

Two Beams, One Detector: MicroBooNE's Definitive Test of Light Sterile Neutrinos

Jay Hyun Jo

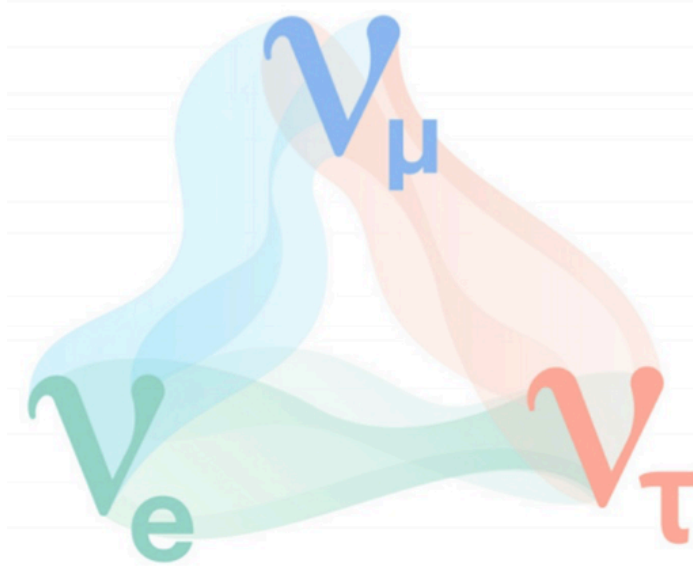
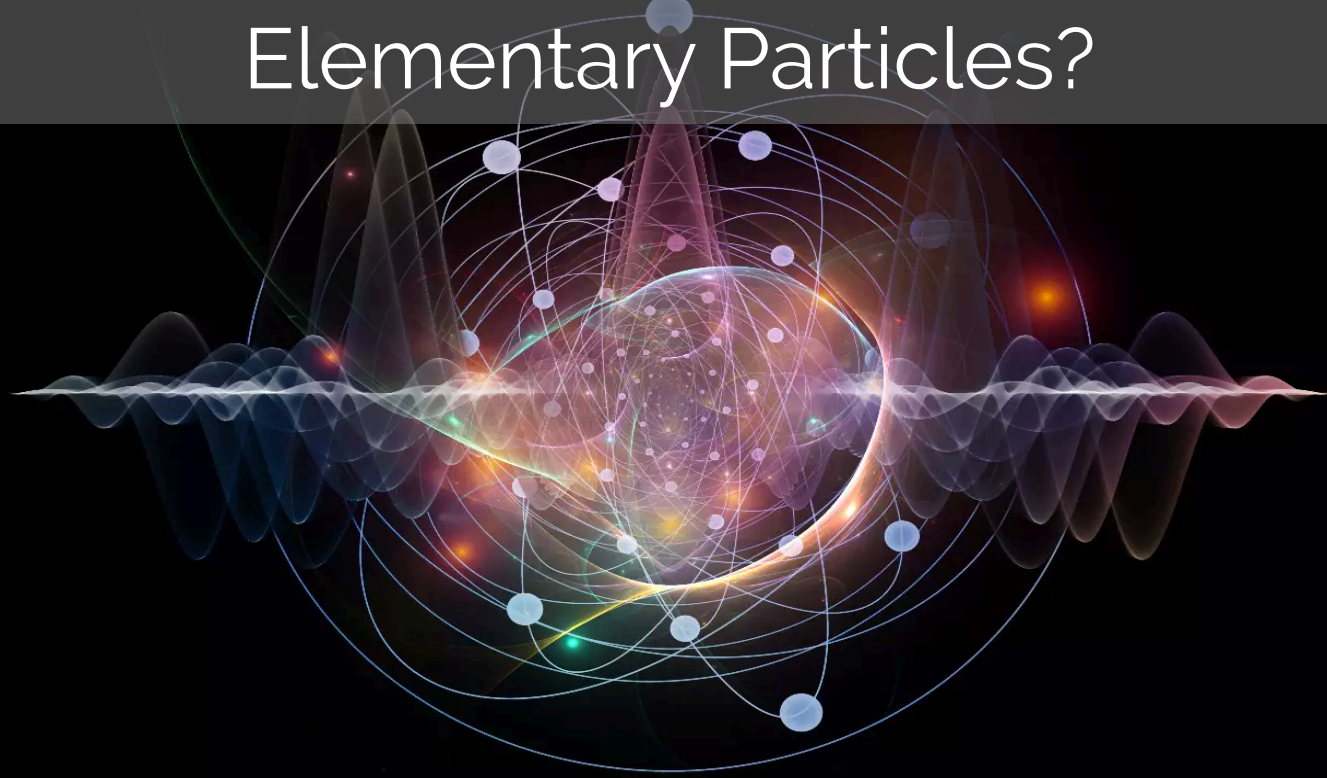
Physics Department, Brookhaven National Laboratory

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Physics Colloquium

Little Neutrinos, Big Science

Neutrinos challenge and inspire physics. They provide a unique window for probing big questions such as...

Extension of the Standard Model of Elementary Particles?



Why does matter win over anti-matter in the universe?



How does a supernova explode and how is a black hole formed?



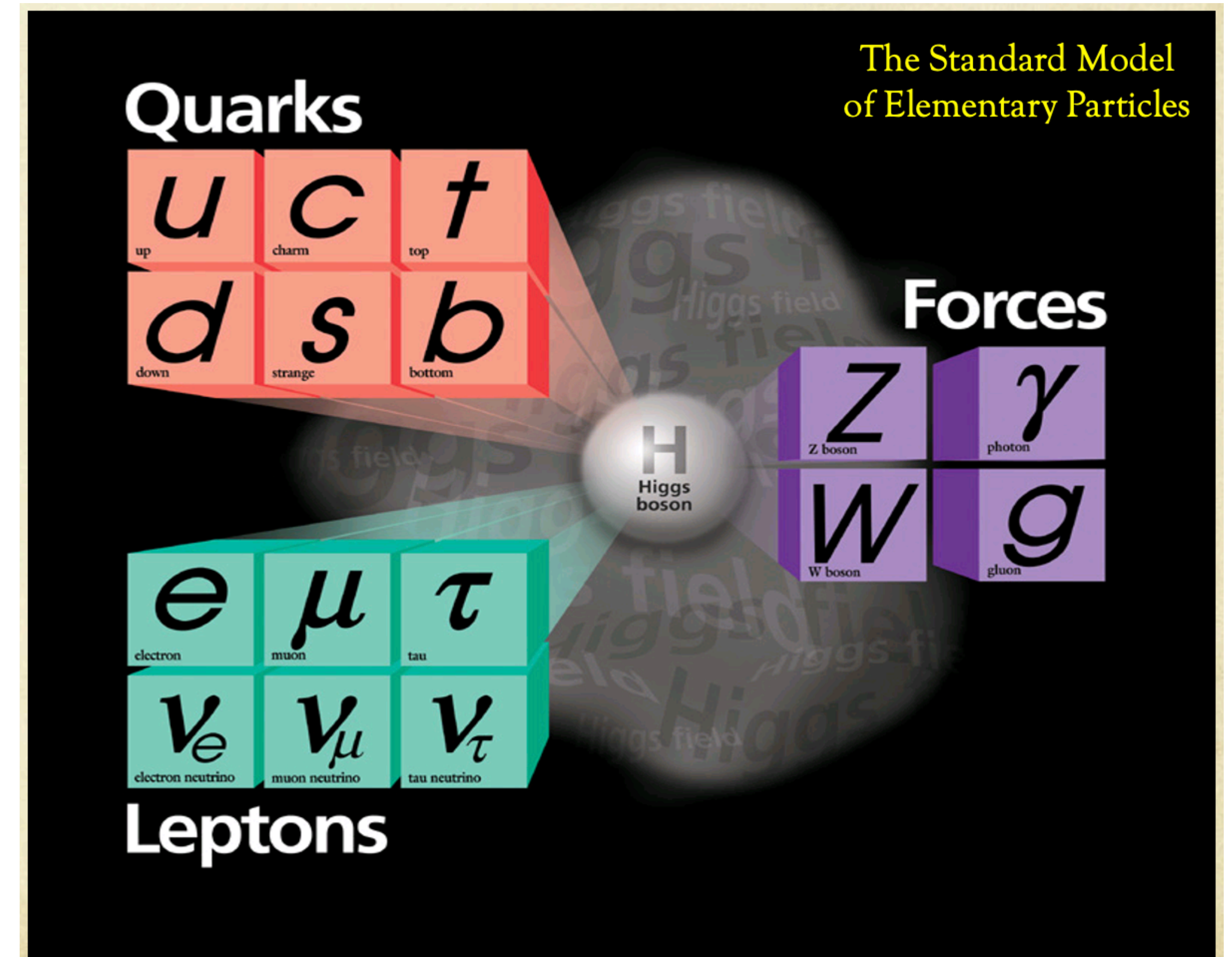
A "dark sector" of the universe?



Introduction: Sterile Neutrino & Oscillation Parameter Degeneracy

Neutrinos in the Standard Model

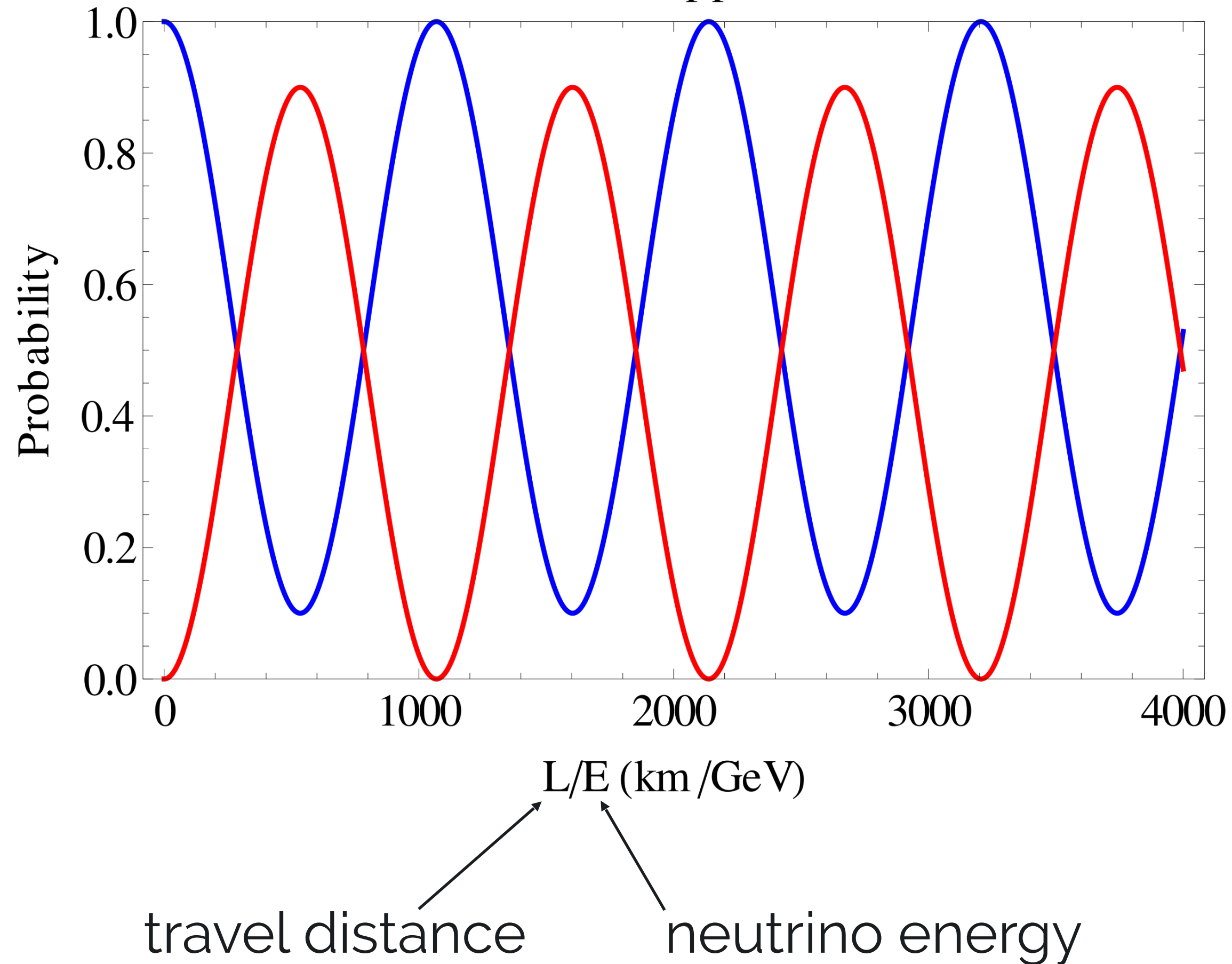
- Elementary fermions/matter particles
- **Three generations/flavors**
- Second-most abundant in the universe
- neutral, and **expected to be massless**
- Only weak interactions



Neutrinos beyond the Standard Model

Neutrinos **OSCILLATE** from one flavor into another as they travel --- **they have MASS!**

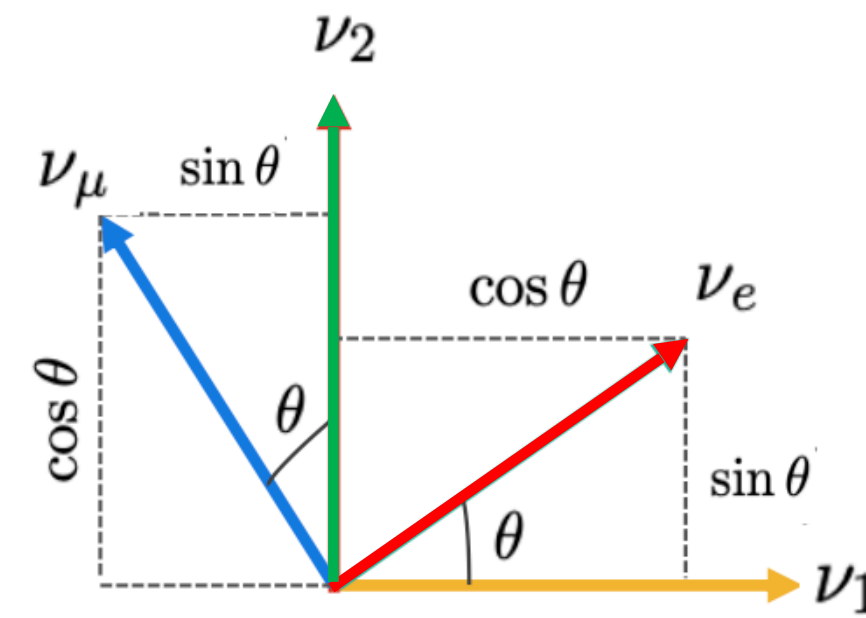
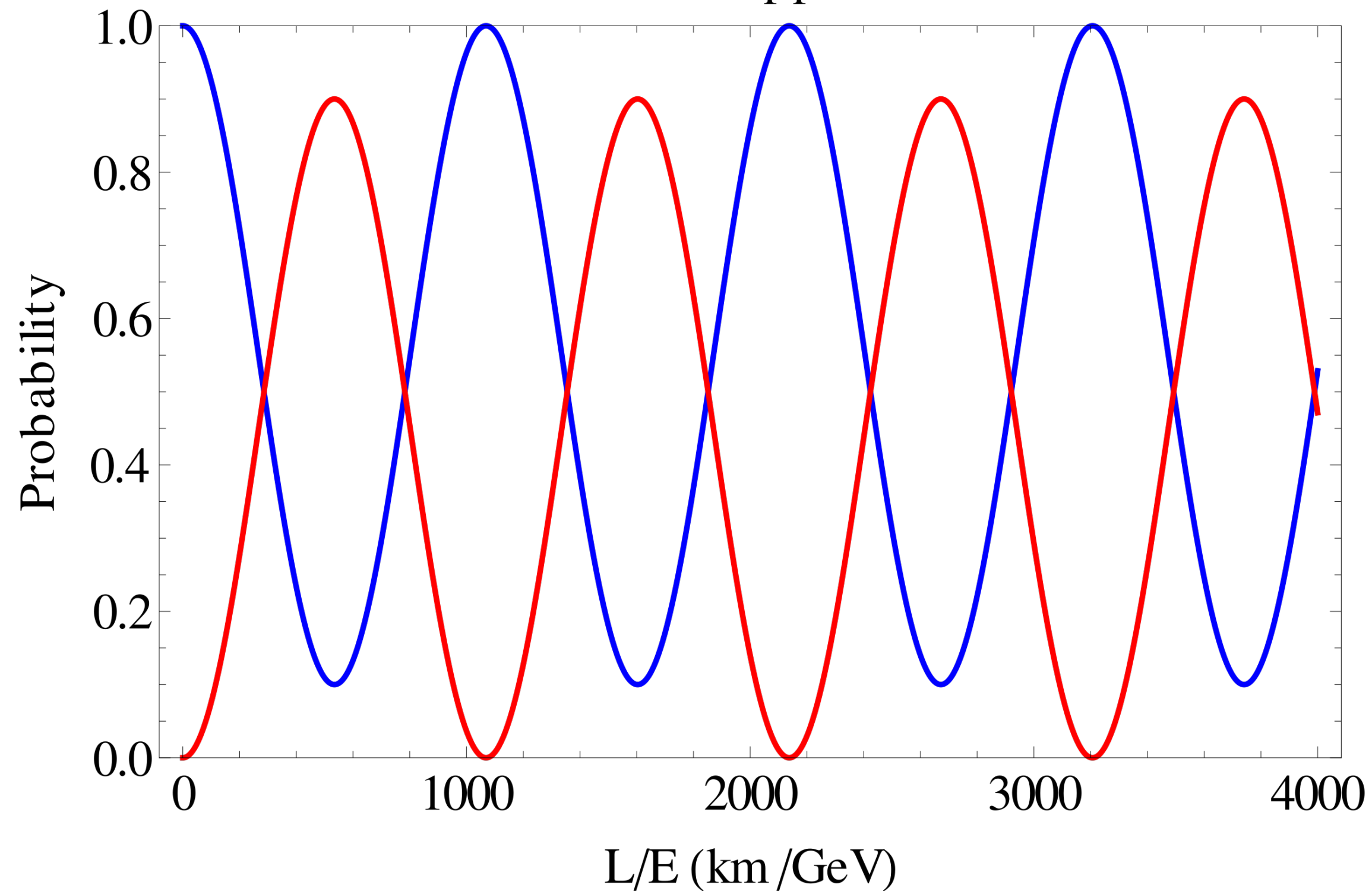
Two neutrino approximation



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Two neutrino approximation



Neutrino mixing

$$\begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}$$

Propagation of each mass eigenstate

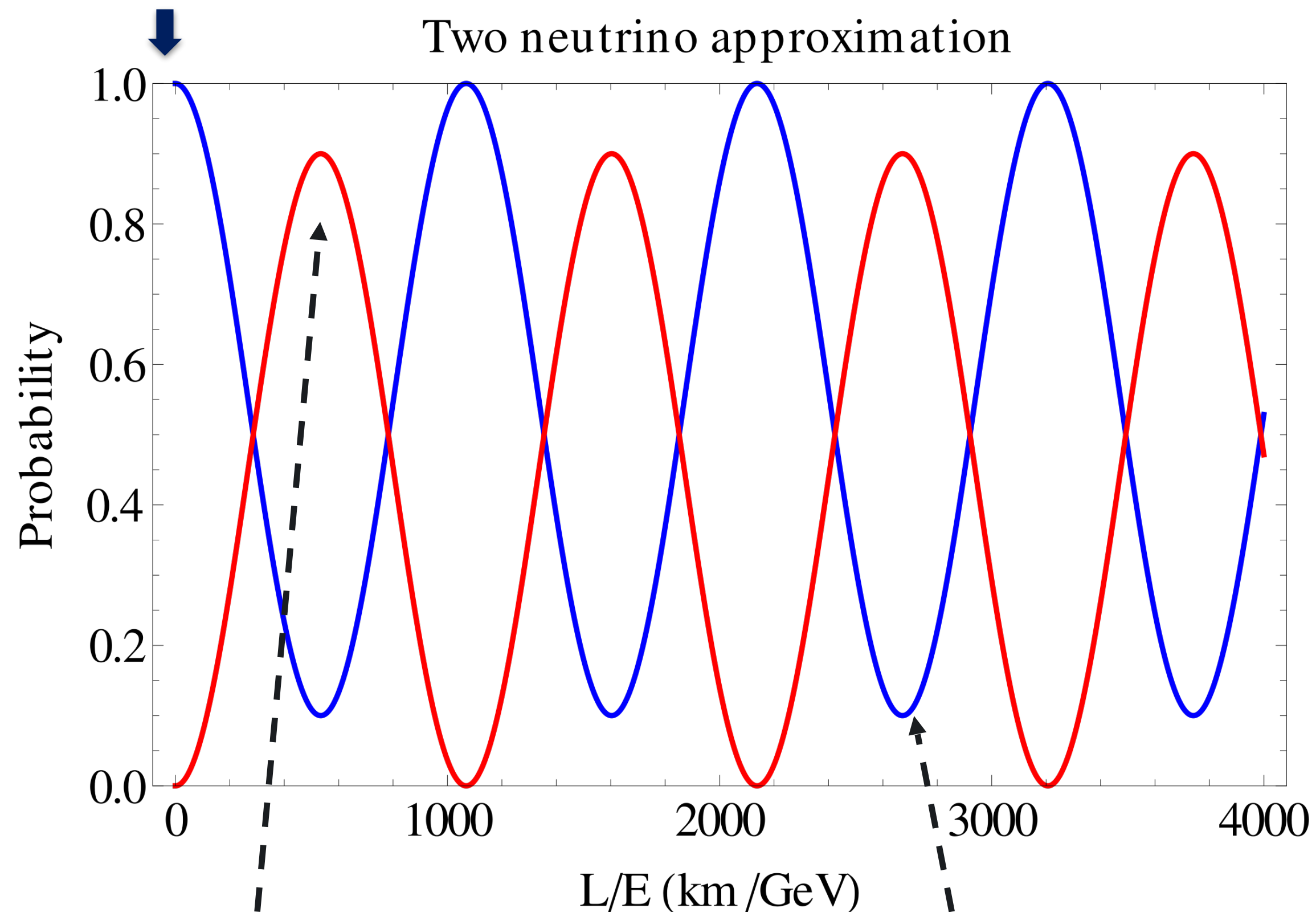
$$\nu_i(t \approx L) = e^{-i\frac{m_i^2 L}{2E}} \nu_i(0)$$

Neutrinos beyond the Standard Model

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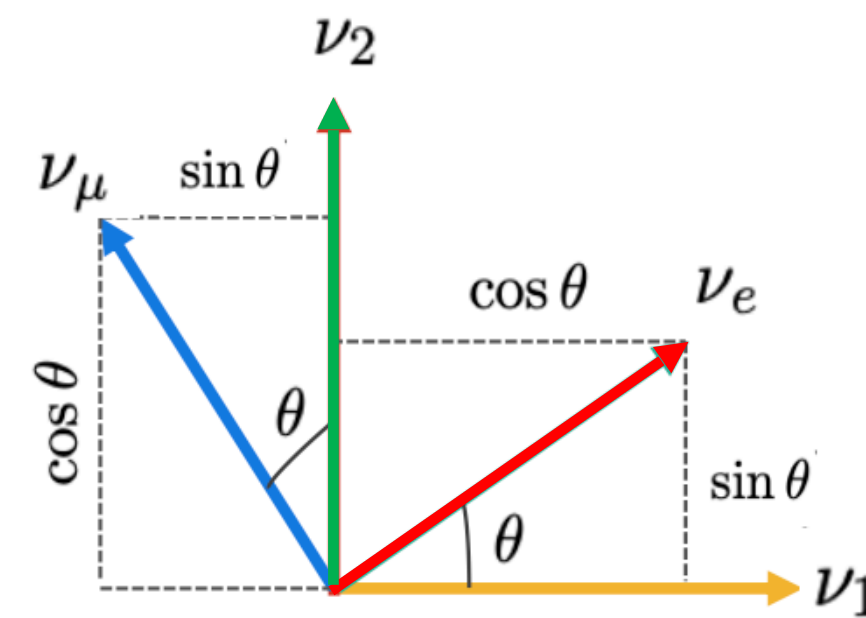
ν_μ @ Neutrino Source

Two neutrino approximation



ν_e appearance

ν_μ disappearance



Neutrino mixing

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Propagation of each mass eigenstate

$$\nu_i(t \approx L) = e^{-i\frac{m_i^2 L}{2E}} \nu_i(0)$$

Appearance probability:

$$P_{\alpha \rightarrow \beta} = \sin^2(2\theta) \cdot \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

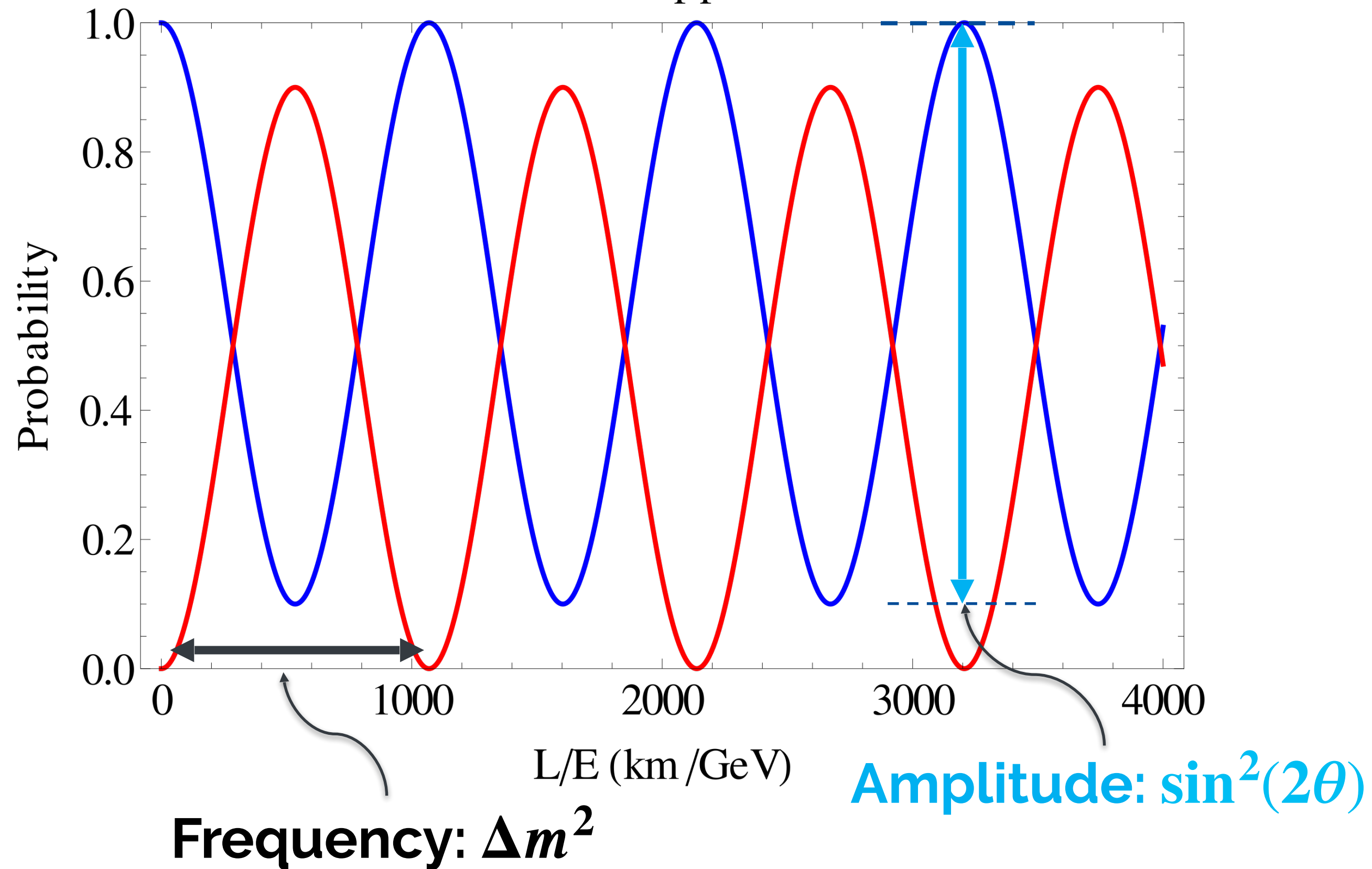
Disappearance probability:

$$P_{\alpha \rightarrow \alpha} = 1 - \sin^2(2\theta) \cdot \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrinos beyond the Standard Model

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Two neutrino approximation

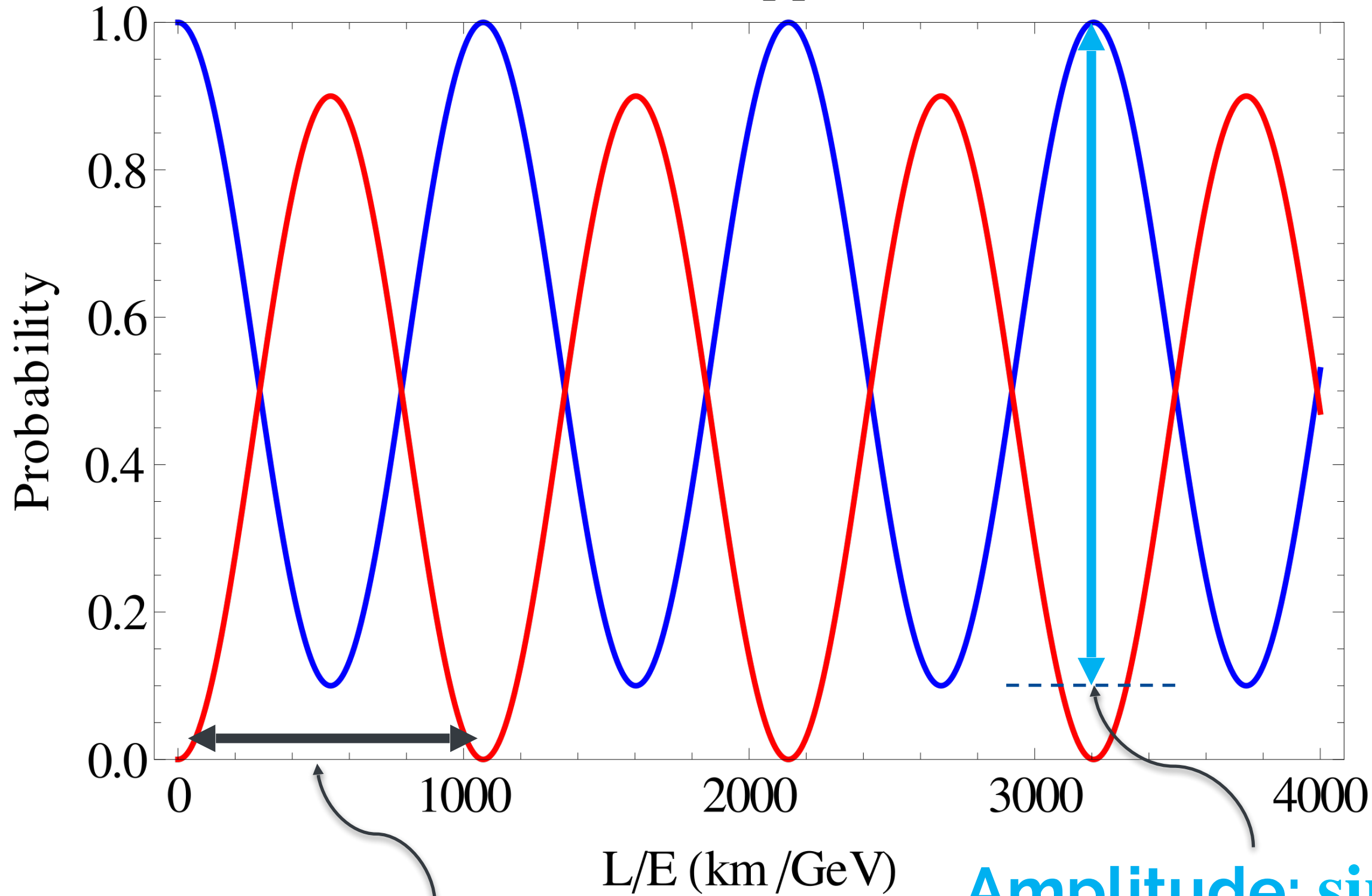


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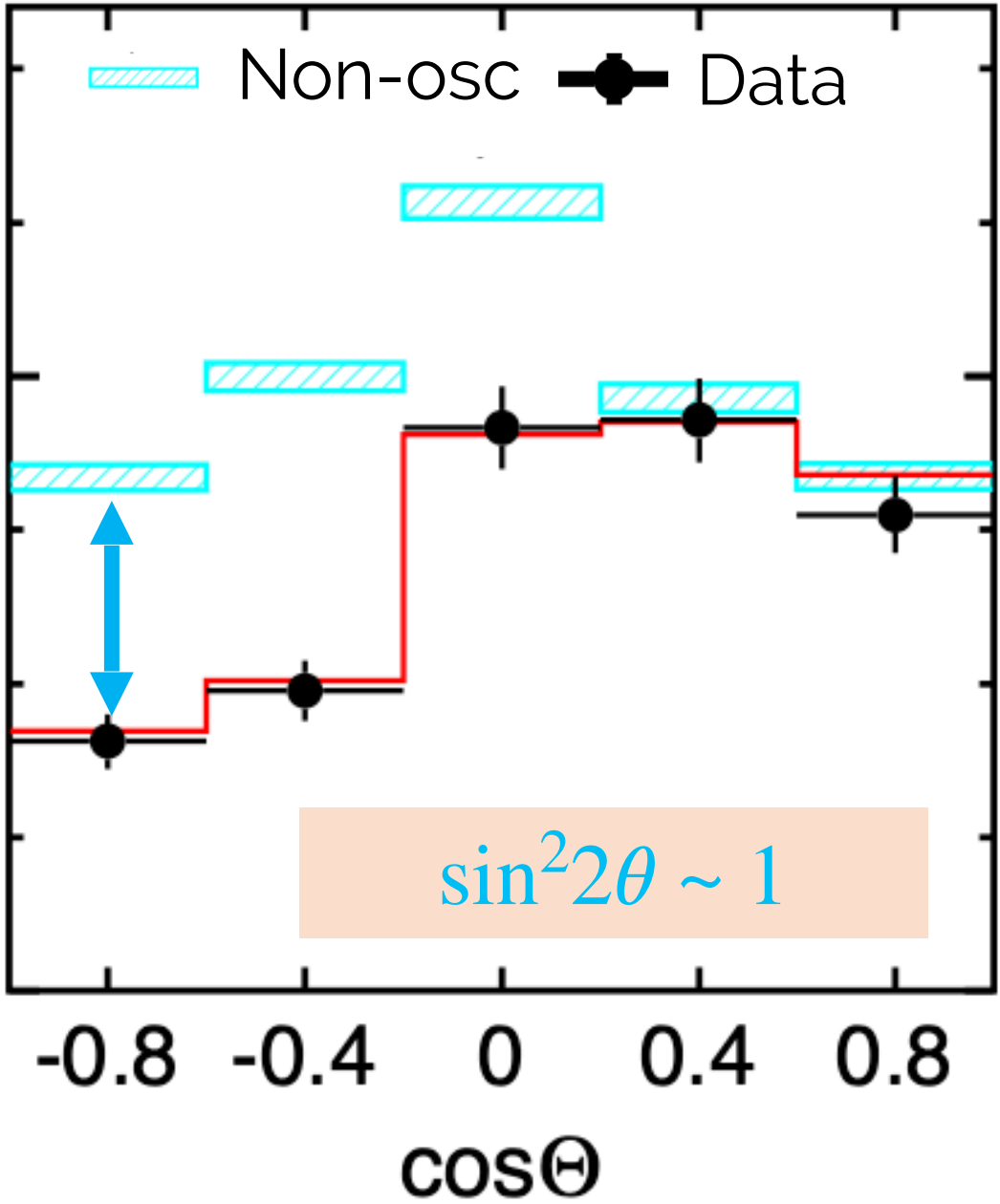
Two neutrino approximation



Frequency: Δm^2

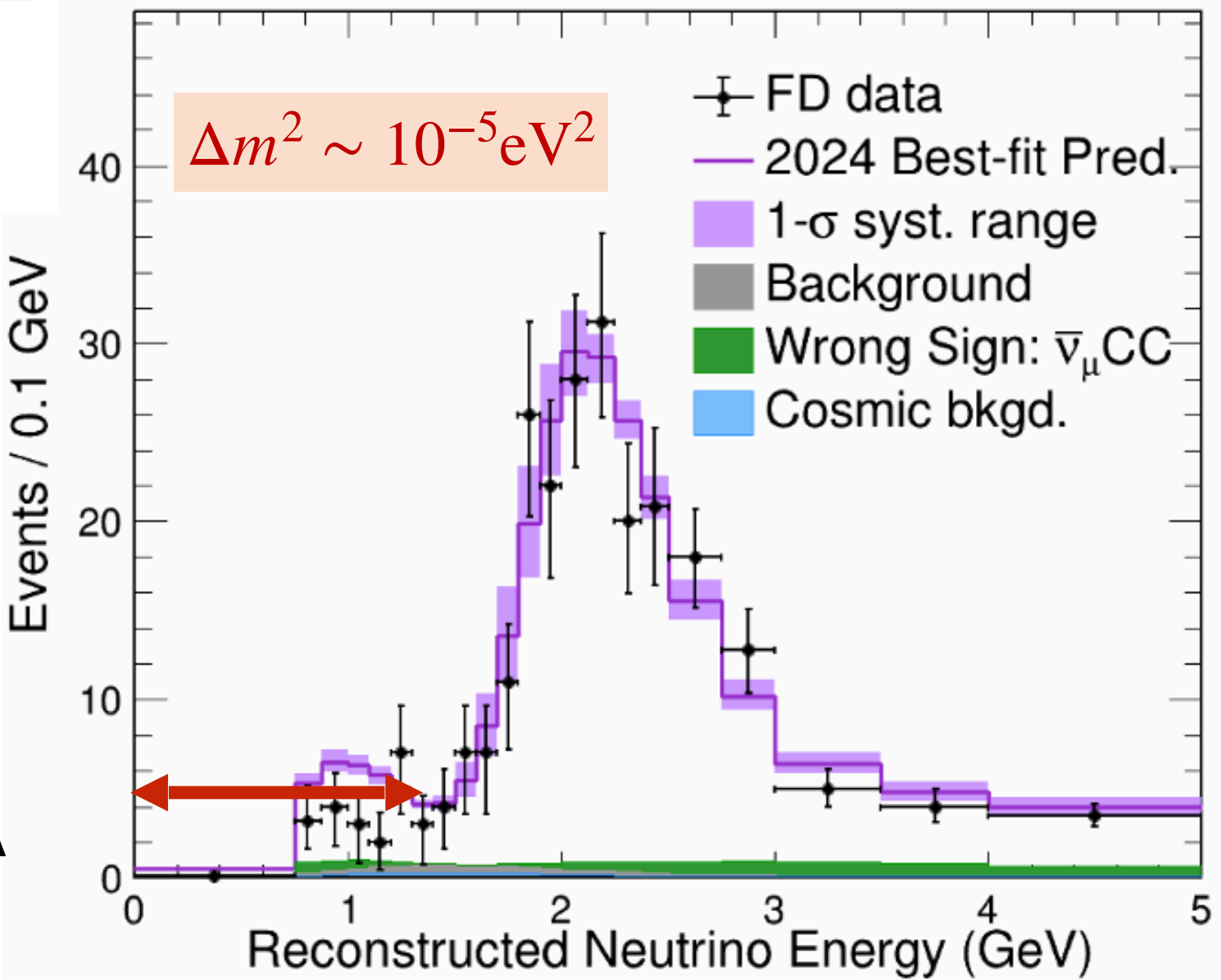
Amplitude: $\sin^2(2\theta)$

$$P_{\alpha \rightarrow \beta} = \sin^2(2\theta) \cdot \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Super-Kamiokande

NOvA



Three-flavor neutrino oscillations

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \boxed{\begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} ? \\ ? \\ ? \end{pmatrix}$$

Two-flavor mixing Atmospheric, Accelerator
 $\theta_{23} \sim 48^\circ$
 $|\Delta m_{32}^2| \simeq 2.5 \times 10^{-3} \text{eV}^2$

Combination of three pairs of two-flavor mixings

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 3 \times 3 \\ U_{\text{PMNS}} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

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Atmospheric,
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 $\theta_{23} \sim 48^\circ$

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Reactor
 $\theta_{13} \sim 9^\circ$

$$|\Delta m_{31(2)}^2| \simeq 2.5 \times 10^{-3} \text{eV}^2$$

Solar, KamLAND, JUNO
 $\theta_{12} \sim 34^\circ$

$$\Delta m_{21}^2 \simeq 7 \times 10^{-5} \text{eV}^2$$

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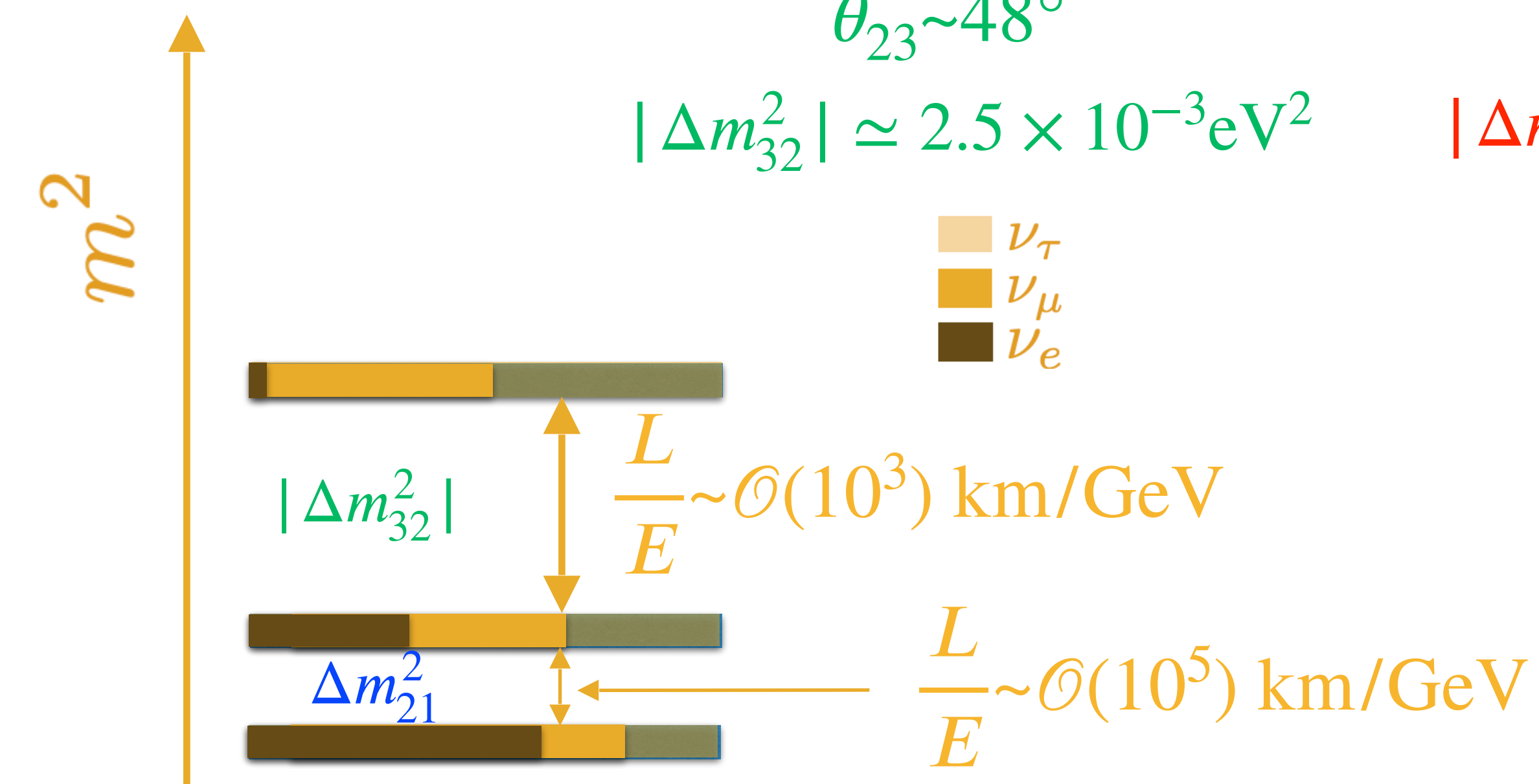
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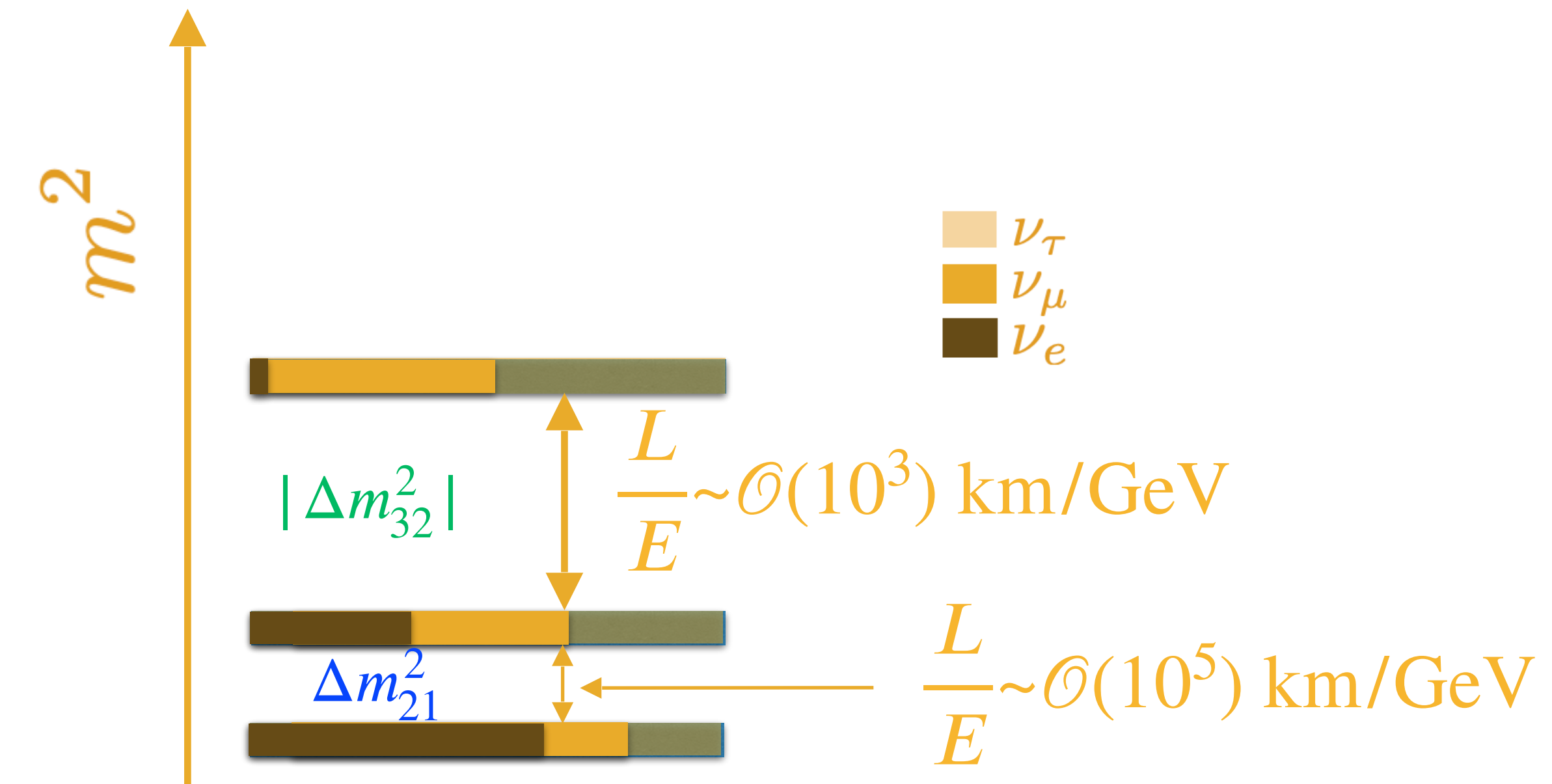
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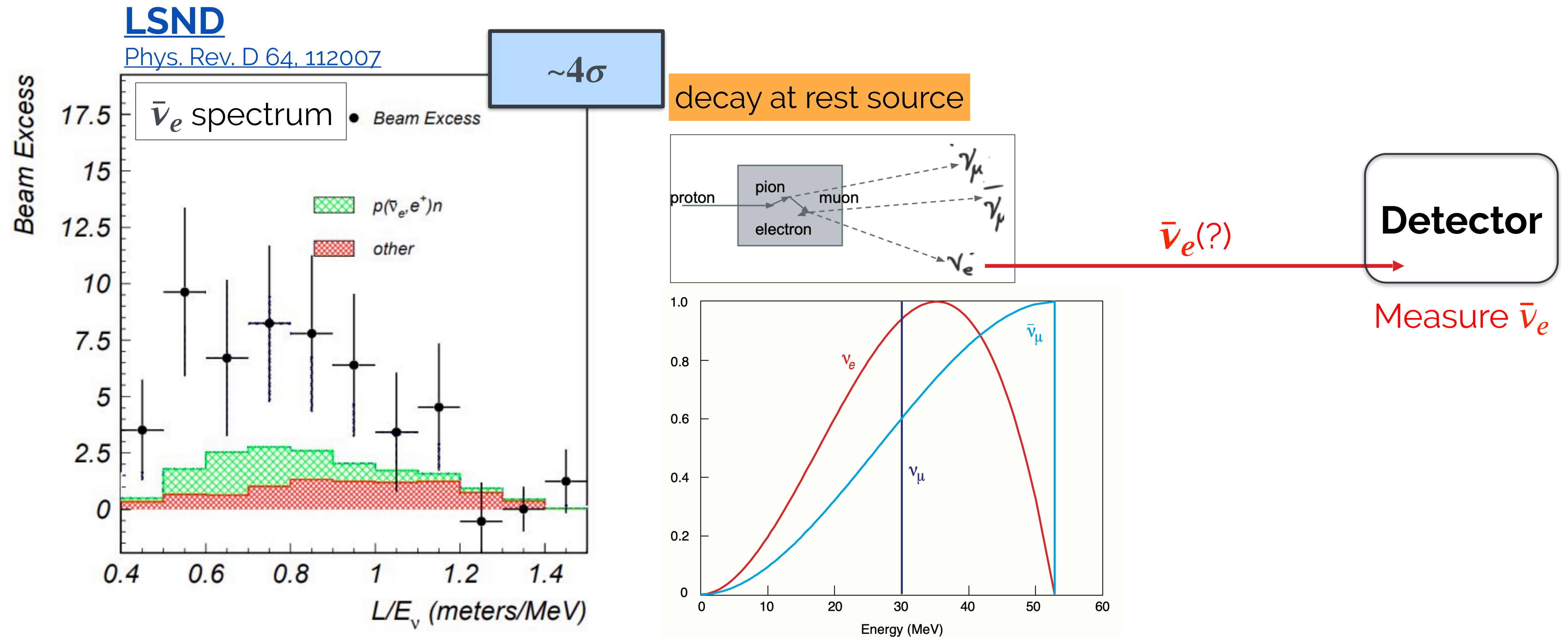
Experimental Anomalies

Majority of the experimental results align with the “standard” three-active-flavor scenario, but several “anomalies” do exist at much smaller L/E than expected.

?

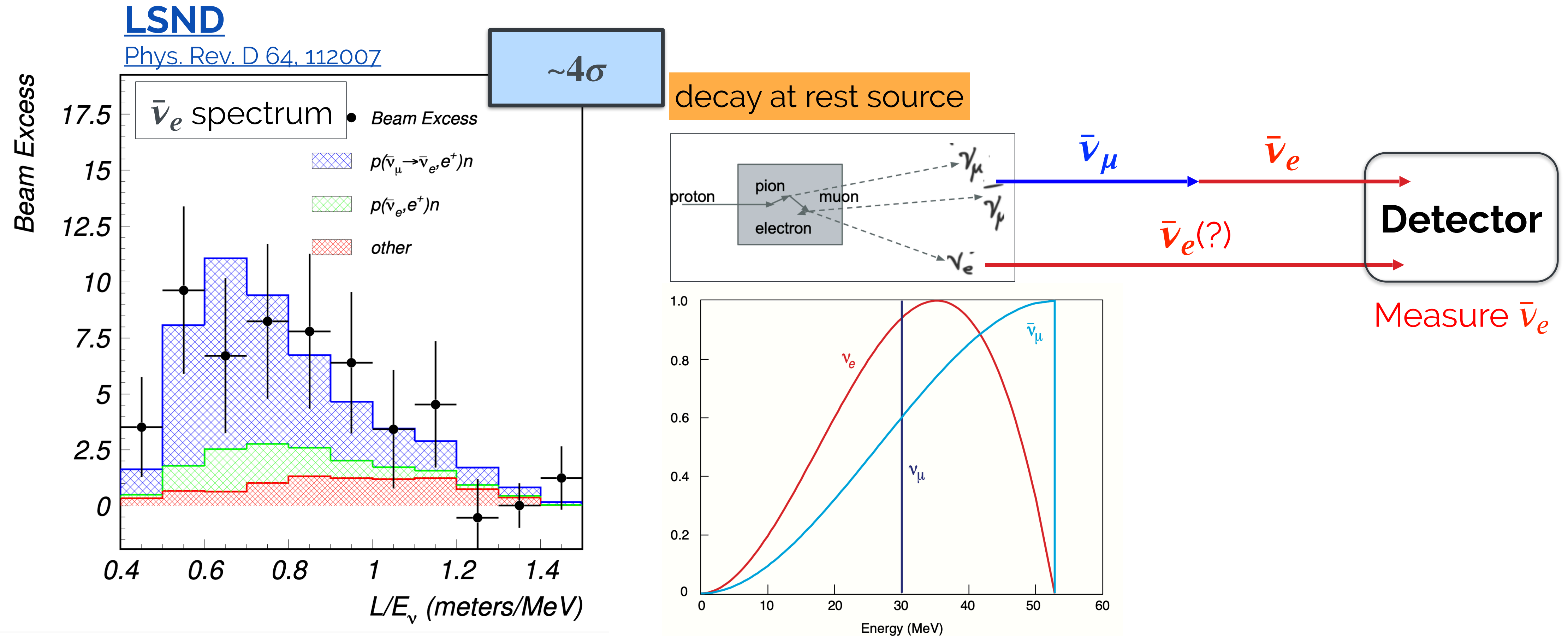


LSND and MiniBooNE ν_e appearance anomalies



- LSND observed a significant excess of 20-50 MeV $\bar{\nu}_e$ from a $\nu_e/\bar{\nu}_\mu$ -dominated μ^+ DAR source

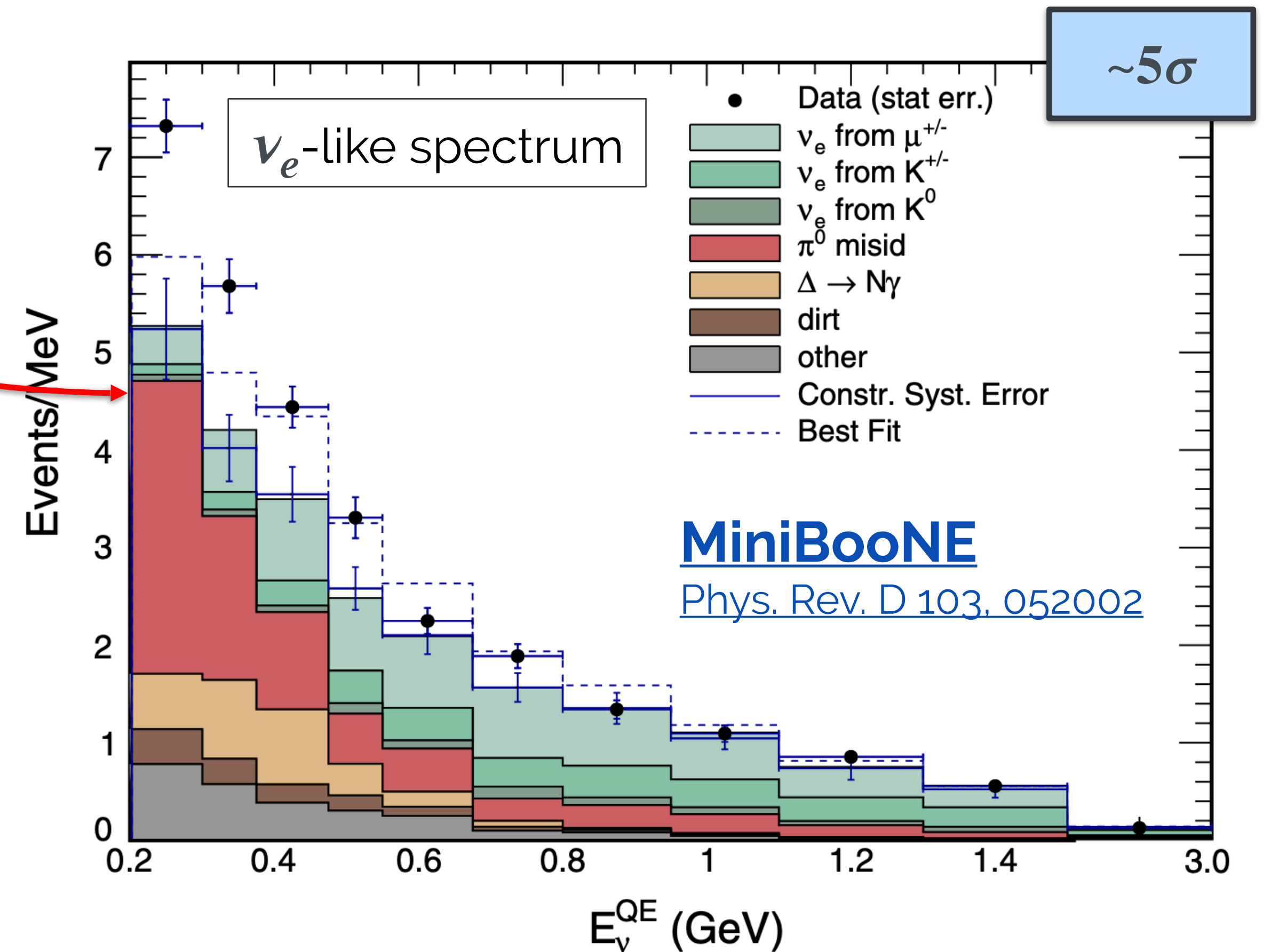
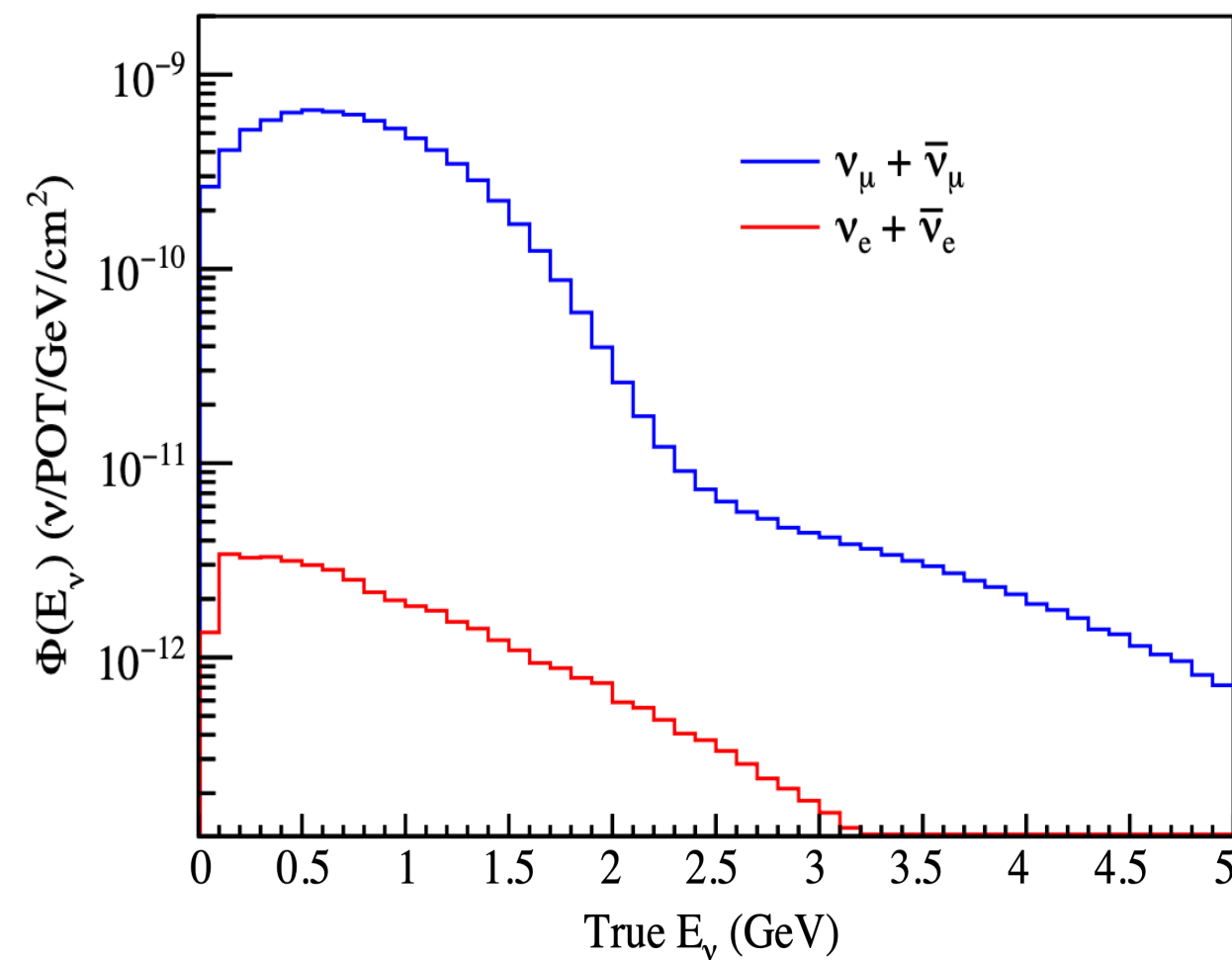
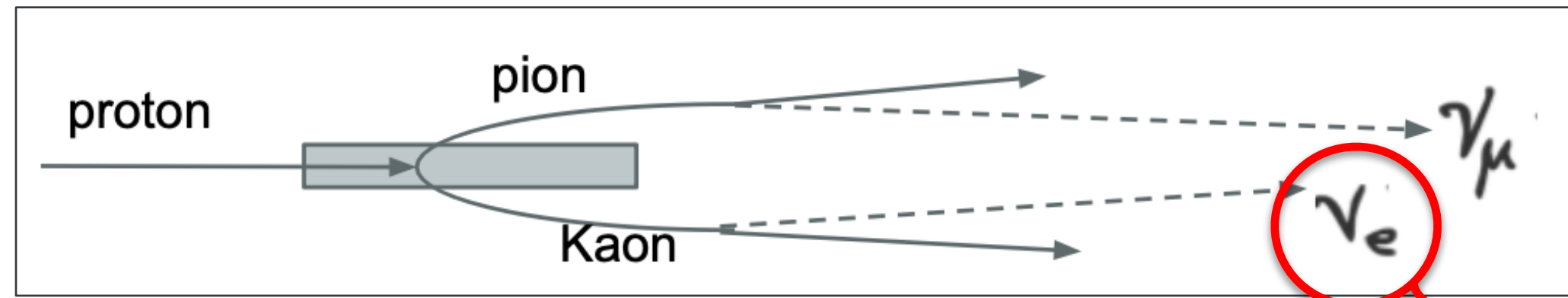
LSND and MiniBooNE ν_e appearance anomalies



- LSND observed a significant excess of 20-60 MeV $\bar{\nu}_e$ from a $\nu_e/\bar{\nu}_\mu$ -dominated μ^+ DAR source
- The excess can be interpreted as a $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillation
- The excess covers L/E from 0.4-1.4 m/MeV

LSND and MiniBooNE ν_e appearance anomalies

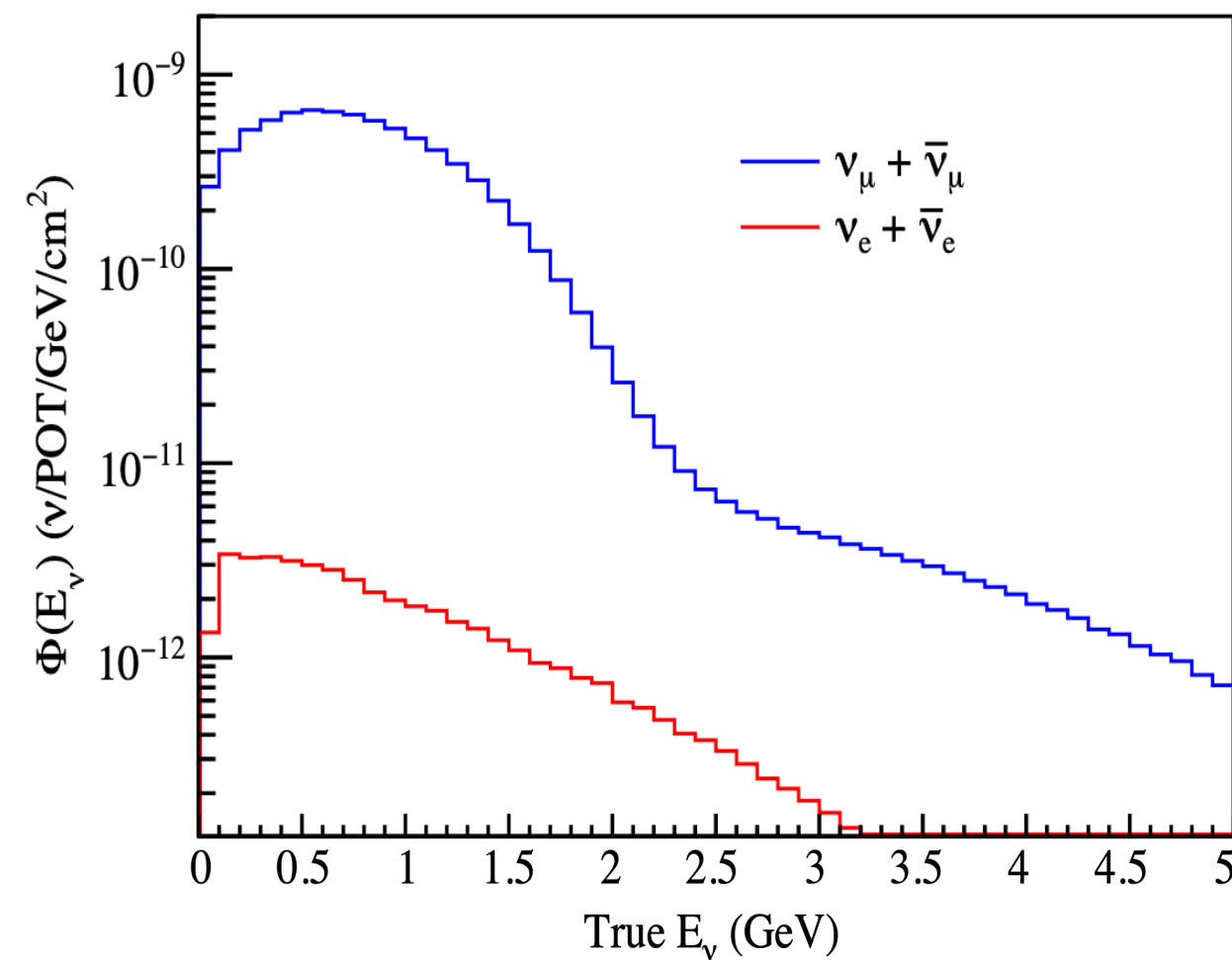
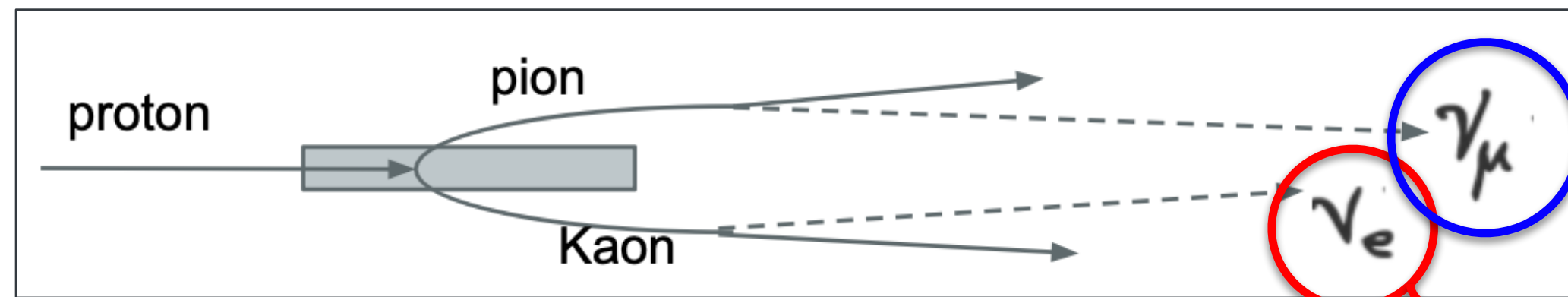
decay in flight source



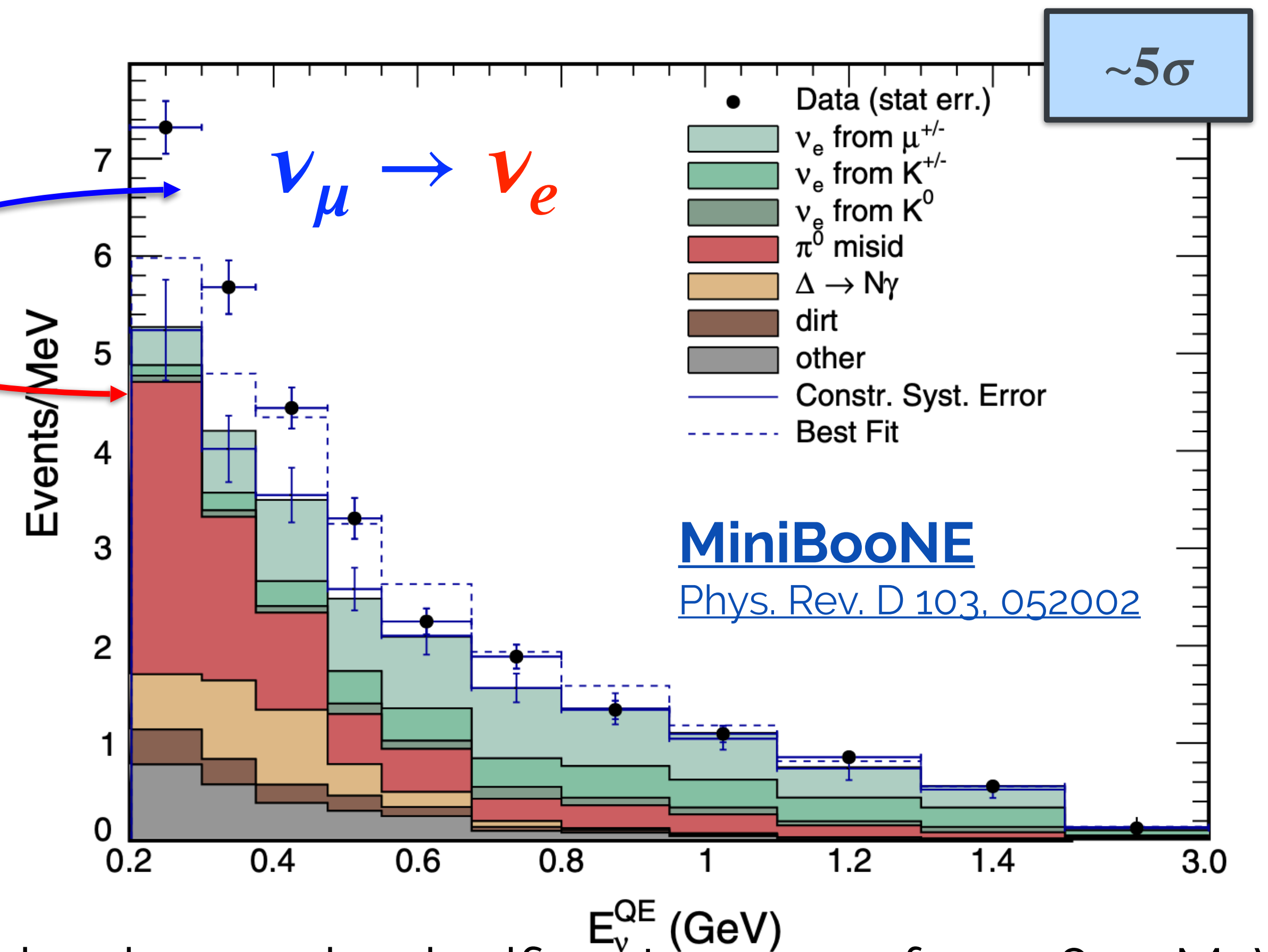
- MiniBooNE, motivated by the LSND anomaly, observed a significant excess of 200-600 MeV neutrinos from a typical accelerator neutrino beam
- The excess covers L/E from 0.2-2 m/MeV (or km/GeV), similar to the LSND anomaly

LSND and MiniBooNE ν_e appearance anomalies

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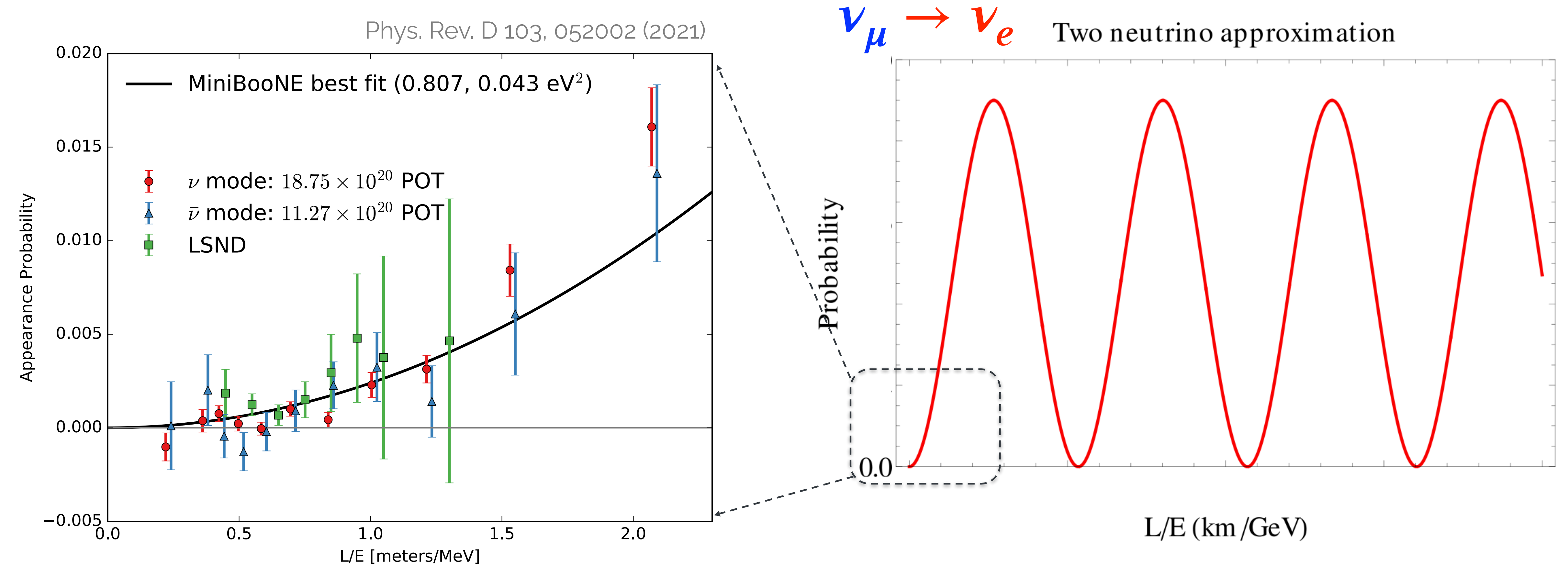


Excess : a fraction of ν_μ oscillating to ν_e



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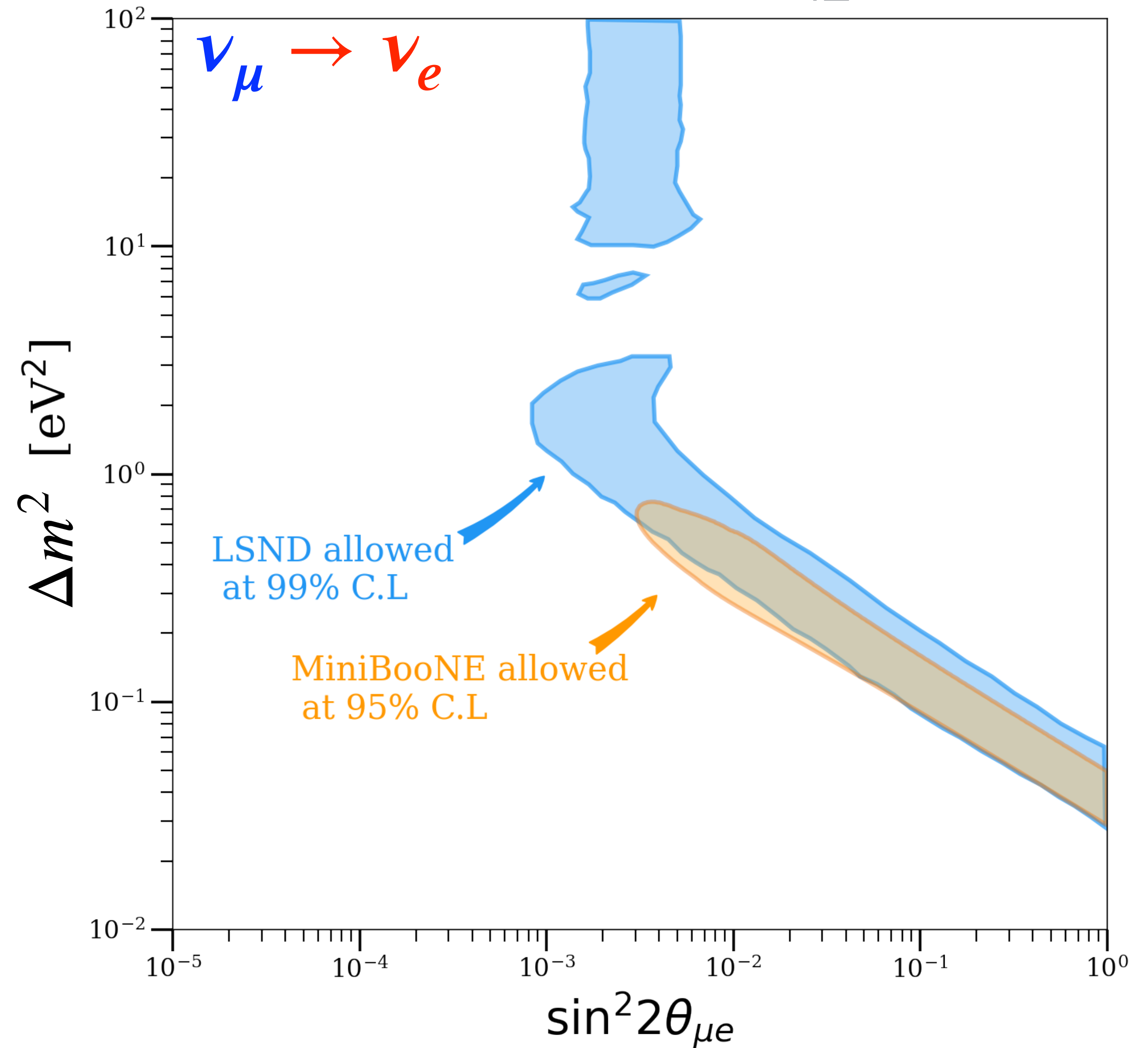
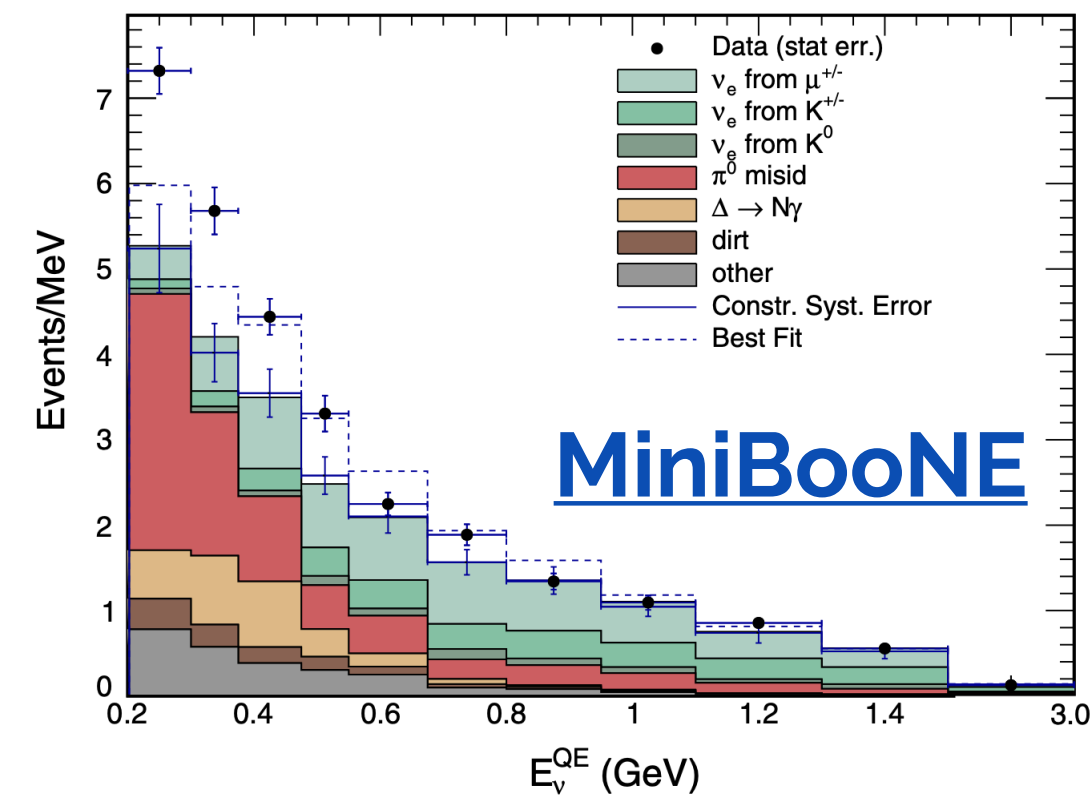
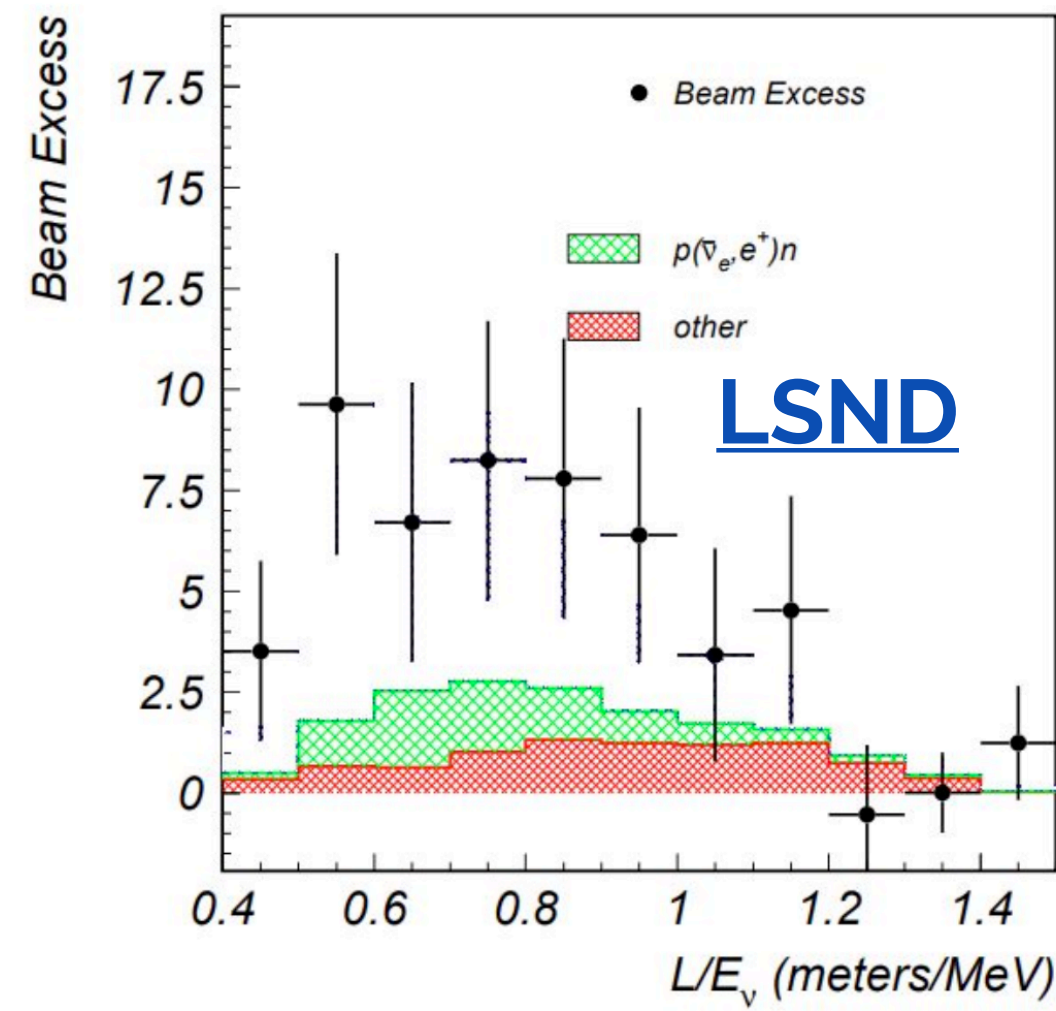
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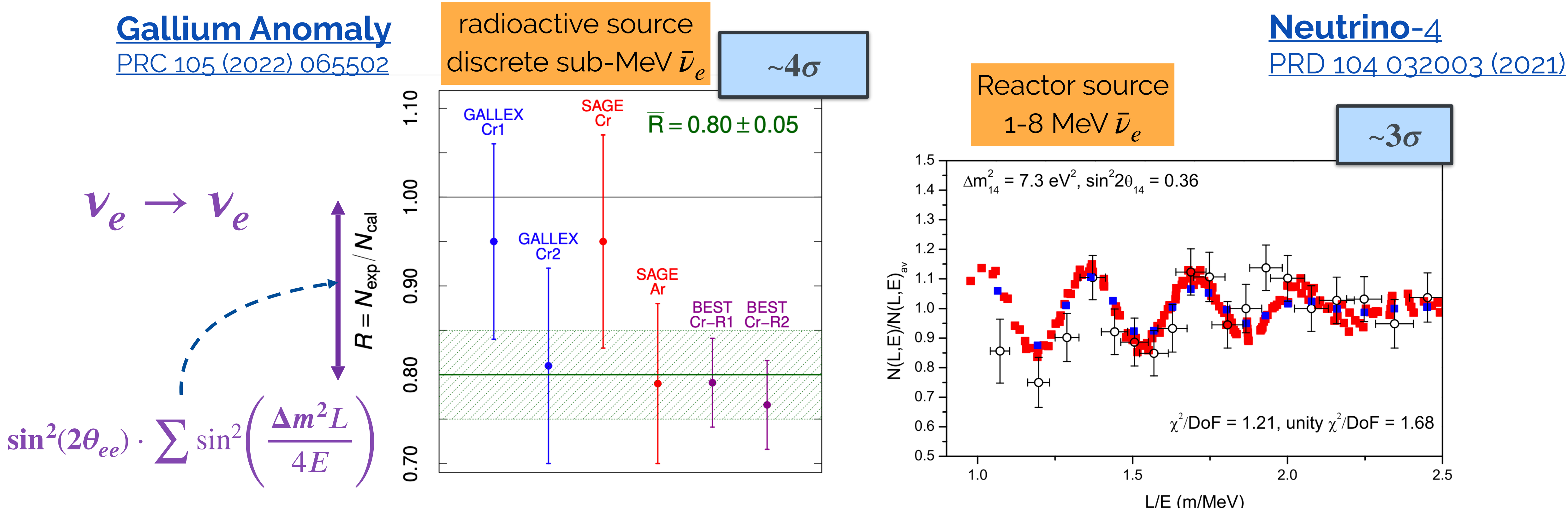
$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2(2\theta_{\mu e}) \cdot \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

ν_e Appearance Allowed Regions

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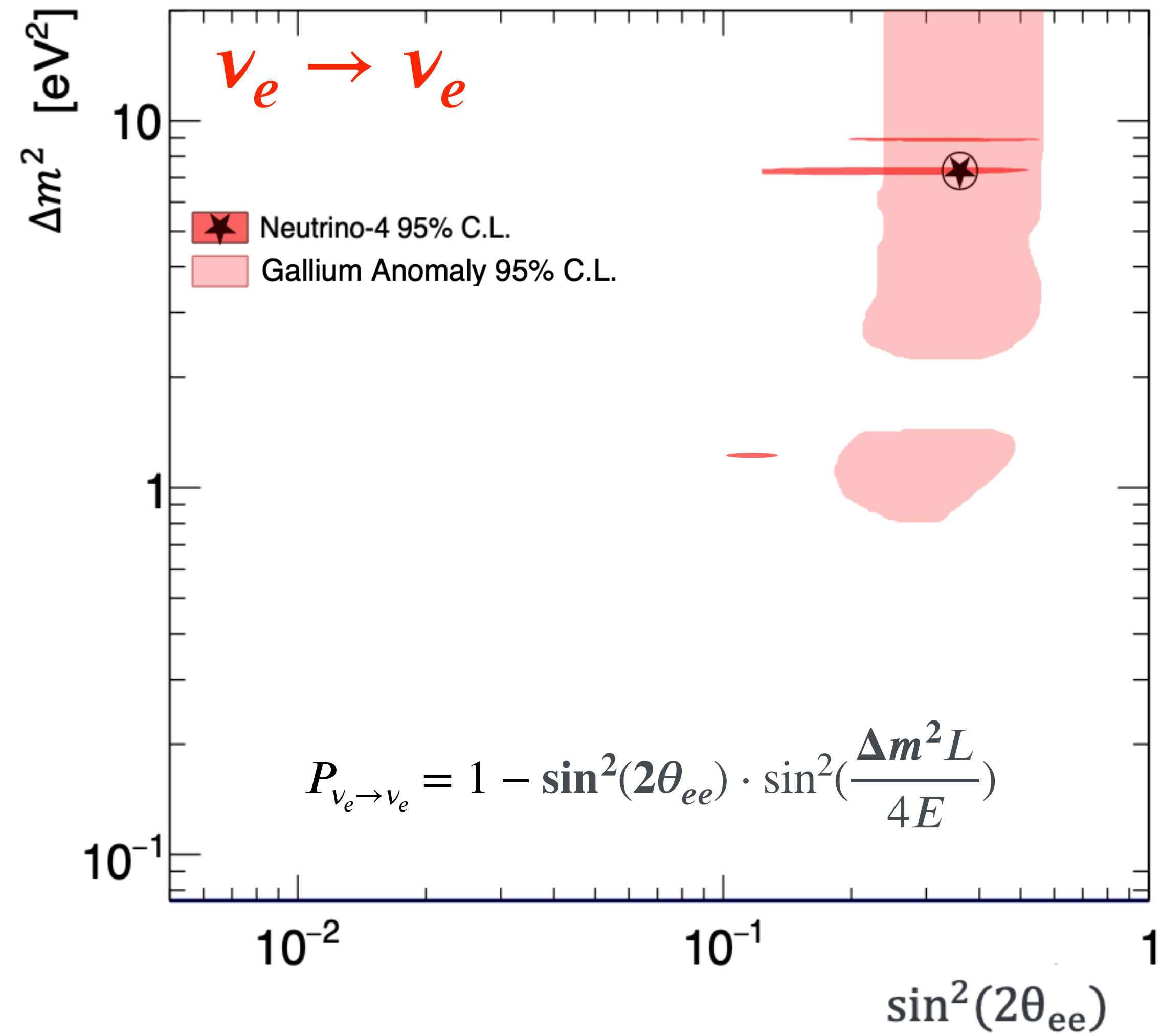


Gallium and Reactor ν_e disappearance anomalies

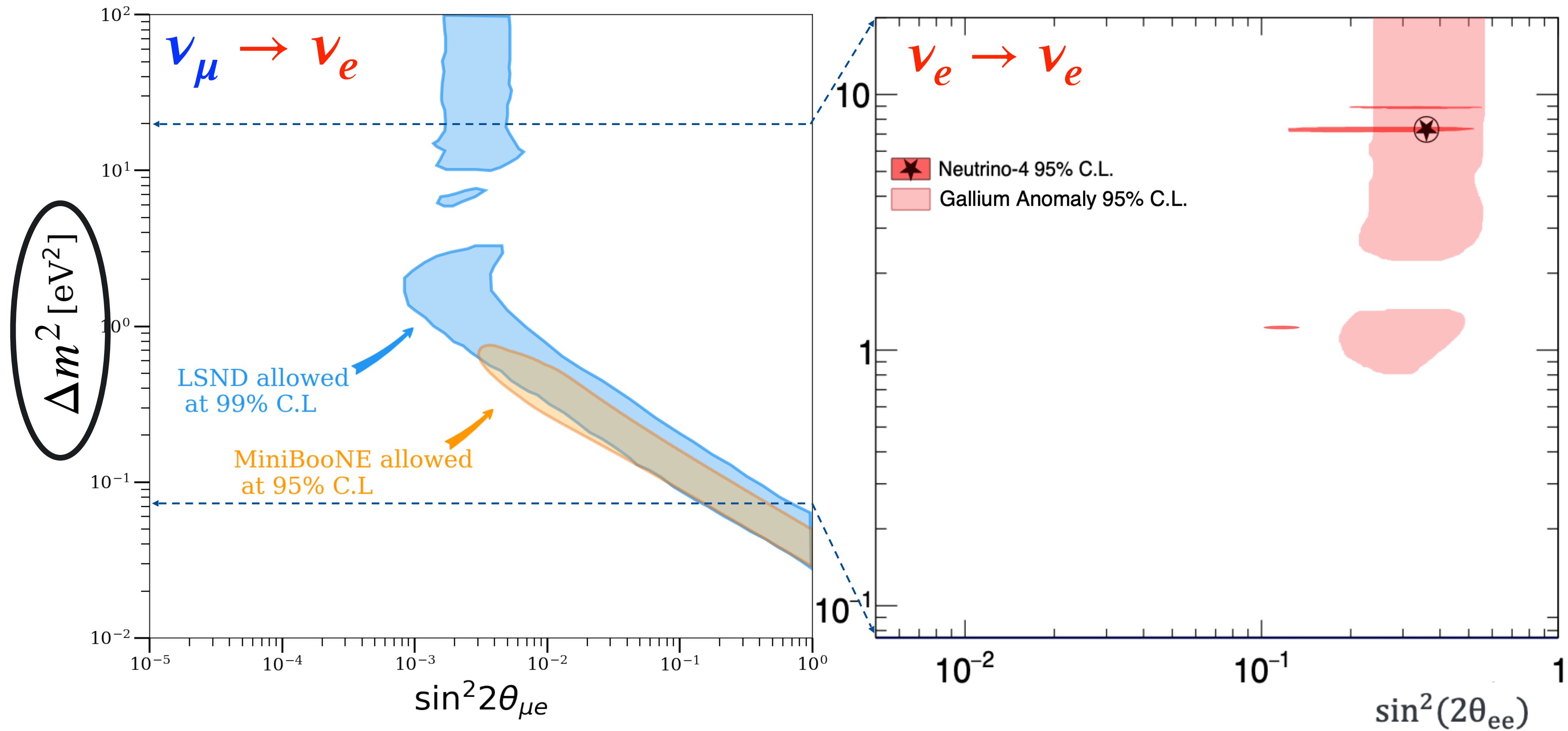


- Radiochemical gallium detectors observed a deficit in the integrated event rate
- The deficit can be interpreted as a disappearance oscillation effect, with discrete L/E values ranging from 0.5-2.5 m/MeV
- The Neutrino-4 experiment also observed a possible oscillation pattern in a similar L/E range

Experimental Anomalies Allowed Regions



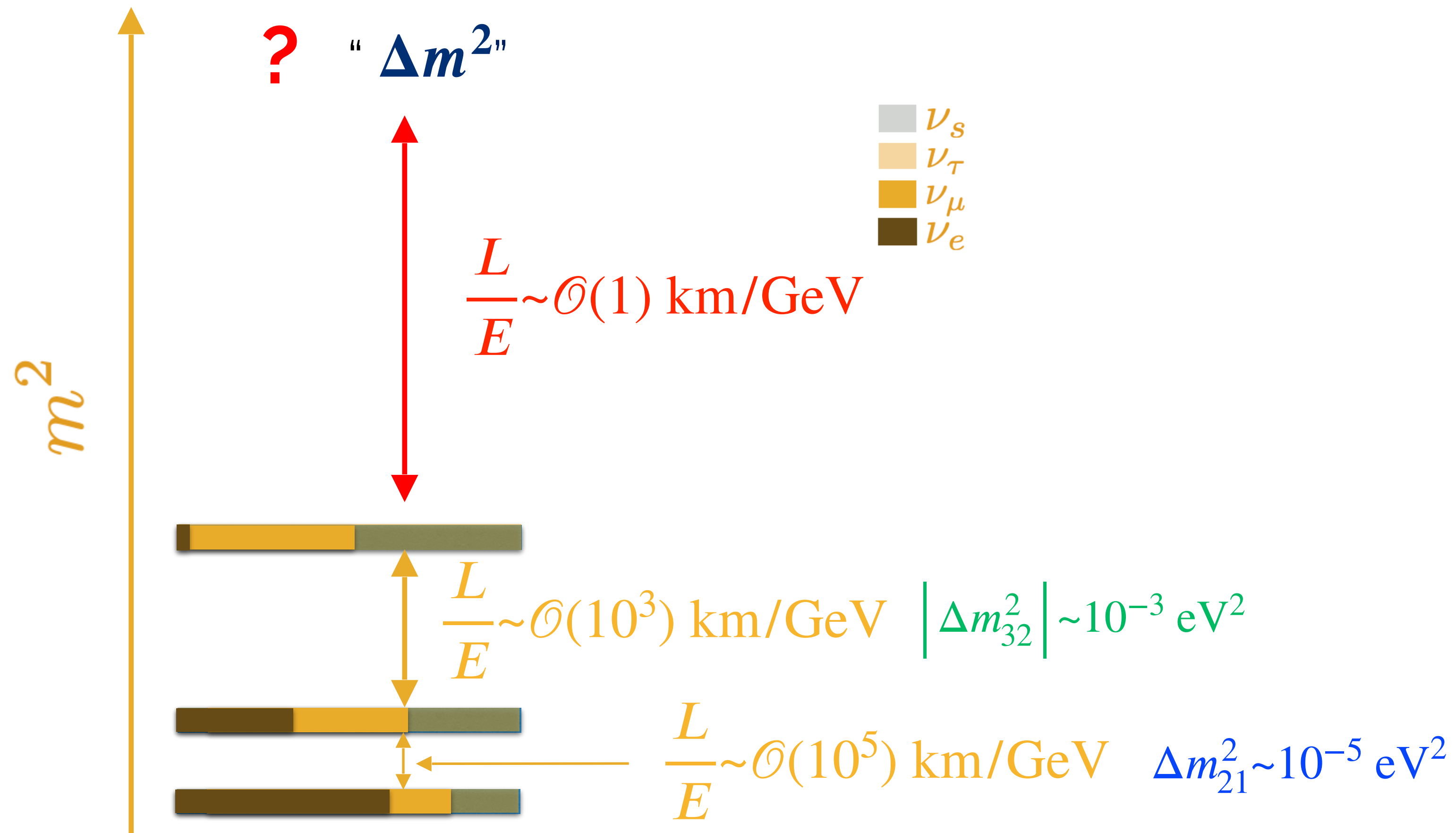
Experimental Anomalies Allowed Regions



- The appearance and disappearance anomalies point to a similar Δm^2 scale, and the oscillation hypothesis provides a plausible explanation for all of them.

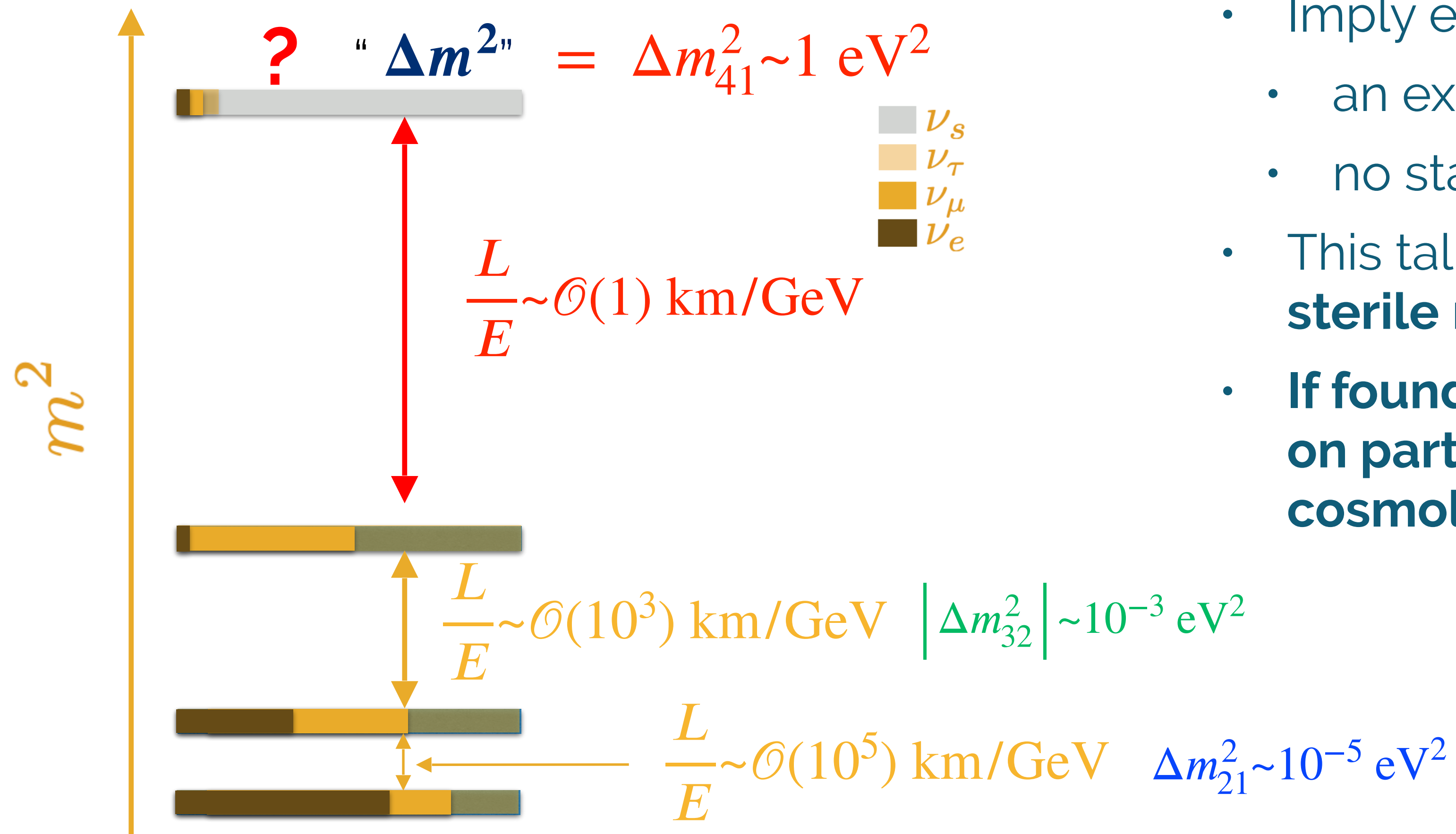
Experimental Anomalies

- Majority of the experimental results align with the “standard” three-active-flavor scenario, but **several “anomalies” do exist at a much smaller L/E** → an oscillation at high Δm^2 , inconsistent with the two known mass splittings



Experimental Anomalies

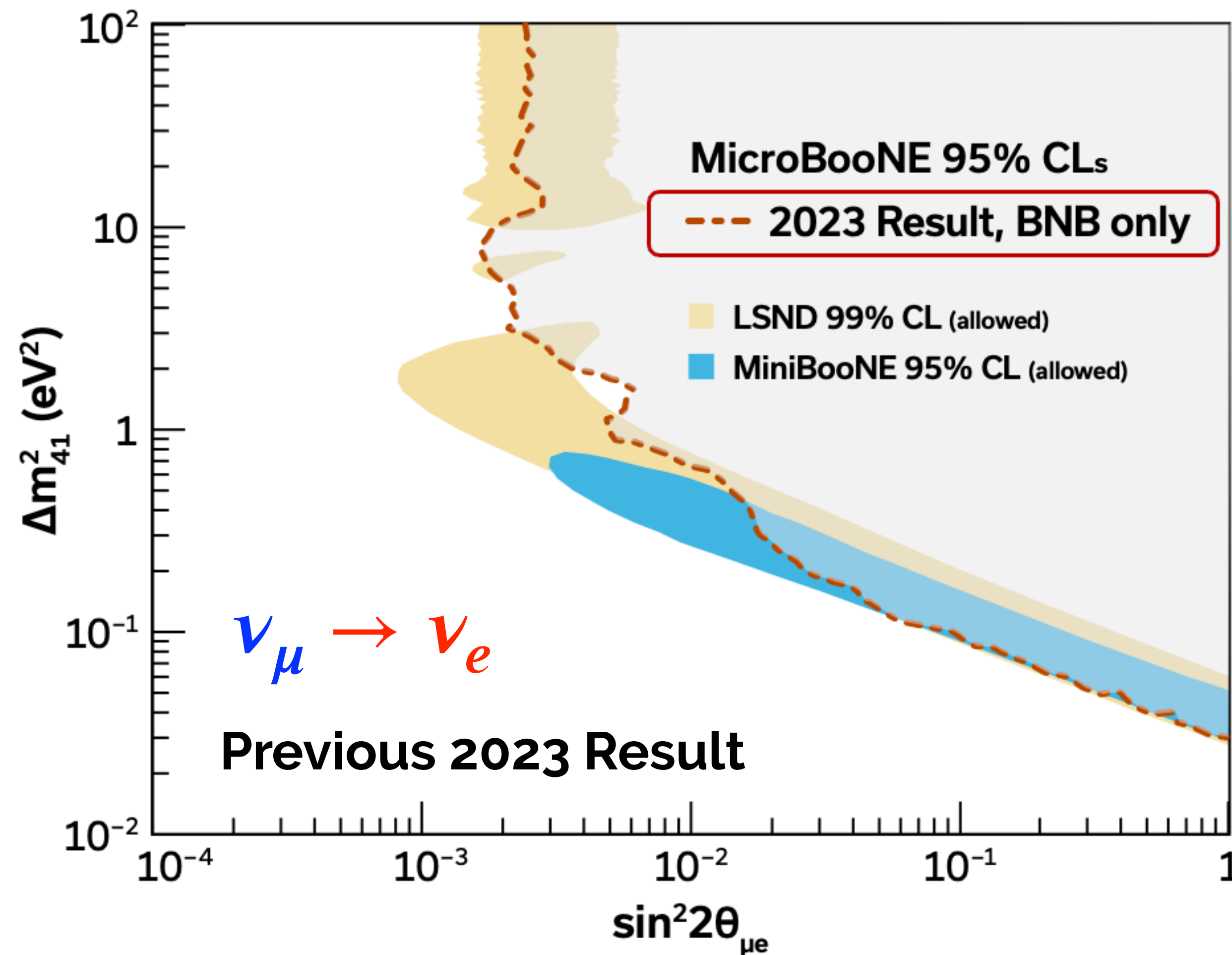
- Majority of the experimental results align with the “standard” three-active-flavor scenario, but **several “anomalies” do exist at a much smaller $L/E \rightarrow$ an oscillation at high Δm^2 , inconsistent with the two known mass splittings**



- Imply existence of a **sterile** neutrino
- an extra heavier flavor/mass eigenstate
- no standard model interactions
- This talk focuses on **eV-scale “light” sterile** neutrinos
- If found, a BSM particle; profound impact on particle /astro-particle physics and cosmology**

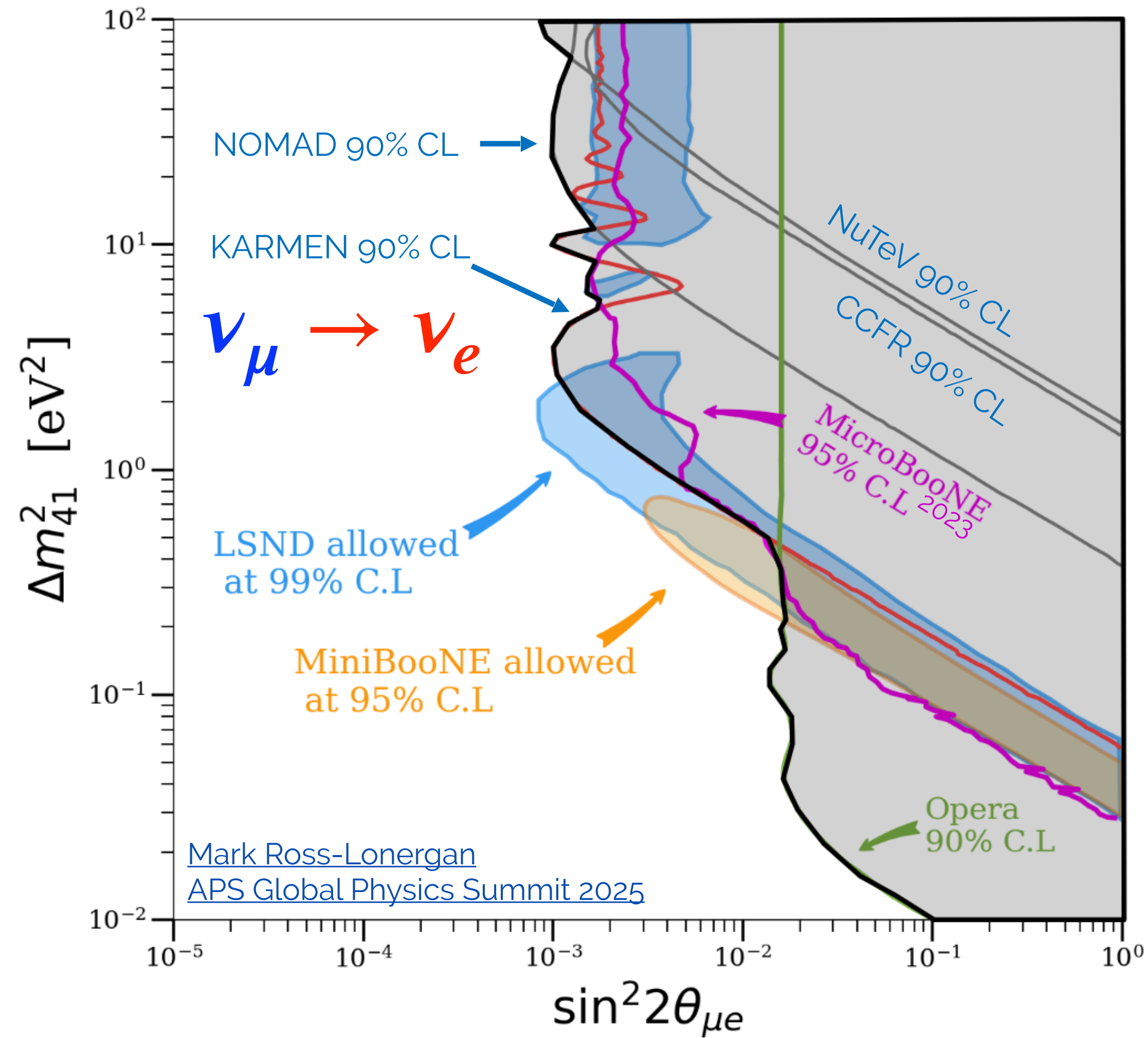
MicroBooNE 2023 Sterile Neutrino Search

- MicroBooNE has contributed to the sterile neutrino interpretation of the anomalies by searching for sterile-neutrino-induced oscillations.



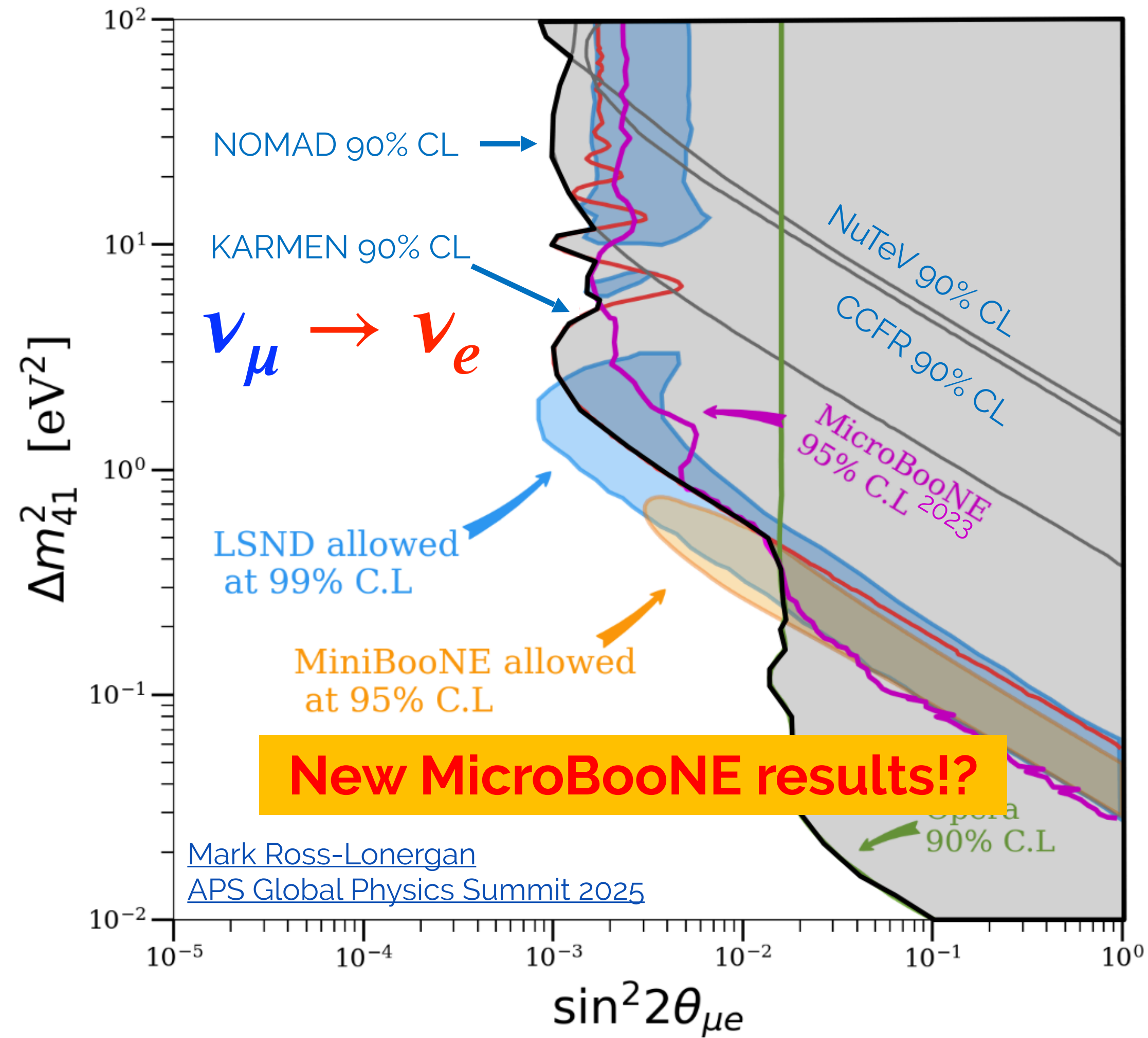
- Observed no evidence of oscillations → an exclusion curve (region), any stronger “signal” would have stood out clearly in data

Constraints on Experimental Anomalies



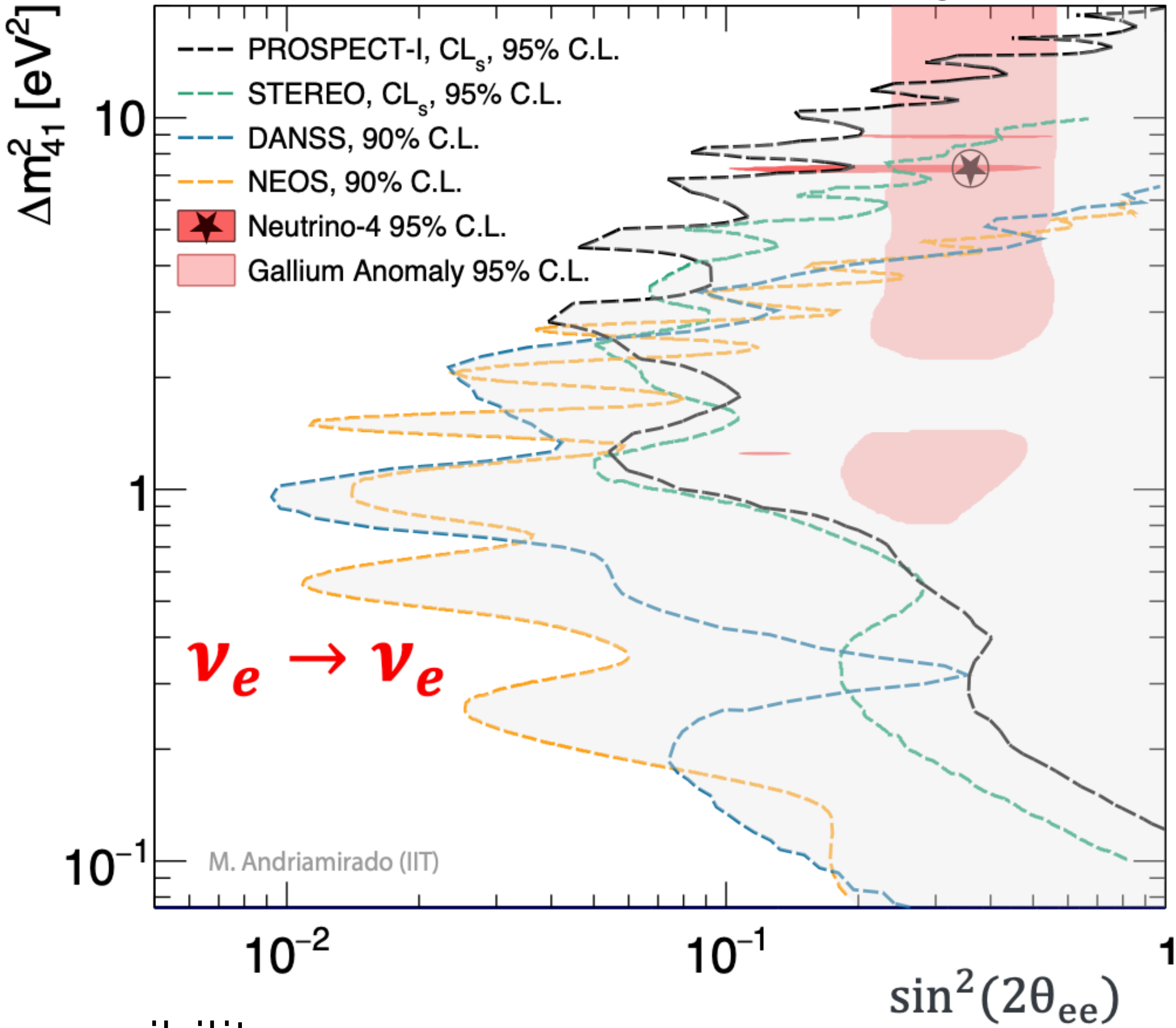
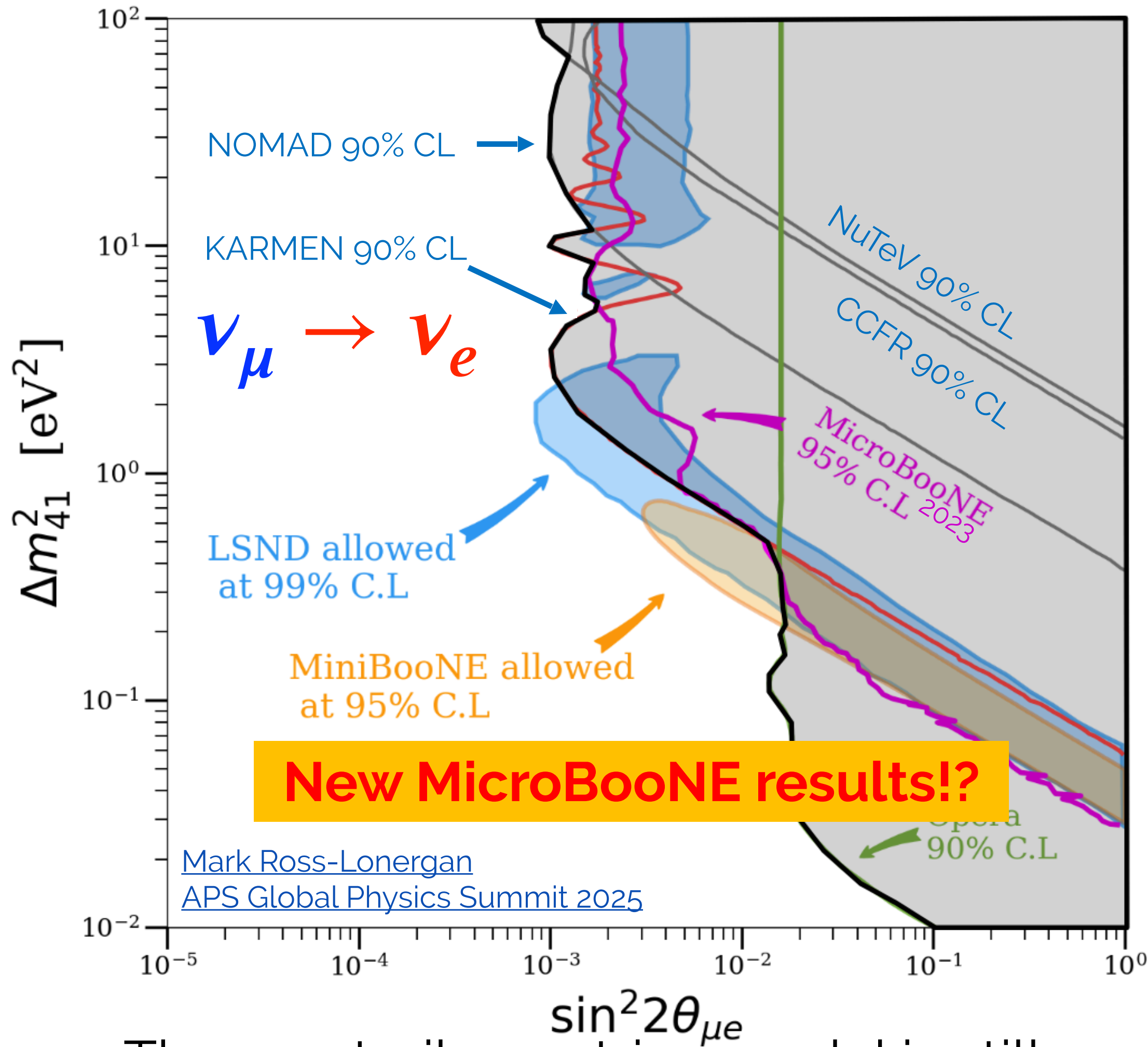
- The 3+1 sterile neutrino model is still an open possibility

Constraints on Experimental Anomalies



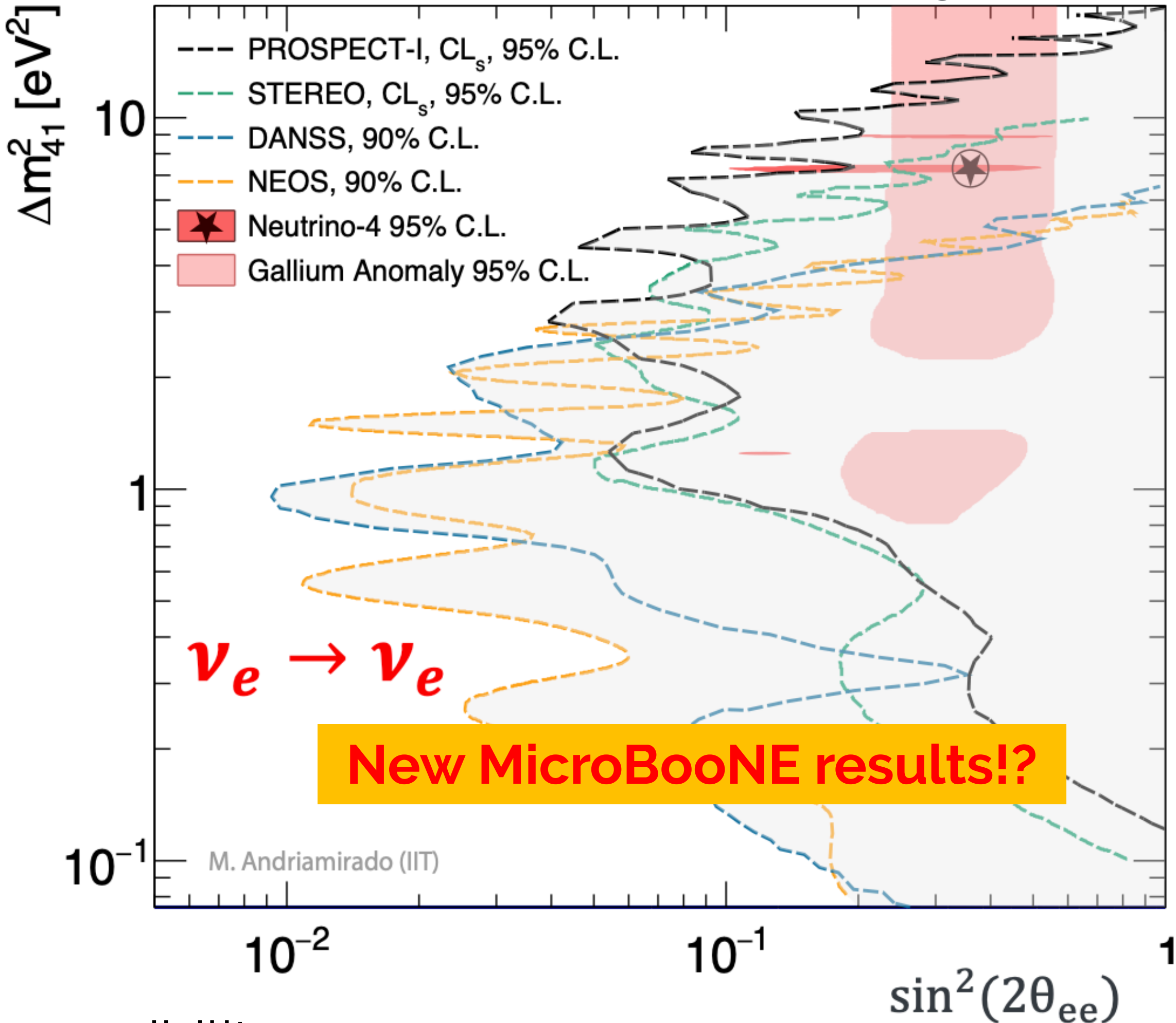
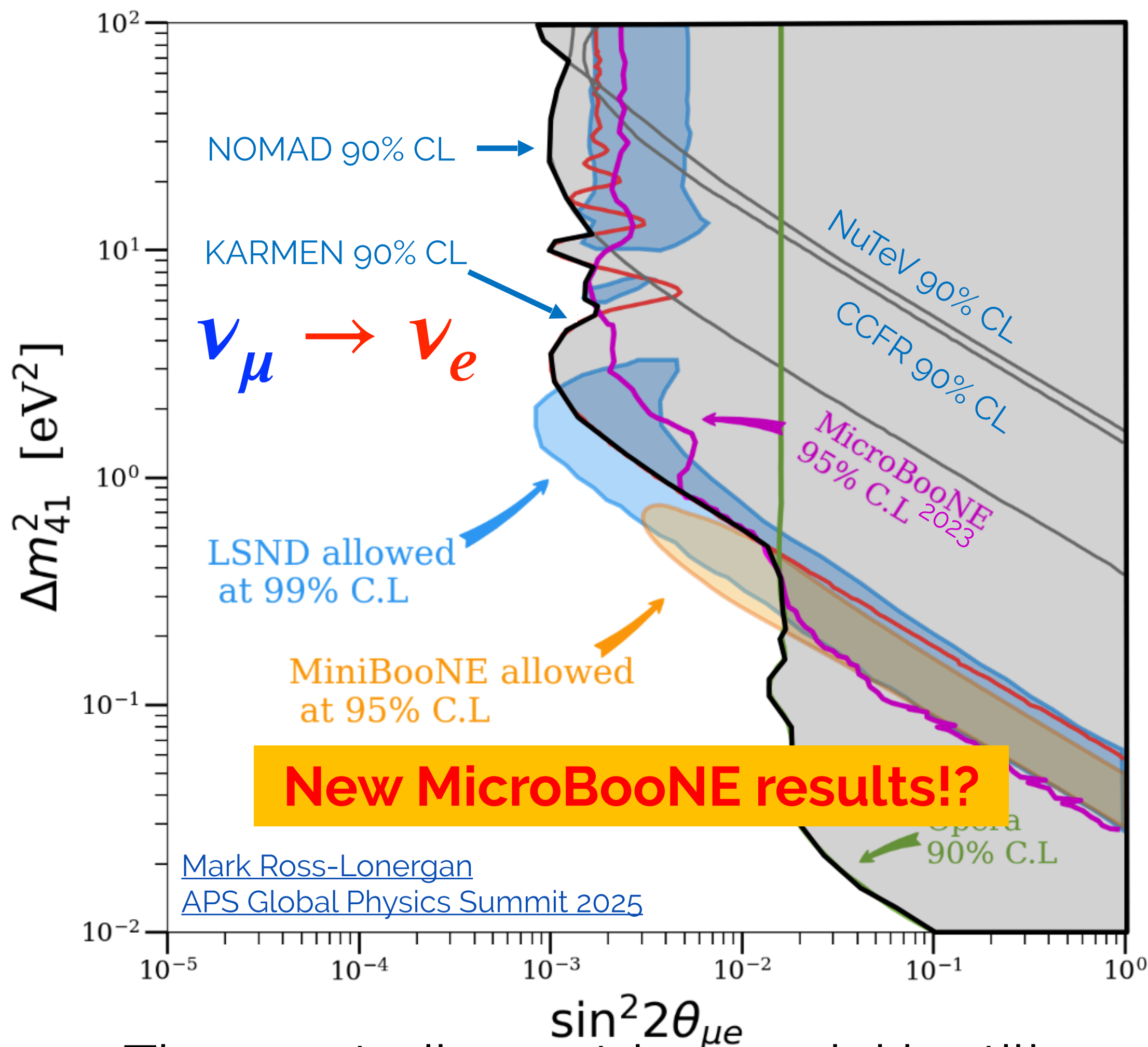
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Constraints on Experimental Anomalies



- The 3+1 sterile neutrino model is still an open possibility
- An interesting situation in the ν_e disappearance channel with most recent PROSPECT and KATRIN results

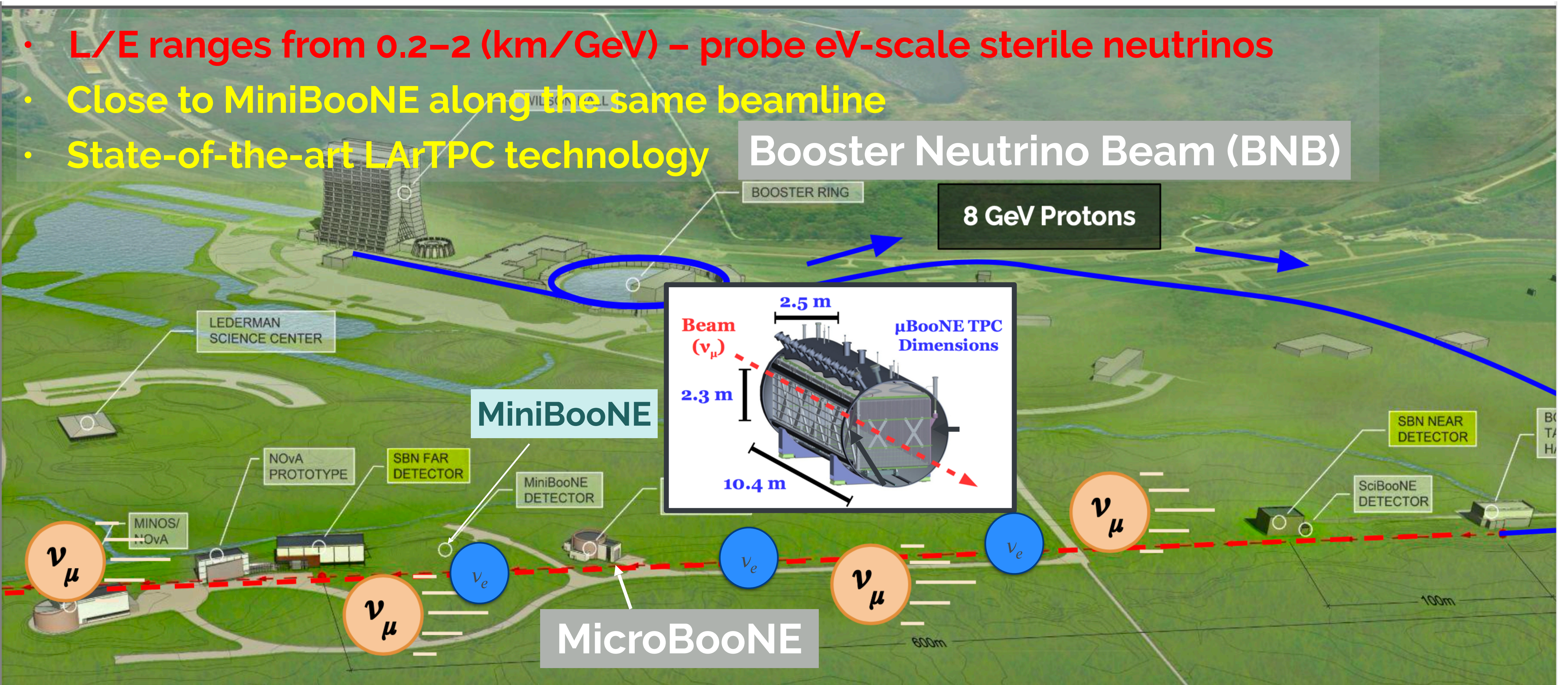
Constraints on Experimental Anomalies



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MicroBooNE at Fermilab's Booster Neutrino Beam

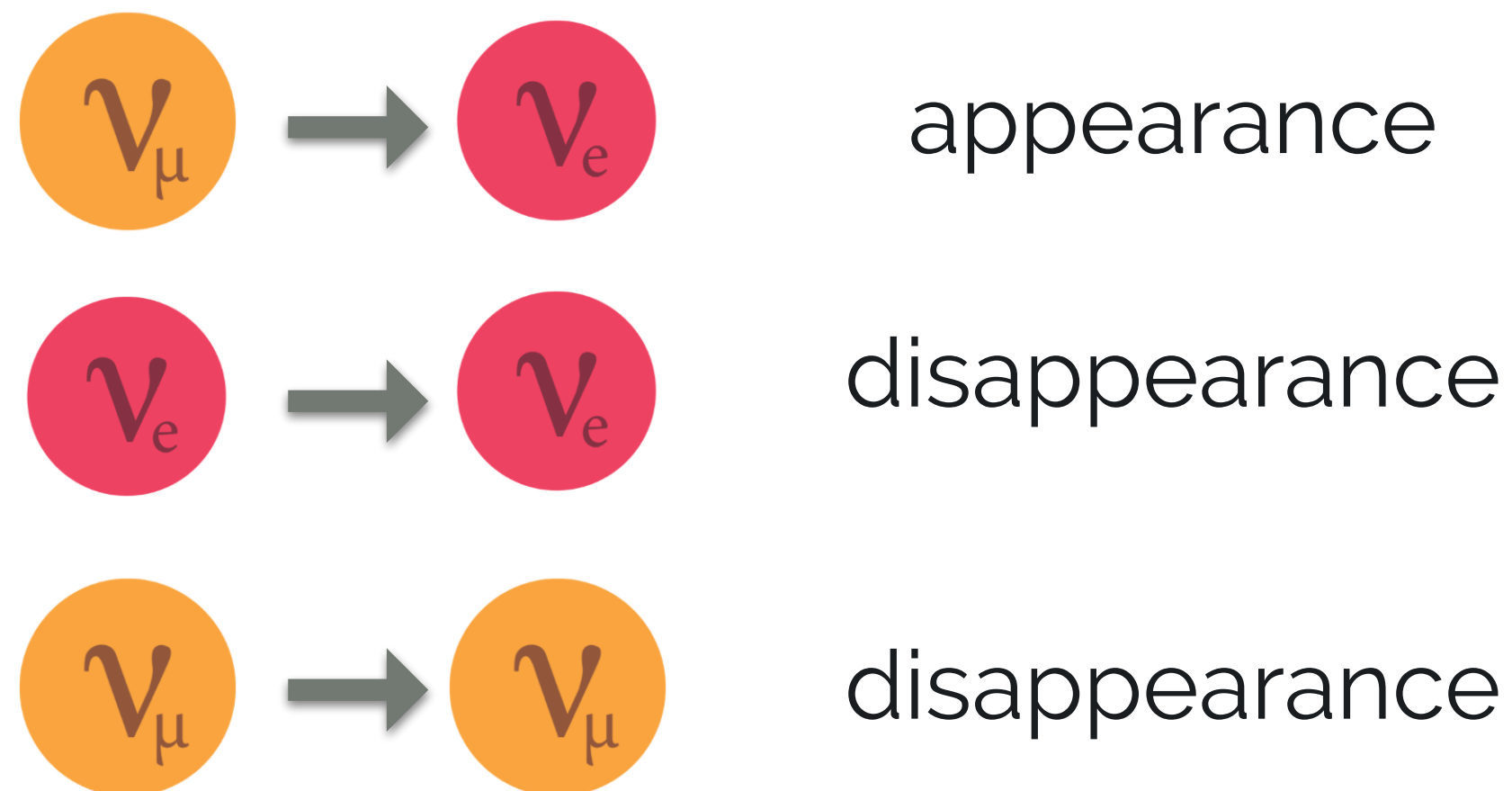
- **L/E ranges from 0.2–2 (km/GeV) – probe eV-scale sterile neutrinos**
- **Close to MiniBooNE along the same beamline**
- **State-of-the-art LArTPC technology**



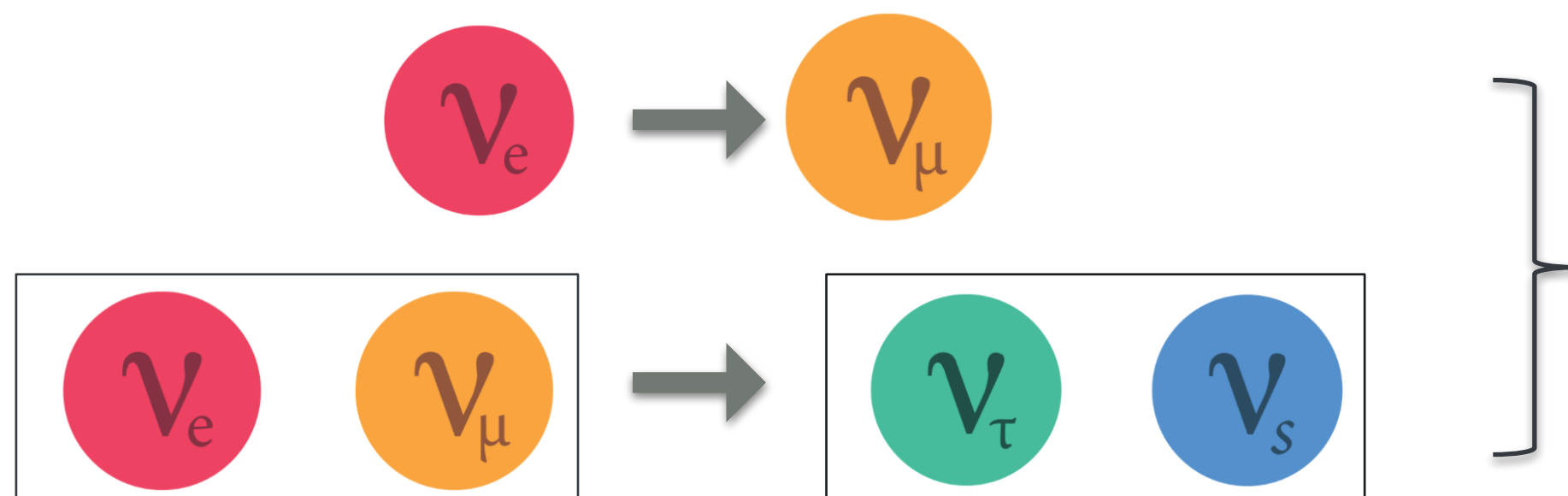
Light sterile neutrino search at MicroBooNE



- **Full “3+1” analysis** – all detectable oscillation effects



**Three main
oscillation
effects**

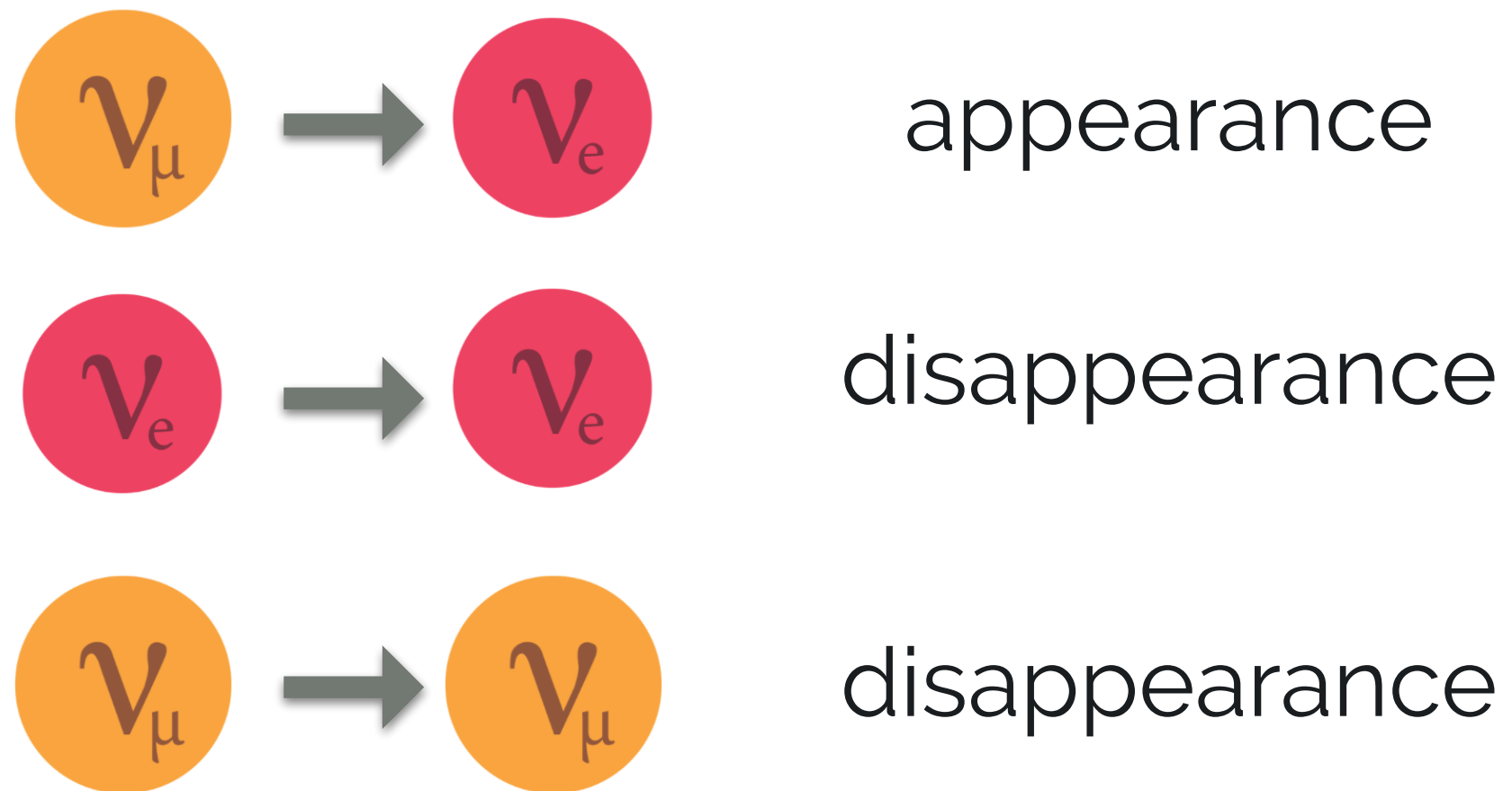


Negligible
channels in data
(small number of ν_e and
neutral current events)

Light sterile neutrino search at MicroBooNE



- **Full “3+1” analysis** – all detectable oscillation effects

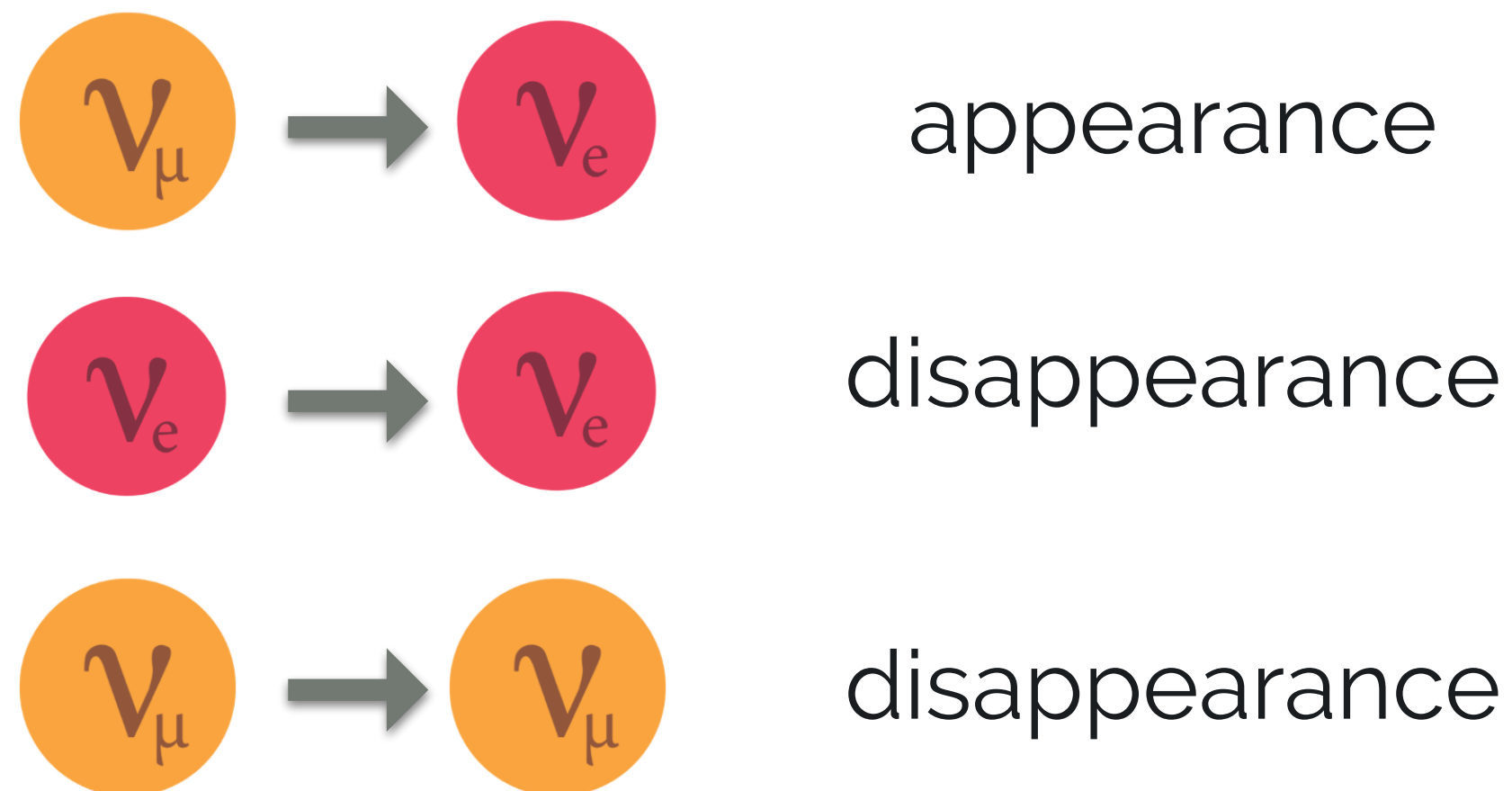


**Simultaneous fit on all
available ν_e and ν_μ
interaction channels**
(reduce shared systematic
uncertainties as well)

Light sterile neutrino search at MicroBooNE

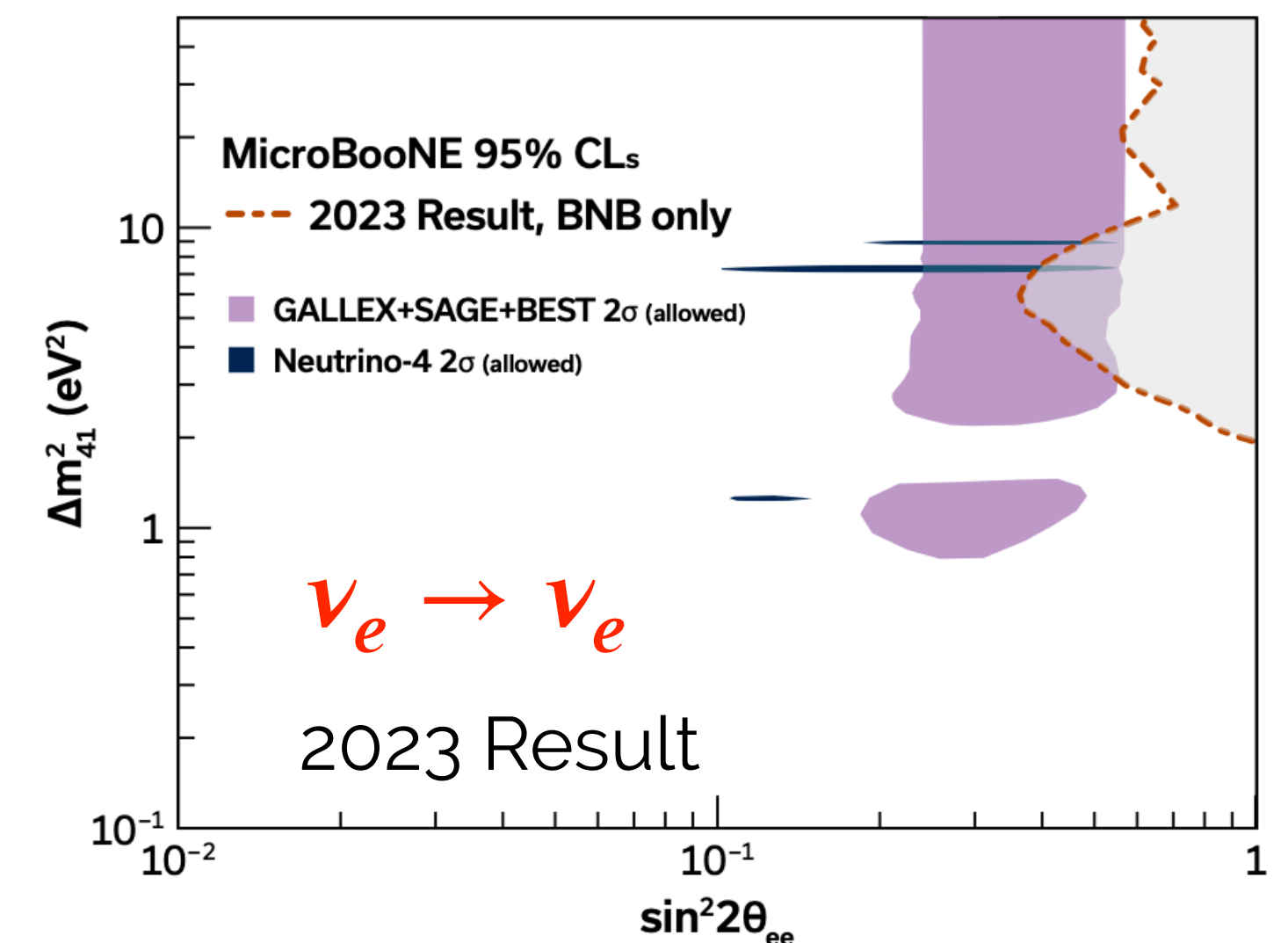
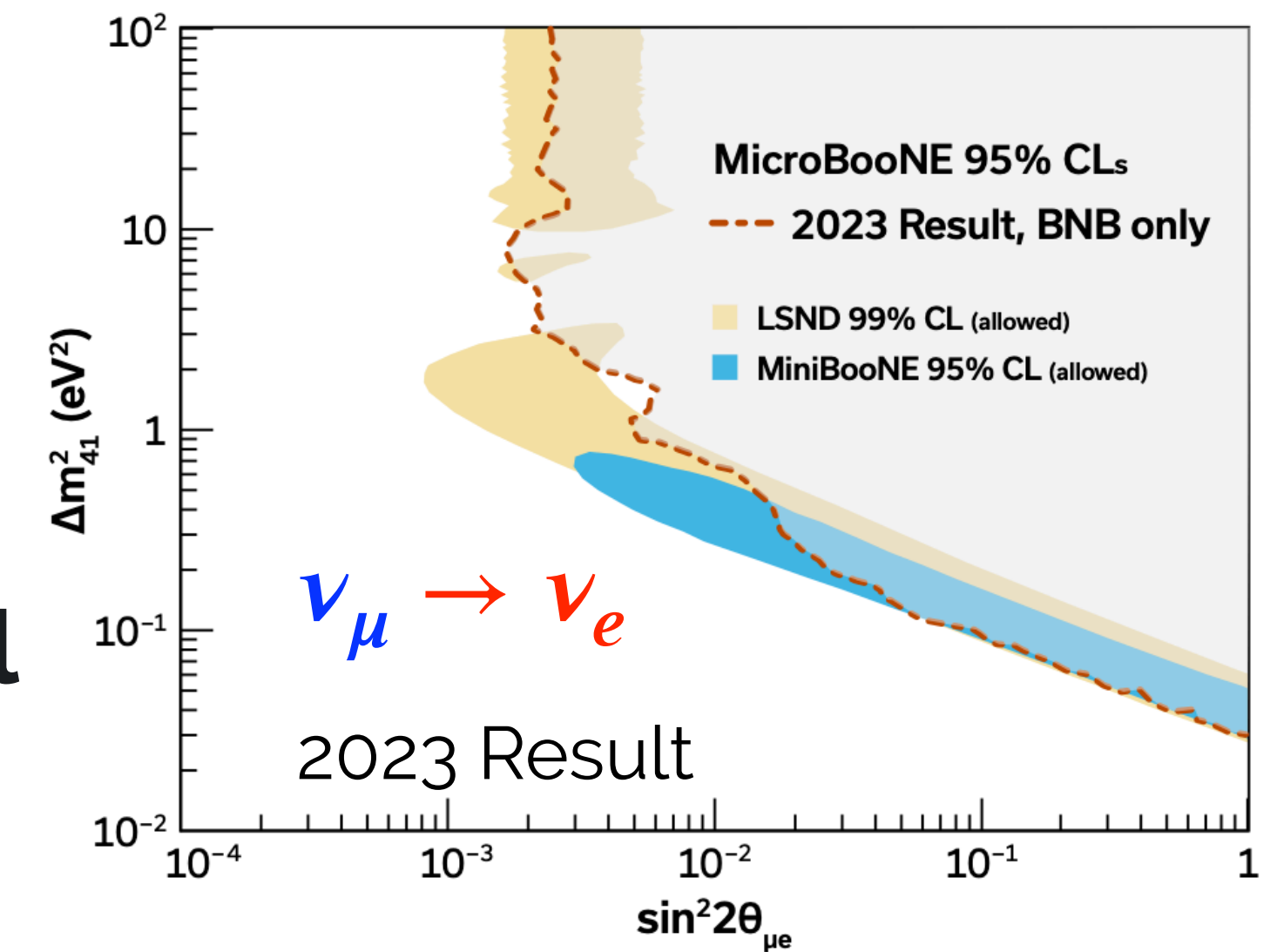


- Full “3+1” analysis – all detectable oscillation effects



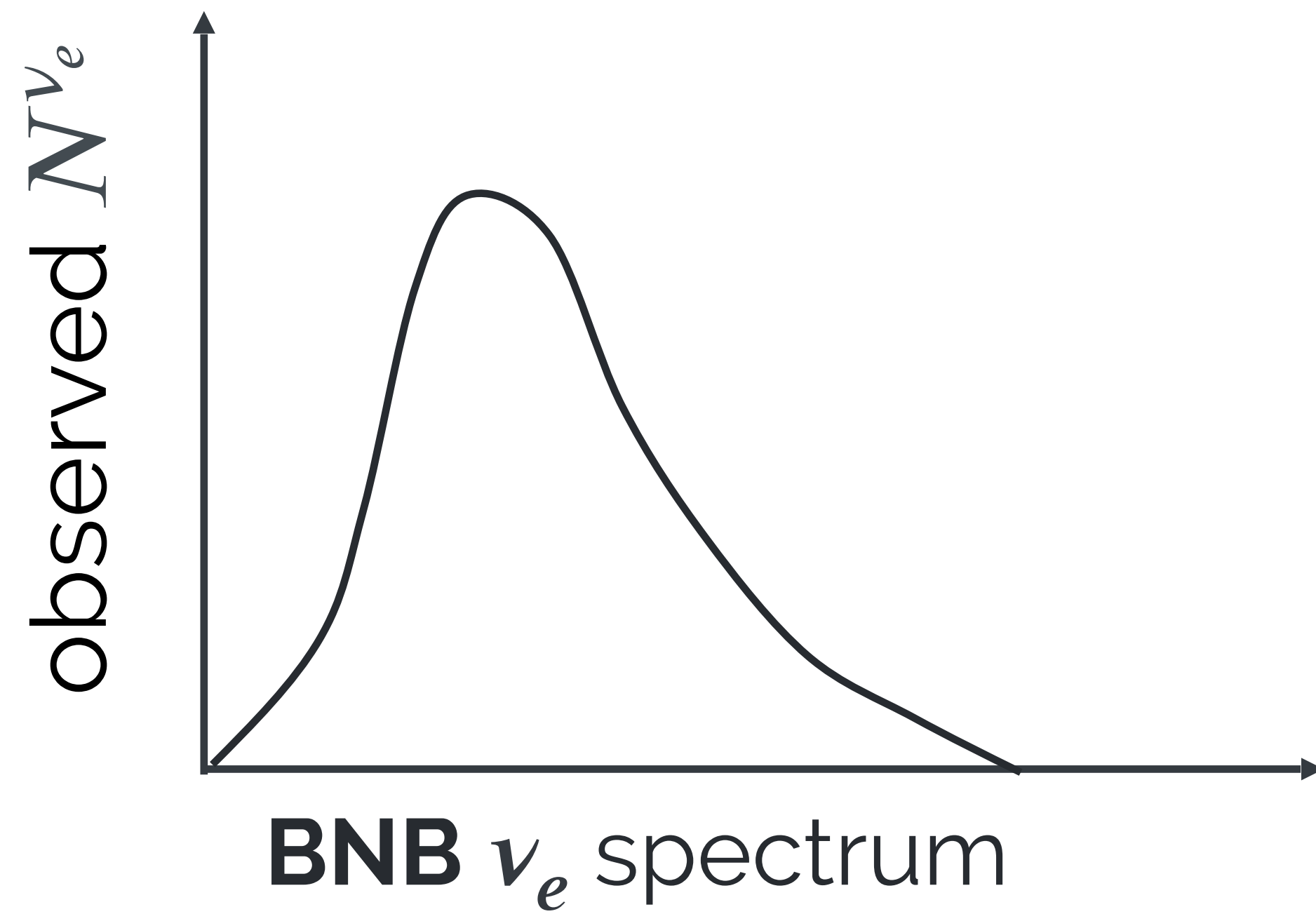
Simultaneous fit on all available ν_e and ν_μ interaction channels
(reduce shared systematic uncertainties as well)

- ✓ Set constraints in **both channels** of ν_e appearance and disappearance
- Sensitivities are quite limited in both channels due to a **degeneracy in oscillation parameters**



Challenge: parameter degeneracy

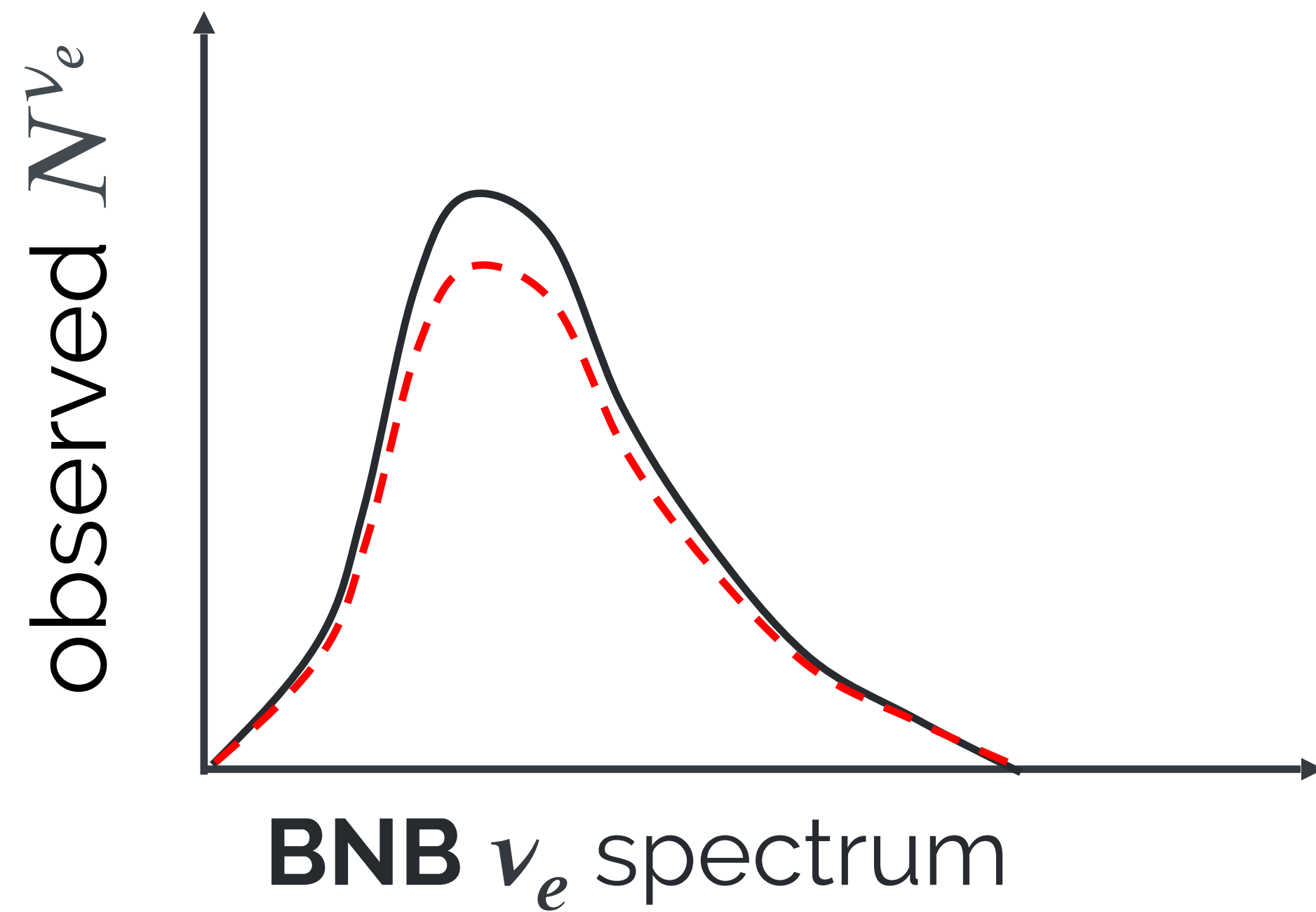
No oscillation: N^{ν_e}



Challenge: parameter degeneracy

No oscillation: N^{ν_e}

Disapp effect: $N^{\nu_e} \times P_{ee}$

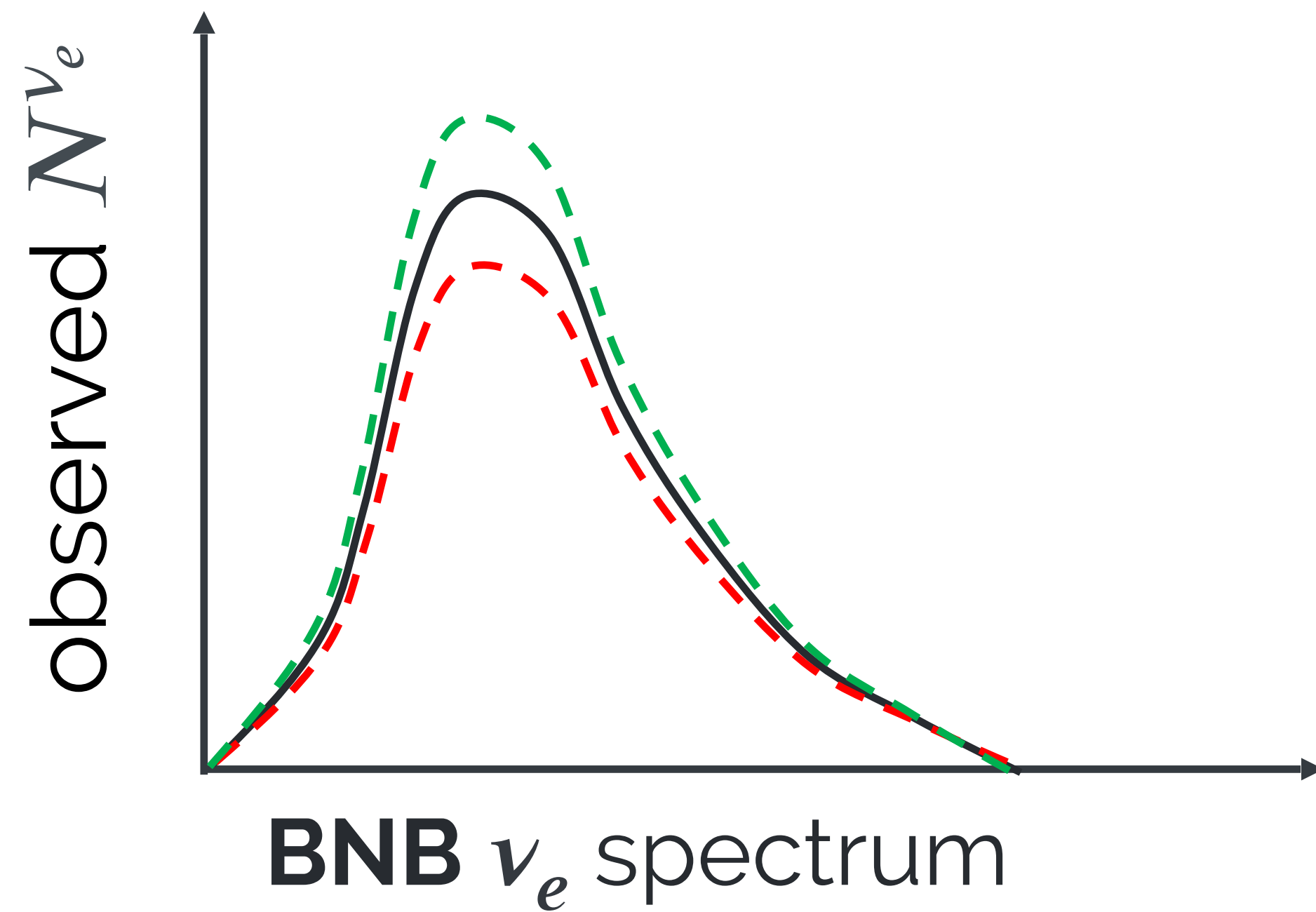


Challenge: parameter degeneracy

No oscillation: N^{ν_e}

Disapp effect: $N^{\nu_e} \times P_{ee}$

App effect: $N^{\nu_\mu} \times P_{\mu e} + N^{\nu_e}$



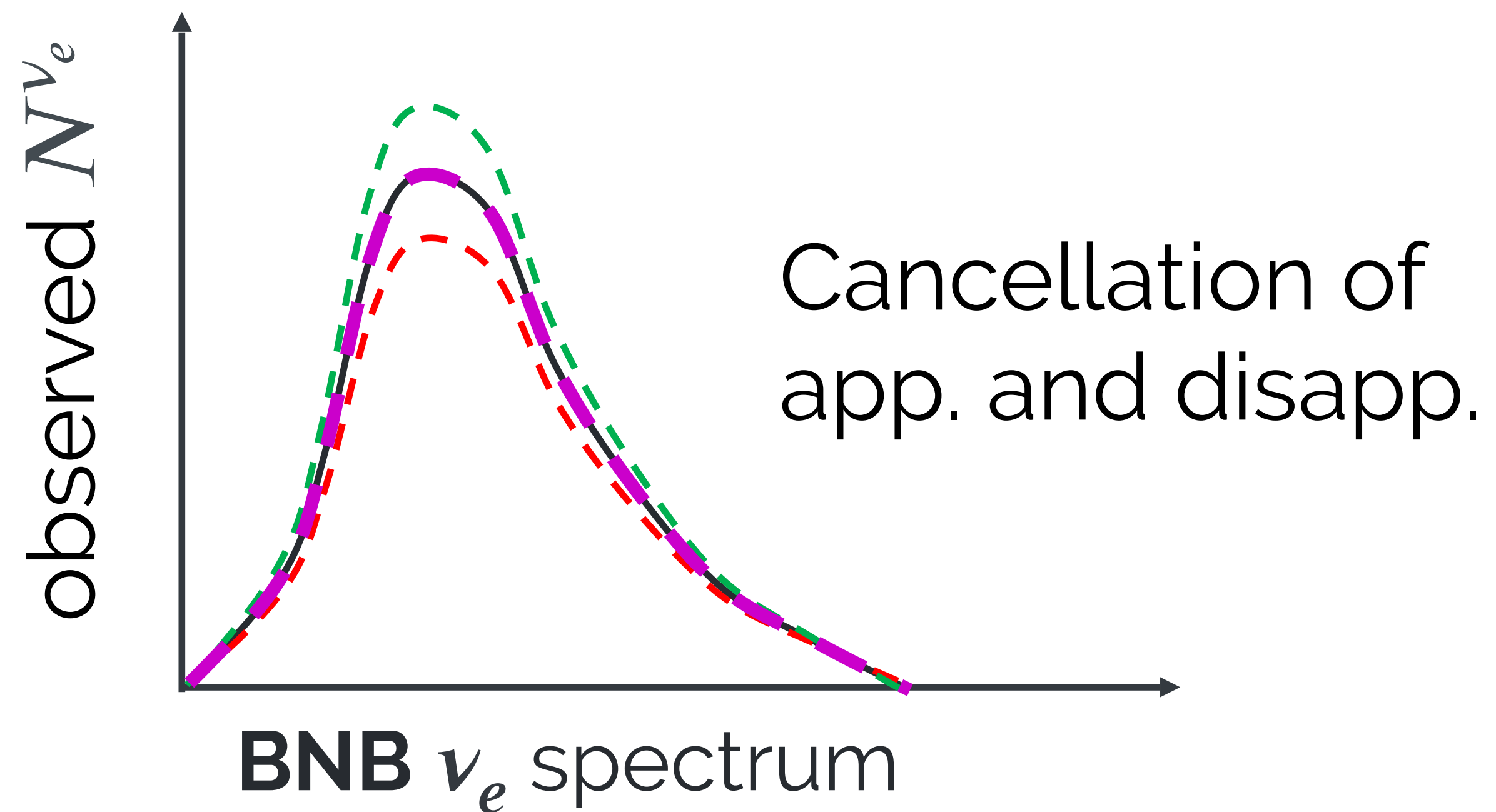
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Net oscillated N^{ν_e}



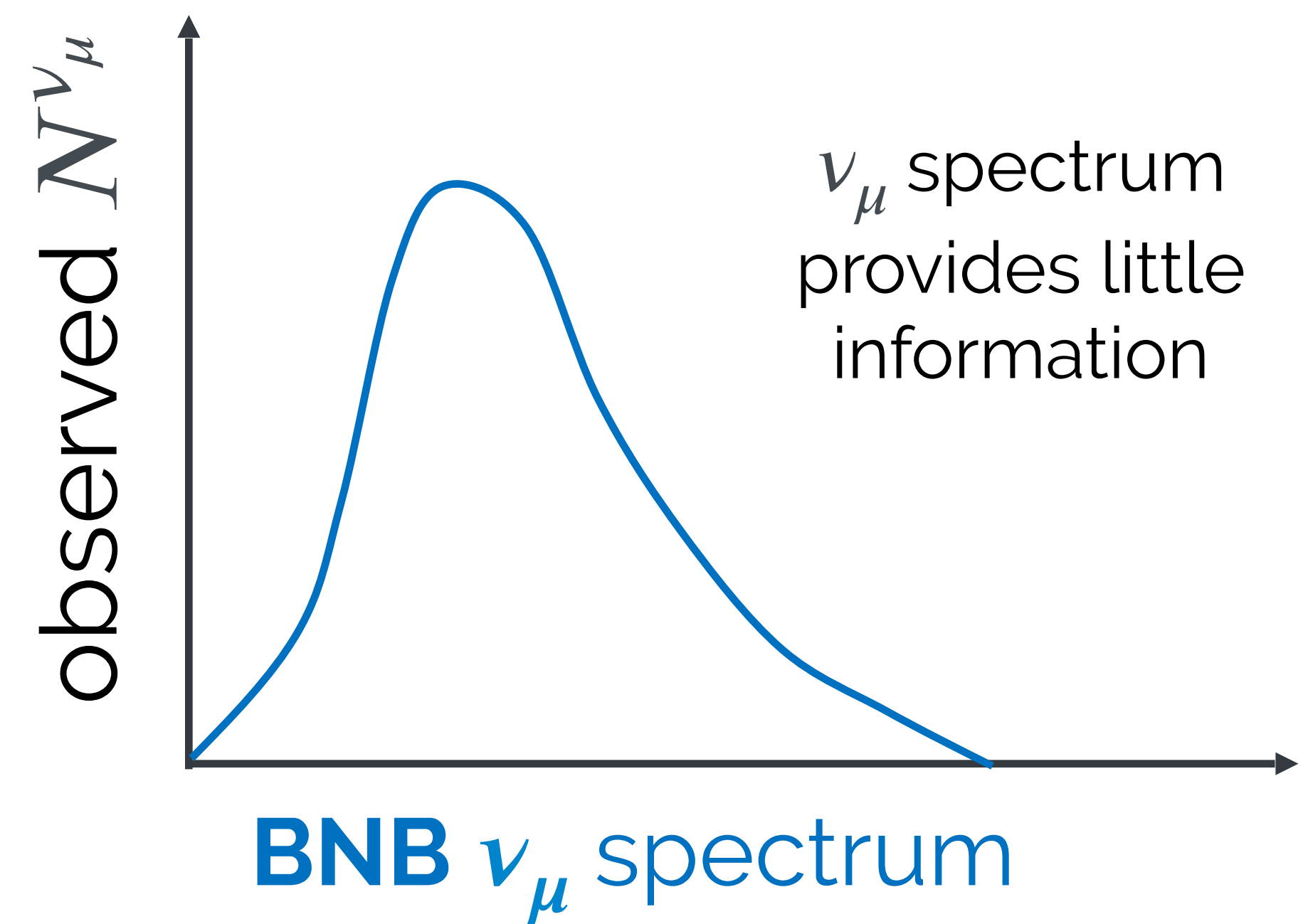
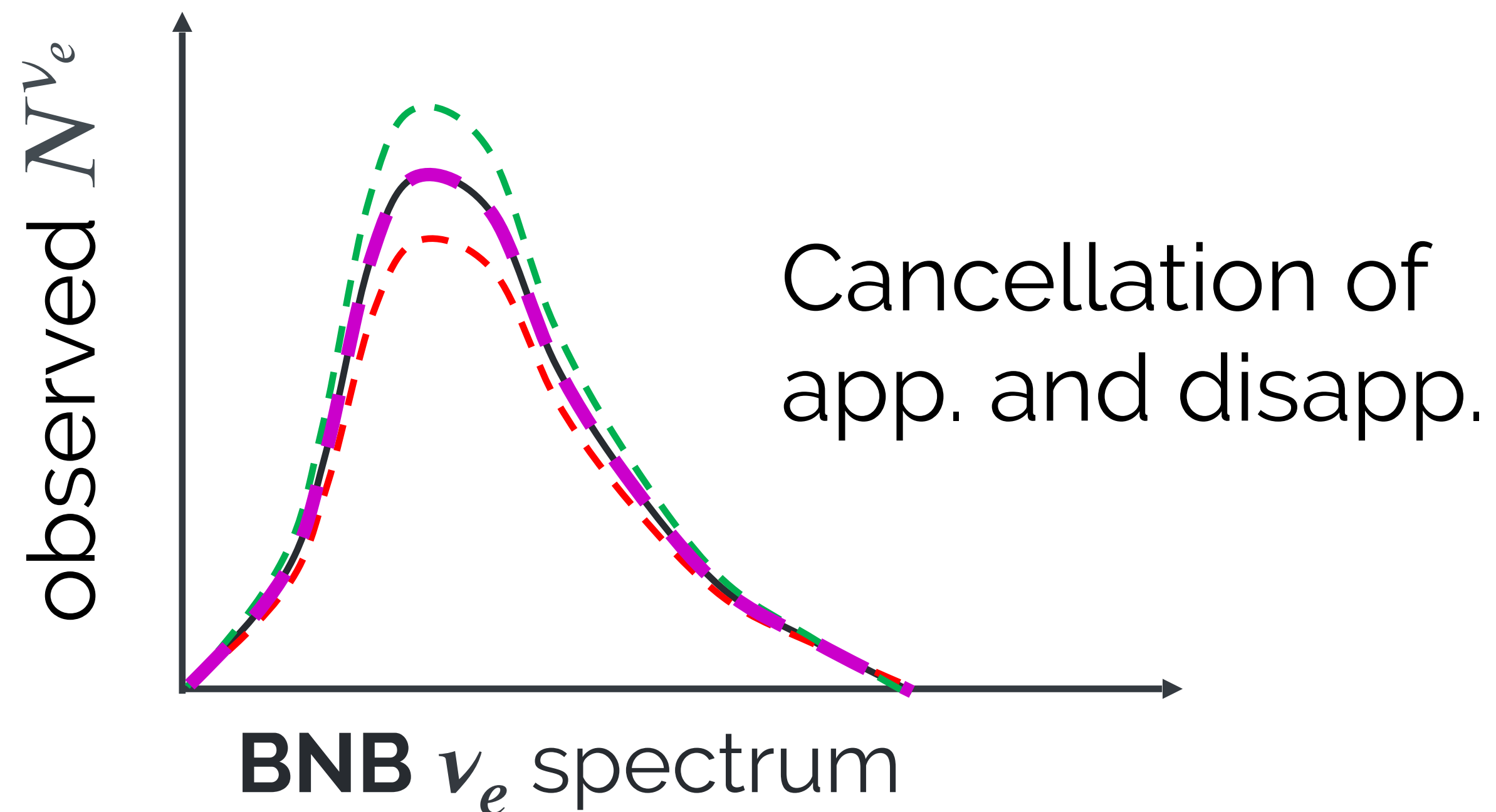
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Net oscillated N^{ν_e}



Challenge: parameter degeneracy

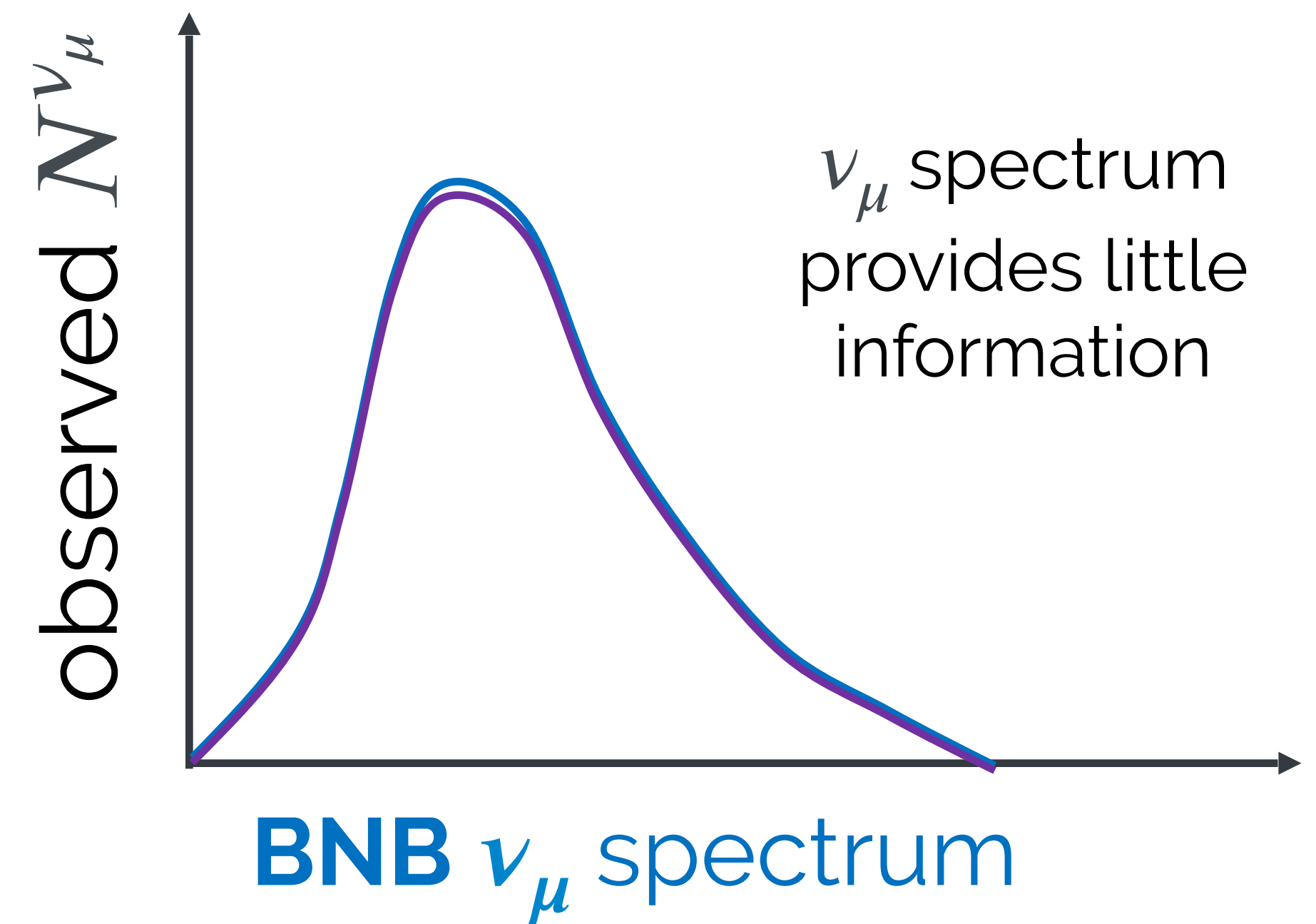
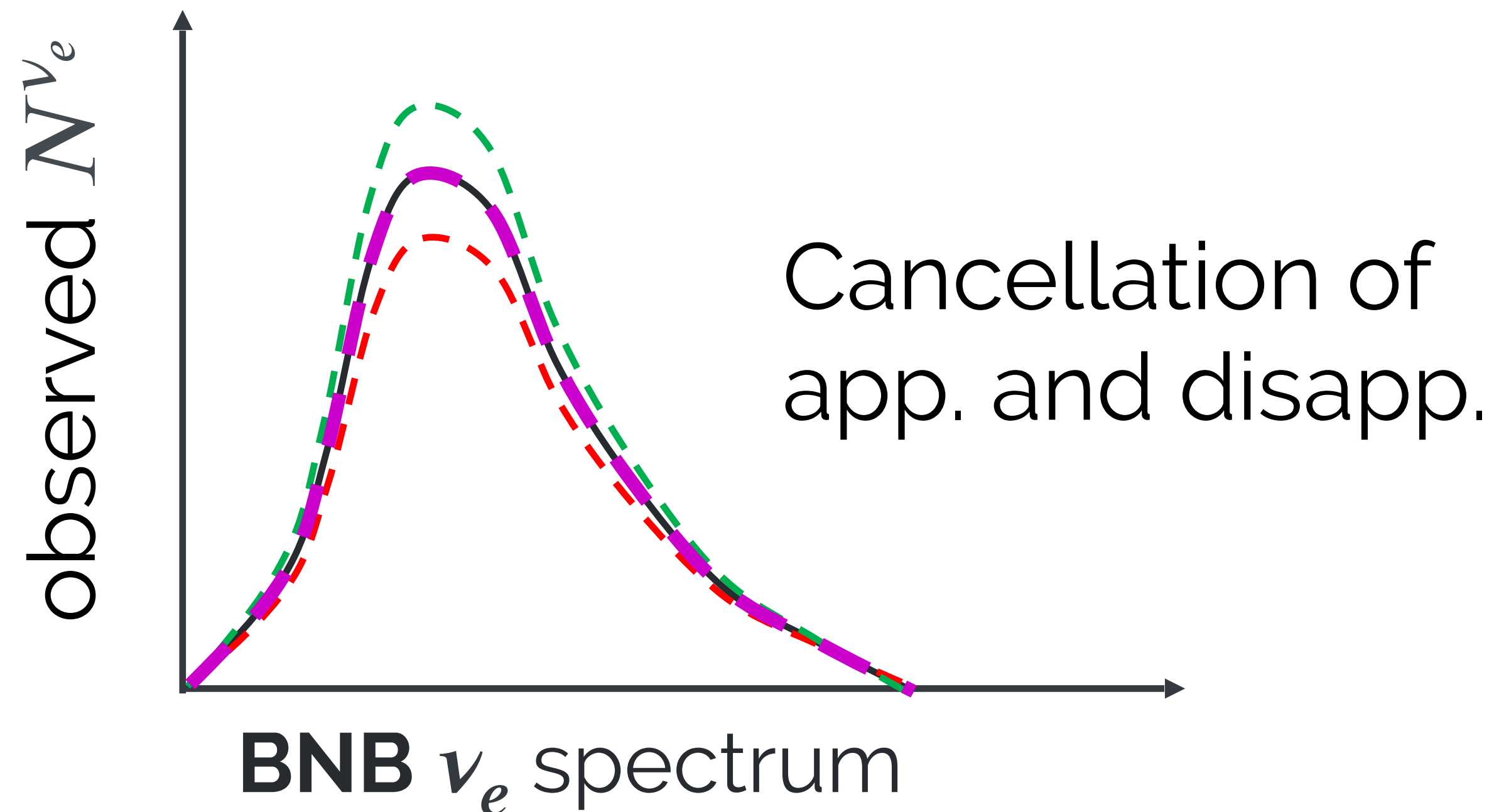
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App effect: $N^{\nu_\mu} \times P_{\mu e} + N^{\nu_e}$

Net oscillated N^{ν_e}

Even if $N^{\nu_\mu} \times P_{\mu e} = N^{\nu_e}$, $P_{\mu e}$ is still small with tiny ν_e component in BNB beam



Challenge: parameter degeneracy

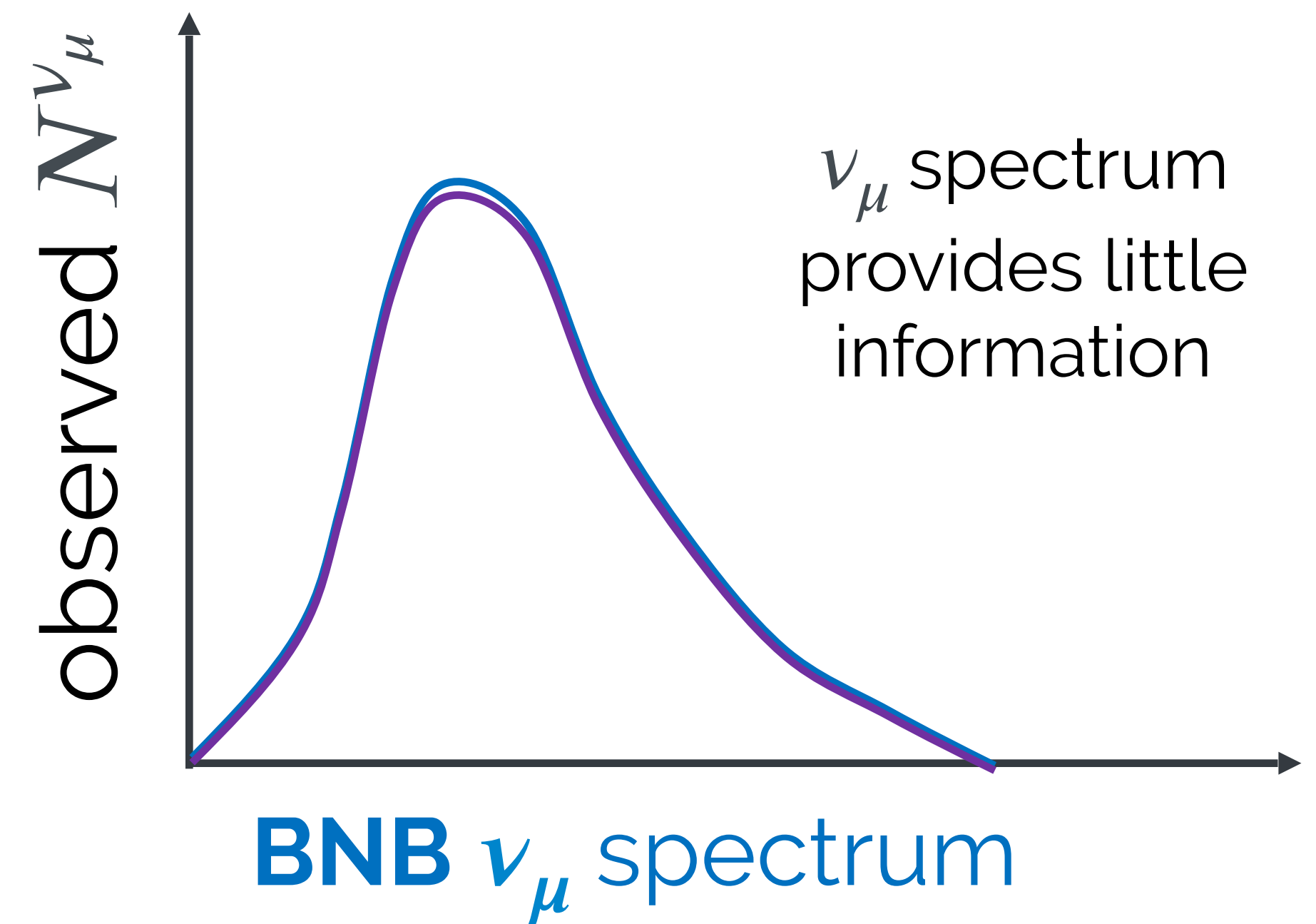
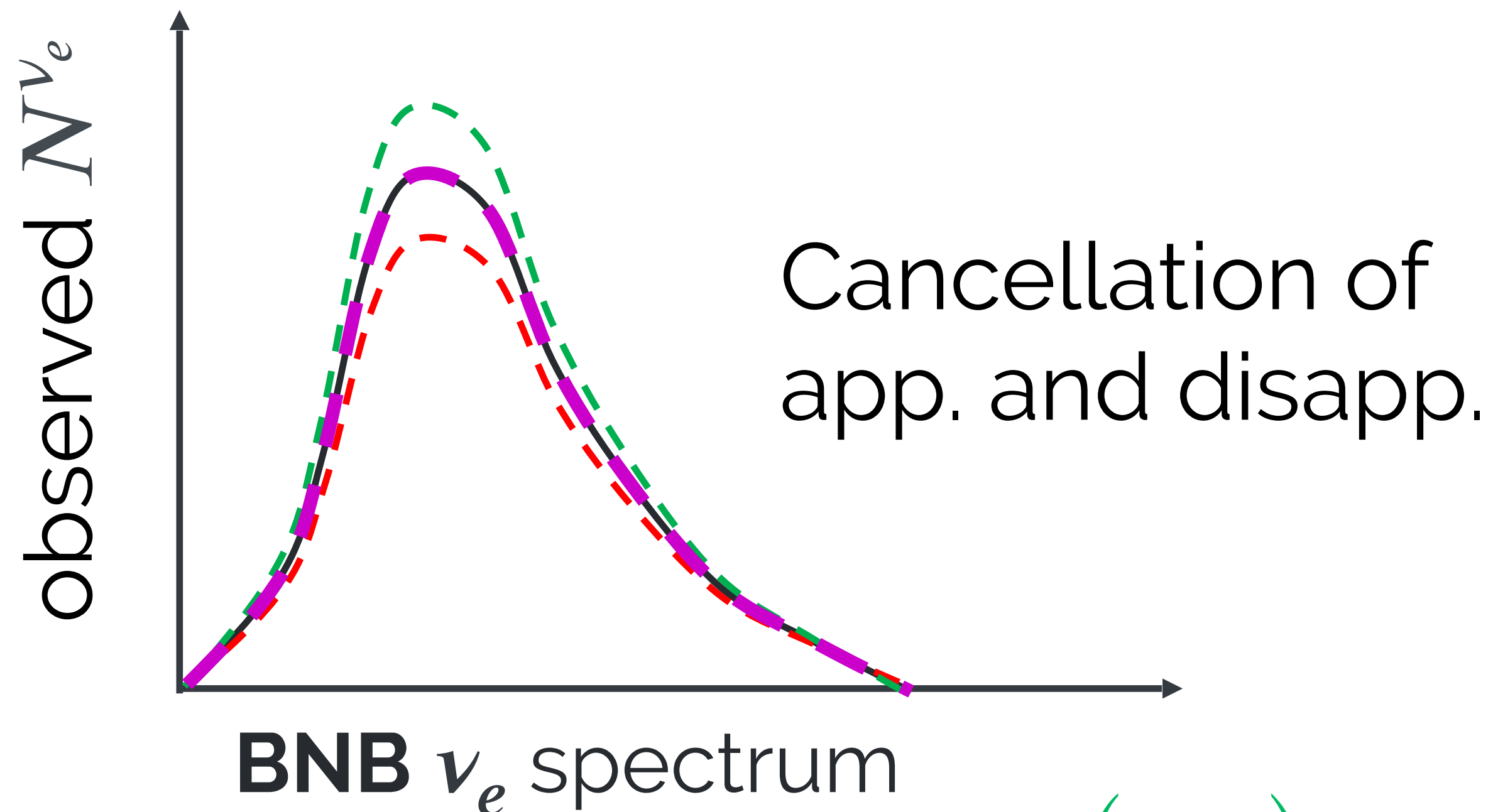
No oscillation: N^{ν_e}

Disapp effect: $N^{\nu_e} \times P_{ee}$

App effect: $N^{\nu_\mu} \times P_{\mu e} + N^{\nu_e}$

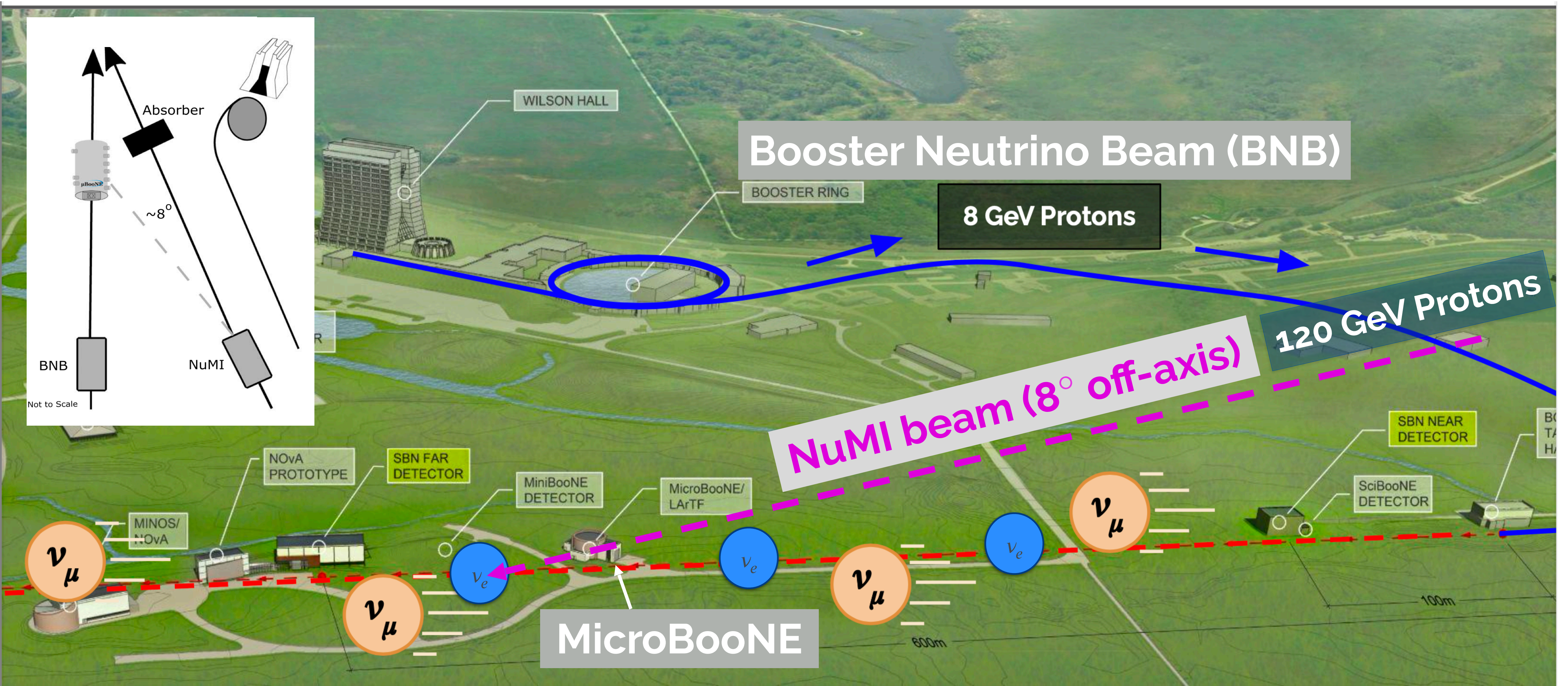
Net oscillated N^{ν_e}

Even if $N^{\nu_\mu} \times P_{\mu e} = N^{\nu_e}$, $P_{\mu e}$ is still small with tiny ν_e component in BNB beam

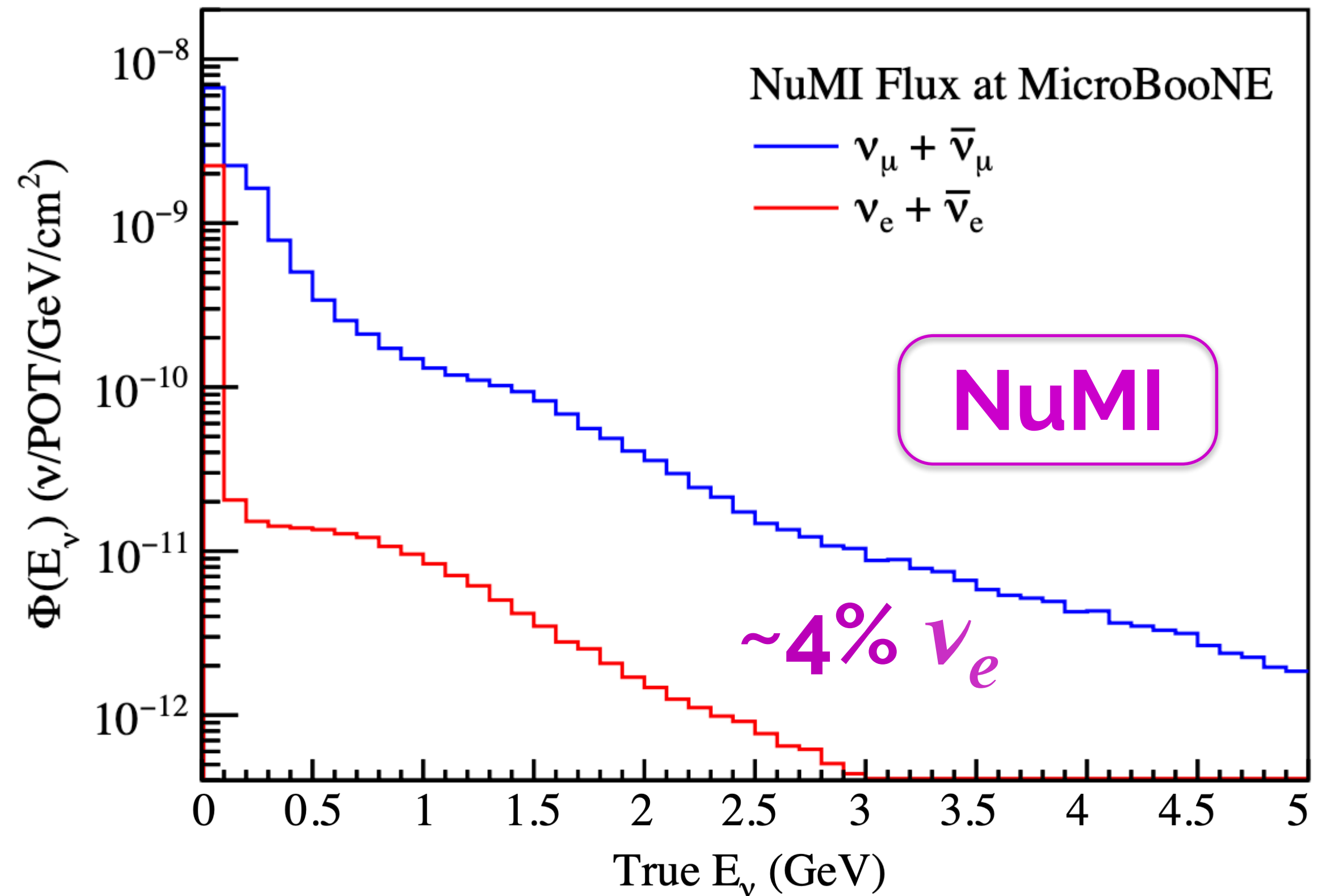
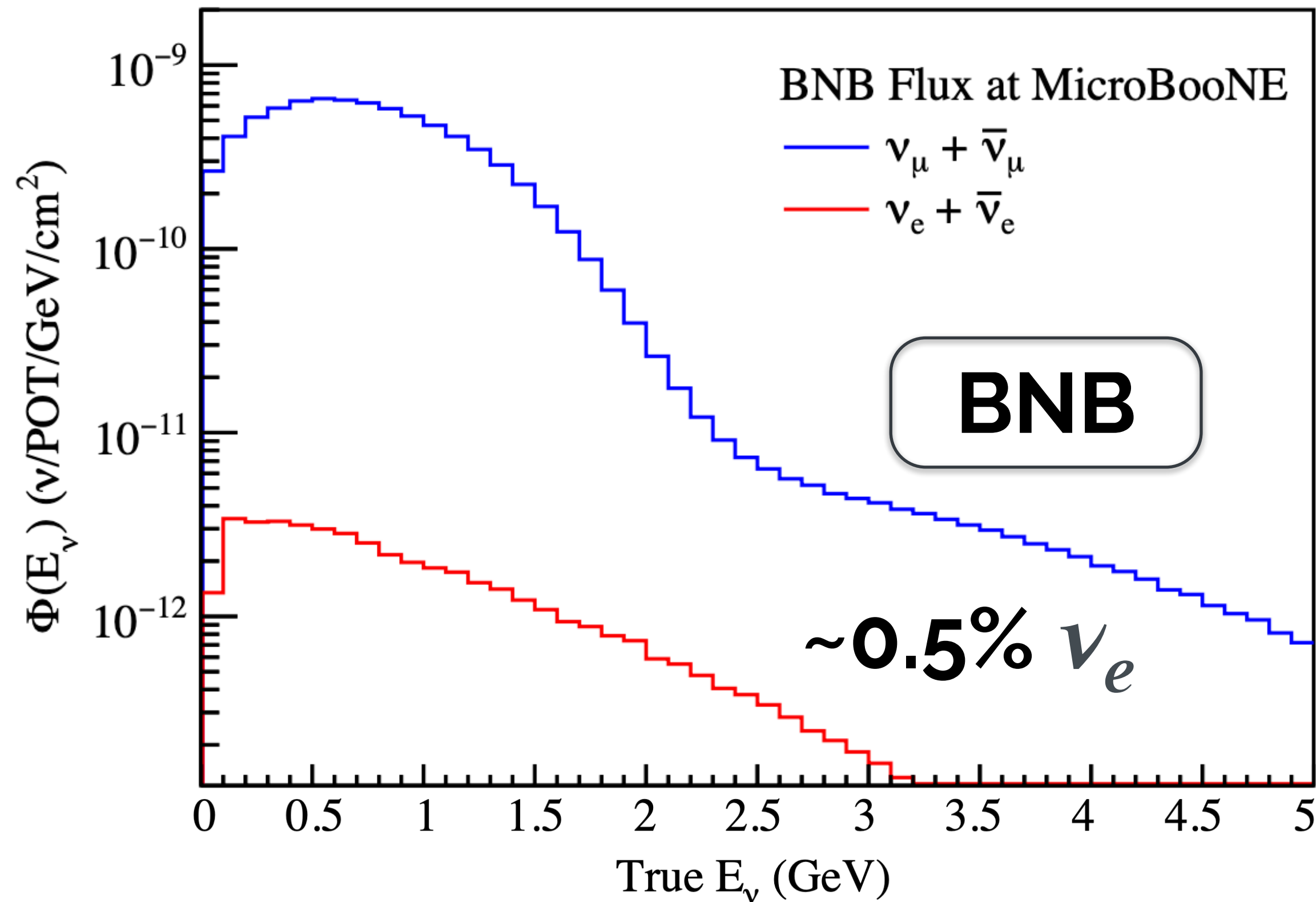


Degeneracy "point": $\frac{P_{\mu e}}{P_{ee}} = \frac{\sin^2(2\theta_{\mu e})}{\sin^2(2\theta_{ee})} = \frac{N^{\nu_e}}{N^{\nu_\mu}}$ almost a fixed value for a beam

MicroBooNE at Fermilab's Booster Neutrino Beam



Degeneracy Breaking using Two Beams

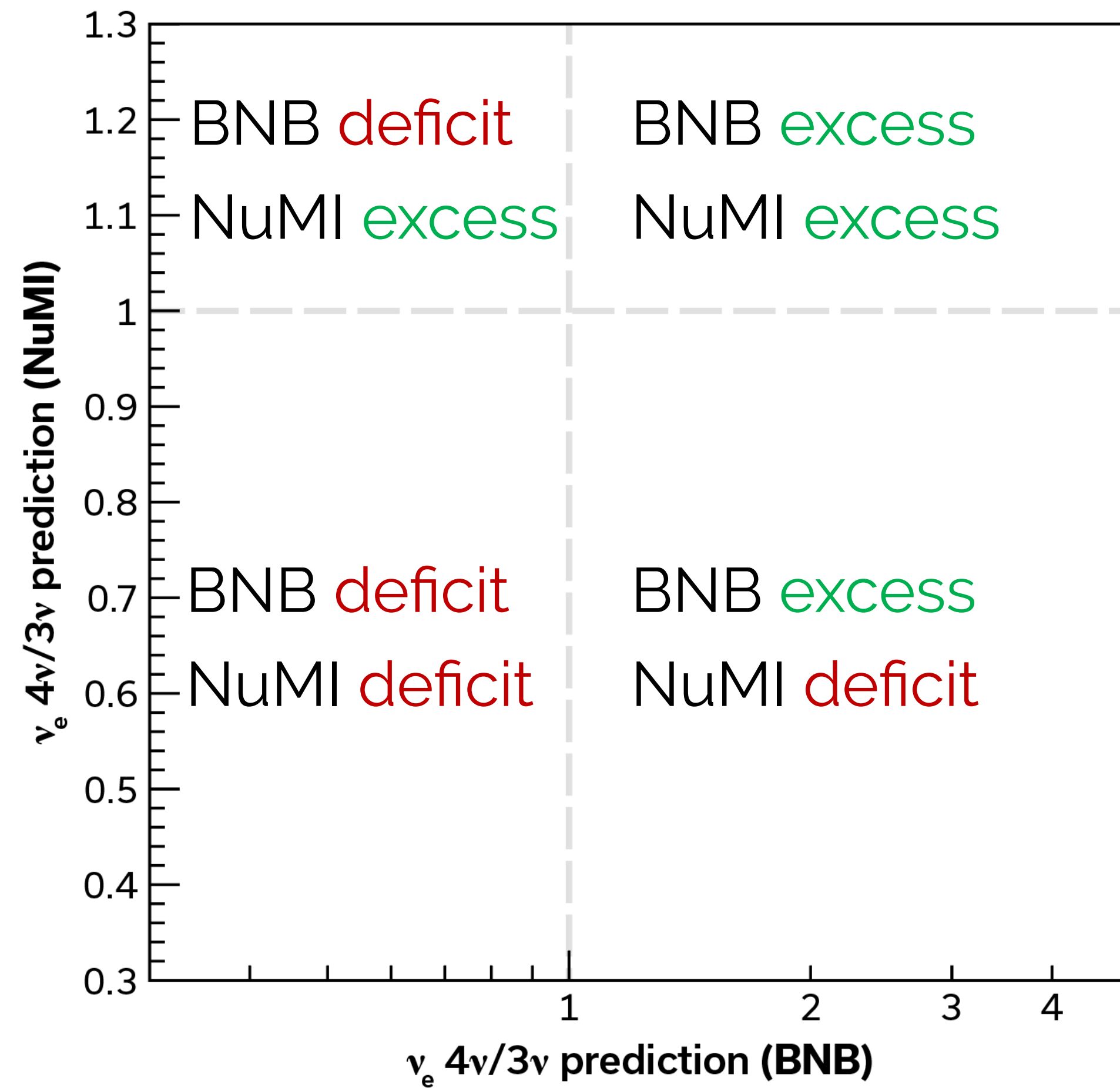


Beam ν_μ -to- ν_e ratios: BNB~200 vs NuMI~25

They have quite different degeneracy points!

So we have two “handles” to lift the appearance-disappearance degeneracy.

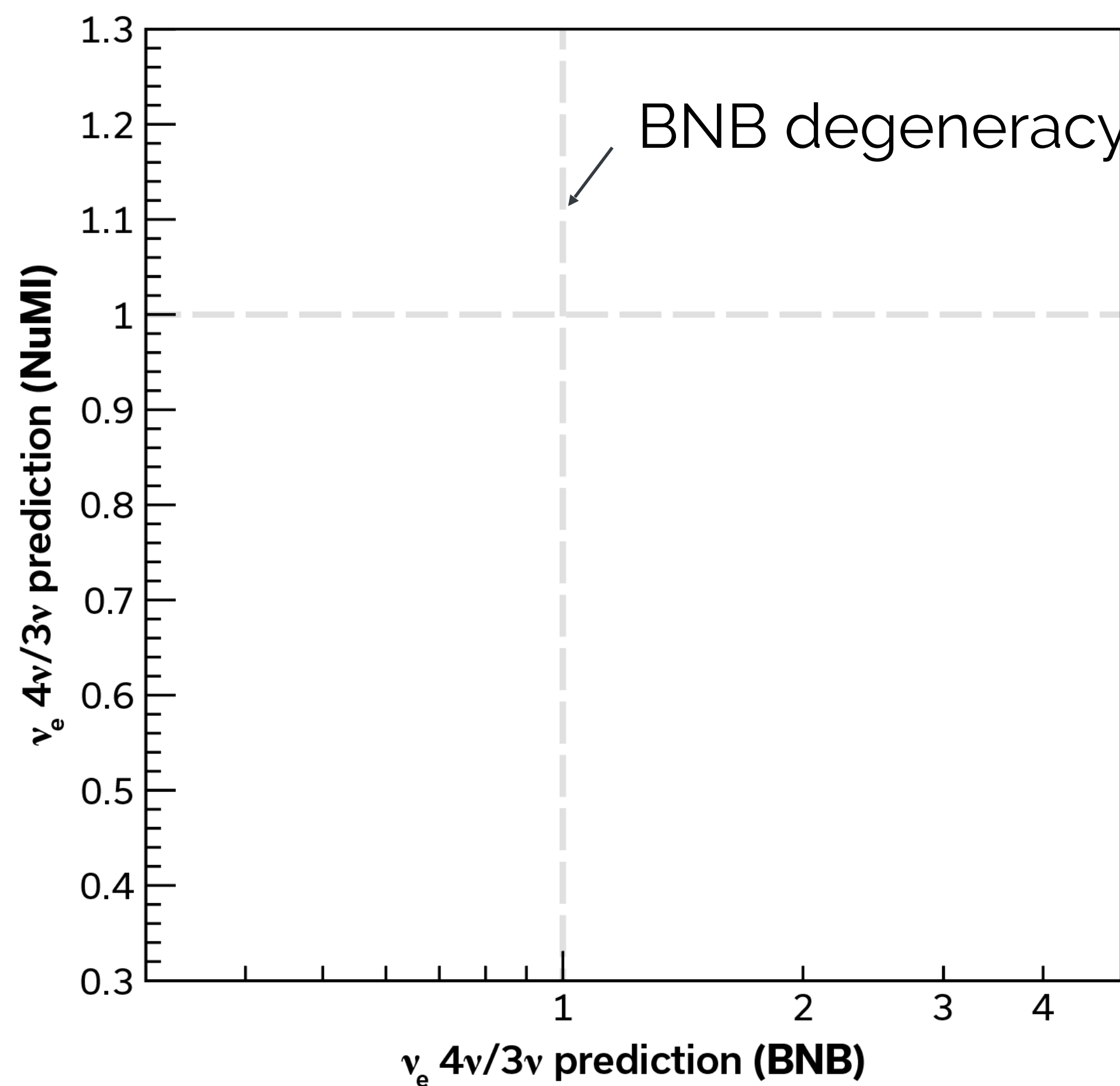
Degeneracy Breaking using Two Beams



- X- and Y-axes are BNB and NuMI

$$N_{\nu_e}^{osc} / N_{\nu_e}^{non-osc}$$

Degeneracy Breaking using Two Beams



$$\frac{\sin^2(2\theta_{\mu e})}{\sin^2(2\theta_{ee})} = \frac{1}{200}$$

$$\frac{\sin^2(2\theta_{\mu e})}{\sin^2(2\theta_{ee})} = \frac{1}{25}$$

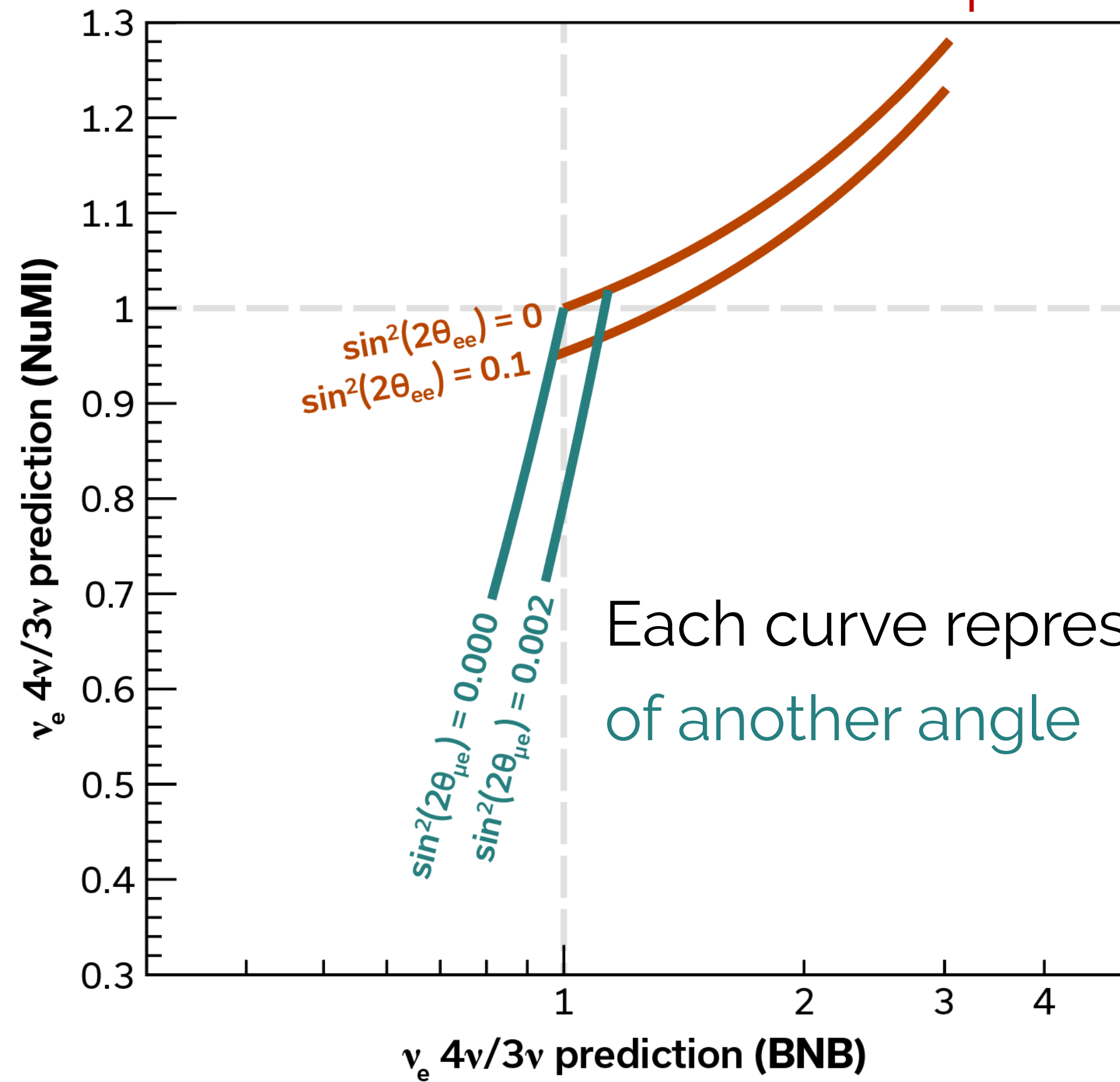
Where are those
mixing angles?

- X- and Y-axes are BNB and NuMI

$$N_{\nu_e}^{osc} / N_{\nu_e}^{non-osc}$$

Degeneracy Breaking using Two Beams

Each curve represents a constant value

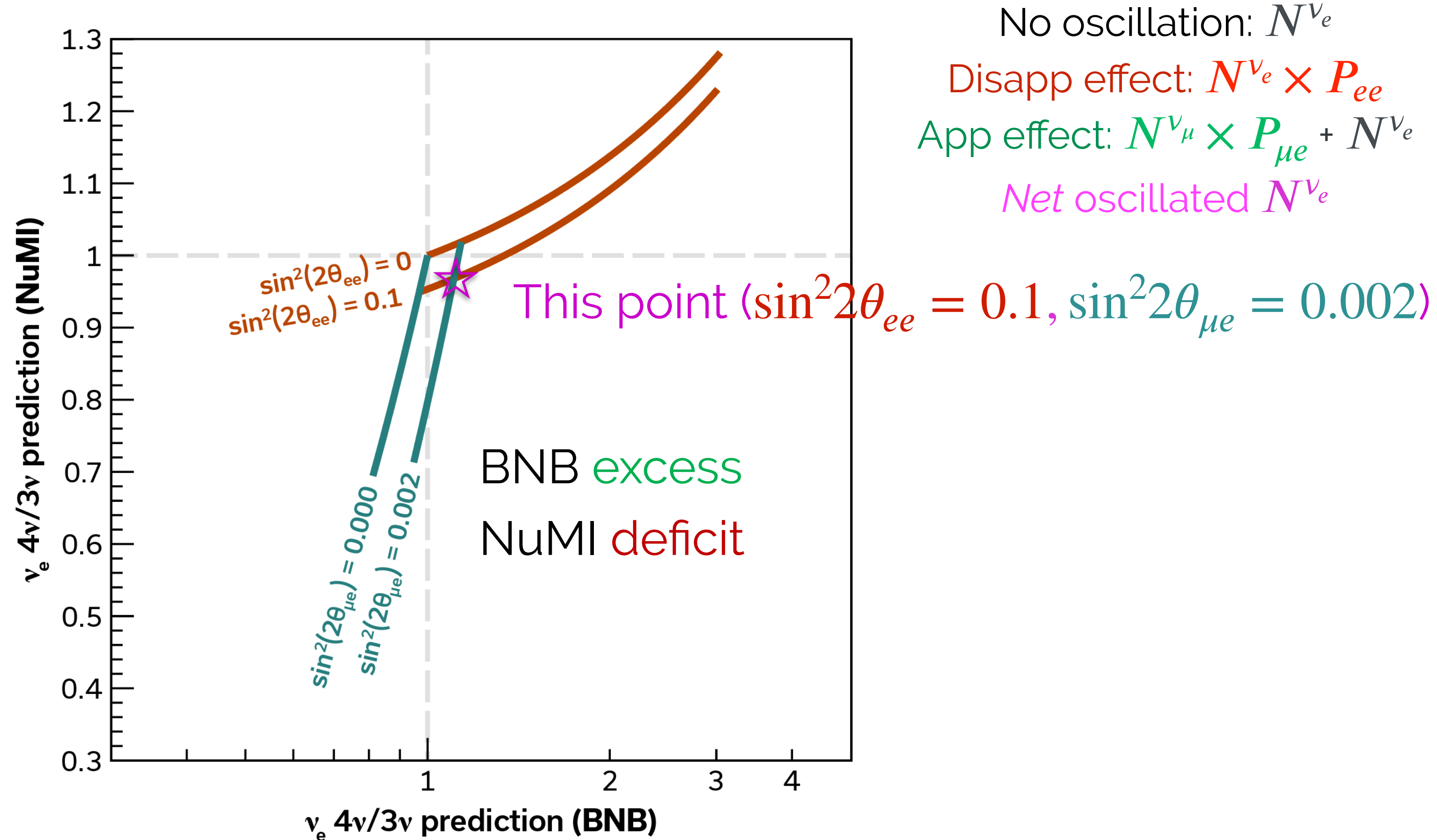


Each curve represents a constant value of another angle

- X- and Y-axes are BNB and NuMI

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Degeneracy Breaking using Two Beams

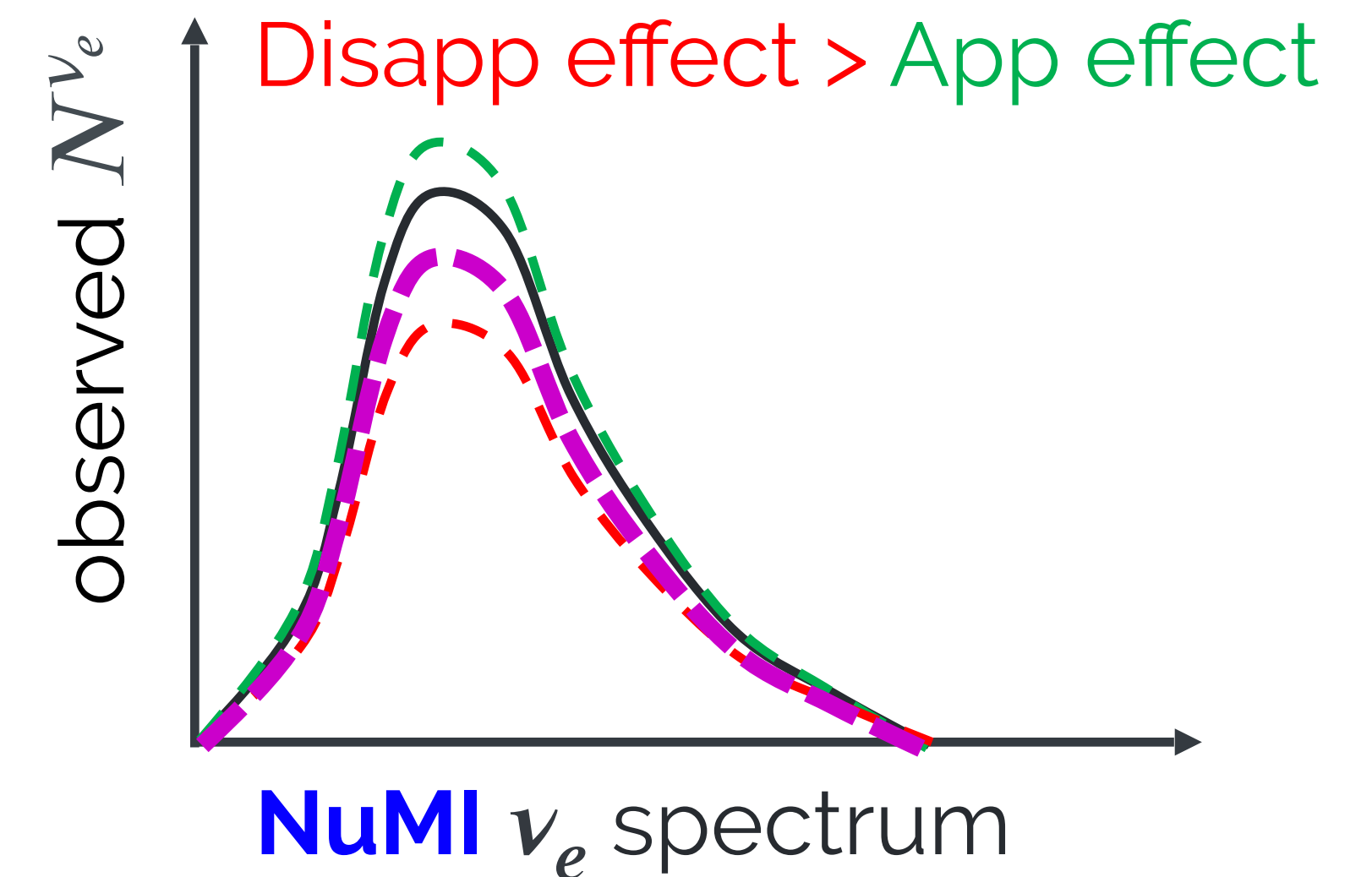
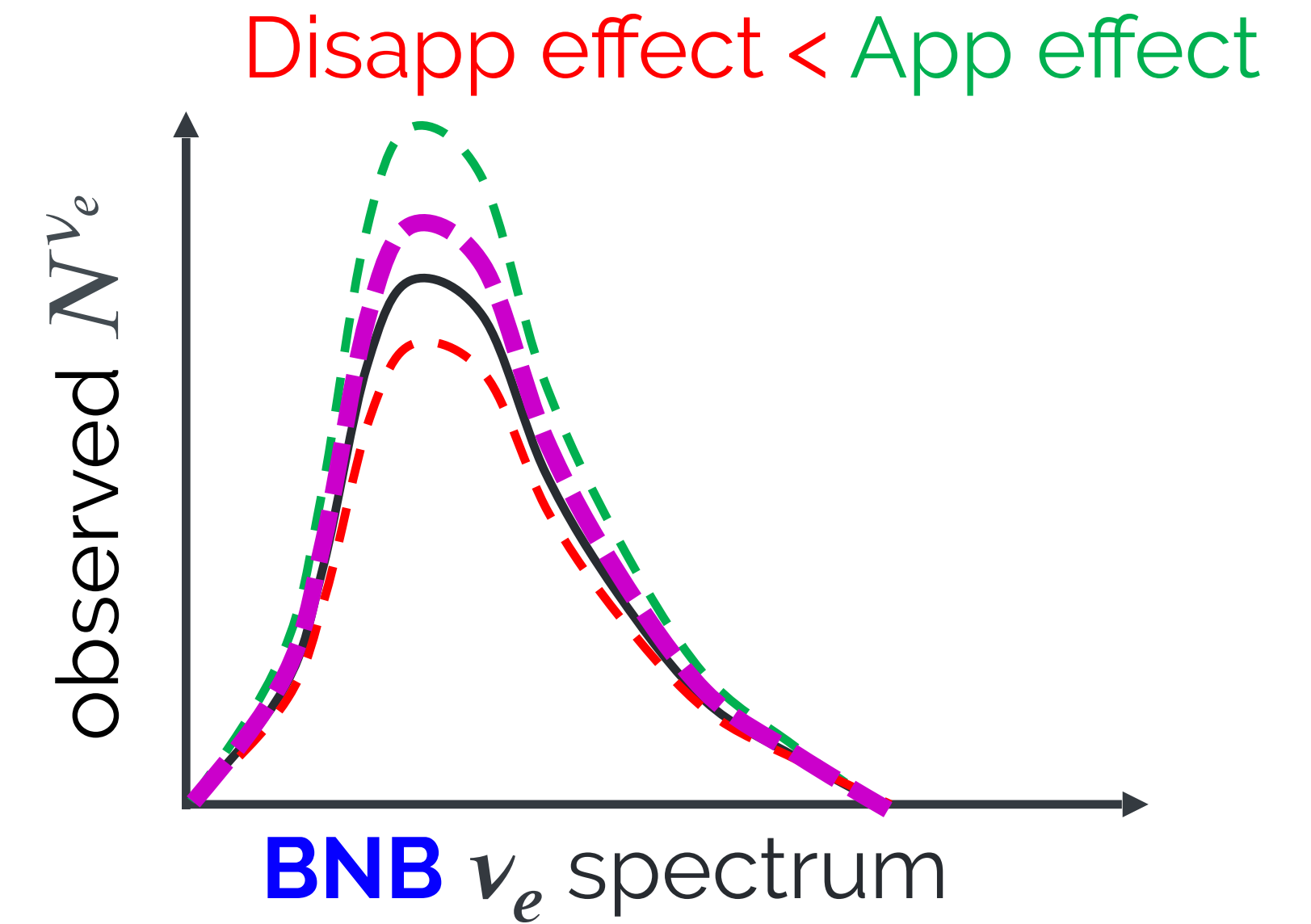


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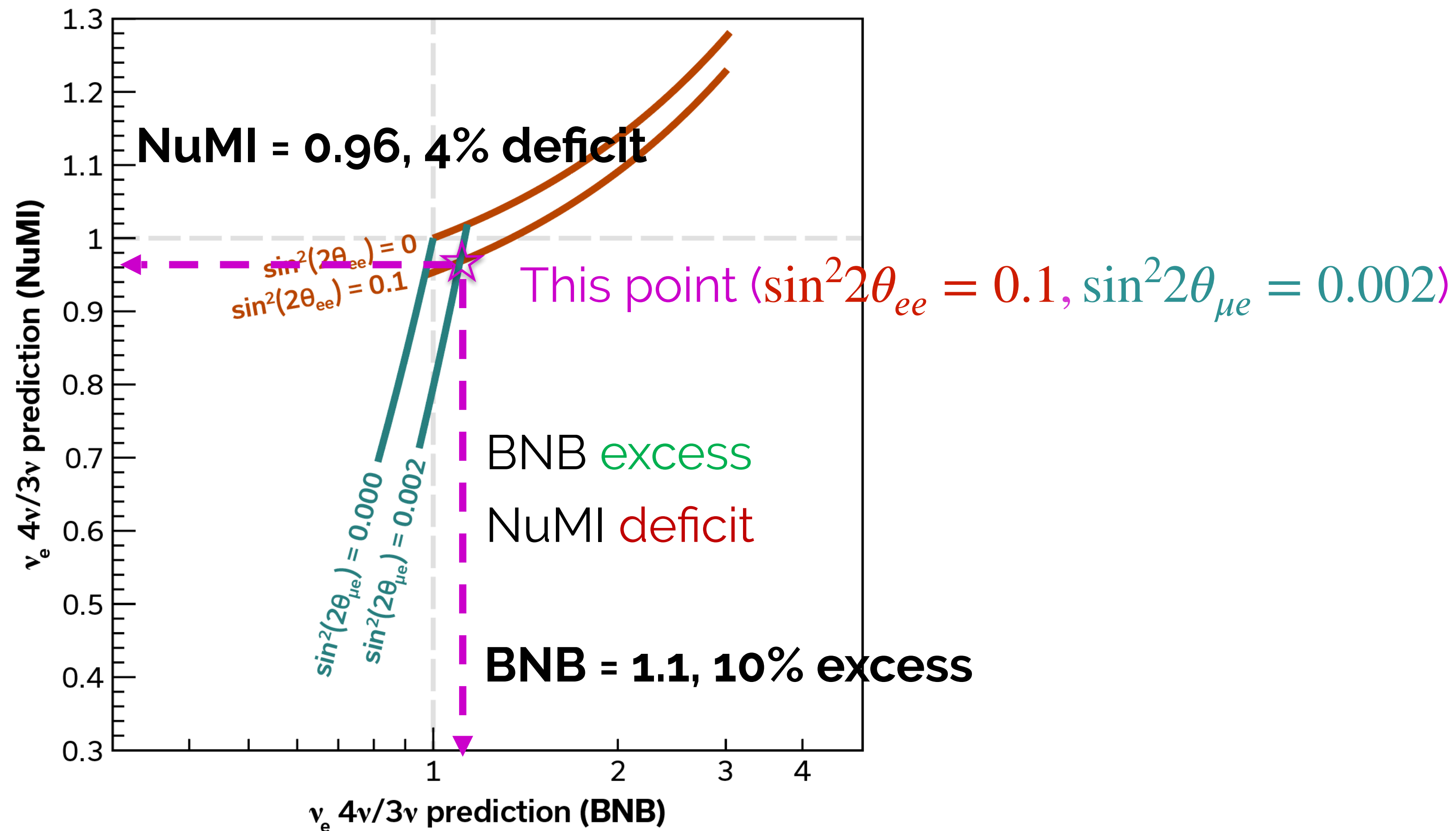
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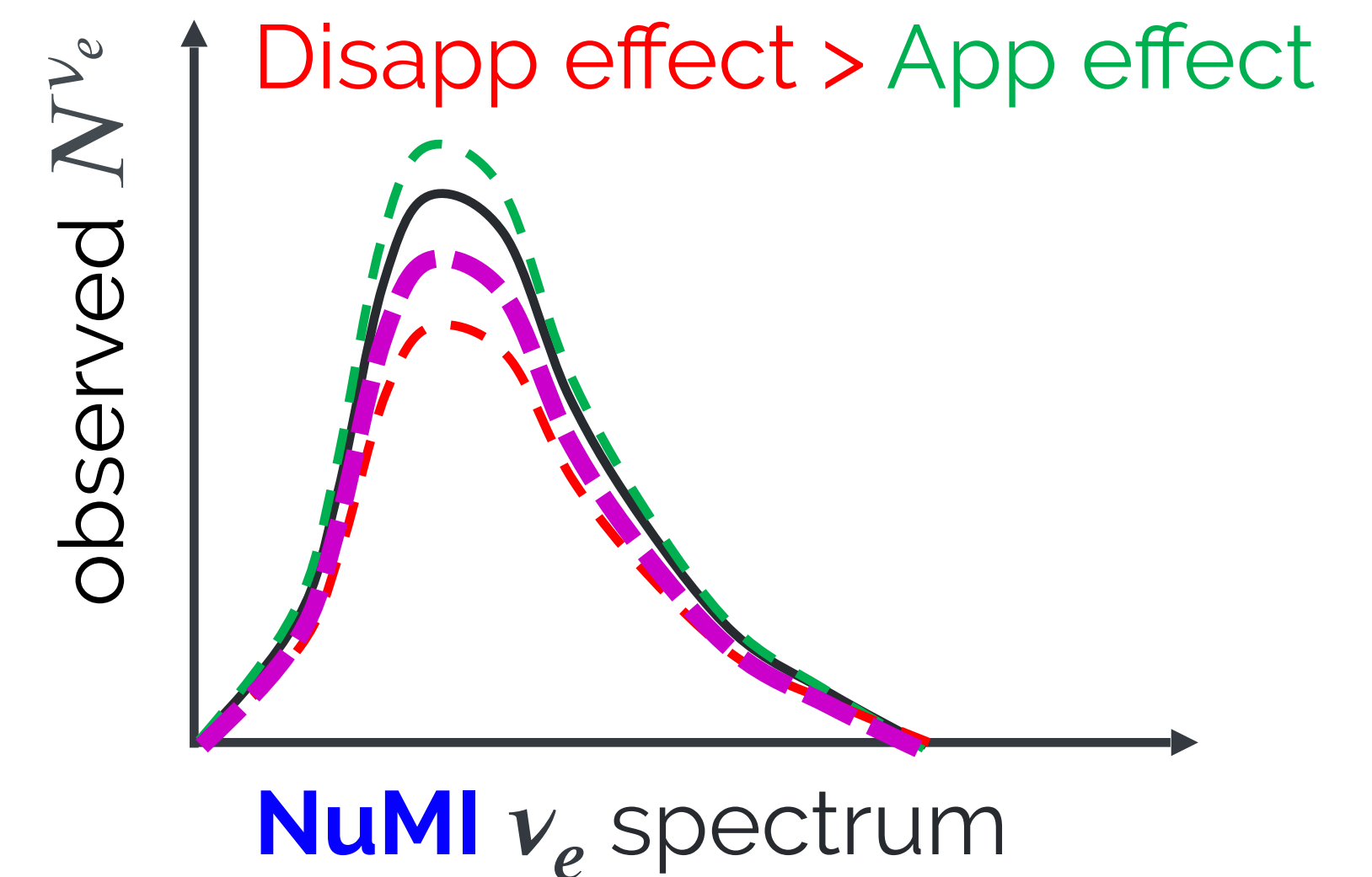
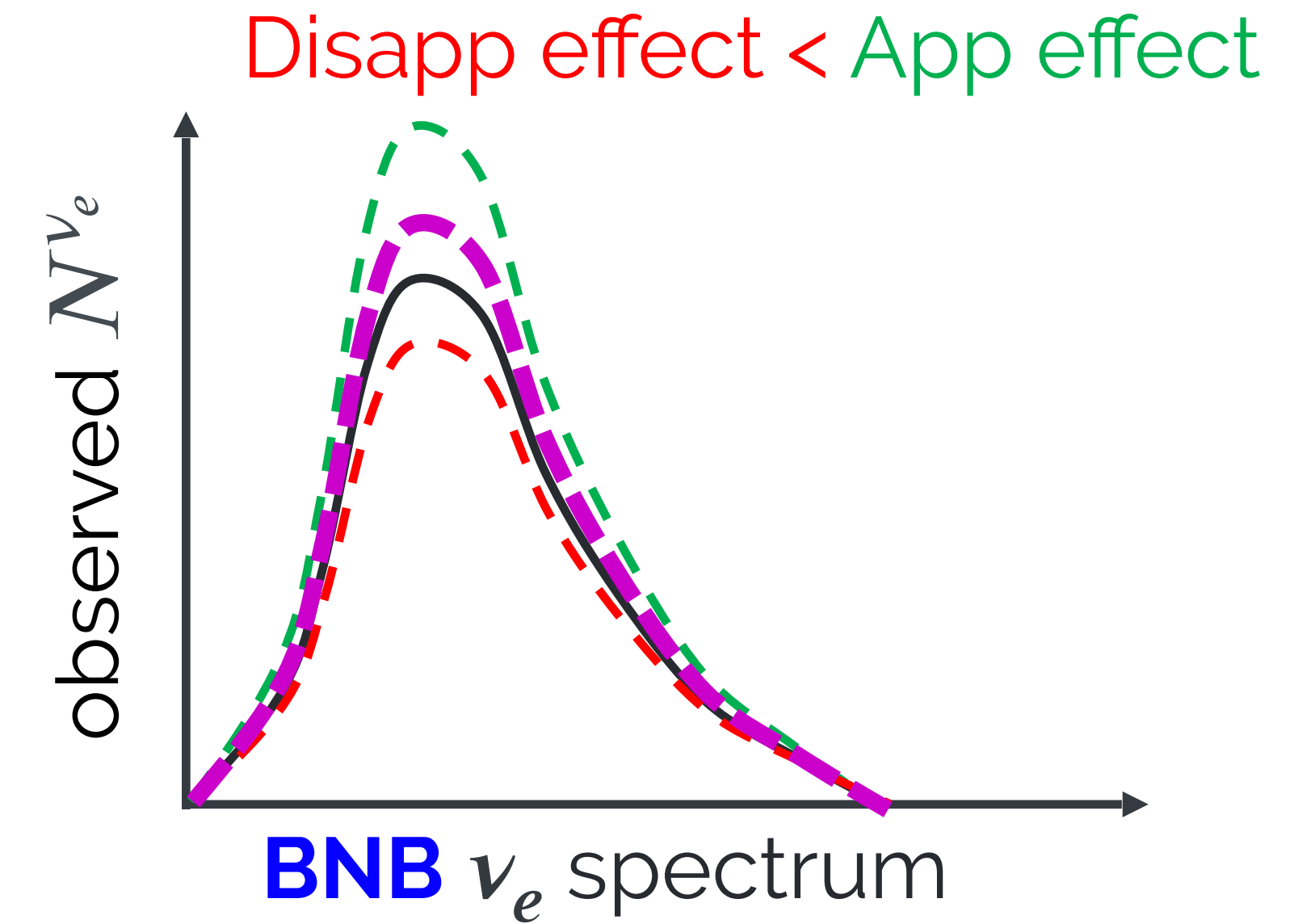
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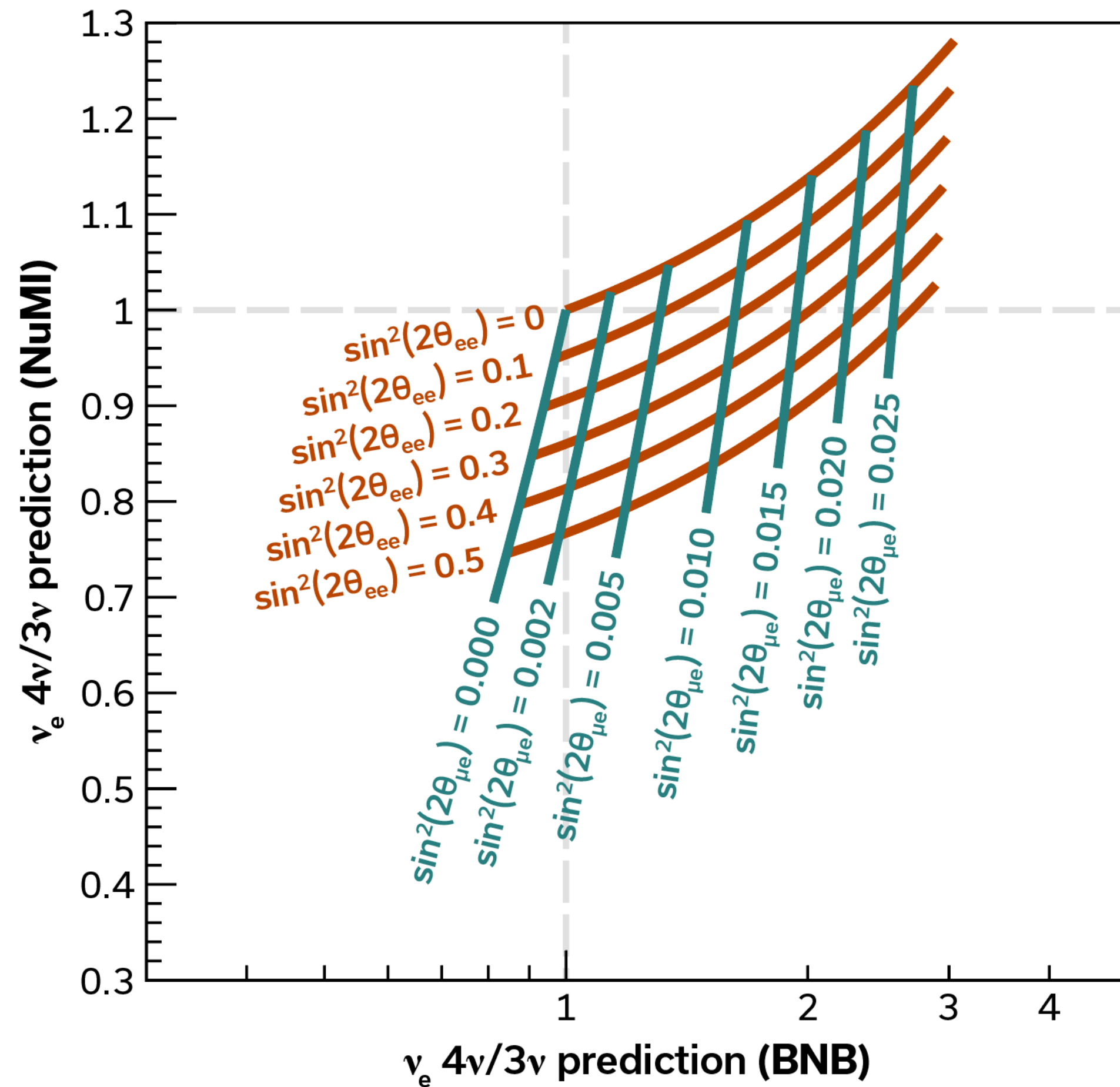


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Degeneracy Breaking using Two Beams



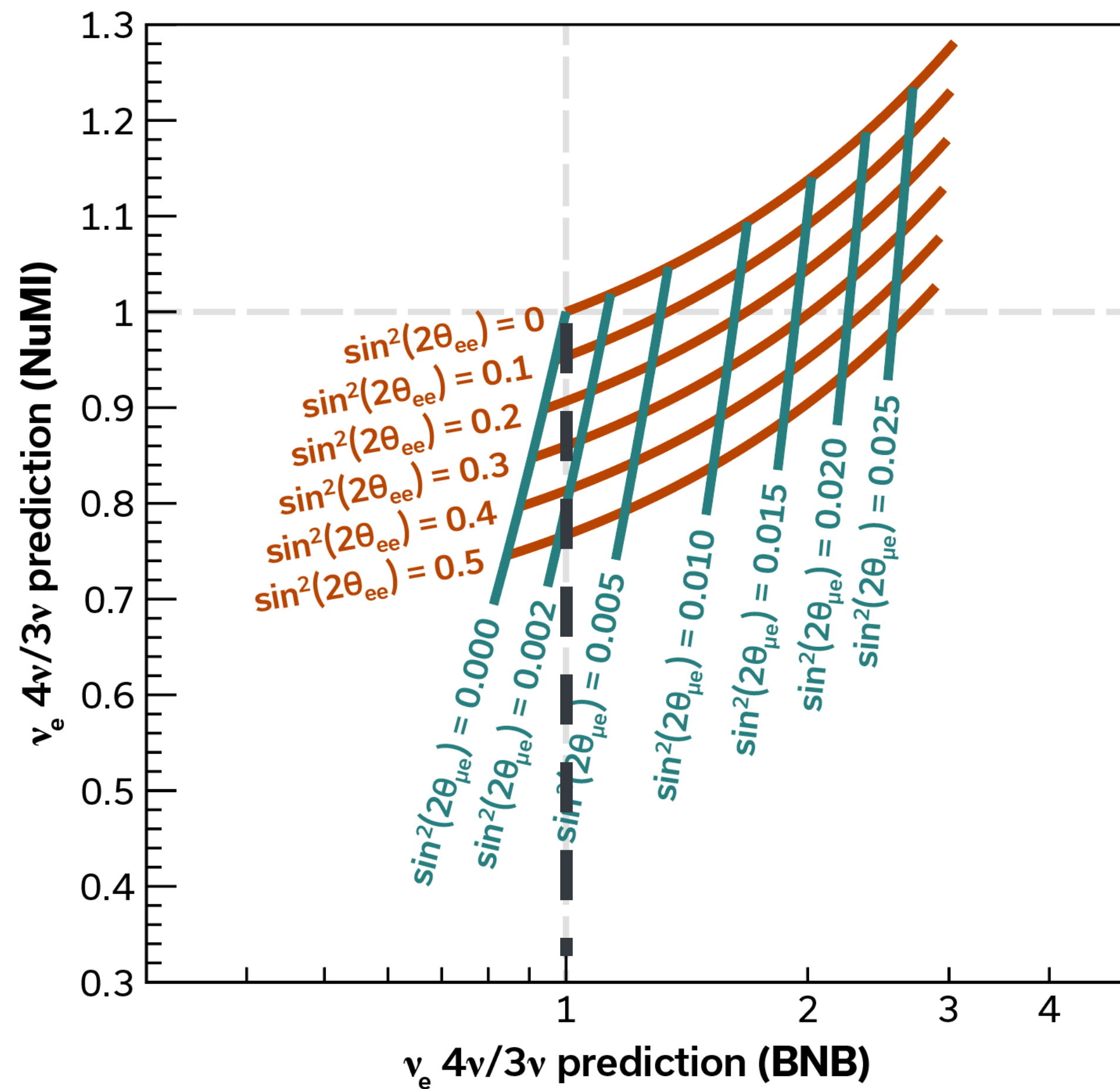
We have a 2D grid to tell us the values of the two mixing angles

X and Y axes tell us the NuMI and BNB excess/deficit **with oscillations**

- X- and Y-axes are BNB and NuMI

$$N_{\nu_e}^{osc} / N_{\nu_e}^{non-osc}$$

Degeneracy Breaking using Two Beams



From this plot, we can sense how the BNB degeneracy is broken

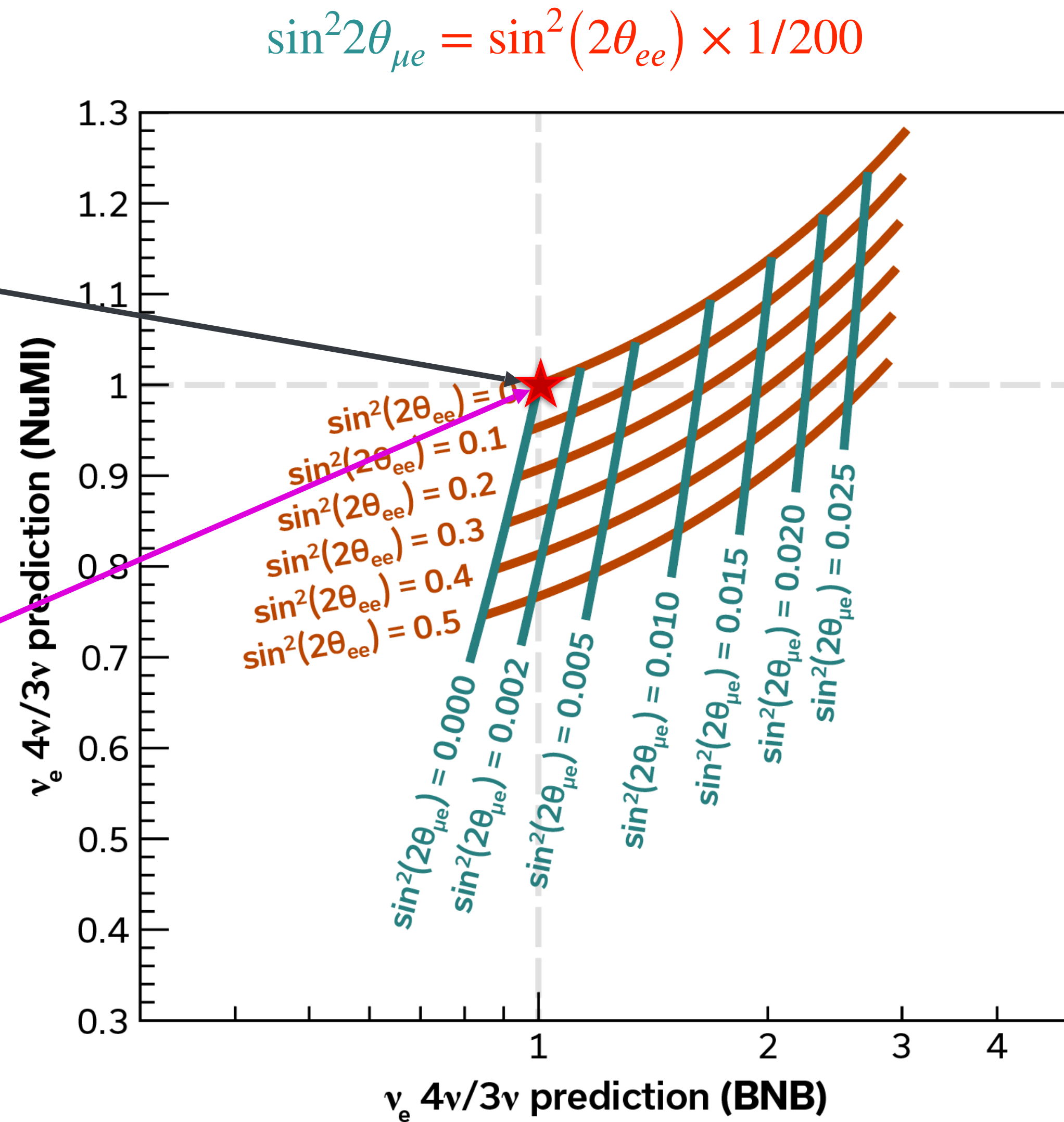
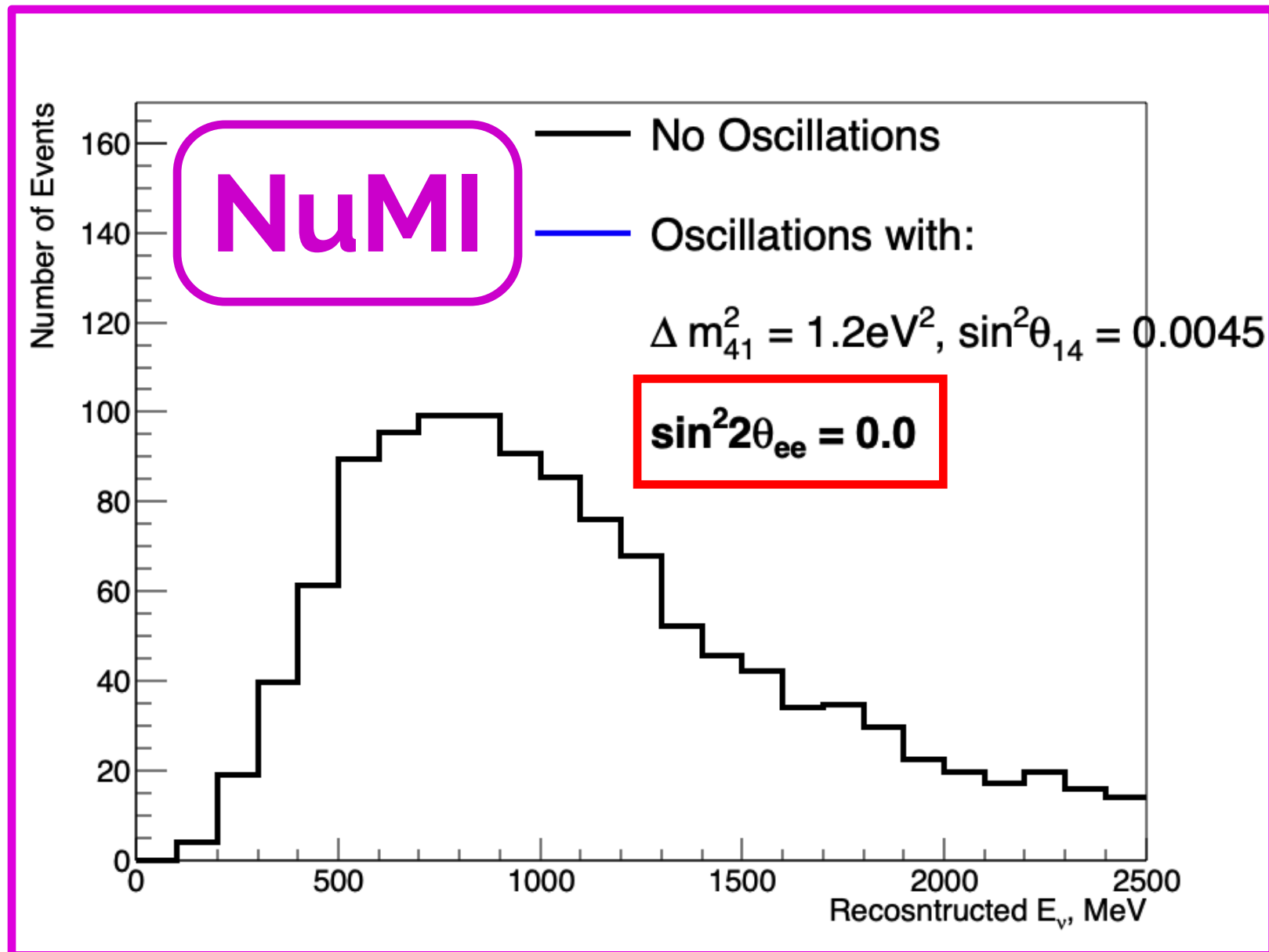
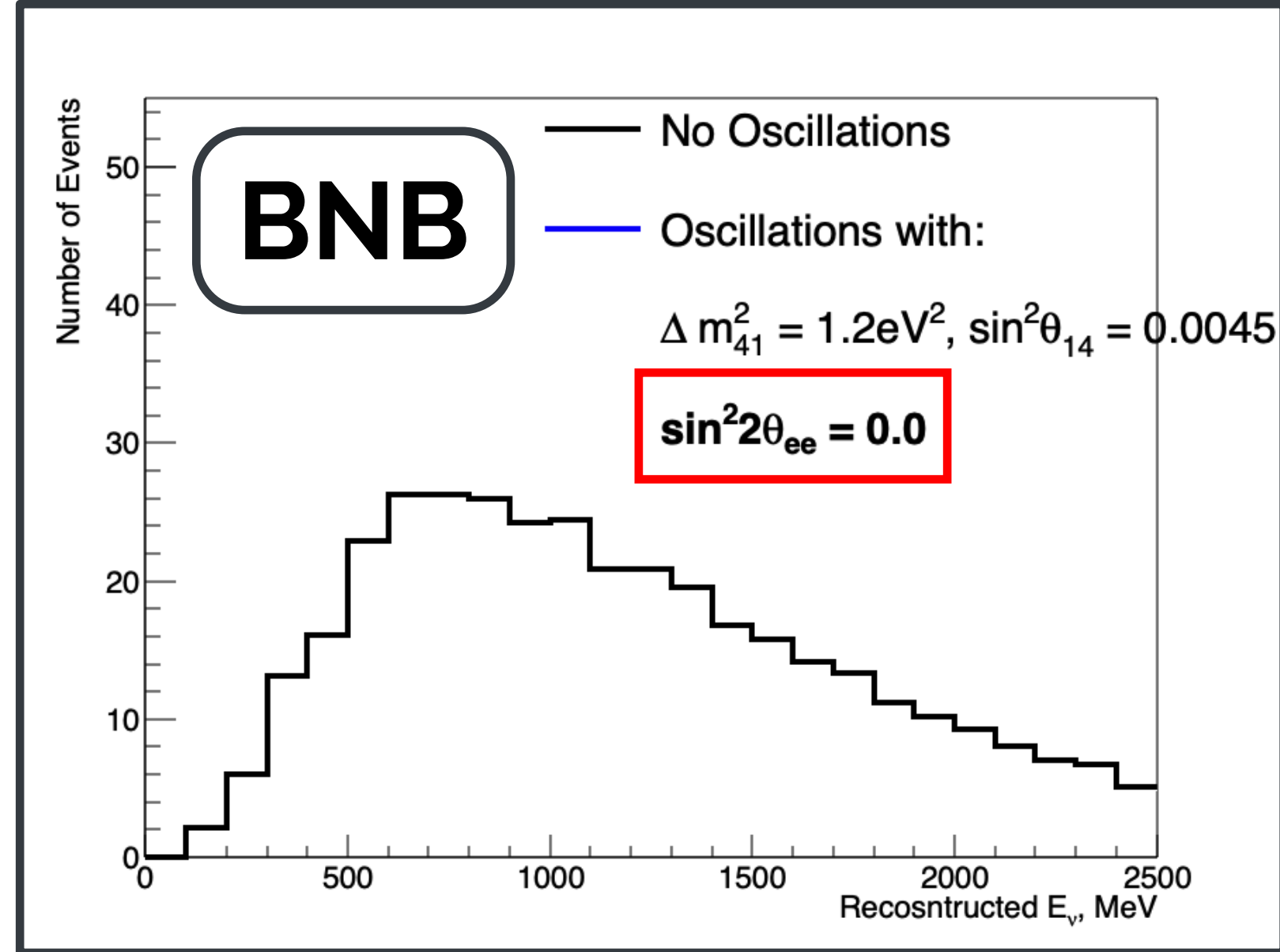
**Scan along the BNB degeneracy line
– the black dashed line**

- BNB no change
- NuMI deficit grows rapidly with $\sin^2(2\theta_{ee})$ [little impact from $\sin^2 2\theta_{\mu e}$]
- disentangle disappearance from appearance

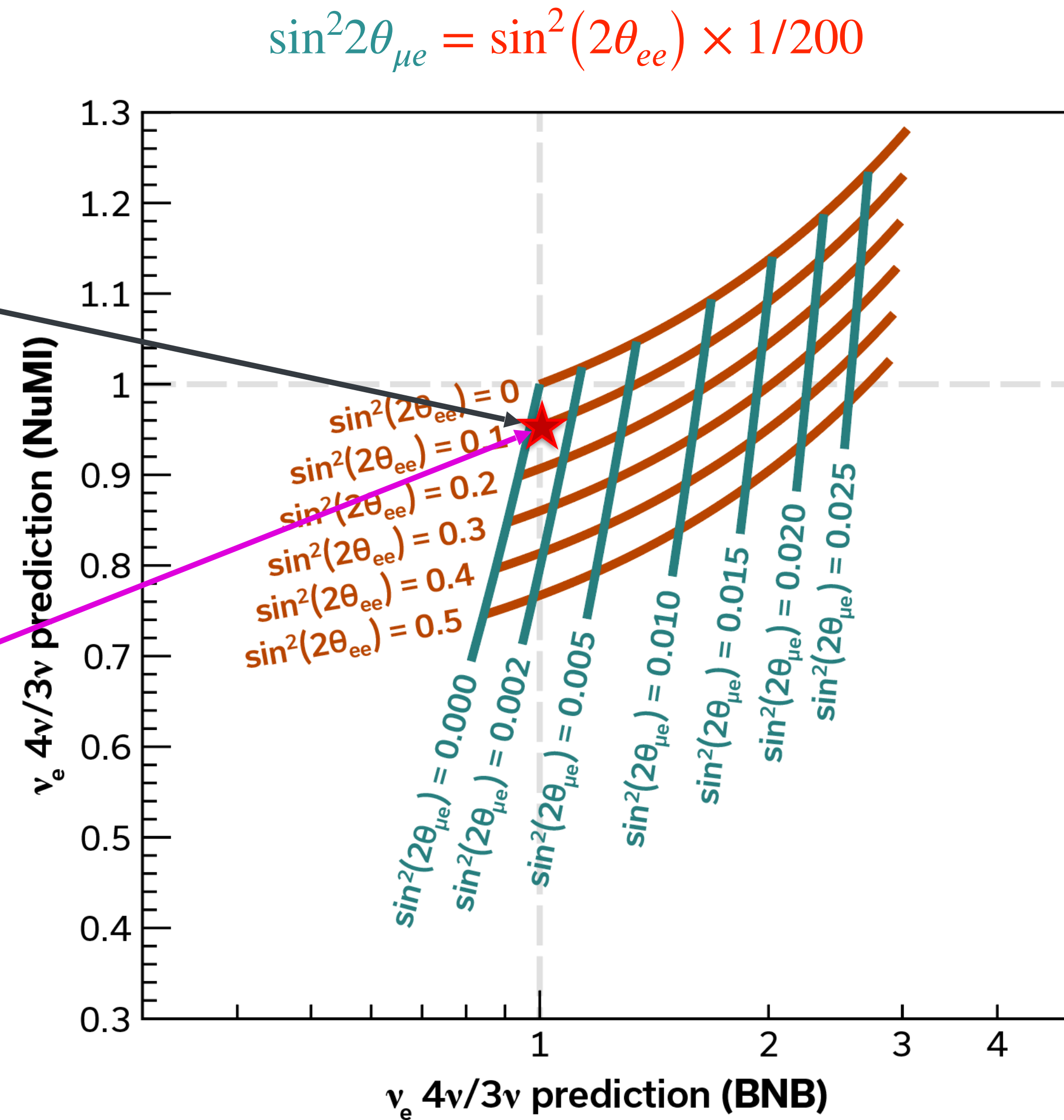
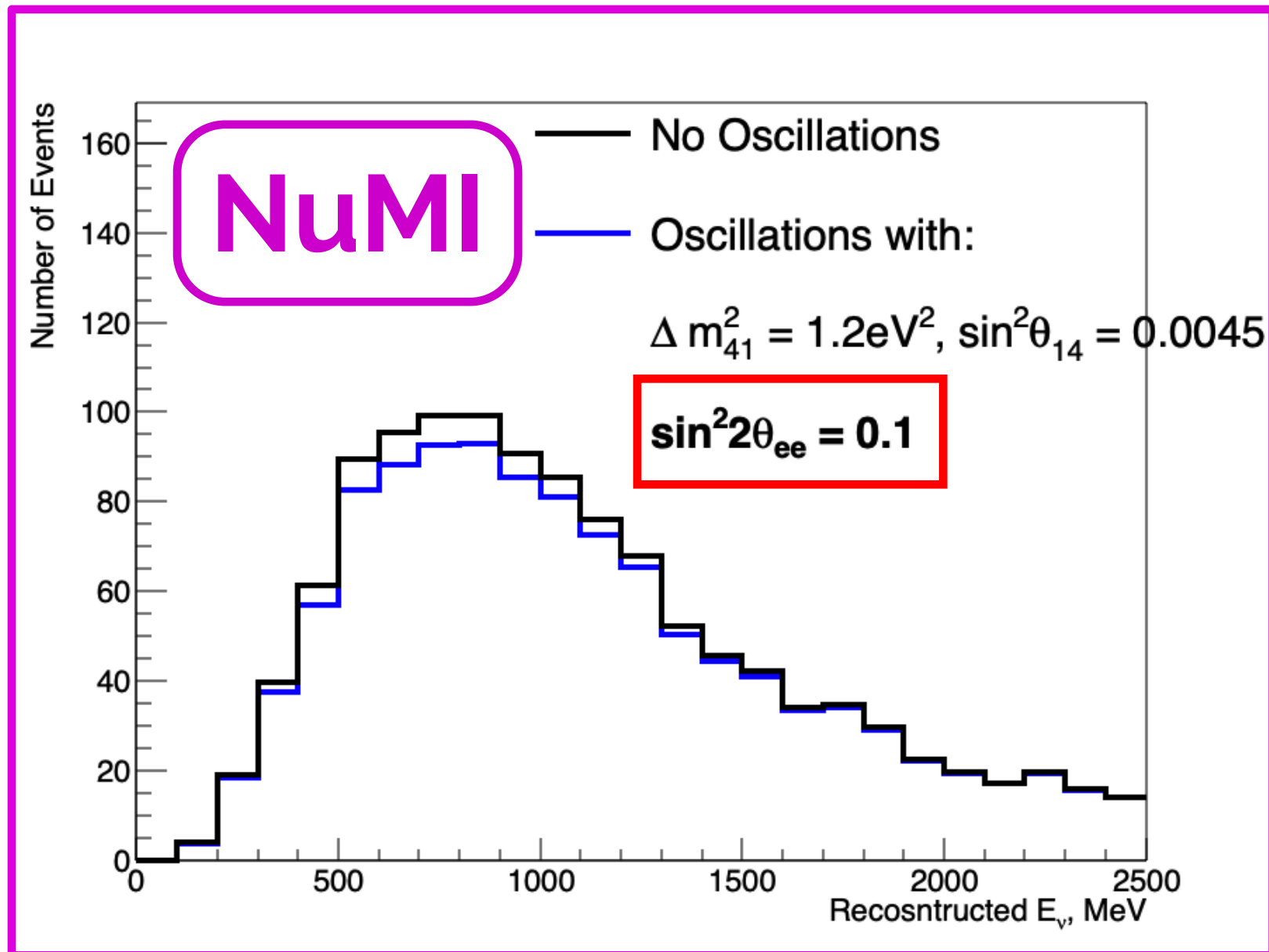
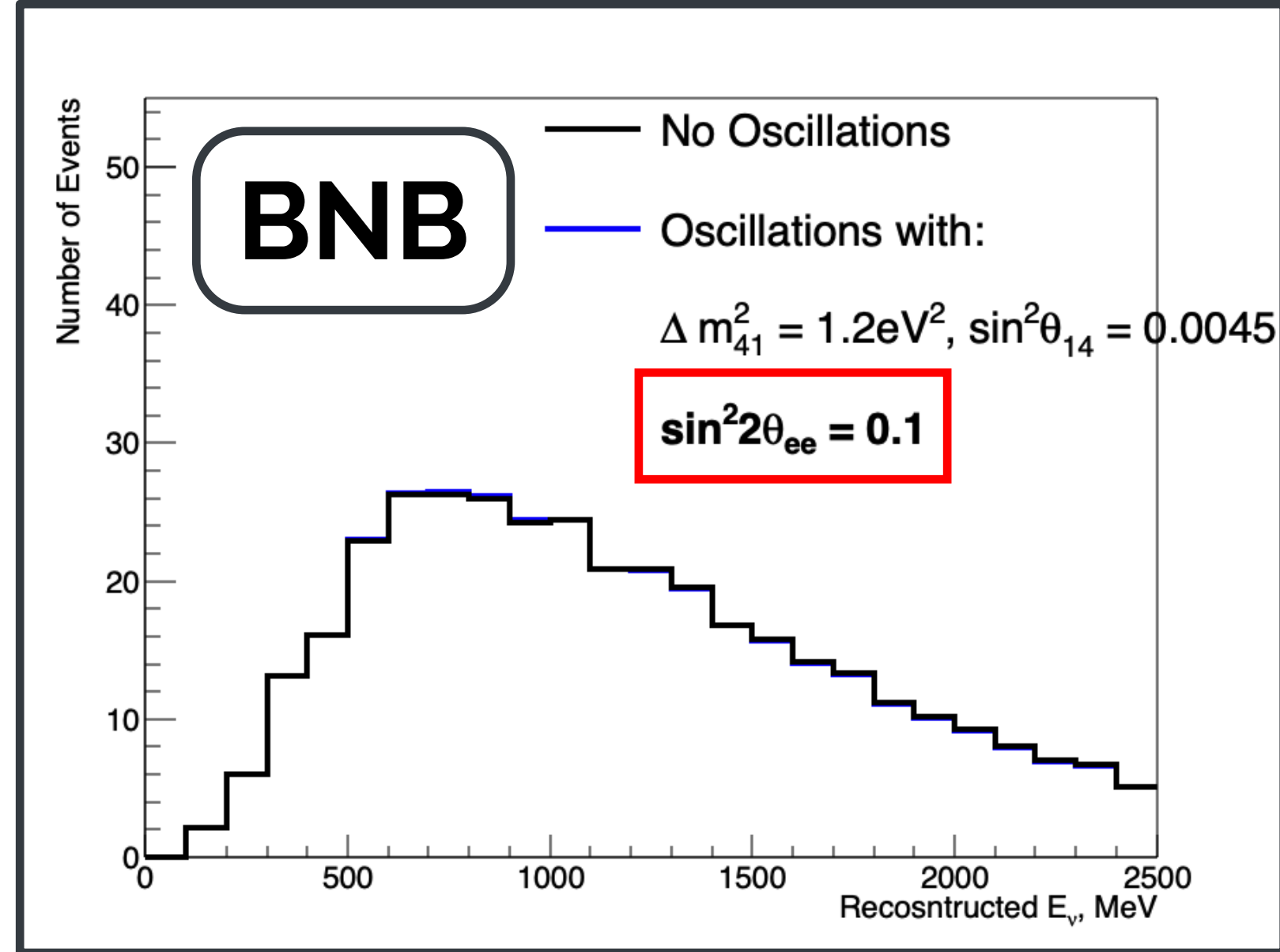
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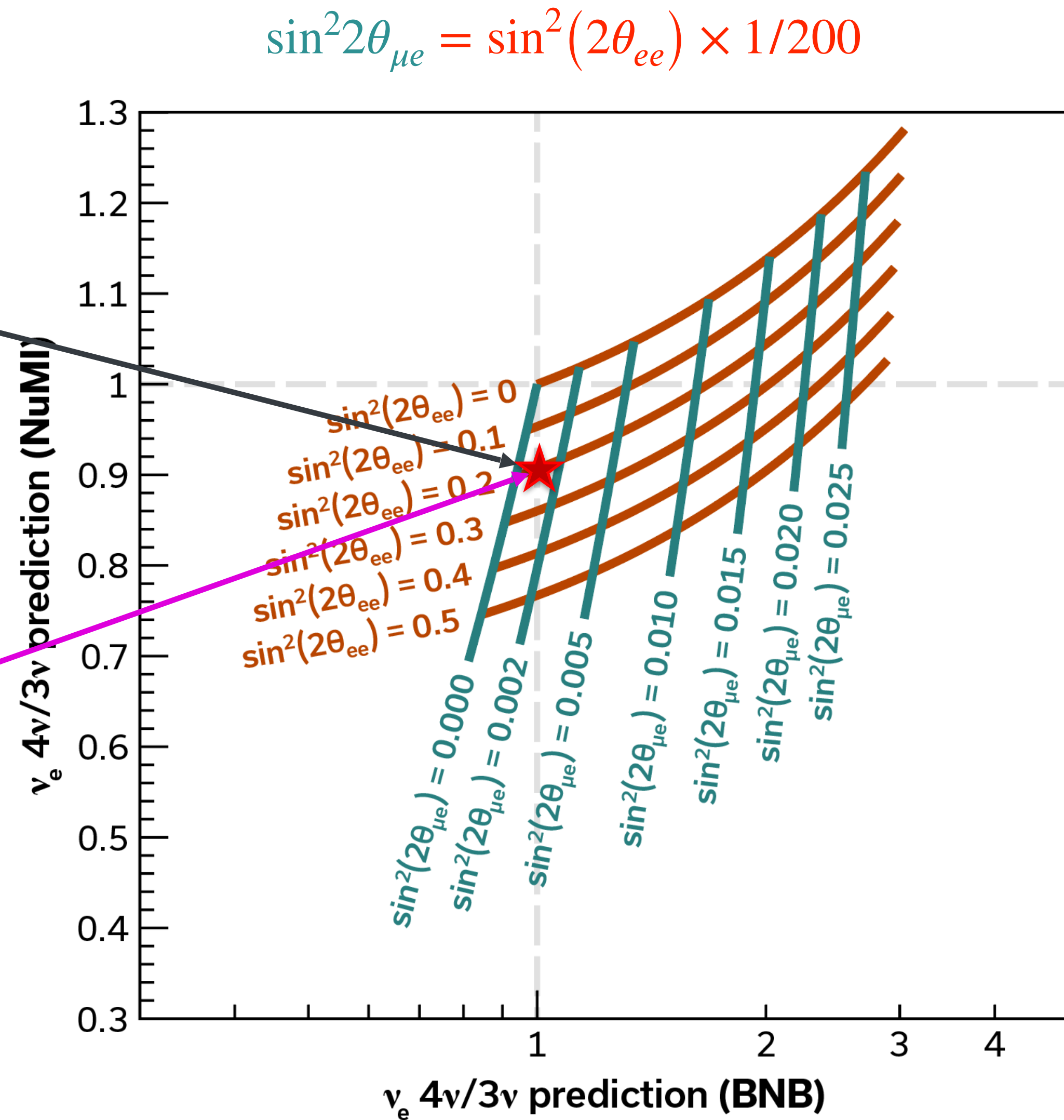
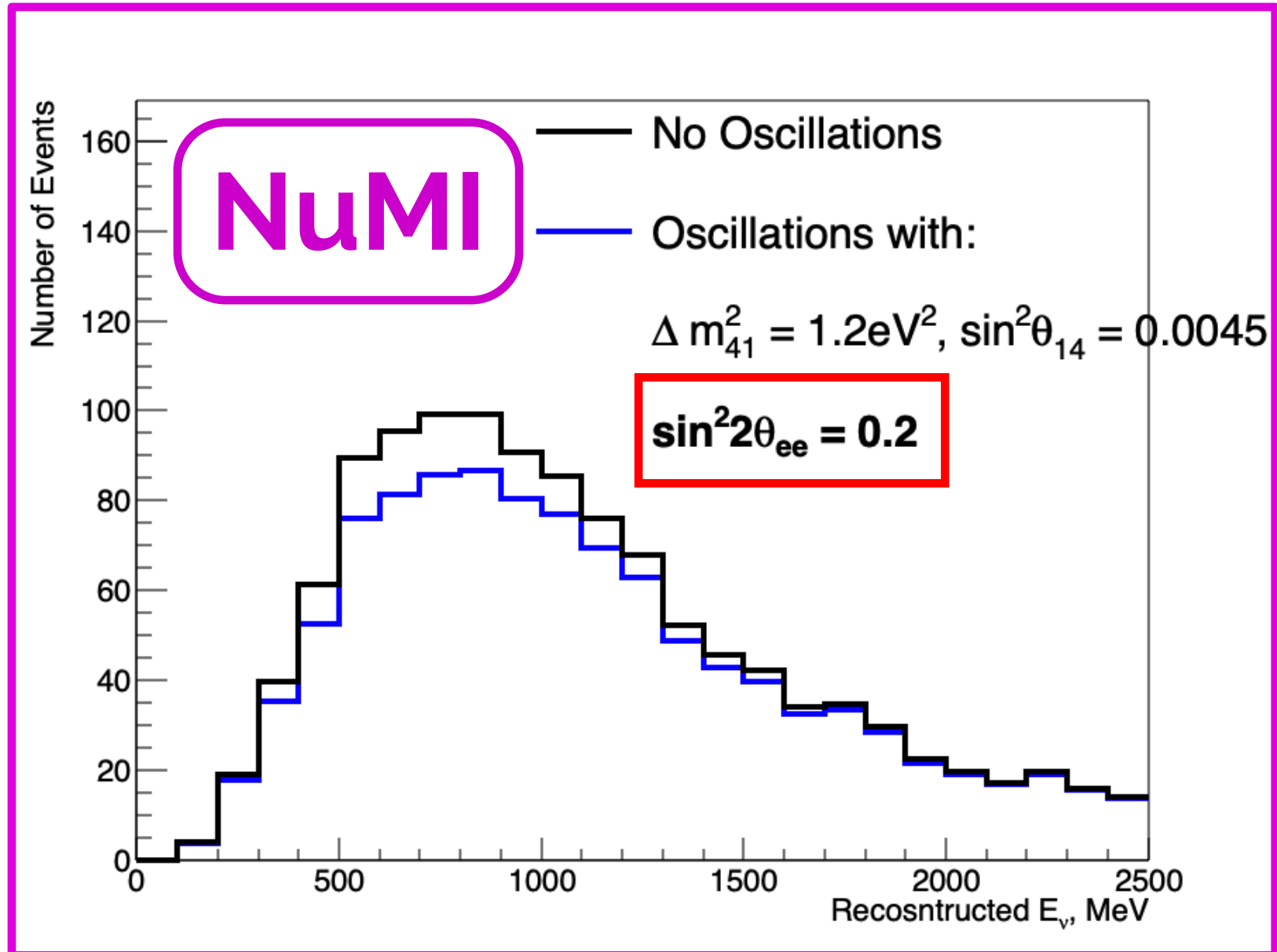
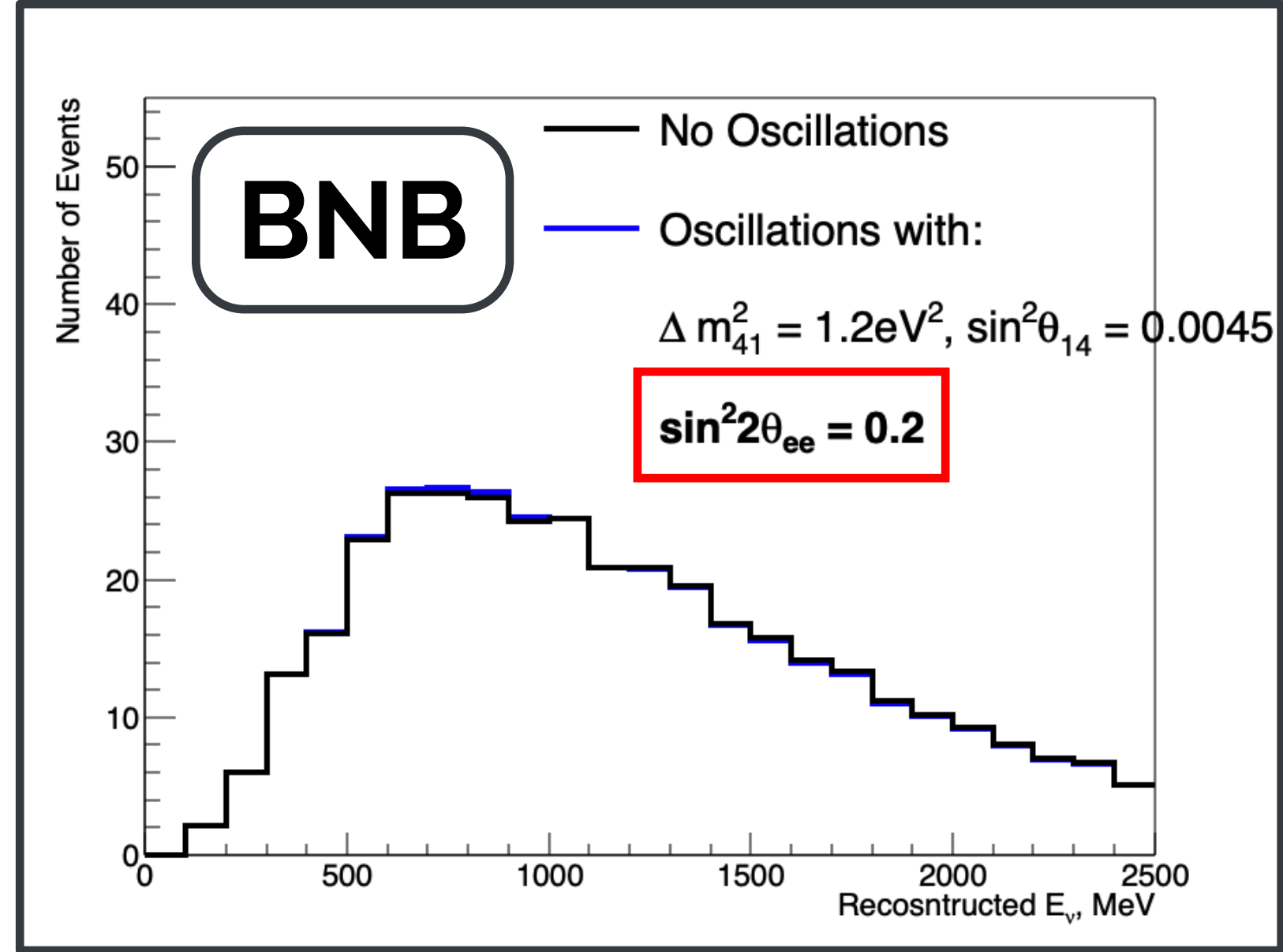
Degeneracy Breaking using Two Beams



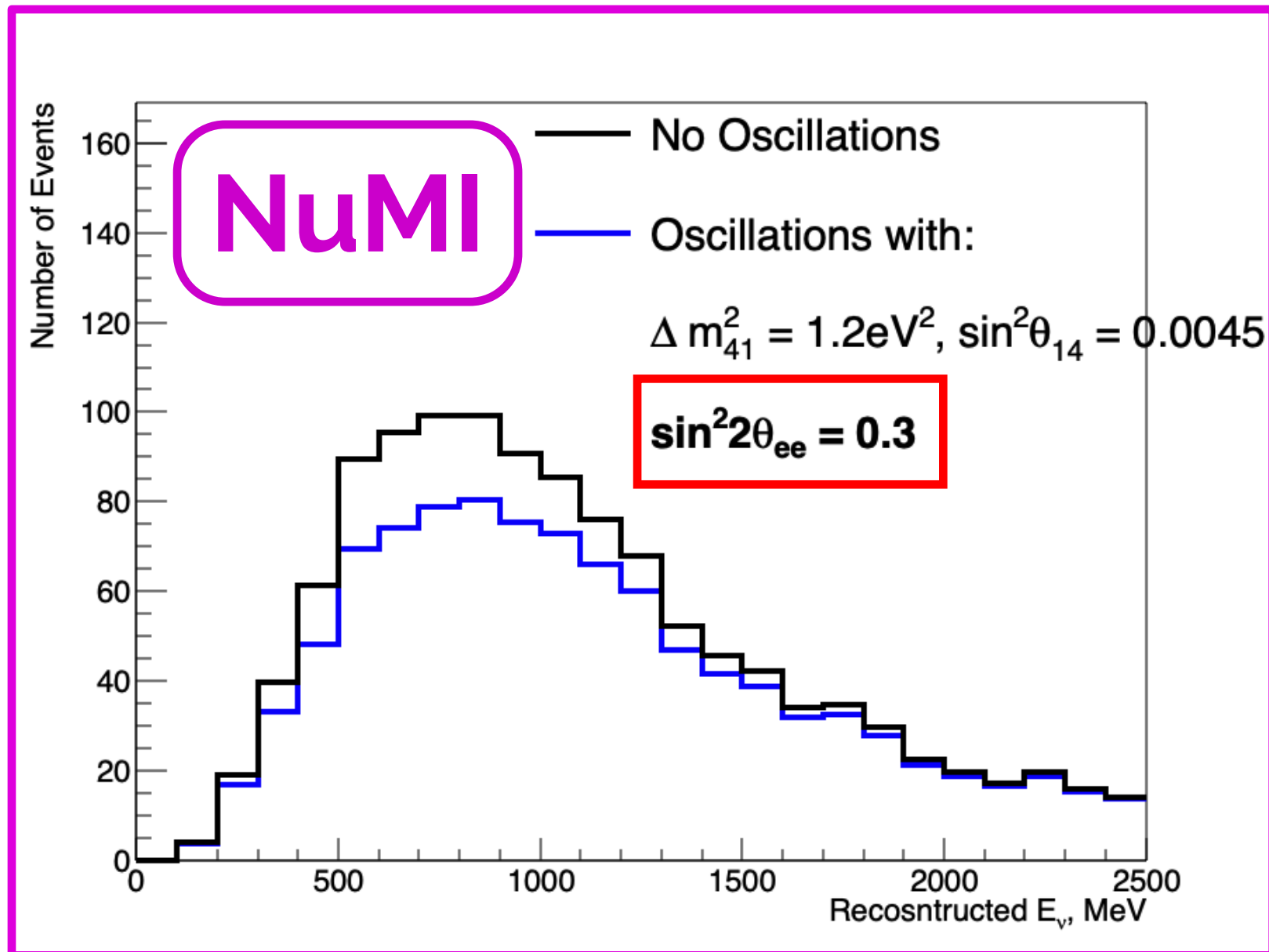
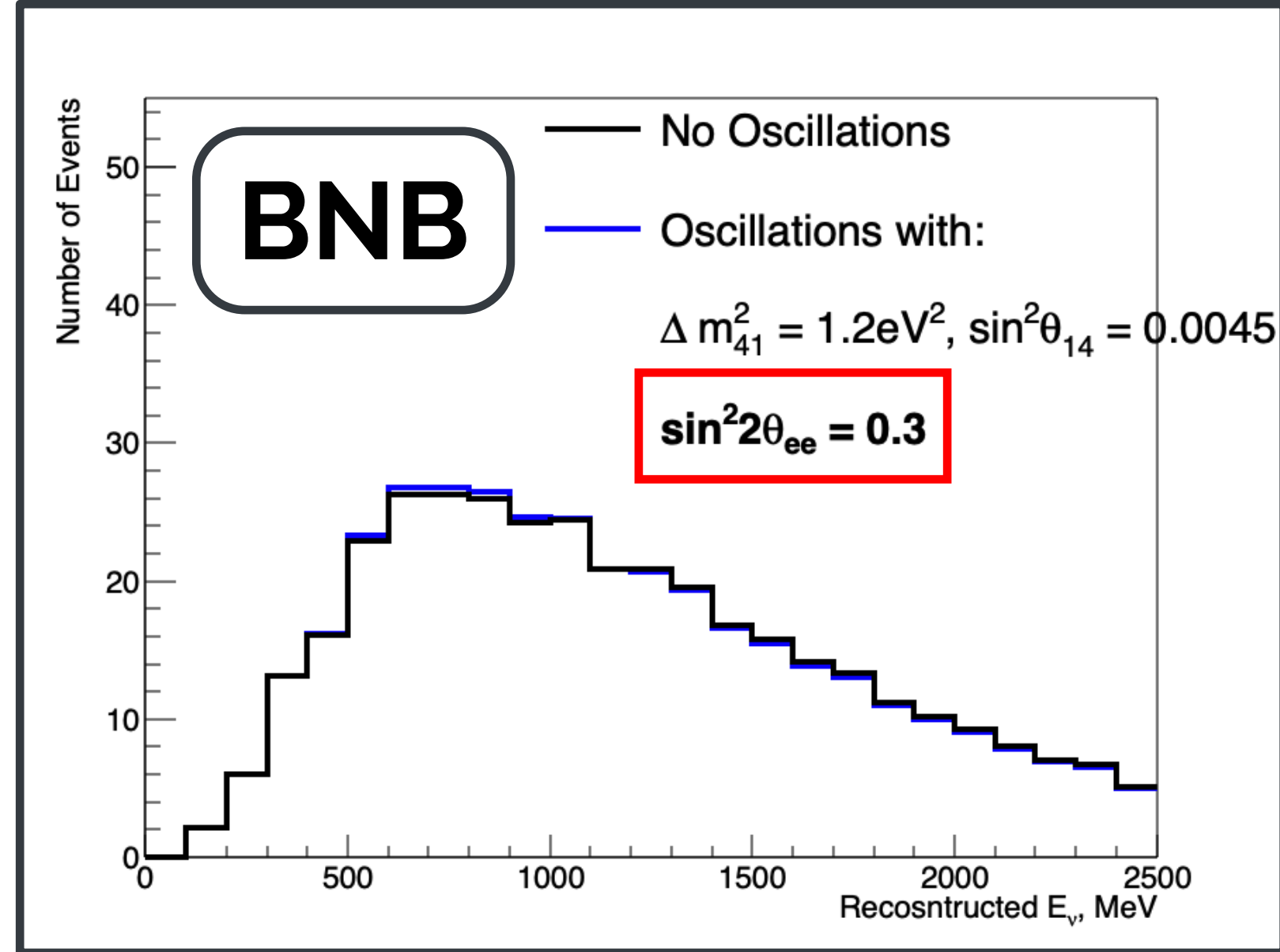
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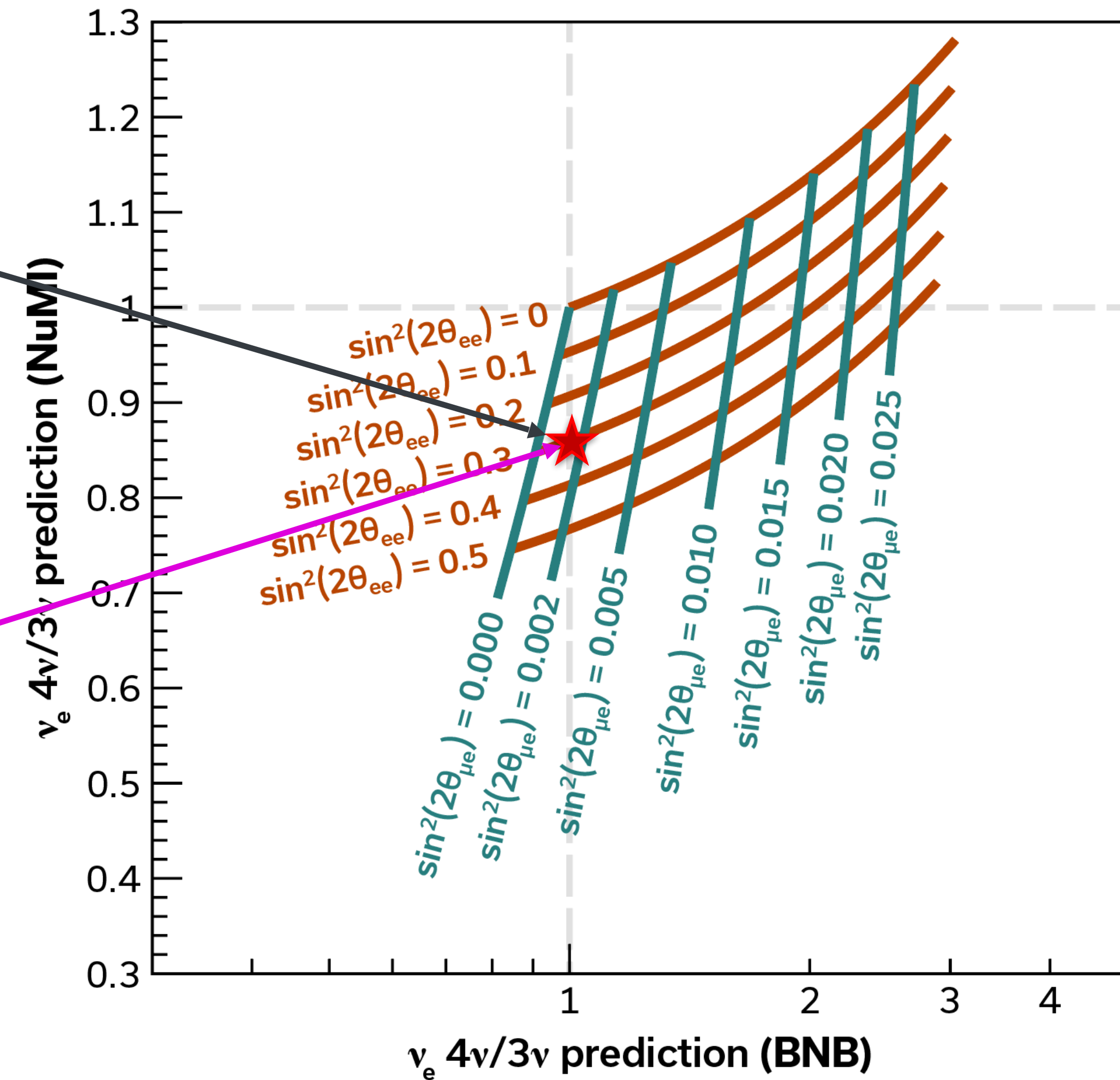
Degeneracy Breaking using Two Beams



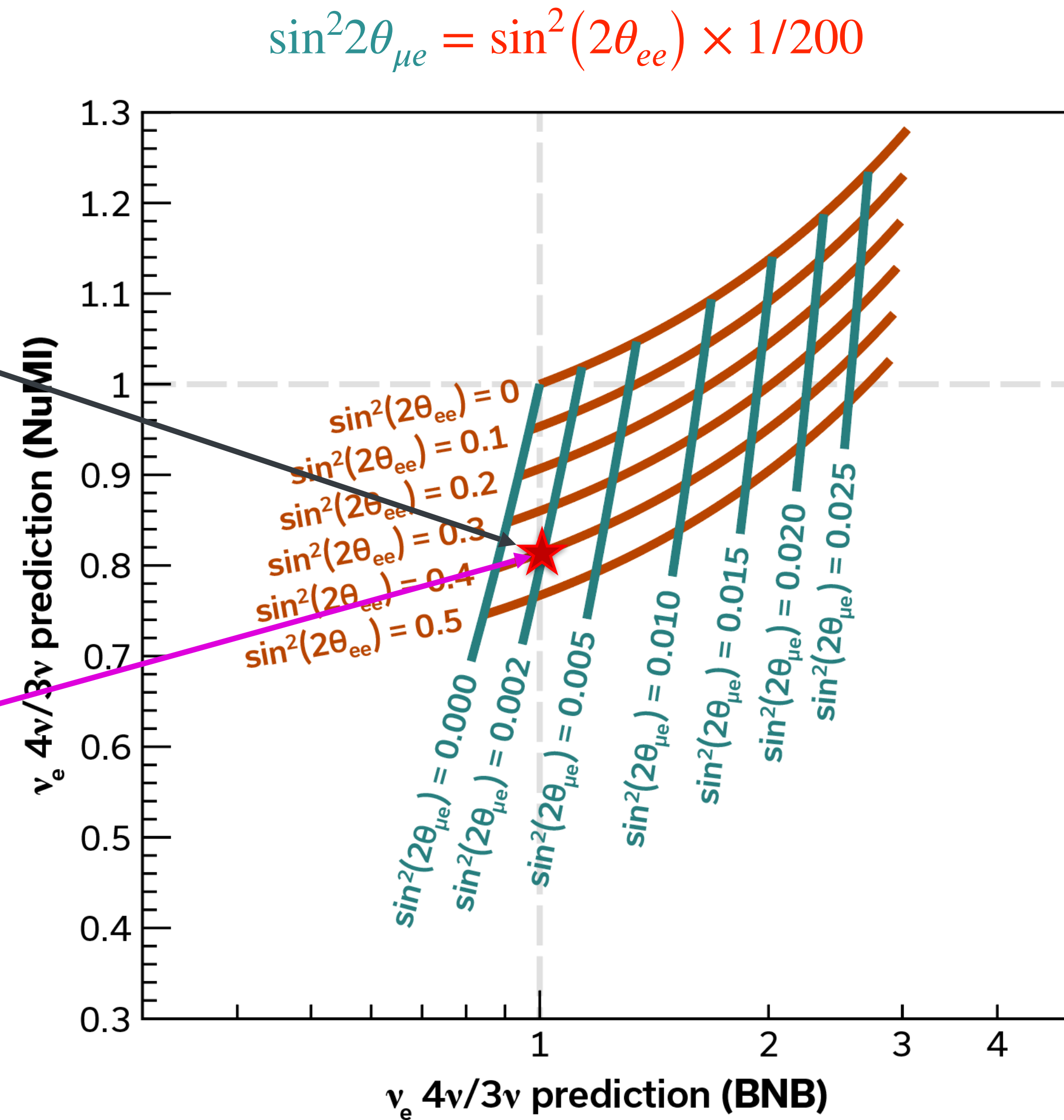
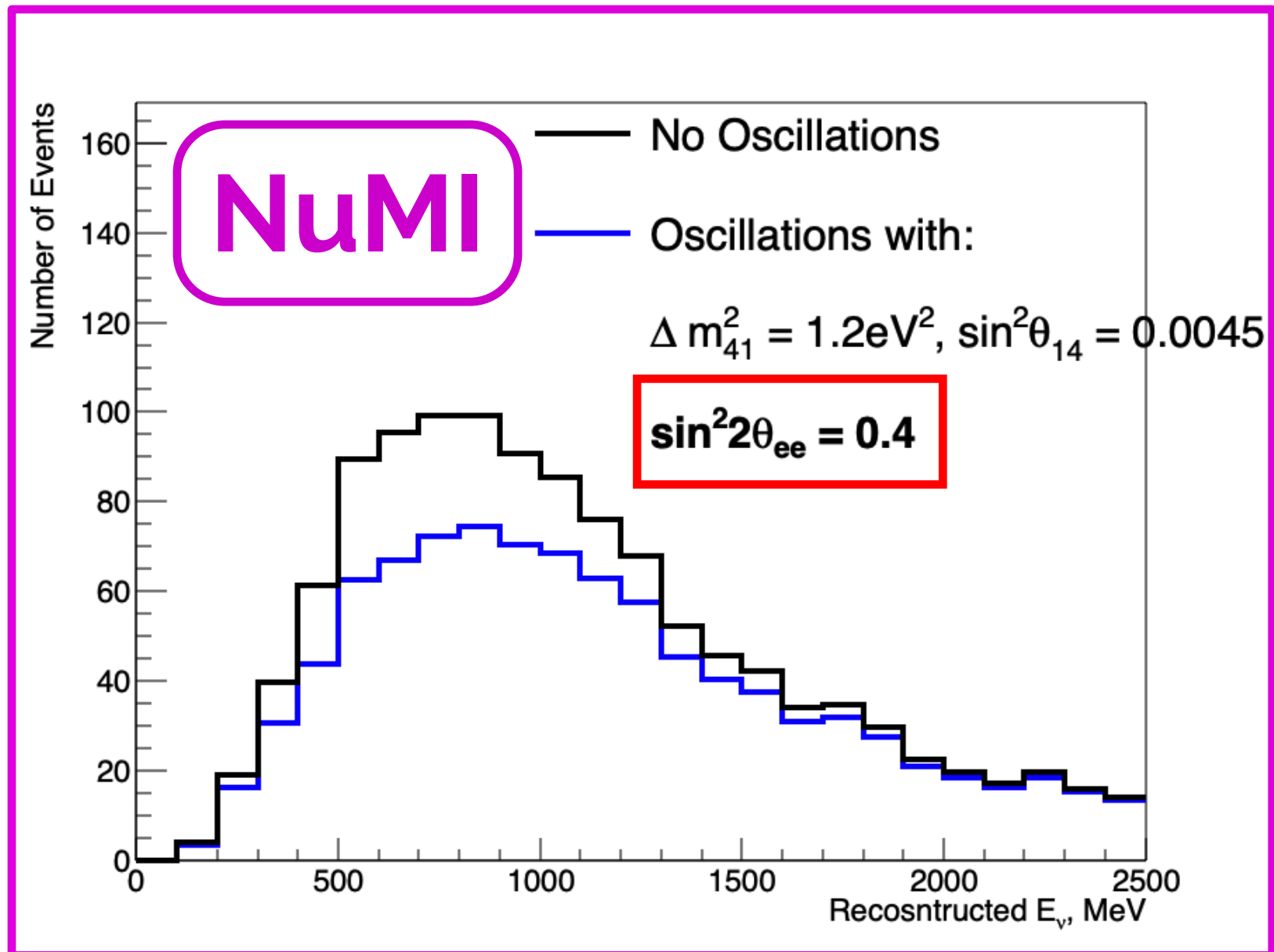
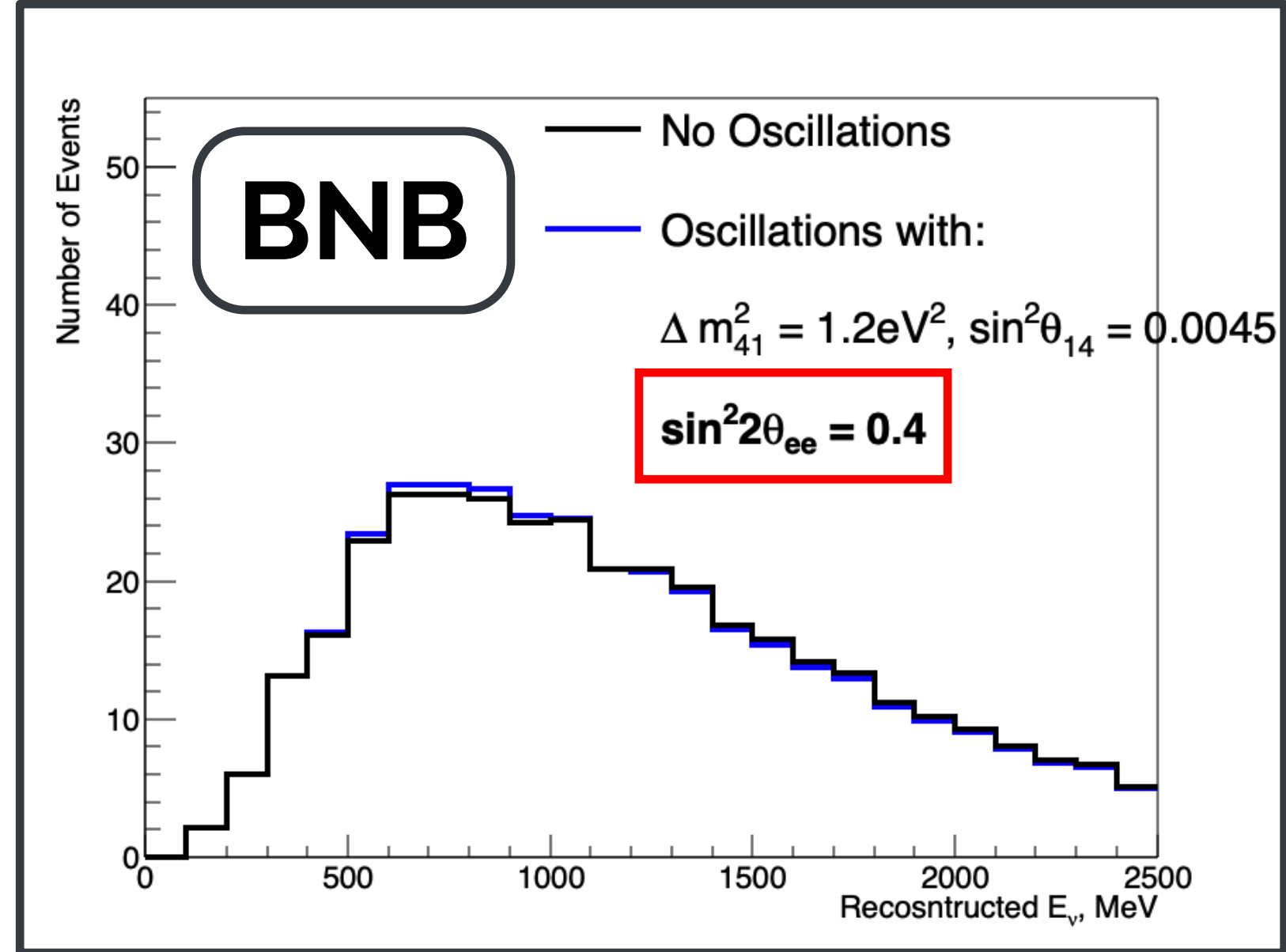
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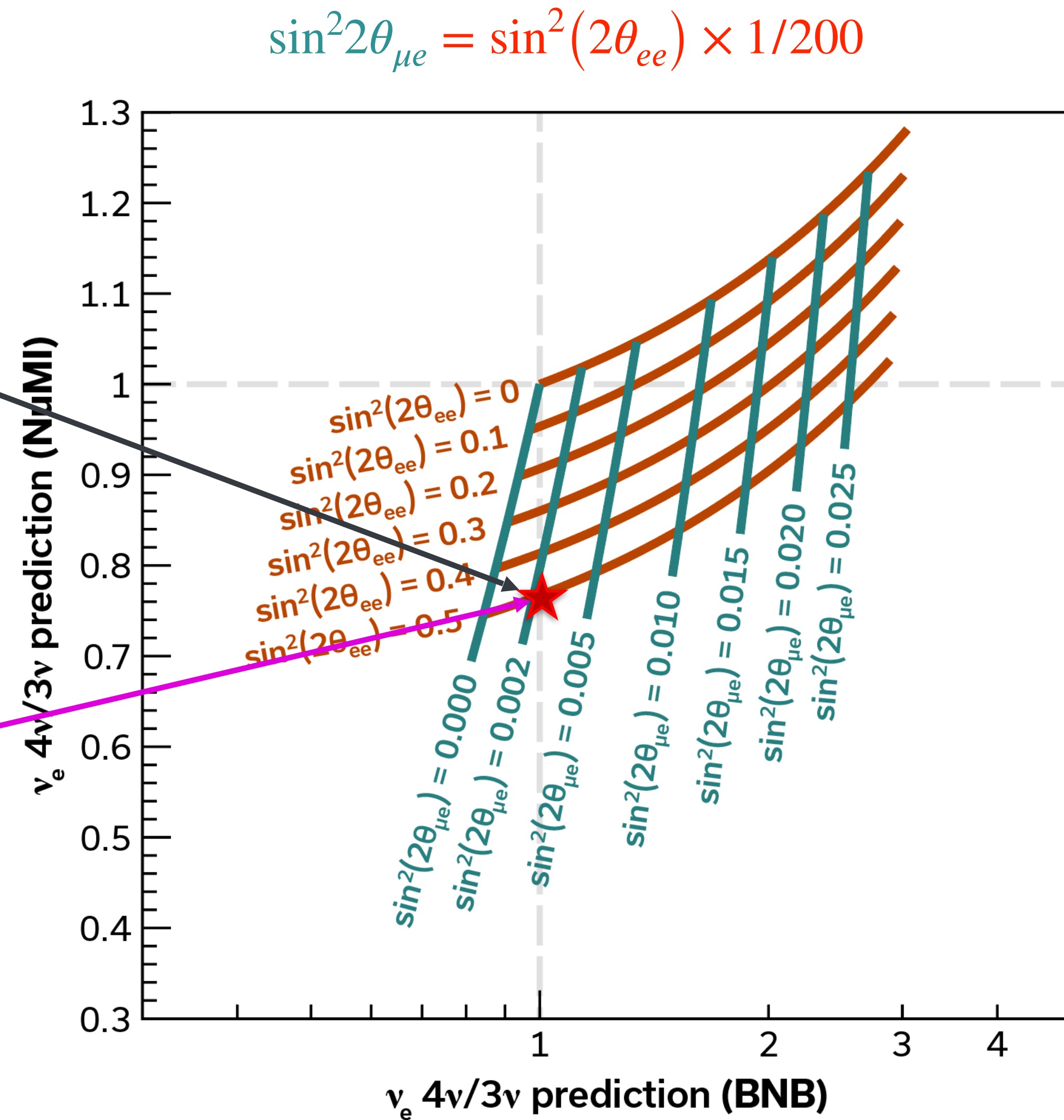
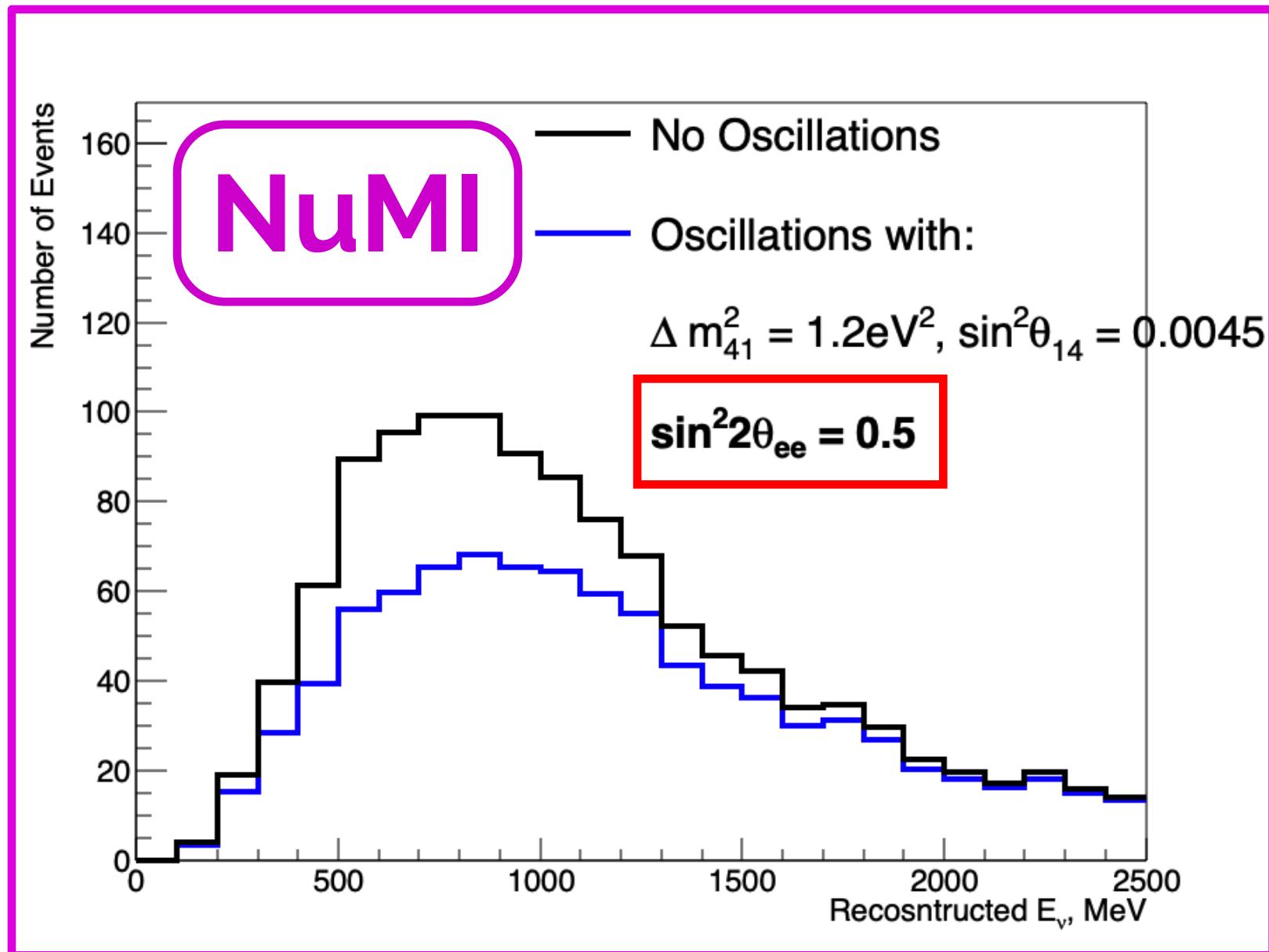
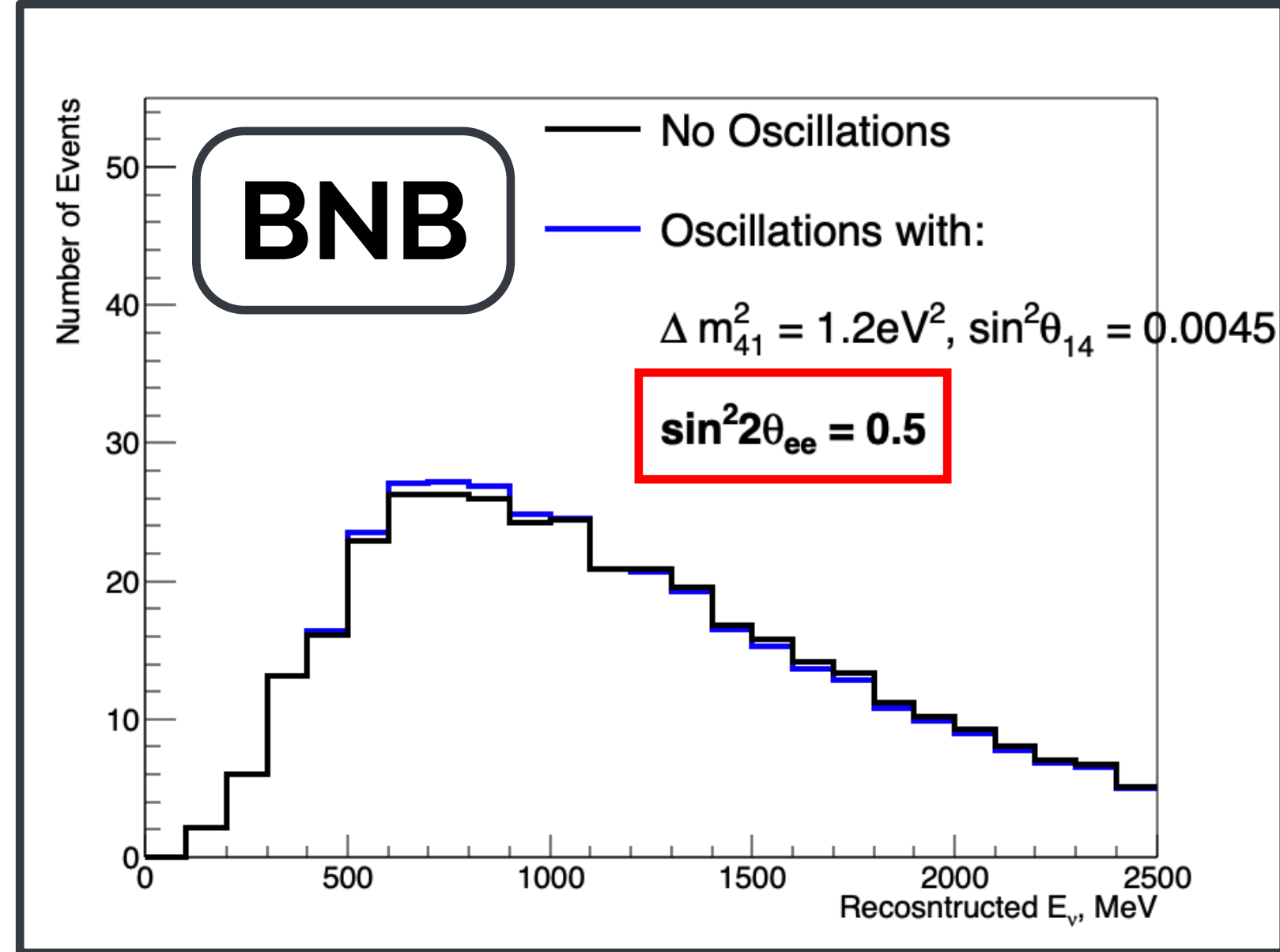
$$\sin^2 2\theta_{\mu e} = \sin^2(2\theta_{ee}) \times 1/200$$



Degeneracy Breaking using Two Beams

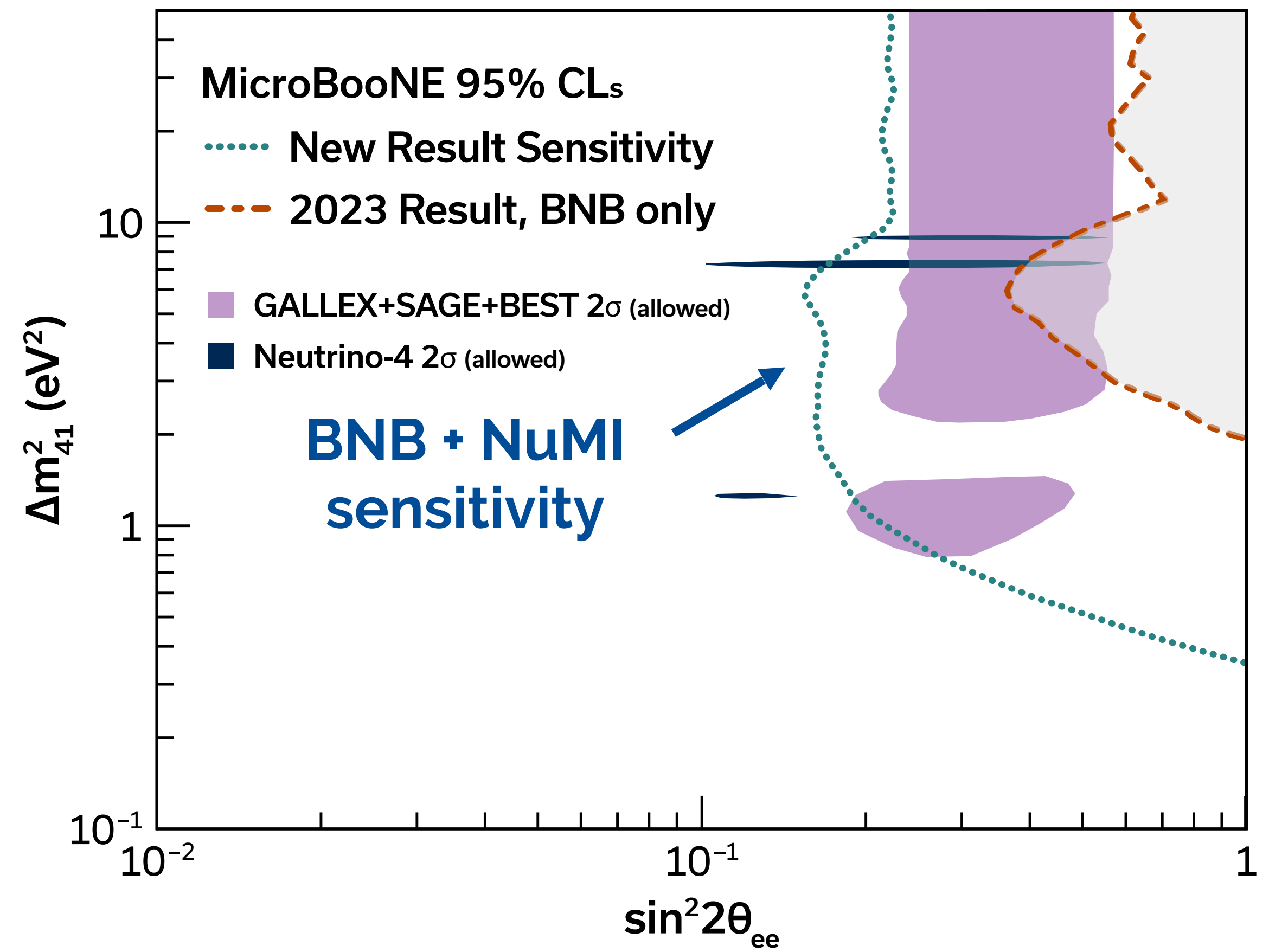
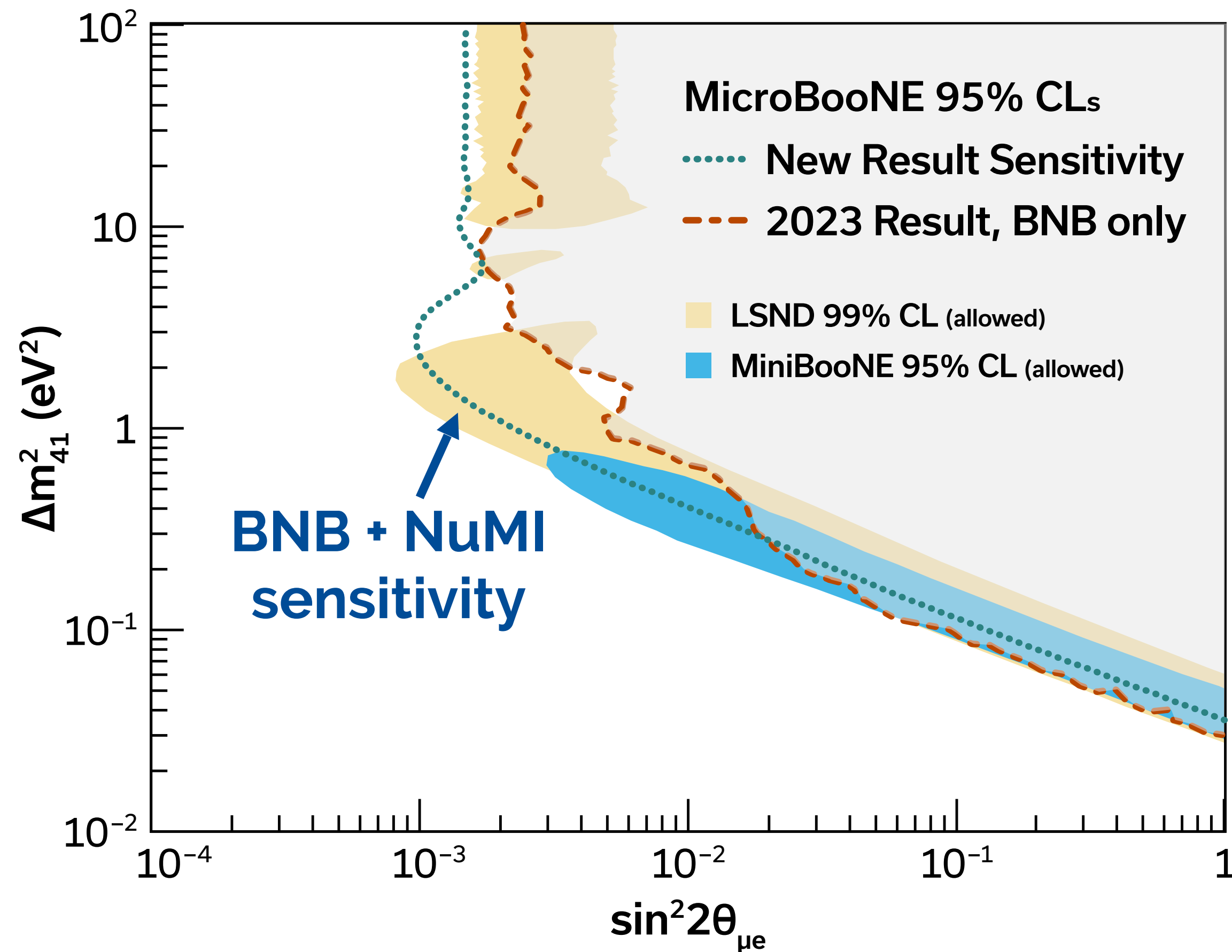


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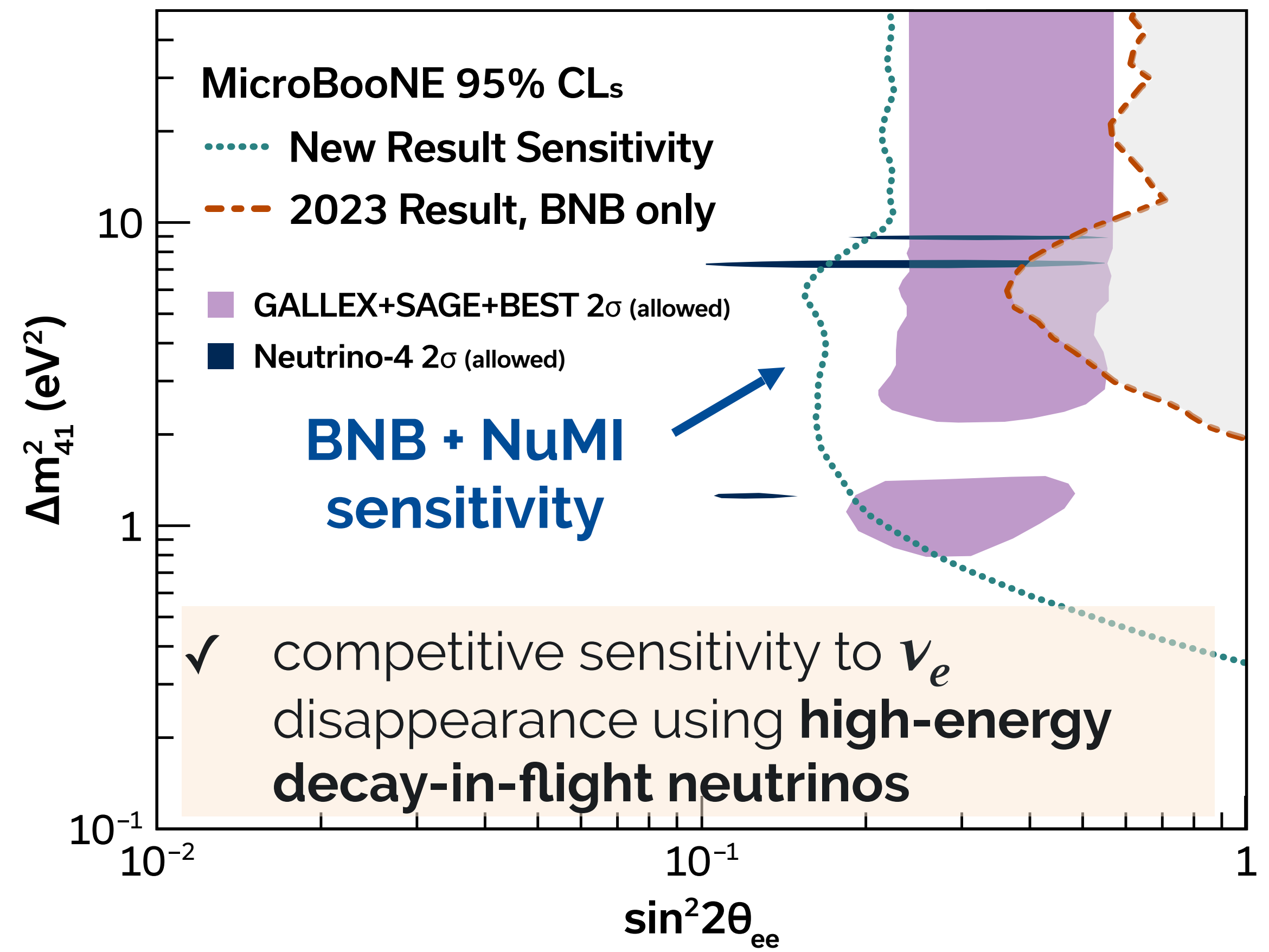
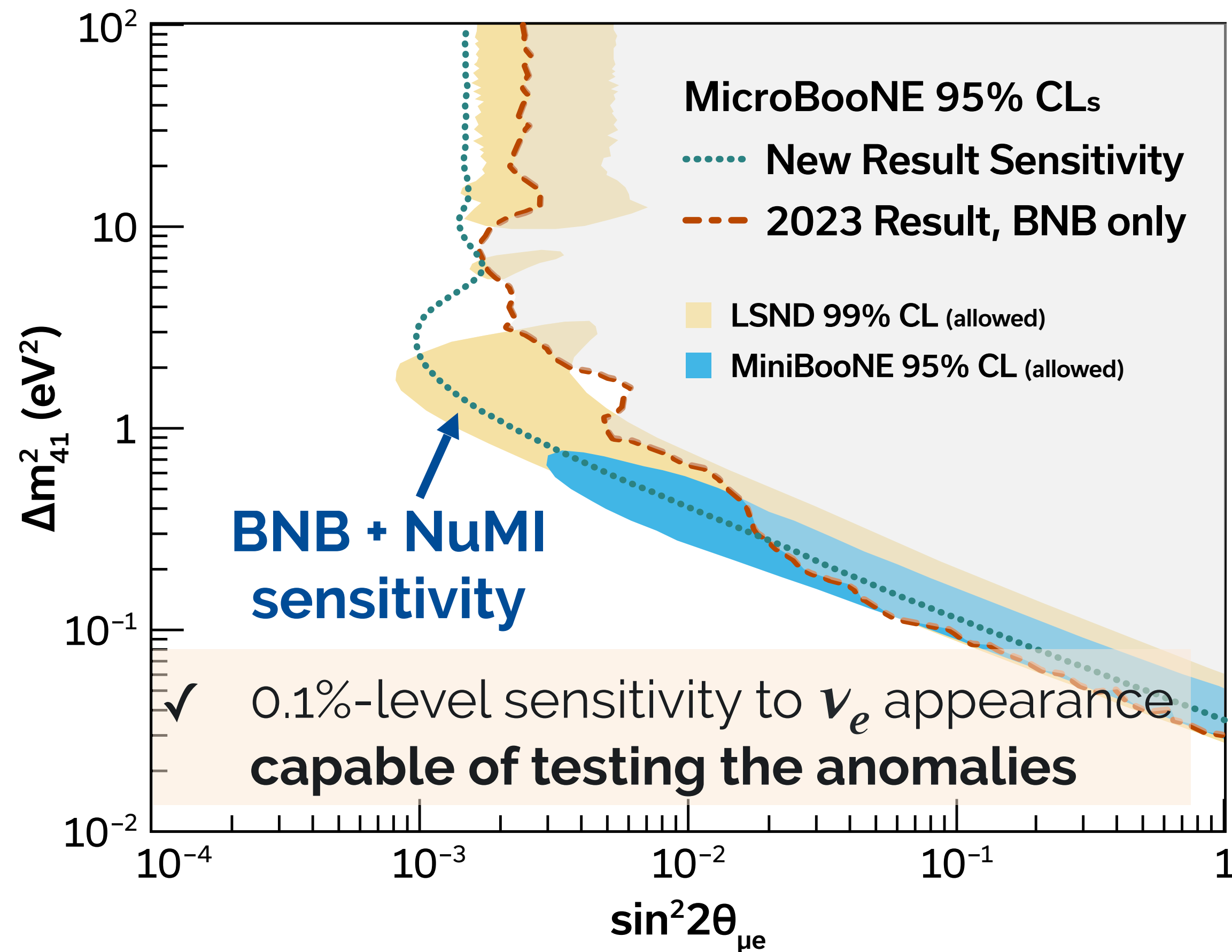
One detector, two beams

- New result (*Nature* **648**, 64-69 (2025)) uses the first three years of **BNB and NuMI data**
- Combining the two beam datasets **unlocks their full power** to test the 3+1 model

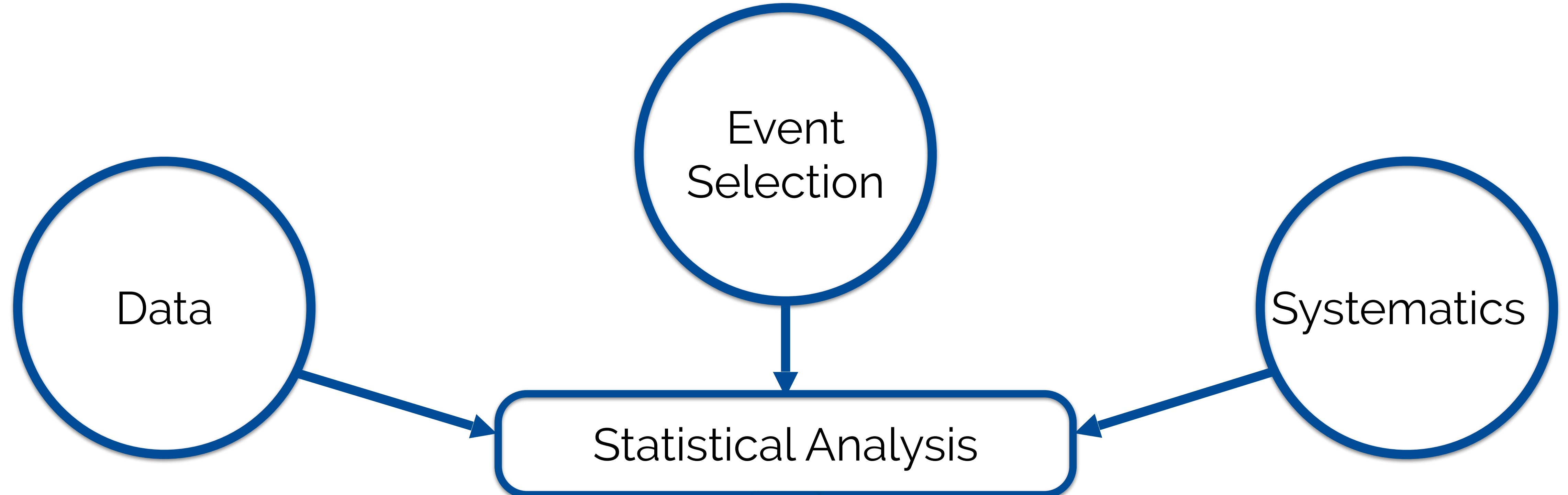


One detector, two beams

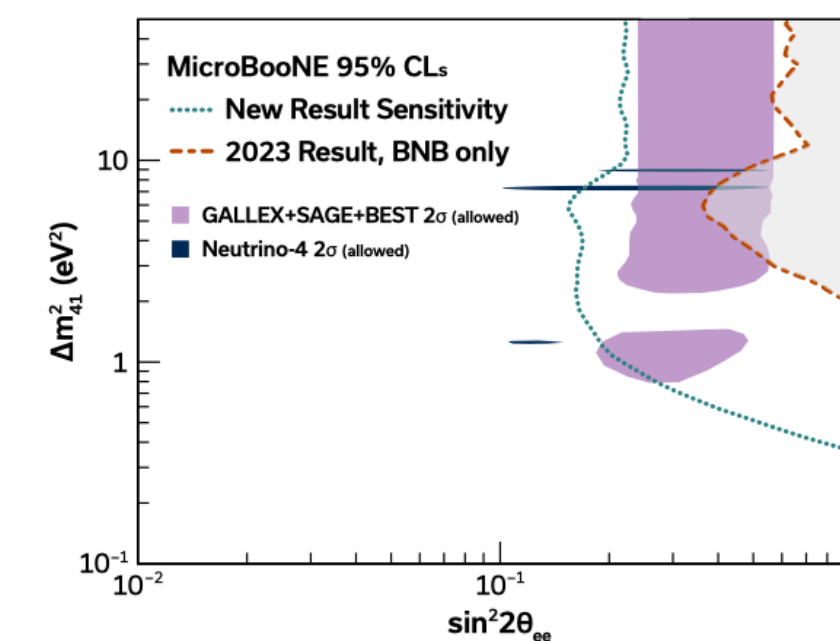
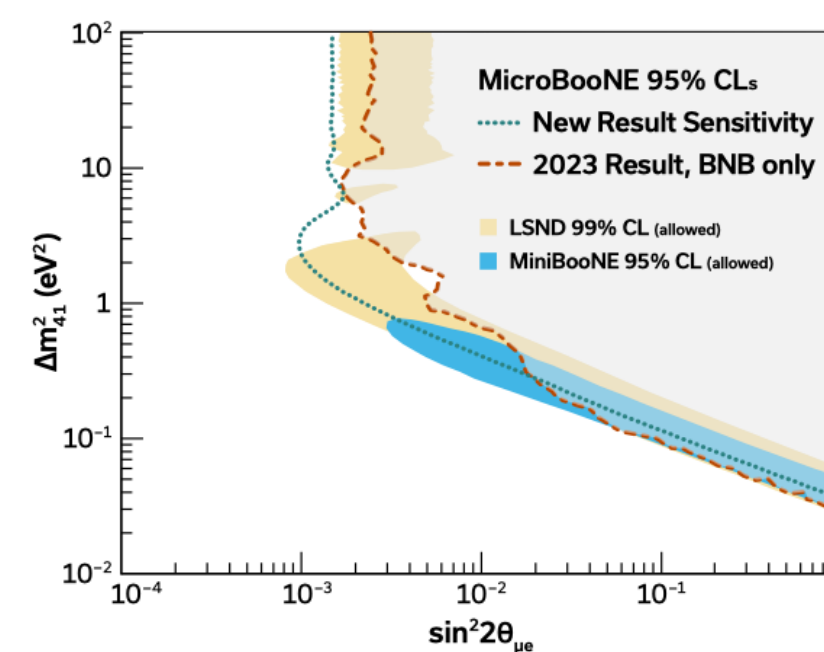
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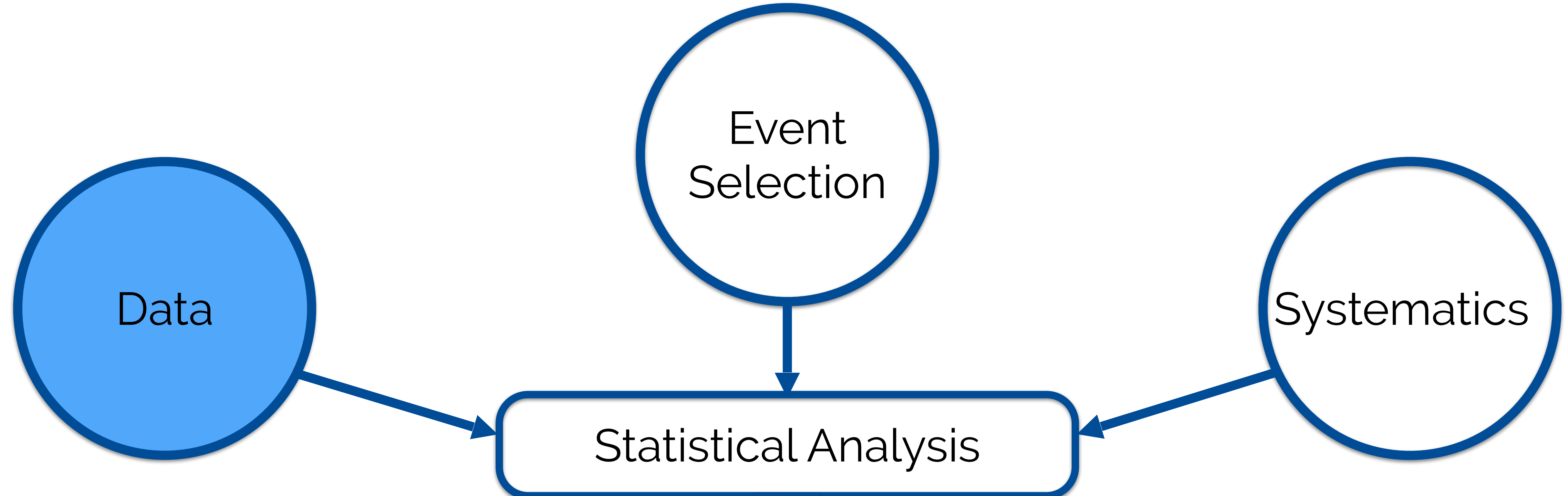


Method and Result

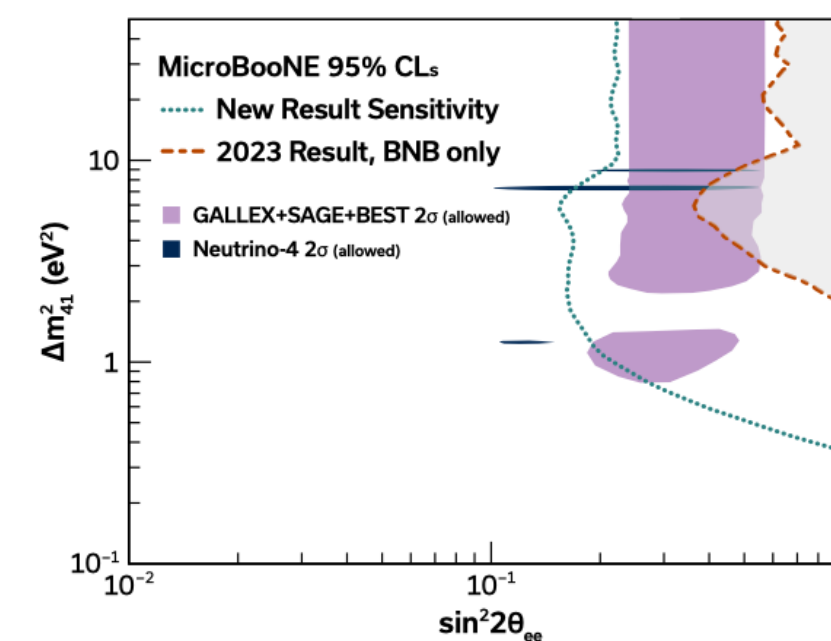
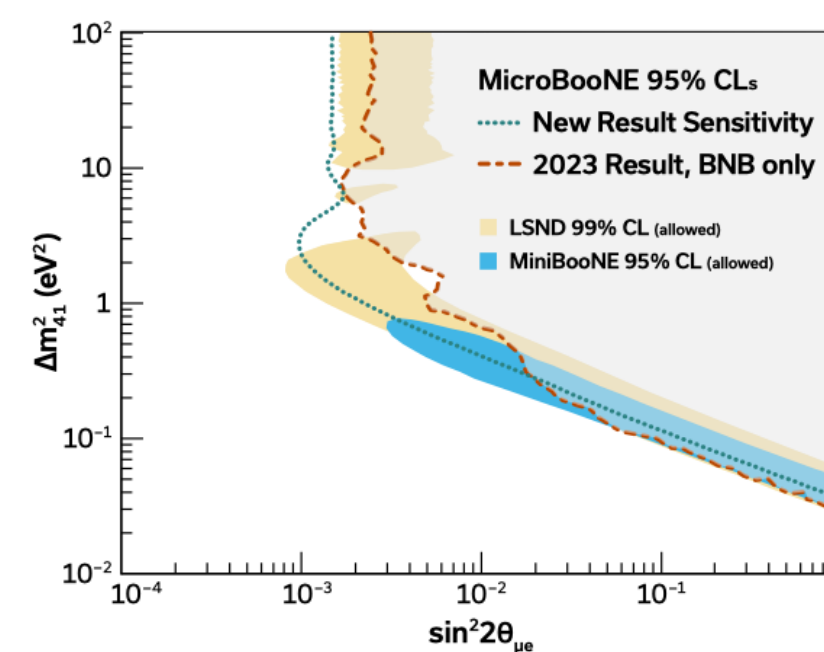


MicroBooNE 3+1 Result

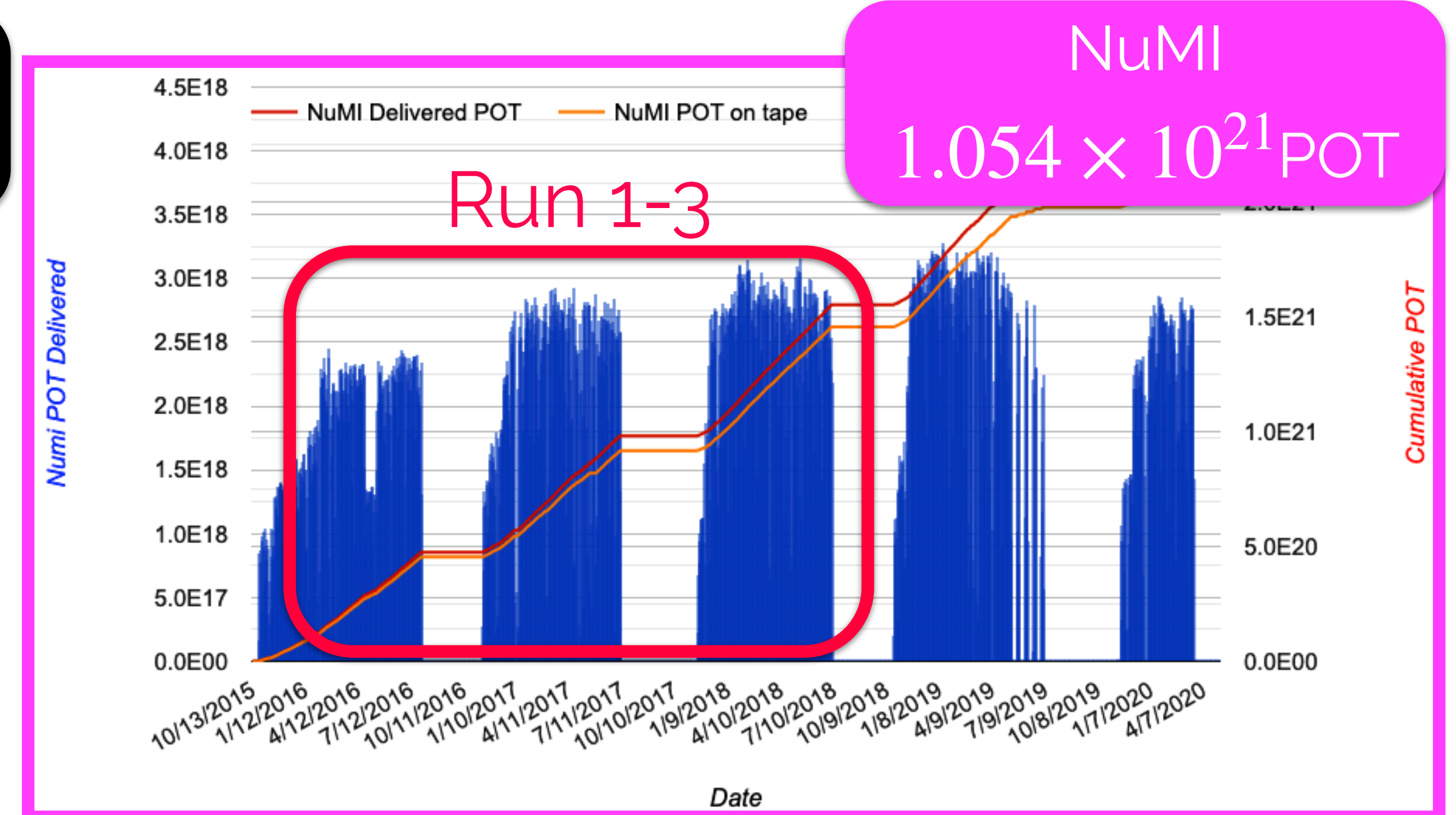
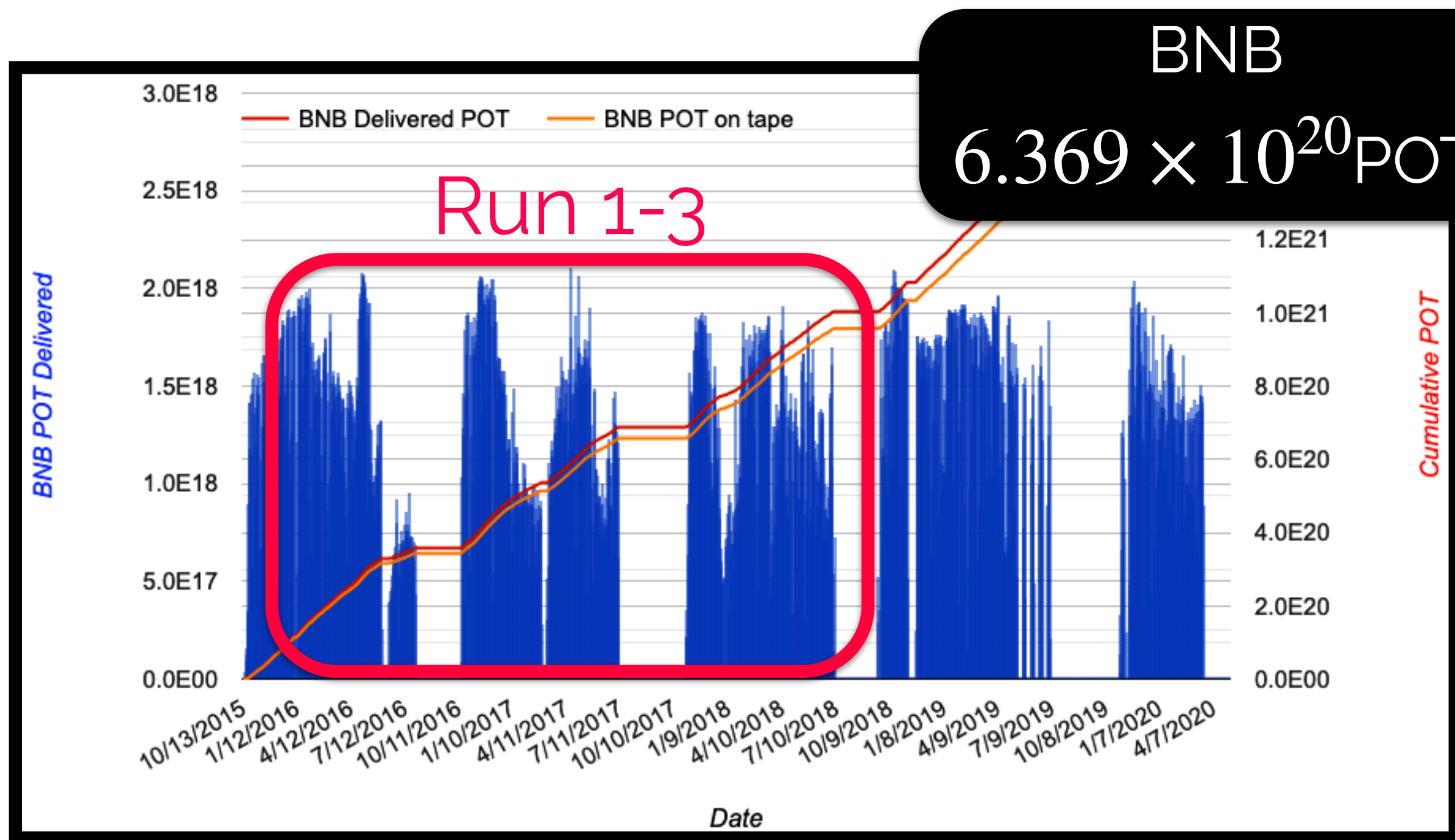




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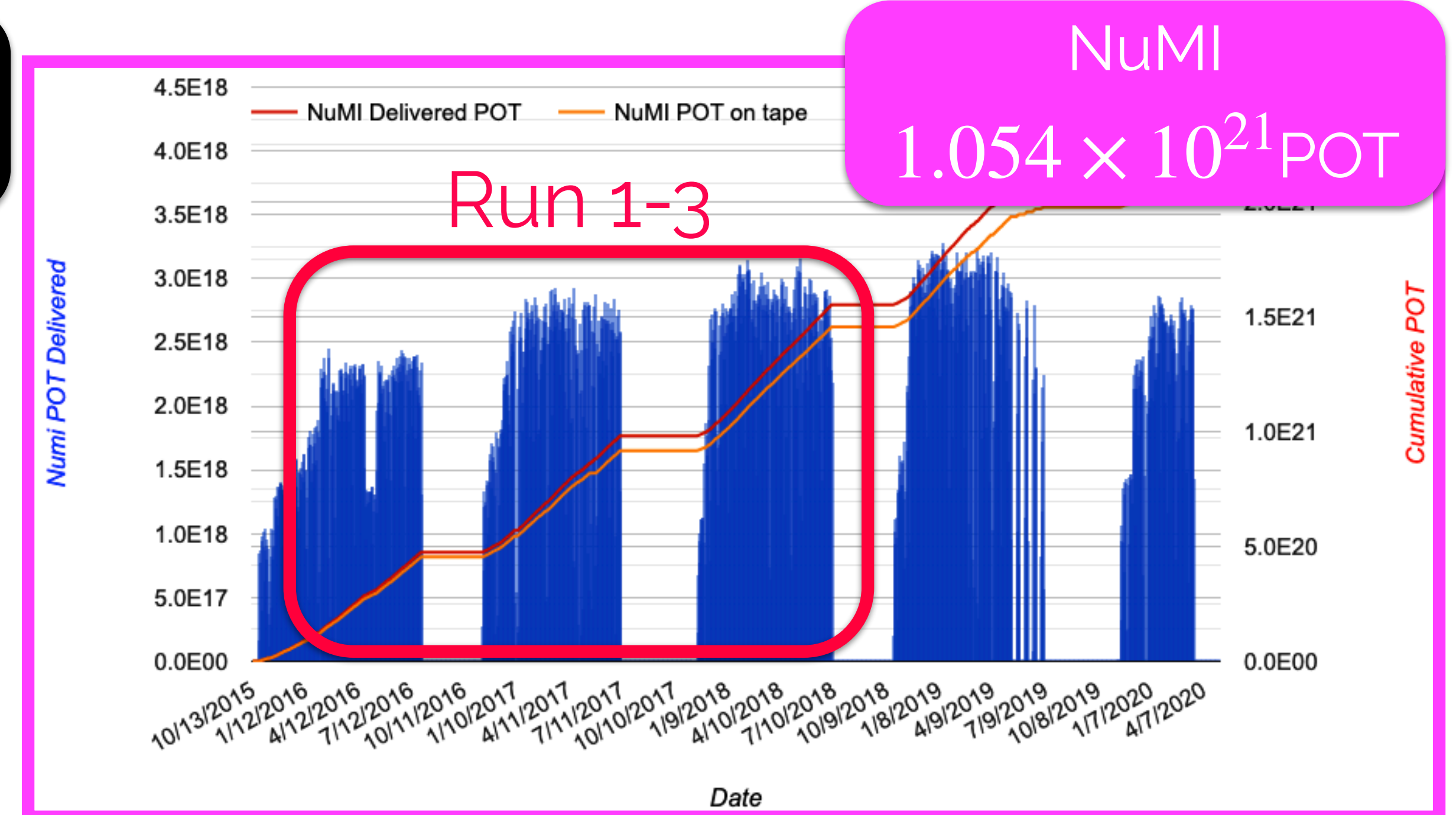
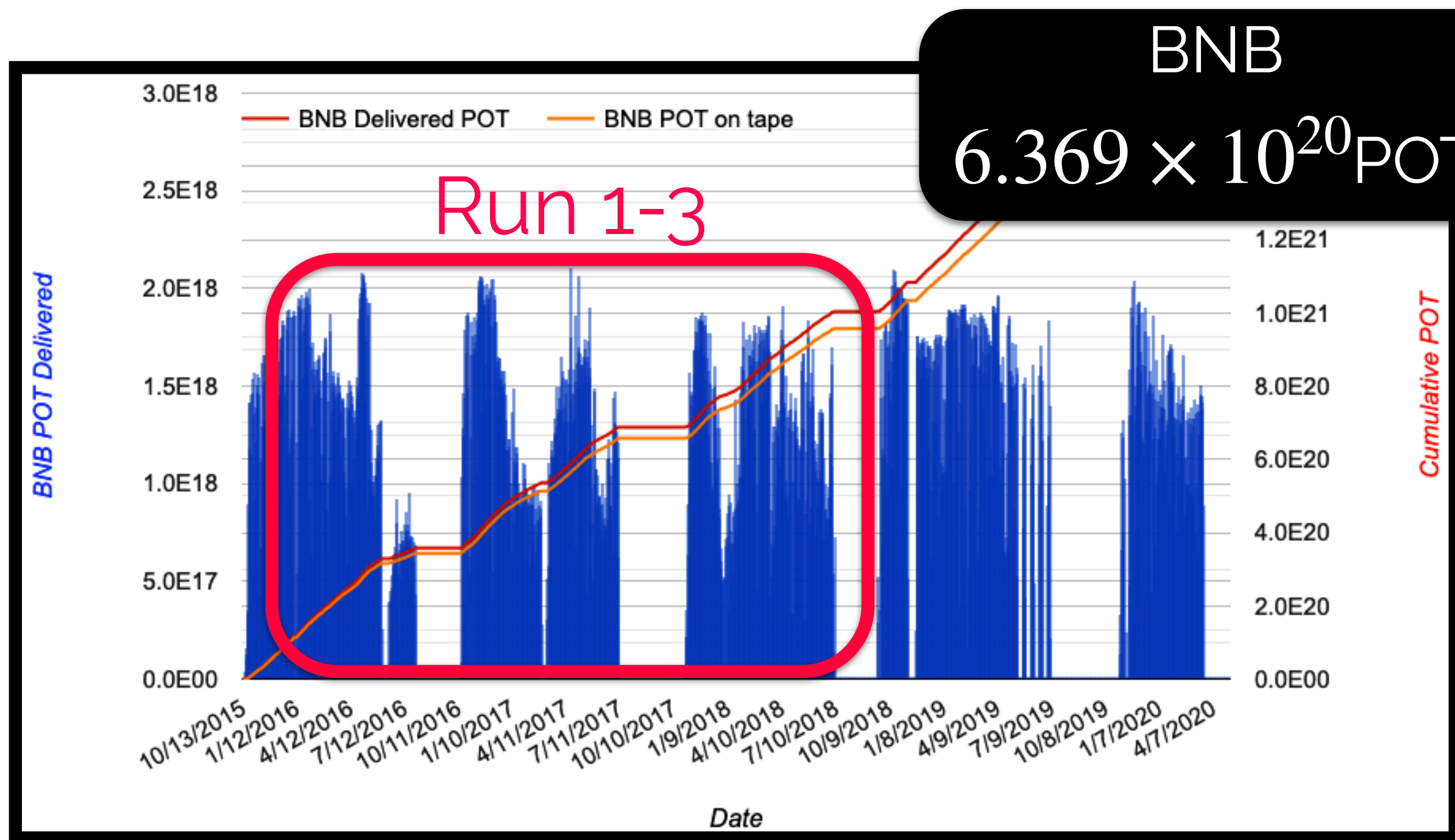


Data used for the analysis



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

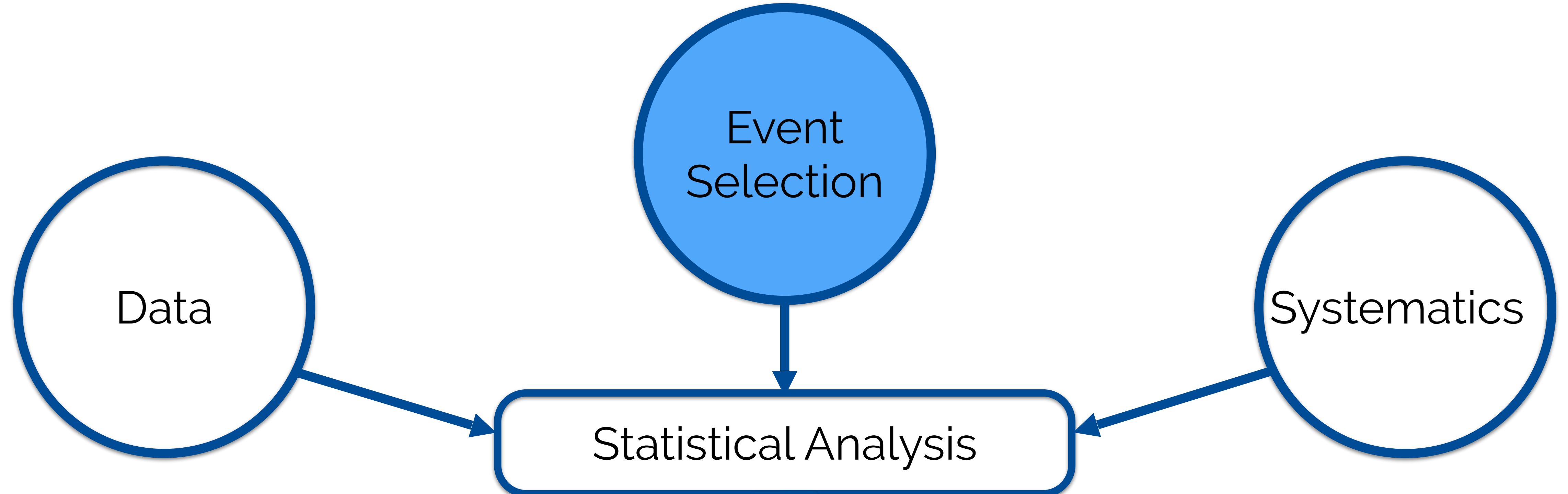
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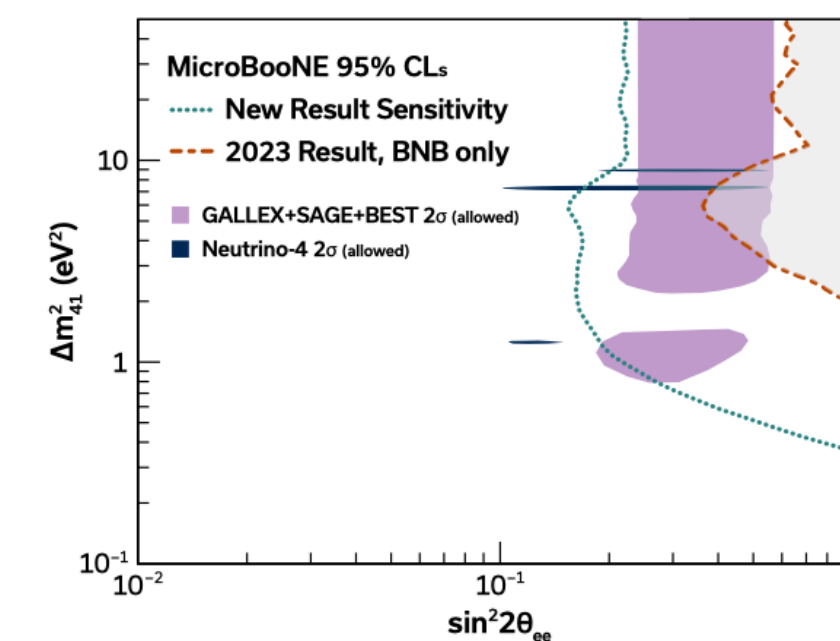
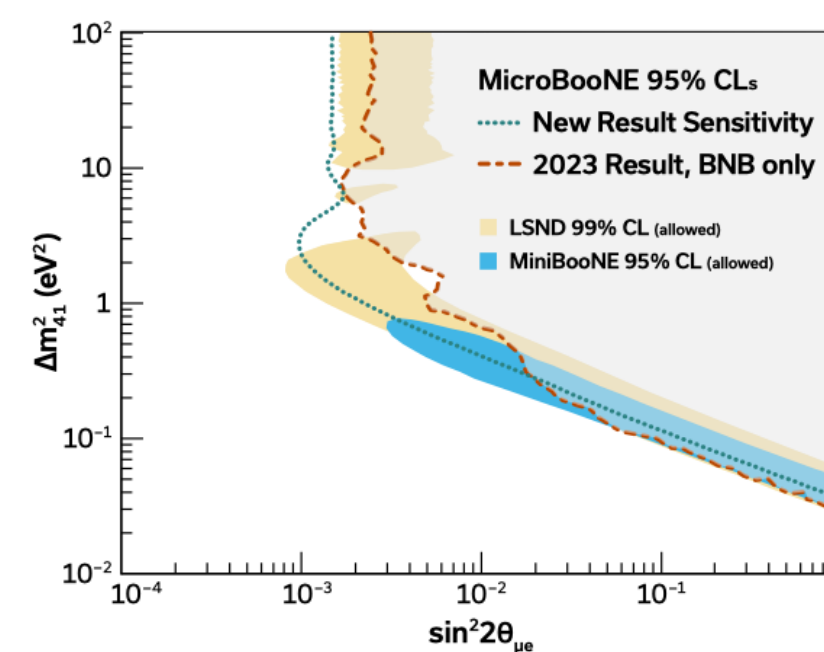
Current Analysis uses ~half of available MicroBooNE data across two beams

BNB [almost pure ν_μ]
very sensitive to ν_e appearance!

NuMI [much larger ν_e content]
more sensitive to ν_e disappearance!



MicroBooNE 3+1 Result



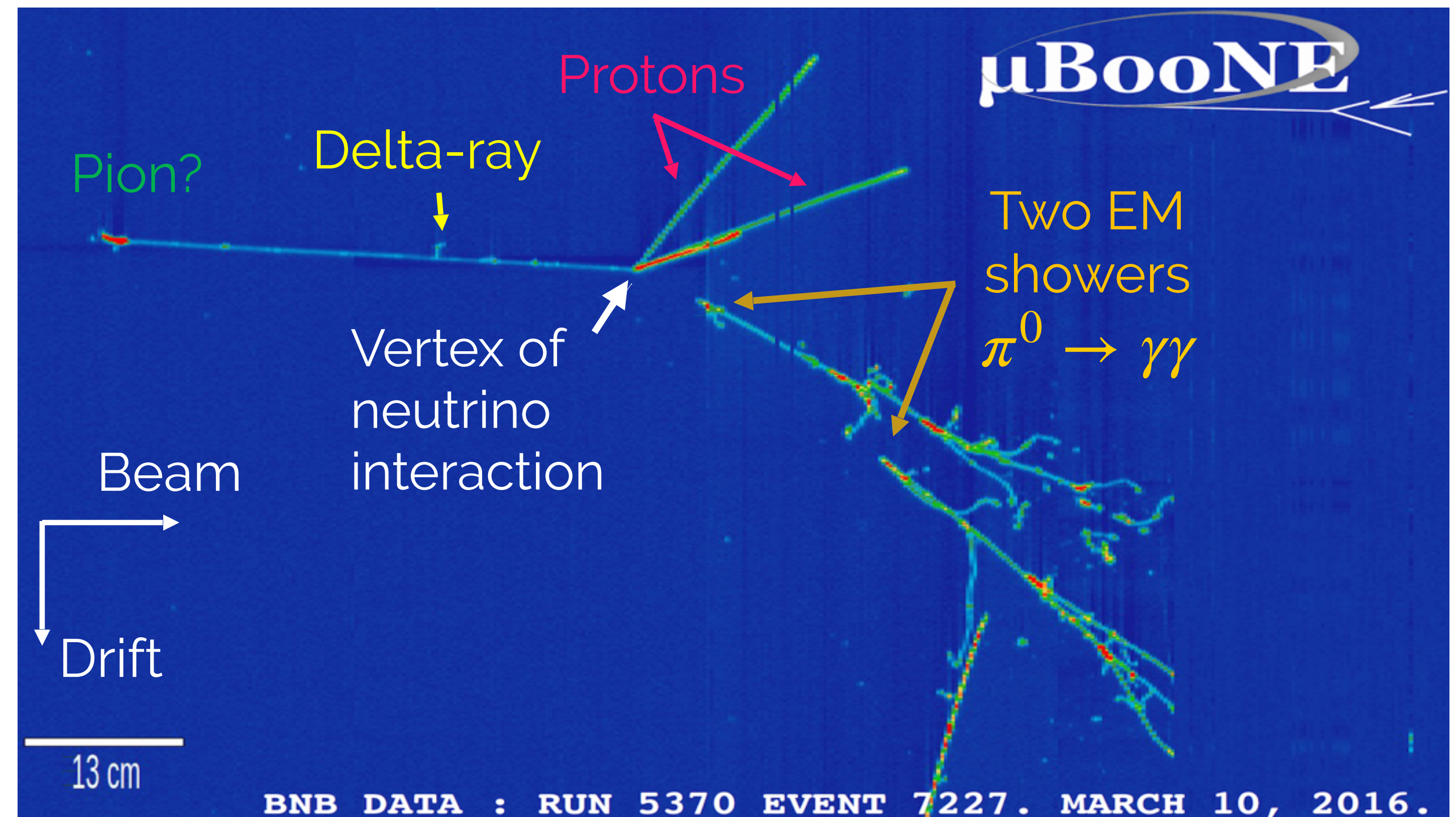
LArTPC: an enabling technology

A low-energy-threshold fully active liquid-argon calorimeter + high energy and position resolution TPC

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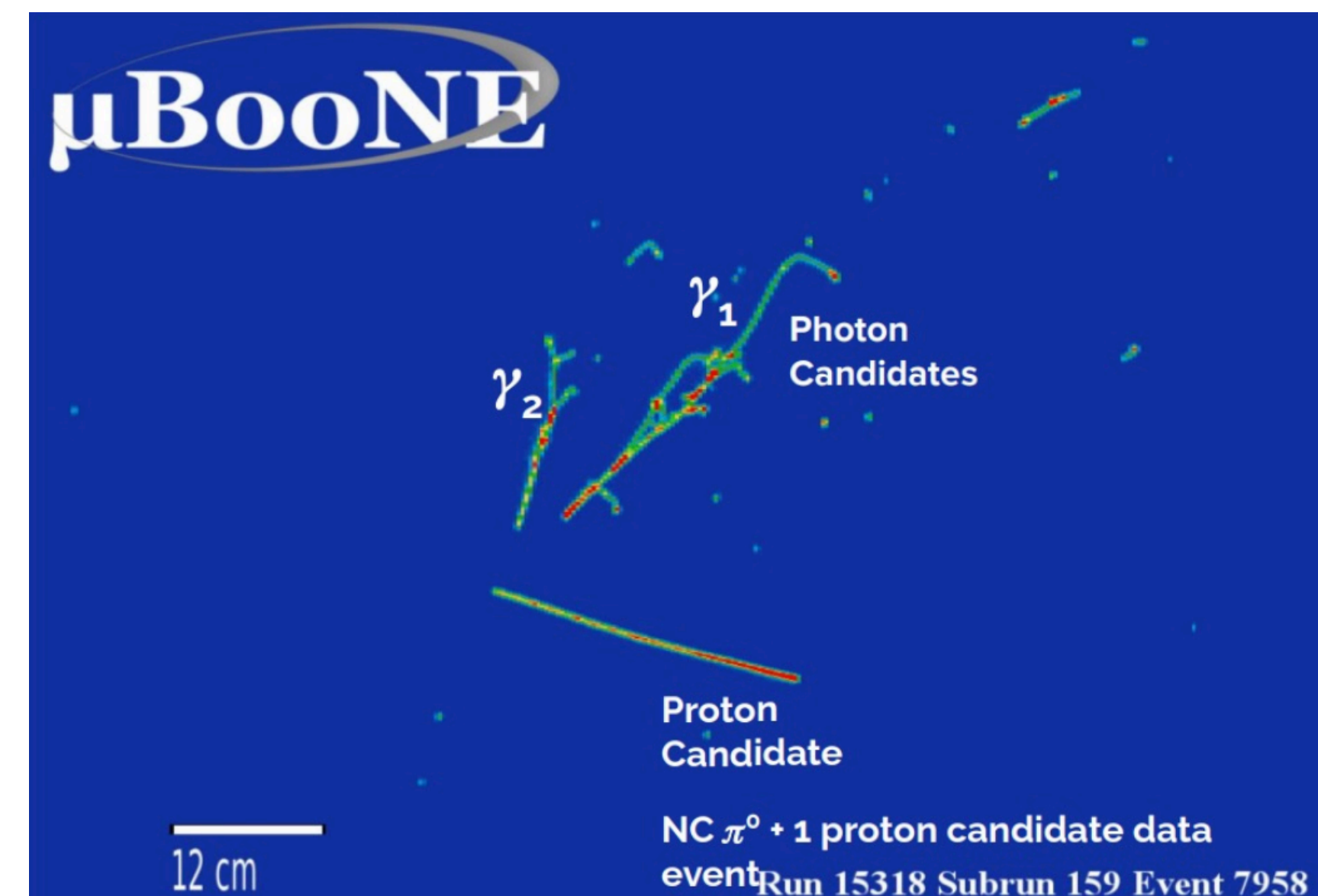
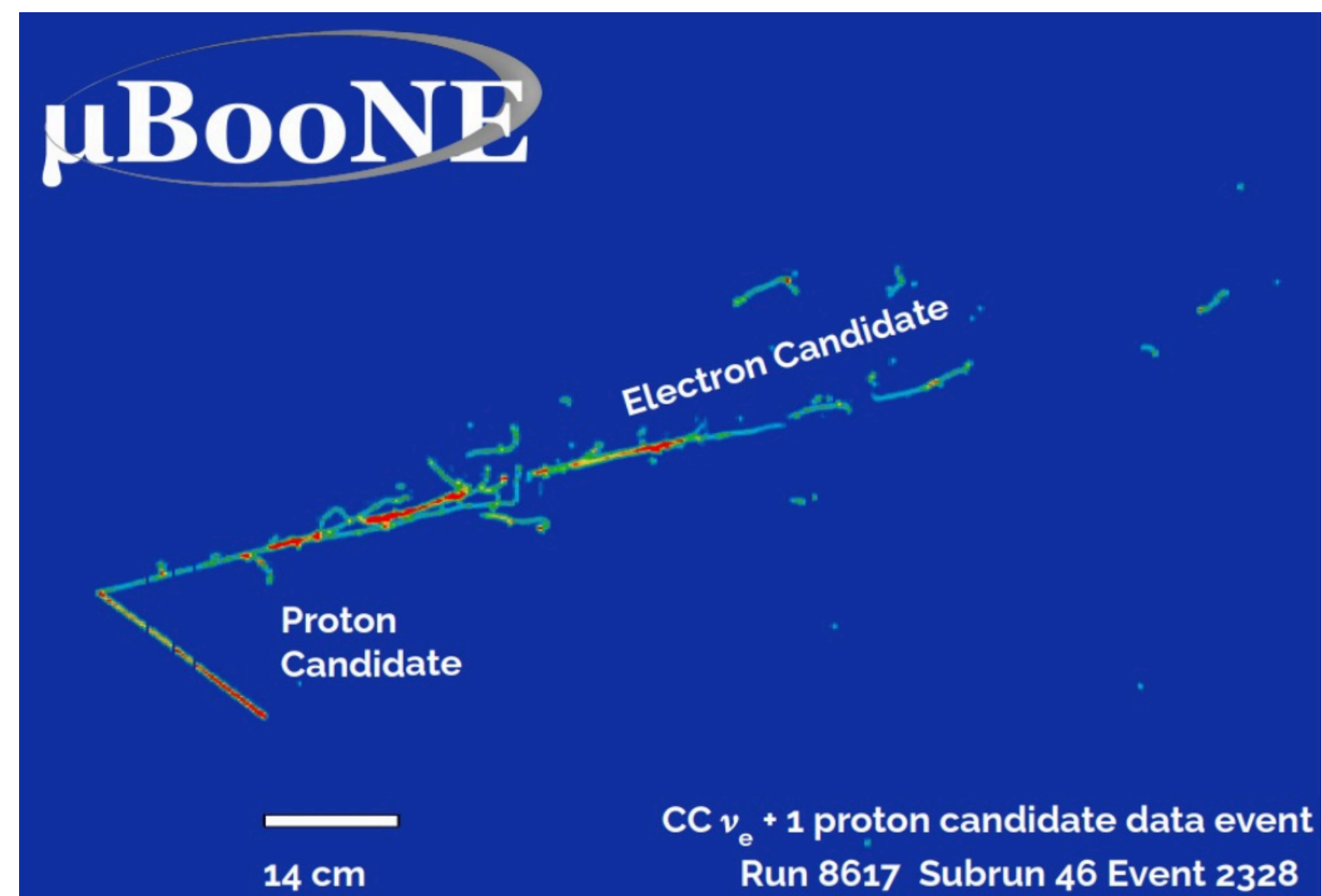
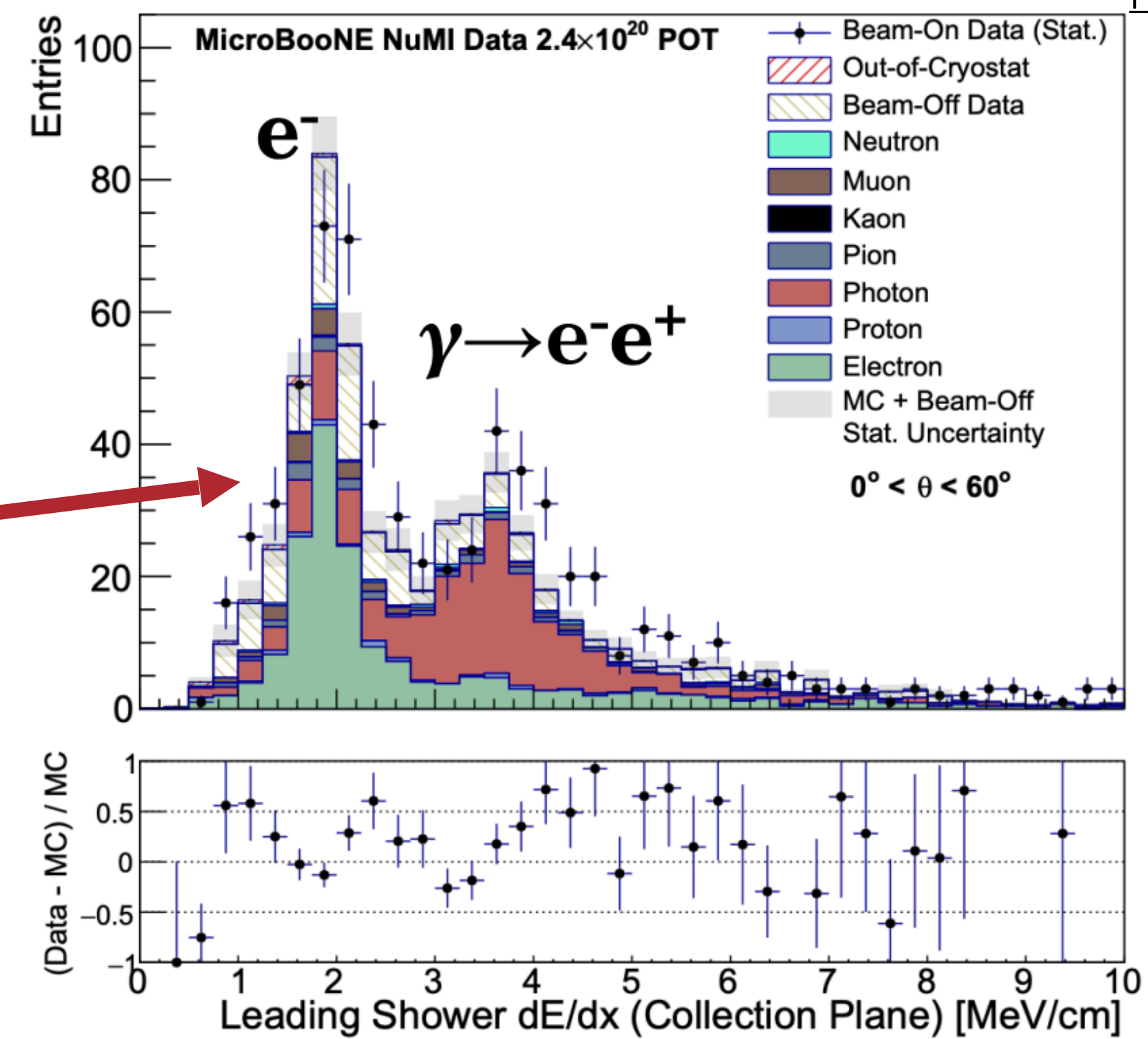
Excellent at identifying different species of particles and reconstructing 3D images with fine-grained information



LArTPC: an enabling technology

Great **electron-photon** (e^+e^- pair production) separation:

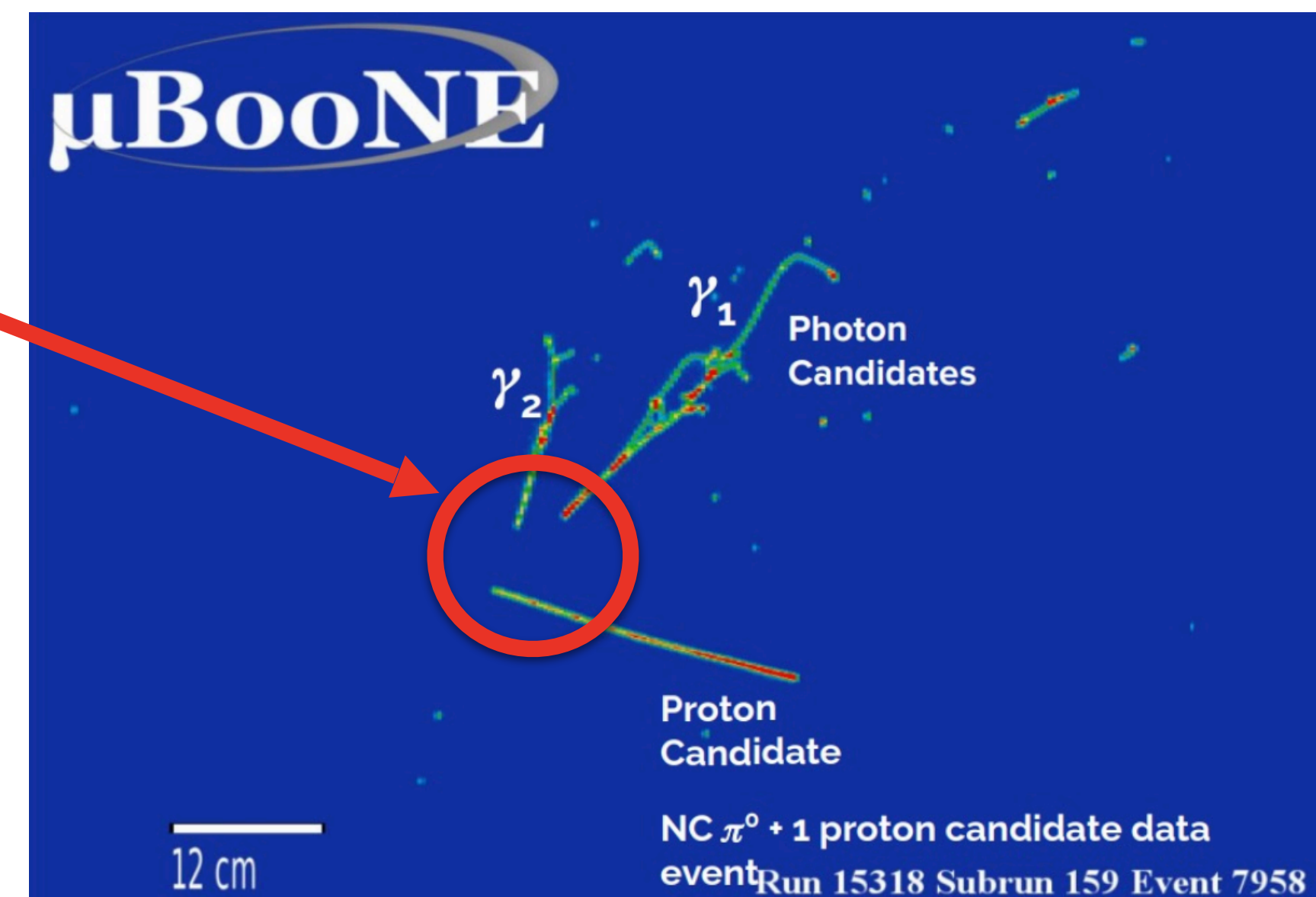
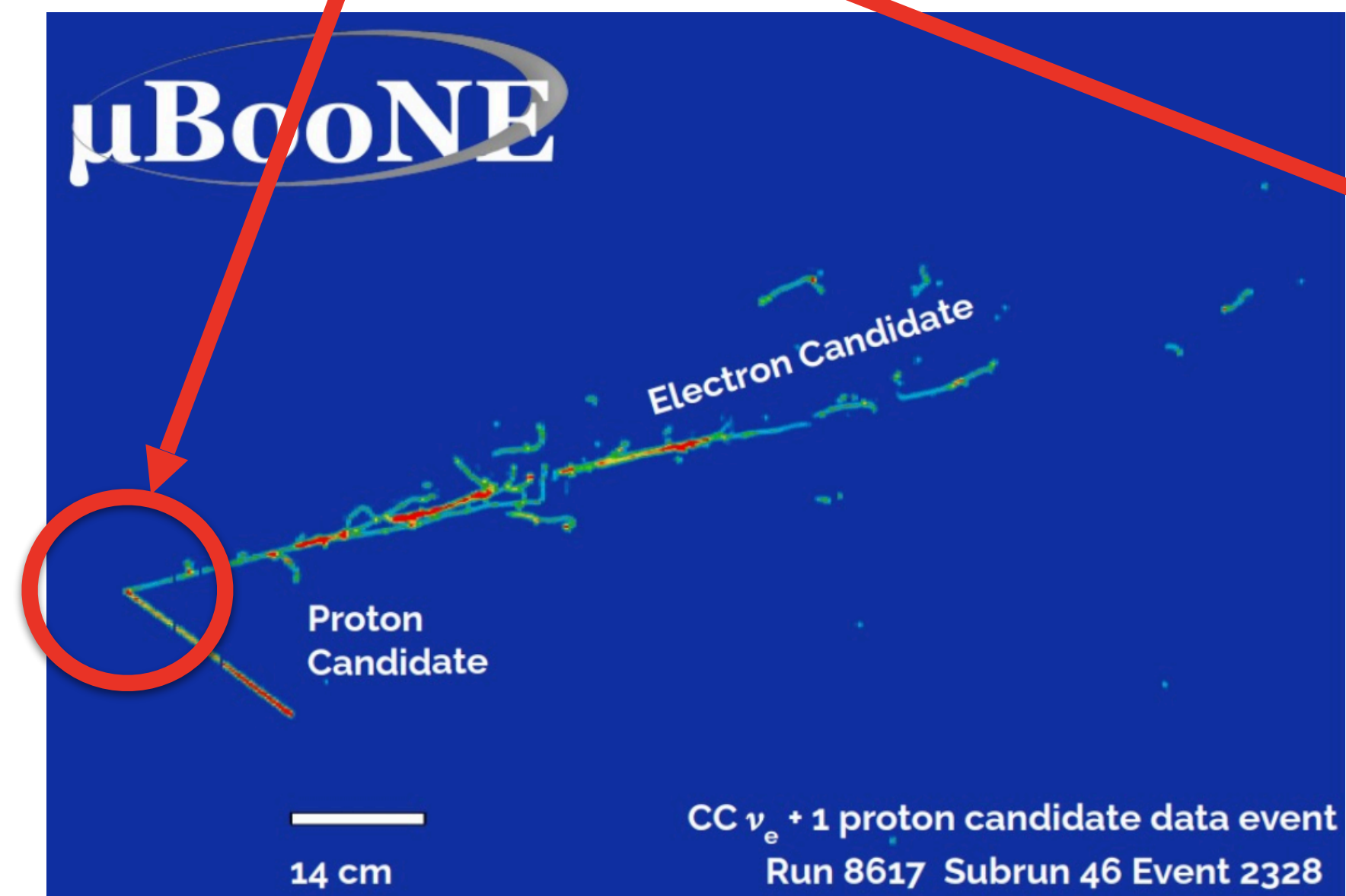
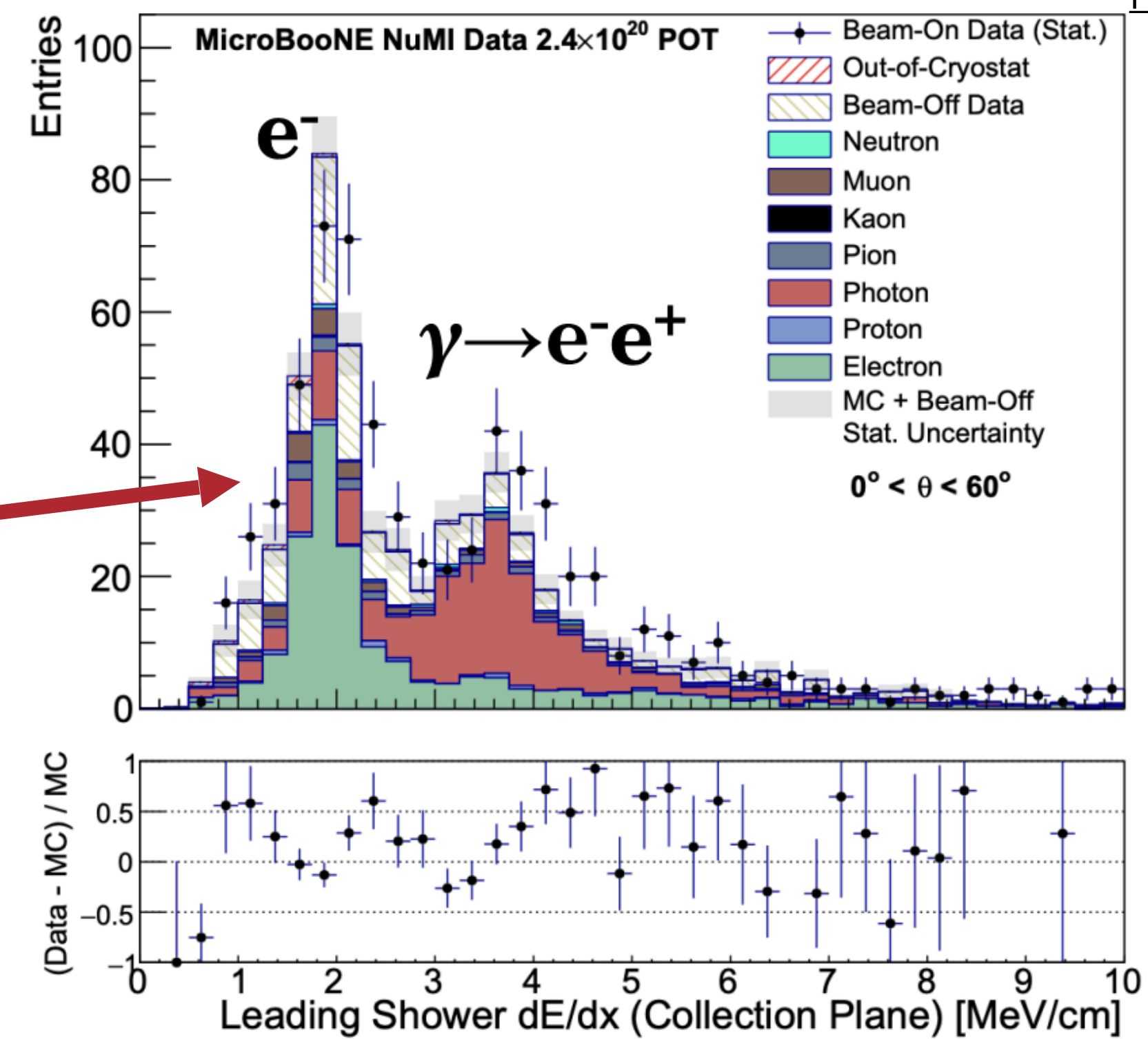
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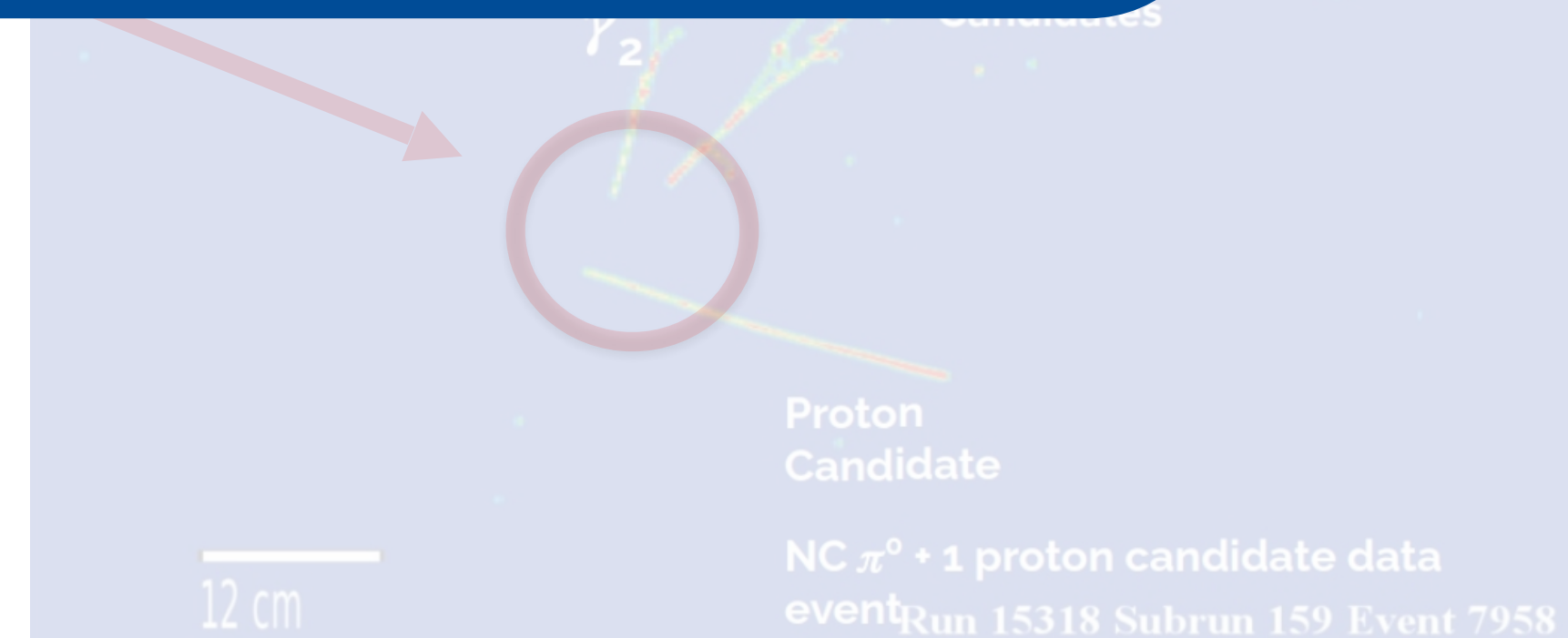
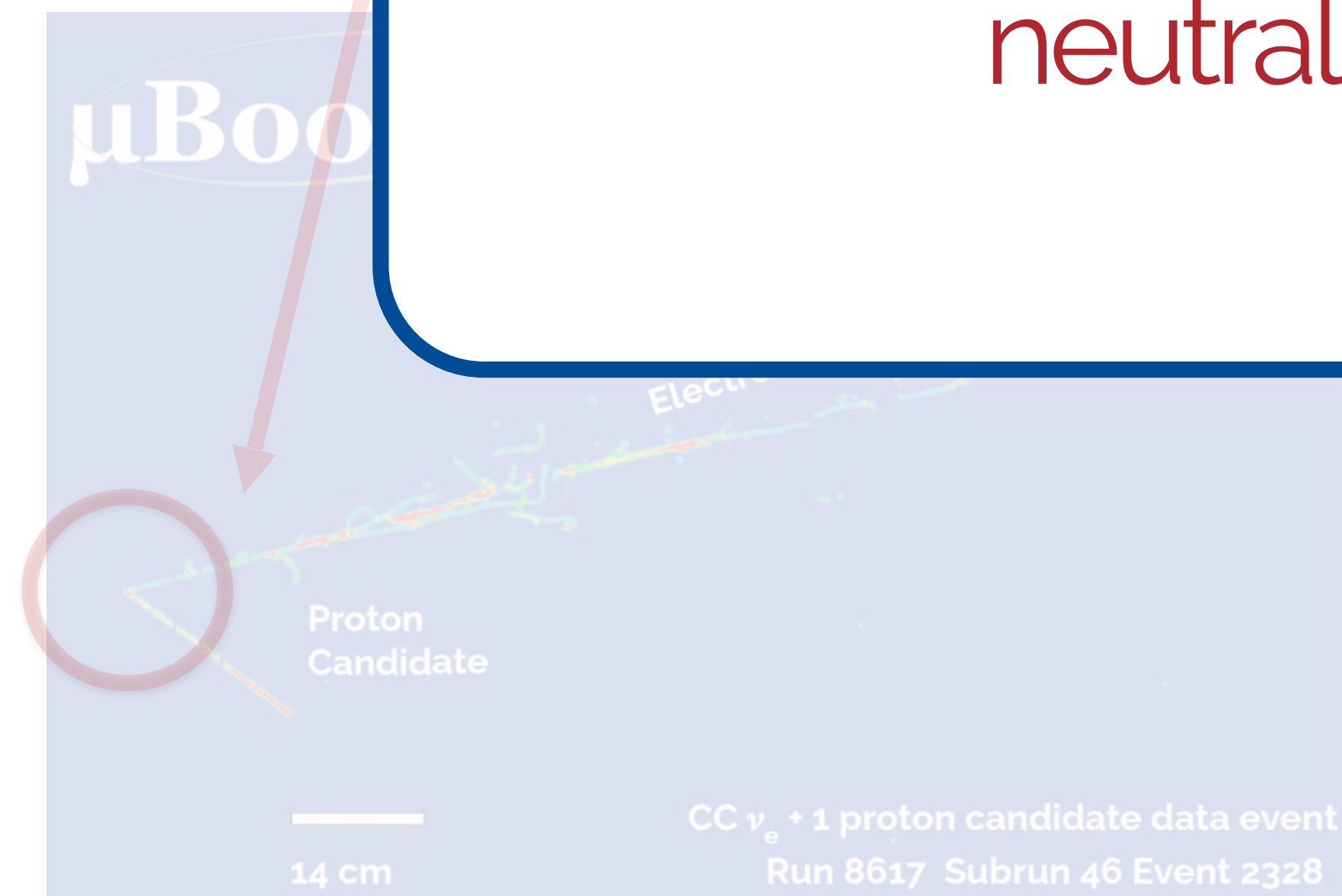
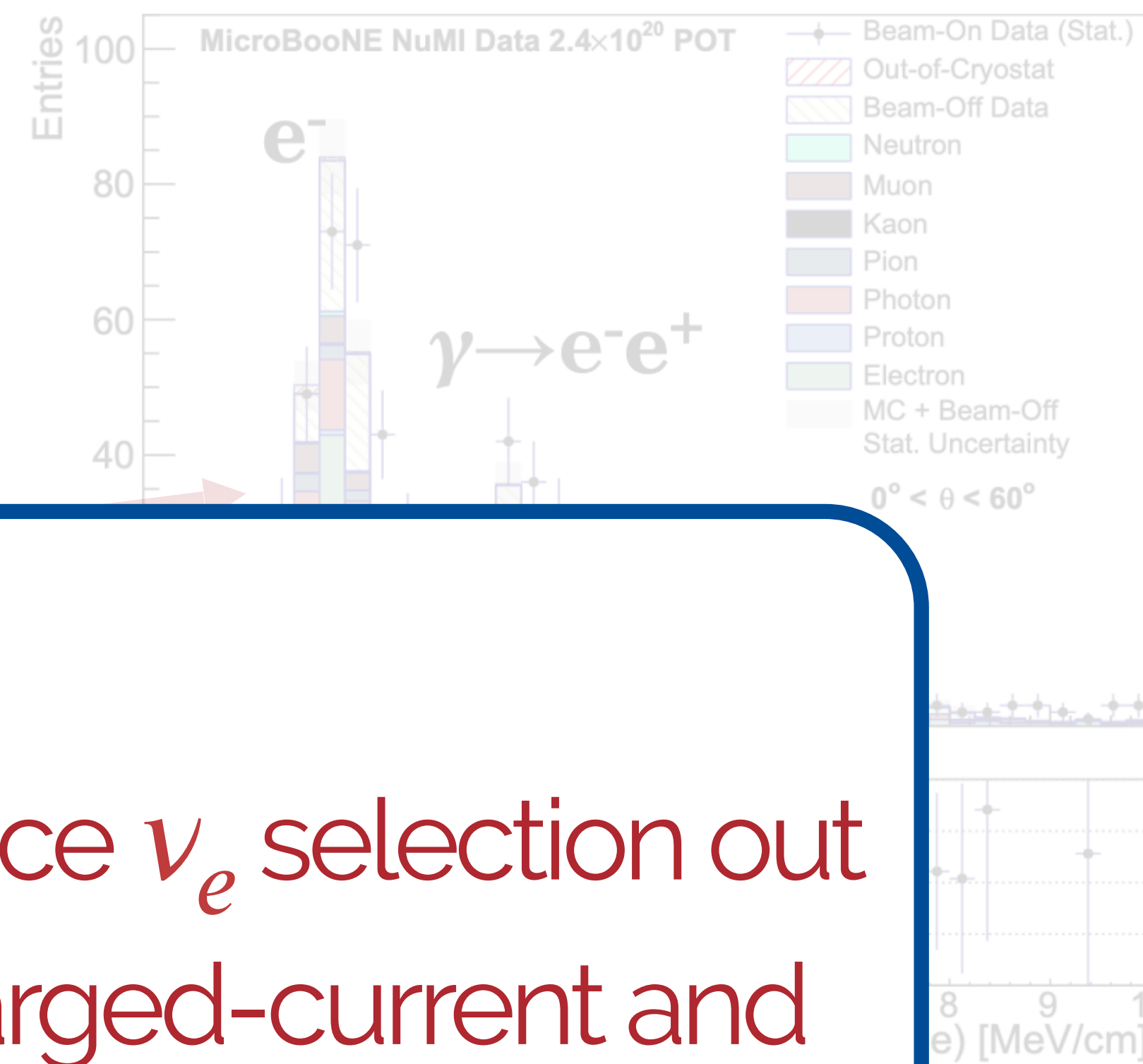


LArTPC: an enabling technology

Great **electron-photon** (e^+e^- pair production) separation:

1. dQ/dx [ionization difference (1 MeV/cm)]
2. Gap between s

Enable a high-performance ν_e selection out of overwhelming ν_μ charged-current and neutral-current events



Reconstruction pipeline

[JINST 12 P08003 \(2017\)](#) [JINST 16 P06043 \(2021\)](#)
[JINST 13 P07006 \(2018\)](#) [Phys. Rev. Applied 15 064071 \(2021\)](#)
[JINST 13 P07007 \(2018\)](#) [Wire-Cell PatRec Paper](#)
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Reconstruction for the analysis is performed via **Wire-Cell** package:

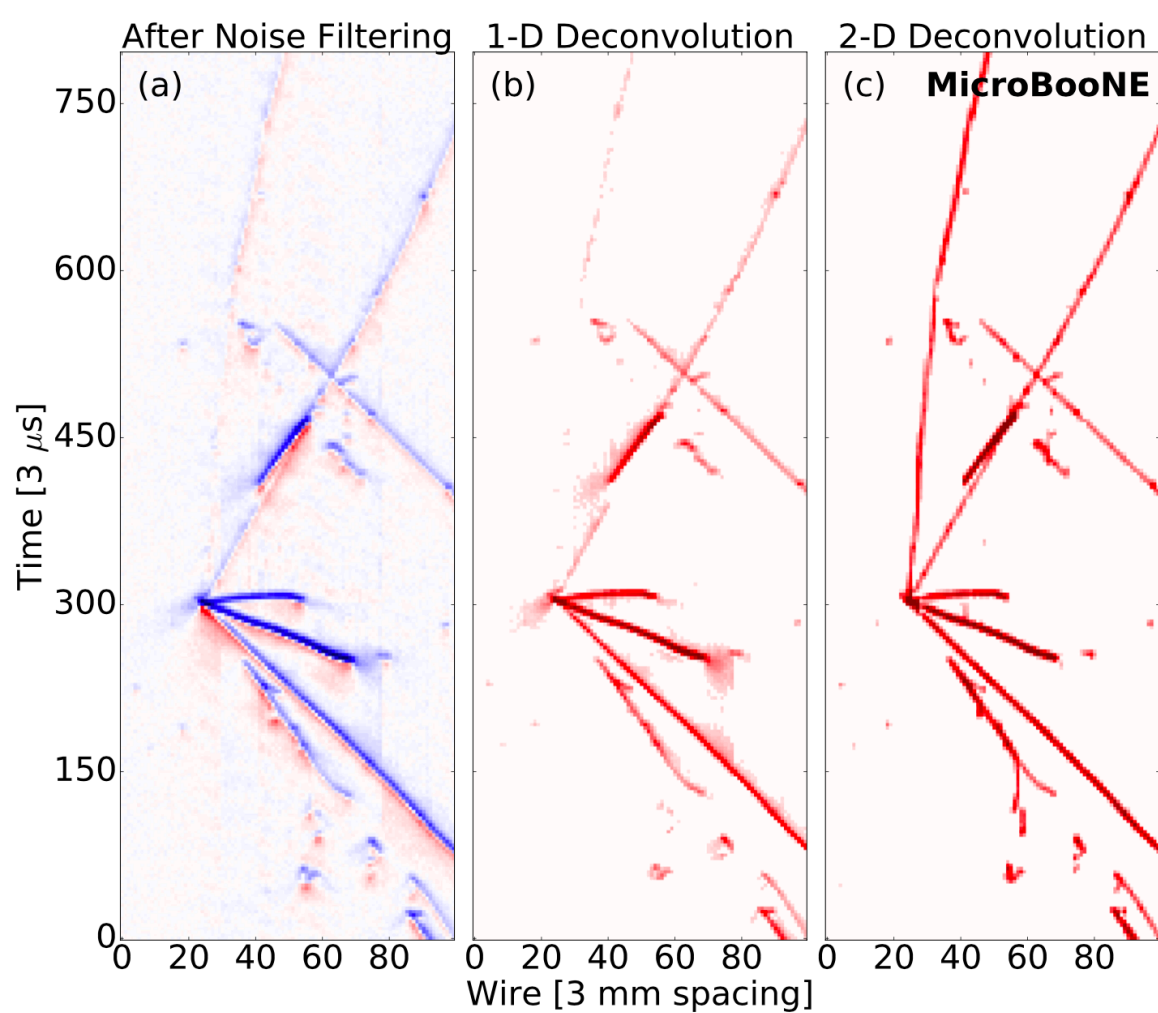
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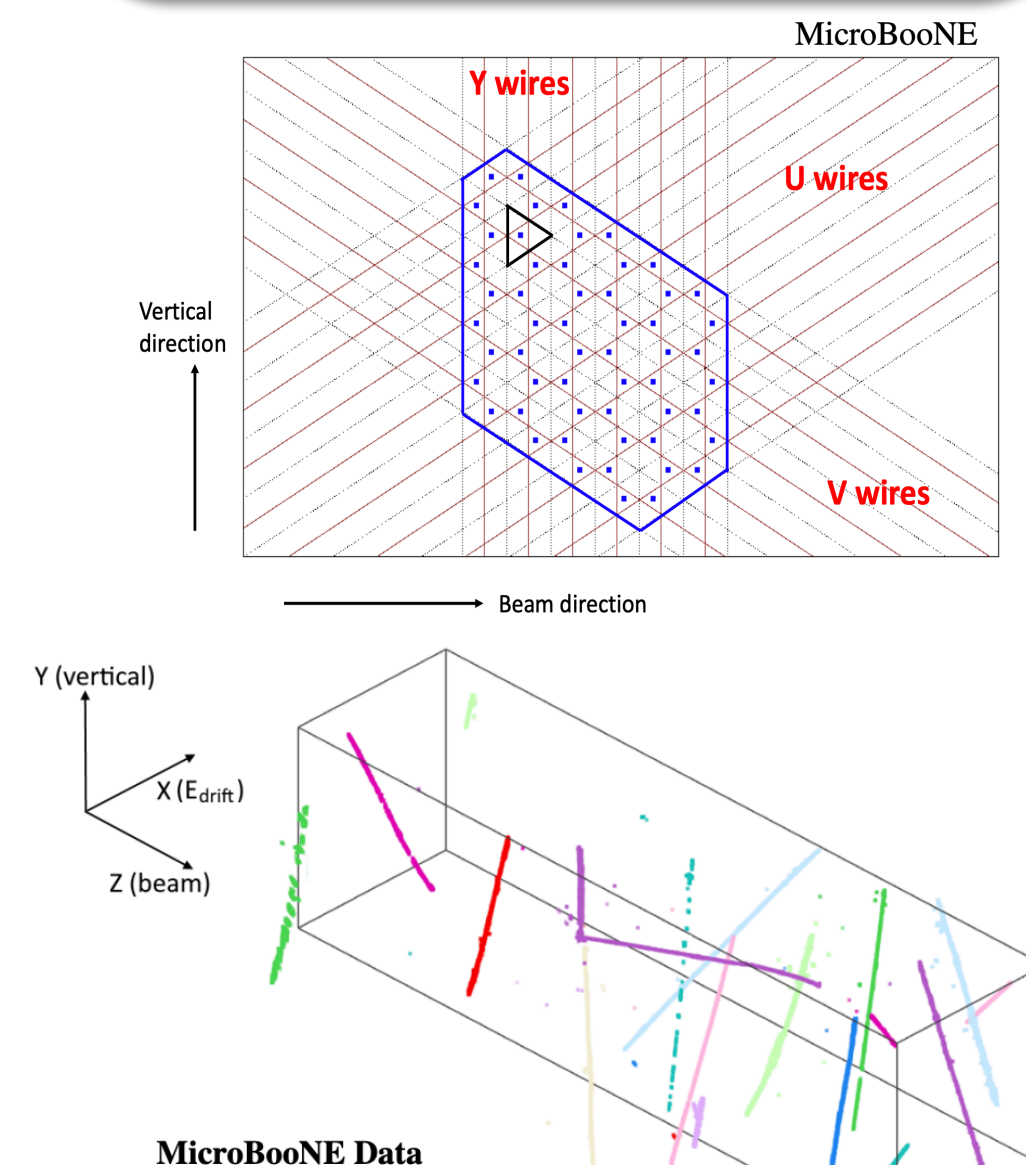
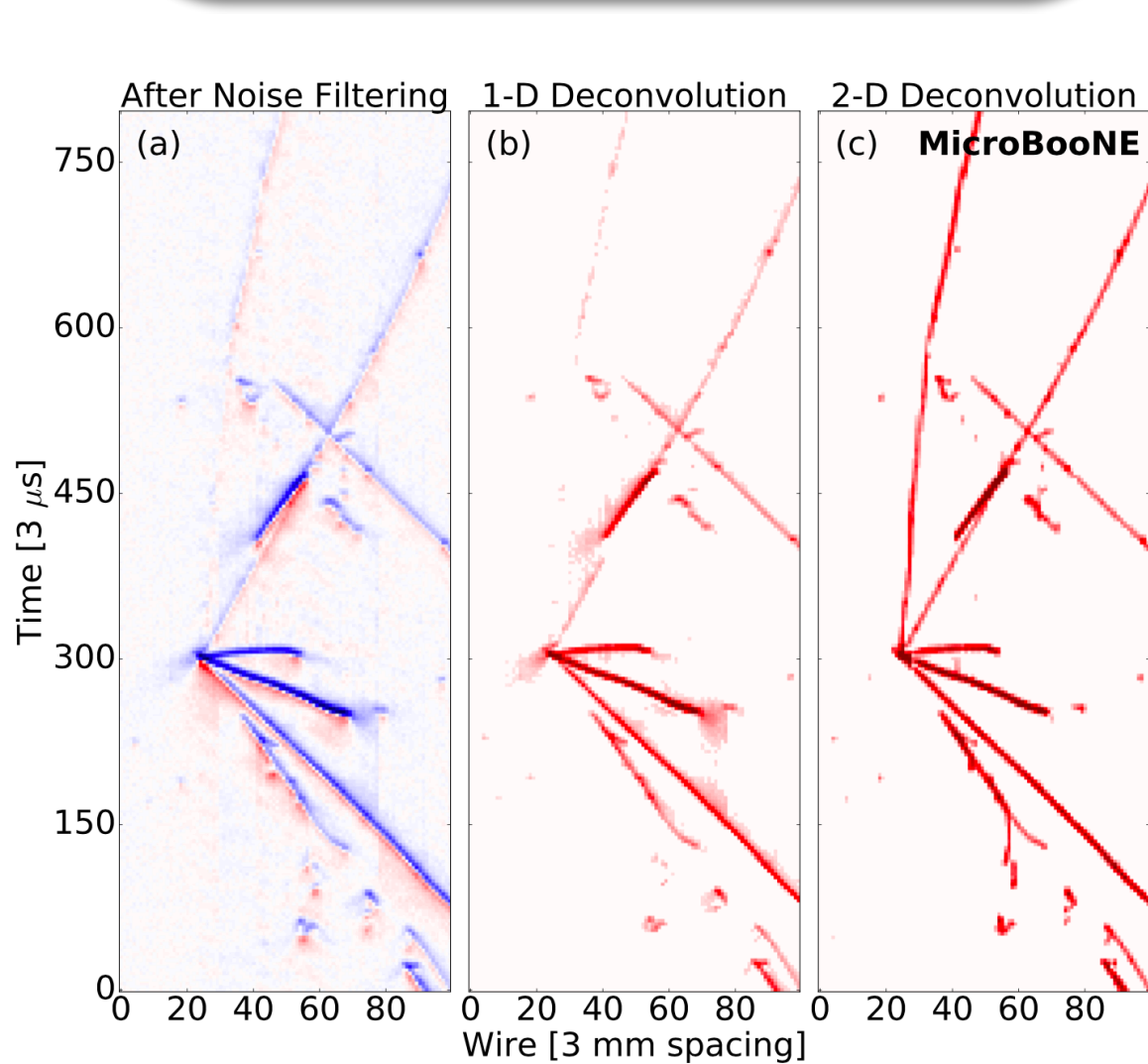
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Reconstruction pipeline

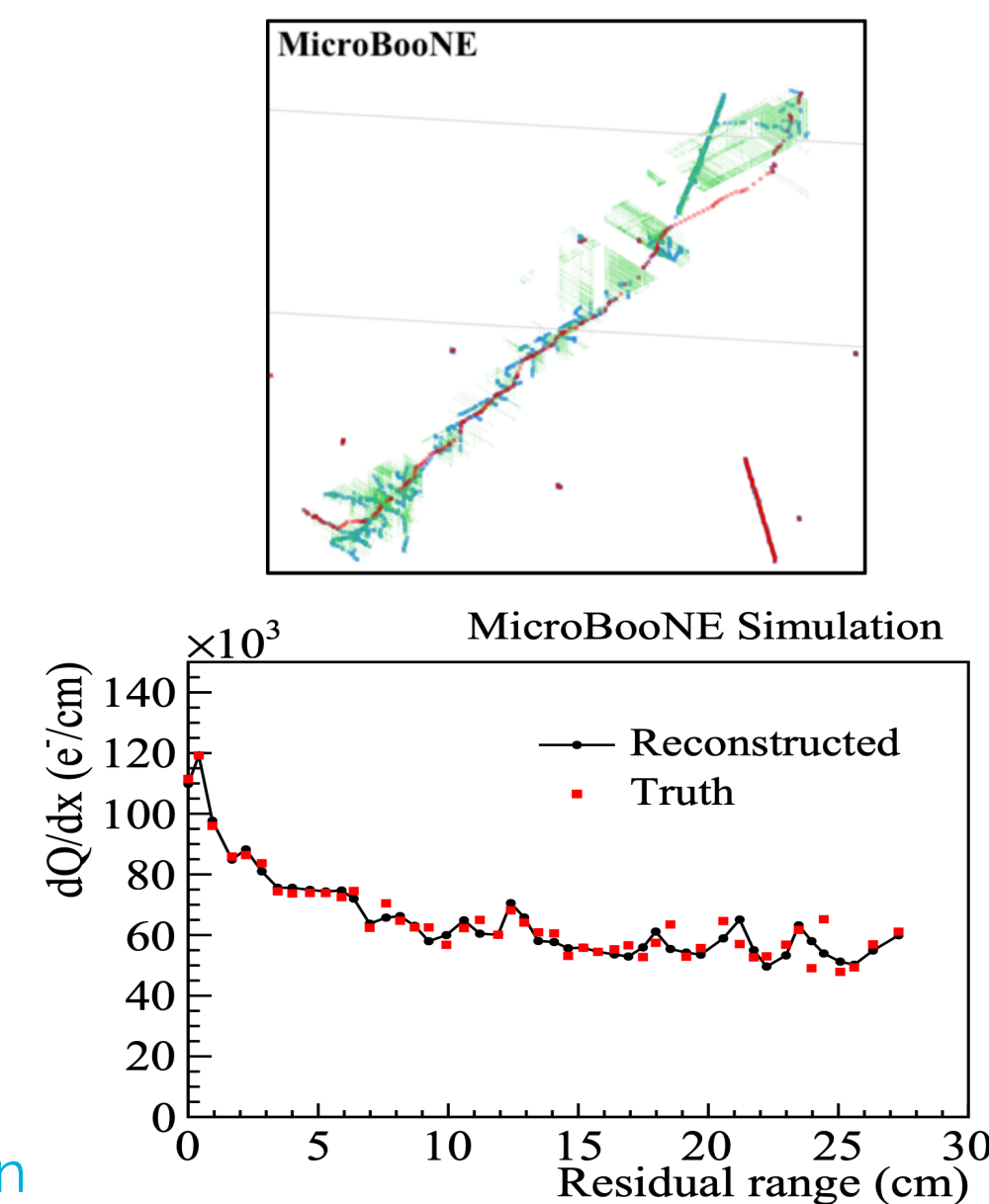
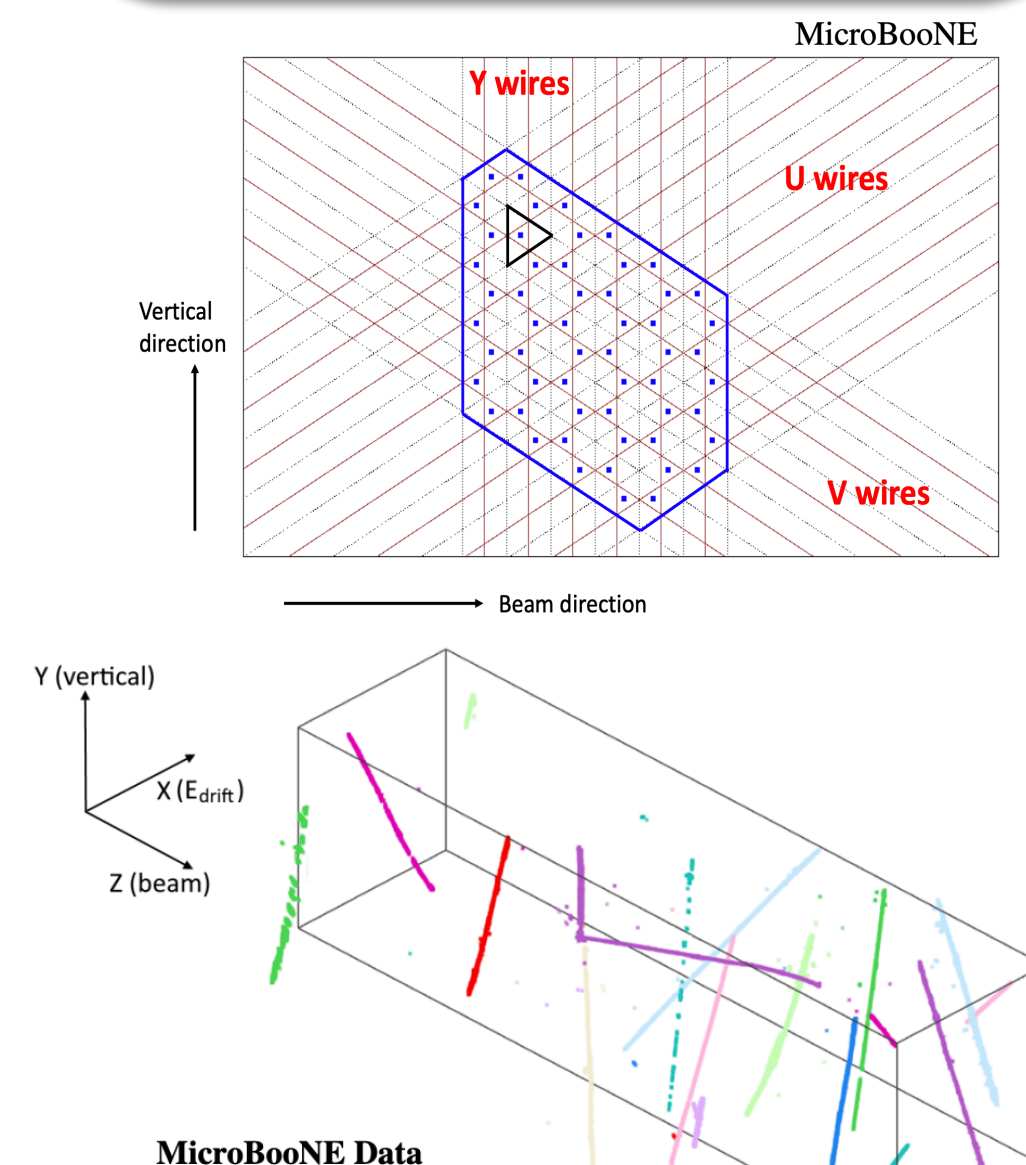
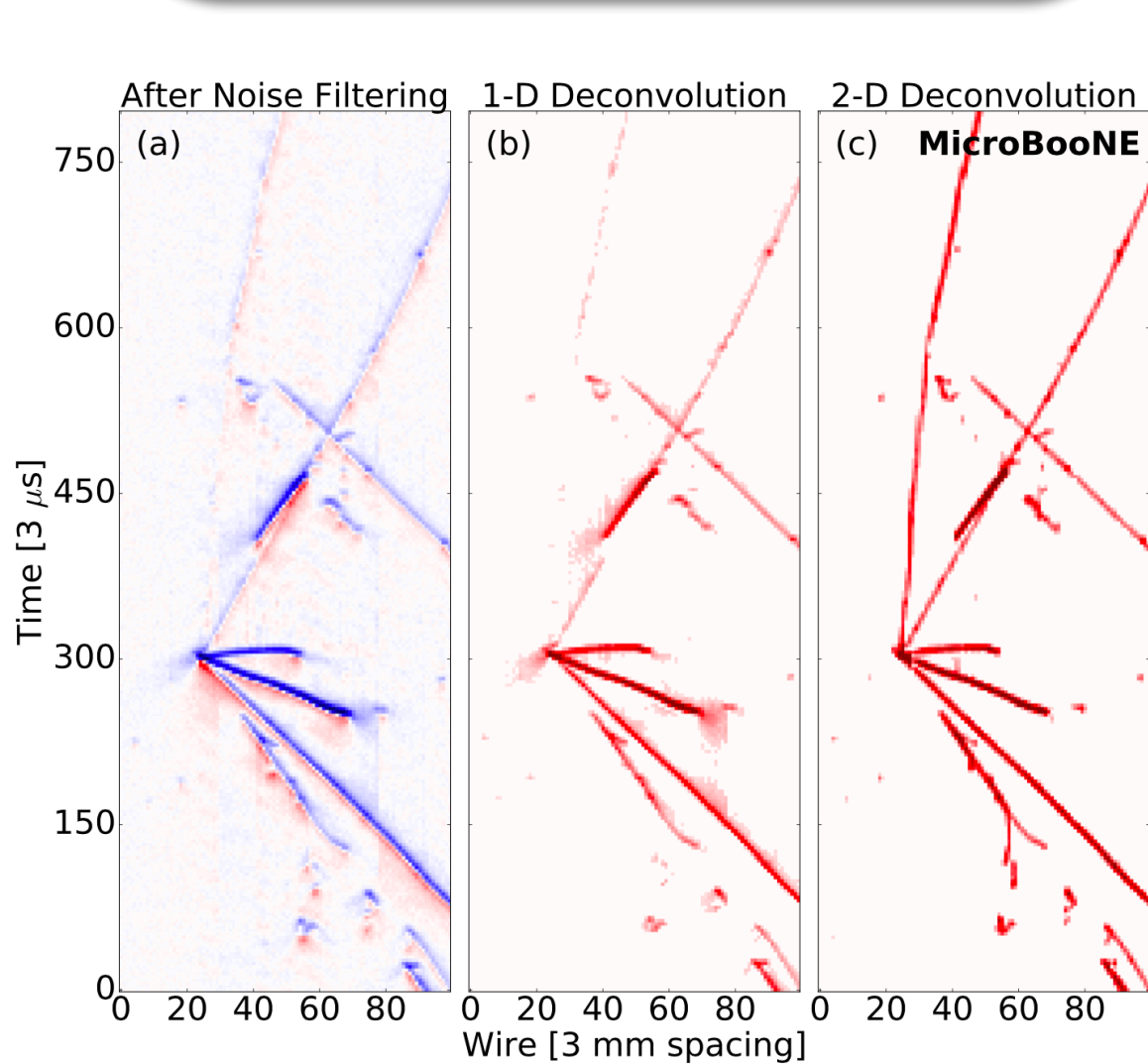
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&
dQ/dx fitting
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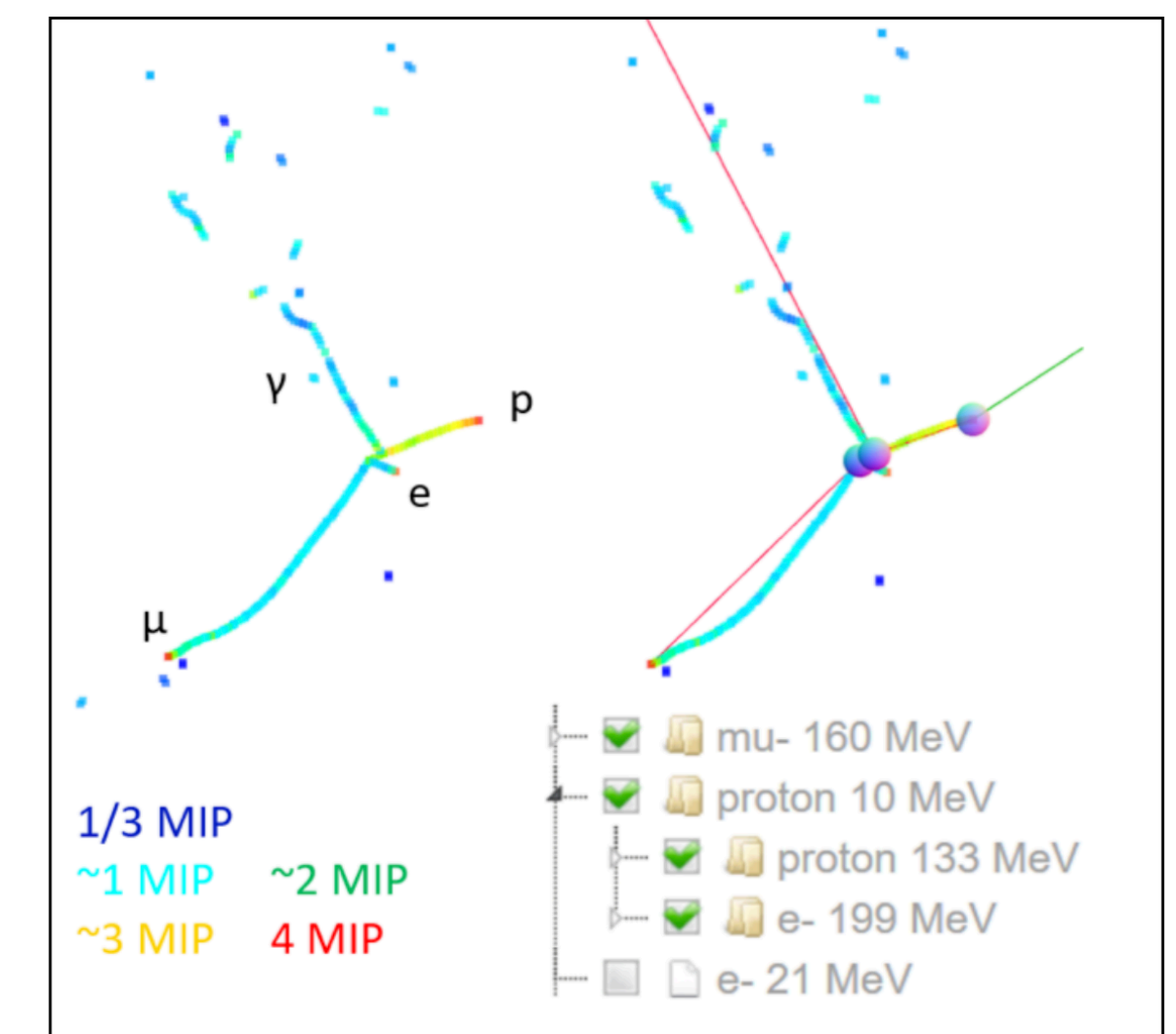
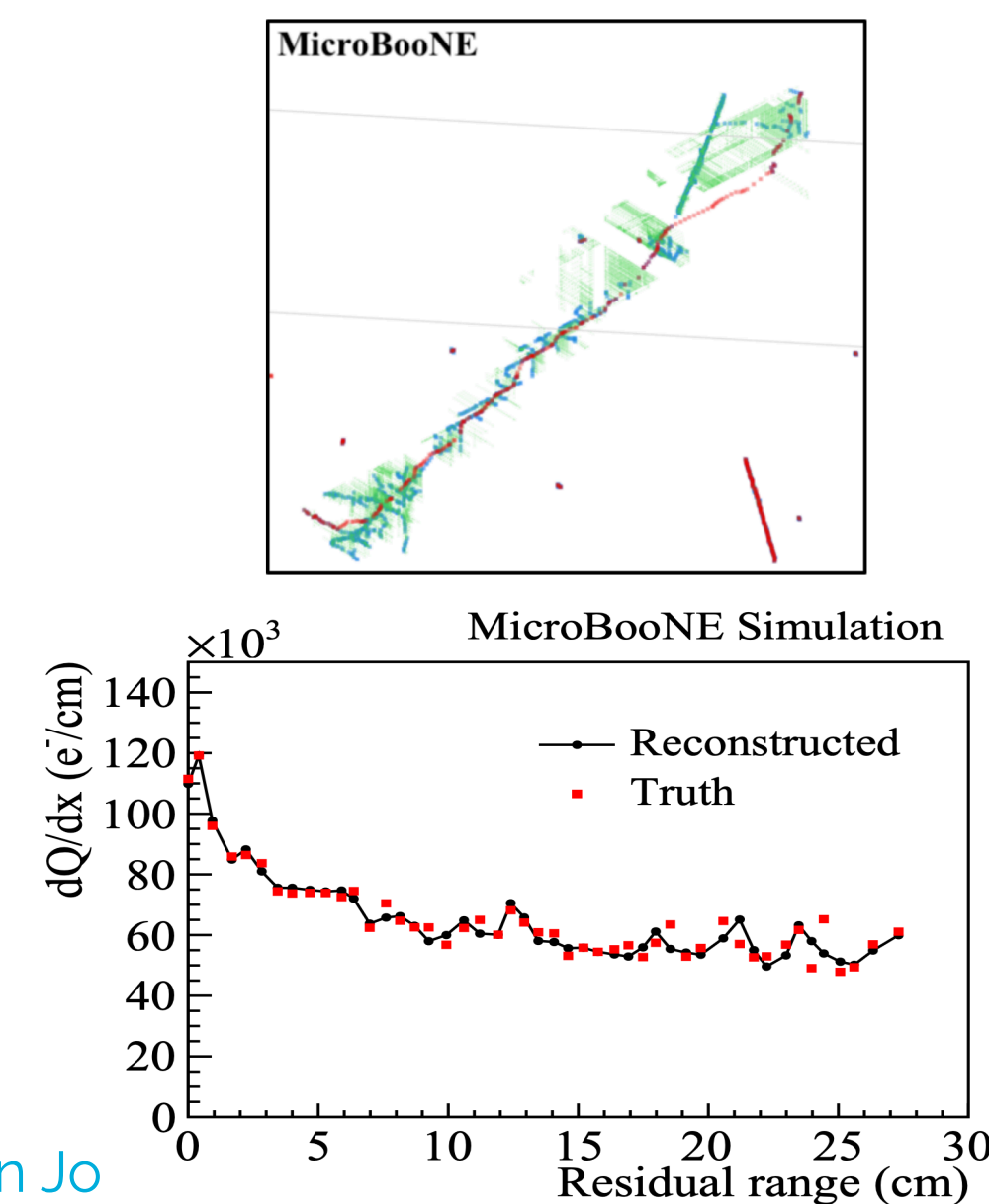
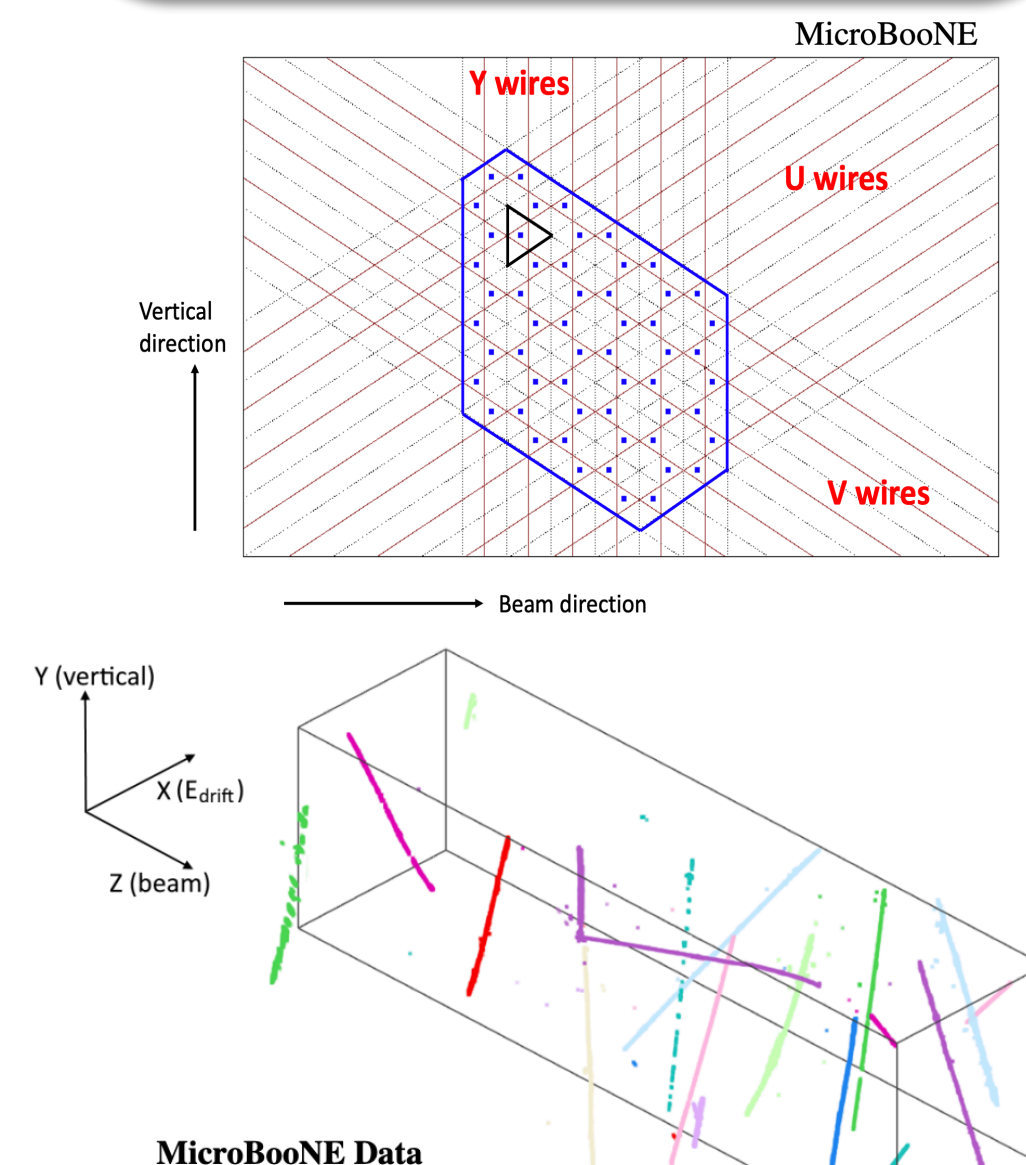
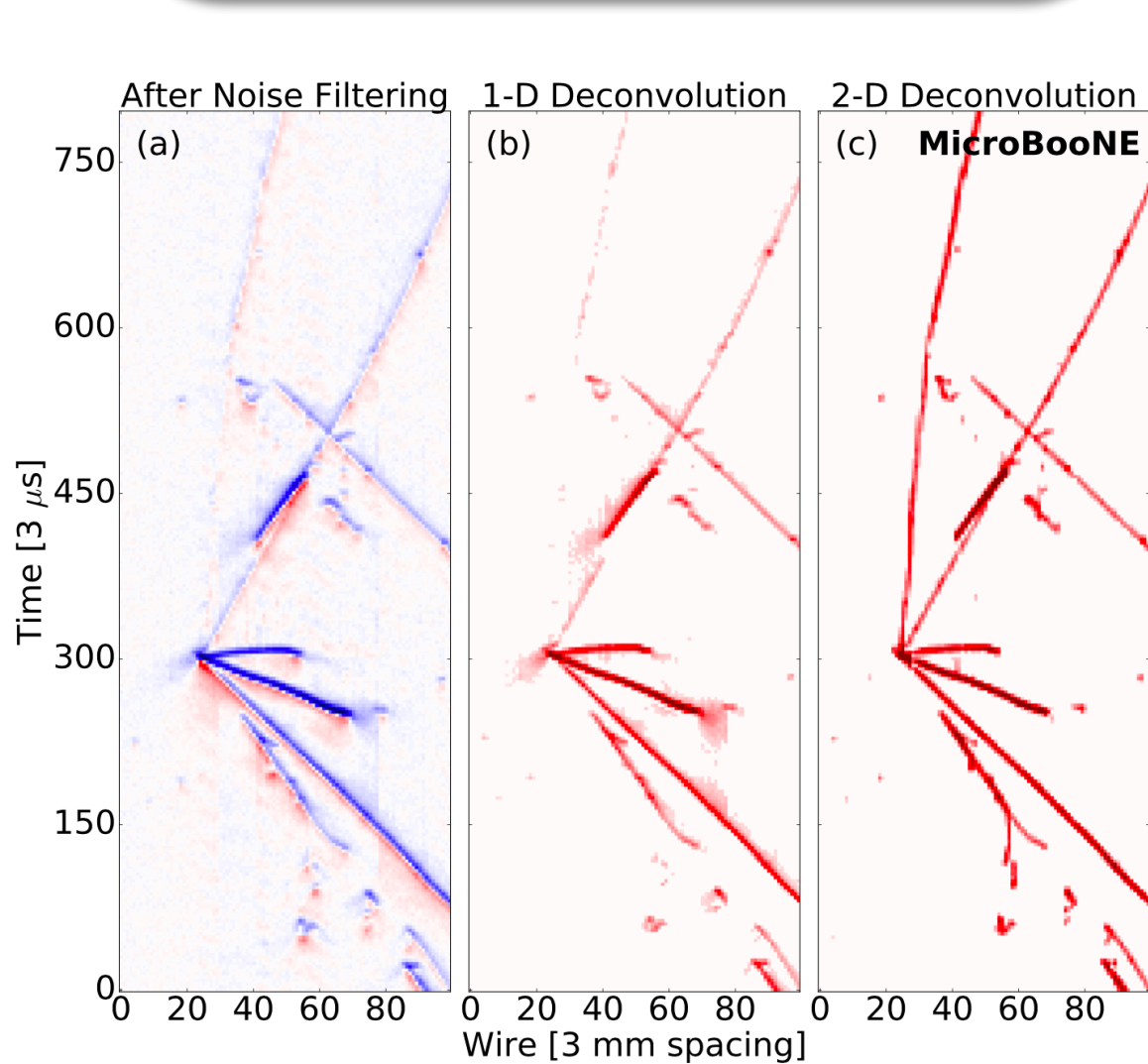
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dQ/dx fitting
Cosmic muon tagger

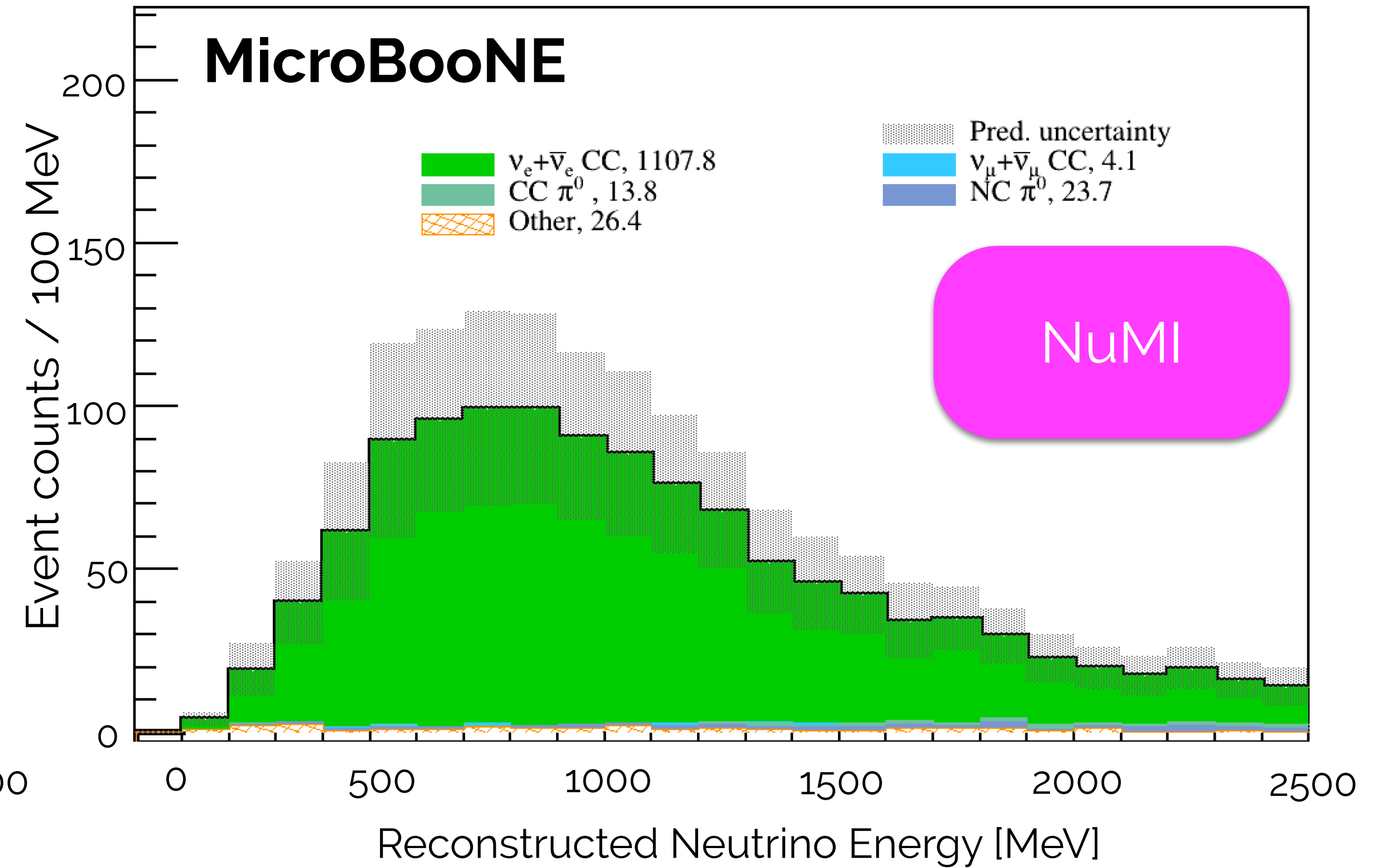
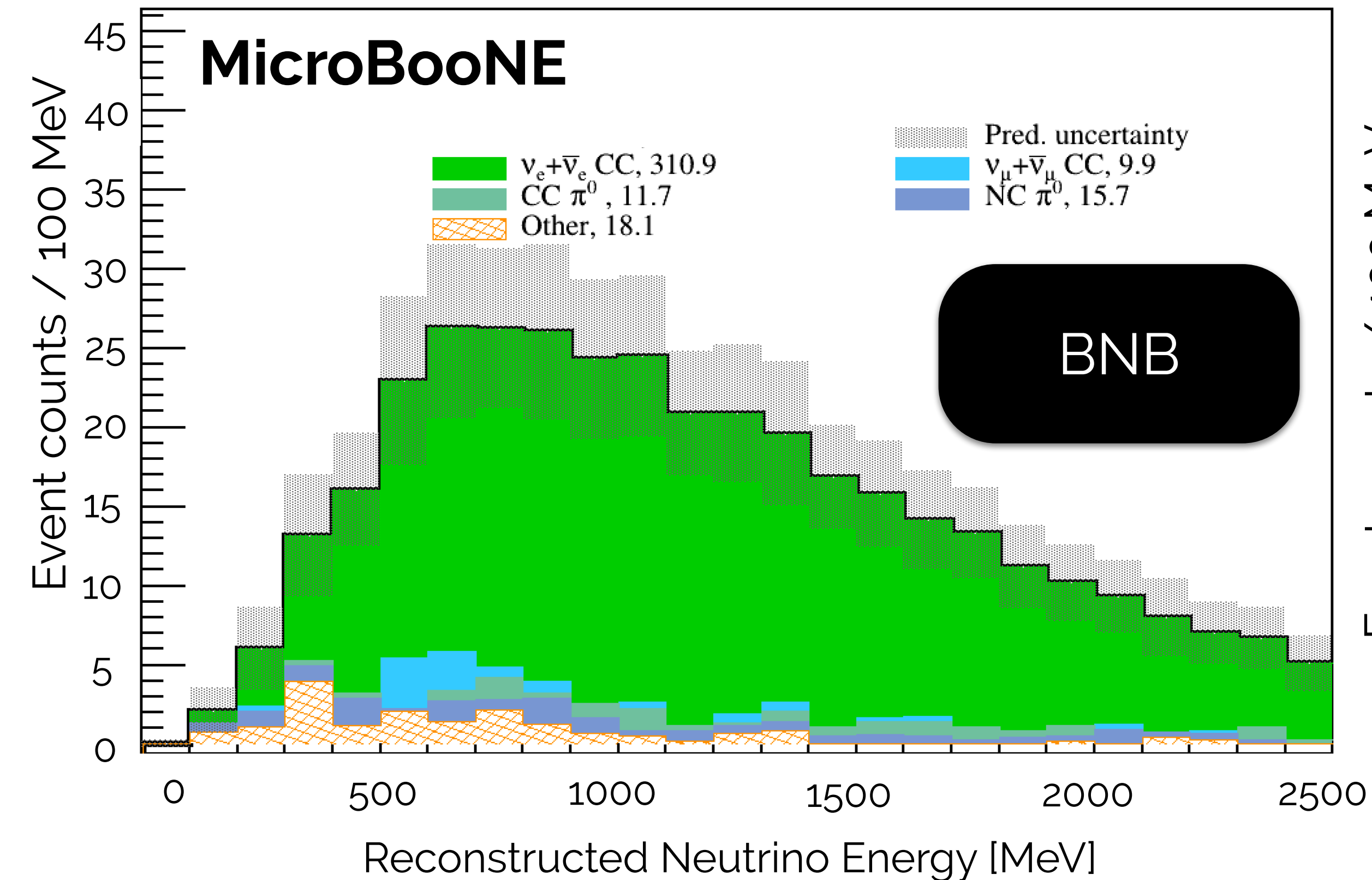
Multi track fitting
3D vertexing
Particle identification



Target channels

Very pure selections of ν_e !

Main Backgrounds: ν_μ and π^0



All Selection Channels

ν_e CC Fully
Contained

ν_e CC Partially
Contained

Reconstructed particles are fully or partially in fiducial volume
[increased statistics]

All Selection Channels

ν_e CC Fully
Contained

ν_e CC Partially
Contained

ν_μ CC Fully
Contained

ν_μ channels constrain ν_e
prediction $\rightarrow$ universality of
cross section modeling for CC
interactions

ν_μ CC Partially
Contained

All Selection Channels

ν_e CC Fully
Contained

ν_e CC Partially
Contained

ν_μ CC Fully
Contained

π^0 are main background for ν_e
search $\rightarrow$ mimics ν_e signature

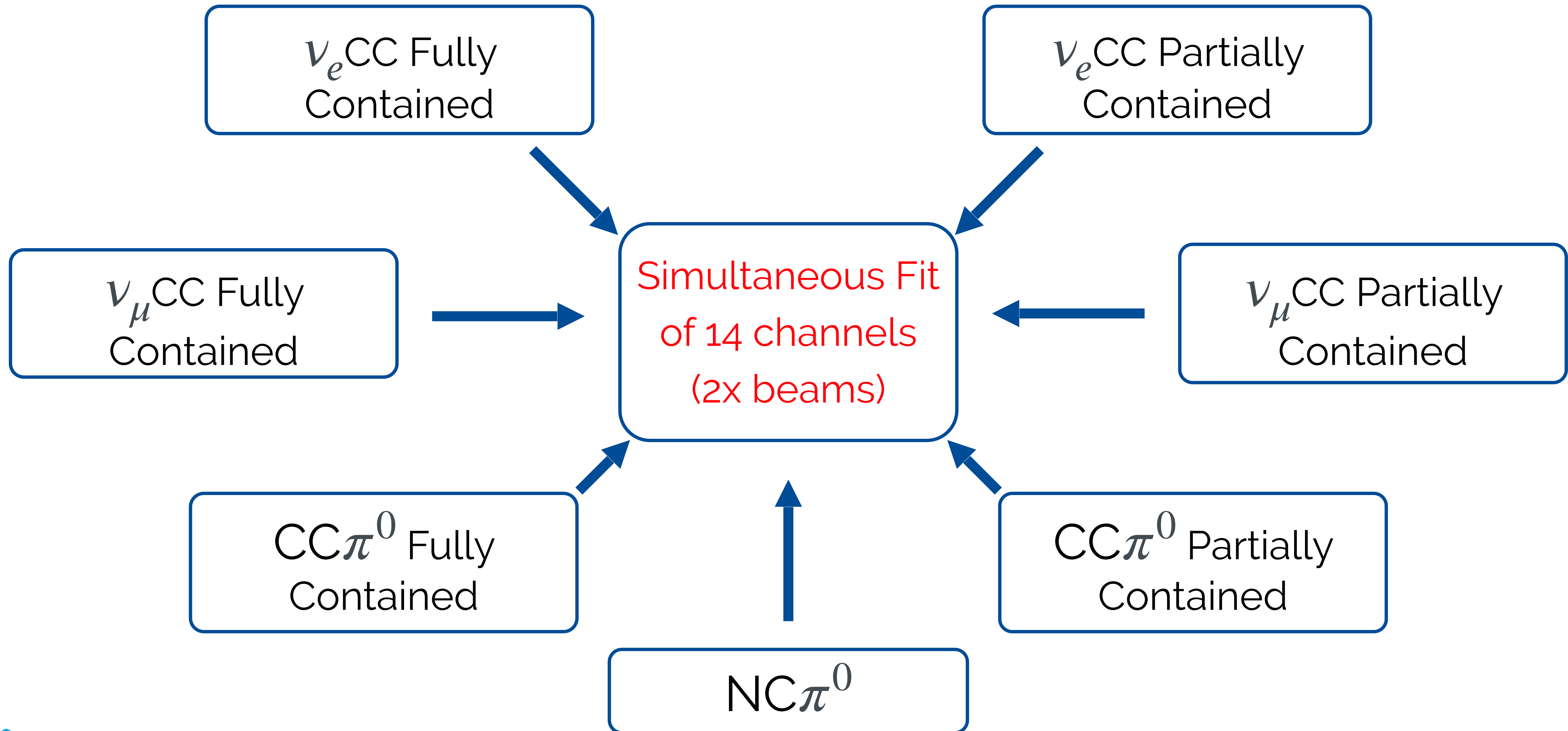
ν_μ CC Partially
Contained

CC π^0 Fully
Contained

CC π^0 Partially
Contained

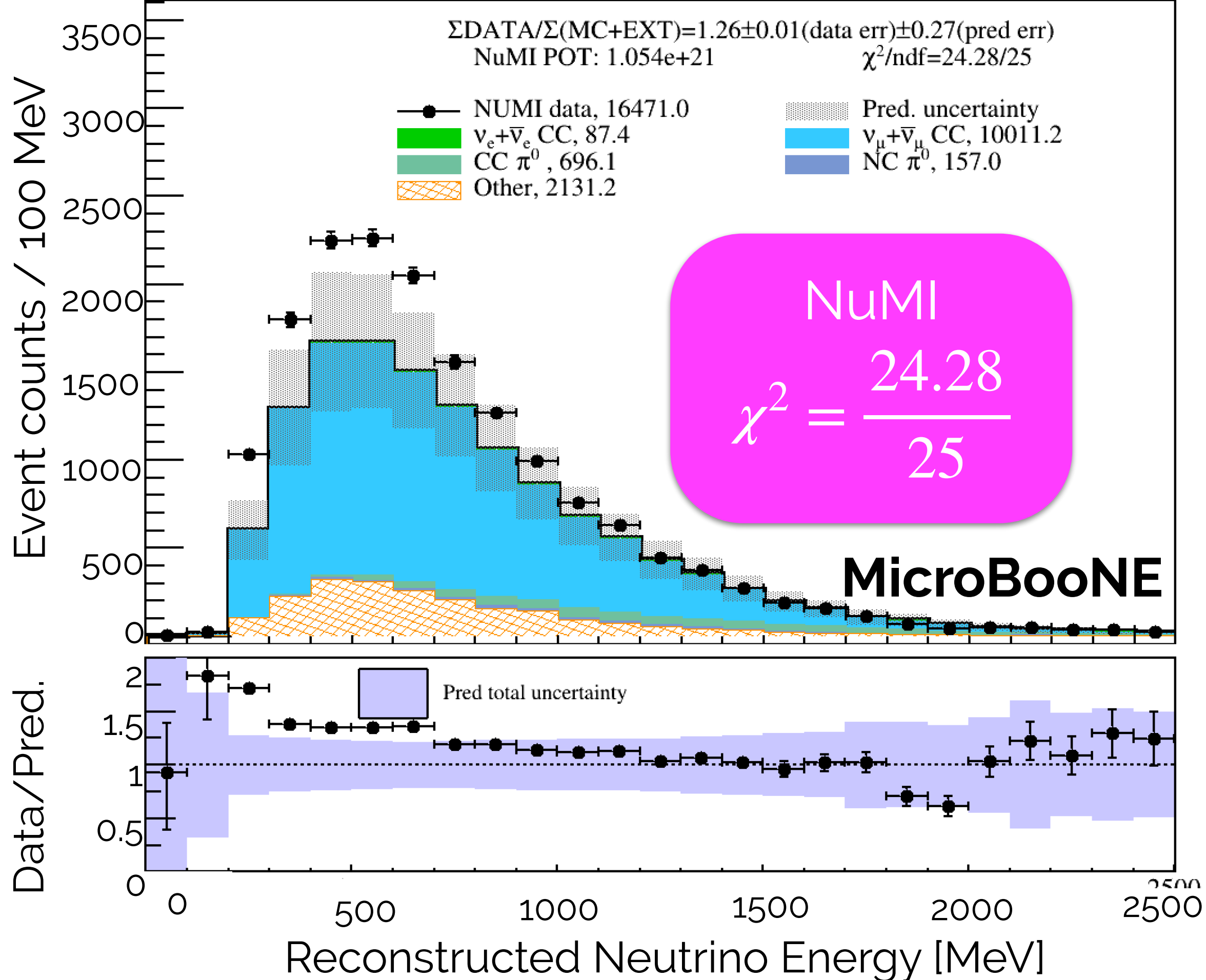
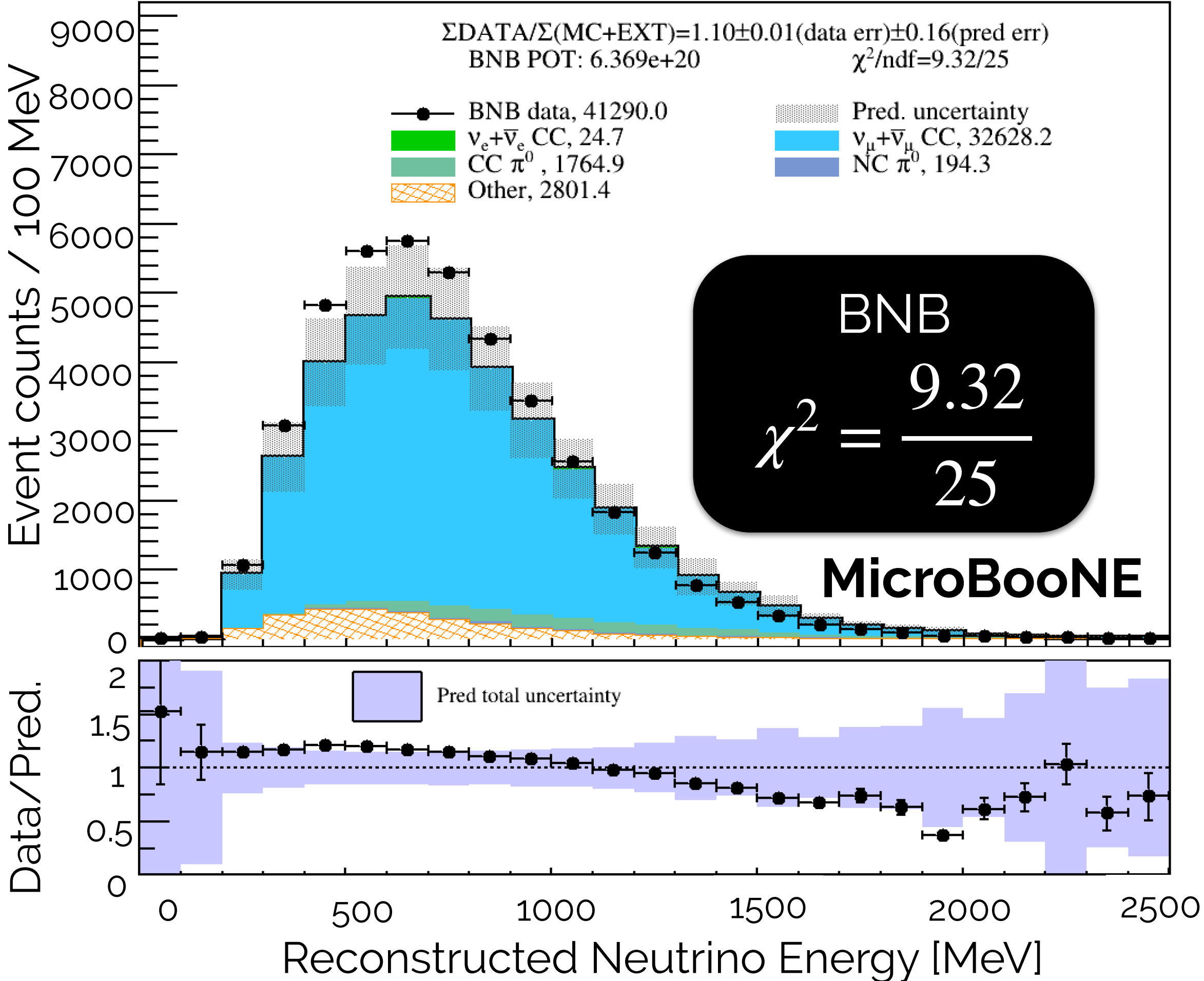
NC π^0

All Selection Channels



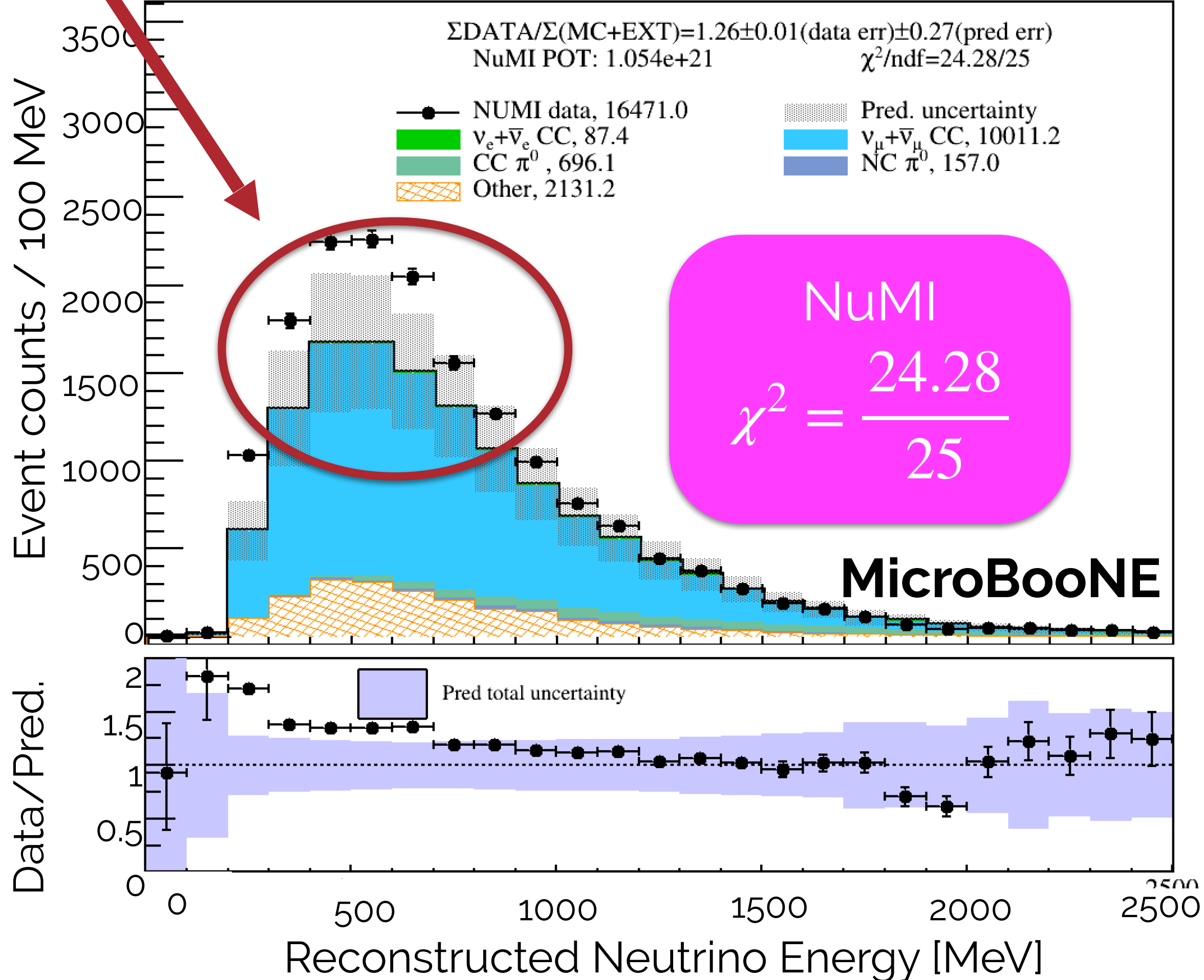
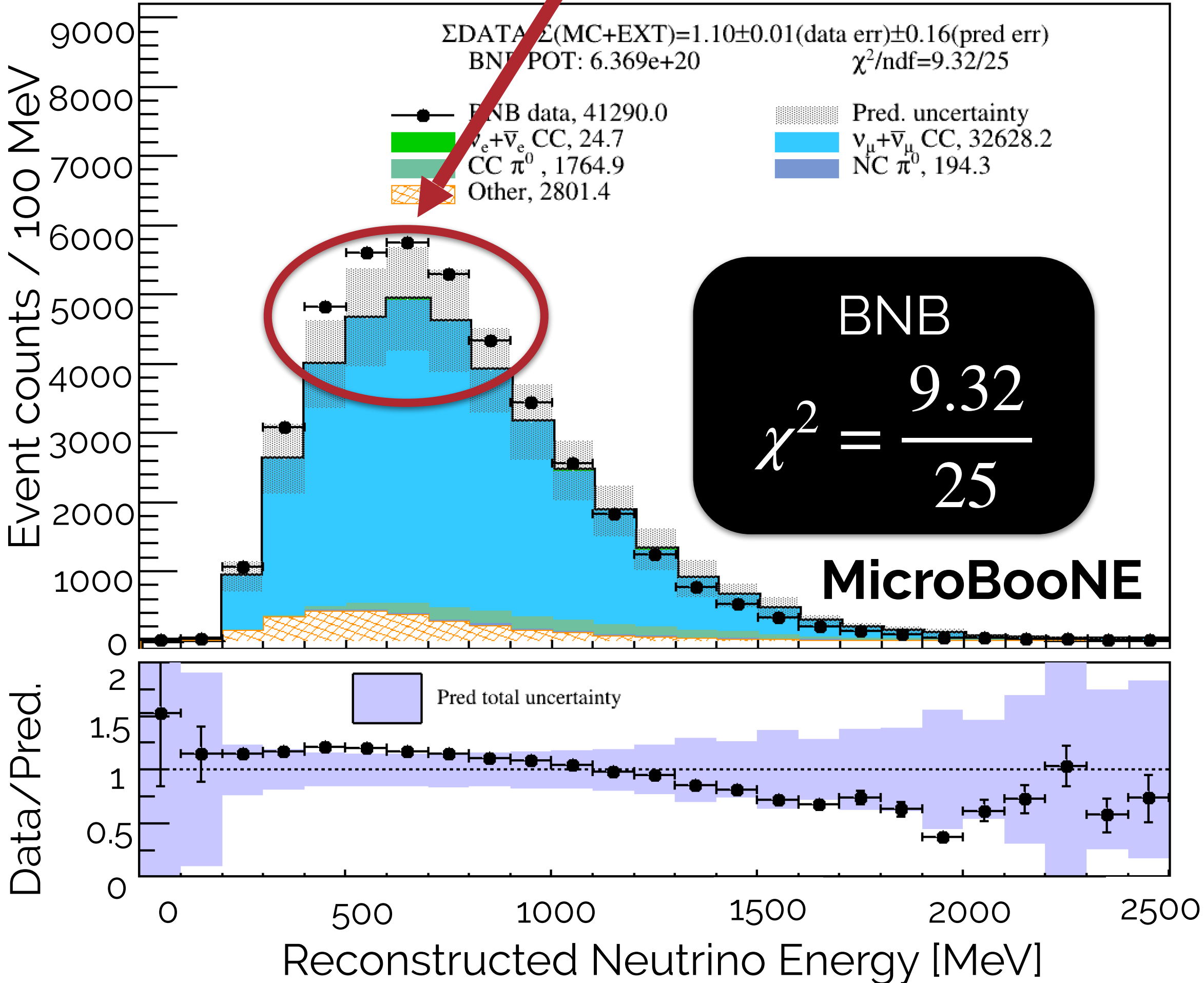
Sideband channels : ν_μ

ν_μ channels constrain ν_e prediction $\rightarrow$
universality of cross section modeling for CC interactions



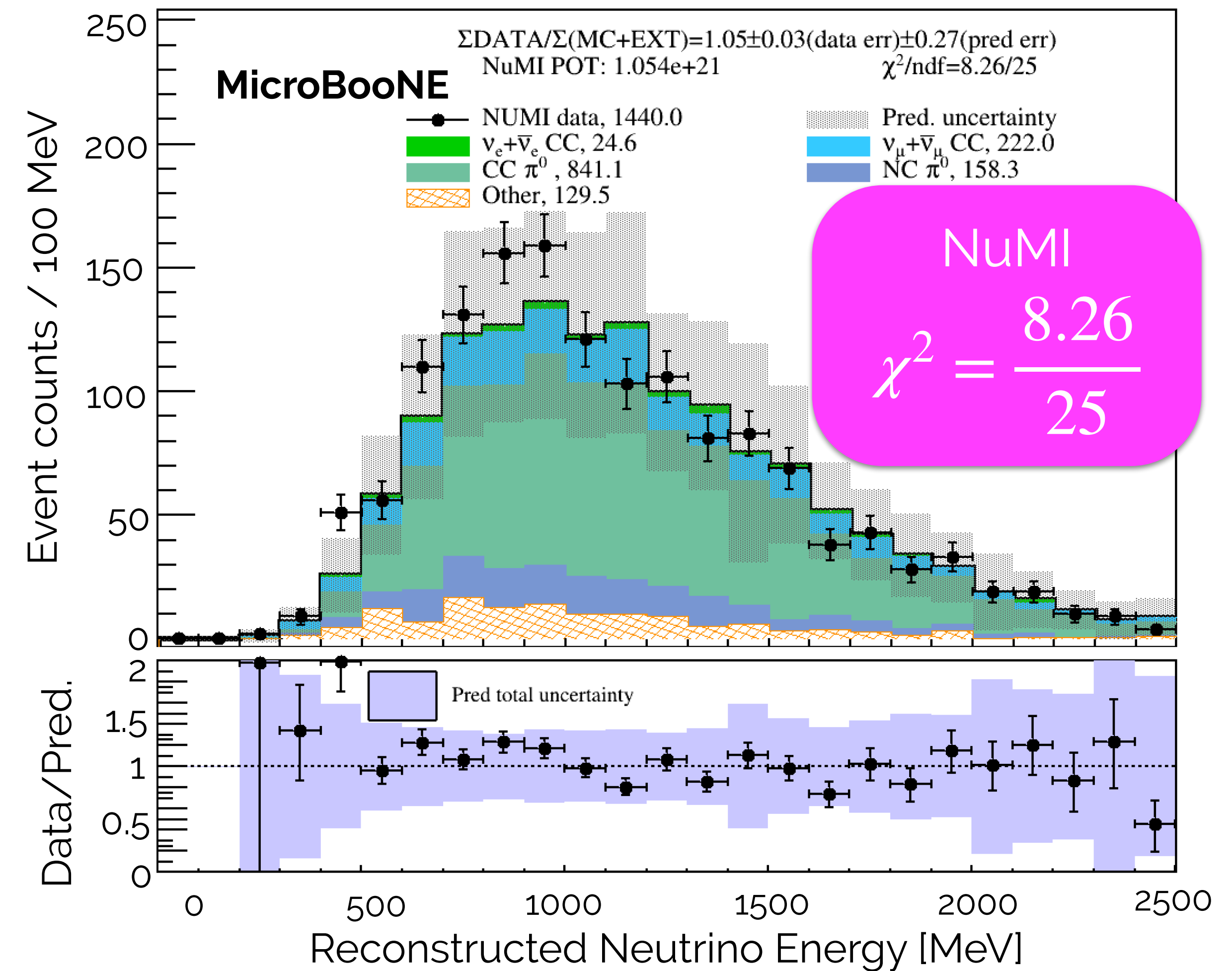
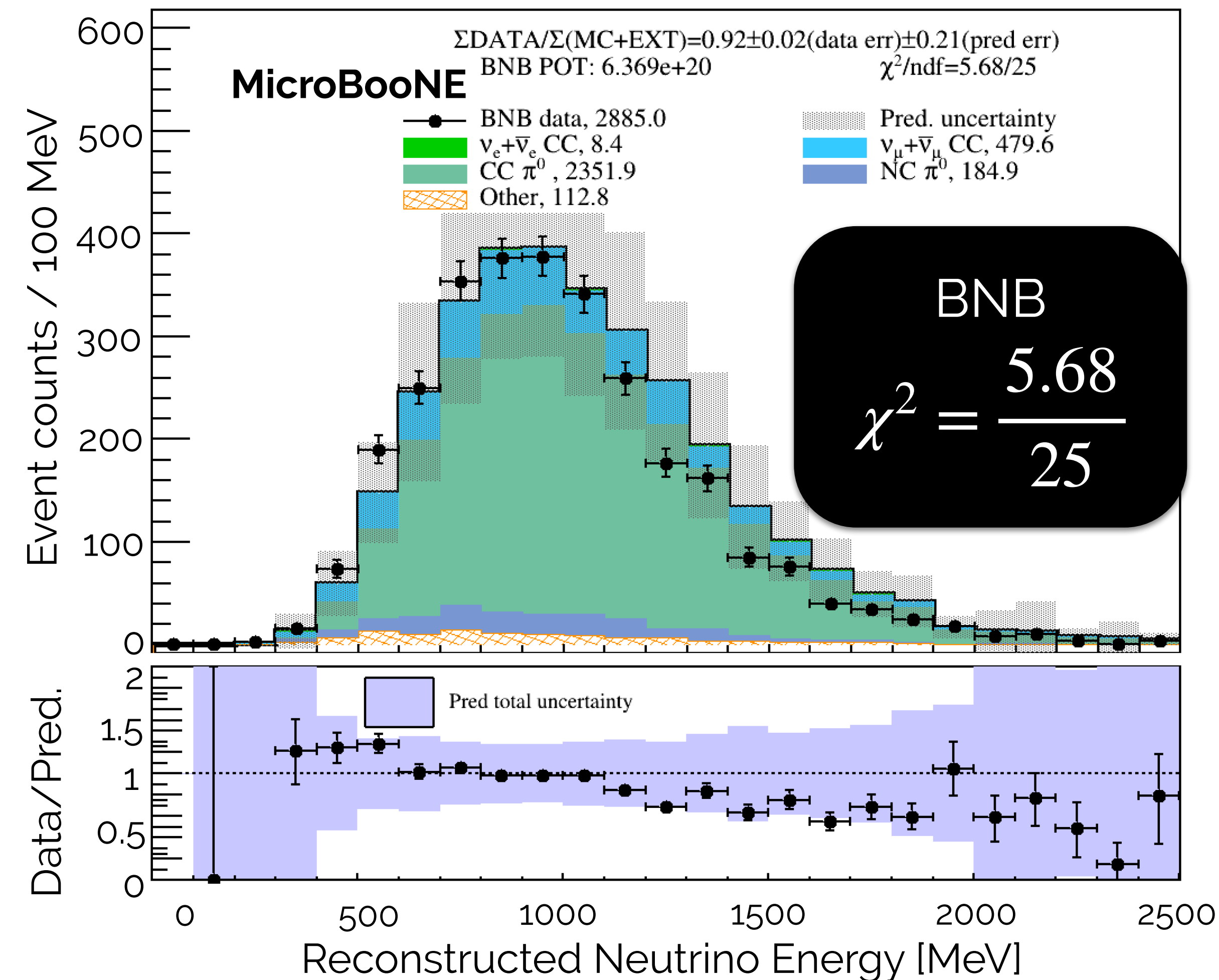
Sideband channels : ν_μ

MC under-prediction
[consistent at 1σ level]



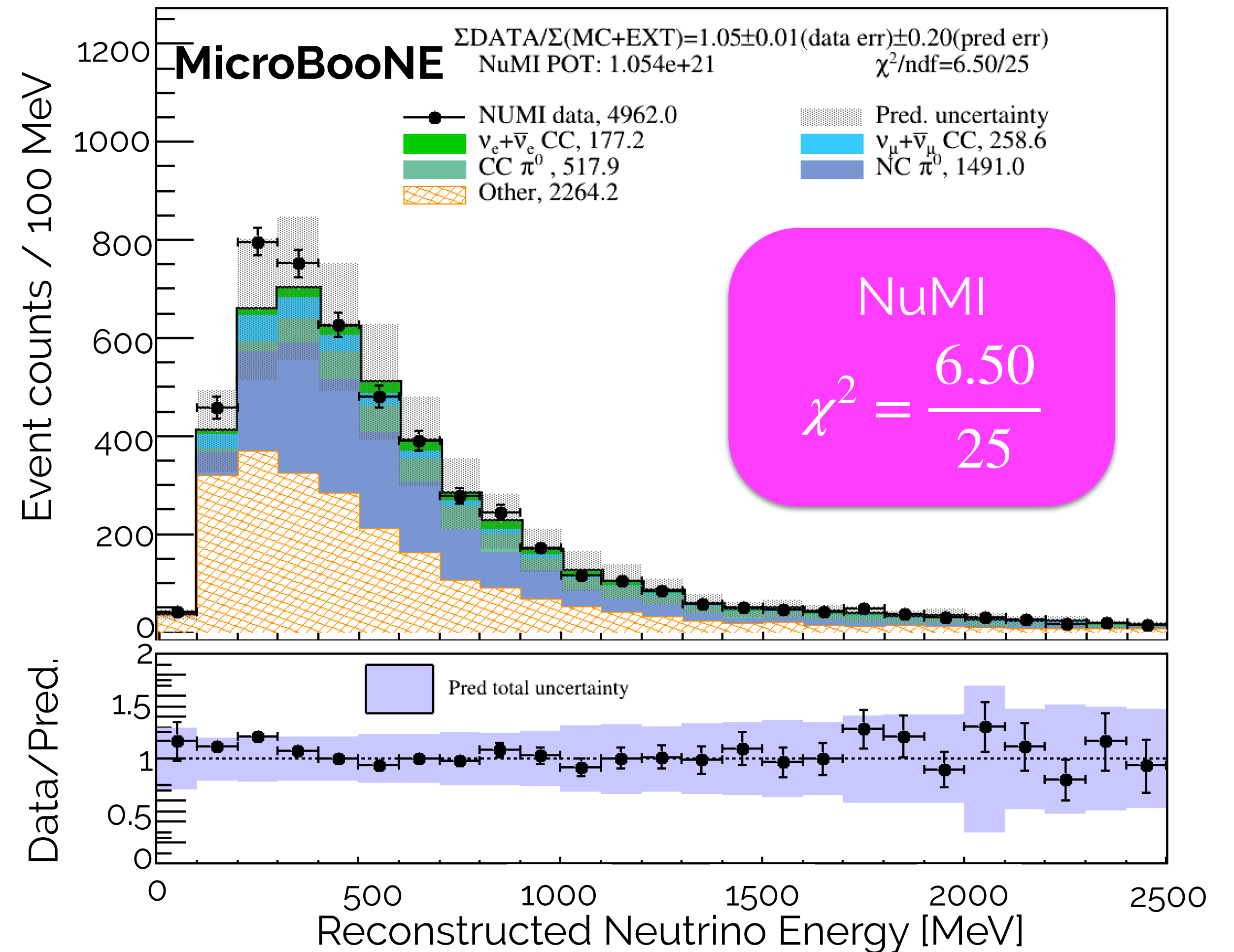
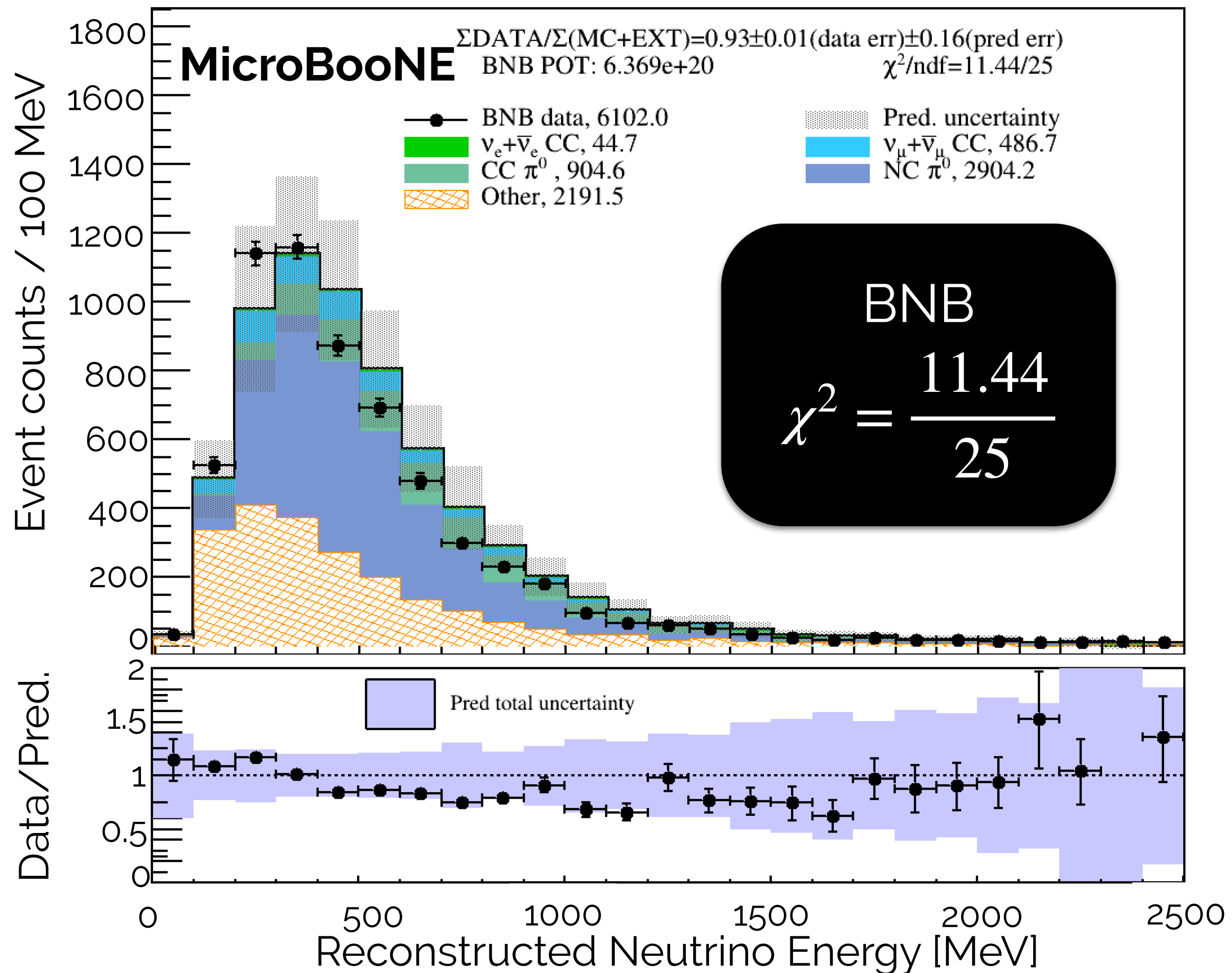
Sideband channels : CC π^0

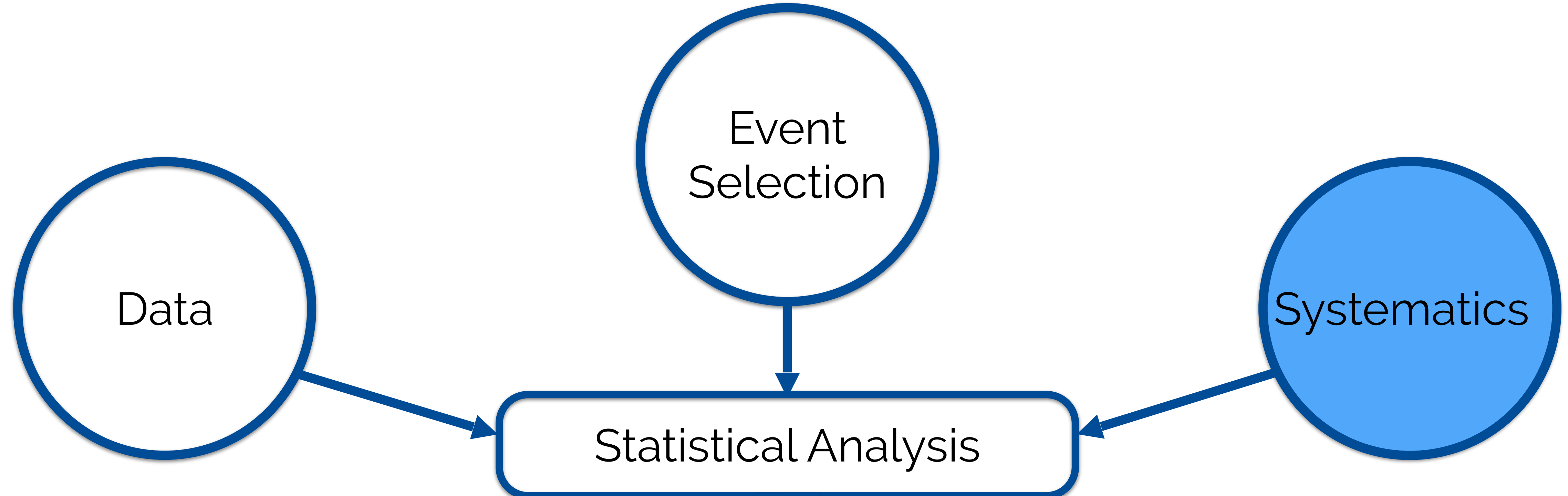
π^0 are main background for ν_e search $\rightarrow$ mimics ν_e signature



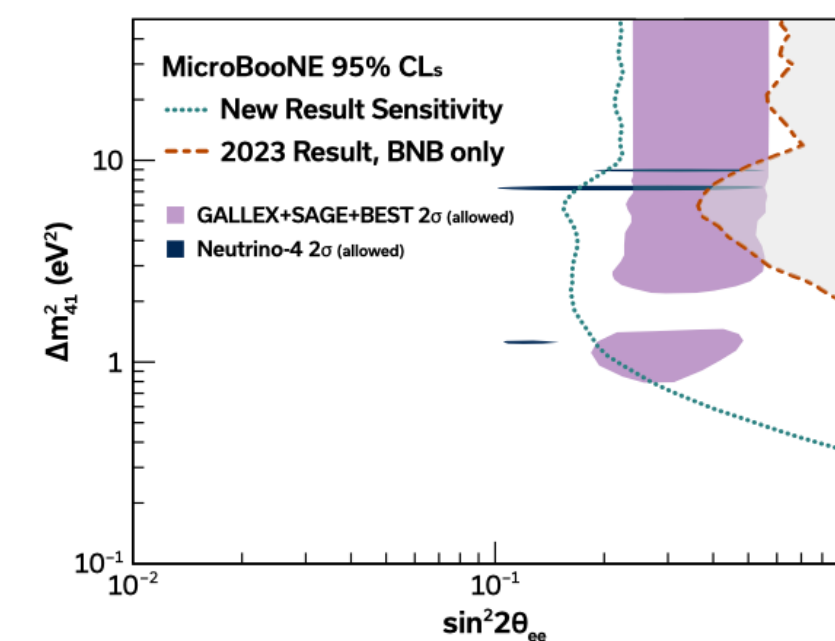
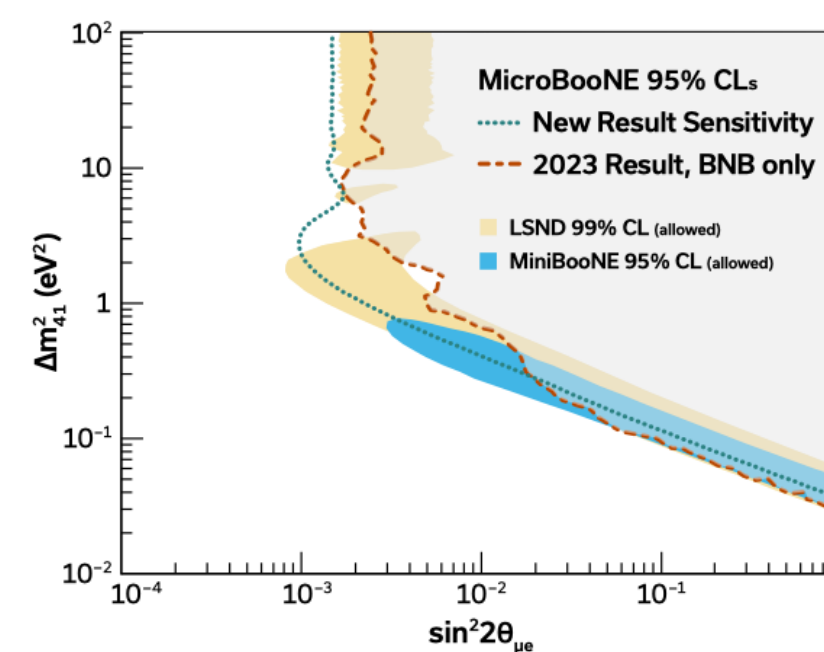
Sideband channels : NC π^0

π^0 are main background for ν_e search $\rightarrow$ mimics ν_e signature





MicroBooNE 3+1 Result



Detector systematics treatment

[JINST 15 P07010](#)

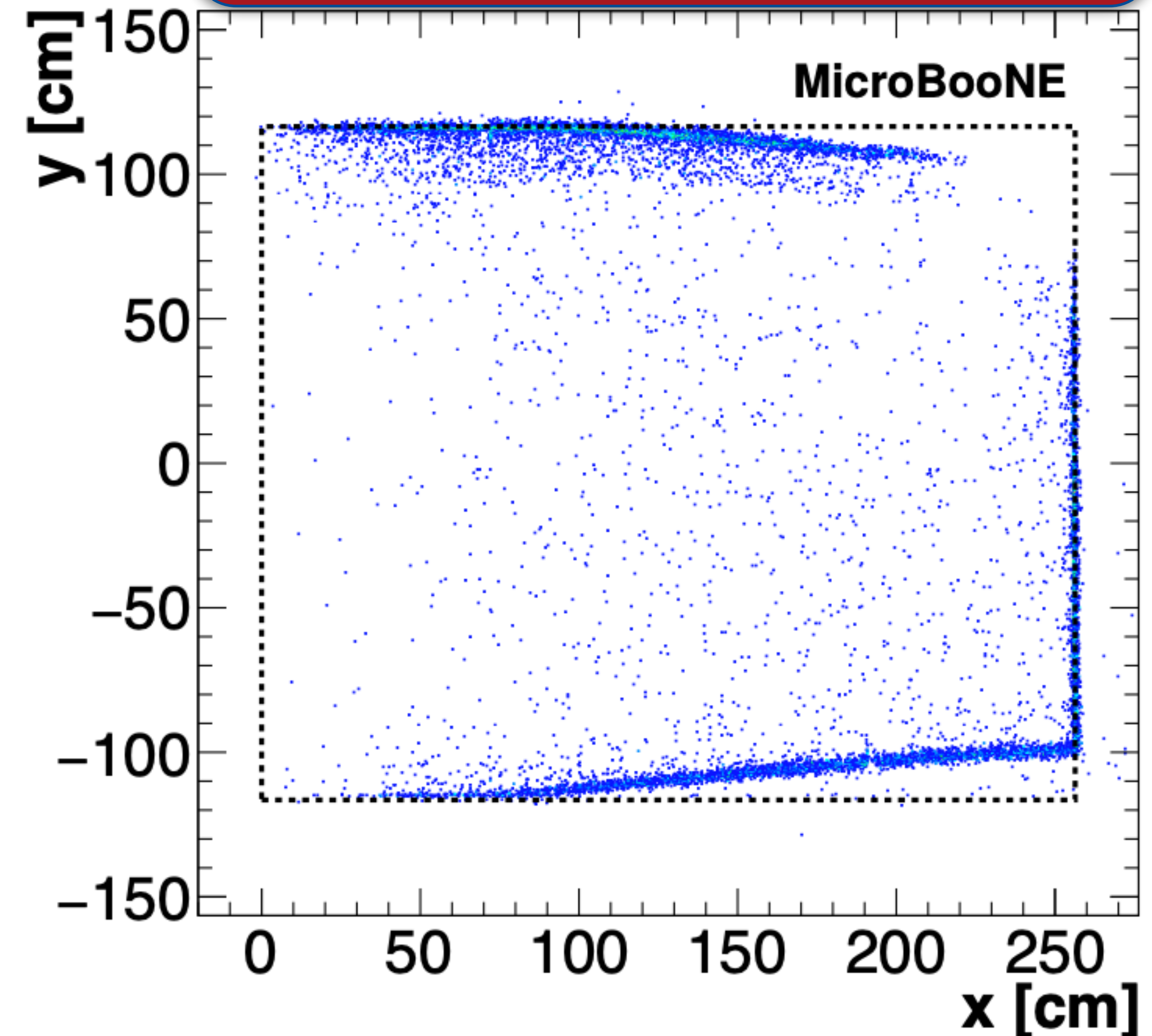
[MICROBOONE-NOTE-1075-PUB](#)

[JINST 15 P12037](#)

[Eur. Phys. J. C 82, 454 \(2022\)](#)

- Utilize a range of tools [cosmic muons, protons, laser] to characterize the detector
- Evaluate a range of systematic uncertainties covering light yield, space charge, recombination, wire waveform simulation.
- Compare data to Monte Carlo to assess uncertainty magnitude from each effect
- Use modified Monte Carlo samples to assess the impacts of these uncertainties on the analysis.

Reconstructed entry and exit points of cosmic muons



Detector systematics treatment

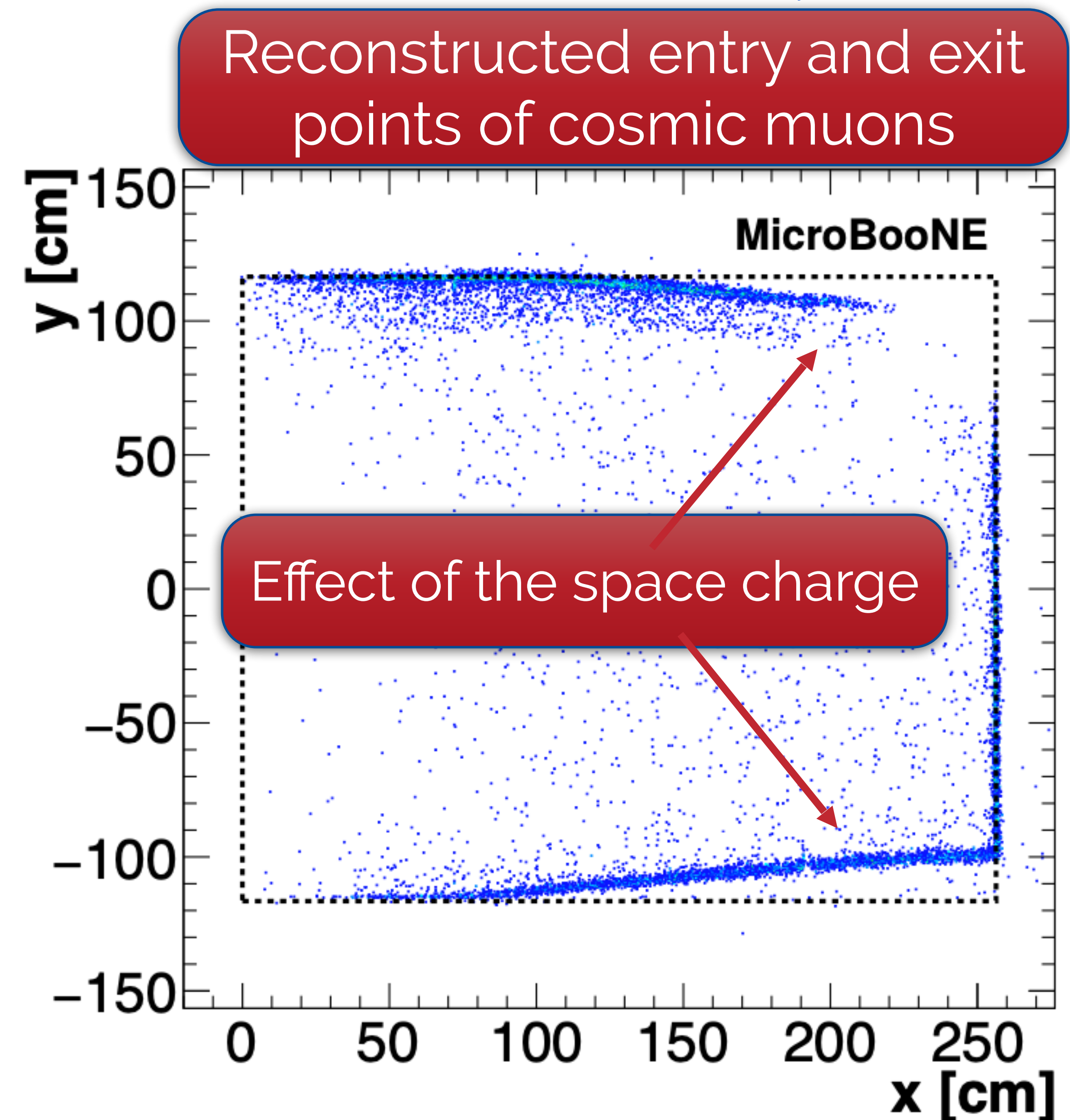
[JINST 15 P07010](#)

[MICROBOONE-NOTE-1075-PUB](#)

[JINST 15 P12037](#)

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Detector systematics treatment

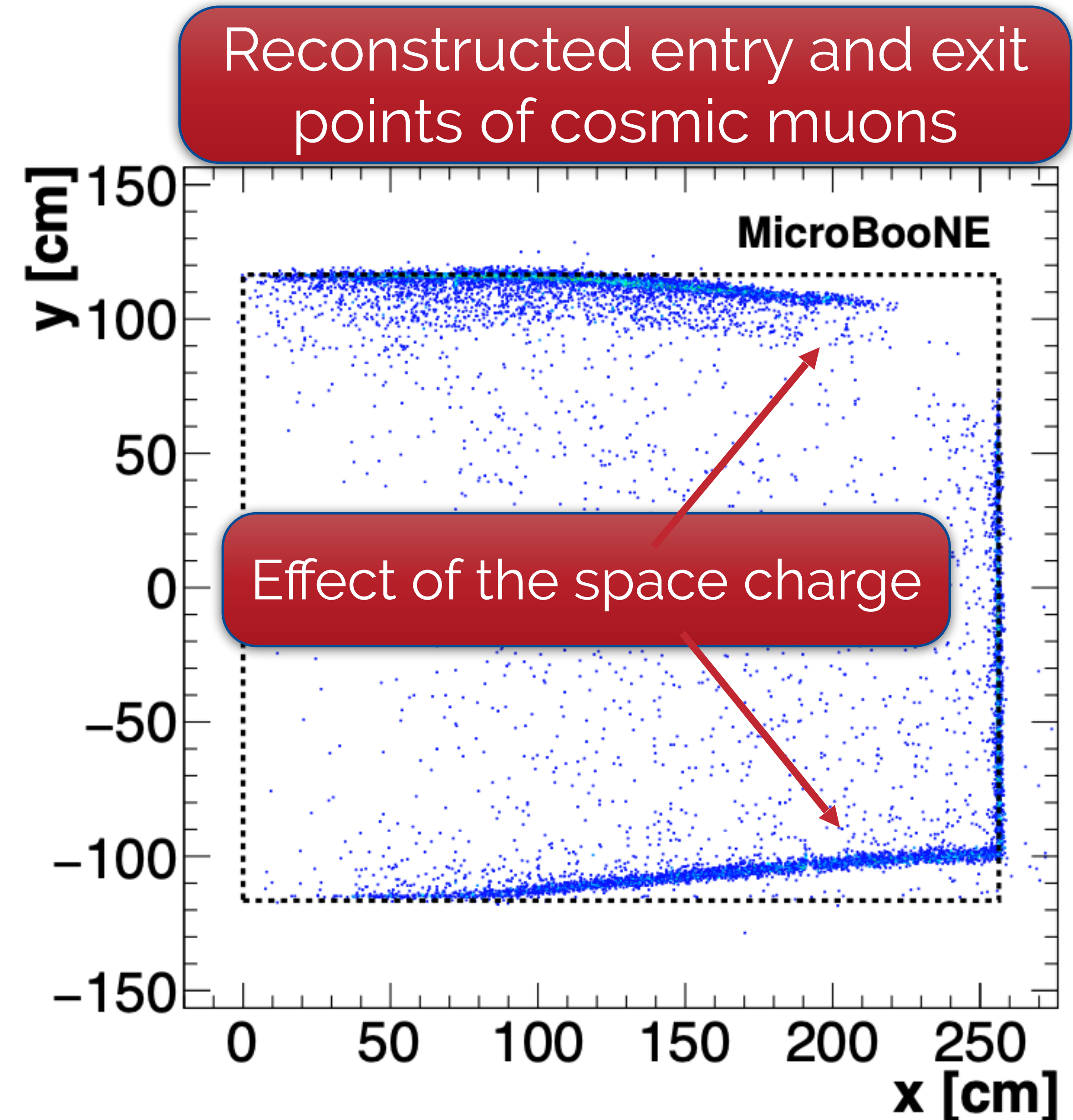
[JINST 15 P07010](#)

[MICROBOONE-NOTE-1075-PUB](#)

[JINST 15 P12037](#)

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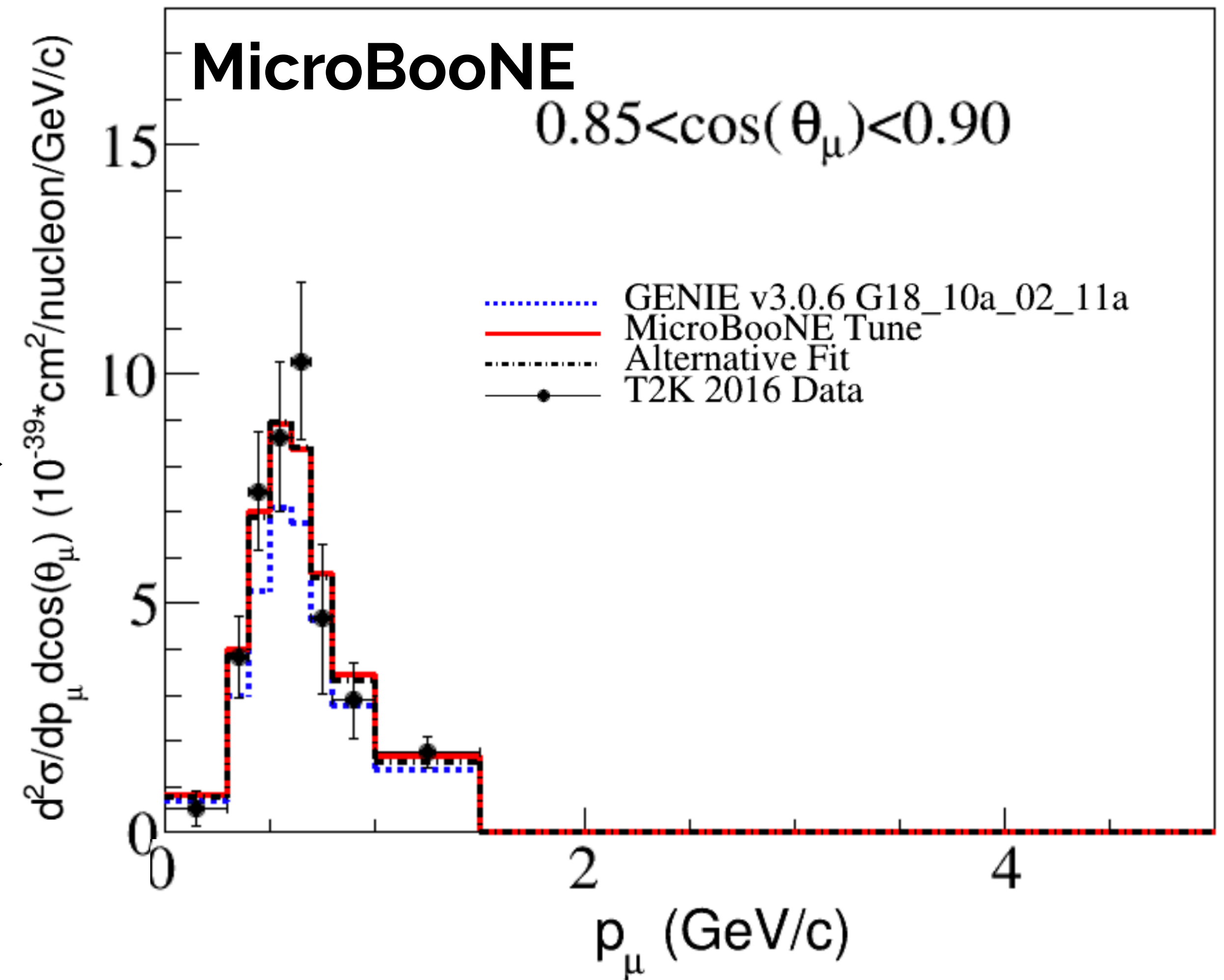
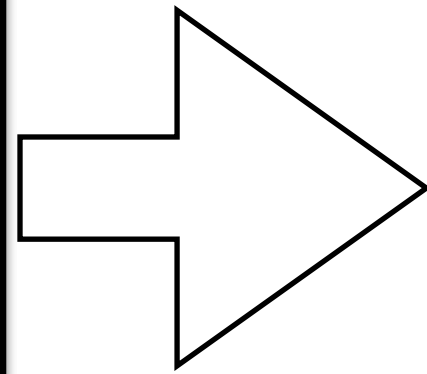
Cross Section Model

[Phys. Rev. D 105, 072001](#)

Base Cross section model:

GENIE v3.0.6

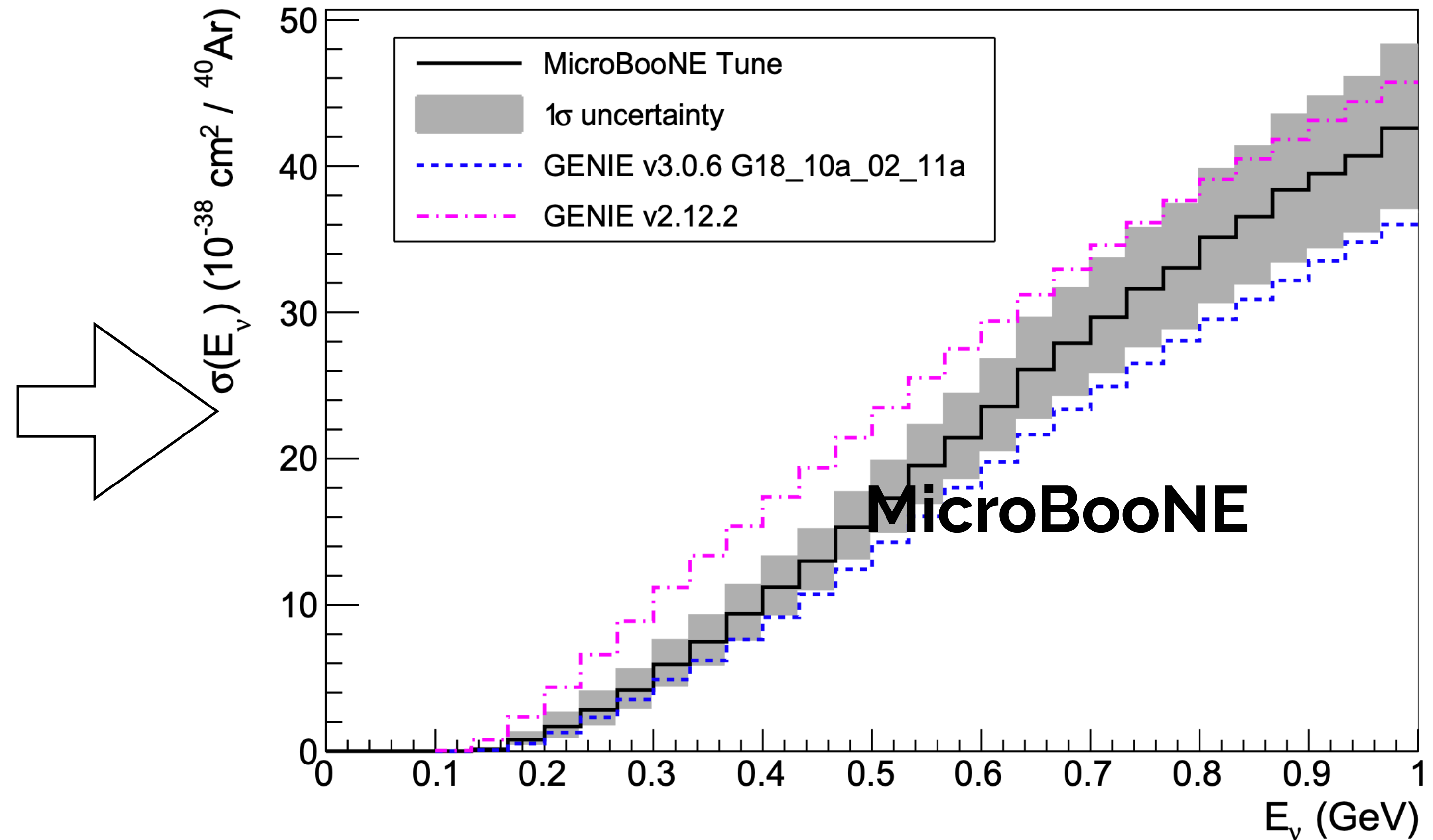
Tune to T2K $\nu_\mu CC0\pi$
cross section



Cross section systematics

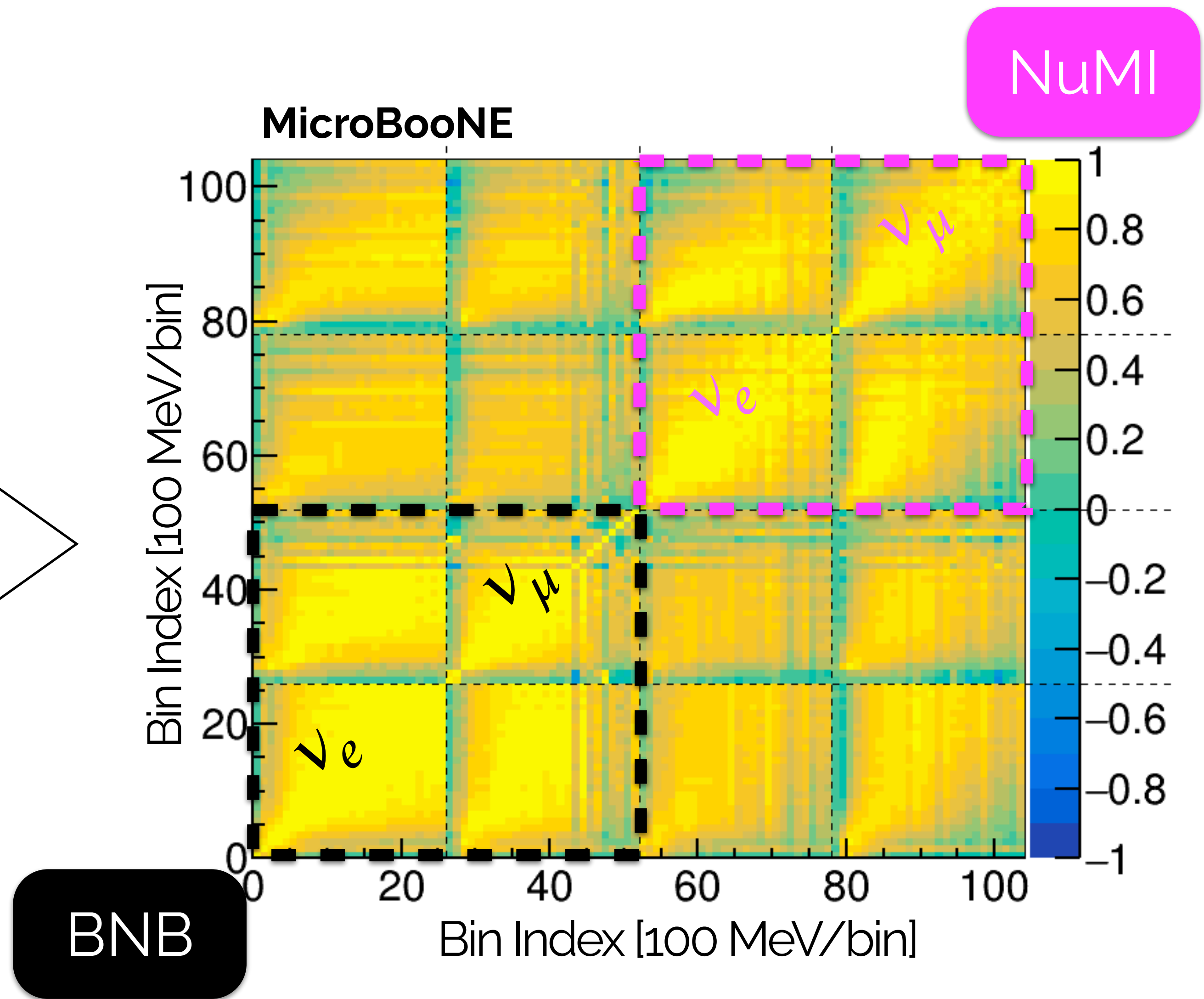
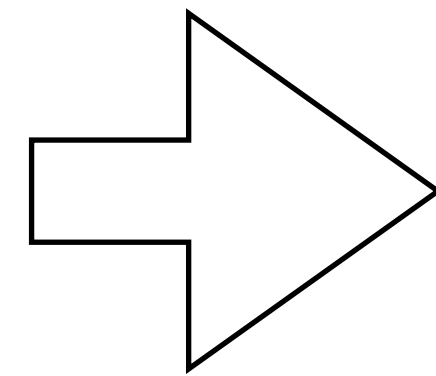
[Phys. Rev. D 105, 072001](#)

- Vary a set of cross-section parameters around the tuned model
- QE axial mass, 2p2h normalization/shape, RPA strength, pion production, etc. [57 total]
- Propagate the same parameter variations to event rates to build covariance matrix



Cross section systematics

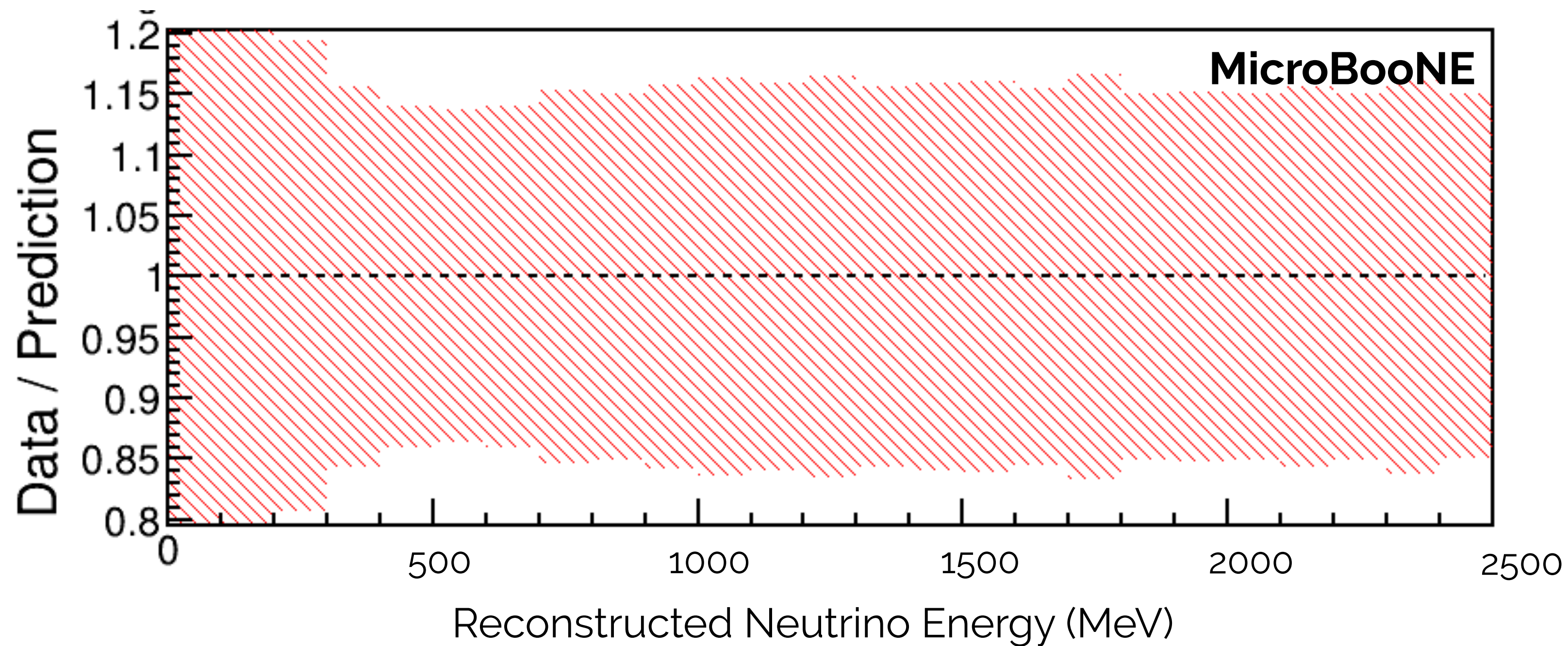
Strong correlation between ν_e CC and ν_μ CC channels $\rightarrow$ universality of cross section models for CC interaction



Constrain Cross Section model and its uncertainty

Leverage correlations to
constrain the cross section
model and its uncertainty

BNB ν_e
Only Cross Section Syst.

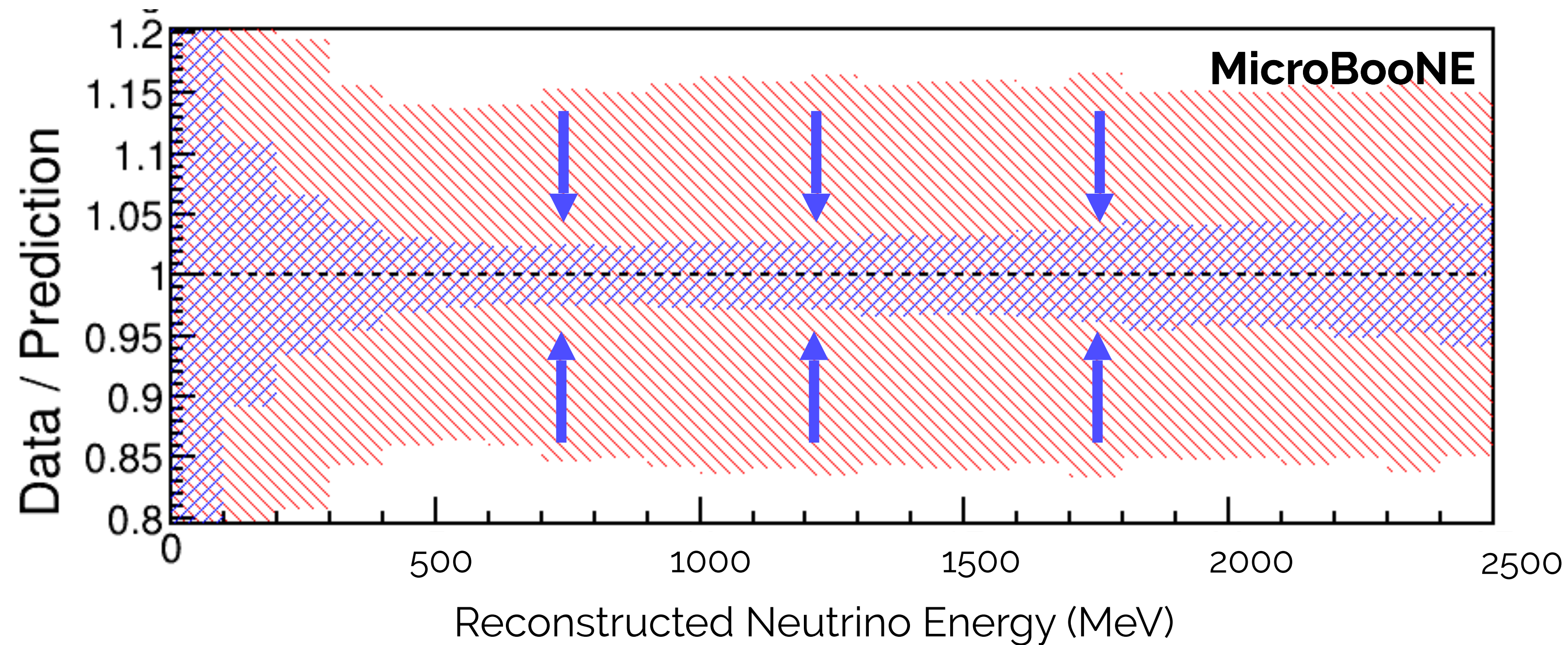


Constrain Cross Section model and its uncertainty

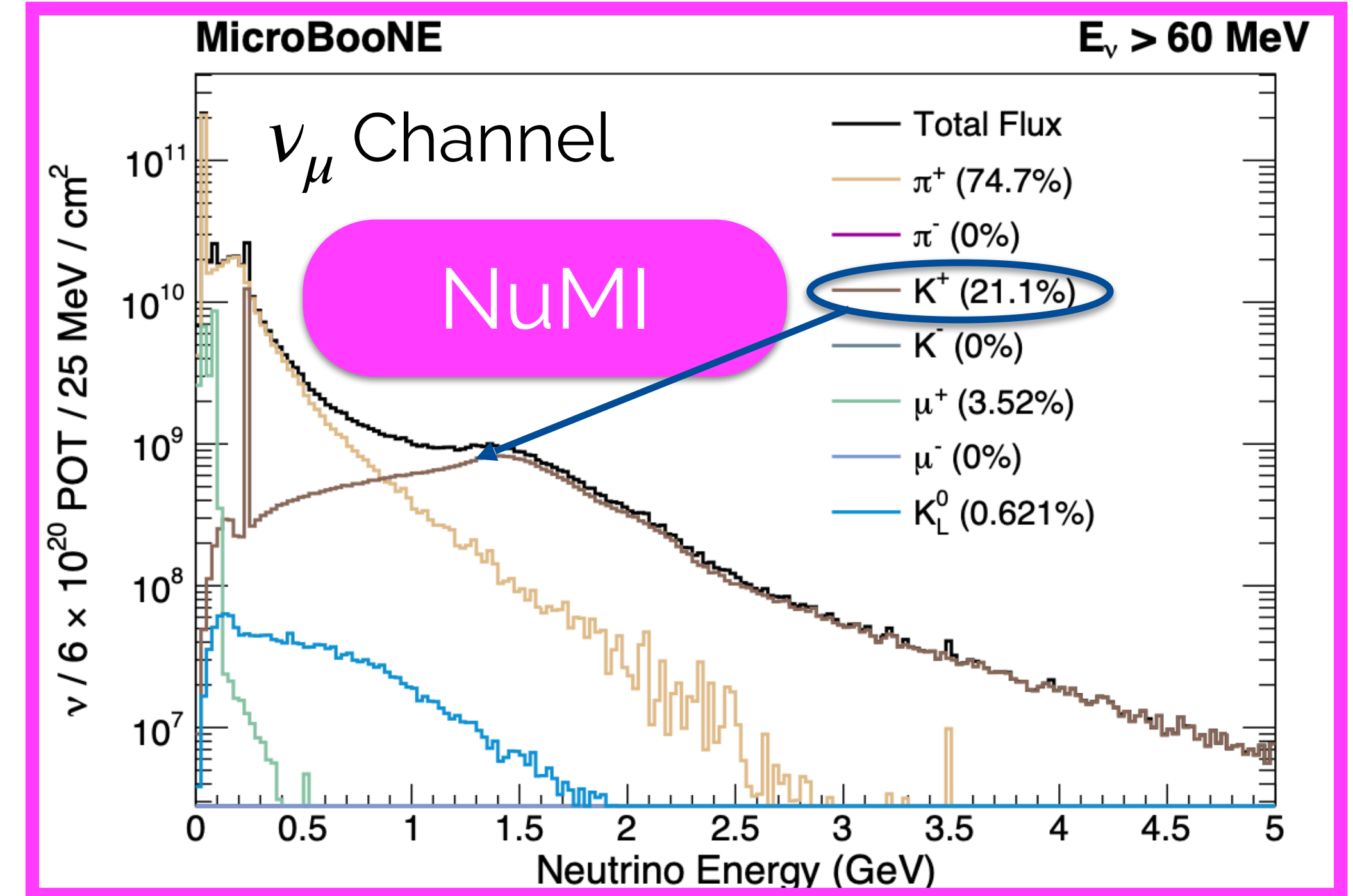
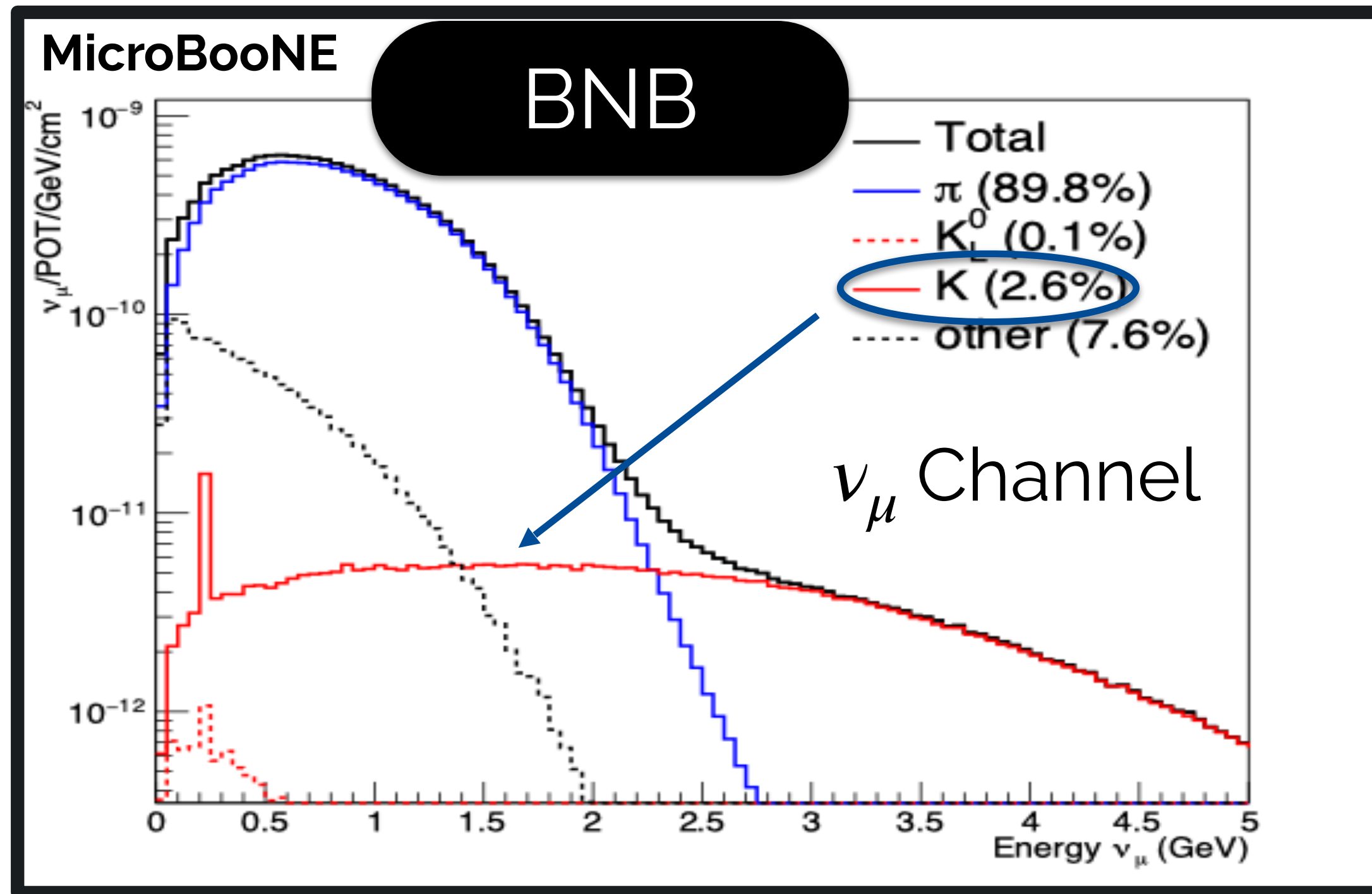
Leverage correlations to constrain the cross section model and its uncertainty

Constraint with BNB ν_μ

BNB ν_e
Only Cross Section Syst.



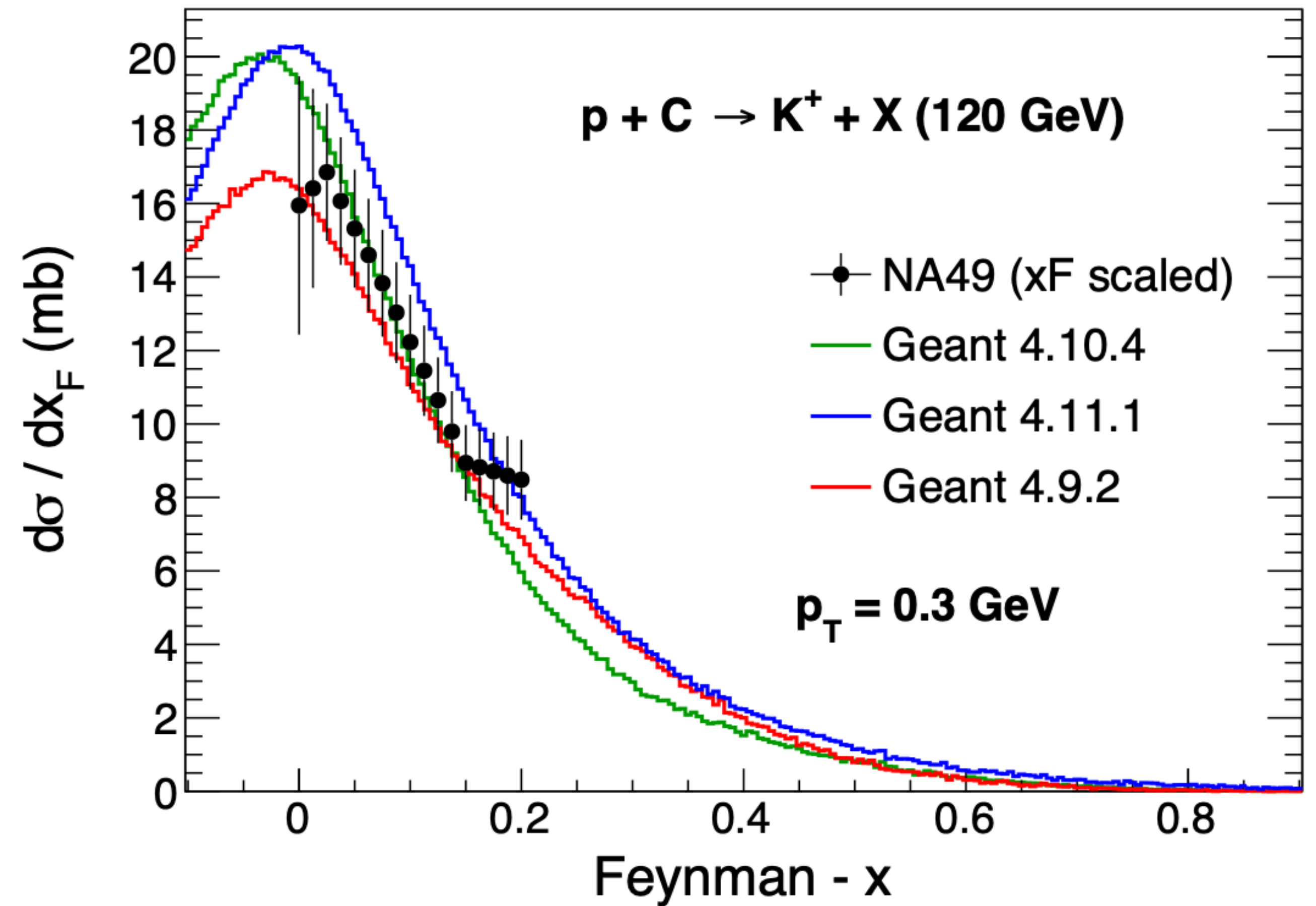
Updating NuMI Flux Model



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

Updating NuMI Flux Model

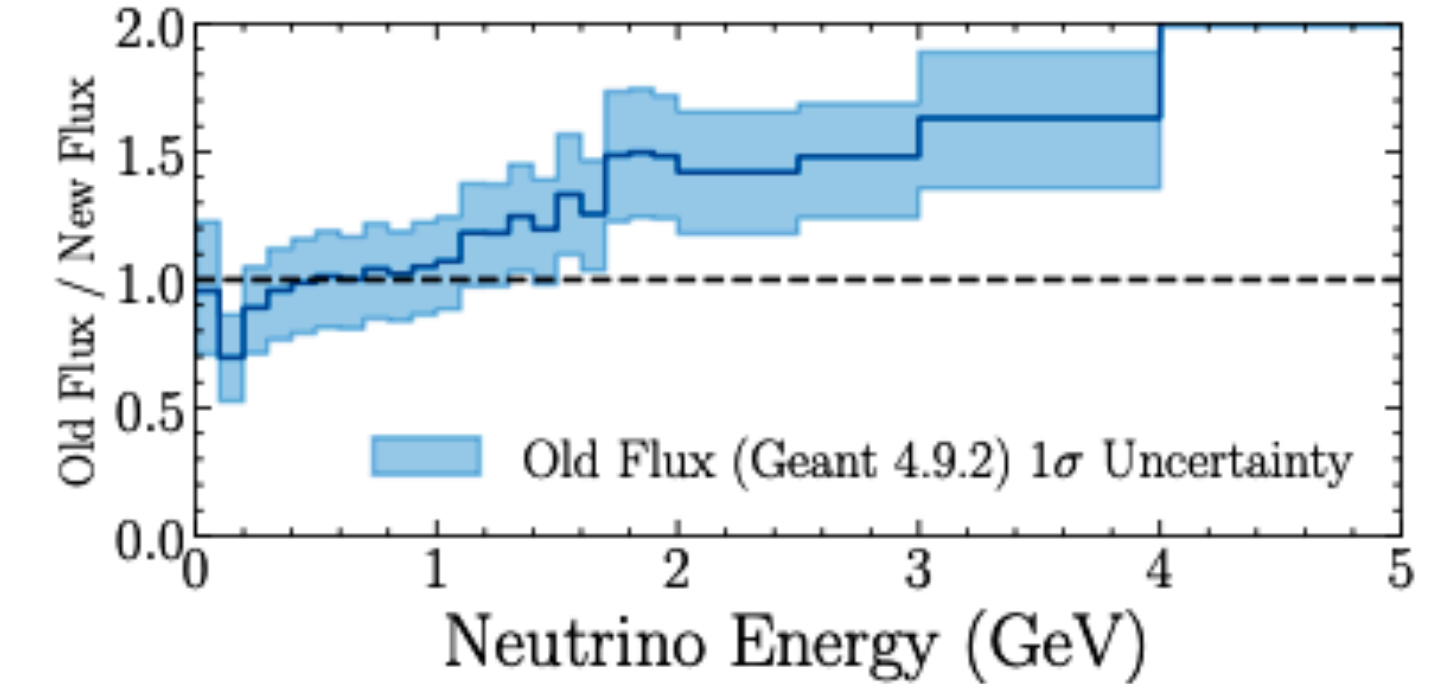
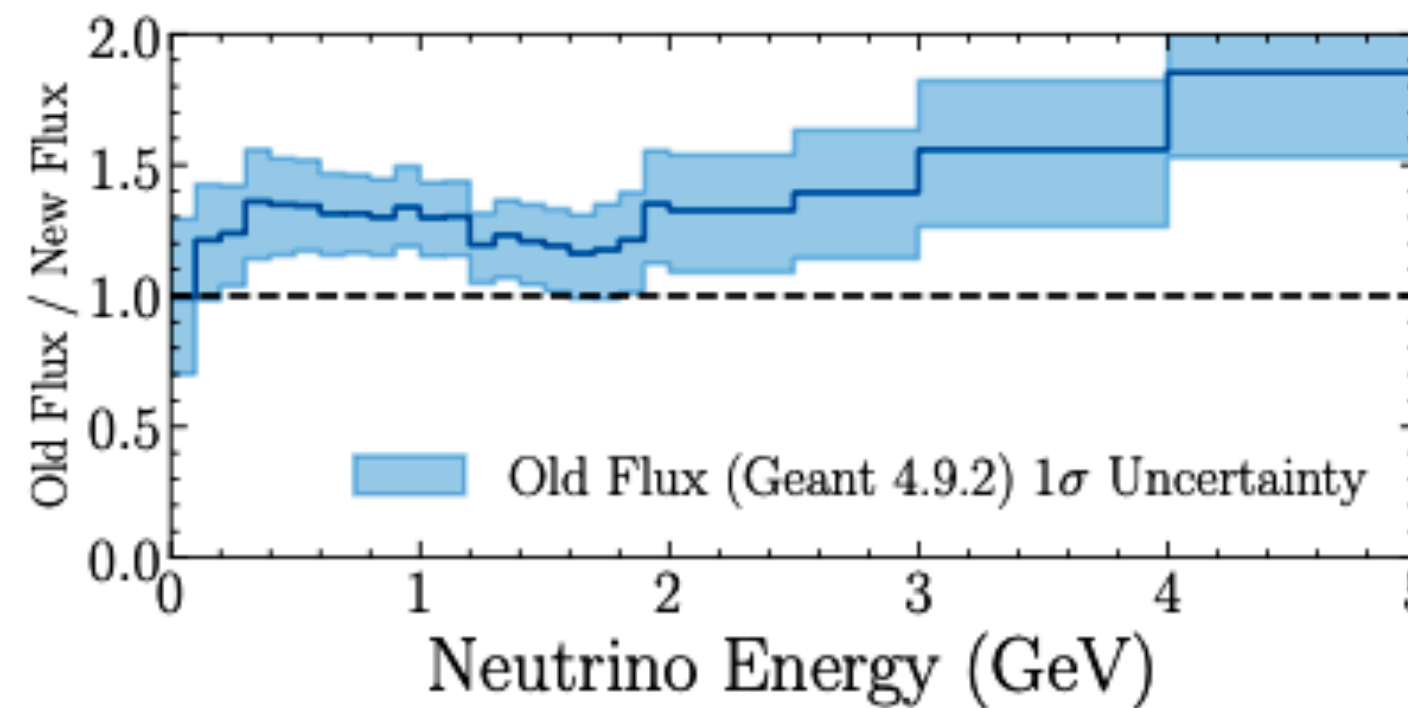
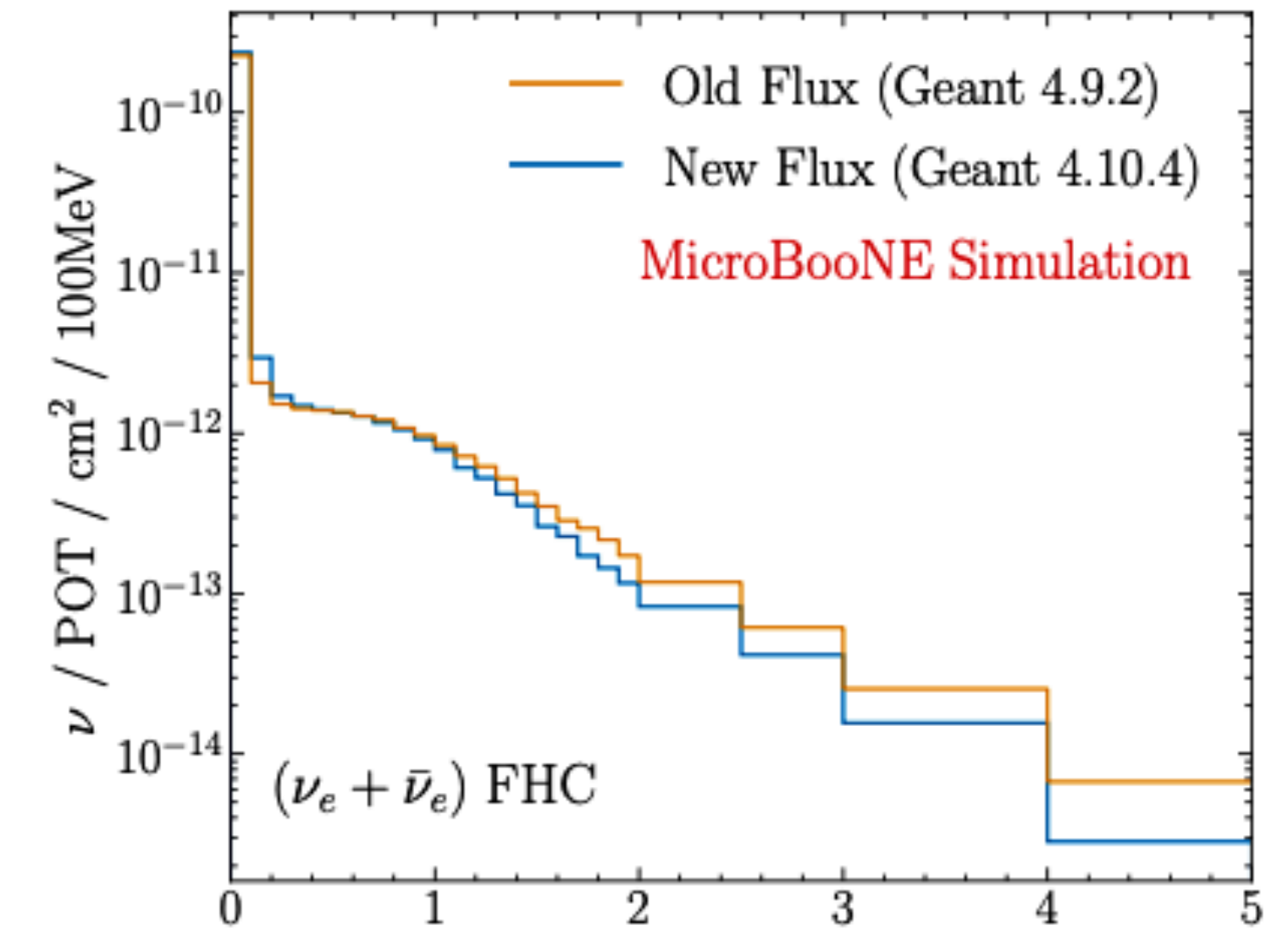
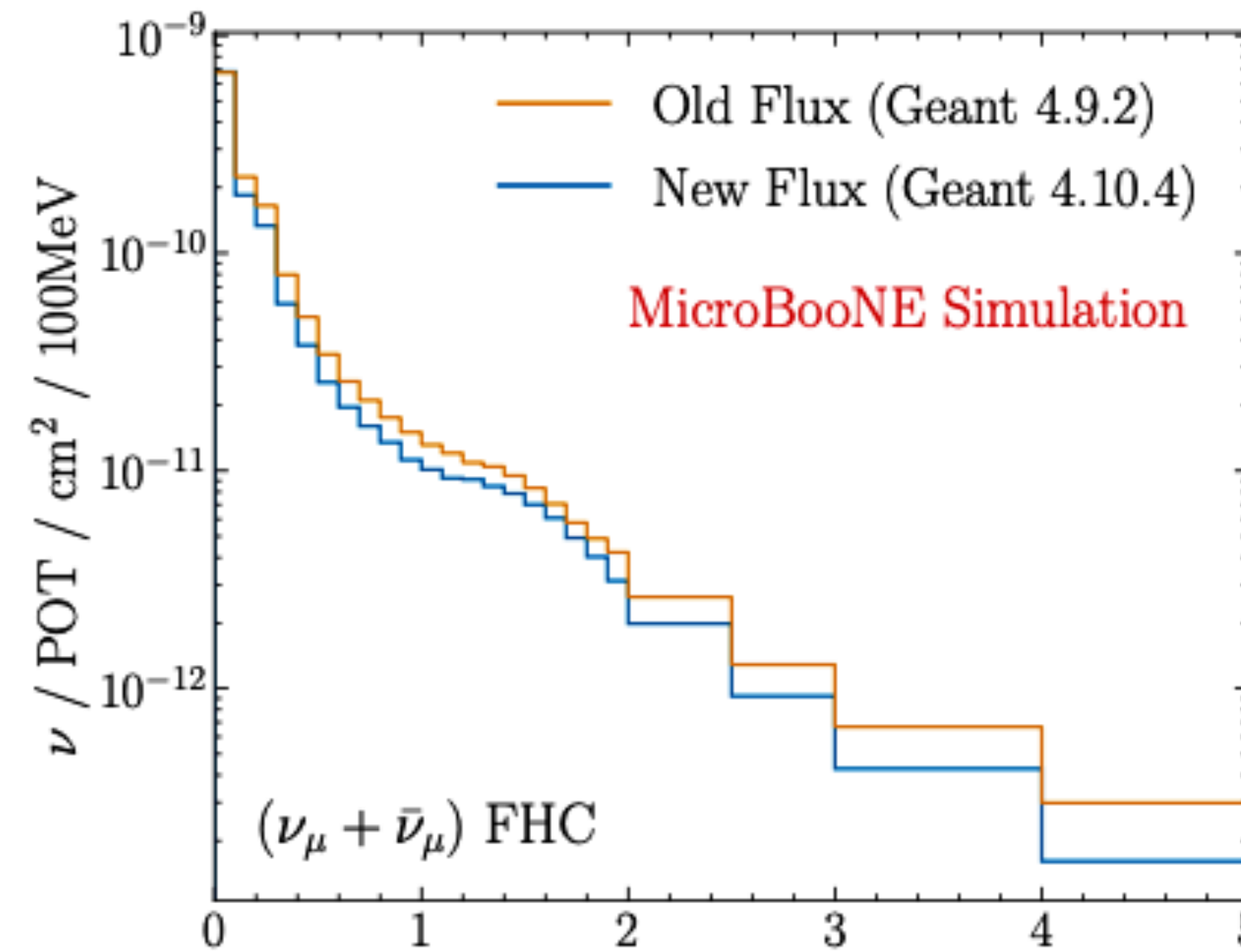
- Hadron production models (especially for K^+ at 120 GeV) disagree significantly
- Not much data that exists to constrain K^+ production in the NuMI beam
- We use base model that agrees best (G4.10.4) where data exists
- Apply conservative uncertainties ($>40\%$) where there is no coverage, based on model spread



Updated NuMI Flux Model

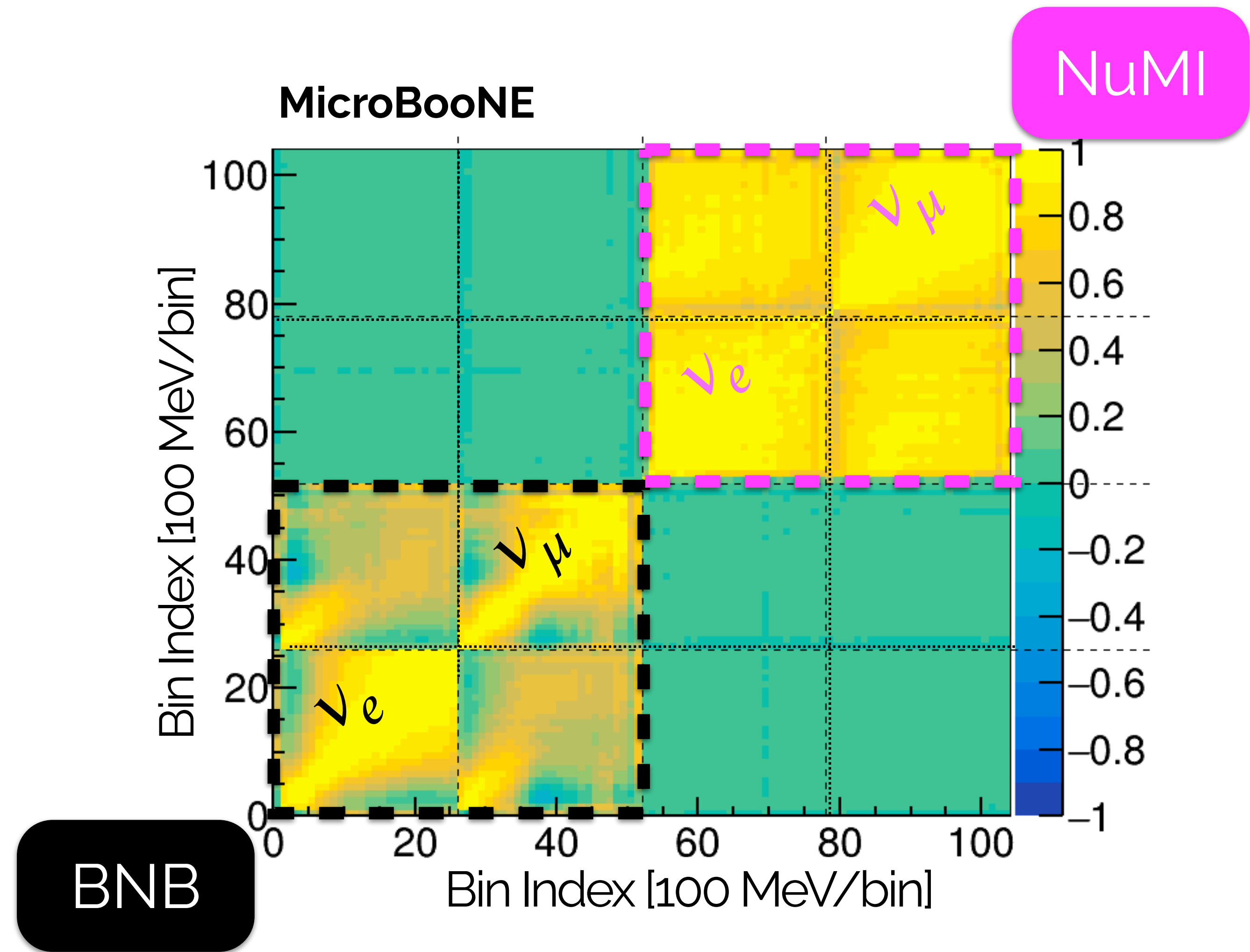
[MICROBOONE-NOTE-1129-PUB](#)

- Flux simulation upgrades:
 - Beam line geometry
 - Updated to a modern G4 version (4.10) for a better base model
 - Constraints from NA49 and others similar to NOvA, MINERvA
 - Conservative treatment of uncertainties outside data coverage



Flux systematics

- 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)



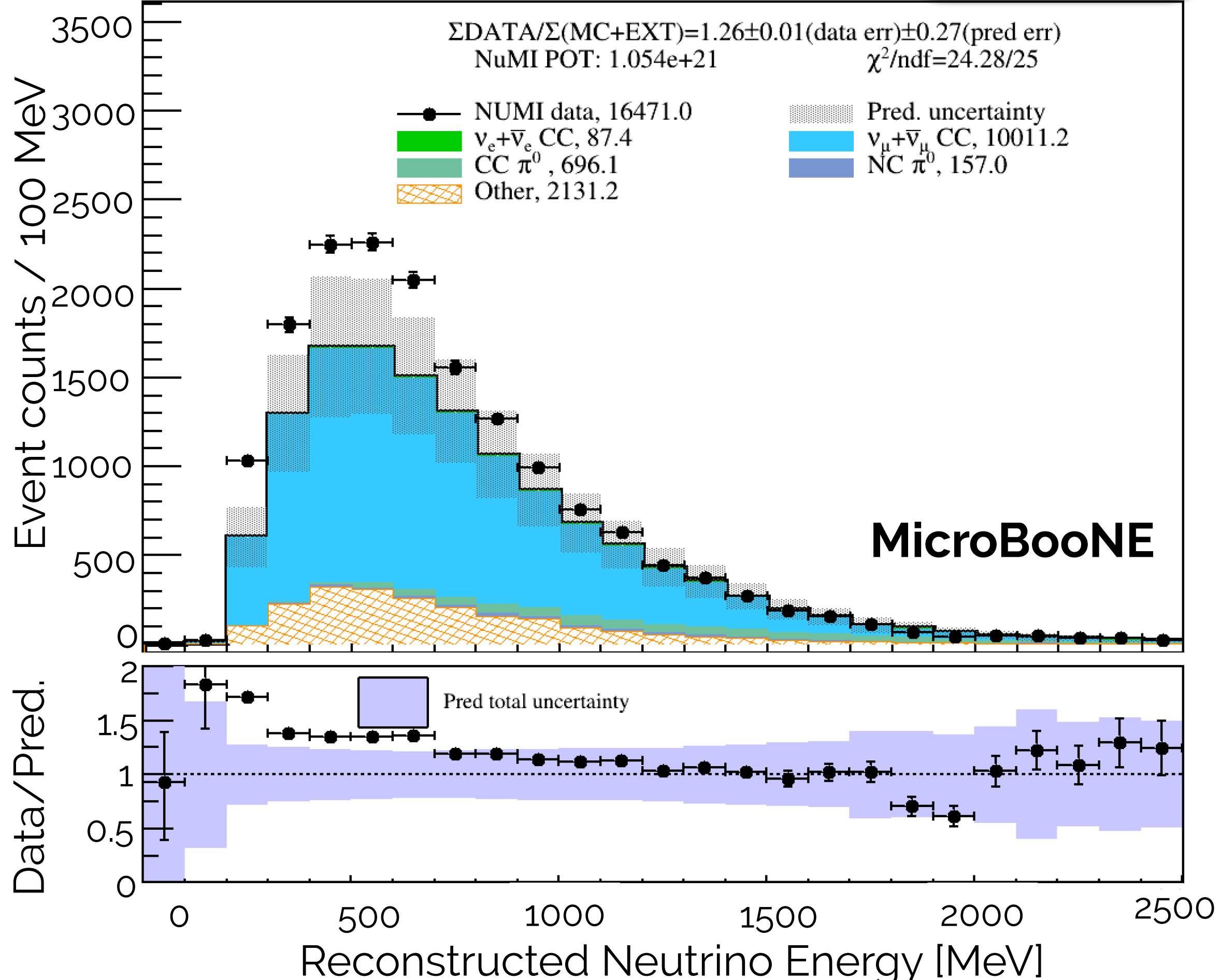
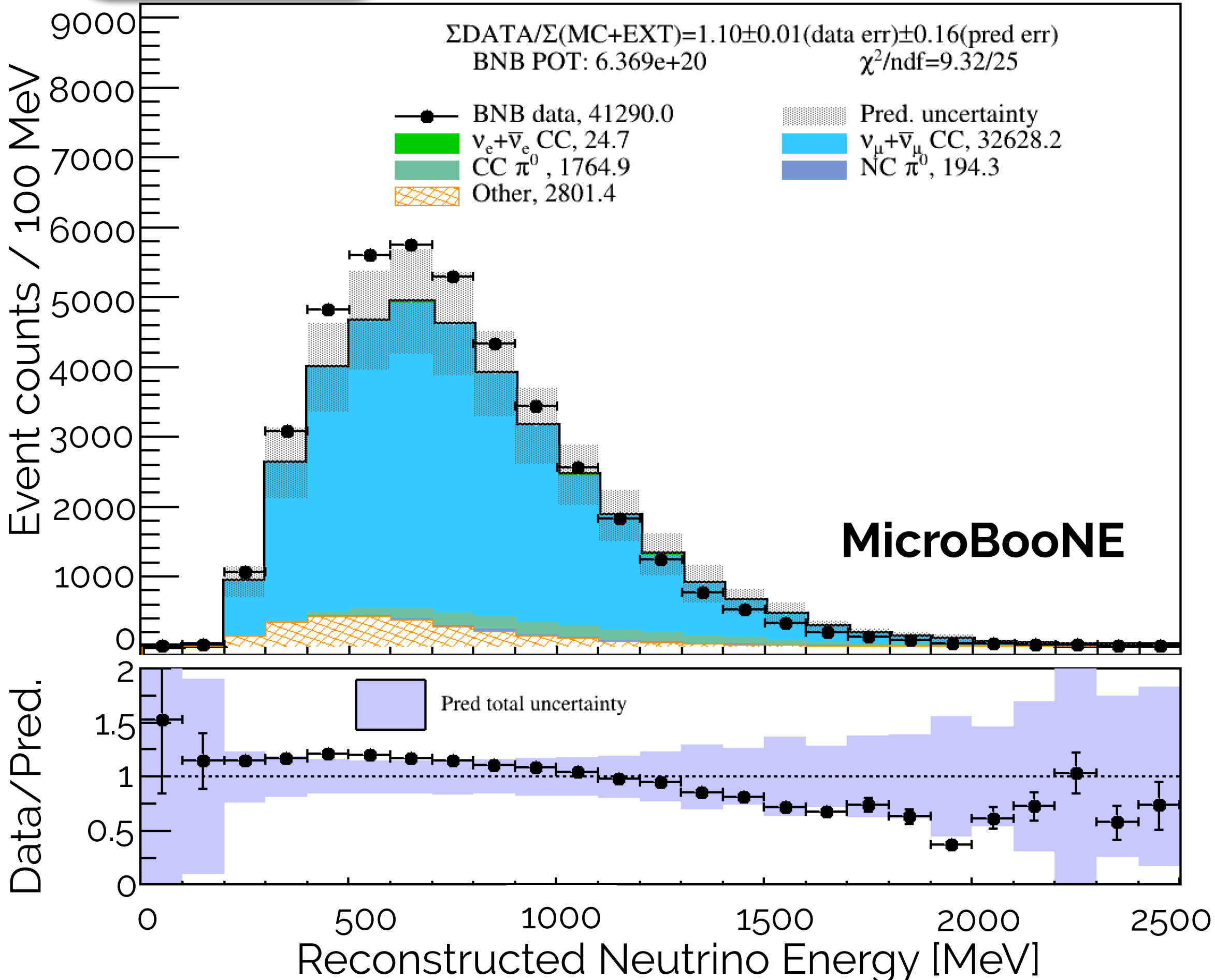
Model Validation

BNB and NuMI

- 1. Correlated in detector and cross section syst.
- 2. Flux systematics is uncorrelated

BNB
 ν_μ CC

NuMI
 ν_μ CC



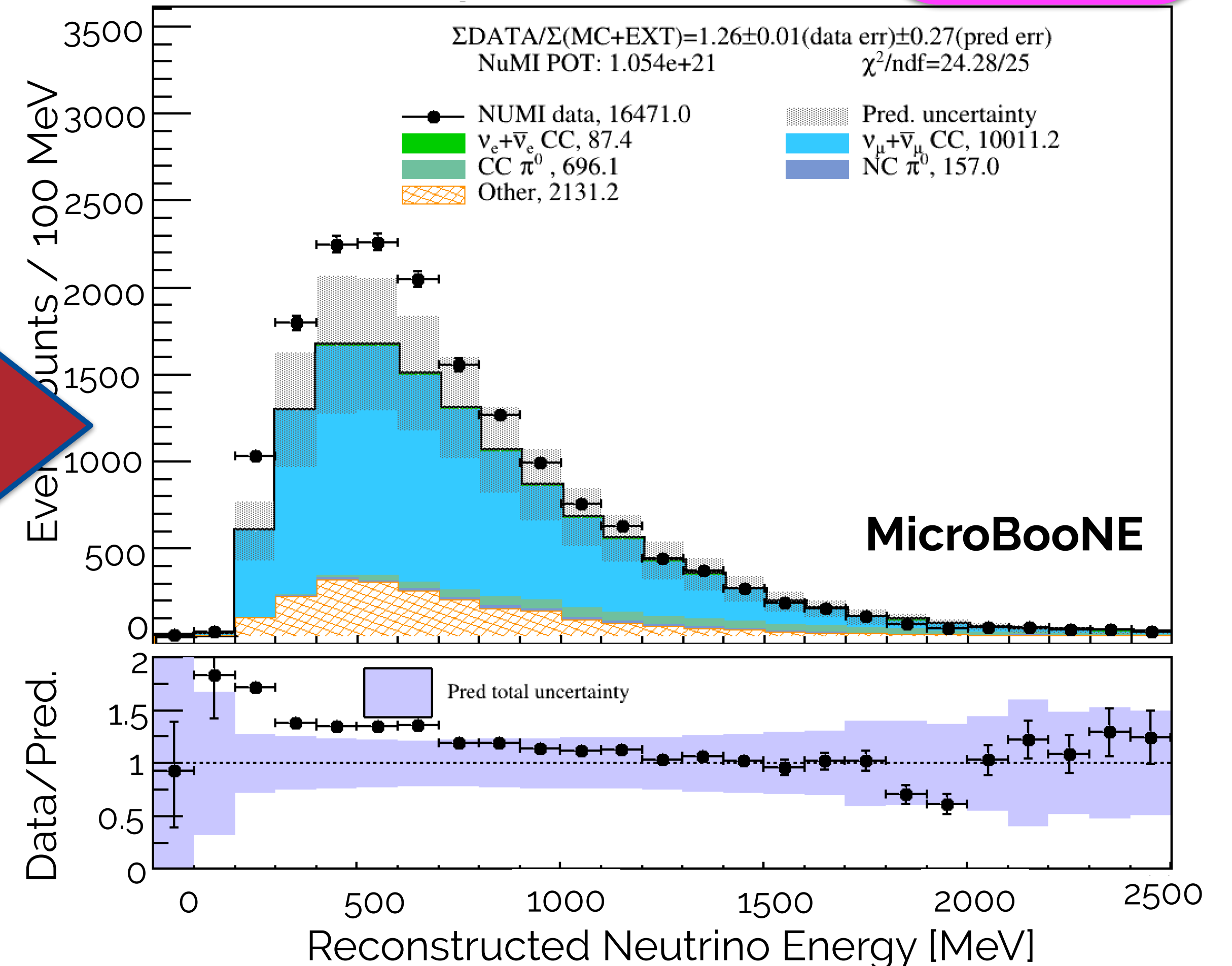
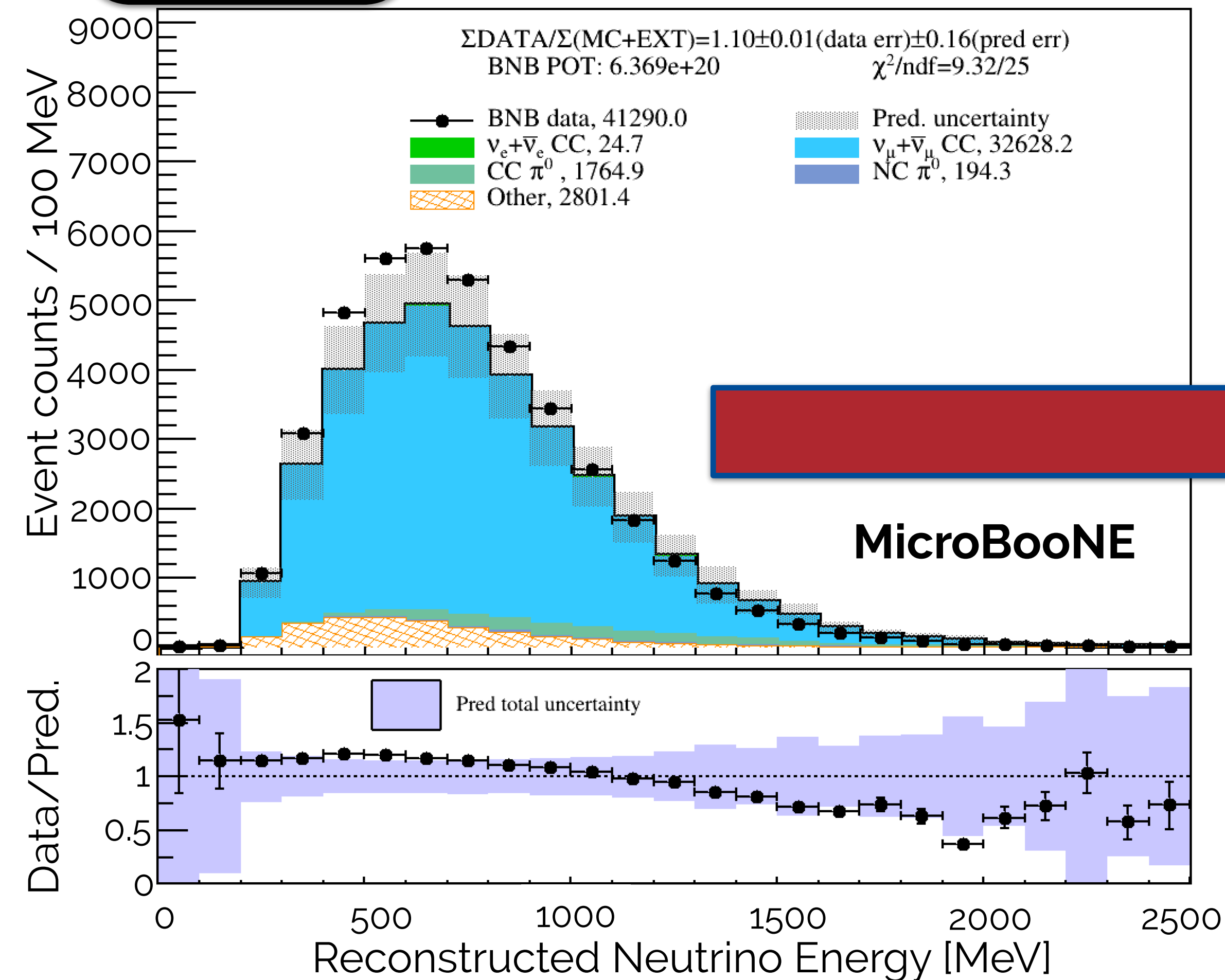
Model Validation

Constrain NuMI ν_μ with BNB ν_μ

BNB
 ν_μ^{CC}

1. Detector and Cross Section syst. largely canceled out [mostly flux left]
2. Update NuMI prediction based on BNB data

NuMI
 ν_μ^{CC}

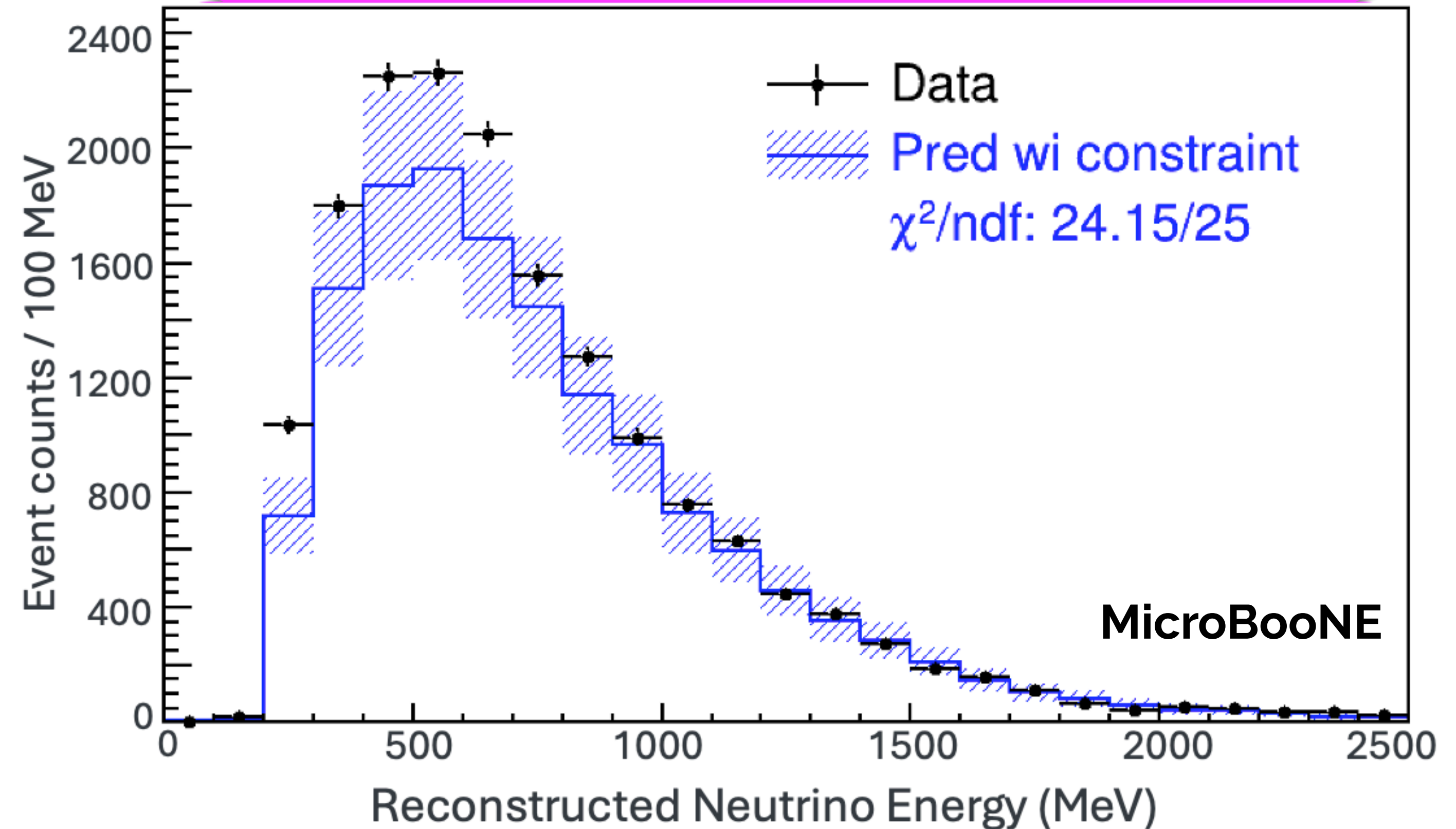


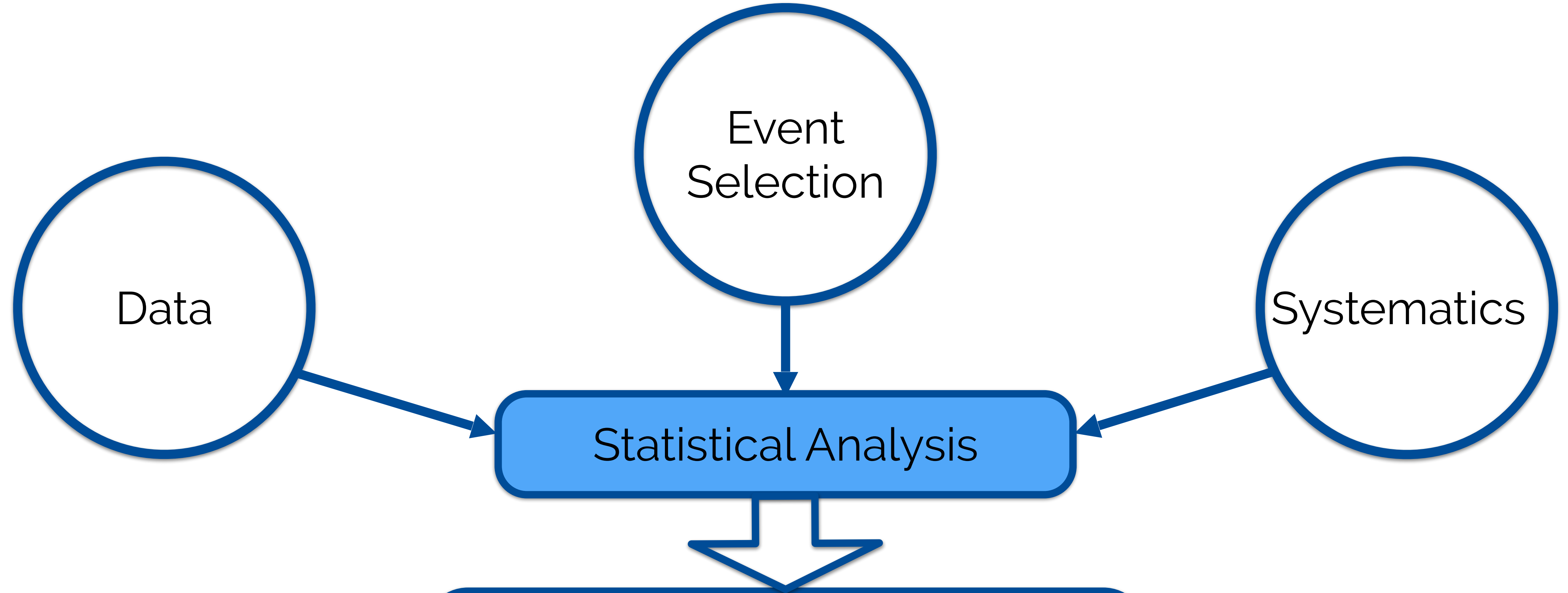
Model Validation

[MICROBOONE-NOTE-1129-PUB](#)

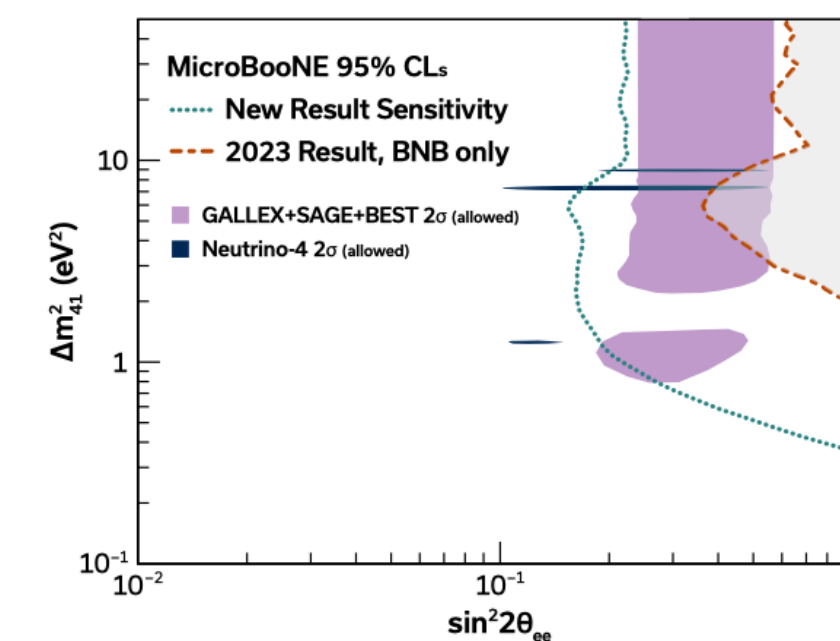
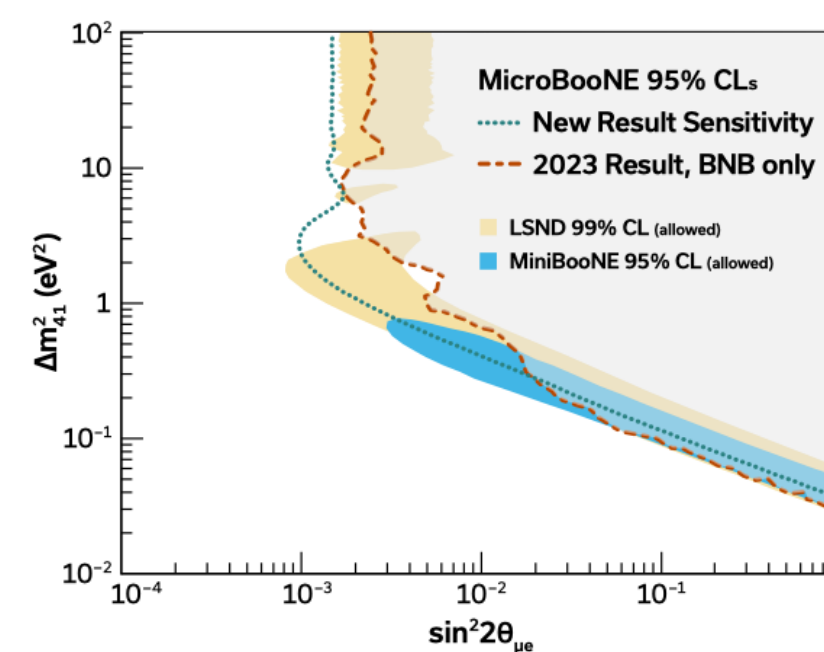
NuMI ν_μ CC constrained by BNB ν_μ CC

- Good data-MC agreement
- Updated prediction agrees well with the data
- Uncertainty is dominated by the flux





MicroBooNE 3+1 Result



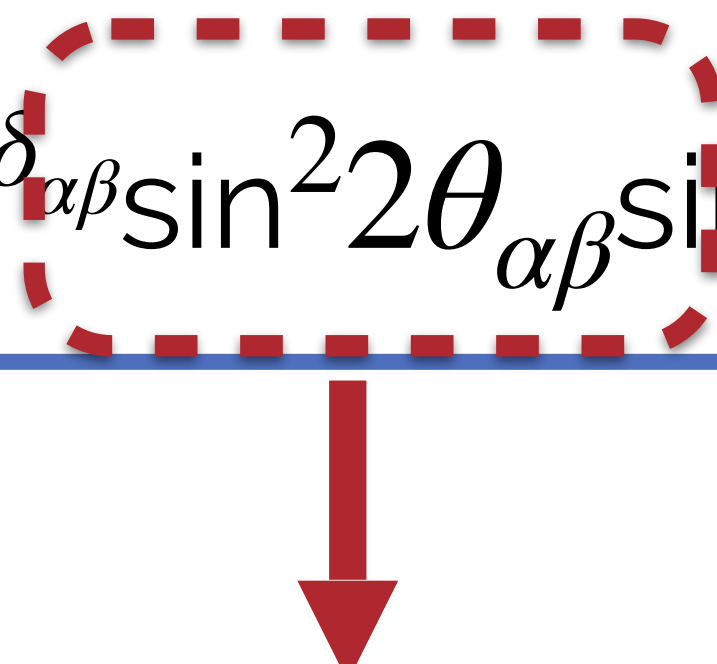
Parameter Space Overview

Oscillation probability at a short baseline :

$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \sin^2 2\theta_{\alpha\beta} \sin^2 \left(1.267 \frac{\Delta m_{41}^2 L}{E} \right)$$

Parameter Space Overview

Oscillation probability at a short baseline :

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$$\nu_e \text{ Appearance : } \sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$$

$$\nu_e \text{ Disappearance : } \sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$$

$$\begin{aligned} &\nu_\mu \text{ Disappearance :} \\ \sin^2 2\theta_{\mu\mu} &= 4\cos^2 \theta_{14} \sin^2 \theta_{24} (1 - \cos^2 \theta_{14} \sin^2 \theta_{24}) \end{aligned}$$

Parameter Space Overview

Oscillation probability at a short baseline :

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \sin^2 2\theta_{\alpha\beta} \sin^2 \left(1.267 \frac{\Delta m_{41}^2 L}{E} \right)$$



Explore 3D parameter space
($\Delta m_{41}^2, \sin^2 \theta_{14}, \sin^2 \theta_{24}$)

ν_e Appearance : $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$

ν_e Disappearance : $\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$

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

Parameter Space Overview

Oscillation probability at a short baseline :

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Explore 3D parameter space
($\Delta m_{41}^2, \sin^2 \theta_{14}, \sin^2 \theta_{24}$)

2D Result
profiled over $\sin^2 \theta_{24}$
($\Delta m_{41}^2, \sin^2 2\theta_{\mu e(ee)}$)

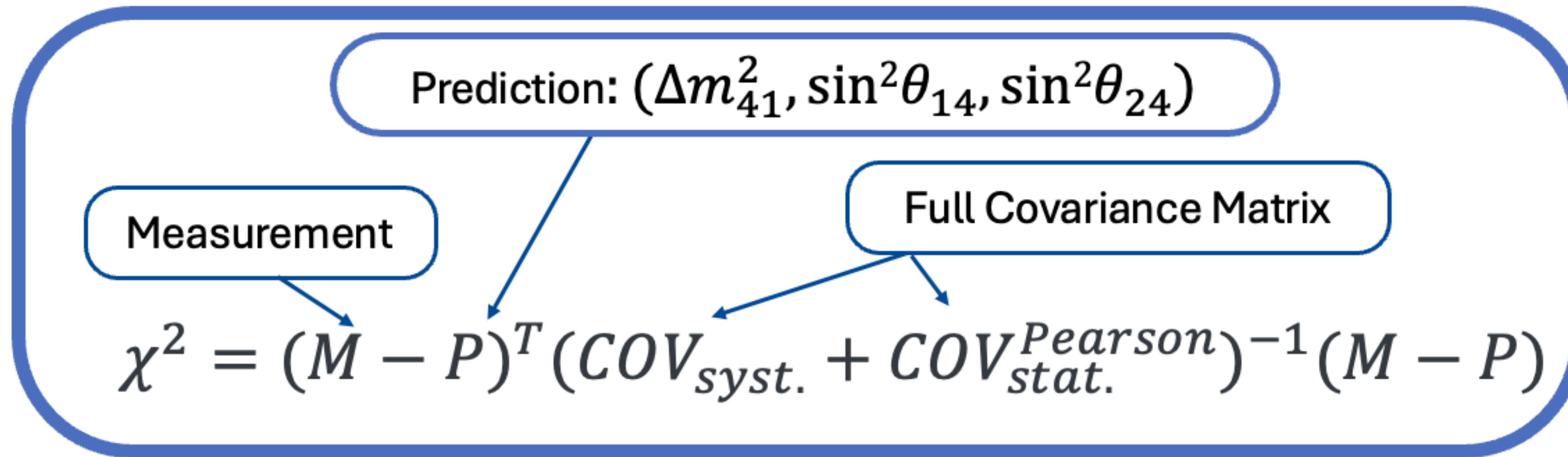
ν_e Appearance : $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 \theta_{24}$

ν_e Disappearance : $\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$

ν_μ Disappearance :

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

Fitter pipeline



Fitter pipeline

Simultaneous Fit
of 14 channels

Prediction: $(\Delta m_{41}^2, \sin^2 \theta_{14}, \sin^2 \theta_{24})$

Measurement

Full Covariance Matrix

$$\chi^2 = (M - P)^T (COV_{syst.} + COV_{stat.}^{Pearson})^{-1} (M - P)$$

Fitter pipeline

Simultaneous Fit
of 14 channels

Measurement

Prediction: $(\Delta m_{41}^2, \sin^2 \theta_{14}, \sin^2 \theta_{24})$

Full Covariance Matrix

$$\chi^2 = (M - P)^T (COV_{syst.} + COV_{stat.}^{Pearson})^{-1} (M - P)$$

Notation

$3 + 1 \equiv 4\nu$

The best-fit values
for the osc.
parameters in the
 4ν hypothesis

Fitter pipeline

Simultaneous Fit
of 14 channels

Prediction: $(\Delta m_{41}^2, \sin^2 \theta_{14}, \sin^2 \theta_{24})$

Measurement

Full Covariance Matrix

$$\chi^2 = (M - P)^T (COV_{syst.} + COV_{stat.}^{Pearson})^{-1} (M - P)$$

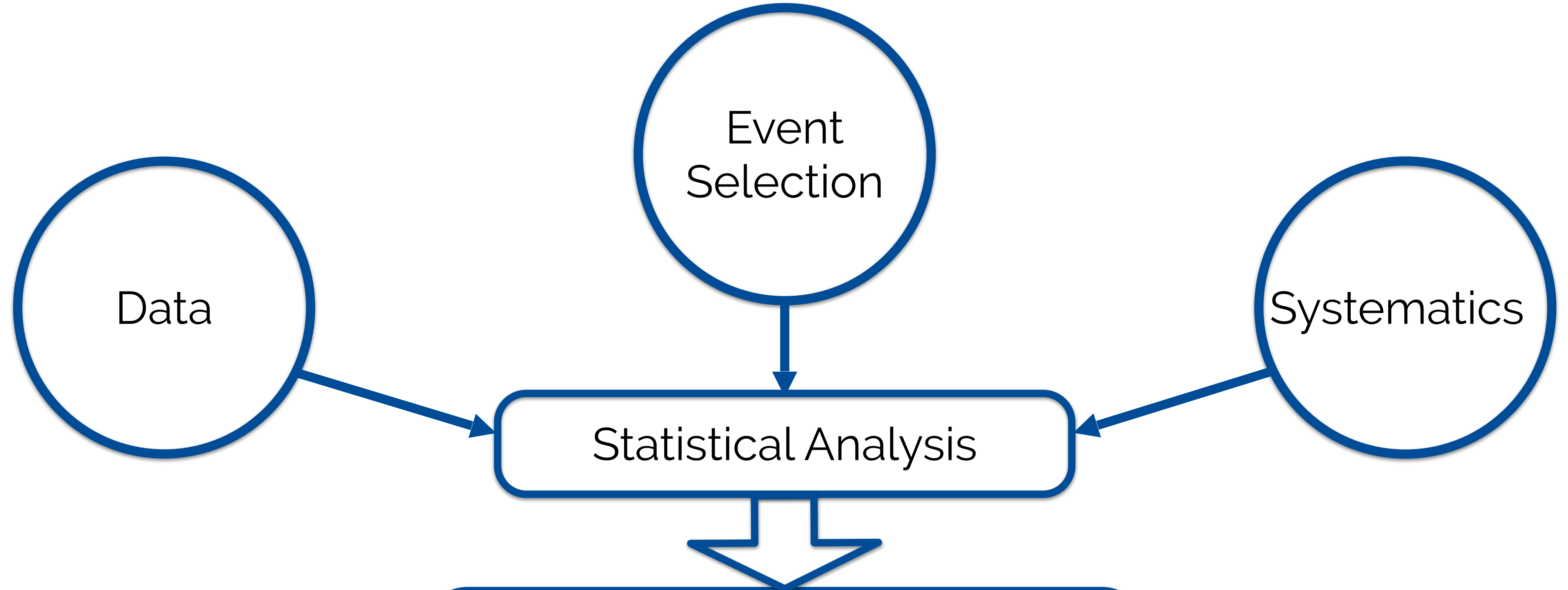
Notation

$3 + 1 \equiv 4\nu$

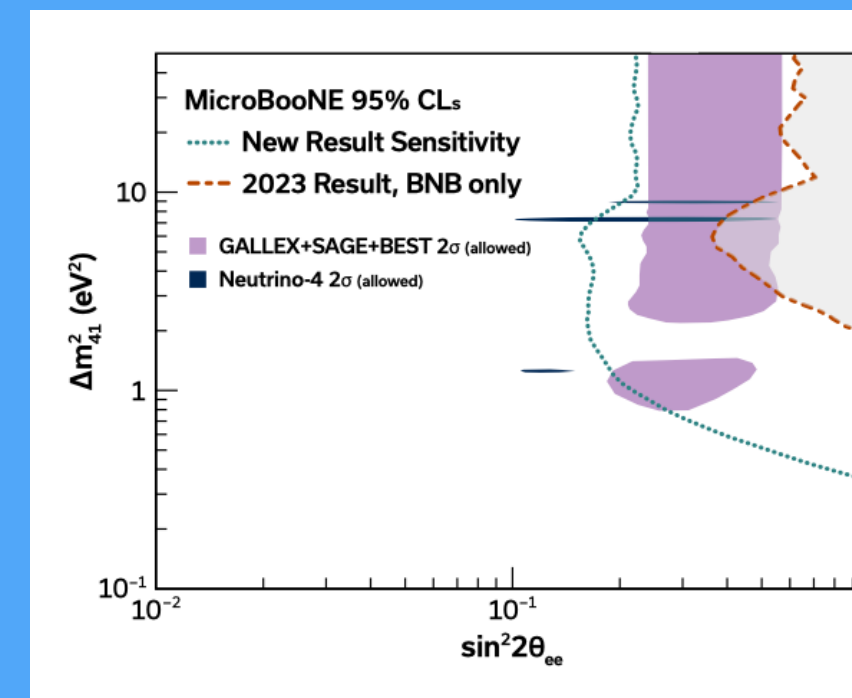
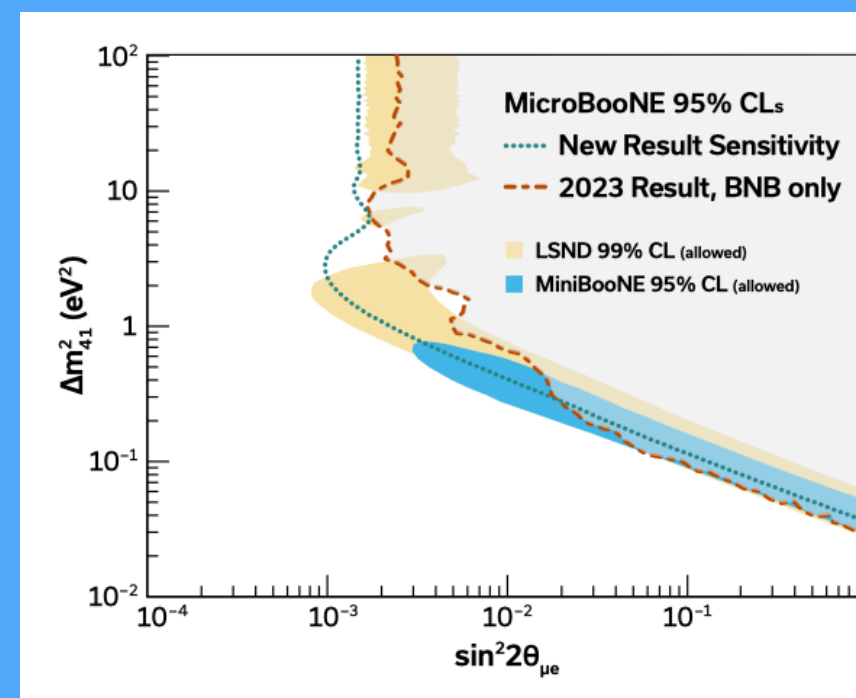
The best-fit values
for the osc.
parameters in the
 4ν hypothesis

Data consistency
test against 3ν
hypothesis
[Feldman-Cousins]

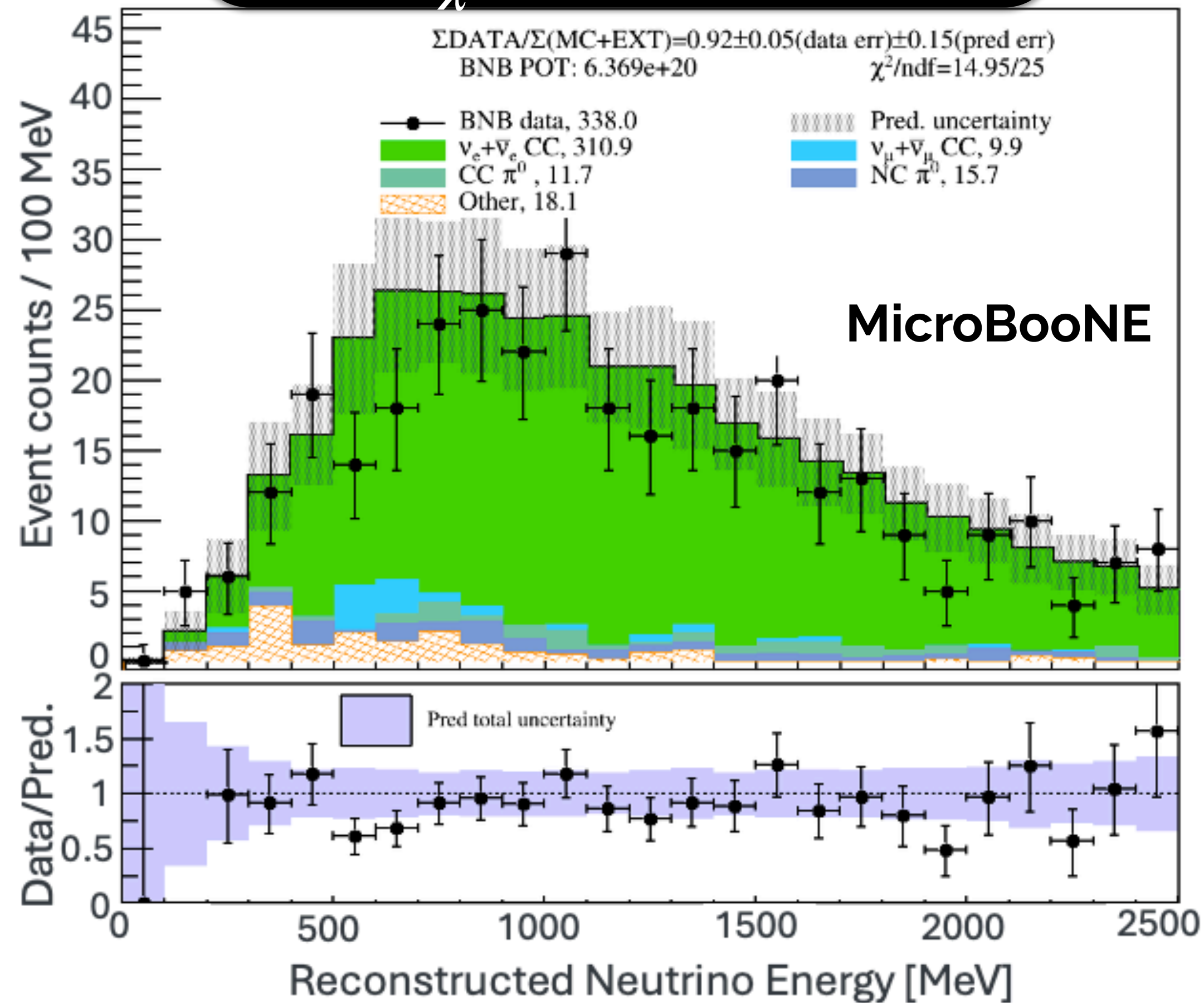
Setting limits via
“Frequentist CLs”
method



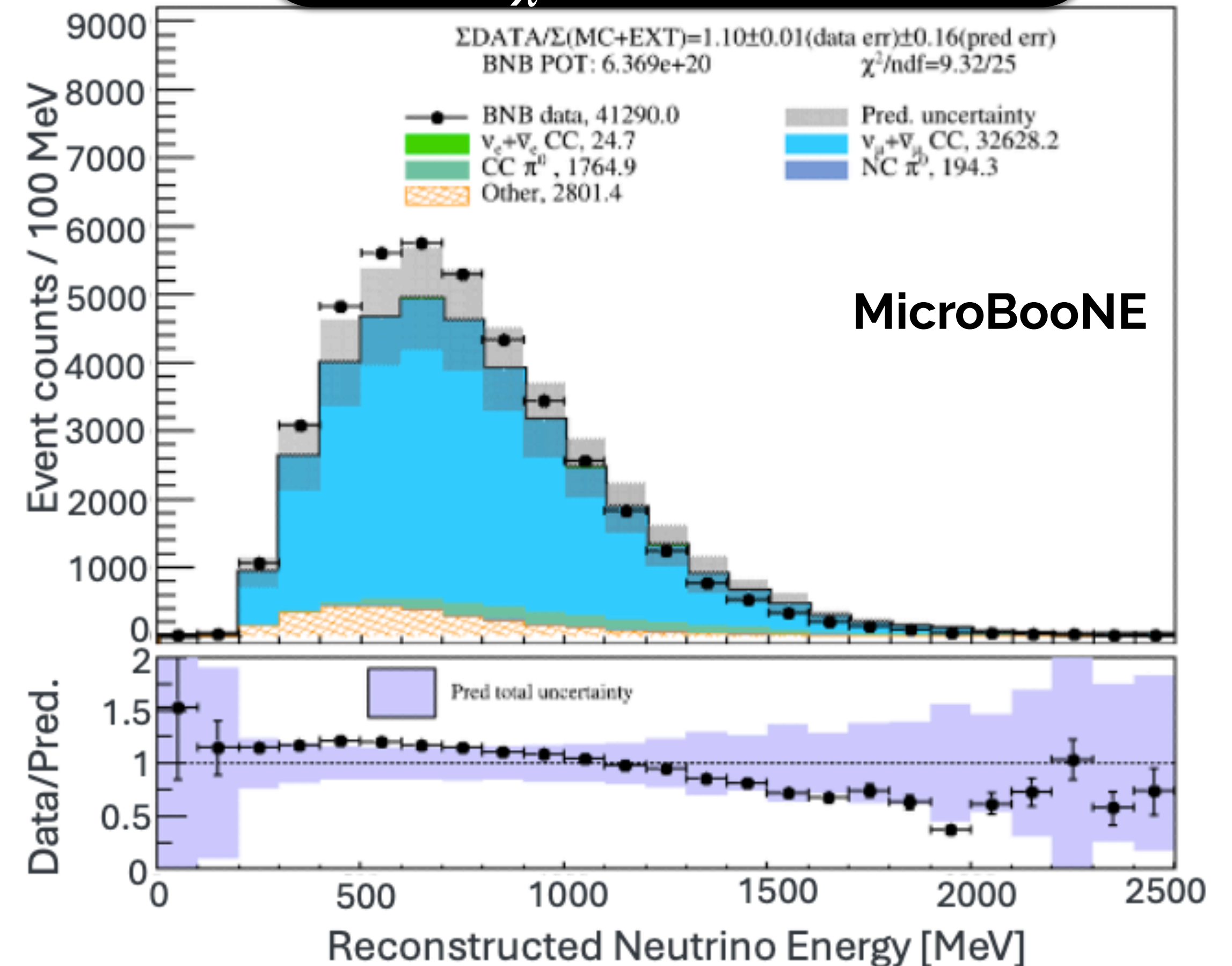
MicroBooNE 3+1 Result



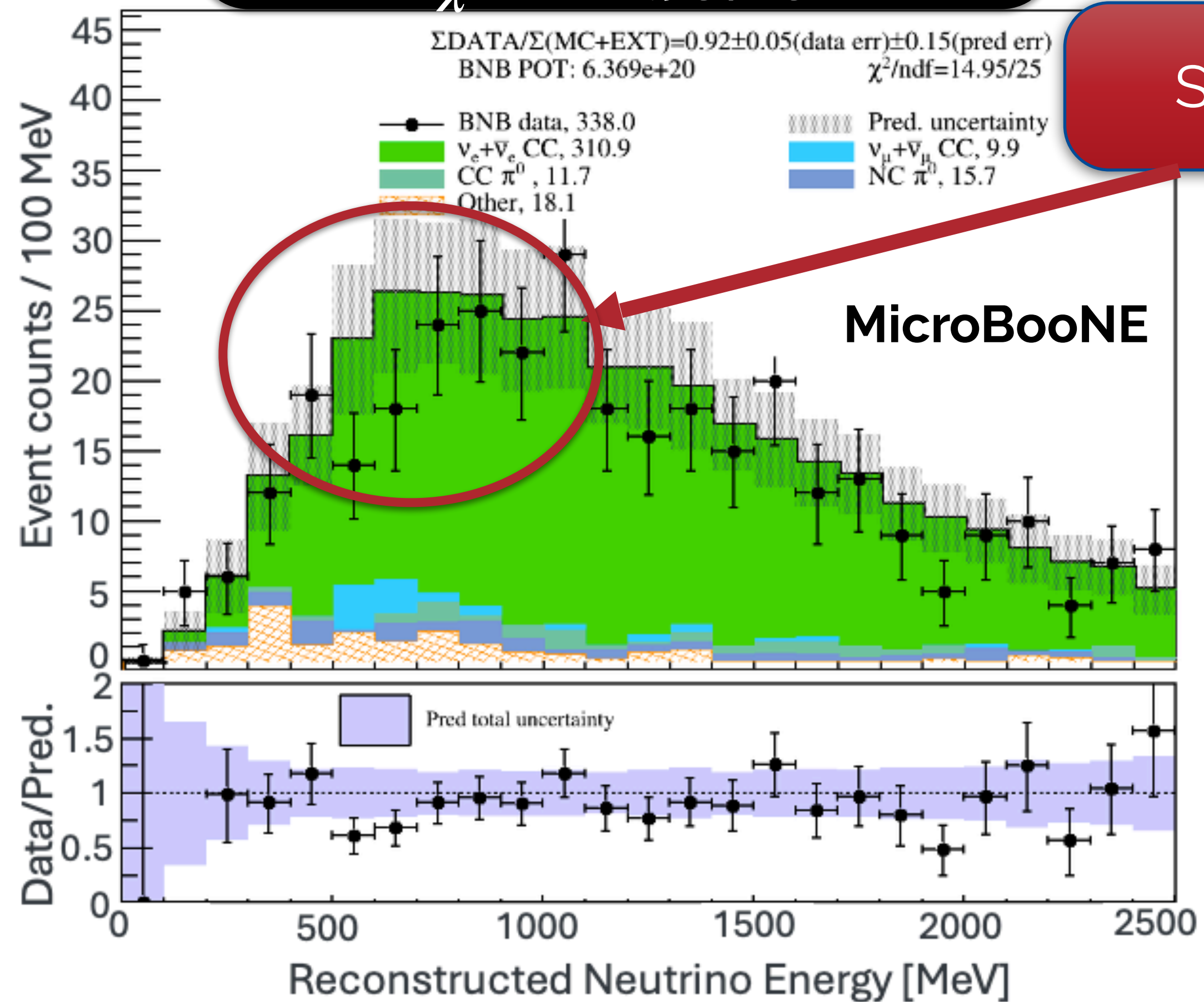
$$\nu_e \text{CC}$$
$$\chi^2 = 14.95/25$$



$$\nu_\mu \text{CC}$$
$$\chi^2 = 9.32/25$$

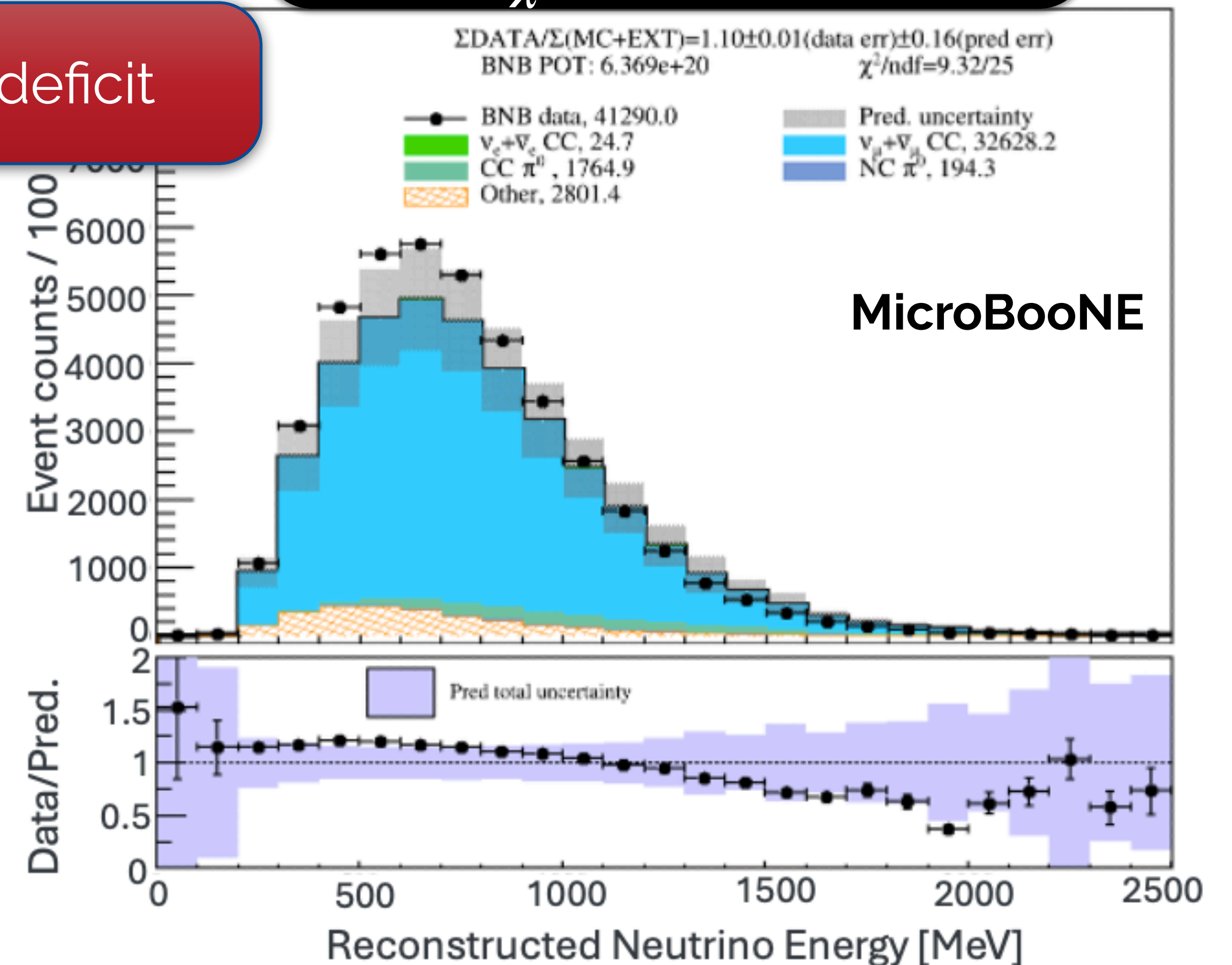


$$\nu_e \text{CC}$$
$$\chi^2 = 14.95/25$$

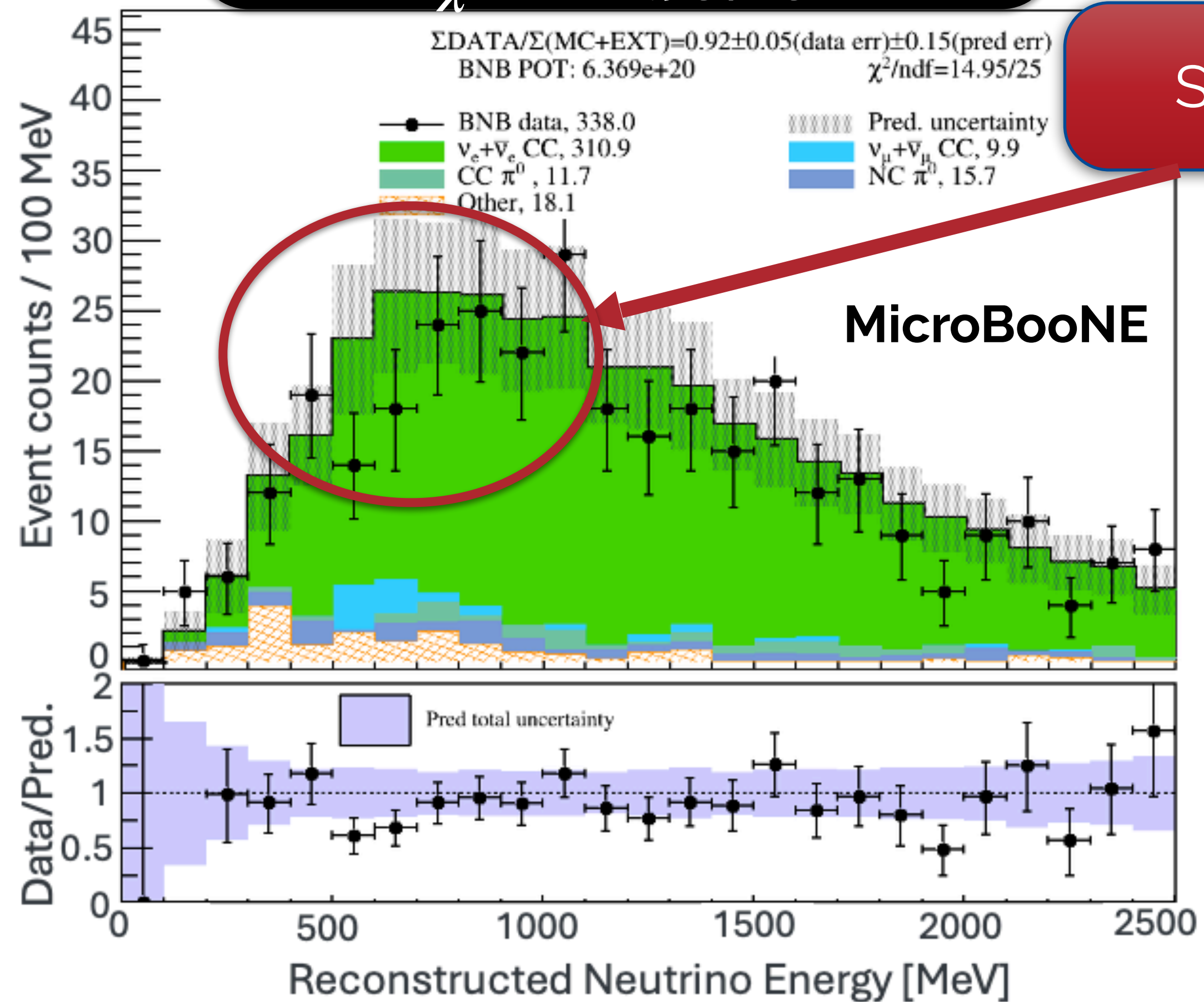


Small deficit

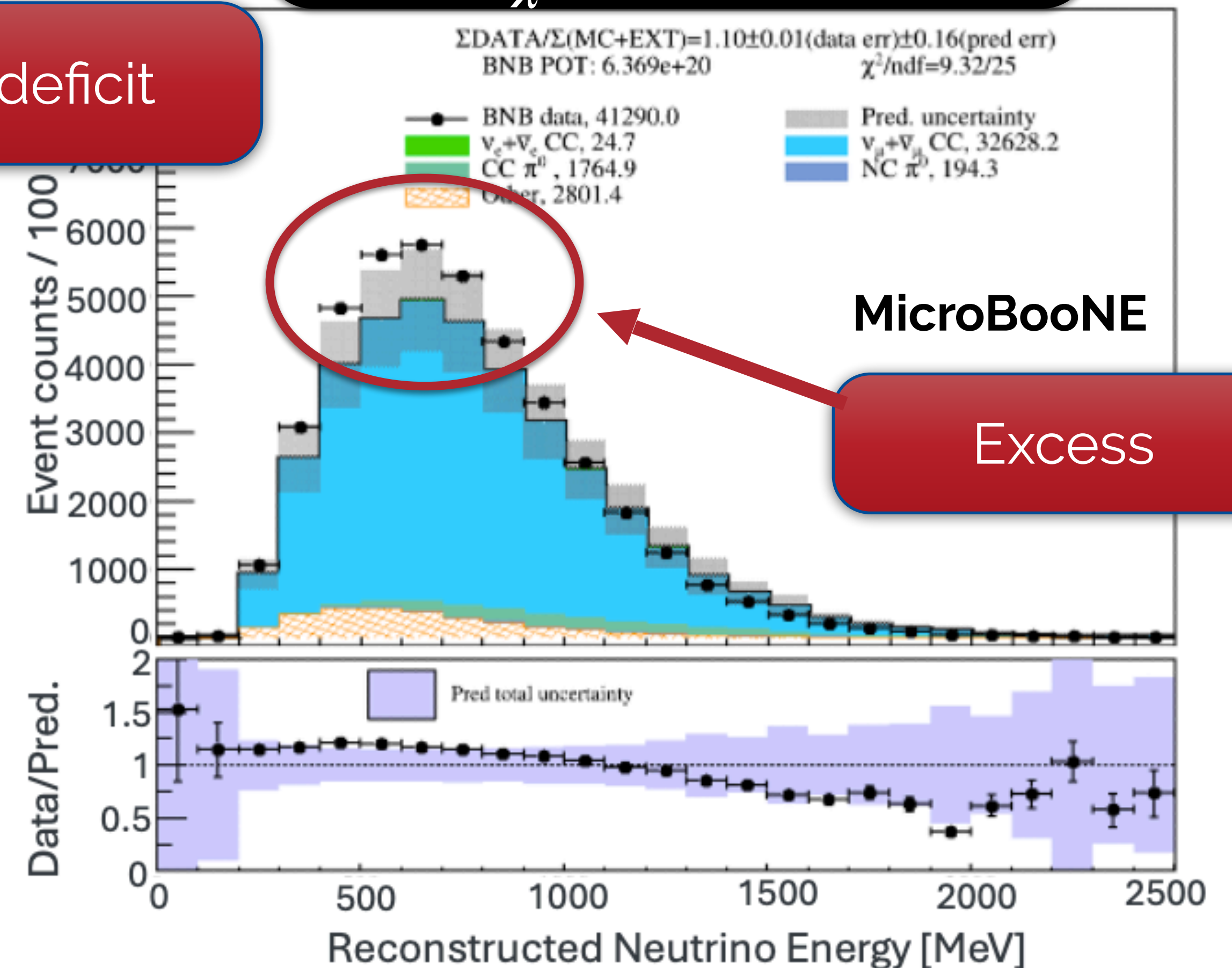
$$\nu_\mu \text{CC}$$
$$\chi^2 = 9.32/25$$



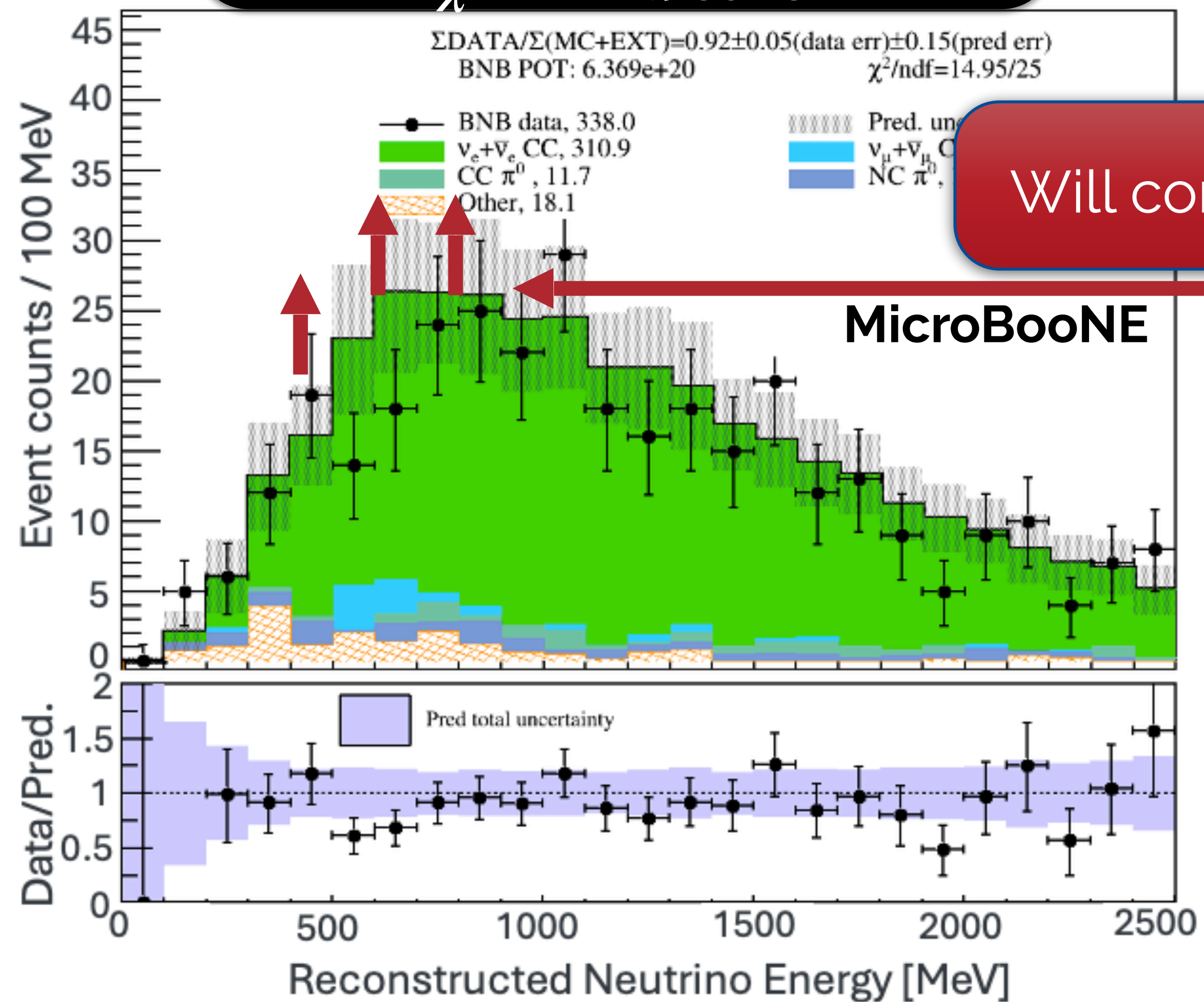
$$\nu_e \text{CC}$$
$$\chi^2 = 14.95/25$$



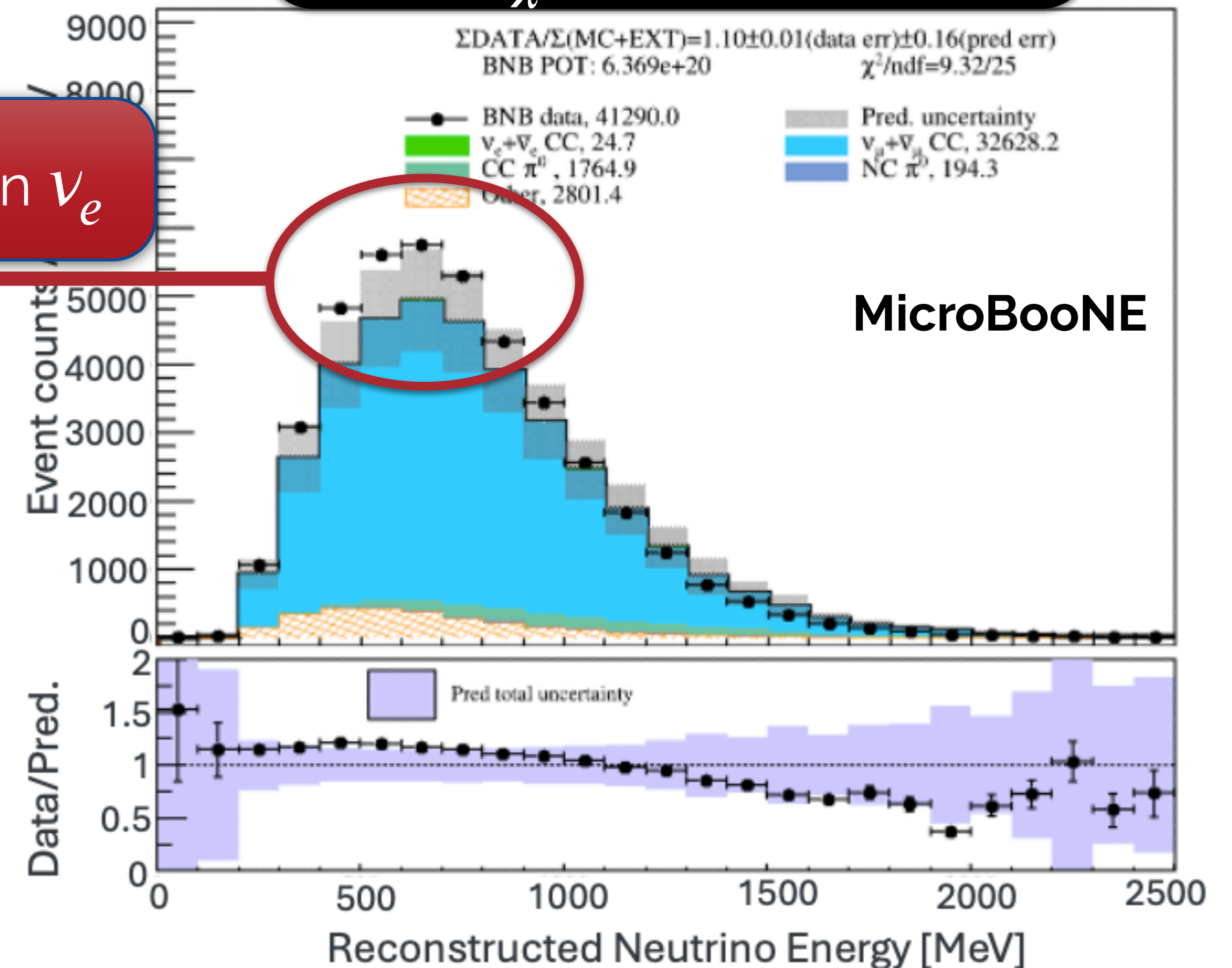
$$\nu_\mu \text{CC}$$
$$\chi^2 = 9.32/25$$



$$\nu_e \text{CC}$$
$$\chi^2 = 14.95/25$$

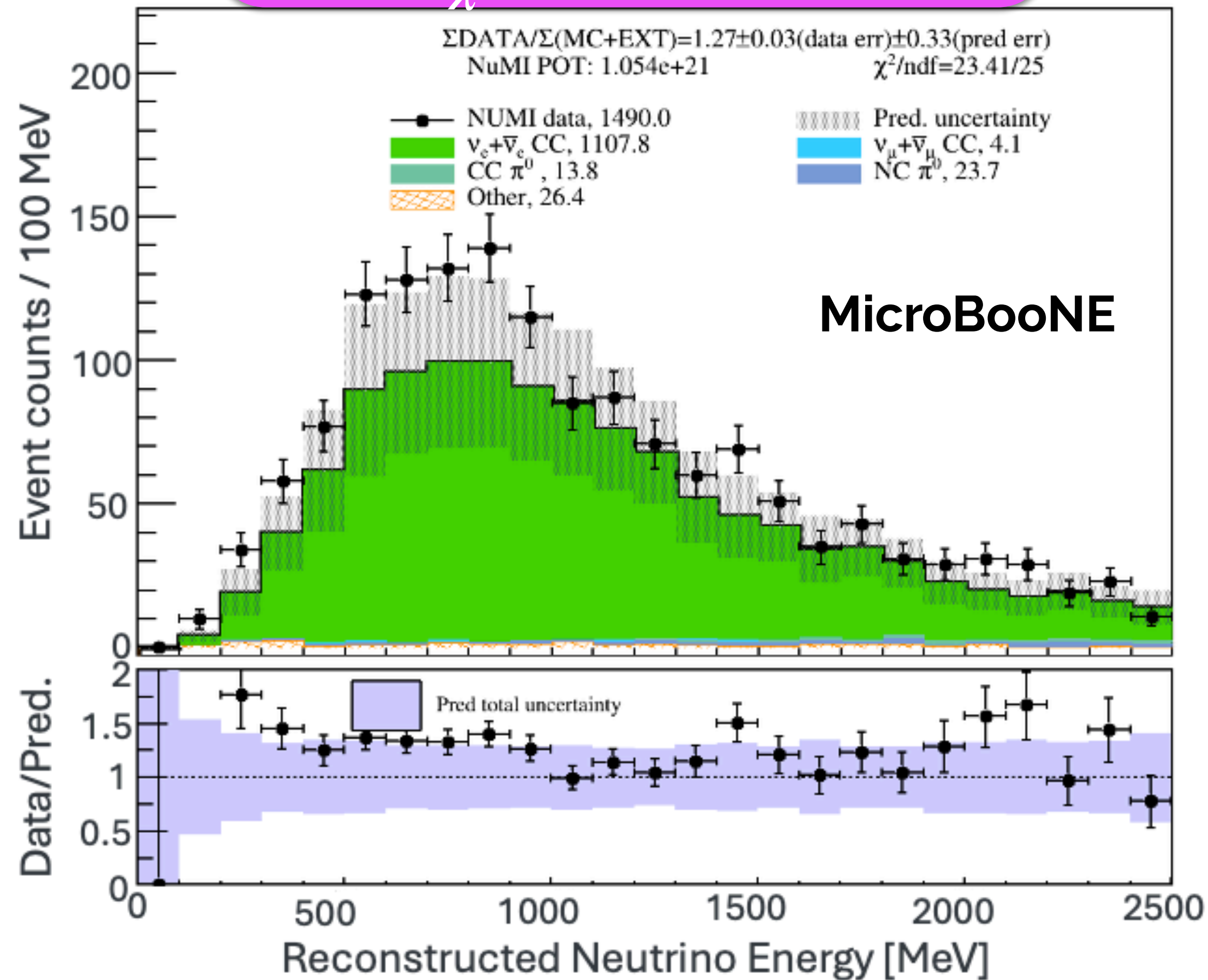
Will constrain ν_e

$$\nu_\mu \text{CC}$$
$$\chi^2 = 9.32/25$$



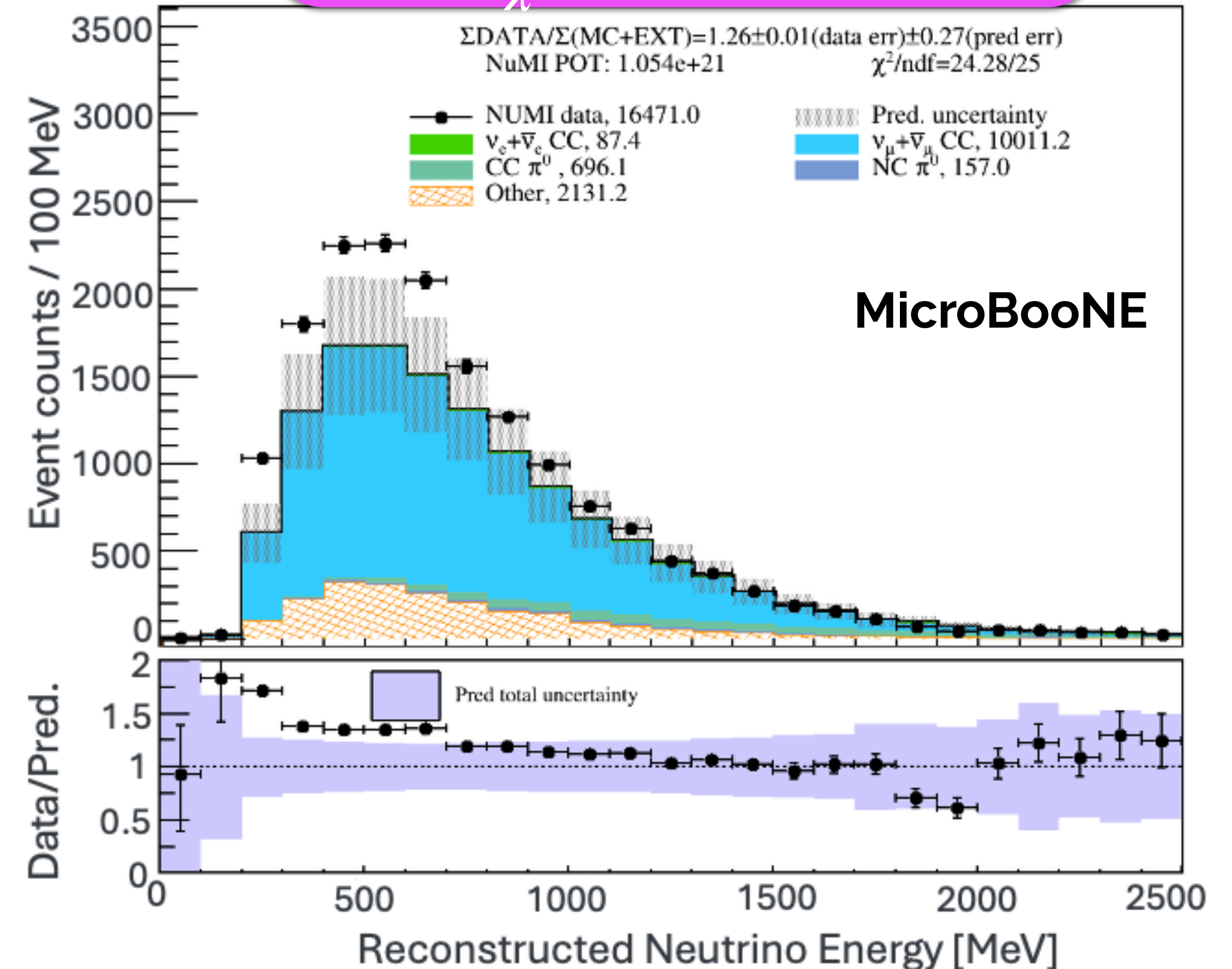
ν_e CC

$$\chi^2 = 23.41/25$$



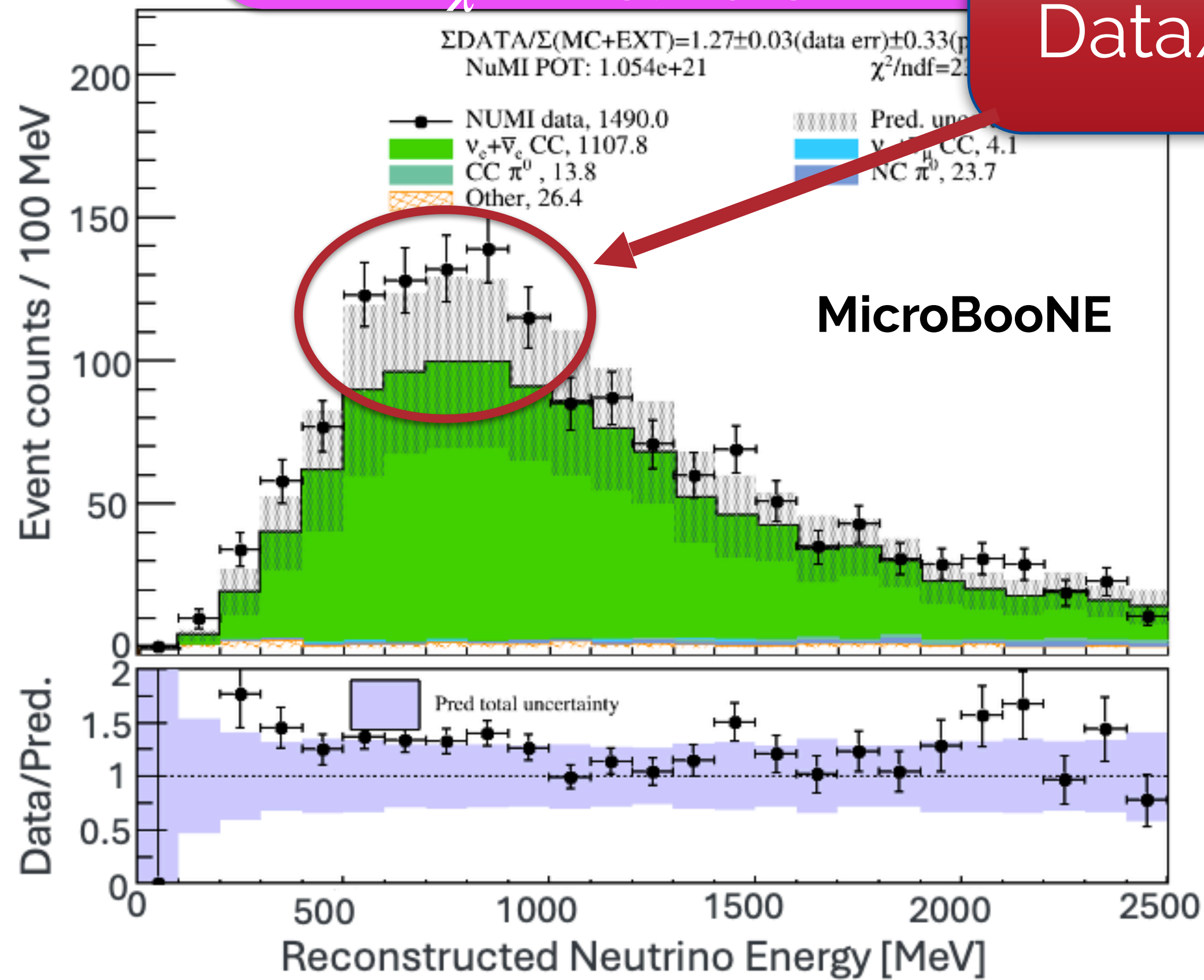
ν_μ CC

$$\chi^2 = 24.28/25$$



ν_e CC

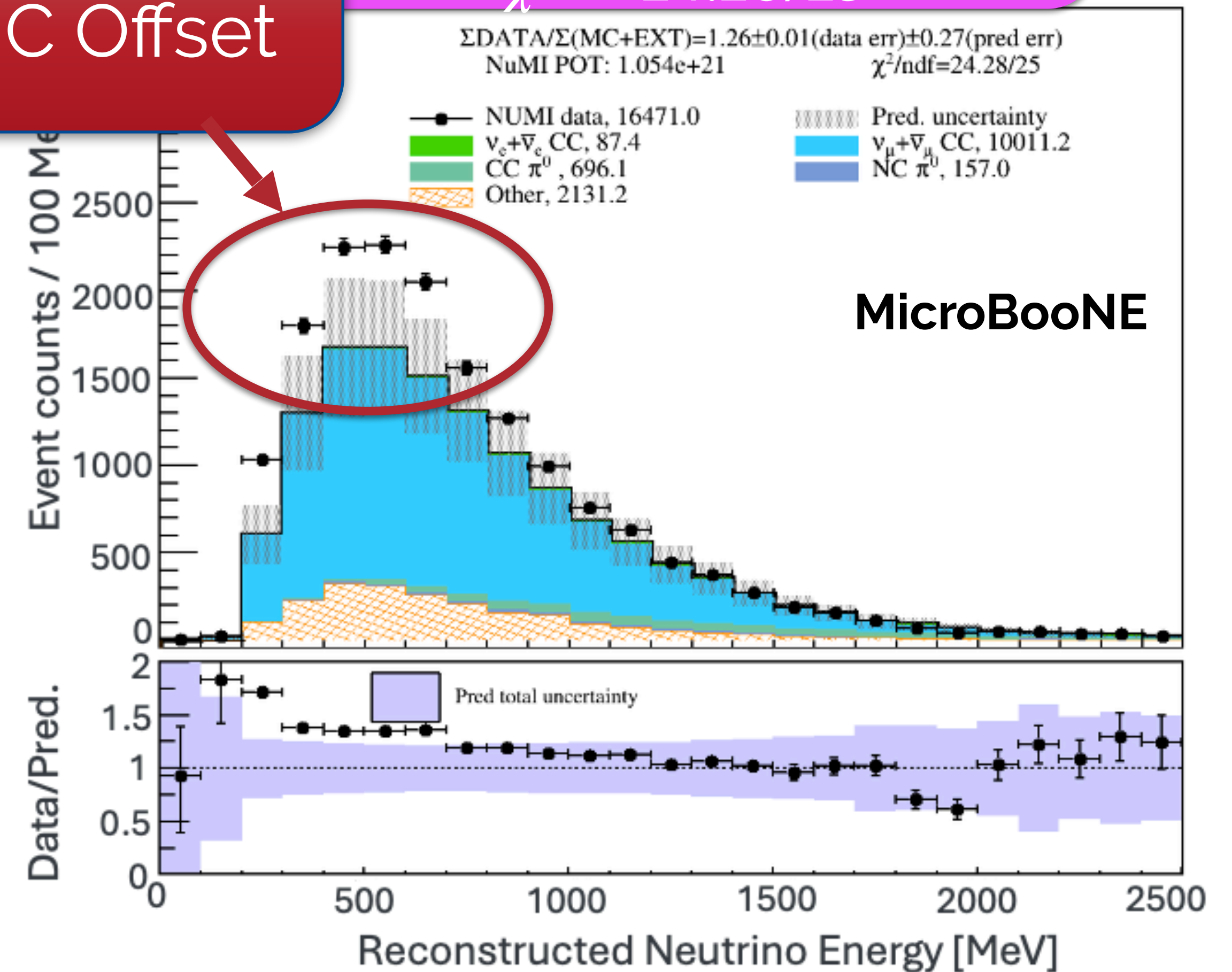
$$\chi^2 = 23.41/25$$



Data/MC Offset

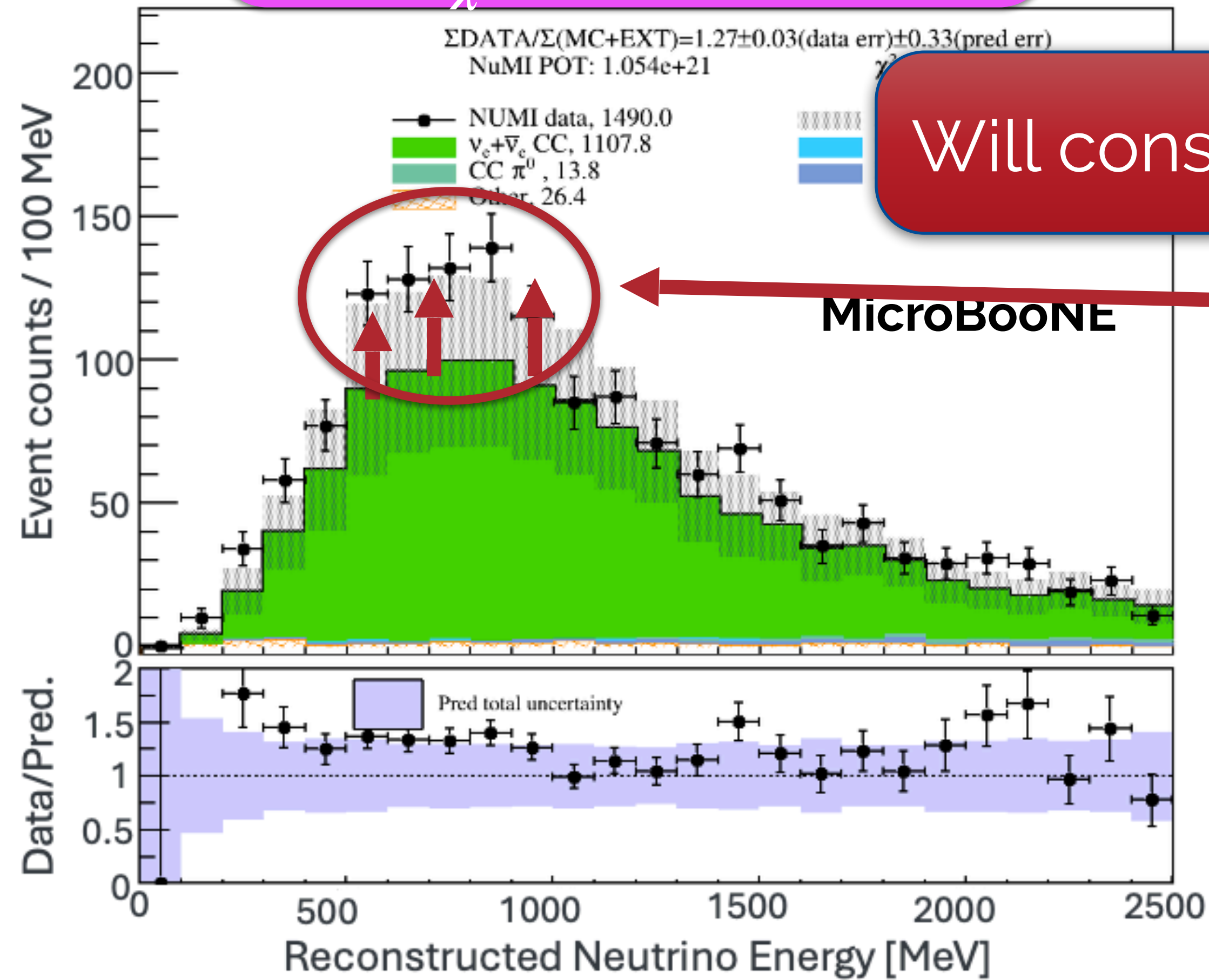
ν_μ CC

$$\chi^2 = 24.28/25$$



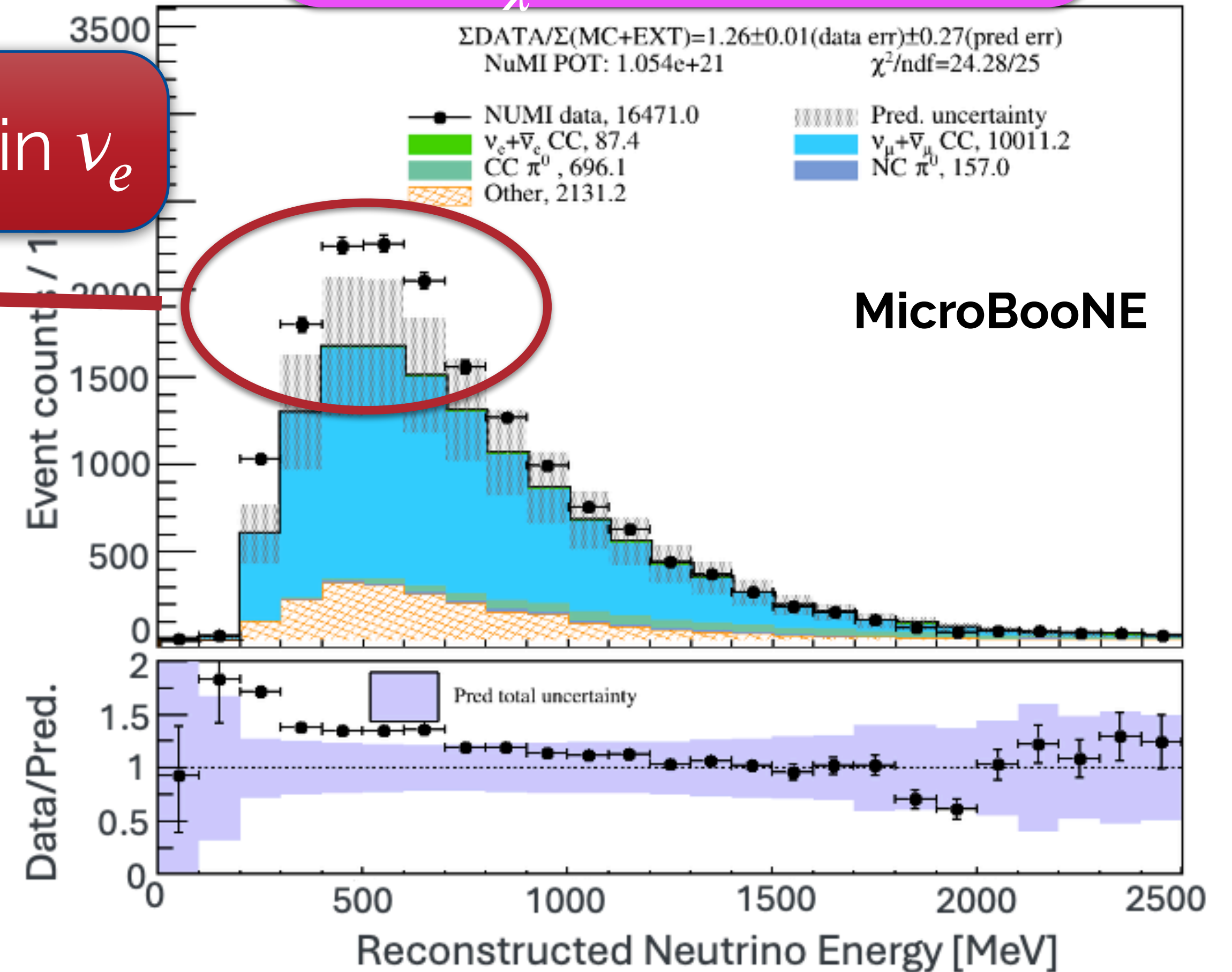
ν_e CC

$$\chi^2 = 23.41/25$$



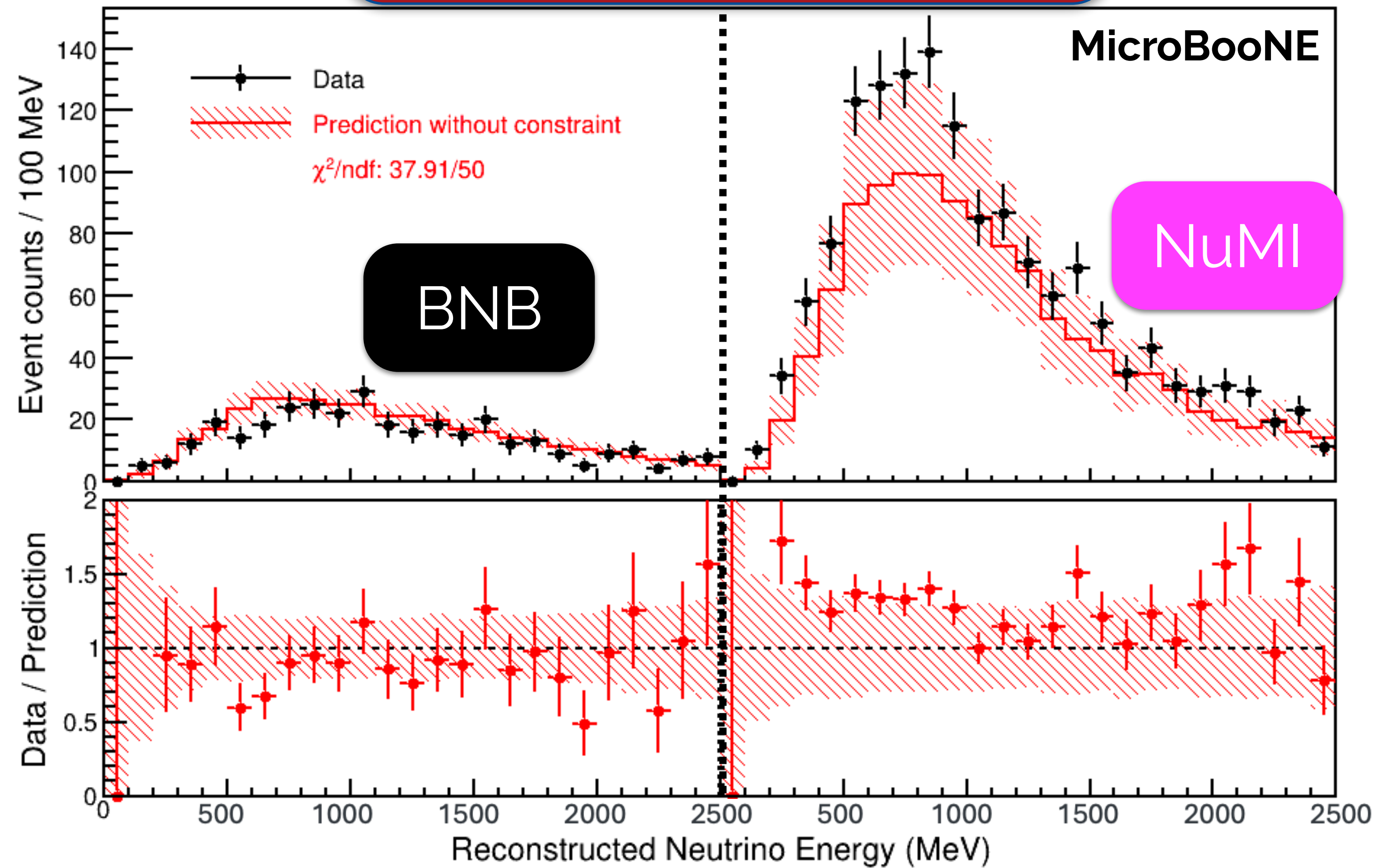
ν_μ CC

$$\chi^2 = 24.28/25$$



Constrained ν_e channels

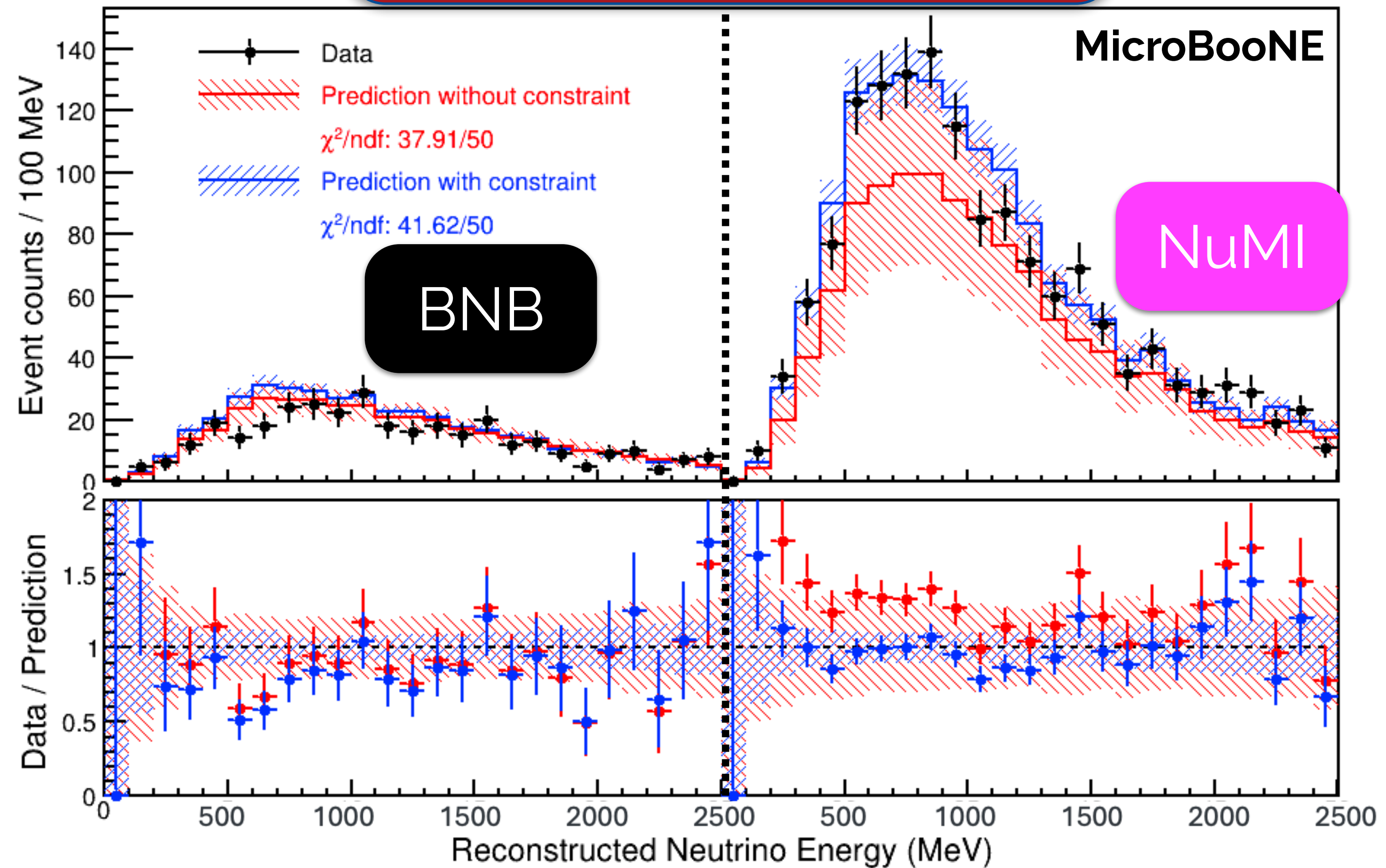
ν_e CC
Without Constraint



Without
Constraint:
 $\chi^2 = 37.91/50$

Constrained ν_e channels

ν_e CC
Without Constraint

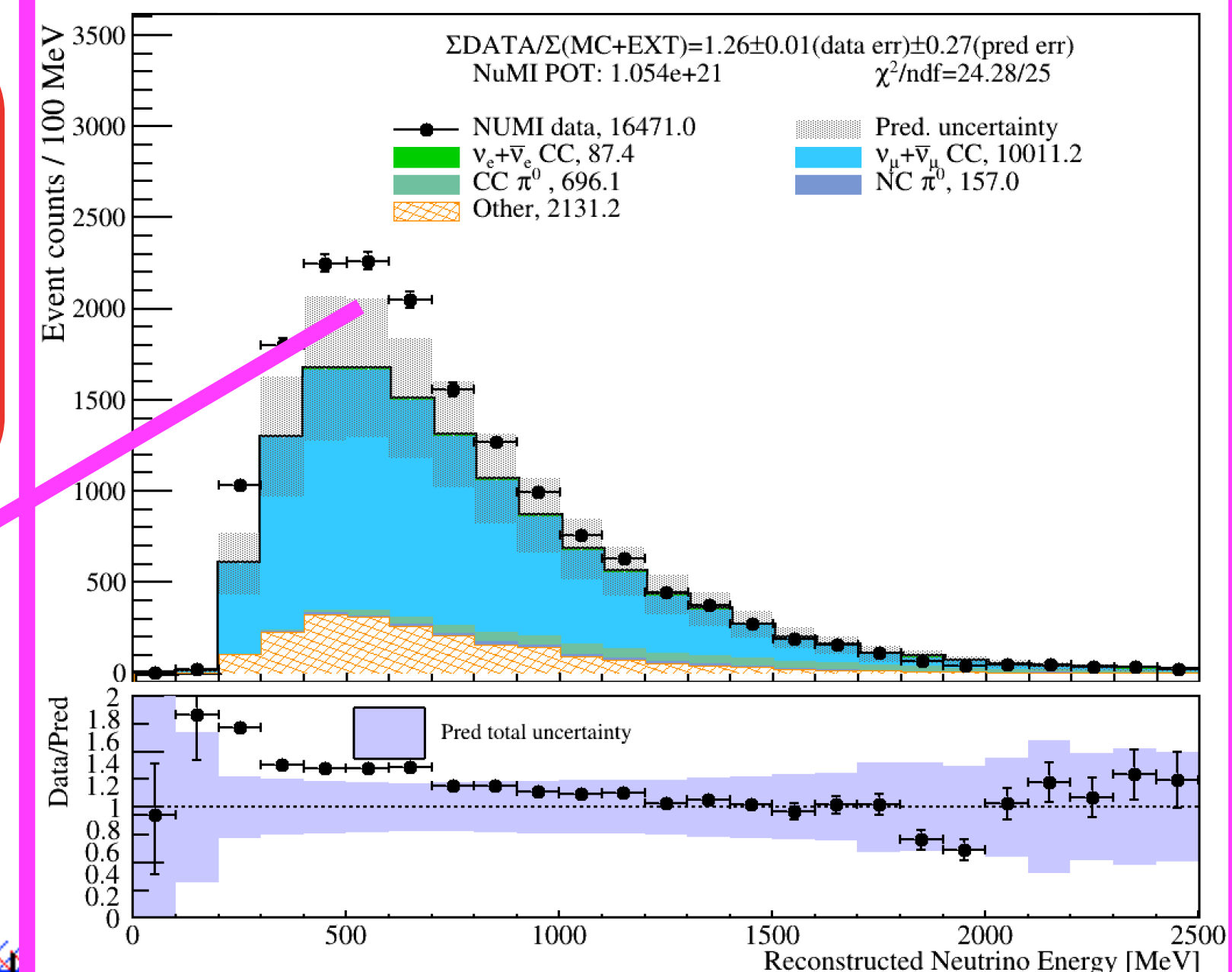
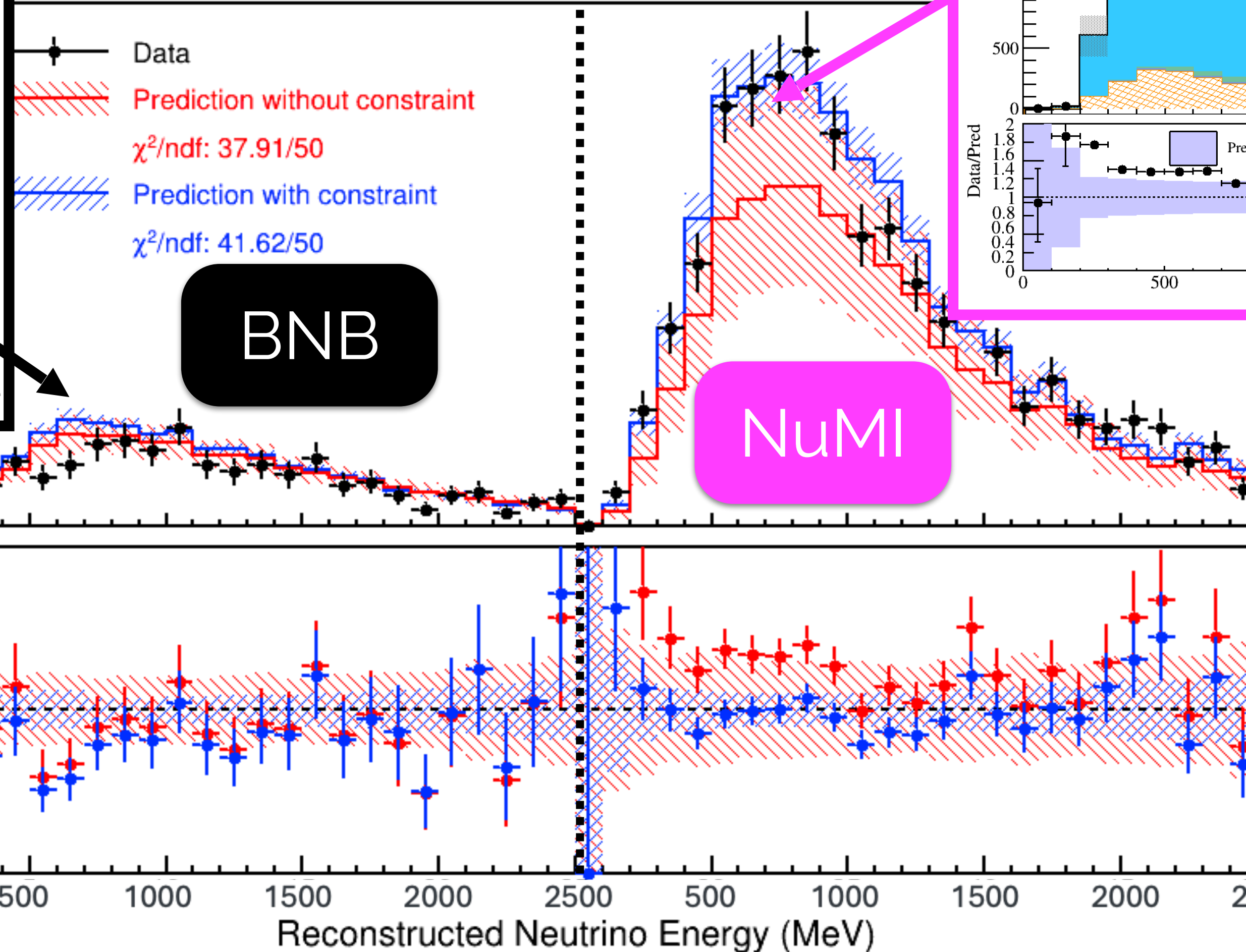
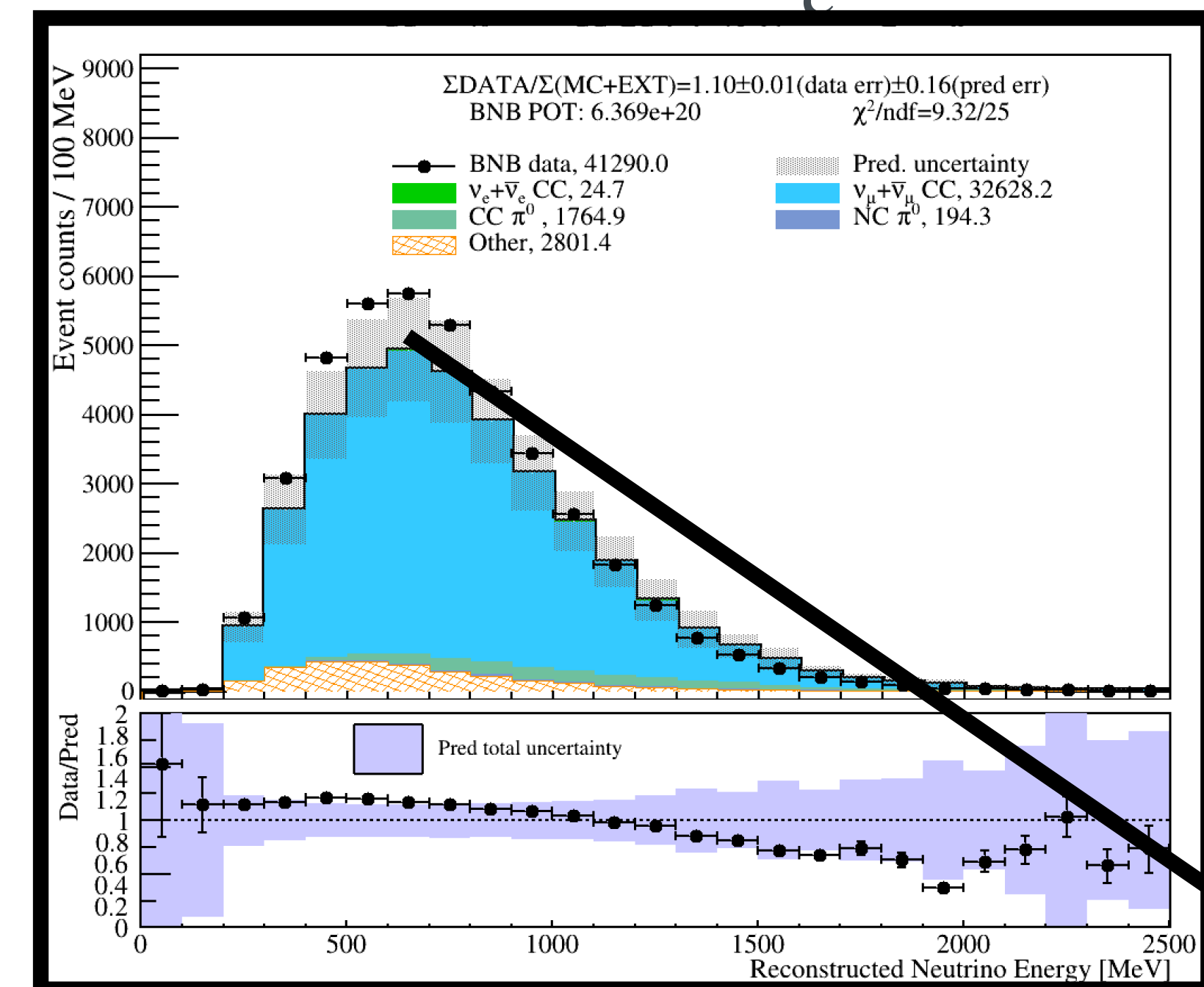


Without
Constraint:
 $\chi^2 = 37.91/50$

With Constraint:
 $\chi^2 = 41.62/50$

Constrained ν_e channel

Most constraining power comes from ν_μ channels

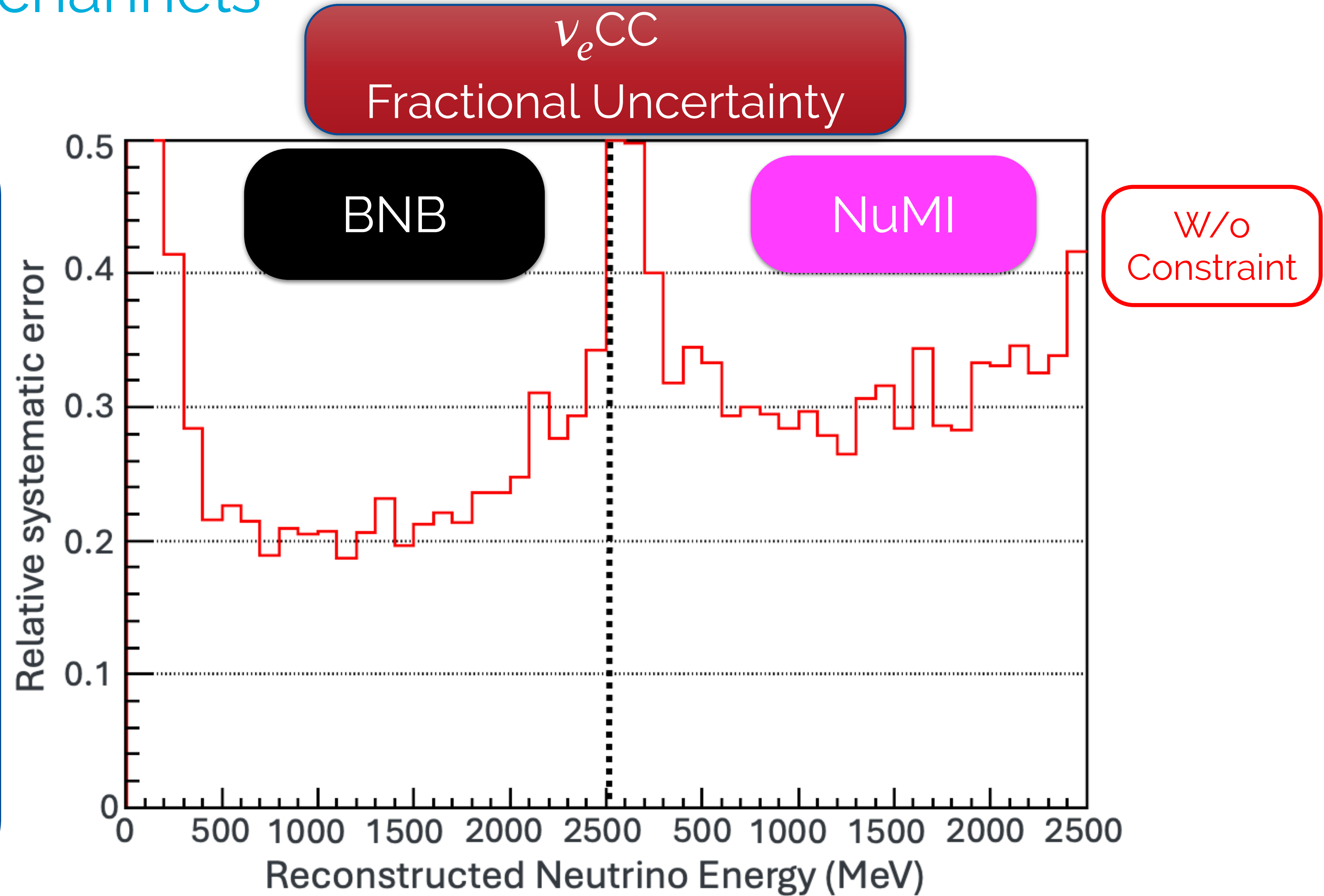


Without
Constraint:
 $\chi^2 = 37.91/50$

With Constraint:
 $\chi^2 = 41.62/50$

Constrained ν_e channels

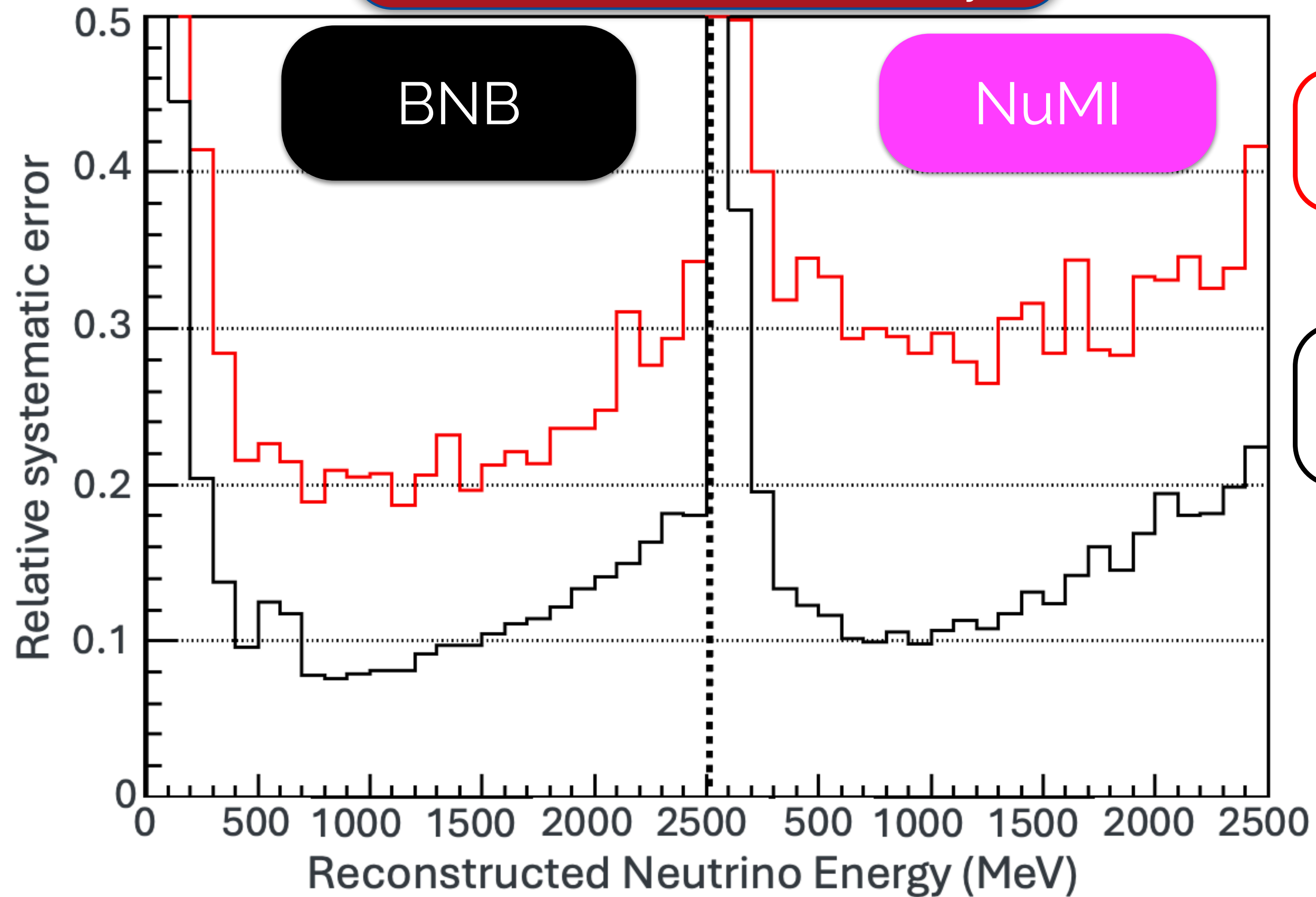
- Systematics limited analysis
- Dominant syst.: Flux and Cross Section
- Need to reduce uncertainties for better result



Constrained ν_e channels

ν_e CC
Fractional Uncertainty

Constraint significantly reduces the fractional systematic uncertainty



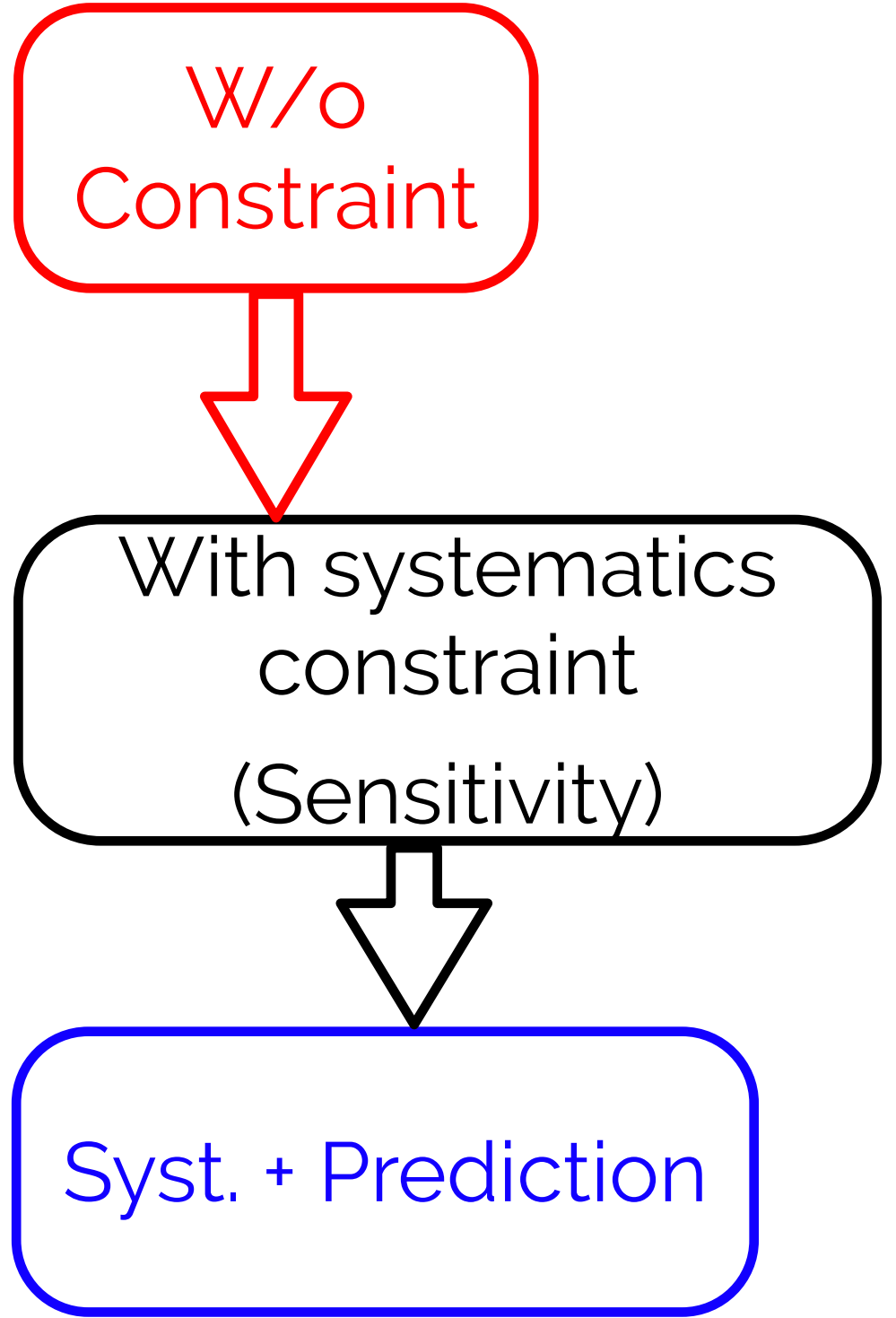
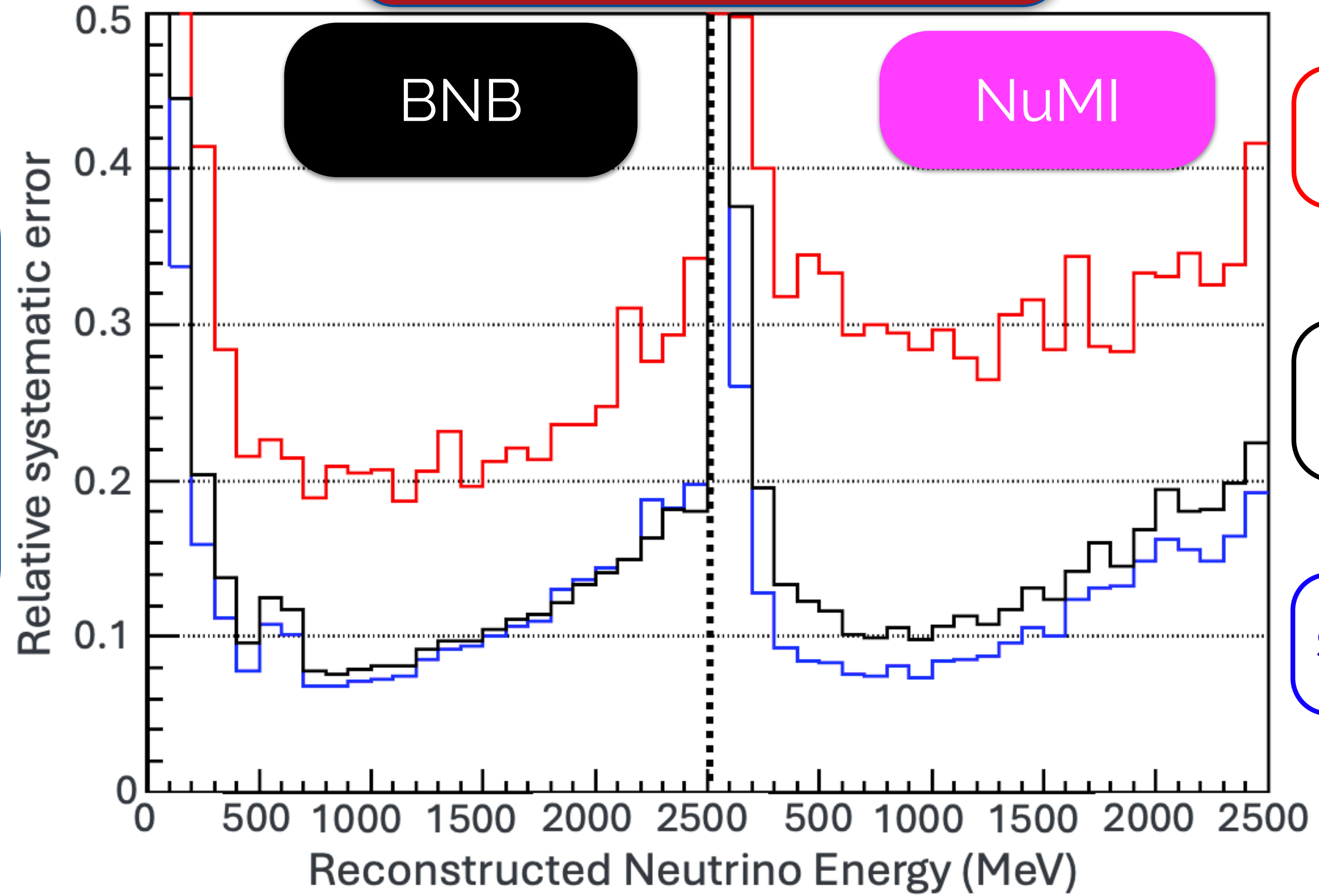
W/o
Constraint

With systematics
constraint
(Sensitivity)

Constrained ν_e channels

ν_e CC
Fractional Uncertainty

Pulled prediction
reduces it even
more



The best-fit values
for the osc.
parameters in the
 4ν hypothesis

Data consistency
test against 3ν
hypothesis
[Feldman-Cousins]

Setting limits via
“Frequentist CLs”
method

The best-fit values
for the osc.
parameters in the
 4ν hypothesis

Data consistency
test against 3ν
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[Feldman-Cousins]

Setting limits via
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method

Best fit values:

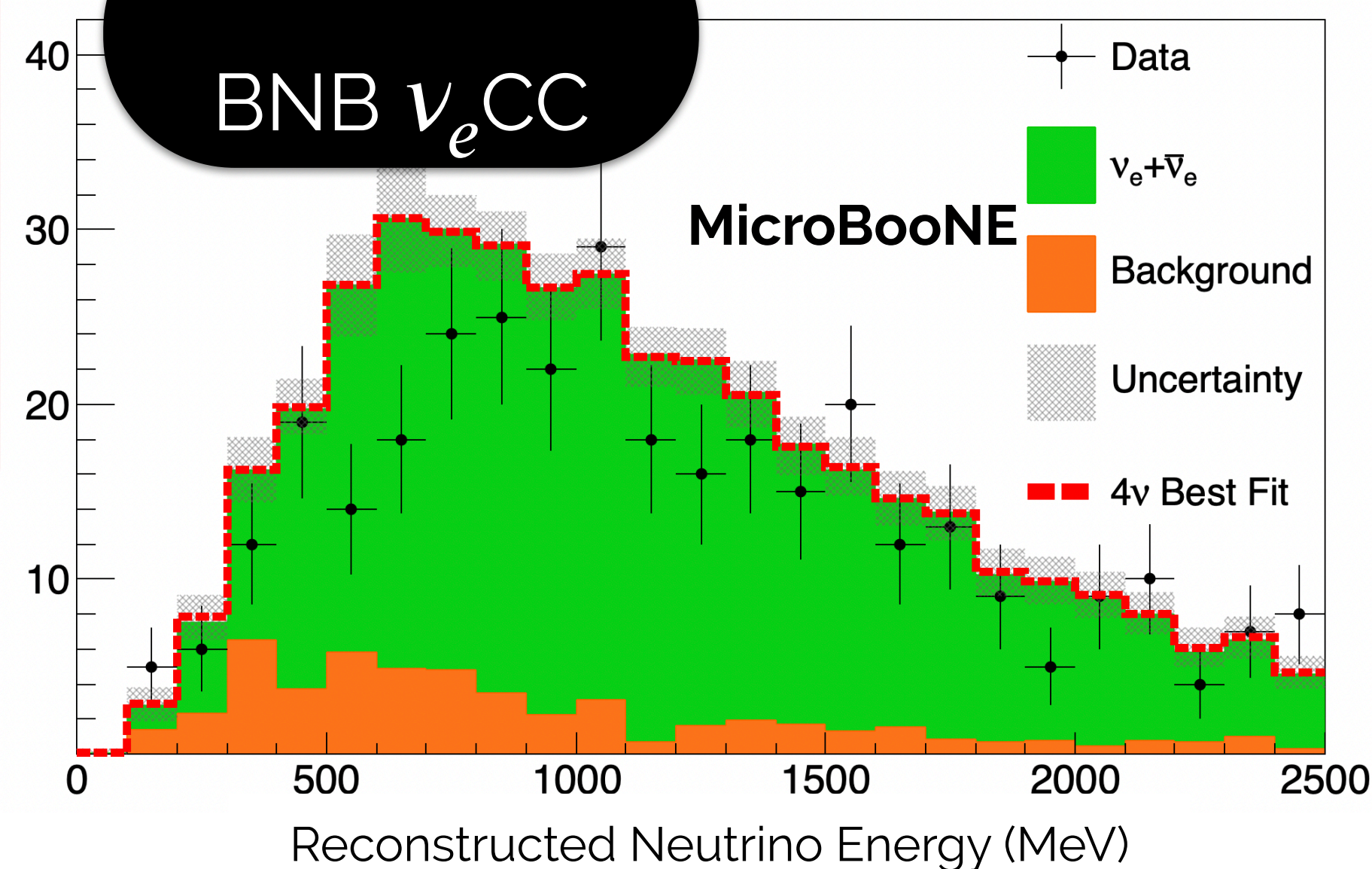
$$\Delta m_{41}^2 = 1.30 \times 10^{-2} \text{eV}^2$$

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

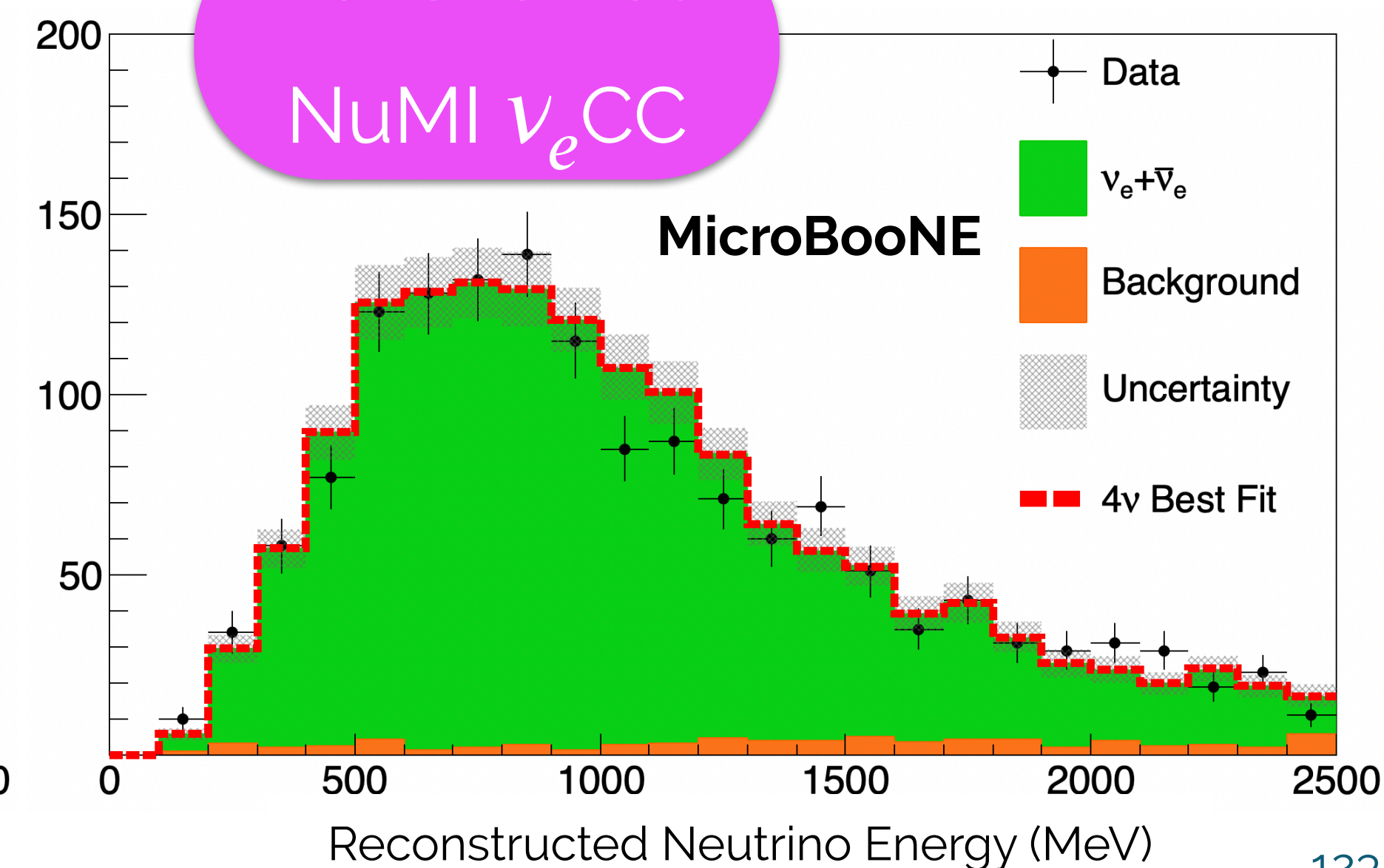
$$\sin^2(2\theta_{ee}) = 0.999$$

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

Constrained
BNB ν_e CC



Constrained
NuMI ν_e CC



The best-fit values
for the osc.
parameters in the
 4ν hypothesis

Data consistency
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Best fit values:

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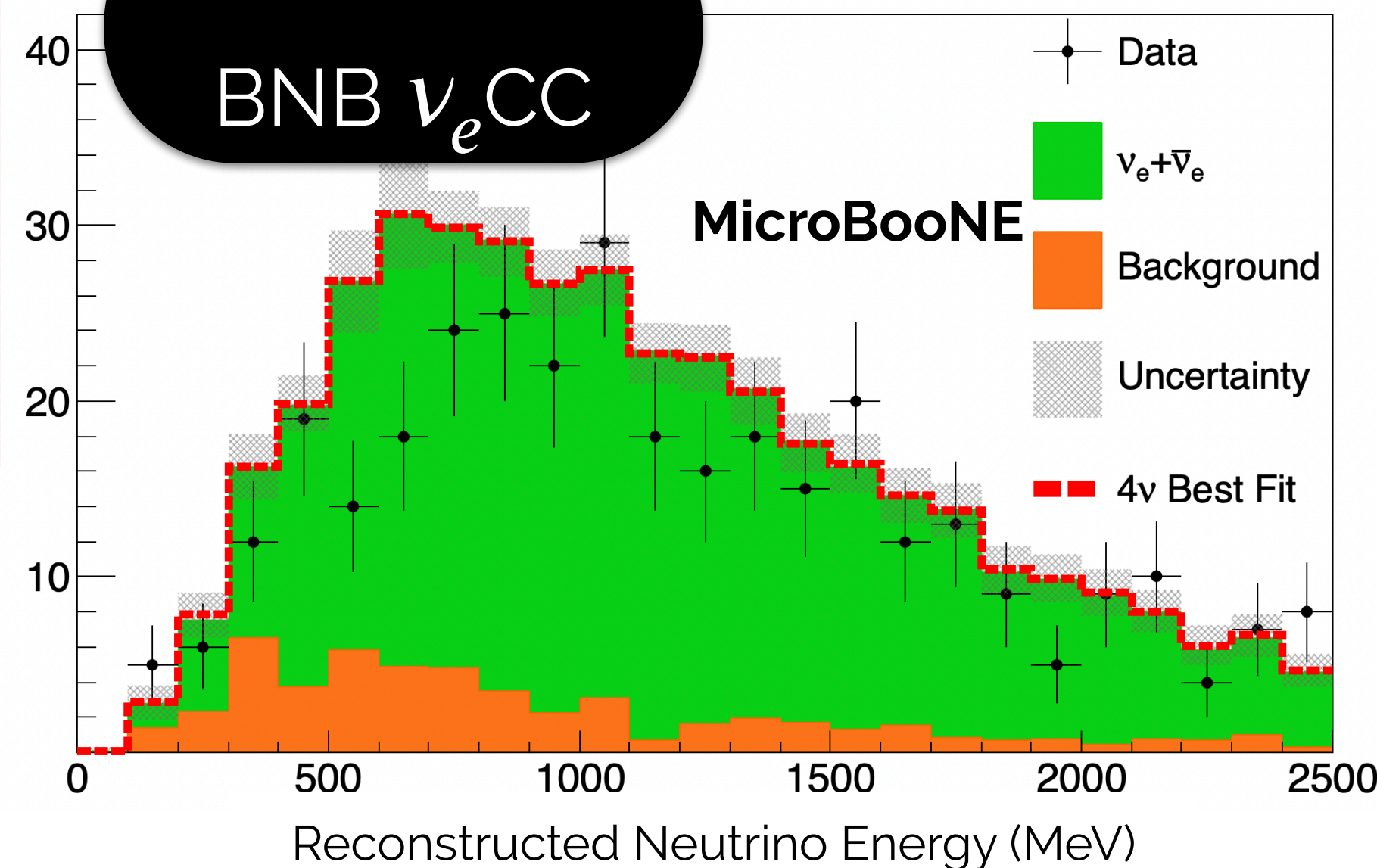
$$\sin^2(2\theta_{\mu e}) = 0.999$$

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

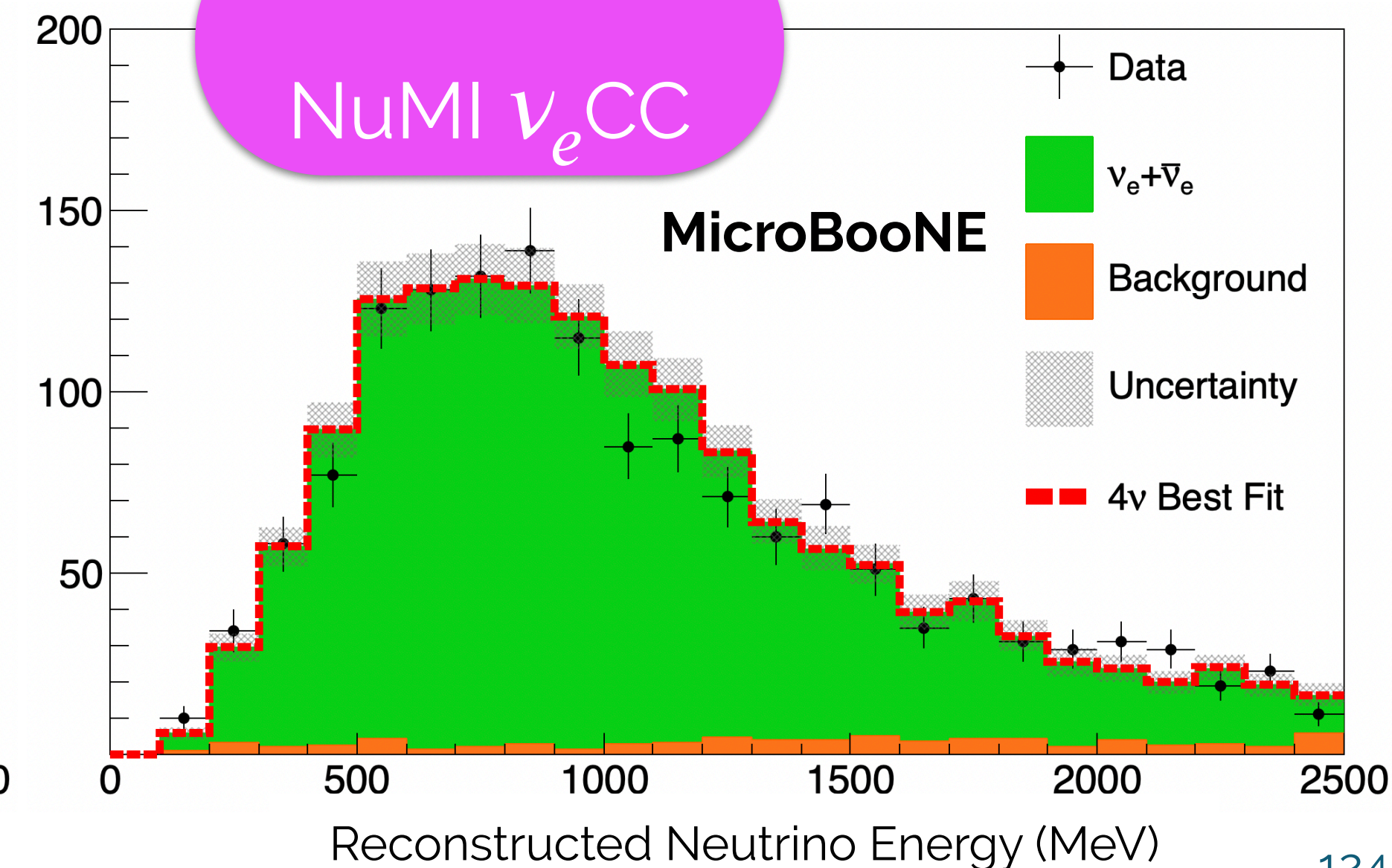
$$\sin^2(\theta_{24}) = 1$$

Low Δm_{41}^2 leads to negligible
oscillation effect

Constrained
BNB ν_e CC



Constrained
NuMI ν_e CC



The best-fit values
for the osc.
parameters in the
 4ν hypothesis

Data consistency
test against 3ν
hypothesis
[Feldman-Cousins]

Setting limits via
“Frequentist CLs”
method

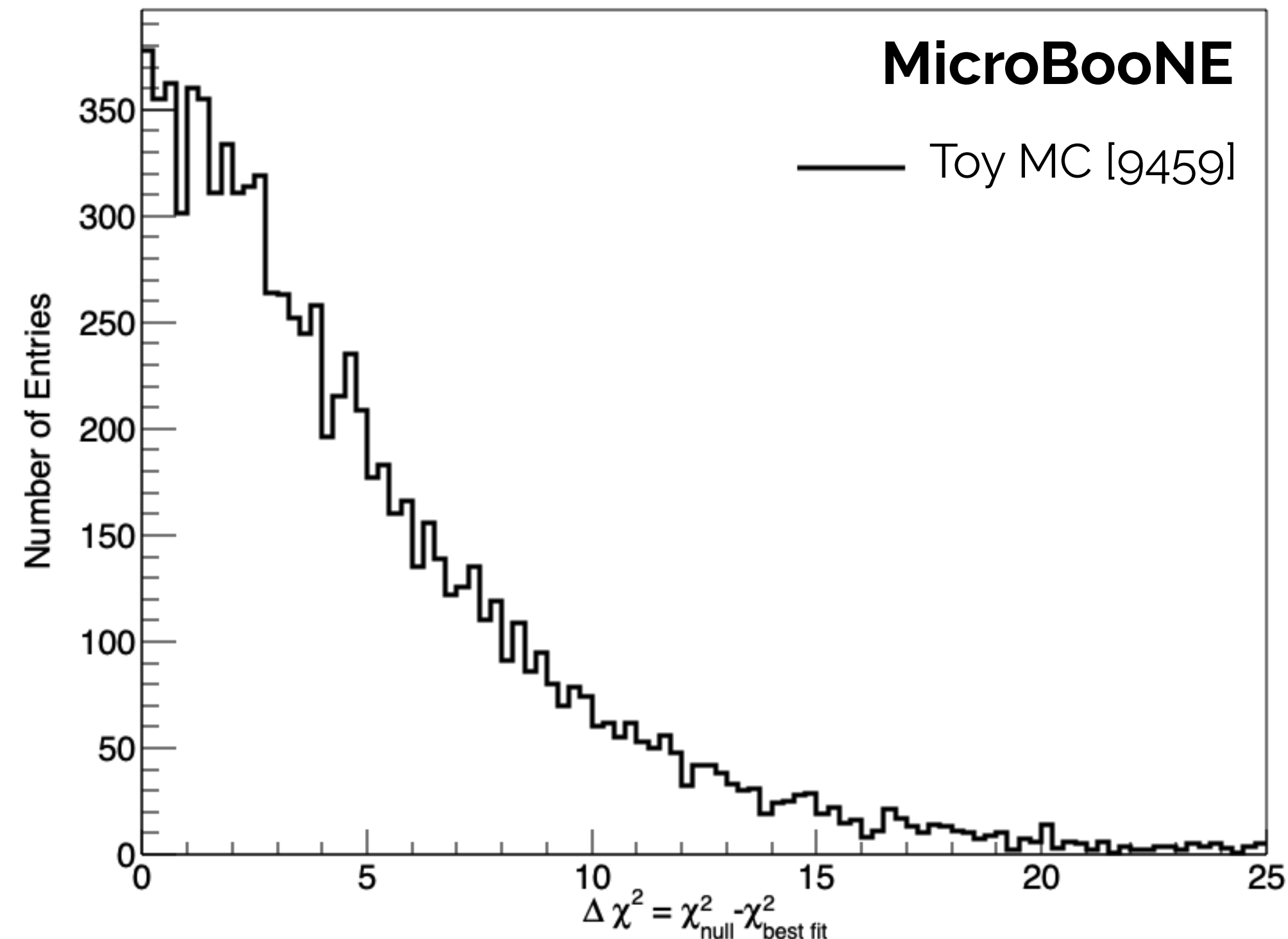
Best fit values:

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

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

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

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



The best-fit values
for the osc.
parameters in the
 4ν hypothesis

Data consistency
test against 3ν
hypothesis
[Feldman-Cousins]

Setting limits via
“Frequentist CLs”
method

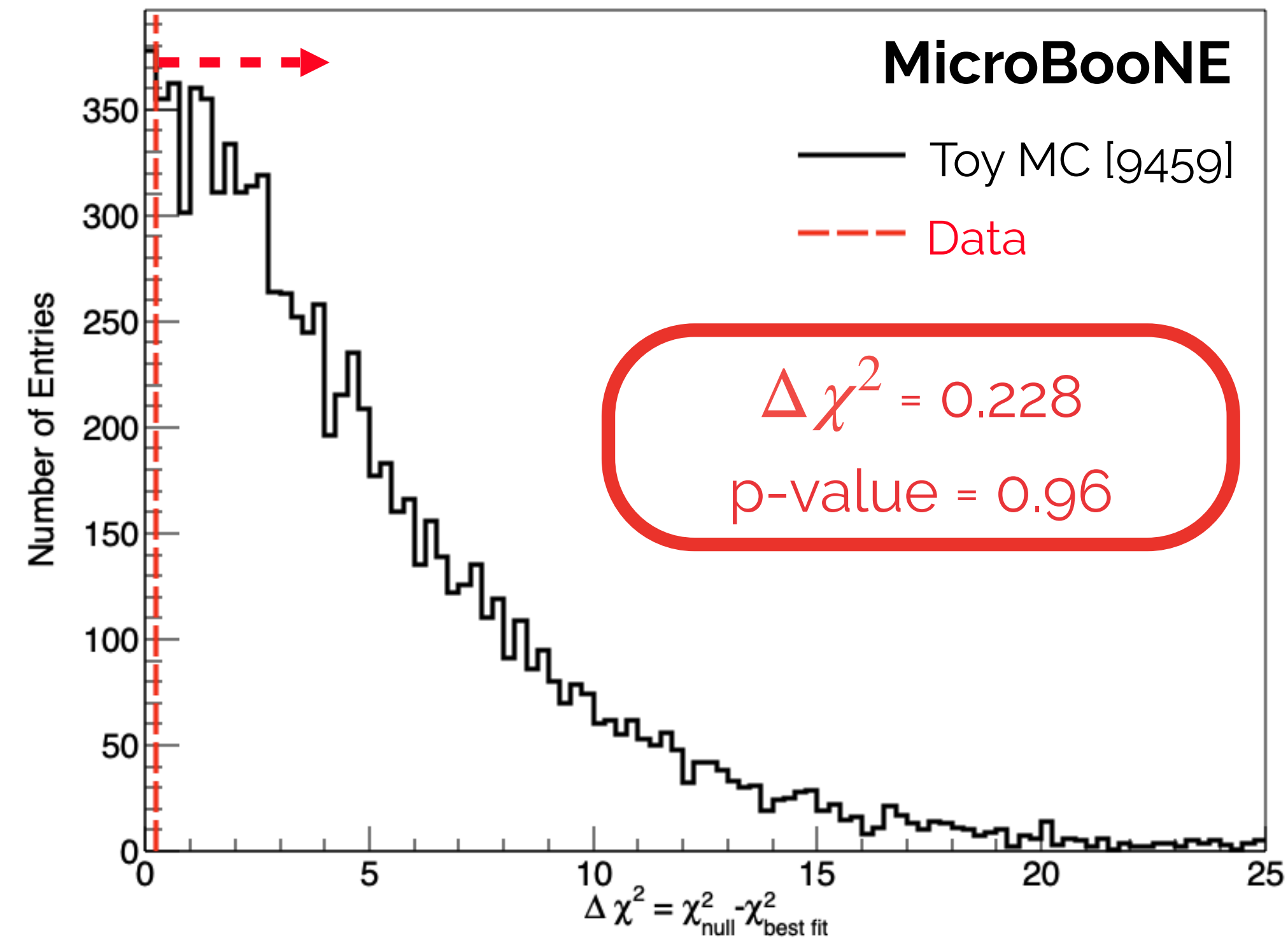
Best fit values:

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

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

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The best-fit values
for the osc.
parameters in the
 4ν hypothesis

Data consistency
test against 3ν
hypothesis
[Feldman-Cousins]

Setting limits via
“Frequentist CLs”
method

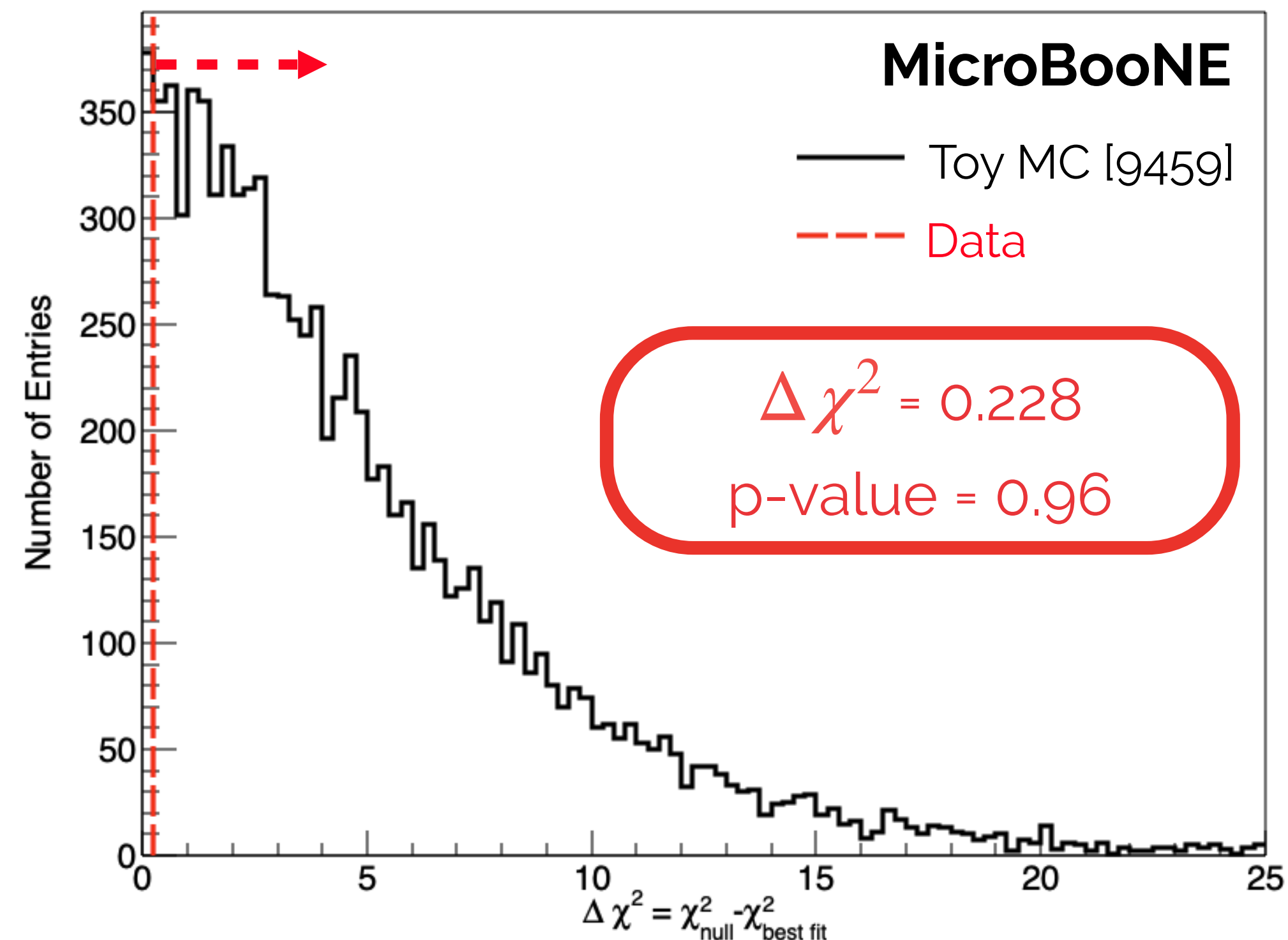
Best fit values:

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

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

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

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



BNB+NuMI data is consistent
with 3ν hypothesis

The best-fit values
for the osc.
parameters in the
 4ν hypothesis

Data consistency
test against 3ν
hypothesis
[Feldman-Cousins]

Setting limits via
“Frequentist CLs”
method

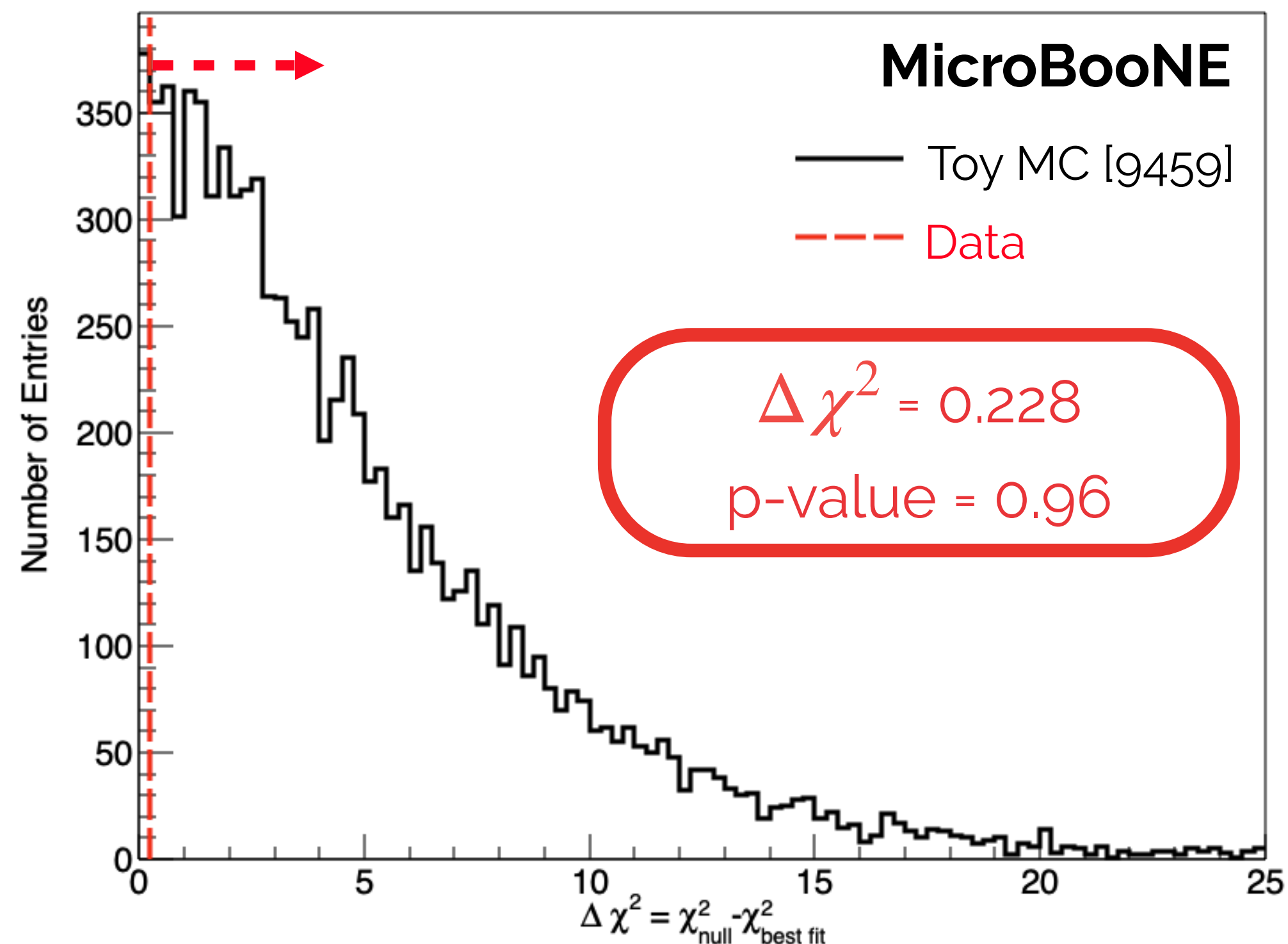
Best fit values:

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

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

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

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

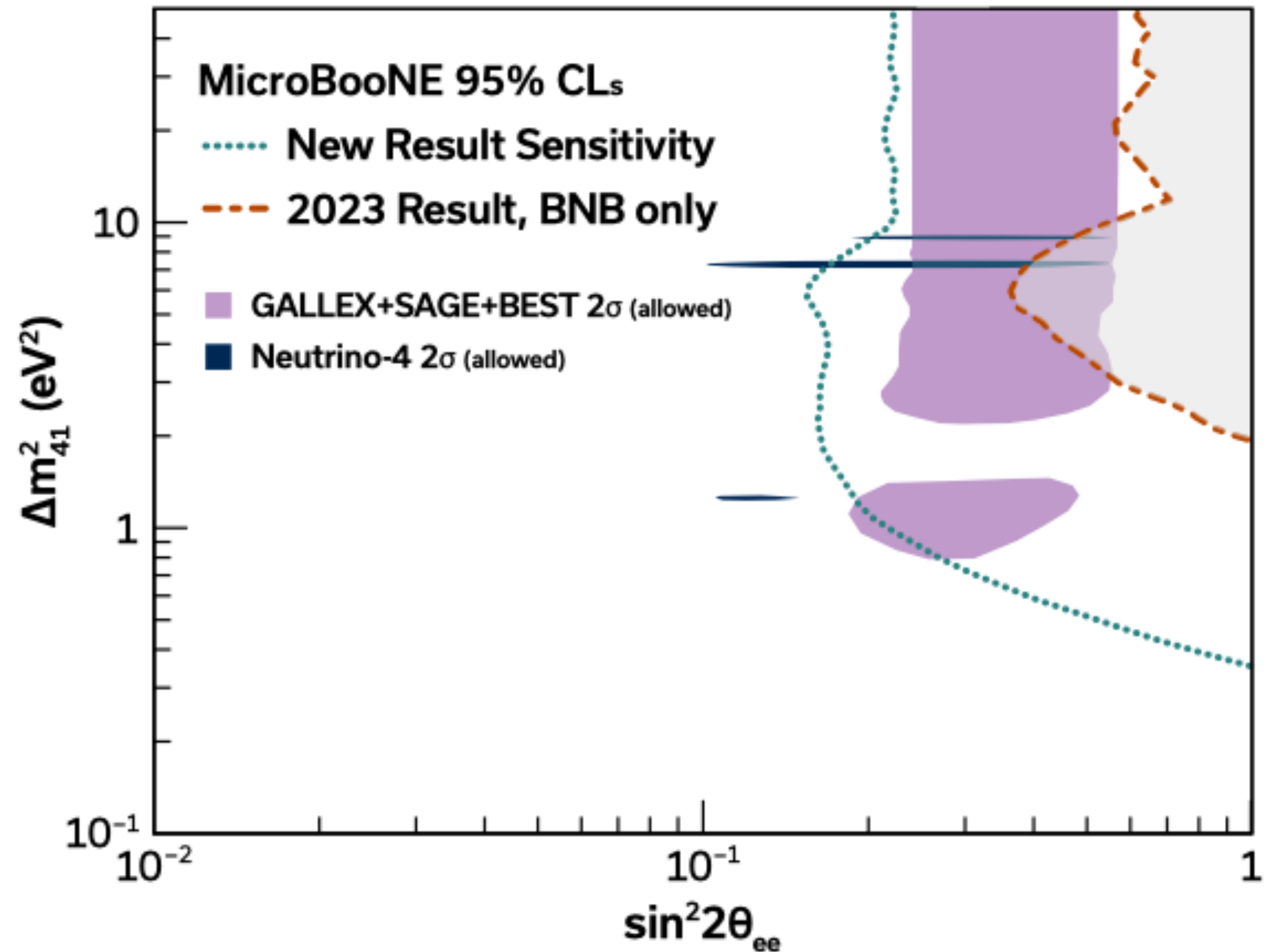


BNB+NuMI data is consistent
with 3ν hypothesis

Two Beam ν_e Disappearance Sensitivity

Sensitivity improves w.r.t. to BNB-only case:

- Degeneracy mitigation
- NuMI ν_e contribution

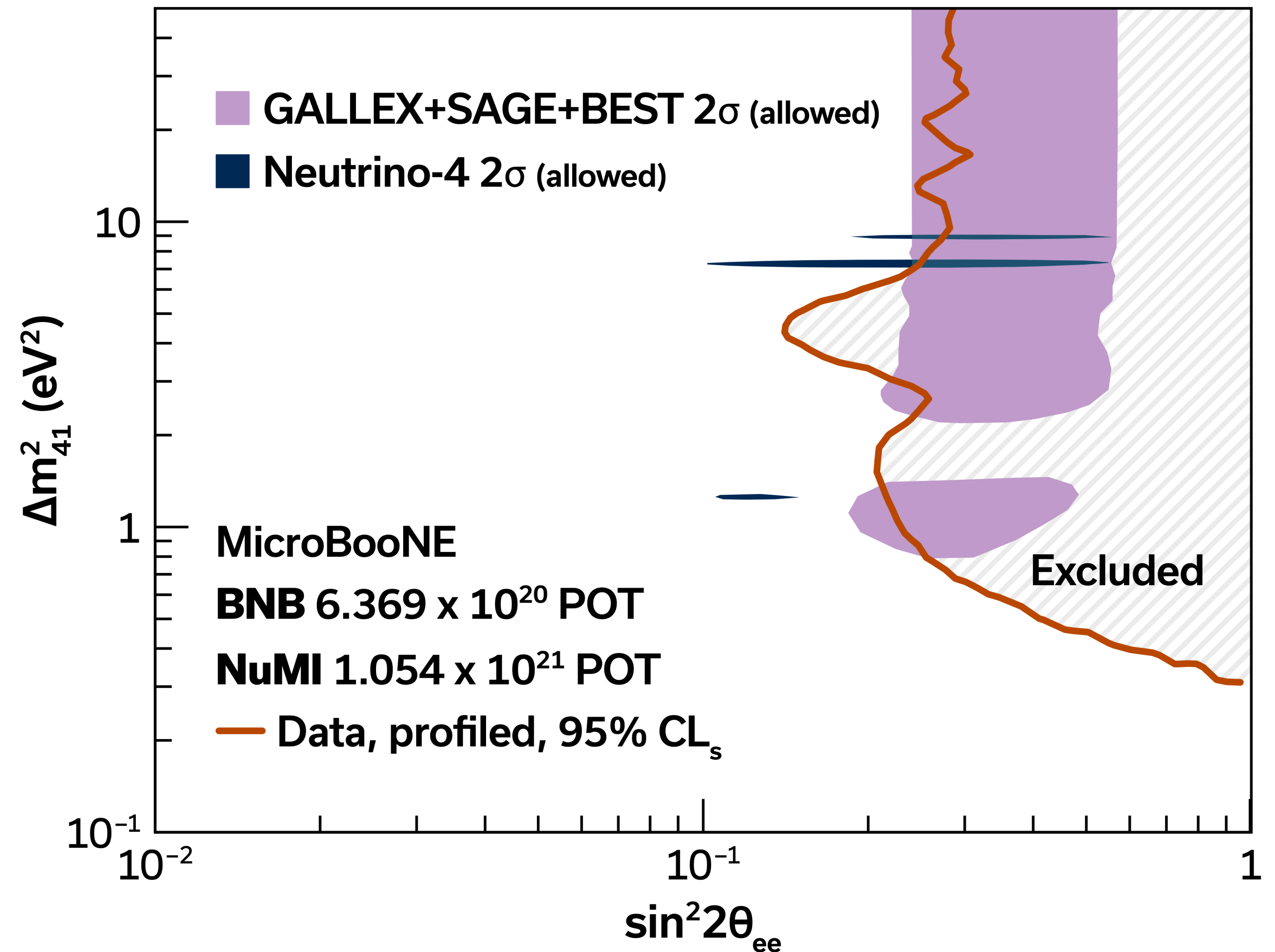


Two Beam ν_e Disappearance Data Exclusion

Disappearance ($\sin^2 2\theta_{ee}$)

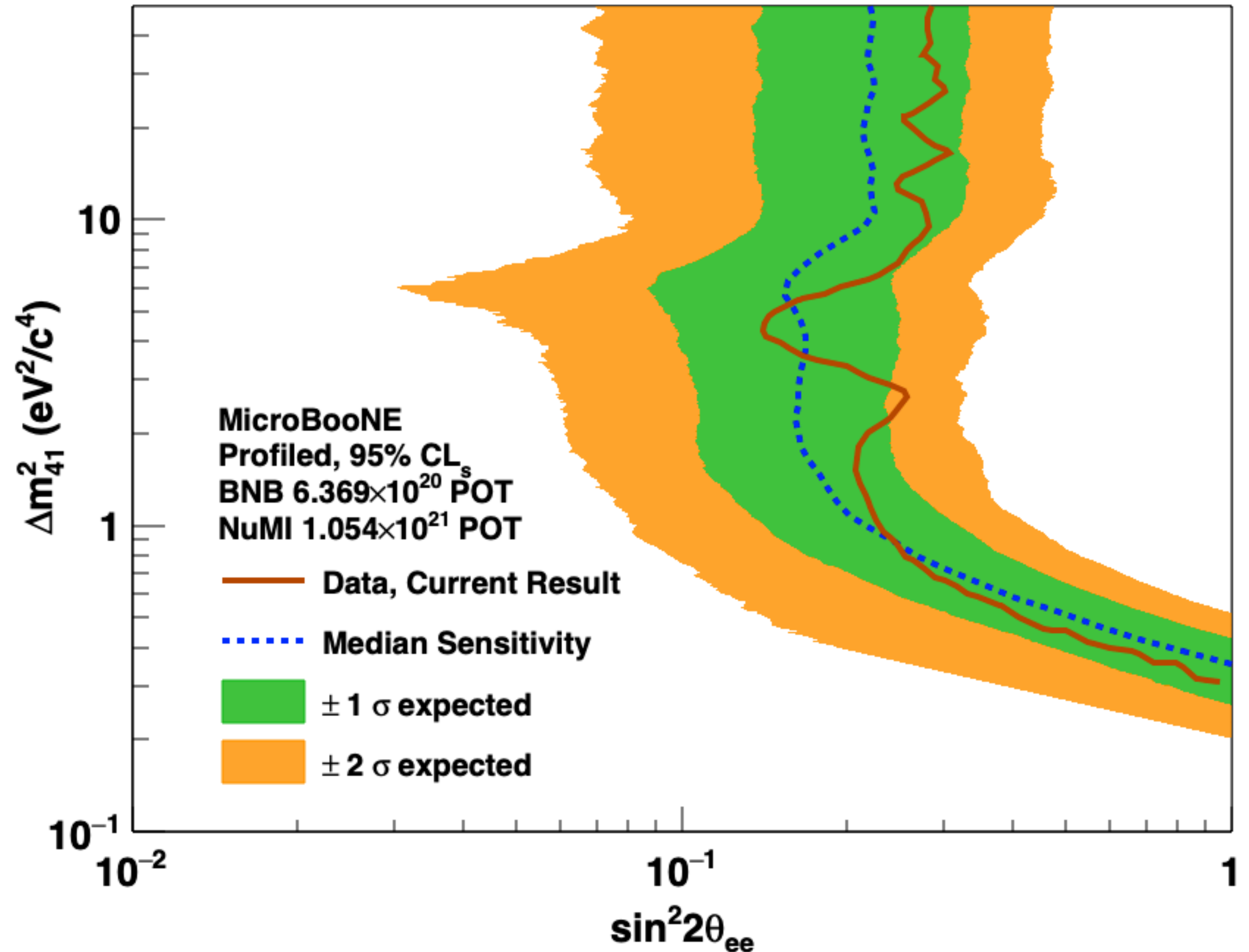
MicroBooNE data at 95% CL:

- Excludes most of Gallium allowed region
- Excludes part of Neutrino-4 allowed region



Two Beam ν_e Disappearance Data Exclusion

Data exclusion is mostly weaker than median sensitivity



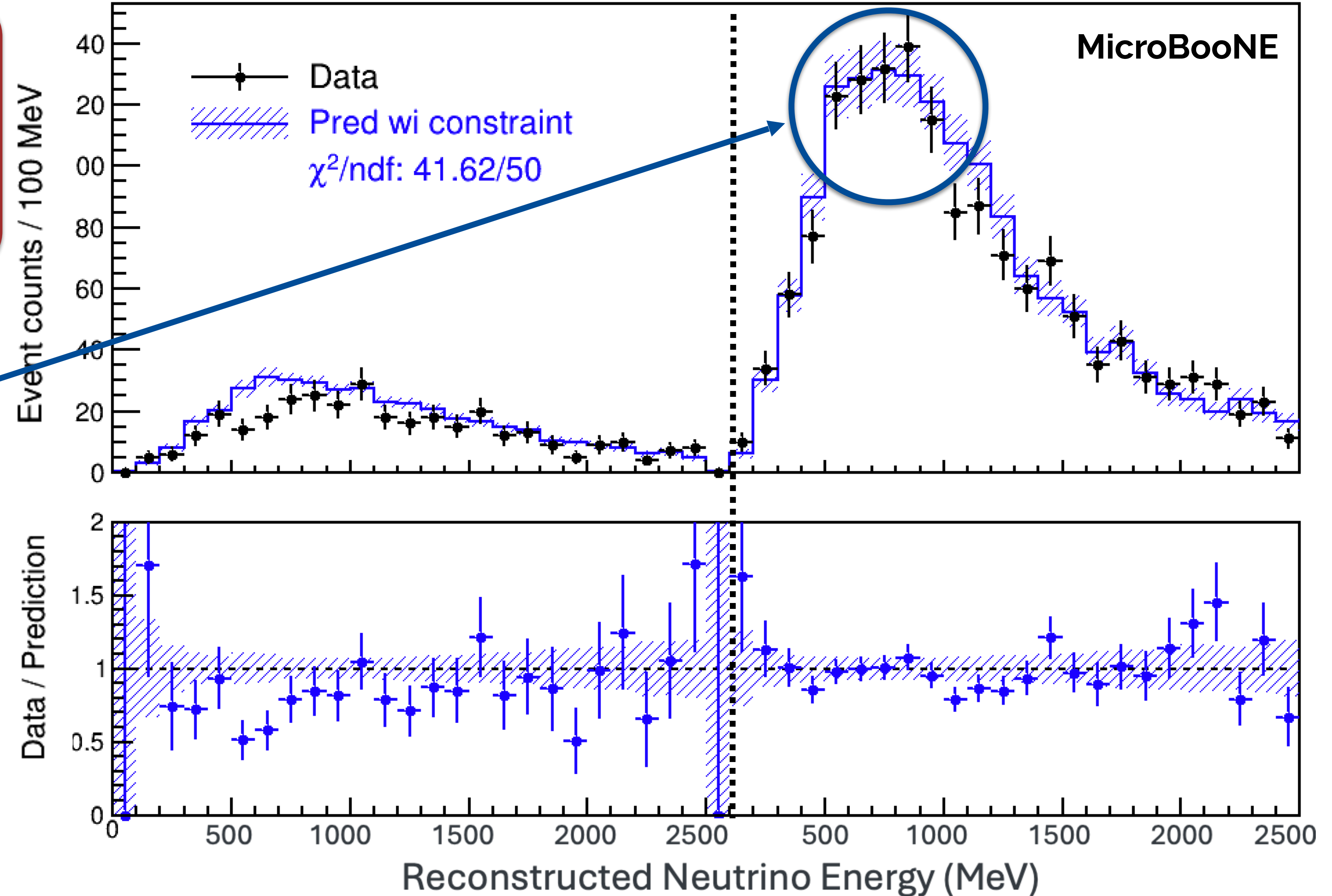
Two Beam ν_e Disappearance Data Exclusion

Disappearance
channel influenced
more by NuMI
(4x more ν_e than BNB)

Two Beam ν_e Disappearance Data Exclusion

Disappearance channel influenced more by NuMI (4x more ν_e than BNB)

NuMI ν_e data matches prediction well after constraint

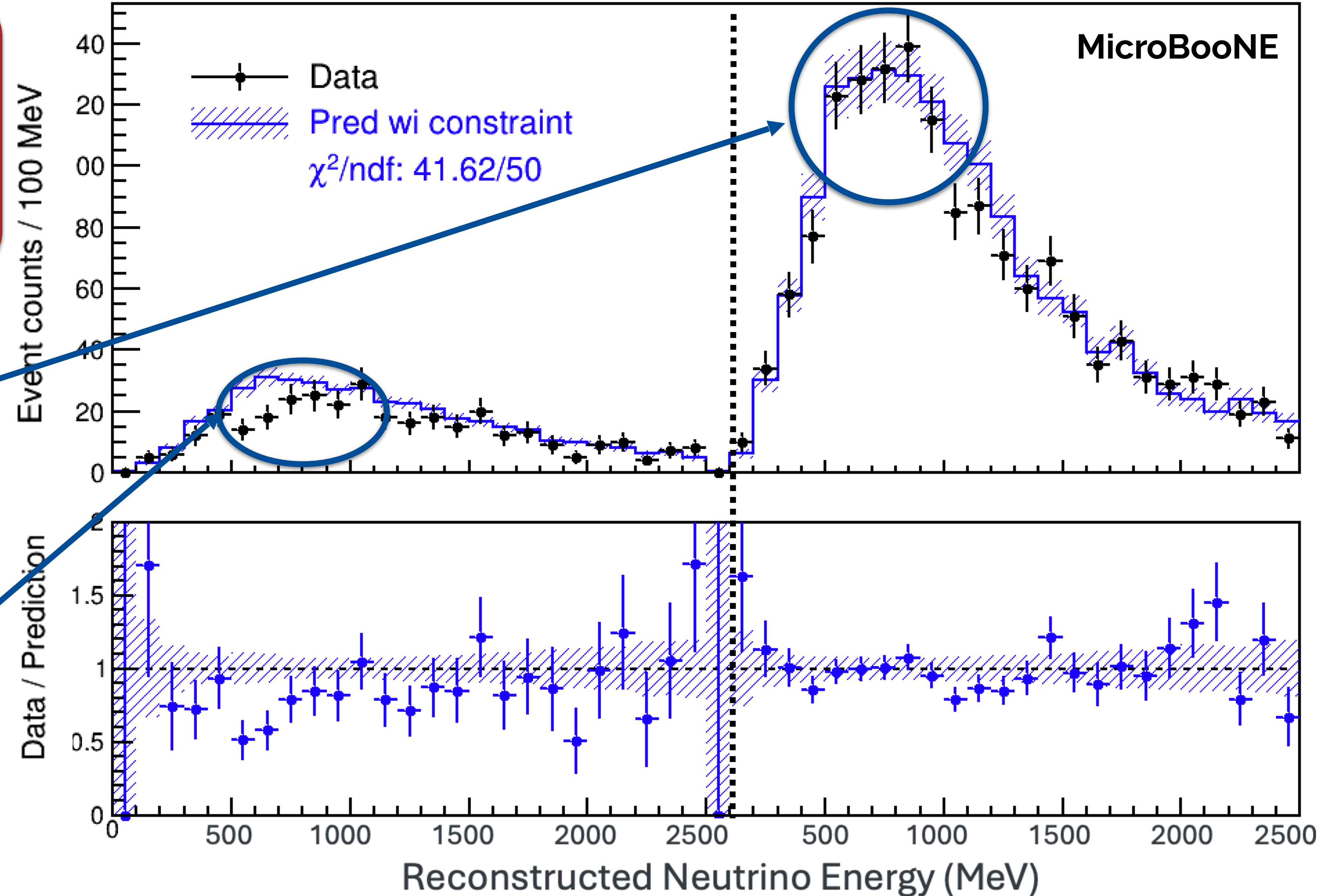


Two Beam ν_e Disappearance Data Exclusion

Disappearance channel influenced more by NuMI (4x more ν_e than BNB)

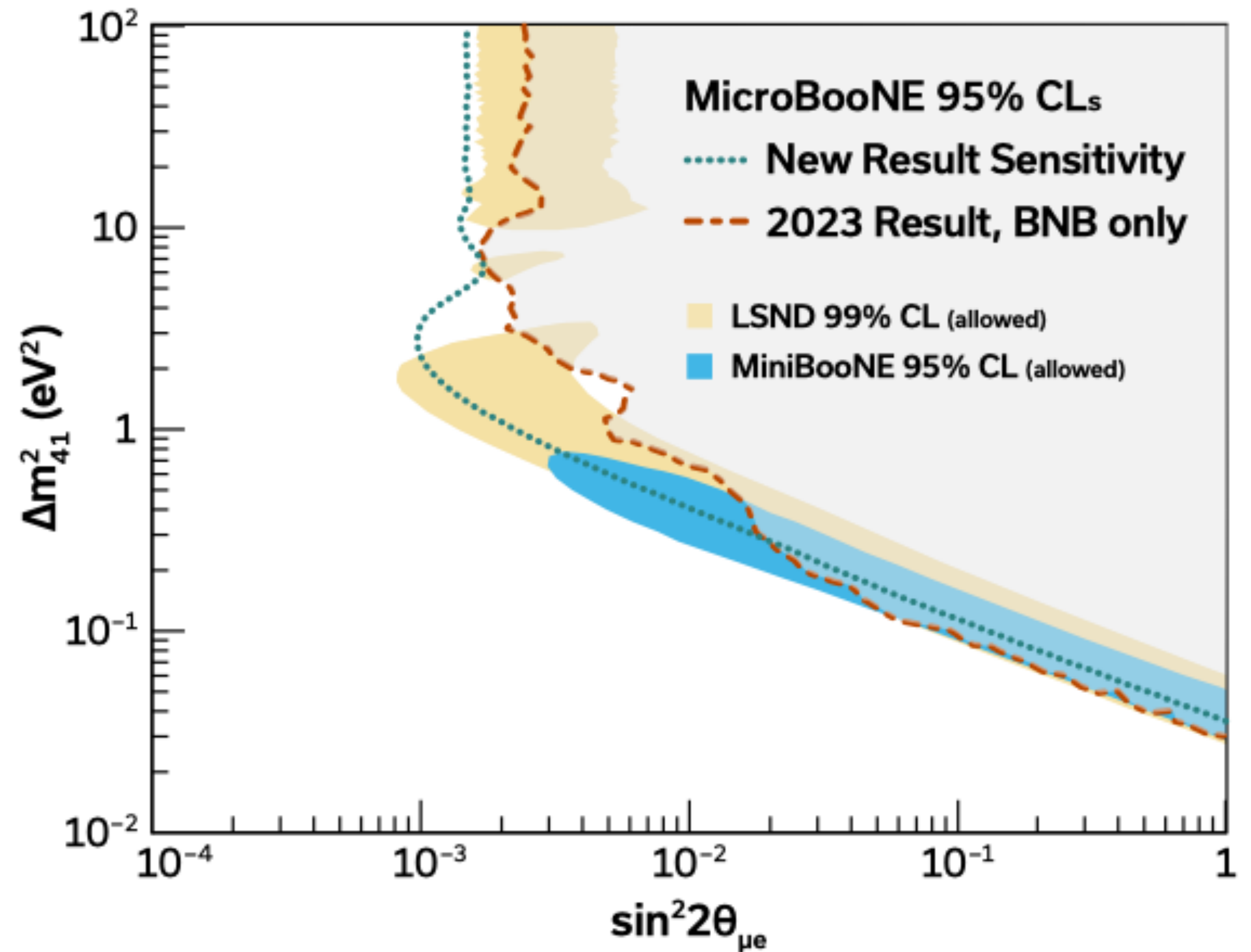
NuMI ν_e data matches prediction well after constraint

BNB data deficit weakens the ν_e disappearance limits



Two Beam ν_e Appearance Sensitivity

Sensitivity improves with respect to BNB-only case due to degeneracy mitigation

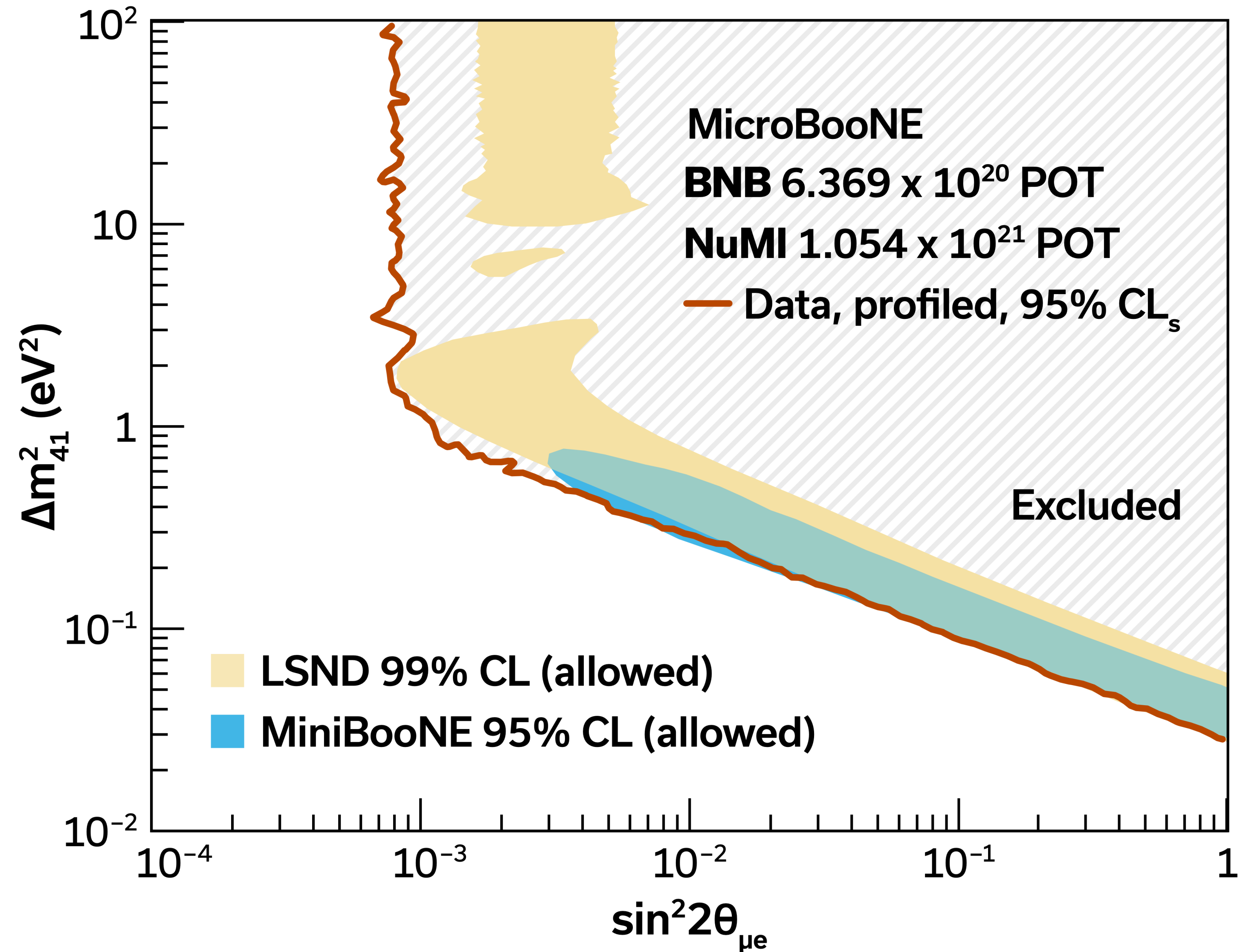


Two Beam ν_e Appearance Data Exclusion

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

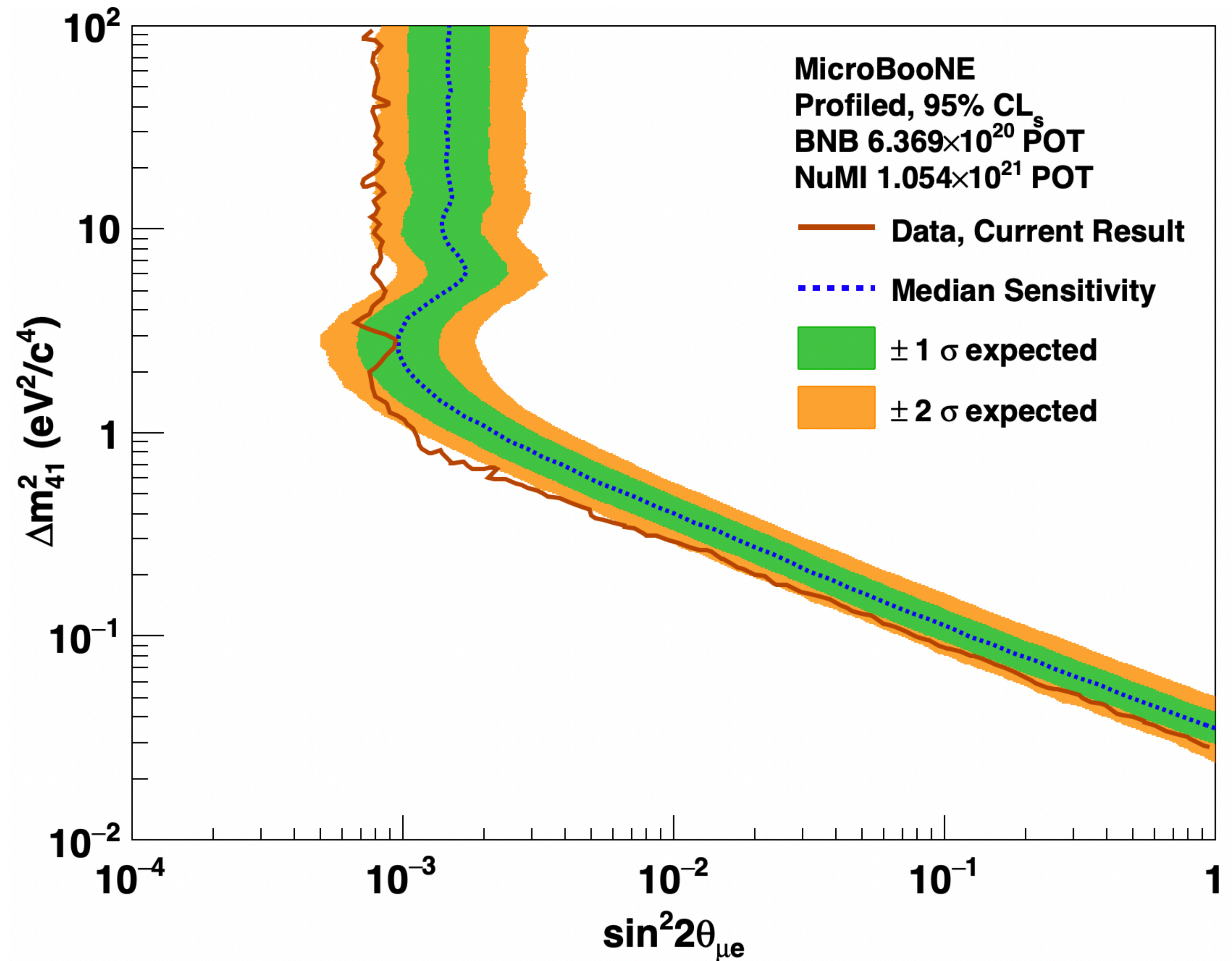
MicroBooNE data at 95% CL:

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



Two Beam ν_e Appearance Data Exclusion

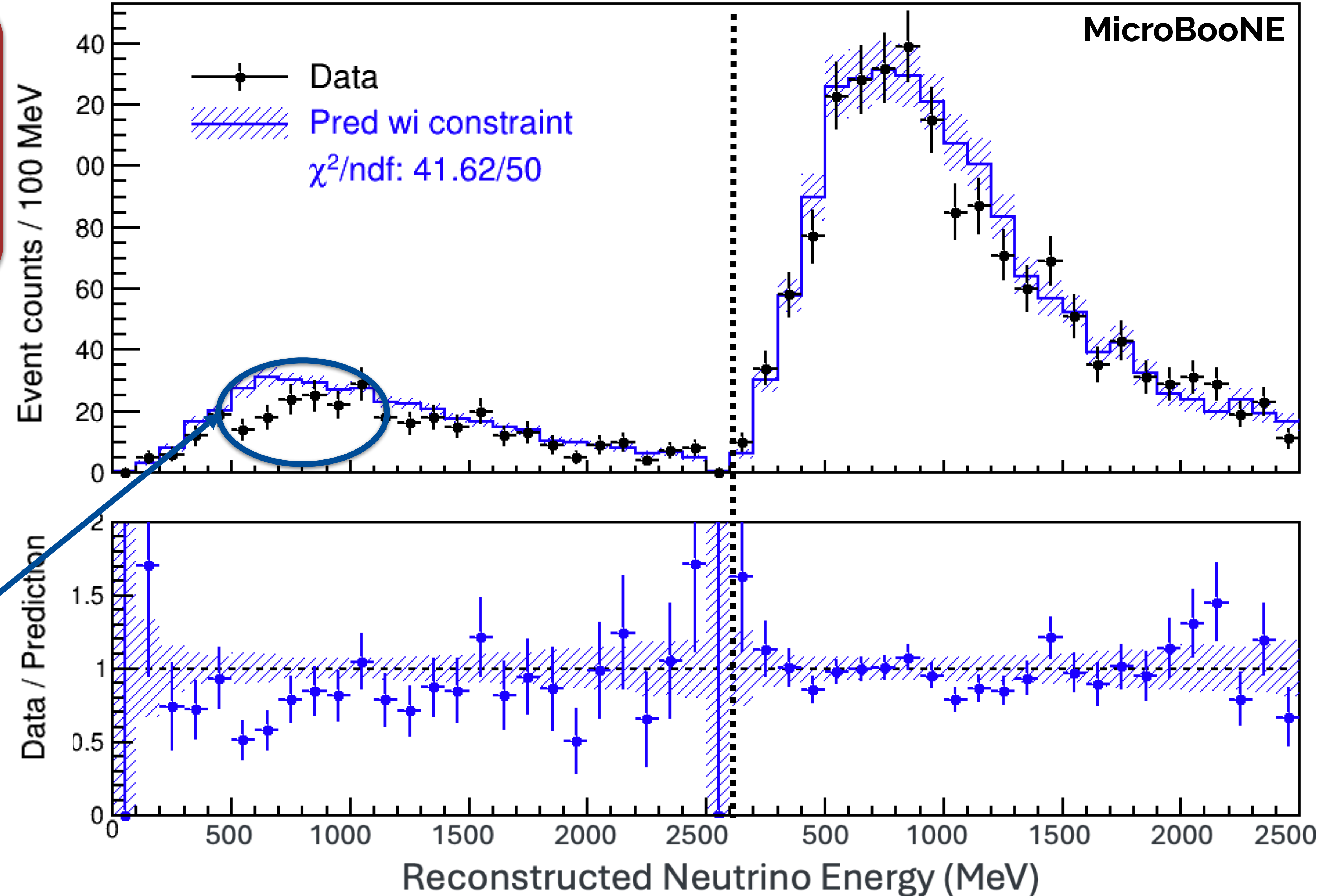
Data exclusion is stronger than median sensitivity



Two Beam ν_e Appearance Data Exclusion

Appearance channel influenced more by BNB (4x less ν_e and 2x more ν_μ than NuMI)

BNB ν_e data has deficit $\rightarrow$ boosts the ν_e appearance limits (smaller appearance angle $\theta_{\mu e}$)



BNB-only ν_e Appearance Data Exclusion

BNB-only

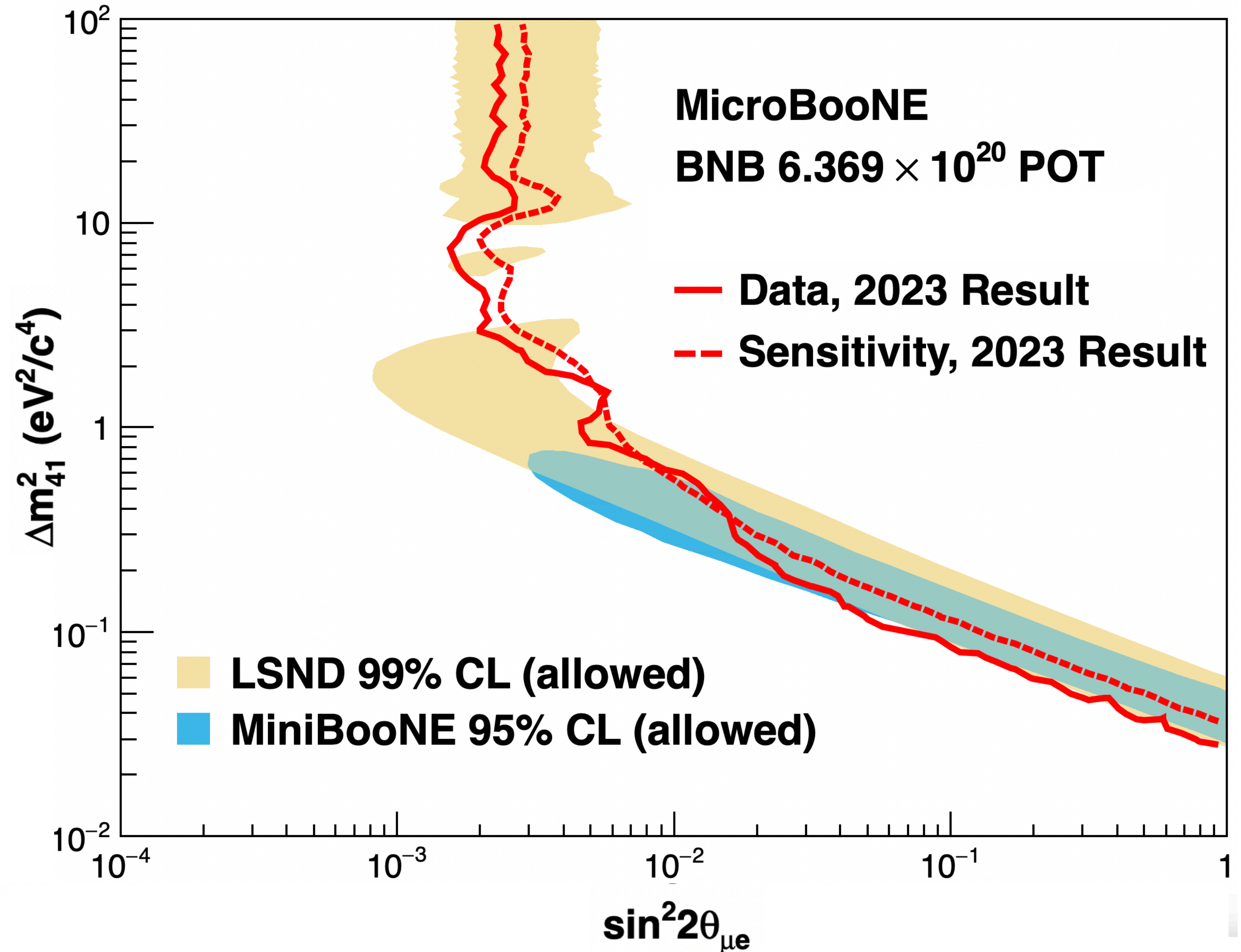
"Full 3+1" result (2023):

$\nu_\mu \rightarrow \nu_e$ appearance

$\nu_e \rightarrow \nu_e$ disappearance

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

Result slightly stronger than
sensitivity $\rightarrow$ BNB deficit

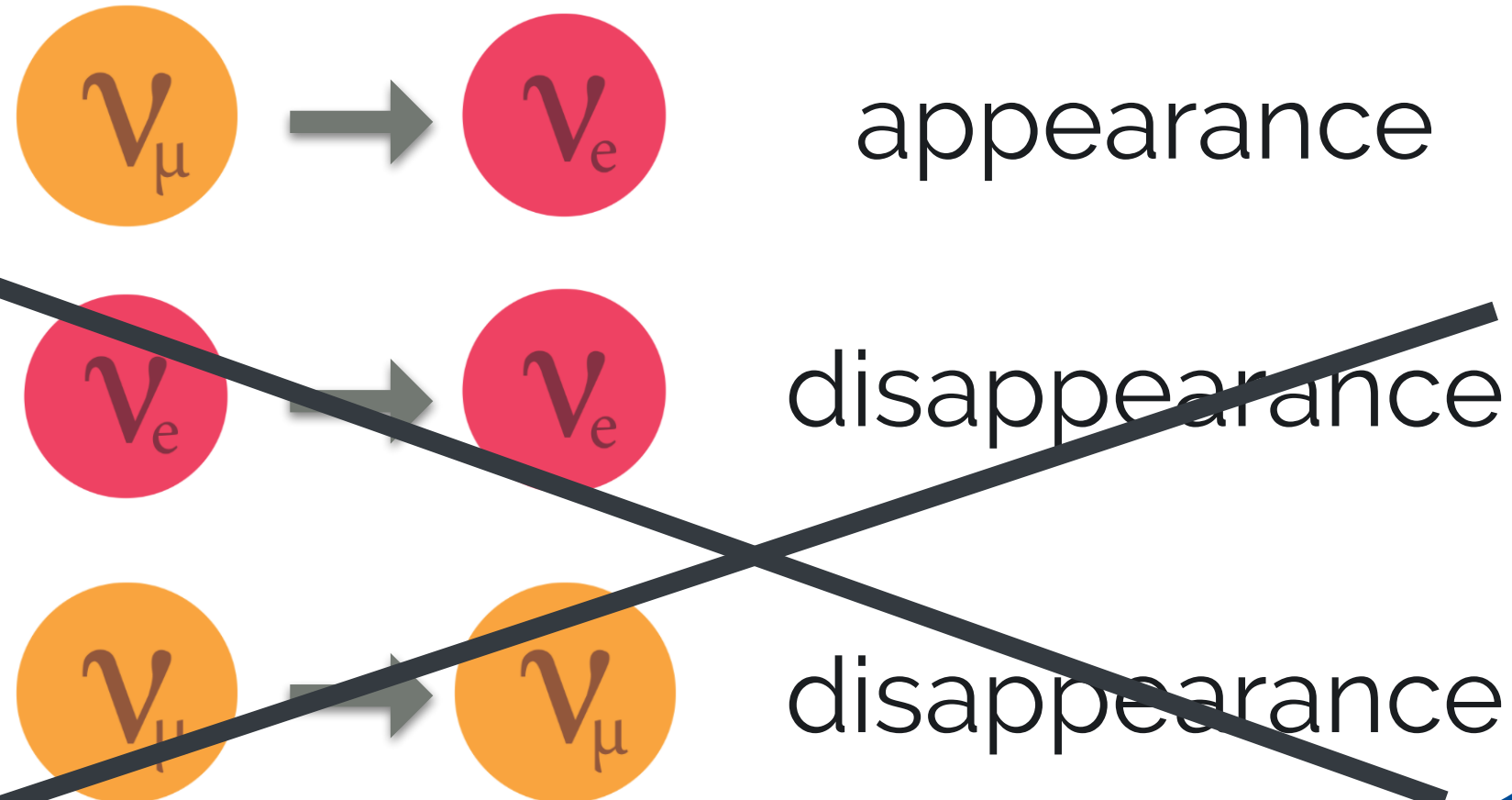


BNB-only ν_e Appearance Data Exclusion

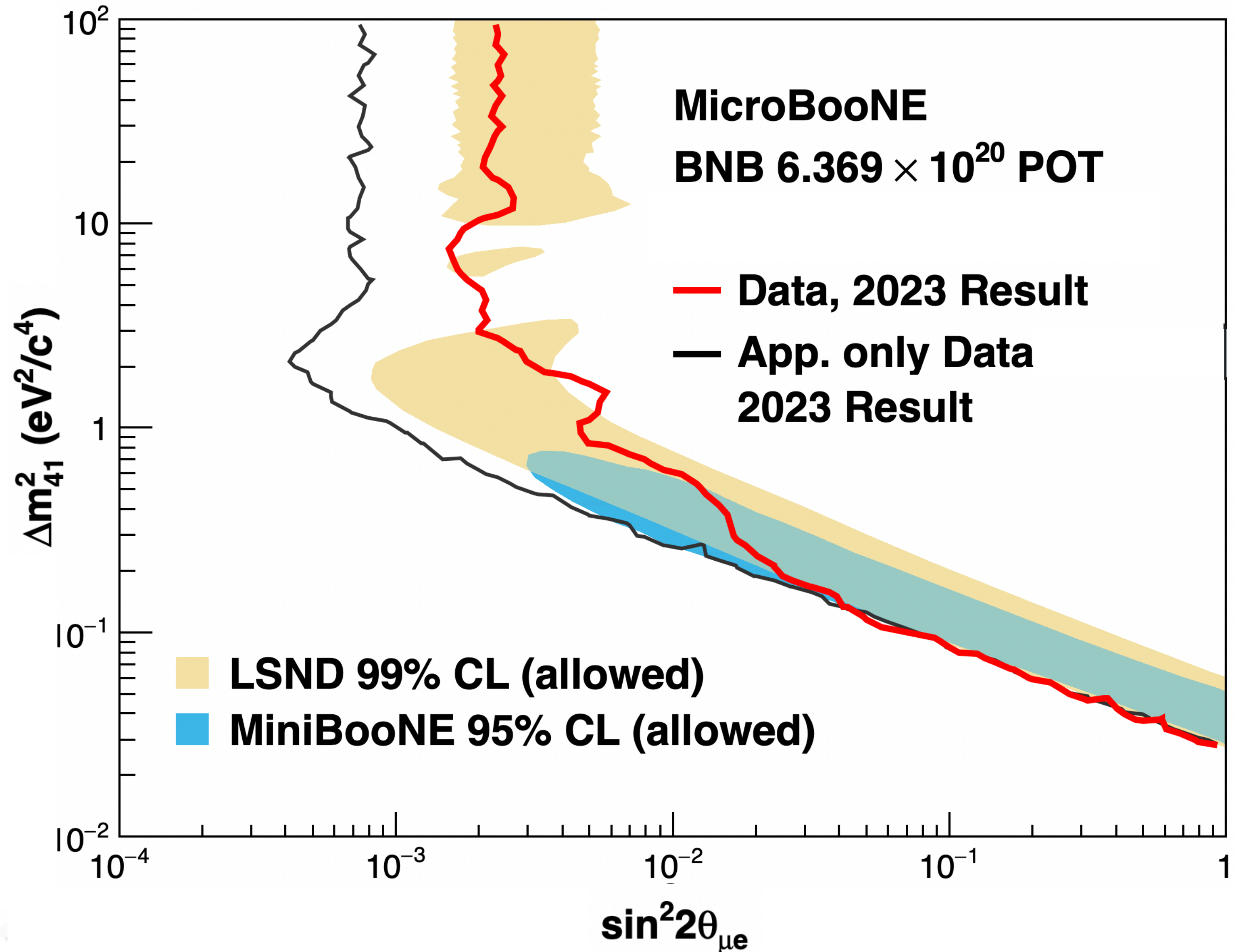
Unphysical

BNB-only

"App. only" result (2023):



Full BNB-only result weaker
than App. only →
degeneracy of oscillation
parameters



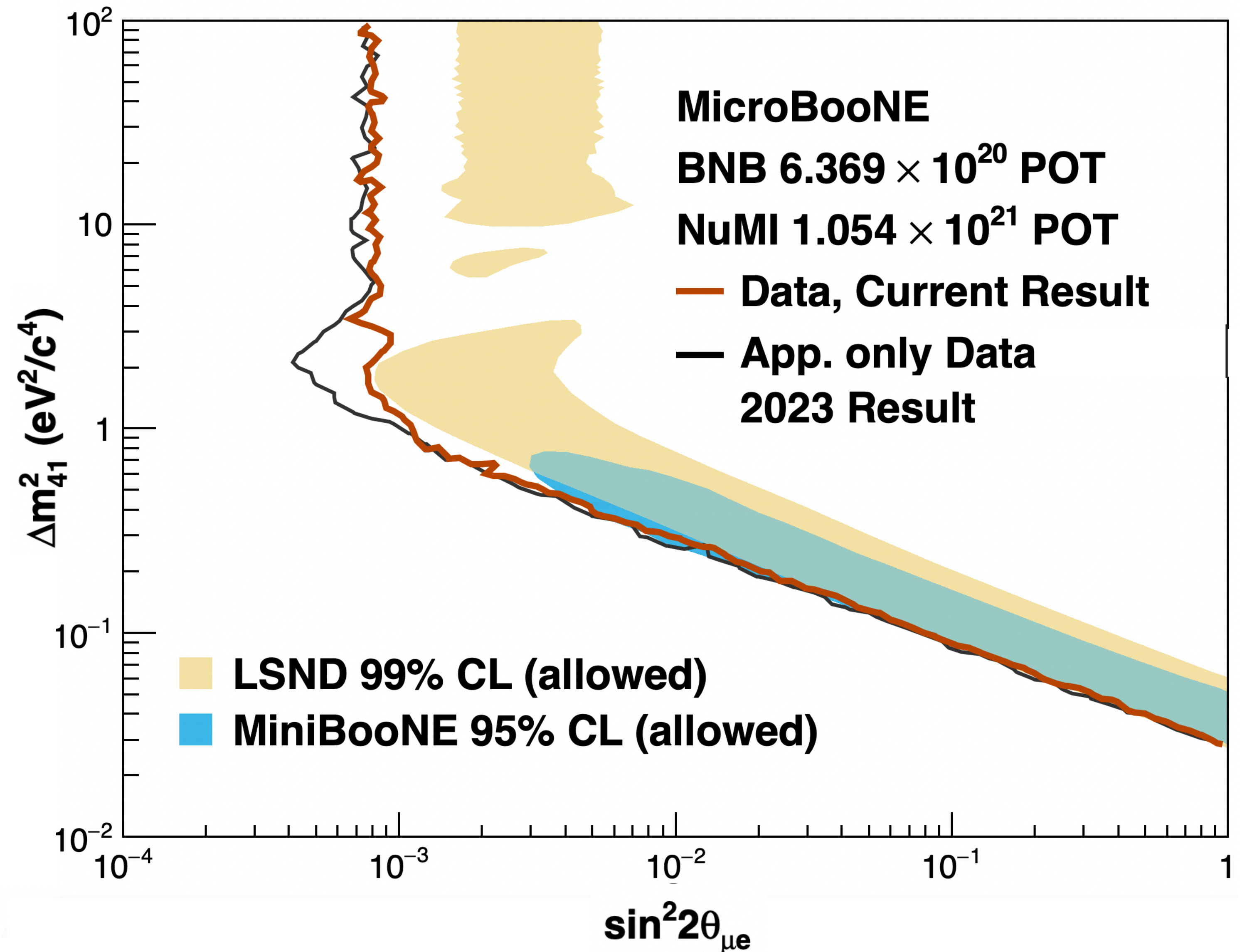
Two Beam ν_e Appearance Data Exclusion

BNB+NuMI "Full 3+1"

VS

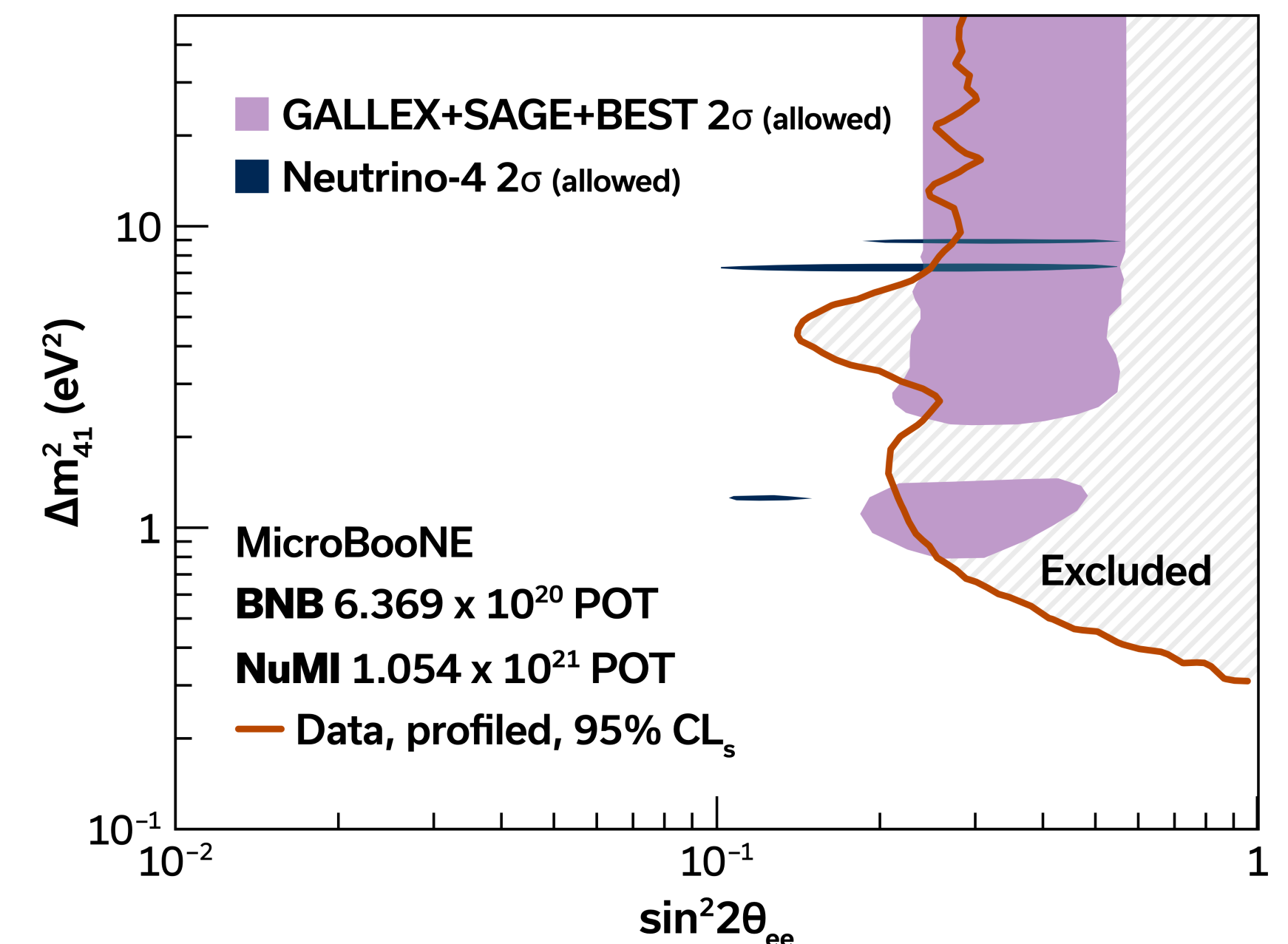
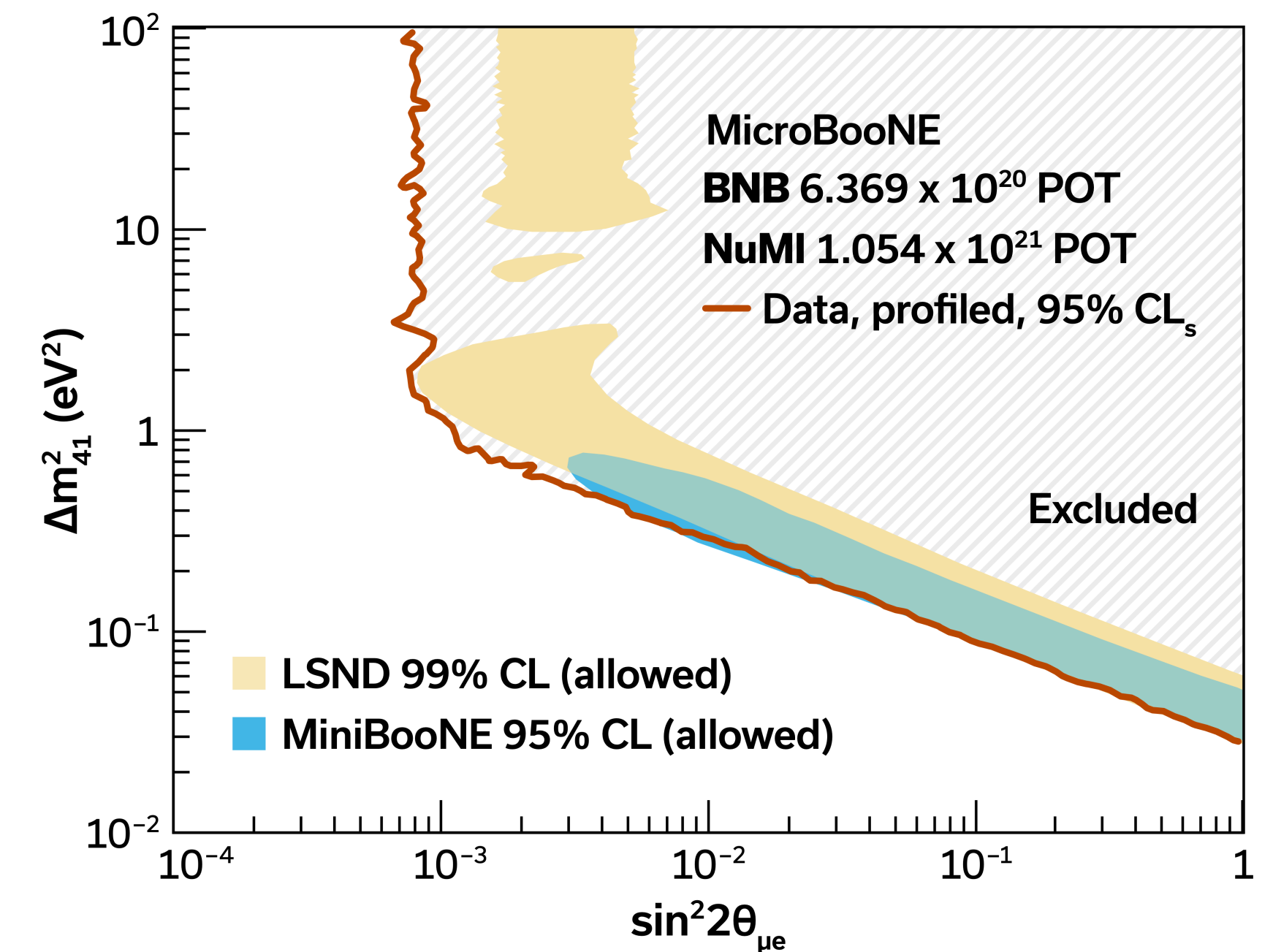
BNB-only App. only

Similar $\rightarrow$ NuMI provides
maximum degeneracy
mitigation to BNB-dominant
appearance channel



Summary of this result

- **No evidence observed for the 3+1 sterile neutrino model**
- **Exclude, at 95% CL, the 3+1 explanation of LSND and MiniBooNE anomalies**
- Exclude most regions allowed by the Gallium and Neutrino-4 anomalies using **a distinct decay-in-flight source**
- **Closed the window for the 3+1 model** as an explanation to the long-standing LSND/MiniBooNE anomalies.



Outlook

Although the 3+1 framework no longer provides a viable explanation, **the LSND and MiniBooNE anomalies themselves haven't gone away.**

The reactor and gallium anomalies also remain unresolved.

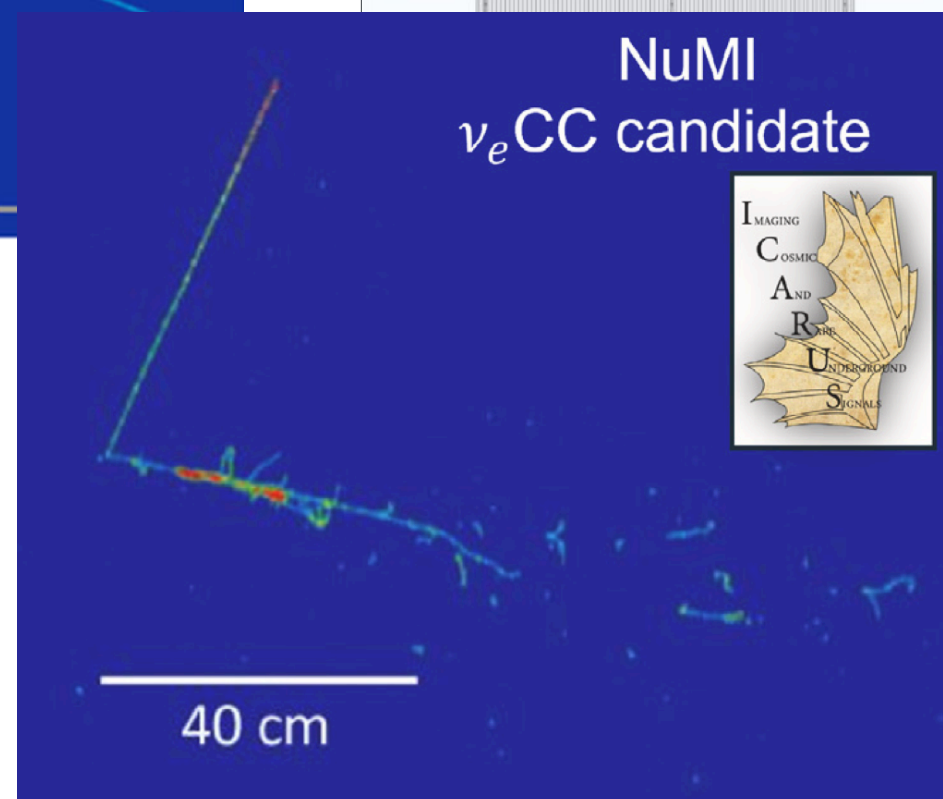
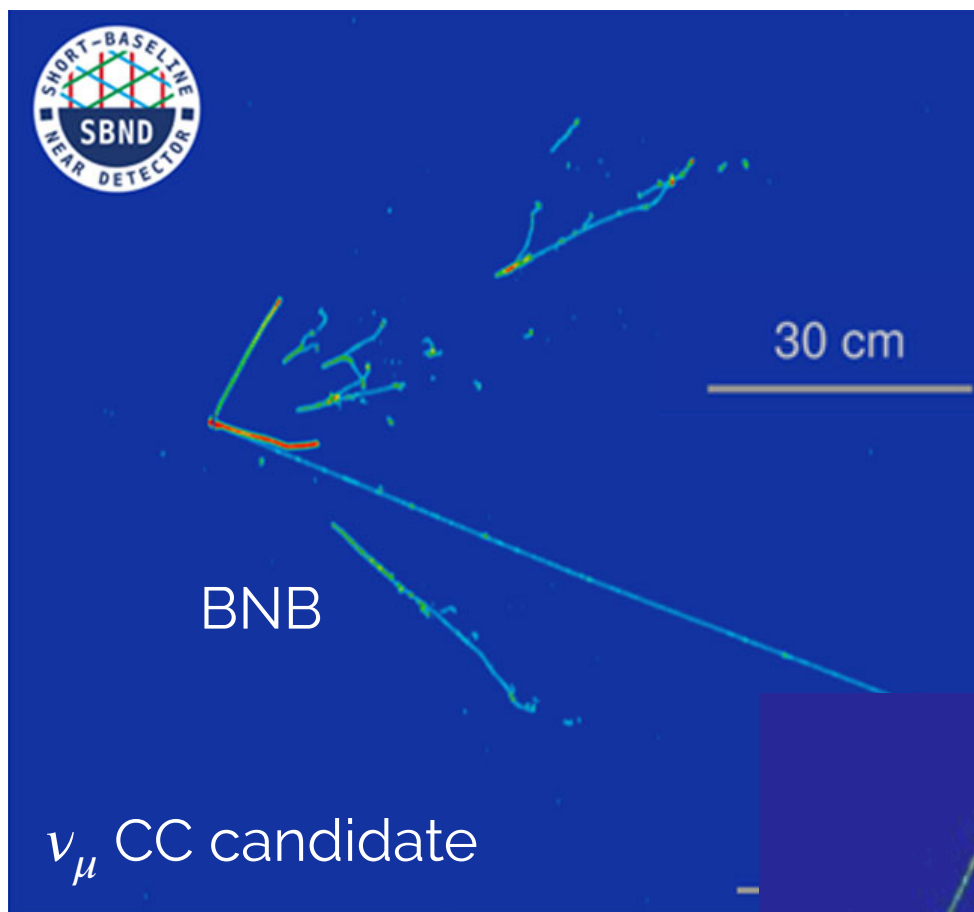
Although the 3+1 framework no longer provides a viable explanation, **the LSND and MiniBooNE anomalies themselves haven't gone away.**

The reactor and gallium anomalies also remain unresolved.

These anomalies continue to drive a global program of current and next-generation experiments aimed at resolving the remaining possibilities.



** Not an exhaustive list*



Short-Baseline Neutrino Program at Fermilab

Target

SBND
2024 -

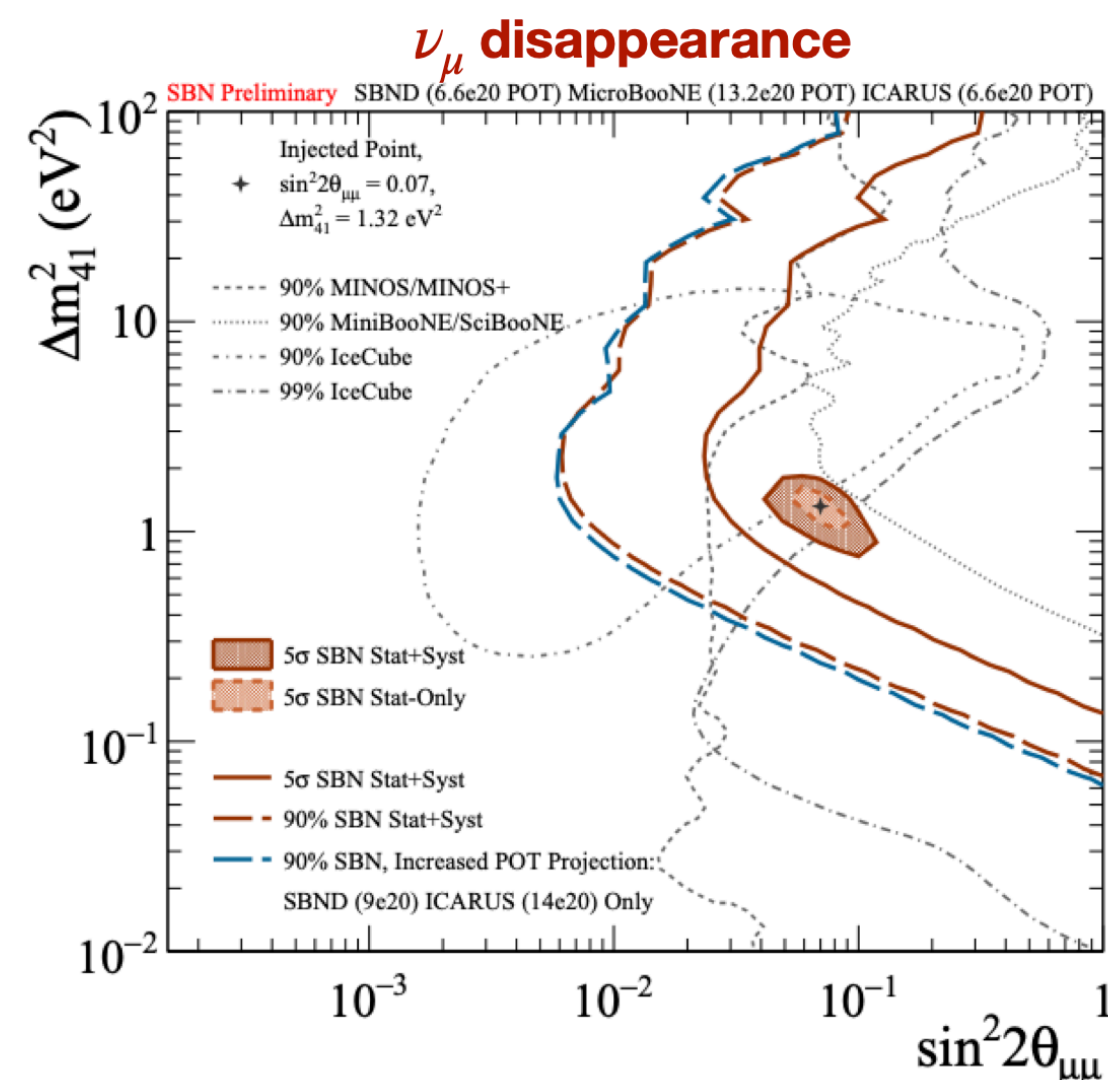
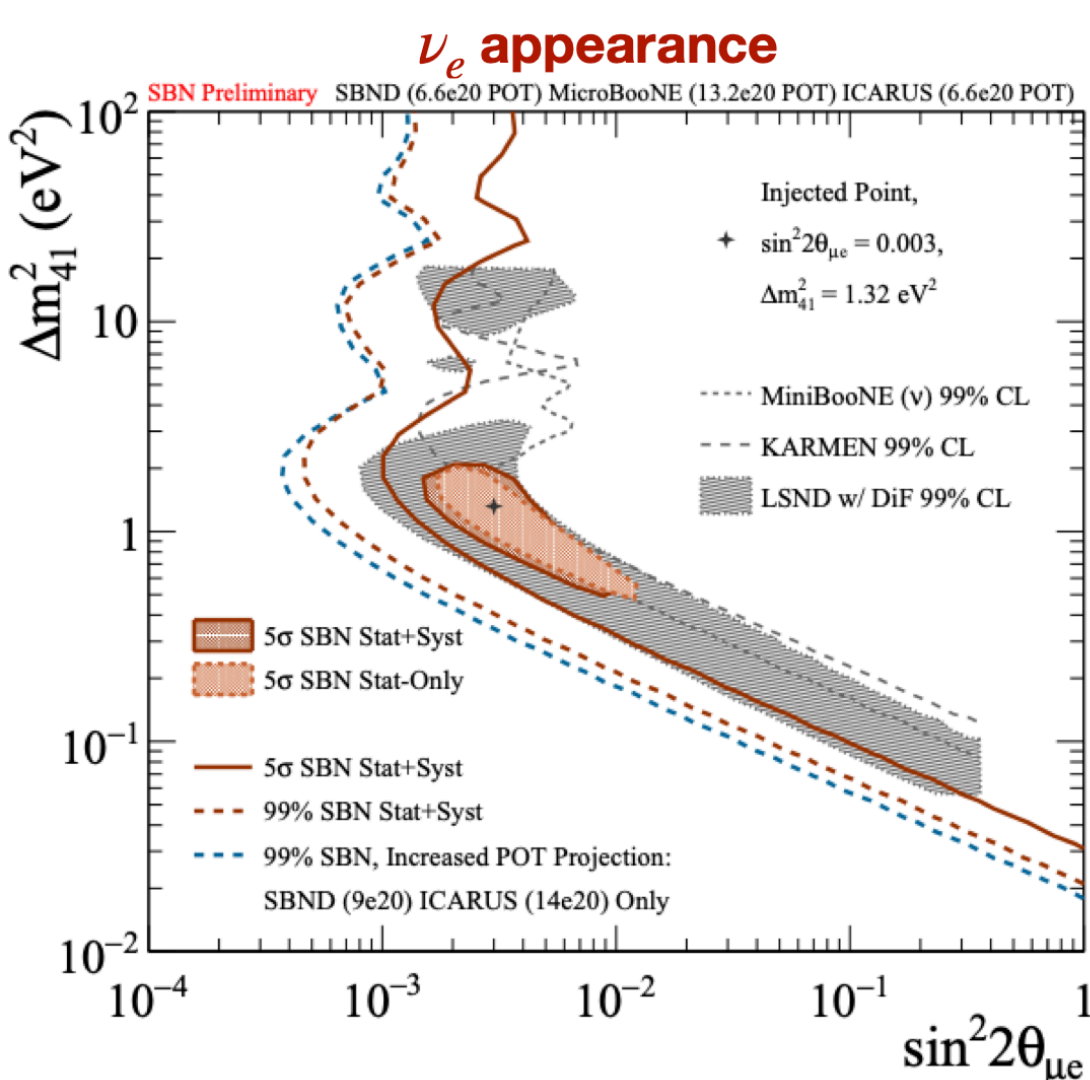
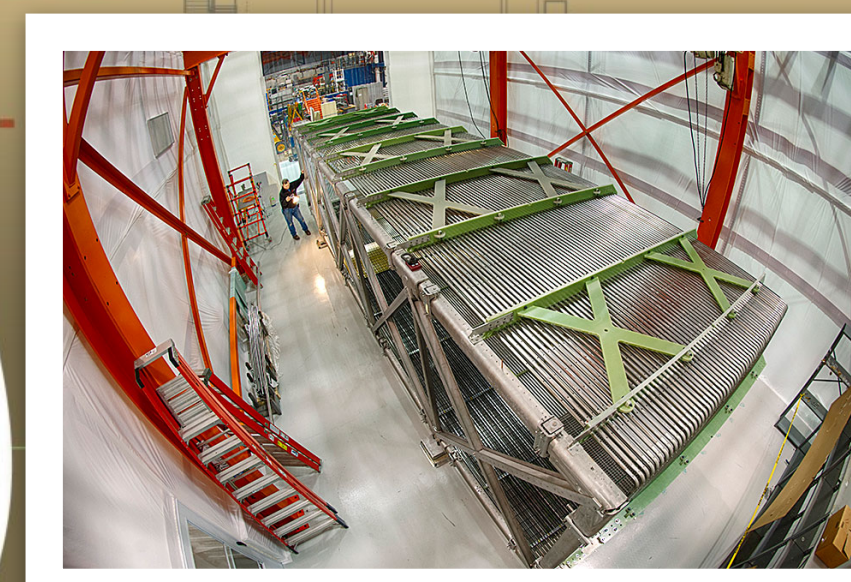
MicroBooNE
2015 - 2021

ICARUS
2020 -

110 m

470 m

600 m



The current **Short-Baseline Neutrino (SBN) Program** at Fermilab extends MicroBooNE with **two additional near and far LArTPC detectors**, expected to provide a **more comprehensive and sensitive exploration** of light sterile neutrinos and other BSM physics.

Outlook: other possible explanations

to account for LSND/MiniBooNE anomalies and ease tensions across datasets

- **Expanded sterile neutrino models**

- ❖ **3 active plus 2 or more sterile flavors**

Phys. Rev. D 84 (2011) 073008

- ❖ **3 + 1 + Non-Standard Interactions**

Phys. Rev. D 99 (2019) 015016

- ❖ **3 + 1 + Decay**

Phys. Rev. D 97 (2018) 055017

- ❖ **3 + 1 + Decoherence**

Phys. Rev. D 107 (2023) 036004

- ❖ **3 + 1 + Resonance Matter Effects**

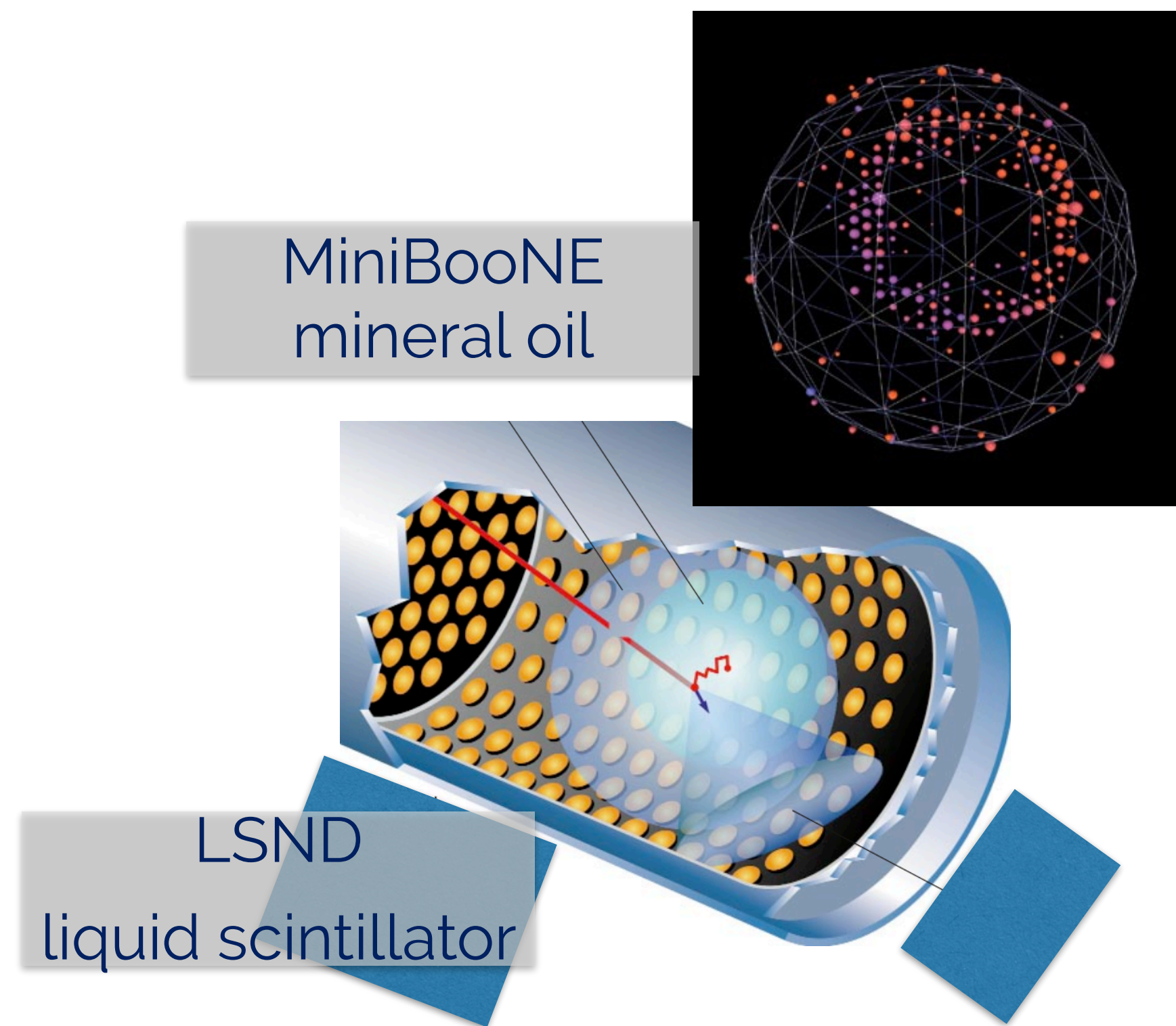
JHEP 08 (2022) 034

** Not an exhaustive list*

Outlook: other possible explanations

to account for LSND/MiniBooNE anomalies and ease tensions across datasets

- **Expanded sterile neutrino models**
- **Non-oscillation physics**
 - photon final state



**Electromagnetic
signature in the
excess events**

Oscillated ν_e

ν_e e^-

Photons

$\gamma \rightarrow e^+e^-$

Outlook: other possible explanations

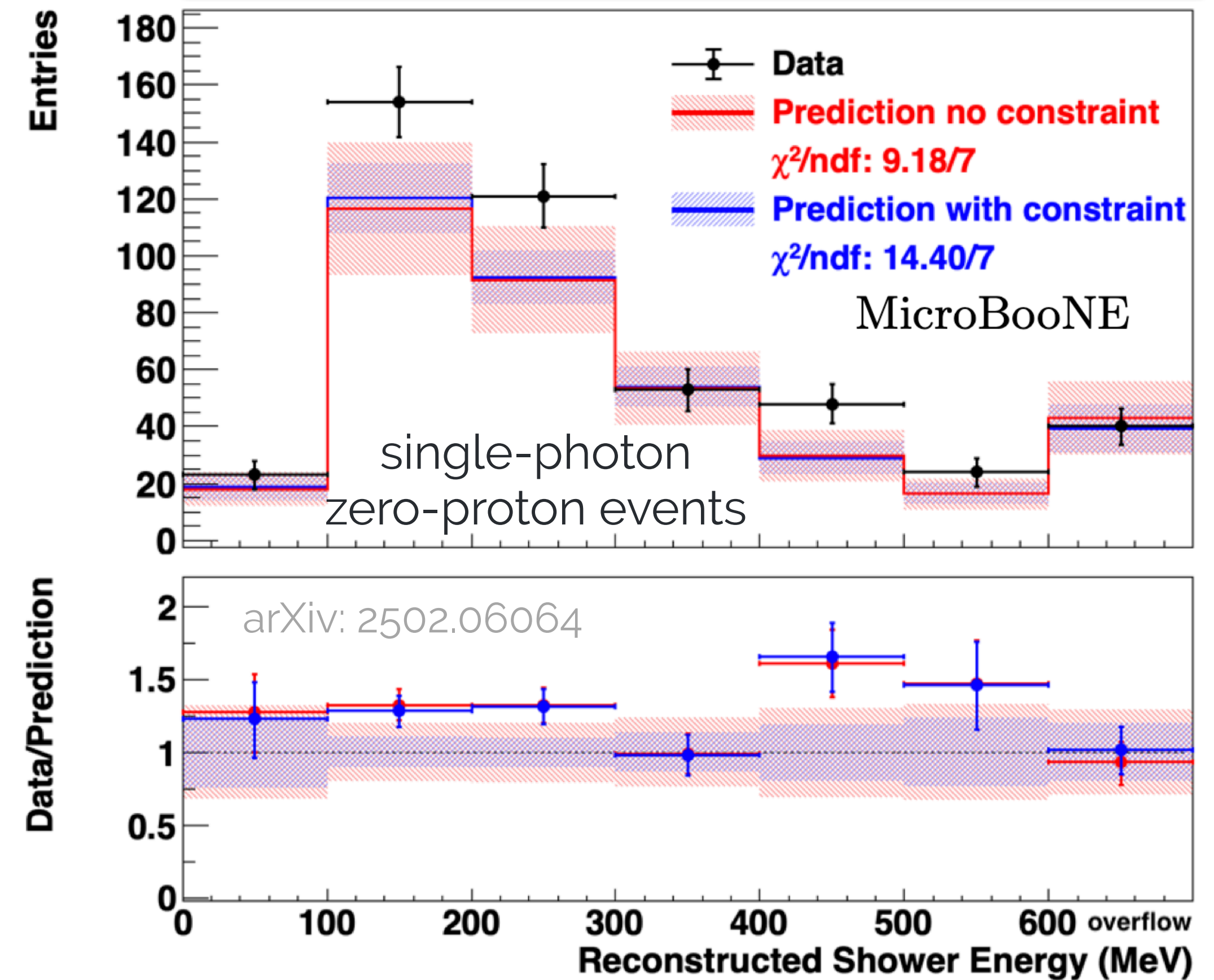
to account for LSND/MiniBooNE anomalies and ease tensions across datasets

- **Expanded sterile neutrino models**
- **Non-oscillation physics**
 - photon final state
 - NC Δ radiative single photon
 - no excess PRD 112 (2025) Log1101 (MicroBooNE)
 - NC coherent single photon
 - no excess arXiv:2502.06091 (MicroBooNE)
 - Model-agnostic inclusive single photon
 - $\sim 2\sigma$ excess in zero-proton events

arXiv: 2502.06064 (MicroBooNE)

**Motivates further investigations
in MicroBooNE and SBN**

MicroBooNE's inclusive photon search



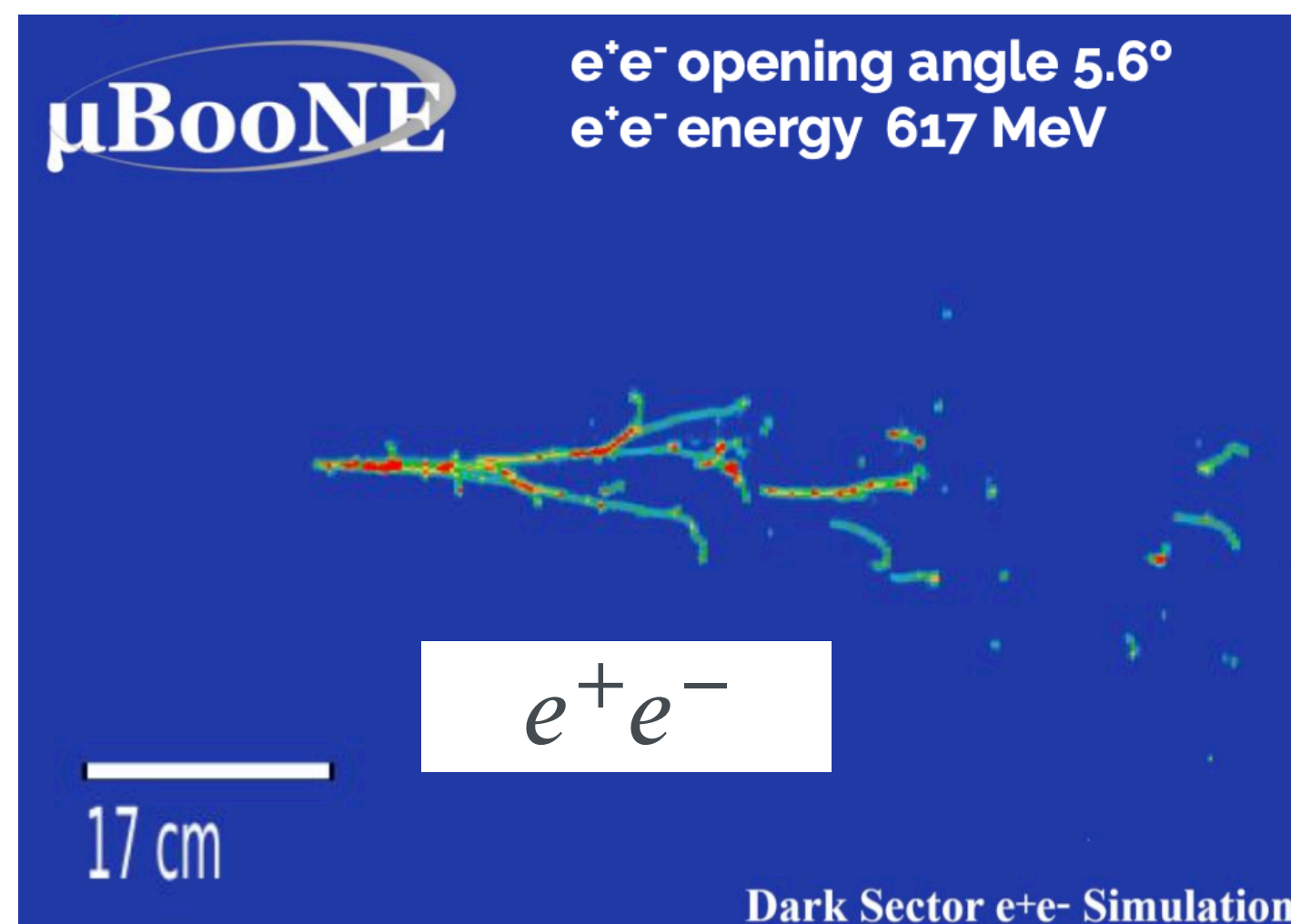
Outlook: other possible explanations

to account for LSND/MiniBooNE anomalies and ease tensions across datasets

- **Expanded sterile neutrino models**

- **Non-oscillation physics**

- photon final state (SM or model-agnostic)
- e^+e^- or photon final state from broader “dark sector” models



- ❖ **Neutrino-induced upscattering**

- ❖ $\nu A \rightarrow NA$ where $N \rightarrow \nu e^+e^-$ or $\nu\gamma(\gamma)$

- ❖ **Heavy ν decay**

- ❖ $N \rightarrow \nu\gamma, N \rightarrow \nu X (X \rightarrow e^+e^- \text{ or } \gamma\gamma)$

- ❖ **Dark matter particle-induced upscattering**

- ❖ $\chi \rightarrow \gamma \text{ or } e^+e^-$

- ❖ ...

See the snowmass white paper

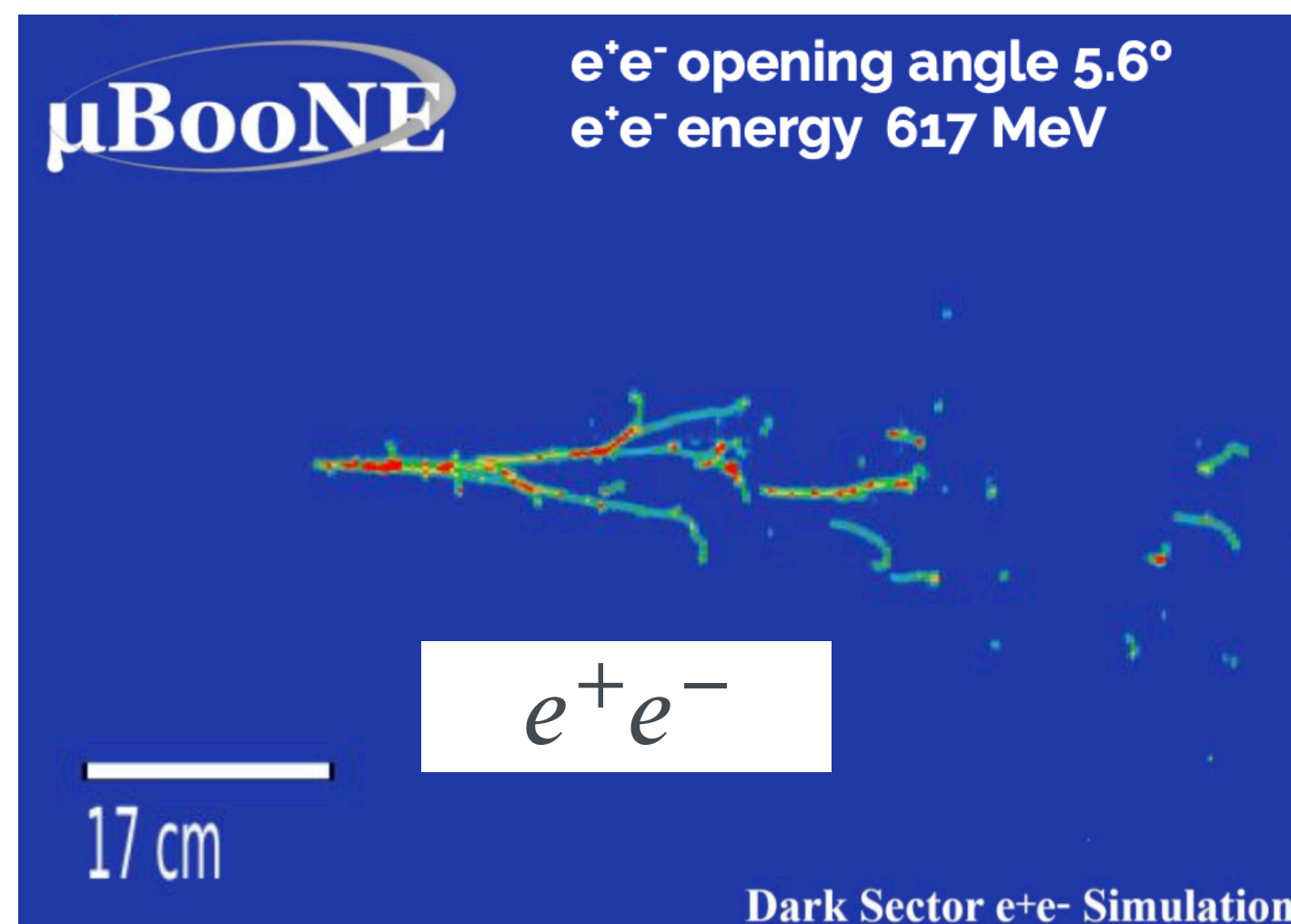
J. Phys. G: Nucl. Part. Phys. 51 120501

for a comprehensive overview and references

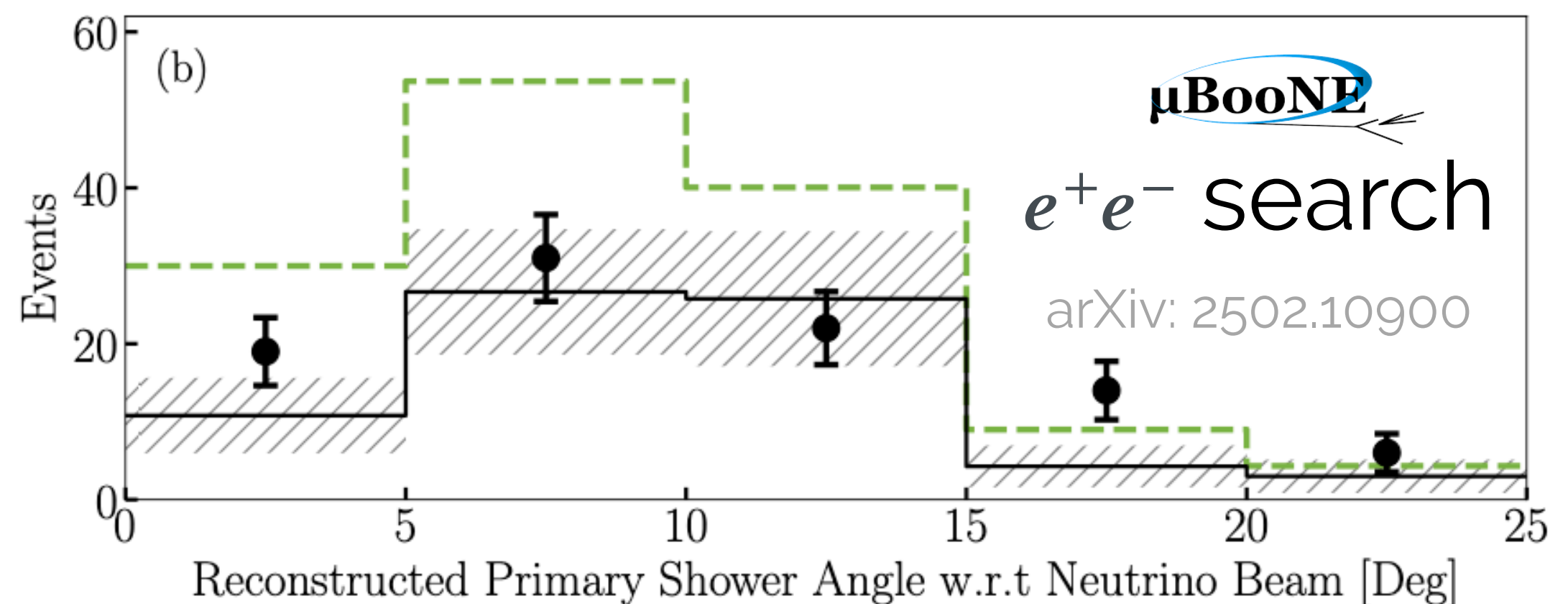
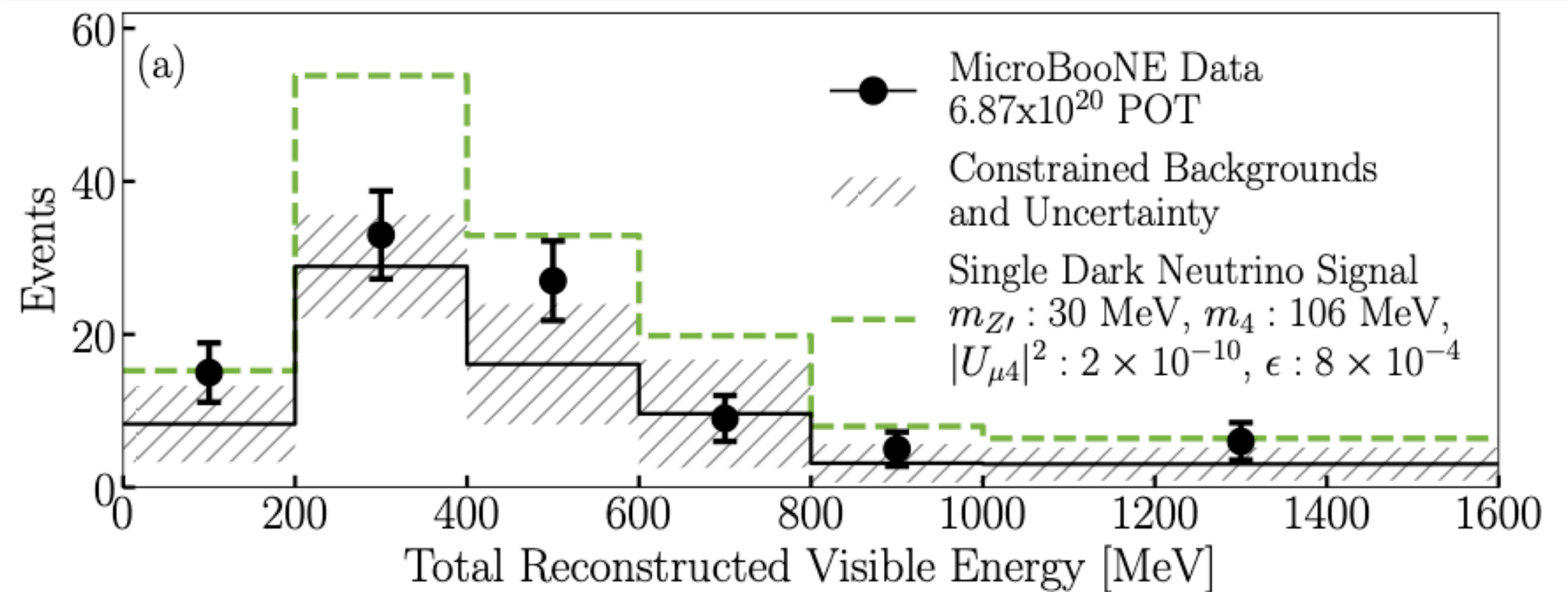
Outlook: other possible explanations

to account for LSND/MiniBooNE anomalies and ease tensions across datasets

- **Expanded sterile neutrino models**
- **Non-oscillation physics**
 - photon final state (SM or model-agnostic)
 - e^+e^- or photon final state from broader “dark sector” models

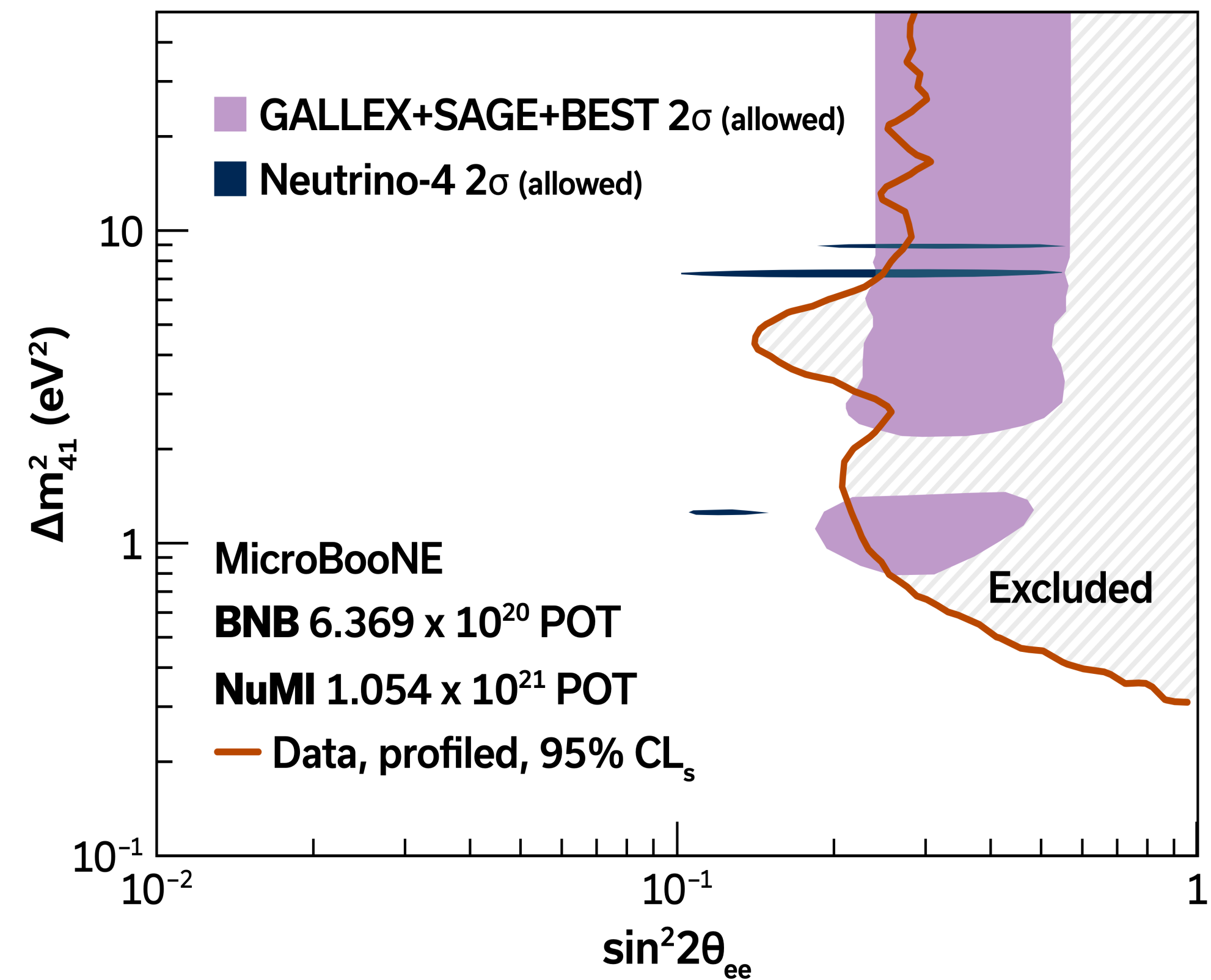
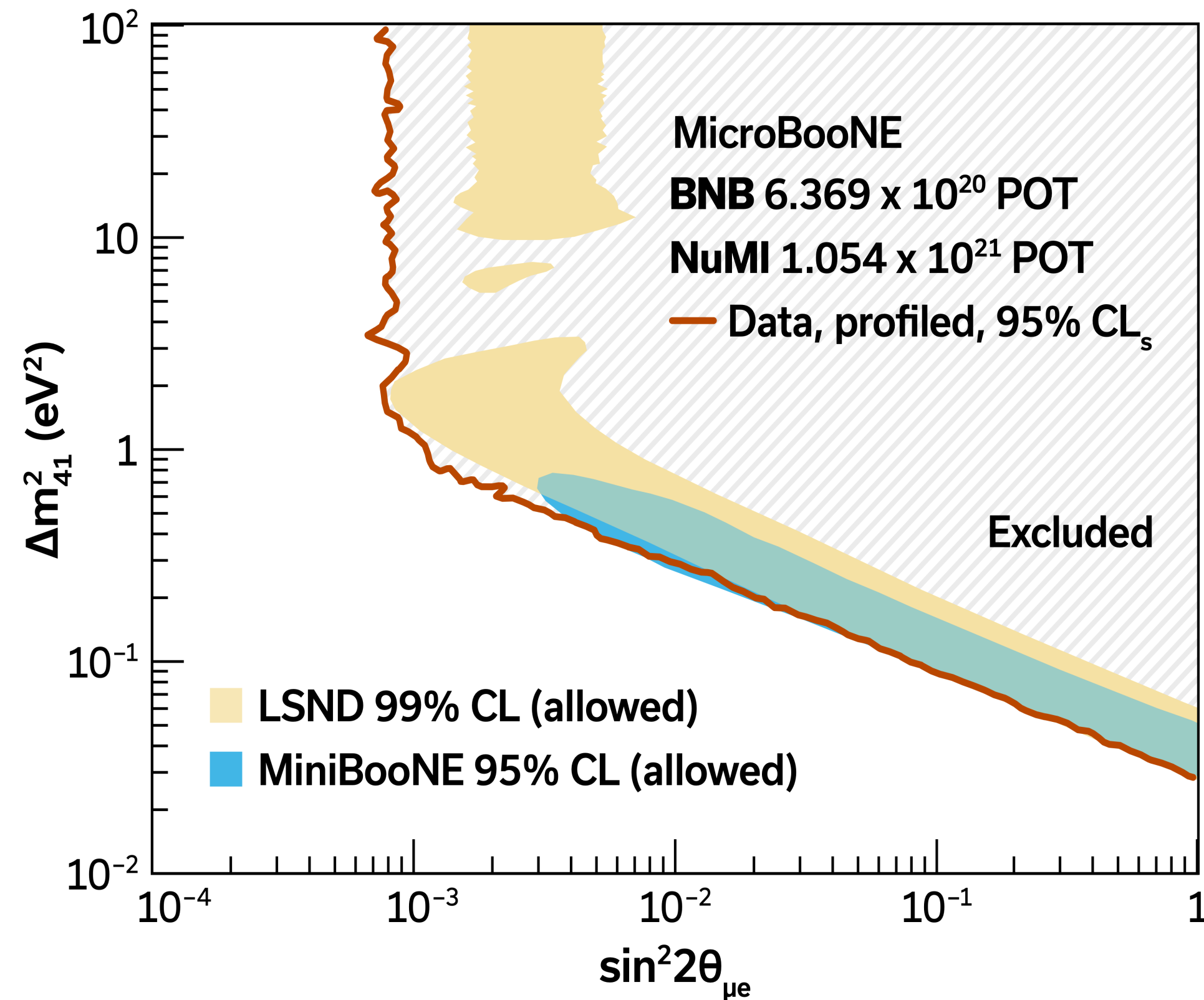


World's first direct search for a dark sector e^+e^- signal as a test of the MiniBooNE anomaly



More dark-sector scenarios remain compelling targets for MicroBooNE and SBN

Search for Light Sterile Neutrinos with Two Neutrino Beams at MicroBooNE



Using the first two-beam, one-detector search of its kind, MicroBooNE sees no sign of sterile-neutrino-induced oscillations in the relevant L/E regime, closing the 3+1 window associated with the anomalies. With this chapter settled, the path is open for new ideas and discoveries in future theoretical and experimental efforts. Stay tuned!

Final remark: Overcoming challenges

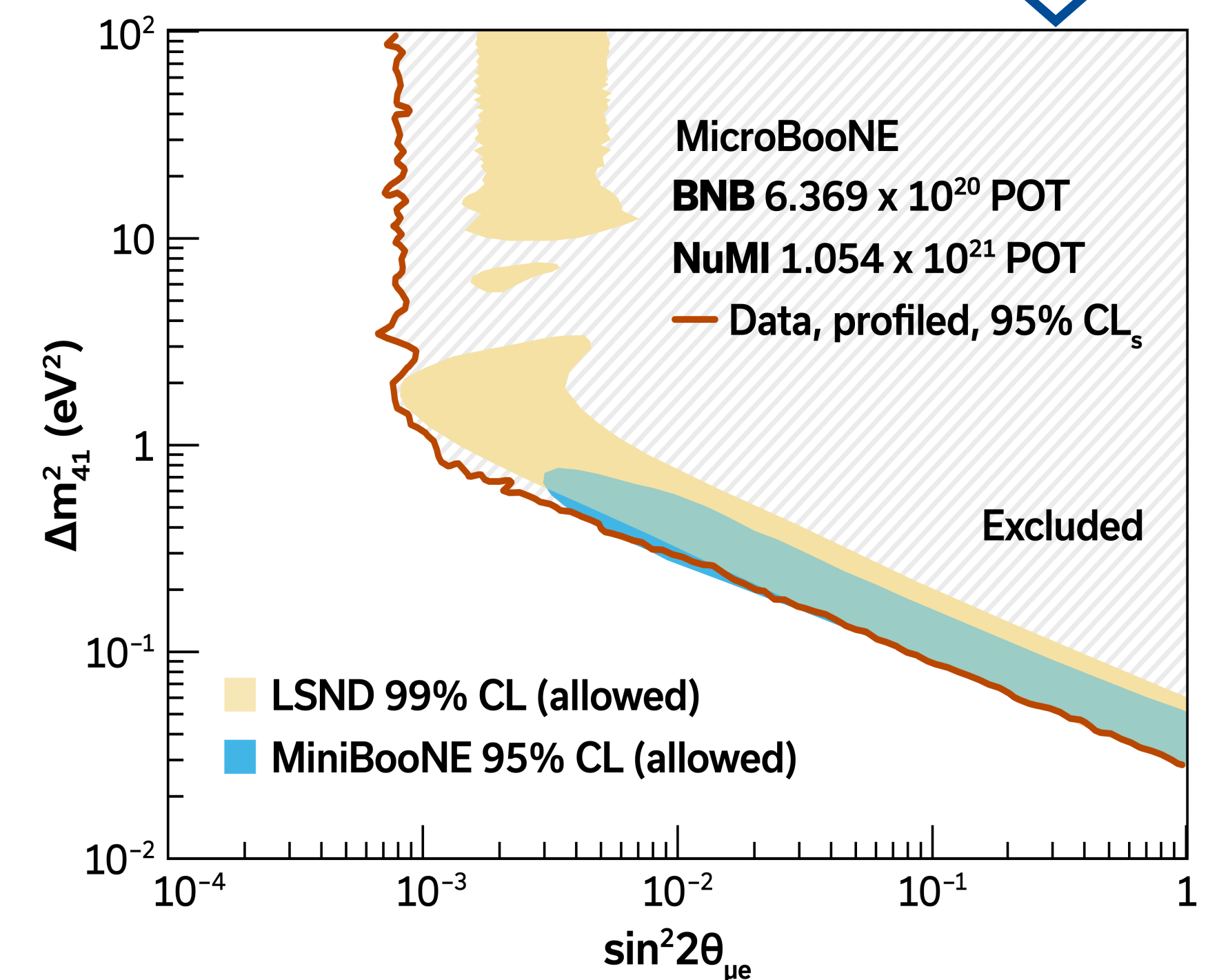
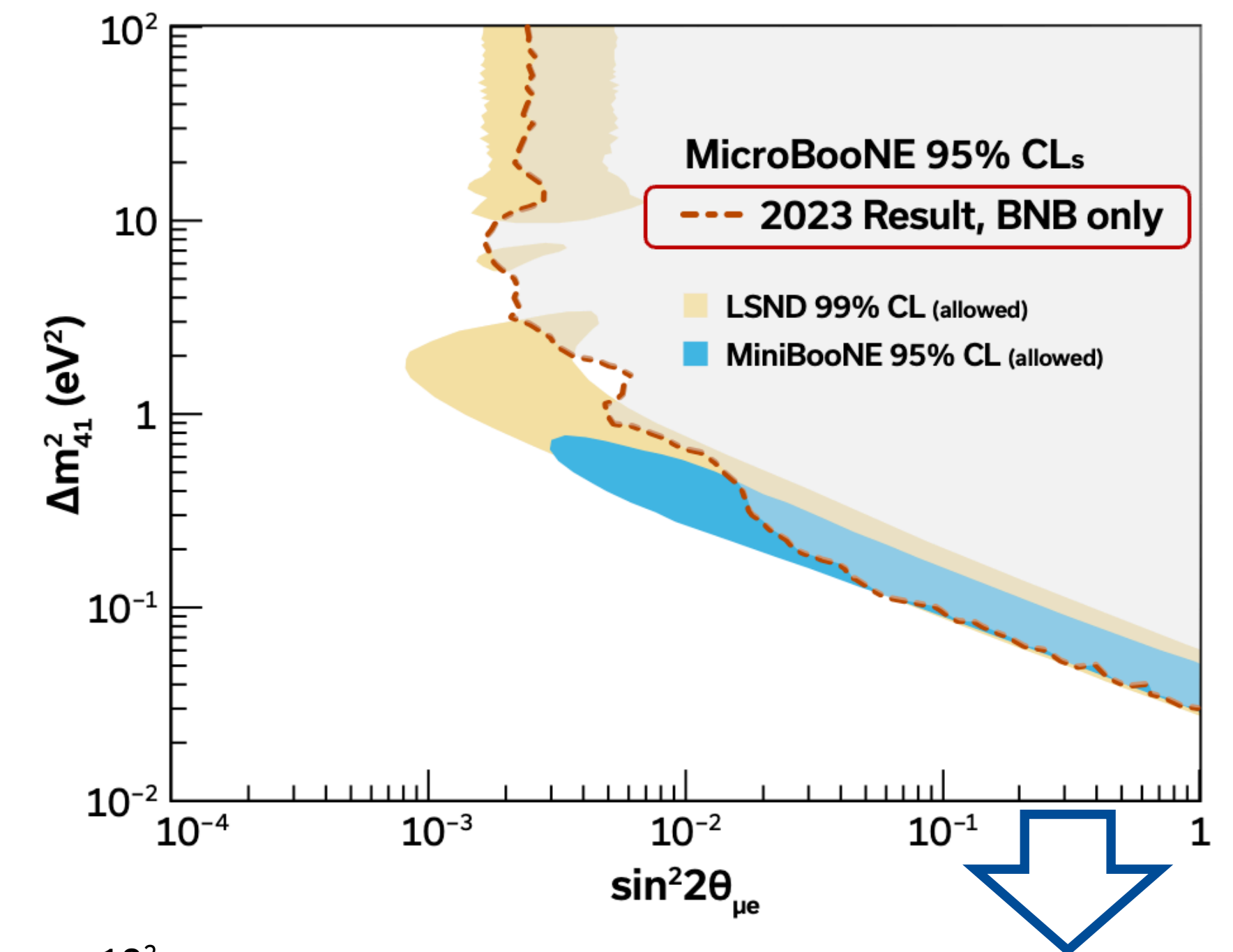
Congratulations everyone!

A typical criticism of MicroBooNE is that it's small compared to MiniBooNE and not easy to reject all phase space of MiniBooNE+LSND.

But you did it! I am impressed.

I do believe a little possibility MiniBooNE excess is an unknown photon production process, (either BSM or exciting nuclear physics) hopefully, SBND can say something for that!

Best,
Teppei





μ BooNE

Backup

Neutrino Energy Reconstruction

$$E_{\nu}^{rec} = \sum_i (K_i^{rec} + m_i + B_i)$$

Neutrino Energy

Neutrino Energy Reconstruction

reconstructed kinetic
energy

$$E_{\nu}^{rec} = \sum_i (K_i^{rec} + m_i + B_i)$$

Neutrino Energy

Neutrino Energy Reconstruction

reconstructed kinetic
energy

rest mass value from the PDG
[added for each $\mu^\pm, e^\pm, \pi^\pm$]

$$E_\nu^{rec} = \sum_i (K_i^{rec} + m_i + B_i)$$

Neutrino Energy

Neutrino Energy Reconstruction

reconstructed kinetic
energy

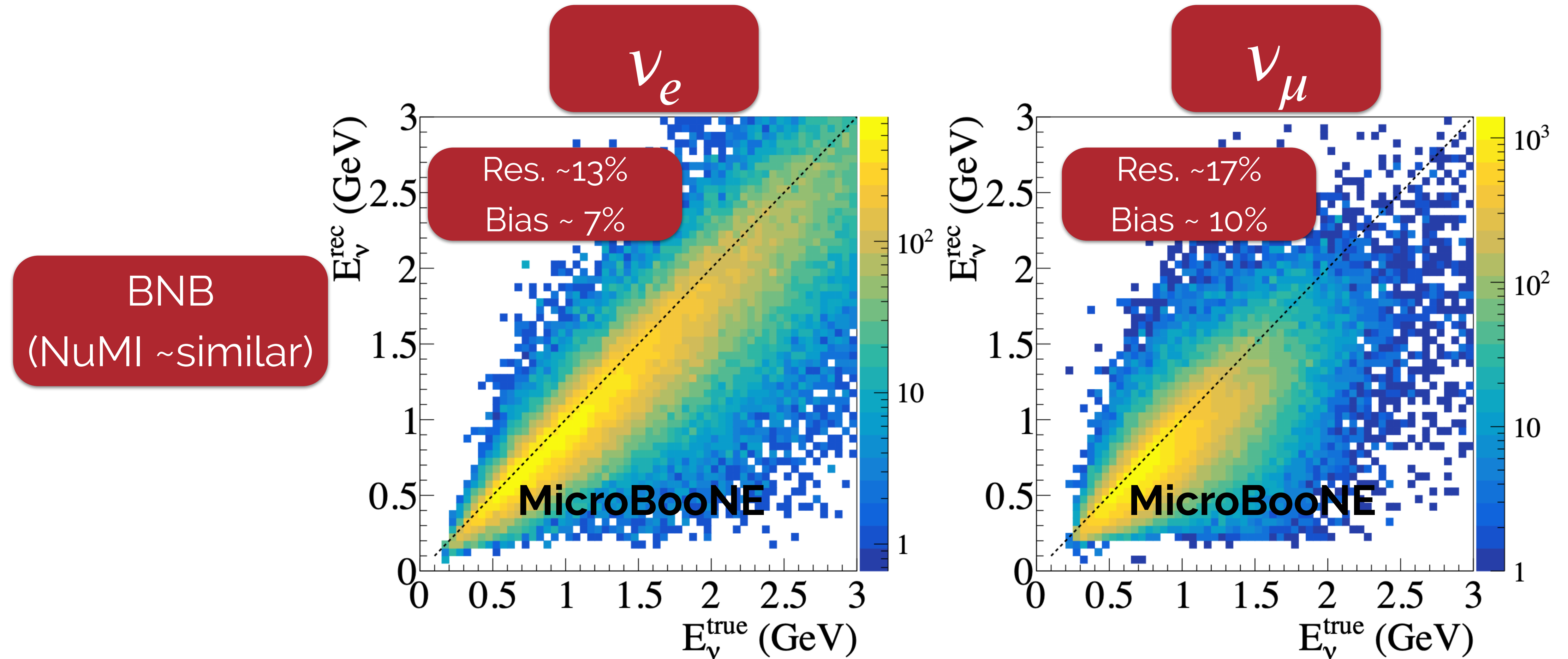
rest mass value from the PDG
[added for each $\mu^\pm, e^\pm, \pi^\pm$]

$$E_\nu^{rec} = \sum_i (K_i^{rec} + m_i + B_i)$$

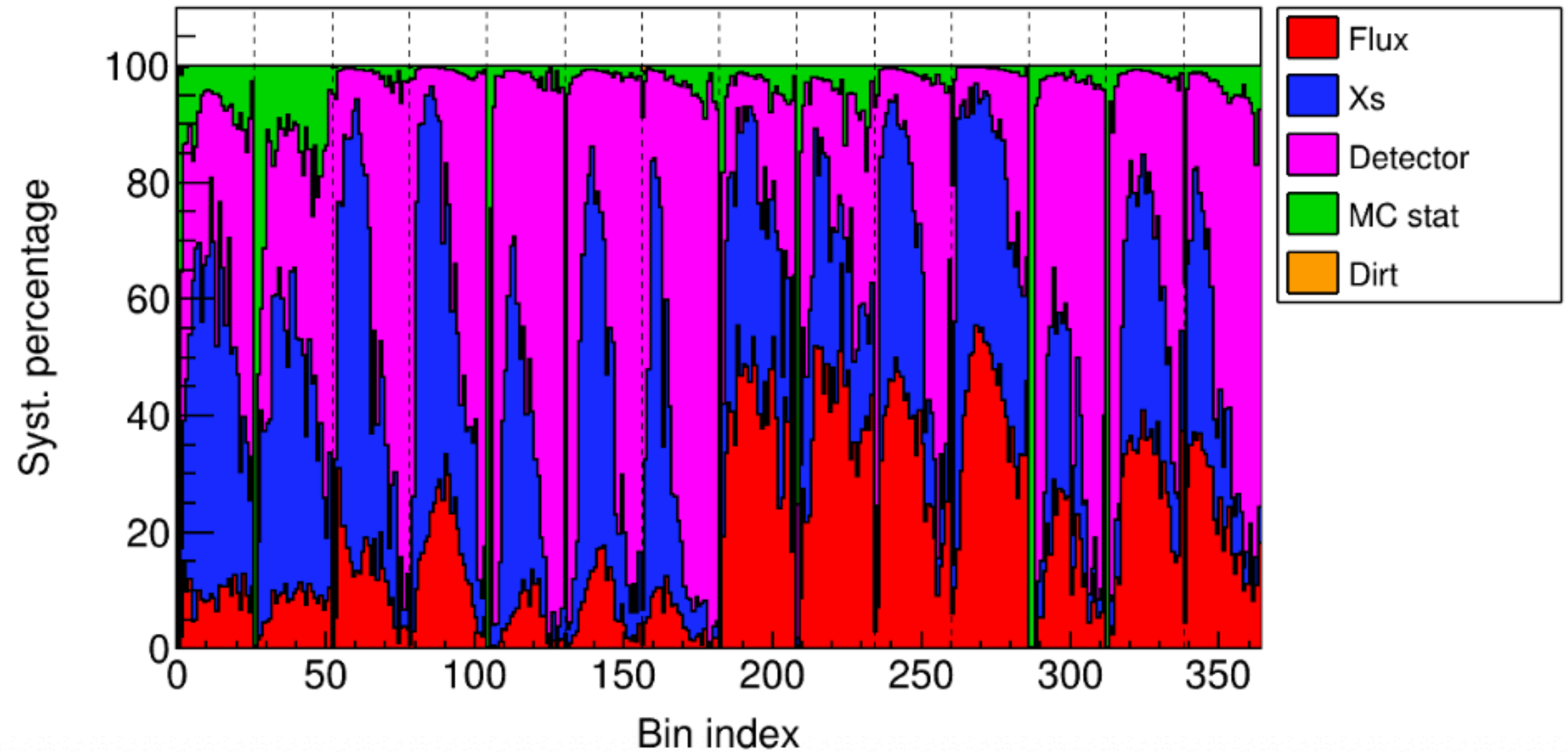
Neutrino Energy

average binding energy
(8.6 MeV) per nucleon
[added for each proton]

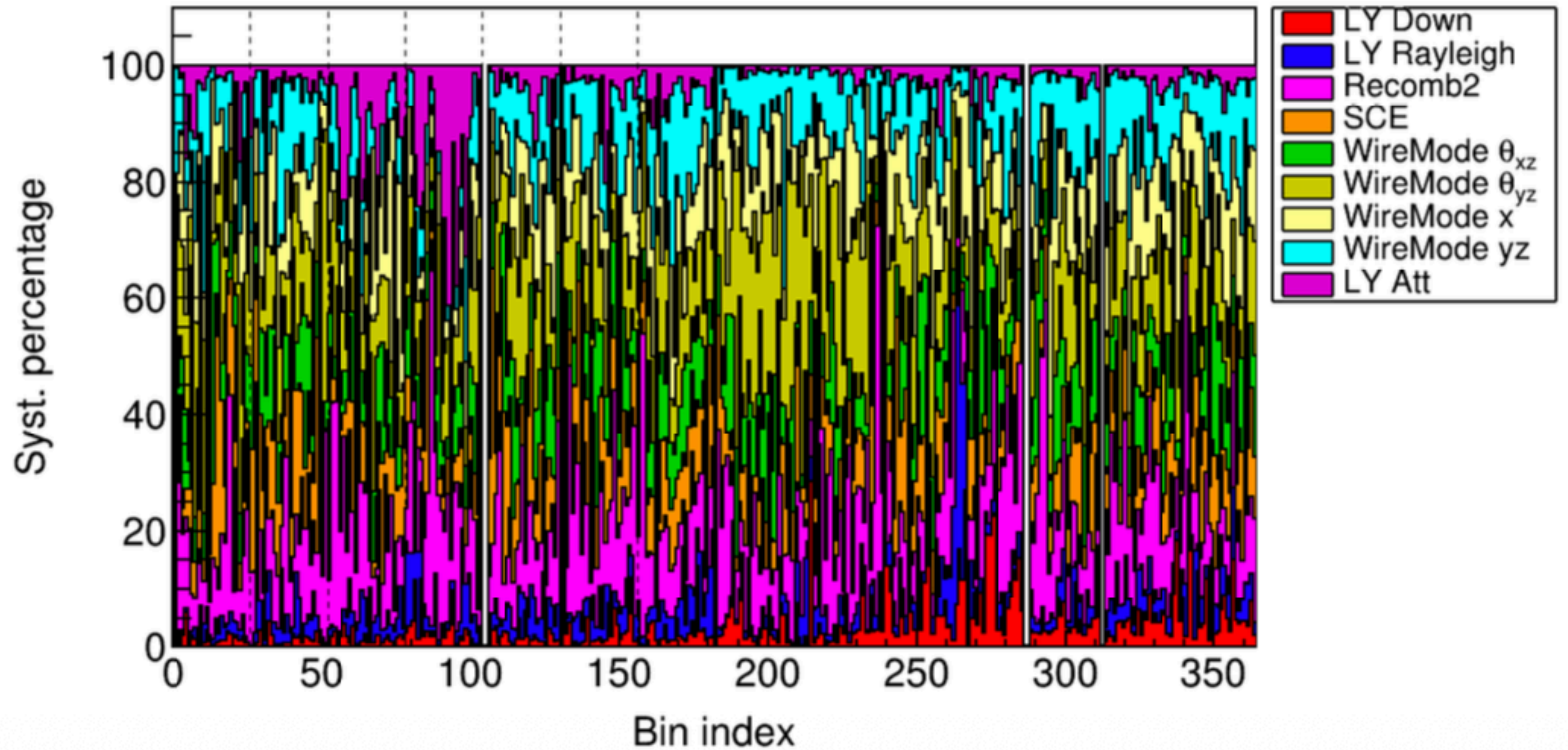
Performance



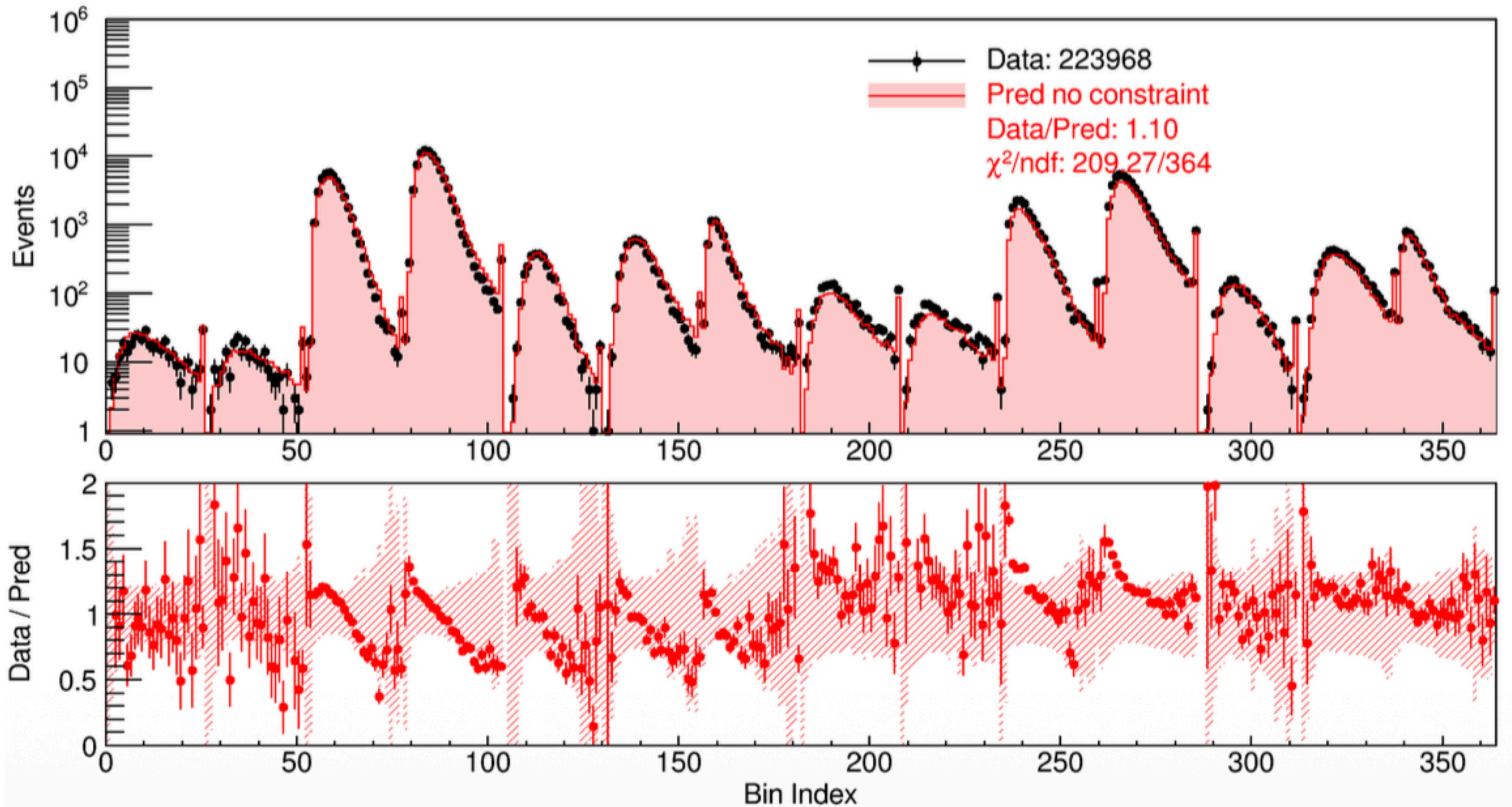
Systematics breakdown



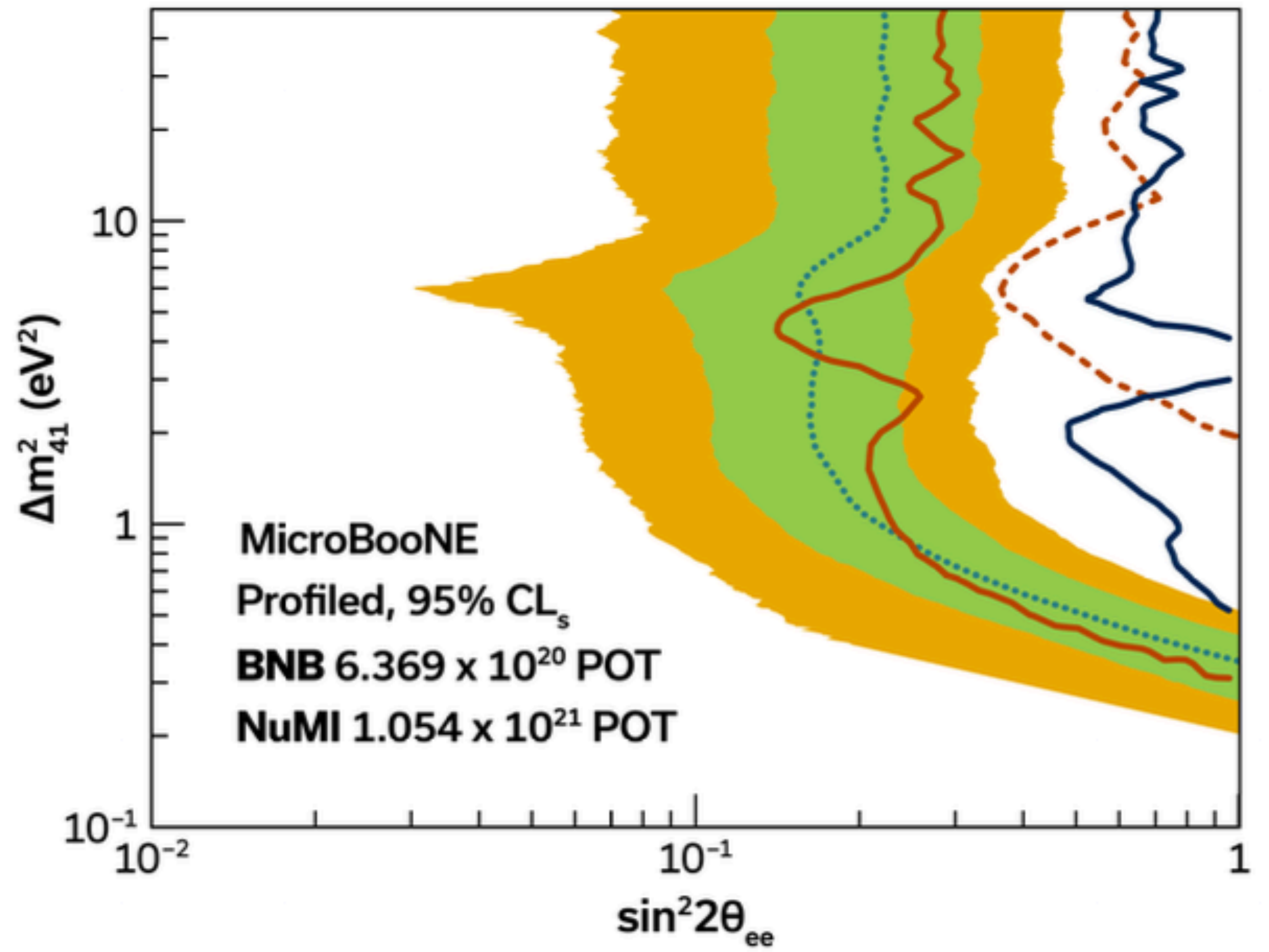
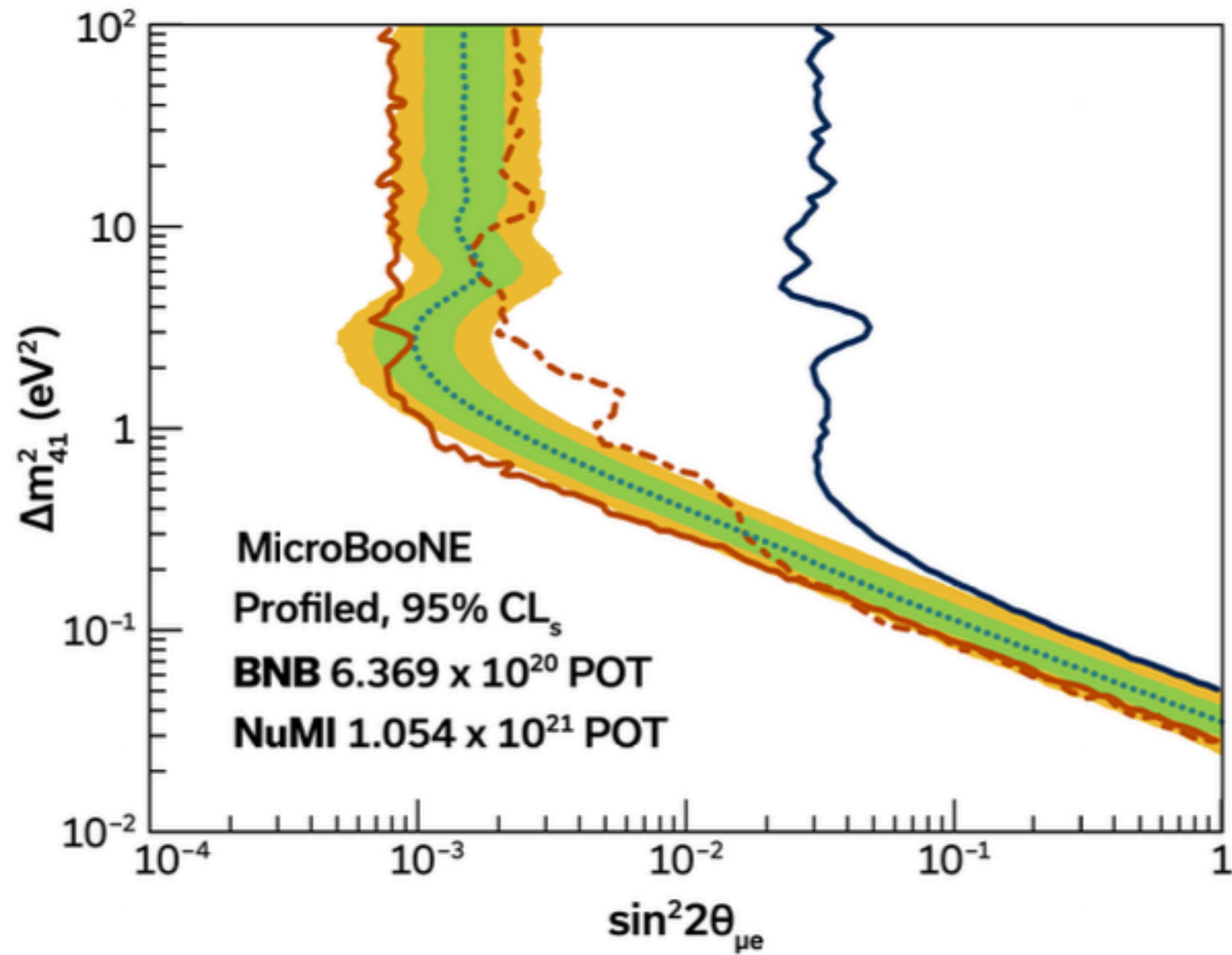
Detector systematics breakdown



Full 14 channels



NuMI-only result

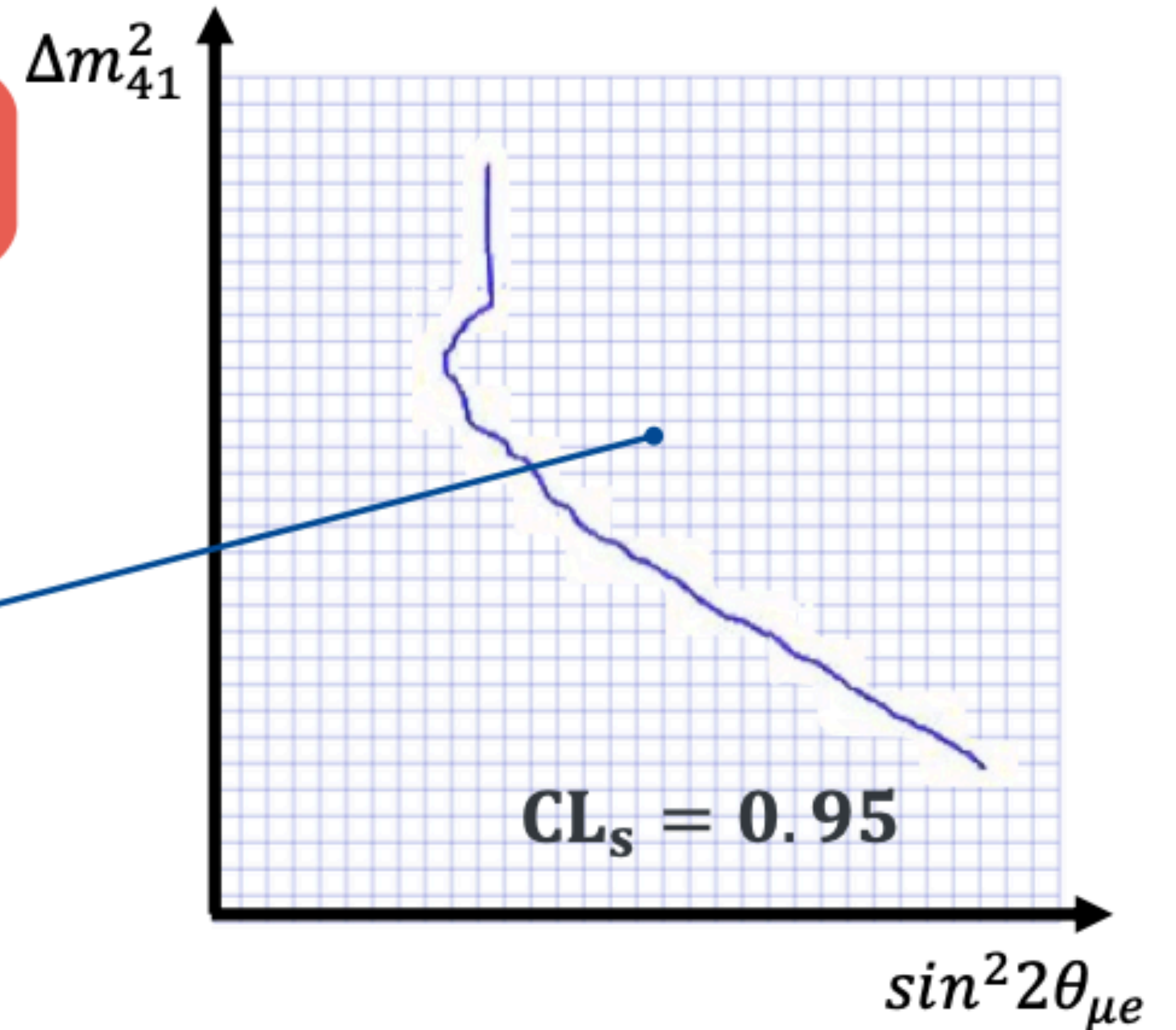
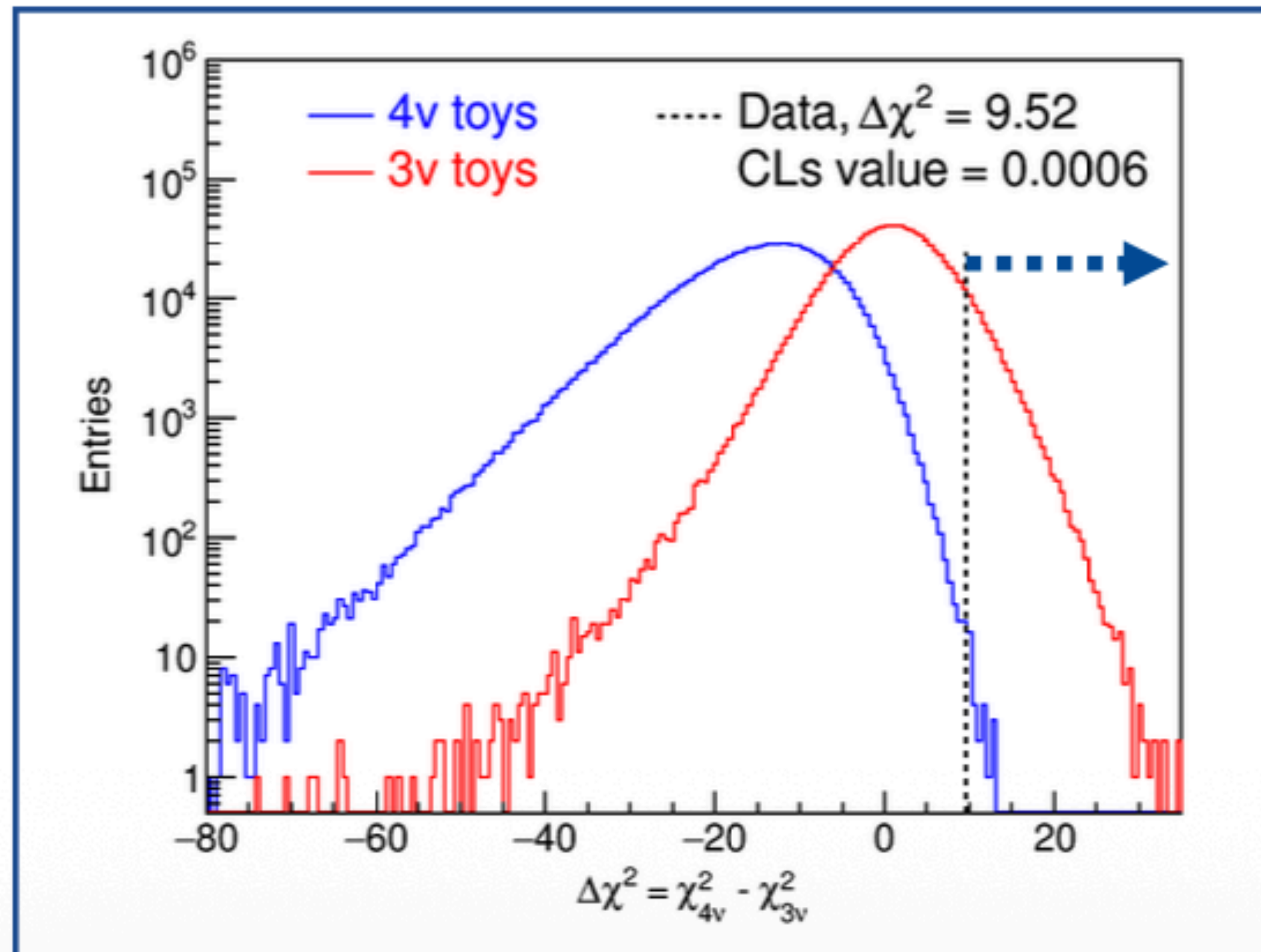


Setting limits with Frequentist CLs method

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

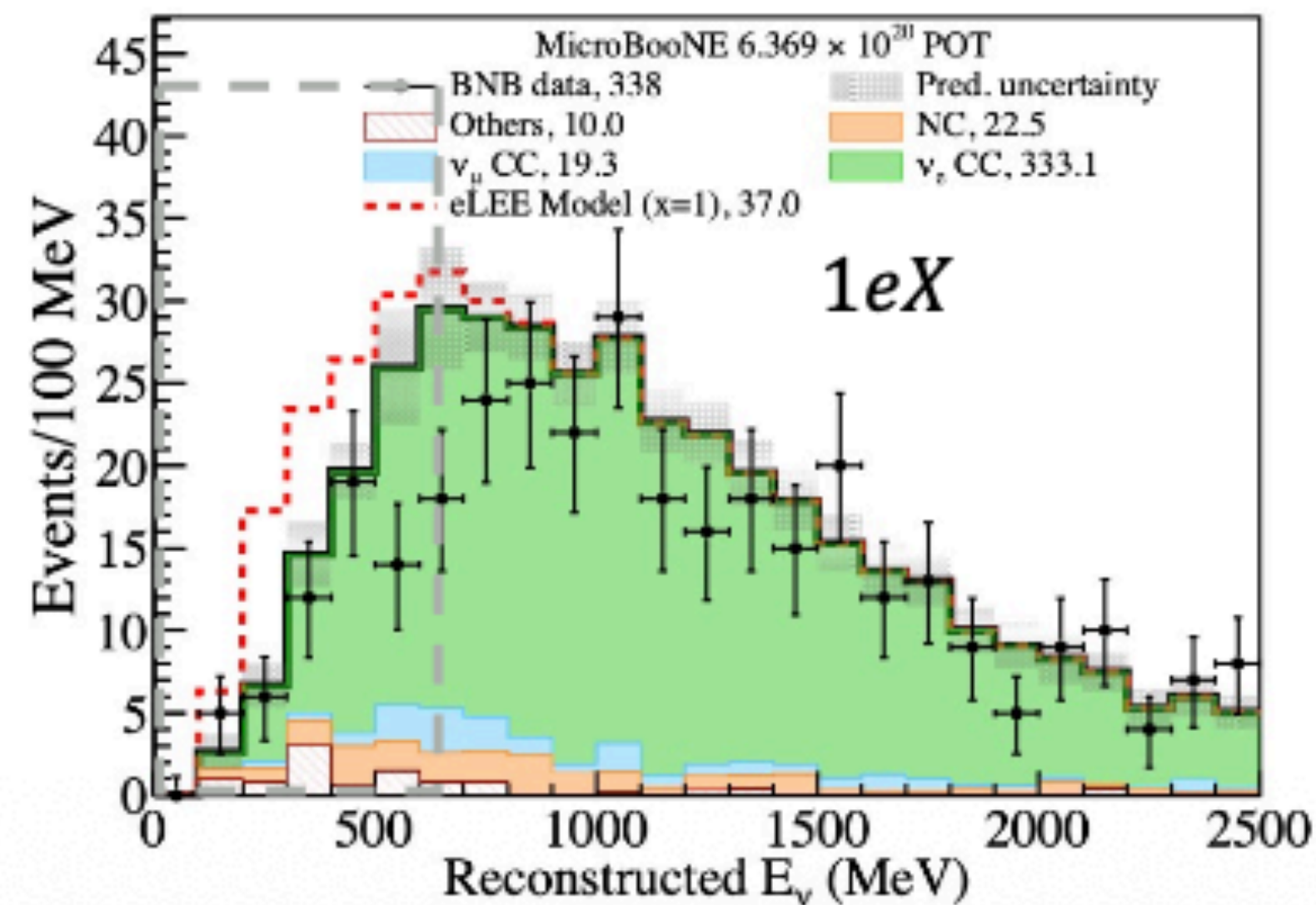
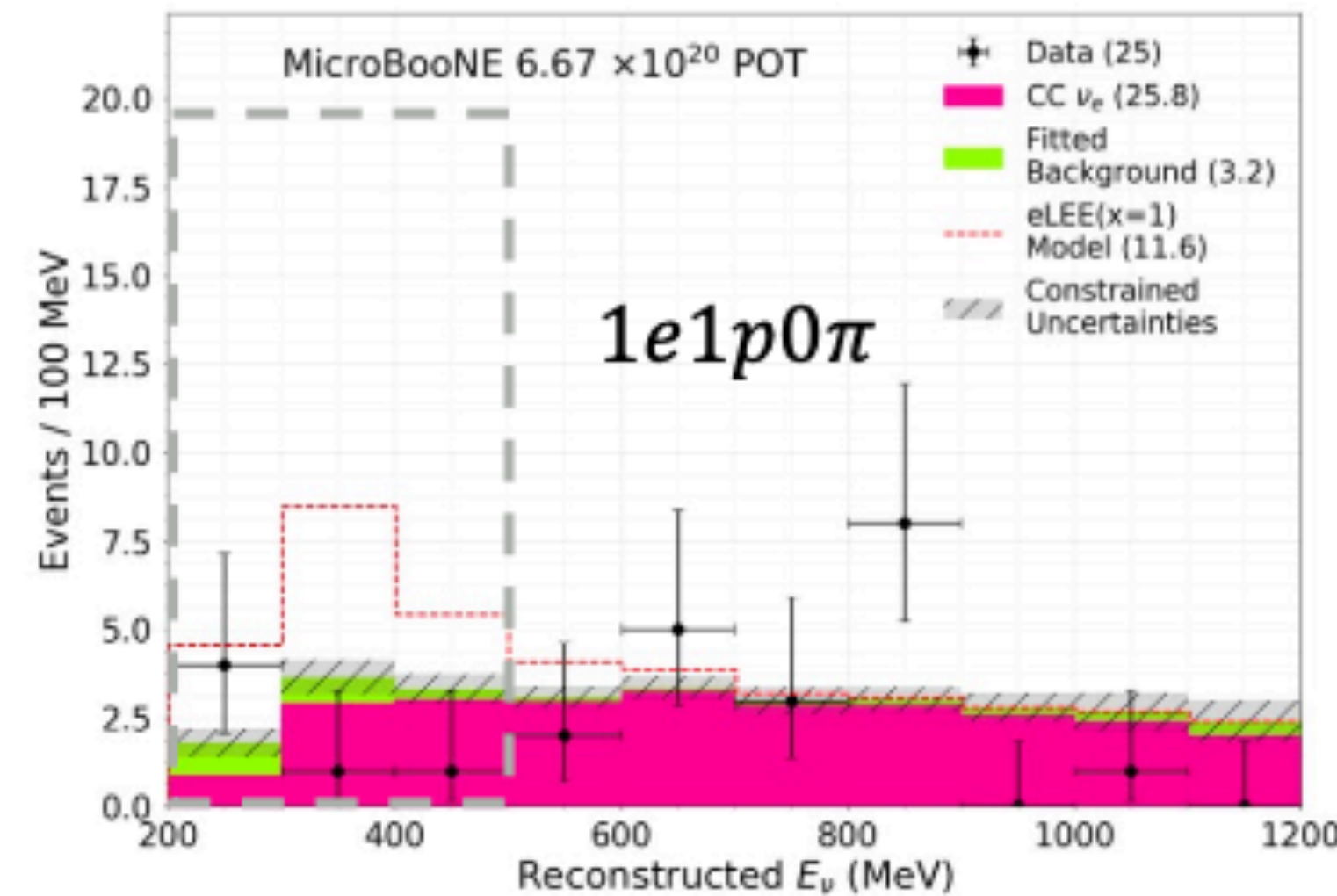
One-sided p-values of $\Delta\chi^2_{CL_s,data}$ under 4ν hypothesis

One-sided p-values of $\Delta\chi^2_{CL_s,data}$ under 3ν hypothesis

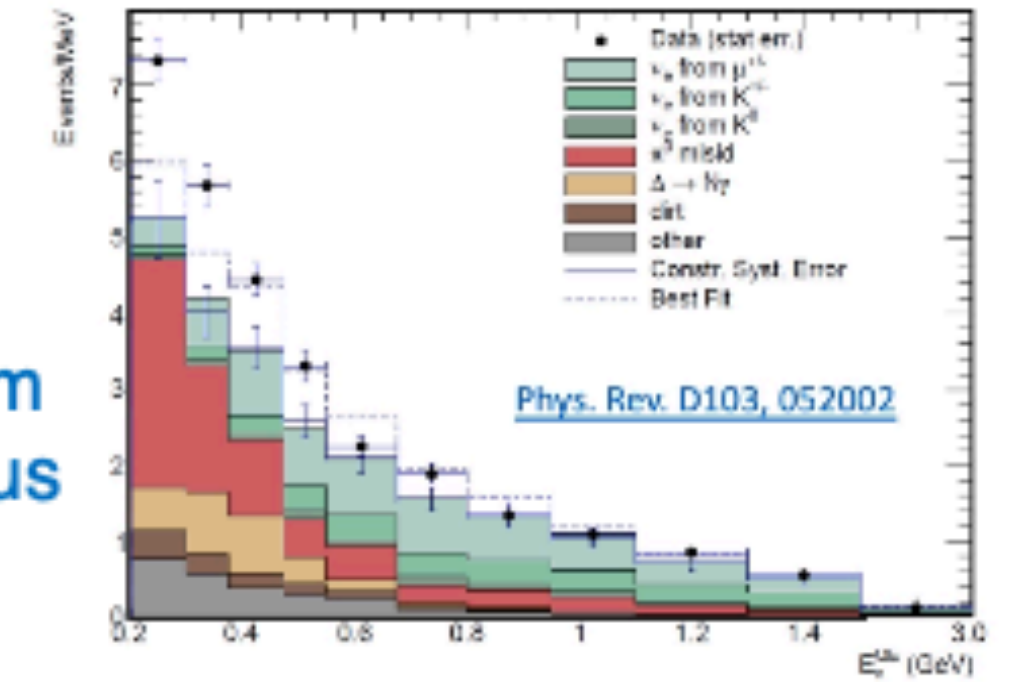


Low-energy excess ν_e template search

- No observation of ν_e excess
- Disfavor a pure ν_e source for the MiniBooNE anomalous low-energy excess at $\sim 3\sigma$ level
- **Solid foundation to the sterile neutrino search**
 - a rigorous unblinding procedure and mock data study
 - a high-performance ν_e reconstruction and selection



A template extracted from the MiniBooNE anomalous low-energy excess



PRL 128, 241801 (2022)
PRD 105, 112003, 112004, 112005 (2022)
PRL 135, 081802 (2025)

