

Recent Results from MicroBooNE

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On behalf of MicroBooNE

Rencontres de Moriond 2026
Electroweak Interactions & Unified Theories
March 17th 2026

The MicroBooNE Experiment

Fermilab

Booster
Accelerator
~8 GeV

Booster Neutrino Beam

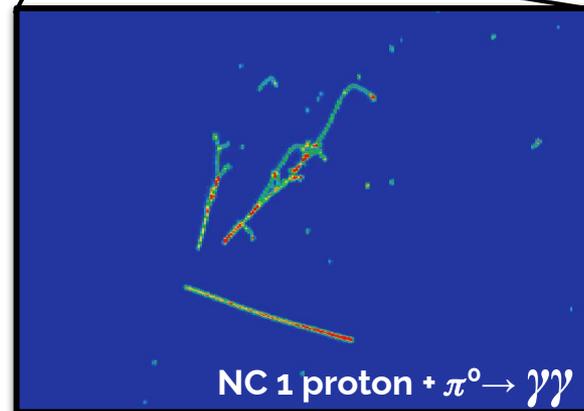
μ BooNE

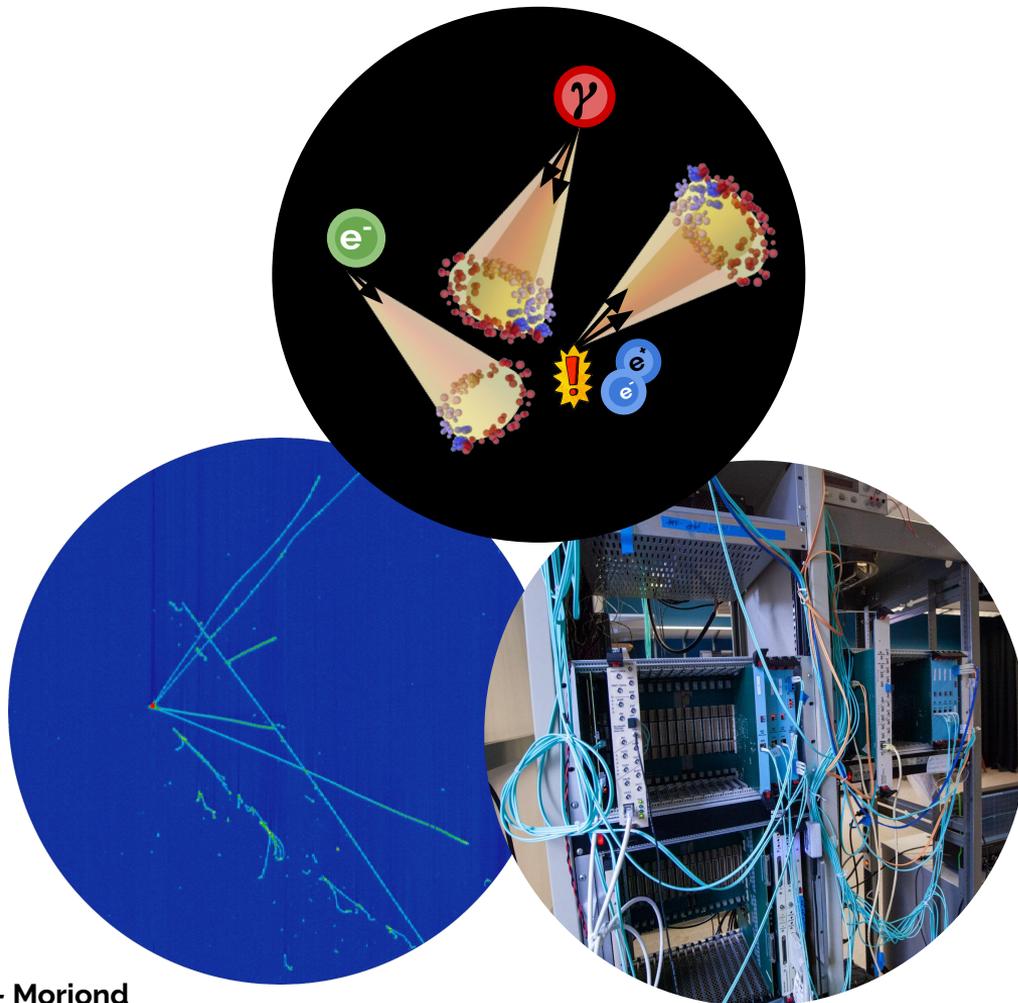


ν
 ν
 ν

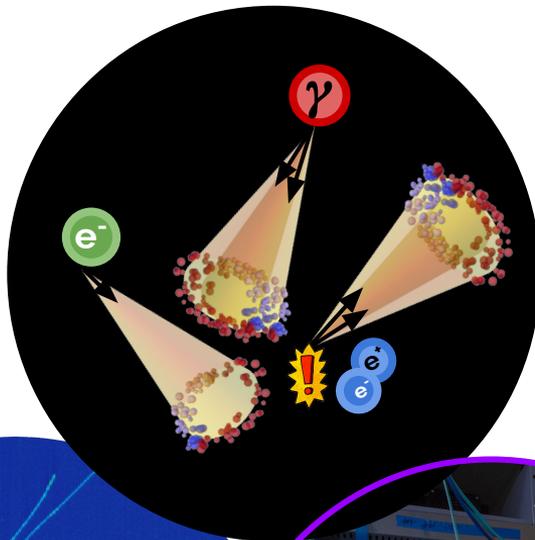
MicroBooNE is a

- 85 metric tonne Liquid Argon Time Projection Chamber (**LArTPC**) neutrino detector
- Sitting **470m** downstream in the **Booster Neutrino Beam (BNB)** at **Fermilab**



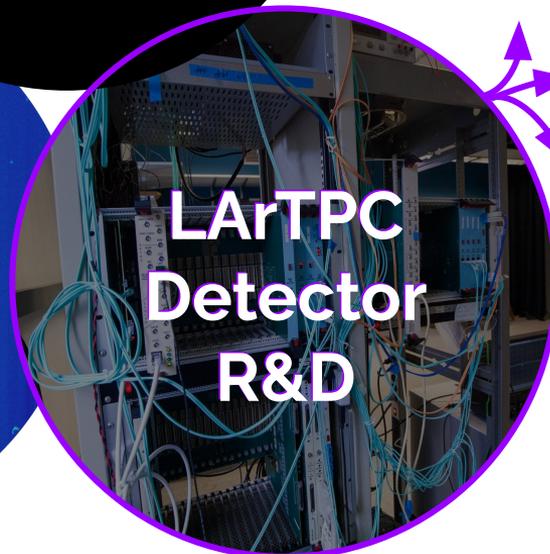
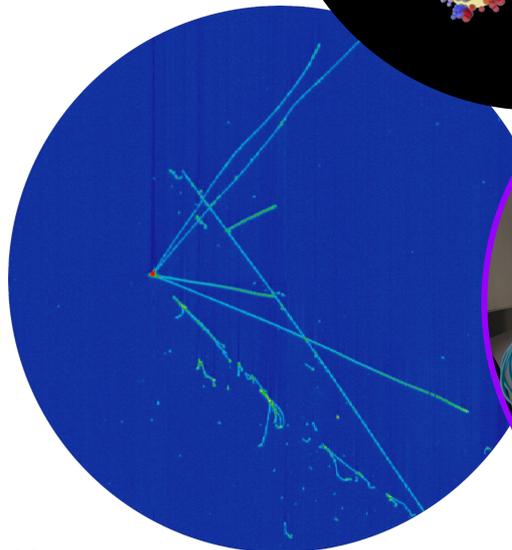


The Goals of MicroBooNE



First demonstration of O(1ns) timing resolution in the MicroBooNE liquid argon time projection chamber

[arXiv:2304.02076](https://arxiv.org/abs/2304.02076) [hep-ex] (2023)



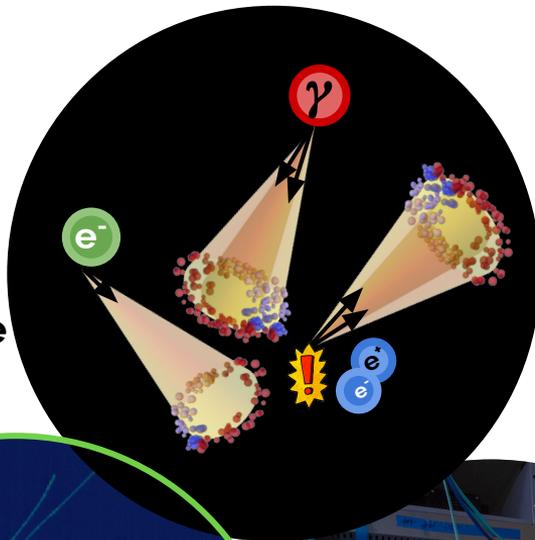
**LArTPC
Detector
R&D**

Demonstration of new MeV-scale capabilities in large neutrino LArTPCs using ambient radiogenic and cosmogenic activity in MicroBooNE Phys. Rev. D 111, 032005 (2025)

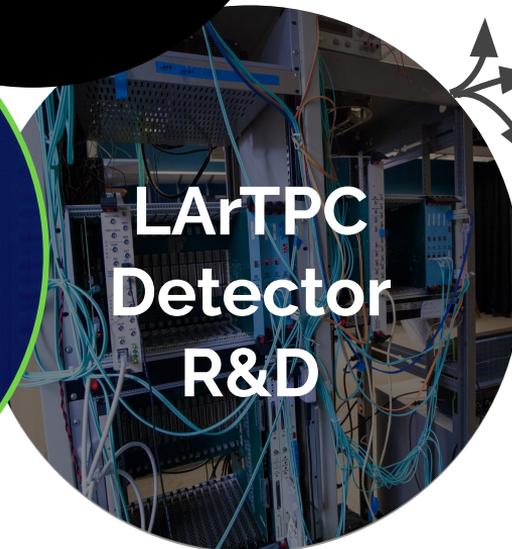
Improving neutrino energy estimation of charged-current interaction events with recurrent neural networks in MicroBooNE [arXiv:2406.10123](https://arxiv.org/abs/2406.10123) [hep-ex] (2024)

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Over 26 published results, and many more under development internally.

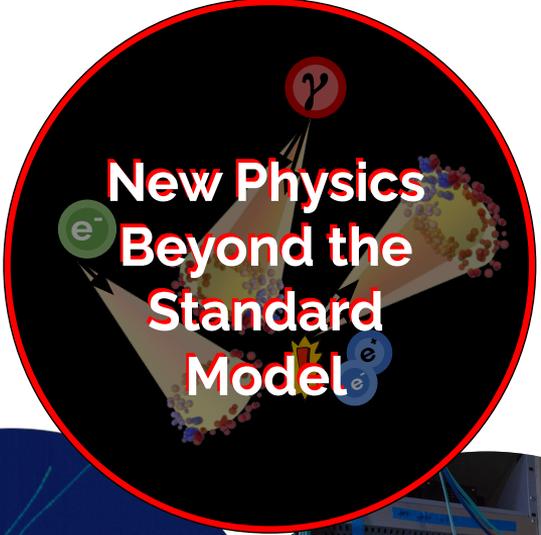


First demonstration of O(1ns) timing resolution in the MicroBooNE liquid argon time projection chamber
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Improving neutrino energy estimation of charged-current interaction events with recurrent neural networks in MicroBooNE
[arXiv:2406.10123](https://arxiv.org/abs/2406.10123) [hep-ex] (2024)

A circular graphic with a red border containing a particle interaction diagram. A central yellow and green cluster of particles is shown with several lines radiating outwards. At the top is a red circle with a white Greek letter gamma (γ). To the left is a green circle with a white e^- . To the right are two blue circles with white e^+ .

**New Physics
Beyond the
Standard
Model**

A circular graphic with a dark blue background and a red border. It features a network of green and blue lines representing particle interactions. A white double-headed vertical arrow is positioned between the text 'Neutrino' and 'Argon Interactions'.

**Neutrino
 \updownarrow
Argon
Interactions**

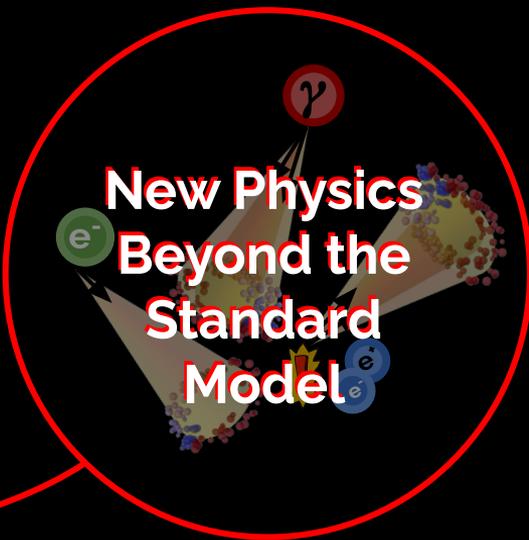
A circular graphic with a red border containing a photograph of a laboratory setting. The image shows a complex arrangement of white metal racks, blue cables, and electronic equipment, representing the LArTPC detector R&D.

**LArTPC
Detector
R&D**



Broad Goals

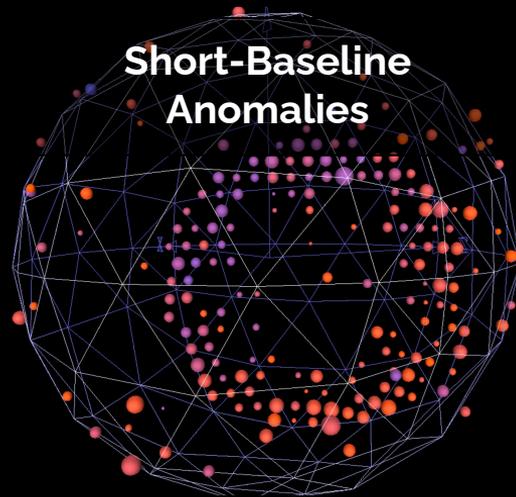
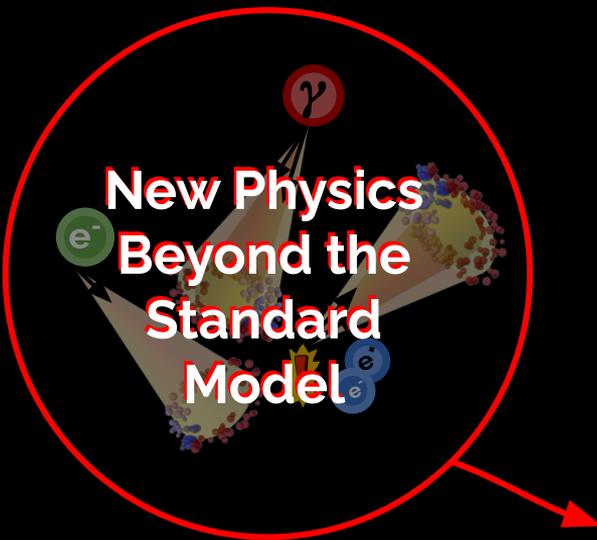
Aims to probe as many forms of “Beyond the Standard Model” (BSM) **new physics** it is sensitive to.





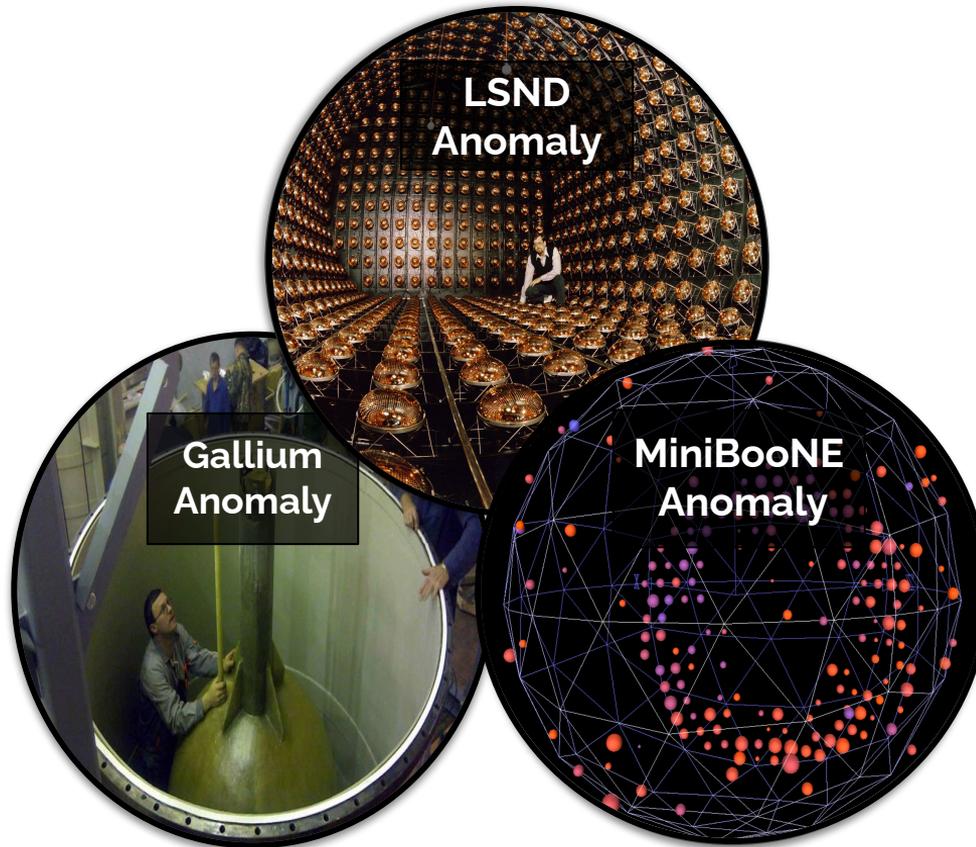
Broad Goals

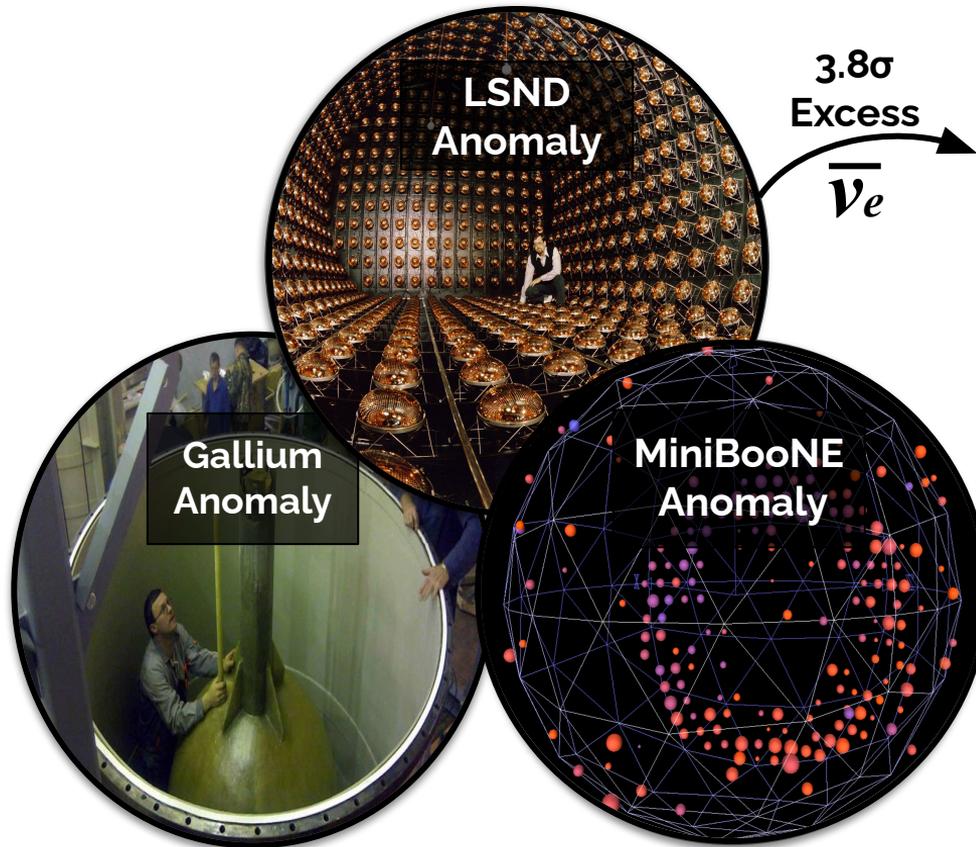
Aims to probe as many forms of “Beyond the Standard Model” (BSM) **new physics** it is sensitive to.



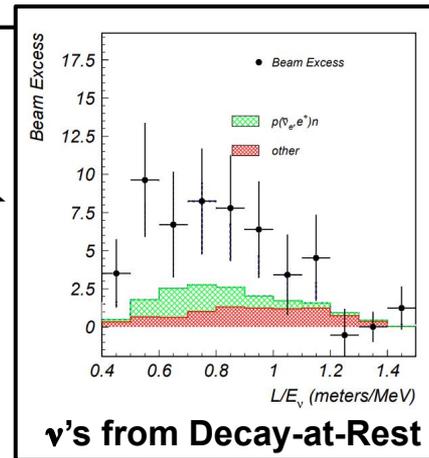
Specific Goals

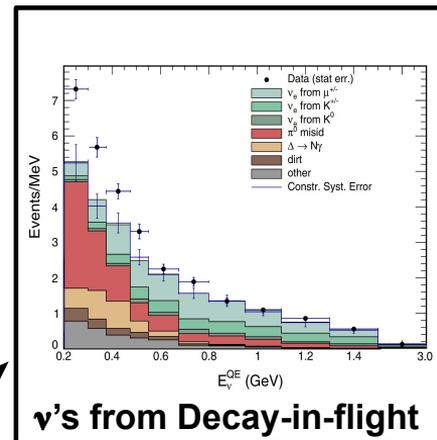
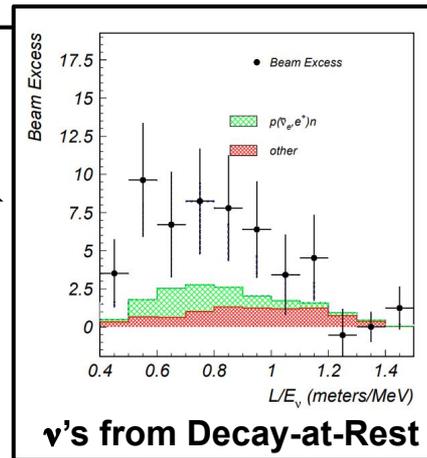
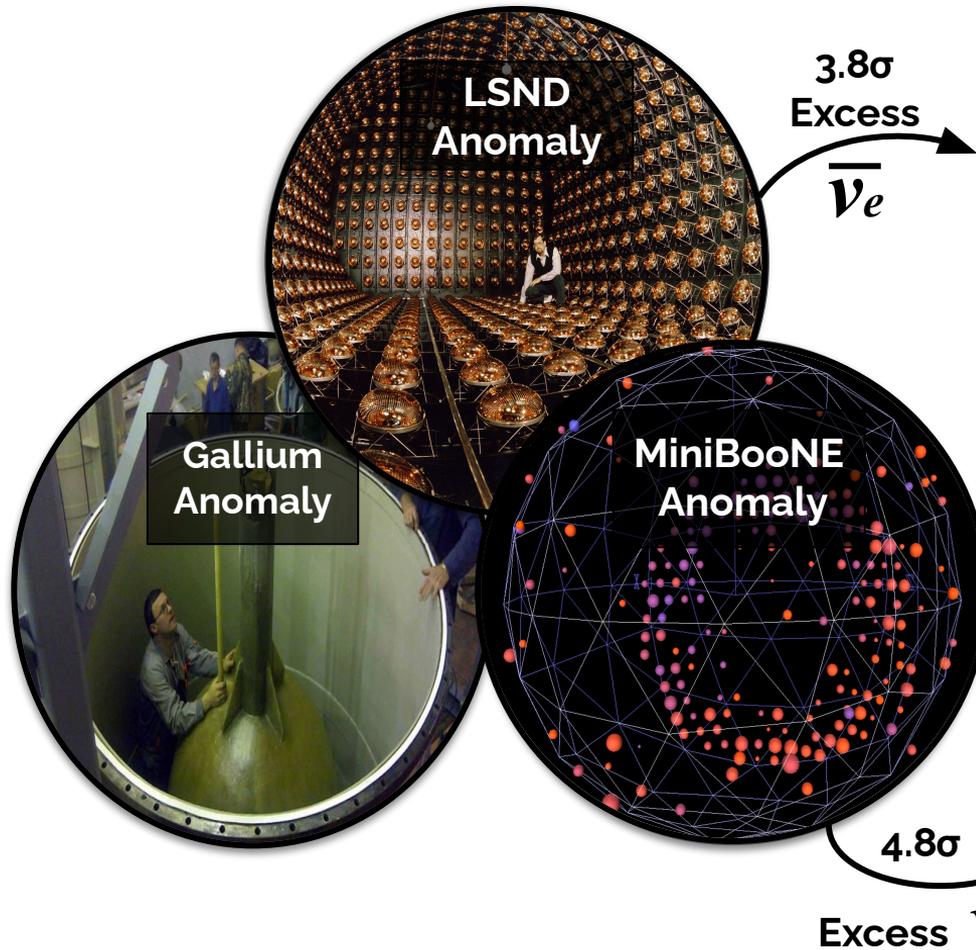
Probe “*1eV Scale Sterile Neutrinos*” as motivated by **Short baseline Anomalies**



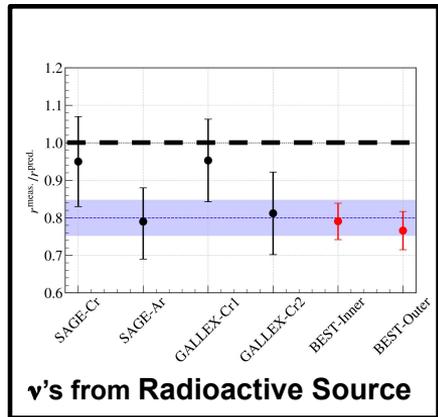


3.8σ
Excess
 $\bar{\nu}_e$



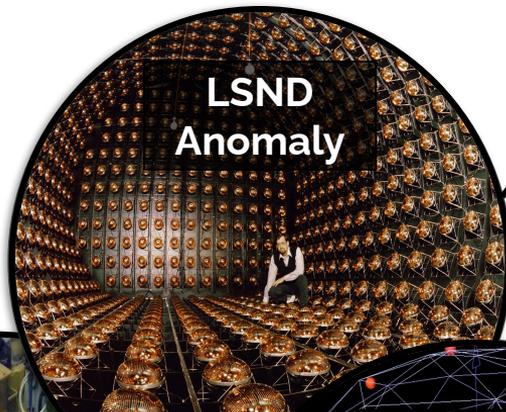
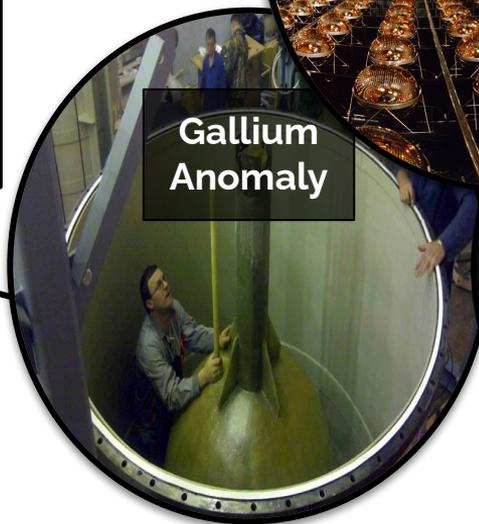


Anomalies...



**4.0 σ
Deficit**

$\bar{\nu}_e$



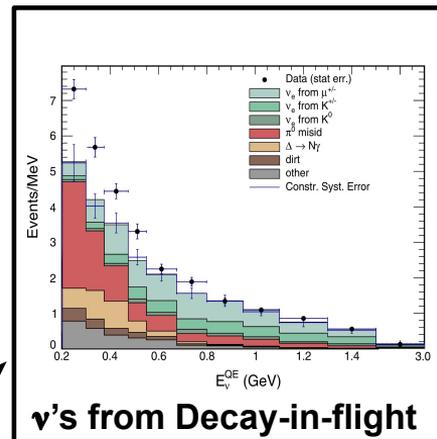
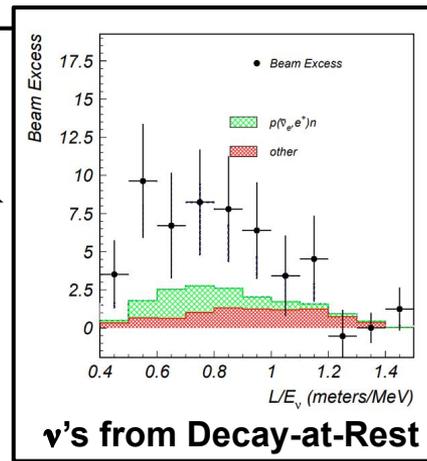
**3.8 σ
Excess**

$\bar{\nu}_e$

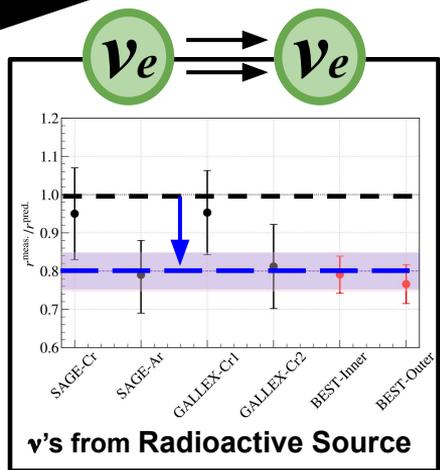


4.8 σ

Excess $\bar{\nu}_e$

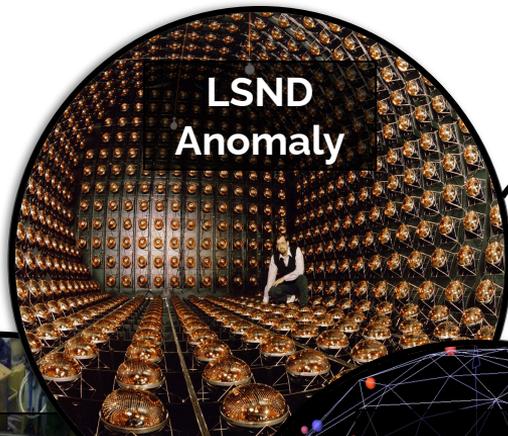
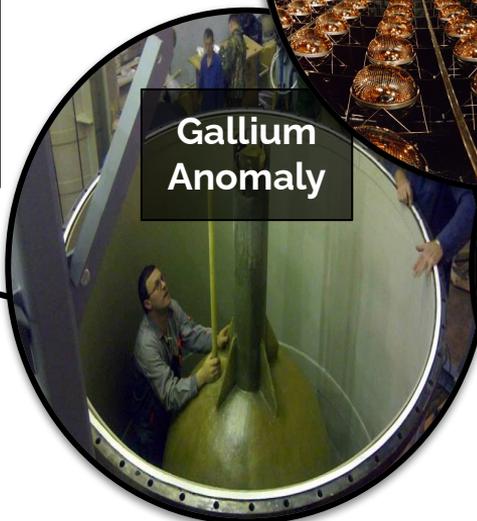


Anomalies *individually* consistent with $\sim eV^2$ oscillations



4.0σ
Deficit

ν_e



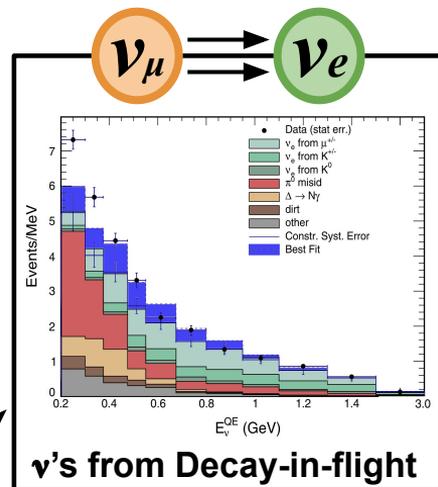
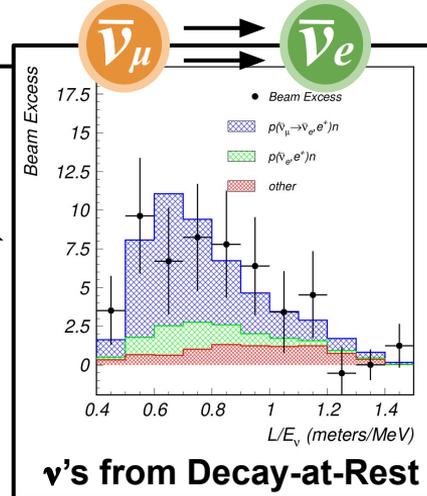
3.8σ
Excess

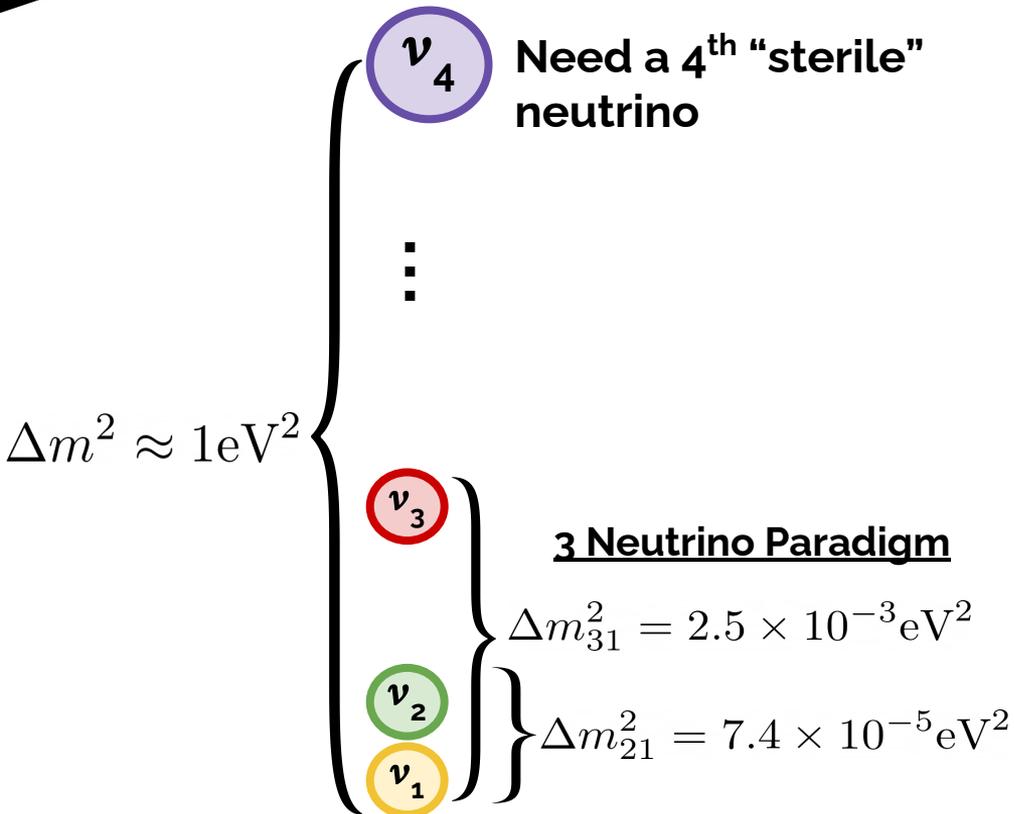
$\bar{\nu}_e$



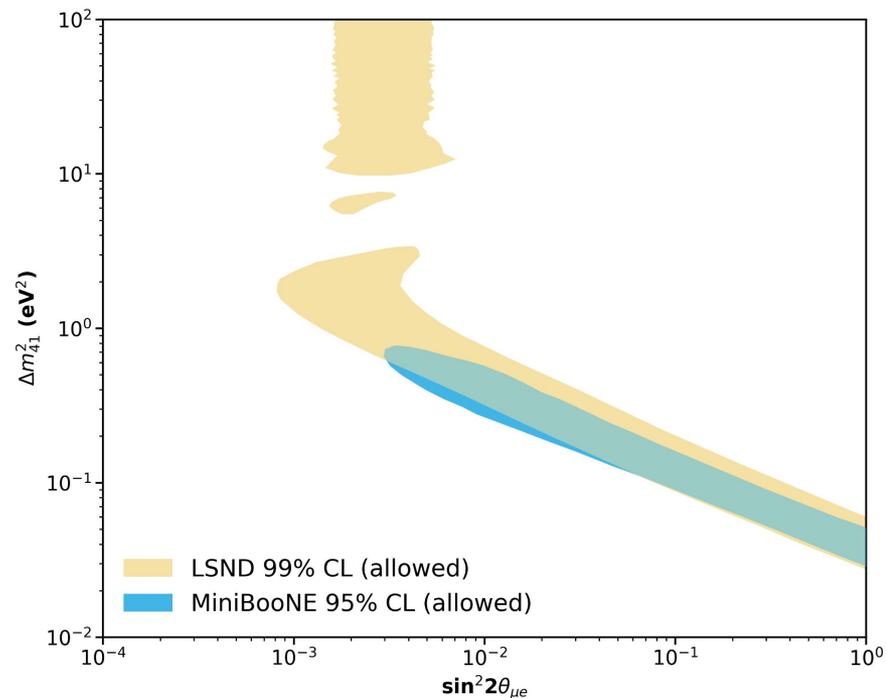
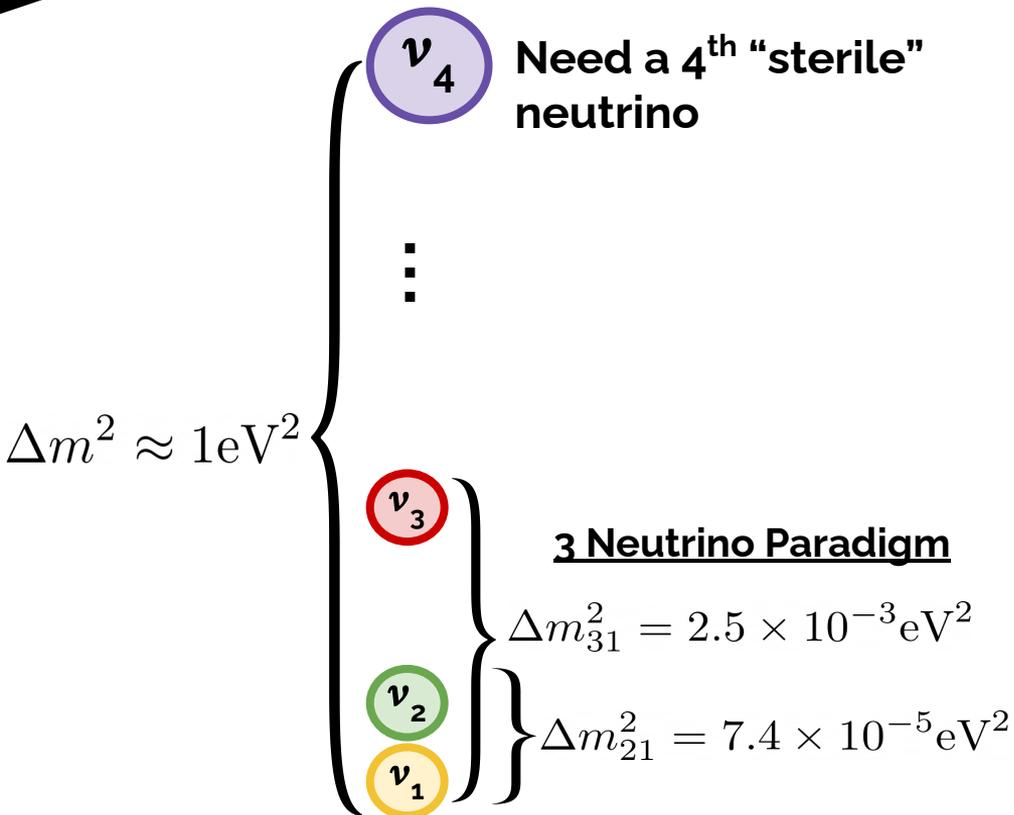
4.8σ

Excess ν_e

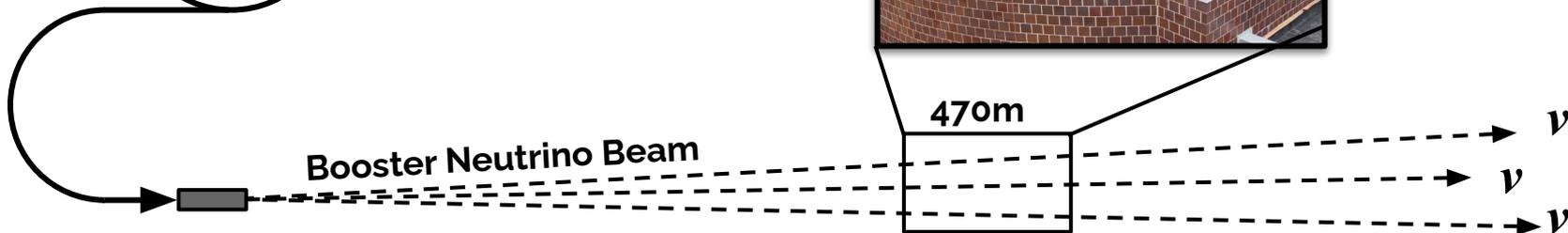
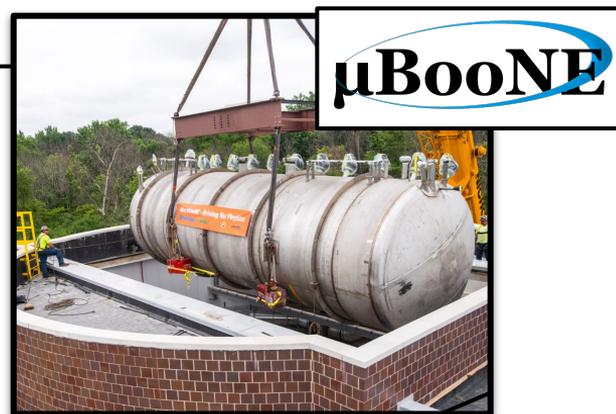
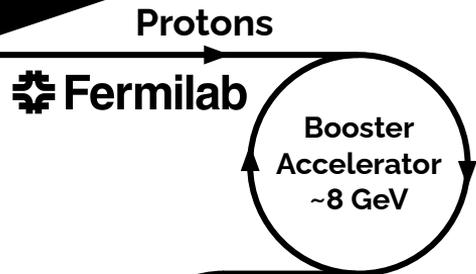




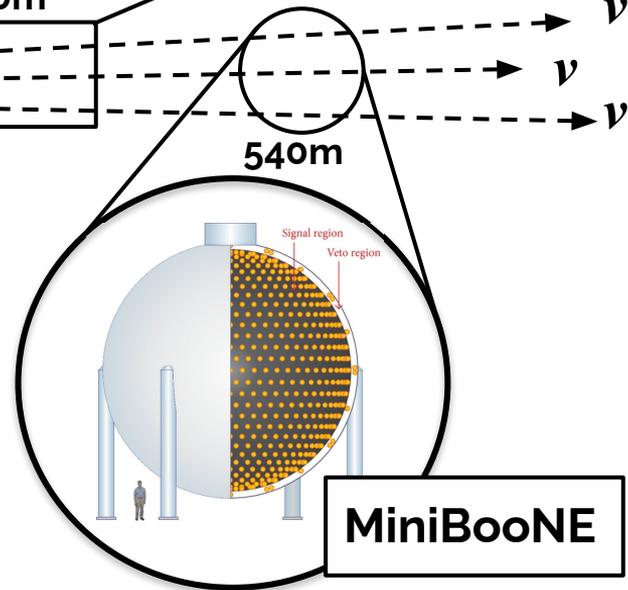
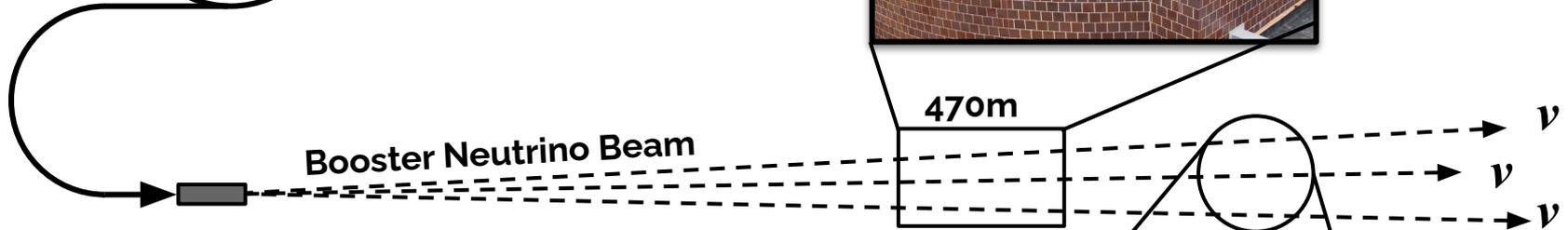
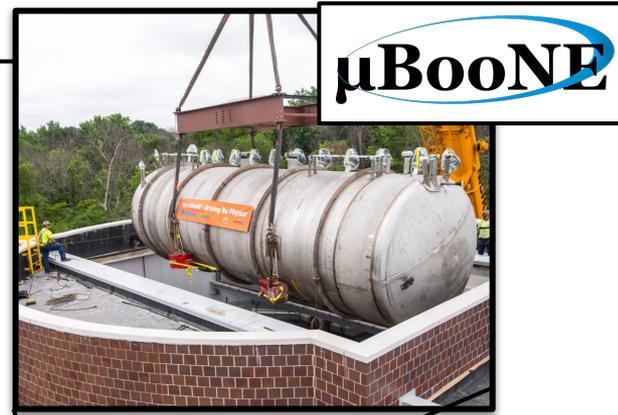
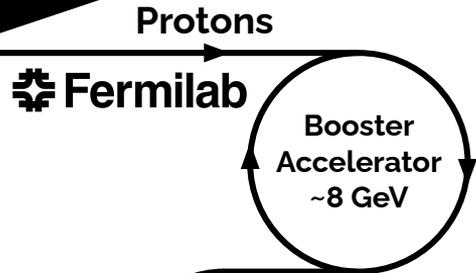
Short-Baseline Oscillations driven by eV^2 scale sterile neutrino



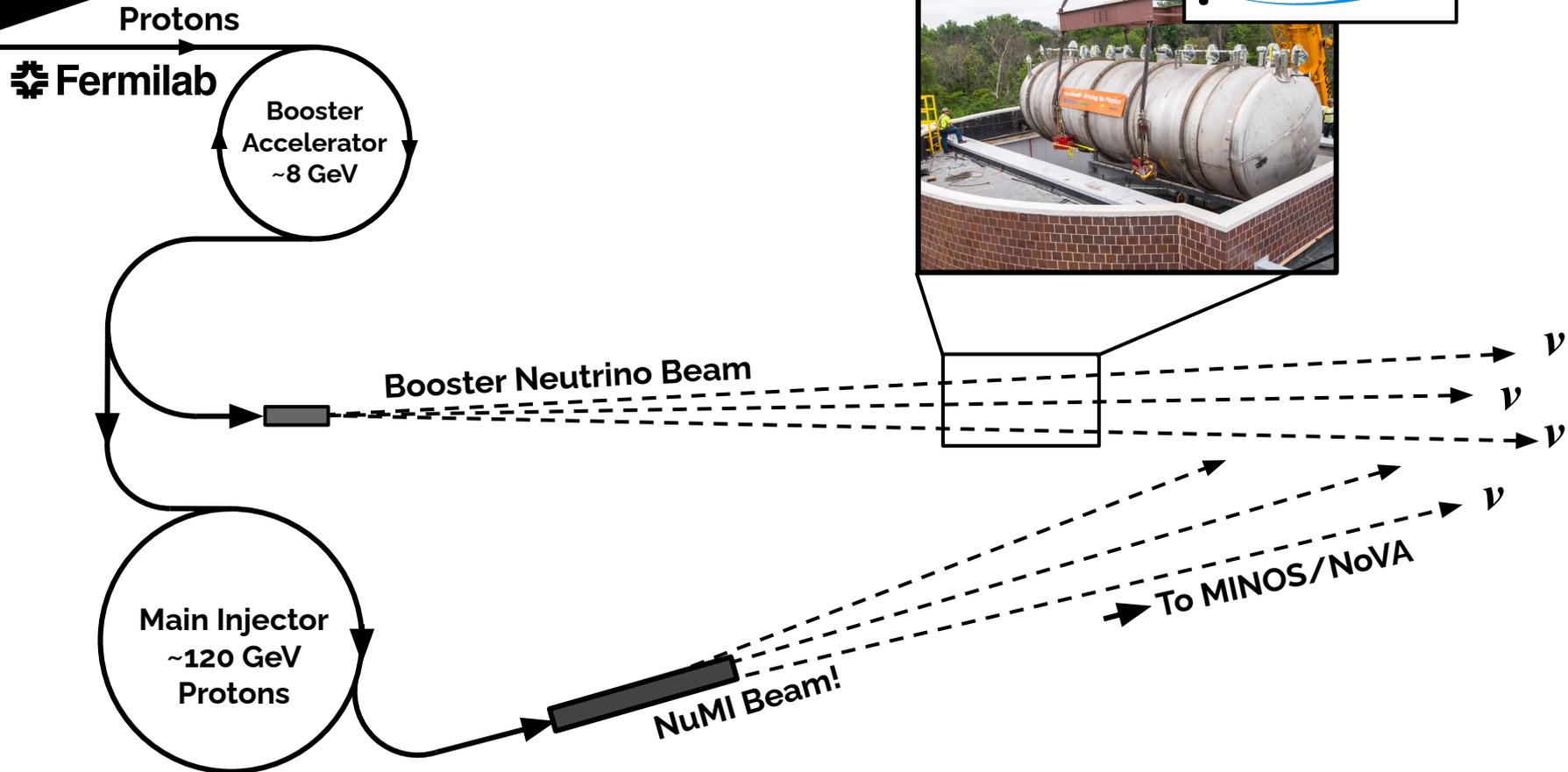
Enter MicroBooNE



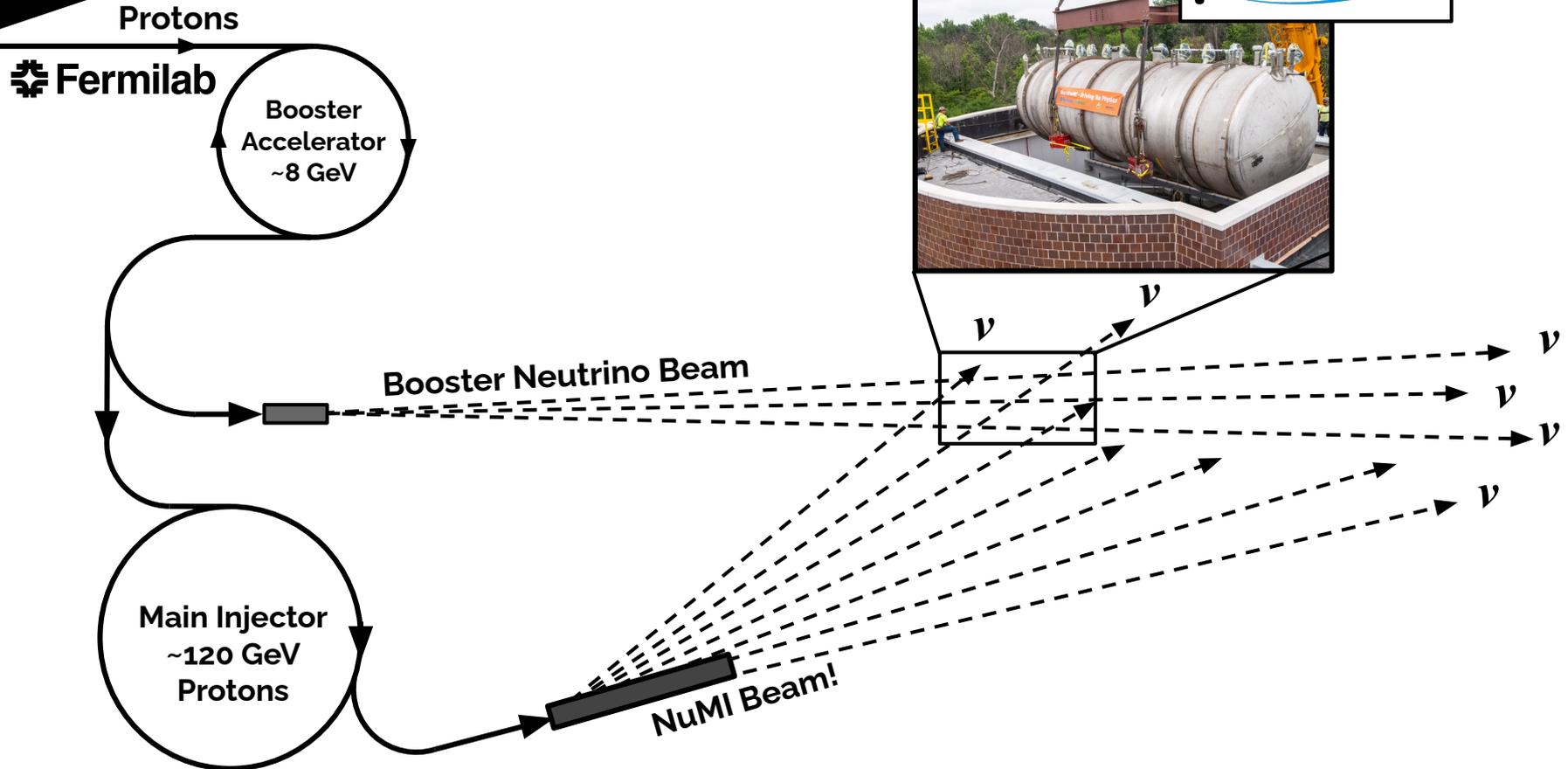
BNB Neighbours



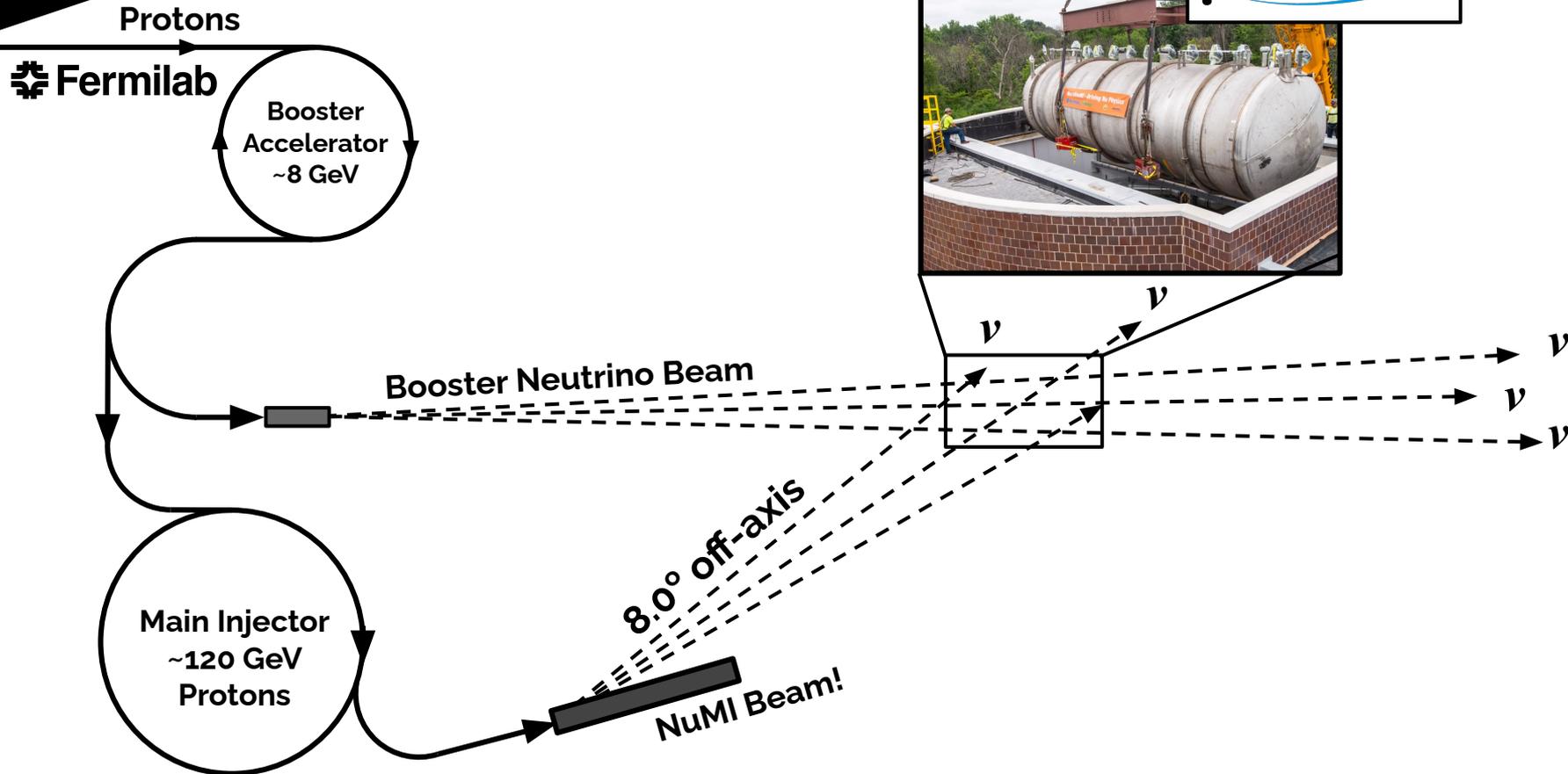
The NuMI Neutrino Beam



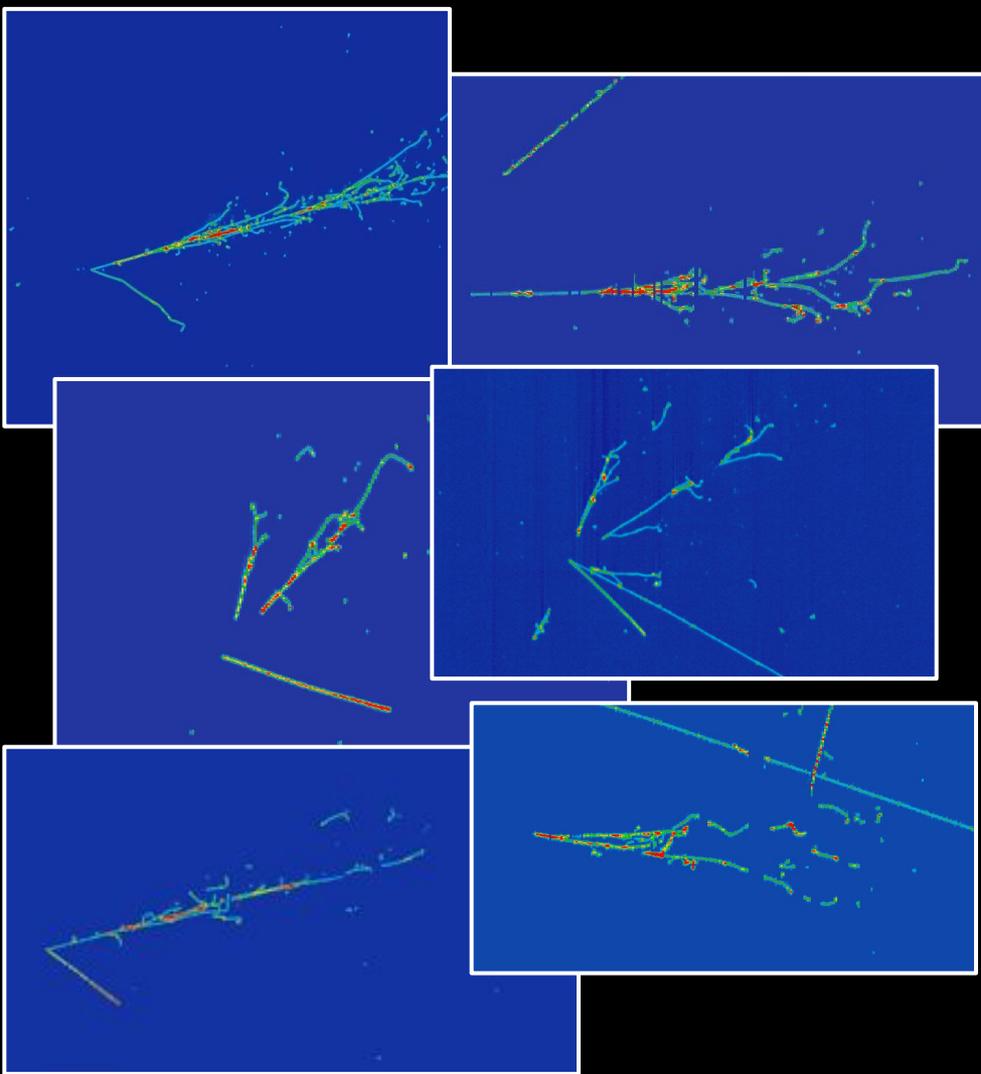
The NuMI Neutrino Beam



The NuMI Neutrino Beam

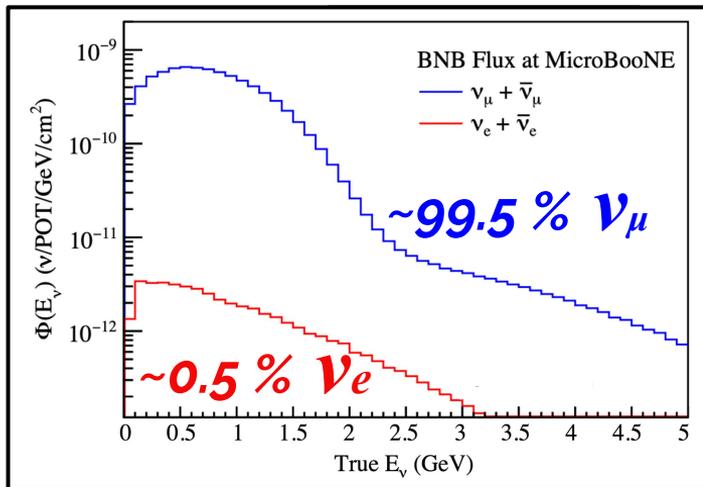


World's first Dual Beam Search for Sterile Neutrino Oscillations

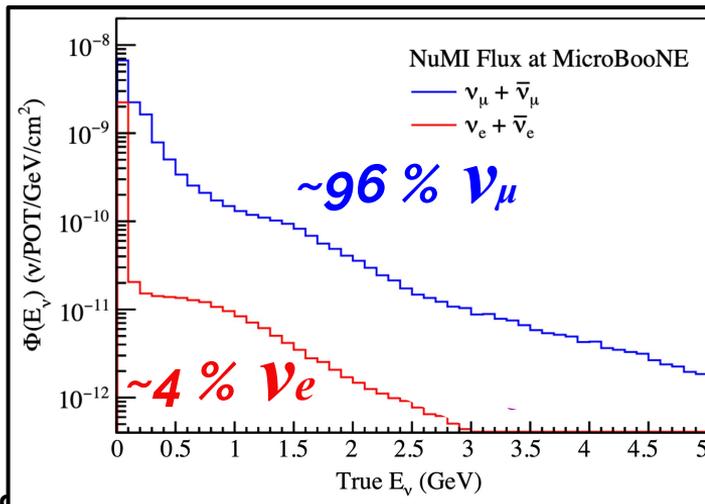


Dual Beam Oscillation Search

BNB

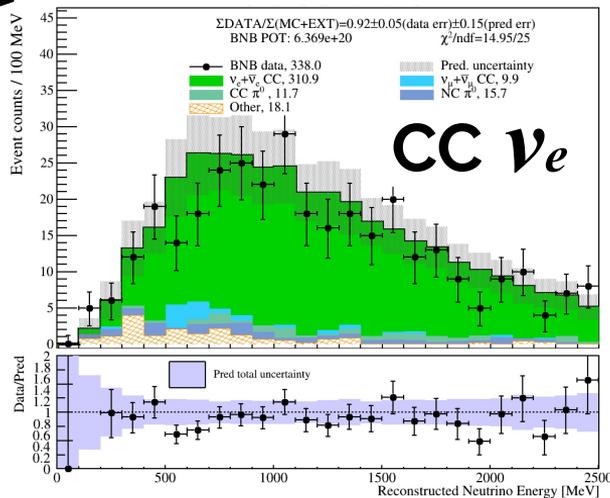


NuMI



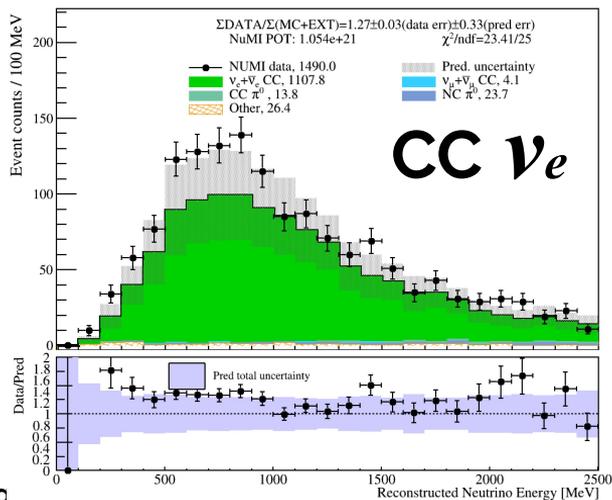
Search for $\nu_\mu \rightarrow \nu_e$ Appearance oscillations on top of **small intrinsic ν_e component** in the beam

BNB



82% Purity
46% Efficiency

NuMI

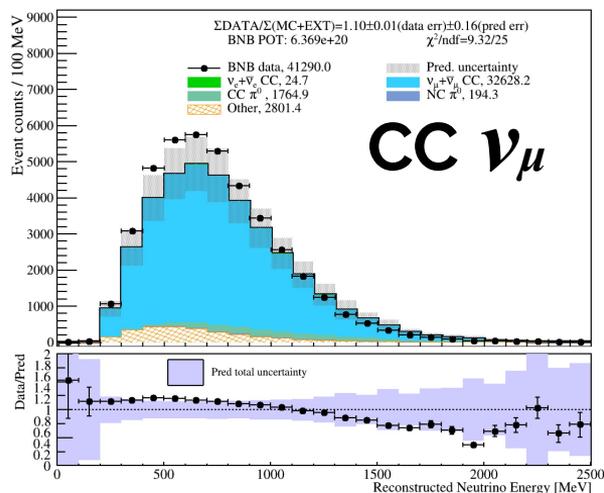
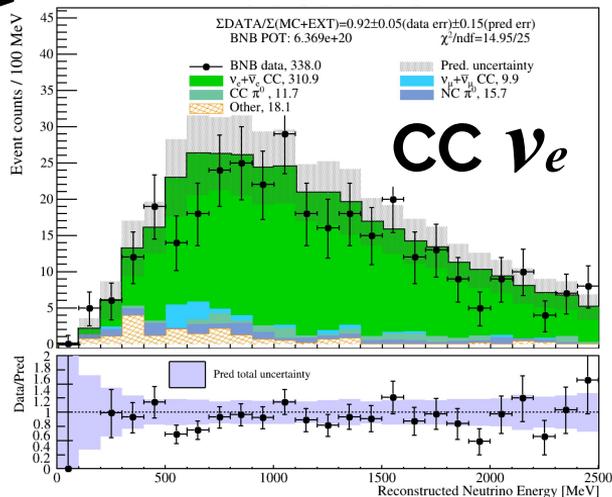


91% Purity
42% Efficiency

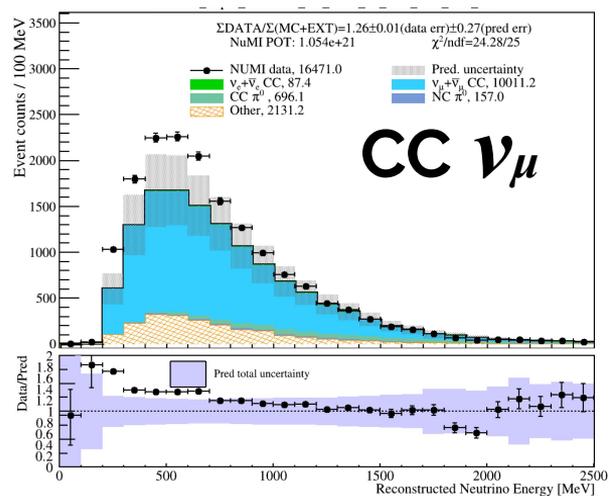
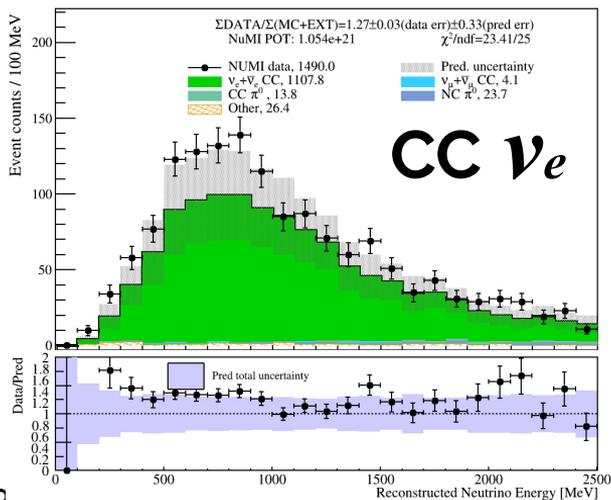
Cross-Section and **Flux** systematics
dominate uncertainty

- ~ 22% total error for BNB
- ~ 30% total error for NuMI

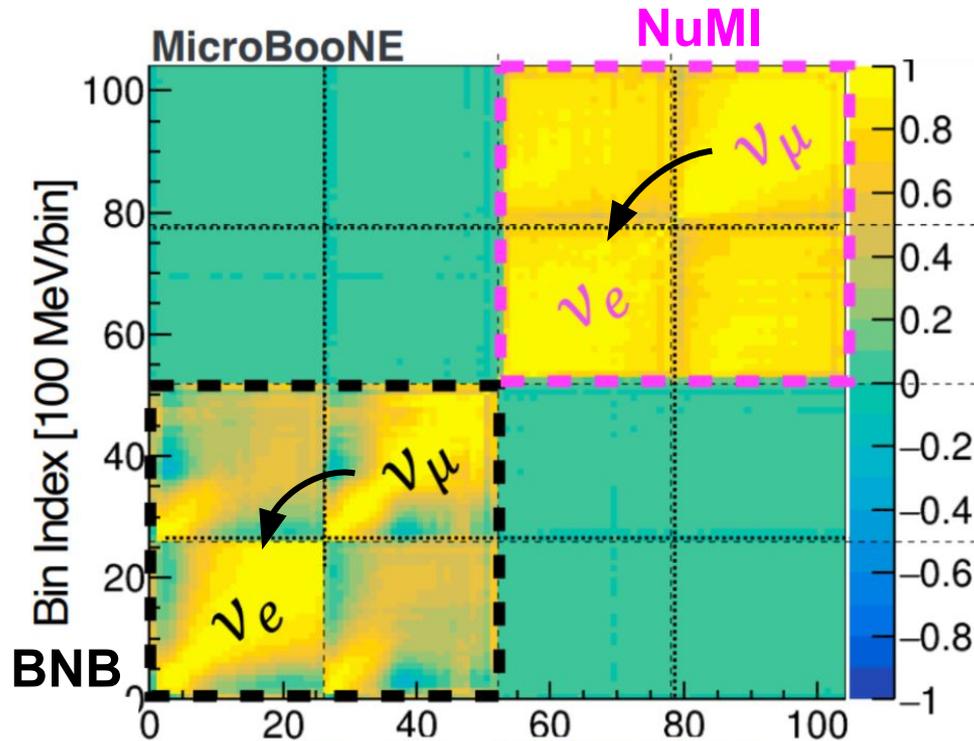
BNB



NuMI



Flux Systematic Correlation Matrix

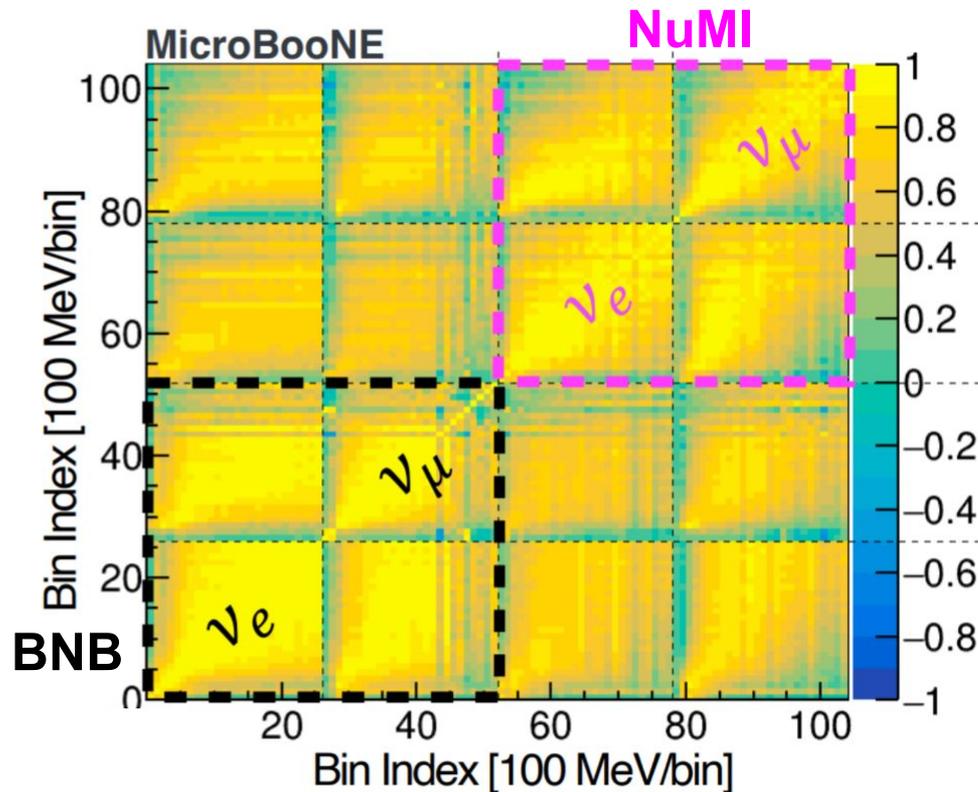


NuMI and BNB fluxes modelled as independent.

Significant updates to our **NuMI flux modelling** to including

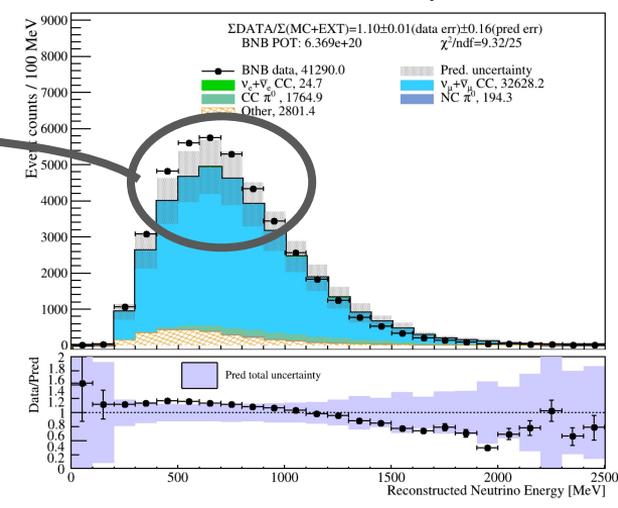
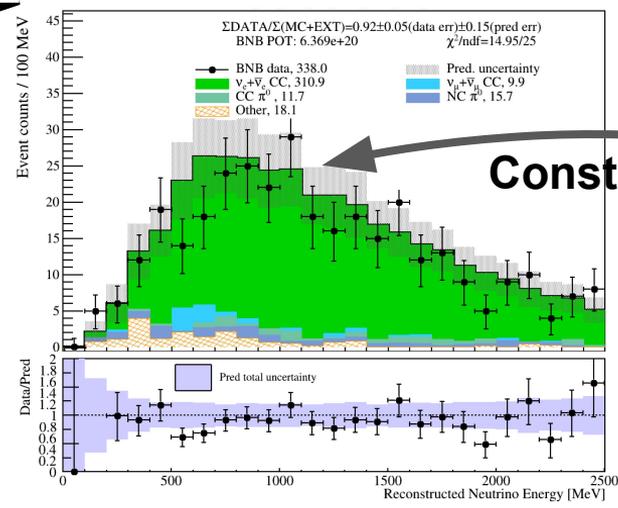
- Updated **beam line geometry**
- Move to **Geant4 v4.10.4** for better agreement with Kaon production external datasets

Cross-Section/Interaction Systematic Correlation Matrix



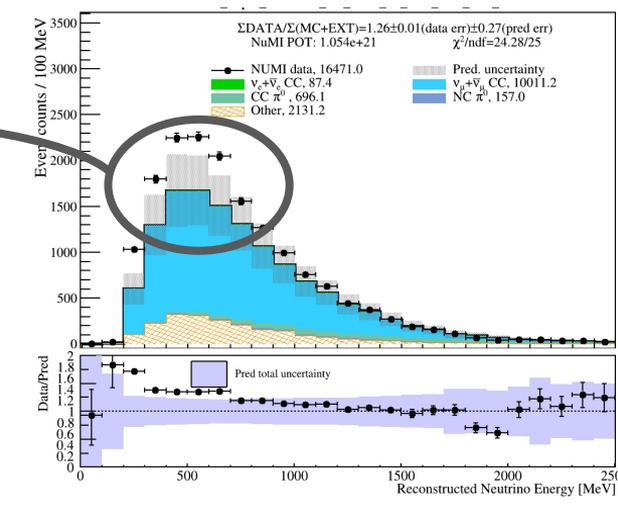
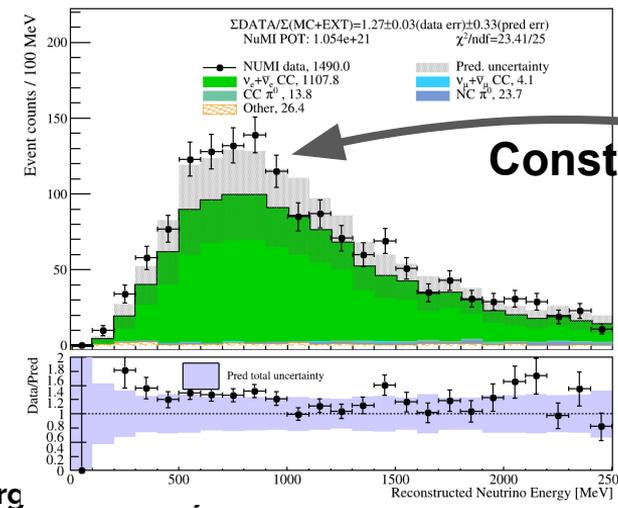
Extremely strong correlations between ν_e and ν_μ due to universality of CC interactions.

BNB



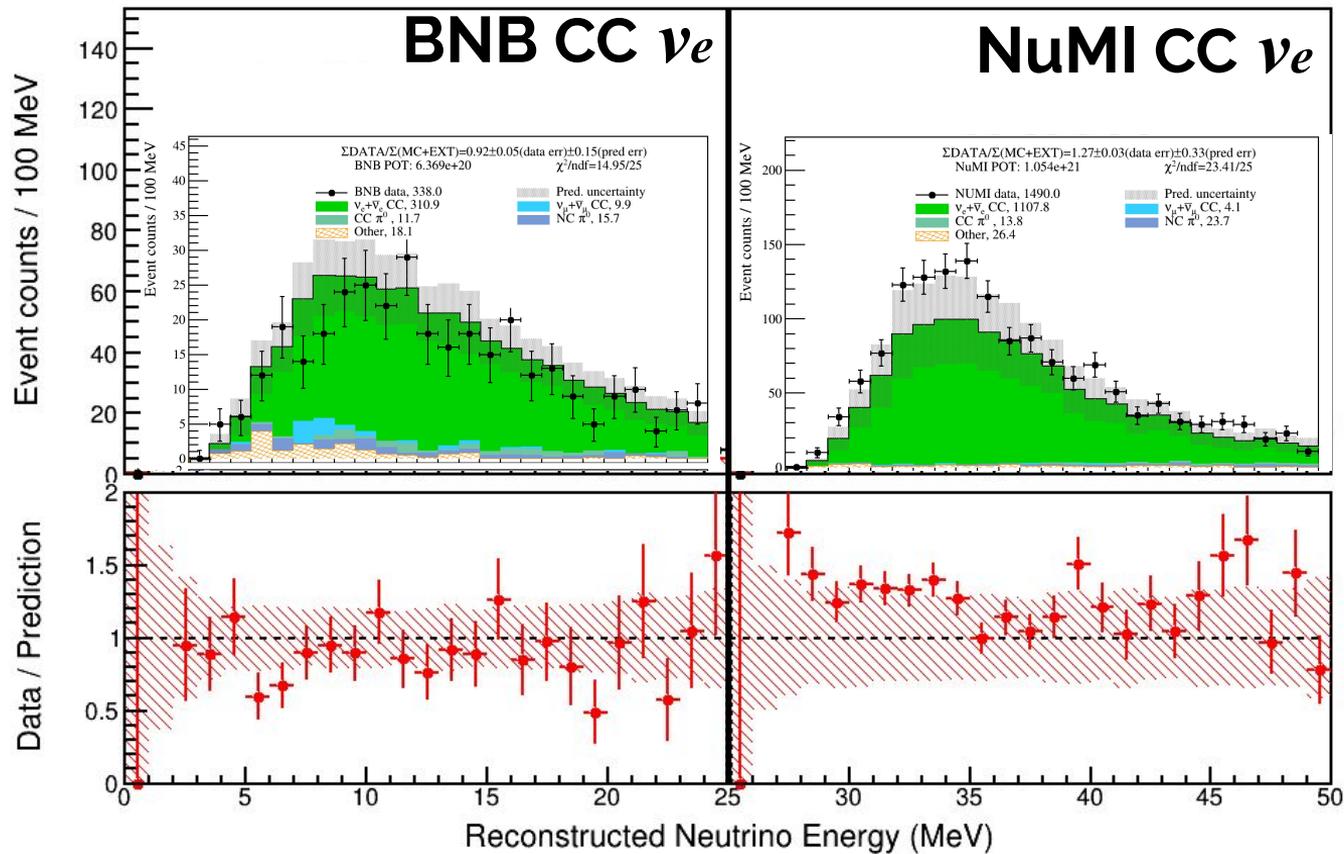
Constrain.

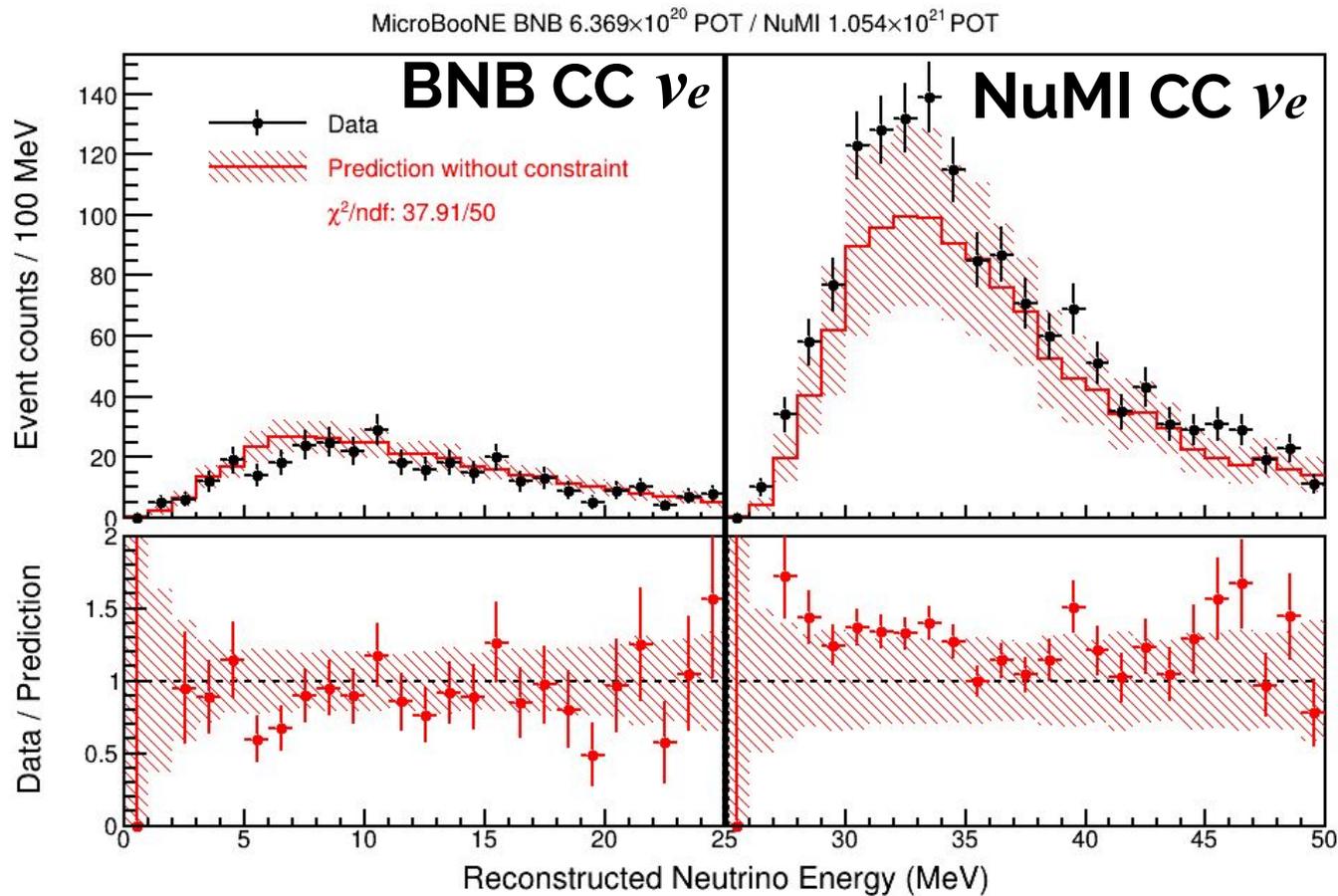
NuMI



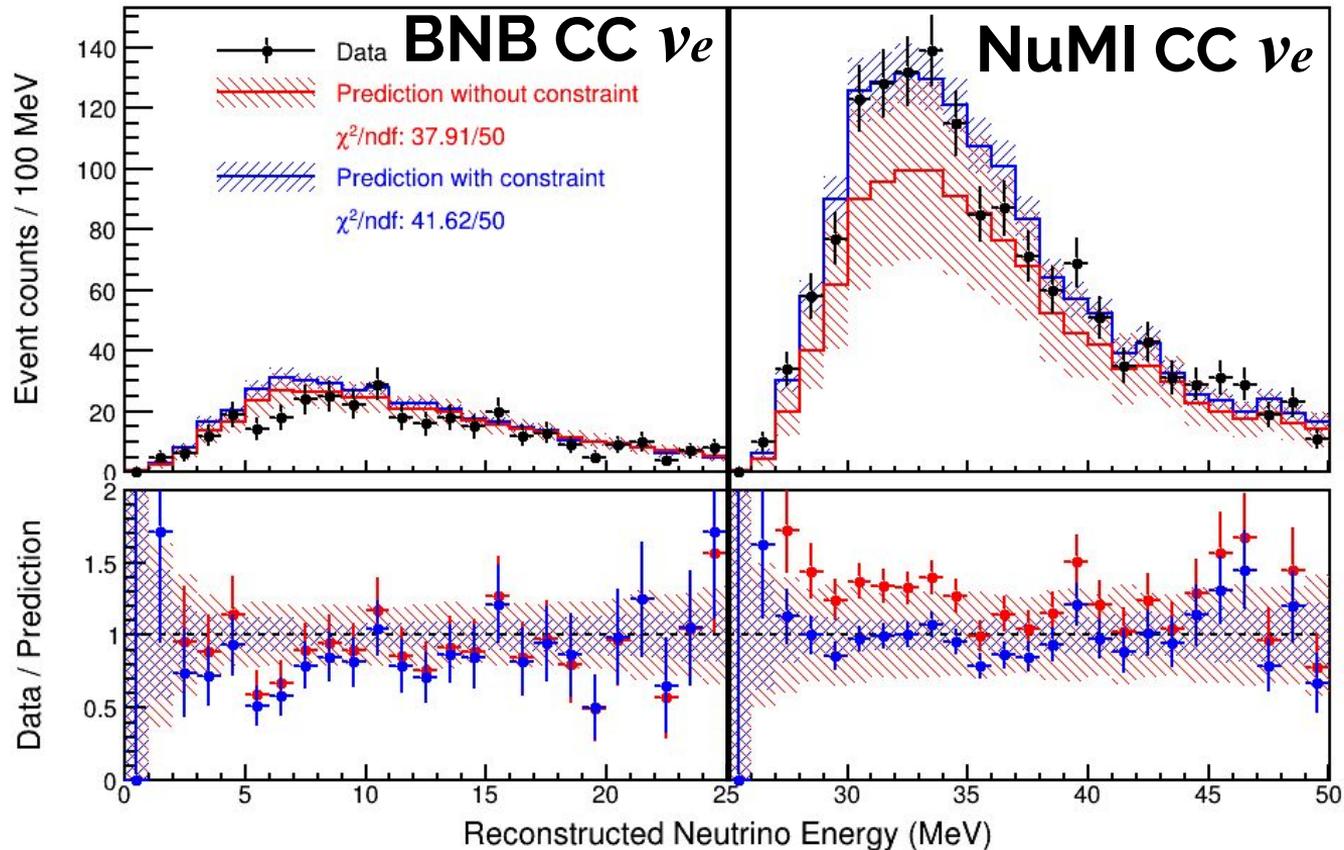
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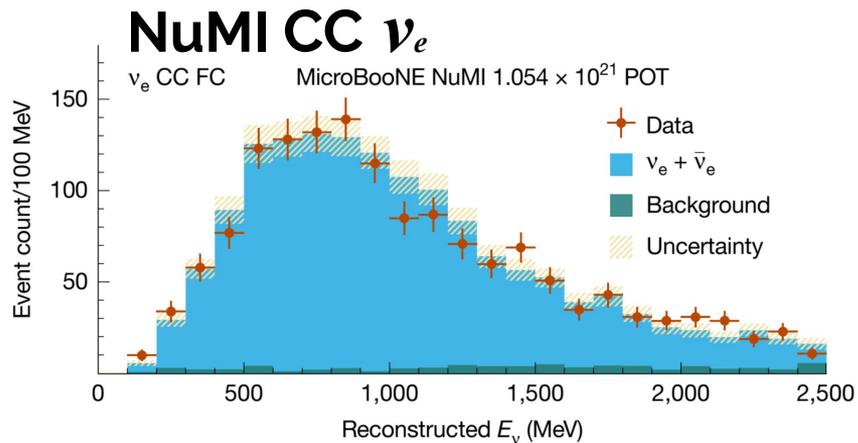
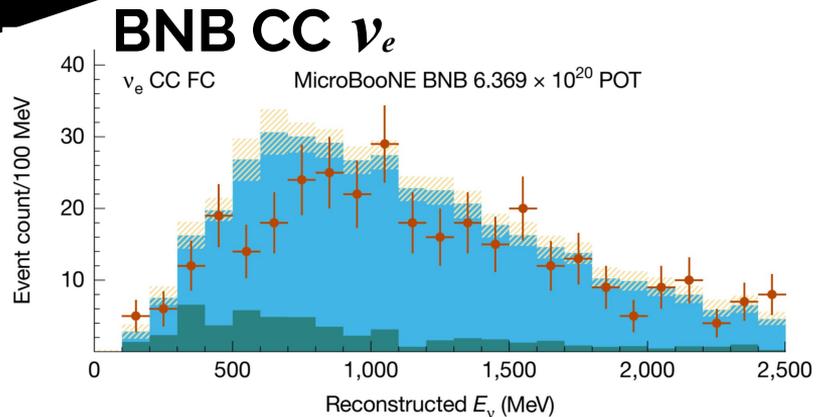
MicroBooNE BNB 6.369×10^{20} POT / NuMI 1.054×10^{21} POT

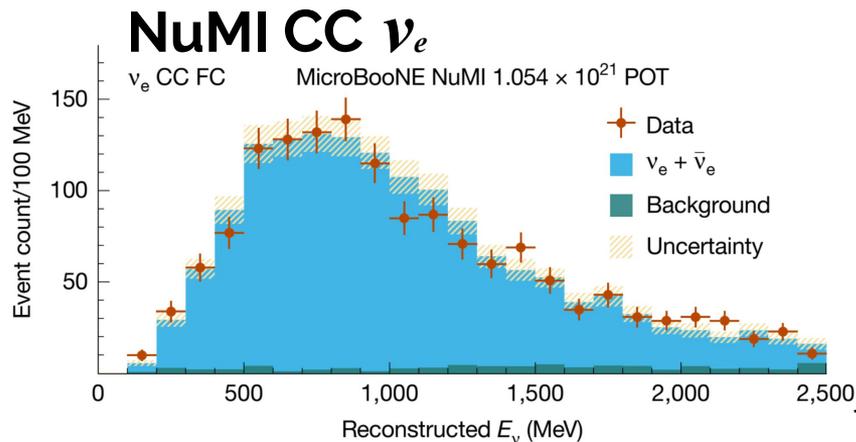
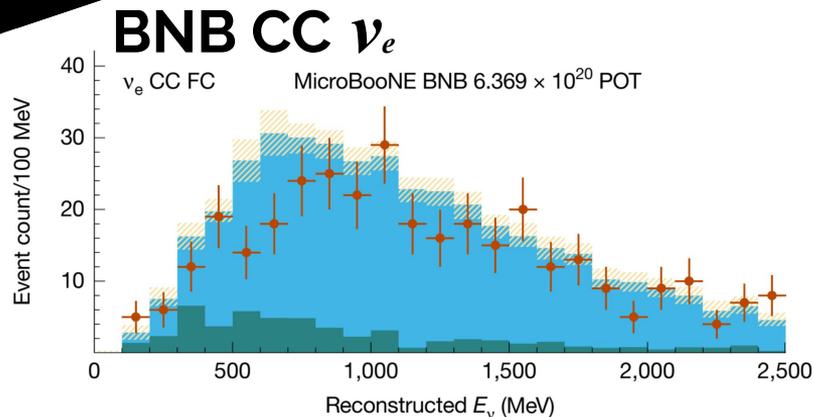




MicroBooNE BNB 6.369×10^{20} POT / NuMI 1.054×10^{21} POT







Best Fit Values:

$$\Delta m_{41}^2 = 1.30 \times 10^{-2} \text{eV}^2$$

$$\sin^2(2\theta_{\mu e}) = 0.999$$

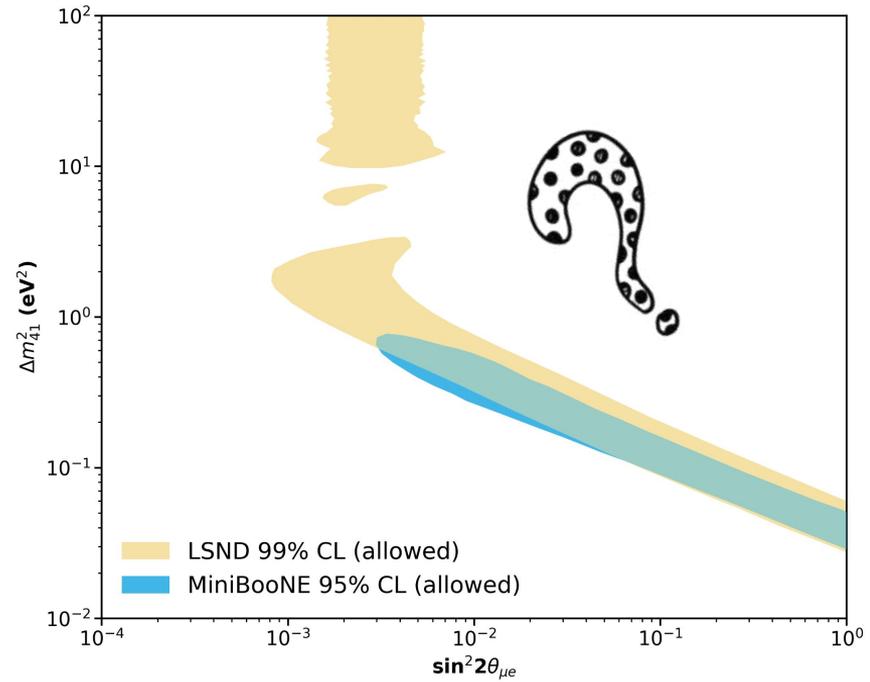
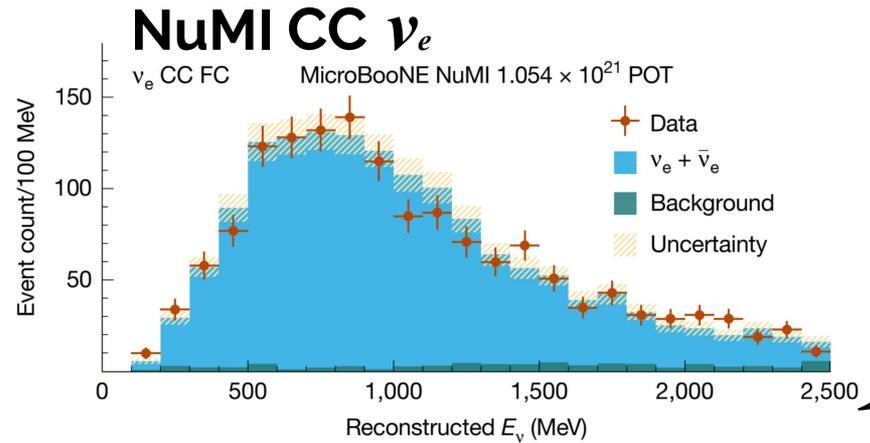
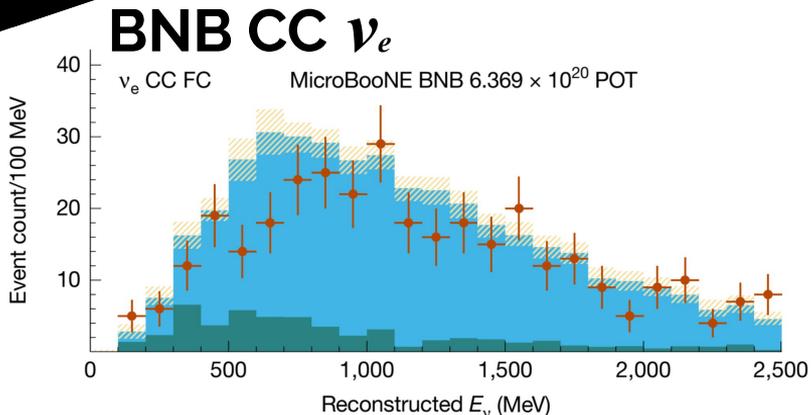
$$\sin^2(2\theta_{ee}) = 0.999$$

$$\sin^2(\theta_{24}) = 1$$

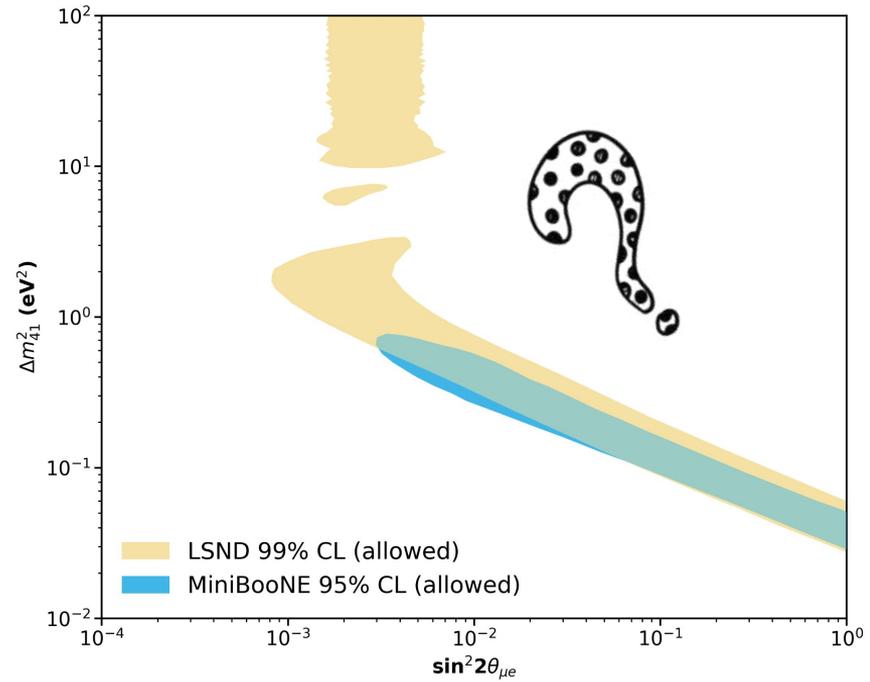
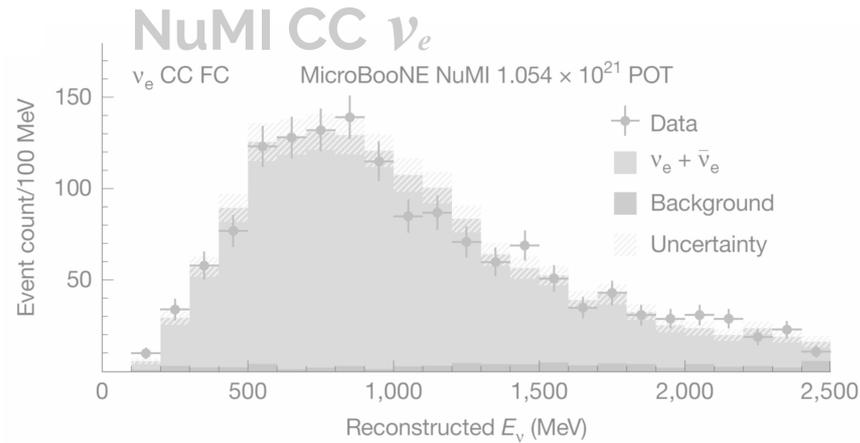
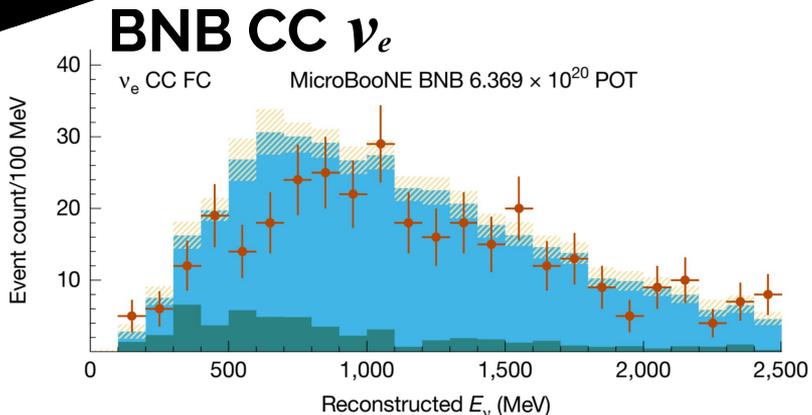
$$\Delta\chi^2 = \chi^2_{\text{No-Osc}} - \chi^2_{\text{Best-Fit}} = 0.228$$

Data is **consistent with no-oscillations**
with a **p-value of 96%** (Feldman Cousins)

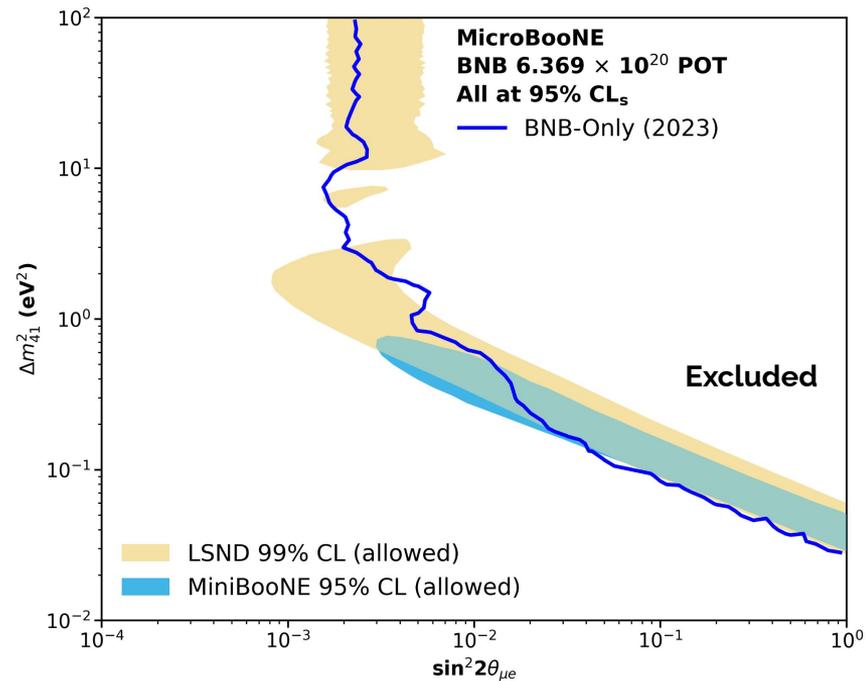
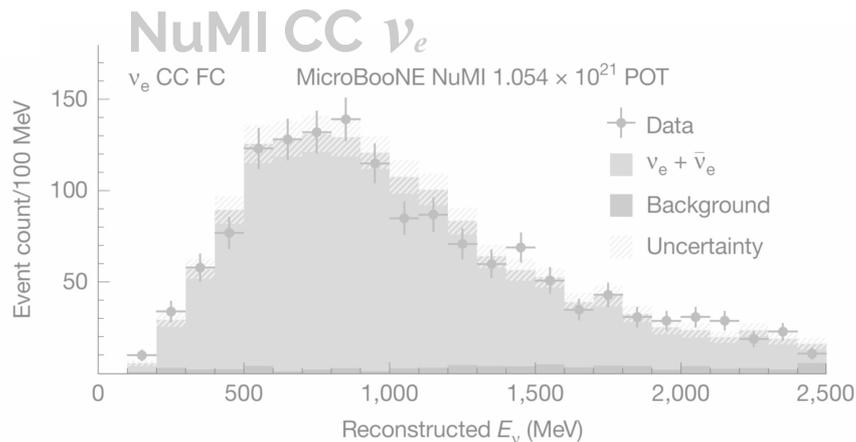
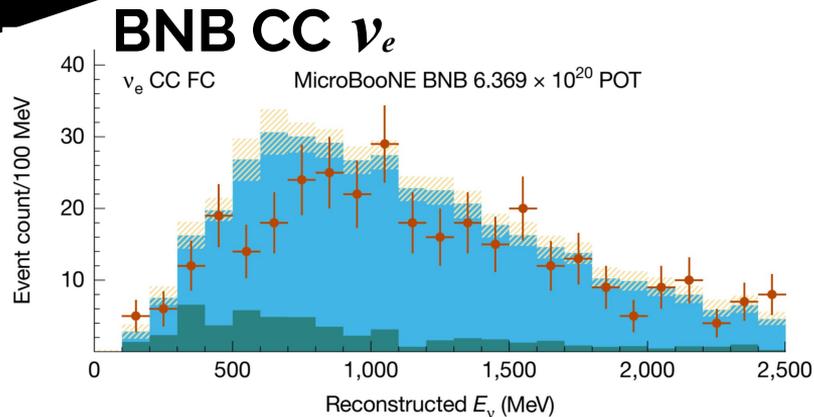
Exclusion Contours



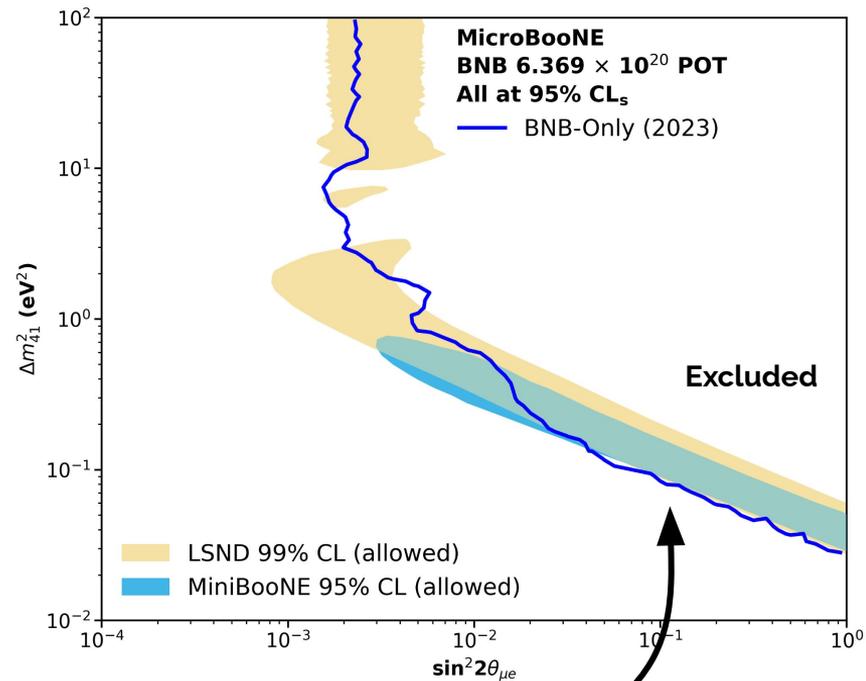
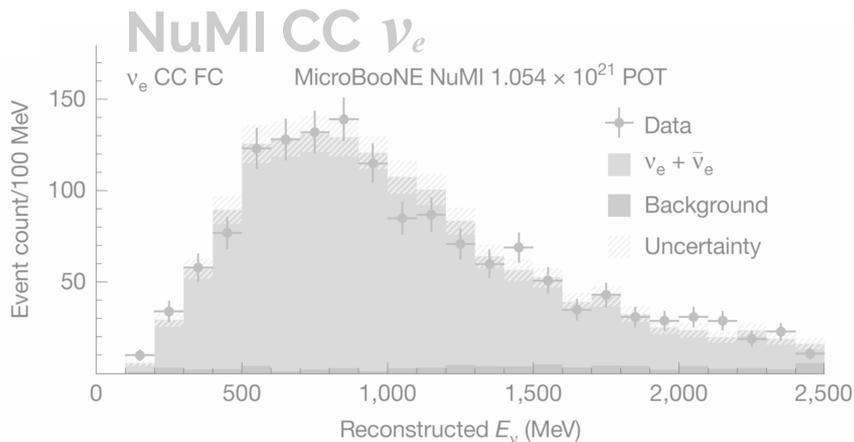
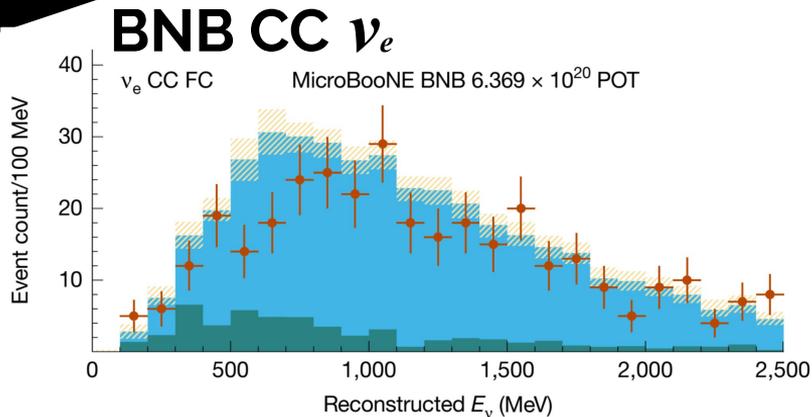
Exclusion Contours



BNB-Only Exclusion Contours

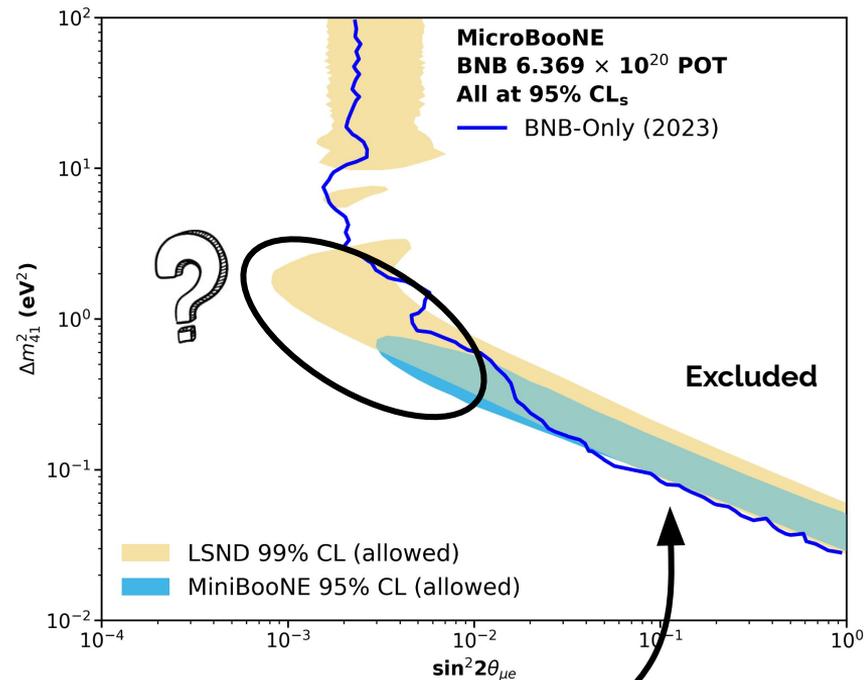
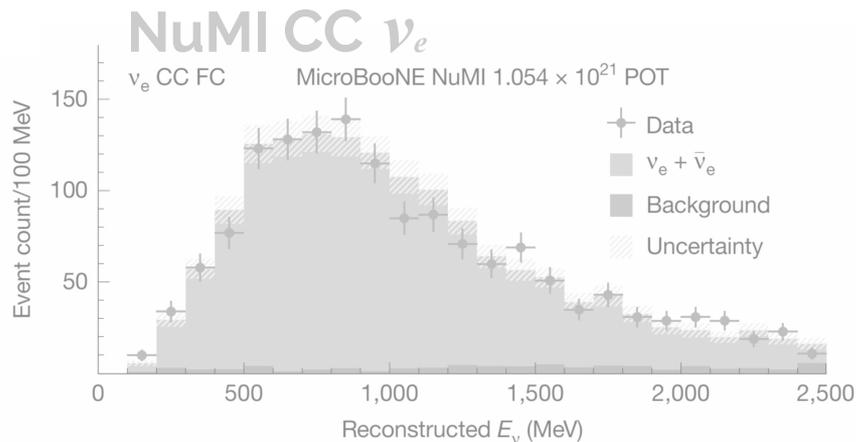
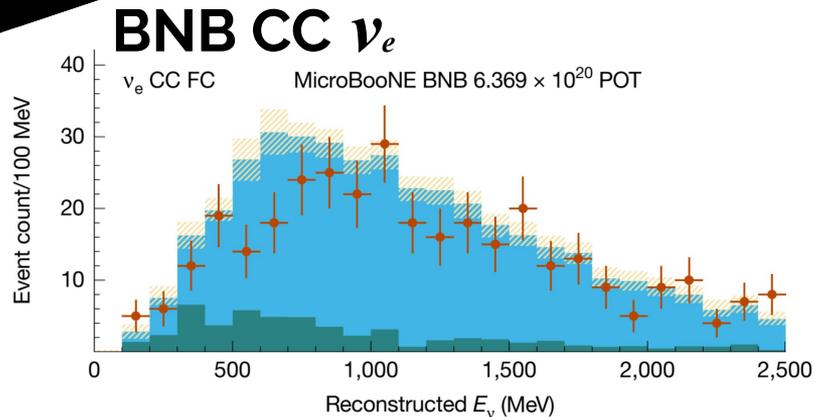


BNB-Only Exclusion Contours



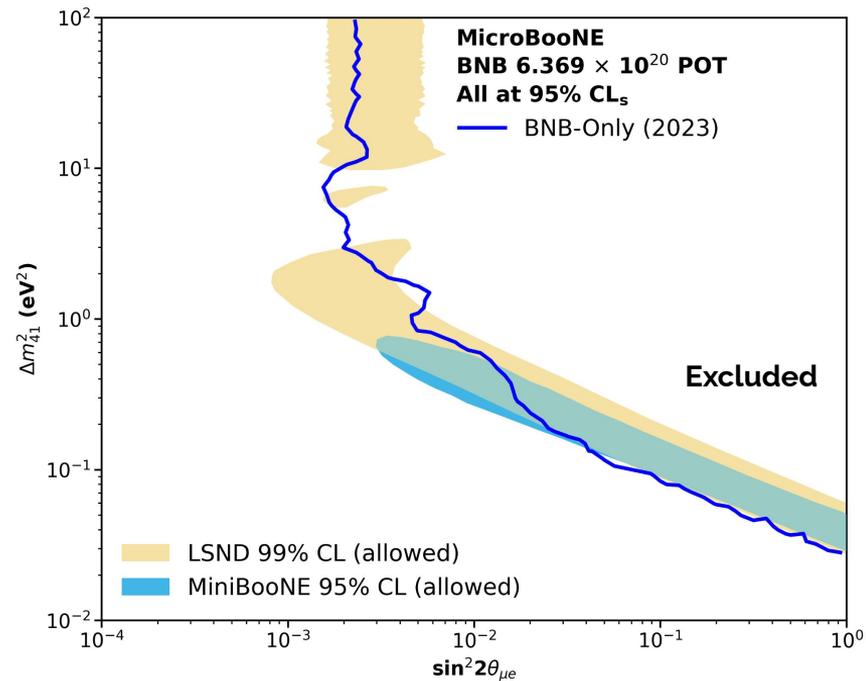
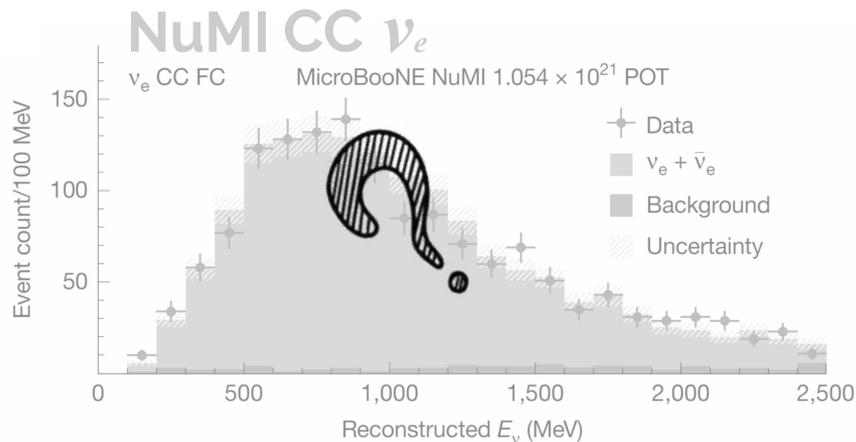
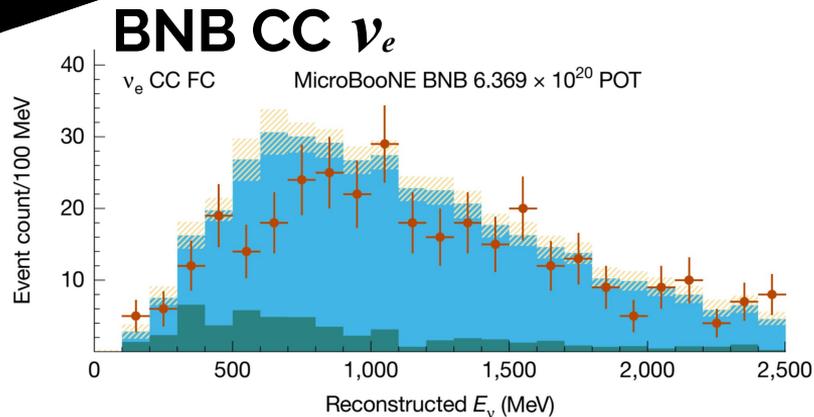
**Low Δm^2 uBooNE 2023 result
excludes MiniBooNE/LSND well**

BNB-Only Exclusion Contours

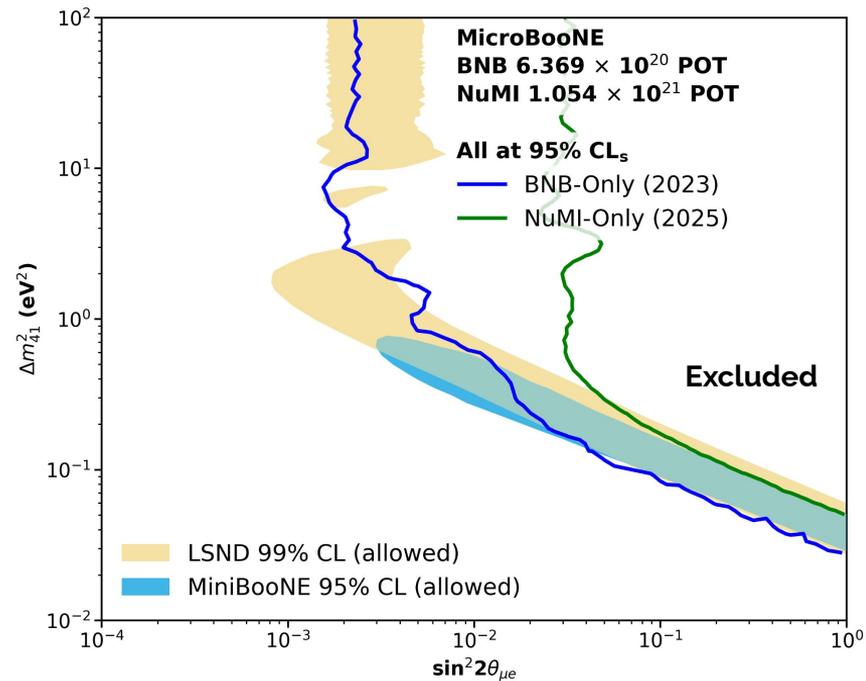
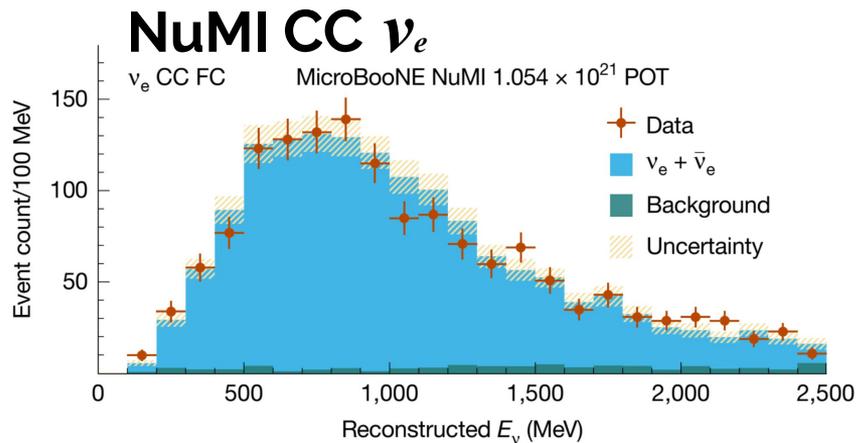
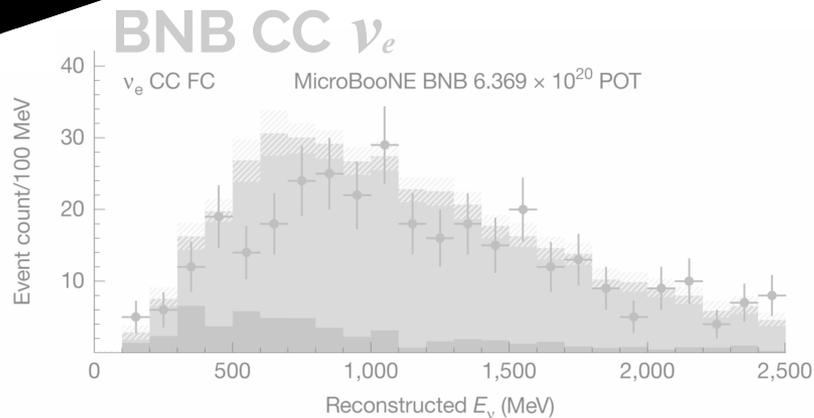


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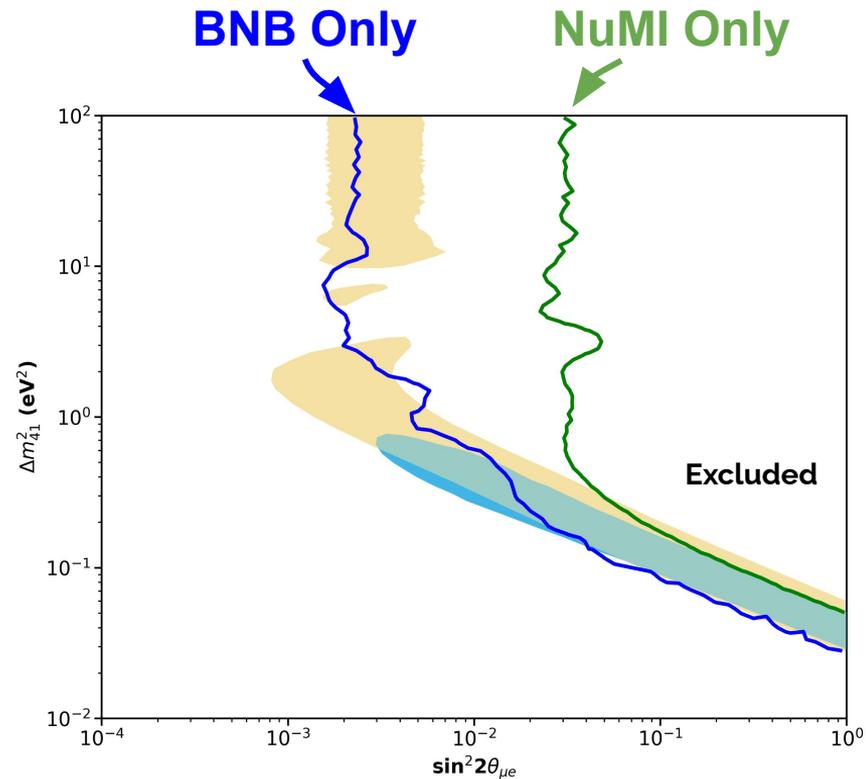
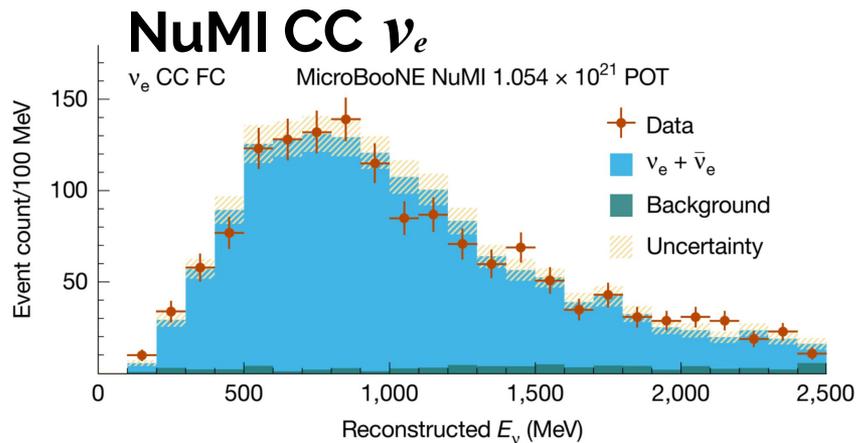
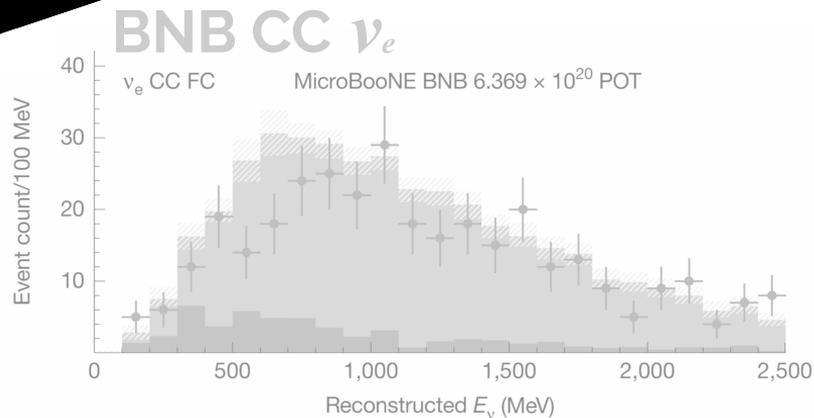
BNB-Only Exclusion Contours



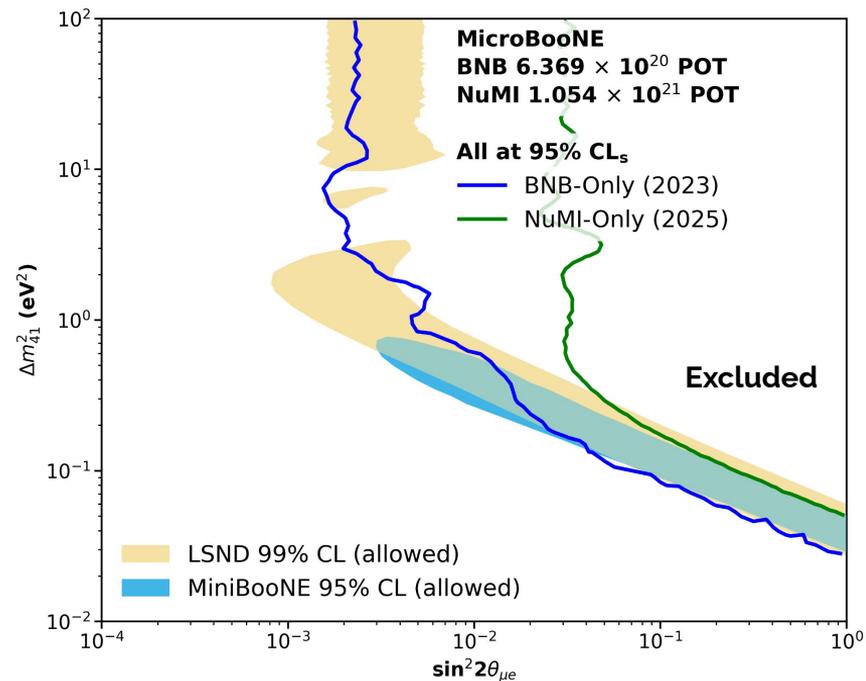
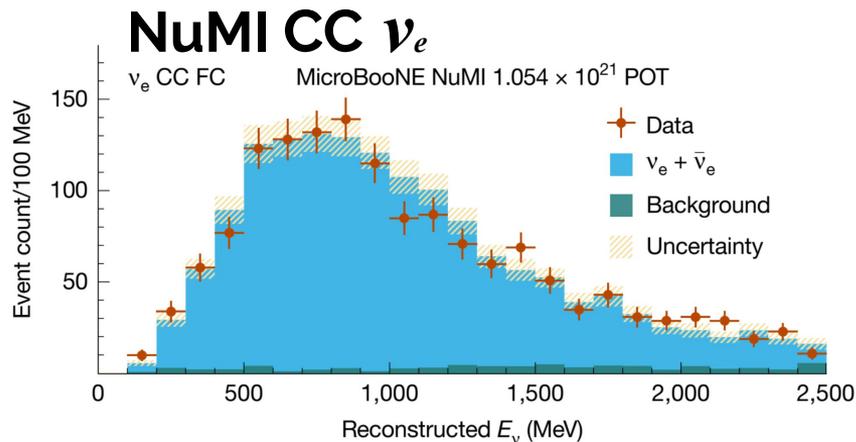
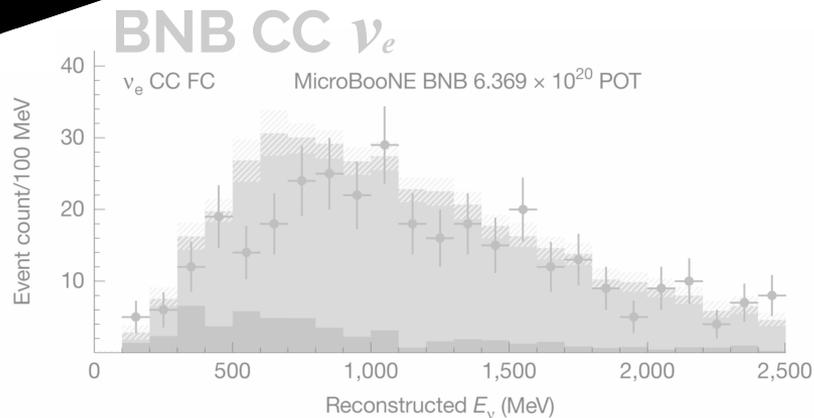
NuMI-Only Exclusion Contours



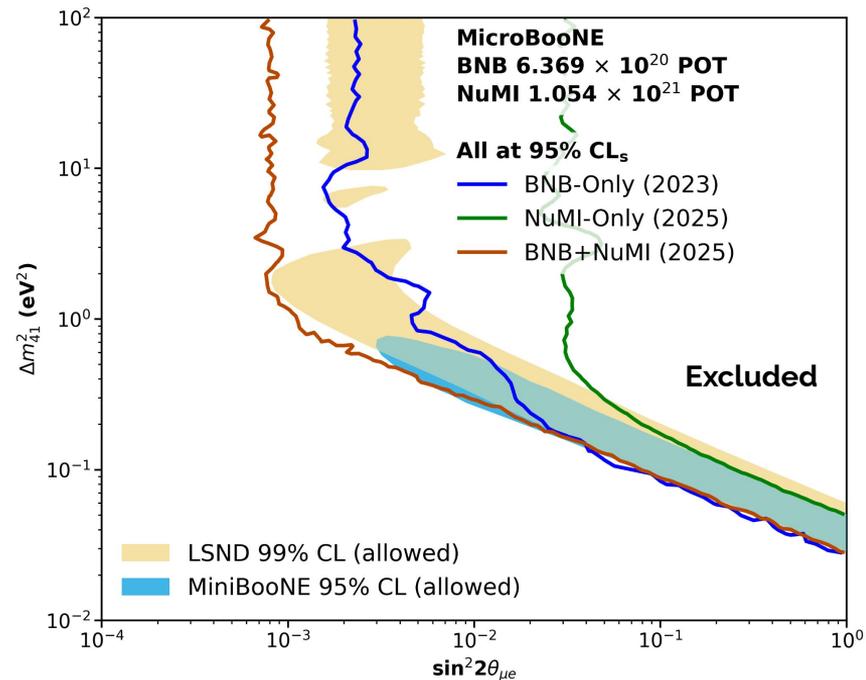
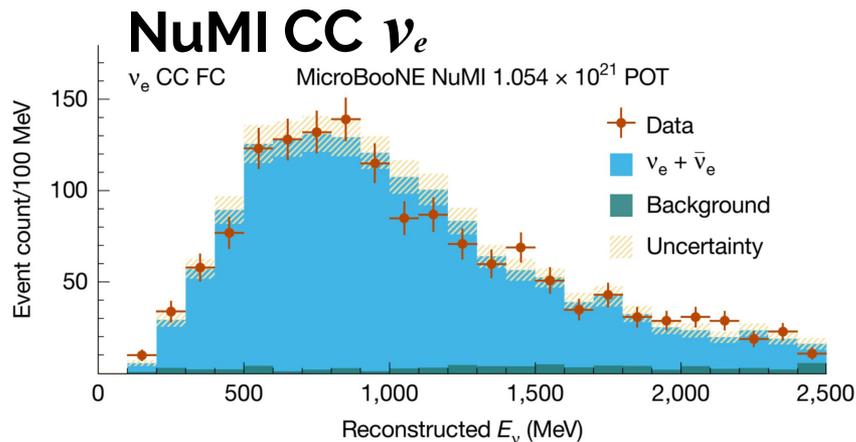
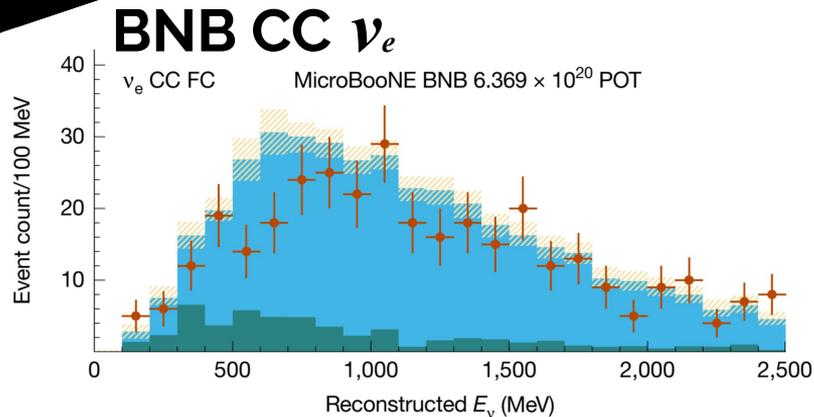
NuMI-Only Exclusion Contours



NuMI-Only Exclusion Contours

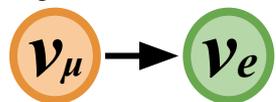


BNB+NuMI, Dual Beam Exclusion Contours

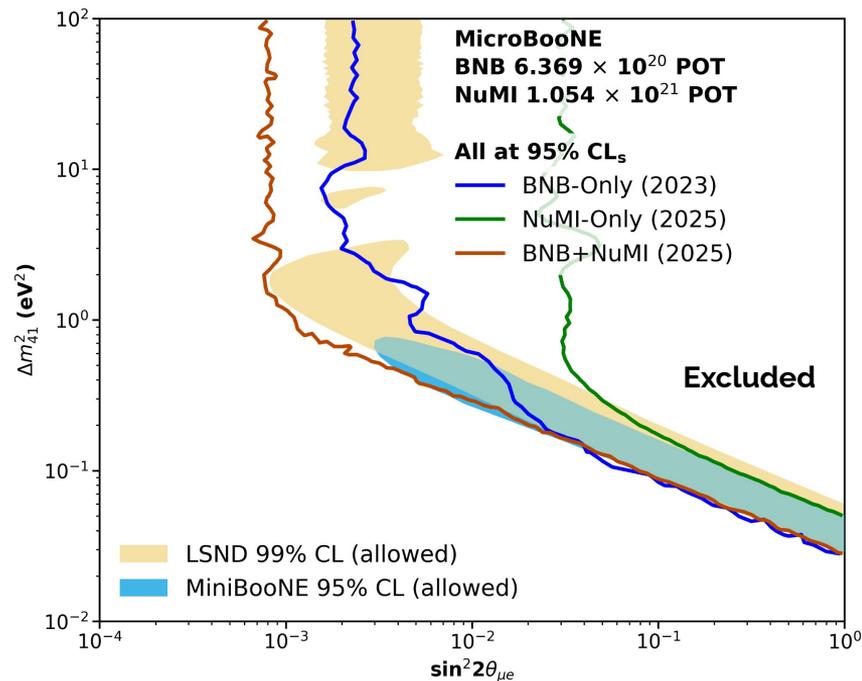


3+1 Parameter Degeneracy

ν_e appearance

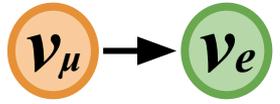


$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$



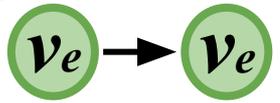
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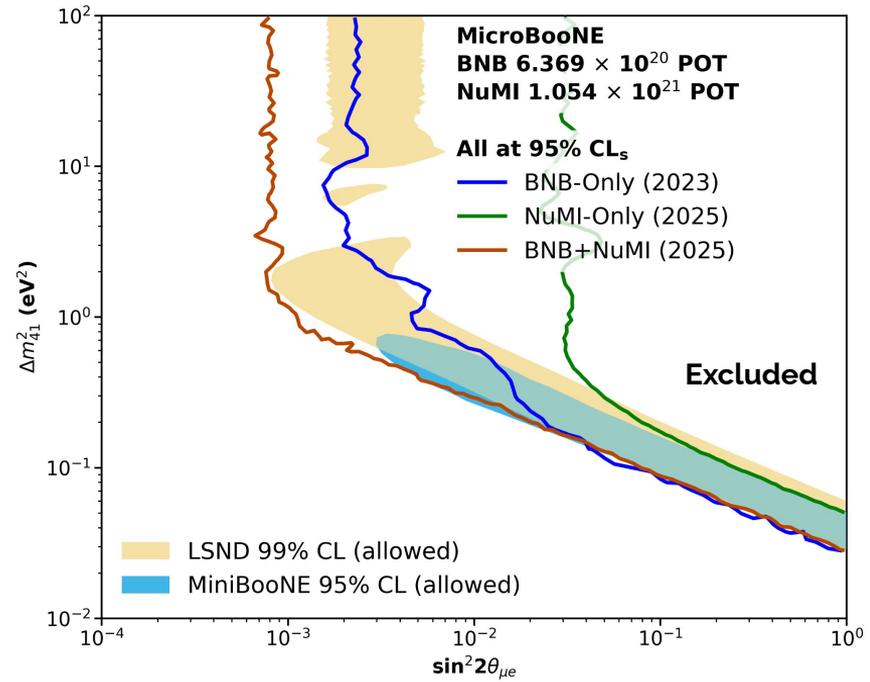
$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

ν_e disappearance



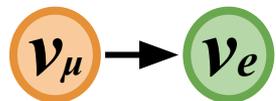
$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

**Not independent.
Can't have appearance without
associated disappearance**



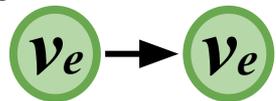
3+1 Parameter Degeneracy

ν_e appearance



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ν_e disappearance

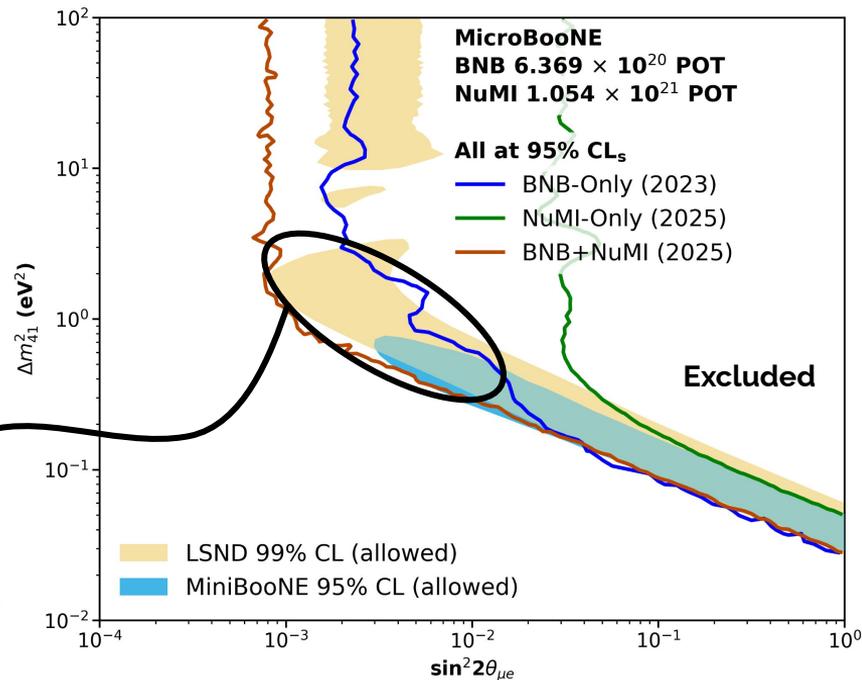


$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

Cancellation/Degeneracy point

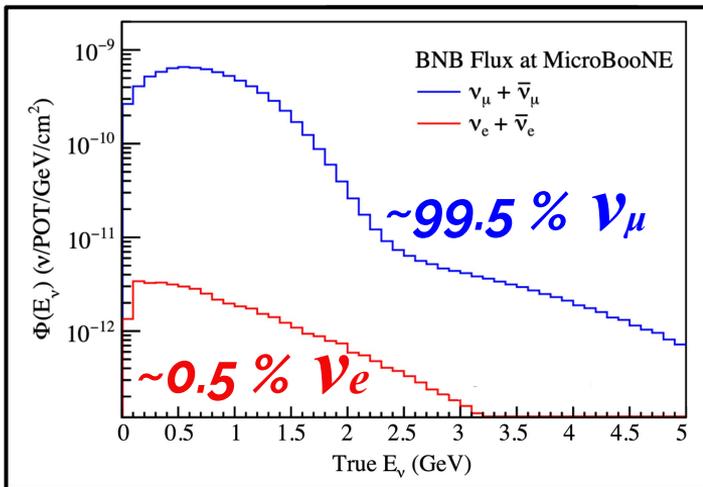
Disappearance
Cancels
Appearance

$$\frac{N_{\nu_\mu}}{N_{\nu_e}} = \frac{\sin^2 2\theta_{ee}}{\sin^2 2\theta_{\mu e}}$$



NuMI Breaks Degeneracy

BNB

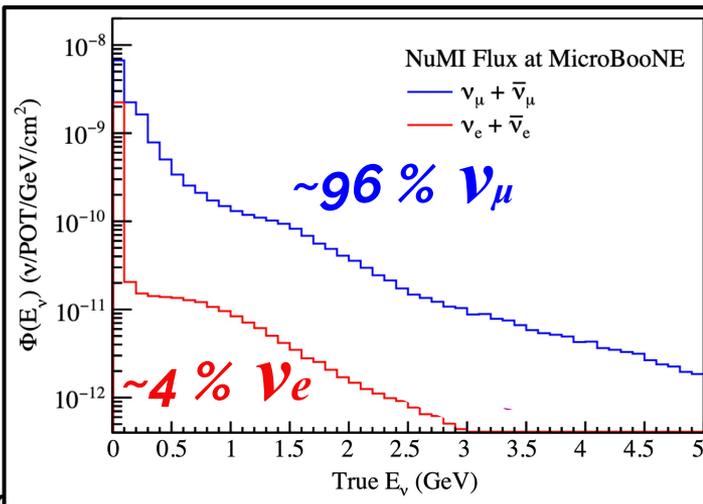


$$\frac{N\nu_\mu}{N\nu_e} \sim 200$$

Cancellation/Degeneracy point

$$\frac{N\nu_\mu}{N\nu_e} = \frac{\sin^2 2\theta_{ee}}{\sin^2 2\theta_{\mu e}}$$

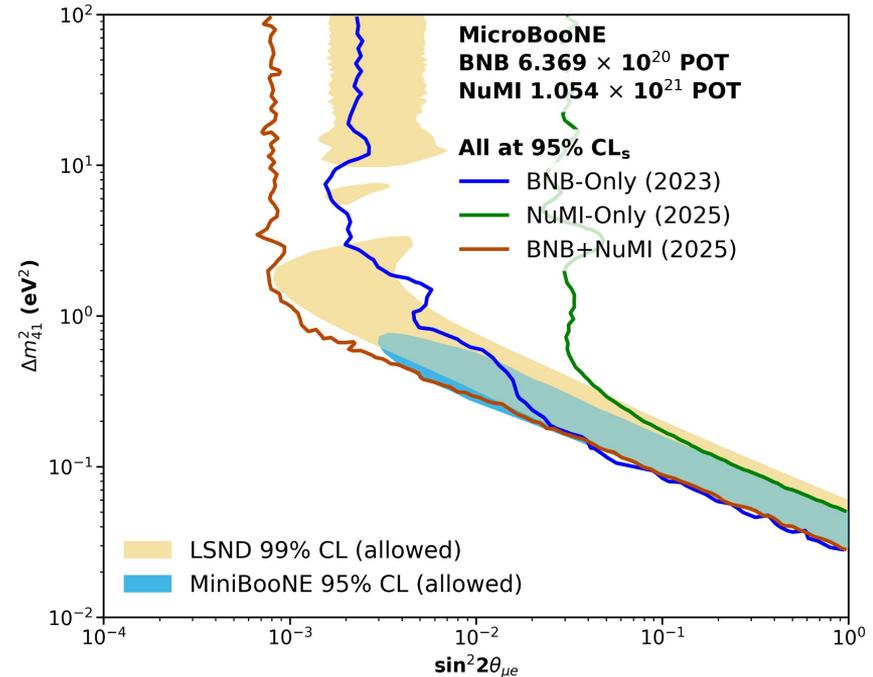
NuMI

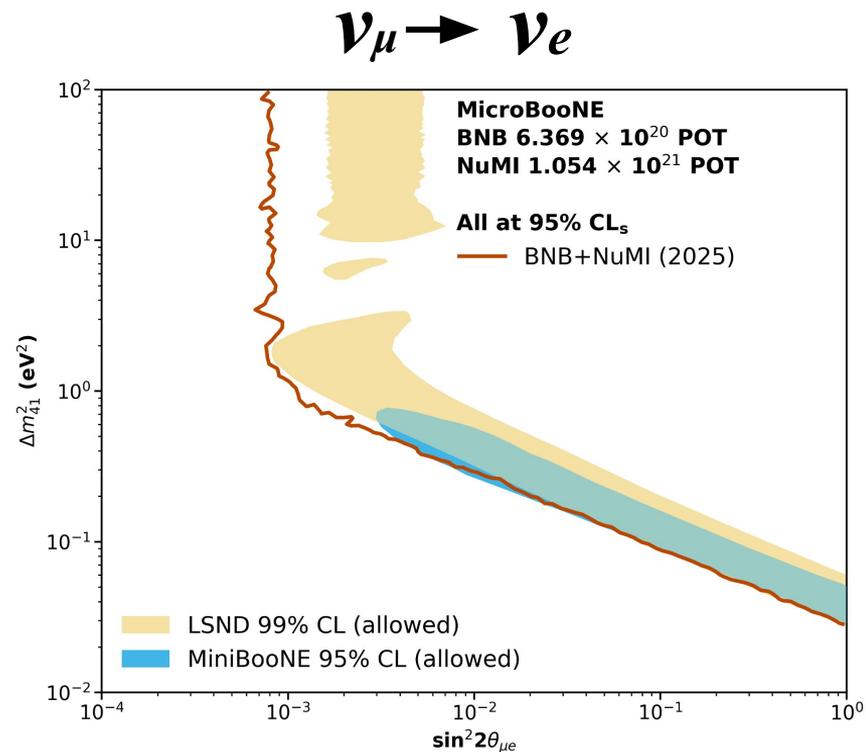


$$\frac{N\nu_\mu}{N\nu_e} \sim 24$$

Addition of NuMI data

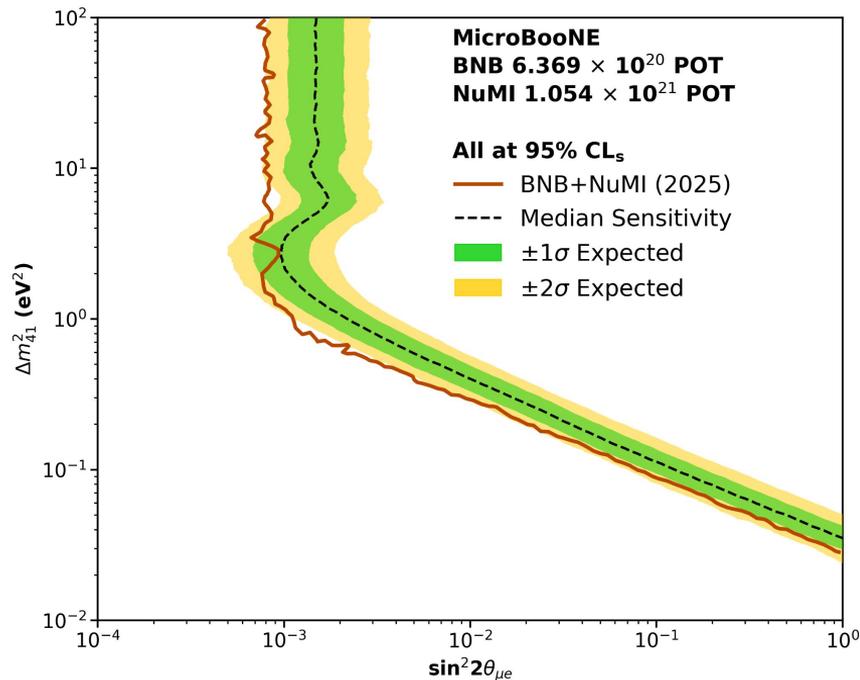
- **Breaks** the degeneracy
- **Constrains the amount of ν_e disappearance allowed**
- **Unlocks full potential of the BNB to constrain ν_e appearance**





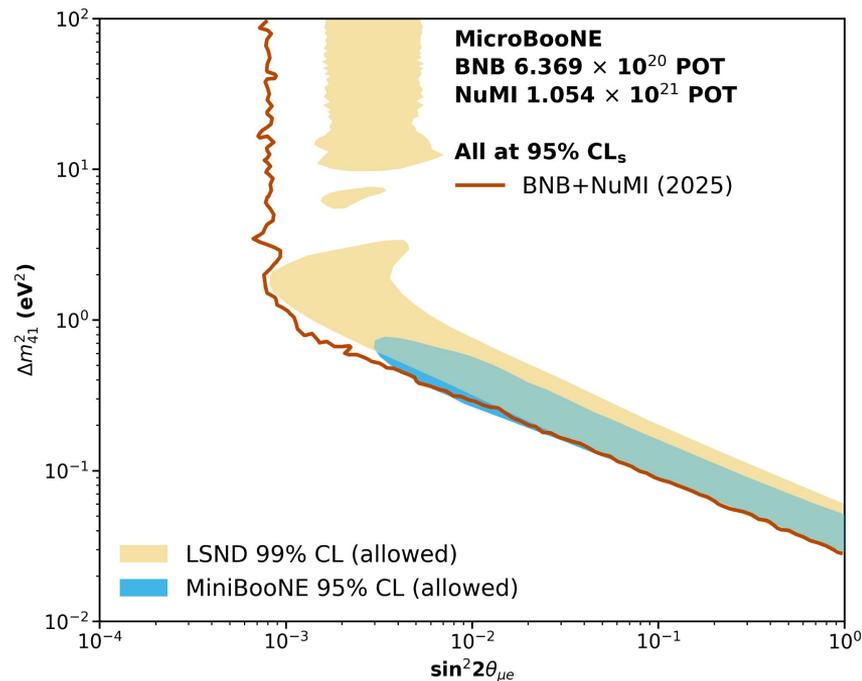
- **Excludes LSND 99% allowed region**
- **Excludes vast majority of MiniBooNE 95% allowed region**

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



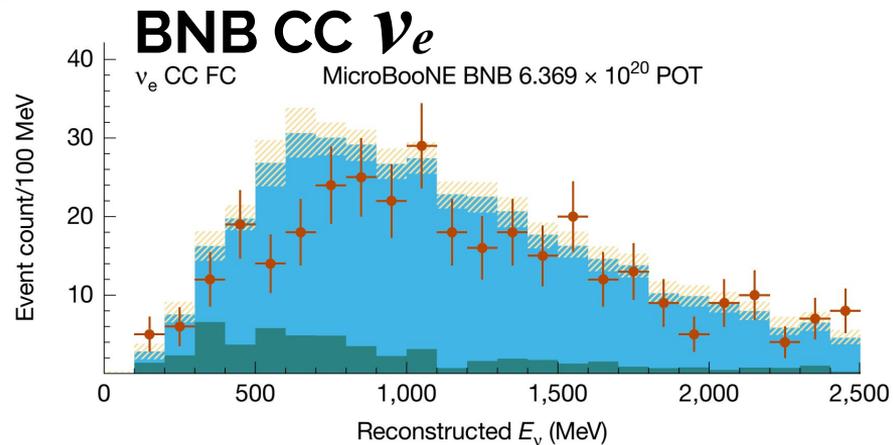
Data exclusion is stronger than median sensitivity.
Lies around the 2σ expected experiment

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



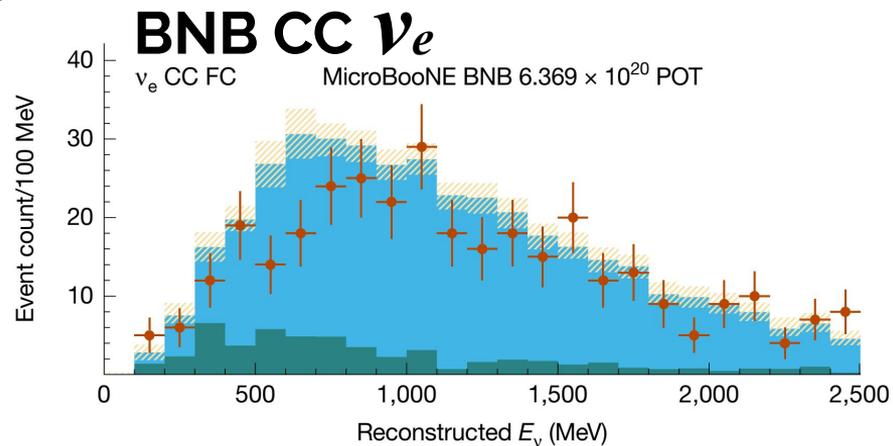
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Strength of Result Driven by BNB ν_e

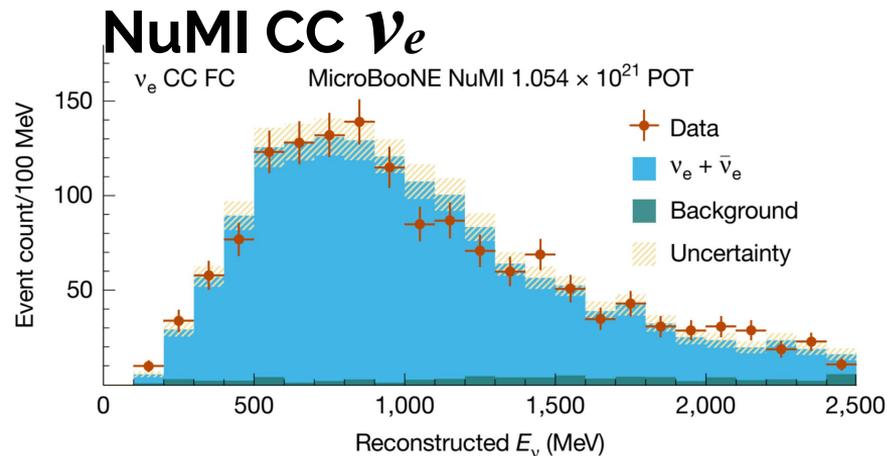


Driven by $\sim 2.1\sigma$ deficit observed in
BNB CC ν_e

Strength of Result Driven by BNB ν_e

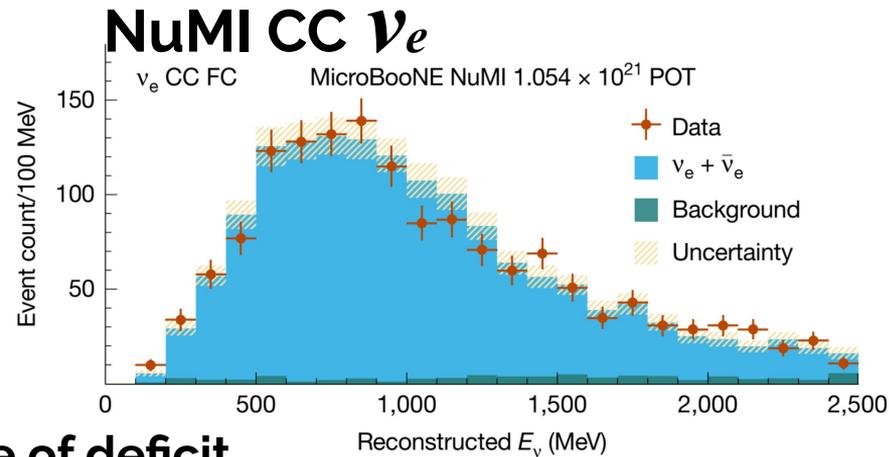
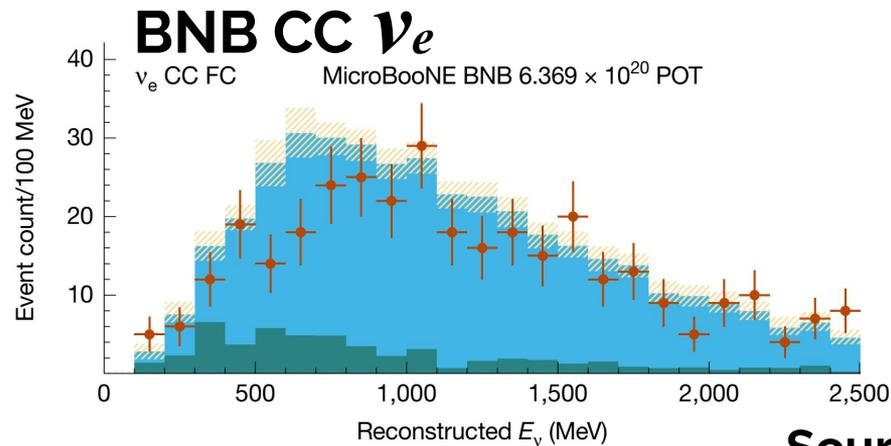


Driven by $\sim 2.1\sigma$ deficit observed in BNB CC ν_e



Excellent agreement in NuMI CC ν_e

Strength of Result Driven by BNB ν_e



Source of deficit

- Interaction Modelling? **Same Model**
- Detector Modelling? **Same Detector/treatment**
- Reconstruction Effect? **Same Reco Framework**
- Flux Modelling? **Different Fluxes/Beams**

- **Statistical**

- **New Physics Driven?**

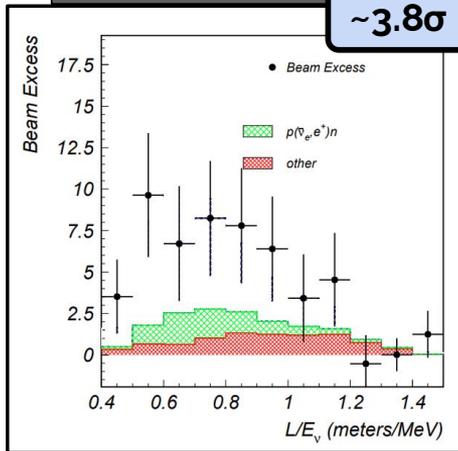
Investigations
Continue
~Double the Data

If not Sterile Neutrinos, then what are we seeing in Short-Baseline Anomalies?

LSND Anomaly

Decay-at-rest

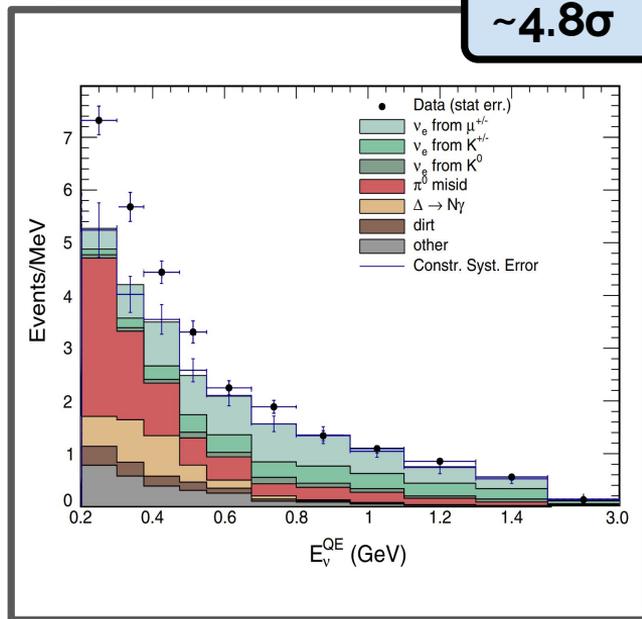
$\sim 3.8\sigma$



MiniBooNE Anomaly

Decay-in-flight

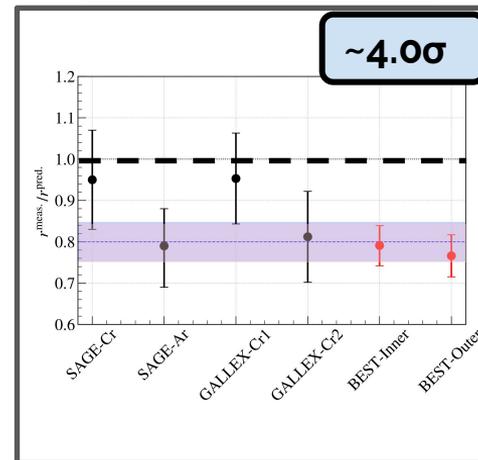
$\sim 4.8\sigma$



Gallium Anomaly

Radioactive Source

$\sim 4.0\sigma$

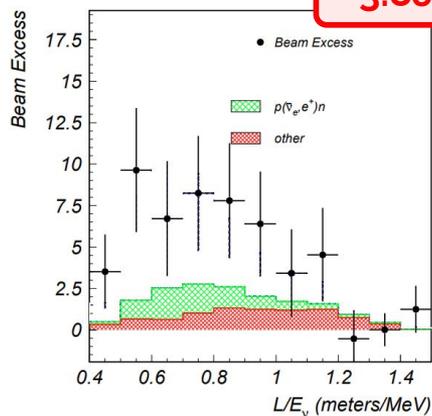


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LSND Anomaly

Decay-at-rest

$\sim 3.8\sigma$

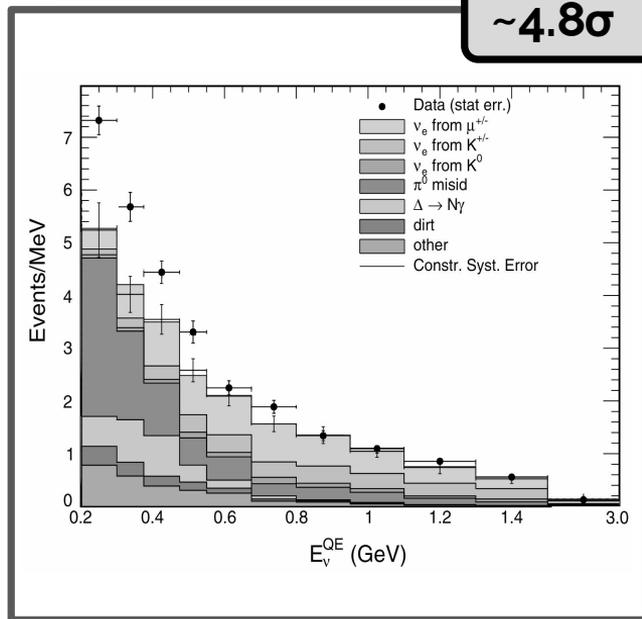


JSNS² and JSNS²-II will provide a direct probe of LSND ([arXiv:2602.06274](https://arxiv.org/abs/2602.06274))

MiniBooNE Anomaly

Decay-in-flight

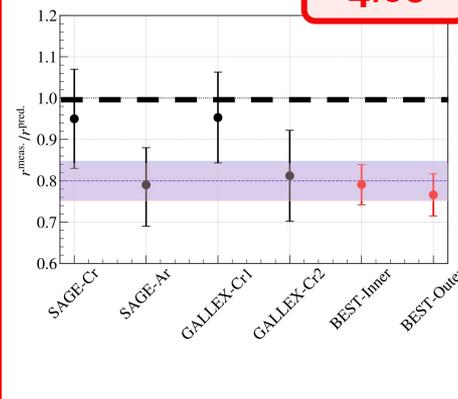
$\sim 4.8\sigma$



Gallium Anomaly

Radioactive Source

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Recent interest in revisiting the theoretical calculation of the neutrino capture cross-section

M. Cadeddu *et al* [Phys. Rev. D 113, 033006 \(2026\)](https://arxiv.org/abs/2512.20560)

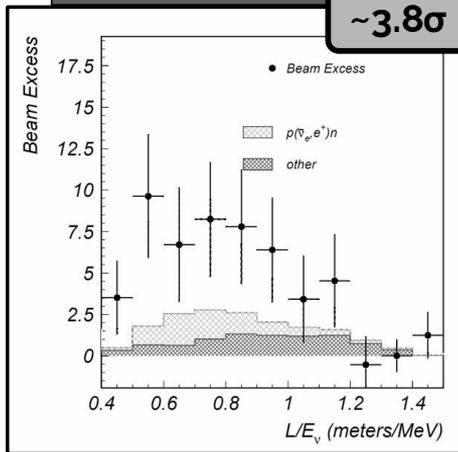
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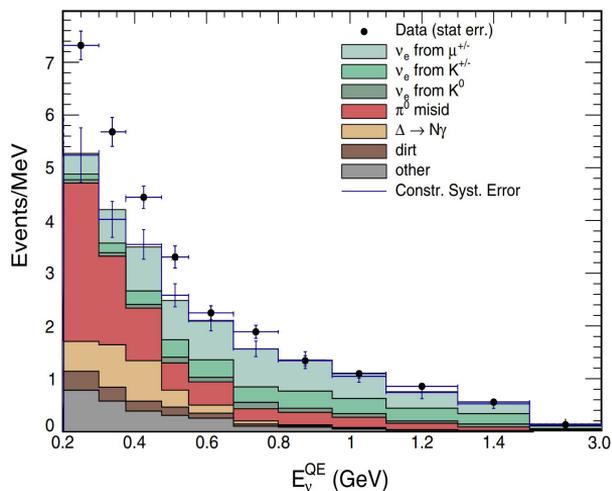


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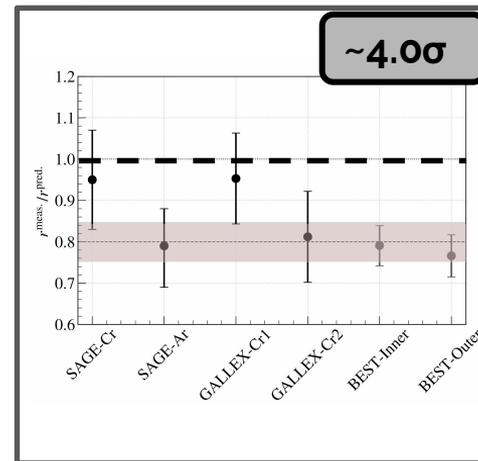
$\sim 4.8\sigma$



Gallium Anomaly

Radioactive Source

$\sim 4.0\sigma$

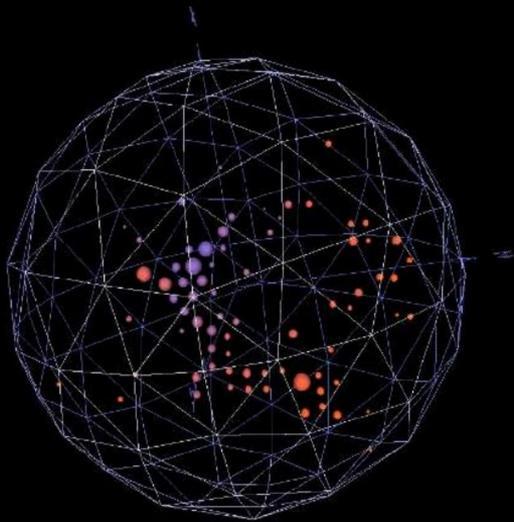


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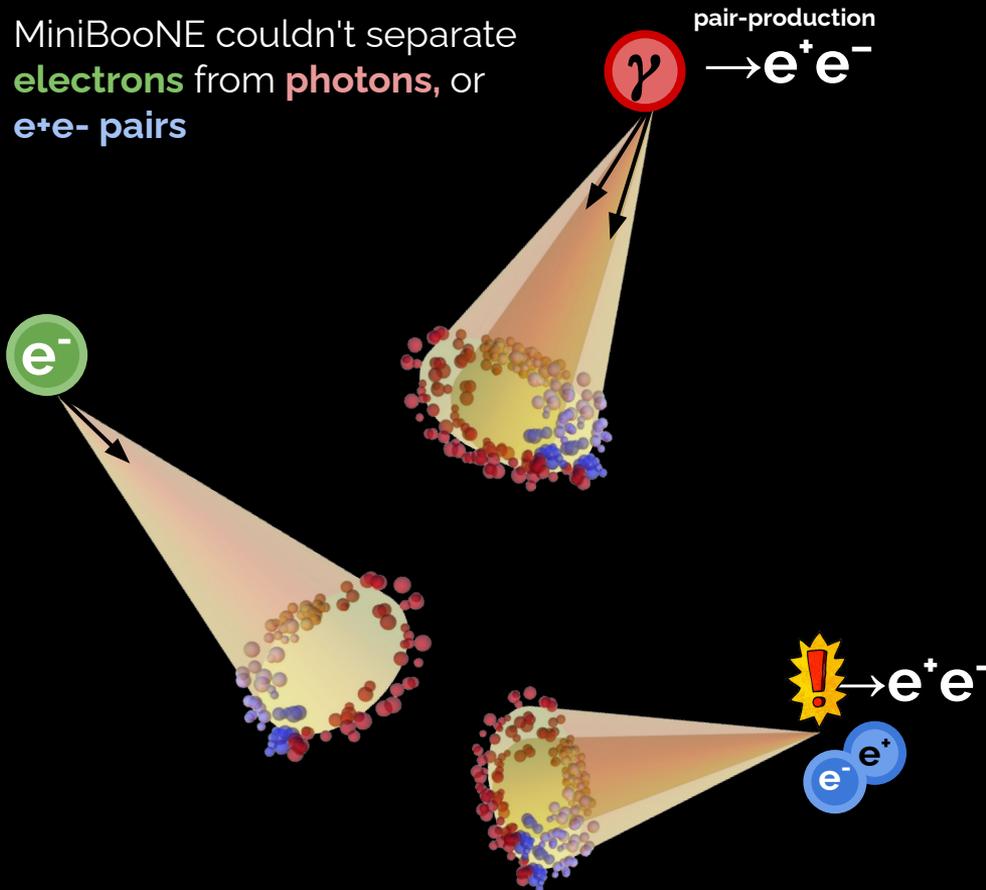
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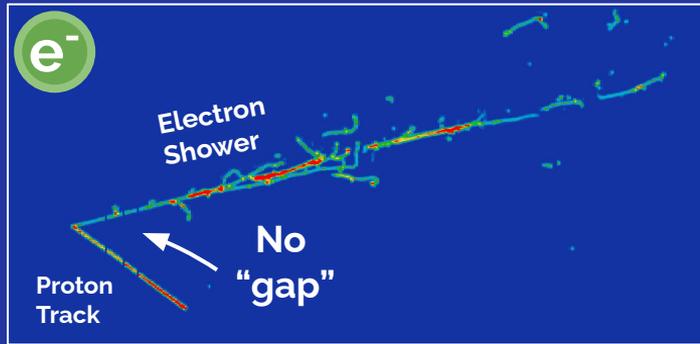
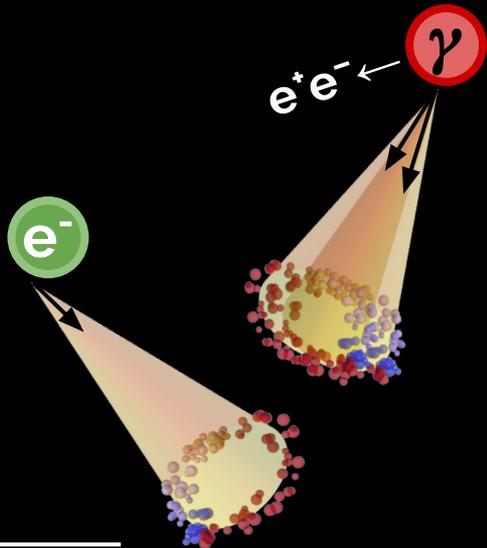
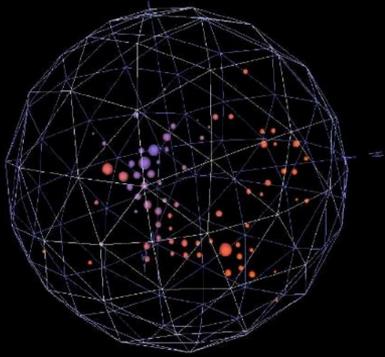
The MiniBooNE Detector



Electron Cherenkov ring event

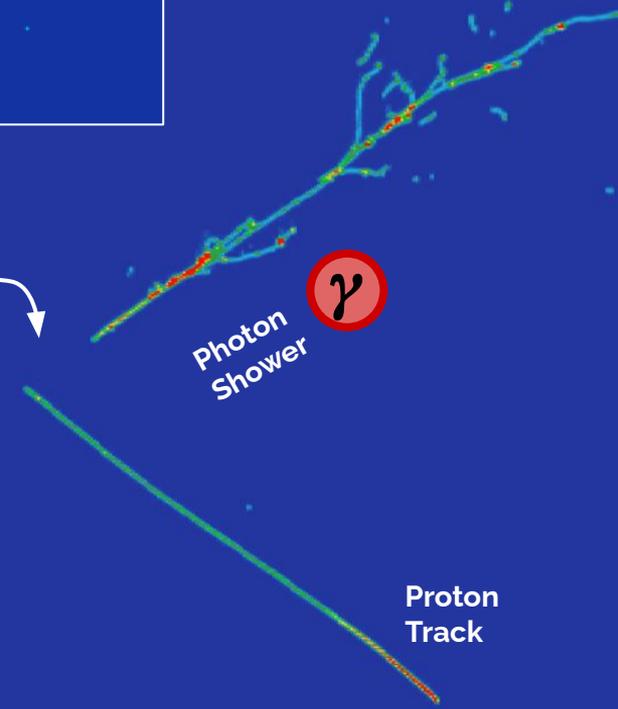


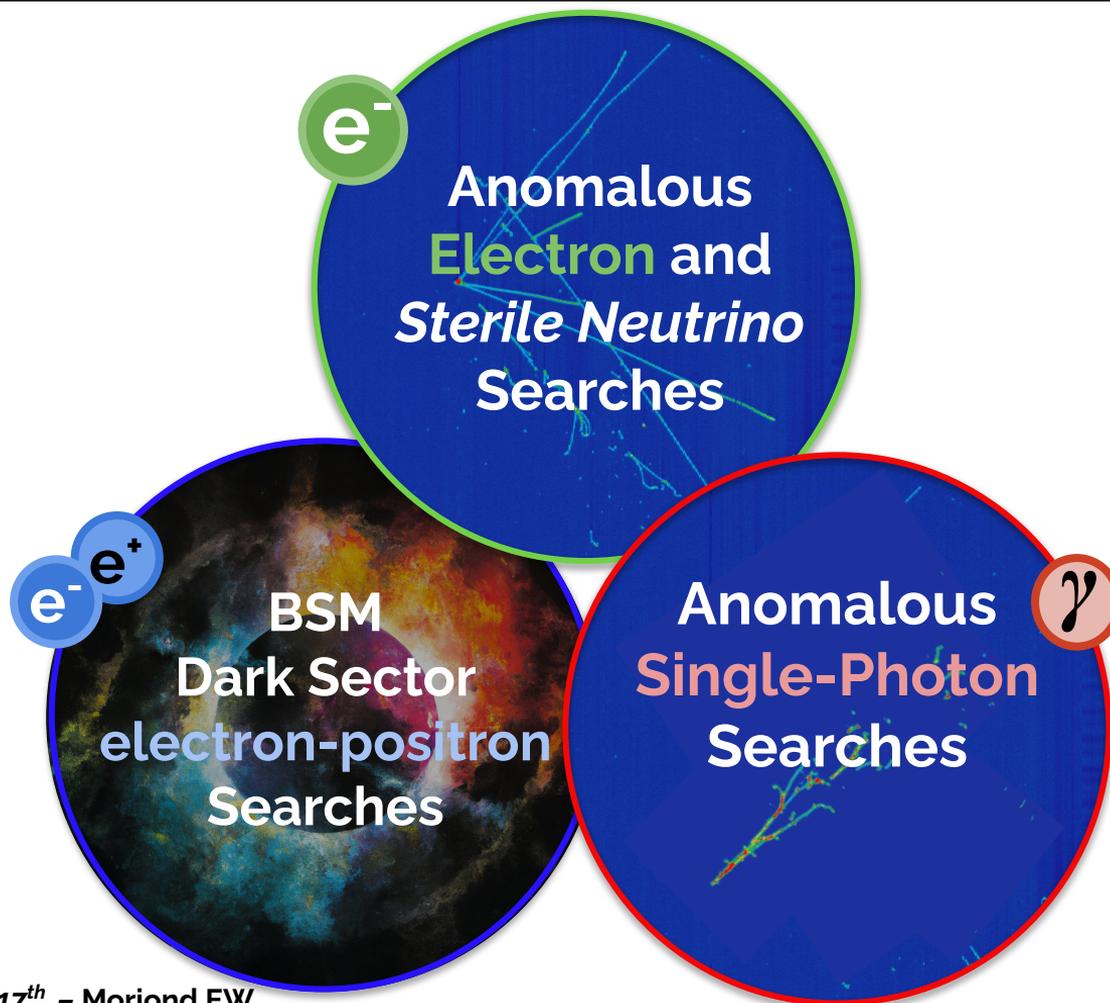
Electrons or Photons?

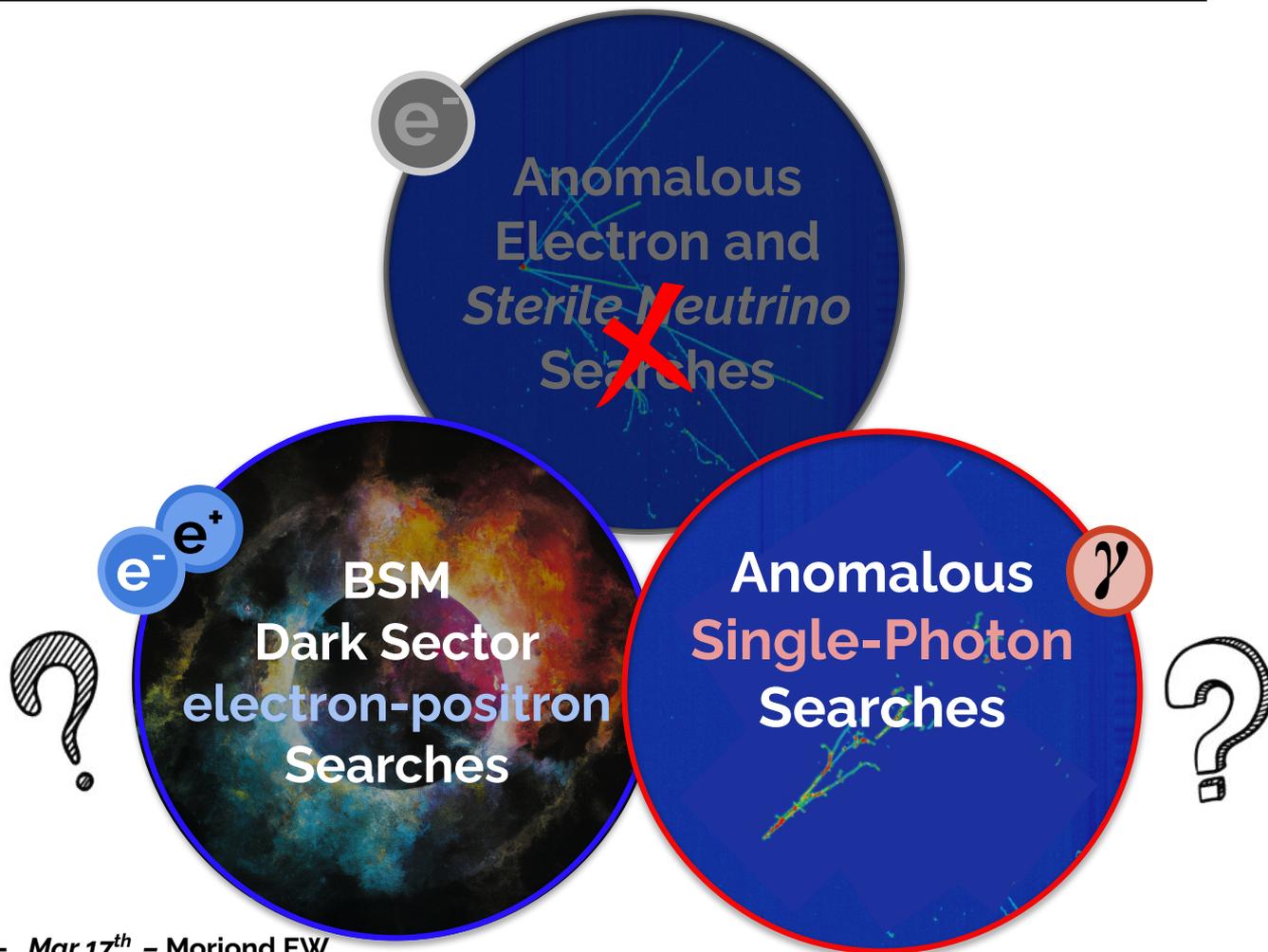


Strong
Electron ↔ photon
separation

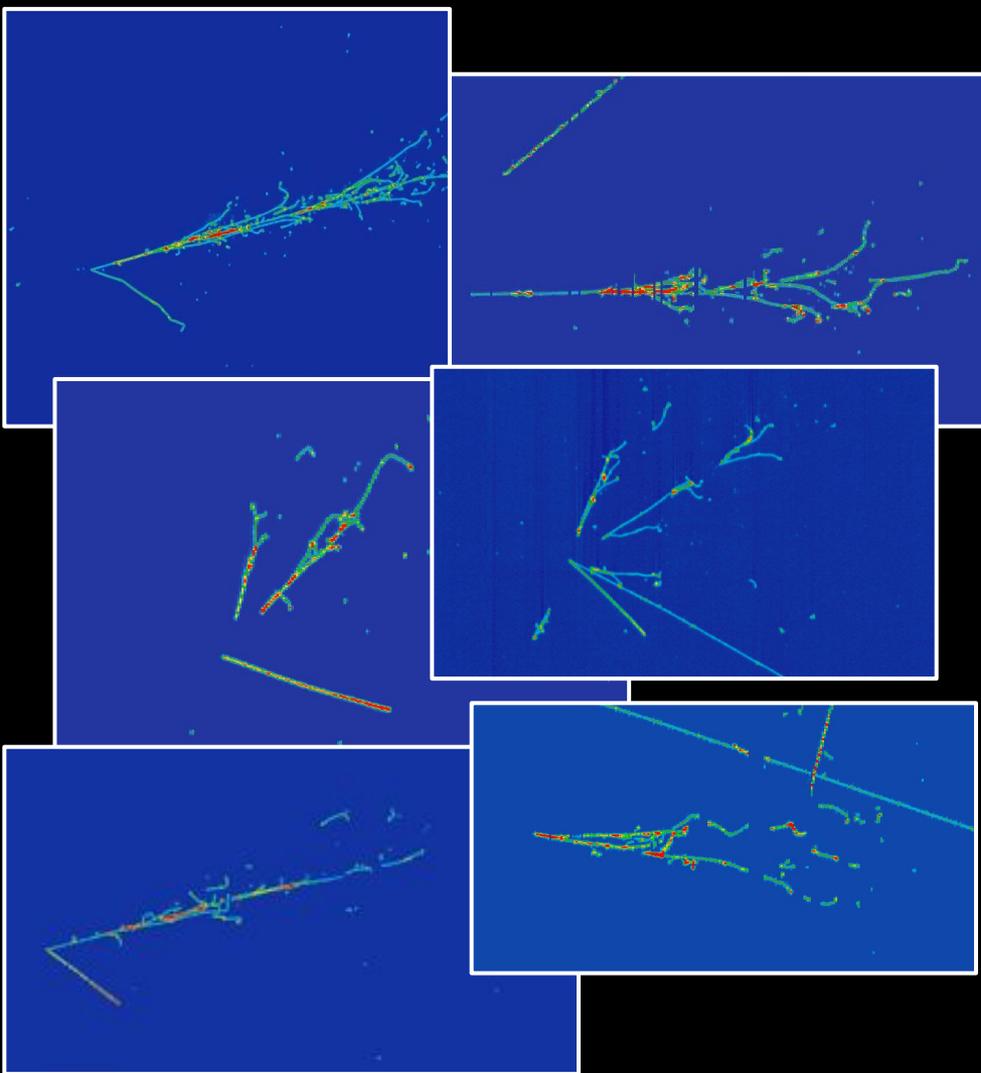
Smoking gun
“gap”



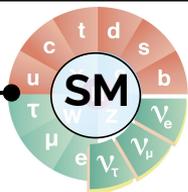




Anomalous Photon and e^+e^- searches in MicroBooNE



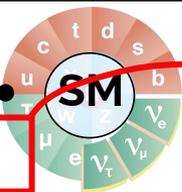
Standard Model



- NC $\Delta \rightarrow N\gamma$ radiative decay
- Coherent Single-Photon Production
- Higher-Order Resonance Decay (e.g N1520)
- QED Radiative Corrections

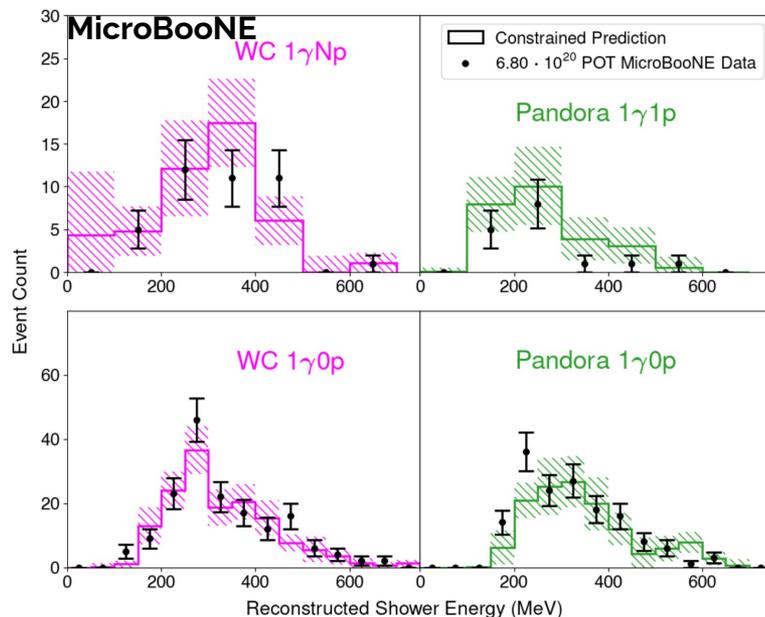
Sources of γ and e^+e^- pairs

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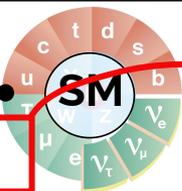
- Enhanced Search for Neutral Current Δ Rad Single-Photon Production in MicroBooNE
 - [Phys. Rev. D 112, L091101 \(2025\)](#)
- MicroBooNE [Phys.Rev.Lett. 128 \(2022\) 11, 111801](#)



No anomalous excess observed

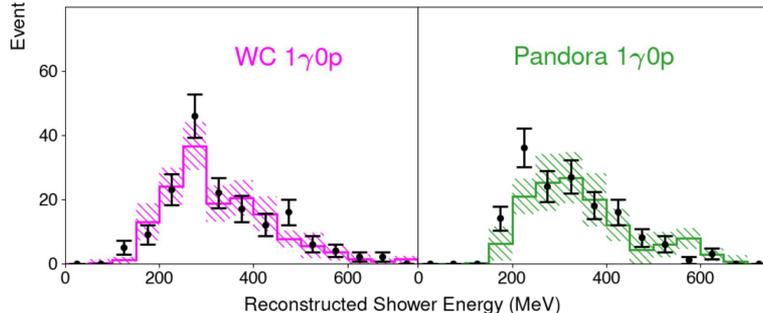
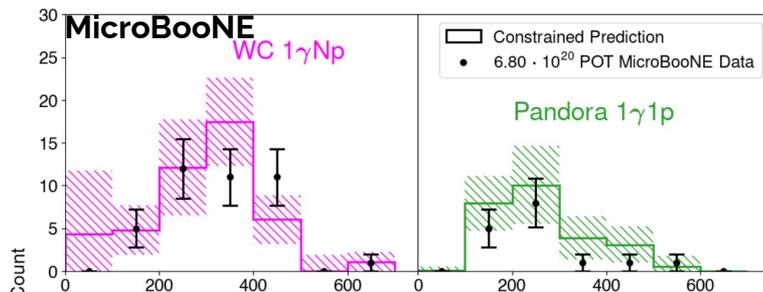
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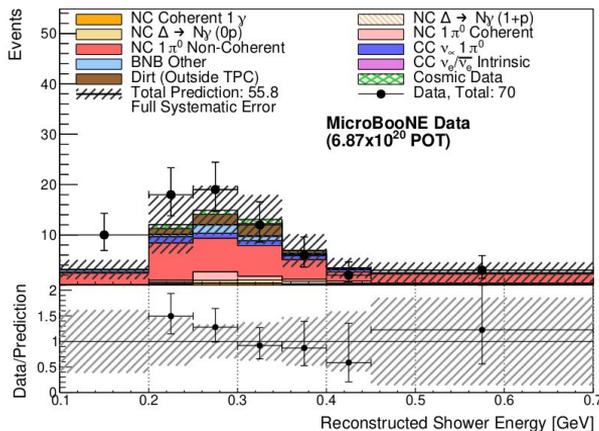


No anomalous excess observed

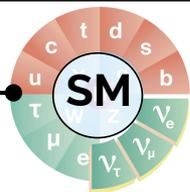
First Search for Neutral Current **Coherent** Single-Photon Production in MicroBooNE

[arXiv:2502.06091 \[hep-ex\] \(2025\)](#)

No anomalous excess consistent with MiniBooNE observed



Standard Model



- NC $\Delta \rightarrow N\gamma$ radiative decay
- Coherent Single-Photon Production
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- QED Radiative Corrections

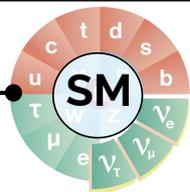
New Physics/BSM



- HNL Decays
- Dark Neutrino Upscattering
- Dark particle/Neutrino induced inverse Primakof scattering
 - + many more (See [White Paper](#) J. Phys. G: Nucl. Part. Phys. 51 120501 (2024)) for in depth review

Sources of γ and e^+e^- pairs

Standard Model



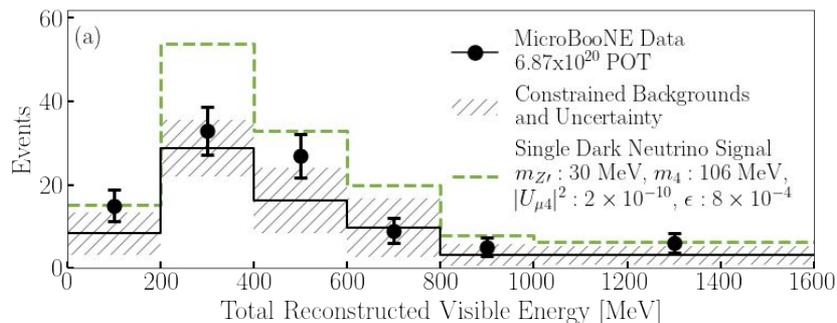
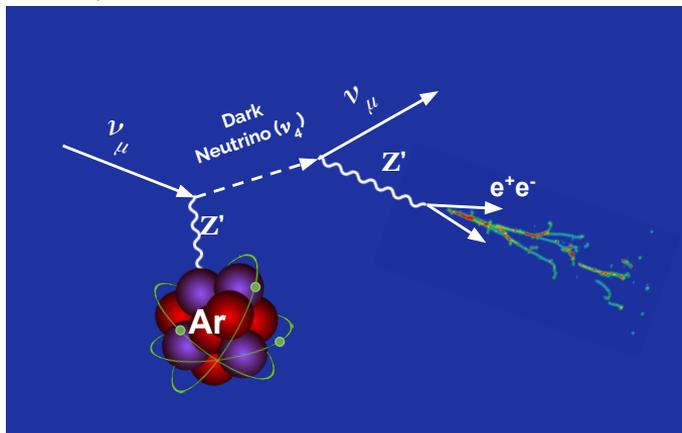
- NC $\Delta \rightarrow N \gamma$ radiative decay
- Coherent Single-Photon Production
- Higher-Order Resonance Decay (e.g N1520)
- QED Radiative Corrections

New Physics/BSM



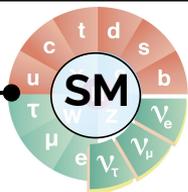
- HNL Decays
- Dark Neutrino Upscattering
- Dark particle/Neutrino induced inverse Primakof scattering

First Search for Dark Sector e^+e^- Explanations of the MiniBooNE Anomaly at MicroBooNE (PRL accepted) [arXiv:2502.10900](https://arxiv.org/abs/2502.10900) [hep-ex]



The **world's first direct limits** on these dark sector models and **excludes the majority of the parameter space** viable as a solution to the MiniBooNE anomaly

Standard Model



- NC $\Delta \rightarrow N\gamma$ radiative decay
- Coherent Single-Photon Production
- Higher-Order Resonance Decay (e.g. N1520)
- QED Radiative Corrections

New Physics/BSM



- HNL Decays
- Dark Matter/Chino Upscattering
- Dark particle/Neutrino induced inverse Primakof scattering
 - + many more (See [White Paper](#) J. Phys. G: Nucl. Part. Phys. 51 120501 (2024)) for in depth review

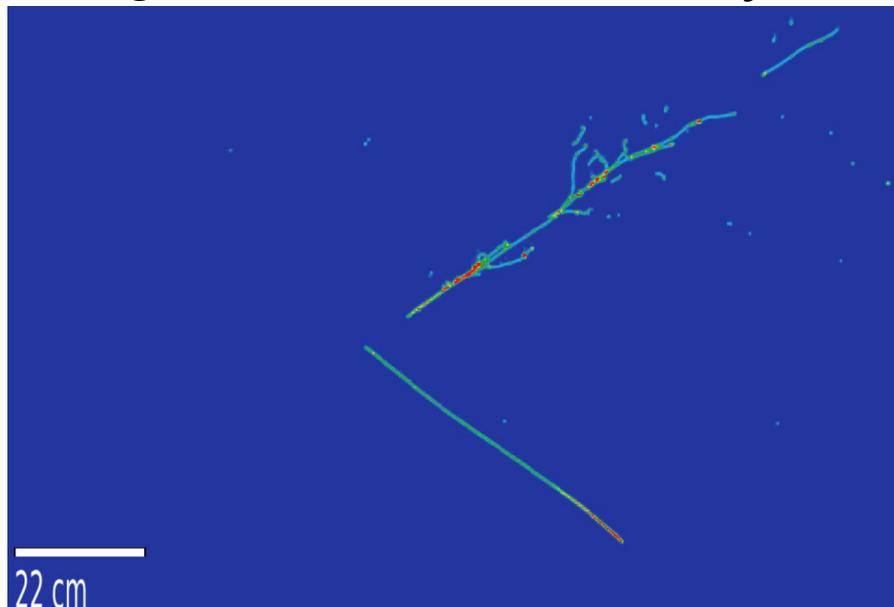
Model Dependent Searches

Inclusive Search for Anomalous Single-Photon Production in MicroBooNE

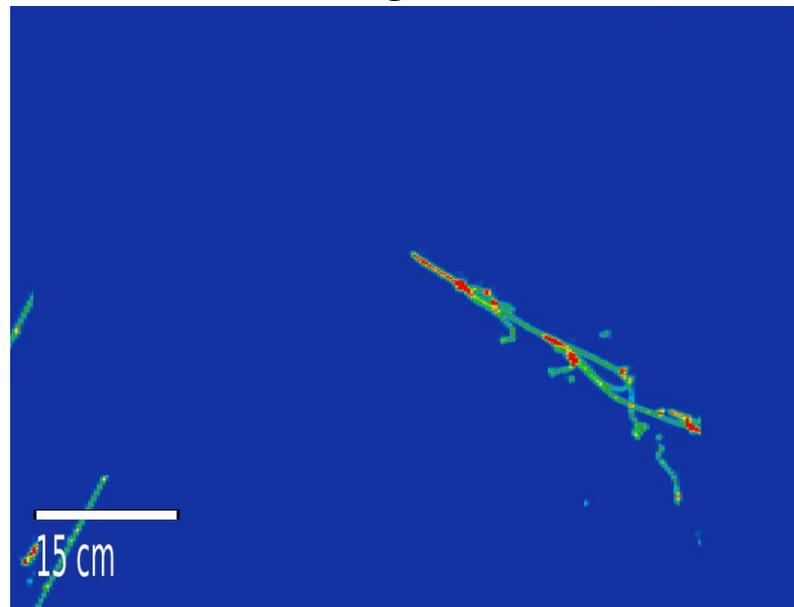
- [arXiv:2502.06064 \[hep-ex\] \(2025\)](https://arxiv.org/abs/2502.06064)

Broadly speaking, two categories of Single-Photon events

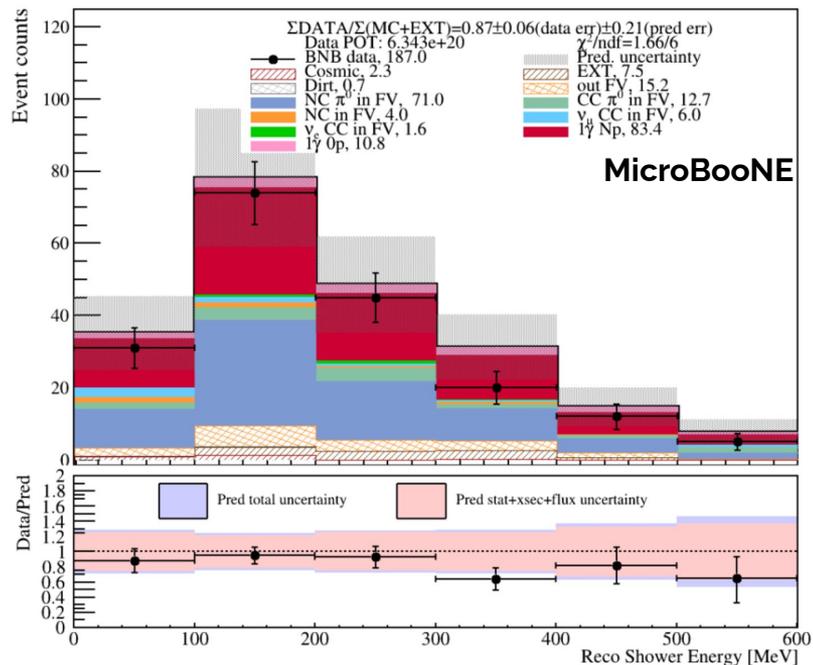
Single-Photon + Proton Activity



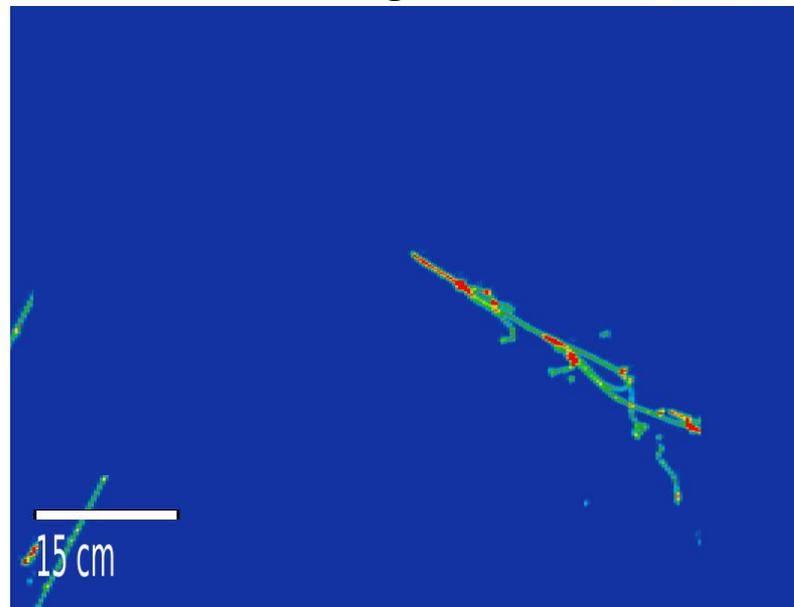
Isolated Single-Photon



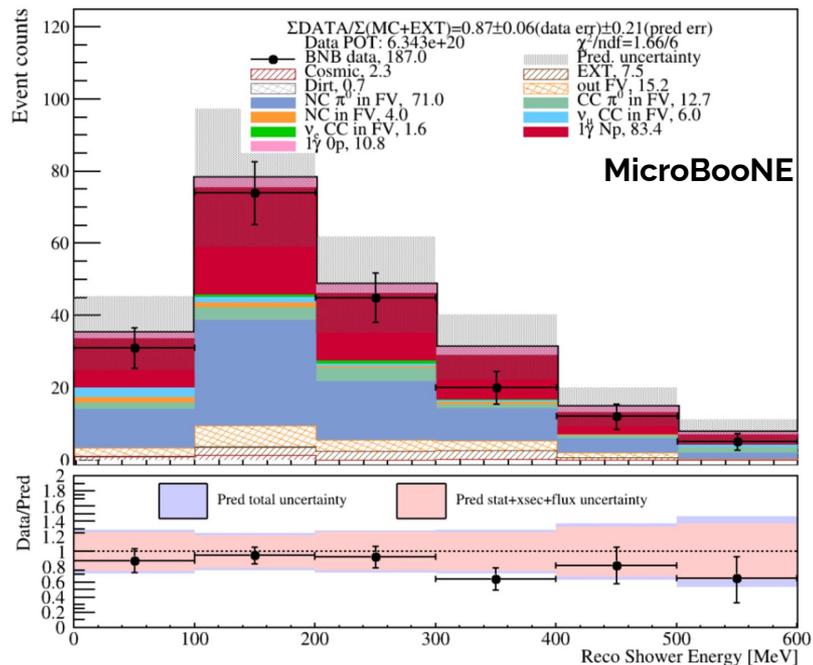
Single-Photon + Proton Activity



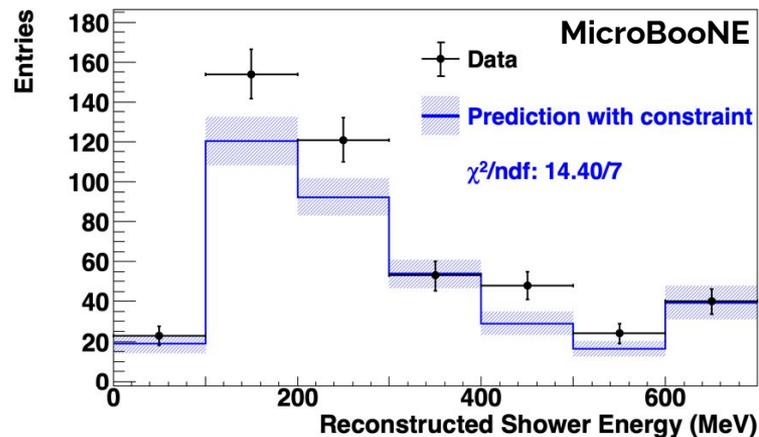
Isolated Single-Photon



Single-Photon + Proton Activity



Isolated Single-Photon



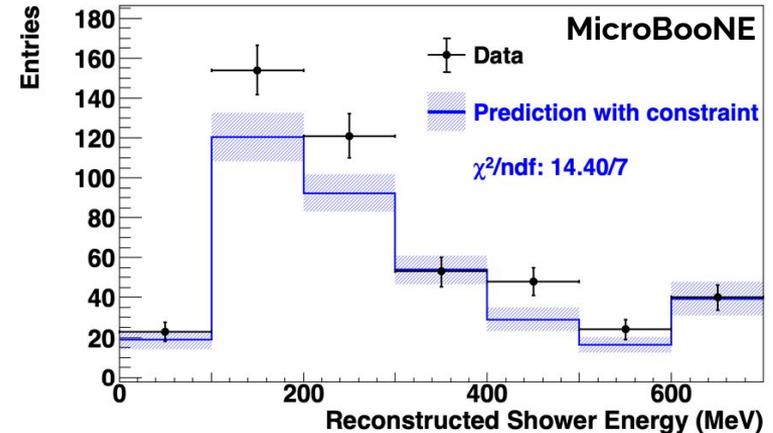
- Mild **2.2 σ** excess of photons contained below 600 MeV.
 - Excess of $93 \pm 22(\text{stat.}) \pm 35(\text{syst.})$ data events
- Kinematically consistent with MiniBooNE excess

2.2σ is not statistically significant, but the **single-photon with no-proton** channel is one of the **last places the MiniBooNE excess could be hiding**

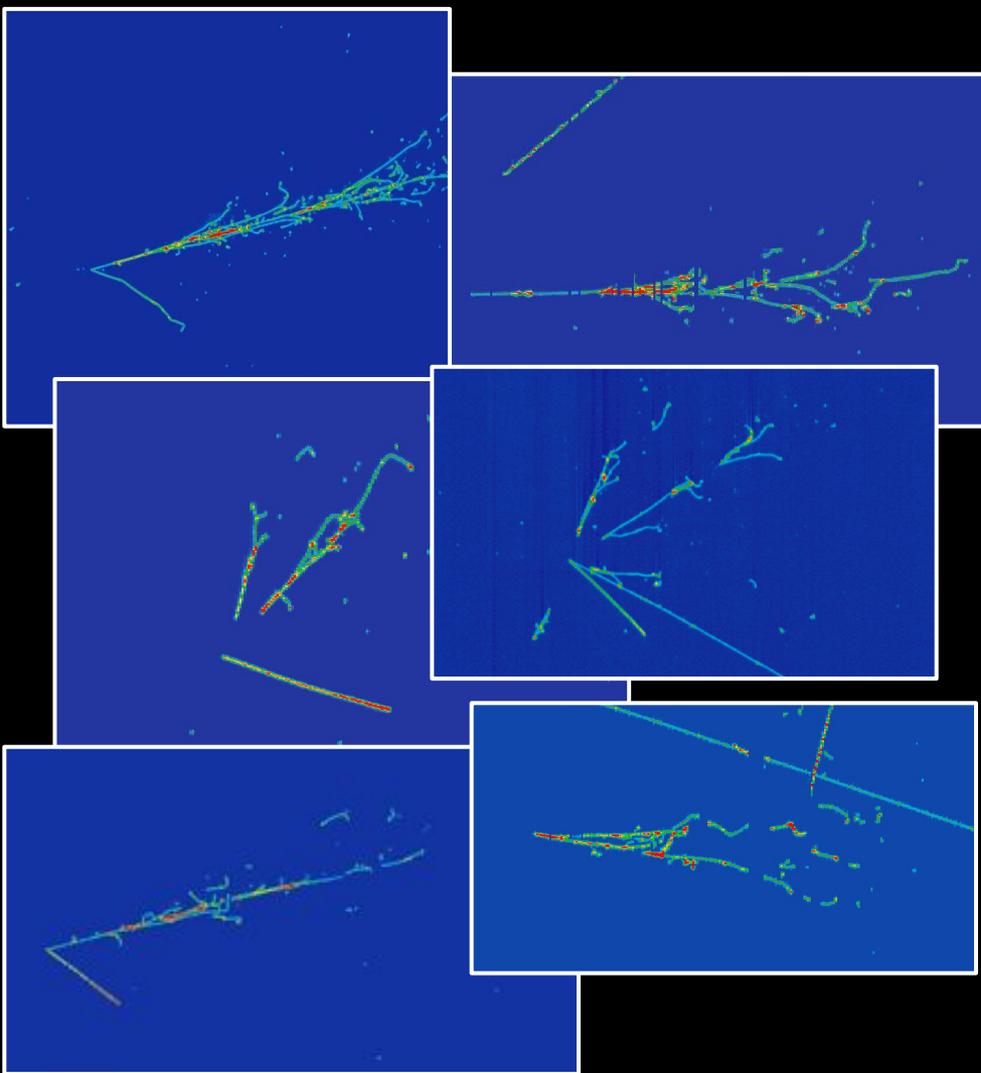
Improved search ongoing with

- Almost **double the data** analyzed
 - 6.3×10^{20} POT \rightarrow 11.1×10^{20} POT
- Improved reconstruction efficiency
- **MeV scale blip reconstruction** to identify low energy proton/neutron activity

Isolated Single-Photon



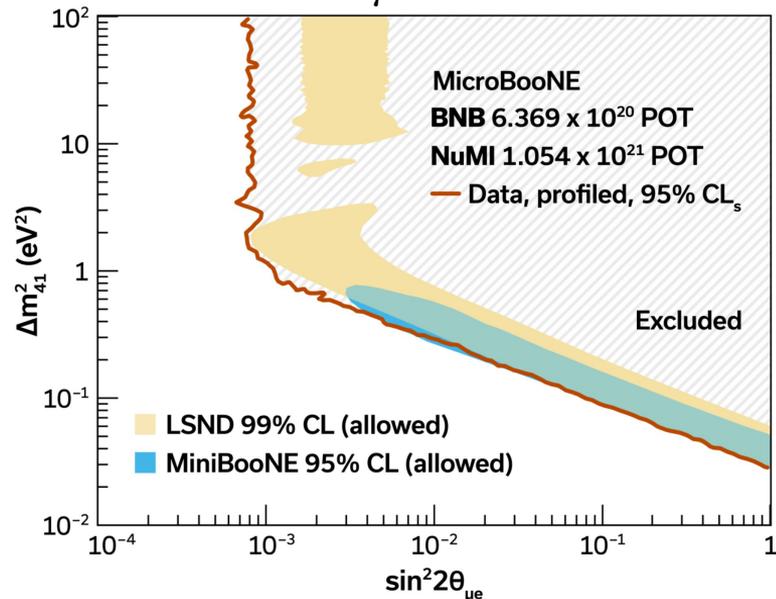
- Mild **2.2σ** excess of photons contained below 600 MeV.
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Conclusions

Conclusions I

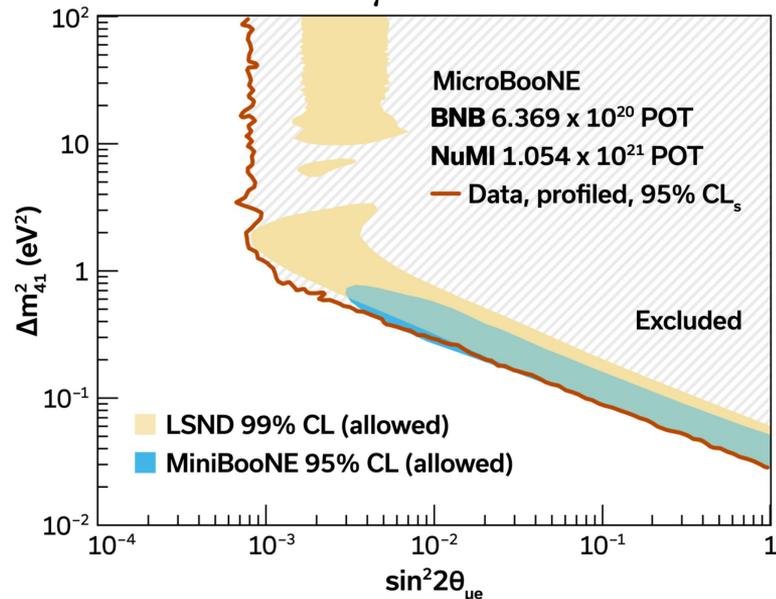
$$\nu_{\mu} \rightarrow \nu_e$$



- **World's first two beam sterile neutrino search**
- Data consistent with no sterile neutrinos
- **Excludes LSND 99% allowed region**
- **Excludes vast majority of MiniBooNE 95% allowed region**

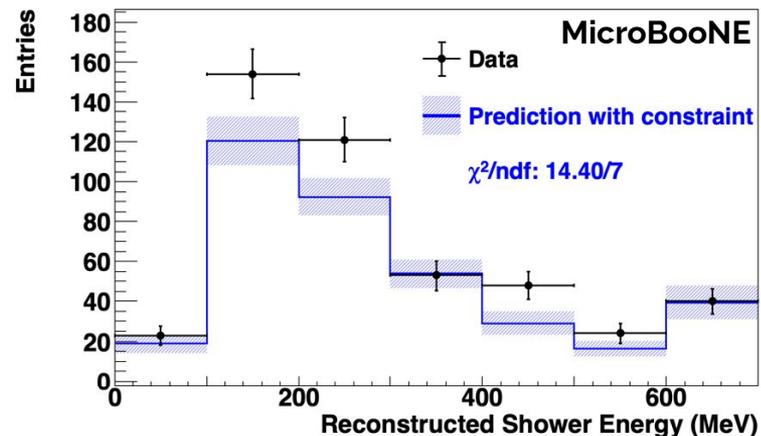
Conclusions II

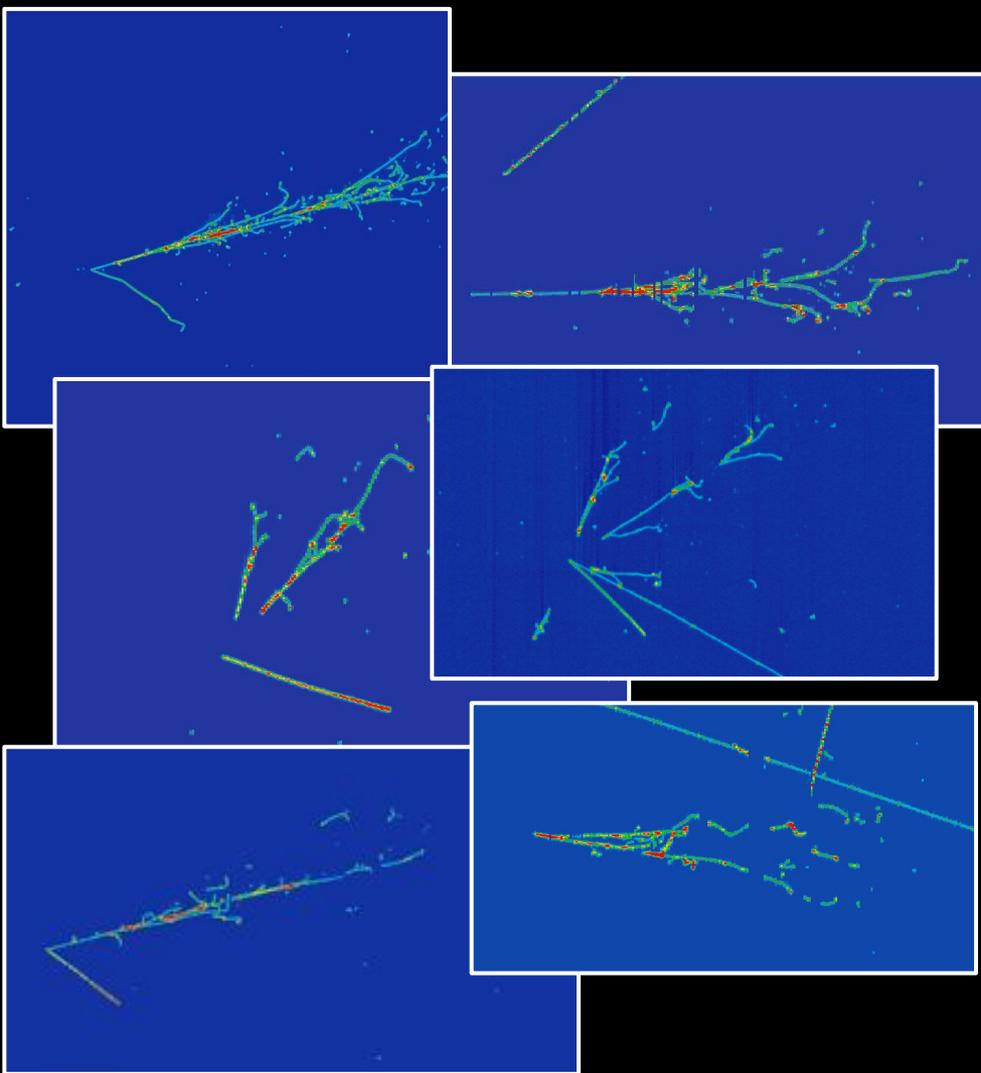
$$\nu_{\mu} \rightarrow \nu_e$$



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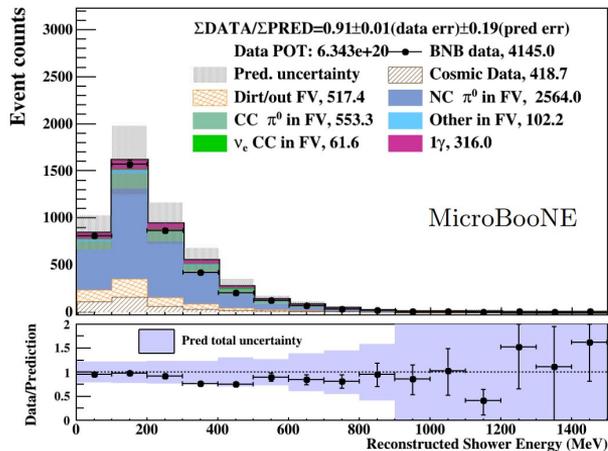
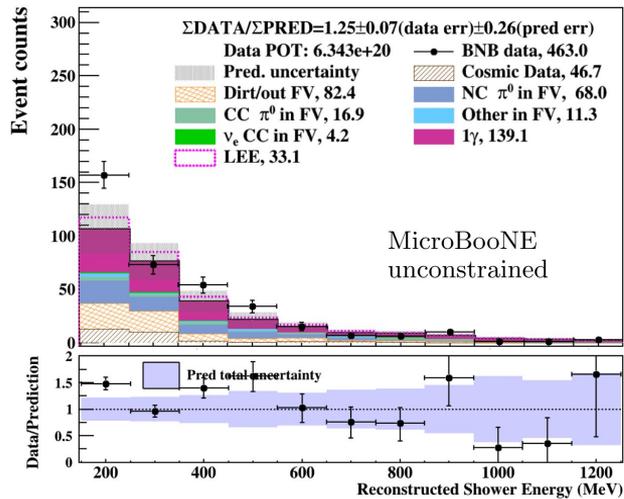
- While the 3+1 sterile neutrino interpretation is **strongly disfavoured**, the anomalies themselves remain unexplained!
- Searches for **single-photon** and **e+e-** signatures continue, with a particular focus on events with **no associated hadronic activity**, one of the last remaining places that the MiniBooNE anomaly could be hiding



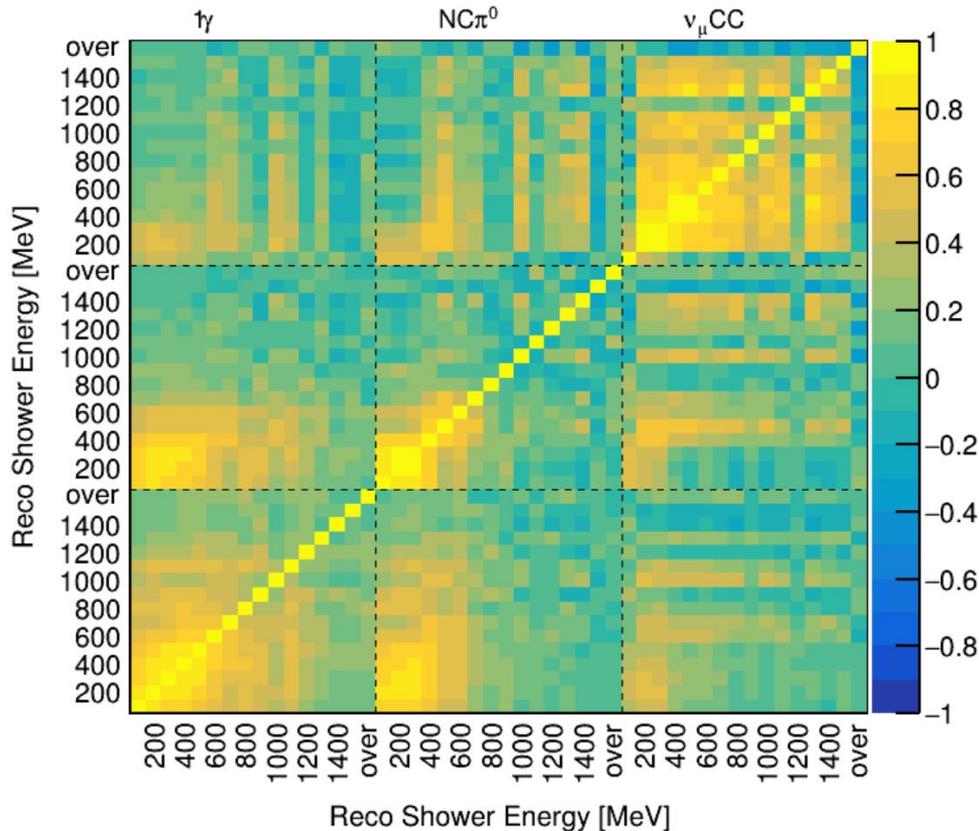


**Backup
Slides**

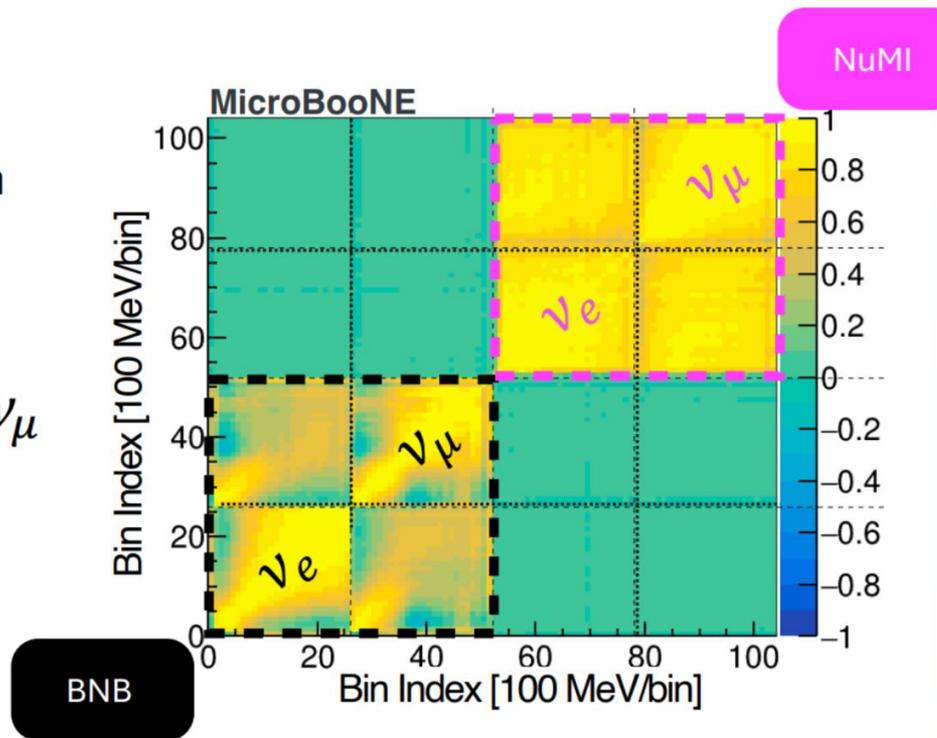
NC π^0 Constraints for inclusive Single- Photon



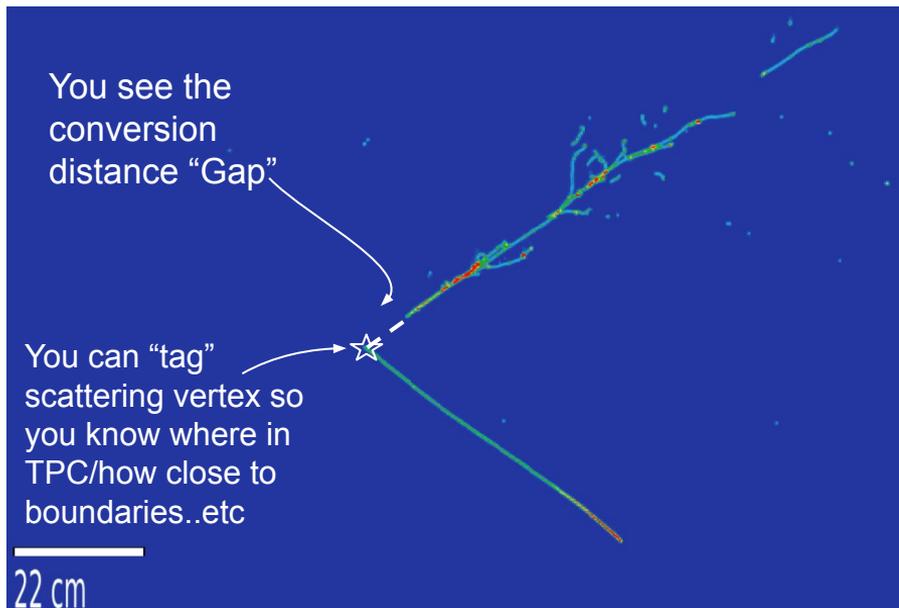
MicroBooNE Simulation



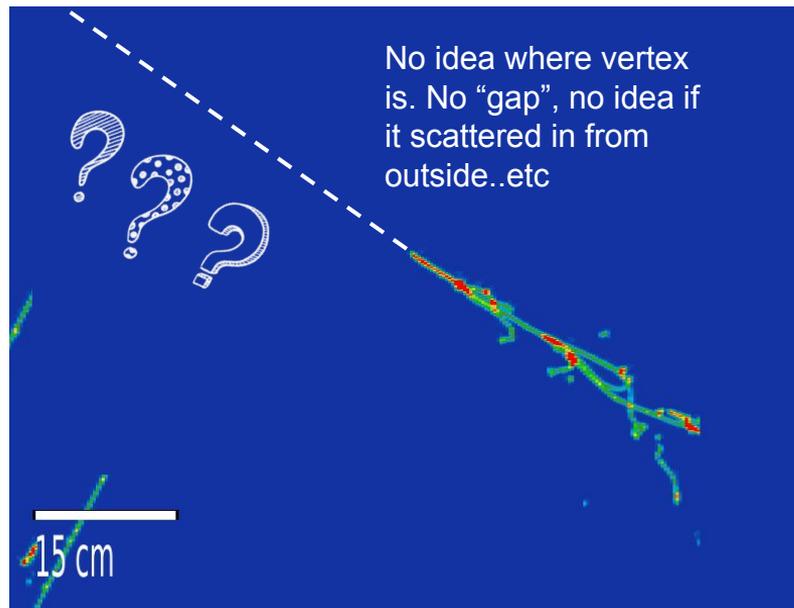
- We treat NUMI and BNB fluxes as uncorrelated :
 - Different hadronic processes, beam energies
- For NuMI, correlation is stronger:
 - Higher fraction of K^+ parents for ν_μ
 - Also, dominant decay for ν_e
 - Higher number of re-interactions (off-axis)



Photon + Protons



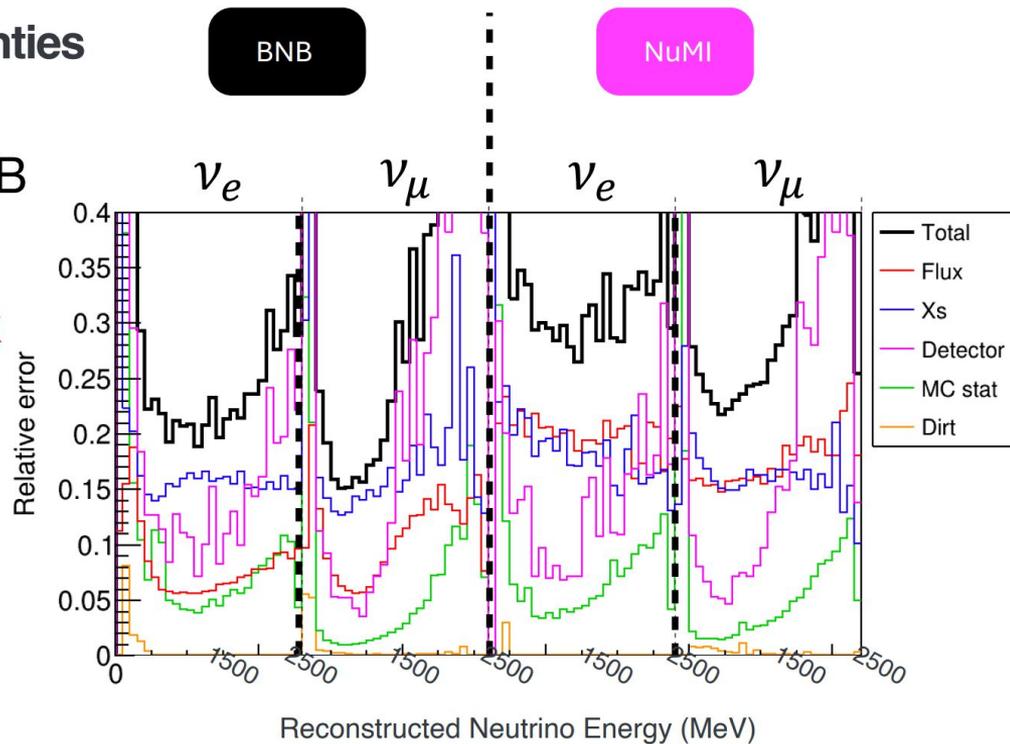
Photon + No Protons



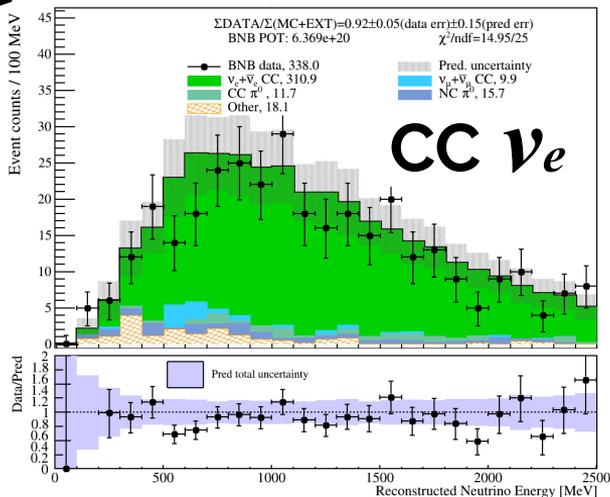
Fractional uncertainties

Final systematics for BNB and NuMI

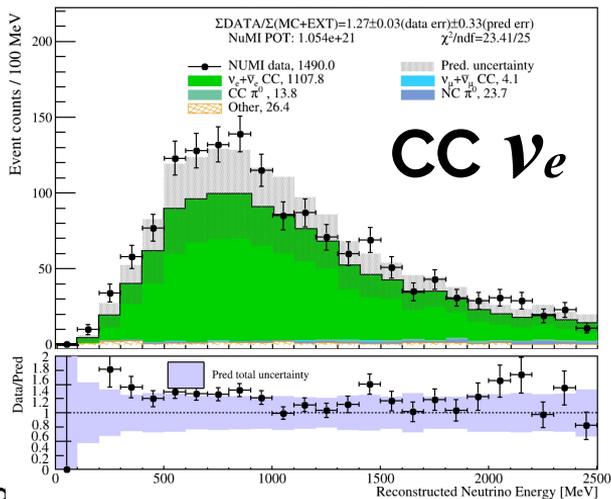
- Cross section and flux are dominant uncertainties
- NuMI has much large flux systematic uncertainty



BNB



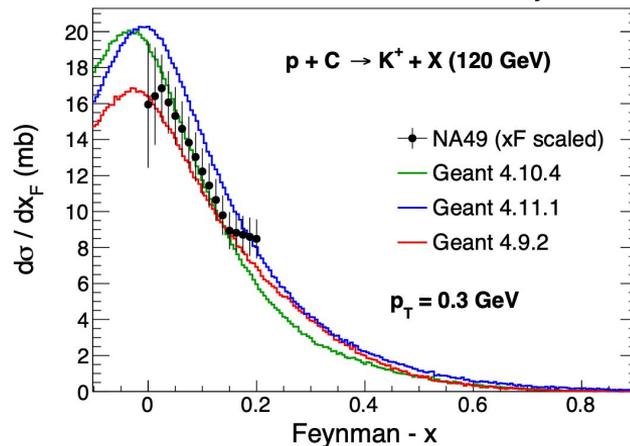
NuMI



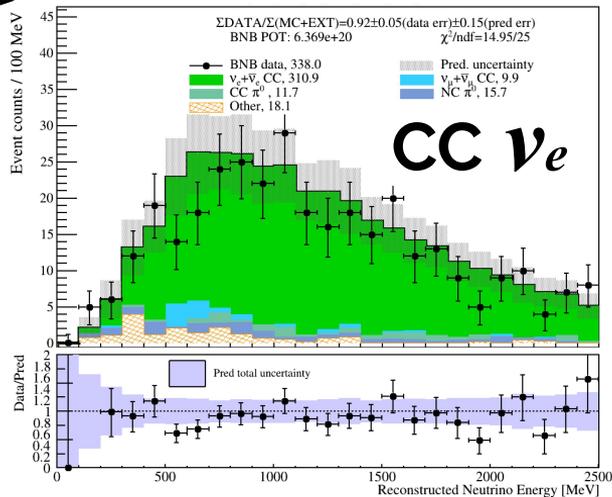
Flux Modelling

- BNB:
 - Same flux model and uncertainties as MiniBooNE [Phys. Rev. D 79, 07200](#)
- NuMI
 - Updated **beam line geometry**
 - Updated to **Geant4 v4.10.4** for better agreement with Kaon production external datasets

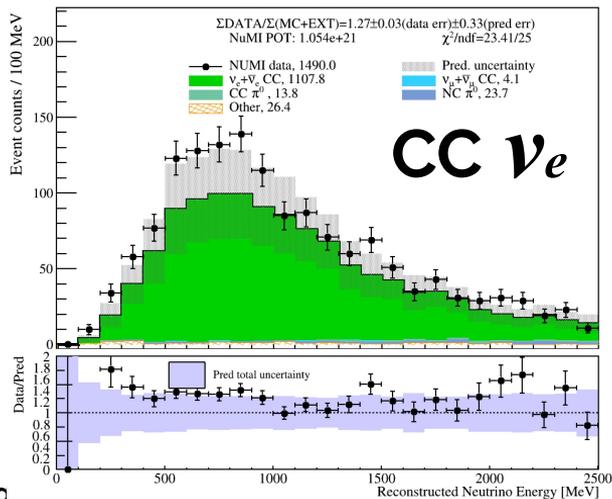
MicroBooNE Preliminary



BNB

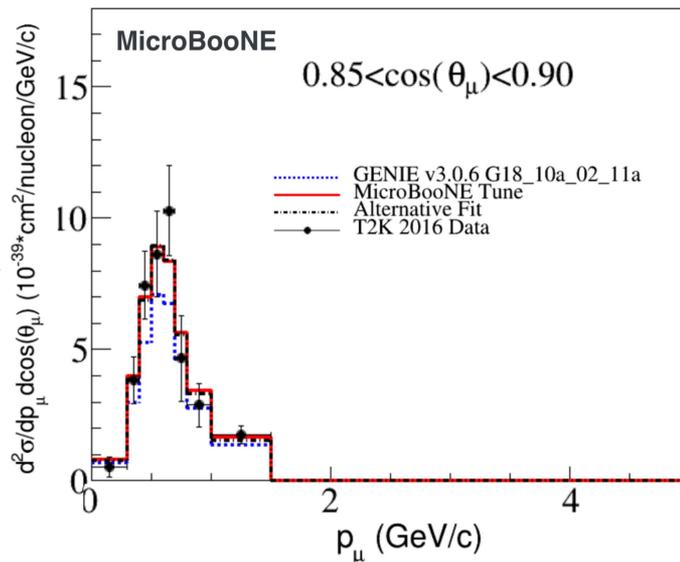


NuMI



Interaction Modelling

- We use a MicroBooNE custom tune of GENIE, built off the **GENIE v3.0.6 G18_10_a02_11a** model set for both BNB and NuMI.
- This base model set is then tuned to **external T2K CC ν_μ 0π** data

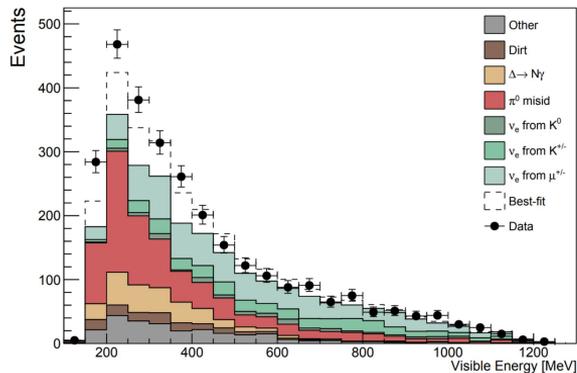


[MicroBooNE: PhysRevD.105.072001](https://arxiv.org/abs/1808.07200)

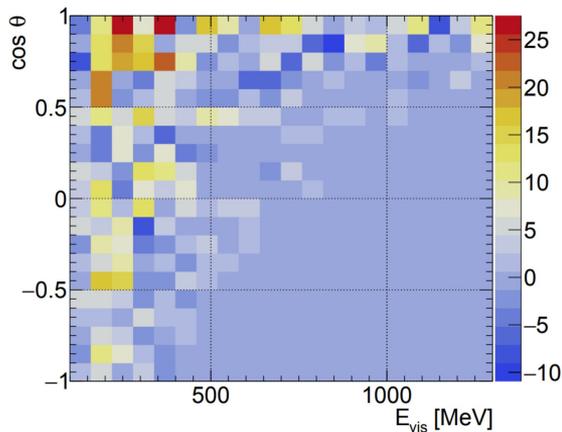
Overall Kinematic Agreement

MiniBoONE

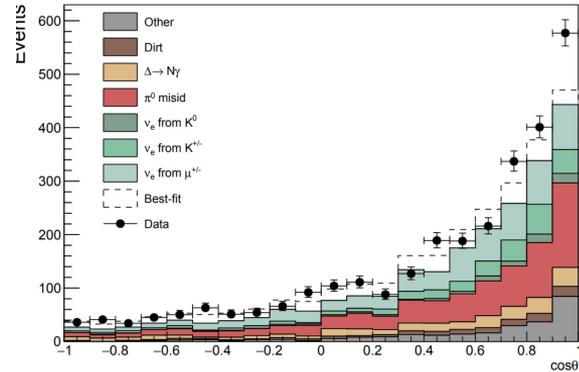
Shower/Visible Energy



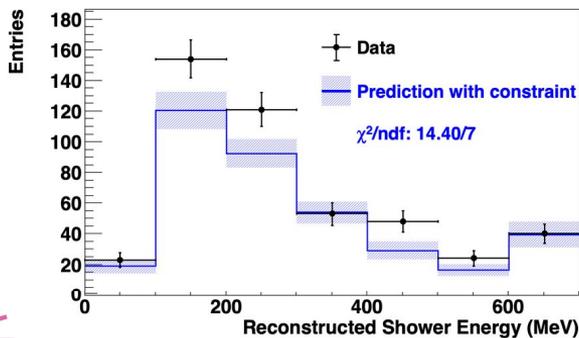
Excess



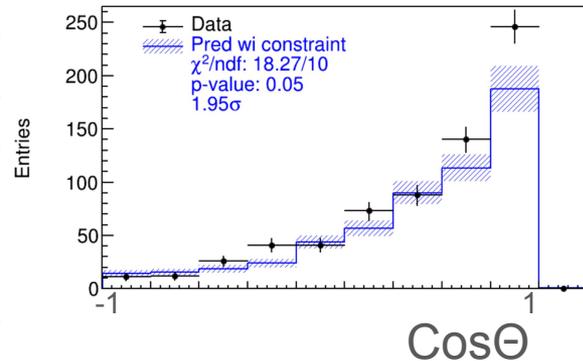
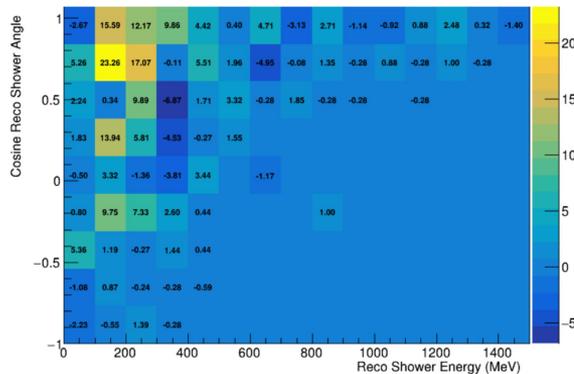
Shower/Visible Angle



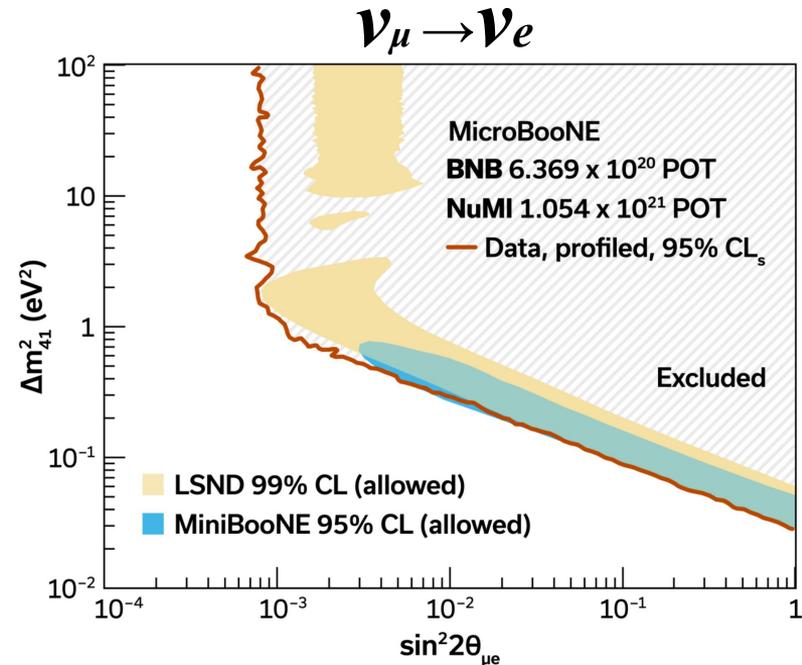
MicroBoONE

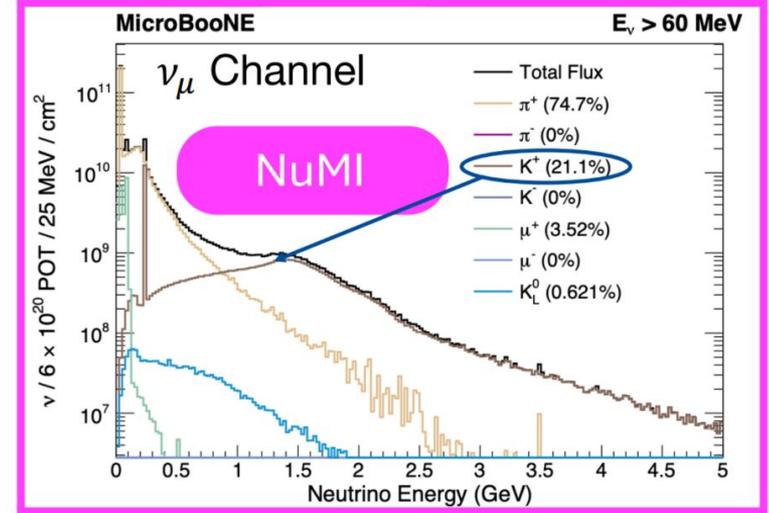
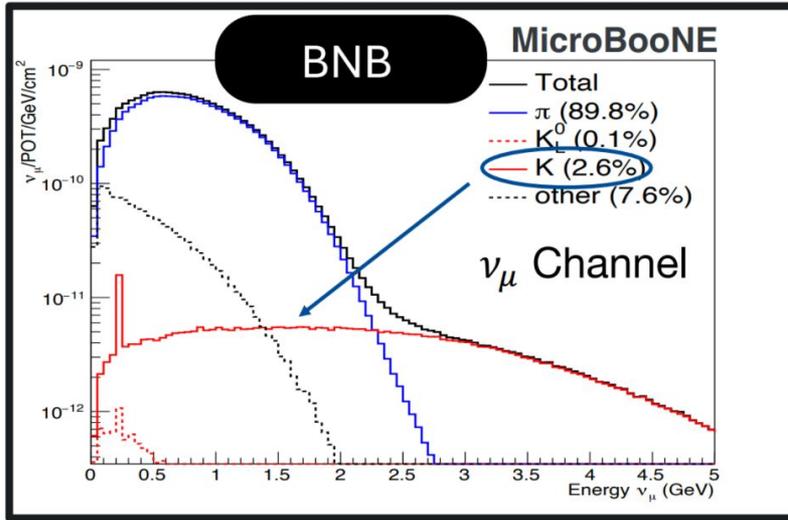


Shower Energy vs Angle - Excess Events



- **Full-Dataset 3+1 analysis**
 - **Almost double data in both BNB & NuMI!**
 - Addition of **External Datasets** (e.g PROspect/KATRIN/ICARUS)
 - Thorough investigation of **3D 3+1**
- Additional Models **Beyond Vanilla 3+1**
 - **3+1+decay** (Invisible and Visible)
 - **3+2** (includes CP violation)
- Expanding framework to allow for **full Feldman-Cousins** analysis and **pull-term/nuisance systematics**





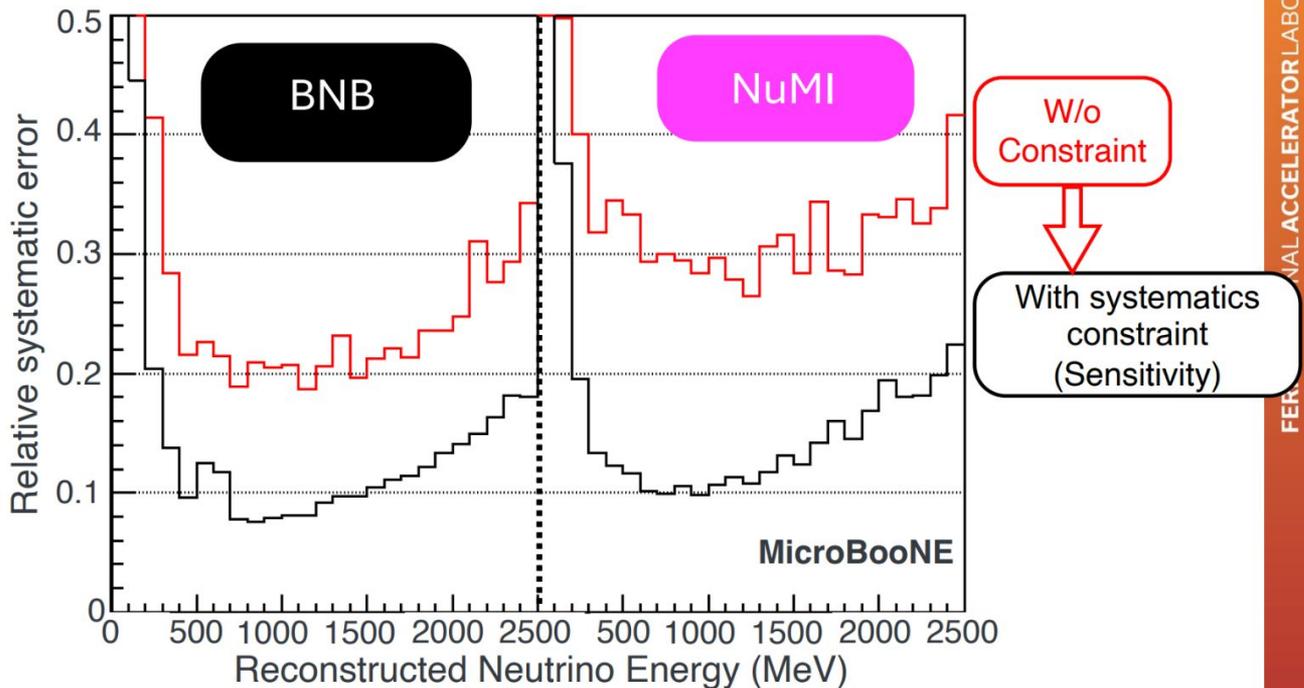
- At 8° off-axis for NuMI, flux is quite different to traditional on-axis
- Many more neutrinos coming from kaon decays → model must account for kaon production carefully



Constrained ν_e channels

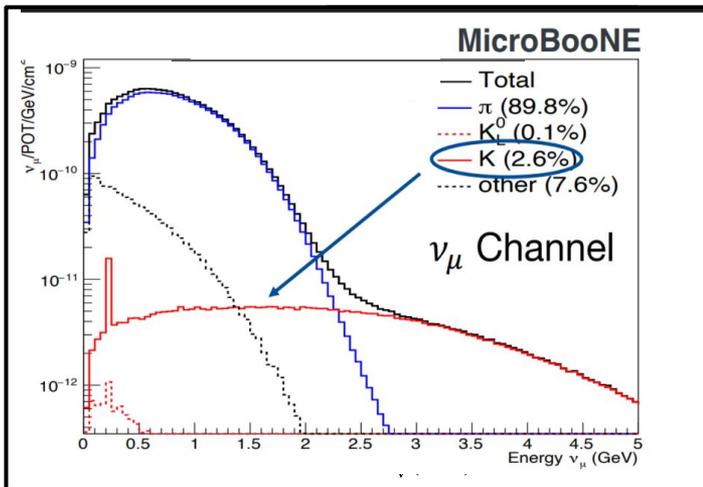
ν_e CC Fractional Uncertainty

Constraint significantly reduces the fractional systematic uncertainty



Dual Neutrino Beams, One Detector

BNB

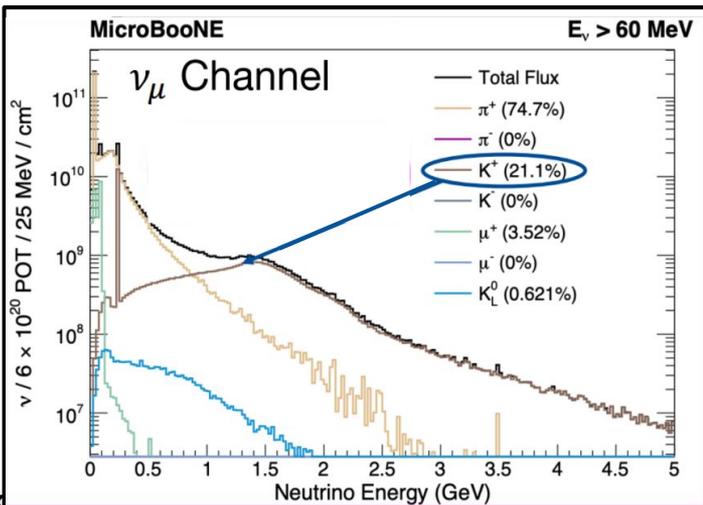


On Axis
Baseline ~470 m

$$\frac{N\nu_\mu}{N\nu_e} \sim 200$$

2.6% of neutrinos from **Kaons**

NuMI

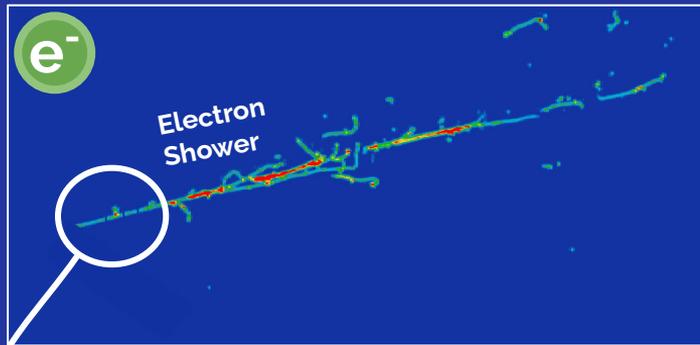
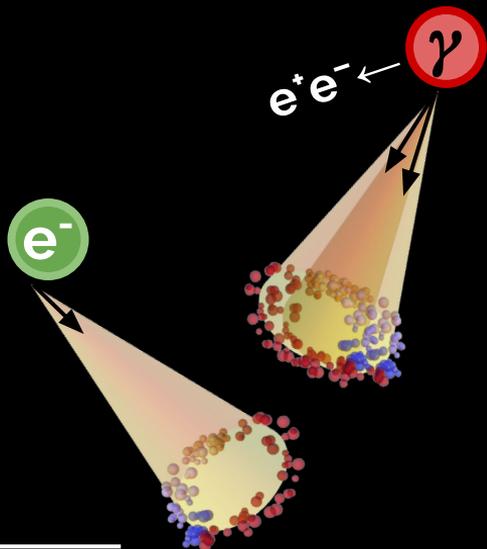
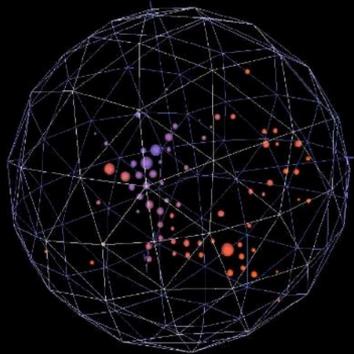


Off-Axis 8°
Baseline ~680 m

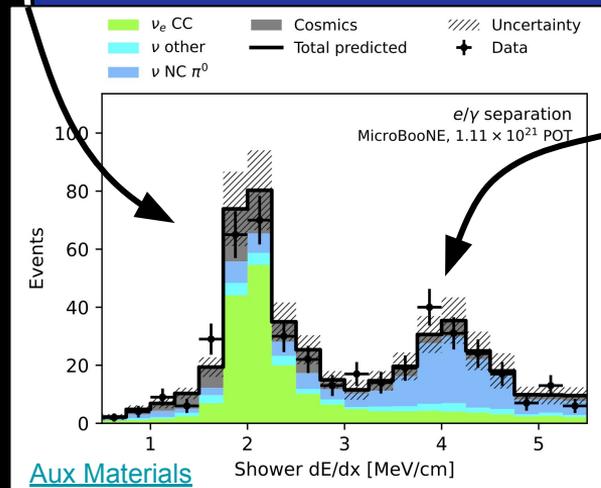
$$\frac{N\nu_\mu}{N\nu_e} \sim 24$$

21.1% of neutrinos from **Kaons**

Electrons or Photons?



Strong
Electron ↔ photon
separation



Photons deposit twice as much energy per unit length at shower start
(Shower dE/dx)



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 μ BooNE

Nue Disappearance

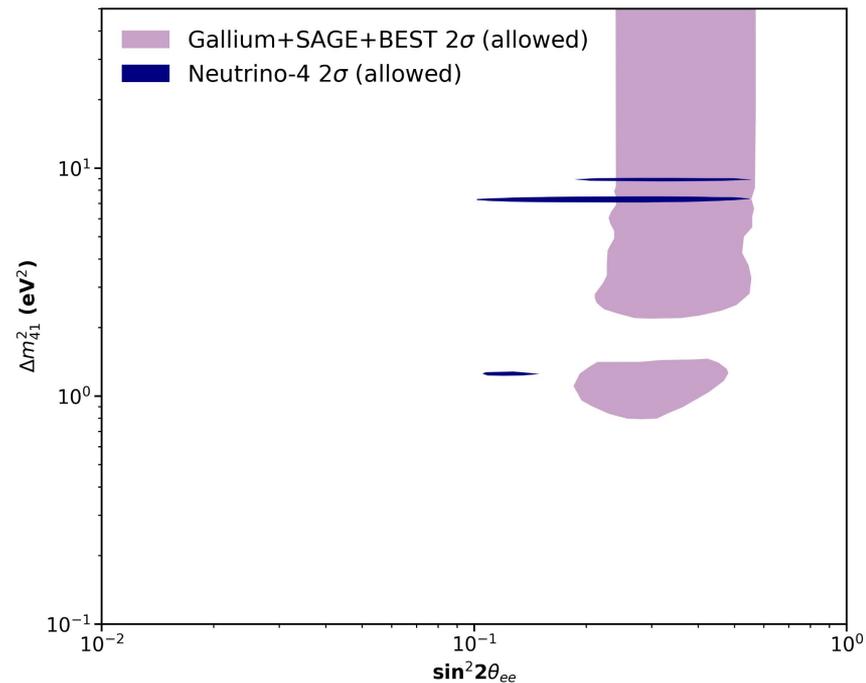


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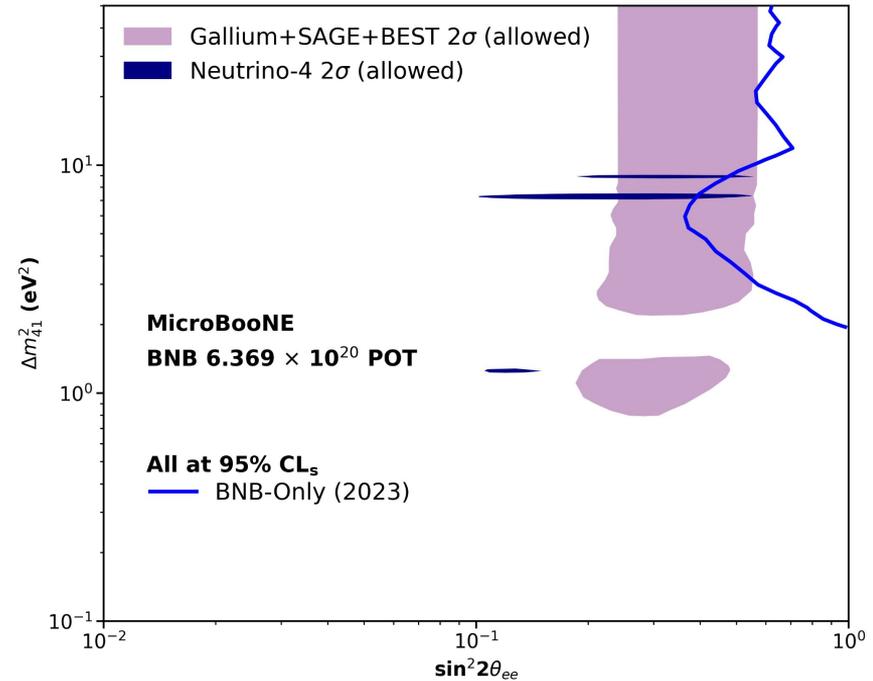
Addition of NuMI data

- **Breaks** the degeneracy
- **Constrains the amount of ν_e disappearance allowed**



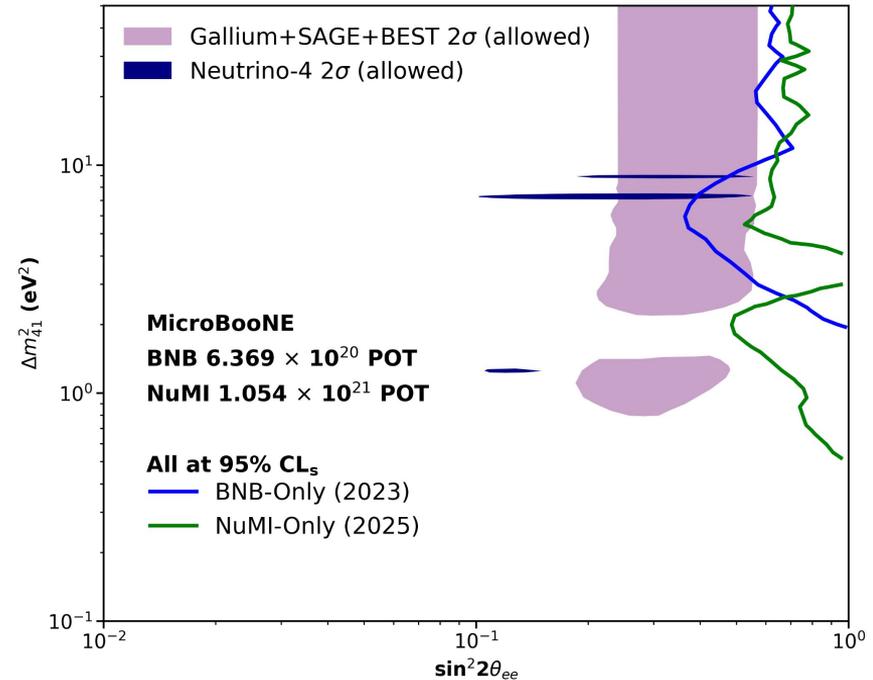
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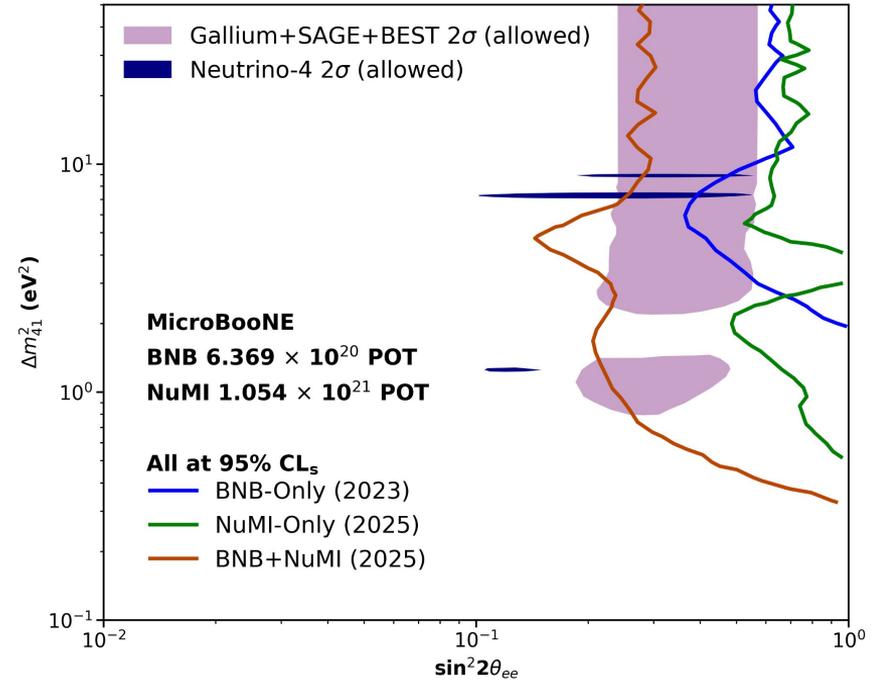
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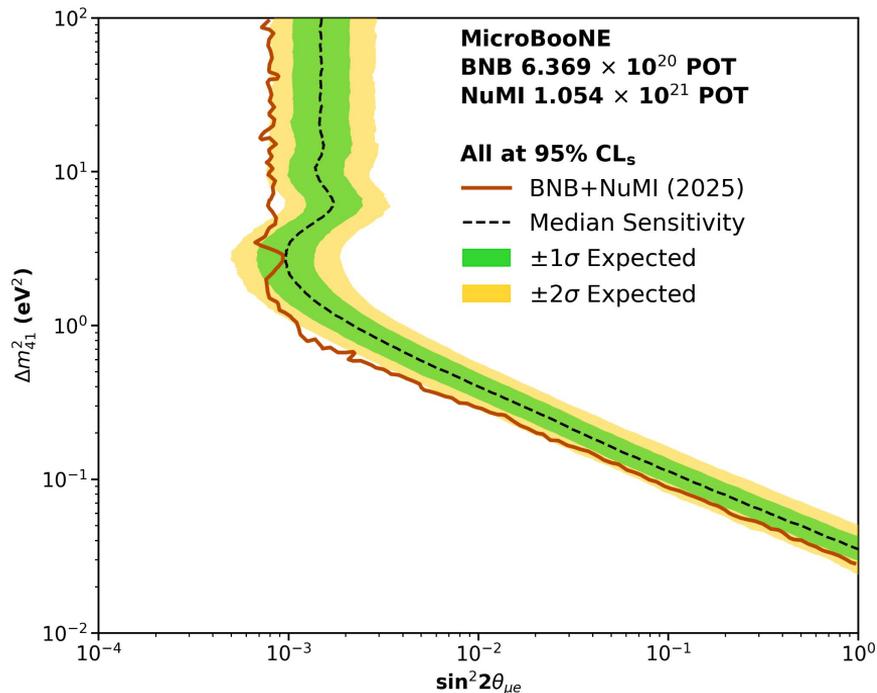
Addition of NuMI data

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- **Constrains the amount of ν_e disappearance allowed**



Predicted Sensitivities

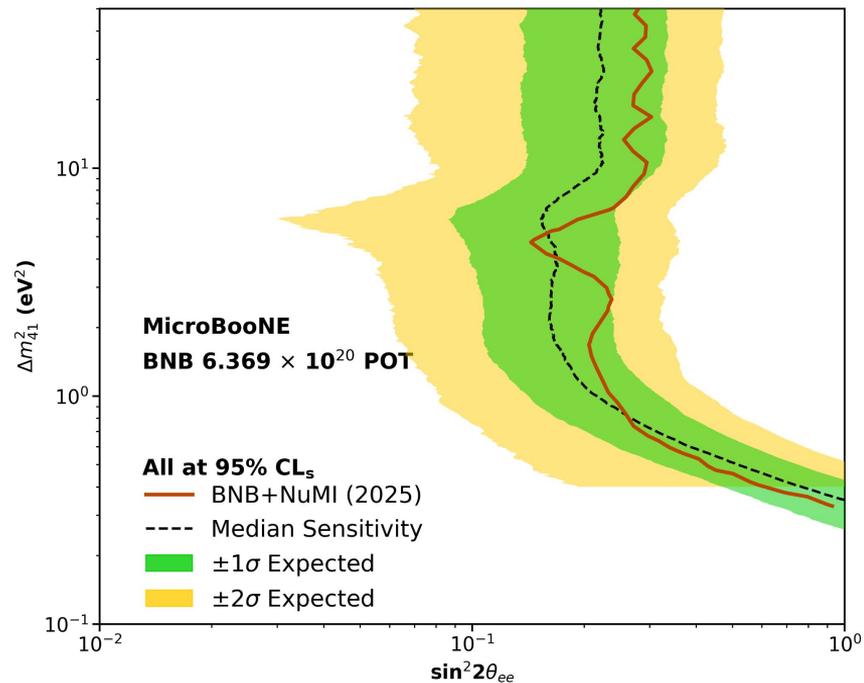
$$\nu_\mu \rightarrow \nu_e$$



Data exclusion is stronger than median sensitivity.
Lies around the 2σ expected experiment

EW

$$\nu_e \rightarrow \nu_e$$



Data exclusion is slightly weaker than median sensitivity.



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 μ BooNE

Deficit in Runs 1-5

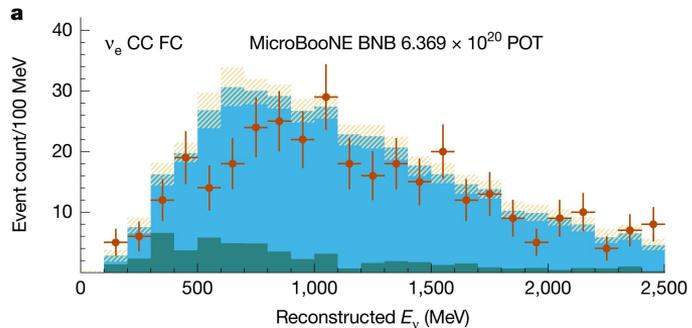


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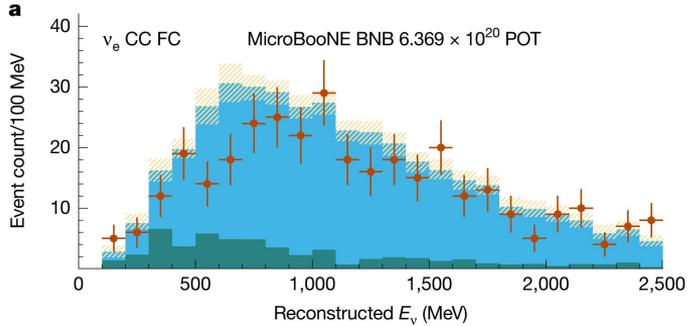
Runs 1-3, BNB data

Wire-Cell Reconstruction

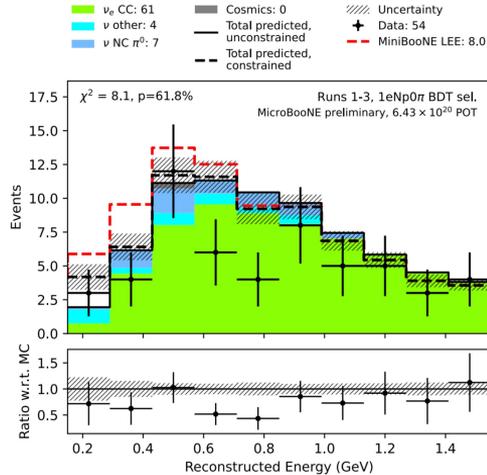


Full Dataset Analysis using Pandora Reconstruction

Runs 1-3, BNB data
Wire-Cell Reconstruction



Runs 1-3, BNB data
Pandora Reconstruction

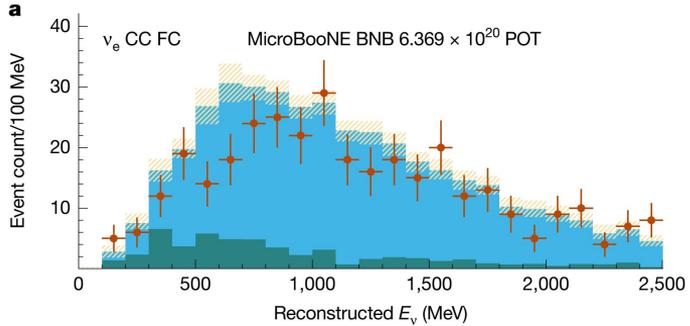


Not independent sample

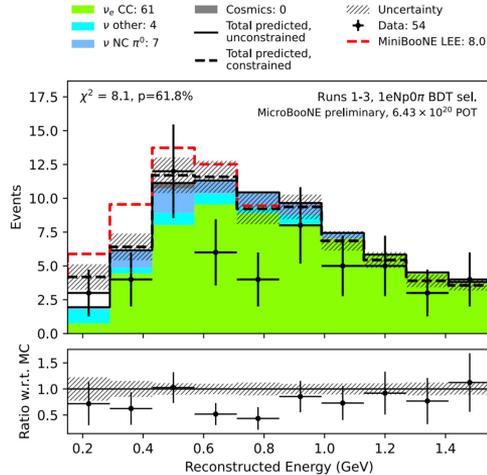
~70% of events also selected
in Wire-Cell

Full Dataset Analysis using Pandora Reconstruction

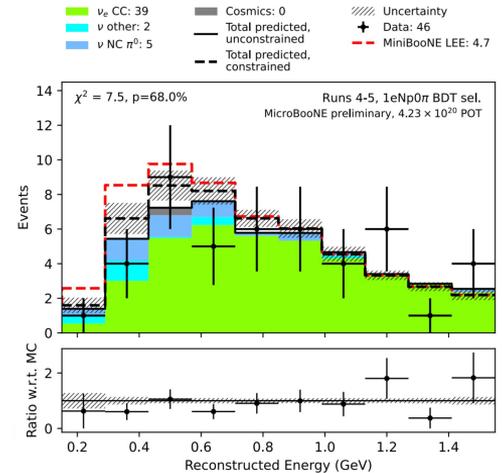
Runs 1-3, BNB data
Wire-Cell Reconstruction



Runs 1-3, BNB data
Pandora Reconstruction



Runs 4-5, BNB data
Pandora Reconstruction

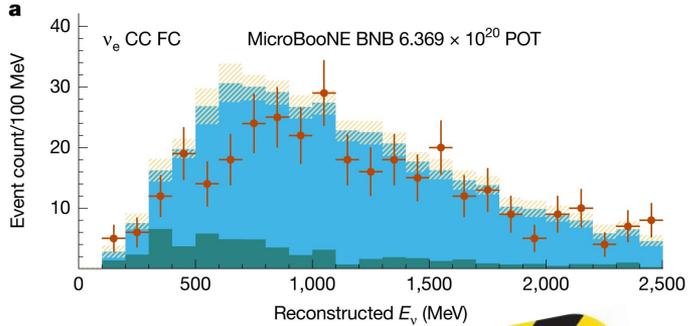


Not independent sample
~70% of events also selected
in Wire-Cell

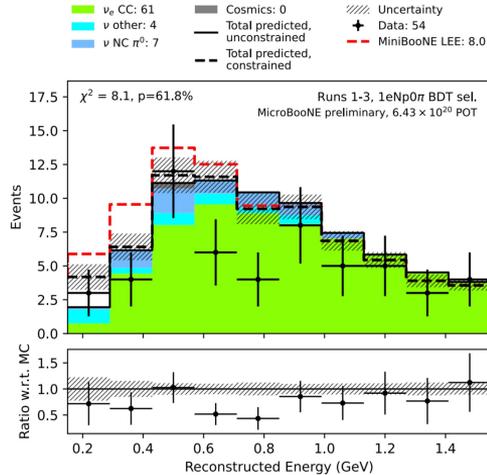
**Independent
data sample**

Full Dataset Analysis using Pandora Reconstruction

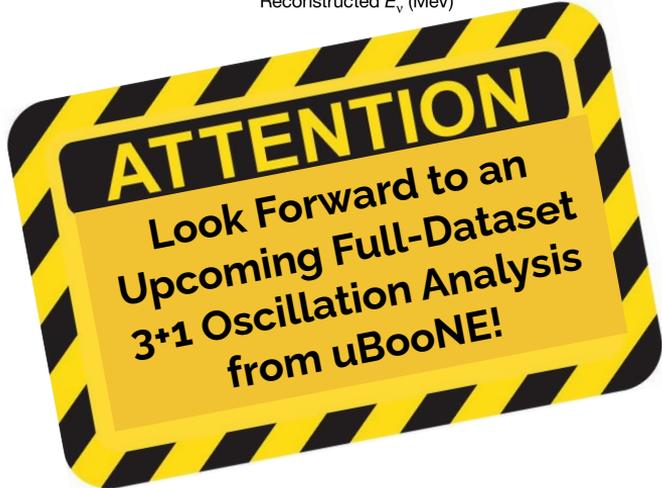
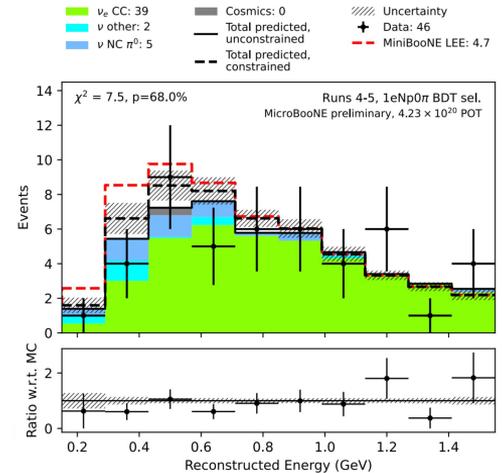
Runs 1-3, BNB data
Wire-Cell Reconstruction



Runs 1-3, BNB data
Pandora Reconstruction



Runs 4-5, BNB data
Pandora Reconstruction



Not independent
~70% of events also selected
in Wire-Cell

Independent



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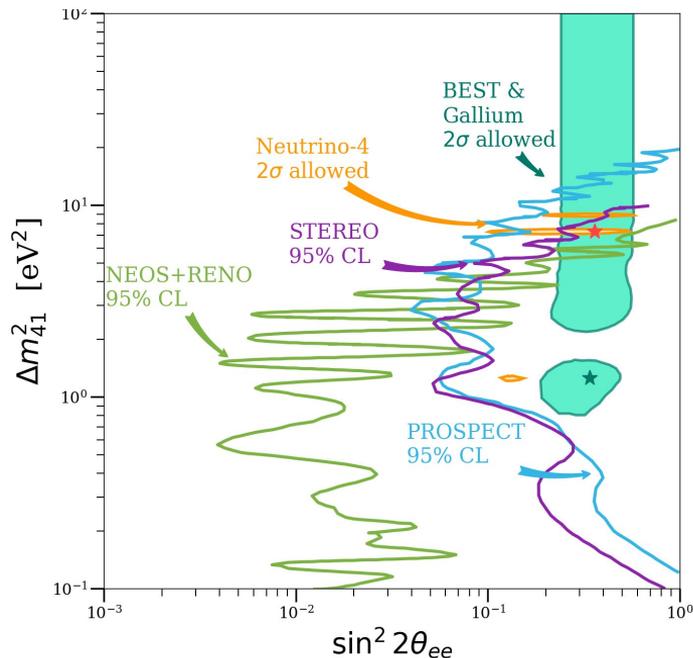
 μ BooNE

External Constraints



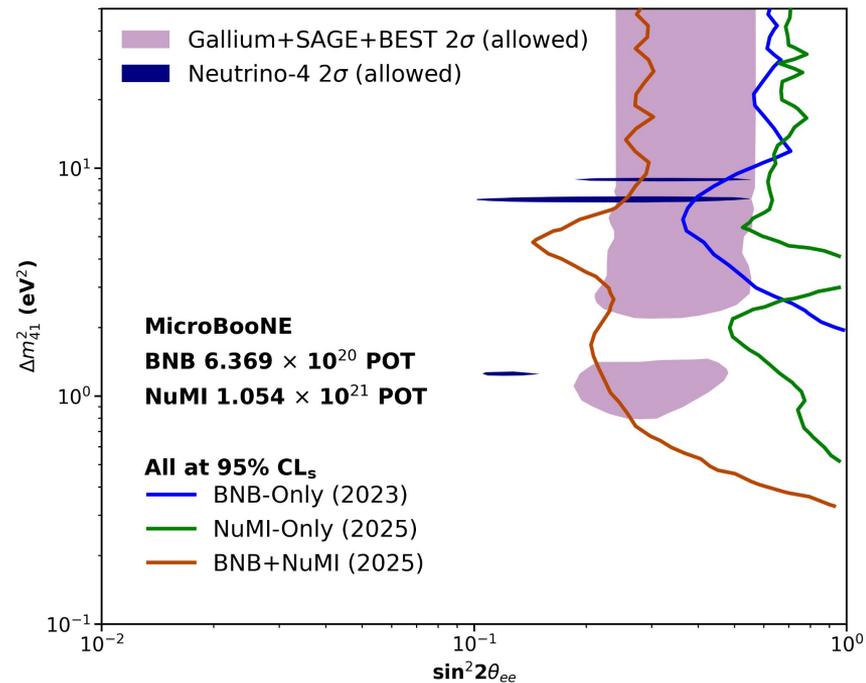
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IN THE CITY OF NEW YORK

External Constraints

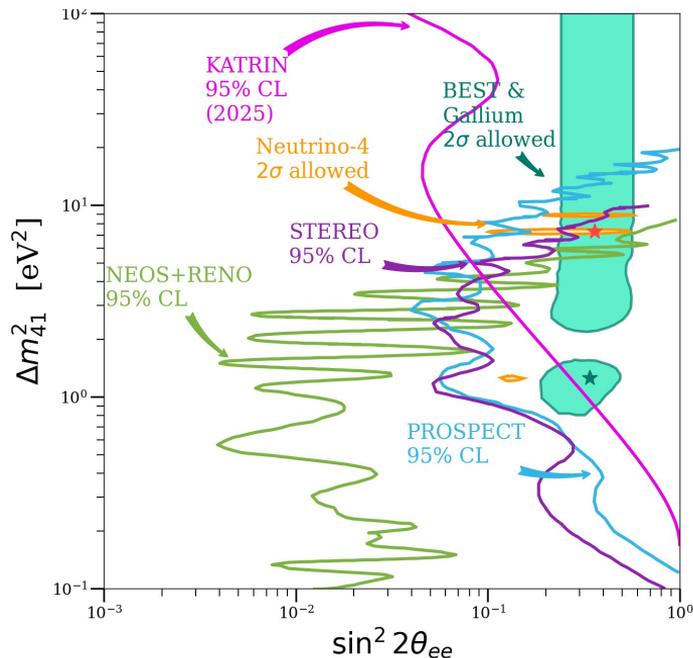


Add **external** reactor constraints?

- **NEOS+RENO**, Phys. Rev. D 105, L111101 (2022)
- **STEREO** Nature 613, 257–261 (2023)
- **PROSPECT** Phys. Rev. Lett. 134, 151802 (2024)

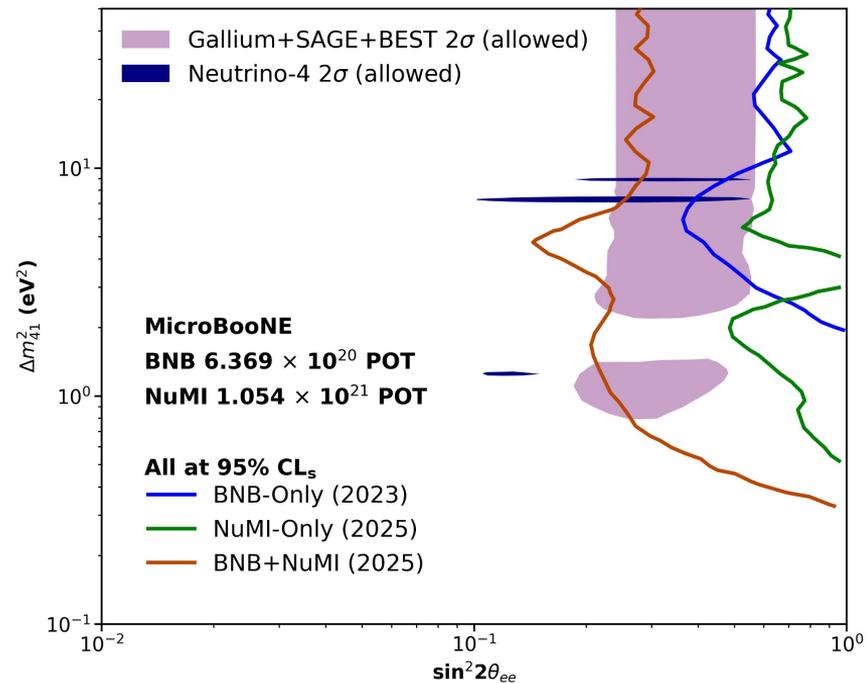


External Constraints

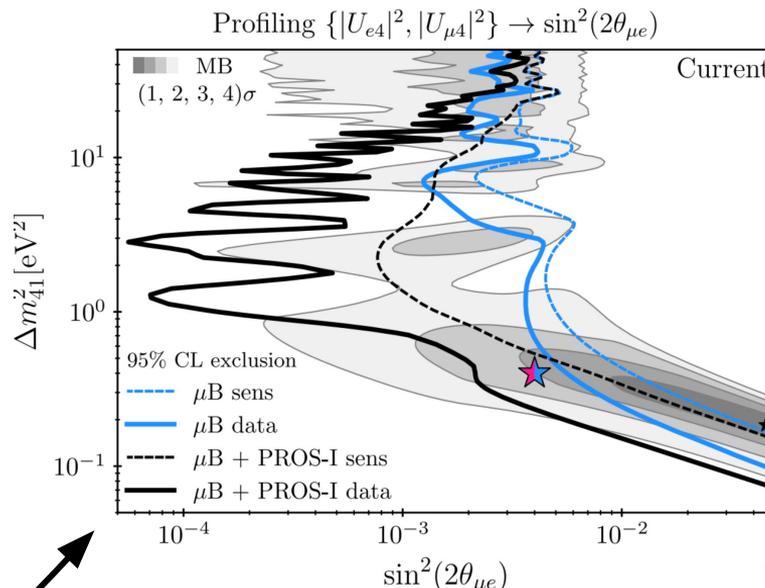
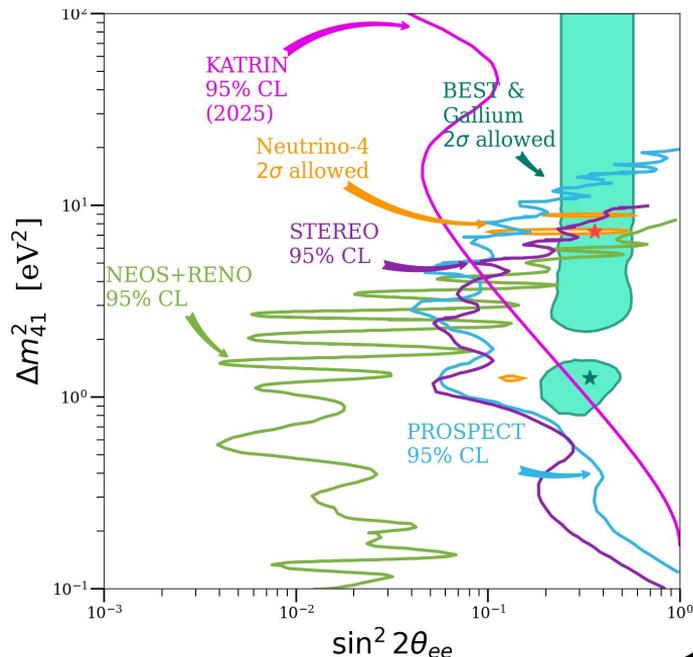


Add *external* constraints?

- **NEOS+RENO**, Phys. Rev. D 105, L111101 (2022)
- **STEREO** Nature 613, 257–261 (2023)
- **PROSPECT** Phys. Rev. Lett. 134, 151802 (2024)
- **KATRIN** Nature 648 (2025) 8092, 70–75 (2025)



External Constraints



Add **external** constraints?

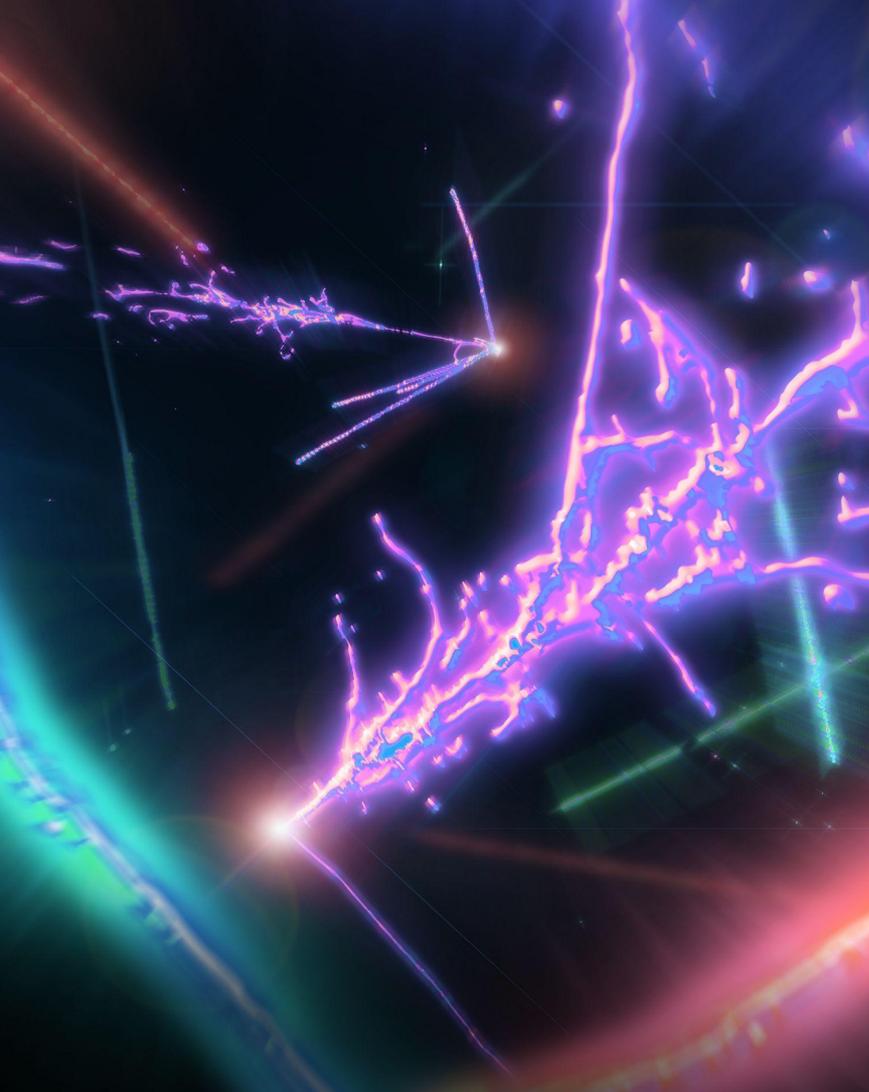
- **NEOS+RENO**, Phys. Rev. D 105, L111101 (2022)
- **STEREO** Nature 613, 257–261 (2023)
- **PROSPECT** Phys. Rev. Lett. 134, 151802 (2024)
- **KATRIN** Nature 648 (2025) 8092, 70–75 (2025)

“Toward a Robust Confirmation or Refutation of the Sterile-Neutrino Explanation of Short-Baseline Anomalies”

O.B Rodrigues, M. Hostert, K.Kelly, B.Littlejohn, P.A.N. Machado, I. Safa, T. Zhou [Phys. Rev. Lett. 135, 081801](#)

Pheno reinterpretation of our BNB only result

Pheno reinterpretation of our BNB only result + PROSPECT Reactor data



 Fermilab

 μ BooNE

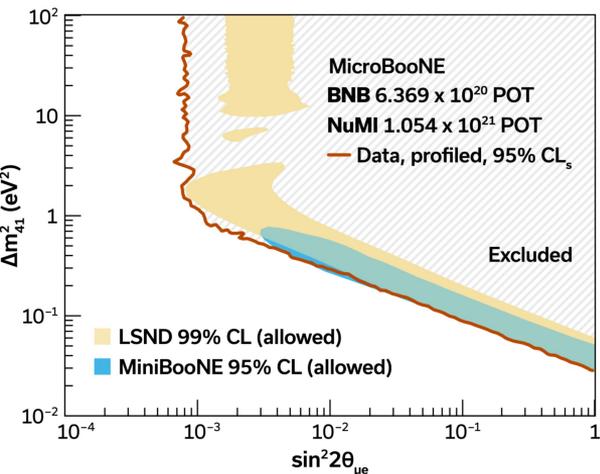
NuMU

 COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

What About ν_μ Disappearance?

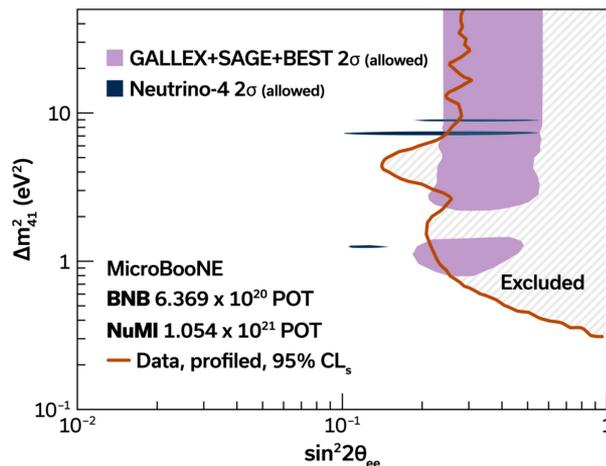
$$\nu_\mu \rightarrow \nu_e$$

$$\frac{\sin^2 2\theta_{\mu e}}{\sin^2 2\theta_{14} \sin^2 \theta_{24}}$$



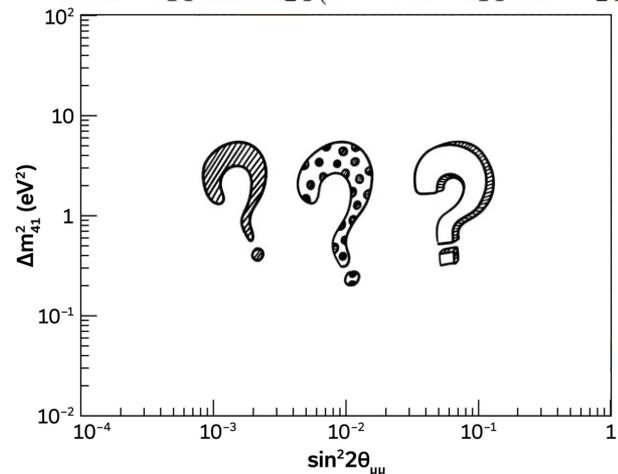
$$\nu_e \rightarrow \nu_e$$

$$\frac{\sin^2 2\theta_{ee}}{\sin^2 2\theta_{14}}$$



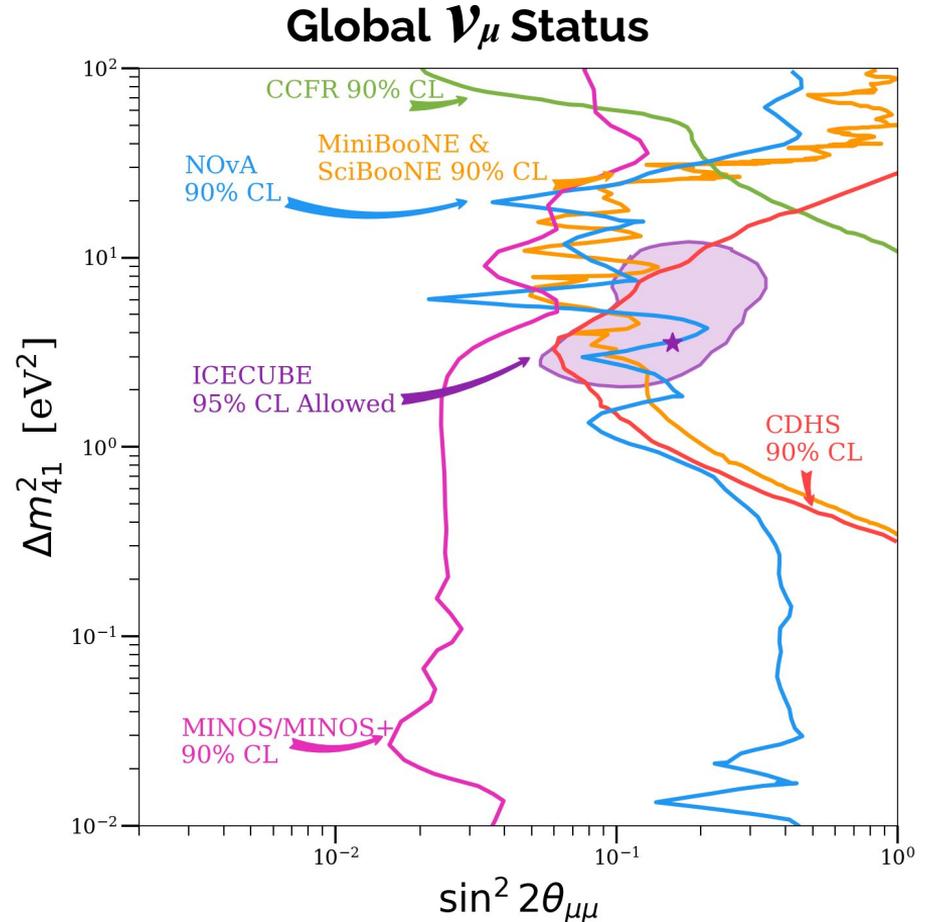
$$\nu_\mu \rightarrow \nu_\mu$$

$$\frac{\sin^2 2\theta_{\mu\mu}}{4 \cos^2 \theta_{14} \sin^2 \theta_{24} (1 - \cos^2 \theta_{14} \sin^2 \theta_{24})}$$



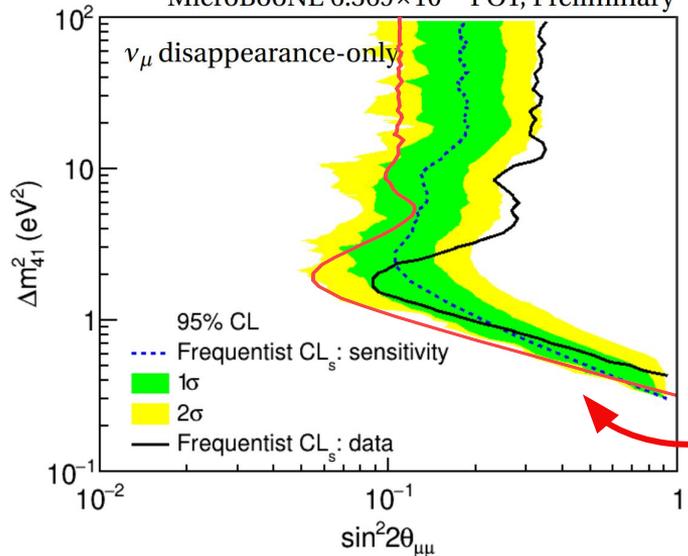
What About ν_μ Disappearance?

- Our single detector MicroBooNE result relies on **powerful CC ν_μ constraints** to **enable our ν_e appearance** measurements
- The systematic uncertainty on the **absolute CC ν_μ rate and shape**, needed for a powerful ν_μ disappearance measurement, are **large and unconstrained**
- As such, our sensitivity is **not competitive** in terms of the global bounds and **we focused on ν_e appearance**



MicroBooNE BNB-Only

MicroBooNE 6.369×10^{20} POT, Preliminary



“MicroBooNE and the ν_e Interpretation of the MiniBooNE Low-Energy Excess”

C.A. Argüelles et al, [Phys.Rev.Lett. 128 \(2022\) 24, 241802](#)

Phenomenologists **interpretation of our BNB-Only ν_μ -disappearance** using our data release $\Delta\chi^2$ maps

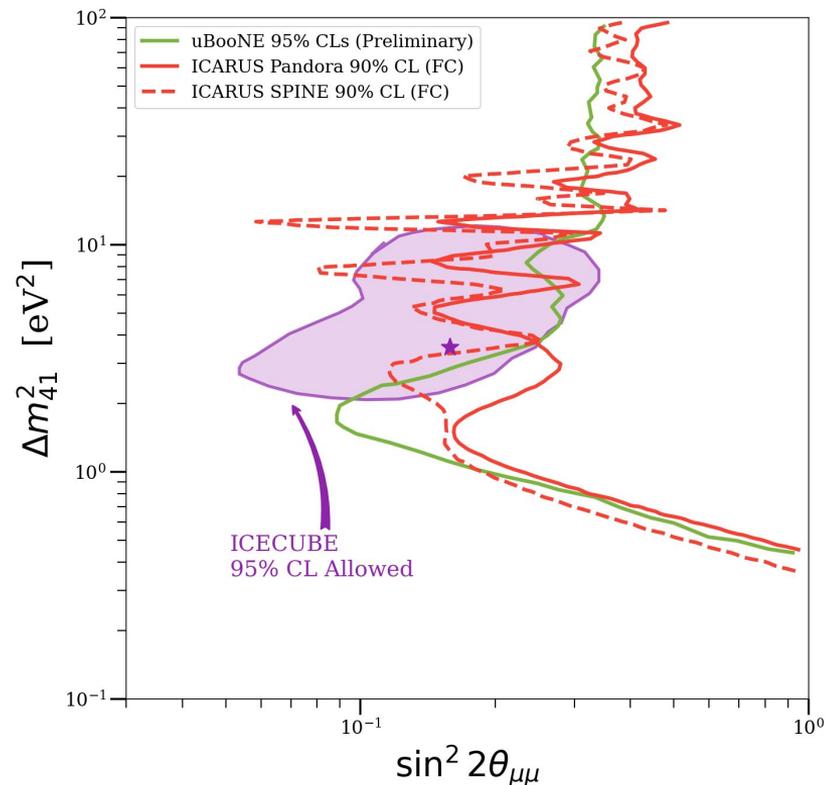
Wilks theorem does not accurately model the exclusions for the ν_μ -disappearance results.

The same is true for our latest BNB+NuMI data release

MicroBooNE Public Note

[MICROBOONE-NOTE-1116-PUB](#)

BNB-Only Results (Not Apples-to-Apples!)

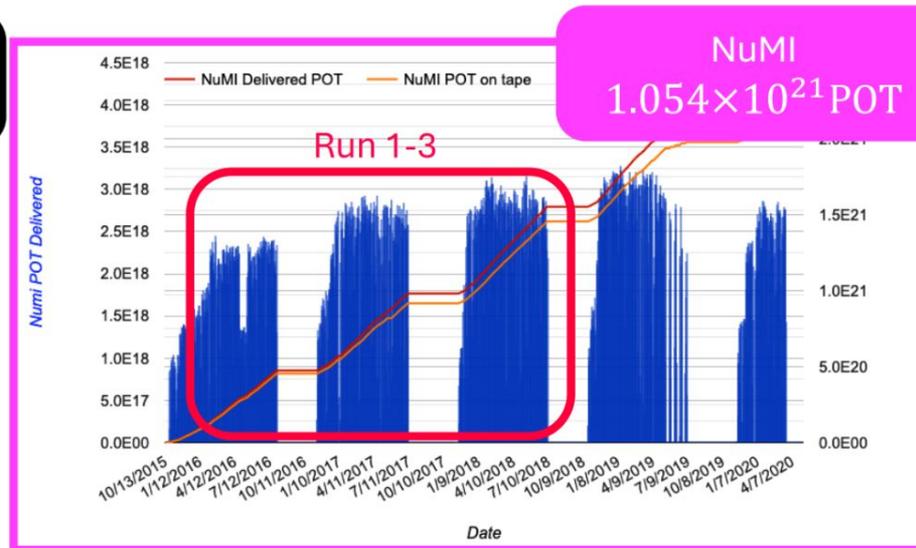
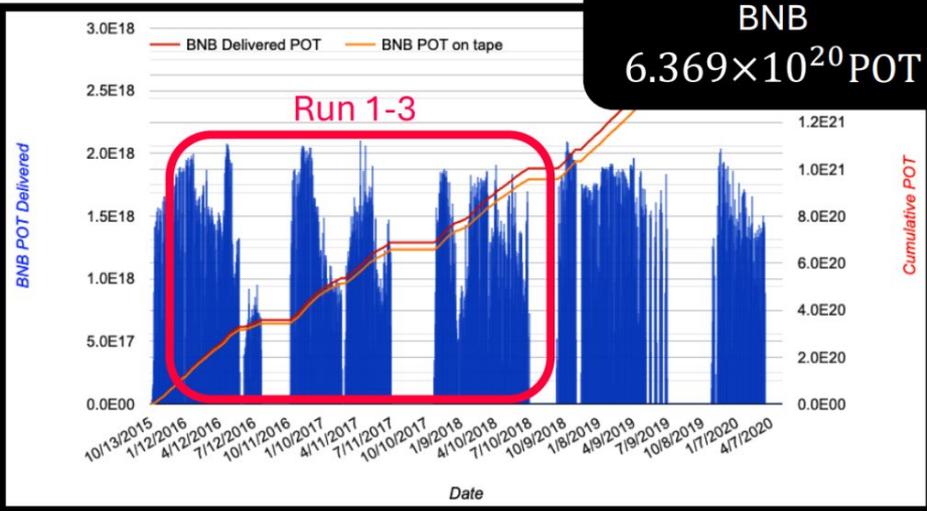


Overlaid contours from previous slide

Broadly consistent picture emerging from multiple experiments on the BNB but we need to begin to understand differences

- This is the **first oscillation comparison that can be made from modern LArTPC's in the BNB**
- Is the first time, but won't be the last, we see some differences as SBN ramps up results
- We note that there is zero overlap in run-periods of the BNB between this ICARUS & uBooNE work
 - ***Exciting possibilities of joint-fits to improve our understanding in the future!***

Data used for the analysis



Current Analysis uses ~half of available MicroBooNE data across two beams

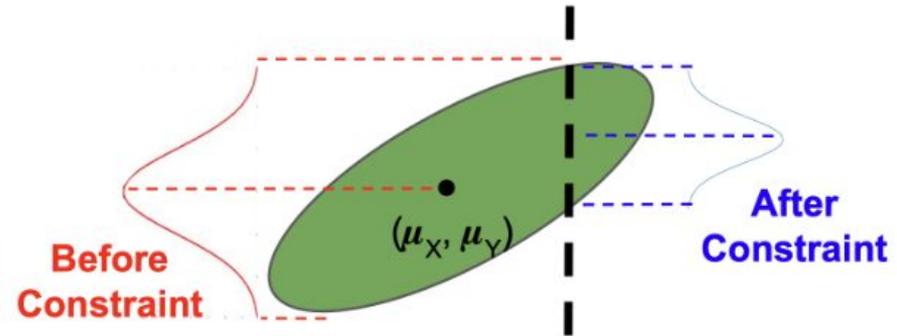
Conditional Constraint

- Using covariance matrix formalism, we can use Bayes' theorem to update our prediction in one channel given the observation in a different channel
- We call this the “conditional constraint”

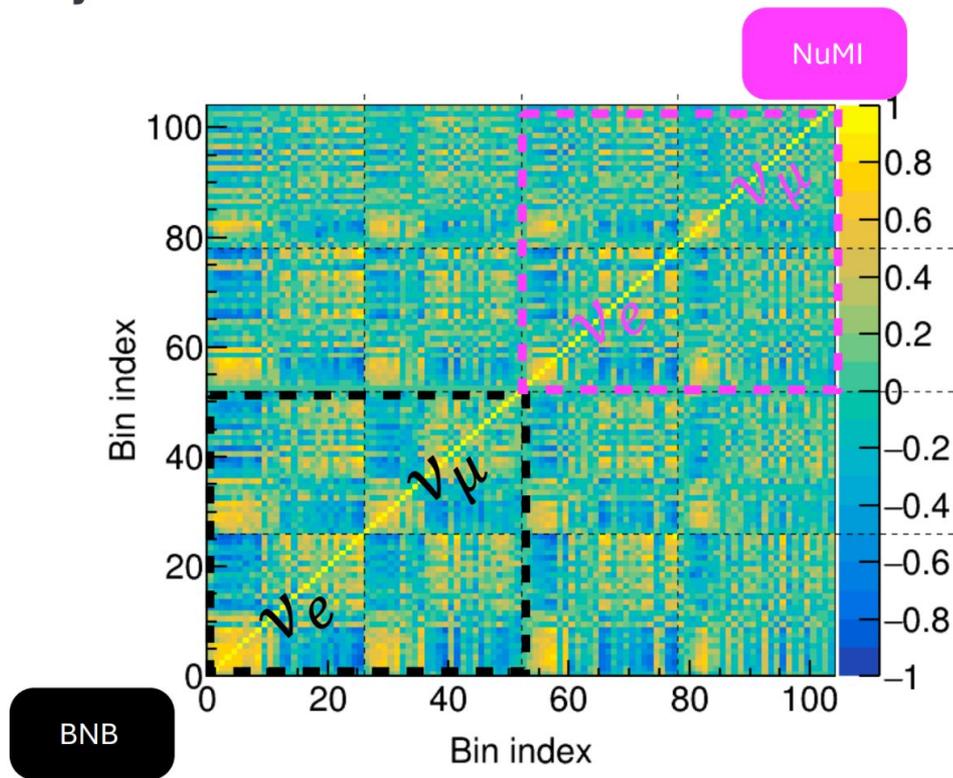
$$\Sigma = \begin{pmatrix} \Sigma^{XX} & \Sigma^{XY} \\ \Sigma^{YX} & \Sigma^{YY} \end{pmatrix}, \quad n: \text{measurement}, \quad \mu: \text{prediction}$$

$$\mu^{X,\text{const.}} = \mu^X + \Sigma^{XY} \cdot (\Sigma^{YY})^{-1} \cdot (n^Y - \mu^Y)$$

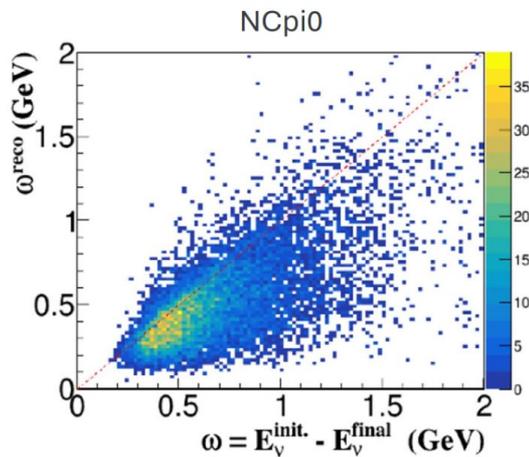
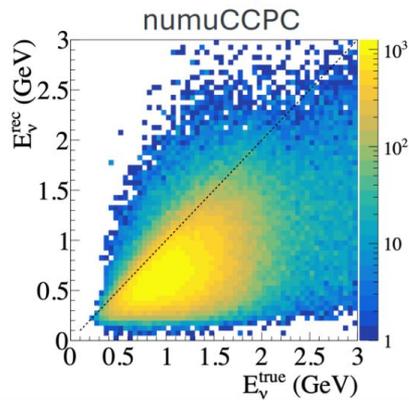
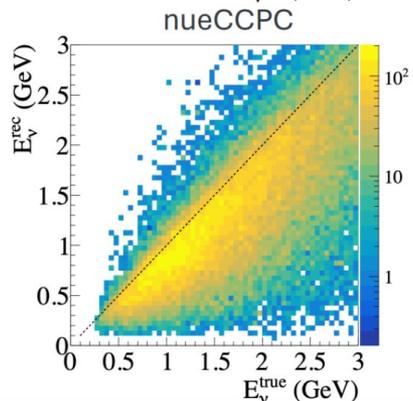
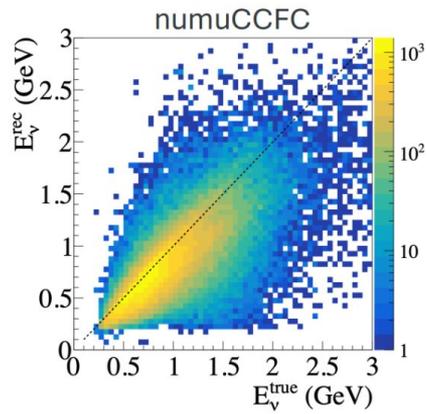
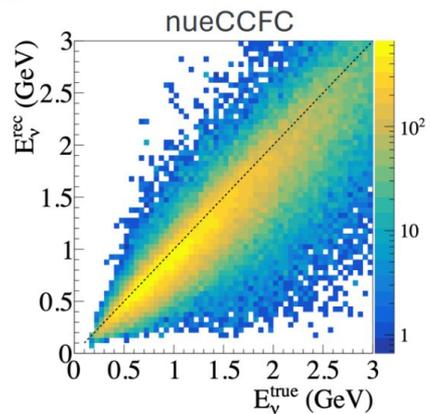
$$\Sigma^{XX,\text{const.}} = \Sigma^{XX} - \Sigma^{XY} \cdot (\Sigma^{YY})^{-1} \cdot \Sigma^{YX}$$



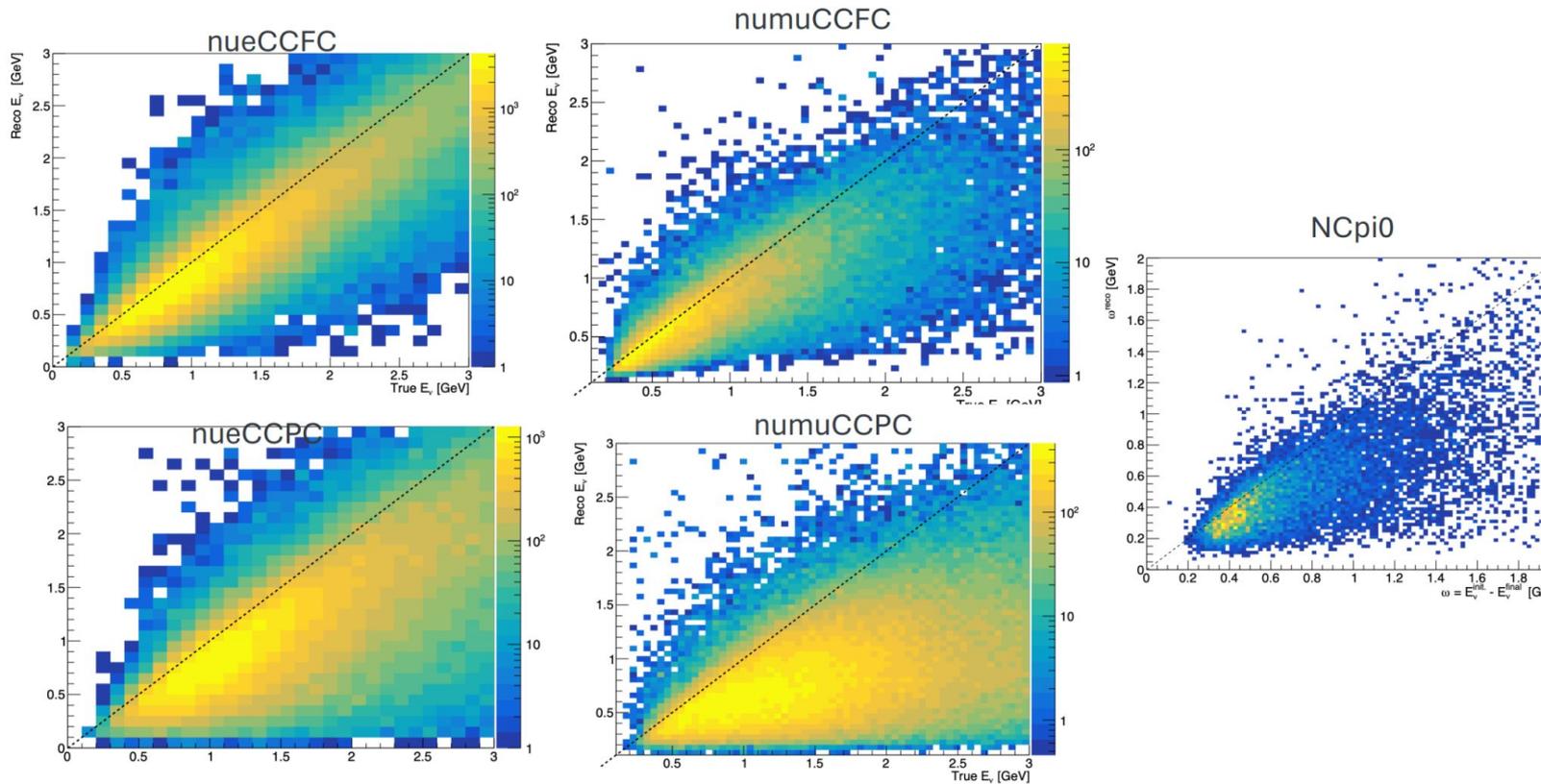
Detector systematics treatment



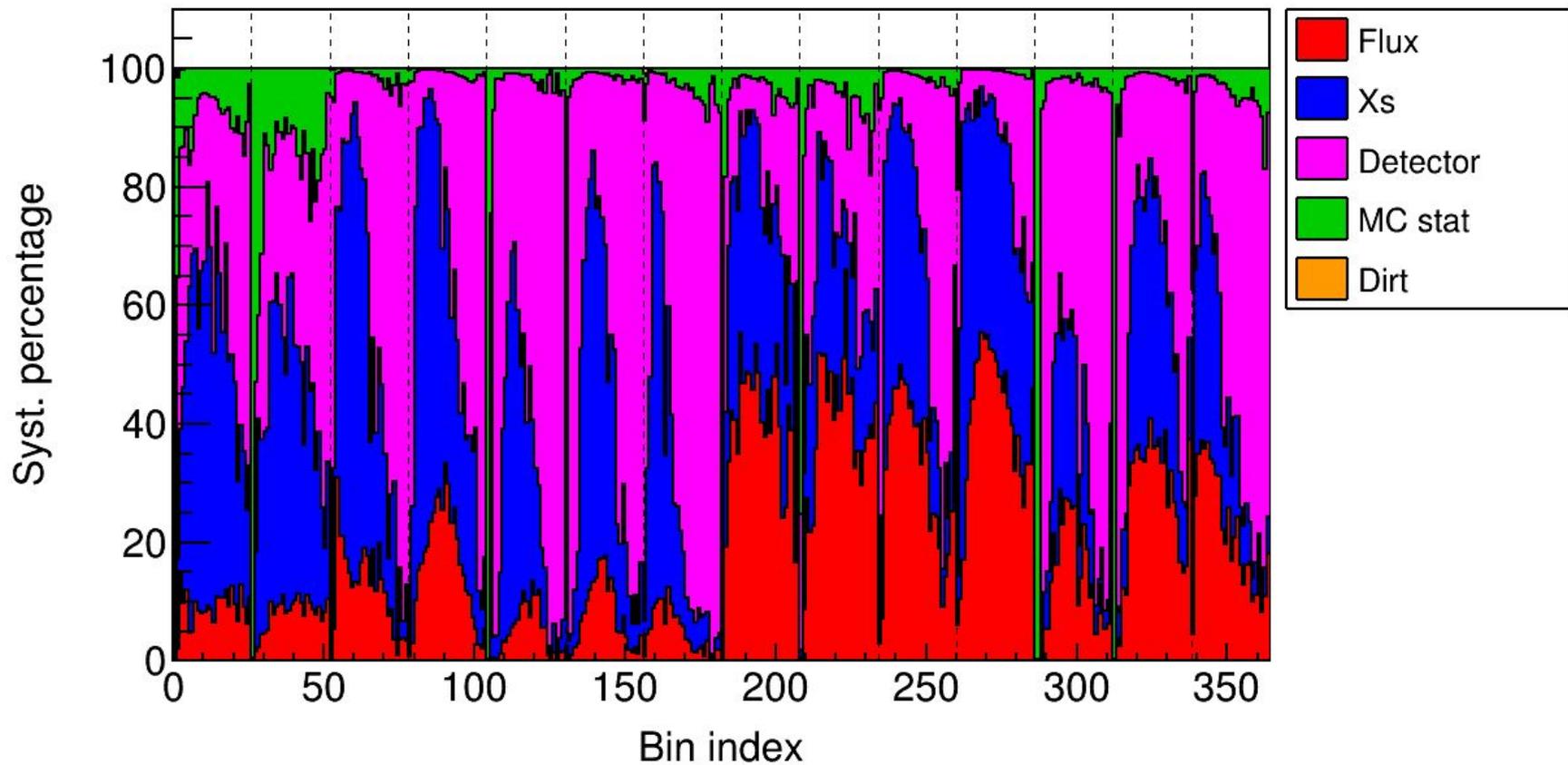
BNB selection performance



NuMI selection performance



Syst Breakdown





Full Covariance

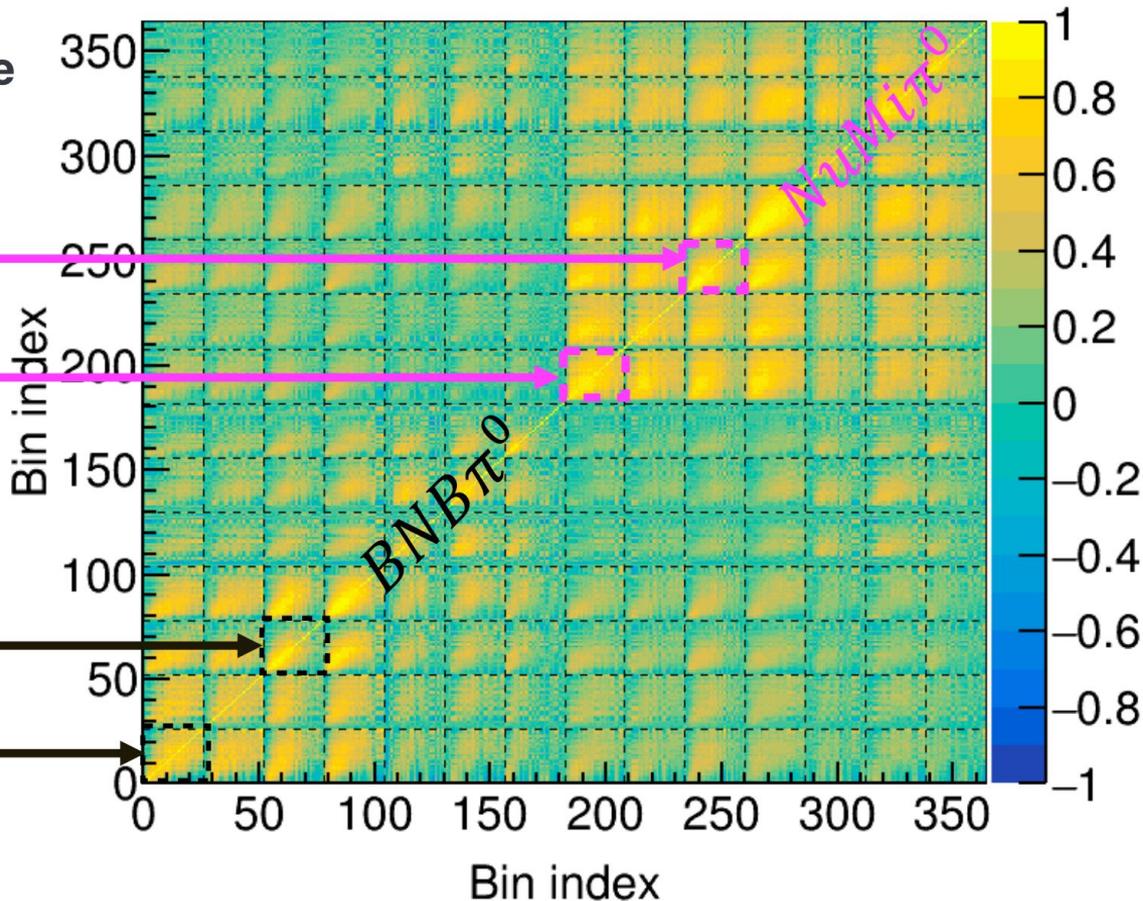
$NuMiv_{\mu}CCFC$

$NuMiv_eCCFC$

Full 364x364
channel
covariance matrix

$BNB\nu_{\mu}CCFC$

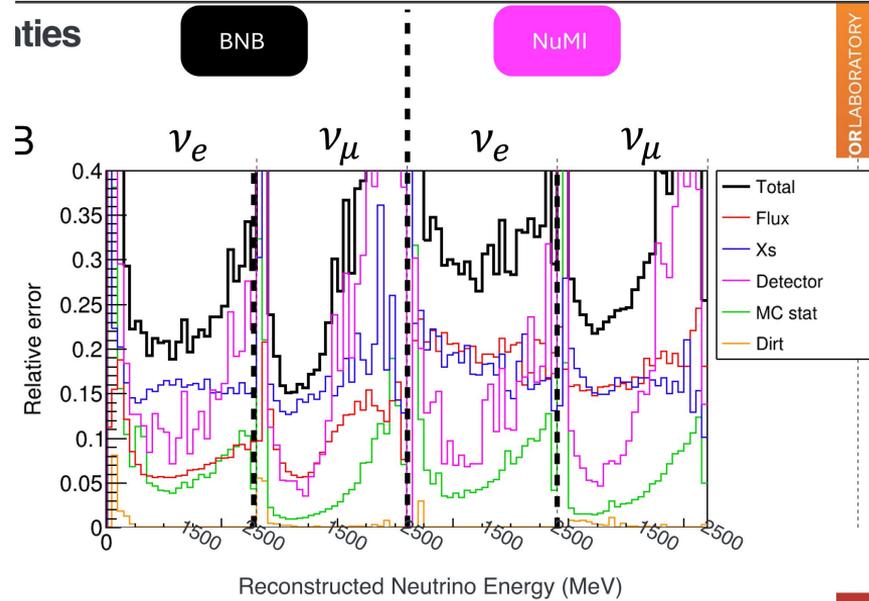
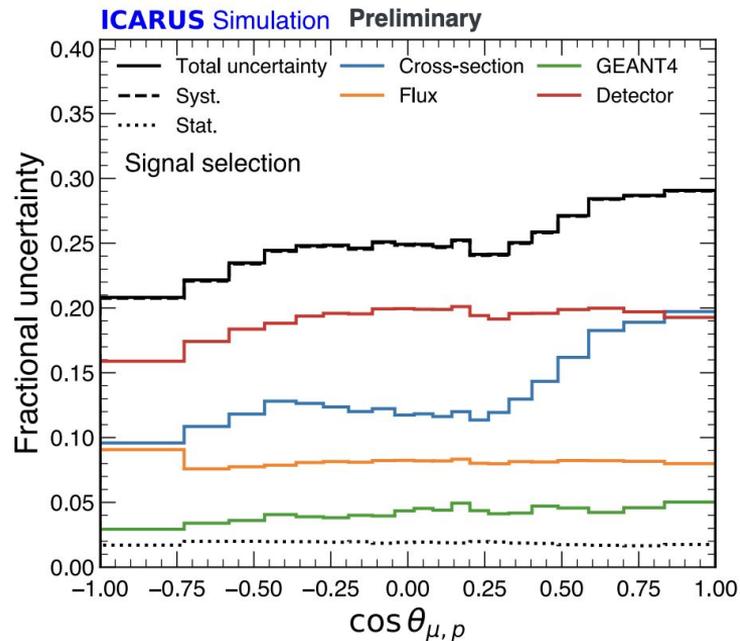
$BNB\nu_eCCFC$



MicroBooNE Tune built off
GENIE **G18_10a_02_11a**

GENIE AR23 AR23_20i_00_000
(Shared with DUNE/SBND)

Differences	G18T	AR23
QE/MEC tune	Tuned to T2K data	No tune
Nuclear model	local Fermi gas	local Fermi gas with correlated tail
CCQE form factors	dipole	z-expansion
MEC model	Nieves	SuSAv2
de-excitation photons	no de-excitation photons	emission of de-excitation photons



g4.10.4

G4.10.4

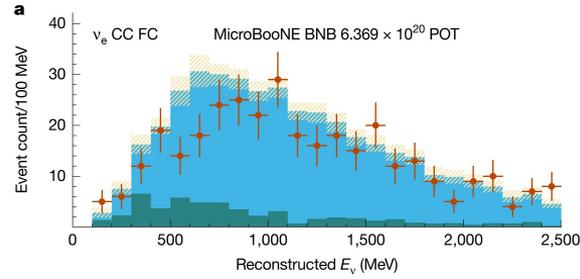
Fix for missing uncertainties for hadron interactions with negative xF.

Blocks

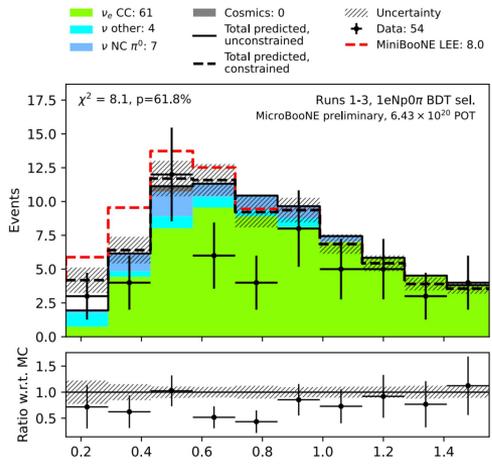
Category	Shared events in W-C and PeLEE	Events only in W-C	Events only in PeLEE	POT
BNB	52 $\left\{ \begin{array}{l} 45 \text{ Np} \\ 7 \text{ 0p} \end{array} \right.$	552	45 $\left\{ \begin{array}{l} 17 \text{ Np} \\ 28 \text{ 0p} \end{array} \right.$	6.35e20
Overlay ν_e	54.1 $\left\{ \begin{array}{l} 46.2 \text{ Np} \\ 7.9 \text{ 0p} \end{array} \right.$	407.1	12.7 $\left\{ \begin{array}{l} 10.1 \text{ Np} \\ 2.6 \text{ 0p} \end{array} \right.$	6.35e20 (scaled)
Overlay ν (BG)	2.4 $\left\{ \begin{array}{l} 0.9 \text{ Np} \\ 1.5 \text{ 0p} \end{array} \right.$	97.9	25.8 $\left\{ \begin{array}{l} 12.2 \text{ Np} \\ 13.6 \text{ 0p} \end{array} \right.$	6.35e20 (scaled)
EXT (BG)	0.4 $\left\{ \begin{array}{l} 0 \text{ Np} \\ 0.4 \text{ 0p} \end{array} \right.$	6.1	5.7 $\left\{ \begin{array}{l} 0.8 \text{ Np} \\ 4.9 \text{ 0p} \end{array} \right.$	6.35e20 (scaled)
DIRT (BG)	0	0	1.0 [0p]	6.35e20 (scaled)

Table 10: Summary of event comparison between PeLEE and Wire-Cell. The "shared" events are the events that are selected by both analyses. The "only" events are the events that are selected by one analysis, but not the other analysis. One can obtain the original selection if combining events from these two categories. For MC, no event weight is applied. The separation of [0p] and [Np] is based on PeLEE's $1e0p$ and $1eNp$ channels, respectively.

Runs 1-3, BNB data Wire-Cell Reconstruction



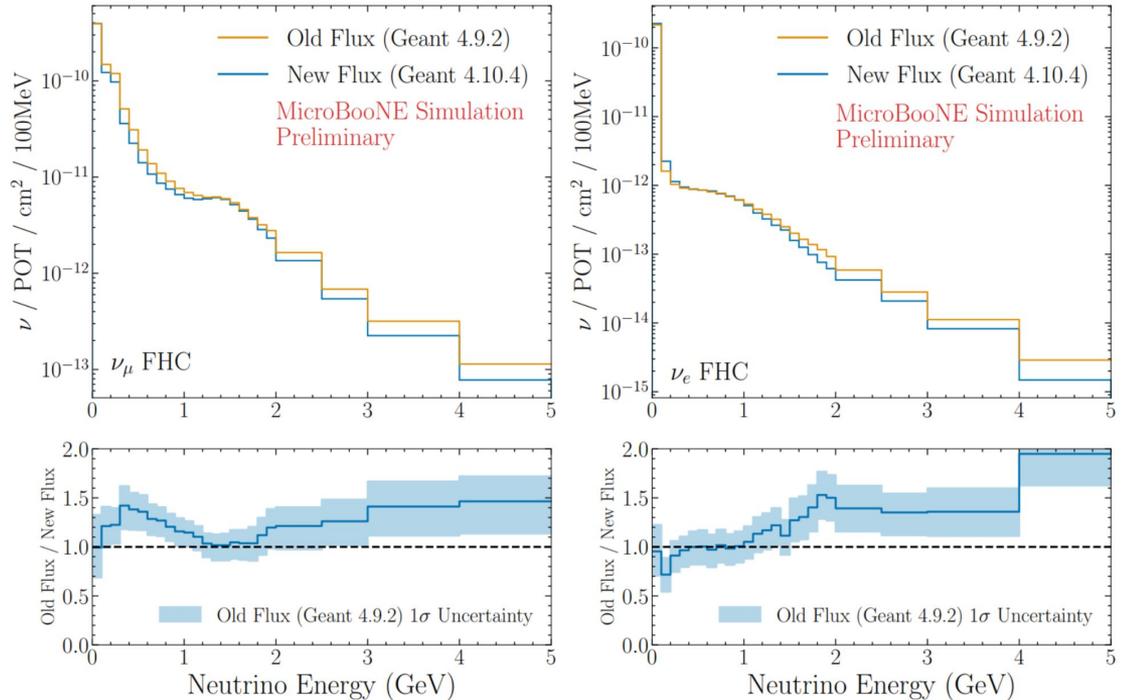
Runs 1-3, BNB data Pandora Reconstruction



Updated Many components of beam simulation:

- Updated beam line geometry
- Updated to Geant4 version (4.10.4) for better agreement with Kaon production external datasets
- Constraints from NA49 and others similar to NOvA, MINERvA
- Conservative treatment of uncertainties outside data coverage

More details in [MICROBOONE-NOTE-1129](#)



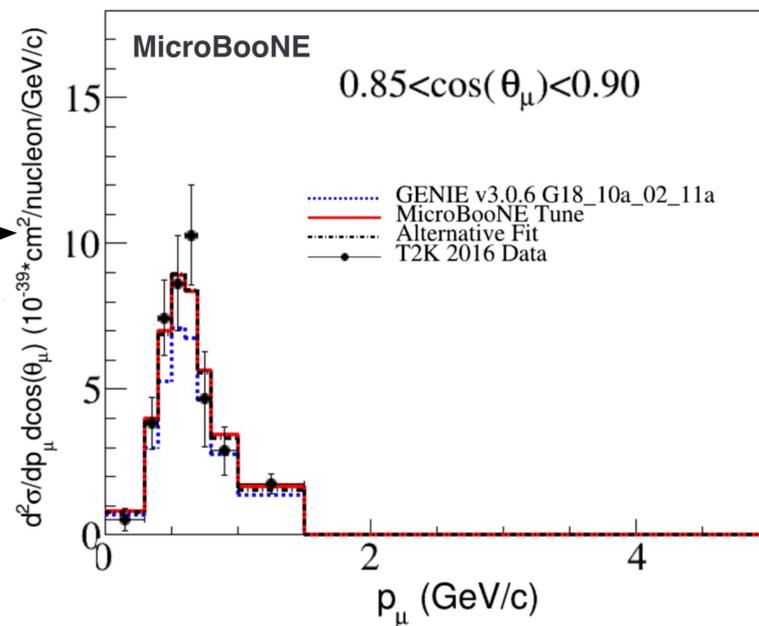
We use a MicroBooNE custom tune of GENIE, built off the **GENIE v3.0.6 G18_10_a02_11a** model set for both BNB and NuMI.

This base model set is then tuned to **external** **T2K CC ν_μ 0π** data

57 internal cross-section parameters are then varied based on their prior uncertainty including

- QE axial mass
- 2p2h normalization/shape
- RPA strength
- pion production
- .. etc

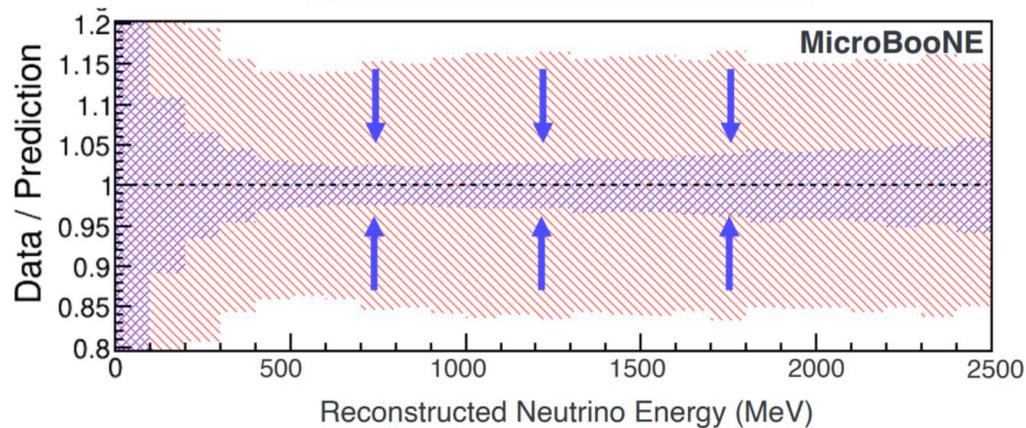
[MicroBooNE: PhysRevD.105.072001](https://arxiv.org/abs/1907.07200)



Leverage correlations to constrain the cross section model and its uncertainty

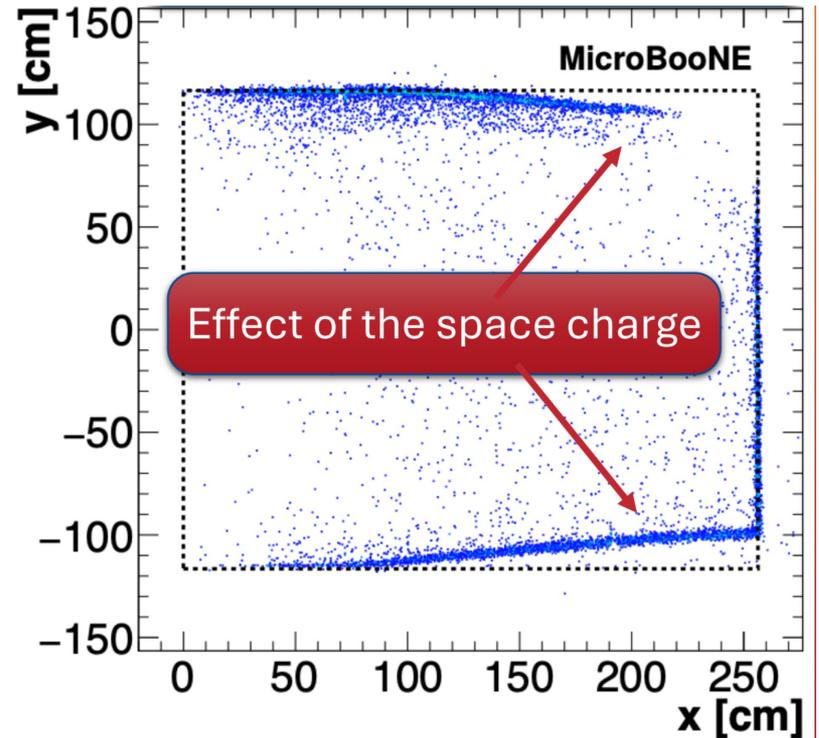
Constraint with BNB ν_μ

BNB ν_e
Only Cross Section Syst.



Detector modelling the **same** as prior **BNB-only** results

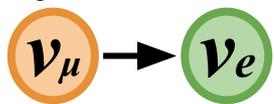
- Space-Charge effect
- Ionization Charge Recombination
- Scintillation light yield and Attenuation
- Simulation of waveforms on wire-readout



For more details see [Phys.Rev. D 105 \(2022\) 11, 112005](#) , [Eur. Phys. J. C 82, 454 \(2022\)](#)

BNB Only Degeneracy Visualization

ν_e appearance



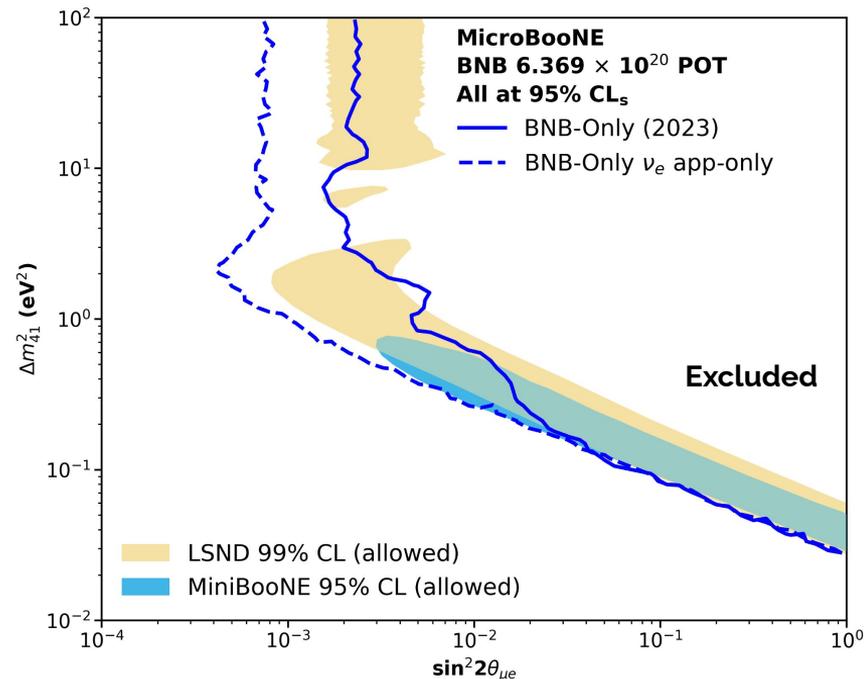
ν_e disappearance



$$\propto N_{\nu\mu} \times \sin^2 2\theta_{\mu e}$$

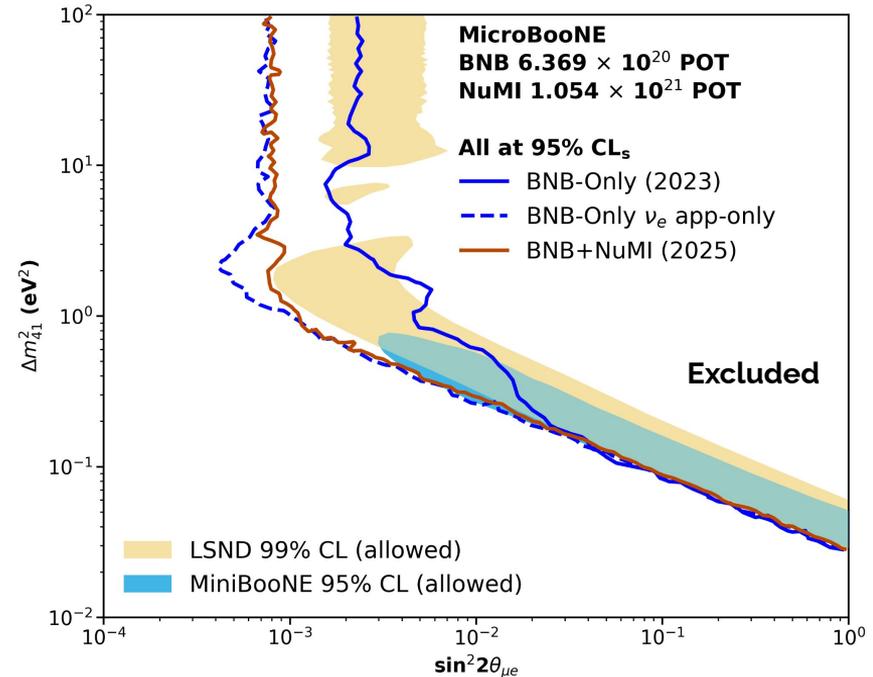
Manually **turn off** ν_e disappearance,

Aka “ ν_e appearance-Only” **Unphysical!**



Addition of NuMI data

- **Breaks** the degeneracy
- **Constrains the amount of ν_e disappearance allowed**
- Unlocks **full potential** of the BNB to **constrain ν_e appearance**



Flux
Modelling

Detector
Modelling

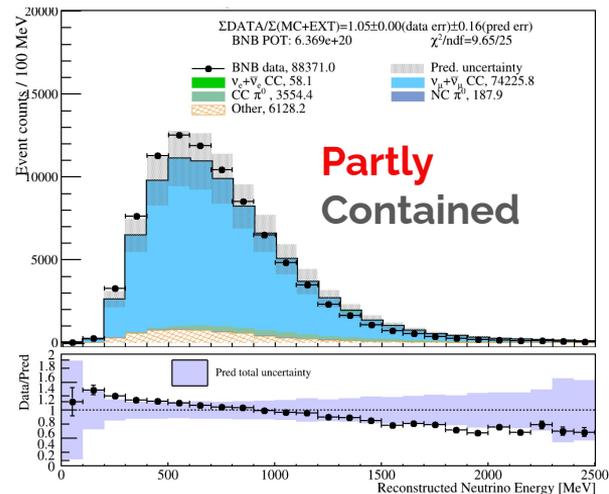
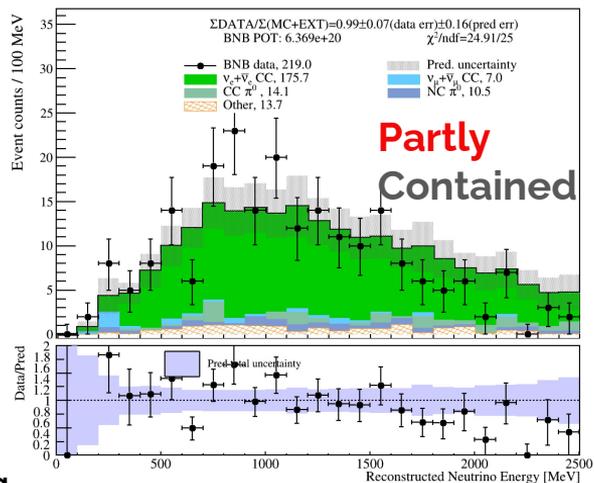
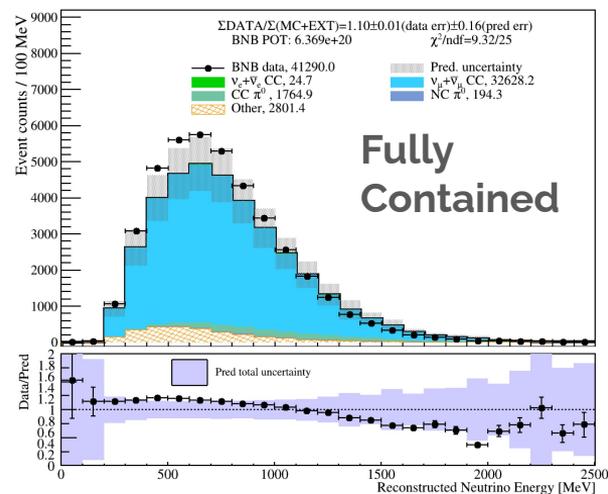
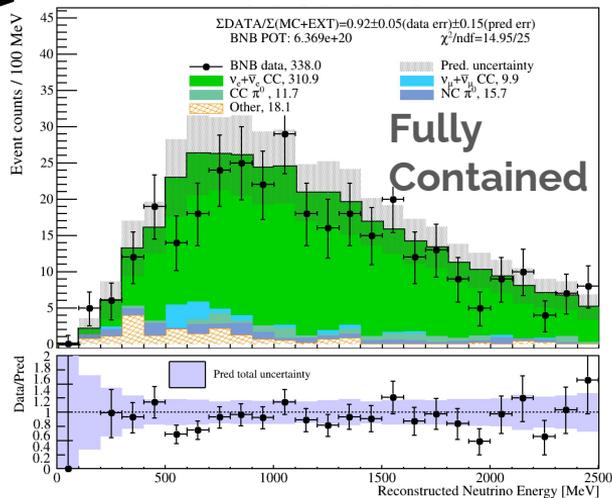


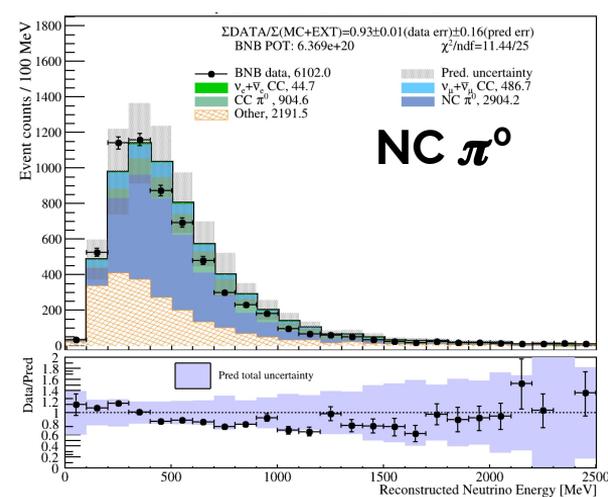
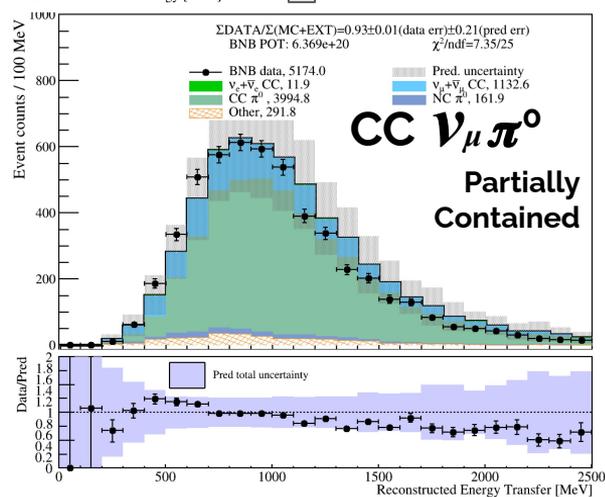
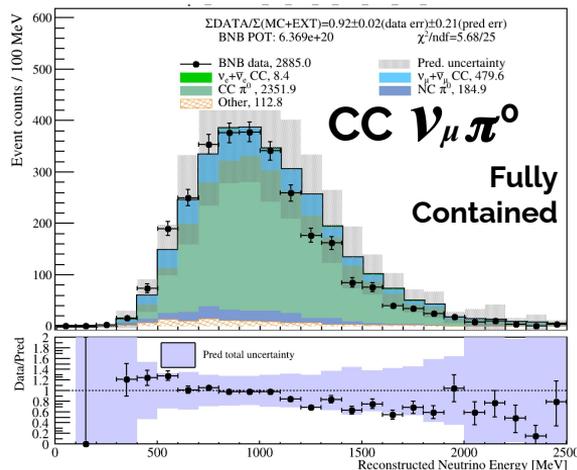
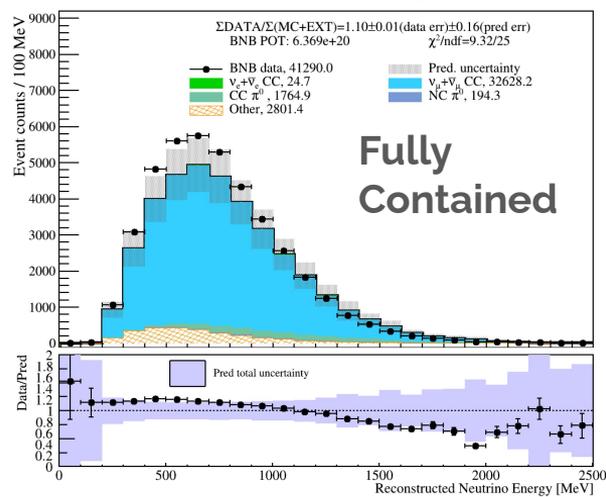
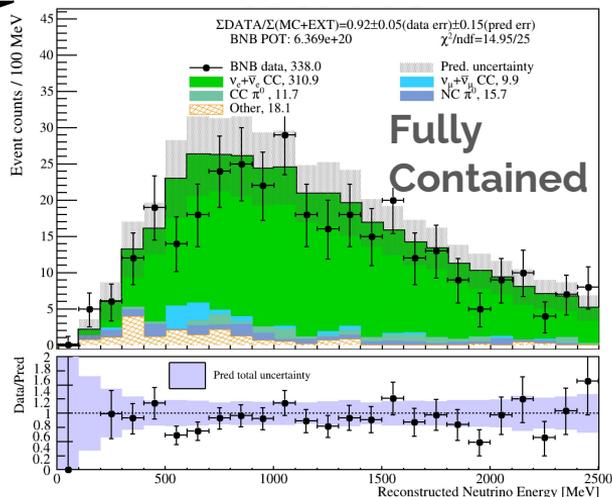
Detector modelling the **same** as prior **MicroBooNE** results

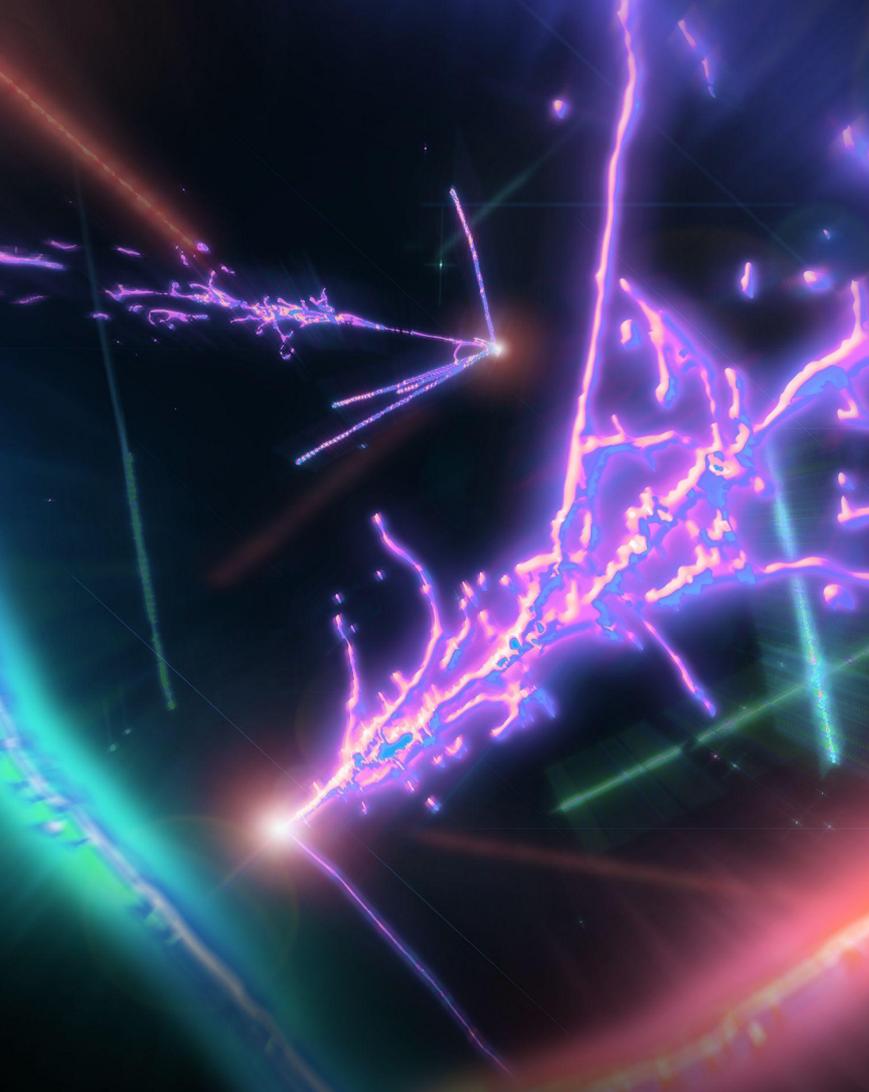
- Space-Charge effect
- Ionization Charge Recombination
- Scintillation light yield and Attenuation
- Simulation of waveforms on wire-readout

For more details see [Phys.Rev. D 105 \(2022\) 11, 112005](#) , [Eur. Phys. J. C 82, 454 \(2022\)](#)

BNB



Data!**CC ν_e** **CC ν_μ** **BNB**



 **Fermilab**

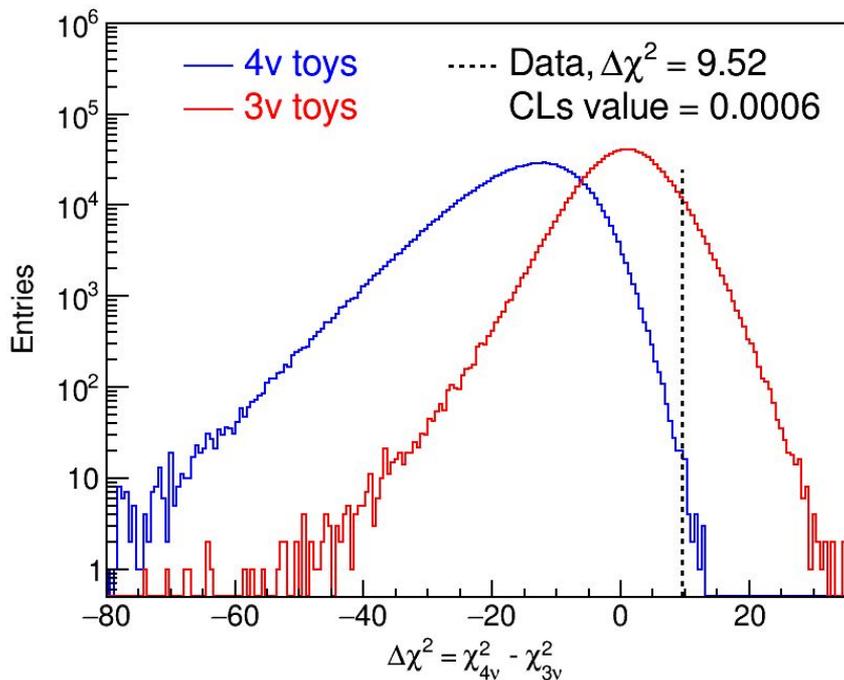
 **μBooNE**

CLs



COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Exclusion Contours with Frequentist CLs

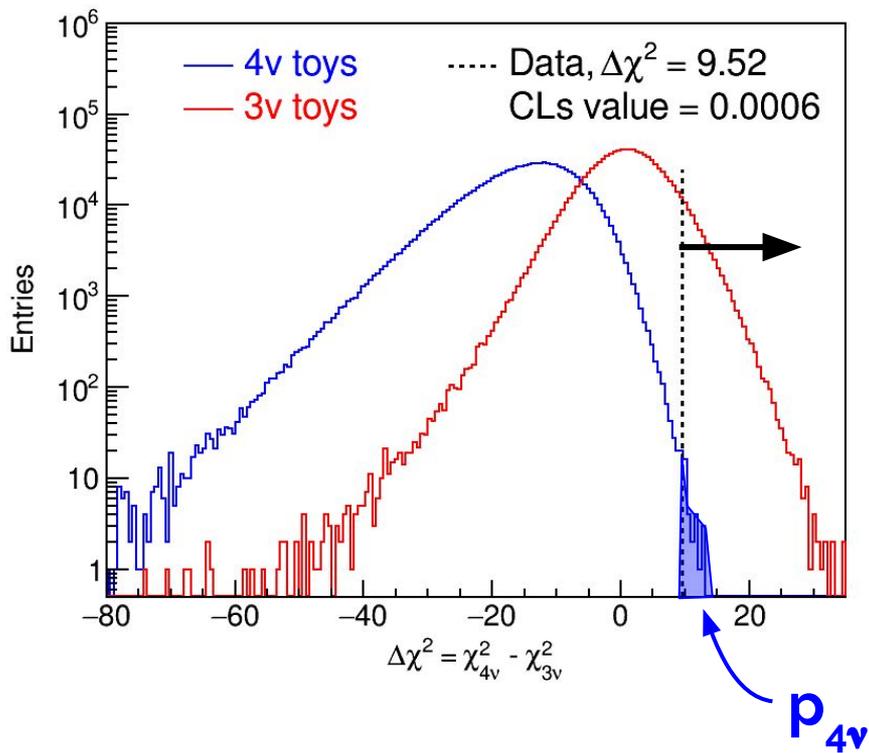


For each point in sterile neutrino parameter space we simulate 100,000's pseudo-universes under both

- 3ν (No-osc) hypothesis
- 4ν (sterile) hypothesis

and find the subsequent expected distributions of $\Delta\chi^2 = \chi_{4\nu}^2 - \chi_{3\nu}^2$

Exclusion Contours with Frequentist CLs



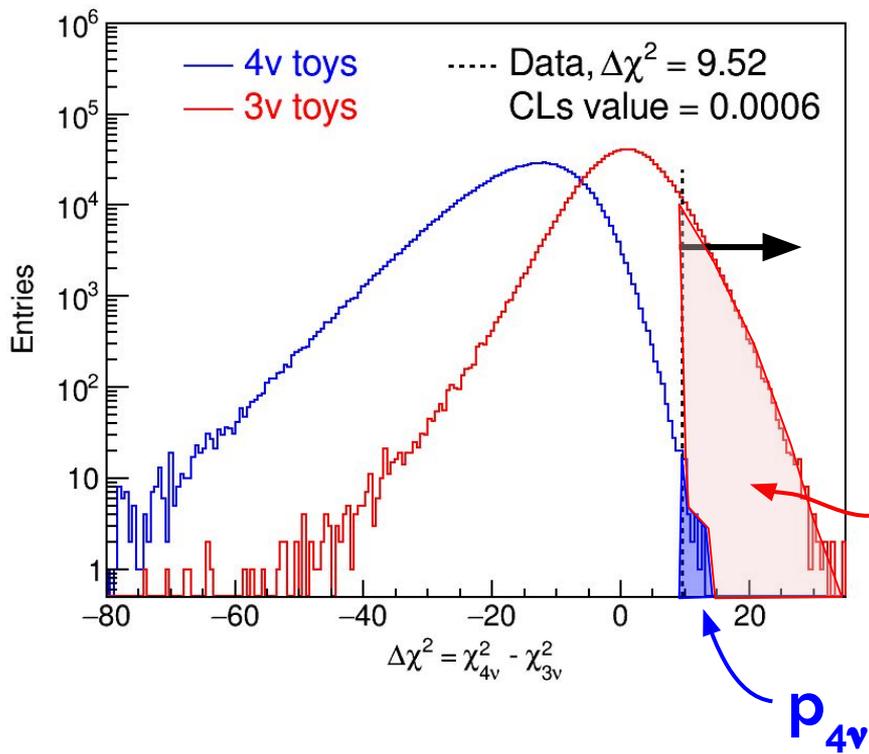
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Given data, find $p_{4\nu}$ and $p_{3\nu}$ pvalues

Exclusion Contours with Frequentist CLs



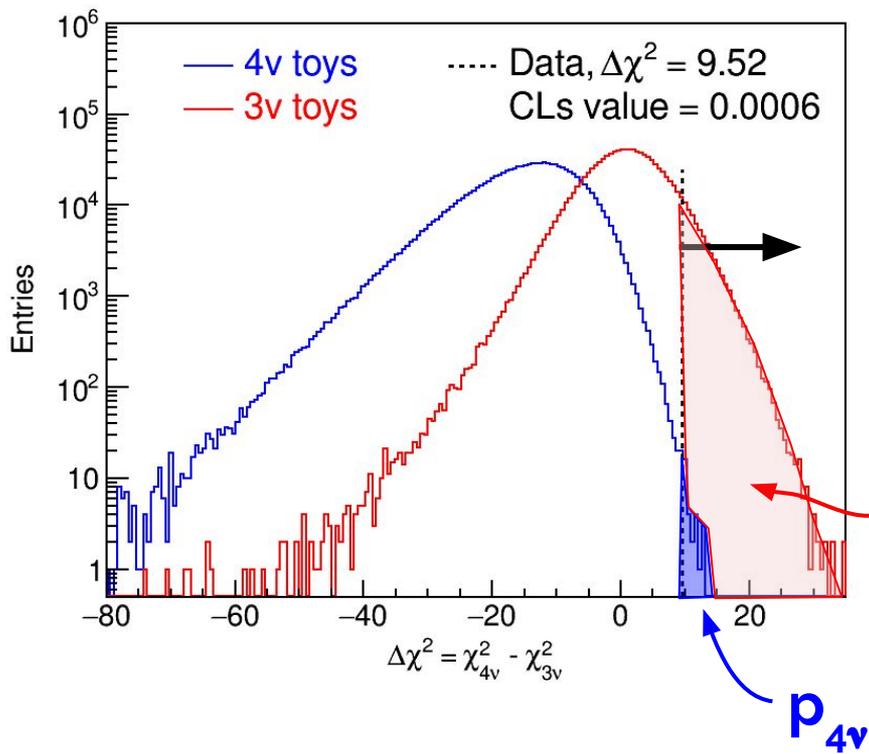
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and find the subsequent expected distributions of $\Delta\chi^2 = \chi_{4\nu}^2 - \chi_{3\nu}^2$

Given data, find $p_{4\nu}$ and $p_{3\nu}$ pvalues

Exclusion Contours with Frequentist CLs



For each point in sterile neutrino parameter space we simulate 100,000's pseudo-universes under both

- 3ν (No-osc) hypothesis
- 4ν (sterile) hypothesis

and find the subsequent expected distributions of $\Delta\chi^2 = \chi^2_{4\nu} - \chi^2_{3\nu}$

Given data, find $p_{4\nu}$ and $p_{3\nu}$ pvalues

$$CL_s = \frac{p_{4\nu}}{p_{3\nu}}$$

Penalizes exclusions where you **lack sensitivity** or when **3ν (No-osc) hypothesis doesn't fit well**