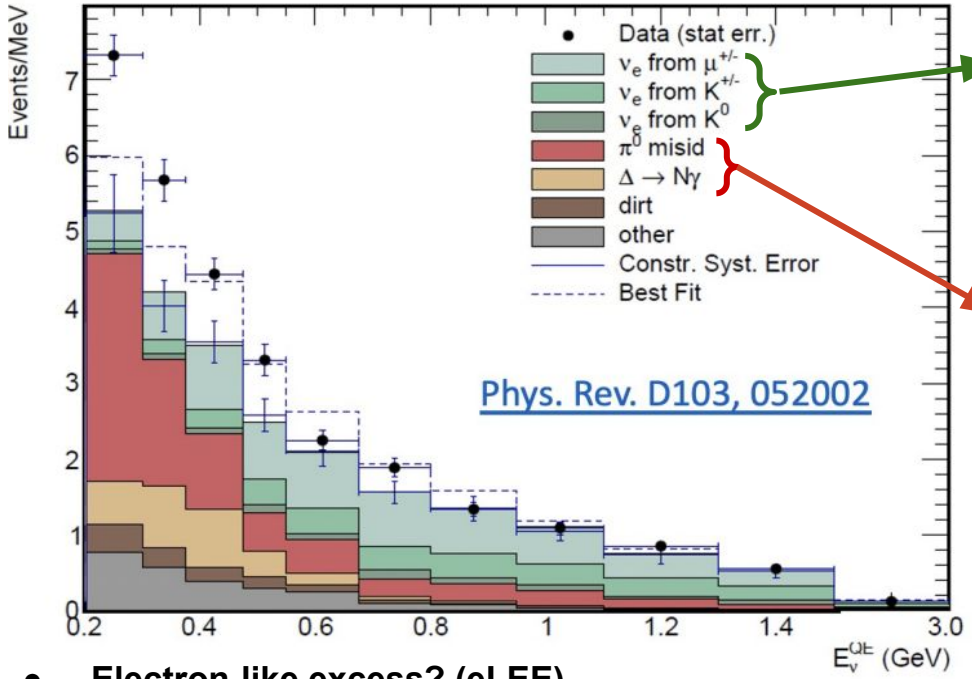
BEST recently confirmed gallium anomaly >4 σ

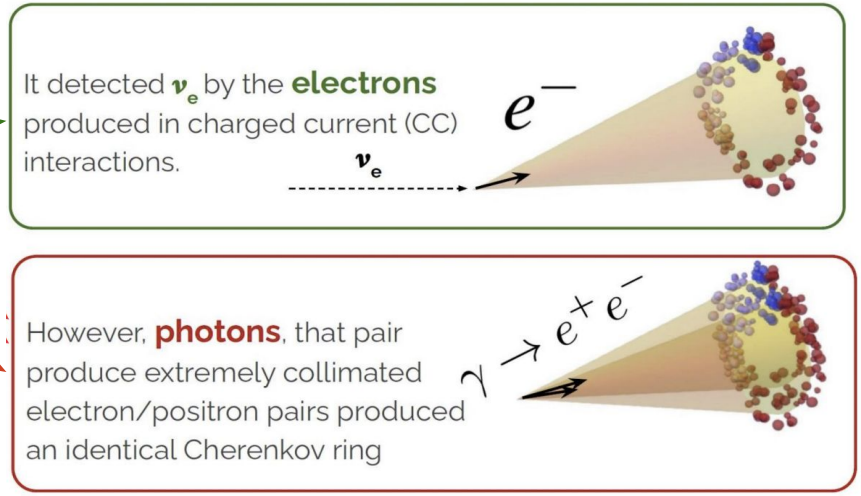


ν_e deficit

Fermilab

MiniBooNE Anomaly





MiniBooNE: Cherenkov detector unable to distinguish between electrons and photons

- **Electron-like excess? (eLEE)**
  - New physics? Sterile neutrino oscillations?
- **Photon-like excess? (gLEE)**
  - SM process, unconstrained by MiniBooNE

[MicroBooNE's Search for Anomalous Single-Photon Production, Lee Hagaman]

Fermilab

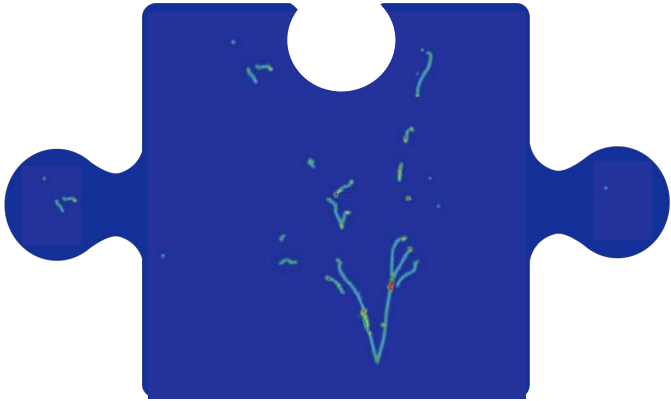
Understanding Neutrinos from LArTPCs Lens

MiniBooNE Excess

Liquid Argon R&D

Data taking 2015 - 2021

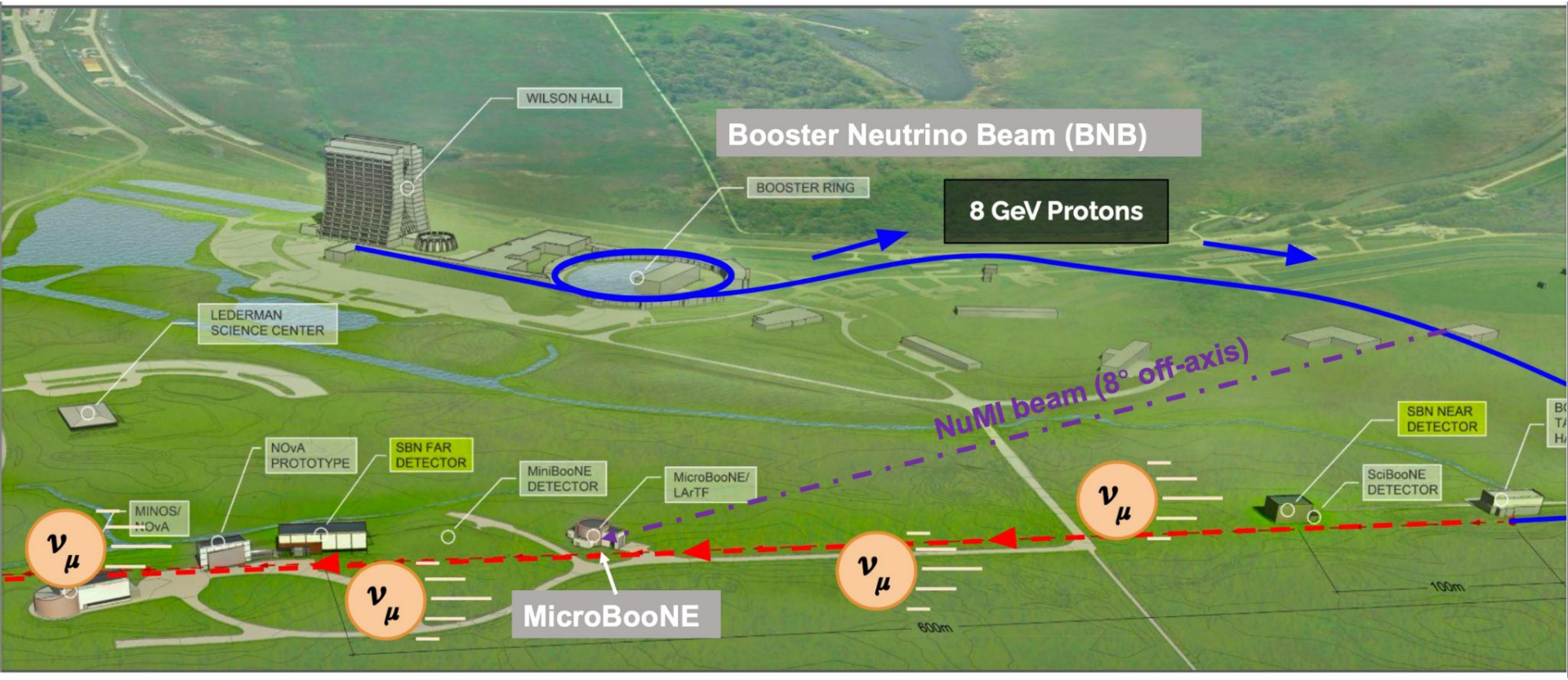
Neutrino-Ar cross section



Wide Range of New Physics Searches

Fermilab

Neutrinos Towards MicroBooNE



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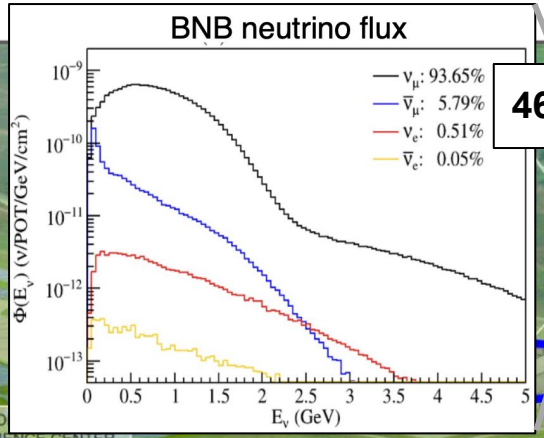
Neutrinos Towards MicroBooNE



468.5 m, On-axis, 0.8 GeV (E_ν), < 1% ν_e

Booster Neutrino Beam (BNB)

BOOSTER RING

8 GeV Protons

LED SCIENCE CENTER

NuMI beam (8° off-axis)

NOvA PROTOTYPE

SBN FAR DETECTOR

MiniBooNE DETECTOR

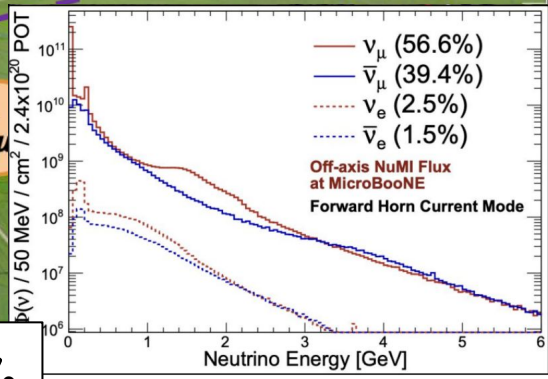
MicroBooNE/ LArTF

MINOS/ NOvA

ν_μ

MicroBooNE

600m



680 m, 8° Off-axis, 0.65 GeV (E_ν), 5% ν_e

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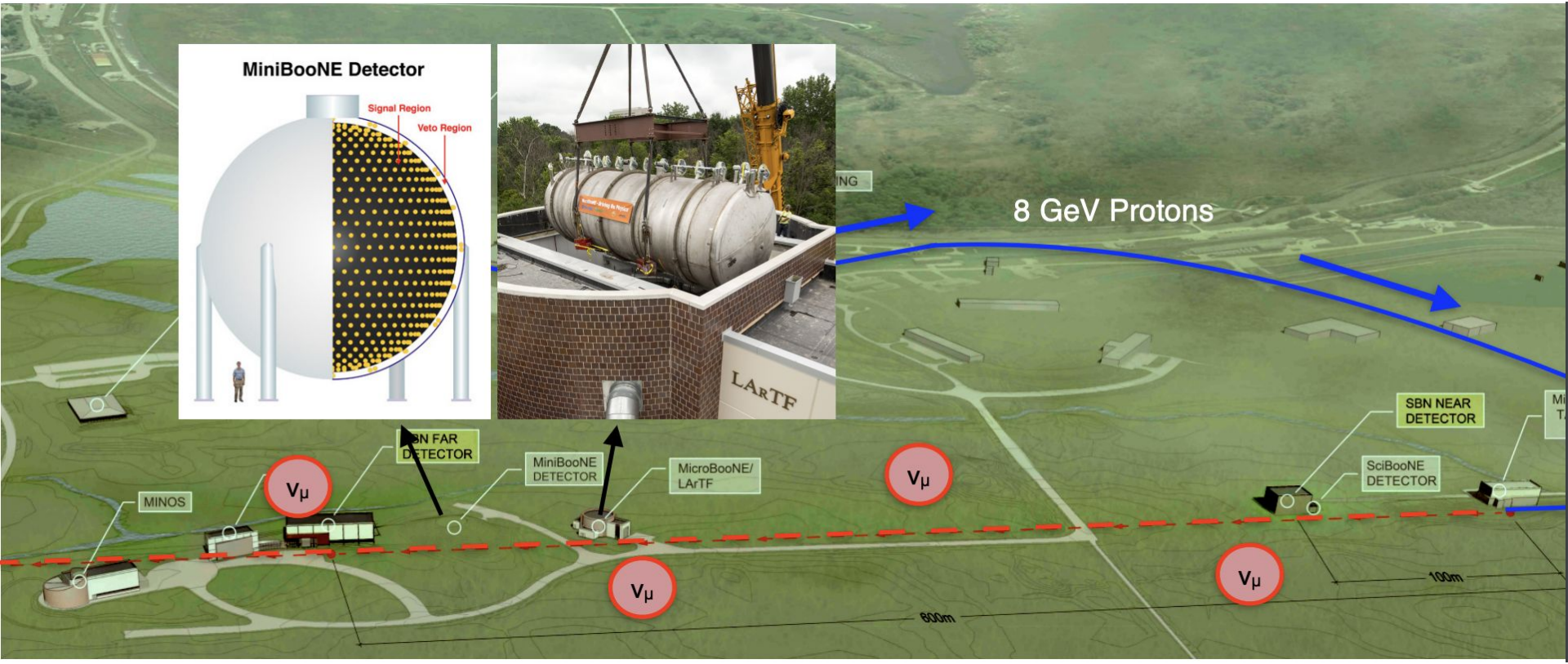
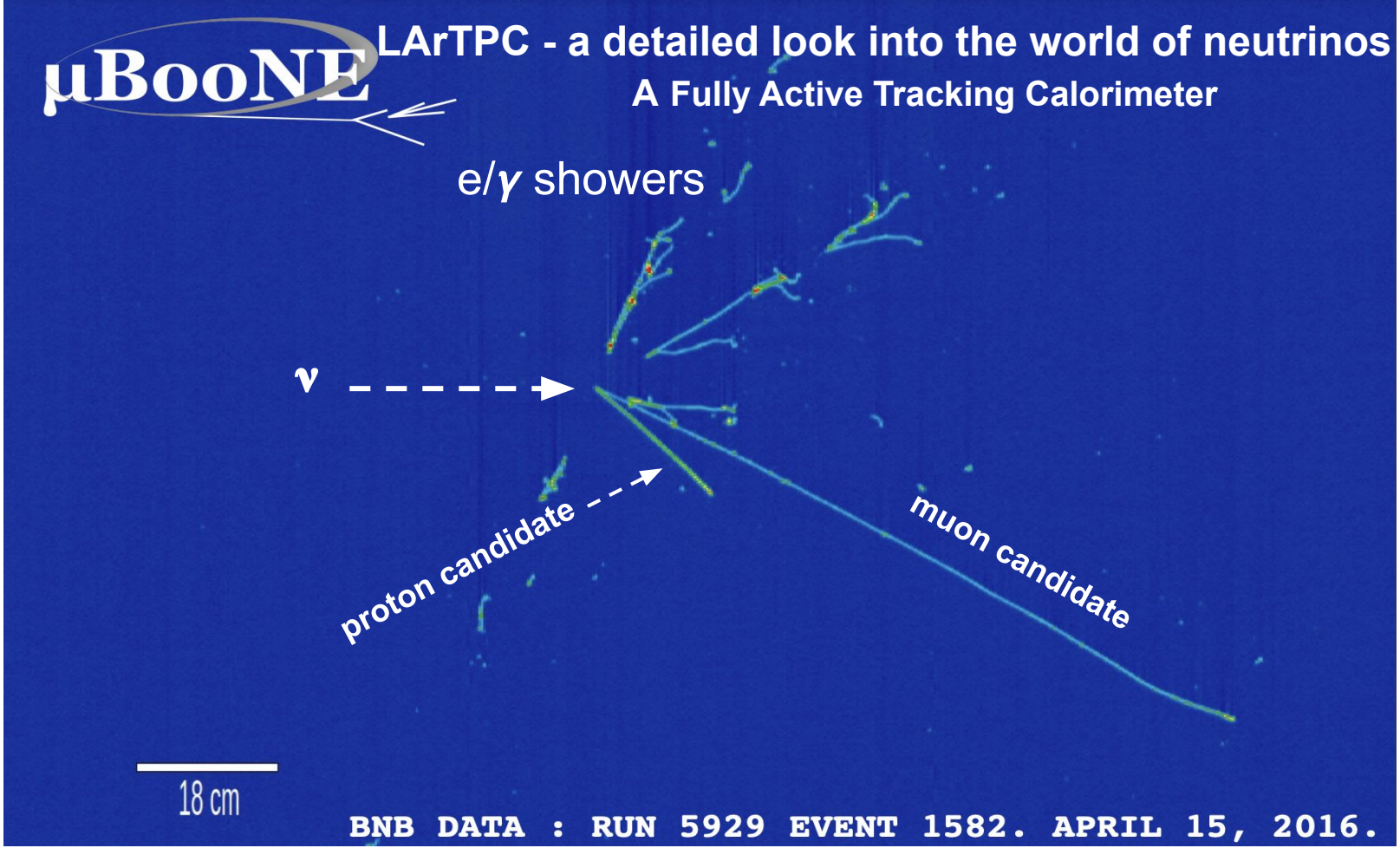
Neutrinos Towards MicroBooNE

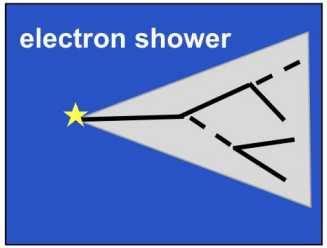


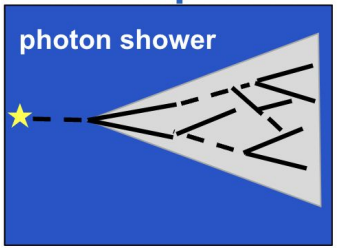
Fermilab

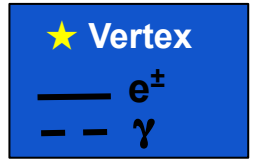

μBooNE
LArTPC - a detailed look into the world of neutrinos
A Fully Active Tracking Calorimeter
e/γ showers
ν
proton candidate
muon candidate
18 cm
BNB DATA : RUN 5929 EVENT 1582. APRIL 15, 2016.

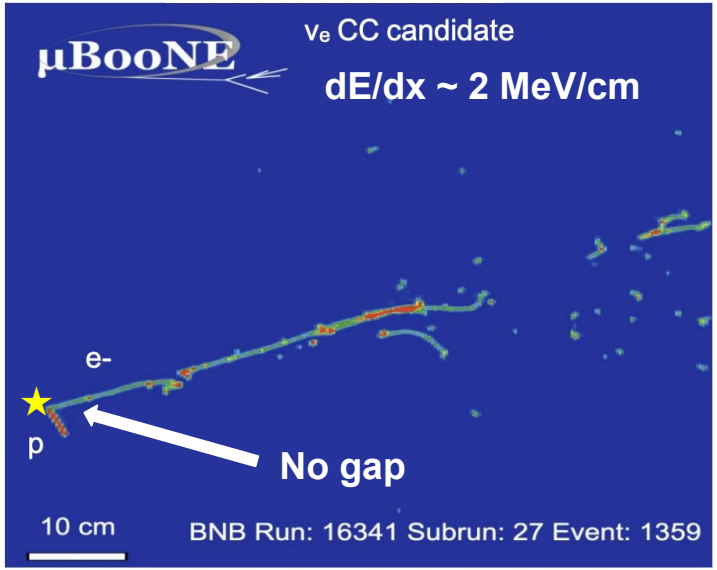
Fermilab

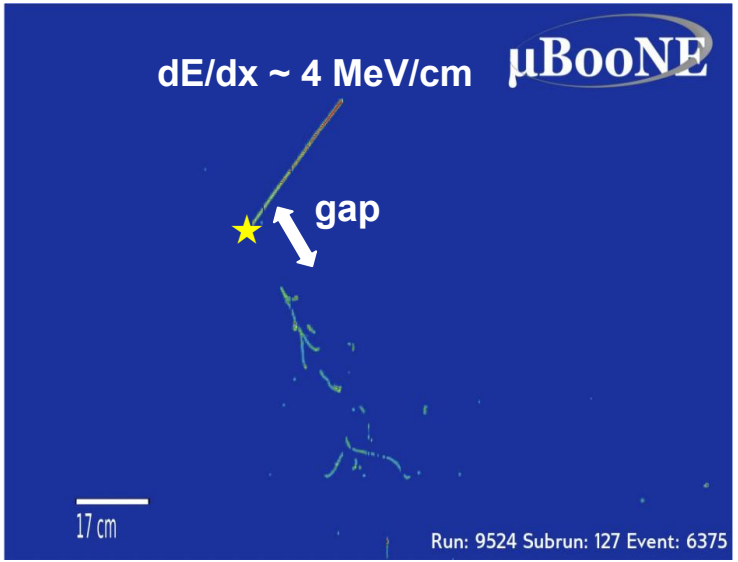
Improvements with LArTPCs - Electron Photon Separation







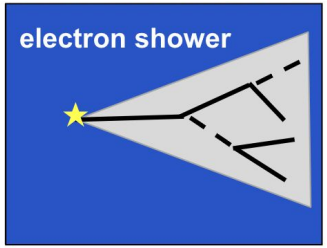


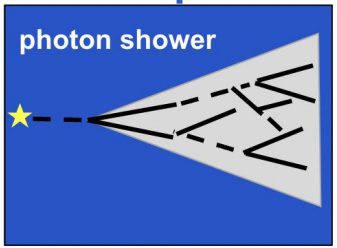


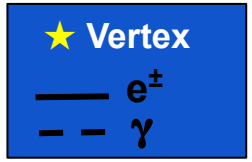
LArTPC provides information needed to separate e from γ

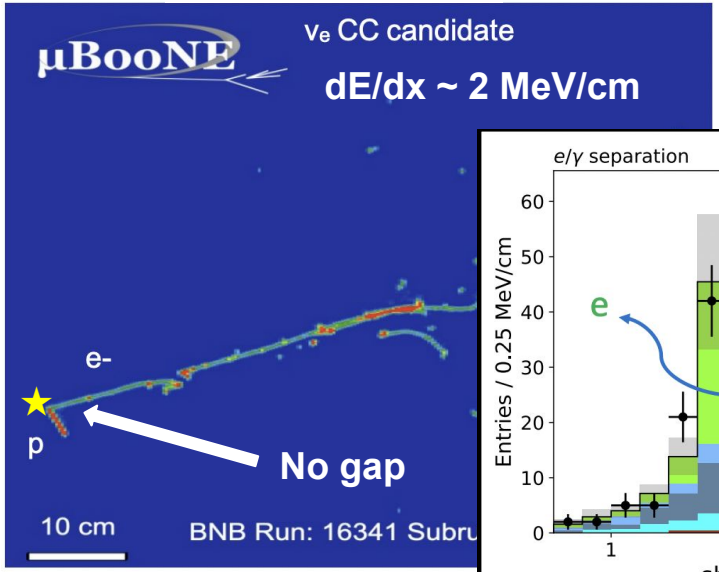
Fermilab

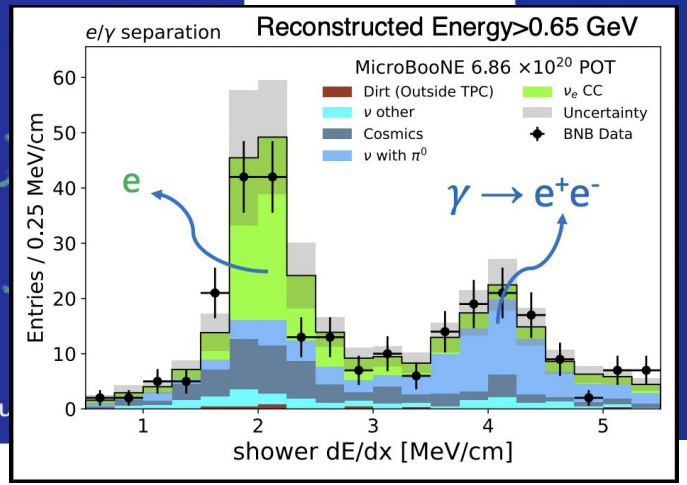
Improvements with LArTPCs - Electron Photon Separation

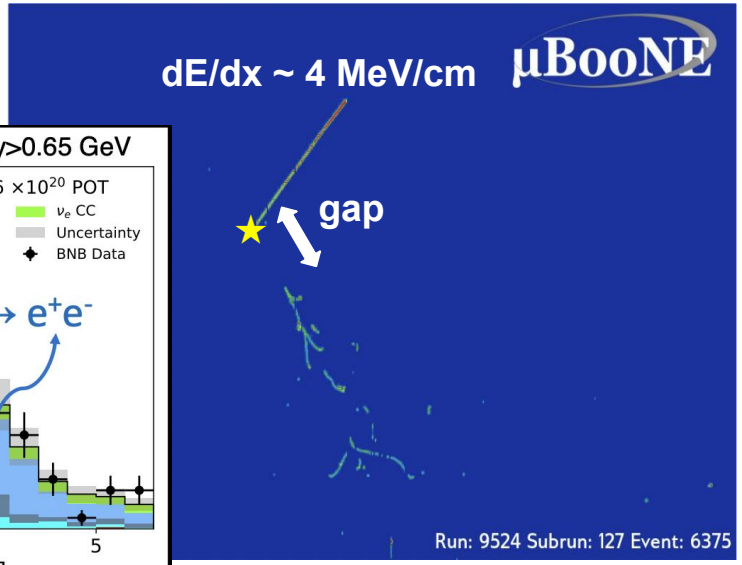












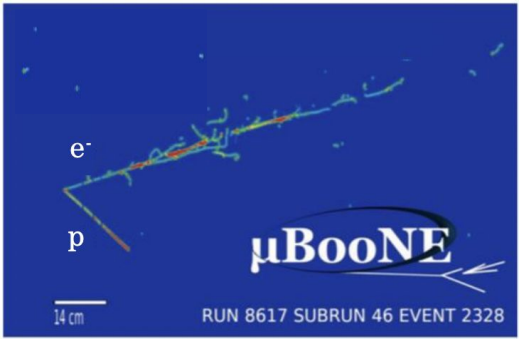
LArTPC provides information needed to separate e from γ

Fermilab

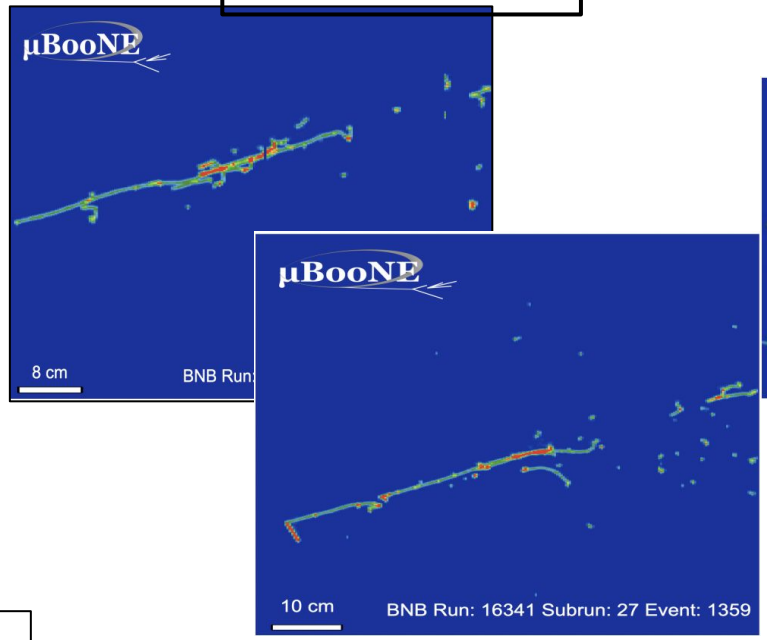
MicroBooNE's Quest : eLEE Search

Measure electron neutrinos: $\nu_e + n \rightarrow e + Xp + X\pi$

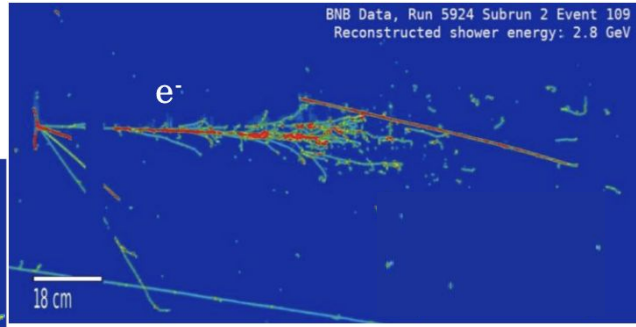
CCQE
1e1p0π



Pionless
1e0p0π + 1eNp0π



Inclusive electron neutrino
1eXpXπ



Dominant interaction at low energies

Match MiniBooNE Signal

Largest statistics and sensitivity

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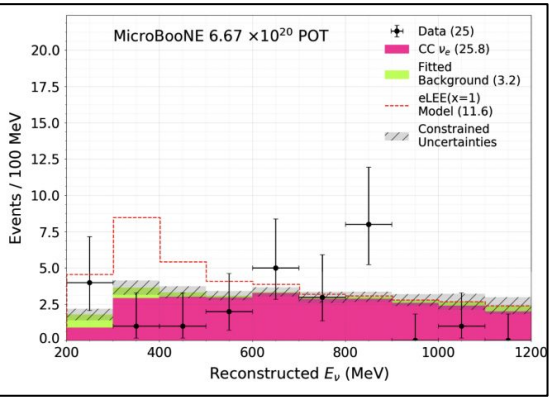
MicroBooNE's Quest : eLEE Search

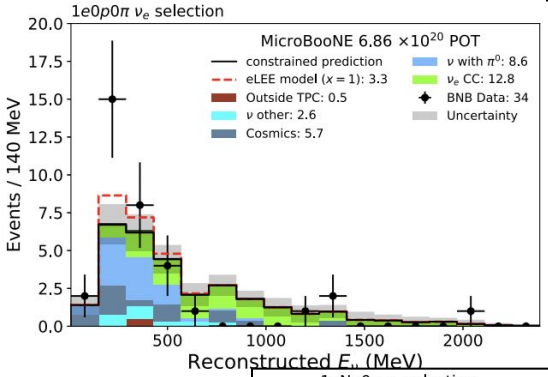
Phys. Rev. Lett. 128, 241801

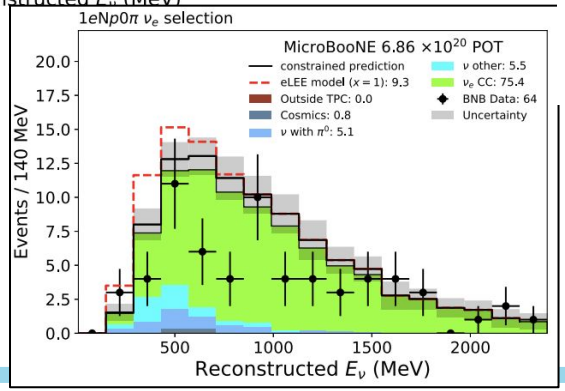
Measure electron neutrinos: $\nu_e + n \rightarrow e + Xp + X\pi$

CCQE
1e1p0π

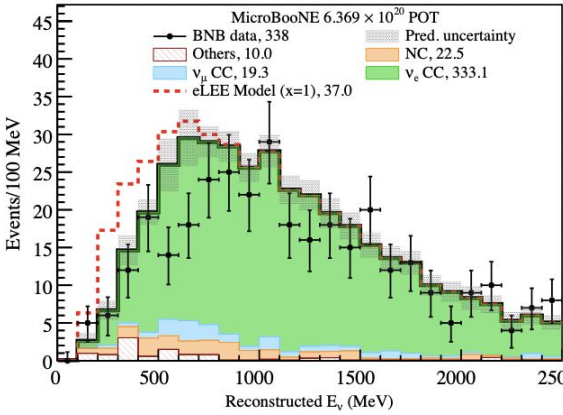


Pionless
1e0p0π + 1eNp0π





Inclusive electron neutrino
1eXpXπ



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MicroBooNE's Quest : eLEE Search

Phys. Rev. Lett. 128, 241801

Measure electron neutrinos: $\nu_e + n \rightarrow e + Xp + X\pi$

CCQE
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Inclusive electron neutrino
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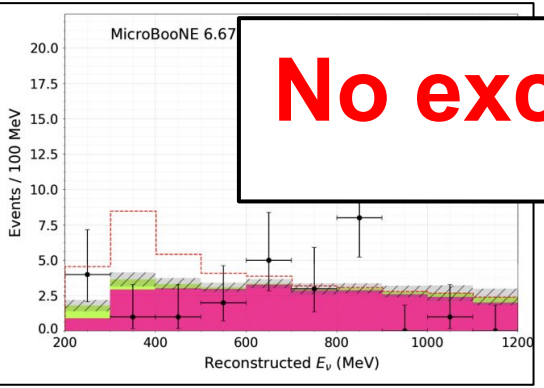
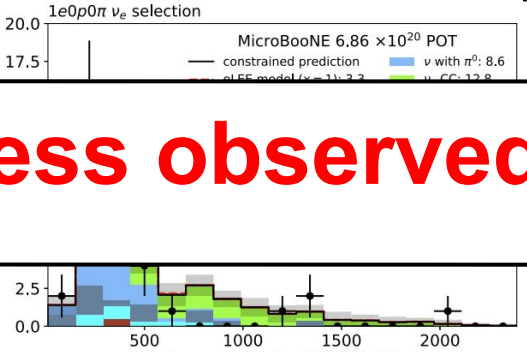
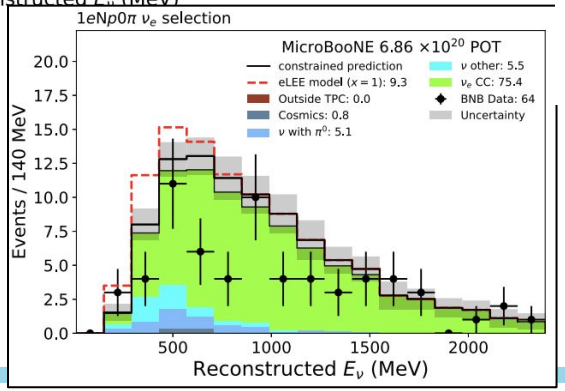
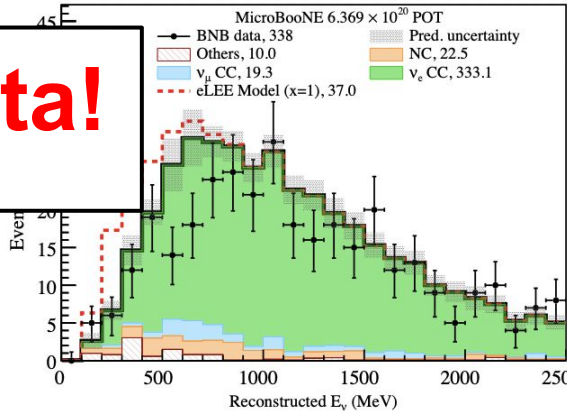




No excess observed in data!





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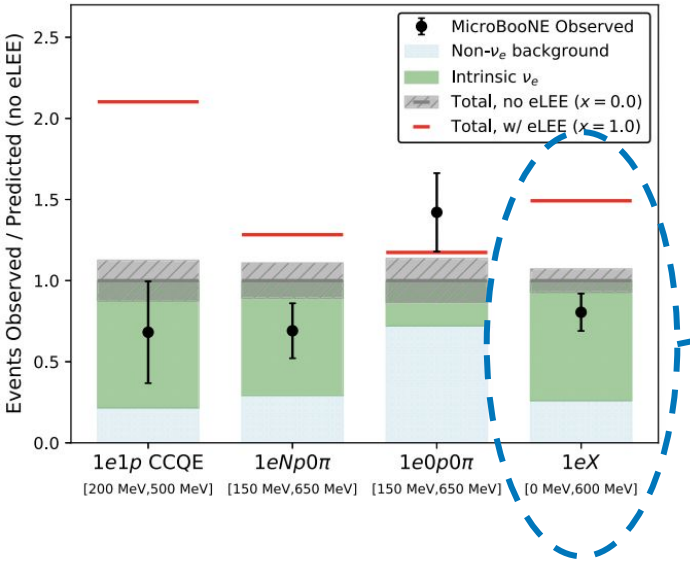
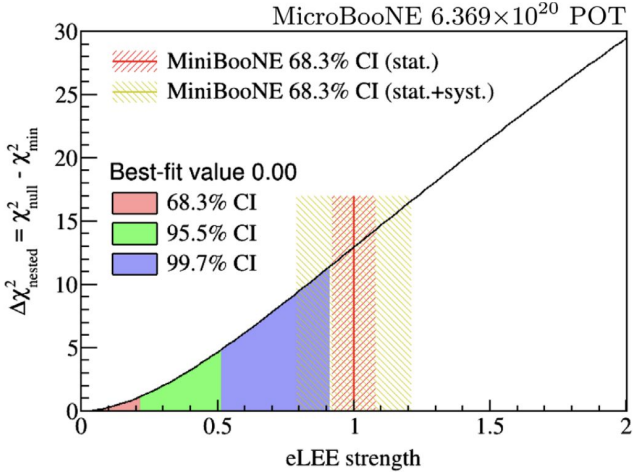
MicroBooNE's Quest : eLEE Search

Phys. Rev. Lett. 128, 241801



- **Rejects electrons as LEE explanation at > 97% CL and >3σ in the inclusive channel**



PhysRevD.105.112005

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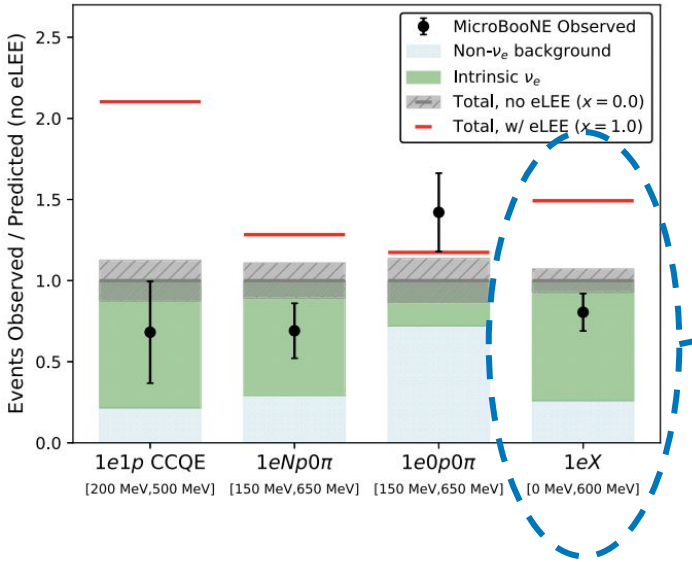
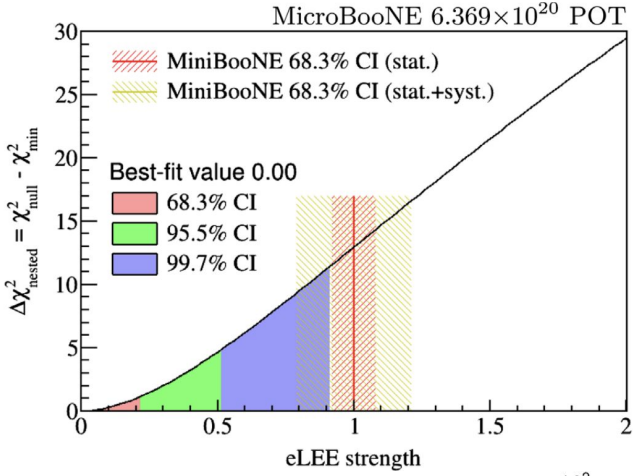
MicroBooNE's Quest : Sterile Neutrinos

Phys. Rev. Lett. 128, 241801

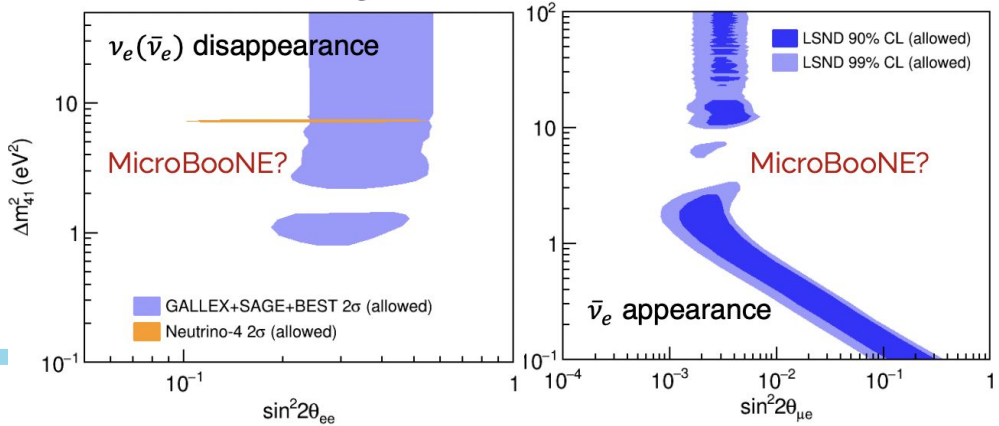


- **Rejects electrons as LEE explanation at > 97% CL and >3σ in the inclusive channel**



PhysRevD.105.112005

Reinterpret eLEE results to test 3+1 oscillation model



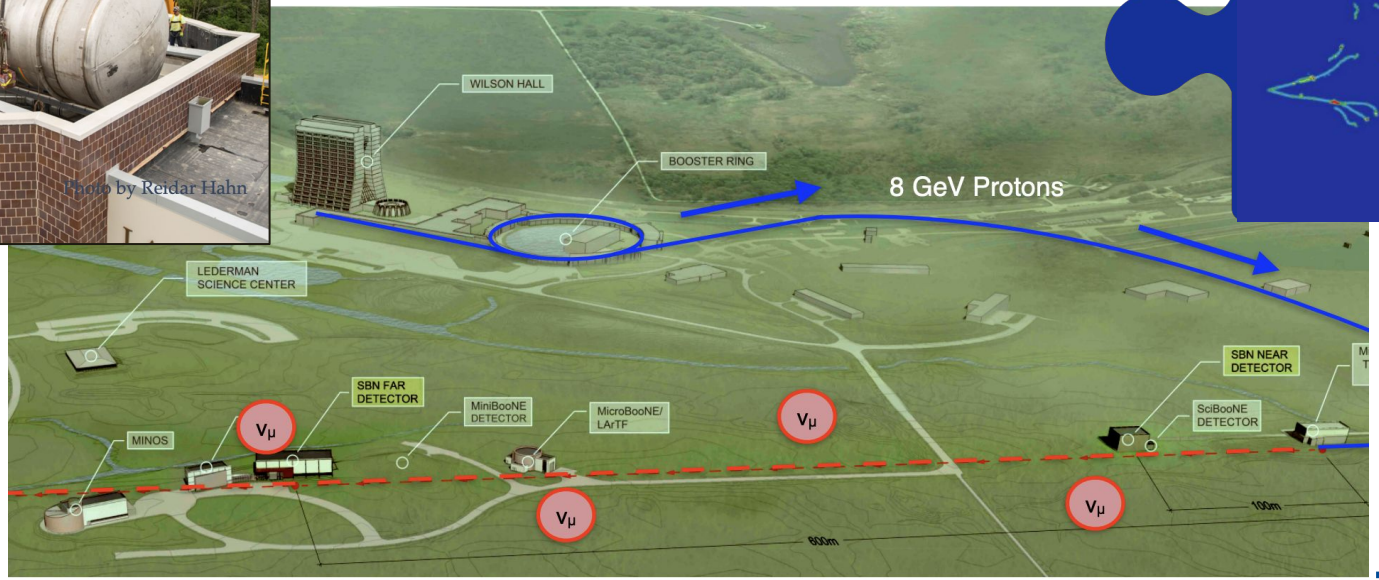
Short baseline anomalies

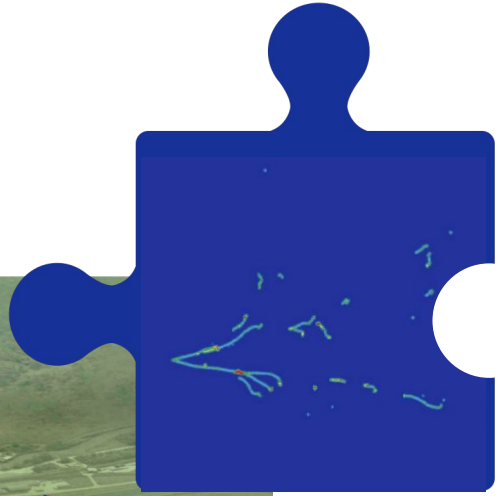
Test new signatures/models

Understanding Neutrinos - Puzzles | Physics | Path Forward

(From LArTPCs Lens)

Sterile neutrinos (3+1 Oscillation)





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Short baseline anomalies

Test new signatures/models

Understanding Neutrinos - Puzzles | Physics | Path Forward

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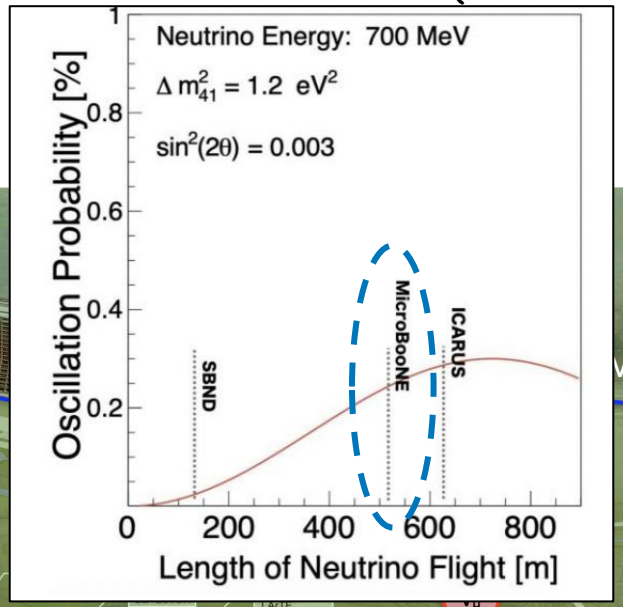
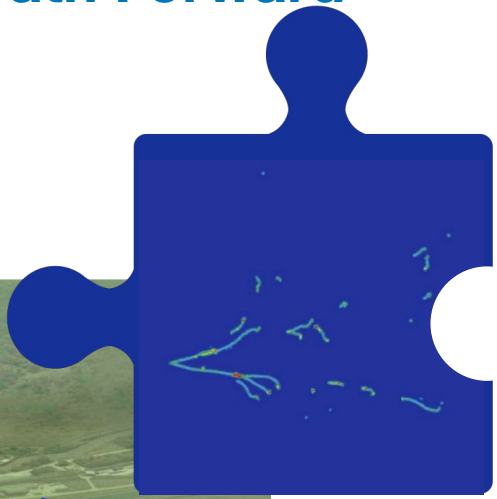
Sterile neutrinos (3+1 Oscillation)





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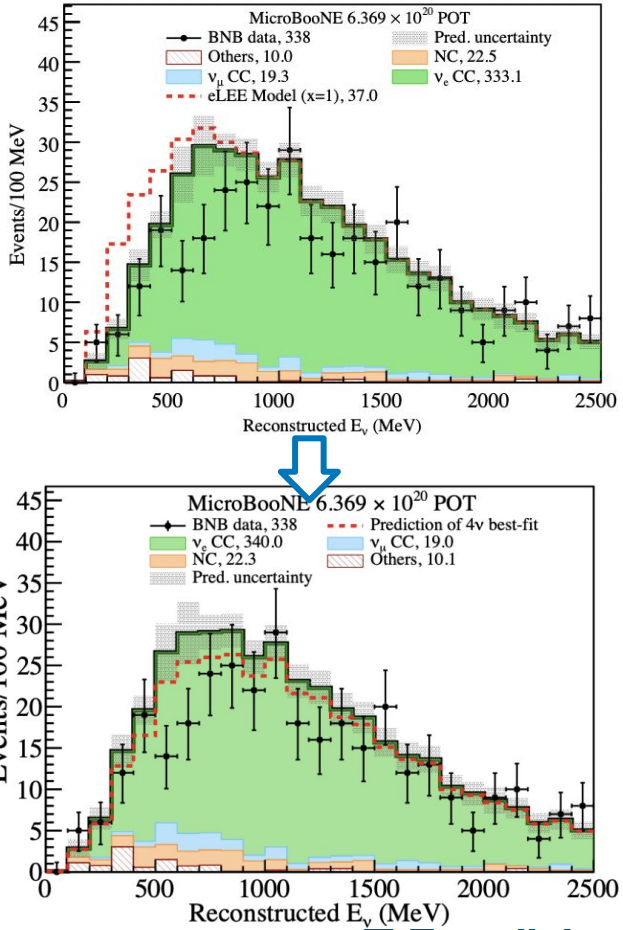
3+1 Oscillation Analysis

PhysRevLett.130.011801

- eLEE results re-interpreted under sterile neutrino oscillation hypothesis
  - Strategy: combination of short-baseline ν_e appearance, ν_e disappearance, and ν_μ disappearance
- considering full 3+1 oscillation, BNB Run1-3 data consistent with 3ν hypothesis within 1σ (Feldman-Cousins approach)
- Set limits on sterile neutrinos



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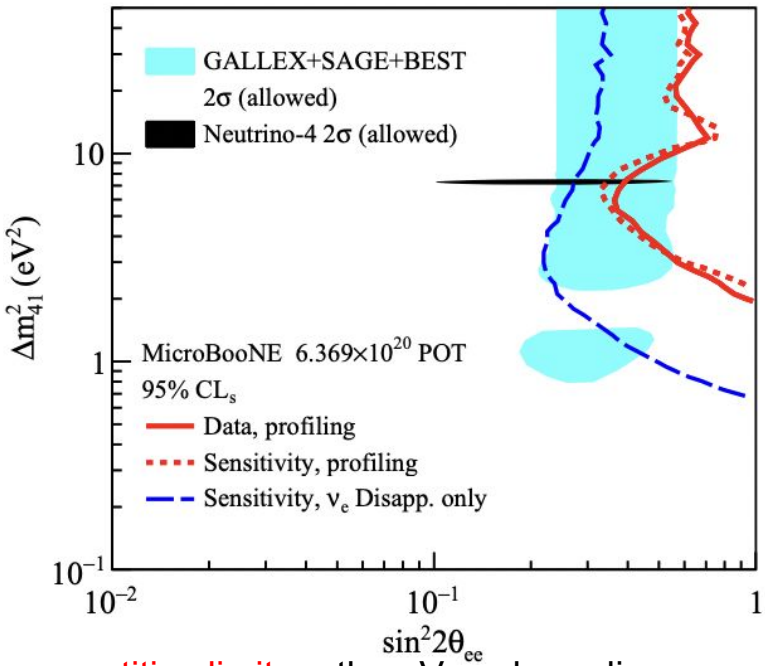
Status Quo: 3+1 Oscillation Analysis

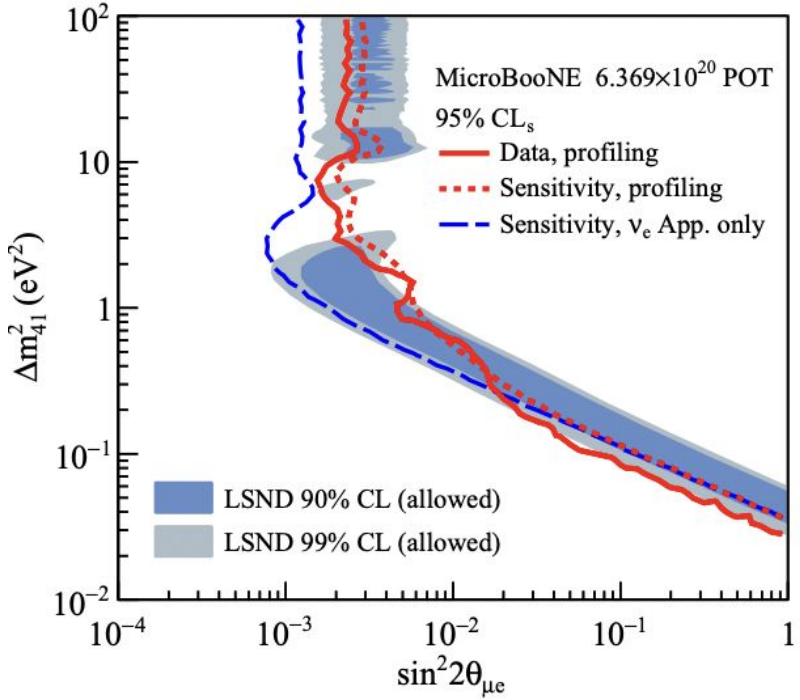
PhysRevLett.130.011801

ν_e disappearance



competitive limit on the eV-scale ν_e disappearance, excludes parts of allowed regions from gallium experiments

ν_e appearance



Excludes part of the LSND allowed region

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3+1 Oscillation Analysis

PhysRevLett.130.011801

- **What :**

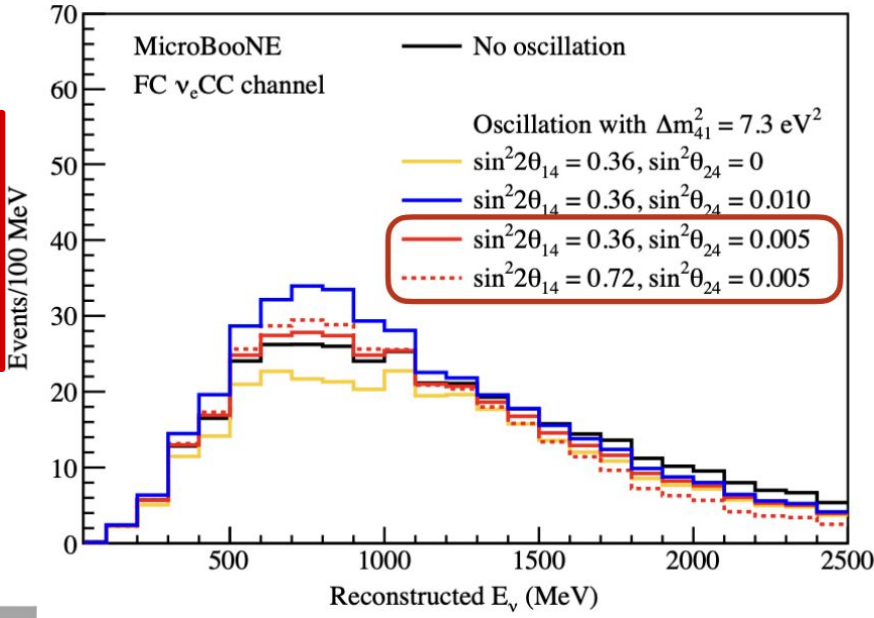
  ν_e disappearance can cancel appearance of ν_e events

  ⬇

  degeneracy of oscillation parameters

- **When :**

  $Sin^2\theta_{24}$ approaches beam intrinsic $\nu_e : \nu_\mu$ ratio



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

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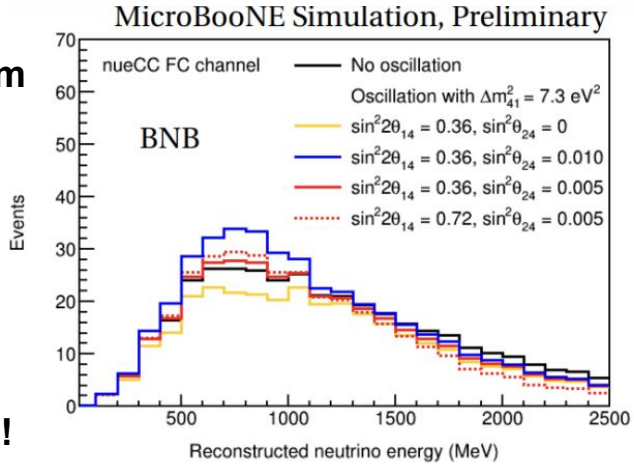
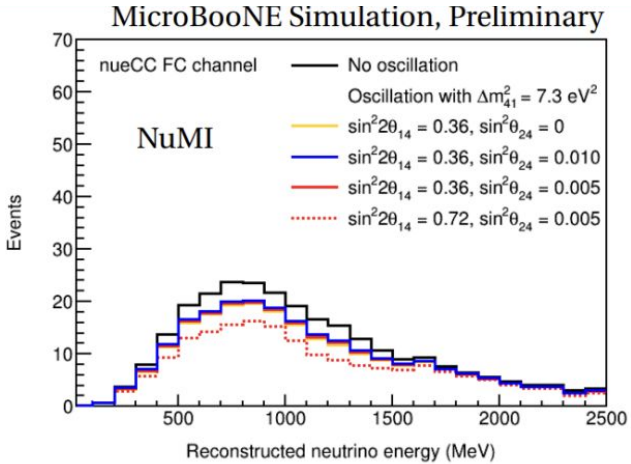
Employ Both BNB & NuMI

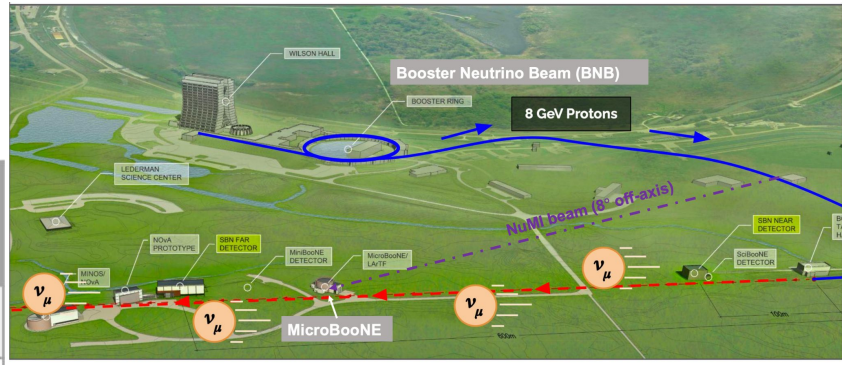
MicroBooNE Public Note #1116

- Change $\nu_e : \nu_\mu$ ratio in beam
- A different beam
- Solution :
  - NuMI data will break this degeneracy – analysis in progress!





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



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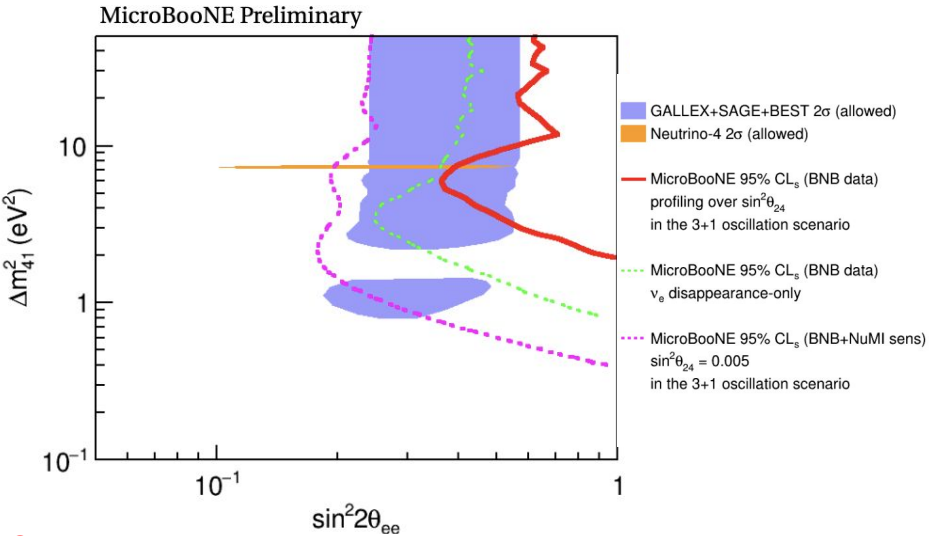
Status Quo: 3+1 Oscillation with BNB + NuMI

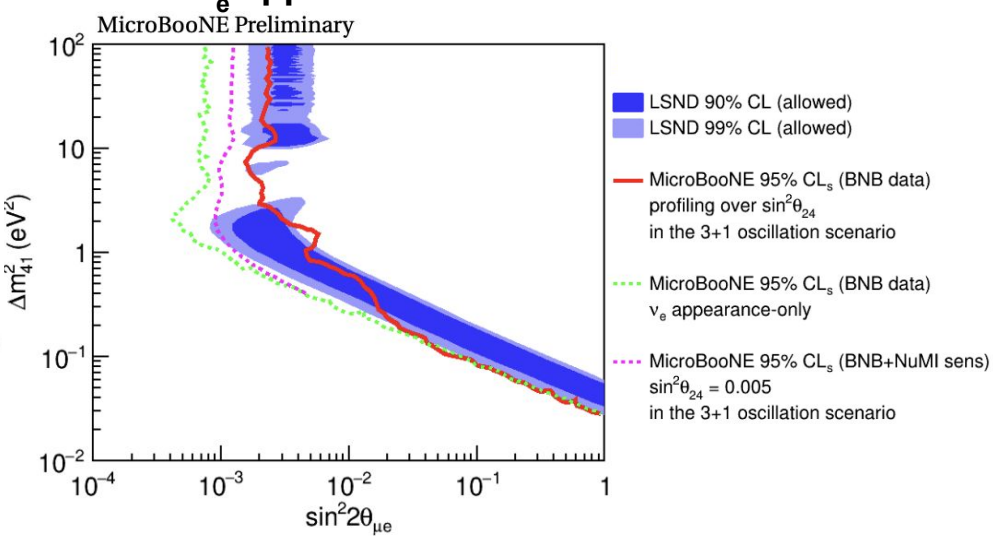
[MicroBooNE Public Note #1116]

ν_e disappearance



Competitive limit on the eV-scale ν_e disappearance, excludes parts of allowed regions from gallium experiments

ν_e appearance



Excludes part of the LSND allowed region

BNB + NuMI

Improved sensitivity: ν_e appearance-disappearance degeneracy mitigation

Expected to cover more of Neutrino-4 and gallium anomaly 2σ allowed region and LSND 90% CL allowed region

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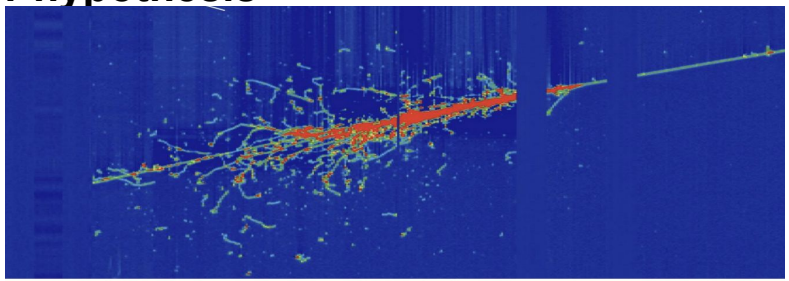
Summary & Prospect :

- Full 3+1 oscillation analyses to interpret the MicroBooNE eLEE results under a sterile neutrino oscillation hypothesis
  - ~ 50% BNB dataset consistent with 3-flavor hypothesis
- Several on going activities
  - Full dataset LEE Analysis
  - Oscillation analysis with BNB & NuMI data underway

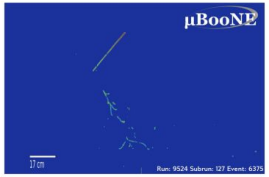


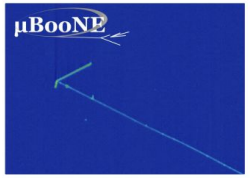
- Further investigation on MiniBooNE excess, BSM searches

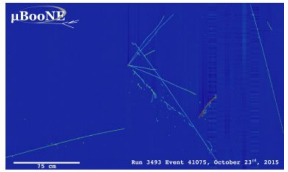
MicroBooNE Pushing Boundaries!

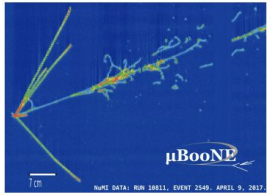
Stay Tuned!

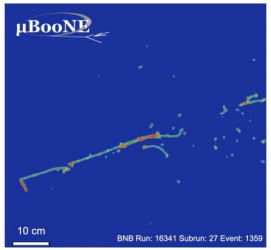
More on MicroBooNE :

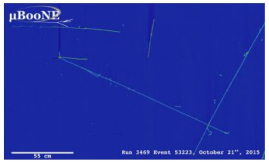


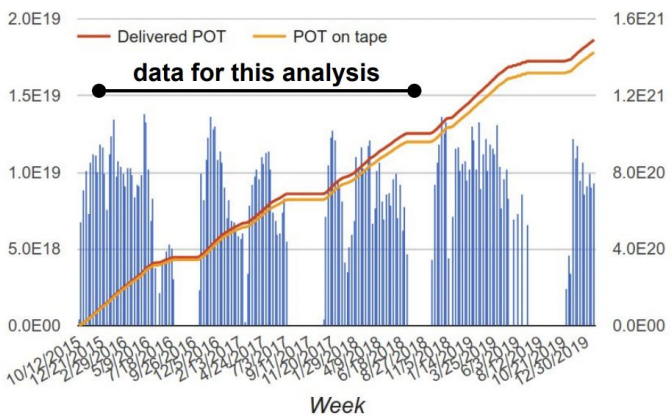


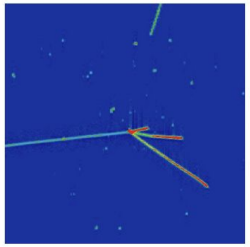


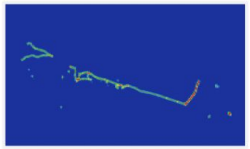


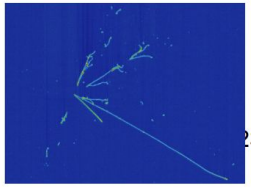












- Longest running large-scale LArTPC to date.
- O(500k) ν interactions collected
- ½ of the dataset used for this work.

- [MicroBooNE's Search for Anomalous Single-Photon Production,](#) Lee Hagaman
- [Status of MicroBooNE](#) Avinay Bhat
- Tantalizing cross section results:
- [The MicroBooNE cross section program, with a special focus on the TKI analysis](#) Afroditi Papadopoulou
- [First measurement of η production in neutrino interactions on argon with the MicroBooNE experiment](#) David Caratelli

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Thank you!

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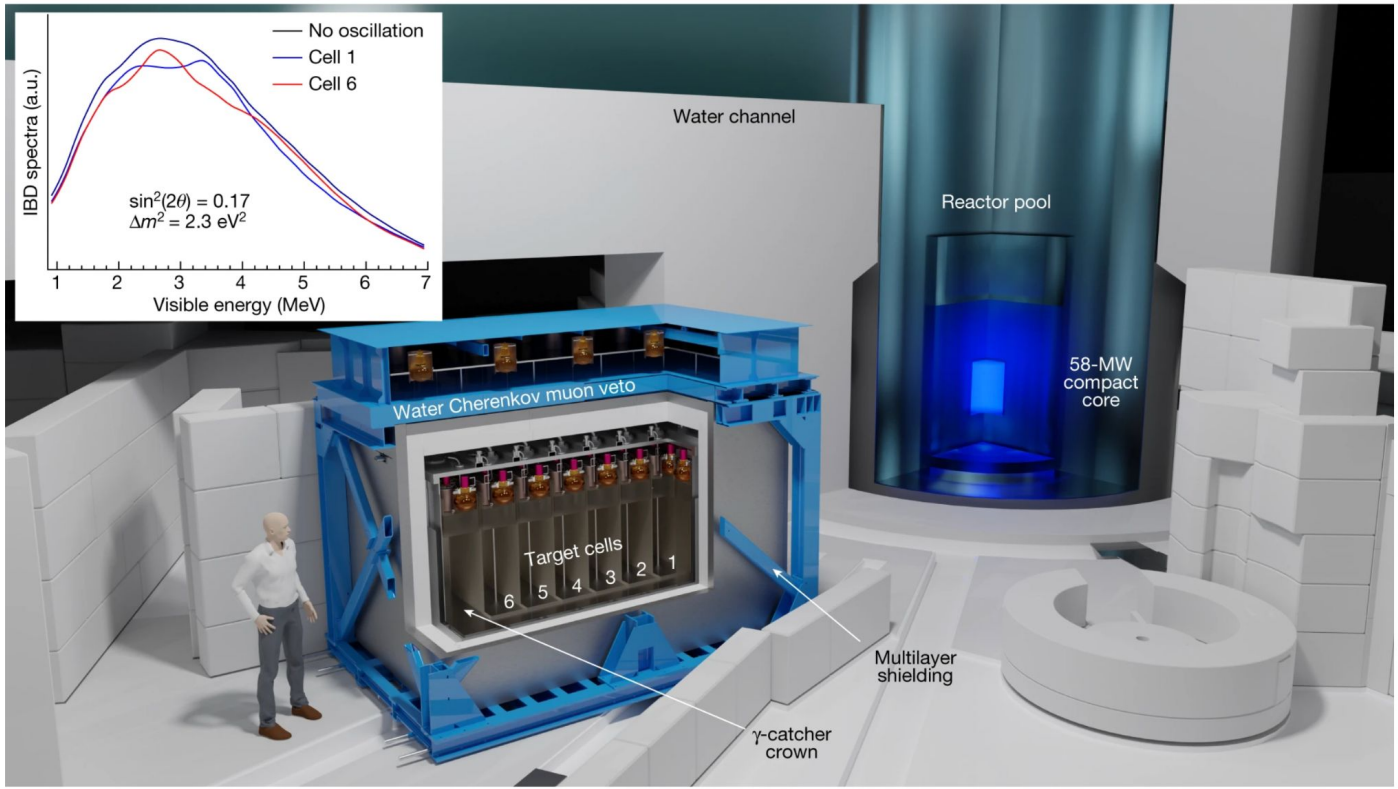
Reactor Anomaly (?)

STEREO neutrino spectrum of ^{235}U fission rejects sterile neutrino hypothesis



Latest result from STEREO experiment, January 11th, 2023

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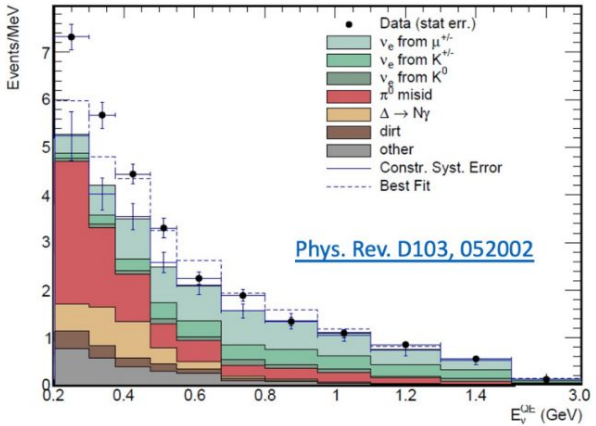
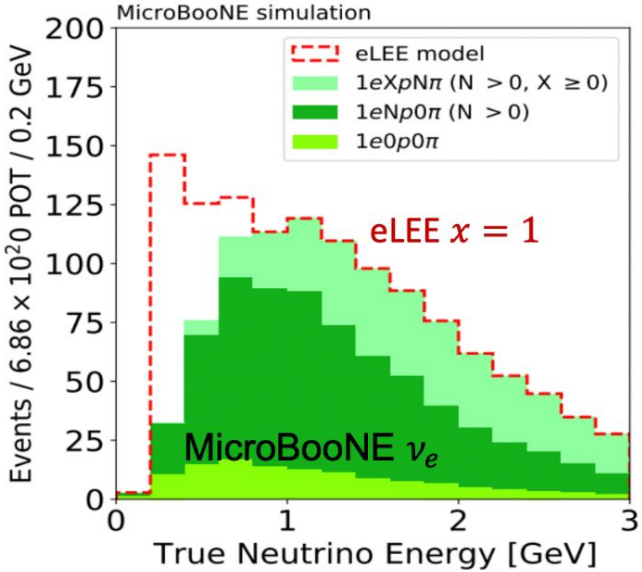
ν_e low-energy excess (eLEE) search



$$\text{MiniBooNE } x = \begin{cases} 1 \pm 0.08 \text{ (stat.)} \\ 1 \pm 0.21 \text{ (full)} \end{cases}$$

Unfolding detector response, acceptance, efficiency

Empirical eLEE model derived from MiniBooNE



- Excess (LEE) is built upon the intrinsic ν_e as a function of neutrino energy
  - Unfolded from MiniBooNE observation and applied to MicroBooNE
- One normalization parameter 'x' built in the model

MicroBooNE Public Note

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3+1 Neutrino Oscillation Framework

- The PMNS matrix is extended to 4x4 unitary matrix, and is parameterized as following

$$U_{PMNS} = R_{34}(\theta_{34}, \delta_{34})\, R_{24}(\theta_{24}, \delta_{24})\, R_{14}(\theta_{14}, 0)\, R_{23}(\theta_{23}, 0)\, R_{13}(\theta_{13}, \delta_{13})\, R_{12}(\theta_{12}, 0)$$

- The effective mixing angles $\theta_{\alpha\beta}$ for short-baseline oscillations are defined below

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \cdot \sin^2 2\theta_{\alpha\beta} \cdot \sin^2\left(1.267 \frac{\Delta m^2_{41}(\mathrm{eV}^2) L(\mathrm{m})}{E(\mathrm{MeV})}\right)$$

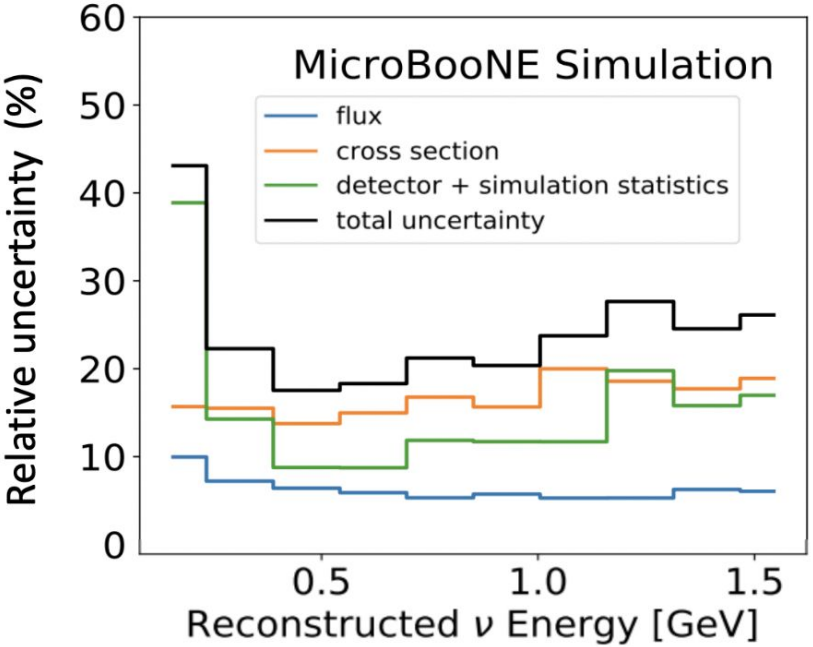
ν_e disappearance ($\nu_e \to \nu_e$): $\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$

ν_μ disappearance ($\nu_\mu \to \nu_\mu$): $\sin^2 2\theta_{\mu\mu} = 4\cos^2\theta_{14} \sin^2\theta_{24} (1 - \cos^2\theta_{14} \sin^2\theta_{24})$

ν_e appearance ($\nu_\mu \to \nu_e$): $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2\theta_{24}$

- In MicroBooNE analysis, the above three oscillation effects are applied to all ν_e and ν_μ events; the ν_μ appearance ($\nu_e \to \nu_\mu$) is ignored because of tiny $\frac{\nu_e \text{ flux rate}}{\nu_\mu \text{ flux rate}} \sim 0.005$

Overview of the Systematic Uncertainties



15-20% cross-section uncertainty
10-20% detector response uncertainty
5-10% flux uncertainty (same treatment as MiniBooNE)

- Apply data constraints from the in-situ measurements of ν_μ and other dedicated background sidebands to suppress the systematic uncertainties

- ✓ Cross-section: MicroBooNE Genie tune, Phys. Rev. D 105, 072001
- ✓ Detector systematics: data-driven, EPJC 82, 454 (2022)

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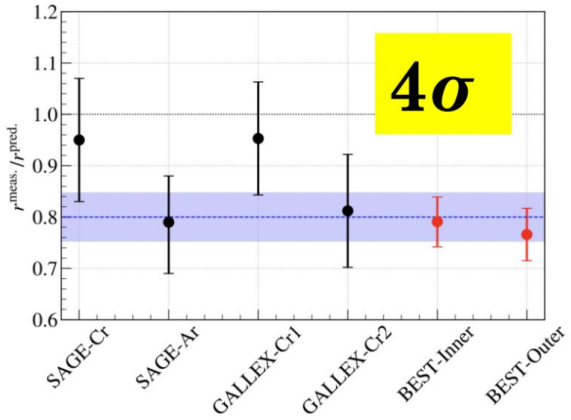
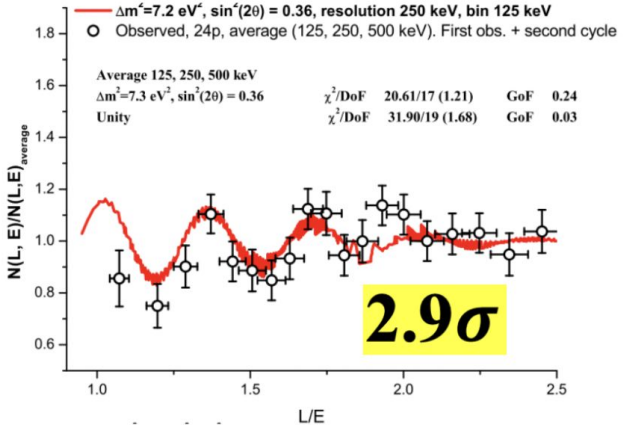
Other Short Baseline Anomalies

- BEST and other gallium experiments see a deficit that could be explained by $\nu_\mu \rightarrow \nu_e$ oscillations.
- Neutrino-4 sees an oscillation as a function of distance/energy that could be explained by $\nu_e \rightarrow \nu_{\mu,\tau,s}$ oscillations.



BEST

Phys. Rev. C 105, 065502



Neutrino-4

Phys. Rev. D 104, 032003

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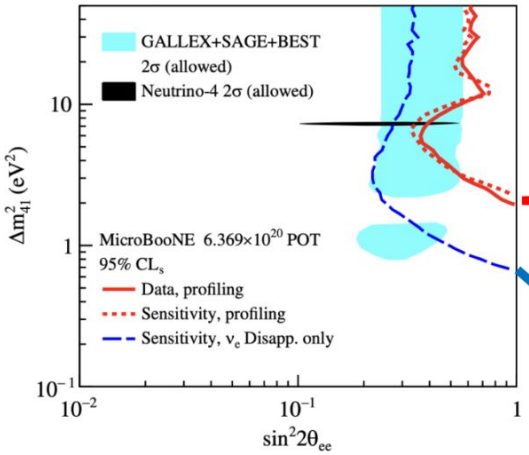
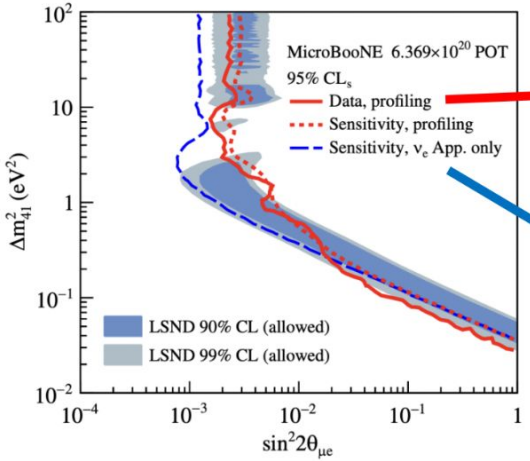
Sterile Neutrinos: 3+1 Framework



2D profiled result, full 3+1 analysis considering ν_μ to ν_e, ν_e to ν_e and ν_μ to ν_μ at each point in the parameter space.

ν_e disappearance-only (only ν_e to ν_e), more stringent limit corresponding to a fixed $\sin^2\theta_{24} = 0$.



2D profiled result, full 3+1 analysis considering ν_μ to ν_e, ν_e to ν_e and ν_μ to ν_μ at each point in the parameter space.

ν_e appearance-only (only ν_μ to ν_e), more stringent limit However, it is physically not allowed in the 3+1 framework. (non-zero ν_e appearance requires both ν_e and ν_μ disappearance)

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