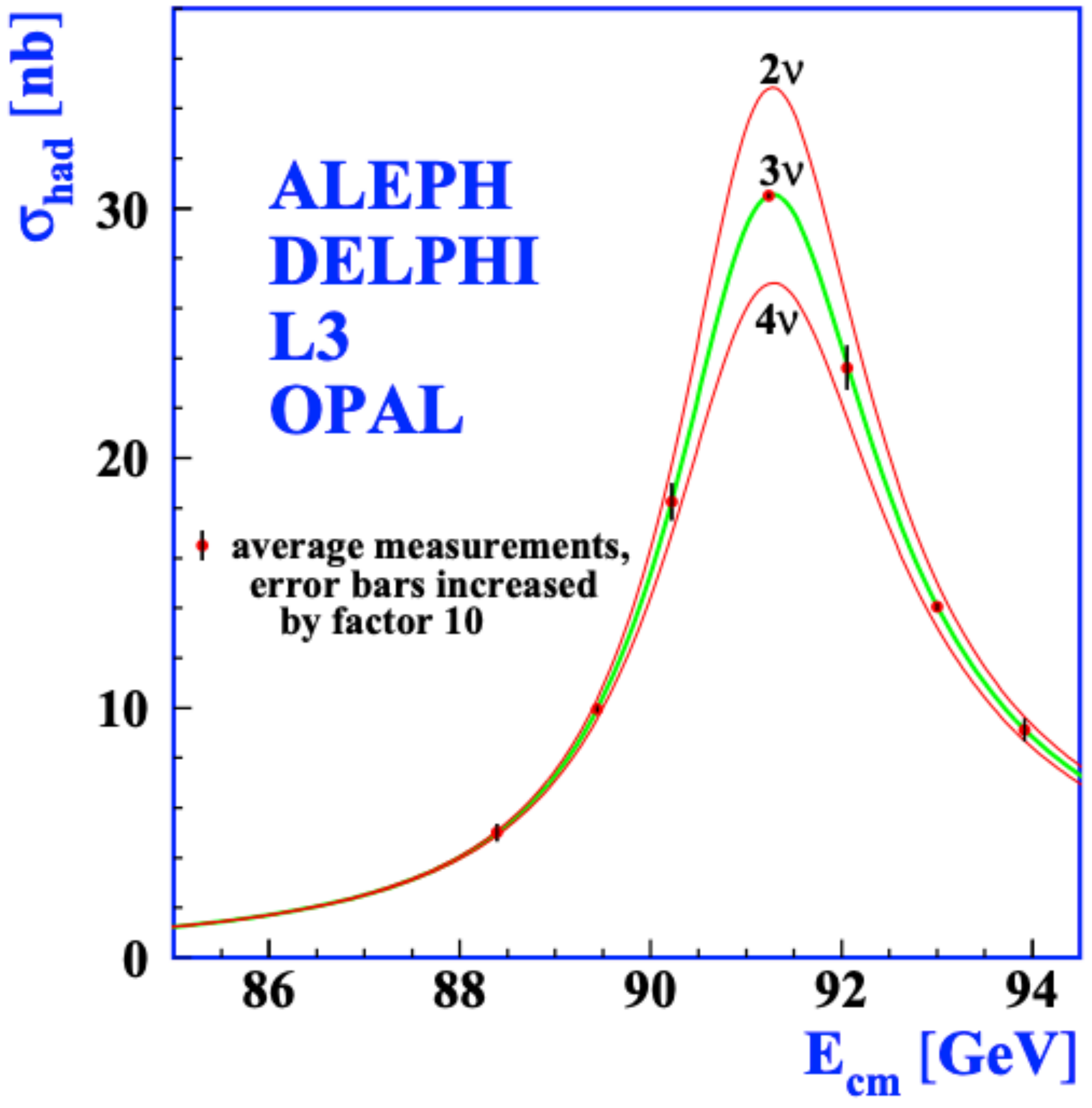
# Low Energy Excess Search and Constraints on eV-Scale Sterile Neutrino Oscillations at MicroBooNE

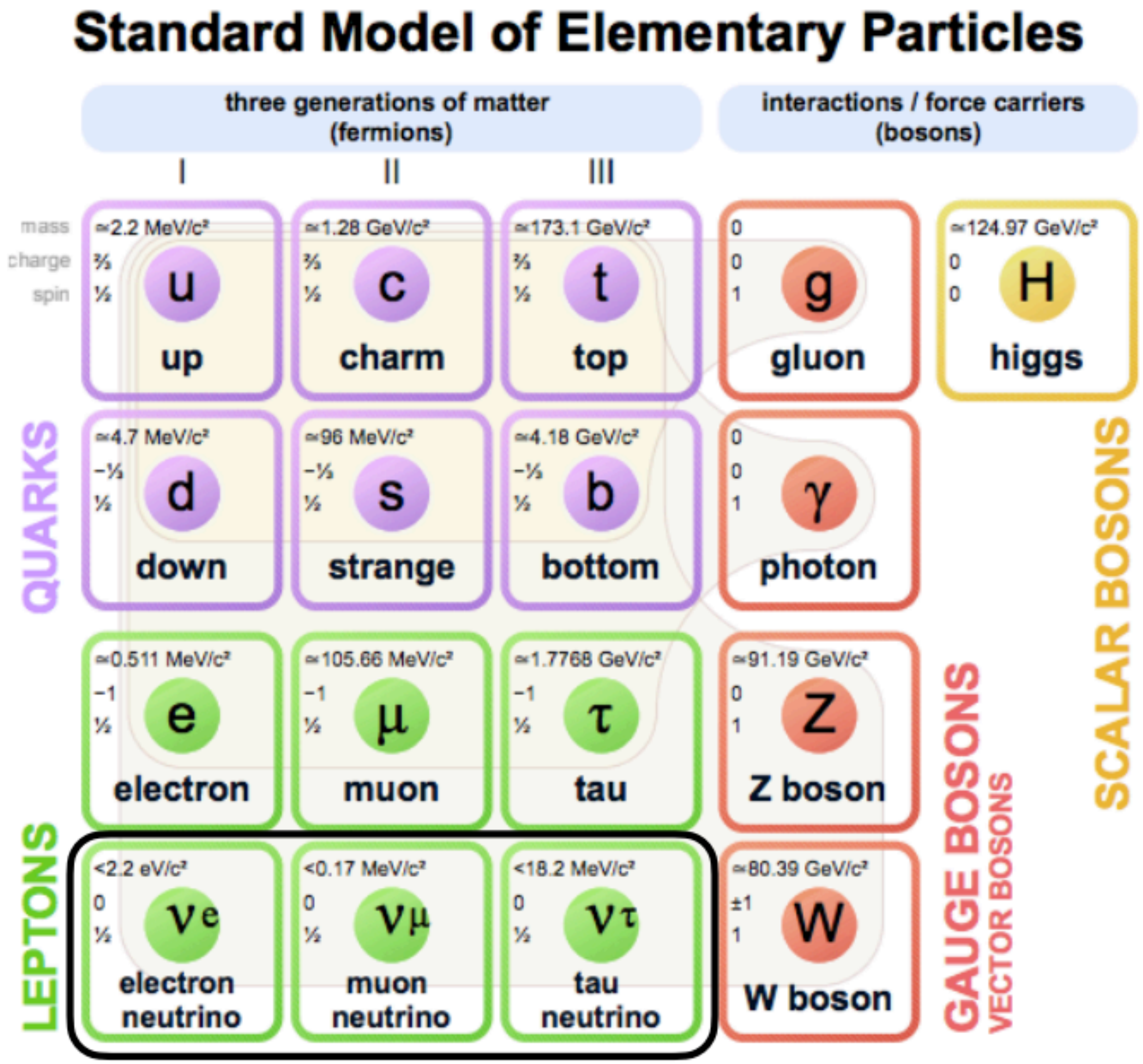
**Sergey Martynenko (Brookhaven National Laboratory)**
**On behalf of MicroBooNE collaboration**

# Standard Model

- Current best theory to describe the most basic building blocks of the universe
- Predicts only three neutrino flavors




Z-boson decay measurements
$N_\nu = 2.984 \pm 0.0082$




* Phys. Rept. 427, 257 (2006)

# Short-Baseline Anomalies

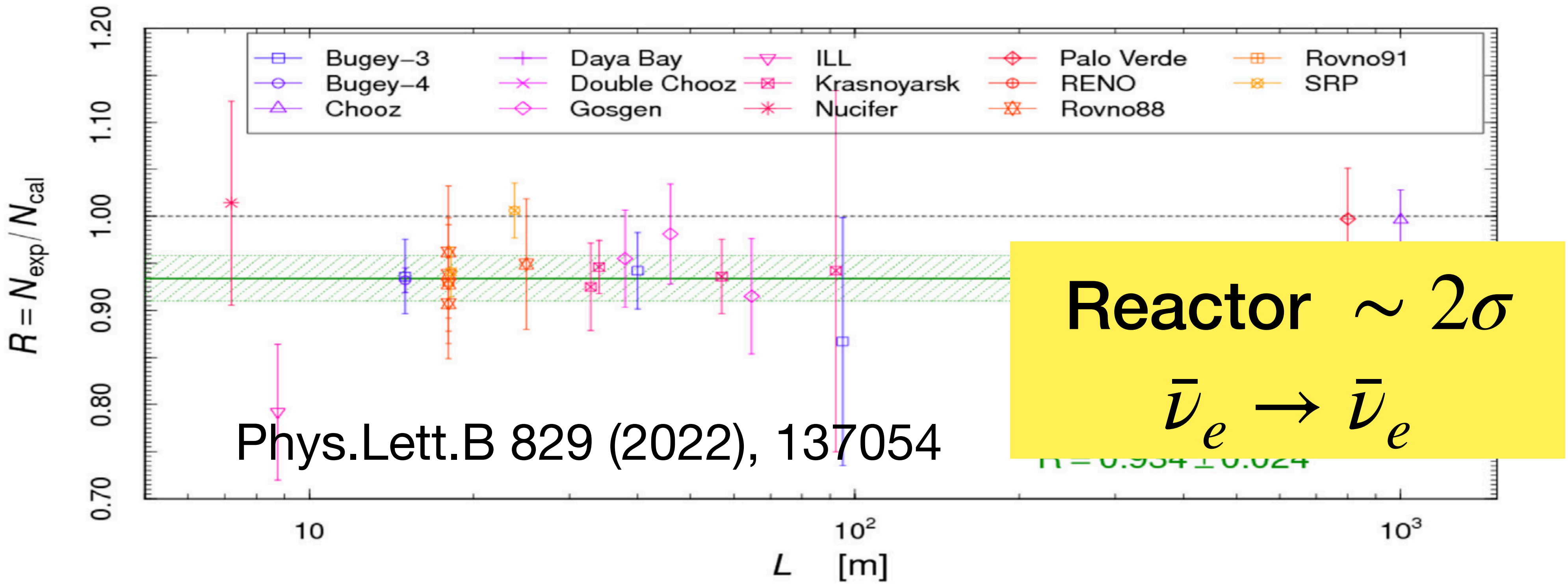
☑ **Reactor Neutrino Flux** → Initially found issue of theory by Daya Bay experiment / Resolved with new input data to flux calculation

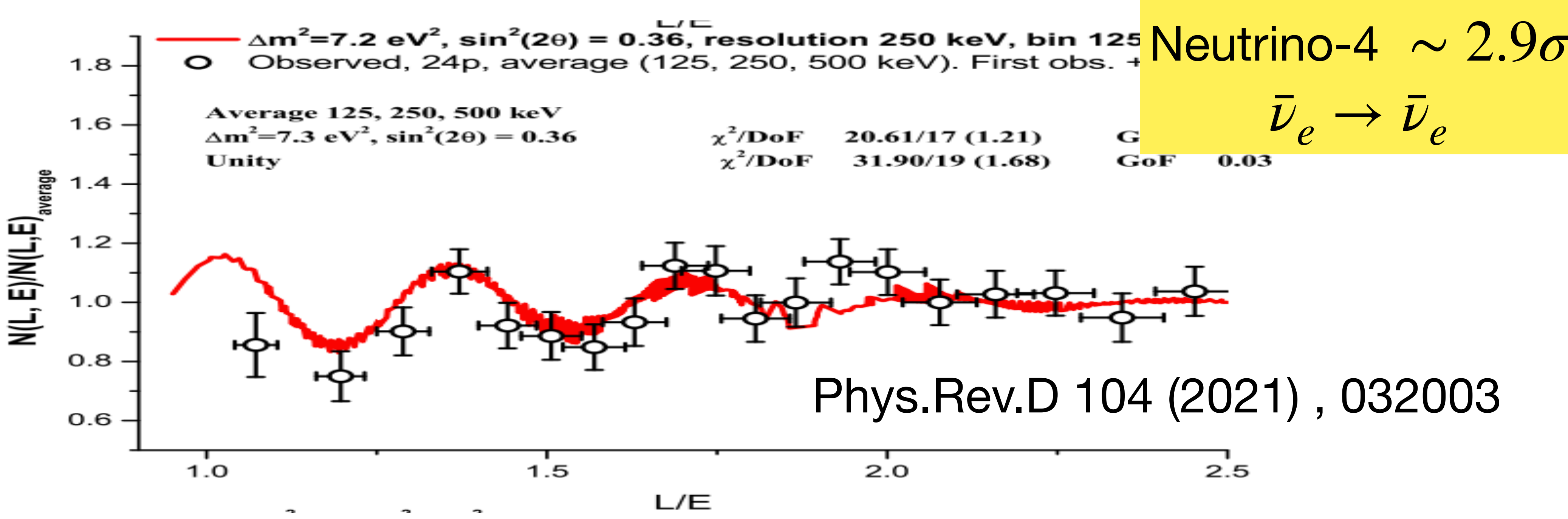
☐ **Neutrino-4 Reactor Spectra** → In tension with other VSBL reactor $\nu$ experiments

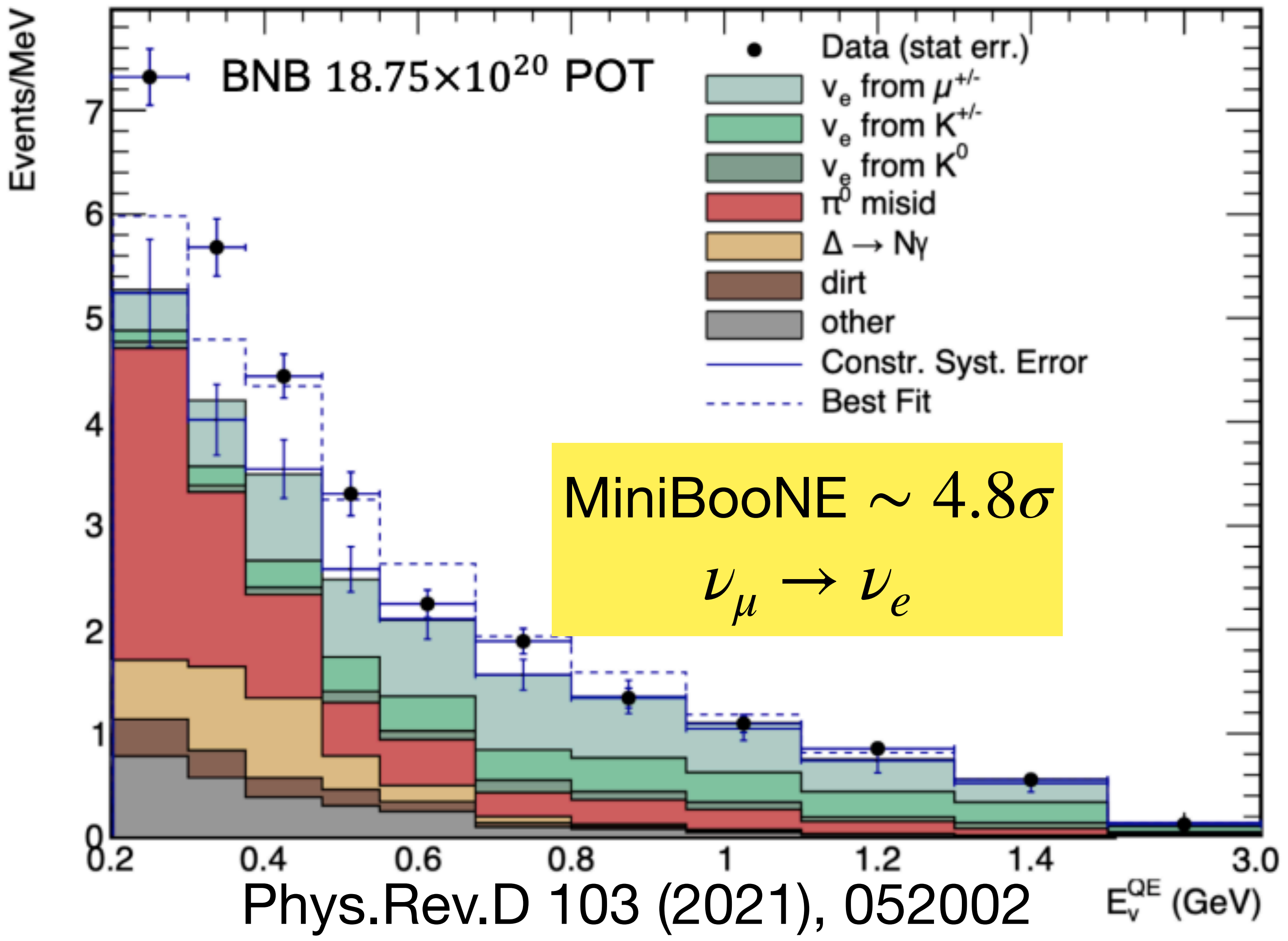
☐ **The Gallium Anomaly** → BEST observed similar results

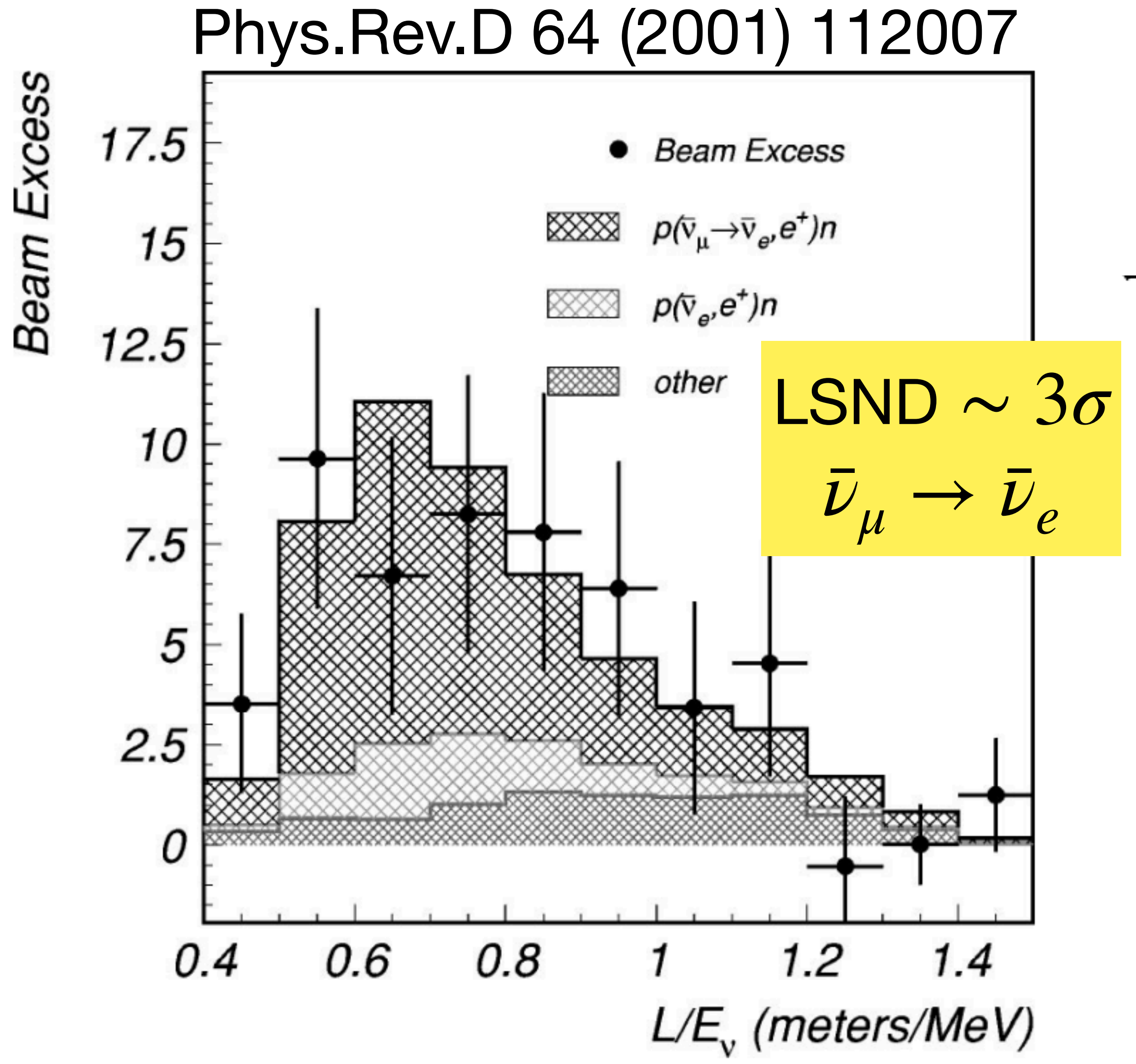
☐ **The LSND Anomaly** → JSNS² will perform direct test

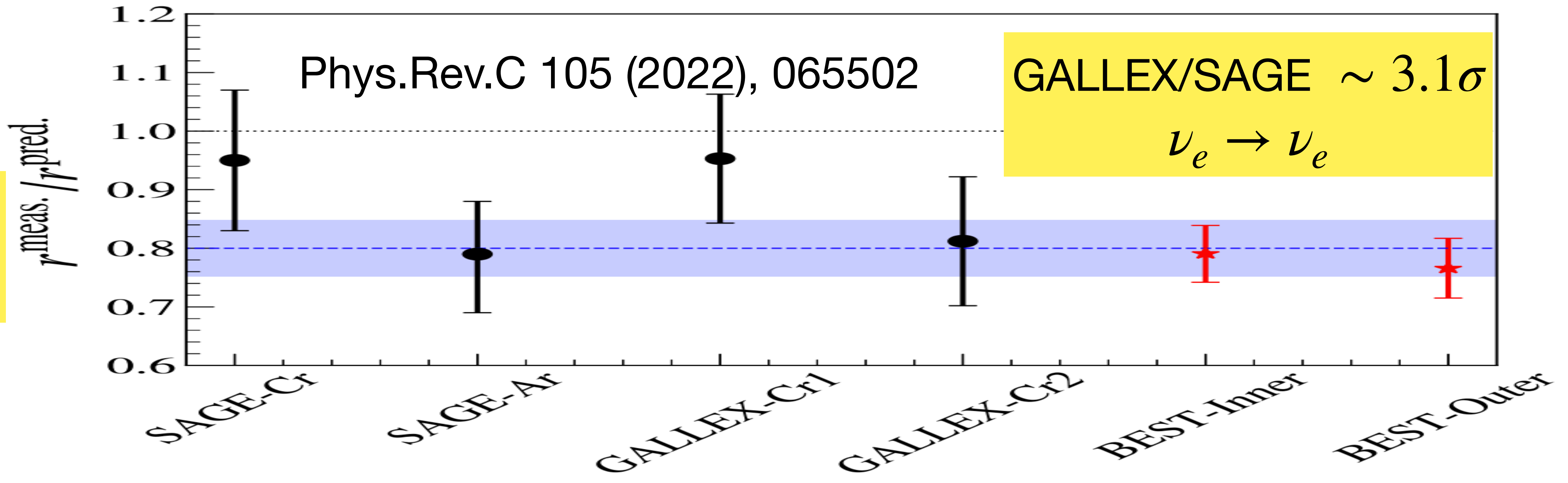
☐ **MiniBooNE LEE** → Tested with MicroBooNE



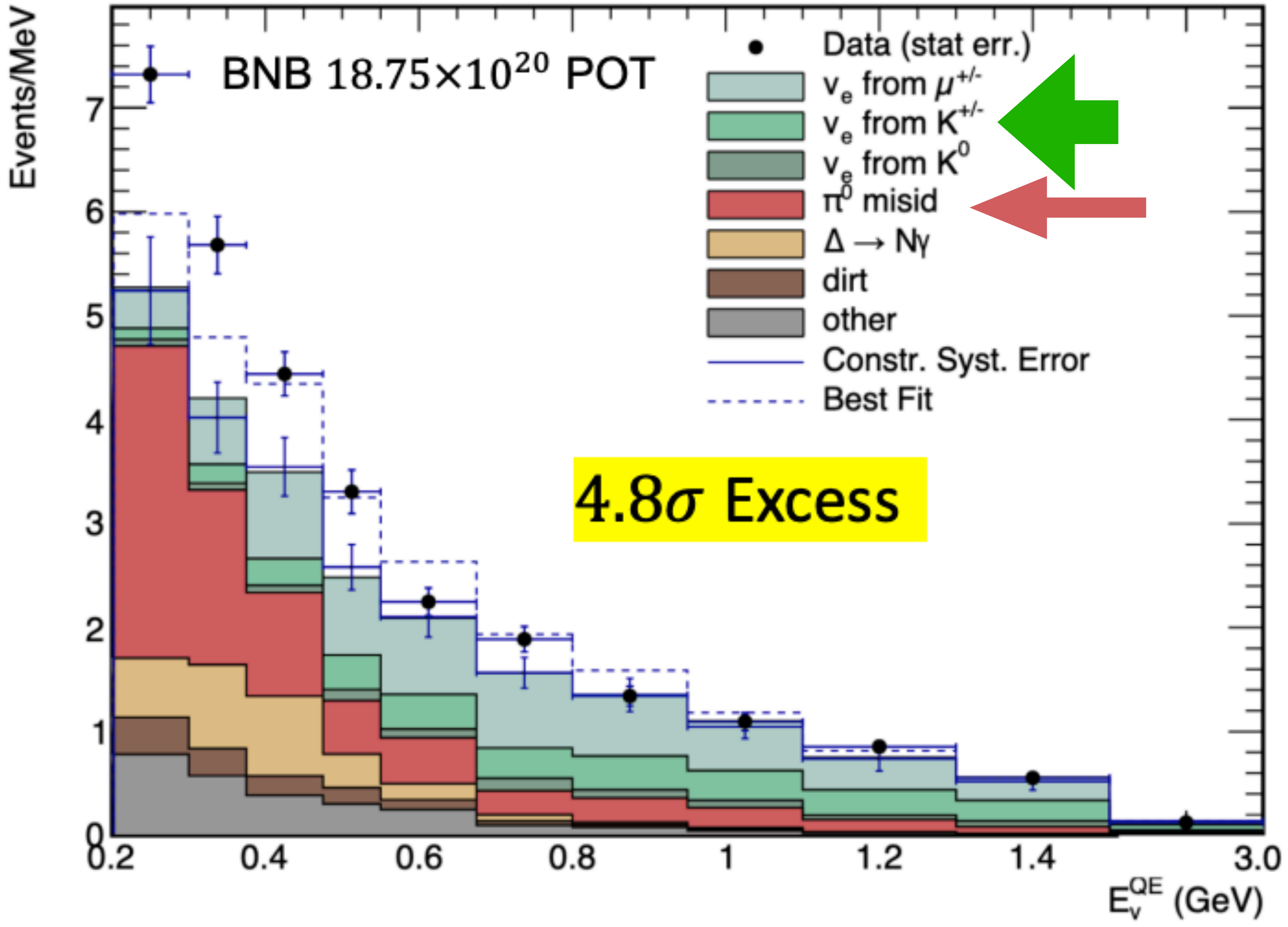



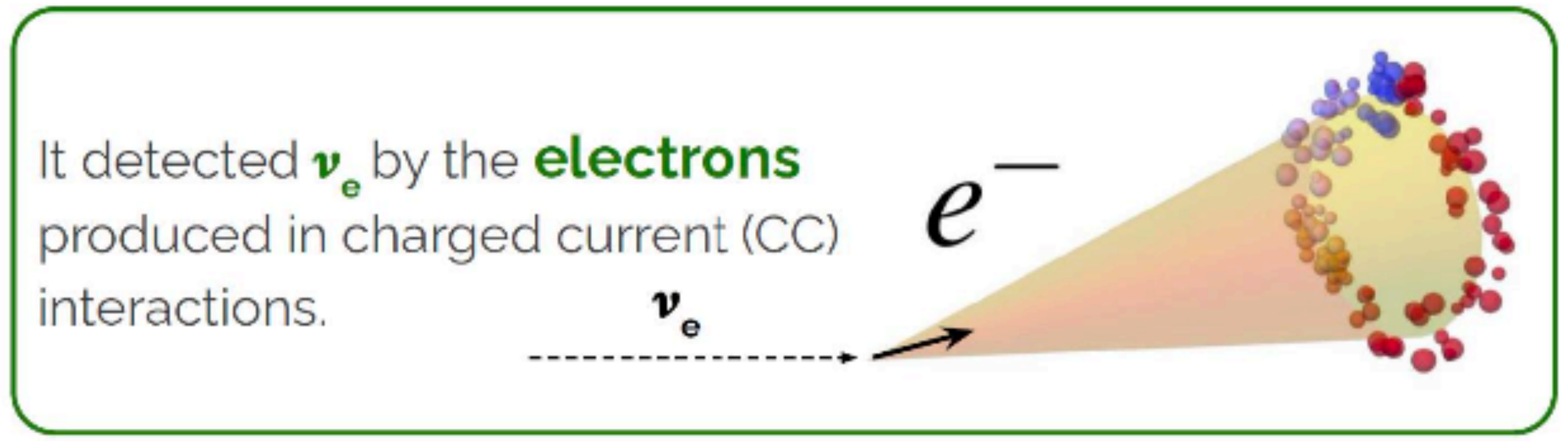



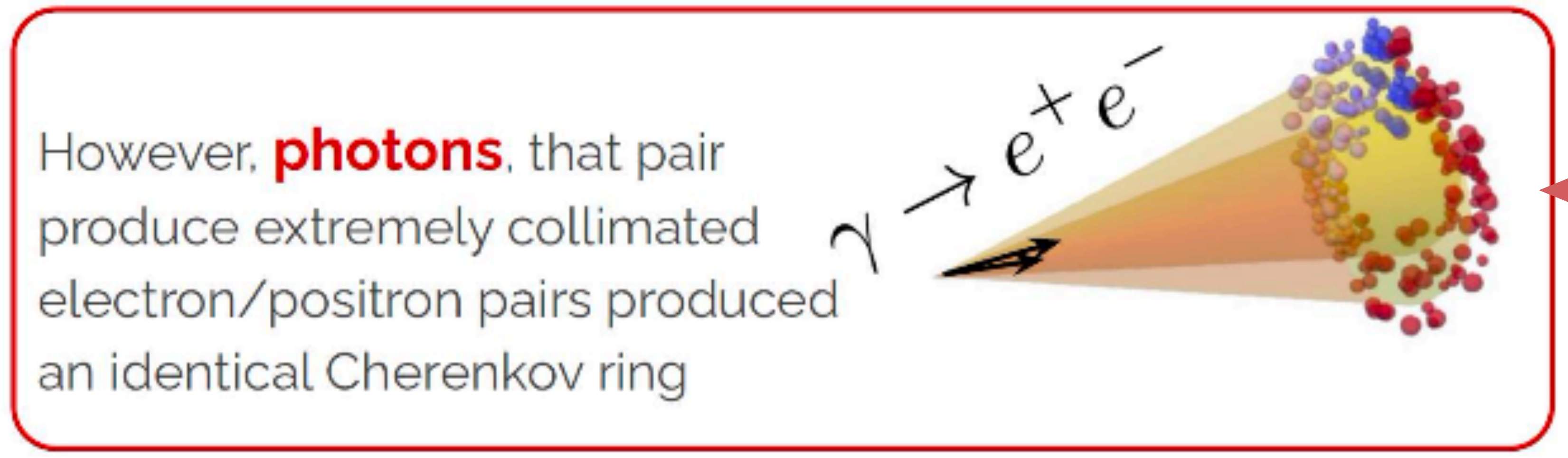
# MiniBooNE anomaly [Low Energy Excess]

- MiniBooNE (2002-2019) observed the LEE of electromagnetic events with 4.8σ significance
- MiniBooNE Cherenkov detector:
  - unable to distinguish between electrons and photons
  - unable to detect hadronic final-state particles below Cherenkov threshold
- Is excess due to electron neutrinos appearing in the muon neutrino beam? Or photons? Or some other electromagnetic activity?

Phys.Rev.D 103 (2021), 052002



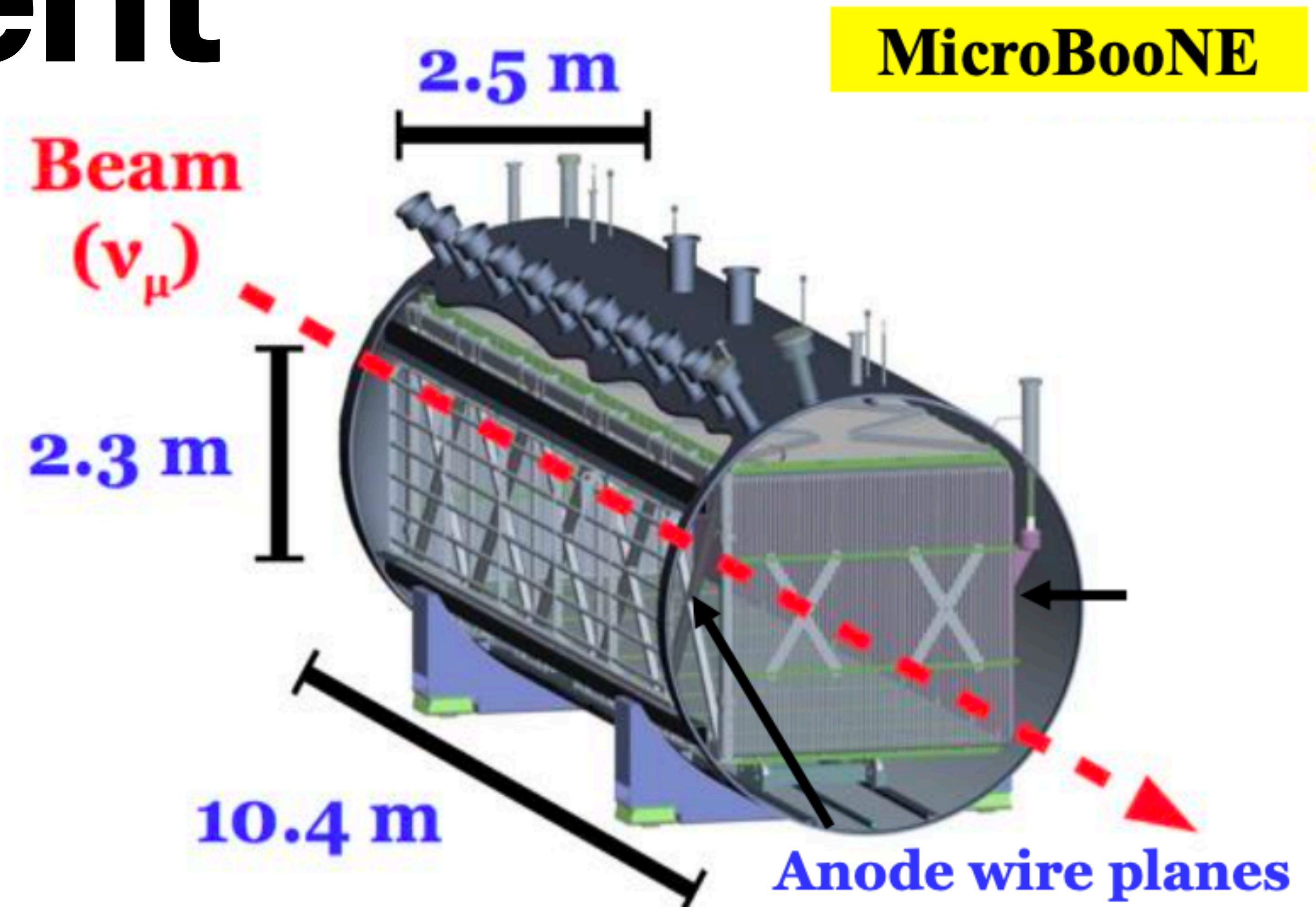



# MicroBooNE Experiment

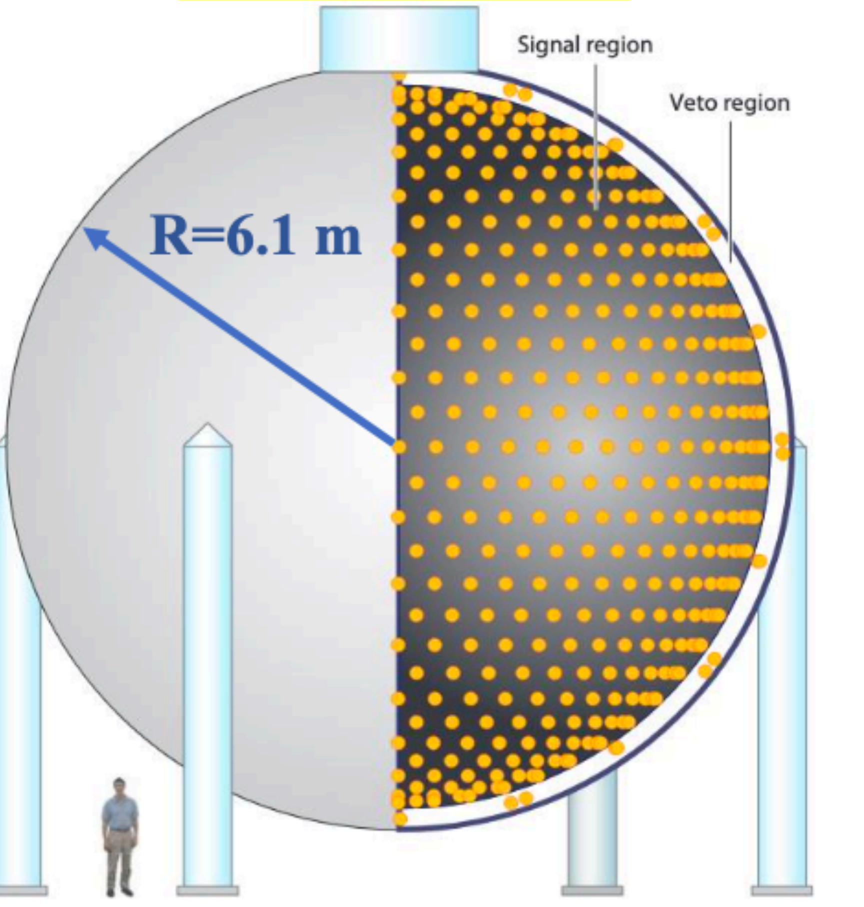
**Experiment Description:**

- MicroBooNE is a surface-level, 85 tonne LArTPC neutrino experiment at Fermilab
- Located at Booster Neutrino Beamline (same as MiniBooNE)
  - Also receives NuMI beam
  - Collected data from 2015-2021. [Results use ½ this data]

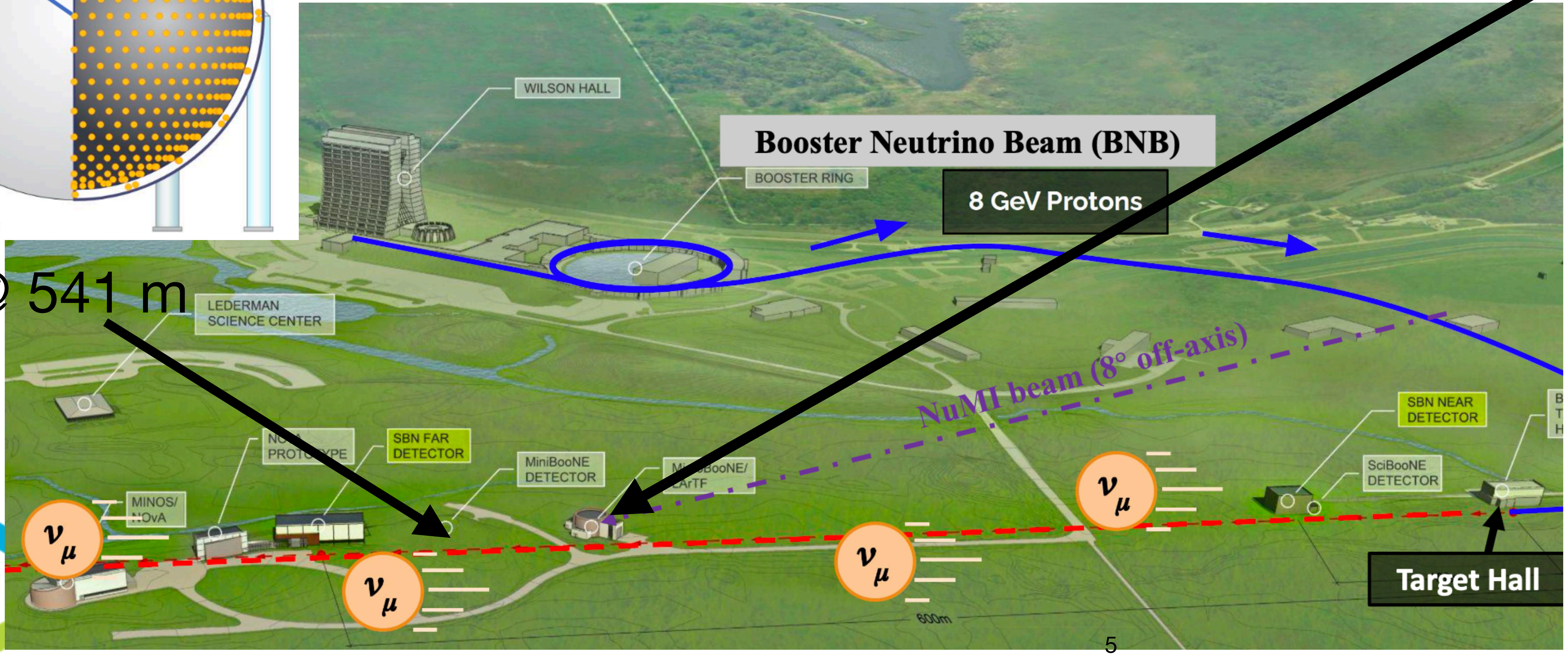



@ 468.5 m

MiniBooNE

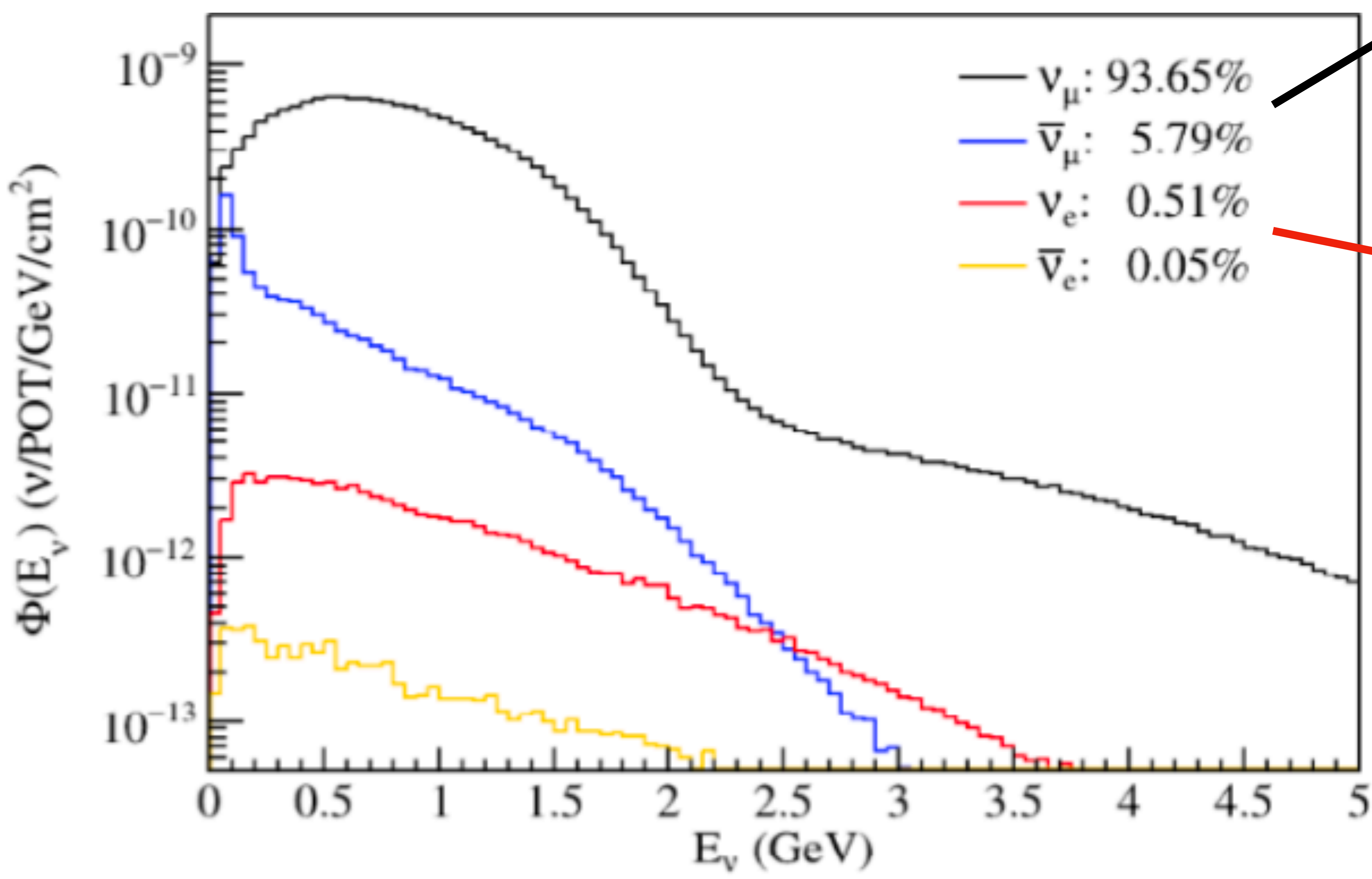



@ 541 m



# MicroBooNE Experiment

Booster Neutrino Beam @ $\langle 0.8 \rangle GeV$




99.44% $\nu_\mu(\bar{\nu}_\mu)$

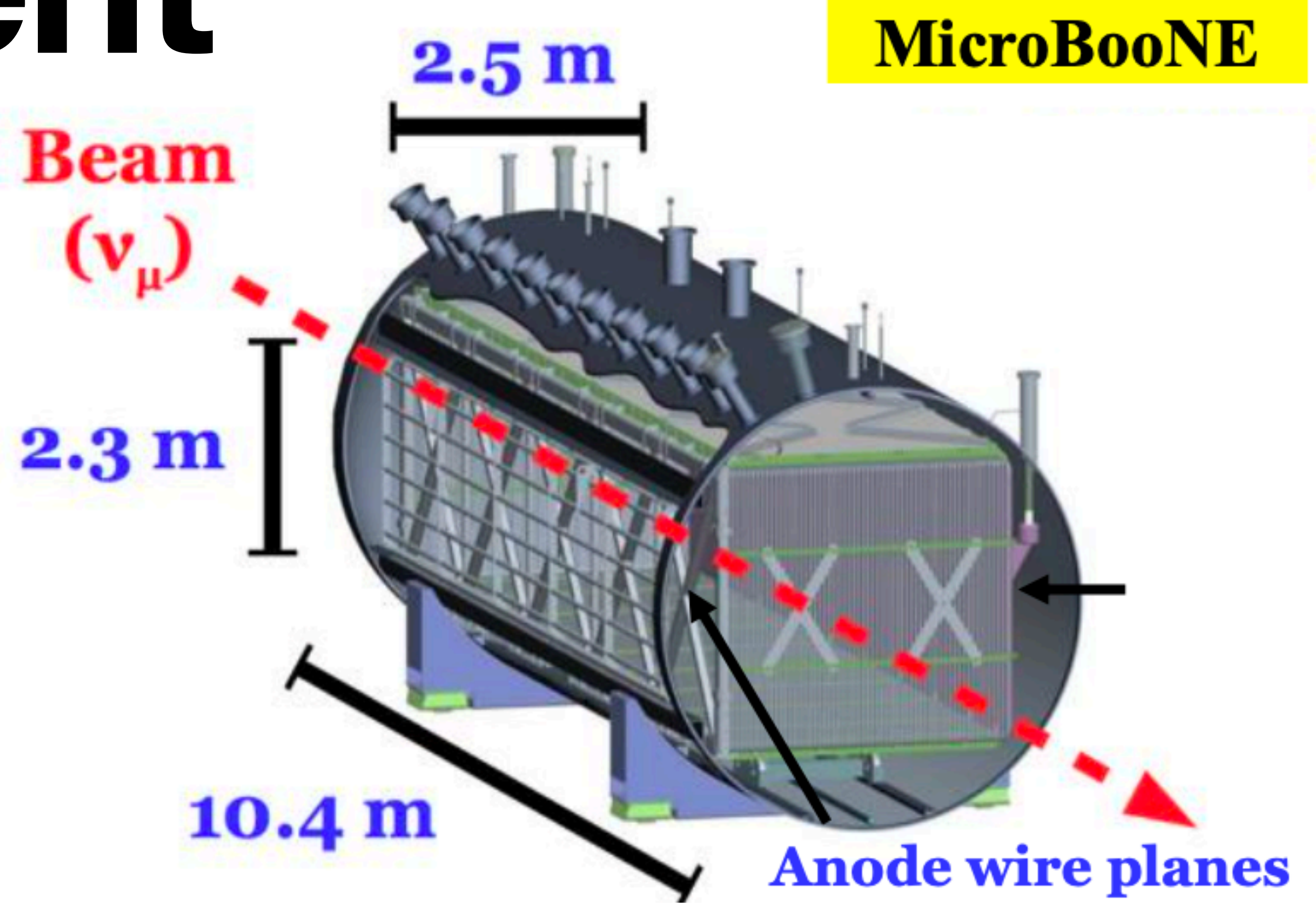
0.56% $\nu_e(\bar{\nu}_e)$

Can Test :

$\nu_\mu \rightarrow \nu_e$

$\nu_e \rightarrow \nu_e$

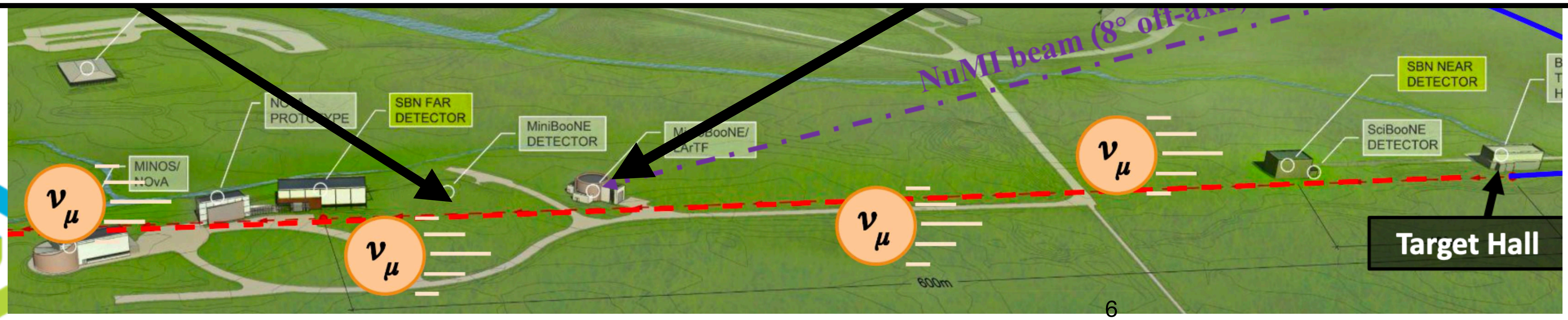
$\nu_\mu \rightarrow \nu_\mu$




@ 468.5 m

**Experimental goals:**

- Investigate MiniBooNE excess & oscillations
- Neutrino cross sections
- BSM searches
- LArTPC R&D

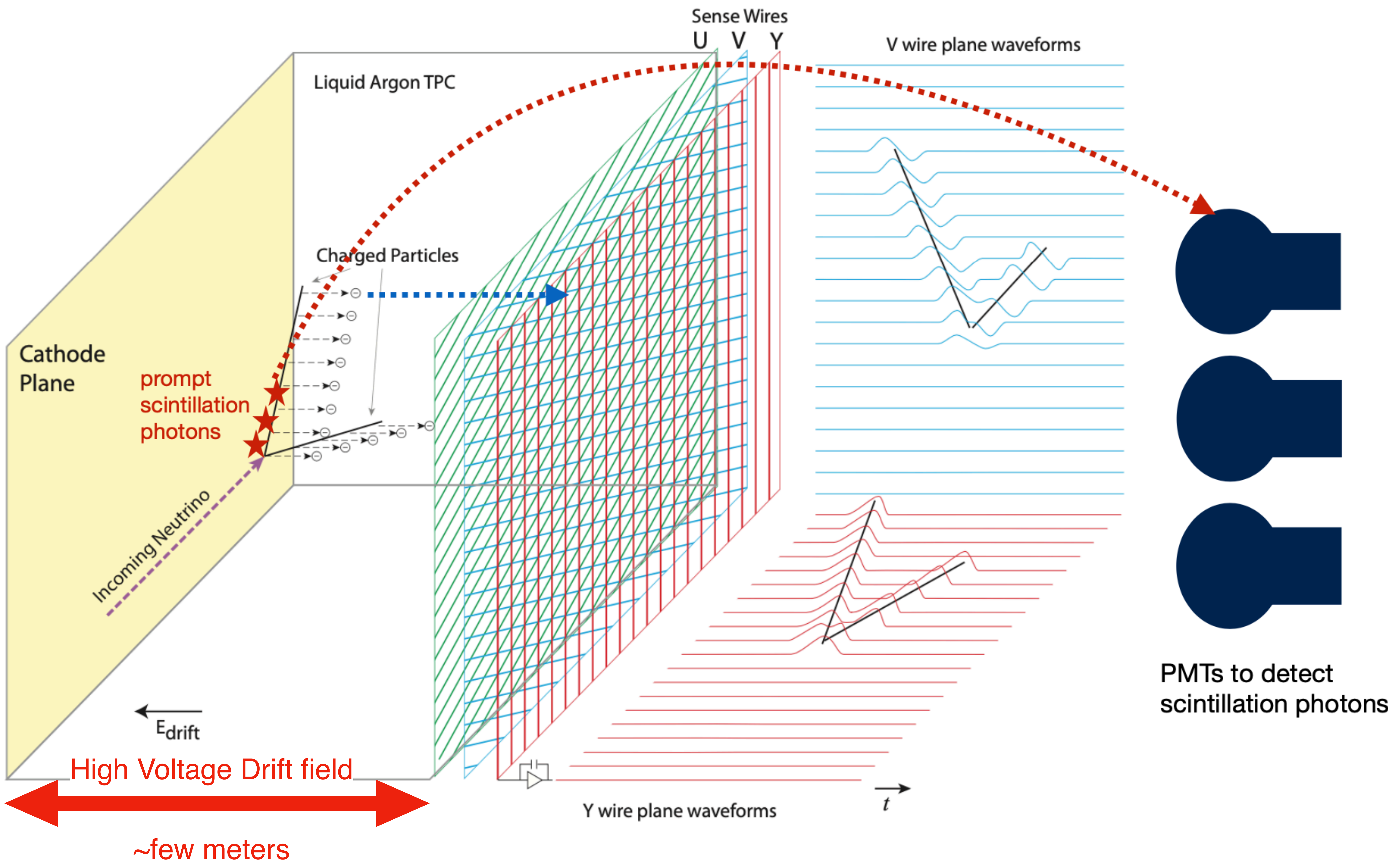


# Liquid Argon Time Projection Chamber (LArTPC)

Charged particle enters detector

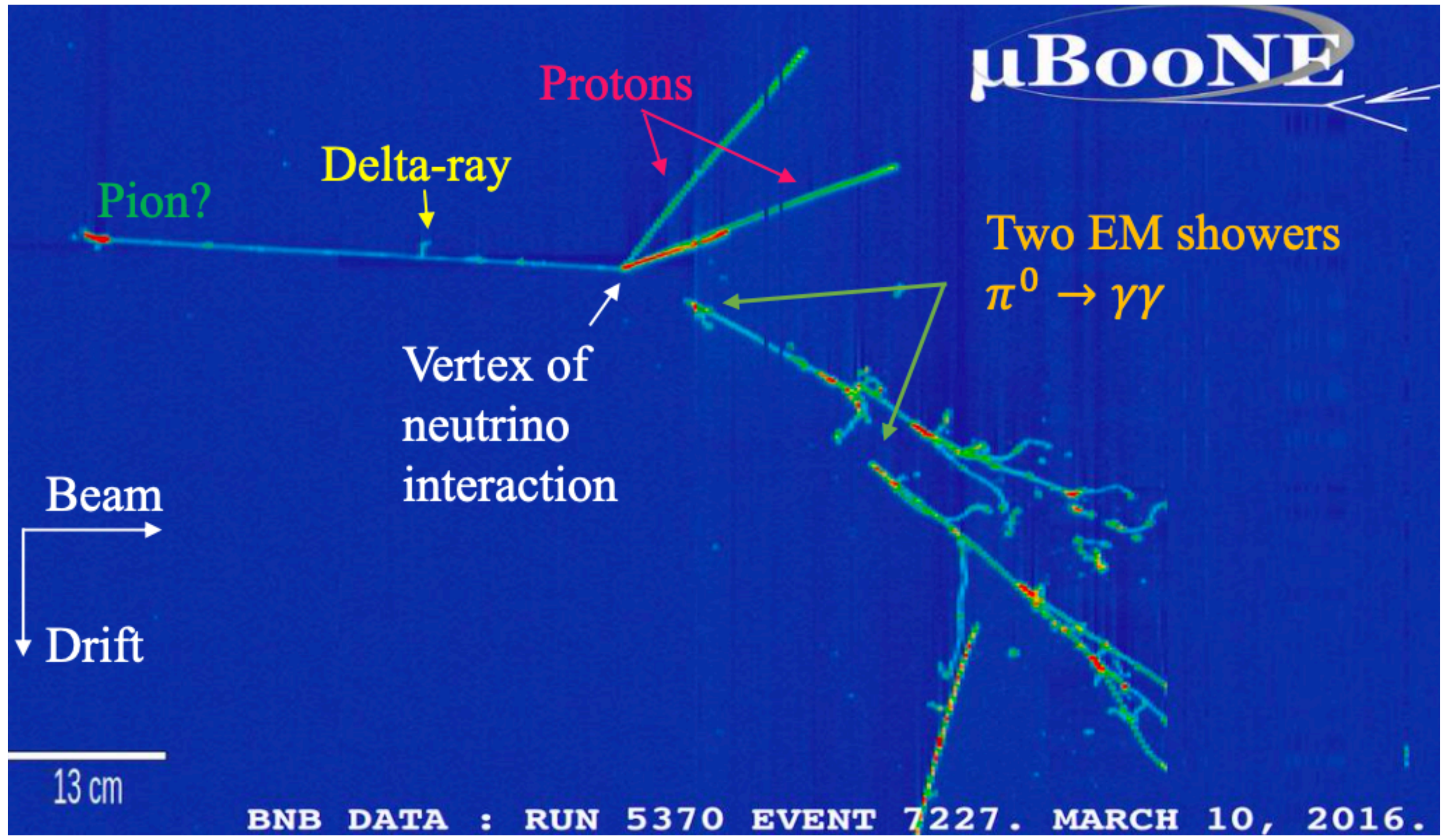
Scintillation light emitted by excited Ar, detected by PMTs

Ionization electrons drift to anode plane [2 induction wire planes and 1 collection]



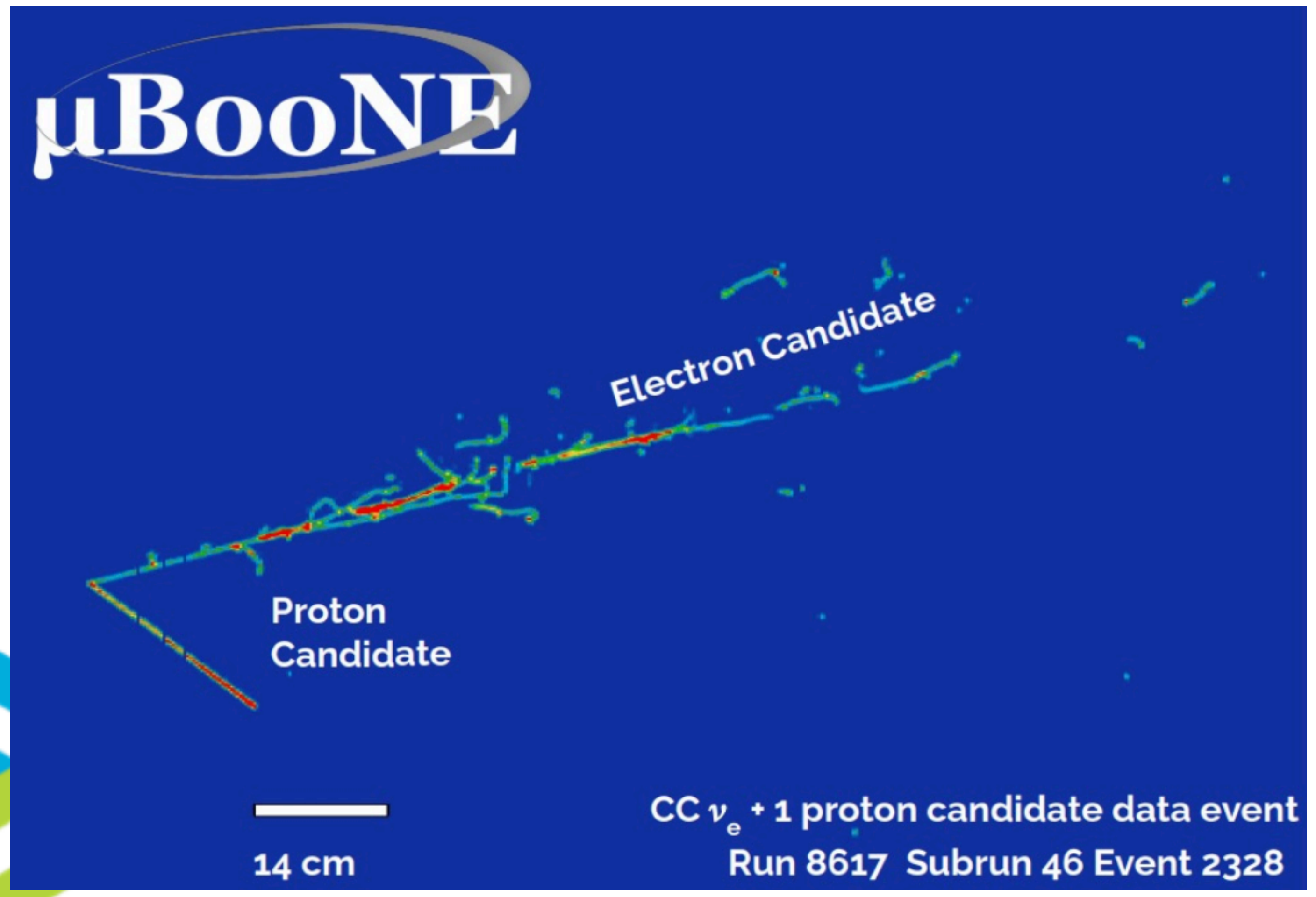
# Liquid Argon Time Projection Chamber (LArTPC)

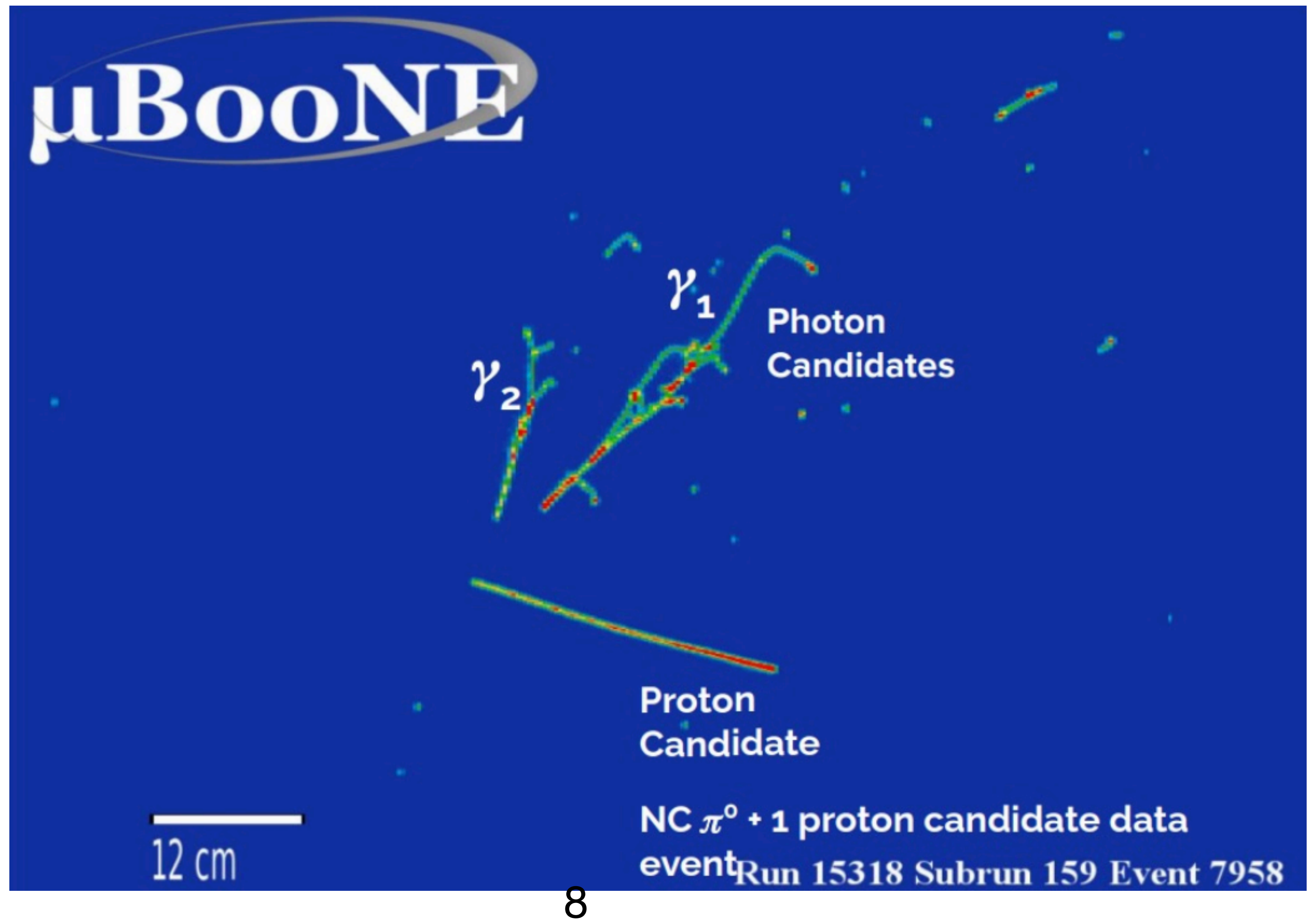
- Capable of identifying different species of particles and reconstructing 3D images with fine-grained information

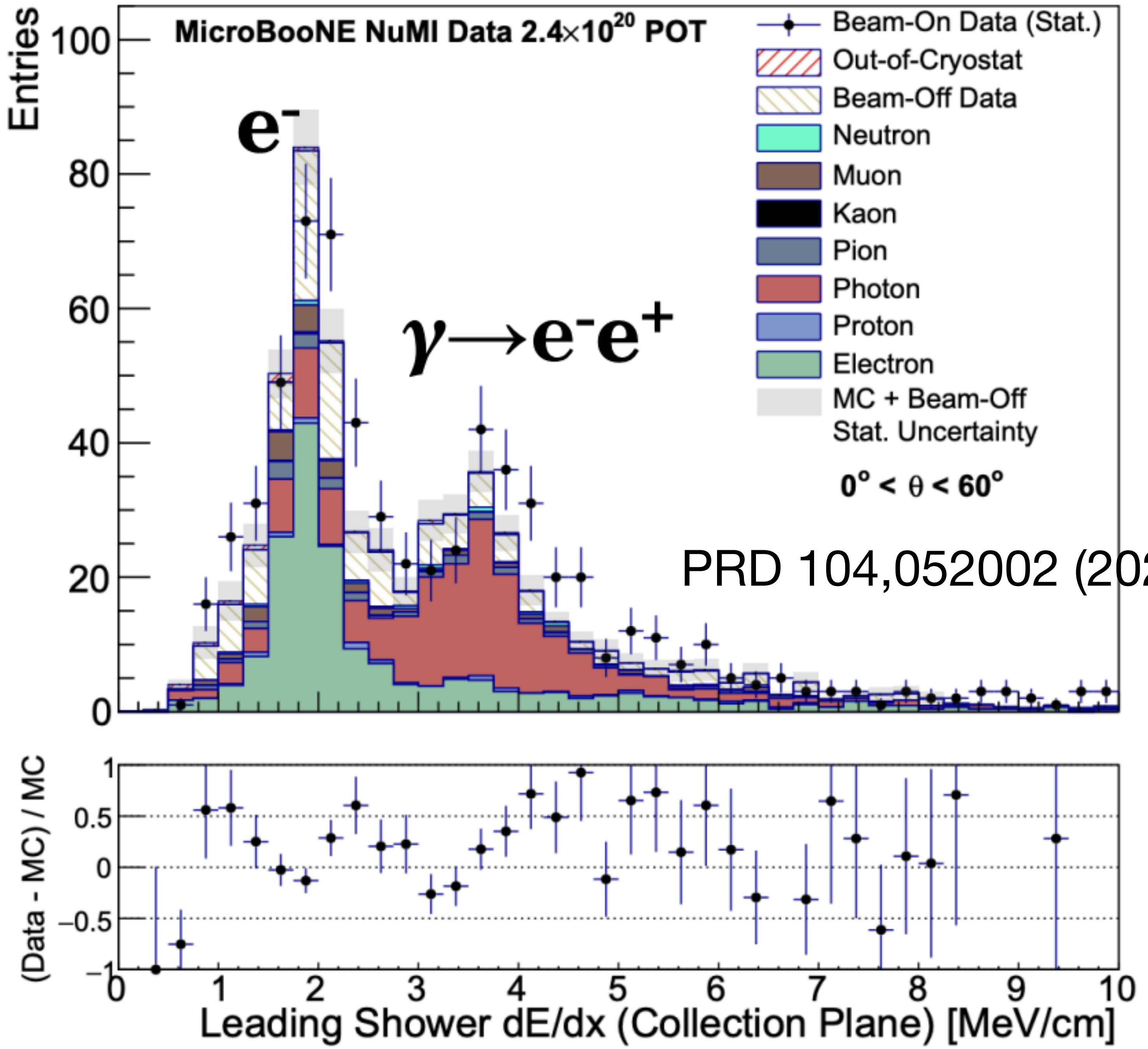



- Neutrino vertex
- Particle flow (mother-daughter relationship)
- Track ($\mu$, $\pi$, $p$ etc.) vs shower (e, γ EM cascade)

- $e$ / $\gamma$ (**e+e**– pair production) separation
  1. Gap between shower start point and $\nu$ vertex
  2. dE/dx two times difference (1 MIP vs 2 MIPs)

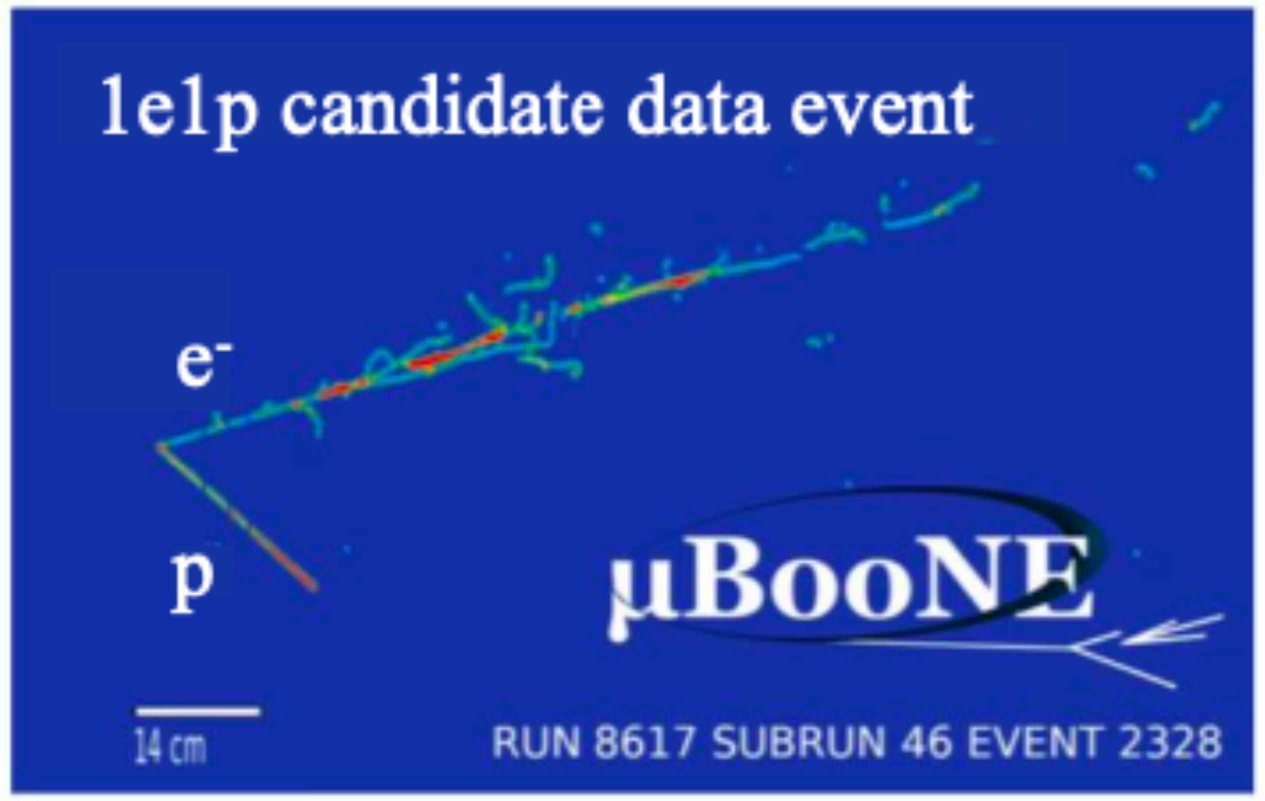



PRD 104,052002 (2021)

# eLEE Search [electron Low Energy Excess]

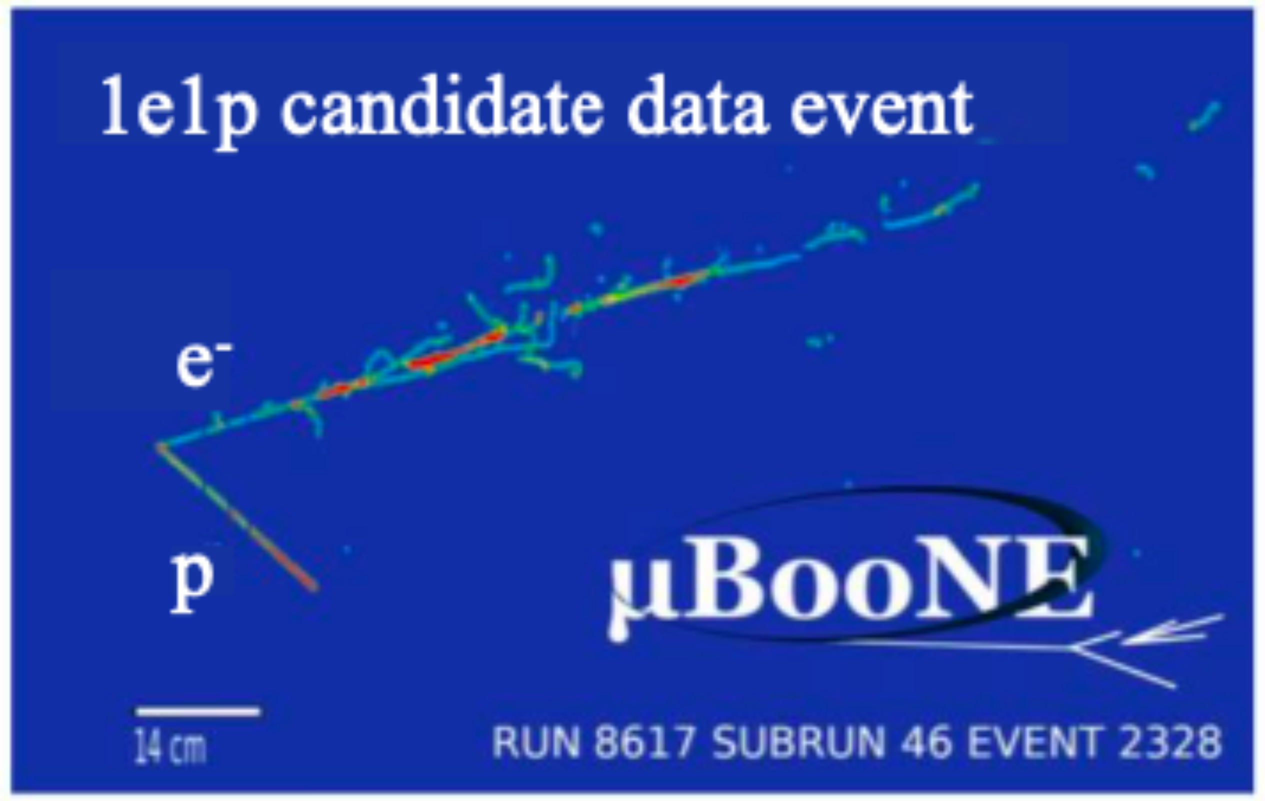



Three independent analyses using different reconstruction paradigms and targeting different final states:

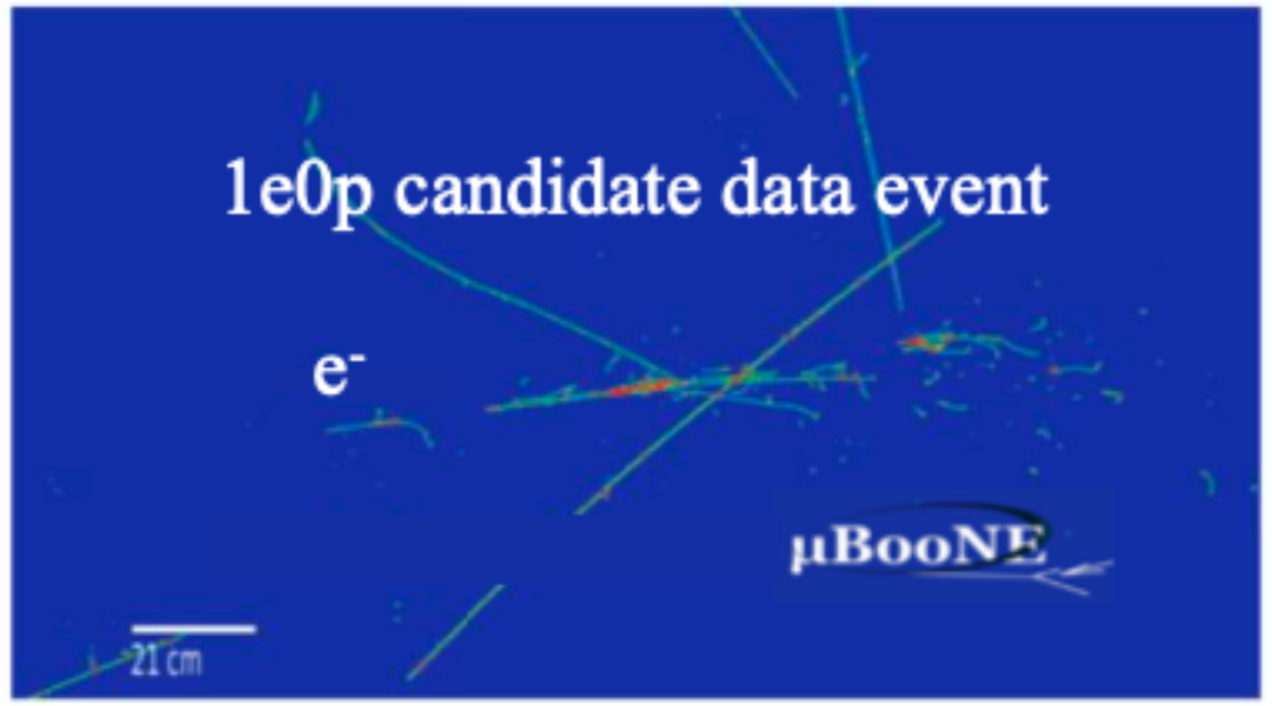
1. Quasi-elastic kinematics:1e1p , Deep-learning-based reco.

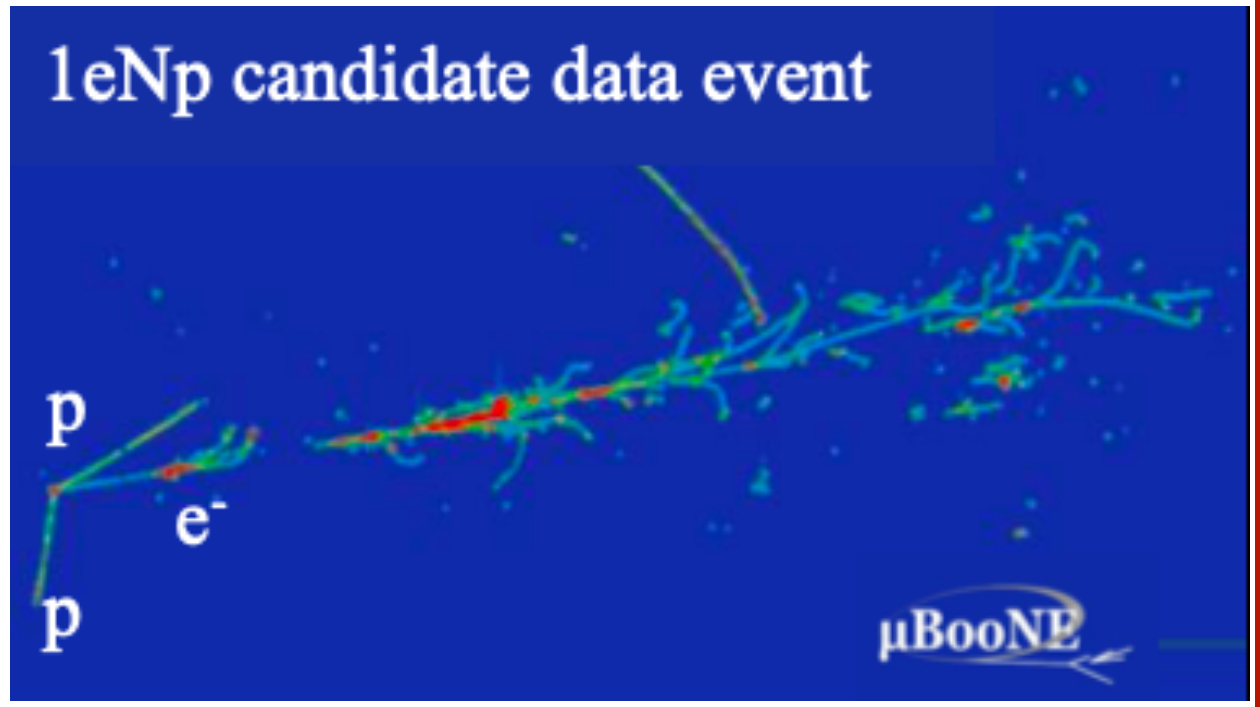
Deep Learning: PRD 103, 052012 (2021)
Pandora: EPJC 75, 439 (2015)
WireCell: JINST 13, 05032 (2018)

# eLEE Search
# [electron Low Energy Excess]




Three independent analyses using different reconstruction paradigms and targeting different final states:



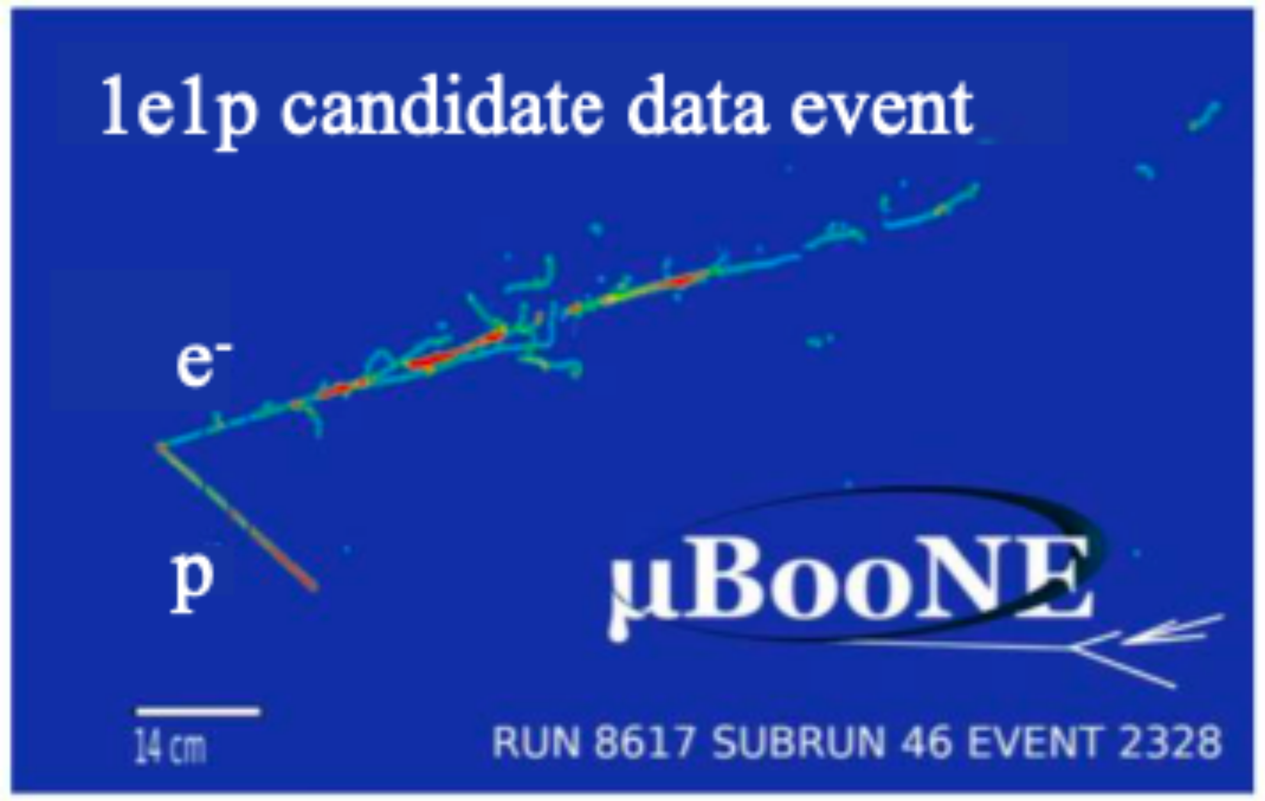

1. Quasi-elastic kinematics:1e1p , Deep-learning-based reco.
2. MiniBooNE like-final state: $1eNp0\pi$ and $1e0p0\pi$ ,Pandora-based reco.

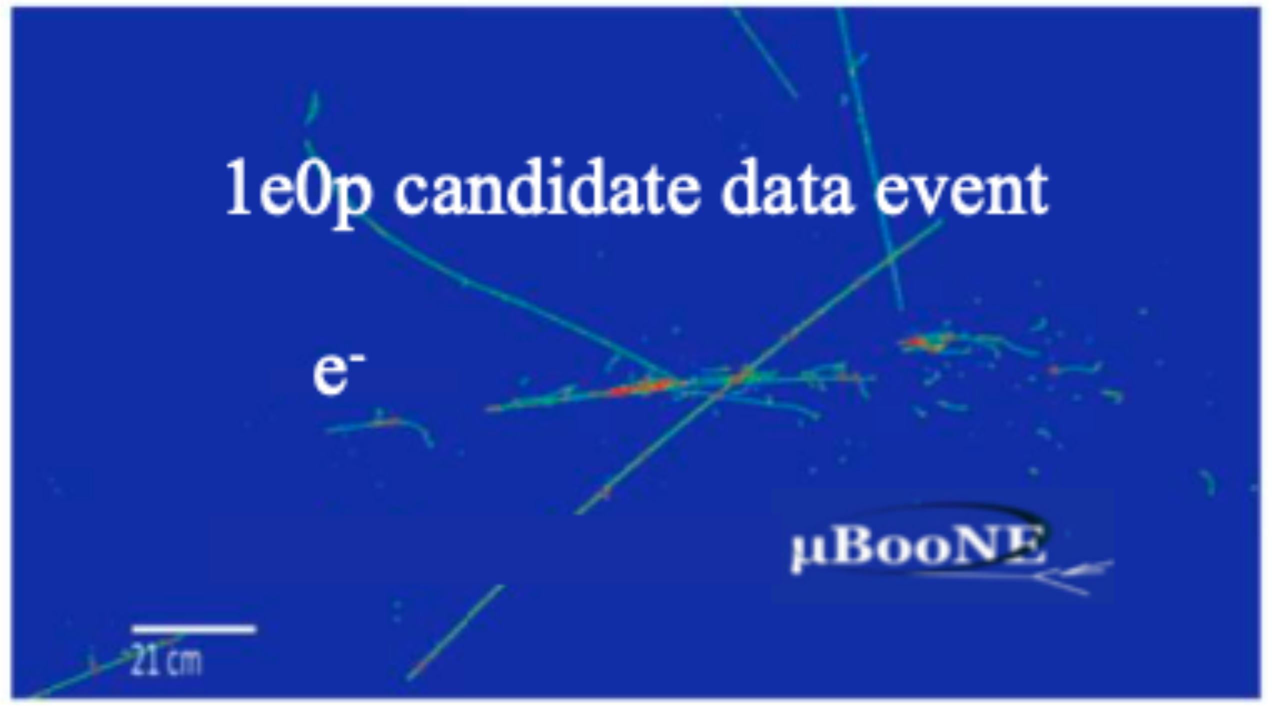
Deep Learning: PRD 103, 052012 (2021)
Pandora: EPJC 75, 439 (2015)
WireCell: JINST 13, 05032 (2018)

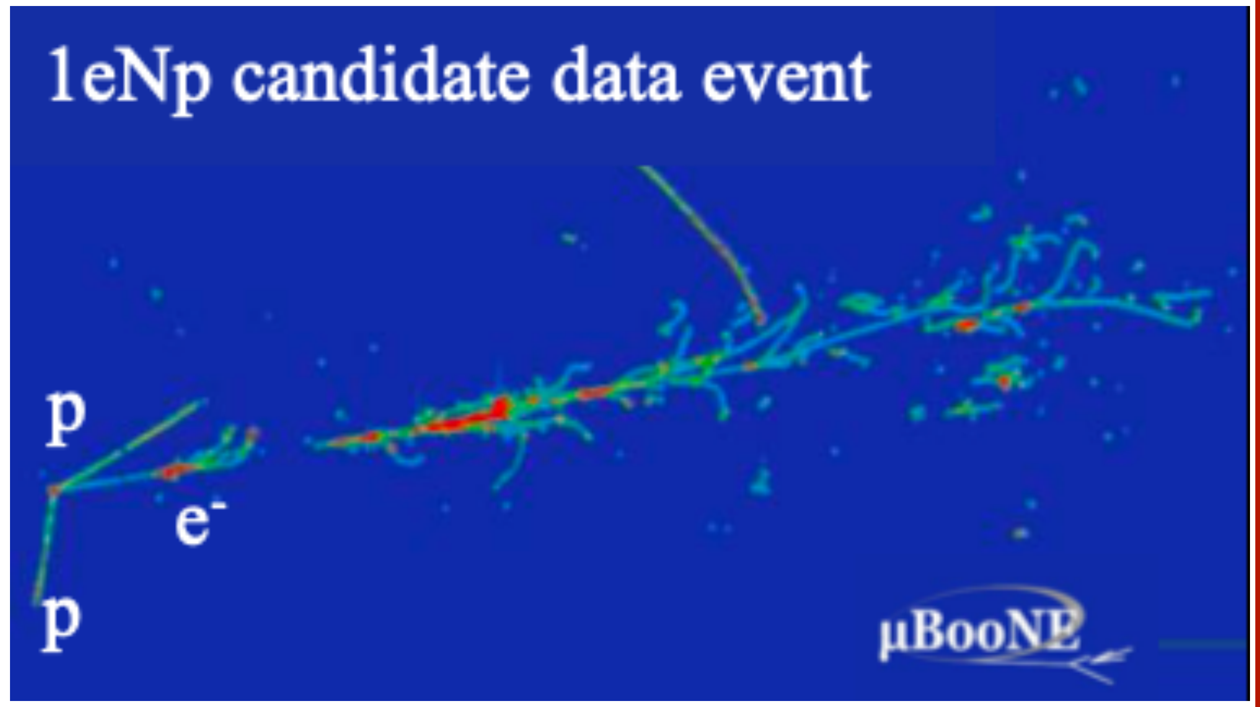
# eLEE Search [electron Low Energy Excess]

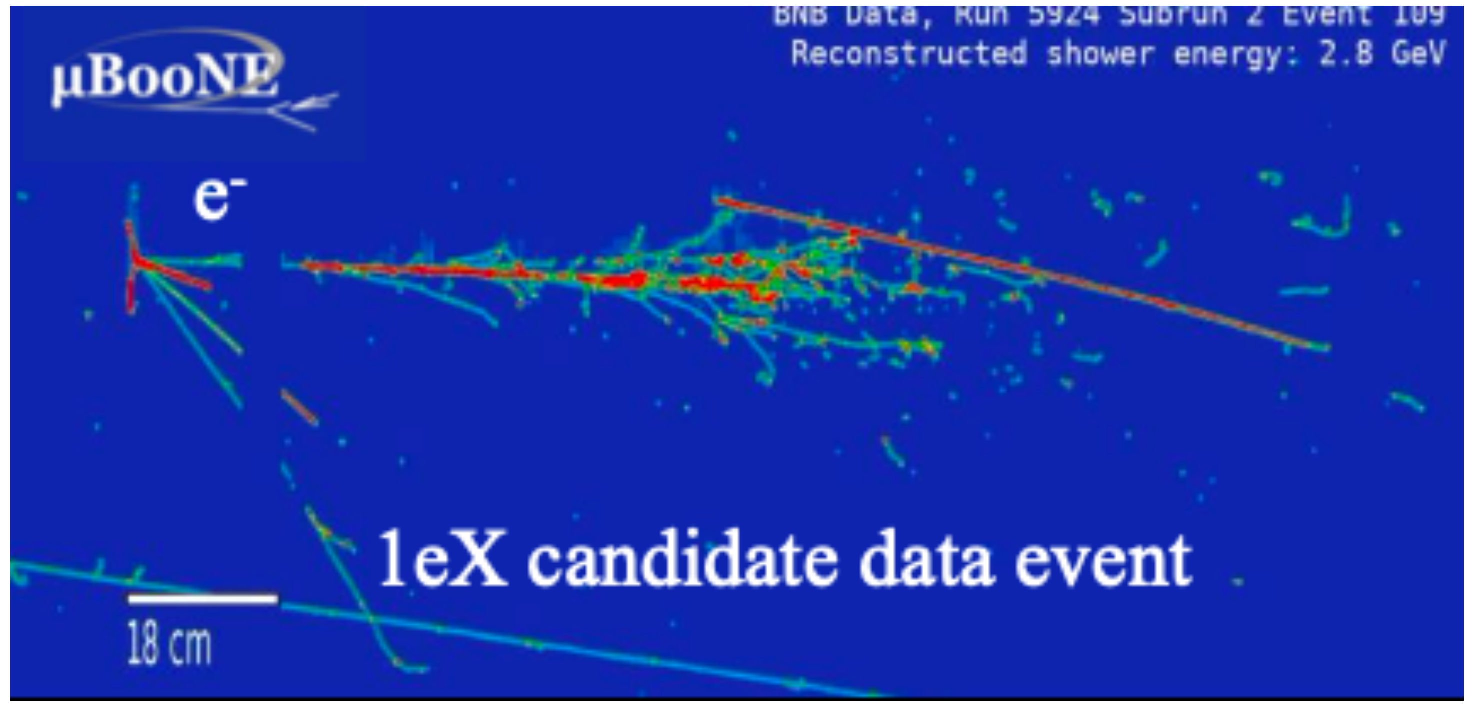
Three independent analyses using different reconstruction paradigms and targeting different final states:

1. Quasi-elastic kinematics:1e1p , Deep-learning-based reco.
2. MiniBooNE like-final state:1eNp0pi and 1e0p0pi ,Pandora-based reco.
3. Inclusive 1eX final states, WireCell reconstruction



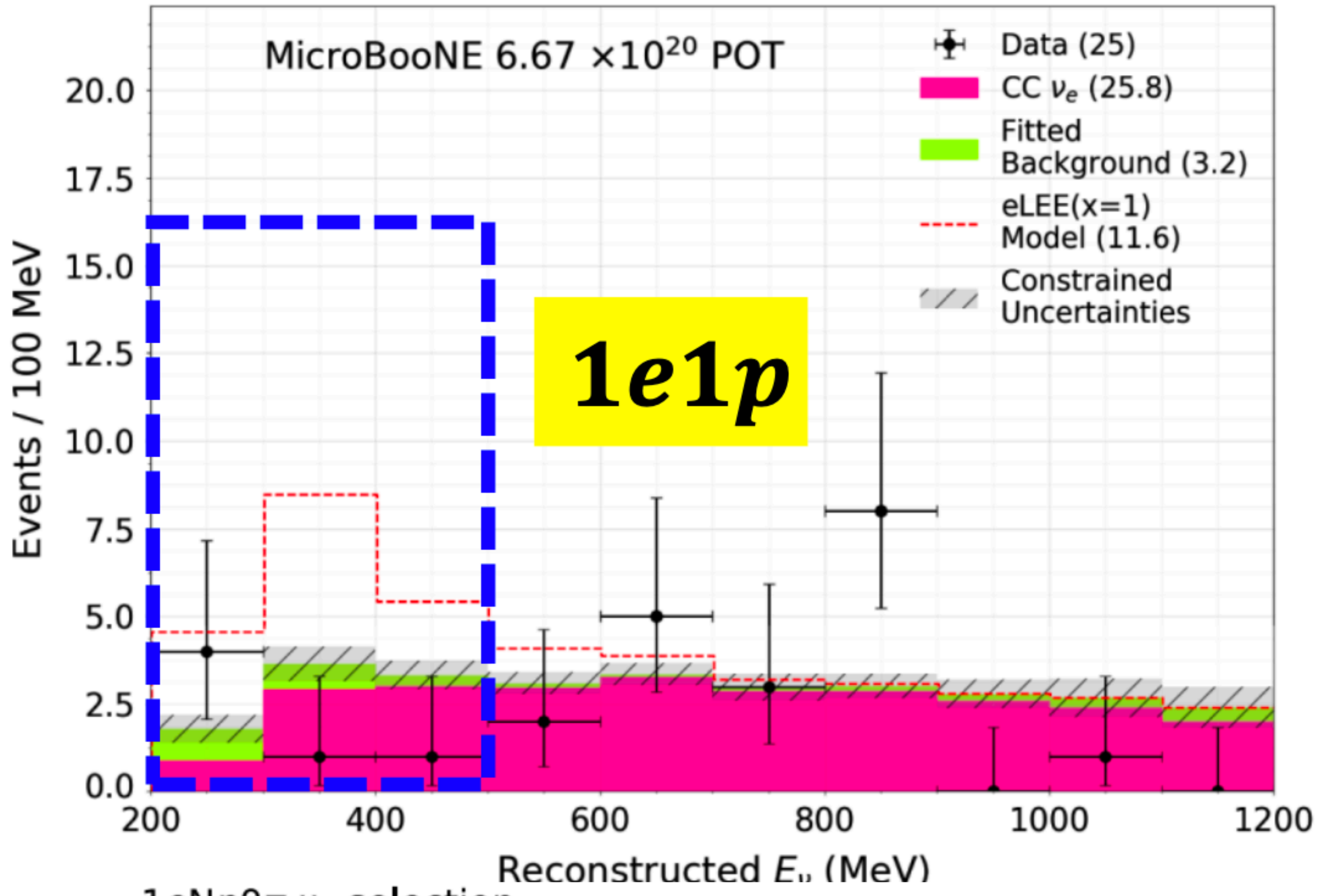



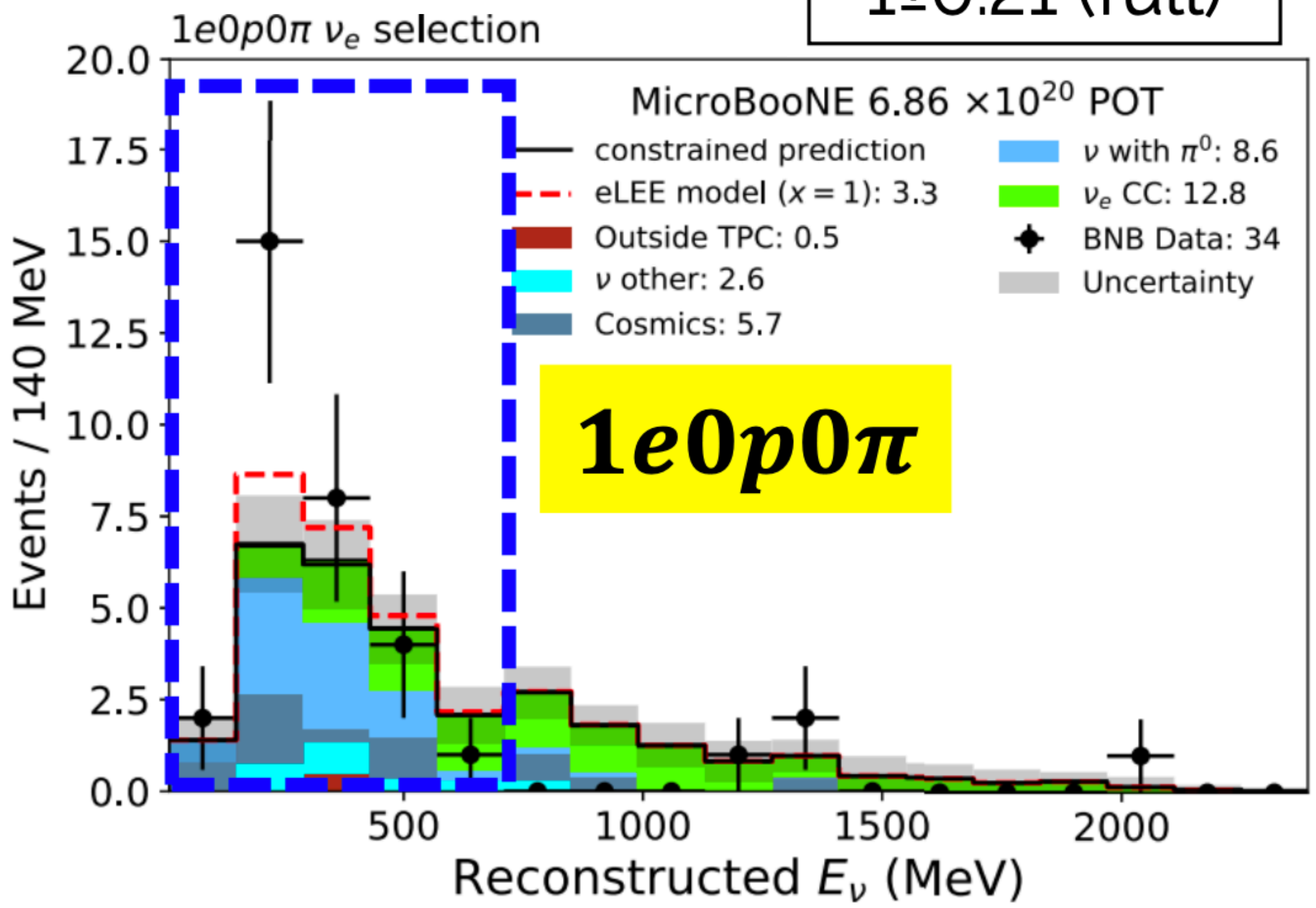

Deep Learning: PRD 103, 052012 (2021)
Pandora: EPJC 75, 439 (2015)
WireCell: JINST 13, 05032 (2018)

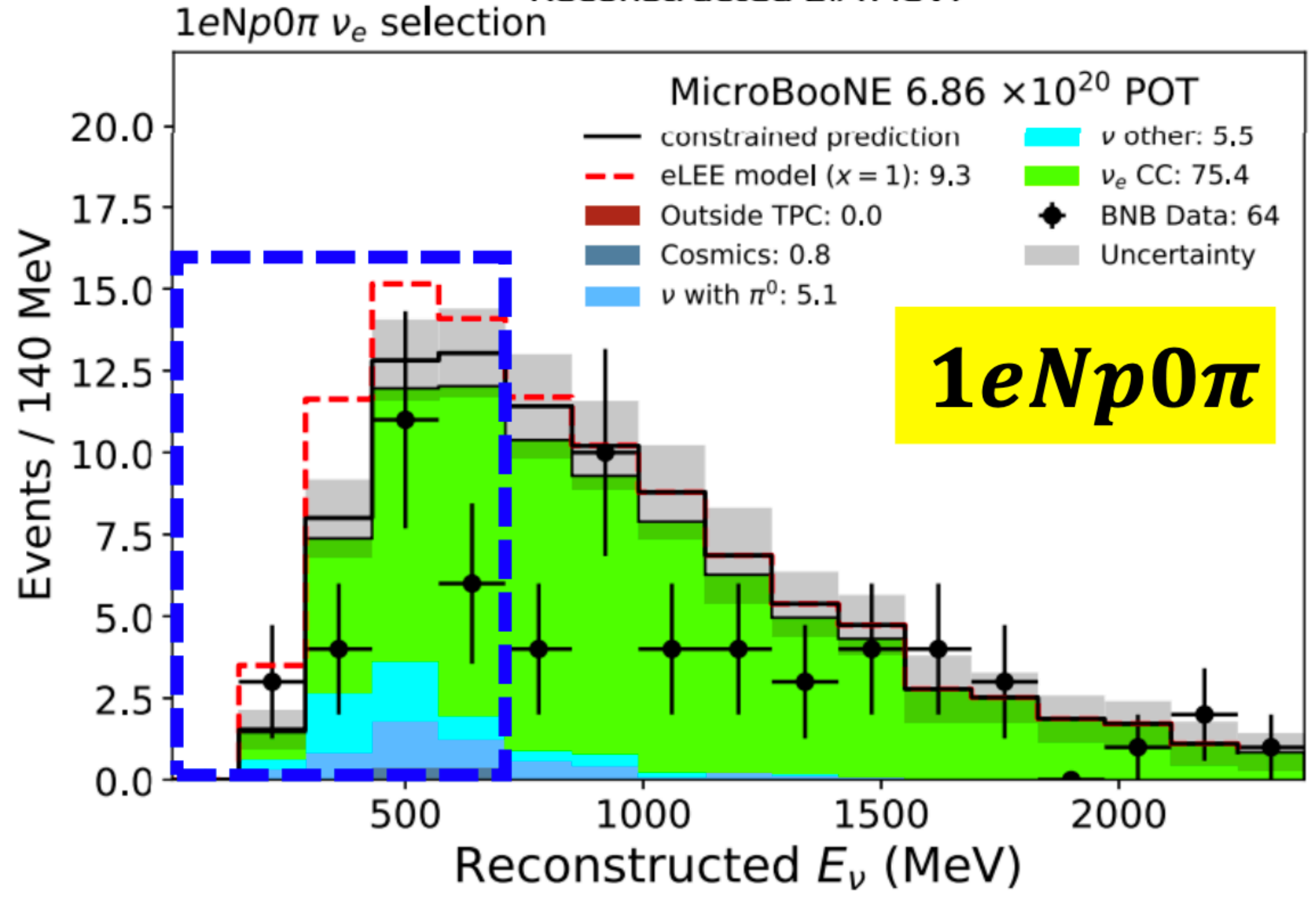
# eLEE Results [by final state]

MiniBooNE **x**:
1±0.08 (stat.)
1±0.21 (full)

- Model : an energy-dependent enhancement of intrinsic $\nu_e$ events in the beam at low energy → derived from MiniBooNE with one normalization parameter "x"
- No observation of $\nu_e$ candidate excess in low energy region; except for the **low $\nu_e$ purity** $\mathbf{1e0p0\pi}$ channel
- Single-electron-alone explanation for MiniBooNE is ruled out at >97% CL

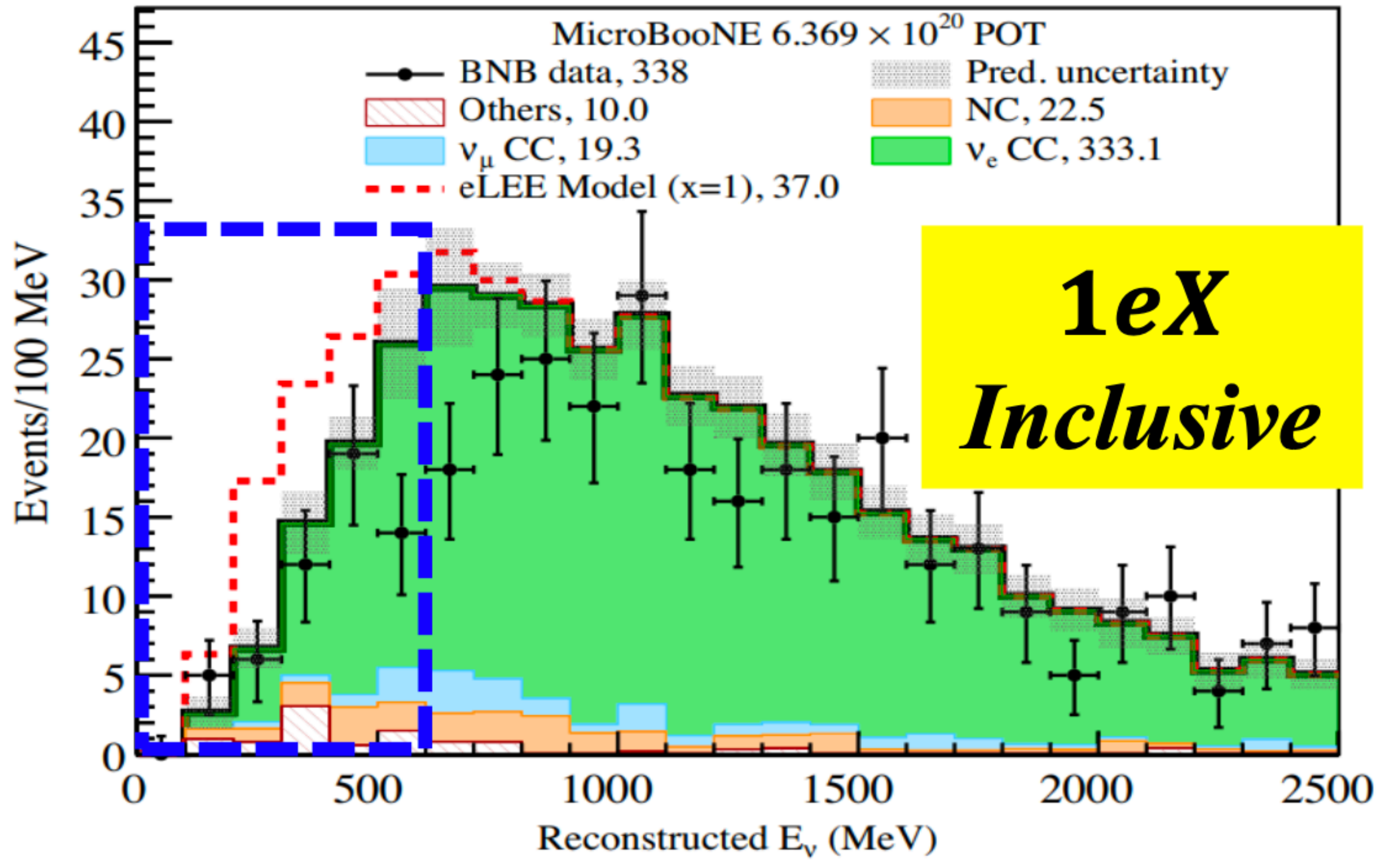



Phys. Rev. D105, 112003 (2022)

Phys. Rev. D105, 112004 (2022)

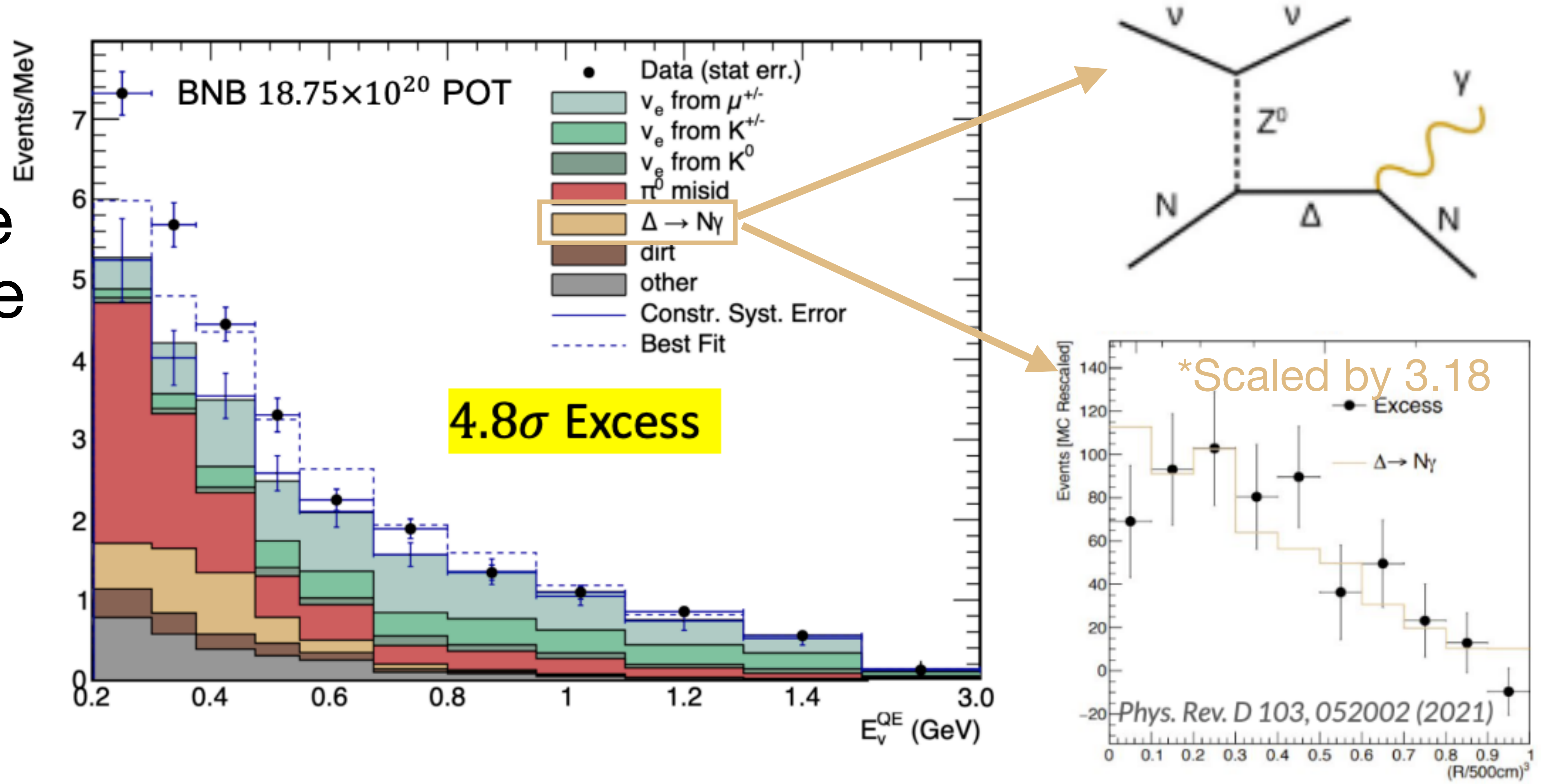


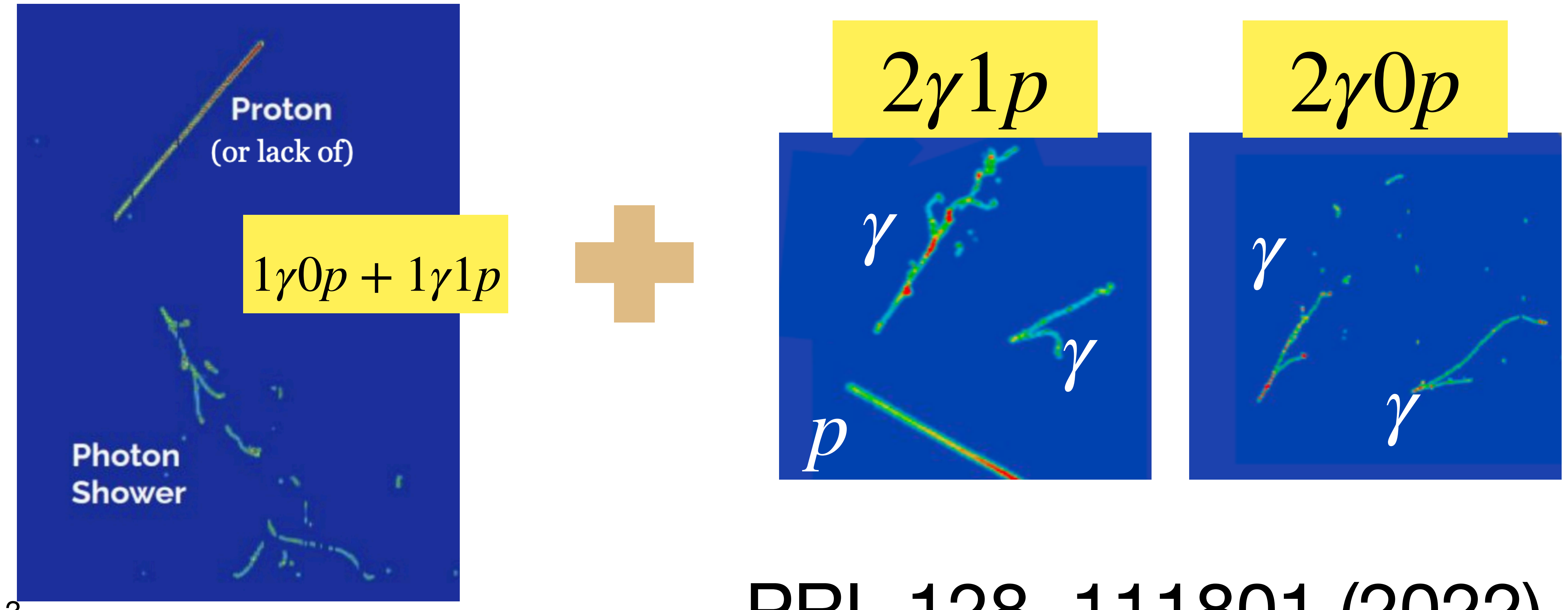

Phys. Rev. D105, 112005 (2022)

Phys. Rev. Lett. 128, 241801 (2022)

# gLEE Search [single photon production]

- Search for single photons from $NC\ \Delta$ radiative decays → predicted to be one major source of single-photons at these energies
- It's a known background, that was not constrained directly by the MiniBooNE experiment
- Enhancement in $NC\ \Delta \rightarrow N\gamma$ (N=p,n) with a factor of x3.18 gave good agreement with the observed LEE in various phase space
- Four channel fit for the analysis:
  - Two $NC\ \Delta \rightarrow N\gamma$ reach single photon selections
  - Two high-statistics $NC\ \pi^0$ reach two-photon selections

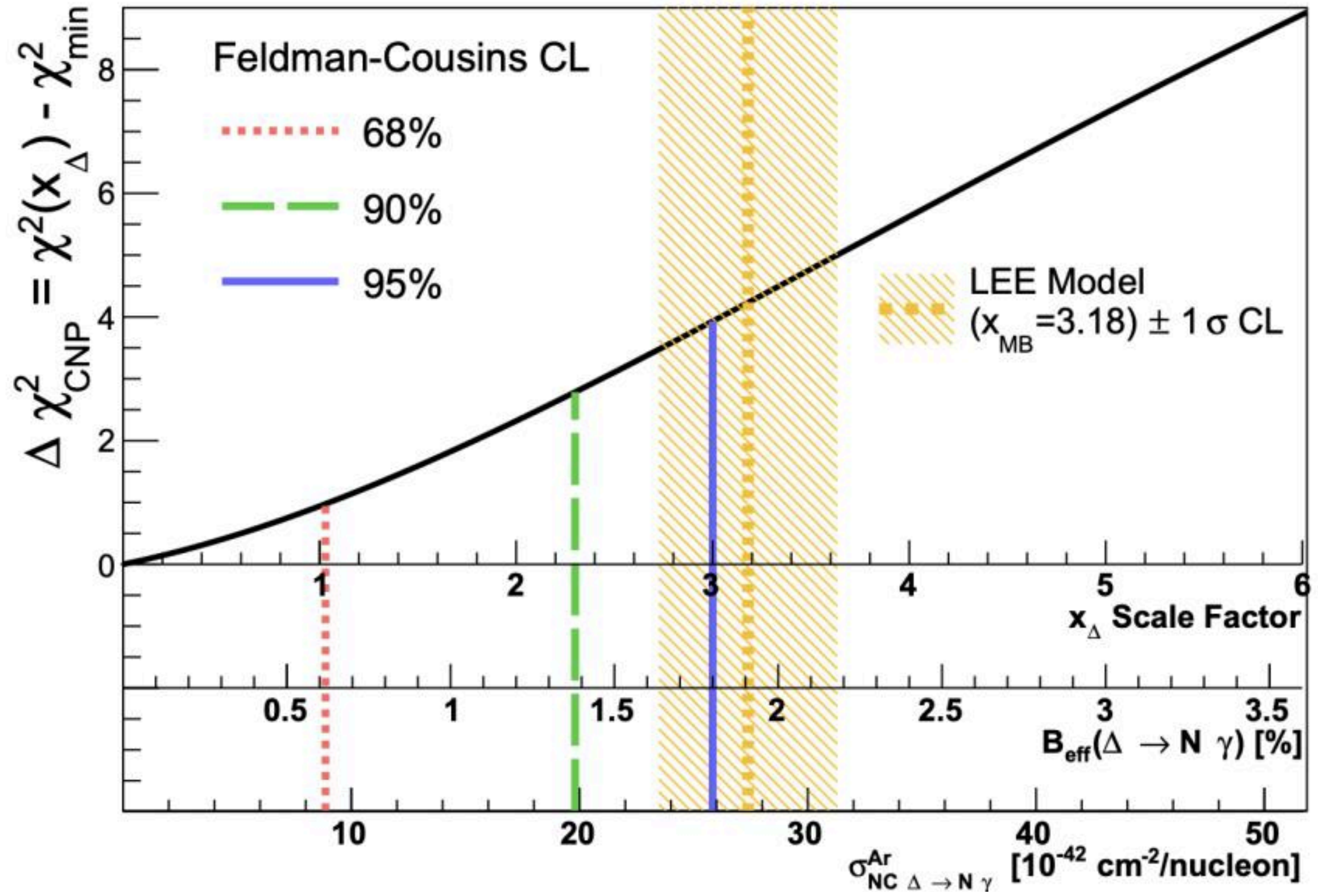



PRL 128, 111801 (2022)

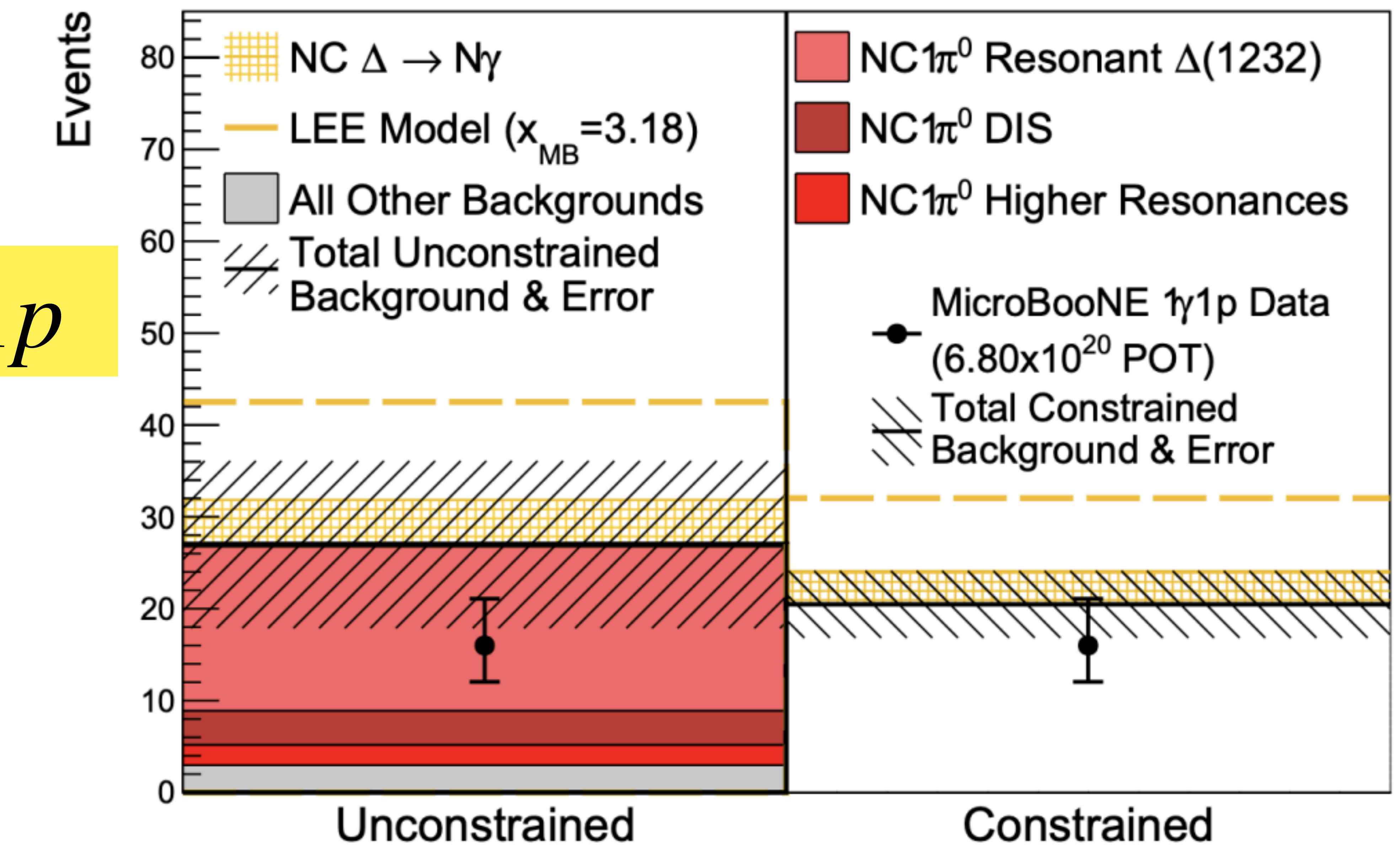
# gLEE Results

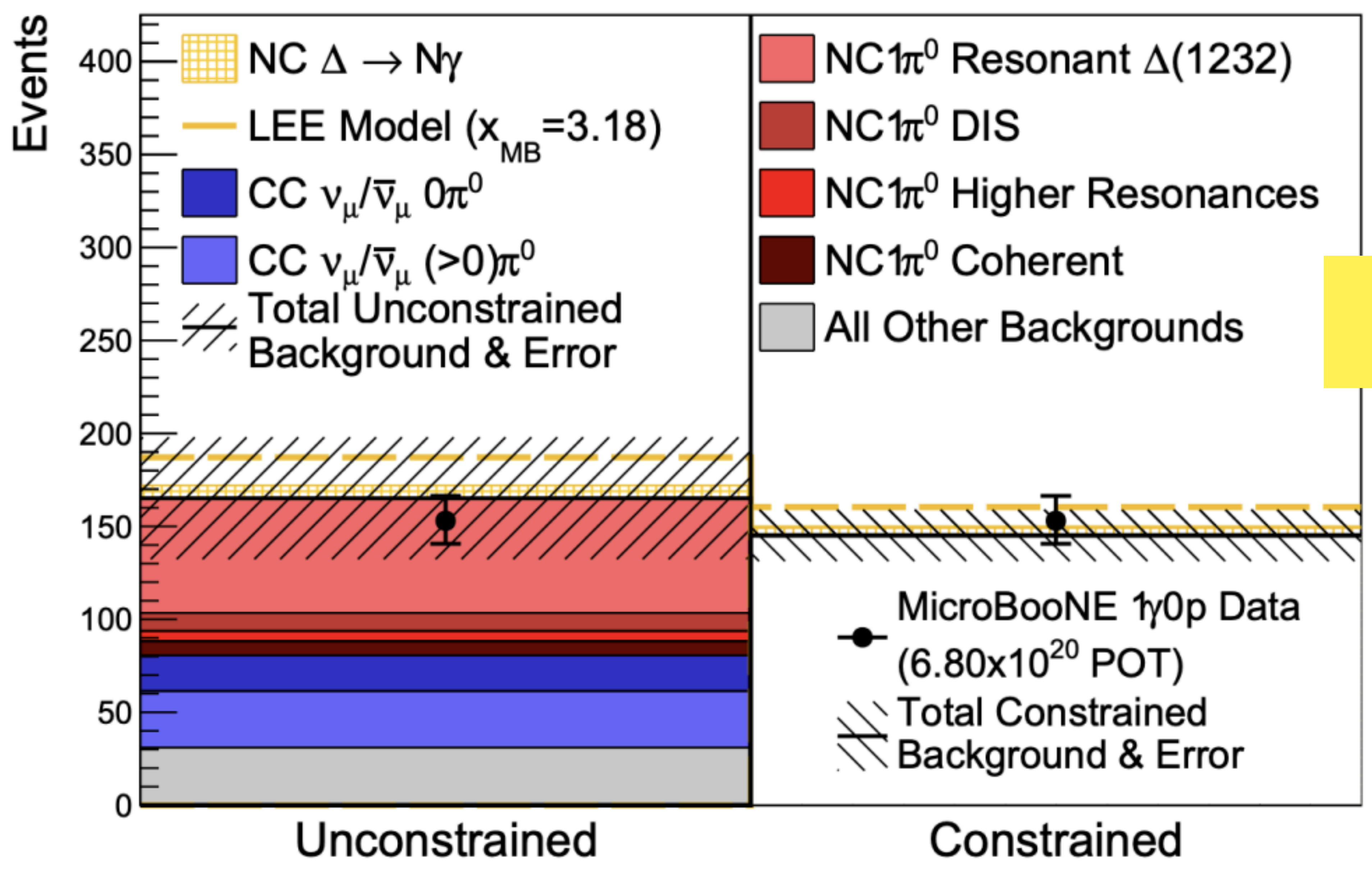
PRL 128, 111801 (2022)




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

$1\gamma1p$

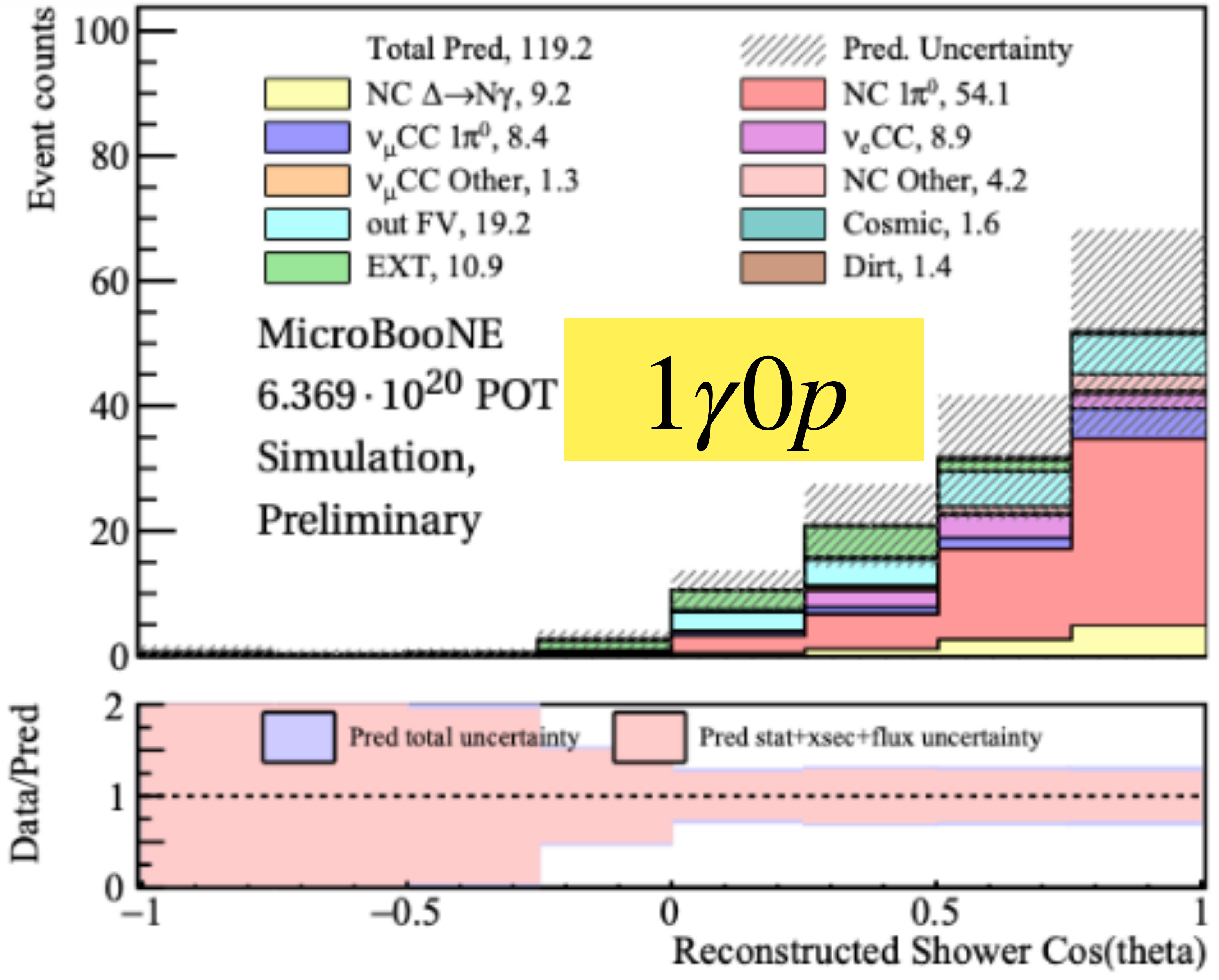


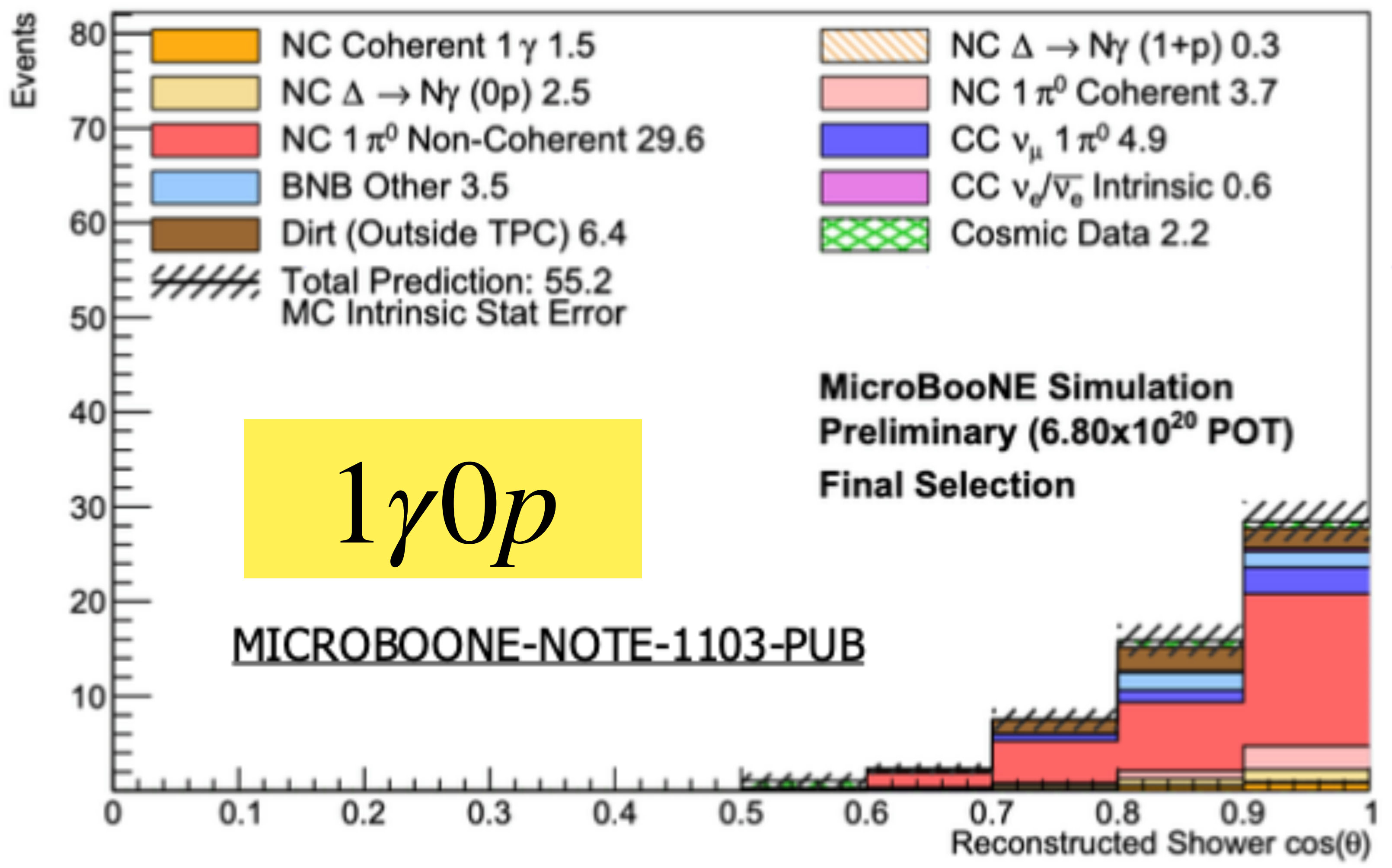

$1\gamma0p$

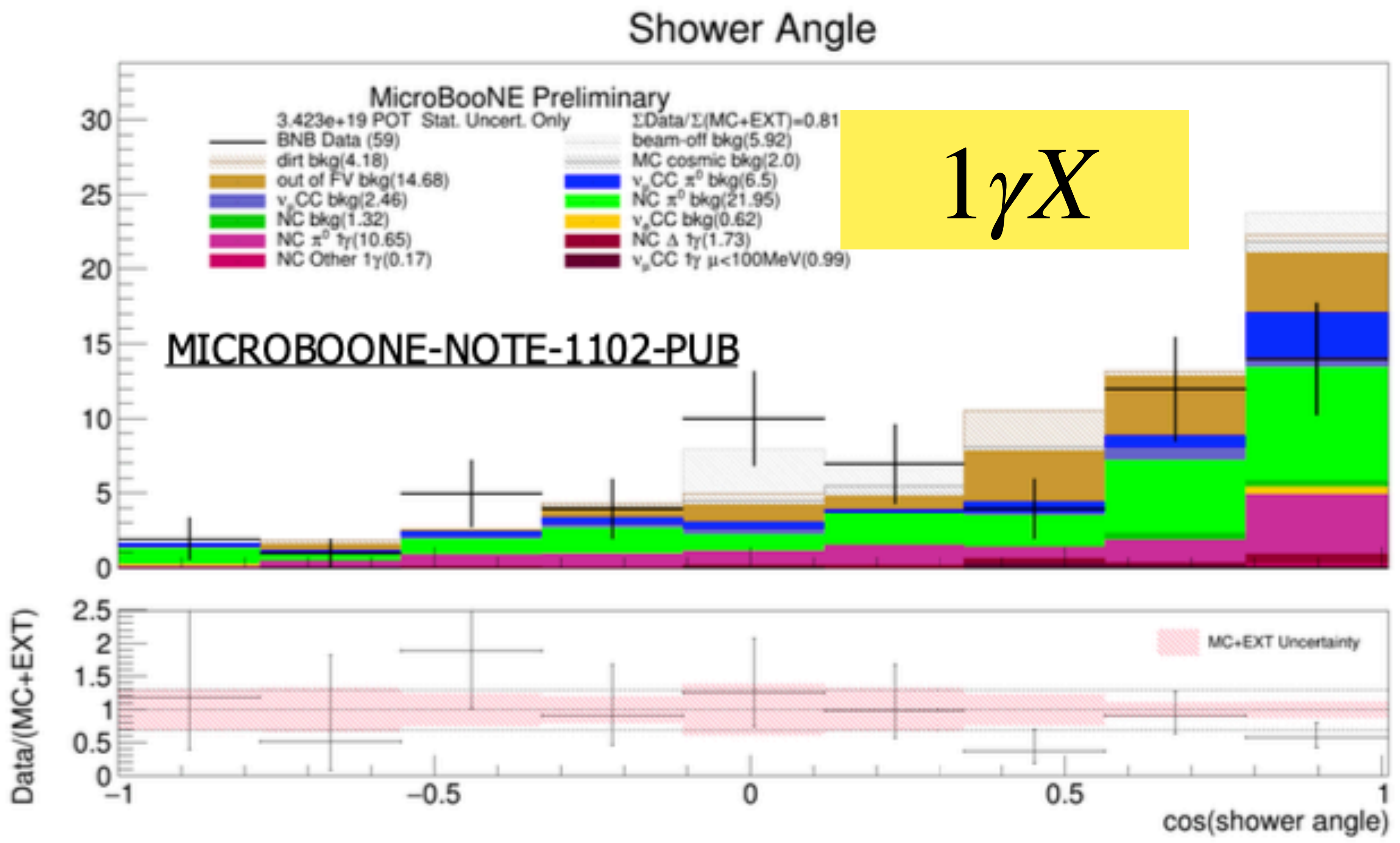
# More Photon Search Coming!

- $NC\ \Delta \rightarrow N\gamma$ cross check using $1\gamma 0p$ and $1\gamma Np$ channels
  - Uses alternative reconstruction
  - More sensitive to the $1\gamma 0p$ channel
- Coherent-like single-photon production search builds on the previous $1\gamma 0p$ result
  - Looking for forward-going photons with no hadronic activity.
  - Closely follows the expected LEE signal.
- Inclusive single photon $(1\gamma X)$ is searching more generally for "single photon-like" final states
  - No dependence on model or requirement on hadronic activity.




MICROBOONE-NOTE-1104-PUB

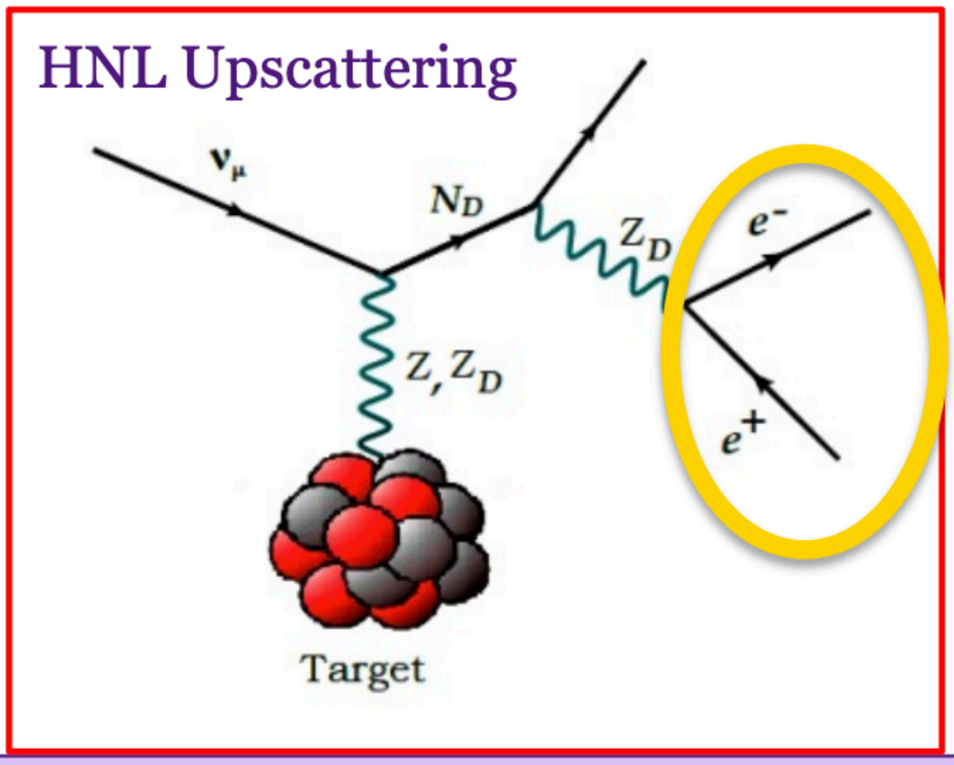


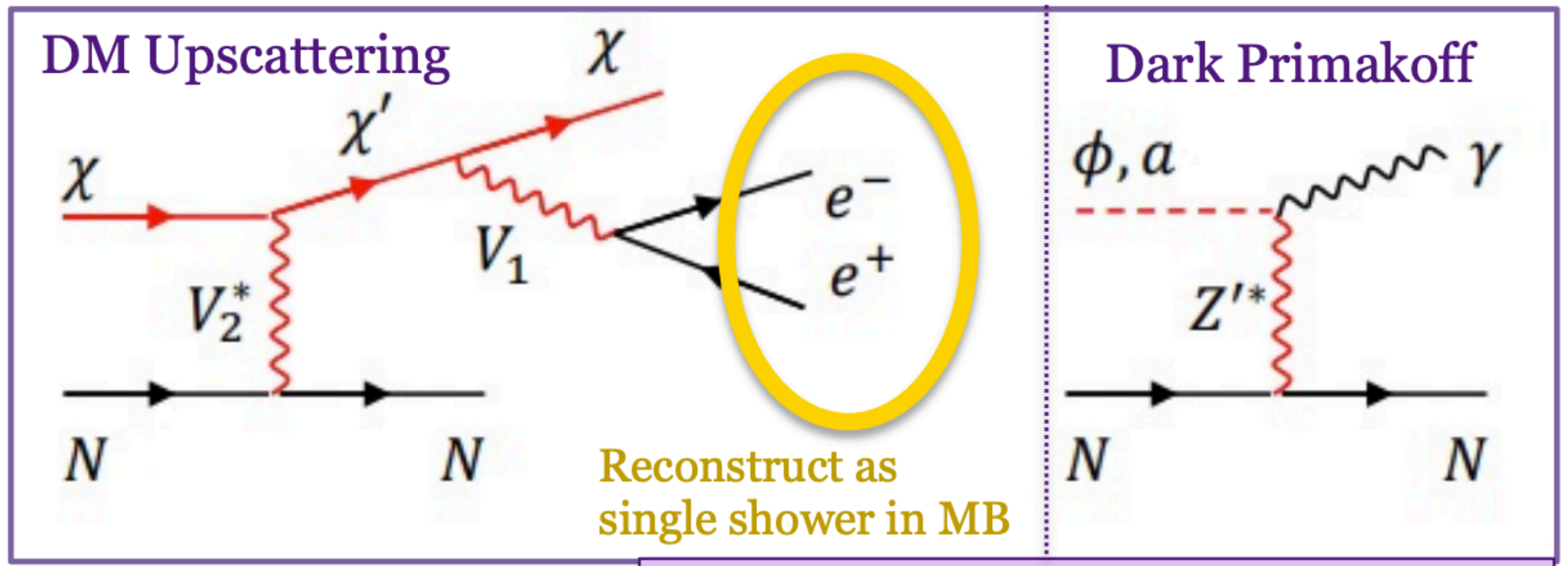
# BSM models

- Many BSM scenarios predict overlapping $e^+e^-$ final states that mimic a single shower topology → could explain the LEE
- Higgs Portal Scalar and Heavy Neutral Lepton searches already published
- Additional Higgs Portal Scalar, Heavy Neutral Lepton, Dark Trident and Millicharged Particles searches are ongoing

**MicroBooNE BSM Searches:**
Phys. Rev. D 101, 052001 (2020)
Phys. Rev. Lett. 127, 151803 (2021)
Phys. Rev. D 106, 092006 (2022)




*Bertuzzo et al, PRL 121, 241801 (2018)*
*Ballett et al, PRD 99, 071701 (2019)*
*Abdullahi et al, PLB 820, 136531 (2021)*




*Dutta et al, PRL 129, 111803 (2022)*

# 3(active) + 1(sterile) Neutrino Oscillation Framework

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

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

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

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

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

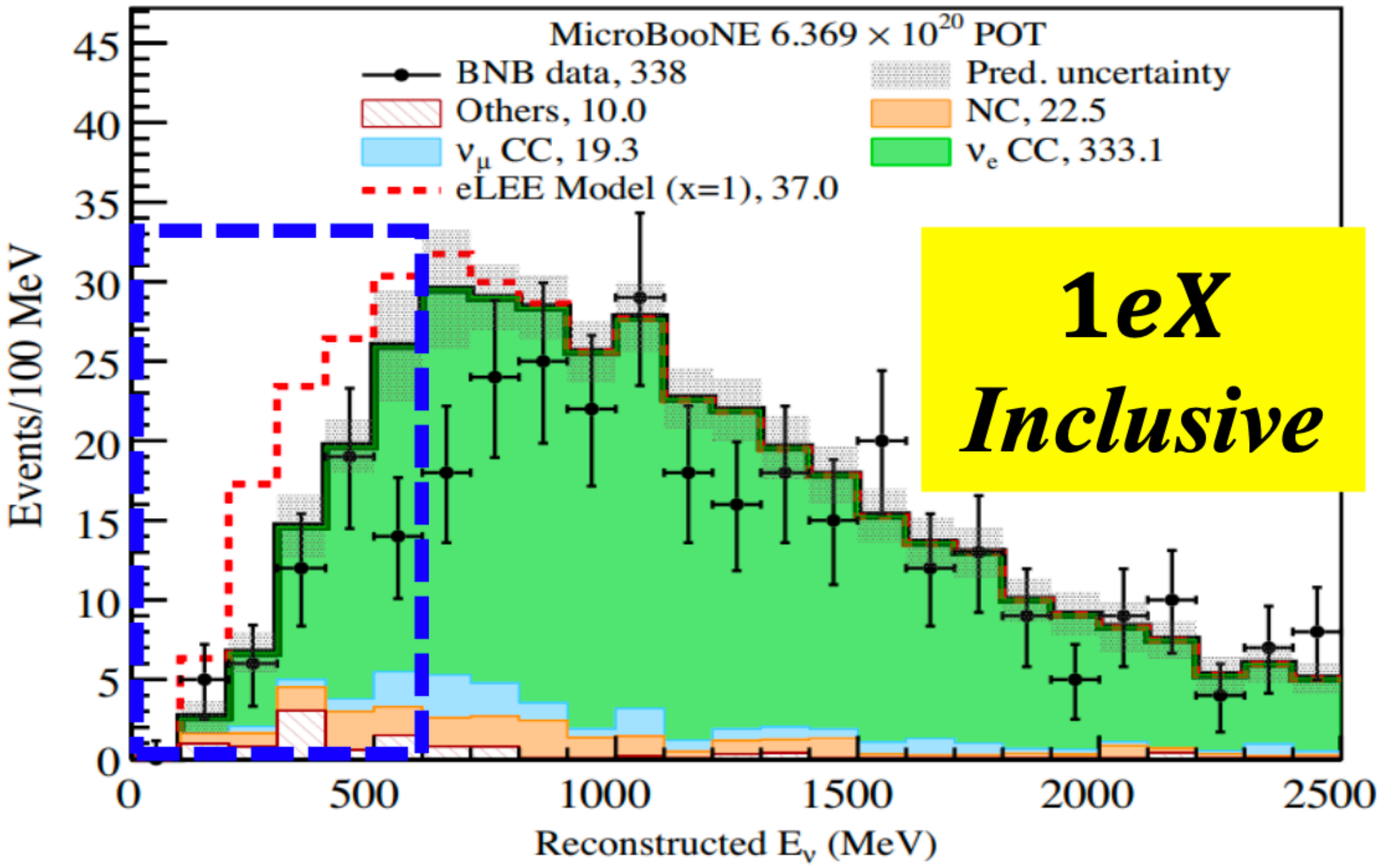
$\nu_\mu$ disappearance ($\nu_\mu \to \nu_\mu$): $\sin^2 2\theta_{\mu\mu} = 4\cos^2\theta_{14}\sin^2\theta_{24}\,(1 - \cos^2\theta_{14}\sin^2\theta_{24})$

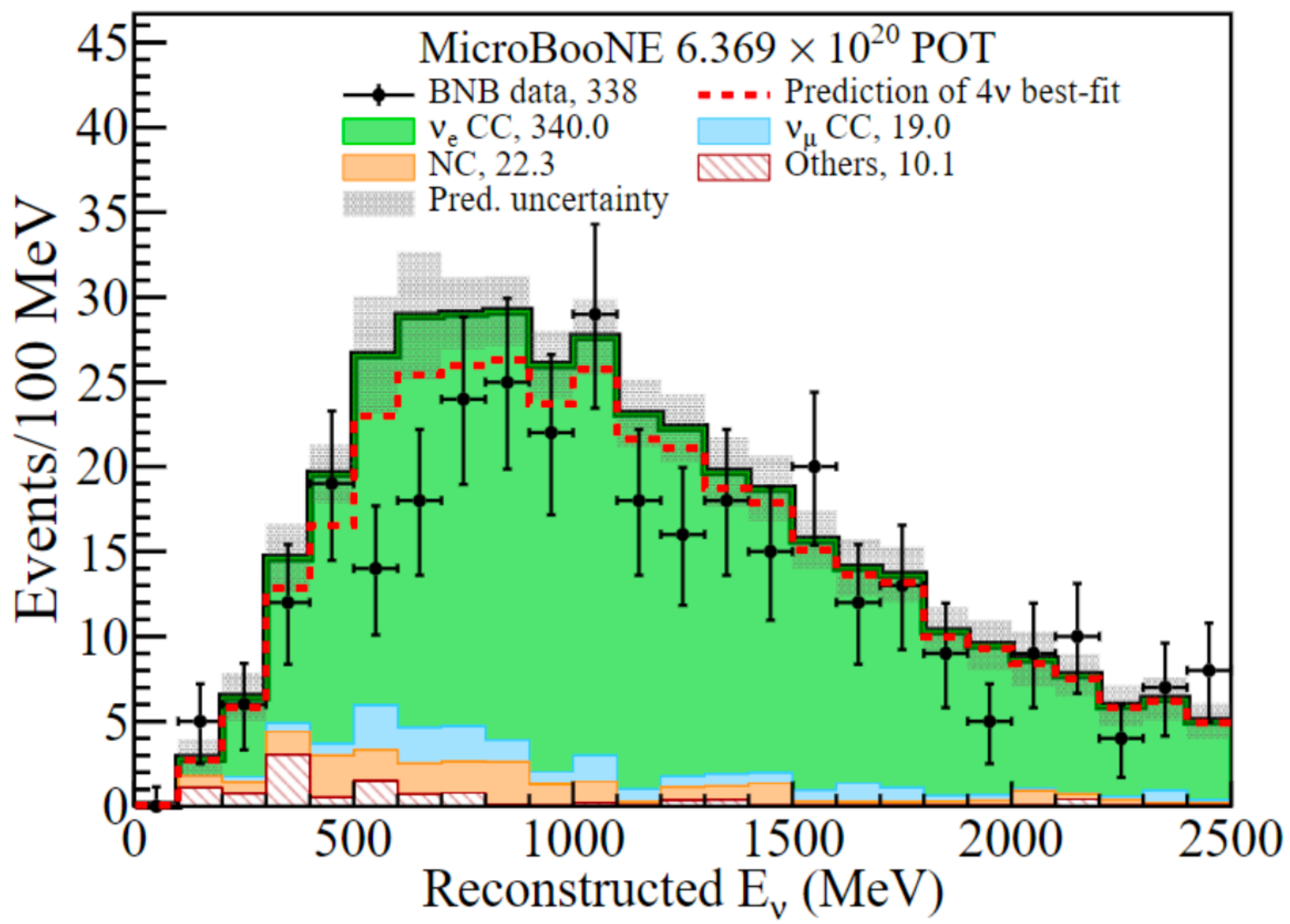
$\nu_e$ appearance ($\nu_\mu \to \nu_e$): $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\sin^2\theta_{24}$

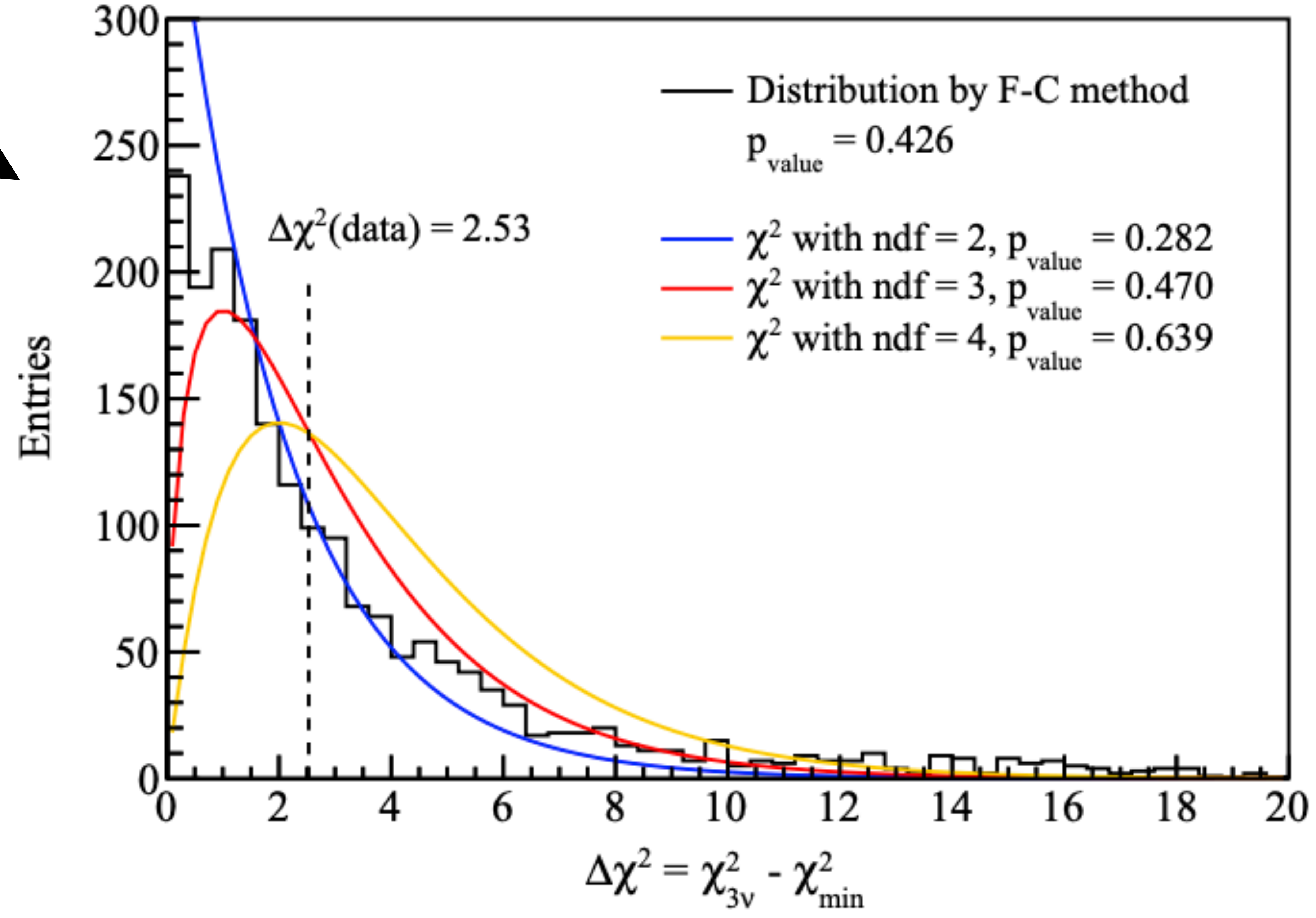
- In MicroBooNE analysis, the above three oscillation effects are applied to all $\nu_e$ and $\nu_\mu$ events; the $\nu_\mu$ appearance ($\nu_e \to \nu_\mu$) is ignored because of tiny $\frac{\nu_e \text{ flux rate}}{\nu_\mu \text{ flux rate}} \sim 0.005$

# 3+1 Oscillation Analysis using Wire-Cell Inclusive Selections

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



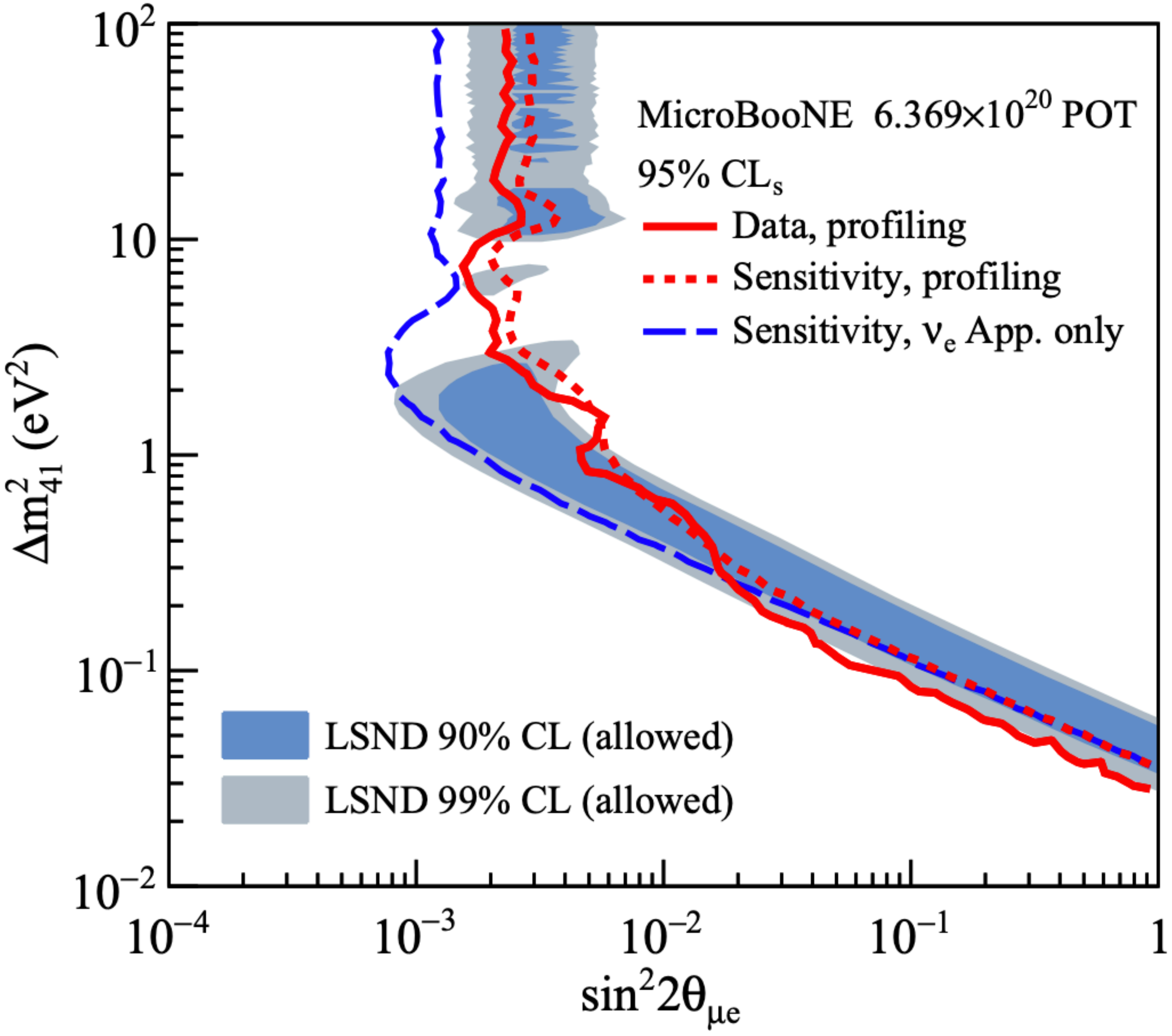




- Inclusive eLEE search was reinterpreted under a sterile neutrino oscillation hypothesis [Considered $\nu_e$ appearance and $\nu_e$ disappearance effects simultaneously]
- The BNB data result is found to be consistent with the $3\nu$ hypothesis within $1\sigma$ following the Feldman-Cousins approach

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

# MicroBooNE 3+1 Exclusion Results [$\Delta m^2_{14}$ vs $\sin^2 2\theta_{\mu e}$]

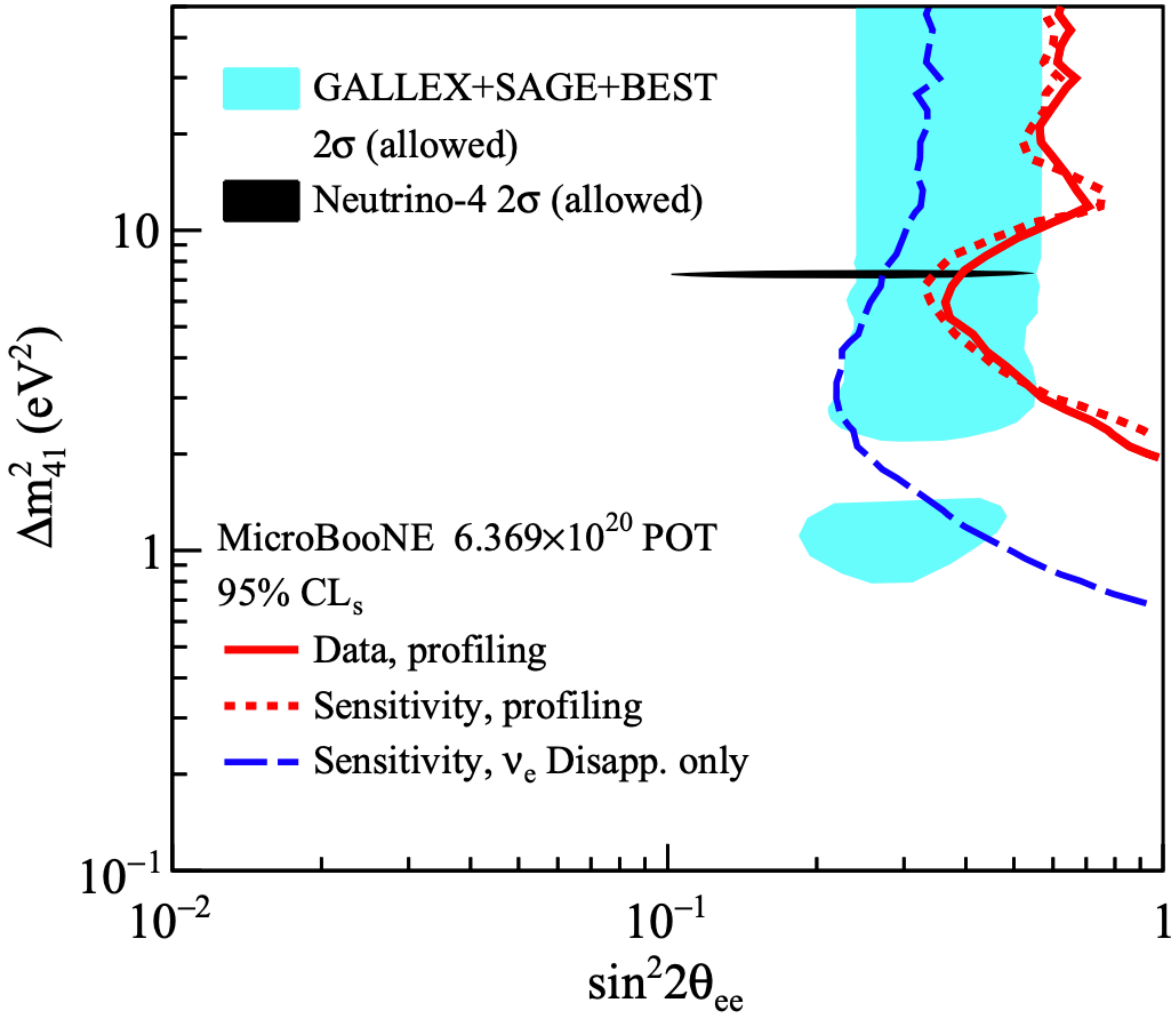
- 2D profiled (on $sin^2\theta_{24}$) result : full 3+1 analysis at each point in the parameter space $[\nu_\mu \rightarrow \nu_e\ ,\ \nu_e \rightarrow \nu_e\ , \nu_\mu \rightarrow \nu_\mu\ ]$
- $\nu_e$ appearance-only : more stringent limit. However, it is physically not allowed in the 3+1 framework. (non-zero $\nu_e$ appearance requires both $\nu_e$ and $\nu_\mu$ disappearance) $[\nu_\mu \rightarrow \nu_e]$



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

# MicroBooNE 3+1 Exclusion Results
# [$\Delta m^2_{14}$ vs $\sin^2 2\theta_{ee}$]

- 2D profiled (on $sin^2\theta_{24}$) result : full 3+1 analysis at each point in the parameter space [ $\nu_\mu \to \nu_e$ , $\nu_e \to \nu_e$ , $\nu_\mu \to \nu_\mu$ ]
- $\nu_e$ disappearance-only : more stringent limit corresponding to a fixed $sin^2\theta_{24} = 0$ [$\nu_e \to \nu_e$]

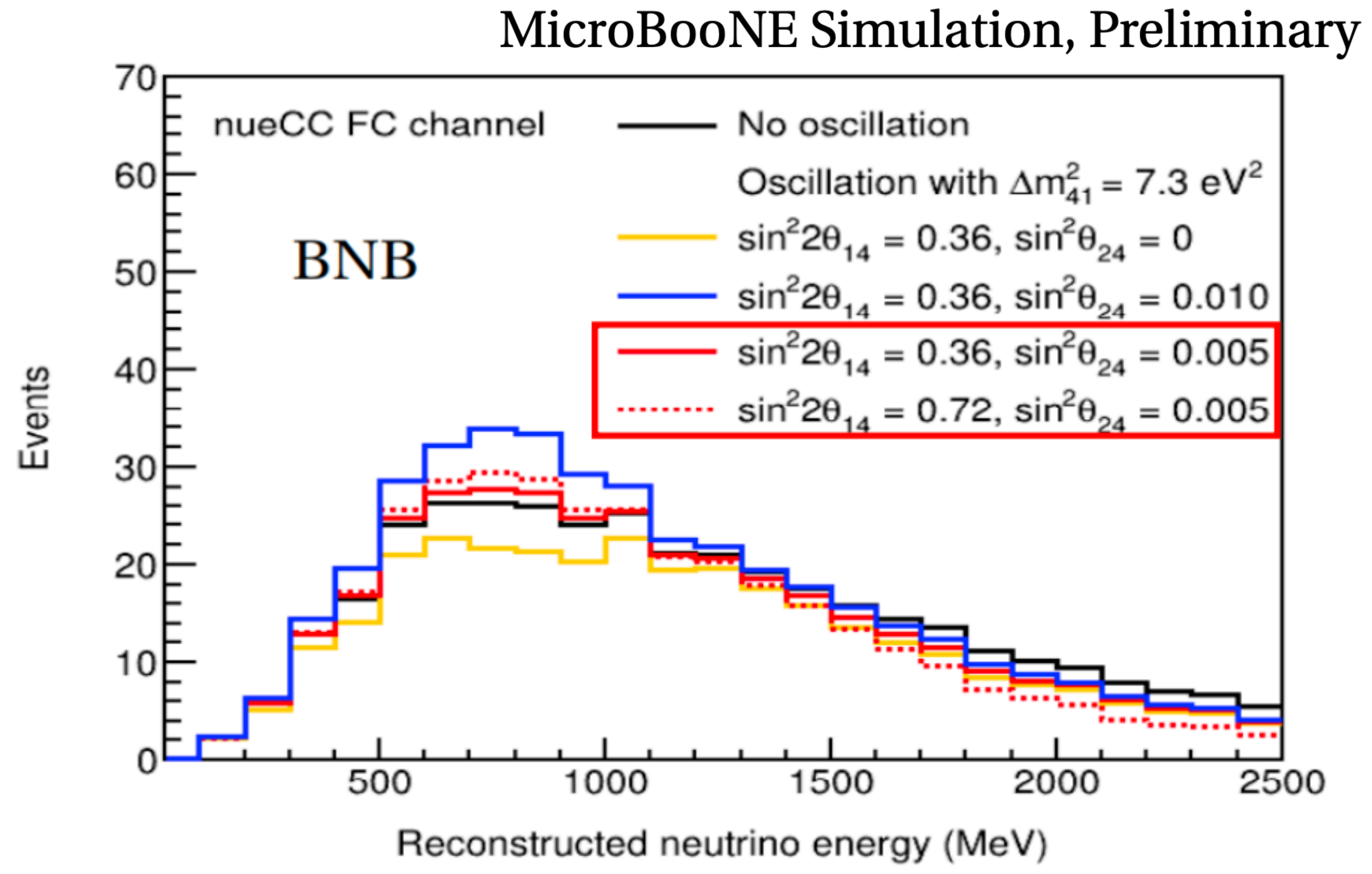


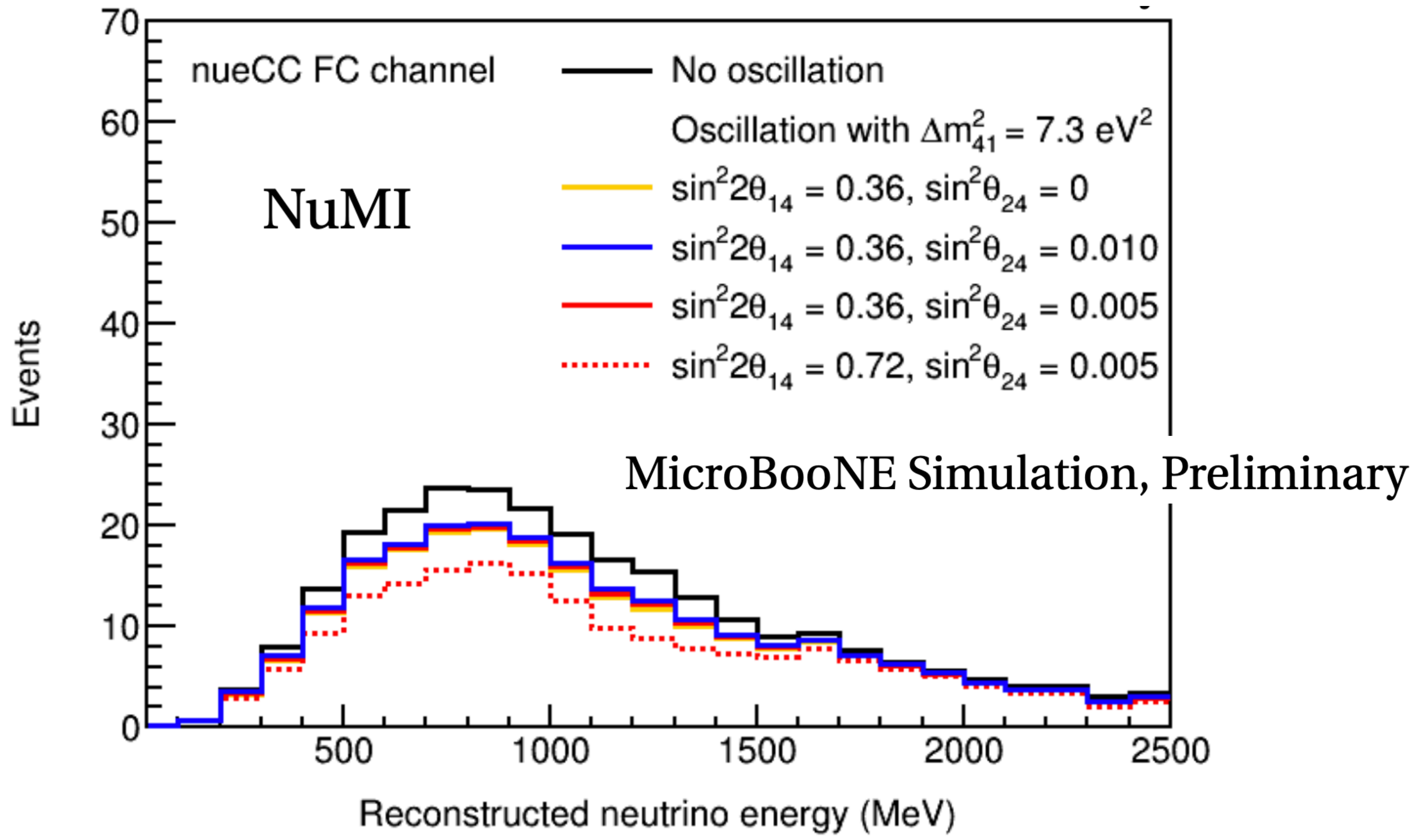
# Degeneracy of Oscillation Parameters

- Observed $\nu_e$ events are a combination result of $\nu_e$ appearance and disappearance:

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

- Degeneracy when $sin^2\theta_{24}$ approaches $R$ (the ratio of beam intrinsic $\nu_e$ and $\nu_\mu$ flux):
- Sensitivity/exclusion limits are much worse near degeneracy point
- BNB and NuMI beams have different degeneracy points:
  - ~0.005 for BNB [on-axis with baseline ~470m]
  - ~0.04 for NuMI [off-axis with baseline ~680m]

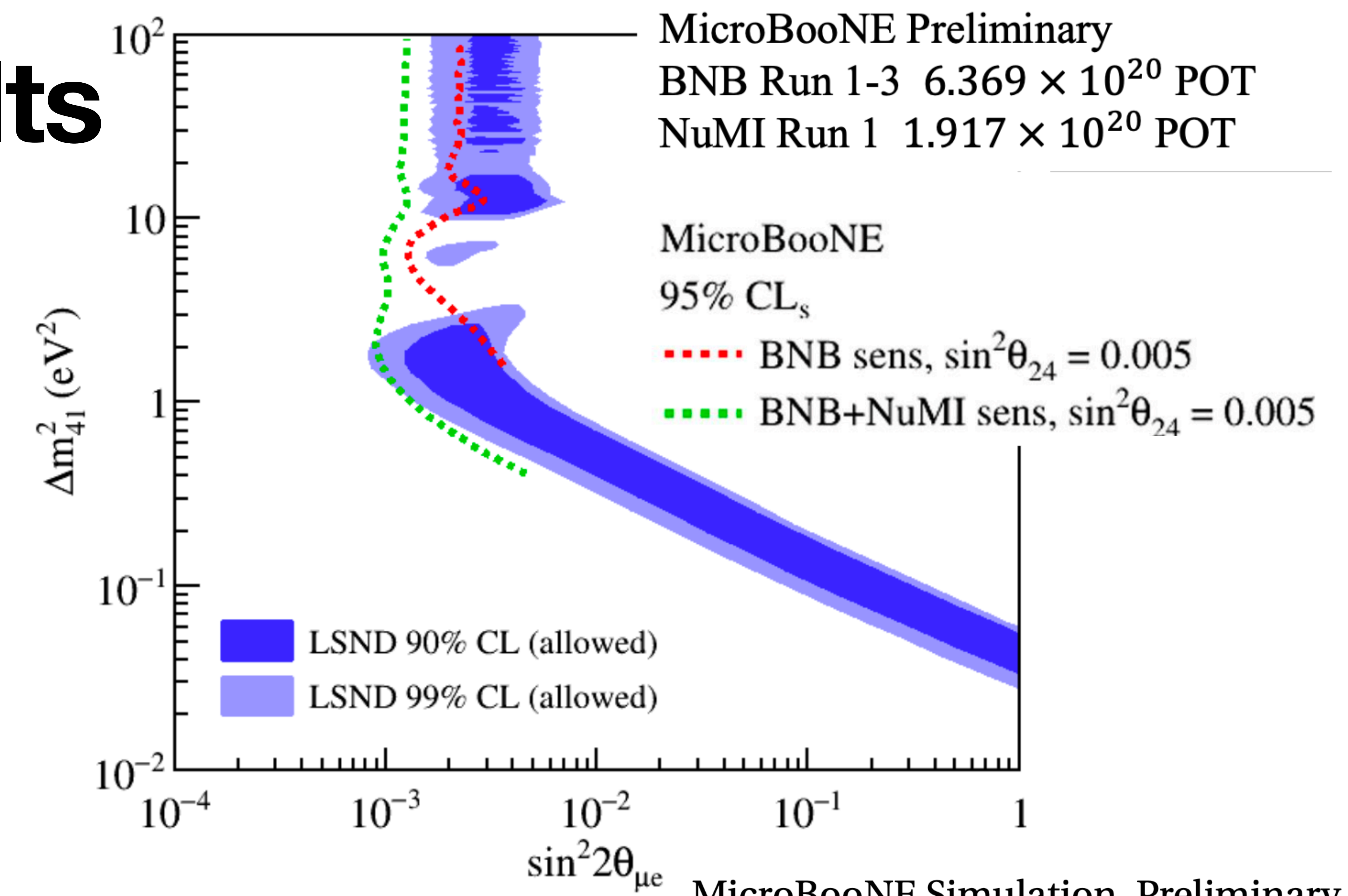


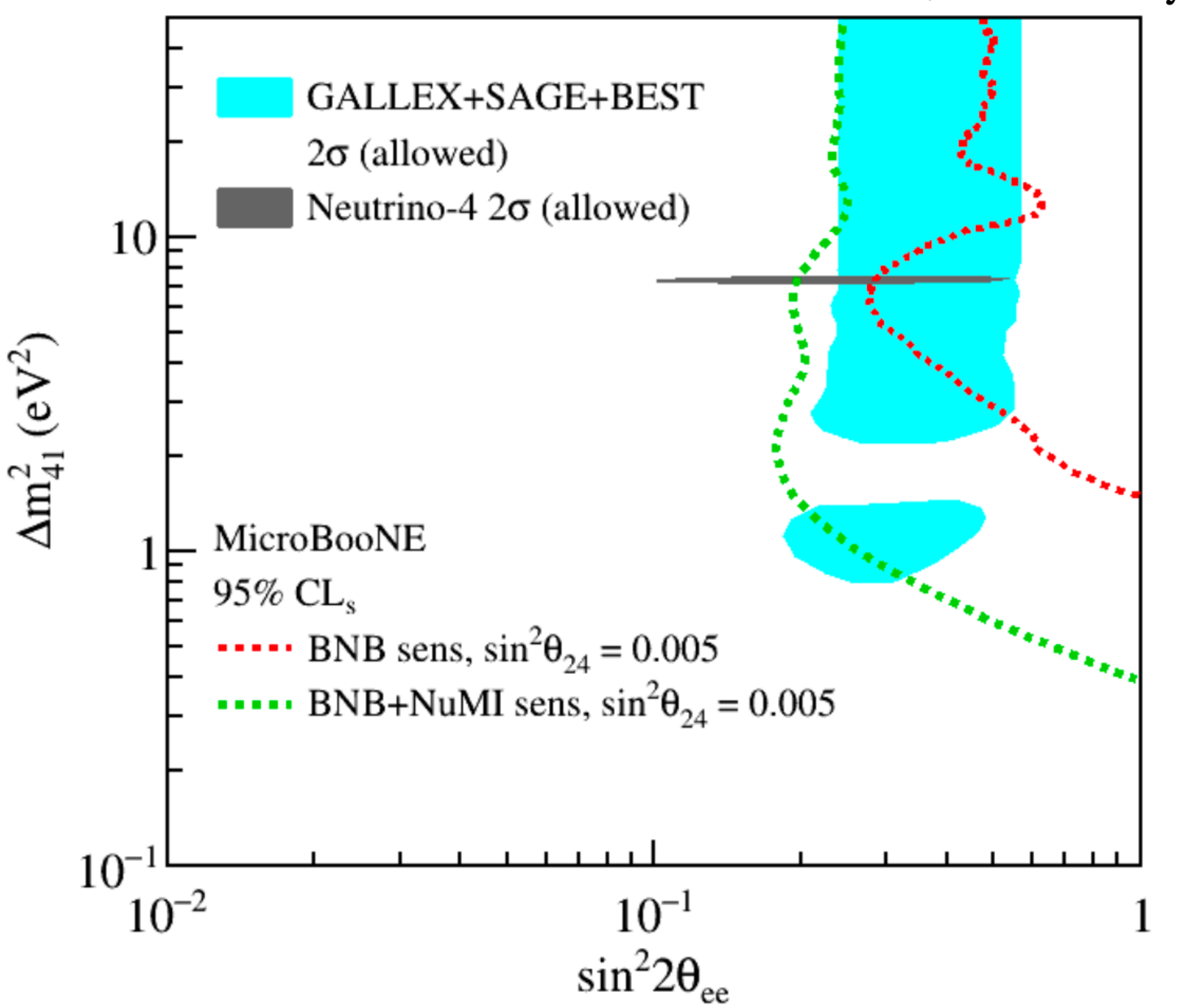




Combination of two beams can break degeneracy!

# MicroBooNE 3+1 Sensitivity Results by using BNB+NuMI

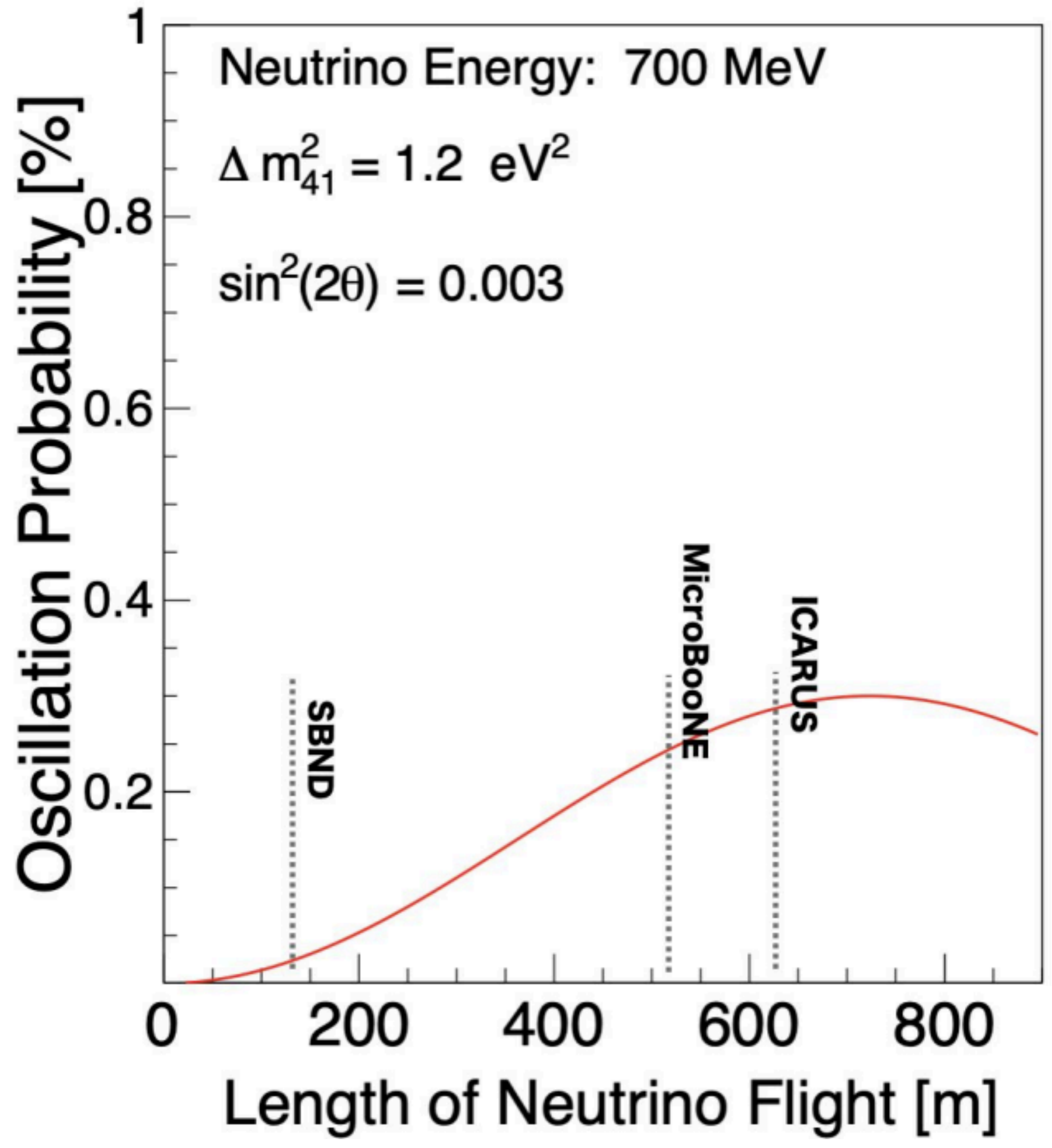
- Sensitivity is significantly improved (~ factor of 2) when combining both BNB and NuMI (mainly due to degeneracy mitigation)
- BNB+NuMI data results are expected to be sensitive to the Gallium/Neutrino-4 results, and LSND results



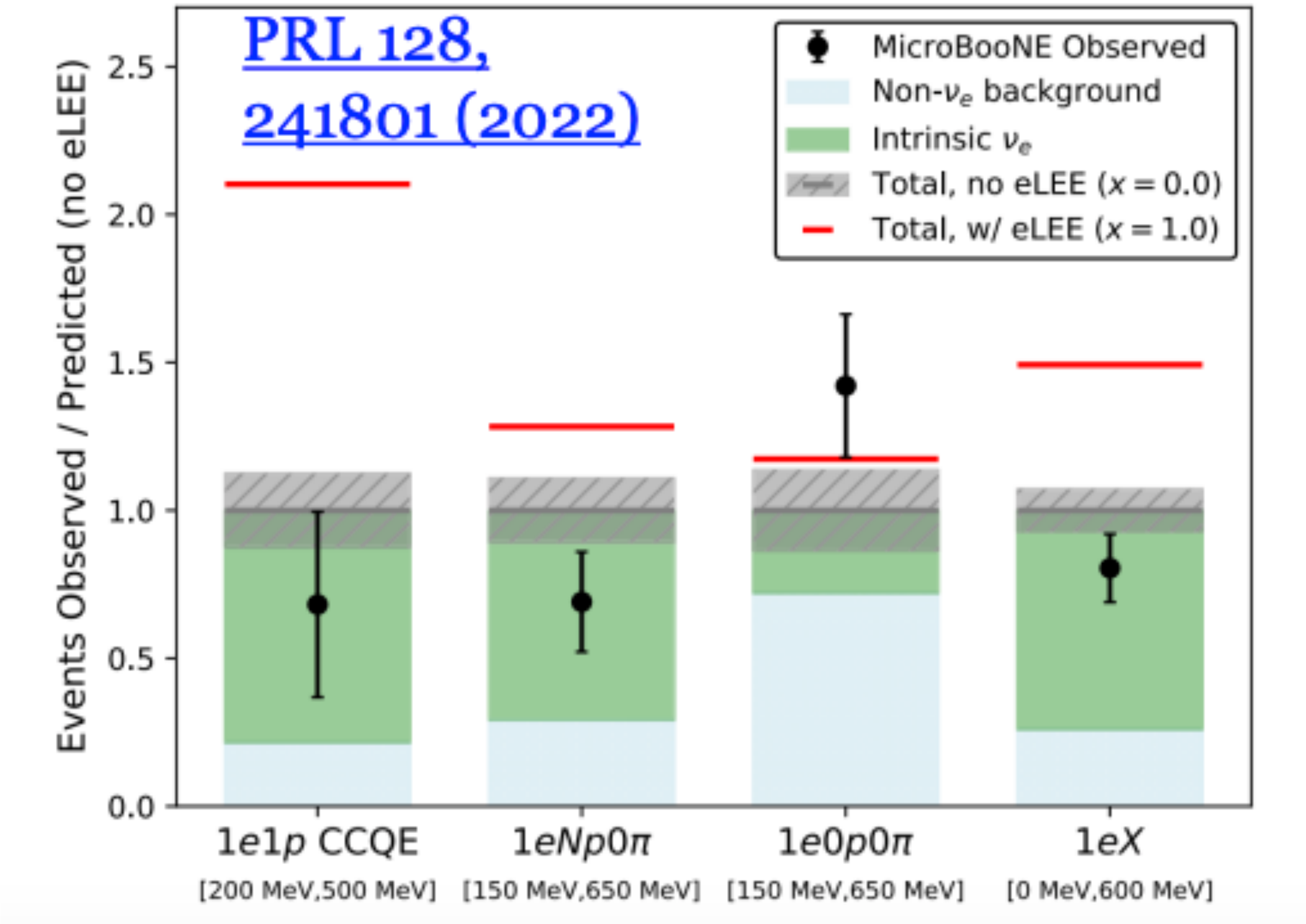
# SBN Program

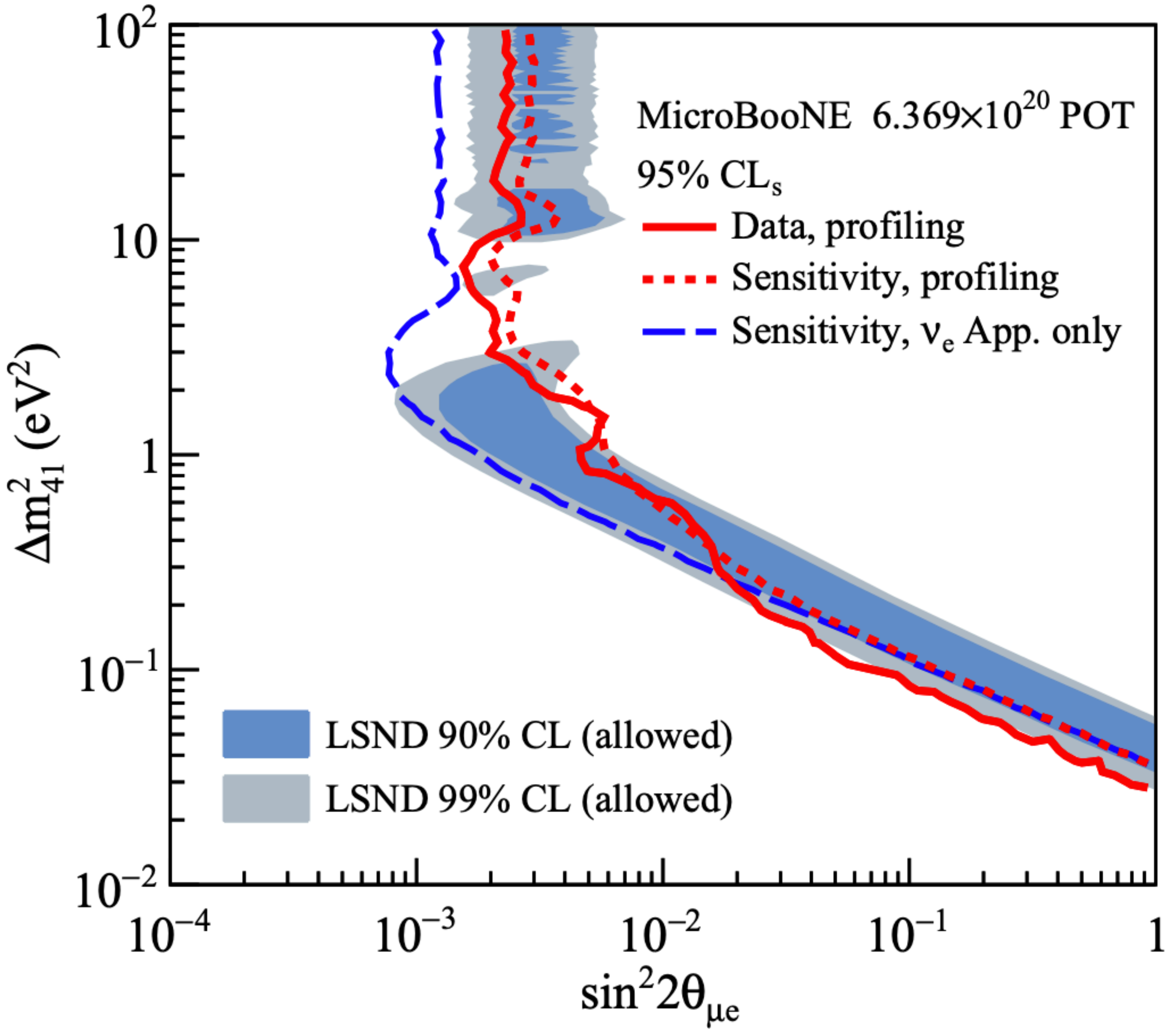
- The SBN program consists of three LArTPC detectors located in the BNB at Fermilab.
    - SBND [launching soon], MicroBooNE, and ICARUS [taking data].
- Goals:
    - New physics → particularly eV-scale sterile neutrinos
    - Detailed studies of neutrino-nucleus interactions at the GeV energy scale
    - Advancement of the liquid argon detector technology → the DUNE/LBNF long-baseline neutrino experiment in the next decade




# Summary

- MicroBooNE was designed to test the electromagnetic nature of the MiniBooNE anomalous excess
- No excess of single photons or single electrons was observed so far
- Full 3+1 oscillation analyses were carried out to interpret the MicroBooNE eLEE results under a sterile neutrino oscillation hypothesis:
  - The data (50% BNB total dataset) was found to be consistent with three-flavor hypothesis and exclusion limits were calculated using a frequentist approach
  - Unitizing both BNB and NuMI data, the 3+1 analysis will be sensitive to Gallium/Neutrino-4 and LSND results
- Search for BSM models involving electron-positron pair production is ongoing




# Thank you!

Brookhaven
National Laboratory

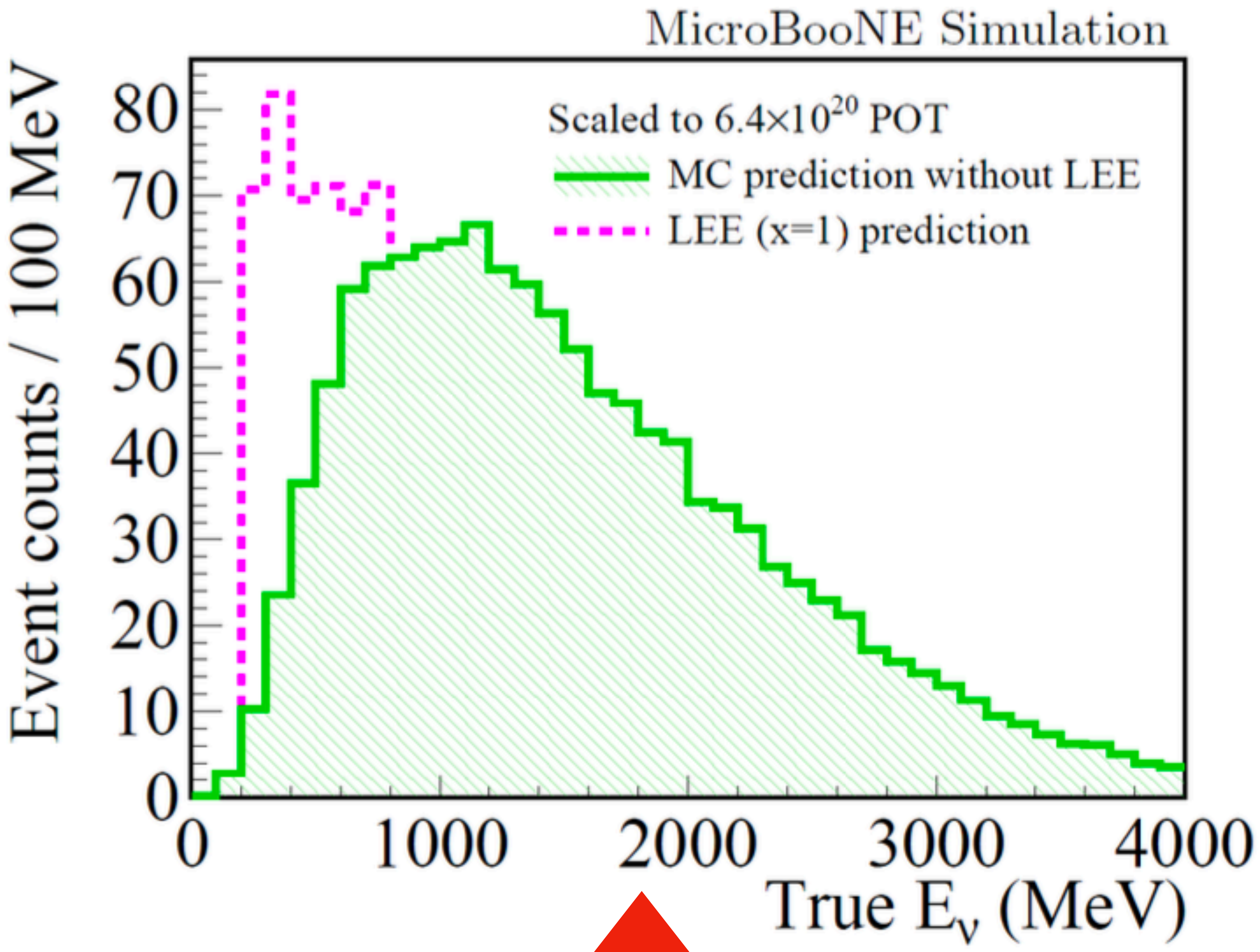
μBooNE
LArTPC

# Back up

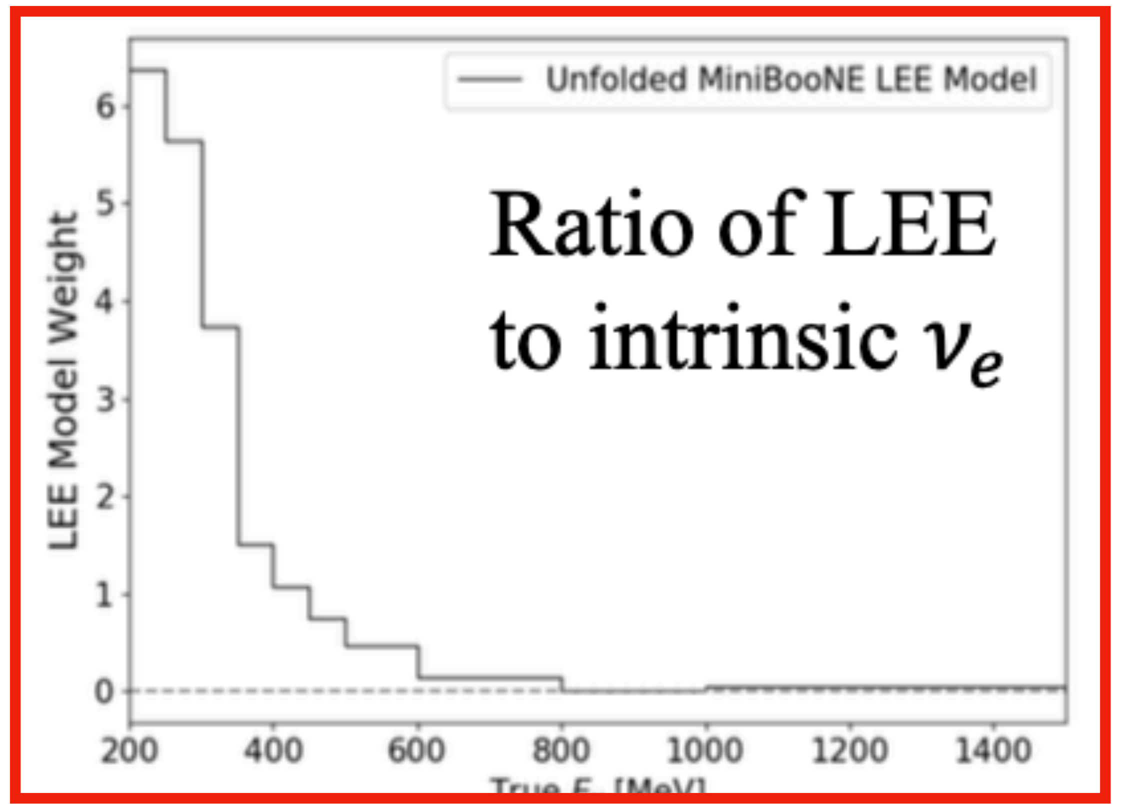
# eLEE Model
# [electron Low Energy Excess]

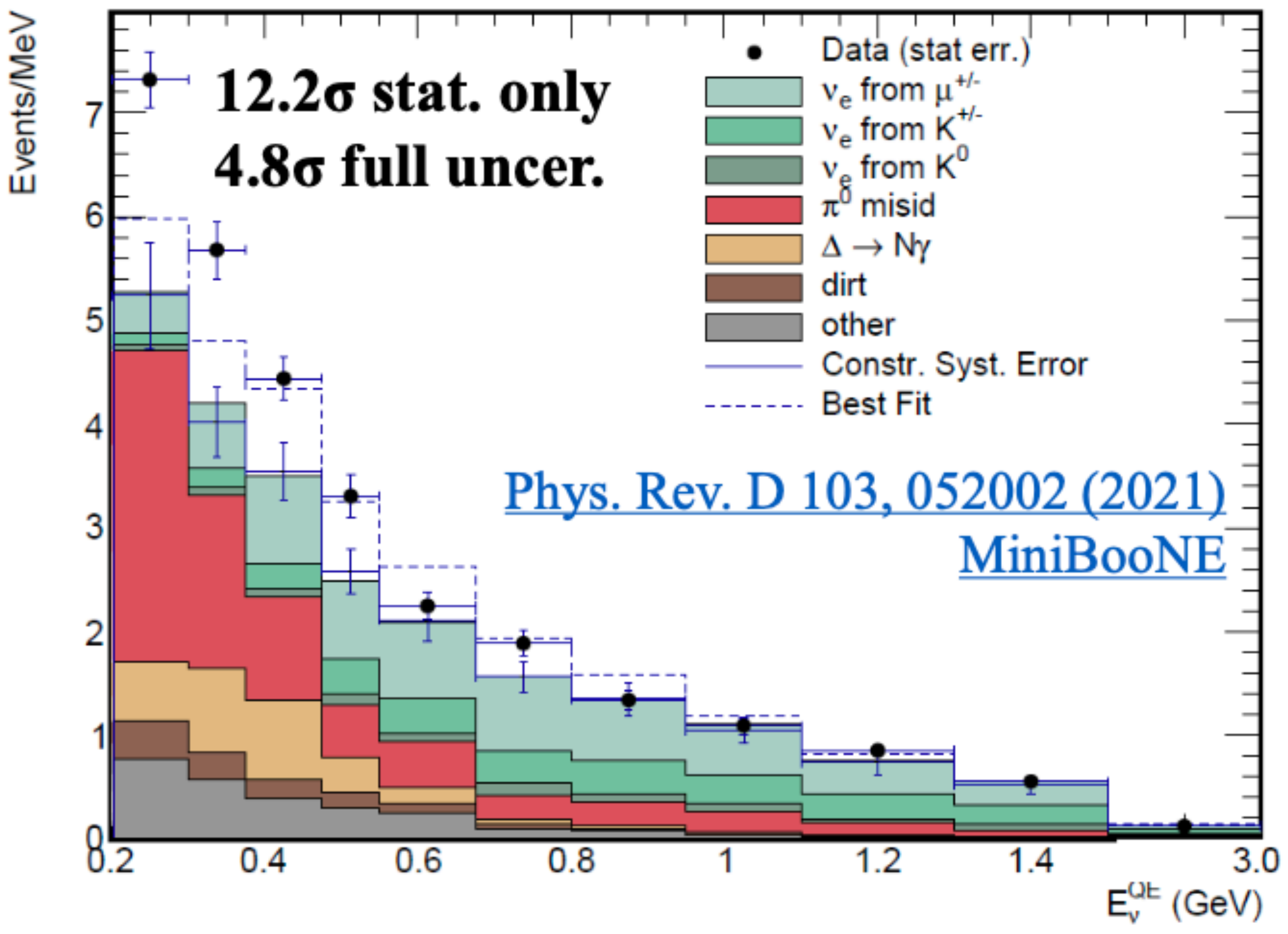
- Assumption : an energy-dependent enhancement of intrinsic $\nu_e$ events in the beam at low energy
- Empirical eLEE model is derived from MiniBooNE, by unfolding detector response, acceptance, efficiency
- One normalization parameter “x” is built in the model

MiniBooNE **x**:
1±0.08 (stat.)
1±0.21 (full)



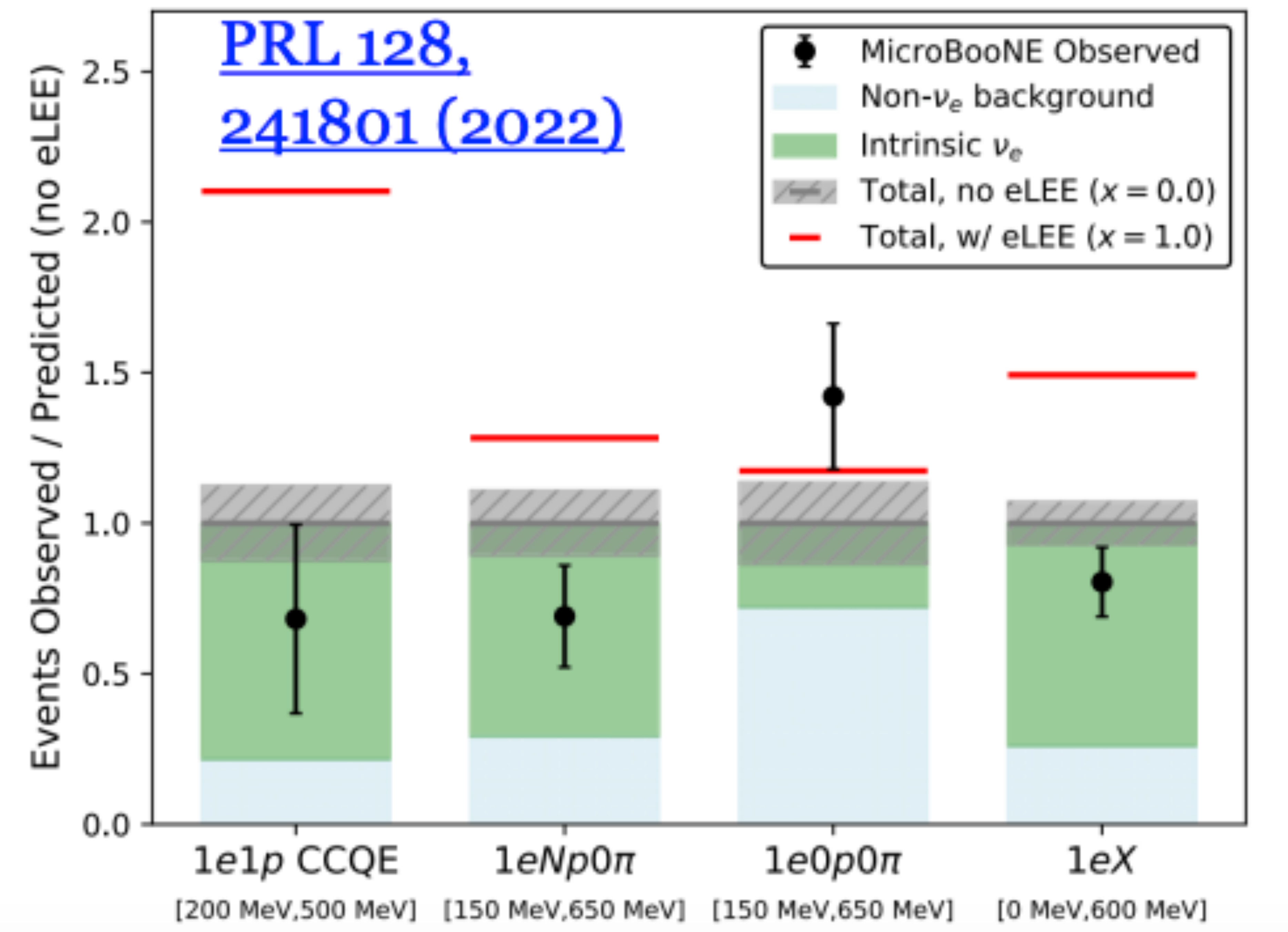

Unfolding



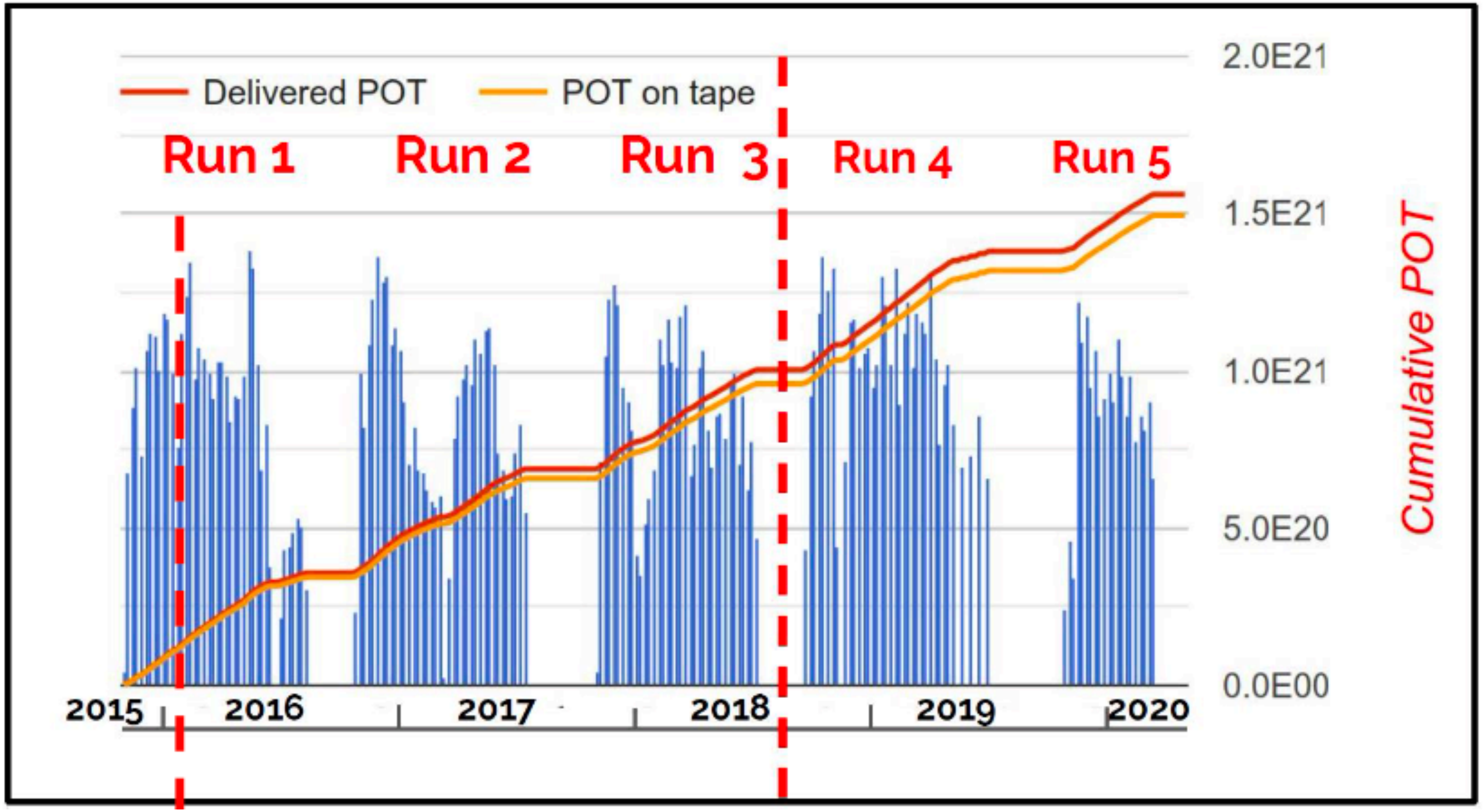
# eLEE Results [single bin]

- No observation of $\nu_e$ candidate excess in low energy region; except for the **low $\nu_e$ purity** $\mathbf{1e0p0\pi}$ channel
- Single-electron-alone explanation for MiniBooNE is ruled out at >97% CL



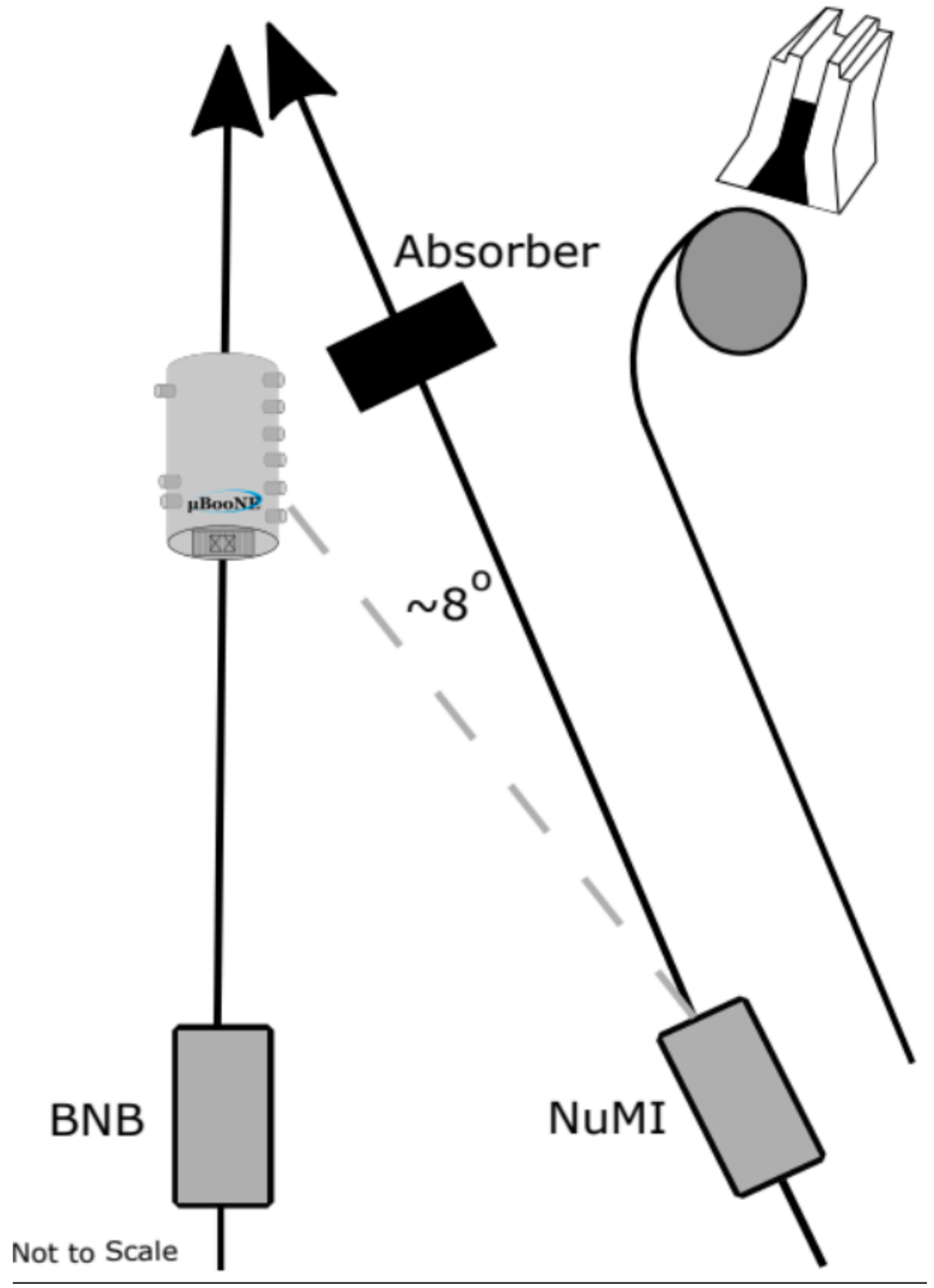

| Channel | Reconstruction | Efficiency | Purity | Data Events |
|---|---|---|---|---|
| CCQE 1e1p | Deep Learning | 6.6% | 75% | 25 |
| $1e0p0\pi$ | Pandora | 9% | **43%** | 34 |
| $1eNp0\pi$ | Pandora | 15% | 80% | 64 |
| Inclusive 1eX | WireCell | 46% | 82% | 606 |

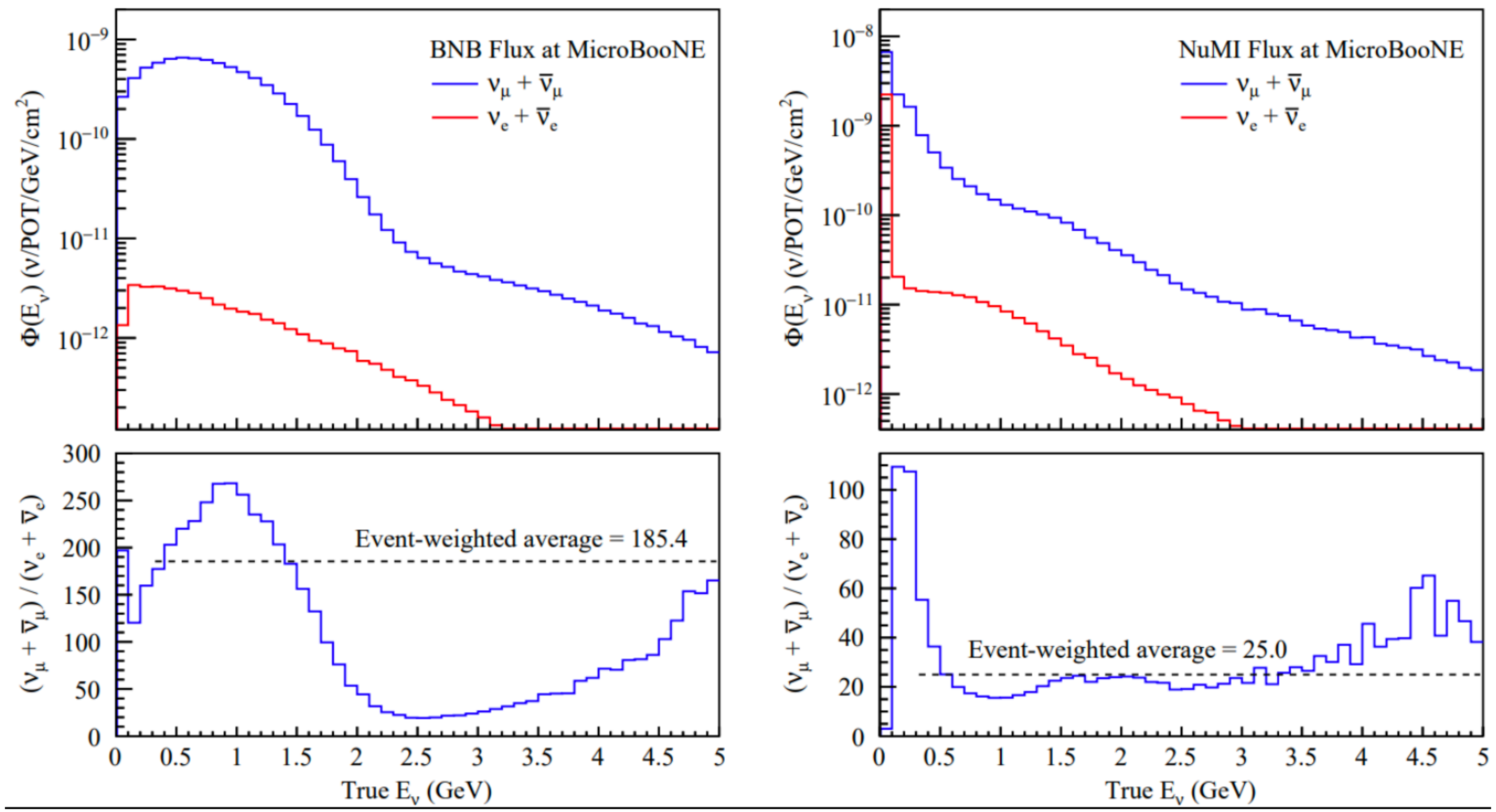
# MicroBooNE data



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

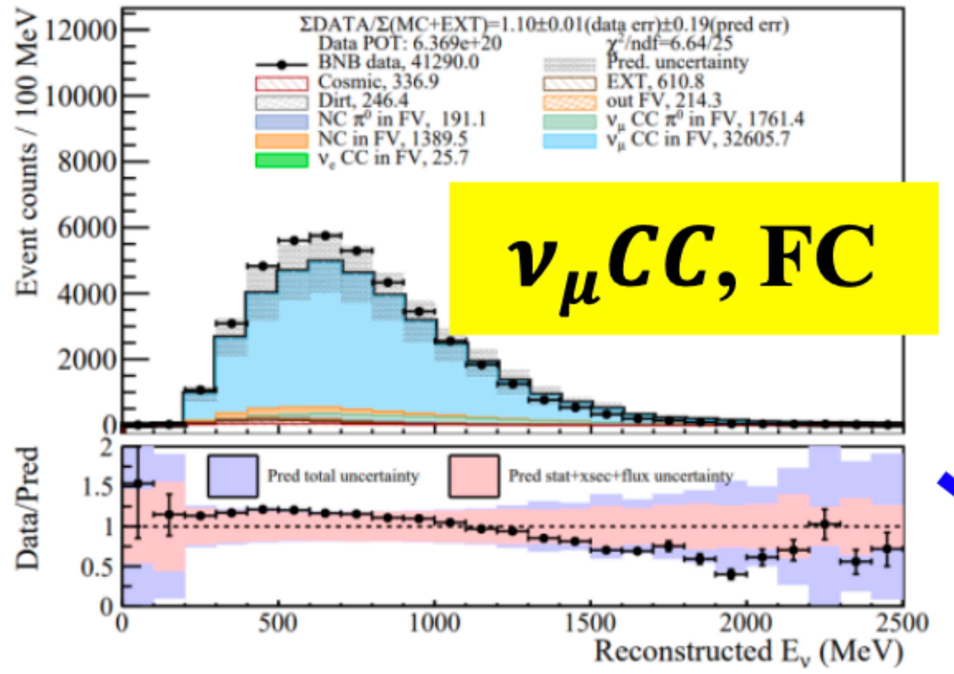
# BNB/NuMI fluxes

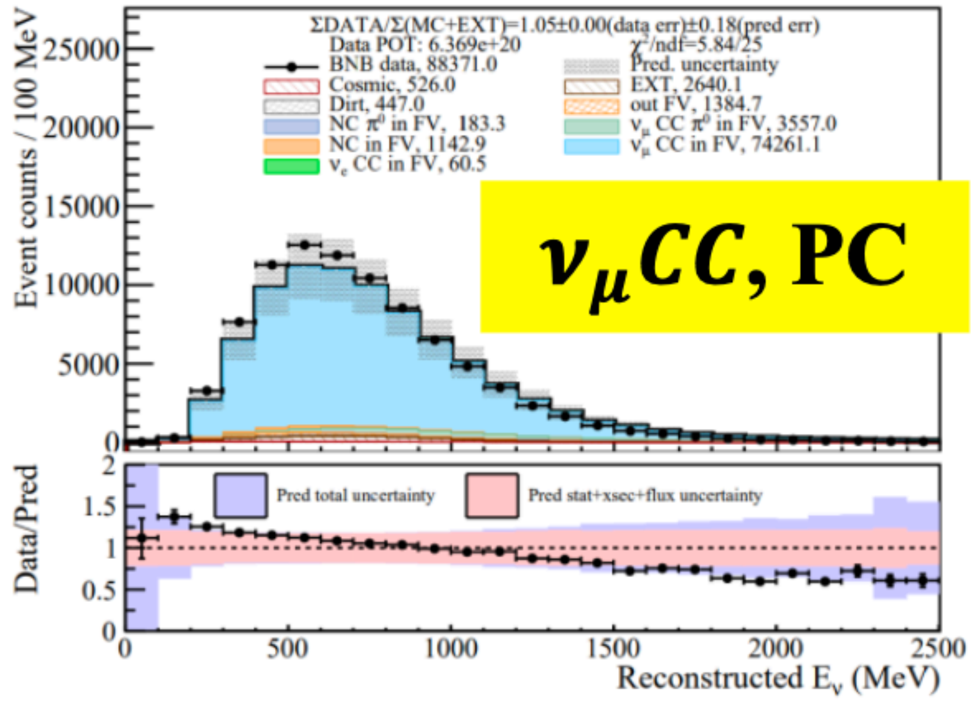


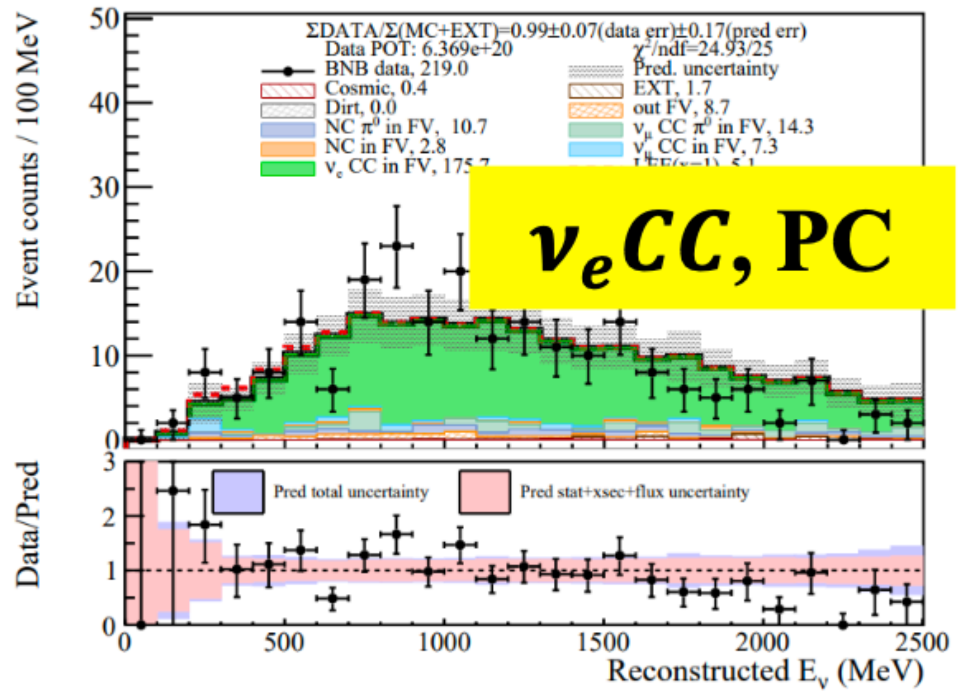



Inclusive 1eX analysis: Phys. Rev. D105, 112005 (2022)

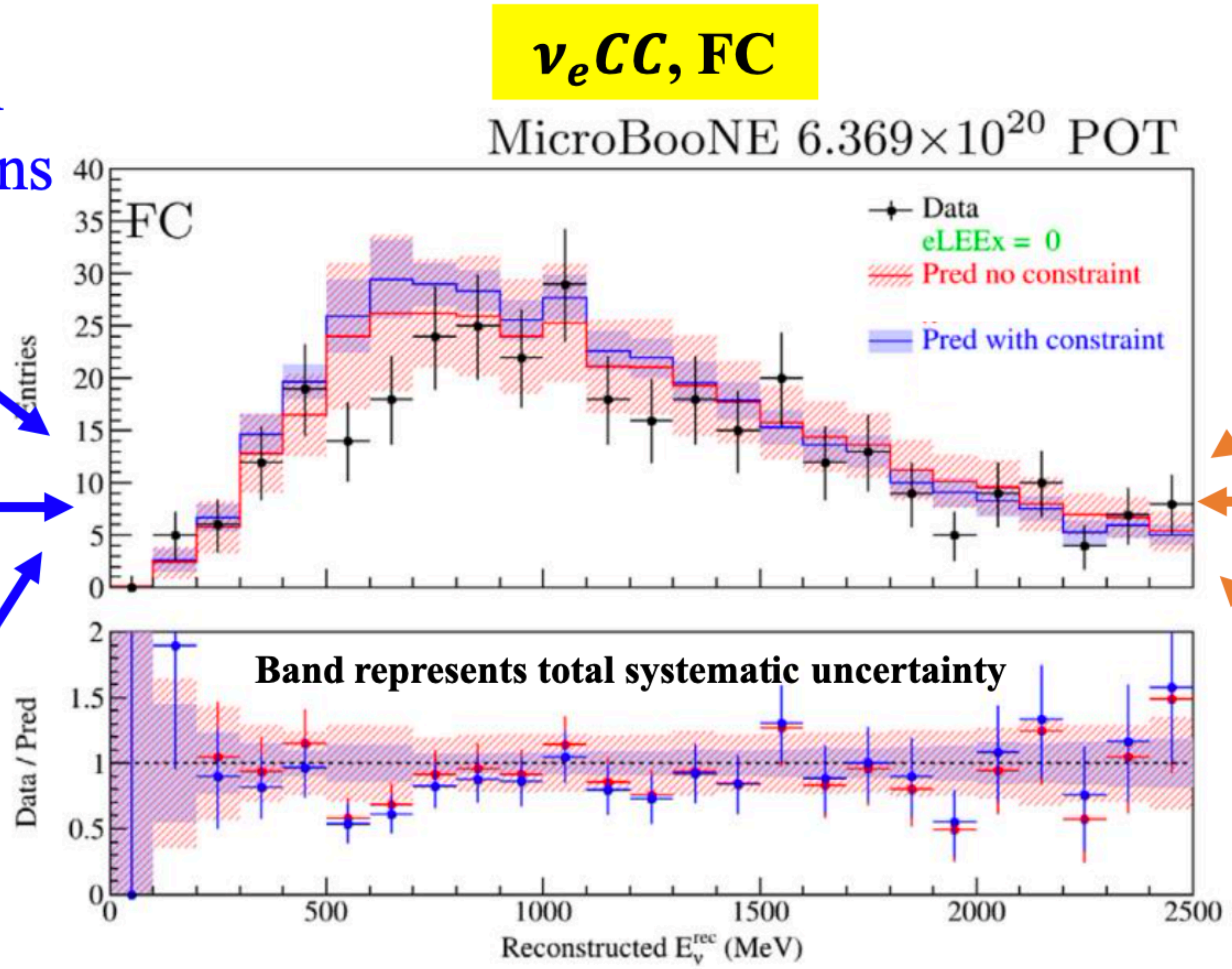
similar constraint procedure used in other two analyses



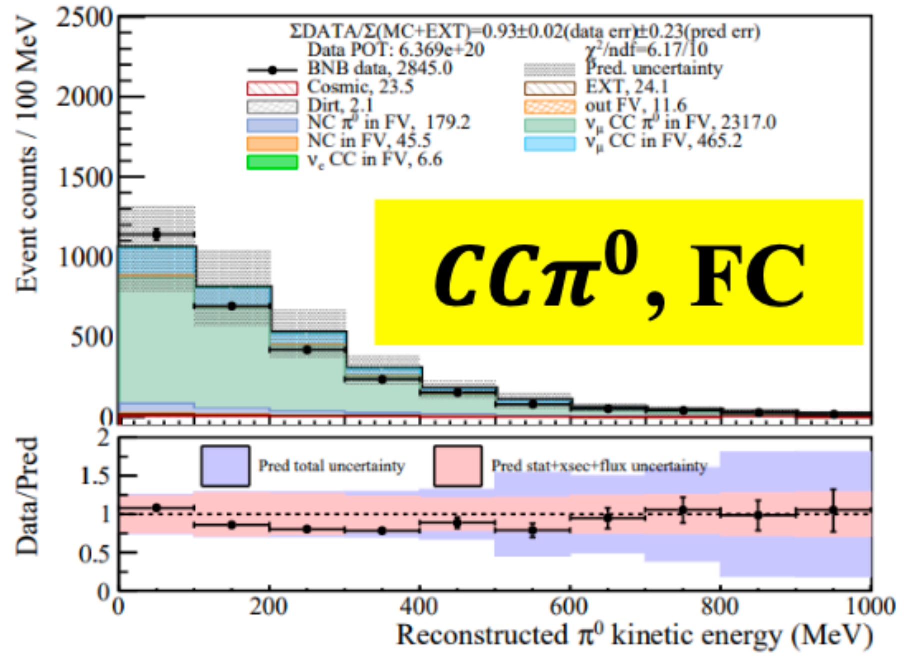



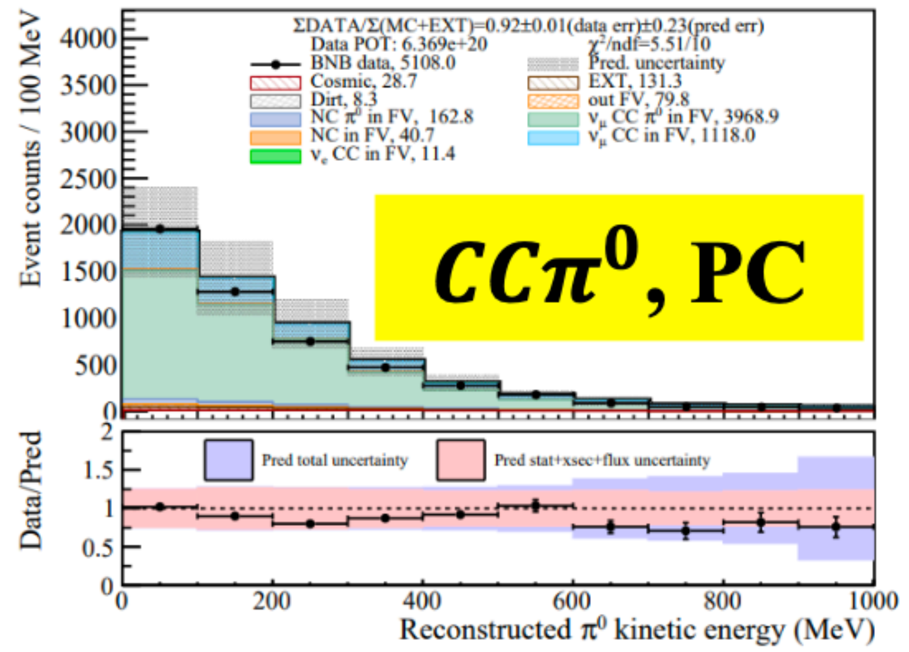



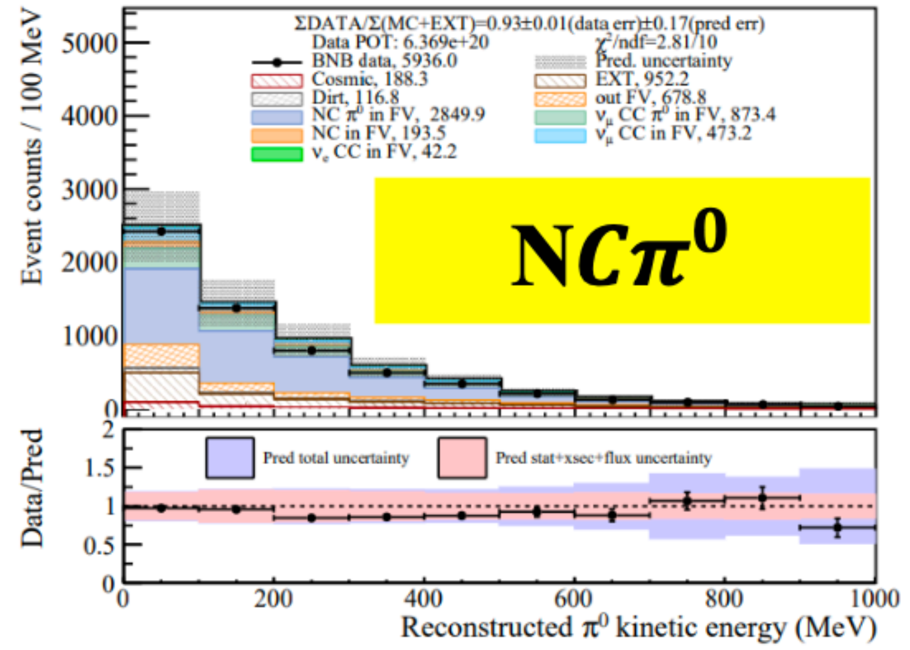

Signal constrains




Background constrains

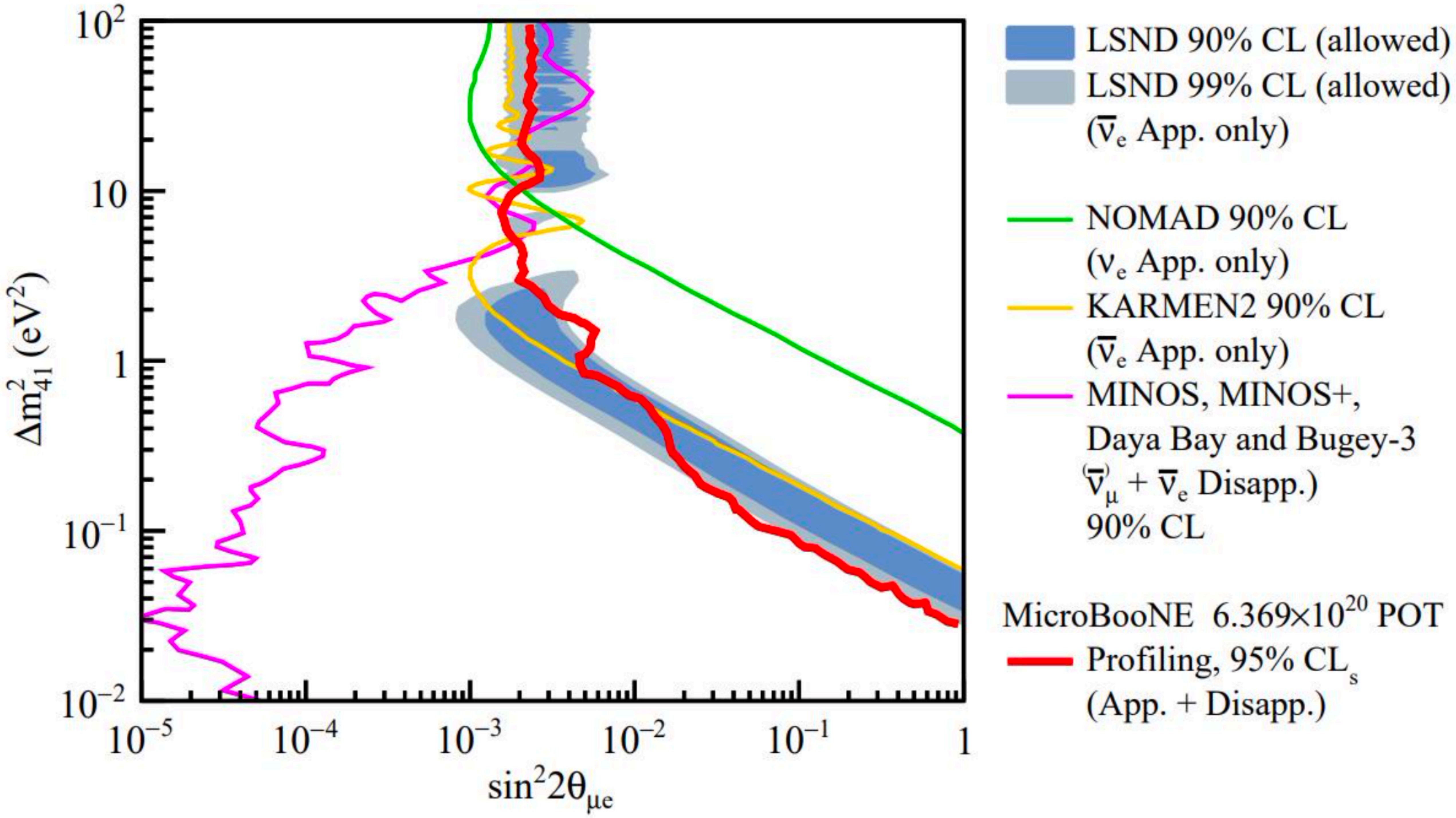



- *FC: fully contained events in the fiducial volume*
- *PC: partially contained events in the fiducial volume*

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




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