MicroBooNE Results on Short-Baseline Neutrino Anomalies

Xiangpan Ji (Nankai University)
On behalf of the MicroBooNE Collaboration

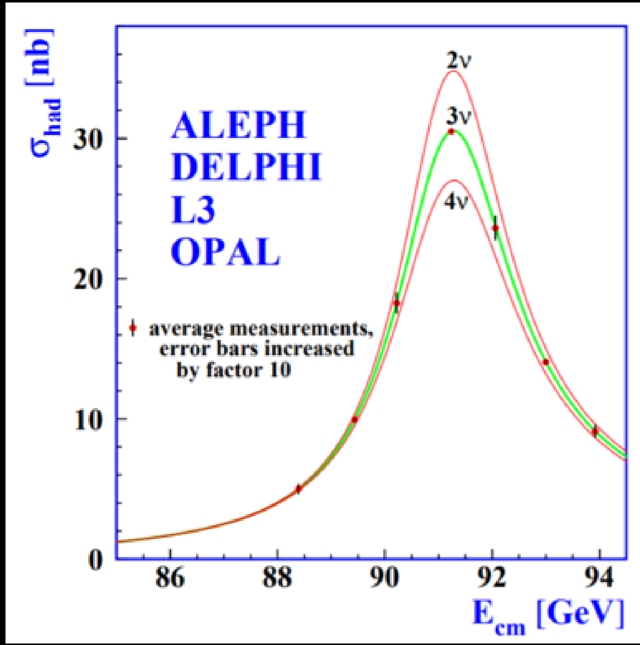
July 3-8, 2023

- Short-Baseline Neutrino Anomalies
- MicroBooNE Search Results

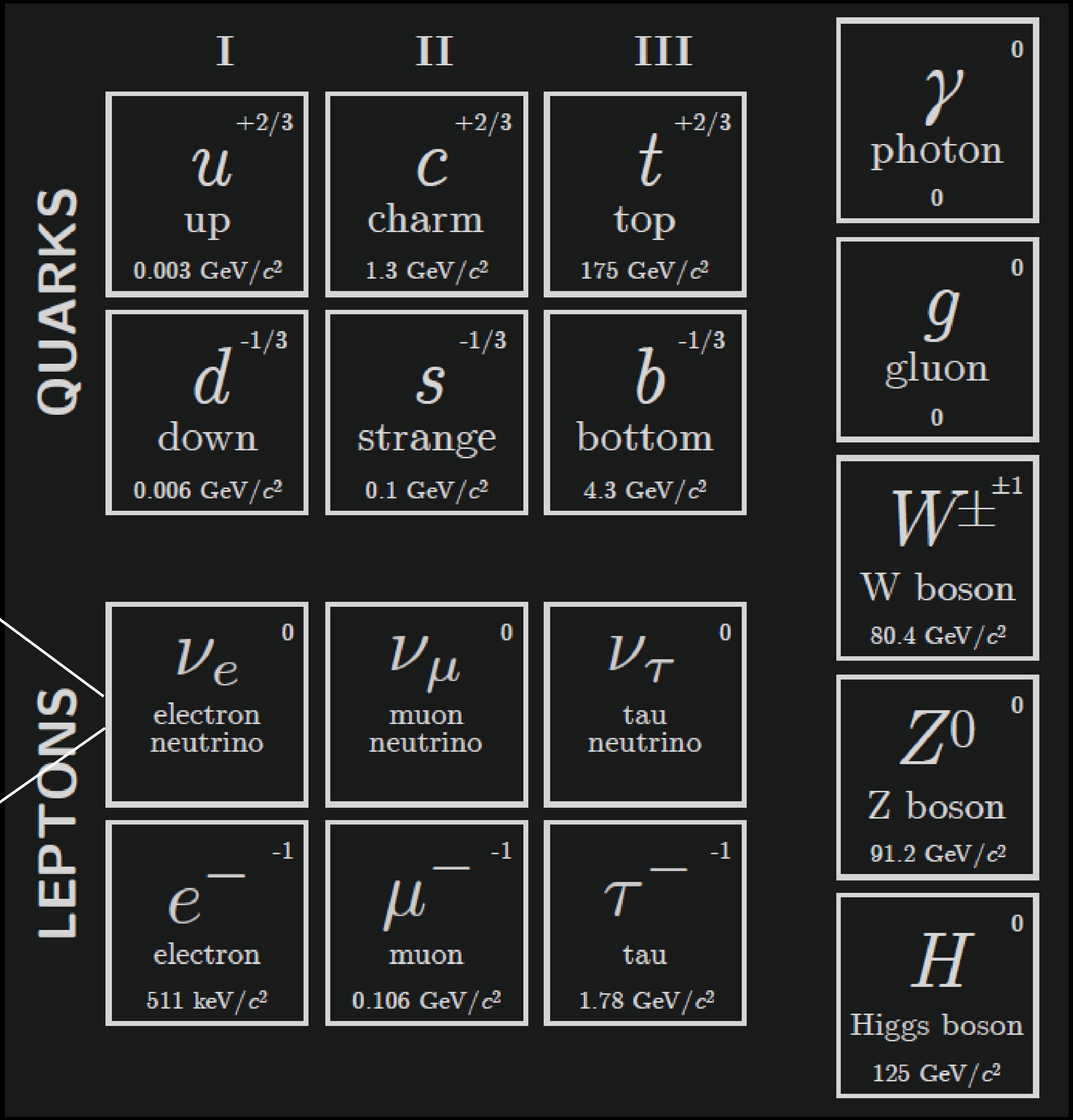
Three-Neutrino Paradigm

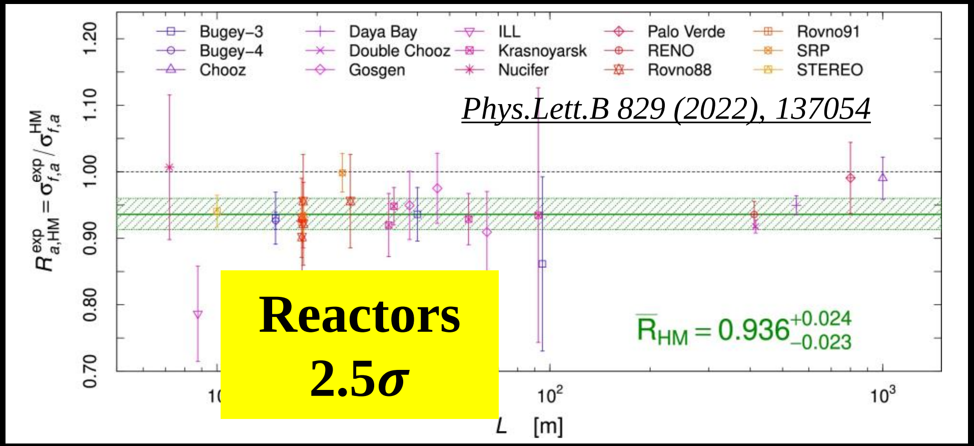
- Only three neutrino flavors in the Standard Model

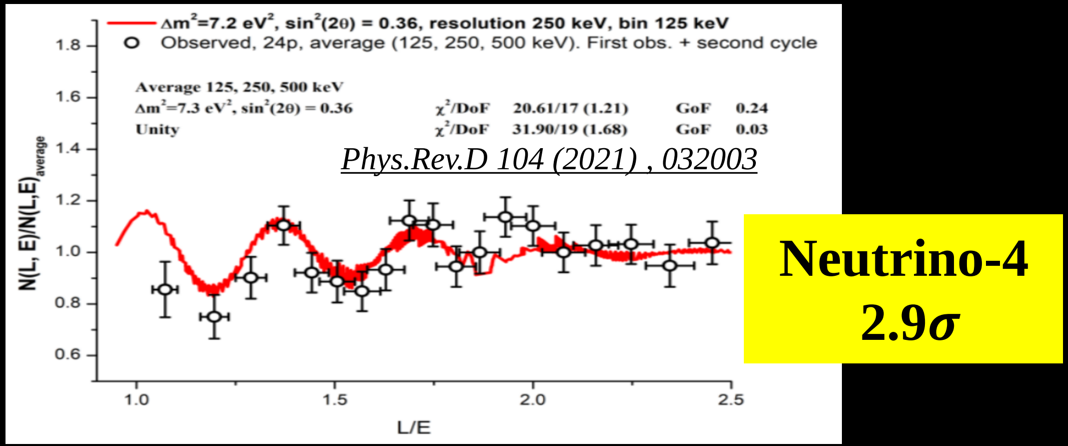
Z-boson decay measurements
$N_\nu = 2.9840 \pm 0.0082$

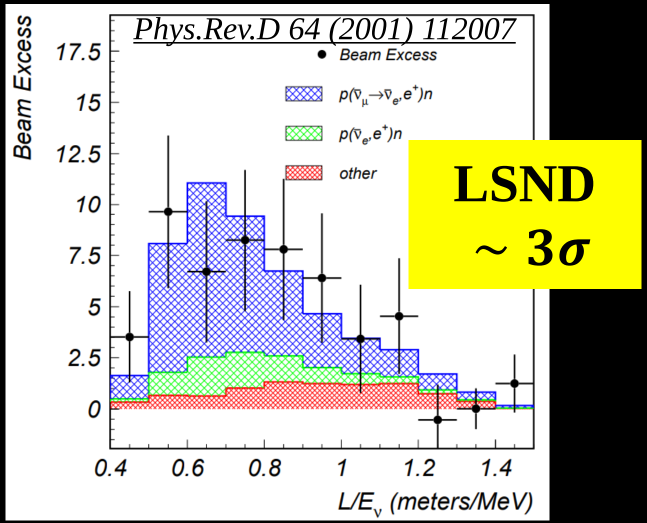


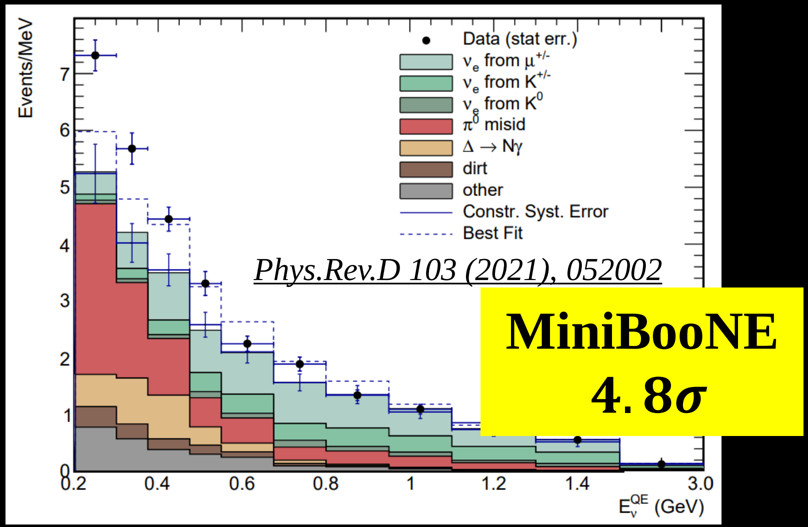
Phys. Rept. 427, 257 (2006)

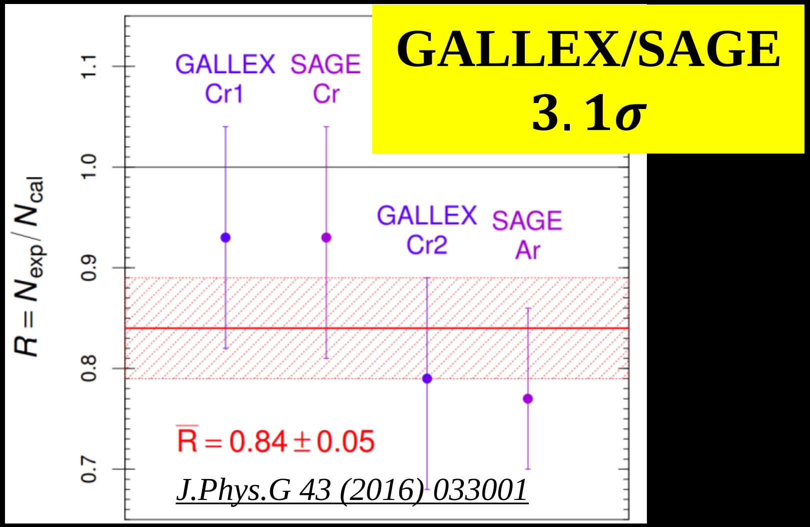




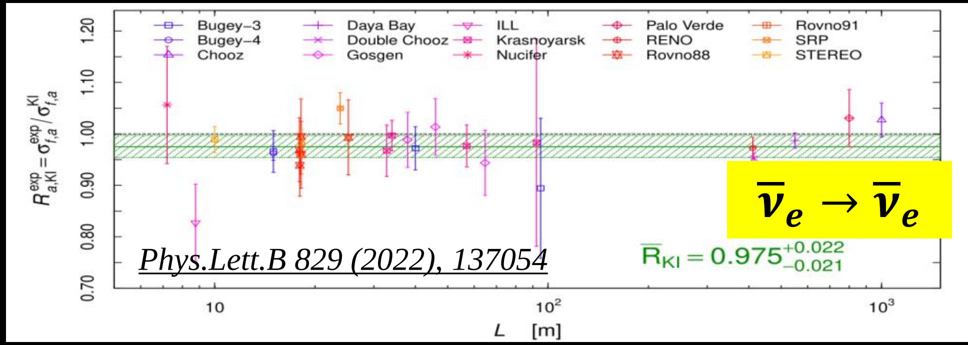








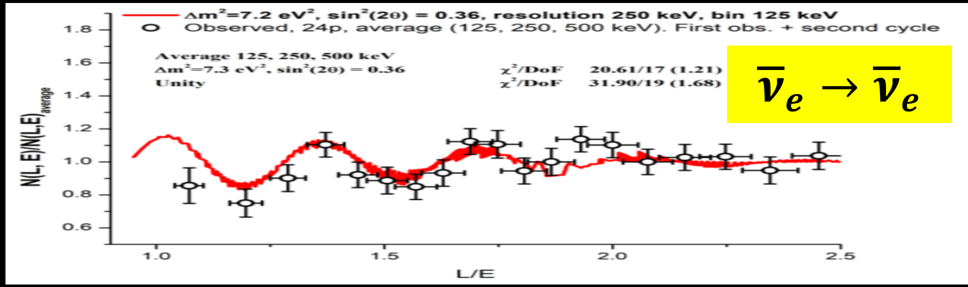
Short-Baseline Neutrino Anomalies
-- Hints of eV-Scale Neutrinos



Anomaly #1: Reactor Neutrino Flux

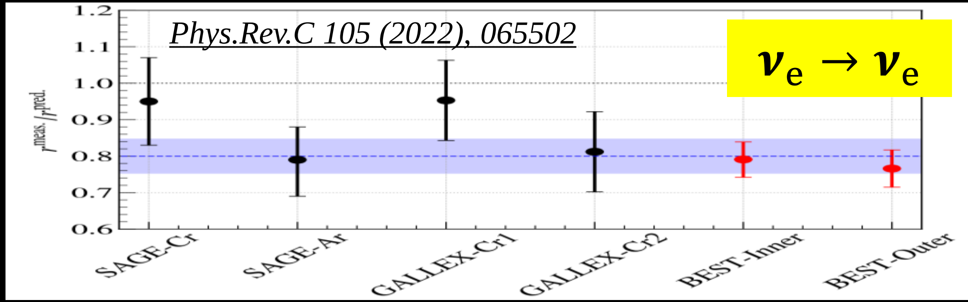
→Initially found issue of theory by Daya Bay experiment

→Resolved with new input data to flux calculation



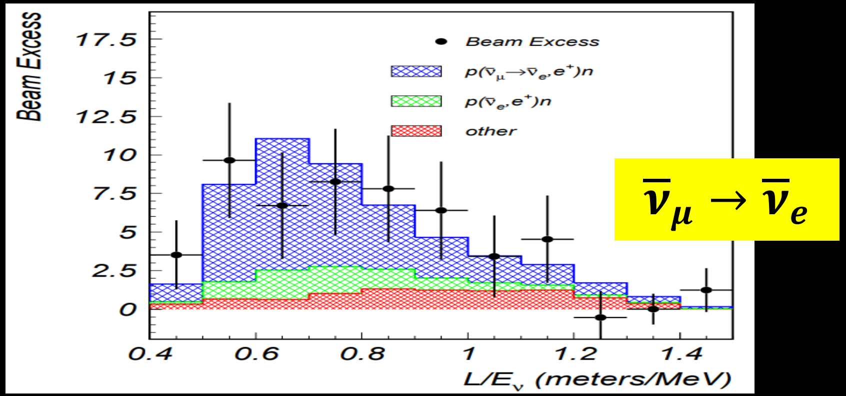
Anomaly #2: Neutrino-4 Reactor Spectra

→ In tension with other VSBL reactor nu expts.



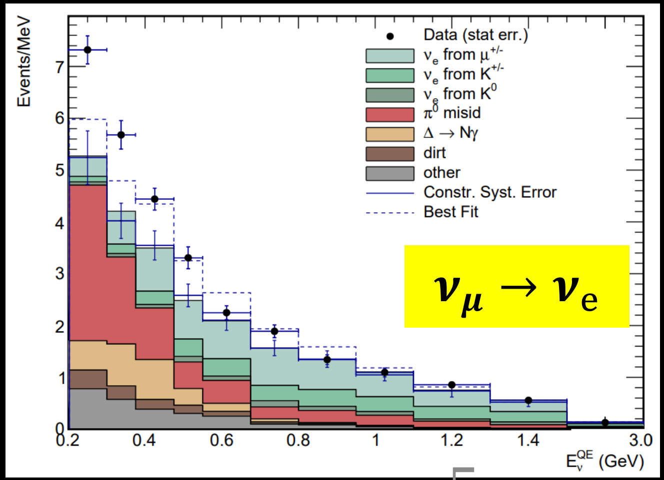
Anomaly #3: the Gallium Anomaly

→ Confirmed by the BEST



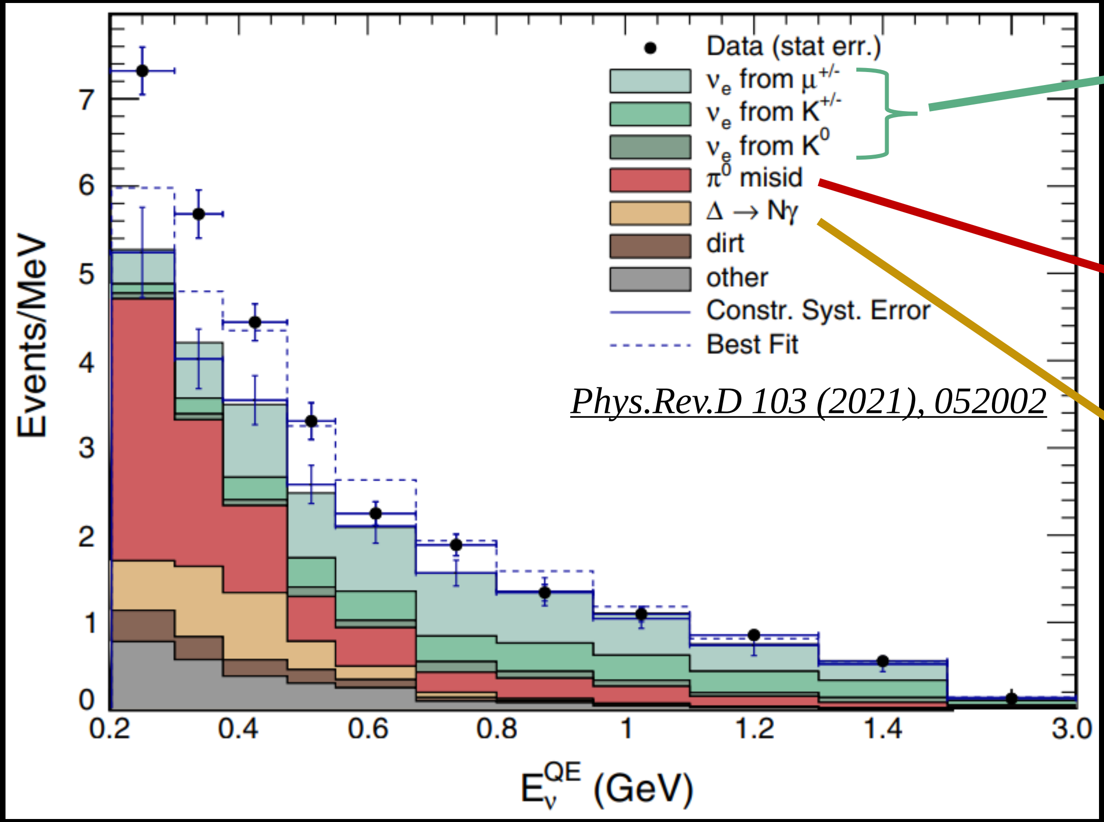
Anomaly #4: the LSND Anomaly

→ To be checked by JSNS^2



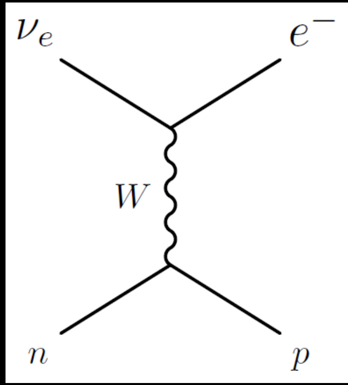
Anomaly #5: MiniBooNE LEE

MiniBooNE Anomaly: Low Energy Excess (LEE)

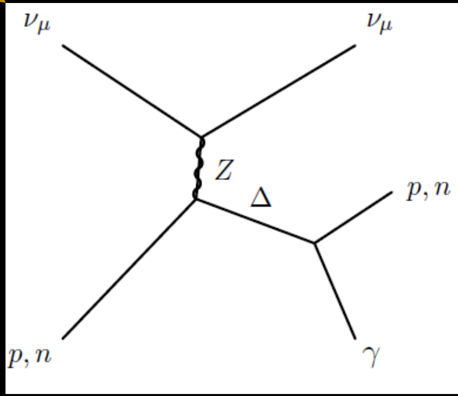


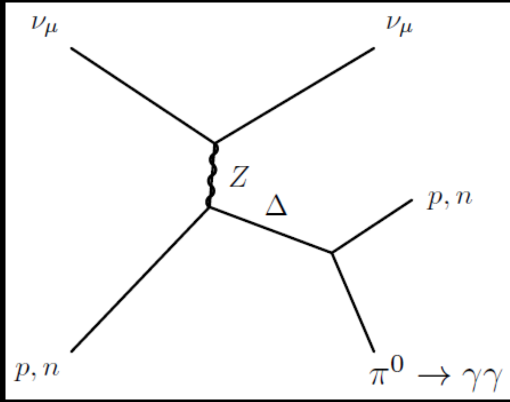
MiniBooNE (2002-2019) observed the LEE of electromagnetic events with 4.8σ significance.

Irreducible backgrounds. These are electron neutrinos from the beam

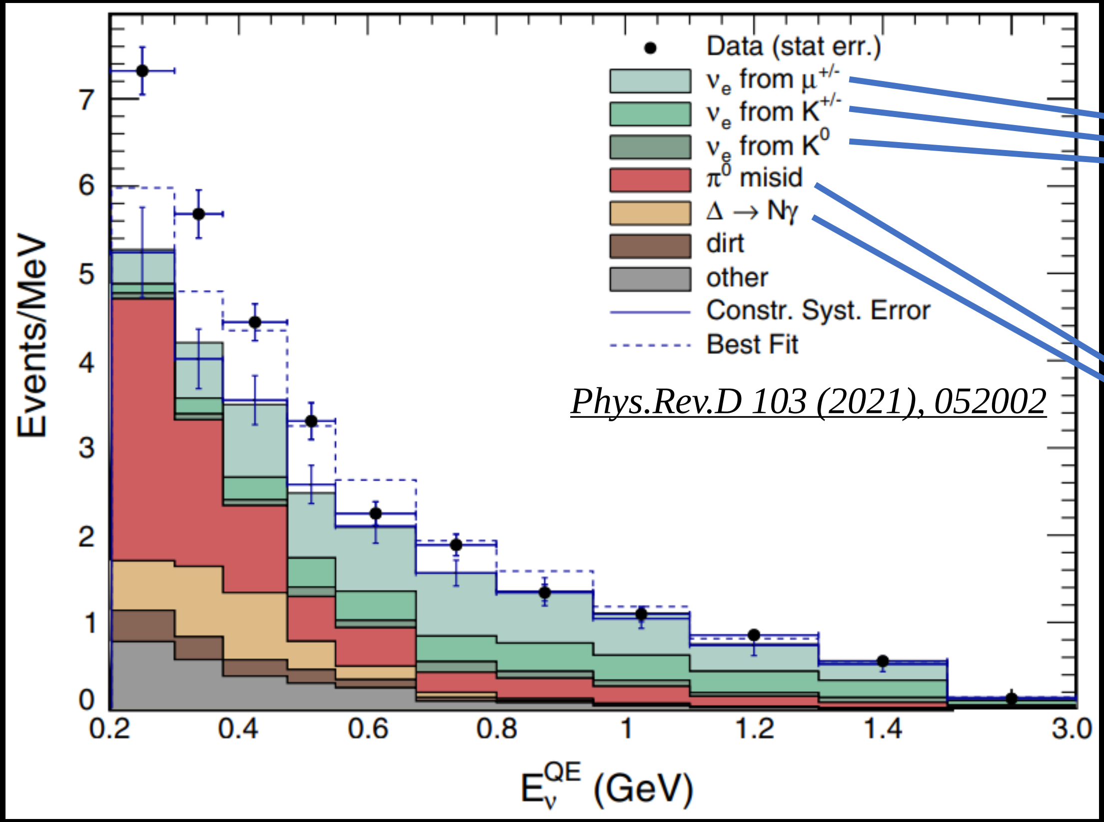


Single-gamma backgrounds





MiniBooNE Anomaly: Low Energy Excess (LEE) eLEE or gLEE?



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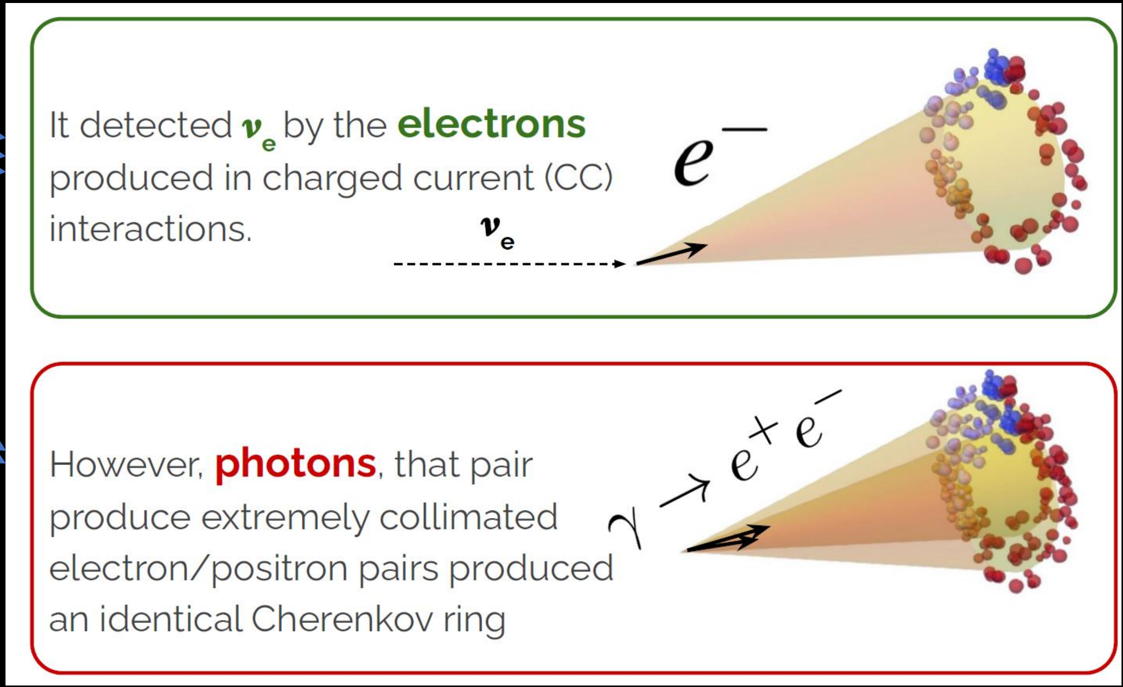
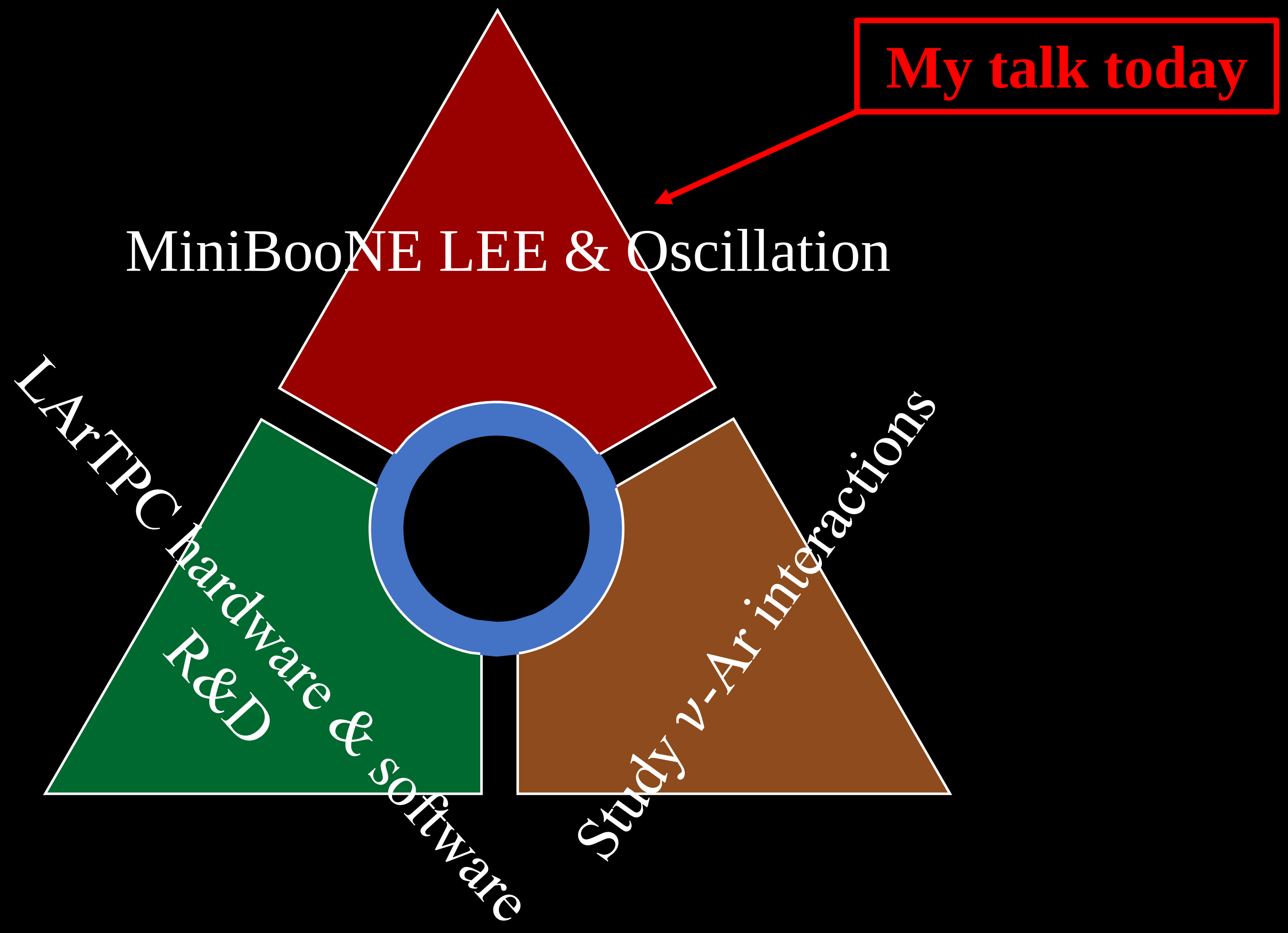


MiniBooNE Cherenkov detector unable to distinguish photons and electrons, and unable to detect hadronic final-state particles below Cherenkov threshold.

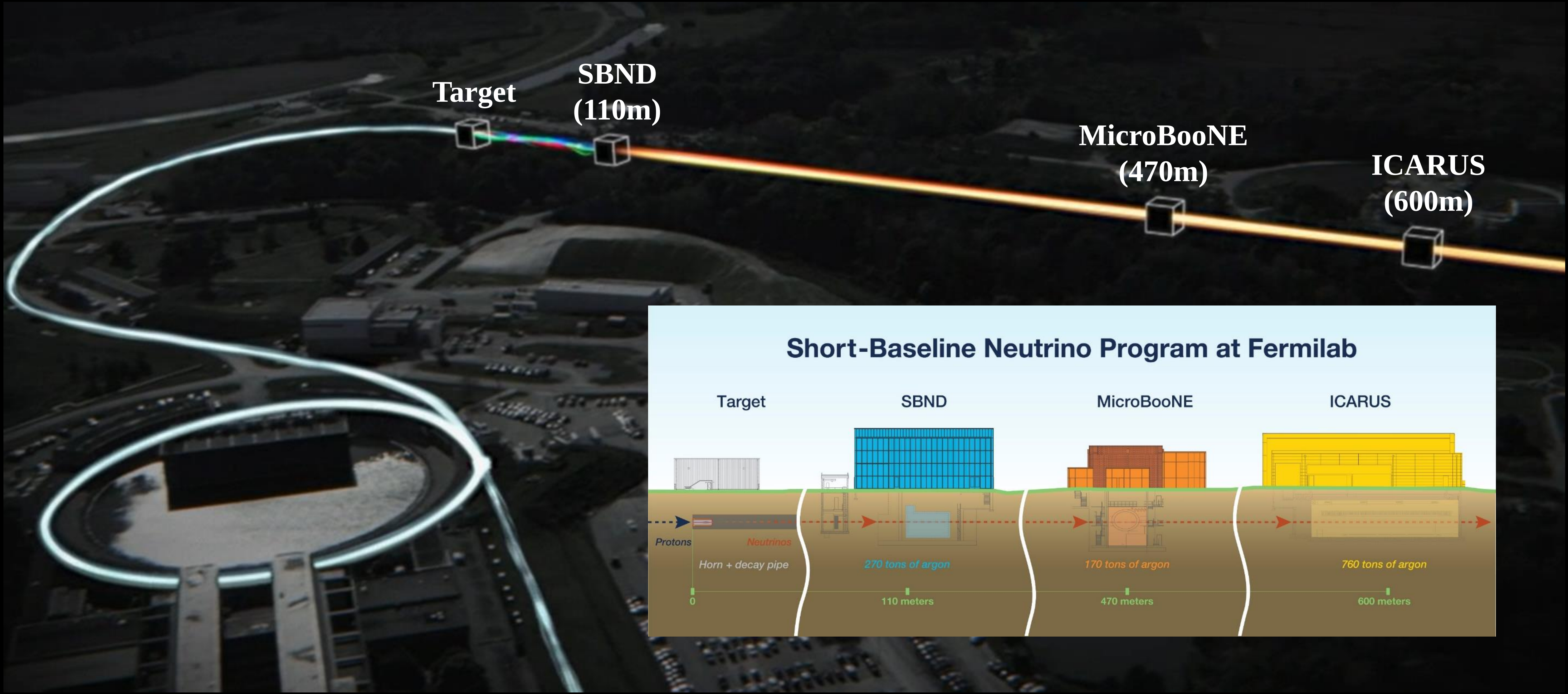
MicroBooNE Goals



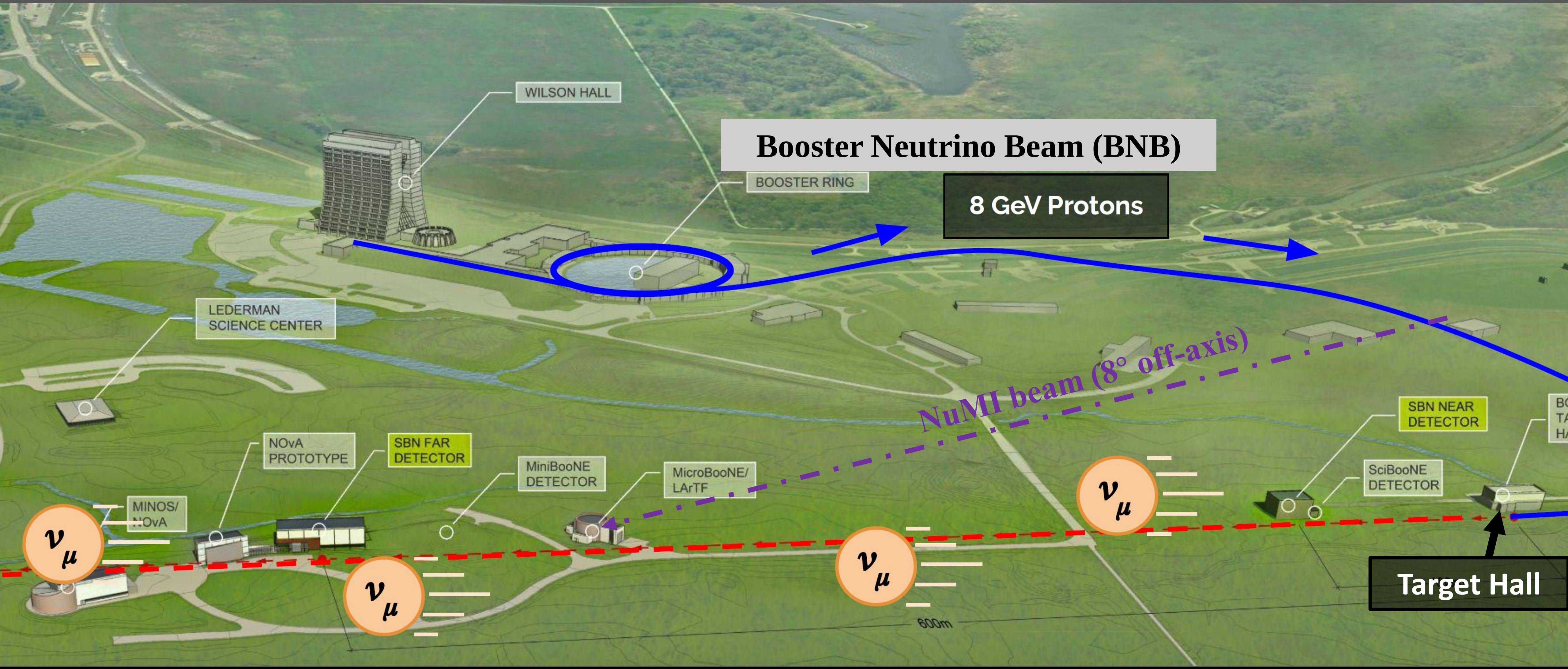
~180 collaborators, 39 institutions

μBooNE

the Micro Booster Neutrino Experiment (MicroBooNE)

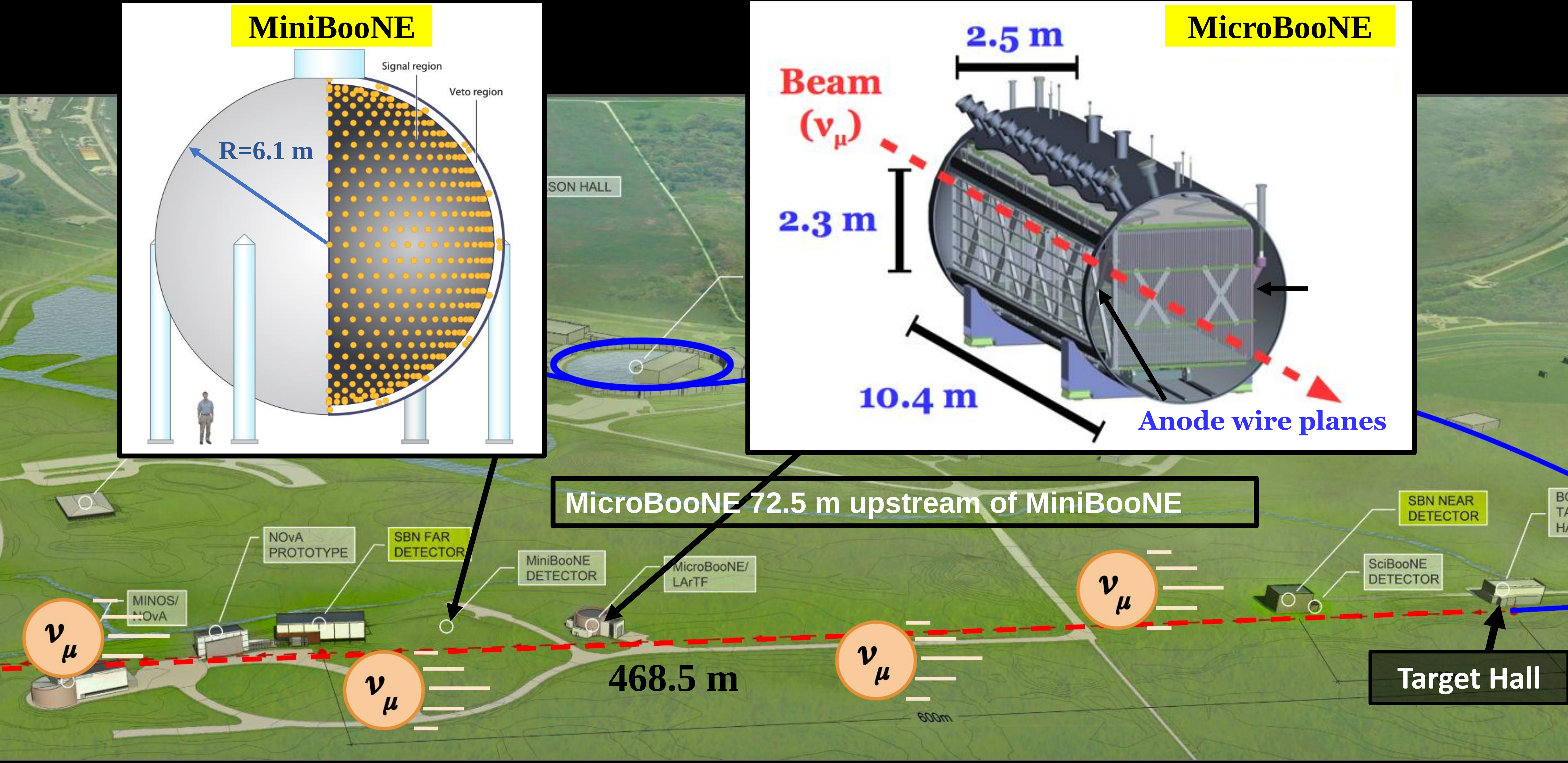

Target
SBND
(110m)
MicroBooNE
(470m)
ICARUS
(600m)
Short-Baseline Neutrino Program at Fermilab
Target
SBND
MicroBooNE
ICARUS
Protons
Neutrinos
Horn + decay pipe
270 tons of argon
170 tons of argon
760 tons of argon
0
110 meters
470 meters
600 meters

MicroBooNE @ Fermilab



Cherenkov detector: 820 ton mineral

170 (85) ton liquid argon in cryostat (TPC) volume

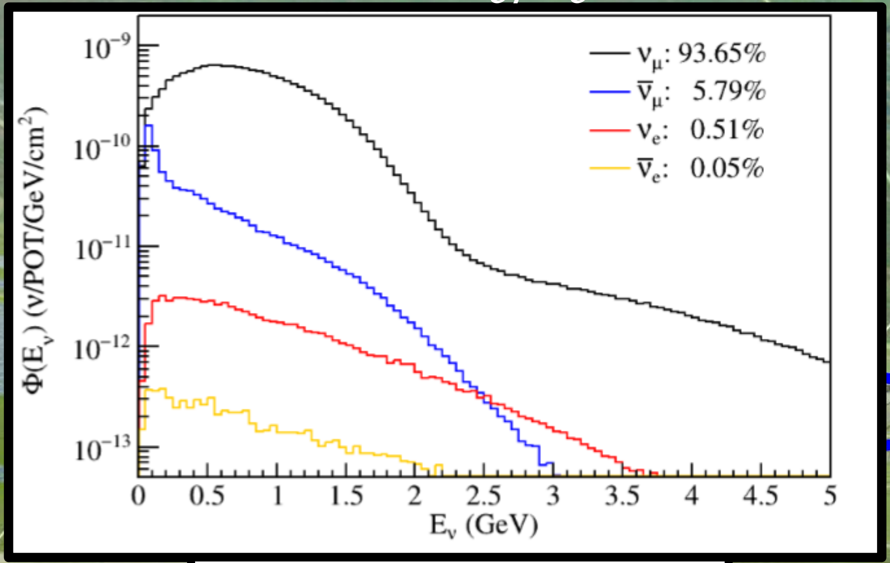


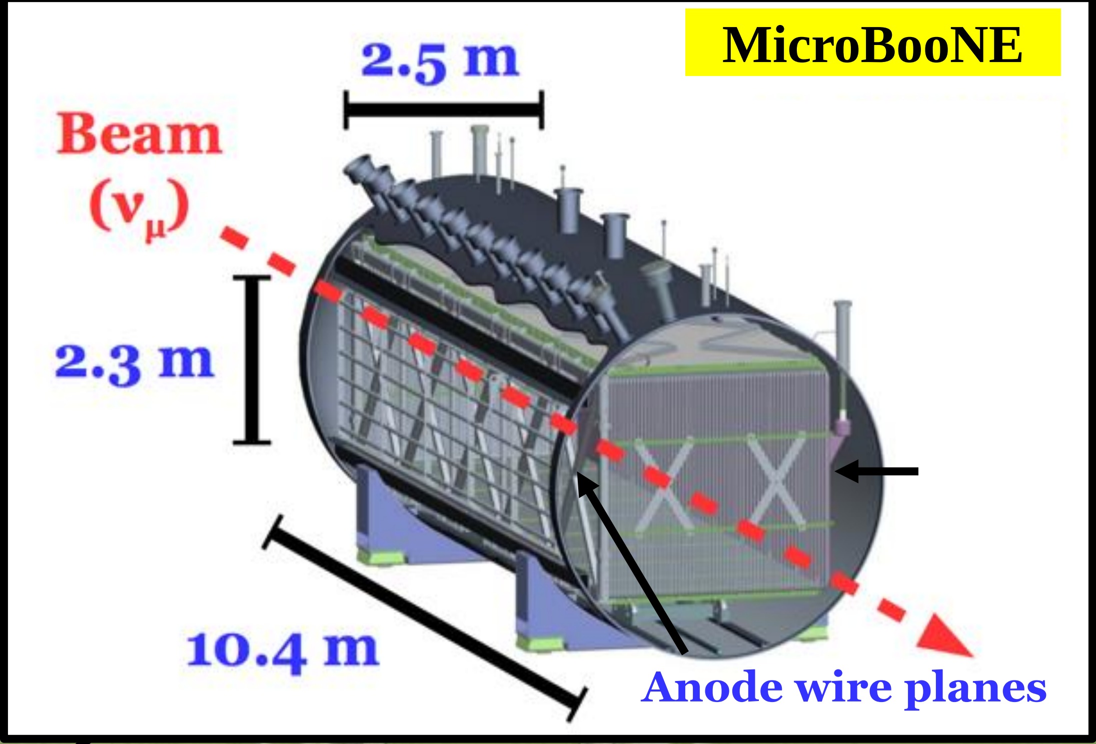
BNB @ MicroBooNE

Mean Neutrino Energy 0.8 GeV.

99.44% $\nu_\mu/\bar{\nu}_\mu$

0.56% $\nu_e/\bar{\nu}_e$



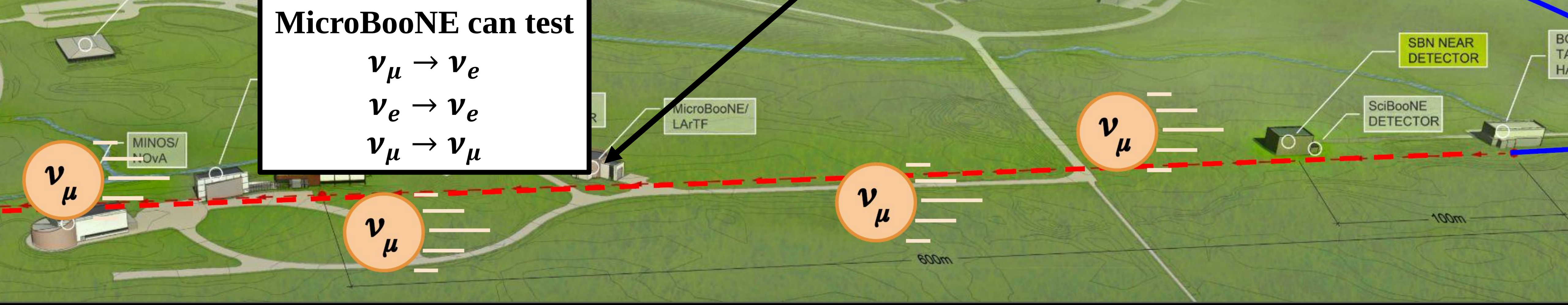


MicroBooNE can test

$\nu_\mu \rightarrow \nu_e$

$\nu_e \rightarrow \nu_e$

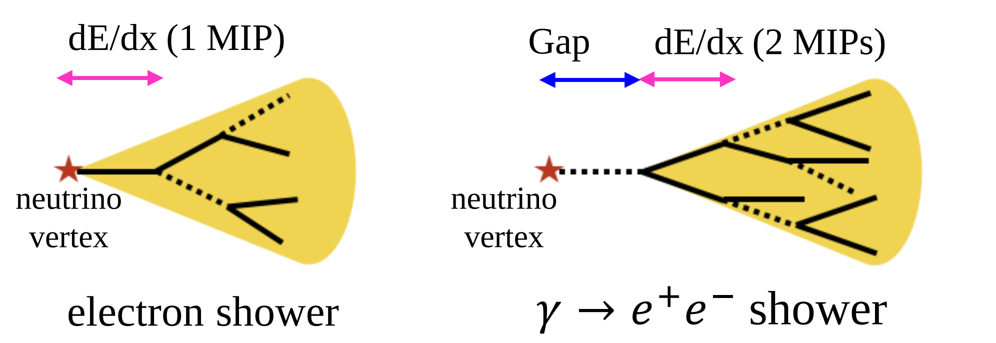
$\nu_\mu \rightarrow \nu_\mu$



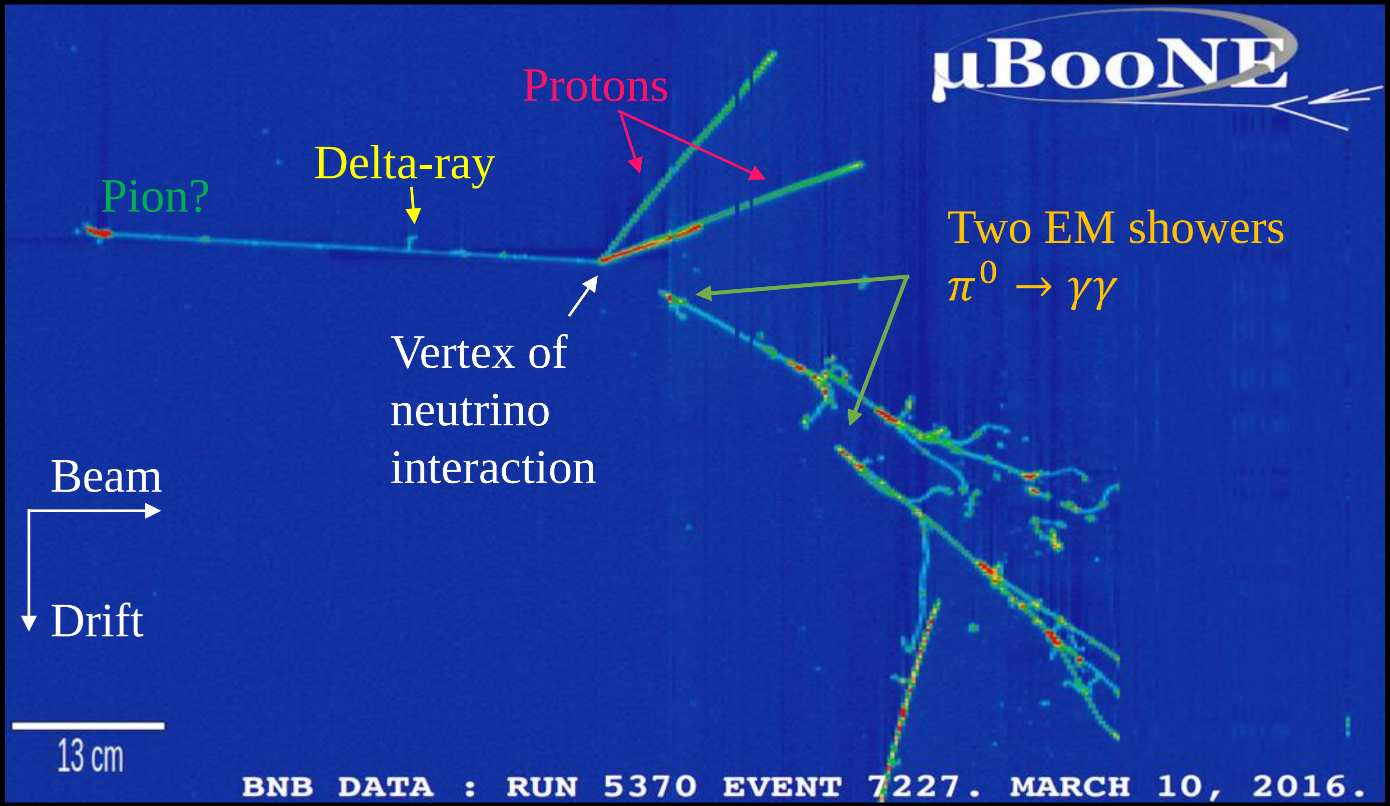
Liquid Argon Time Projection Chamber (LArTPC)

Capable of identifying different species of particles and reconstructing 3D images with fine-grained information

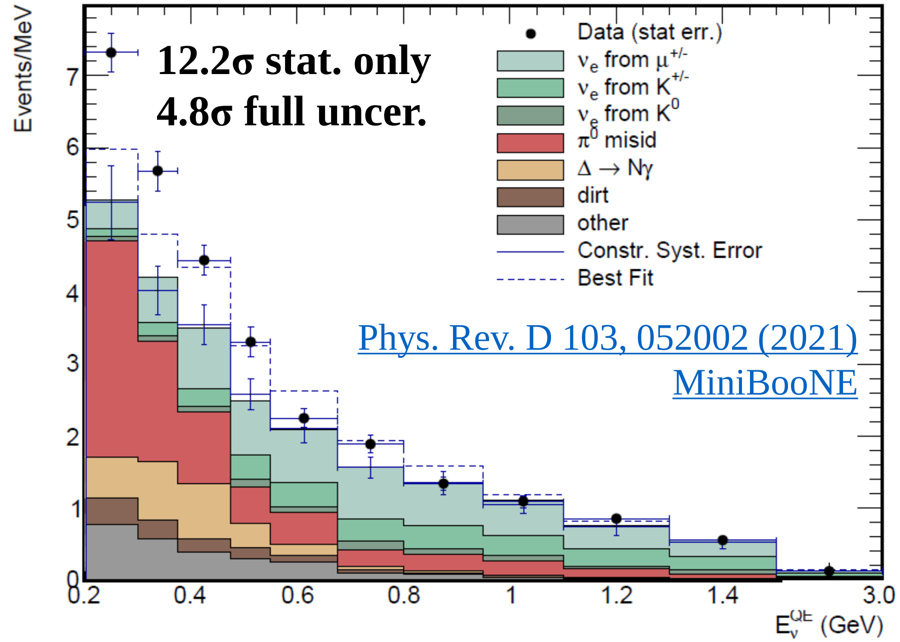
- Neutrino vertex
- Particle flow (mother-daughter relationship)
- Track (μ, π, p etc.) vs shower (e, γ EM cascade)
- ***e* vs γ (e^+e^- pair production) separation**
  - Gap between shower start point and nu vertex?
  - dE/dx in shower stem (1 MIP vs 2 MIPs)

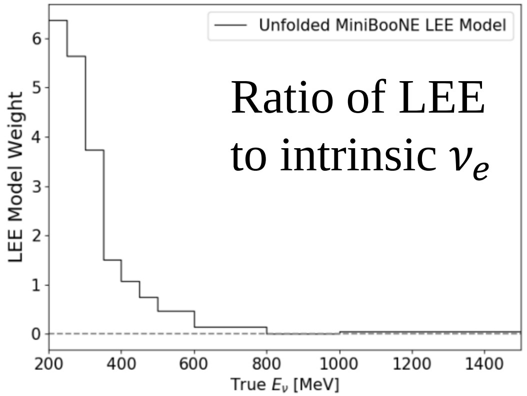


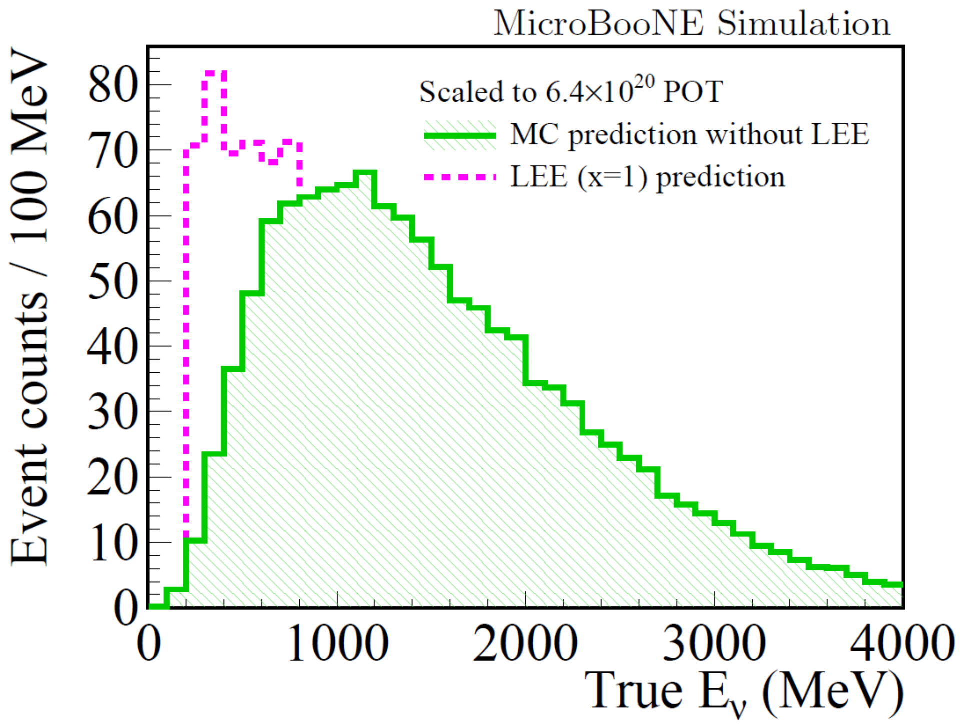
LArTPC: high-resolution tracking + fully active calorimeter



Model of eLEE for the search in MicroBooNE (electron Low Energy Excess)



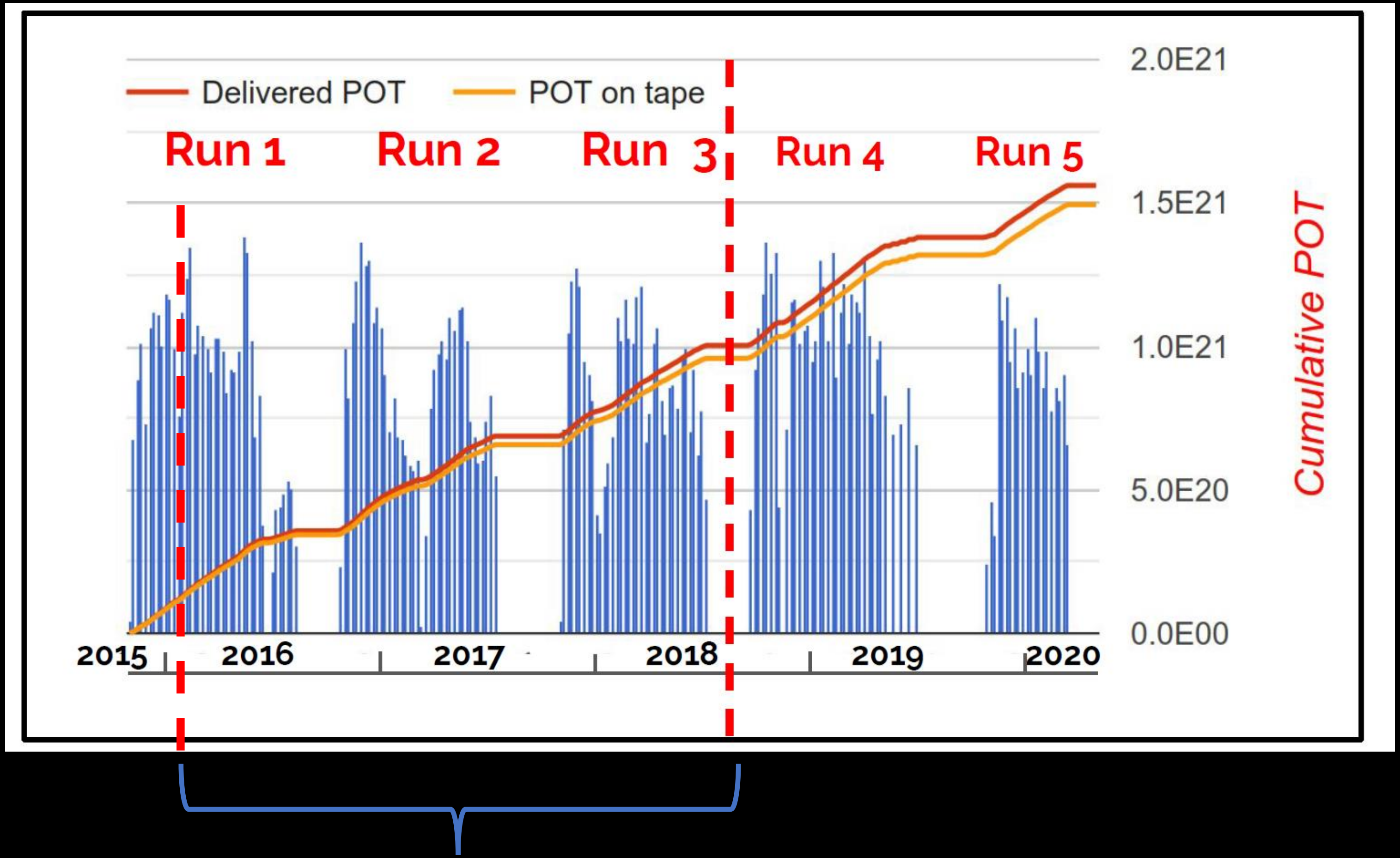




- eLEE is built upon the intrinsic ν_e as a function of neutrino energy
  - Unfolded from MiniBooNE observation and applied to MicroBooNE
- One normalization parameter 'x' built in the model

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

MicroBooNE ran 2015-2021, amassed the largest sample of neutrino interactions on argon in the world



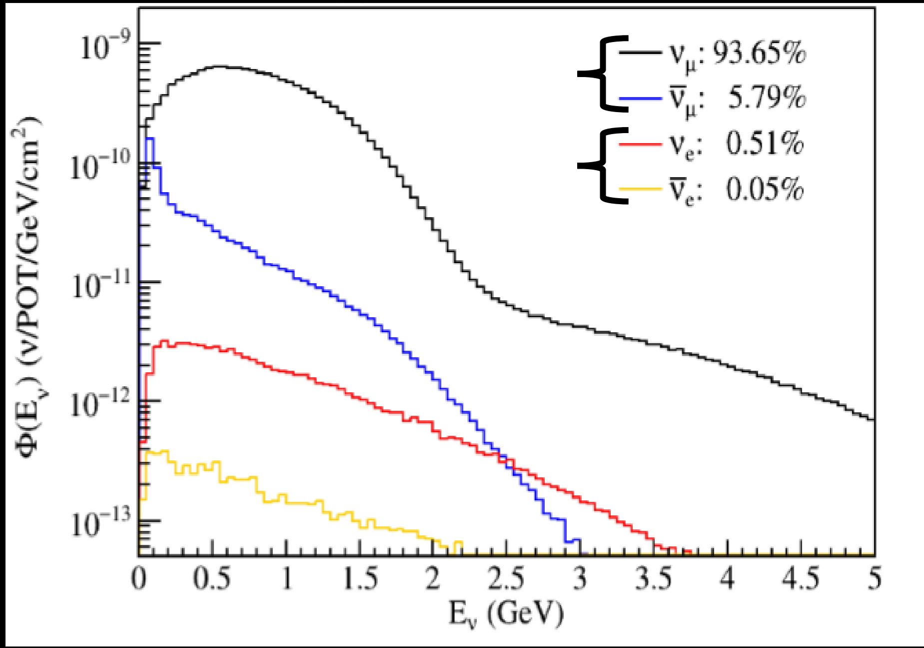
In this talk, I will present results based on $\sim 7 \times 10^{20}$ protons on target (POT) from Run 1-3

Challenging ν_e Selection

Cosmic-ray muon (5.5 kHz) @ MicroBooNE operating near-surface

- BNB beam spill triggers a 4.8 ms TPC window
- ~600 beam spills → 1 nu interaction

BNB neutrino flux
over 99% ν_μ / $\bar{\nu}_\mu$
~0.5% ν_e/ $\bar{\nu}_e$



A sensitive ν_e selection (CC interactions) requires

≳99.999% rejection of cosmic-ray muons and

≳99.9% rejection of other ν background for nue analysis

Developed advanced cosmic rejection techniques, event reconstruction and PID algorithms to exploit LArTPC capability to select ν_e events

Three independent eLEE searches

Targeting different final states with different novel reconstruction approaches developed in MicroBooNE

- Restricting to quasi-elastic kinematics: 1e1p, Deep-learning-based reconstruction
  Phys. Rev. D105, 112003 (2022)
- MiniBooNE like-final state: 1eNp0π and 1e0p0π, Pandora-based reconstruction
- All ν_e final states: 1eX, Wire-Cell reconstruction

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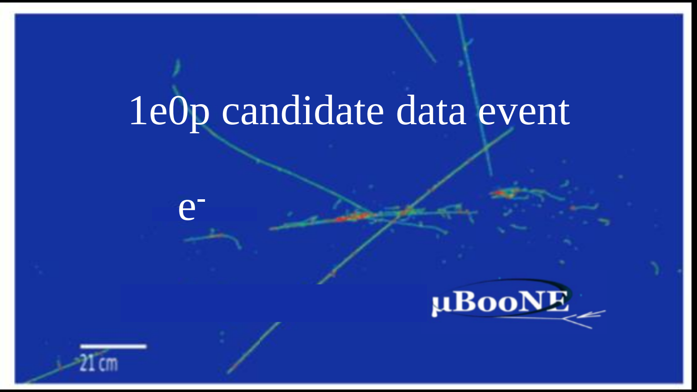

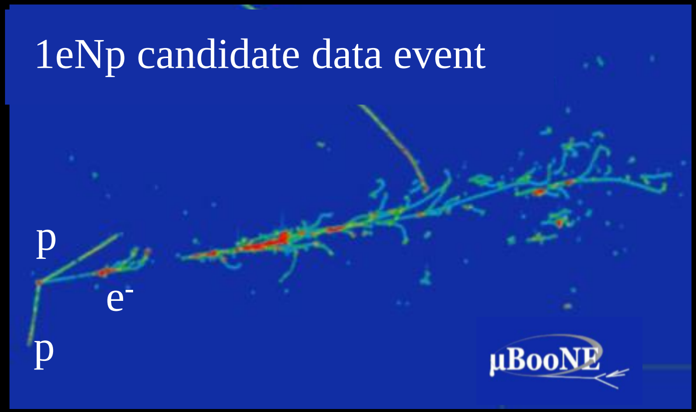

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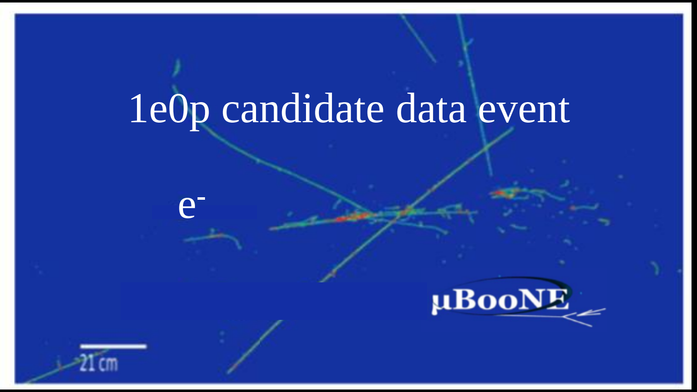
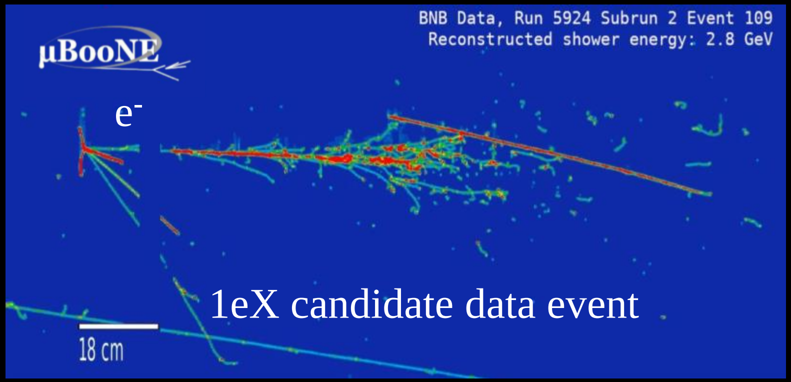
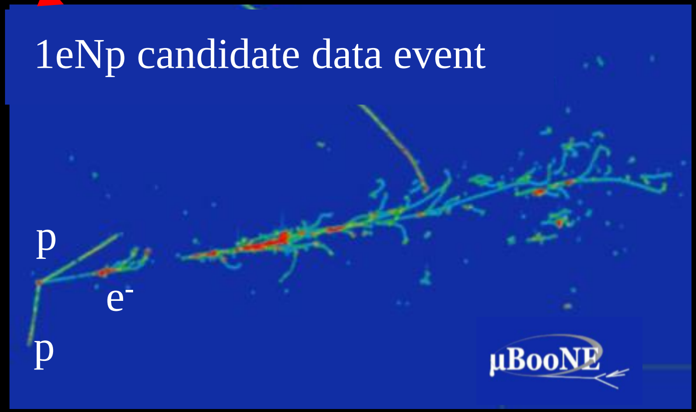
Phys. Rev. D105, 112005 (2022)

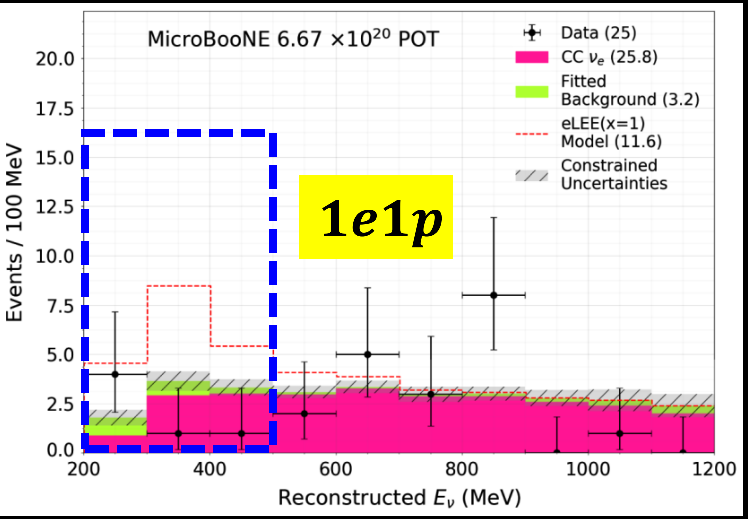


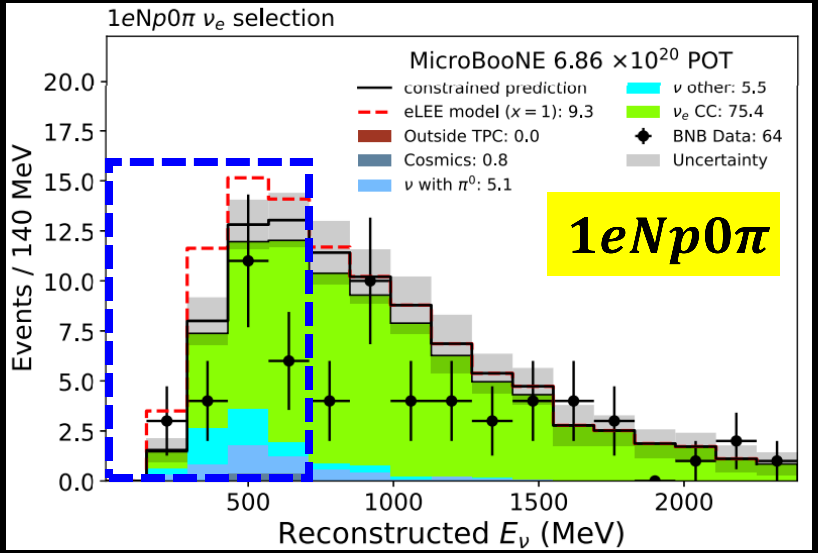


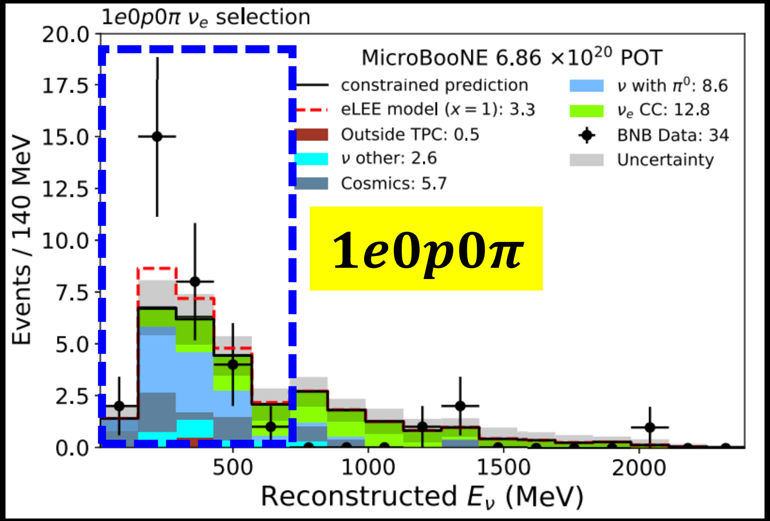


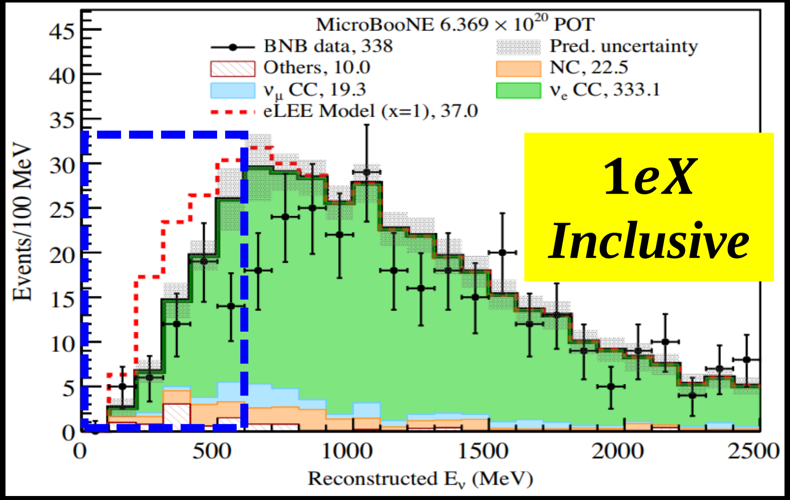
eLEE Search Results

- **No observation of ν_e candidate excess in low energy region, except for the low-ν_e-purity ($1e0p0\pi$) channel**







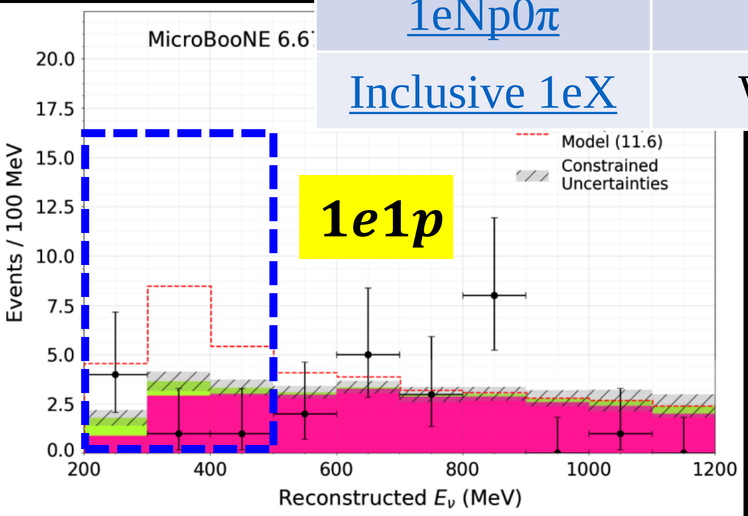


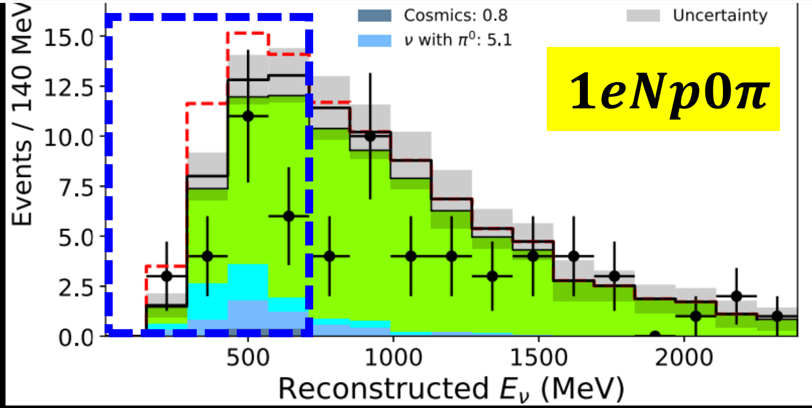
Phys. Rev. D105, 112003 (2022)
Phys. Rev. D105, 112004 (2022)
Phys. Rev. D105, 112005 (2022)
Phys. Rev. Lett. 128, 241801 (2022)

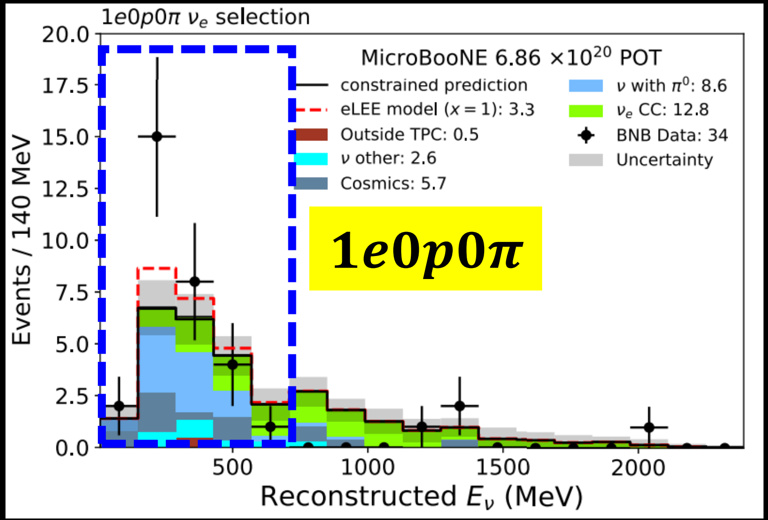
eLEE

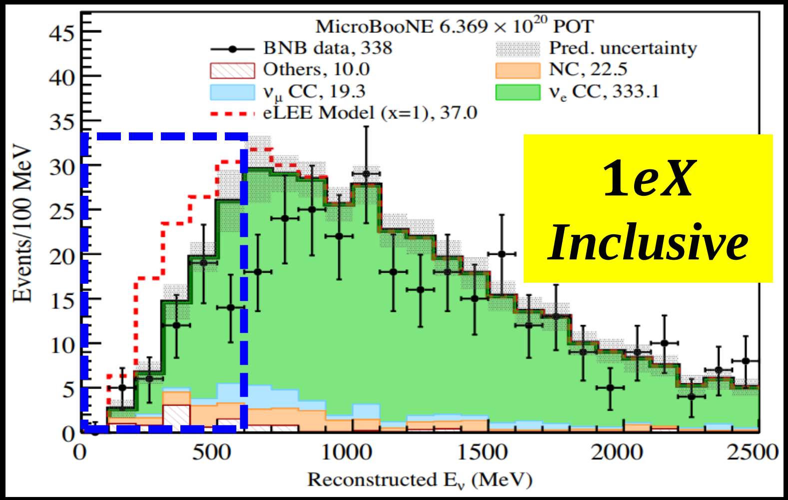
Channels	Reconstruction	Efficiency	Purity	Data Events
CCQE 1e1p	Deep Learning	6.6%	75%	25
1e0p0π	Pandora	9%	43%	34
1eNp0π	Pandora	15%	80%	64
Inclusive 1eX	Wire-Cell	46%	82%	606

- **No observation of ν_e candidate excess in low energy region, except for the low-ν_e-purity ($1e0p0\pi$) channel**









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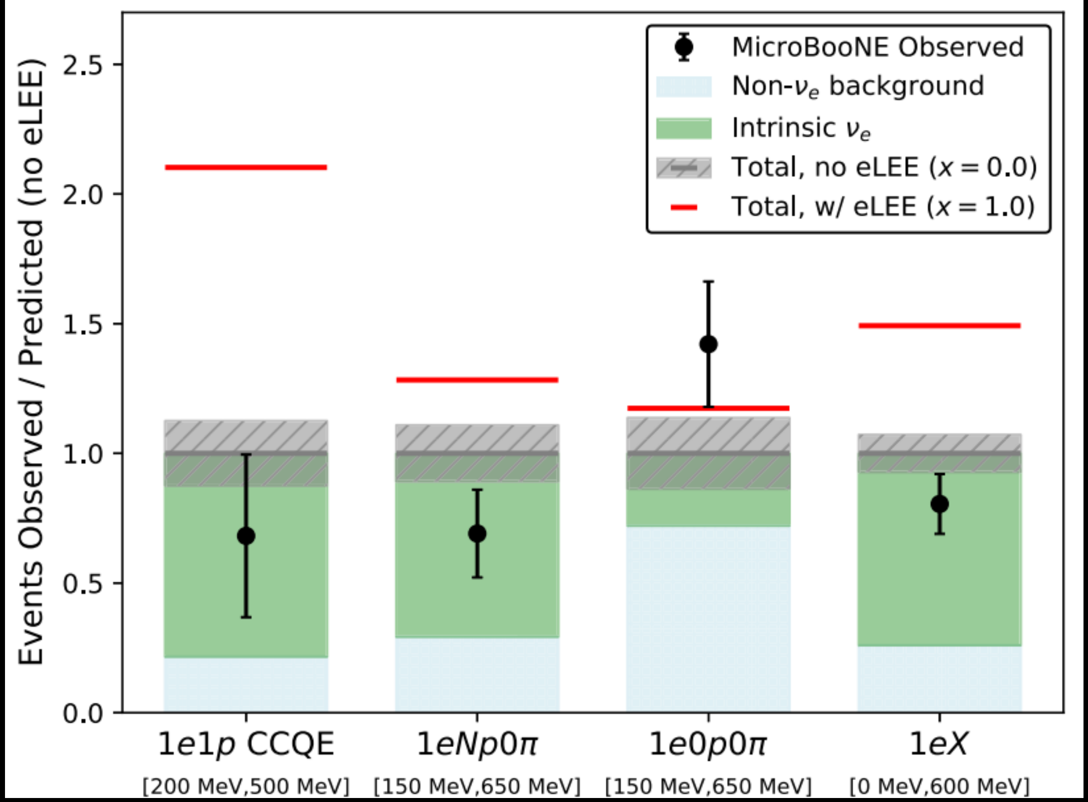
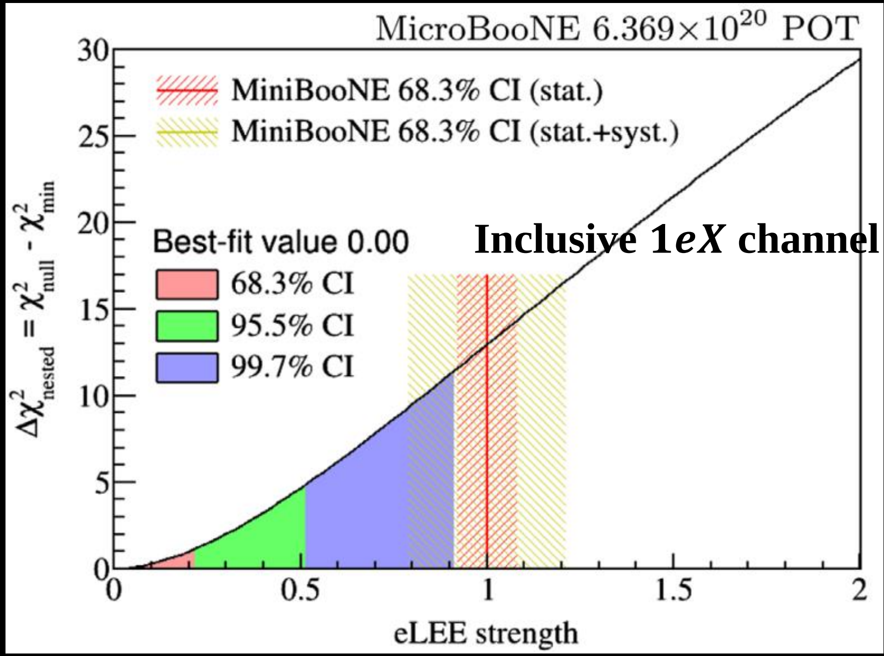
eLEE Search Results



- Observed ν_e candidate rates are statistically consistent with the predicted background rates in the LEE region
- With exception of the low-ν_e-purity ($1e0p0\pi$) channel, the hypothesis that ν_e events are fully responsible for the median MiniBooNE LEE is rejected at > 97% C.L.; > 3σ in the inclusive $1eX$ channel



Phys. Rev. D105, 112003 (2022)
Phys. Rev. D105, 112004 (2022)
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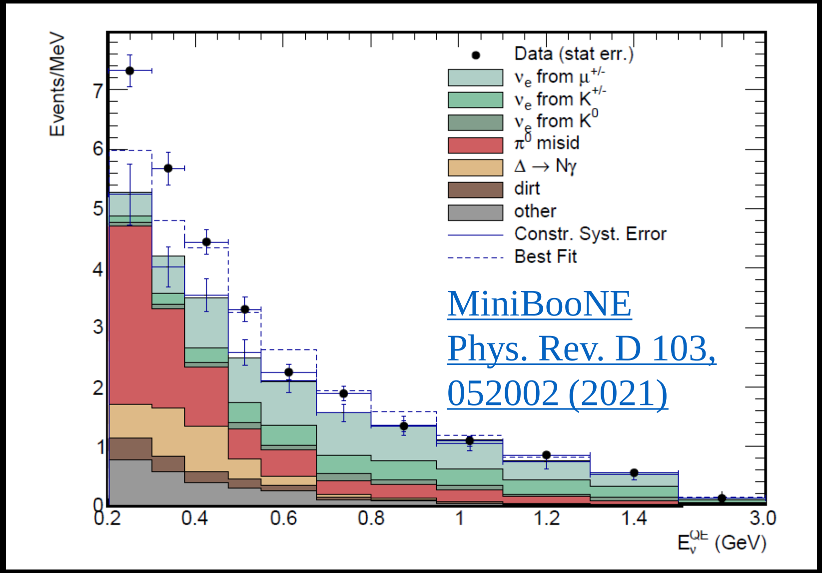
Phys. Rev. Lett. 128, 241801 (2022)

MiniBooNE Excess and Sterile Neutrinos

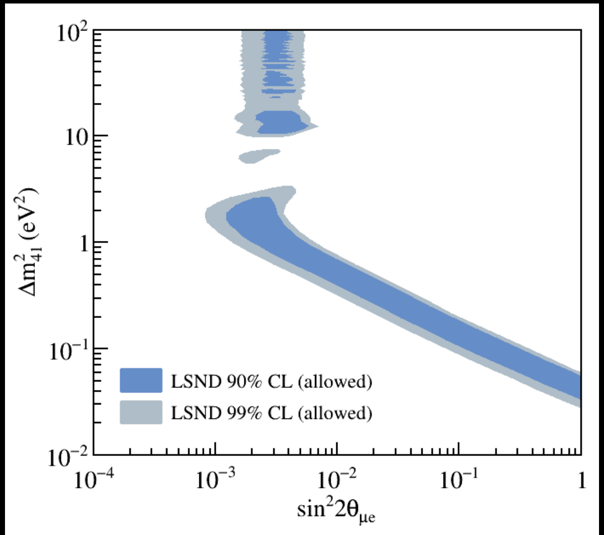


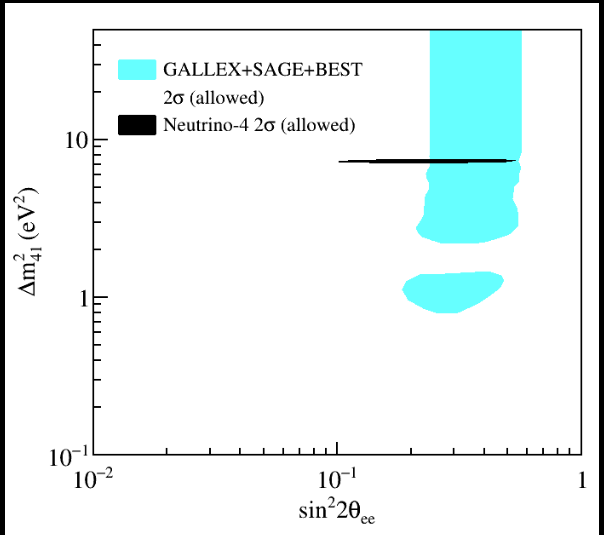
MiniBooNE Phys. Rev. D 103, 052002 (2021)

- The MicroBooNE eLEE result disfavors the MiniBooNE anomaly originating from a pure ν_e excess.
- The existence of sterile neutrinos cannot be ruled out by the MicroBooNE eLEE result which is a generic low energy ν_e excess search.

The MicroBooNE eLEE results can be reinterpreted under a sterile neutrino oscillation hypothesis:

A combination of short-baseline ν_e appearance and ν_e disappearance





3(active)+1(sterile) 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 $\frac{\nu_e \text{ flux rate}}{\nu_\mu \text{ flux rate}} \sim 0.005$

Cancellation of ν_e Appearance and ν_e Disappearance → Degeneracy of Oscillation Parameters

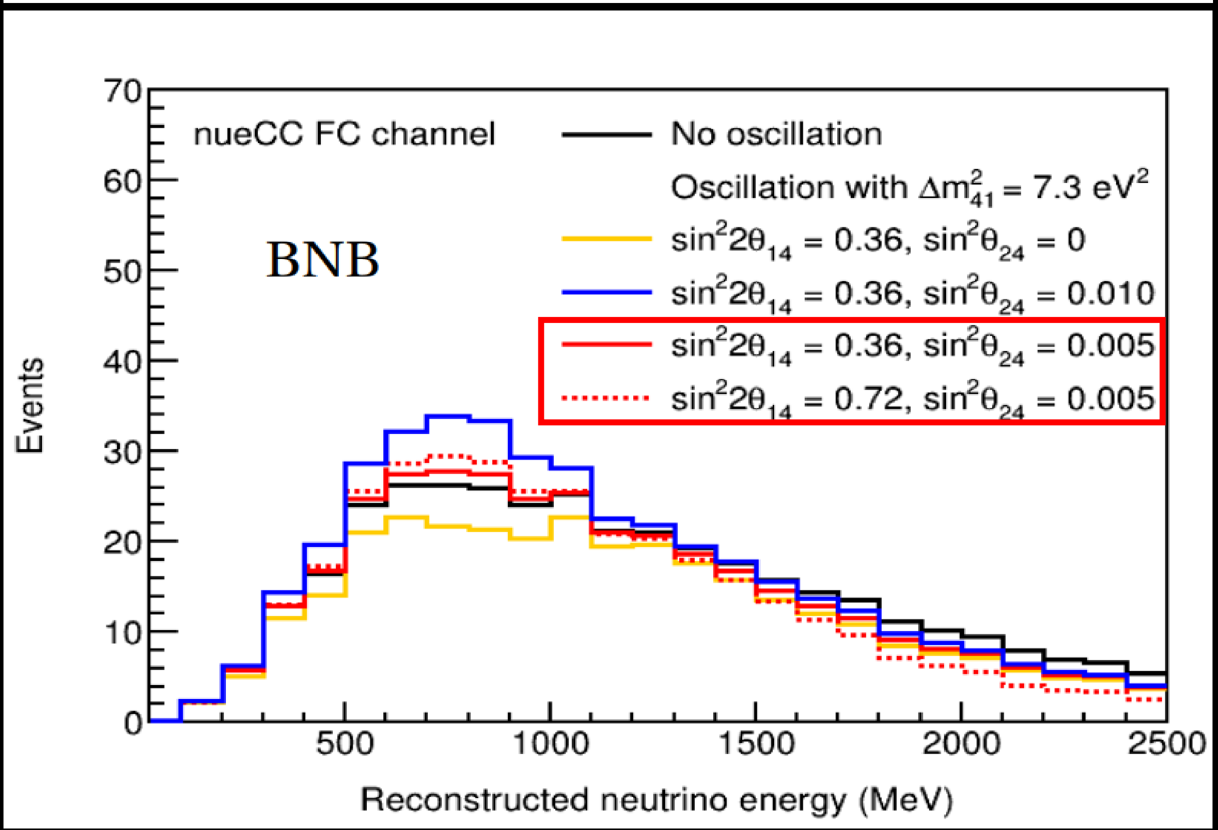
- Observed ν_e events are a combination result of ν_e appearance and disappearance

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

- Degeneracy when $\sin^2\theta_{24}$ approaches R_{ν_e/ν_μ} (the ratio of beam intrinsic ν_e and ν_μ flux)

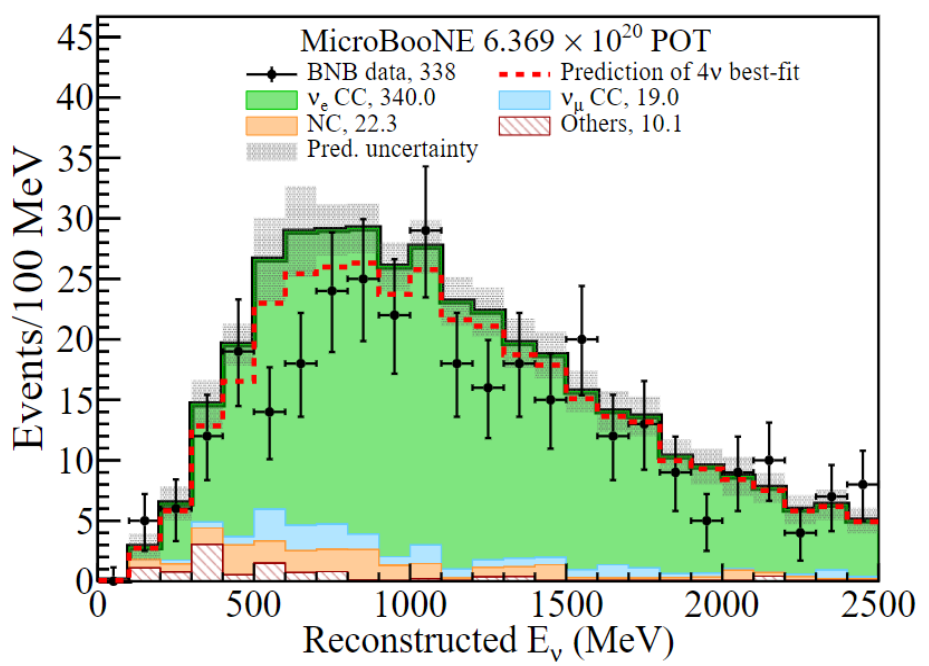
- Sensitivity/exclusion limits become much worse around the degeneracy point

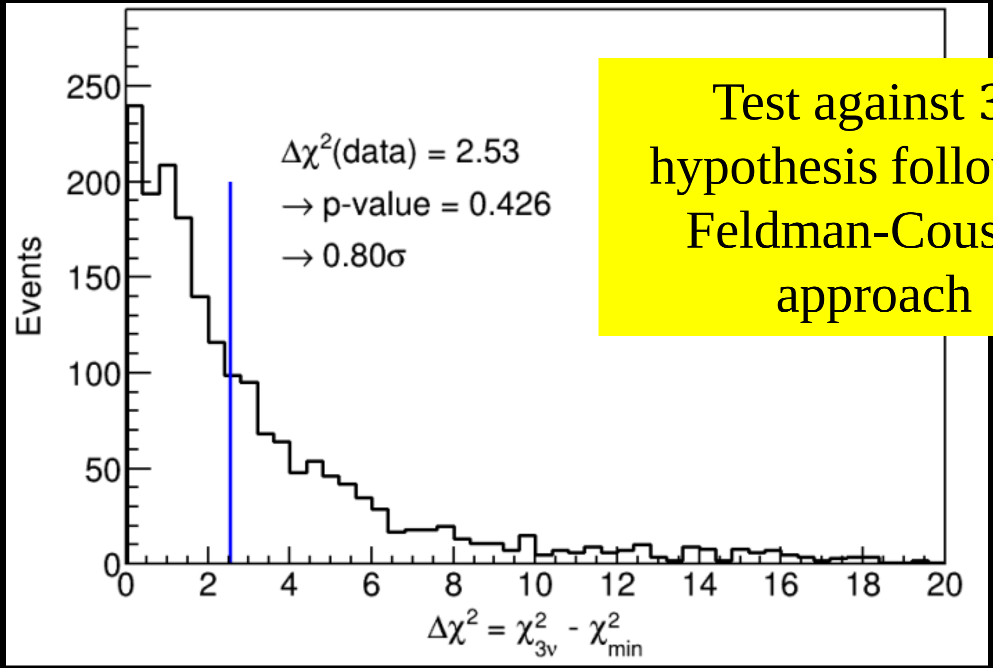
	R_{ν_e/ν_μ} (degeneracy $\sin^2\theta_{24}$ value)
MicroBooNE w. BNB	~0.005 (average)



3+1 Oscillation Analysis using Wire-Cell Inclusive Selections

3+1 oscillation best-fitting results





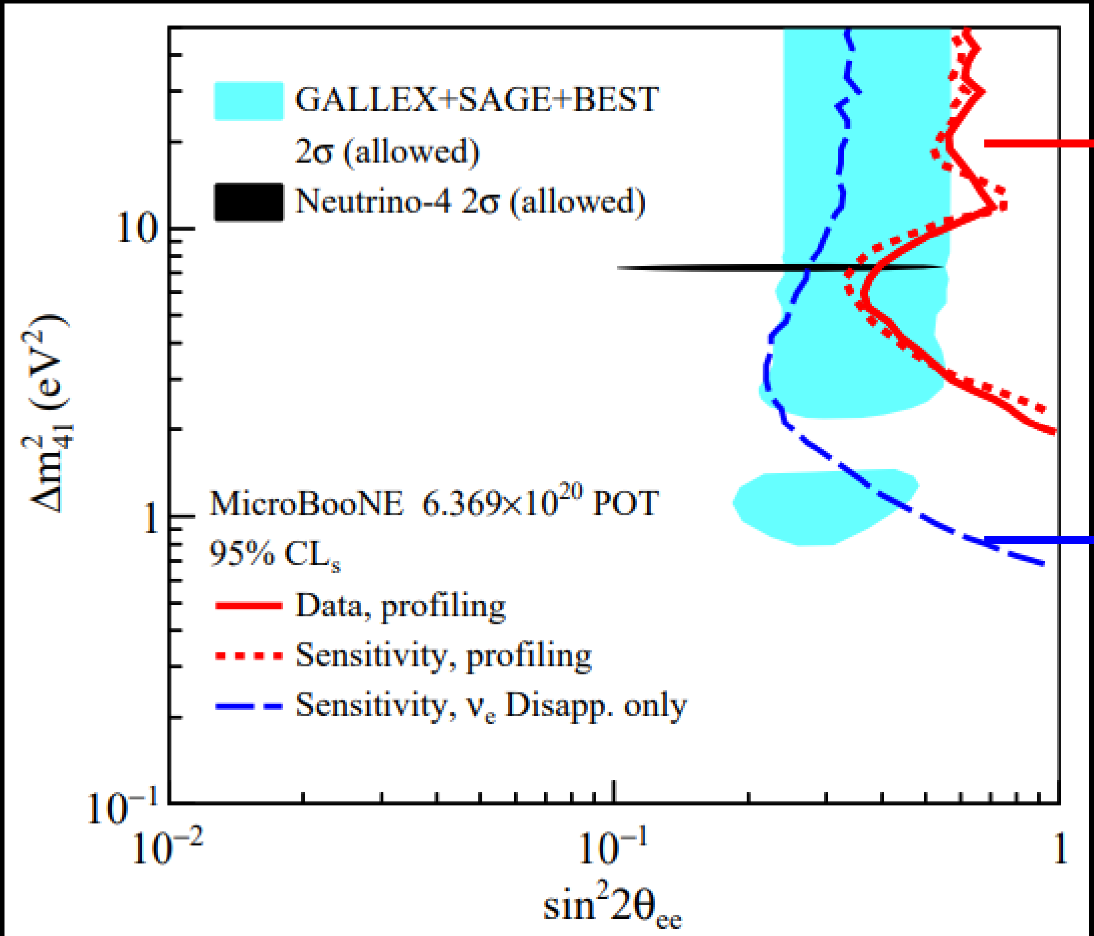
Test against 3ν hypothesis following Feldman-Cousins approach

The BNB data result is found to be consistent with the 3ν hypothesis within 1σ following the F-C approach

MicroBooNE 3+1 Exclusion Results: Δm^2_{41} vs. $\sin^2 2\theta_{ee}$

Phys. Rev. Lett. 130, 011801 (2023)

MicroBooNE: Half of BNB dataset



- 2D profiled result, full 3+1 analysis at each point in the parameter space.
- Oscillation effects considered:

$$\nu_\mu \to \nu_e$$
$$\nu_e \to \nu_e$$
$$\nu_\mu \to \nu_\mu$$

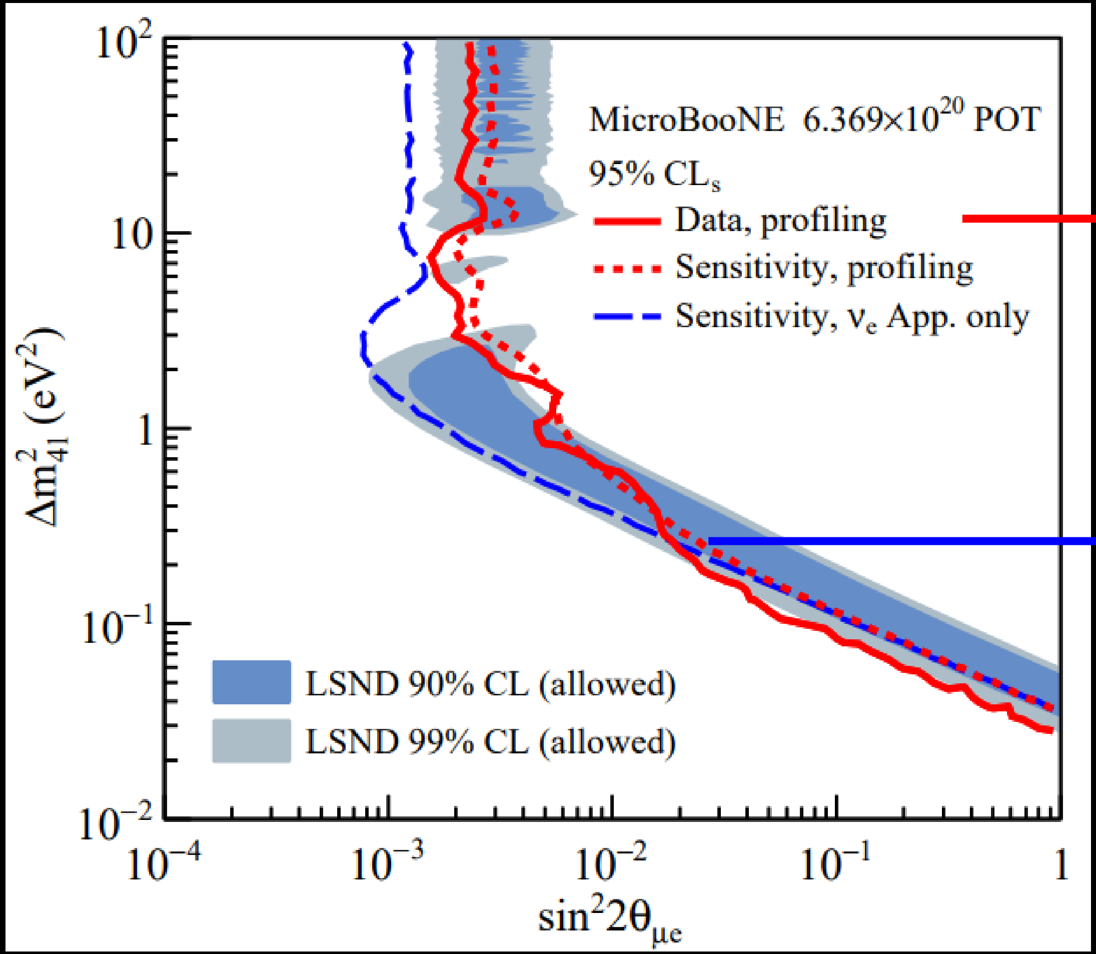
- ν_e disappearance-only, more stringent limit corresponding to a fixed $\sin^2\theta_{24} = 0$.
- Oscillation effects considered:

$$\nu_e \to \nu_e$$

MicroBooNE 3+1 Exclusion Results: Δm^2_{41} vs. $\sin^2 2\theta_{\mu e}$

Phys. Rev. Lett. 130, 011801 (2023)

MicroBooNE: Half of BNB dataset



- 2D profiled result, full 3+1 analysis at each point in the parameter space.
- Oscillation effects considered:

$$\nu_\mu \to \nu_e$$
$$\nu_e \to \nu_e$$
$$\nu_\mu \to \nu_\mu$$

- ν_e appearance-only, 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)
- Oscillation effects considered:

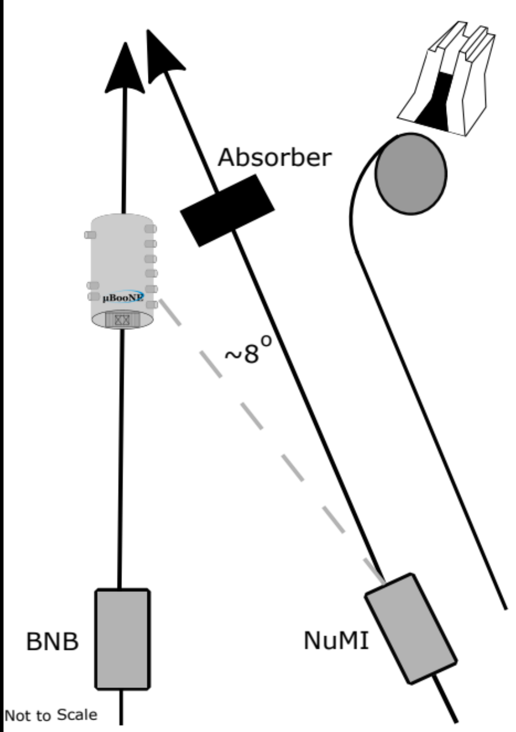
$$\nu_\mu \to \nu_e$$

Breaking the Degeneracy

- Observed ν_e events are a combination result of ν_e appearance and disappearance

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

- Degeneracy when $\sin^2\theta_{24}$ approaches R_{ν_e/ν_μ} (the ratio of beam intrinsic ν_e and ν_μ flux)



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

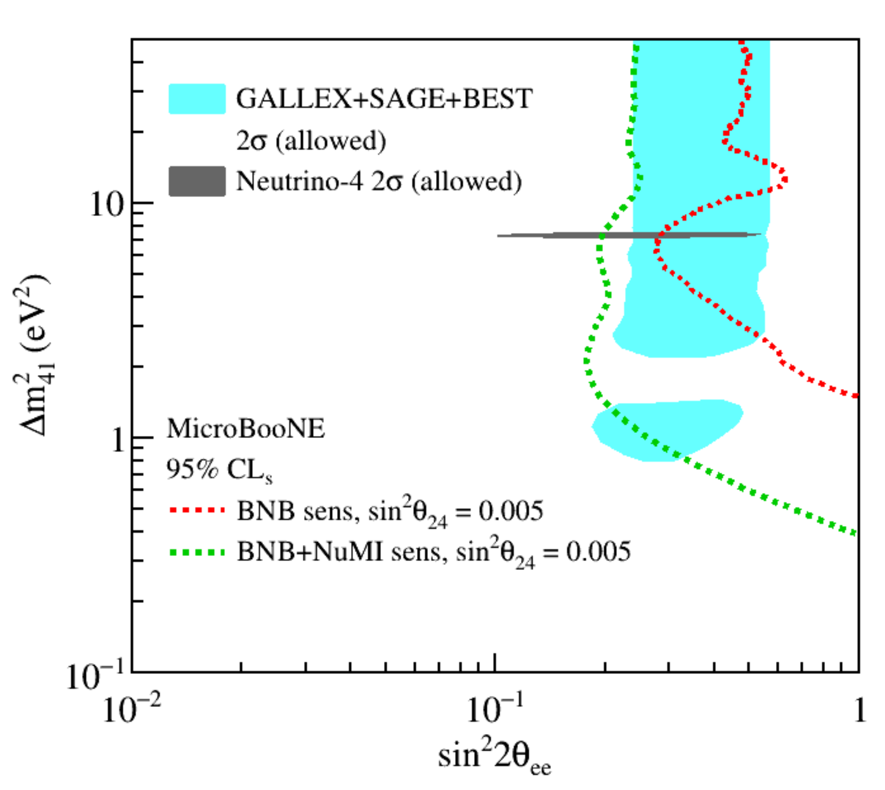
Two neutrino beams at MicroBooNE:

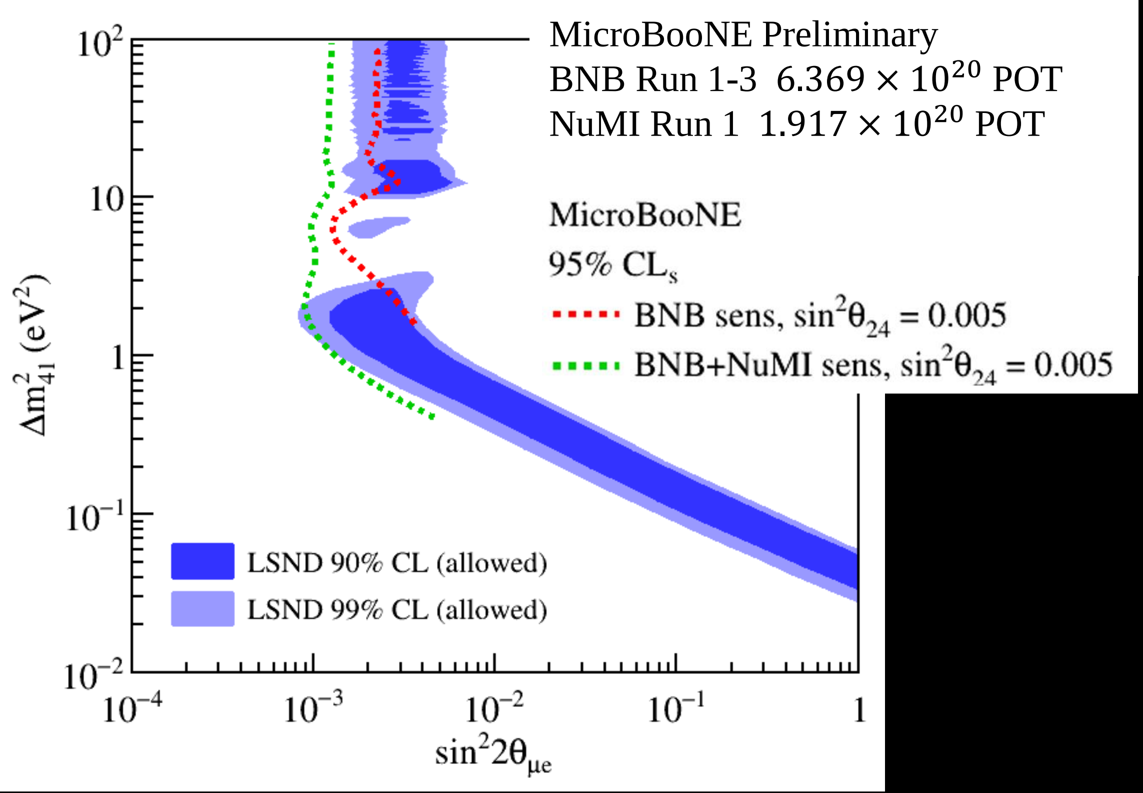
- BNB, on-axis, baseline ~470m
- NuMI, off-axis, baseline ~680m

Significant difference in the numu/nue ratio in BNB and NuMI → mitigate the degeneracy

MicroBooNE 3+1 Sensitivity Results by using BNB+NuMI

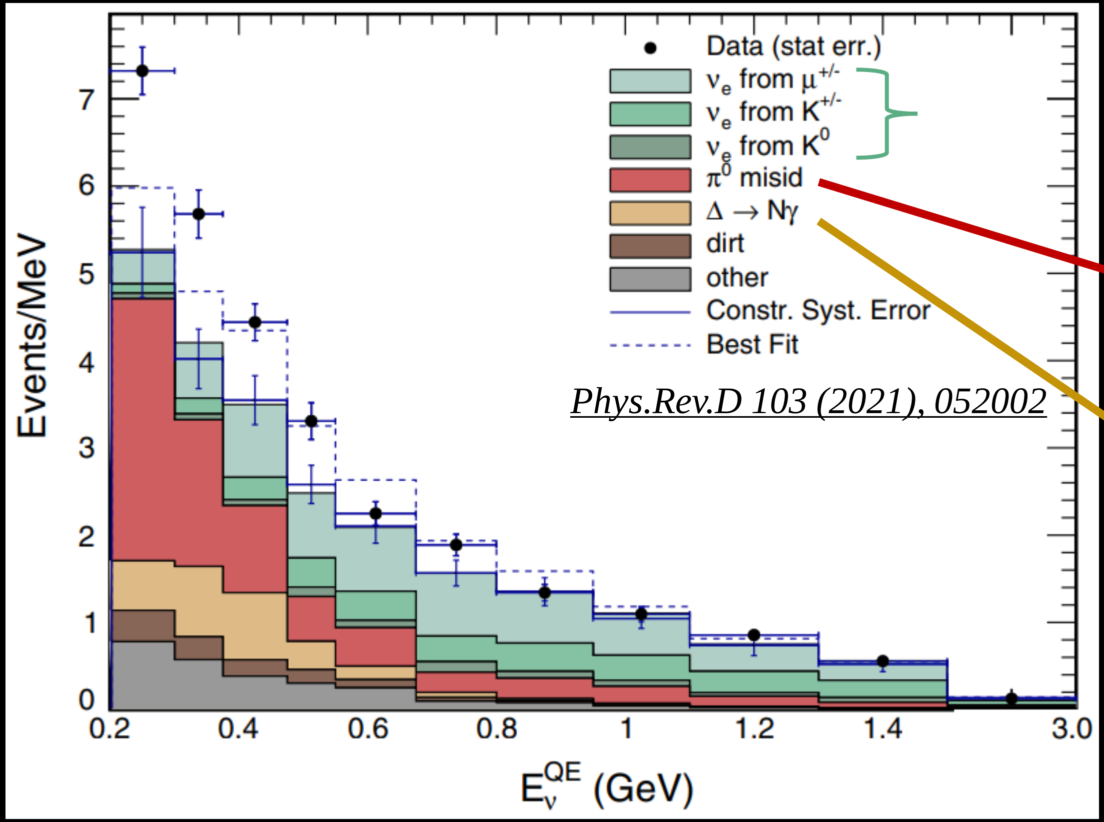
MICROBOONE-NOTE-1116-PUB





- Sensitivity is significantly improved (overall a factor of 2) when combining both BNB and NuMI (mainly due to degeneracy mitigation)
- BNB+NuMI data results are expected to be sensitive to the Gallium/Neutrino-4 results, and LSND results

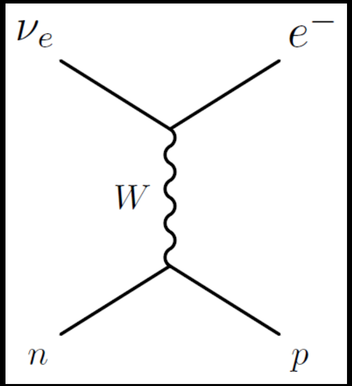
MiniBooNE Anomaly: Low Energy Excess (LEE)



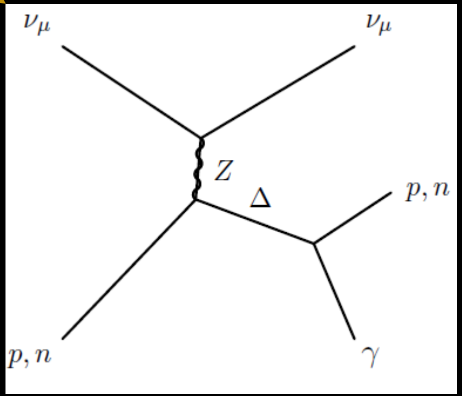
MiniBooNE (2002-2019) observed the LEE of electromagnetic events with 4.8σ significance.

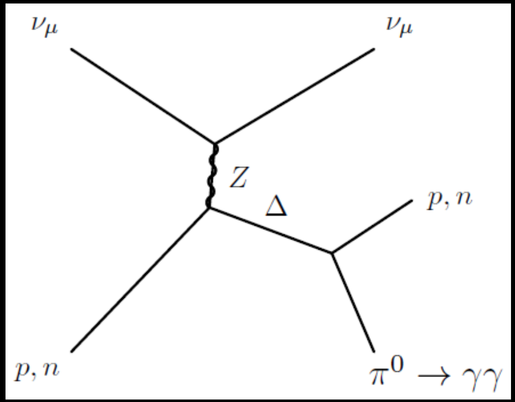
~~eLEE?~~

gLEE?

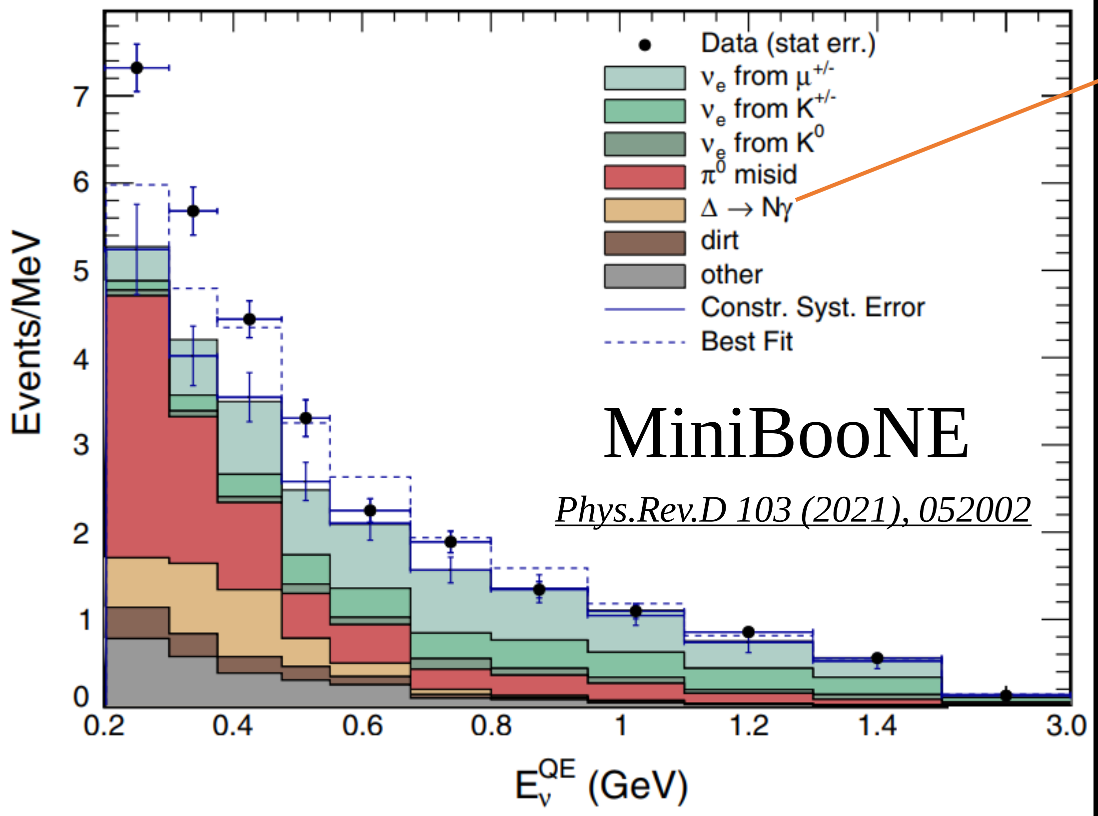


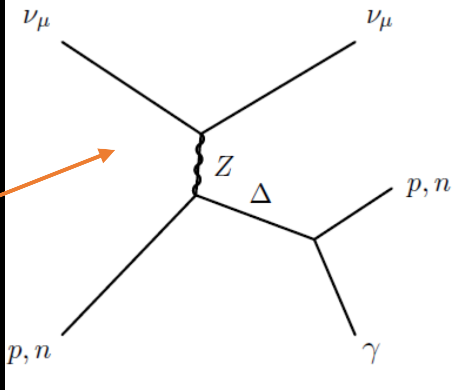
Single-gamma backgrounds

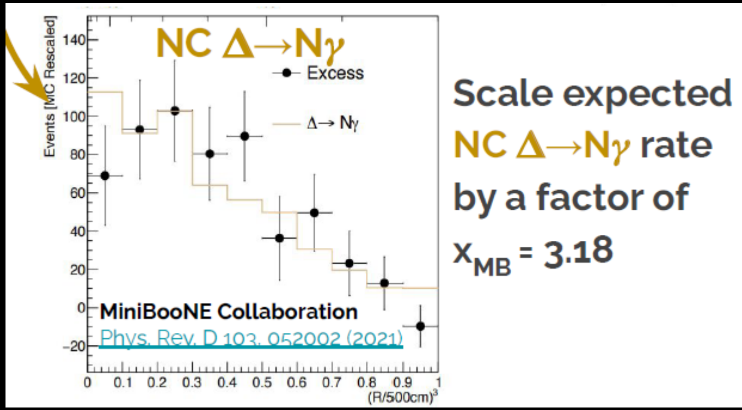




Search LEE in Neutral-Current (NC) $\Delta \rightarrow N\gamma$ -- Single Photon Analysis







- It is predicted to be one major source of single-photons at these energies
- It's a known background, that was not constrained directly by the MiniBooNE experiment.
- An enhancement in NC Δ→Nγ with a factor of x3.18 gave good agreement with the observed LEE in various phase space

- This analysis proceeds with simultaneous fit of four channels

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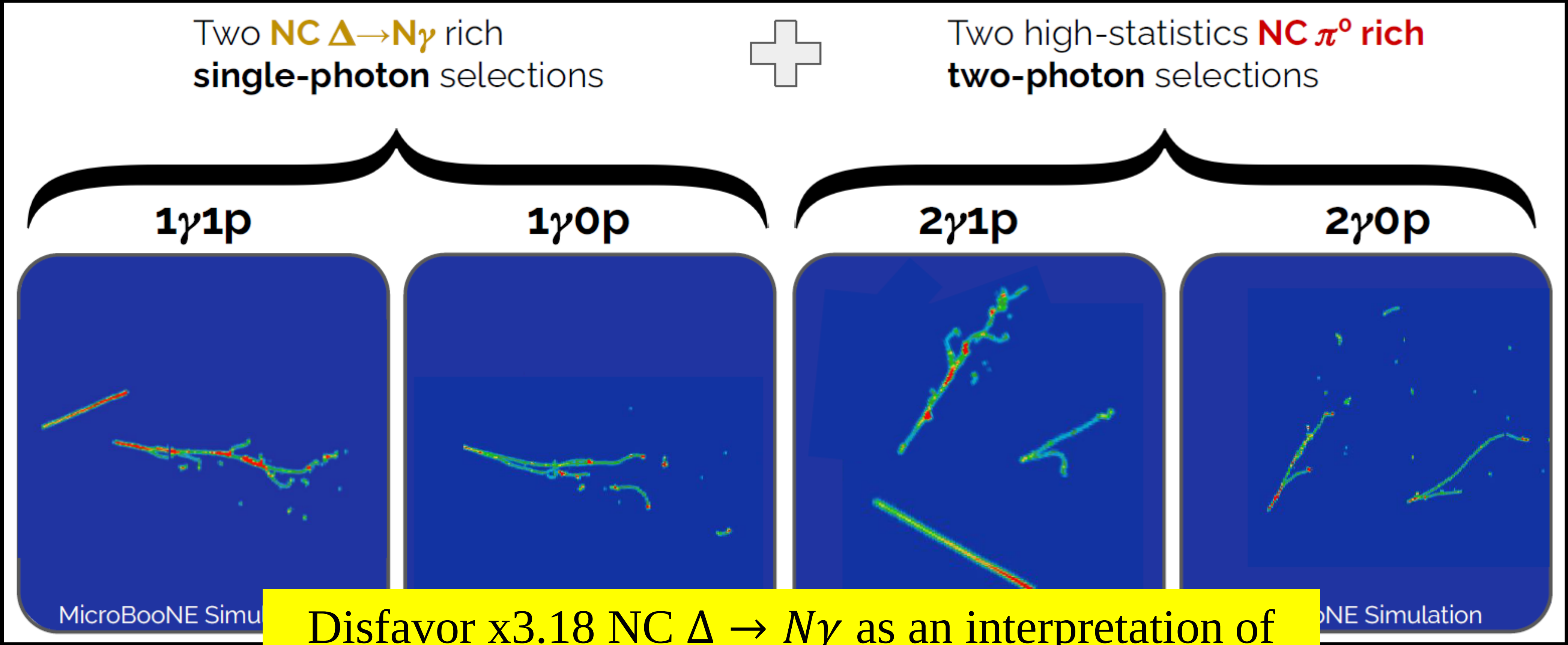


Disfavor x3.18 NC $\Delta \to N\gamma$ as an interpretation of the MiniBooNE LEE at 94.8% C.L.

1γ1p

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

16 Data Events Observed

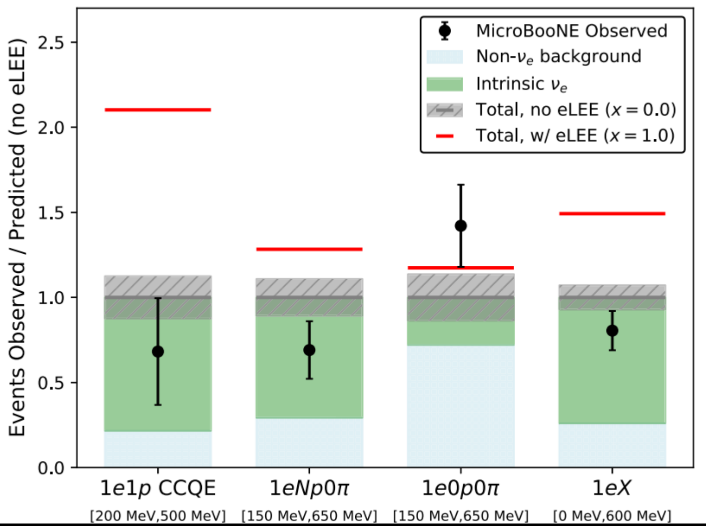
1γ0p

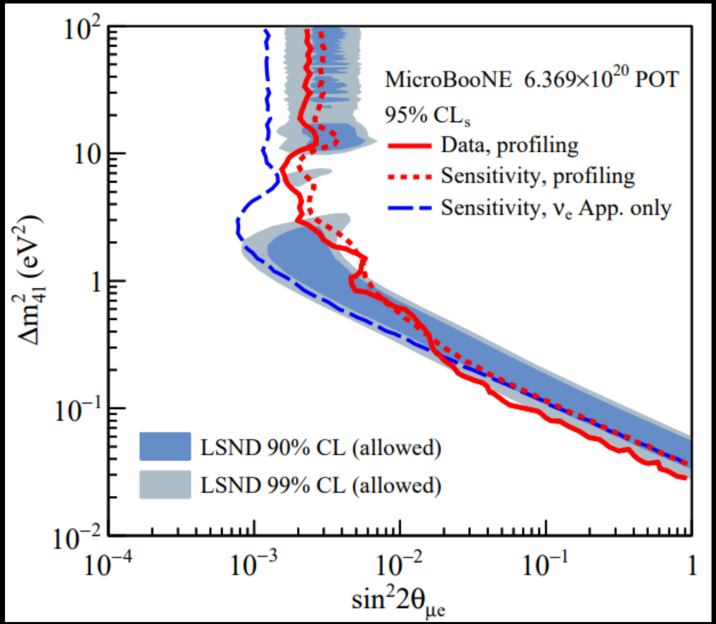
Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
NC $\Delta \to N\gamma$	+ 6.55
LEE ($x_{\rm MB} = 3.18$)	+ 20.1

153 Data Events Observed

Summary

- MicroBooNE's first searches for low energy excess found no evidence of excessive ν_e to explain the MiniBooNE excess
  - *Disfavor pure ν_e excess as a sole source of MiniBooNE excess at 3σ level*
- Full 3+1 oscillation analyses were carried out to interpret the MicroBooNE eLEE results under a sterile neutrino oscillation hypothesis
  - *The data (50% BNB total dataset) was found to be consistent with three-flavor hypothesis and exclusion limits were calculated using a frequentist approach*
  - *Unitizing both BNB and NuMI data, the 3+1 analysis will be sensitive to Gallium/Neutrino-4 and LSND results*
- No evidence for an enhanced NC Δ→Nγ
  - *Disfavors x3.18 NC $\Delta \rightarrow N\gamma$ as an interpretation of the MiniBooNE LEE at 94.8% C.L*



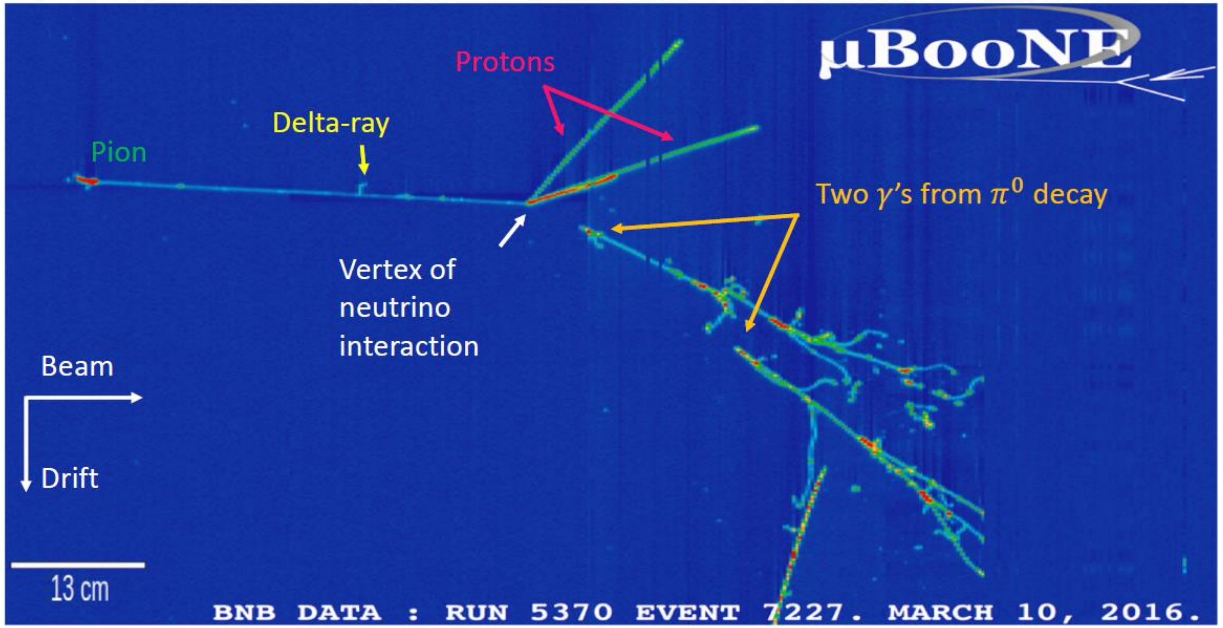


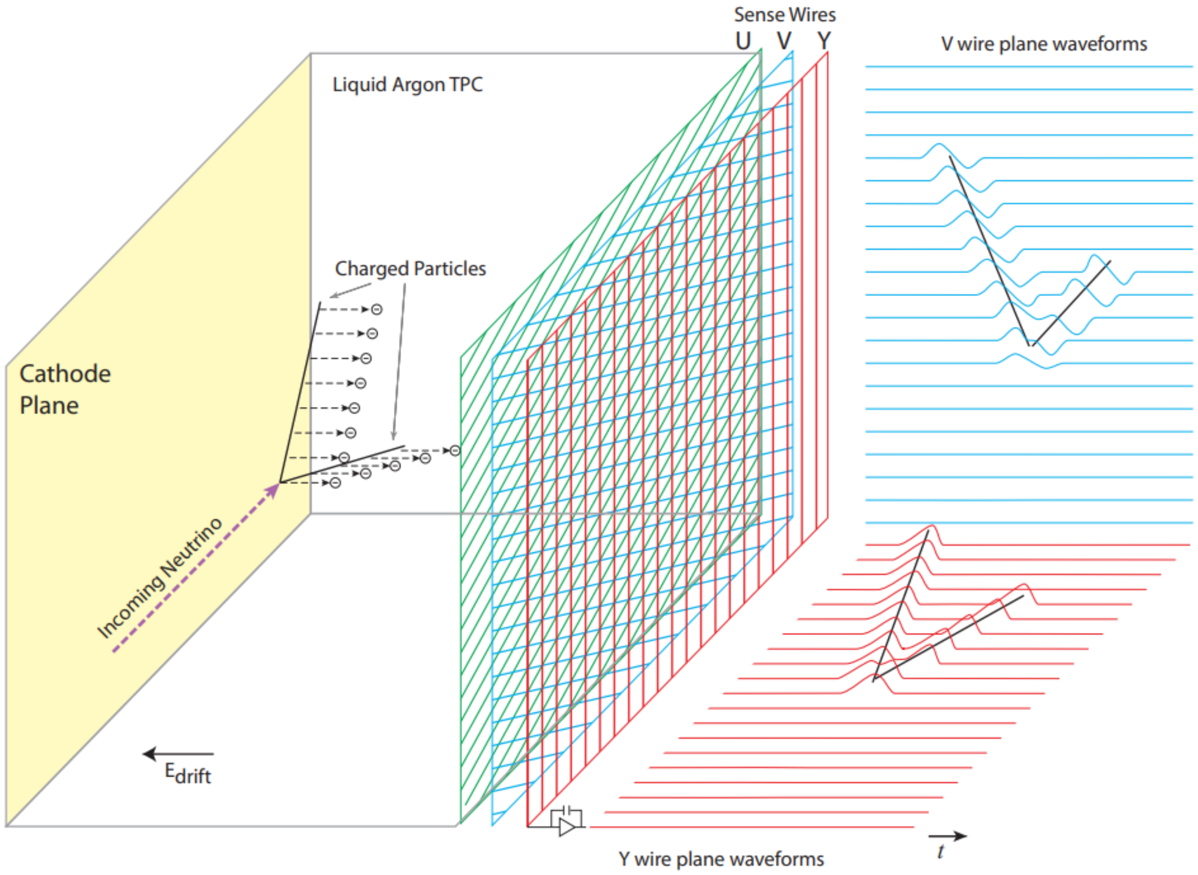
Thank you!

Backup

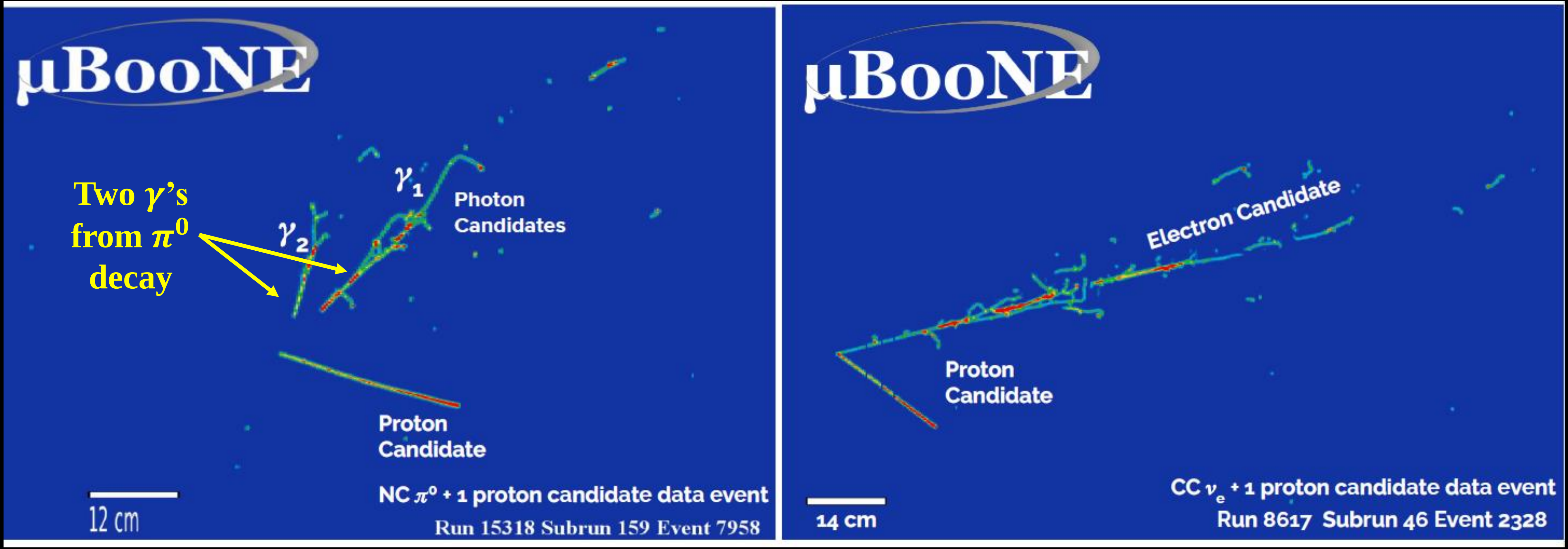
Principle of Single-Phase Liquid Argon Time Projection Chamber (LArTPC)

- ~mm scale position resolution with multiple 1D wire readouts
- Particle identification (PID) with energy depositions and topologies

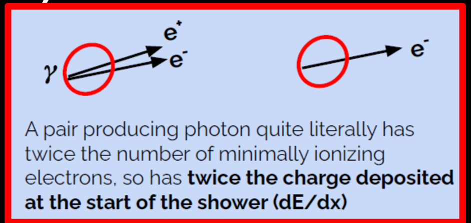




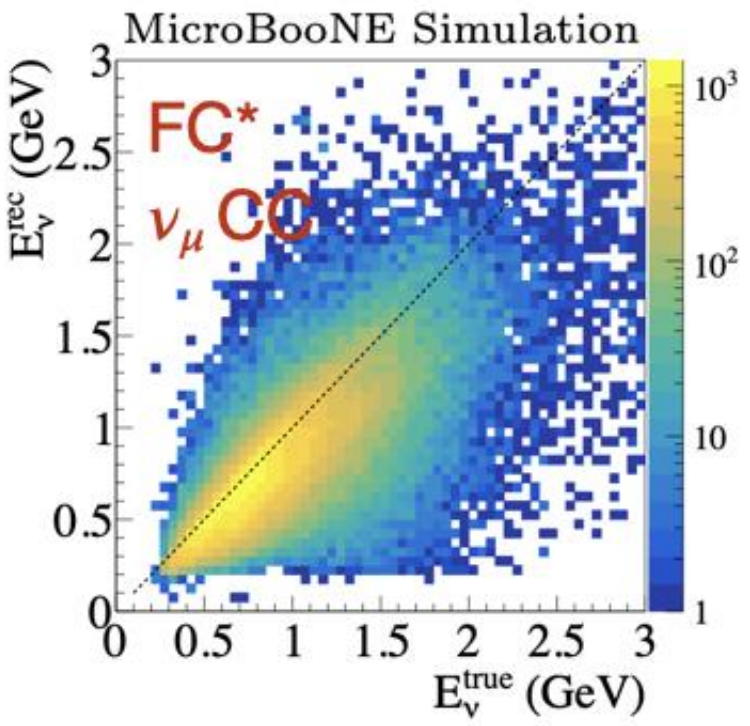
e/γ separation in LArTPC

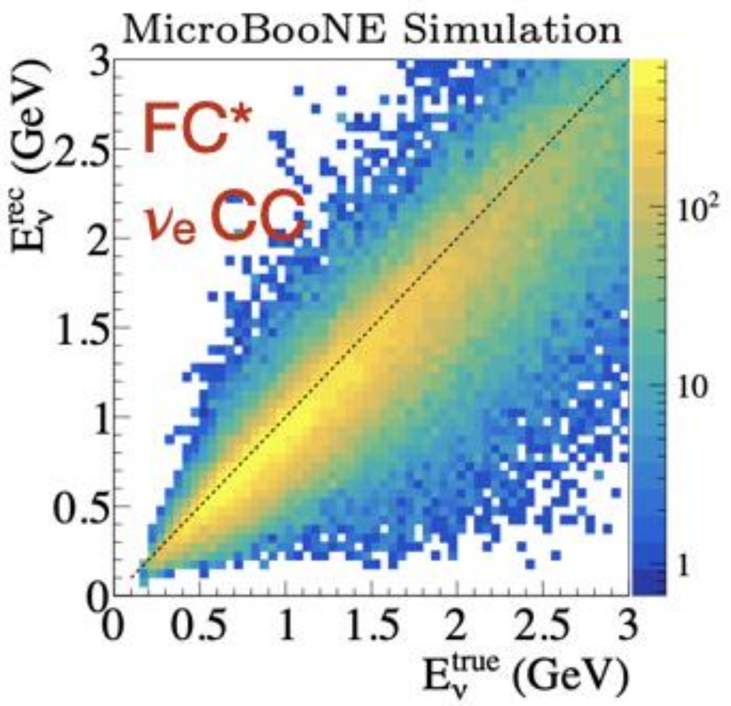


- Event topology to separate EM showers (e/γ) from tracks (proton, muon)
- Separation of e and γ : Gap Identification + dE/dx
- Unique capability to identify ν_e charge-current interactions in LArTPC



Energy Resolution

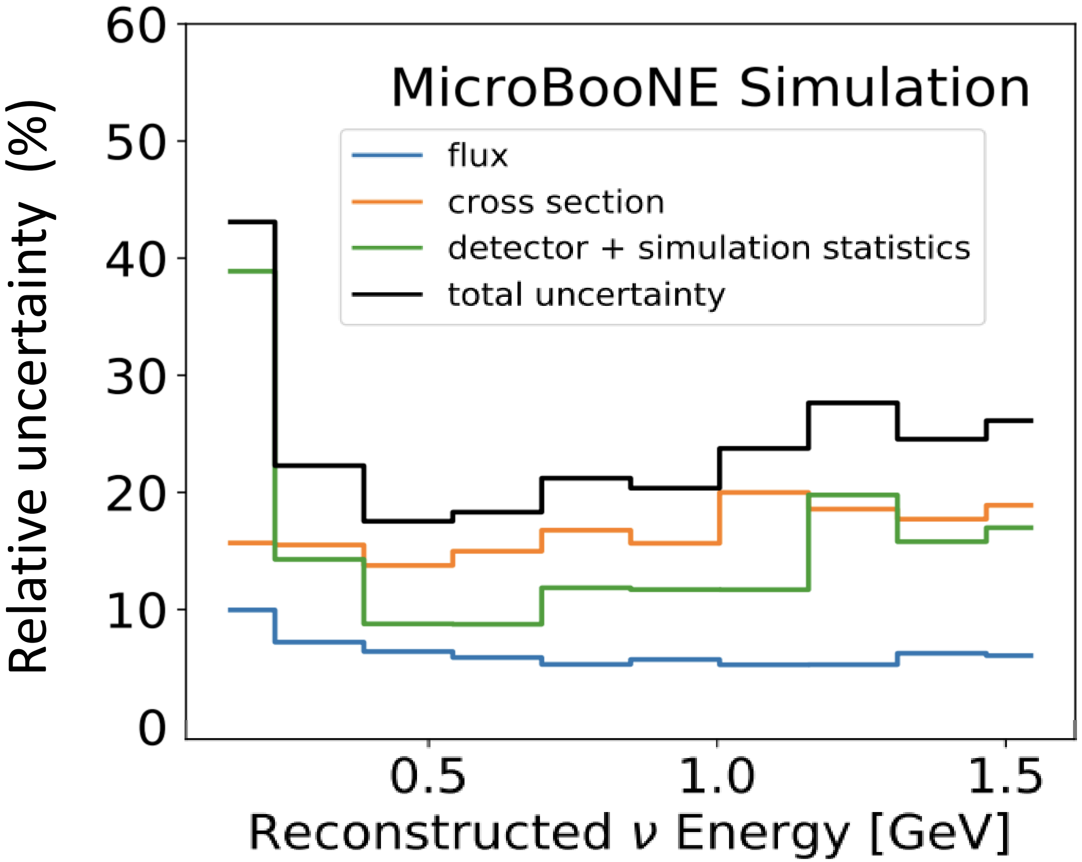




- 15-20% resolution for fully contained ν_μ CC
- 10-15% resolution for fully contained ν_e CC

Neutrino energy reconstruction primarily follows a calorimetric method

Overview of the Systematic Uncertainties



15-20% cross-section uncertainty

10-20% detector response uncertainty

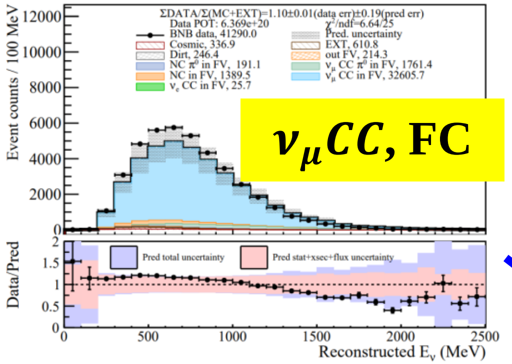
5-10% flux uncertainty (same treatment as MiniBooNE)

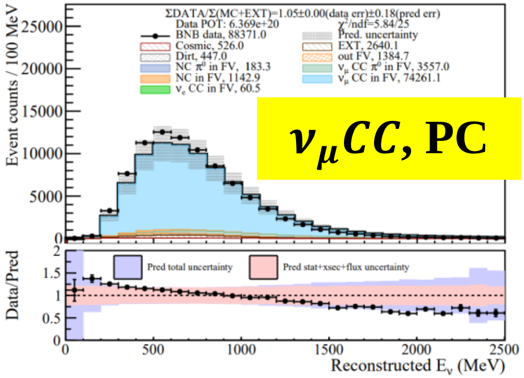
- Apply data constraints from the in-situ measurements of ν_μ and other dedicated background sidebands to suppress the systematic uncertainties

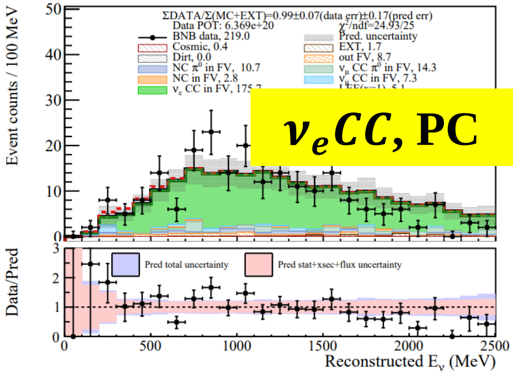
- ✓ Cross-section: MicroBooNE Genie tune, Phys. Rev. D 105, 072001
- ✓ Detector systematics: data-driven, EPJC 82, 454 (2022)

Inclusive 1eX analysis: Phys. Rev. D105, 112005 (2022)

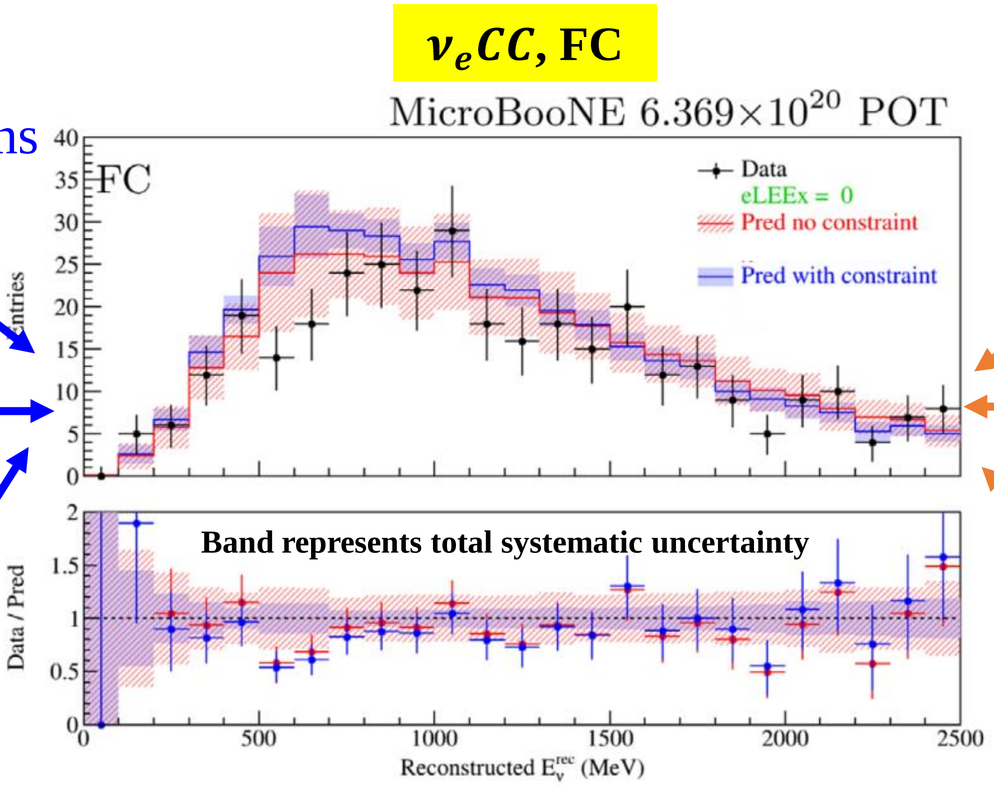
similar constraint procedure used in other two analyses



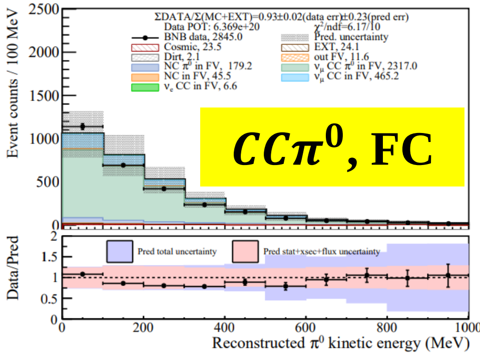


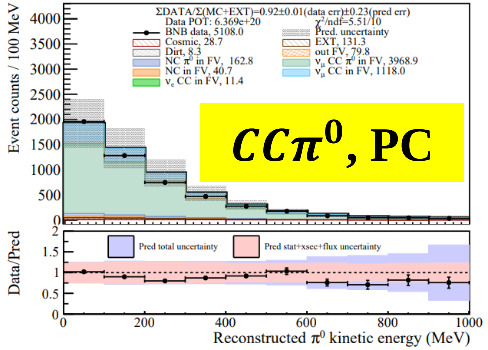


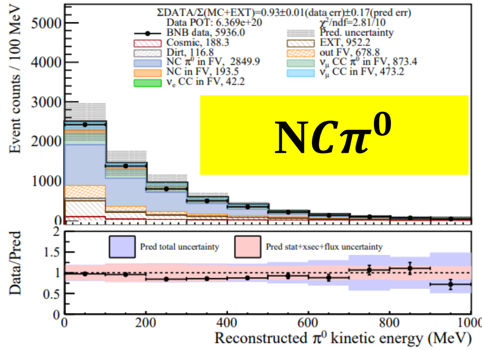
Signal constrains



Background constrains







- *FC: fully contained events in the fiducial volume*
- *PC: partially contained events in the fiducial volume*

After constraints, the total systematic uncertainty is reduced by **a factor of 3.**

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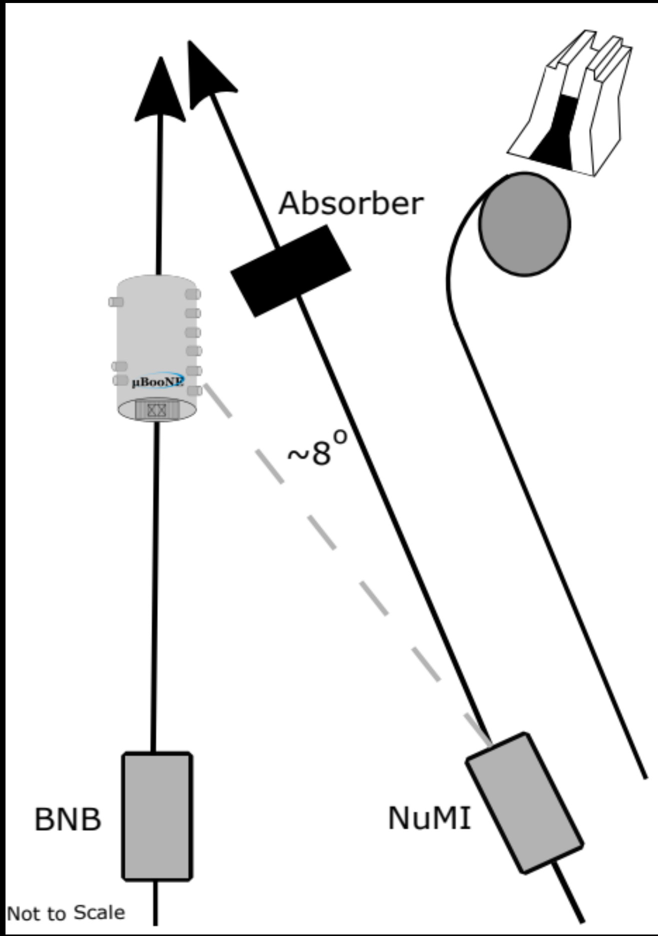
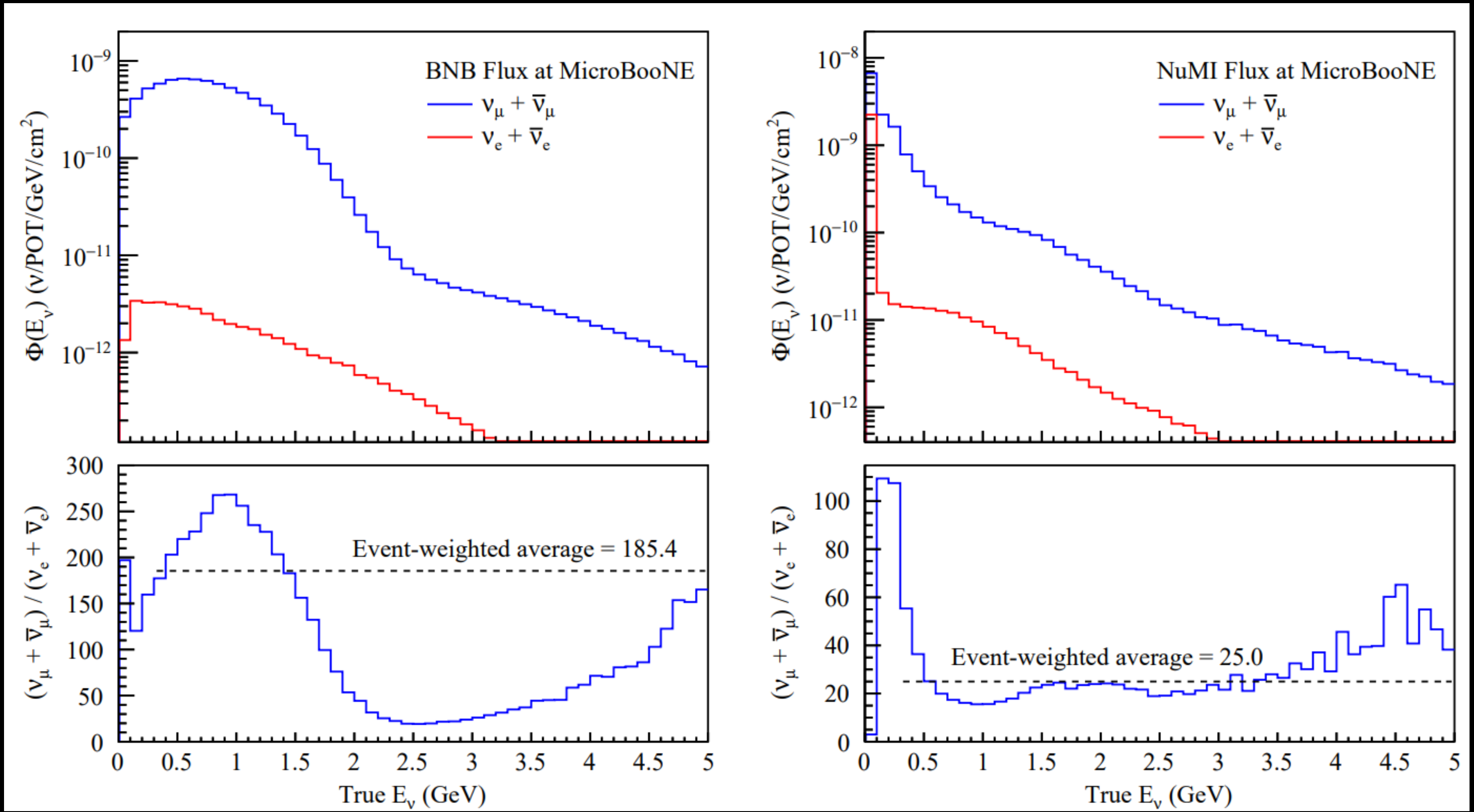
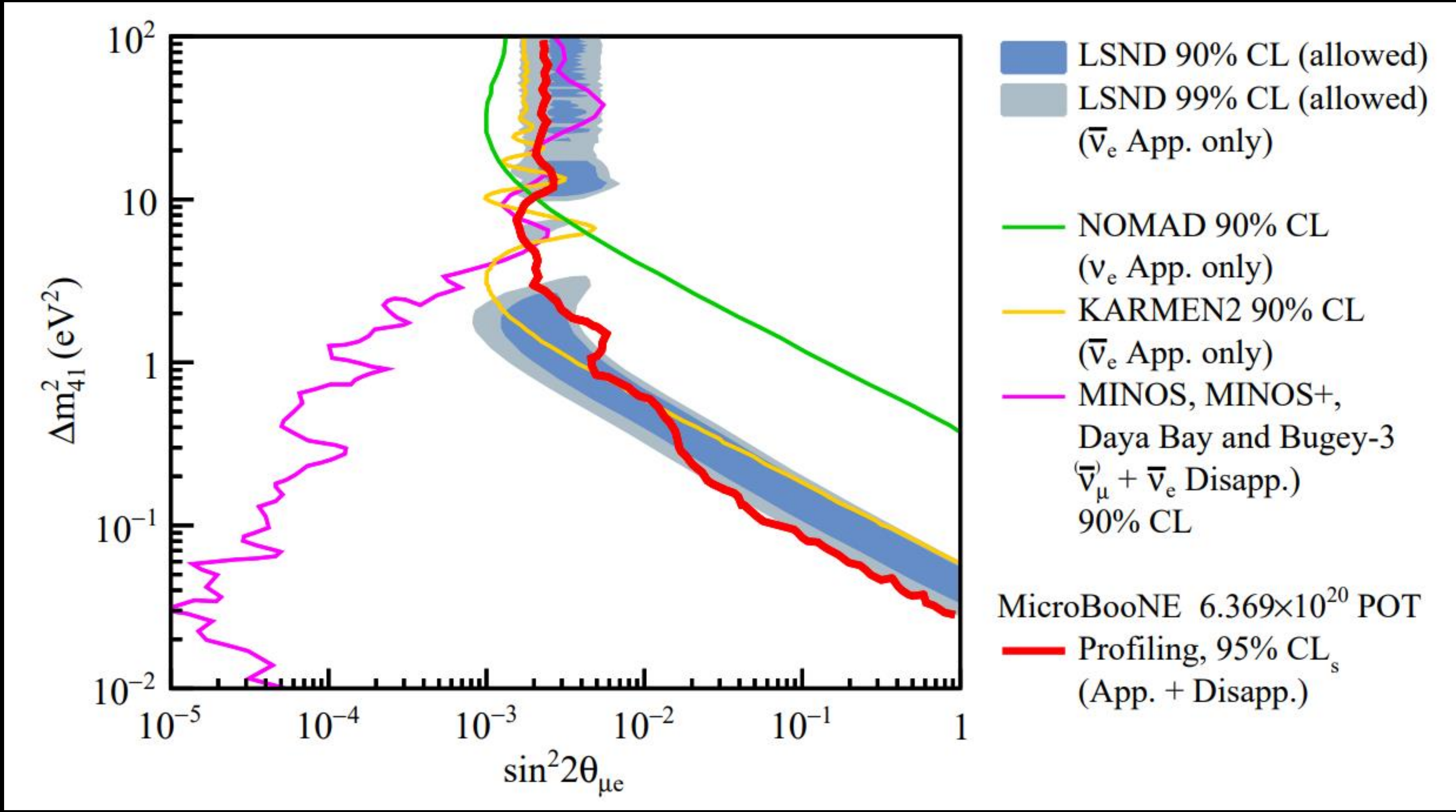
BNB and NuMI Neutrino Fluxes

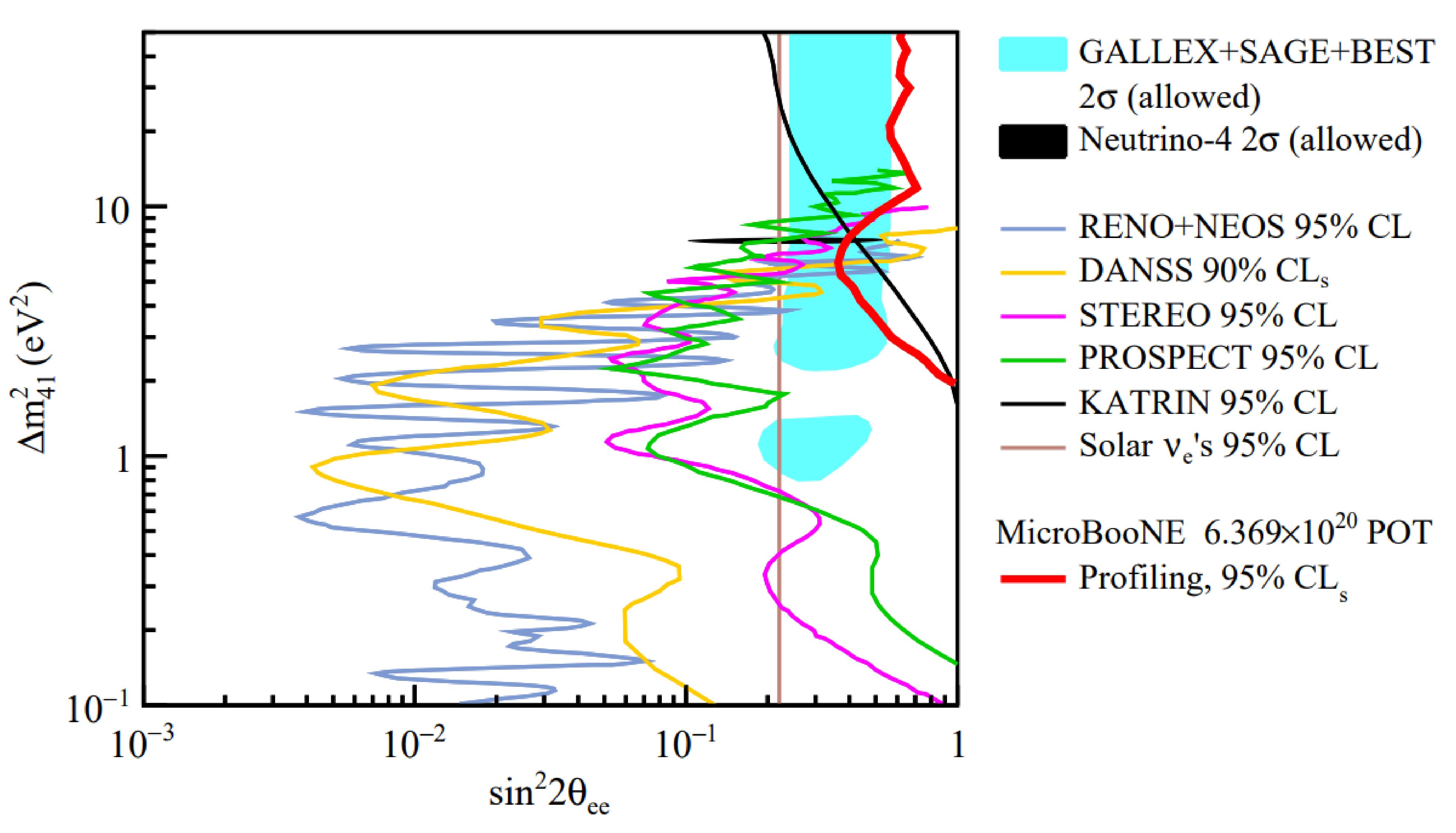


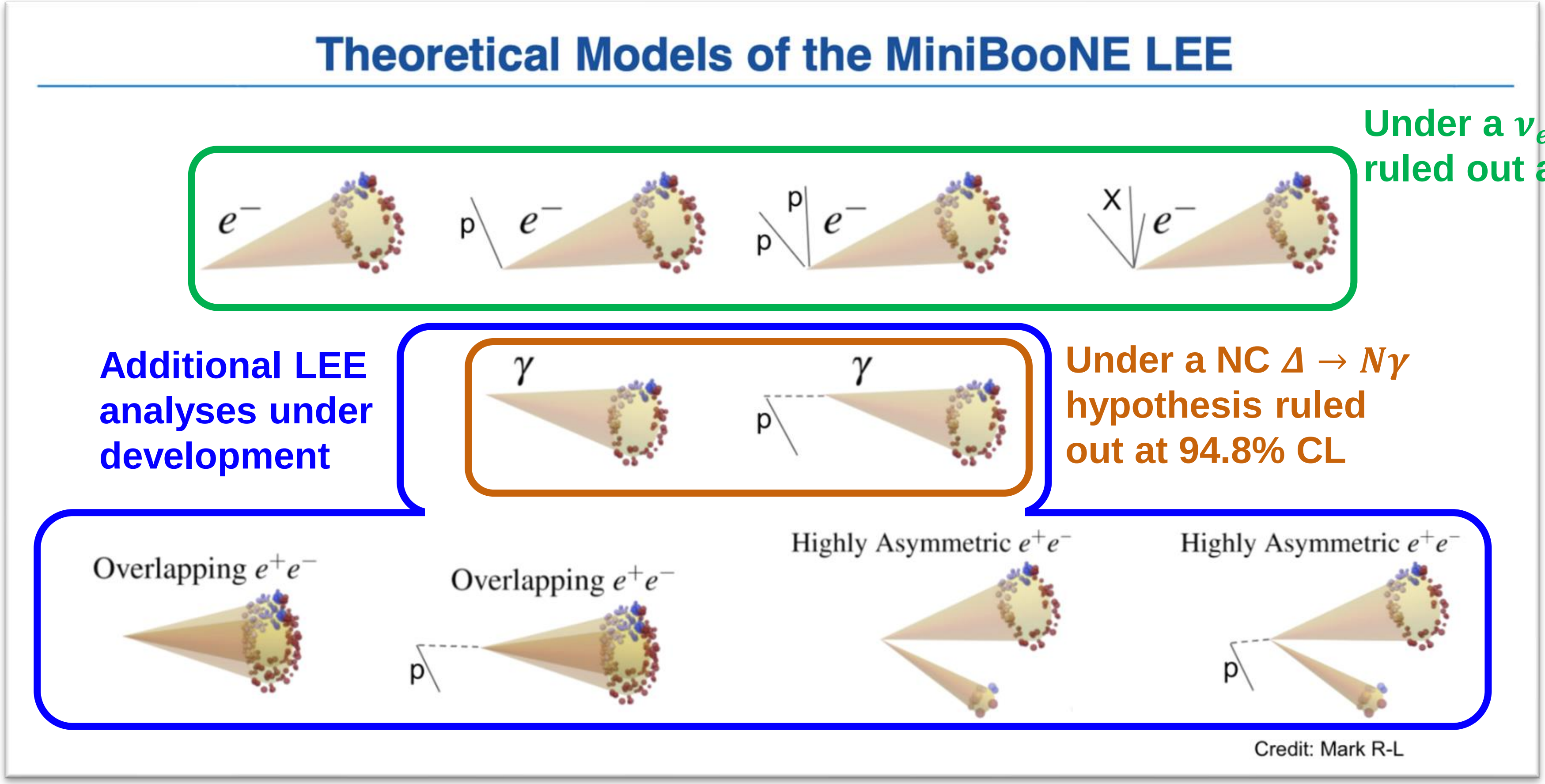


Phys. Rev. Lett. 130, 011801 (2023)



Phys. Rev. Lett. 130, 011801 (2023)





Under a ν_e hypothesis ruled out at over 3σ

Under a NC $\Delta \rightarrow N\gamma$ hypothesis ruled out at 94.8% CL

Evolving theory landscape: standard processes, sterile neutrino, dark sector portals, heavy neutral leptons, non-standard Higgs physics …

- x2 statistics using full MicroBooNE data
  - Present results are statistics-limited
- Test additional LEE models
  - A generic single-photon excess search is underway
- More ν-Ar cross section measurements
- Combined analysis with other SBN experiments (SBND, ICARUS)