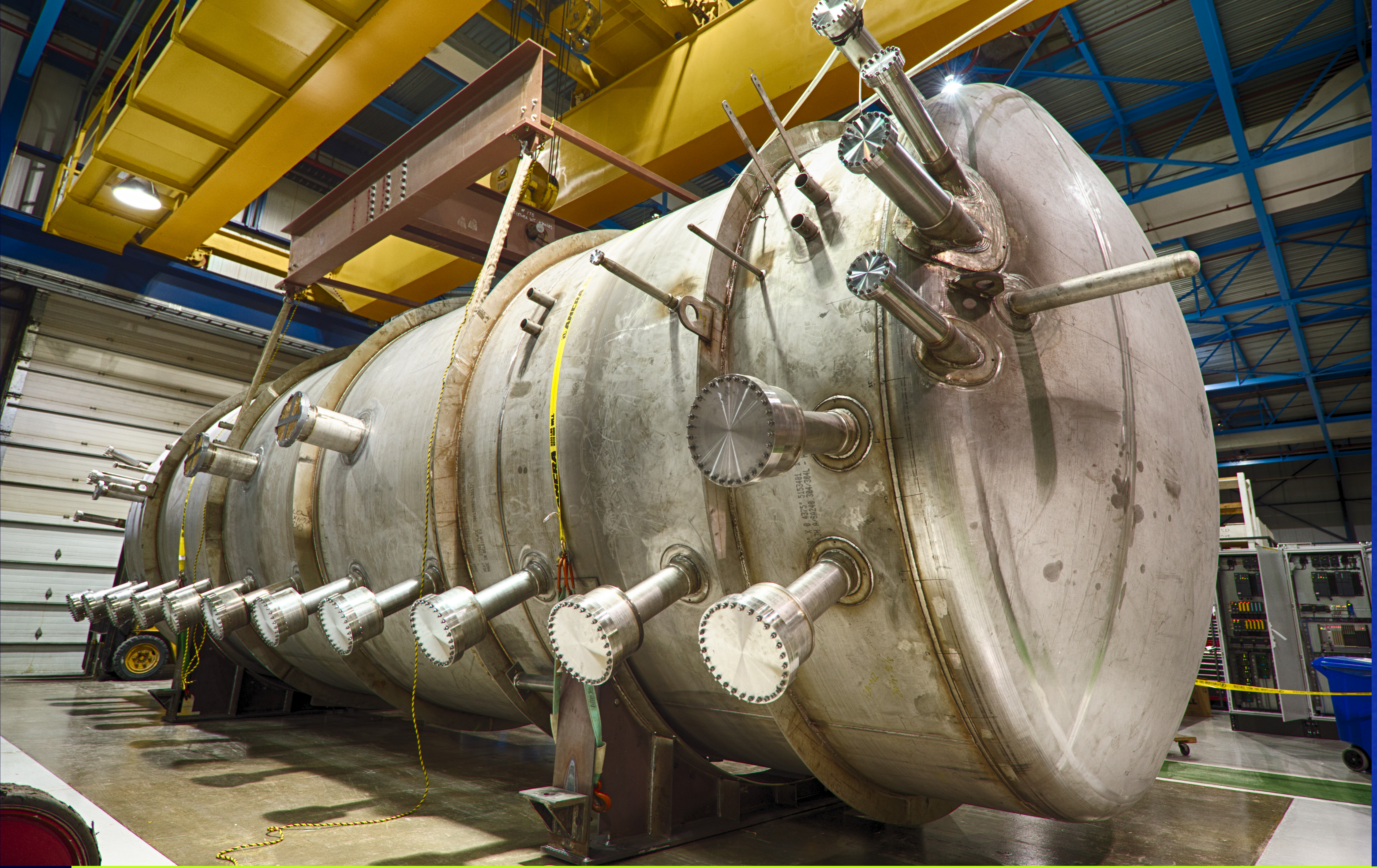
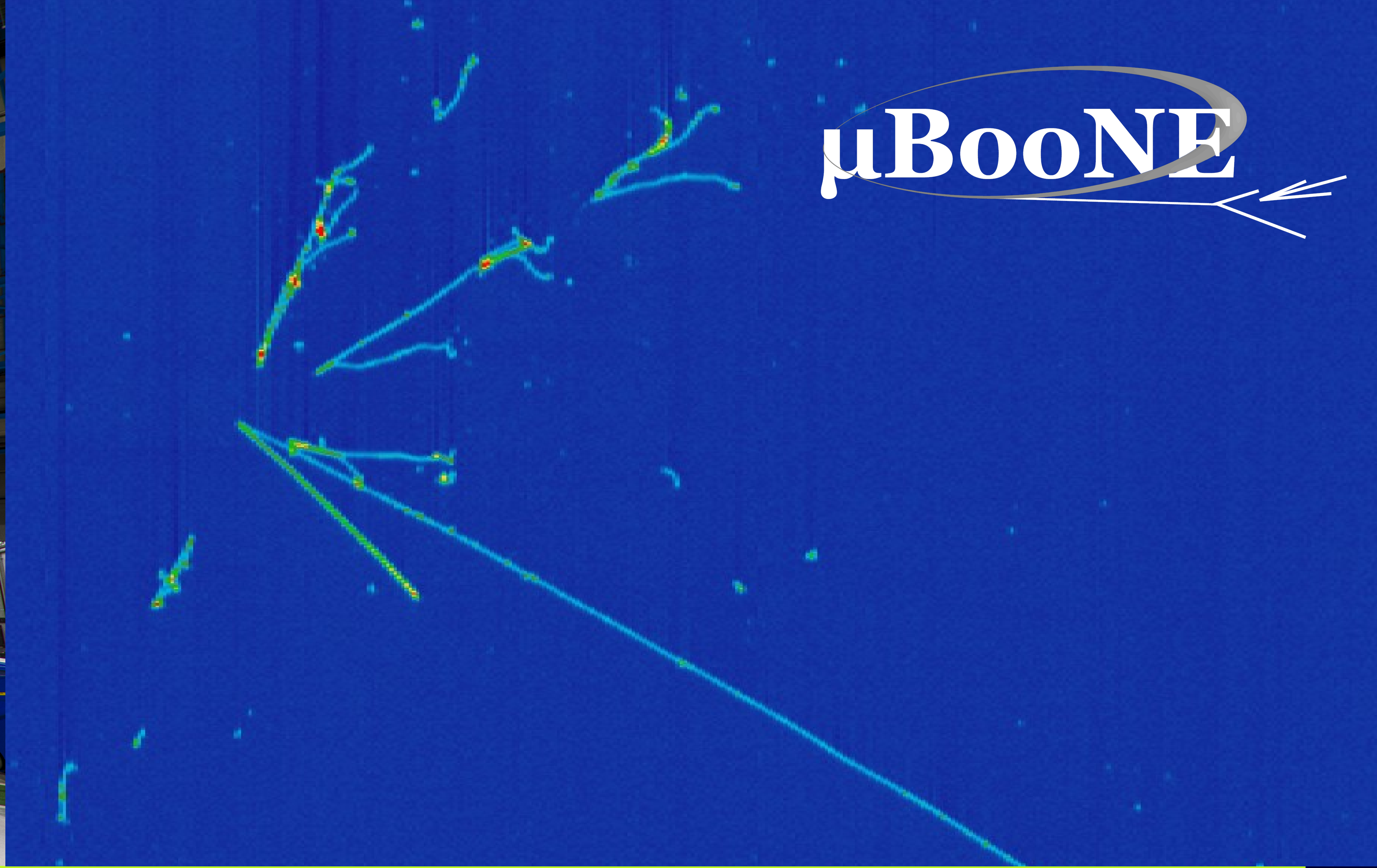




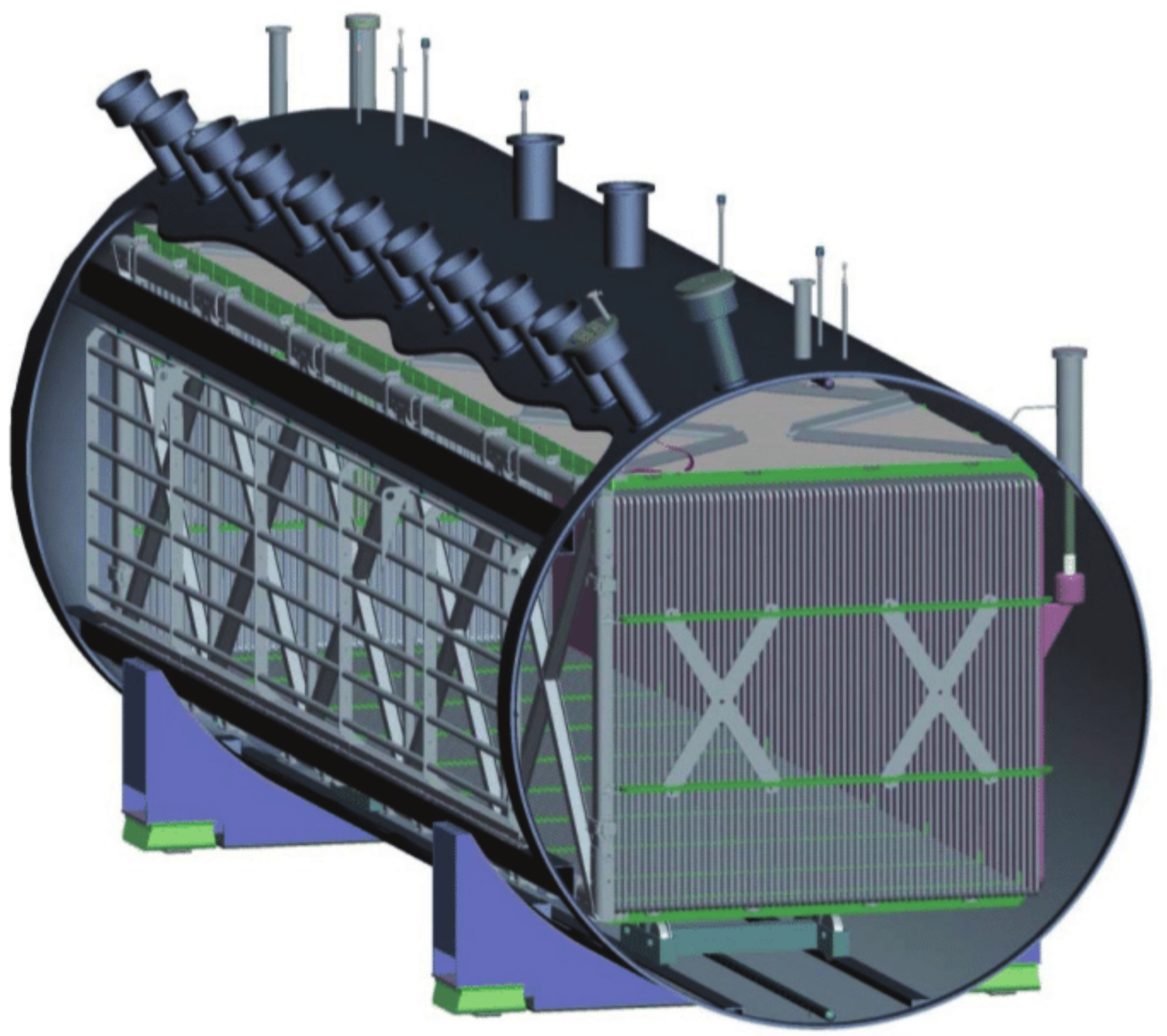
Latest results from MicroBooNE's electron neutrino Low Energy Excess search

Fan Gao
University of California - Santa Barbara
On behalf of the MicroBooNE Collaboration

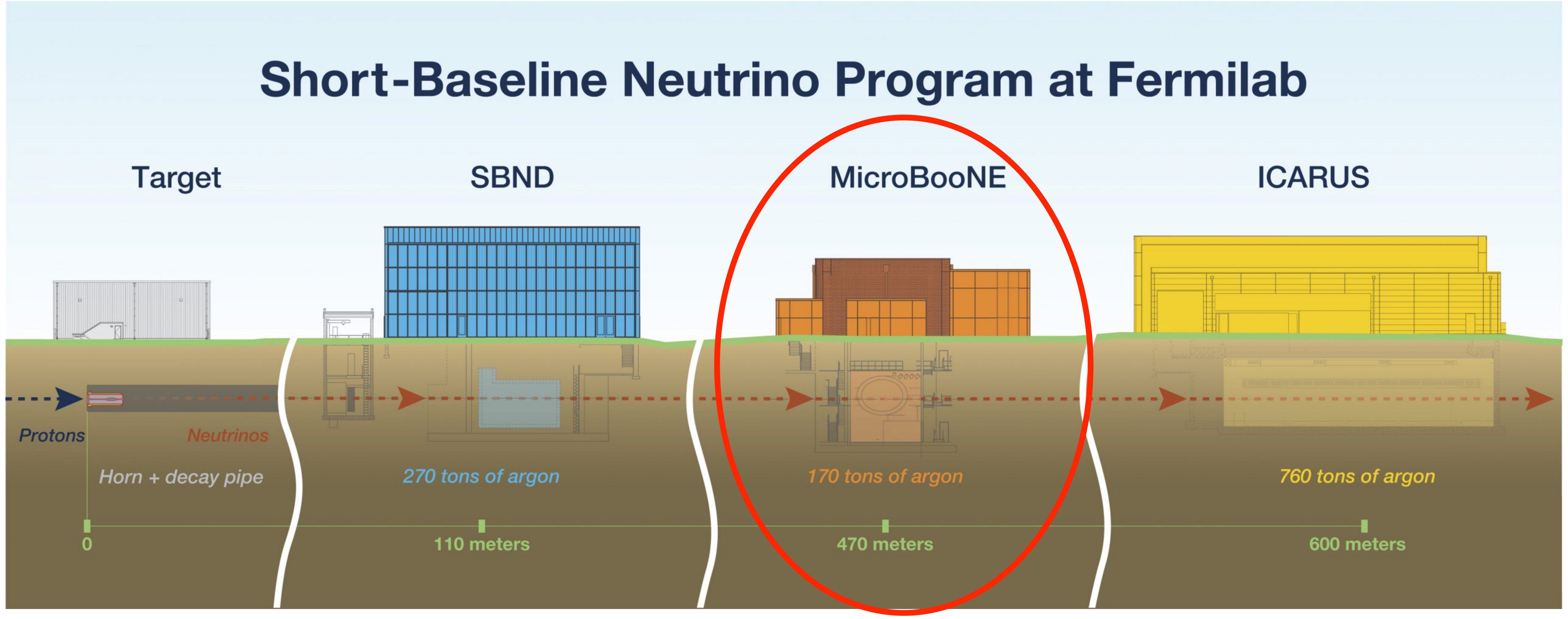
Fermilab

NuFact 2024
Argonne National Laboratory
September 19, 2024

MicroBooNE

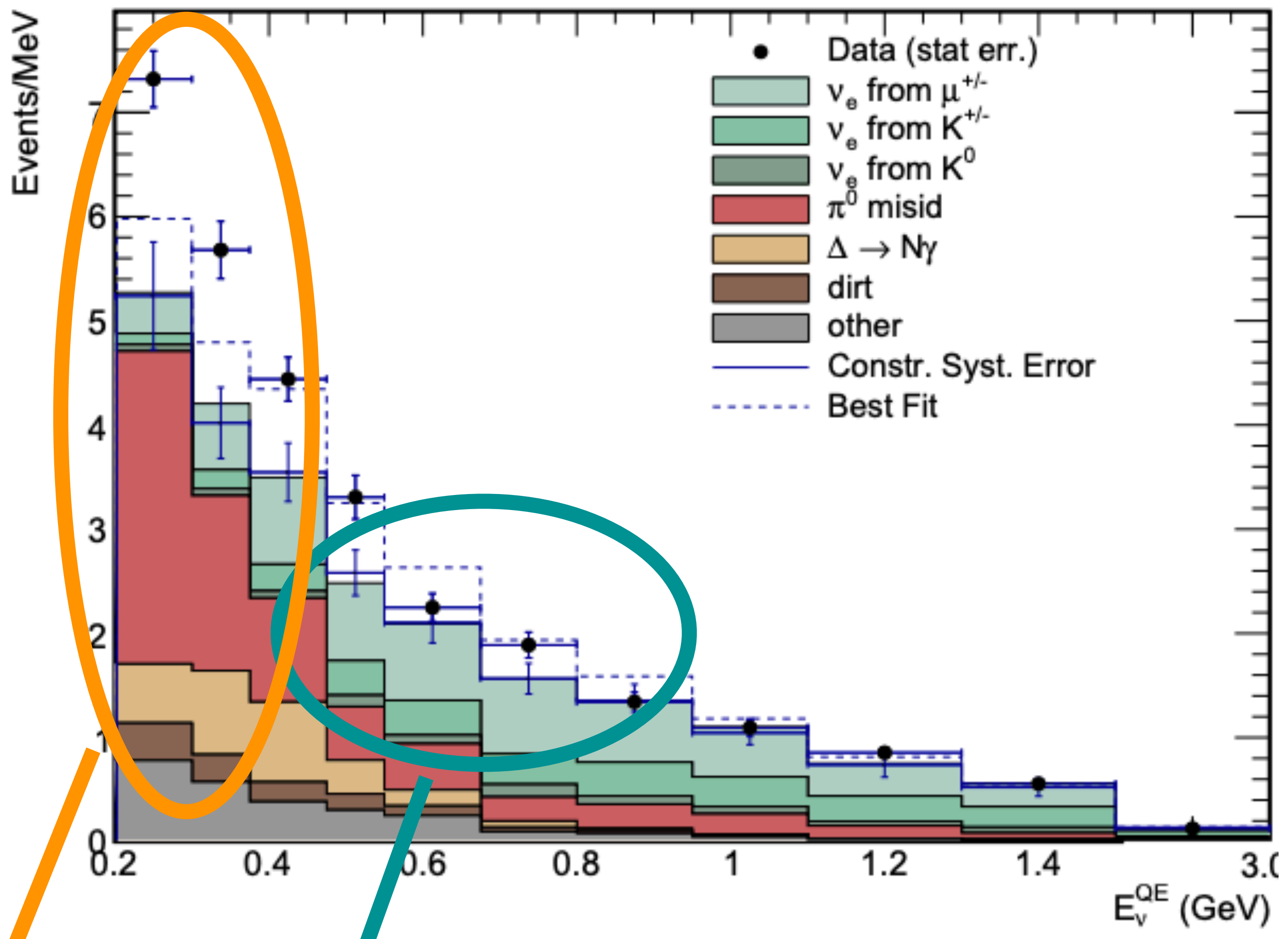


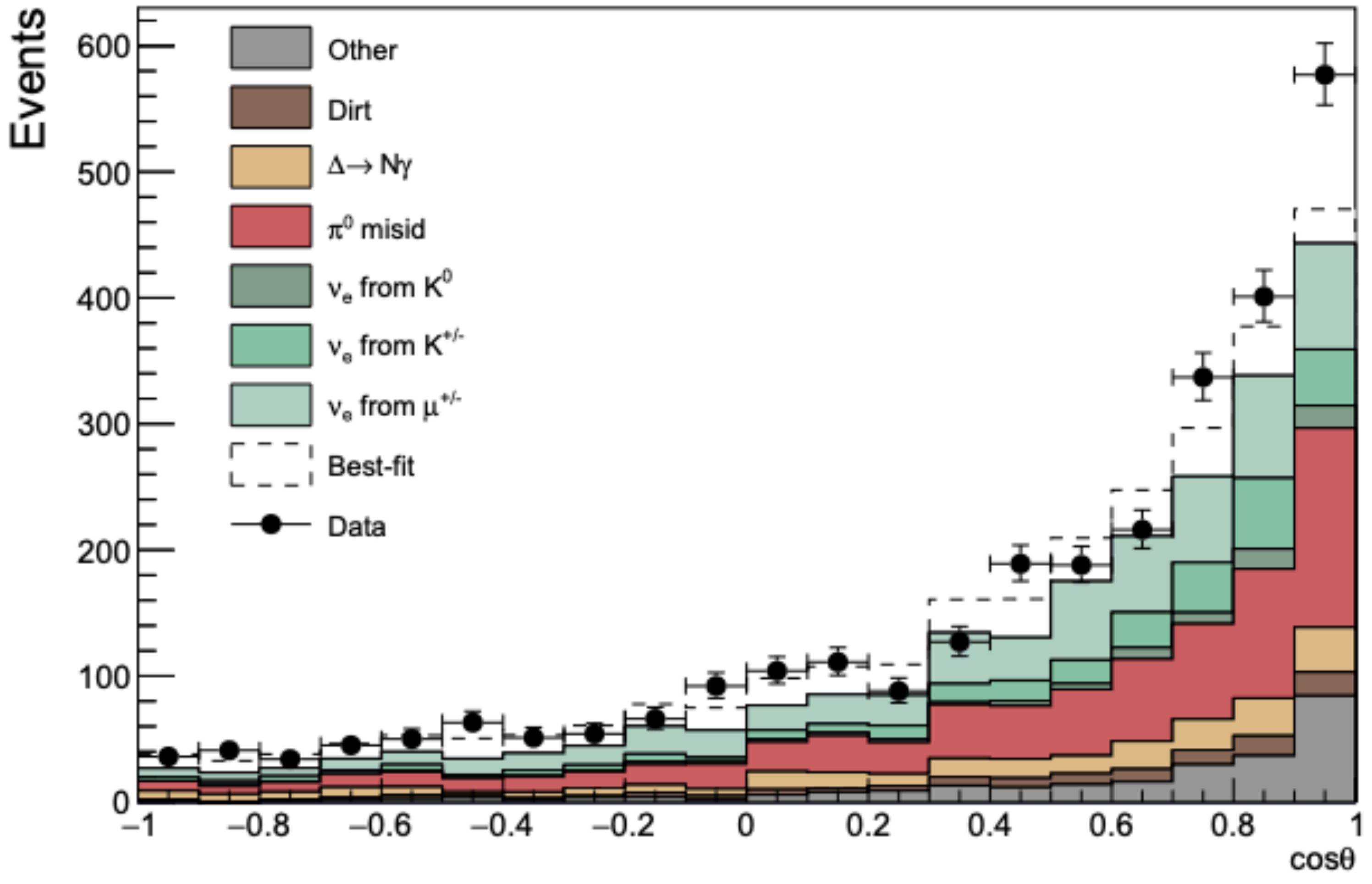
- A surface-level, 170-ton LArTPC neutrino experiment.
- Exposed to both the BNB and the NuMI beams at Fermilab.
- Primarily designed to investigate the **low energy excess (LEE)** anomaly observed by MiniBooNE.
- Collected data from 2015 to 2020.
  - World's largest dataset of ν-Ar interactions.
- A part of the Short-Baseline Neutrino (SBN) program at Fermilab.
- Contributes crucial input towards the construction of massive kiloton scale LArTPC detectors for the future DUNE experiment.



LEE Anomaly and MiniBooNE

- MiniBooNE observed a 4.8σ excess of ν_e candidate events at a low energy range.
  - Neutrino energies ~ 200-800 MeV
  - Forward-going shower angles





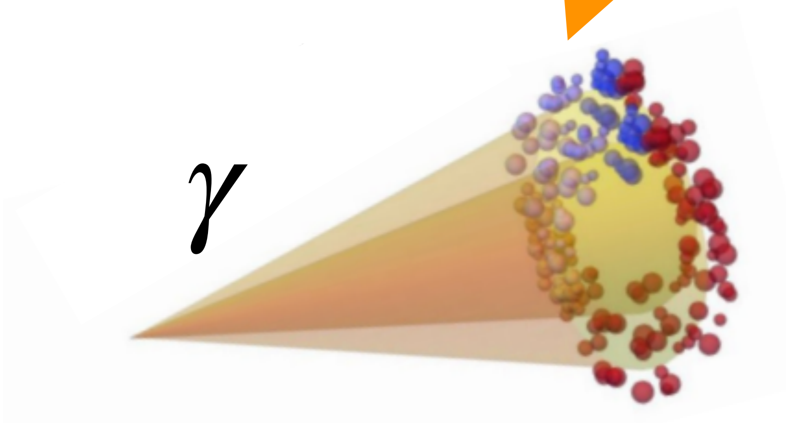
Phys. Rev. D 103, 052002 (2021)

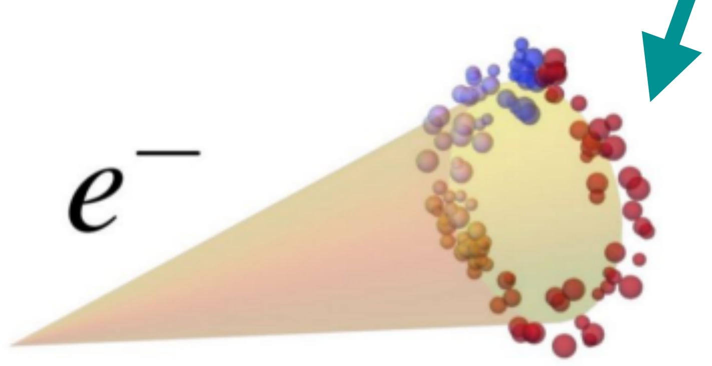
- Possible LEE explanations:
  - Electron-like (eLEE) events
    - ➡ Energy-dependent ν_e enhancements?
    - ➡ Oscillation-driven excess

Main topic of this talk!

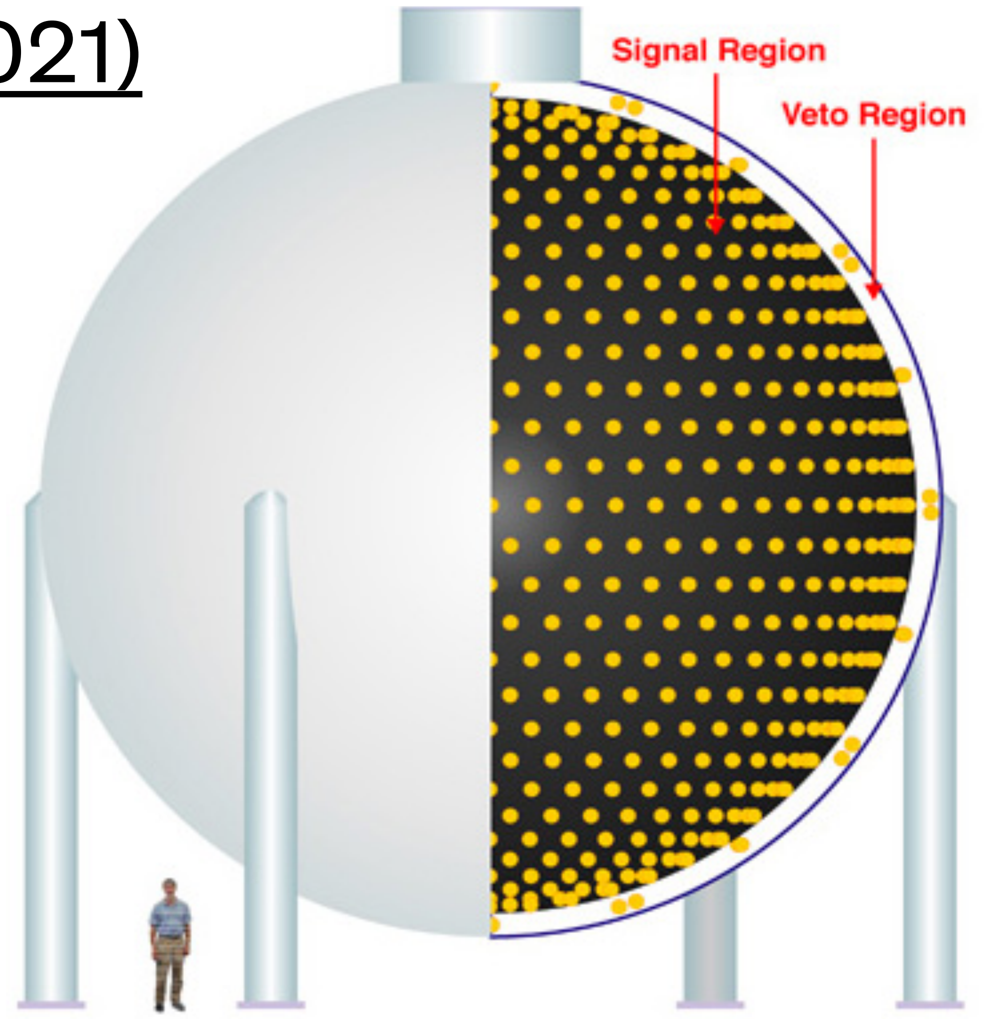
  - Photon-like events
    - ➡ NC Δ resonance decay?
    - ➡ Other mis-modeled or unknown processes?
  - BSM models
    - ➡ Dark sector e+e- pairs?

Erin Yandel's talk on Monday!



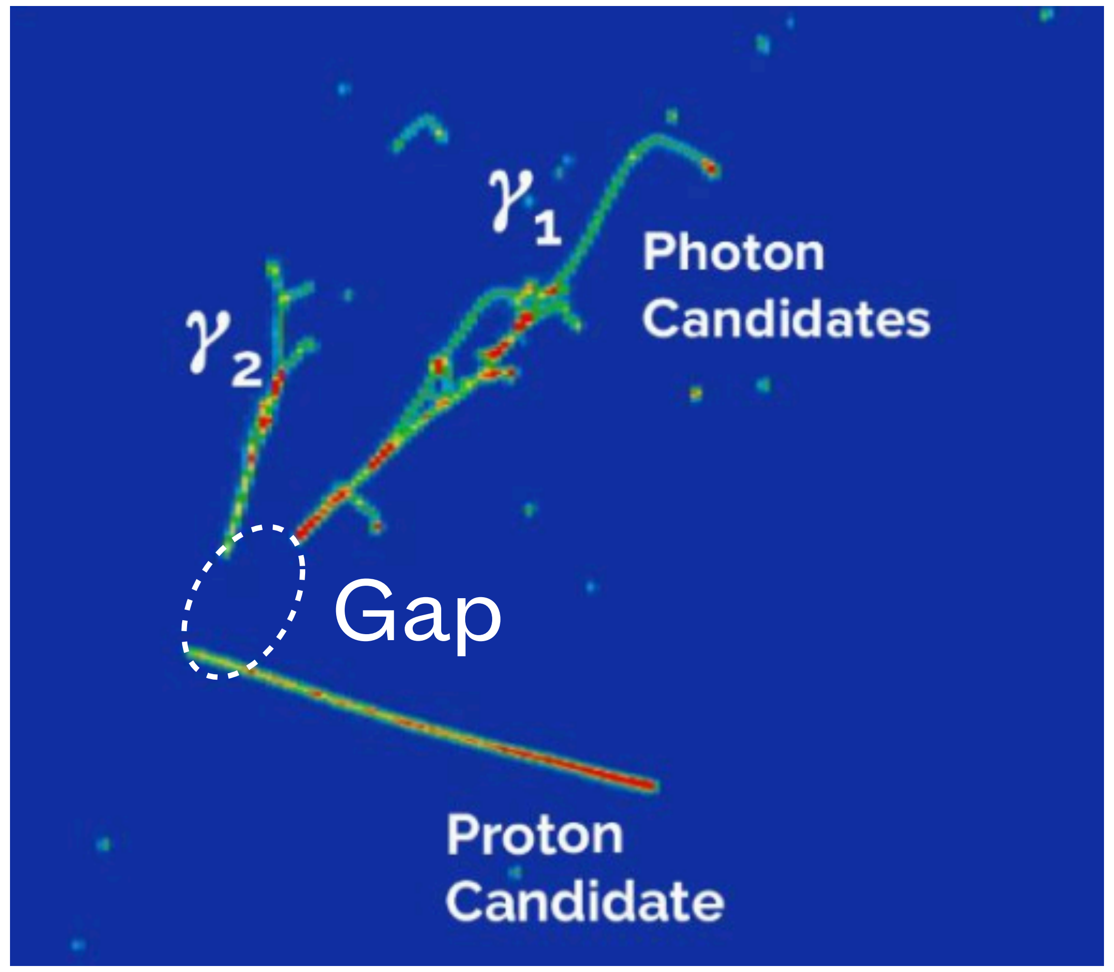


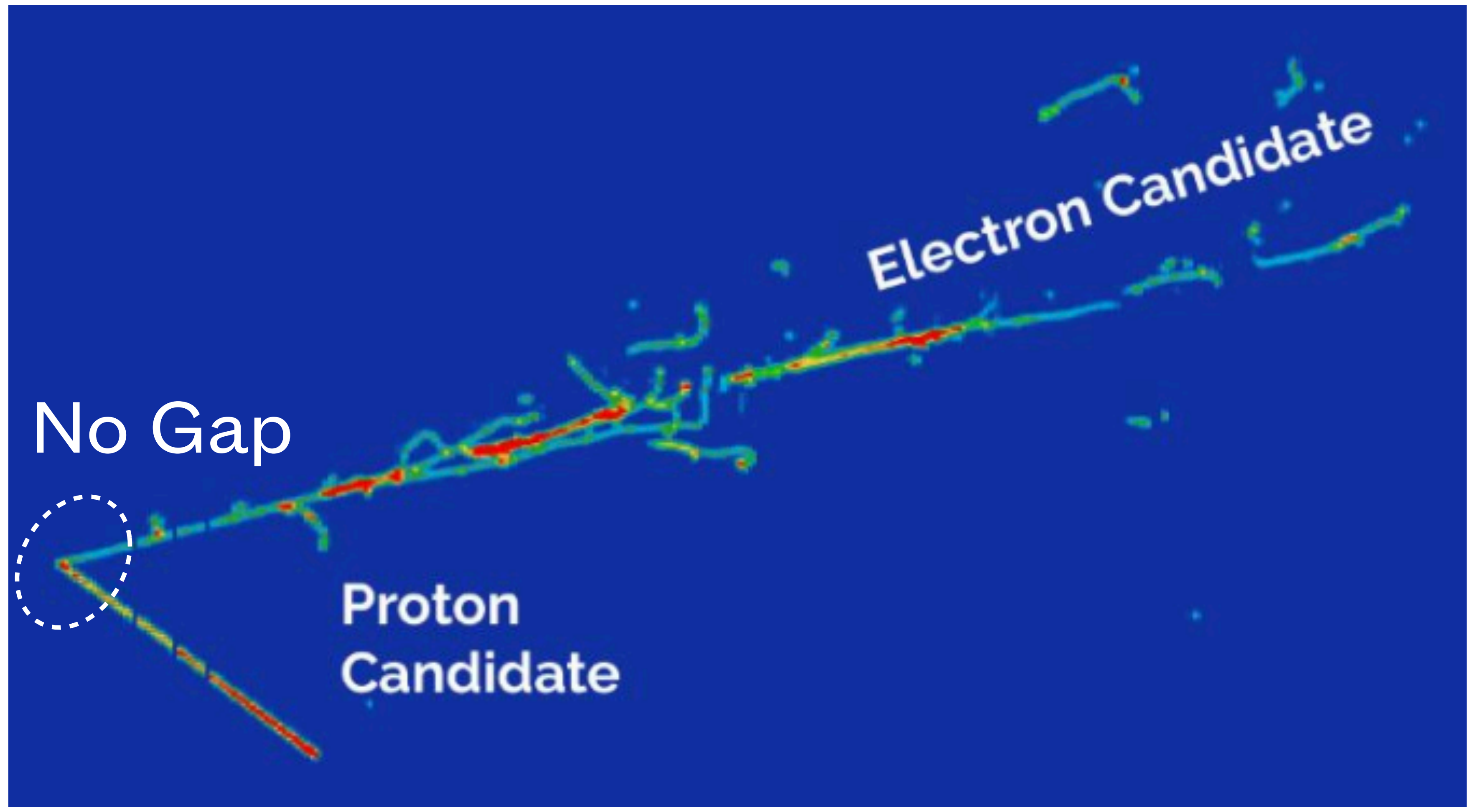
- MiniBooNE, using an oil Cherenkov detector, cannot differentiate between electrons and photons.



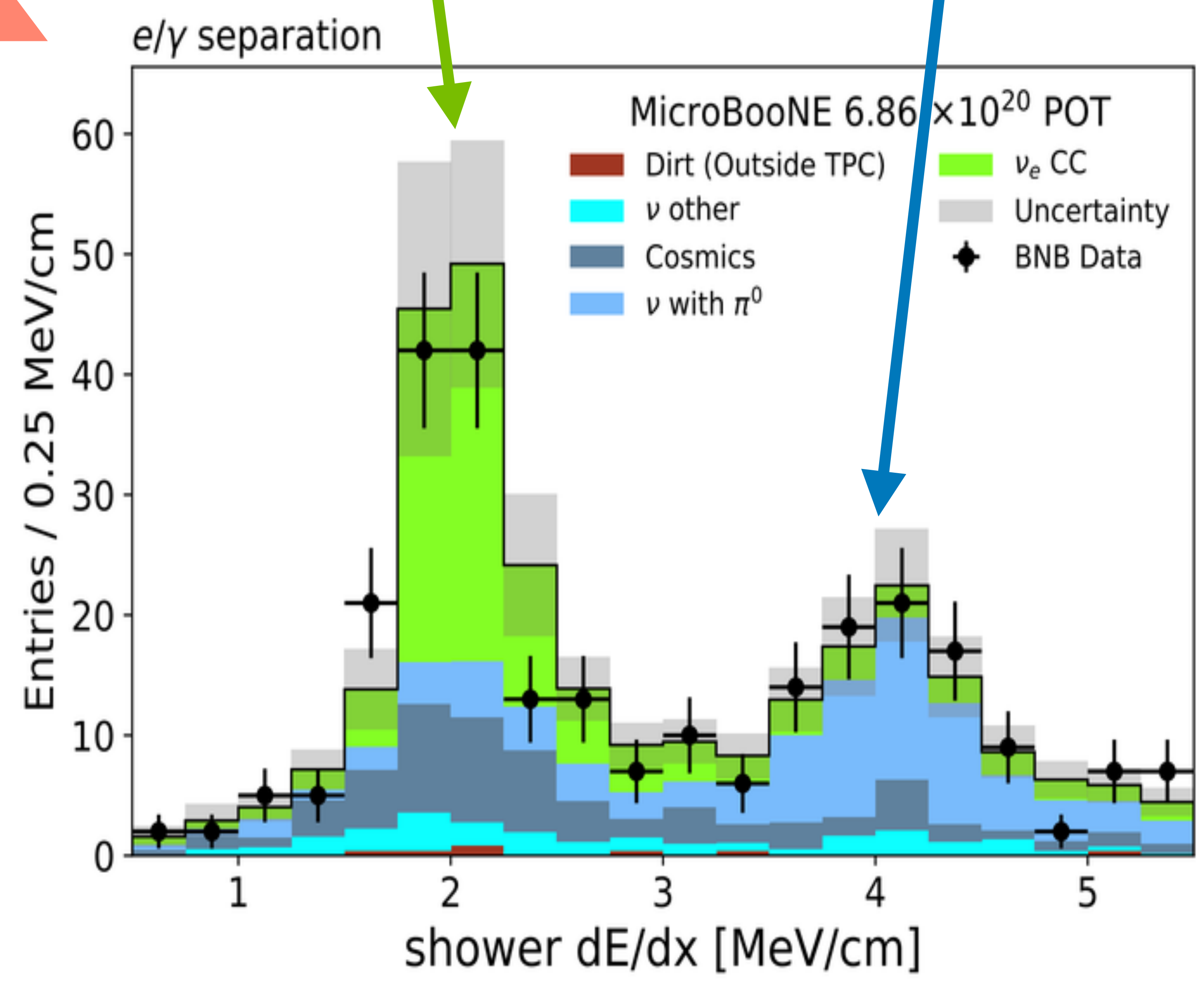
LArTPC Detector

- MicroBooNE's LArTPC is powerful in electron-photon separation.
  - Millimeter spatial resolution and calorimetry.

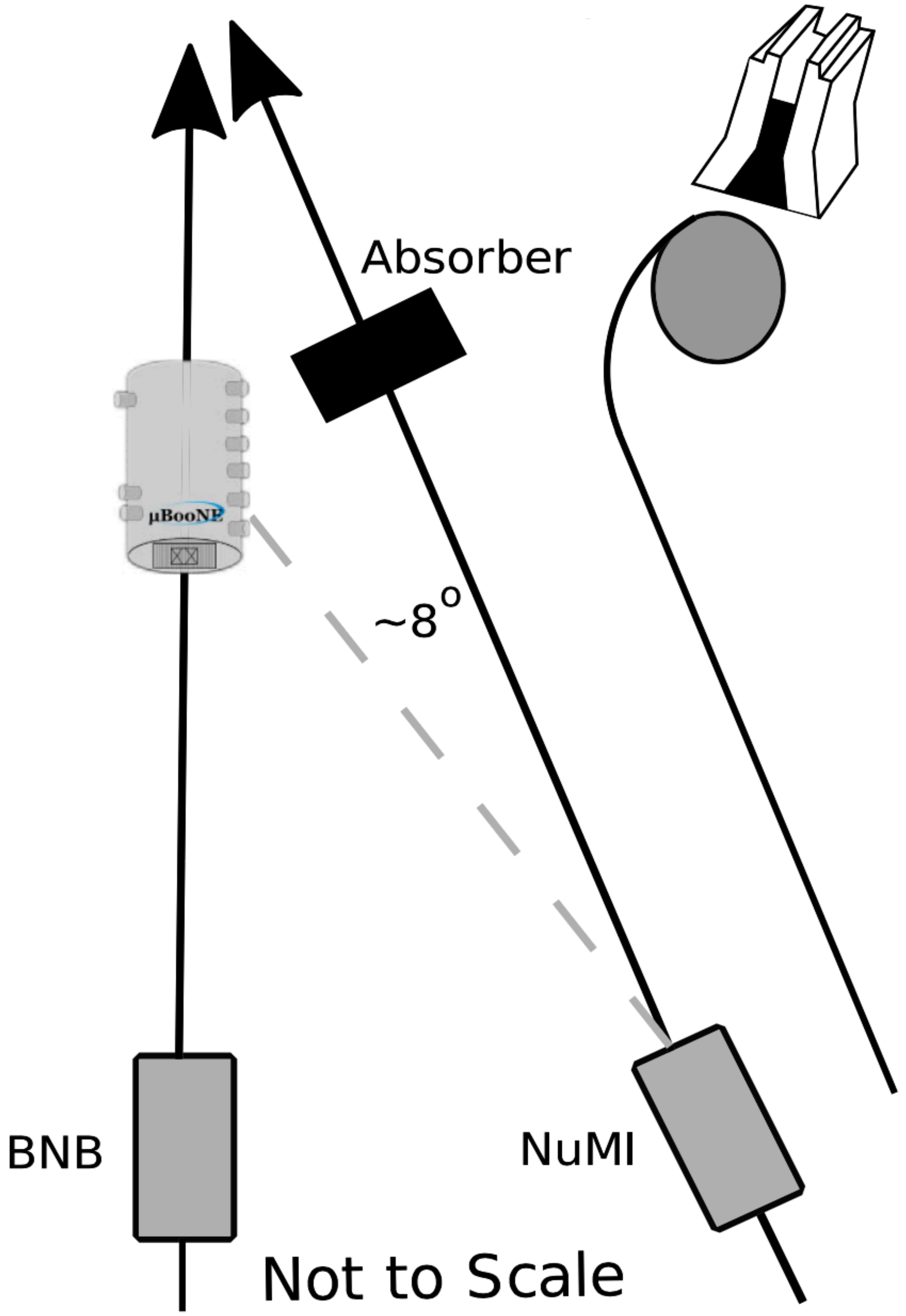


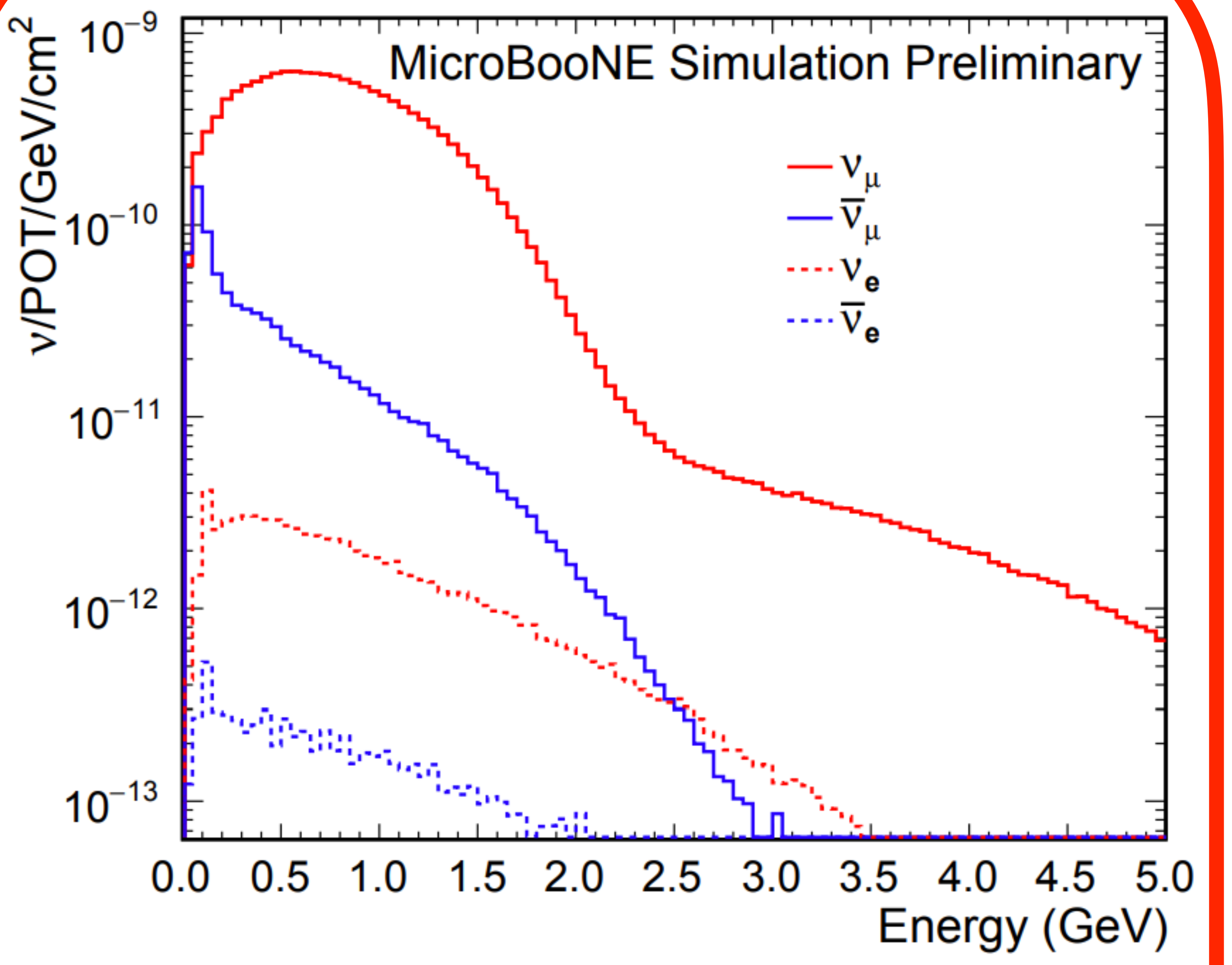


electrons - 1 MIP vs. photons - 2 MIP



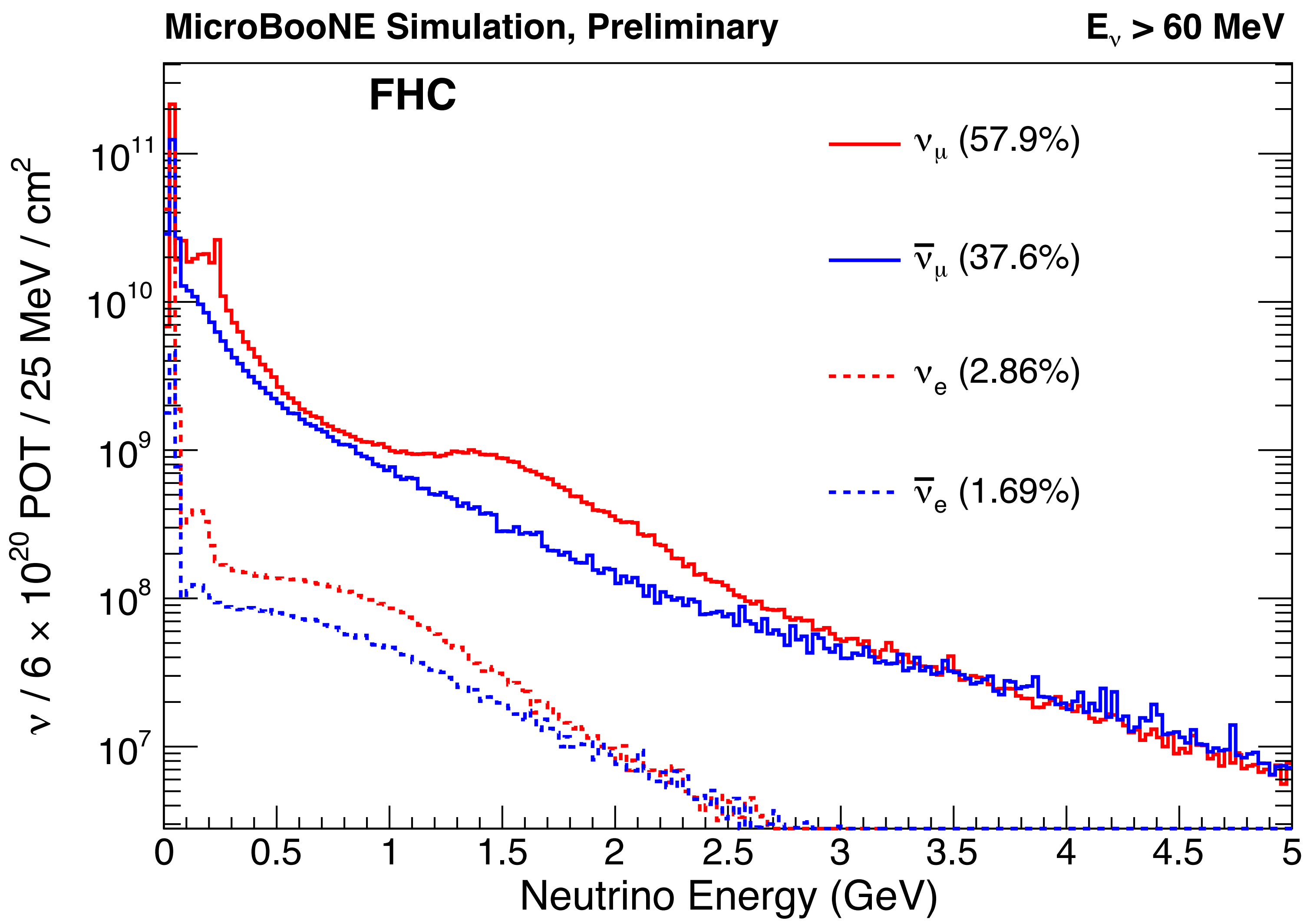
BNB and NuMI at MicroBooNE





BNB:

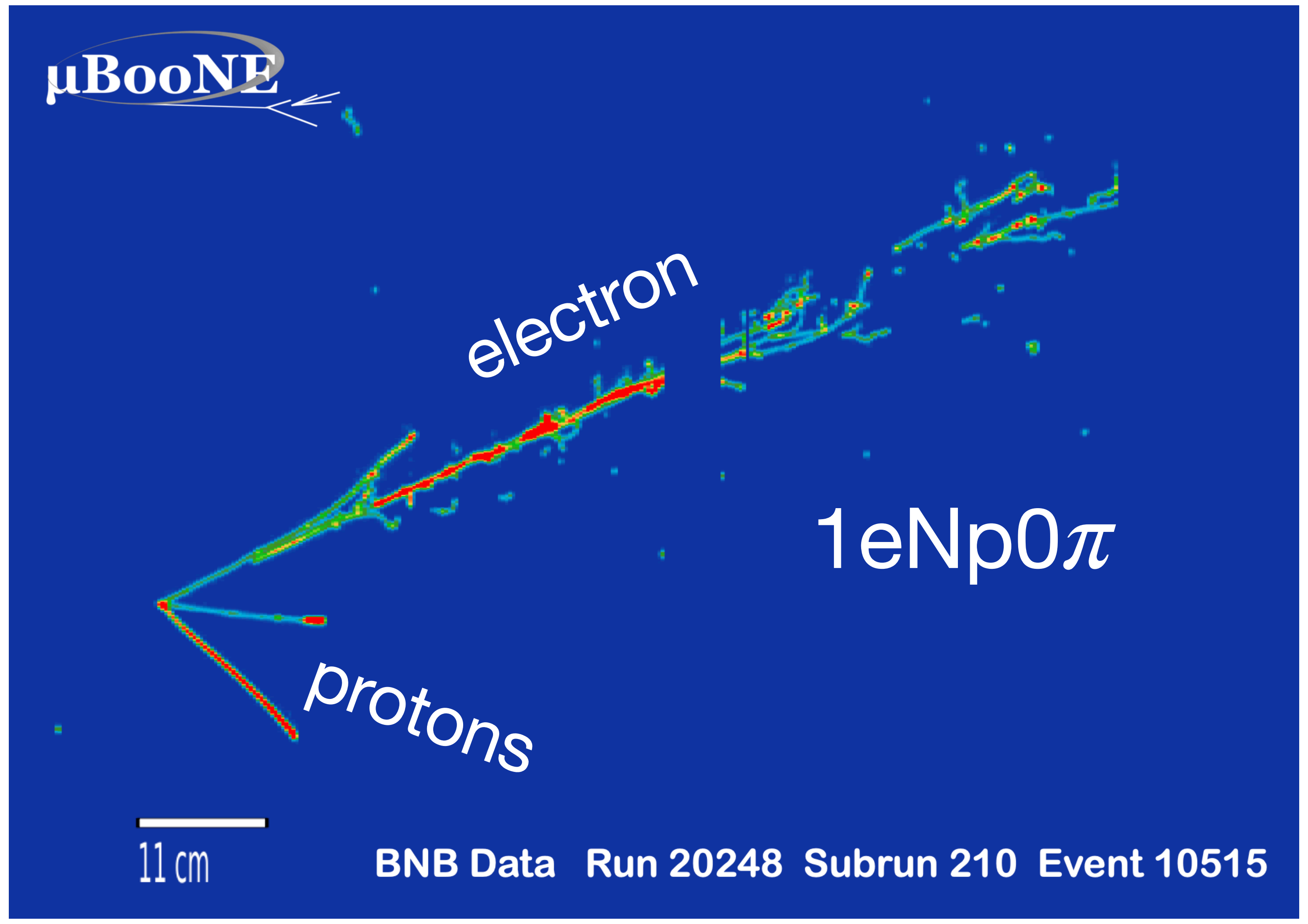
- on-axis
- 99.5% ν_μ / 0.5% ν_e
- 470 meter baseline

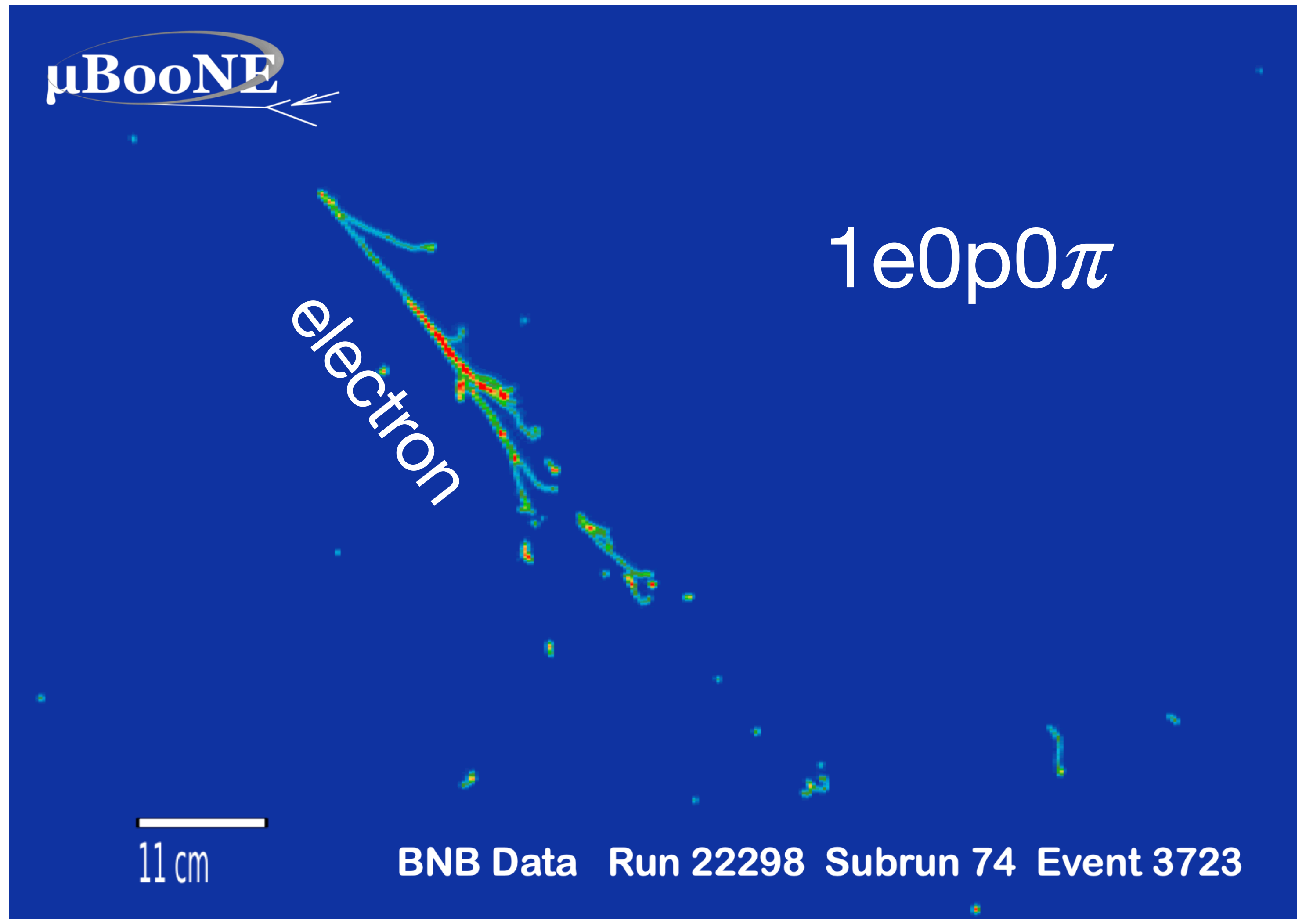


NuMI:

- 8° off-axis
- 95% ν_μ / 5% ν_e
- comparable ν and $\bar{\nu}$
- Flux from target and absorber

LEE Search: ν_e Analysis

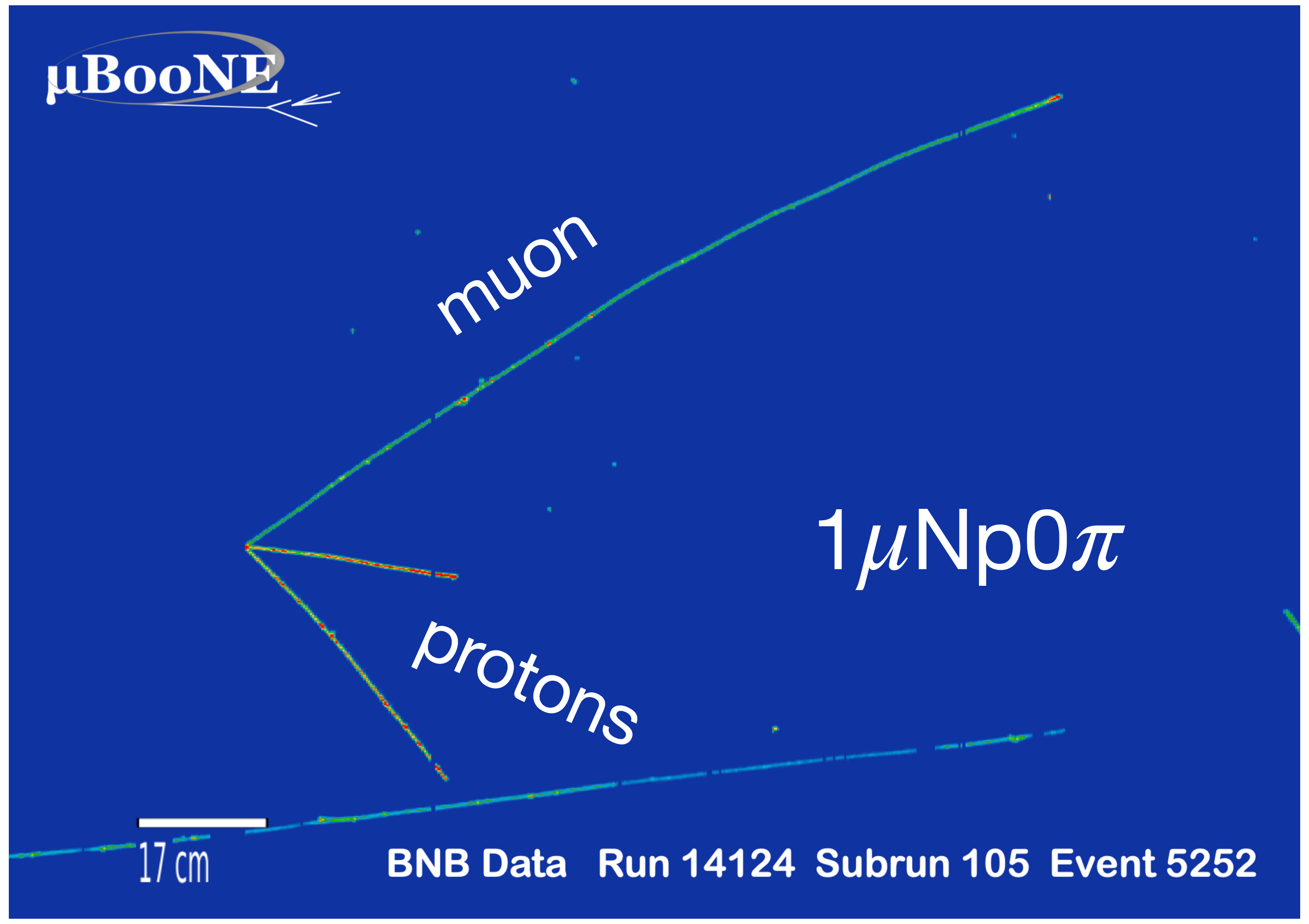


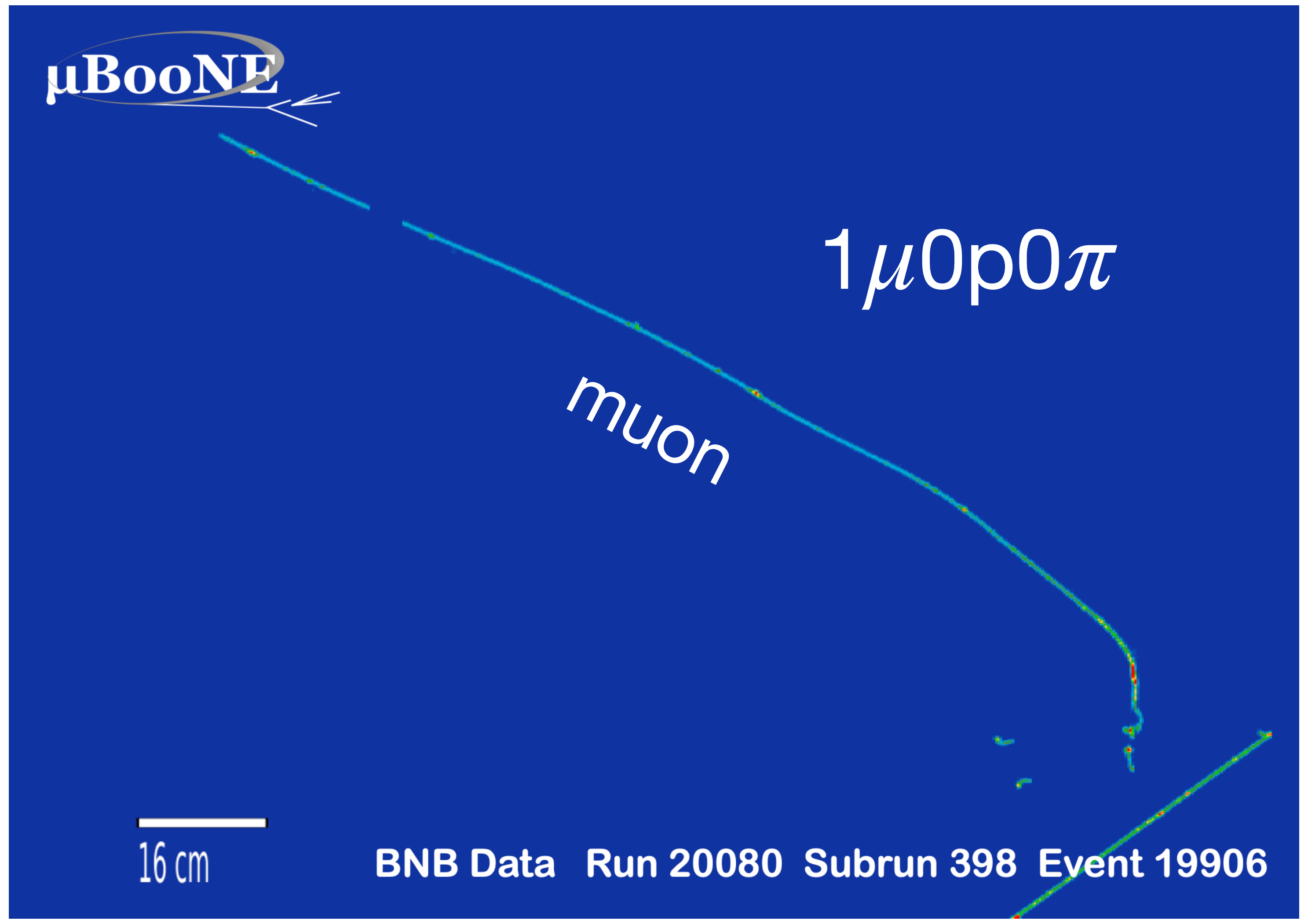


Pionless ν_e LEE analysis:

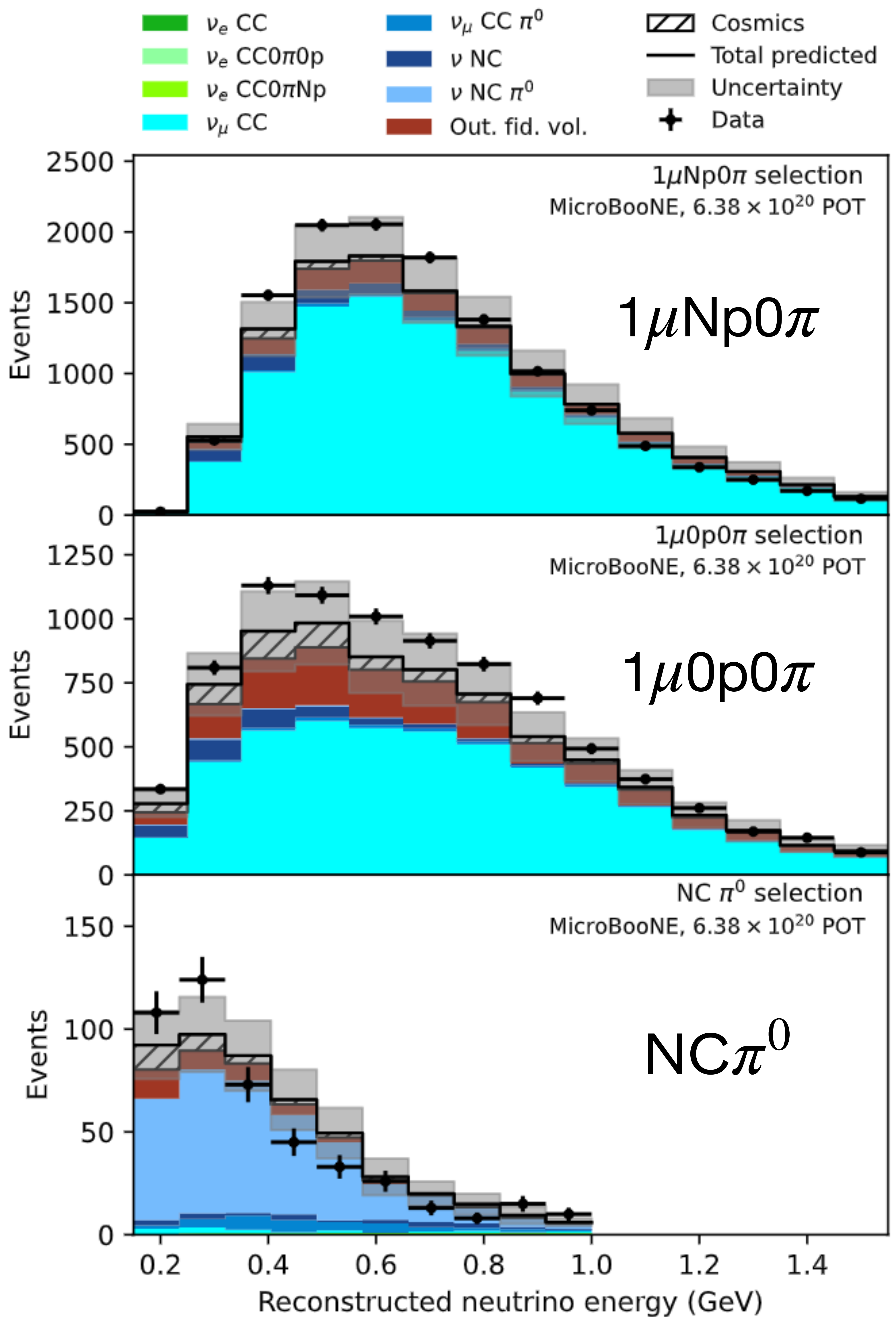
- A generic ν_e selection without assuming underlying LEE physics
- Same topology as MiniBooNE:
  - $1eNp0\pi$ and $1e0p0\pi$
- **An update** based on the earlier analysis Phys. Rev. D 105, 112004 (2022)
  - Other related MicroBooNE ν_e LEE search analyses:
    - Multiple final-state topologies Phys. Rev. Lett. 128, 241801 (2022)
    - Inclusive CC ν_e Phys. Rev. D105, 112005 (2022)
    - Inclusive CCQE ν_e Phys. Rev. D105, 112003 (2022)
- First analysis using data from all five runs of MicroBooNE (2015-2020)
  - $6.8 \times 10^{20} \rightarrow 11.1 \times 10^{20}$ POT of **BNB data**

LEE Search: ν_e Sidebands

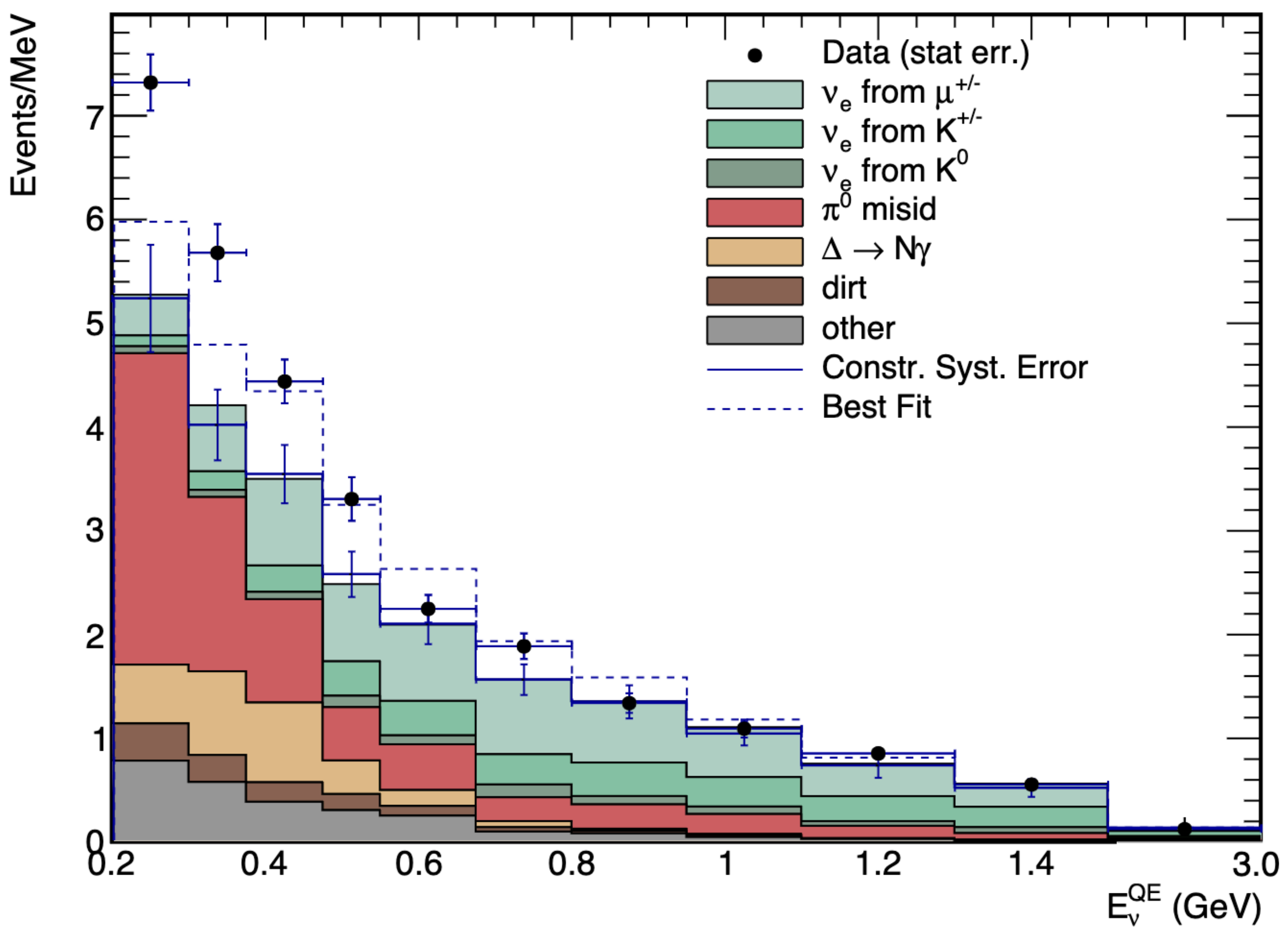


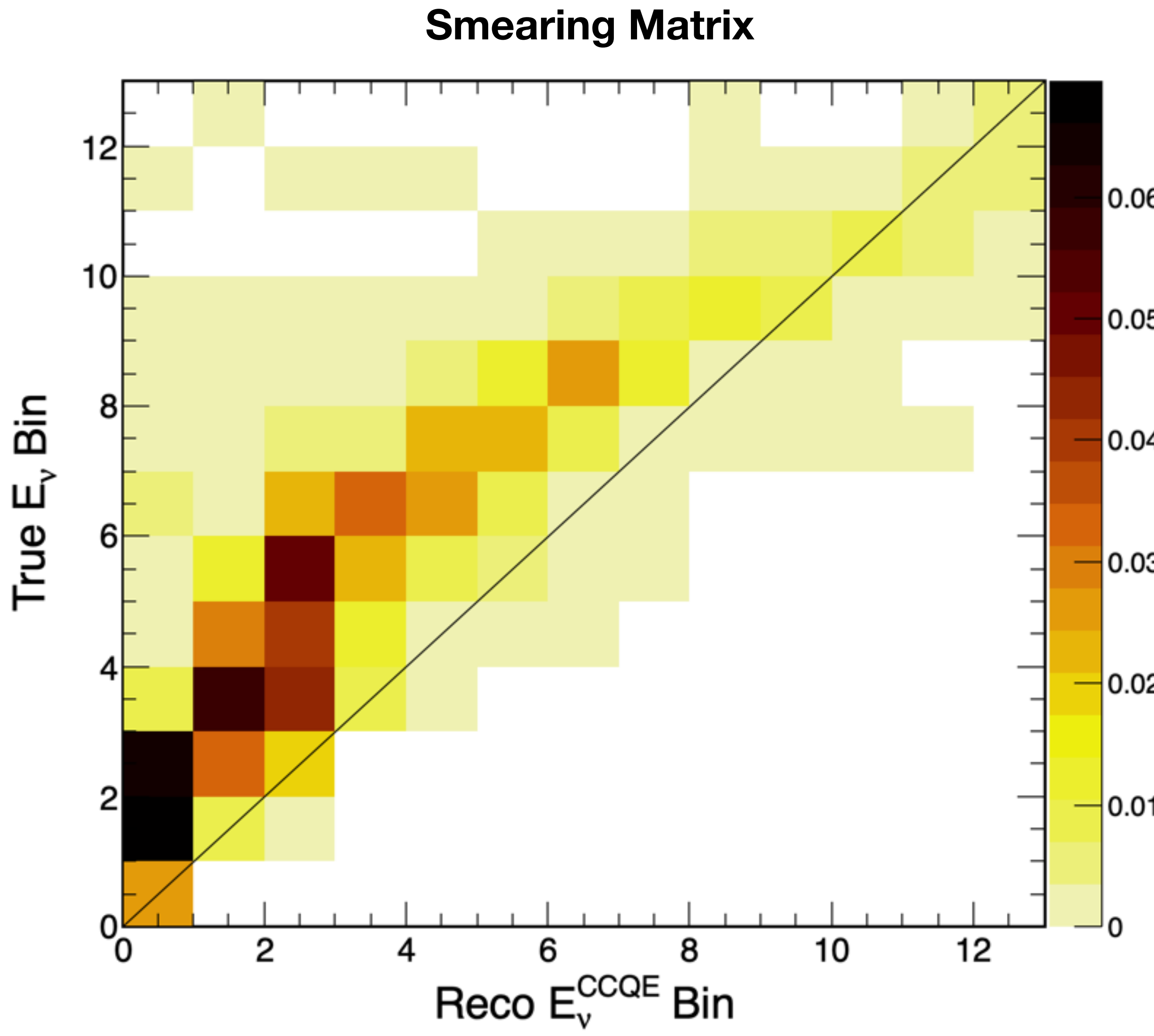


- Updated ν_μ sidebands to better constrain intrinsic ν_e
  - Split into 1μNp0π and 1μ0p0π, to mimic hadronic final states of the ν_e signal channel
- Included an NCπ^0 sideband to particularly constrain the dominant π^0 background for 1e0p0π

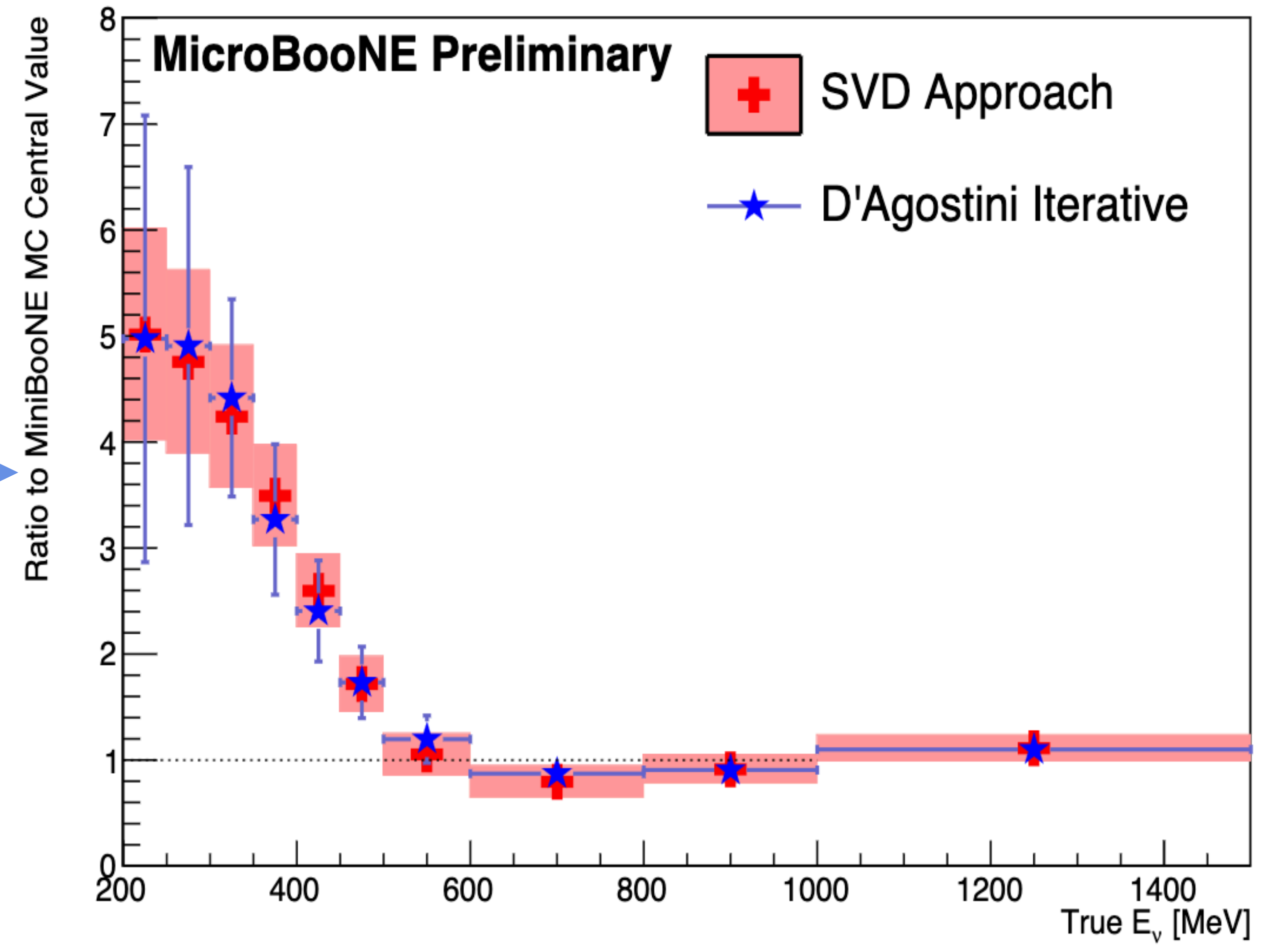


LEE Search: ν_e Signal Models



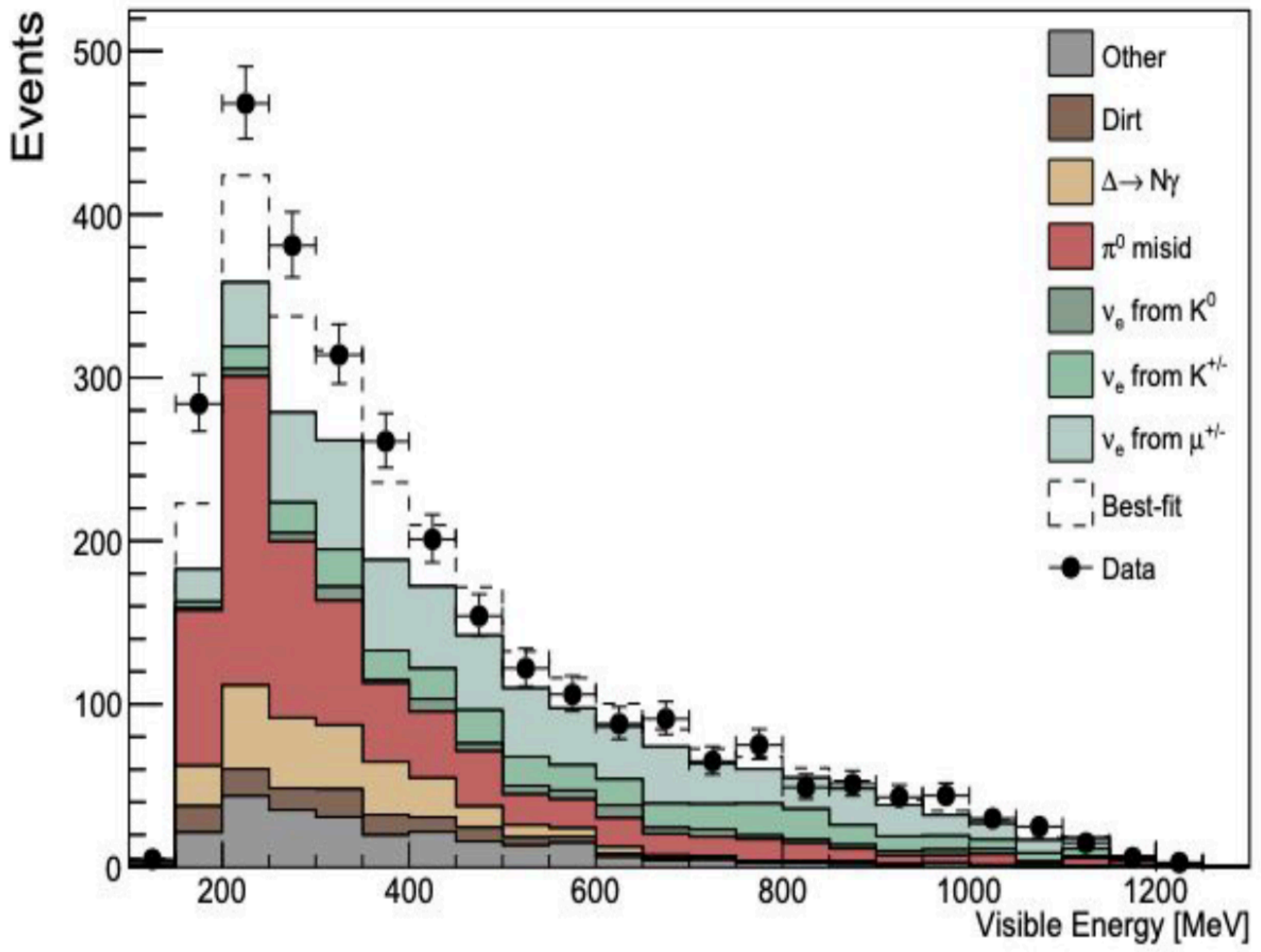


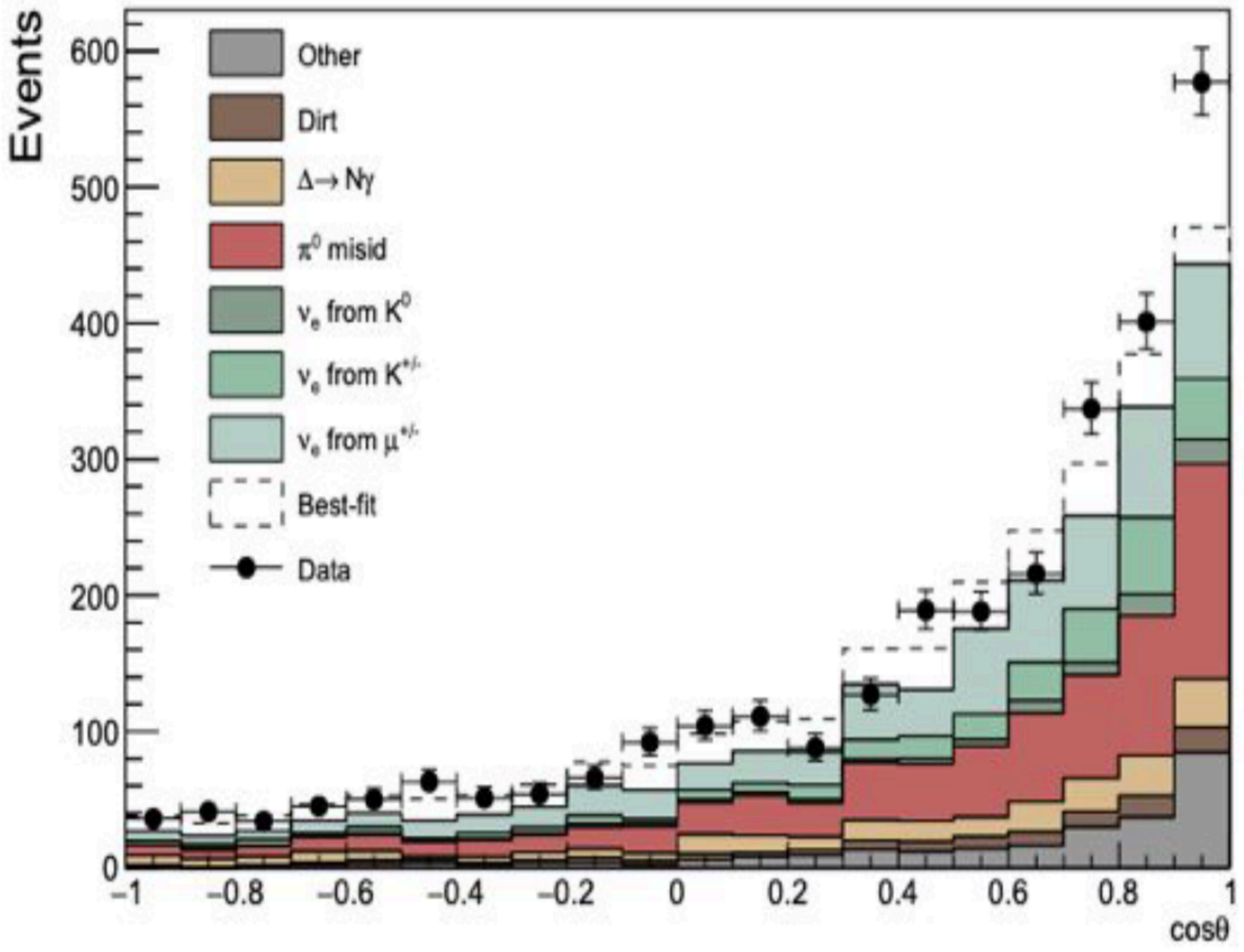
1D Unfold



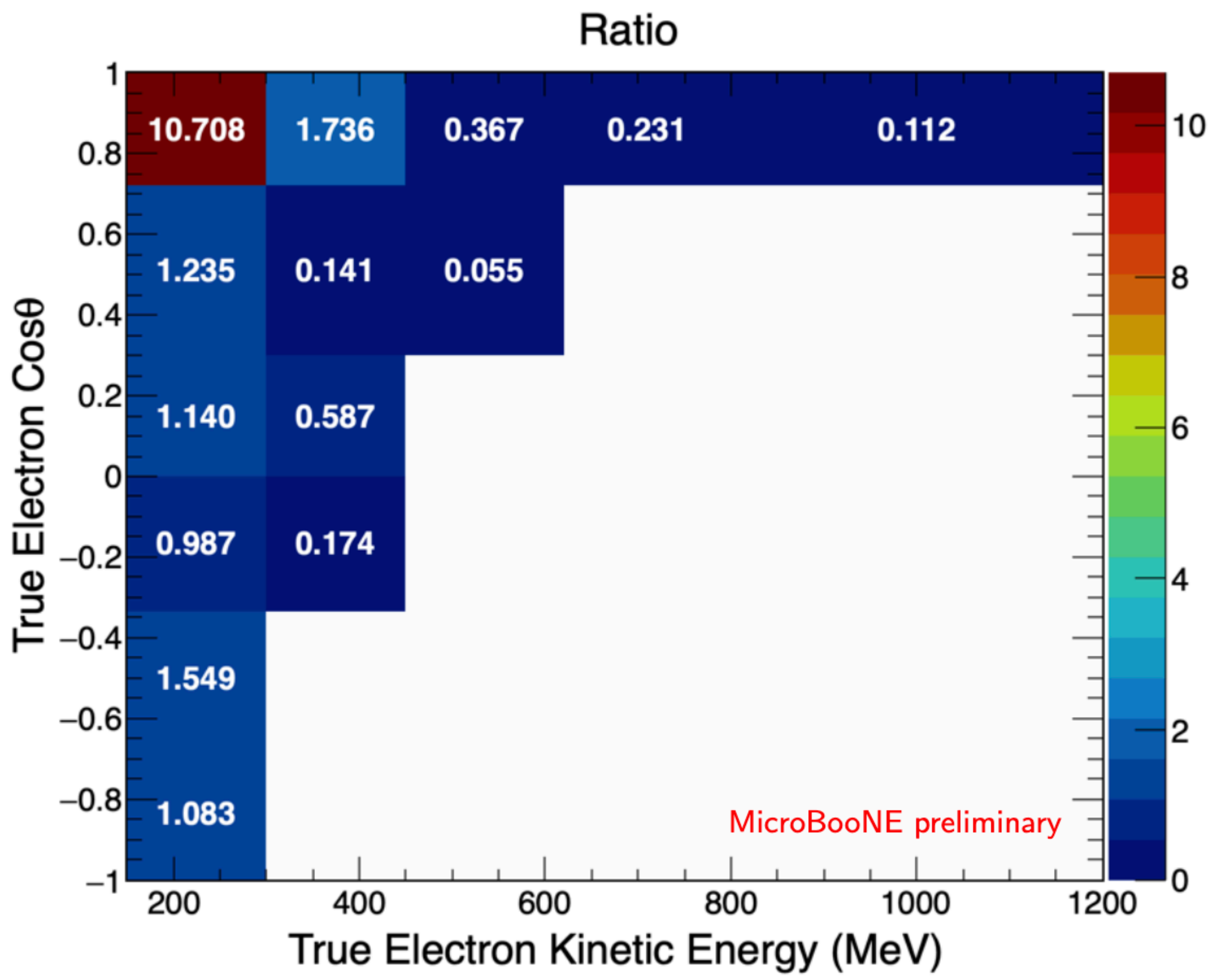
- **Signal Model 1** (details in MICROBOONE-NOTE-1043-PUB):
  - The same ν_e-like LEE model was tested in the earlier analysis.
  - Unfold the MiniBooNE excess in reconstructed neutrino energy using the smearing matrix that describes the reconstructed CCQE electron neutrino energy in MiniBooNE.
  - Scale MicroBooNE's intrinsic ν_e flux from BNB to generate the predicted signal excess.

LEE Search: ν_e Signal Models

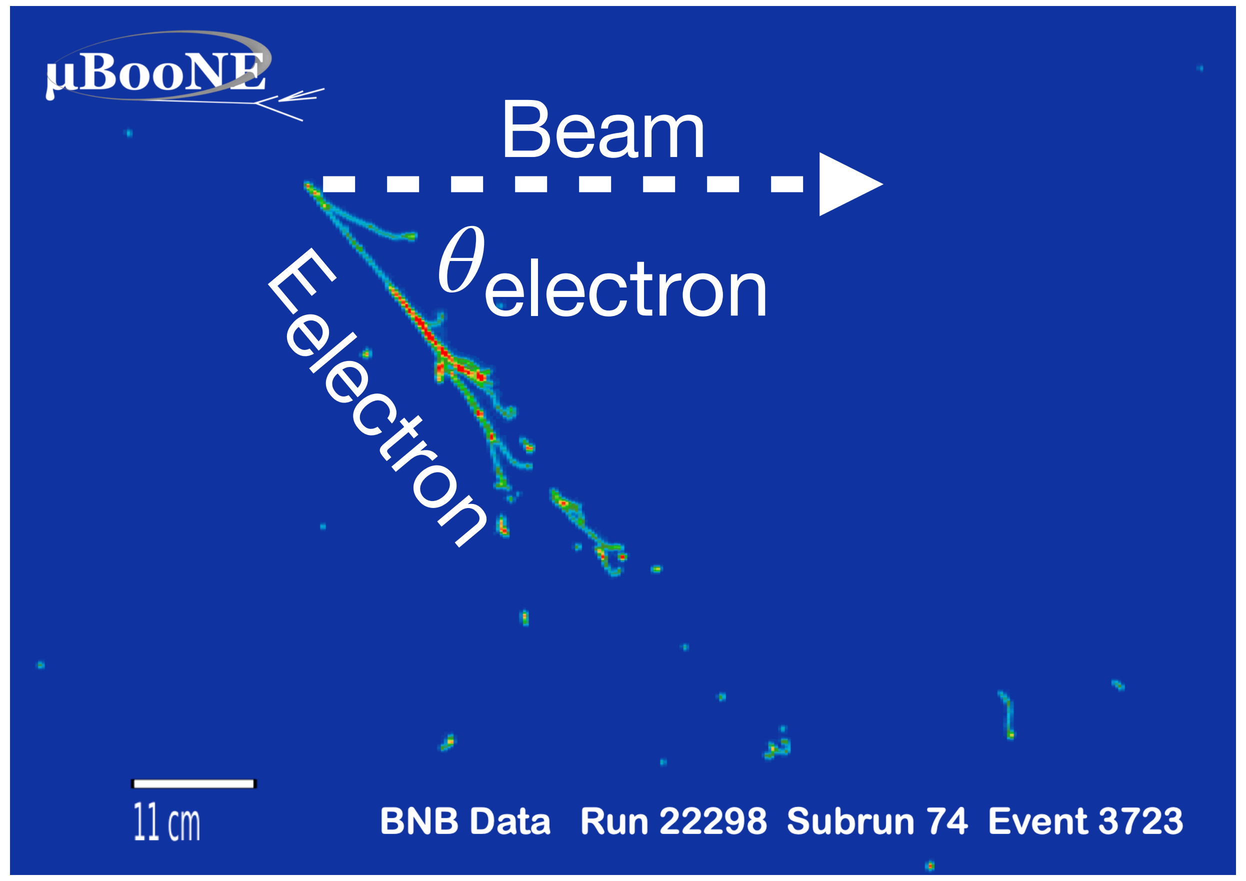




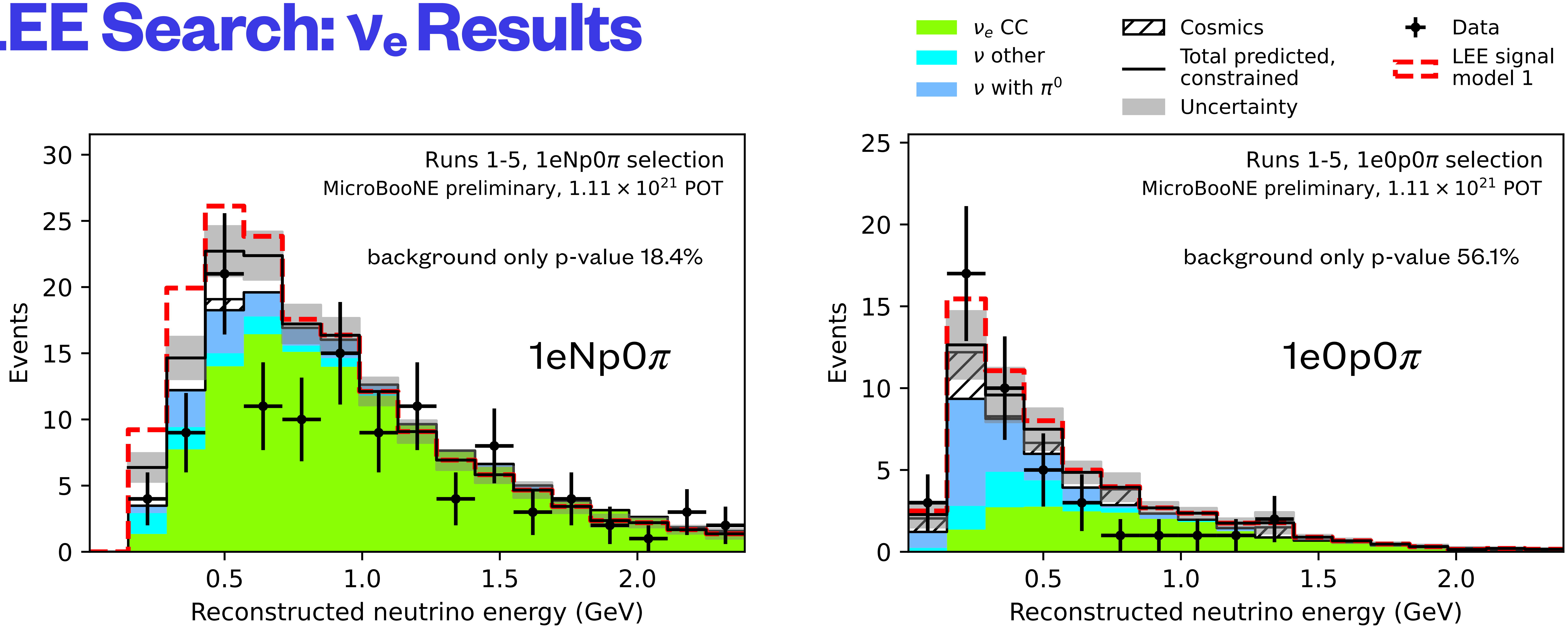
2D Unfold



- **Signal Model 2 (New):**
  - Less dependent on CCQE modeling and better match excess in shower kinematics.
  - Unfold the MiniBooNE excess reconstructed in 2D shower kinematics ($E_{electron}$ and $\theta_{electron}$).
  - Scale true electron kinematics from MicroBooNE's intrinsic ν_e prediction to generate the predicted signal excess.
- Two signal models are complementary to expand the analysis reach.



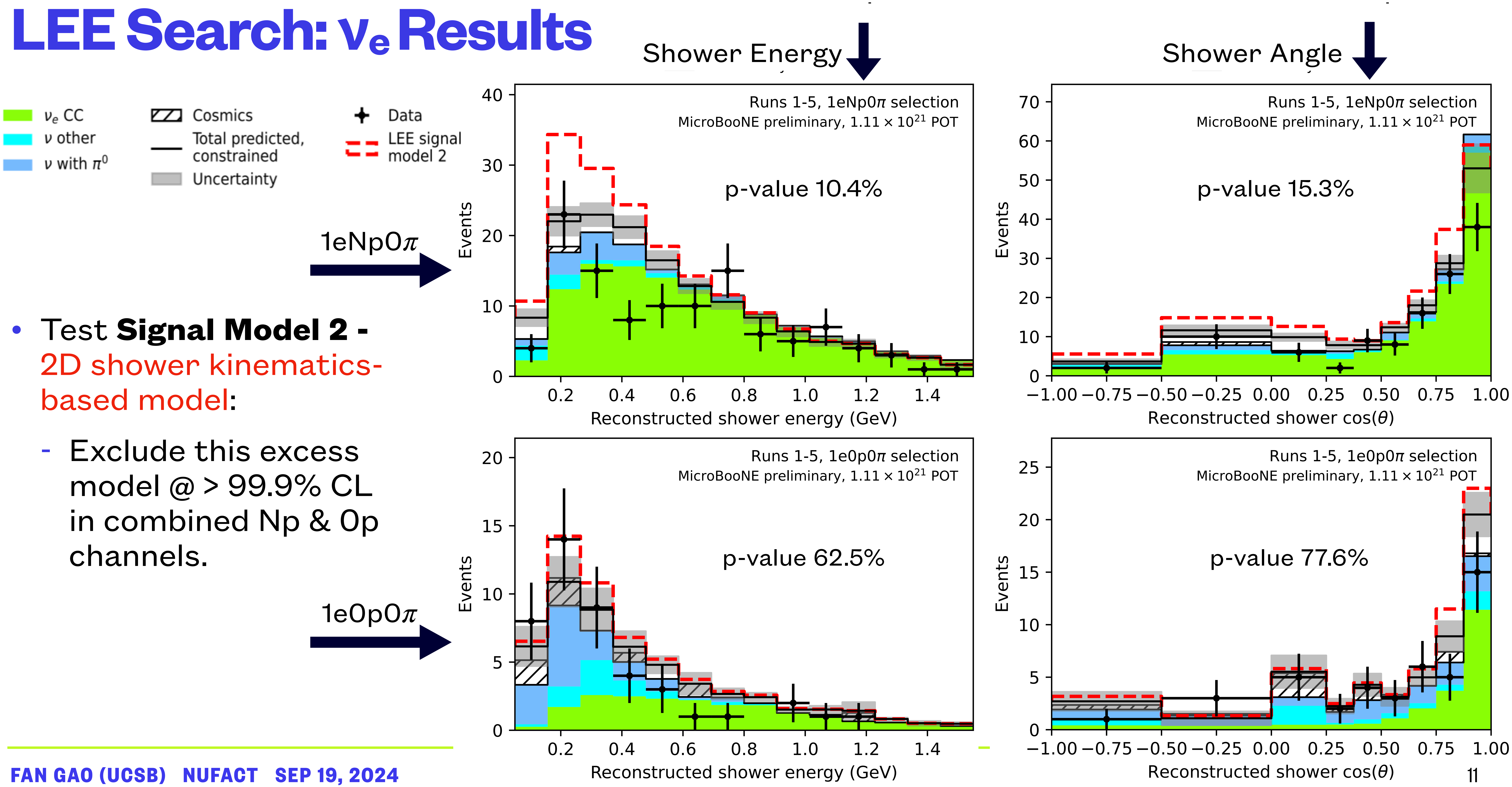
LEE Search: ν_e Results



- Test MiniBooNE excess under **Signal model 1** - neutrino energy-dependent ν_e rate scaling.
  - Data in overall agreement with intrinsic ν_e flux prediction.
  - Rule out this excess model @ 99.5% CL in Np & 0p combined channels.
    - ➡ Results are mostly driven by the Np channel, and the 0p channel is less sensitive due to limited statistics.

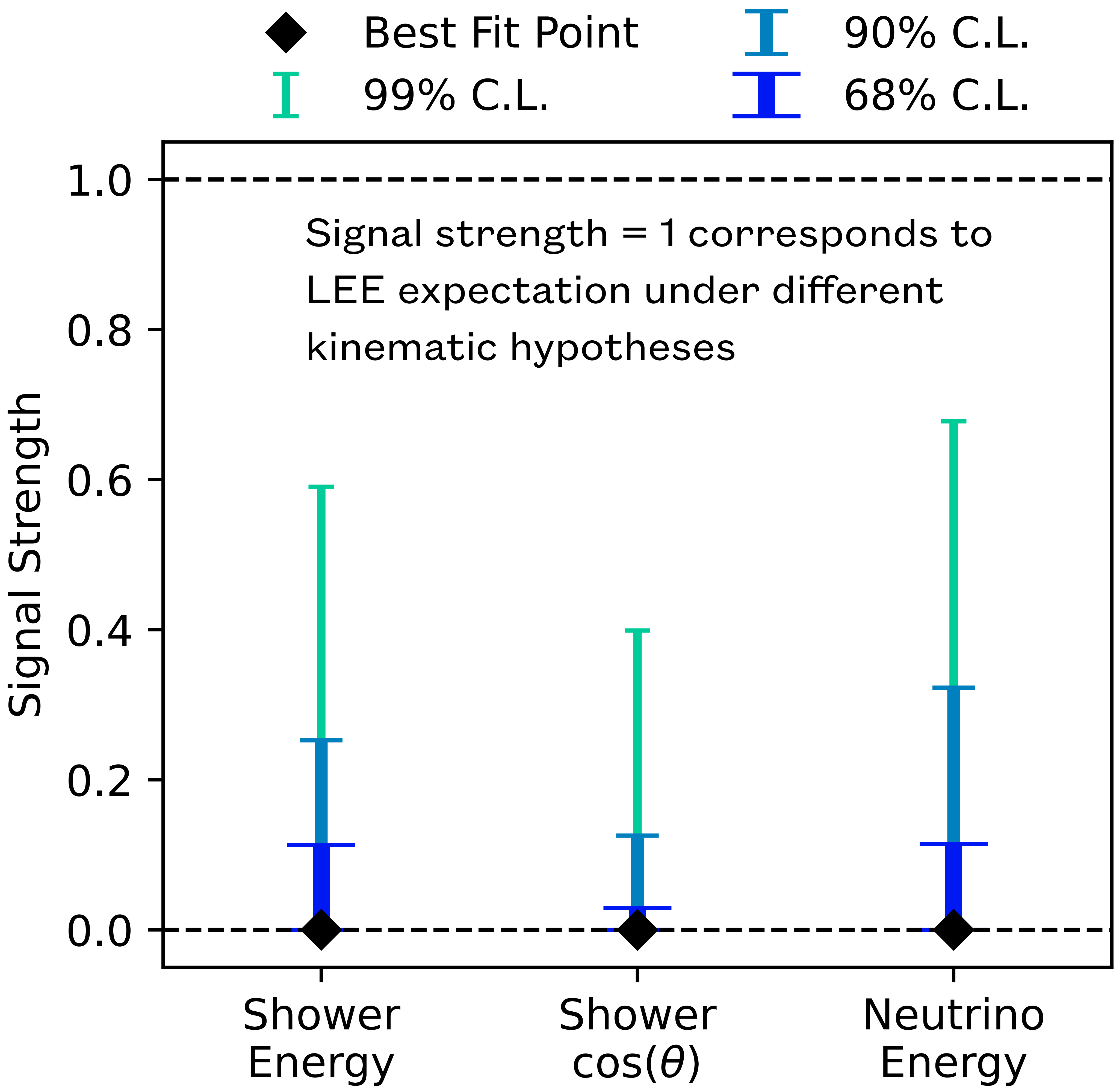
LEE Search: ν_e Results

- Test **Signal Model 2 -** 2D shower kinematics-based model:
  - Exclude this excess model @ > 99.9% CL in combined Np & 0p channels.



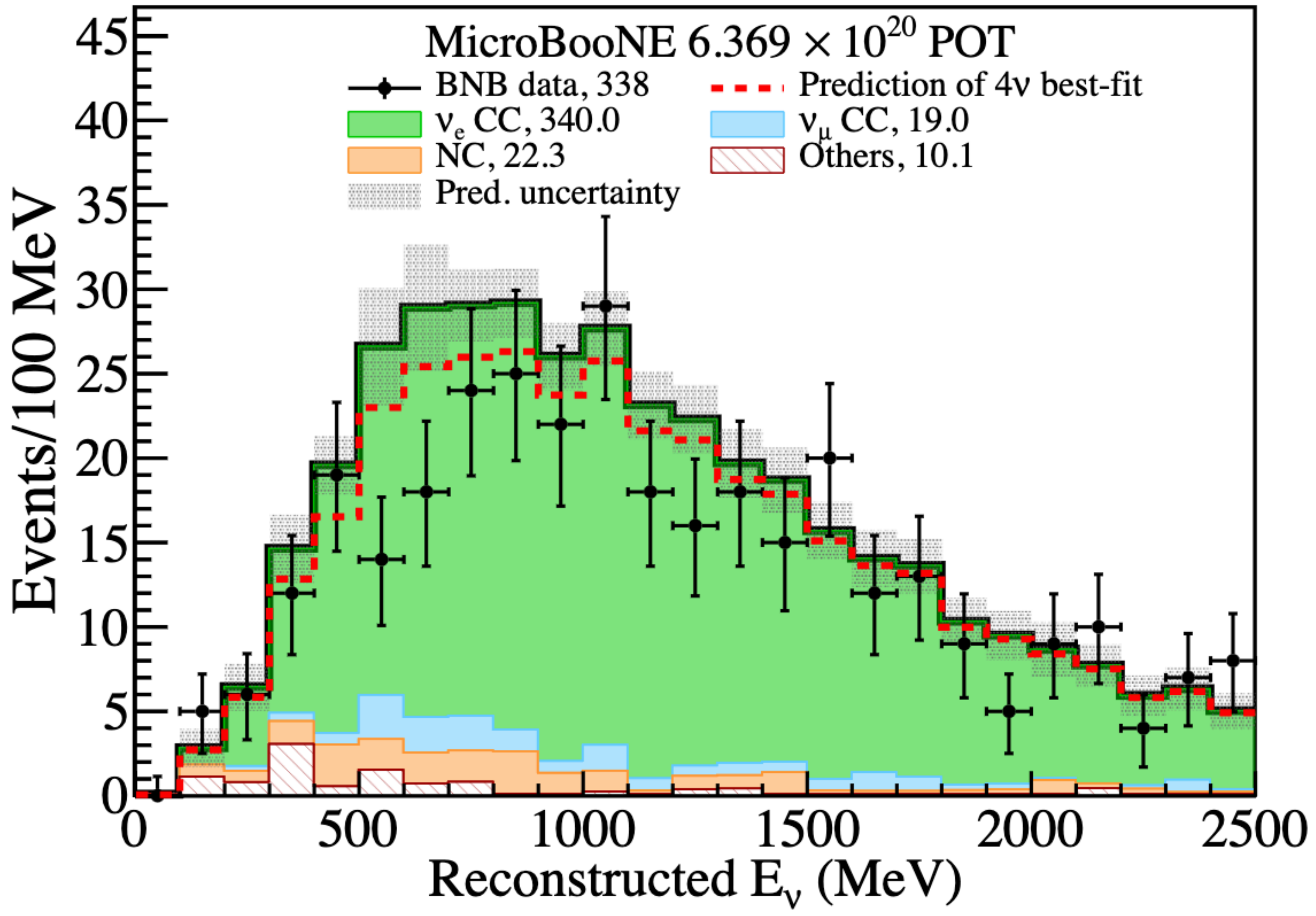
LEE Search: ν_e Analysis

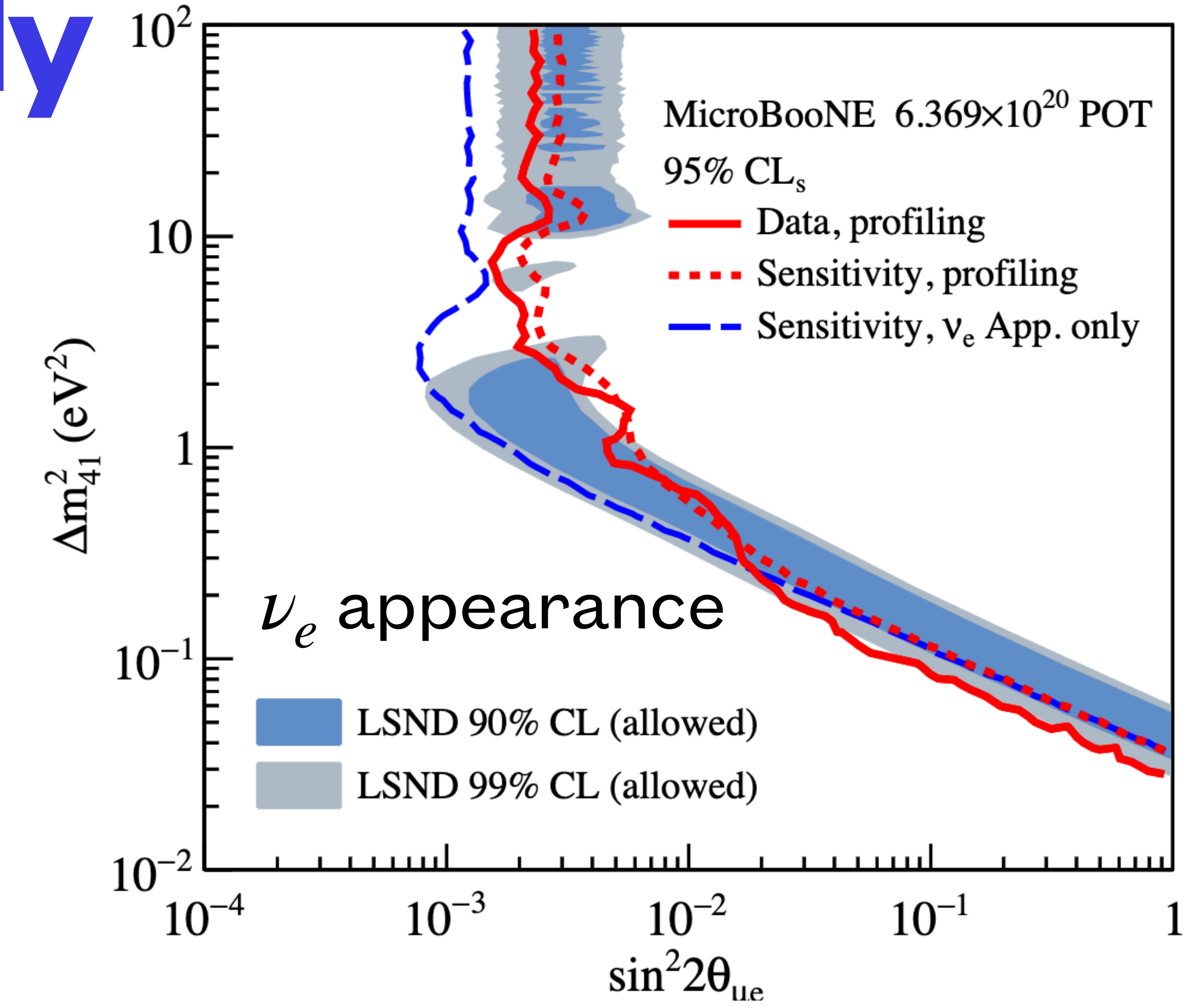
- Expanded investigation of electron-like excess hypothesis:
  - 6.86e20 → 11.1e20 POT of data.
  - New constraint of intrinsic ν_e and π^0 backgrounds.
  - Complementary signal hypotheses: neutrino energy, shower energy, and shower $\cos\theta$.
- Results:
  - Data compatible with background-only prediction.
  - Data inconsistent with ν_e-like excess at > 99% CL.
  - Results consistent across kinematic variables tested.
- More details in MICROBOONE-NOTE-1127-PUB

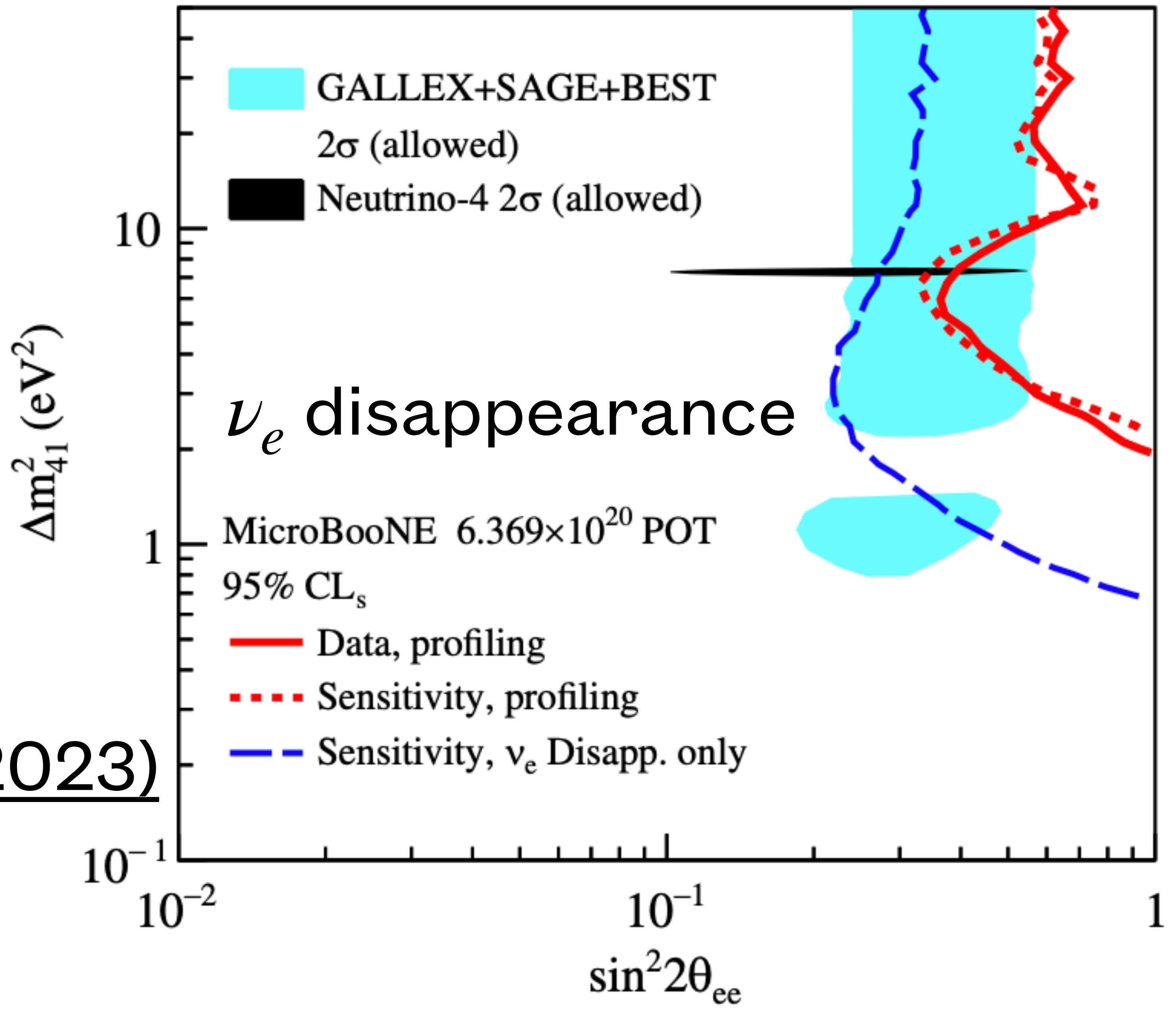


3+1 Sterile Neutrino Search: BNB-Only

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



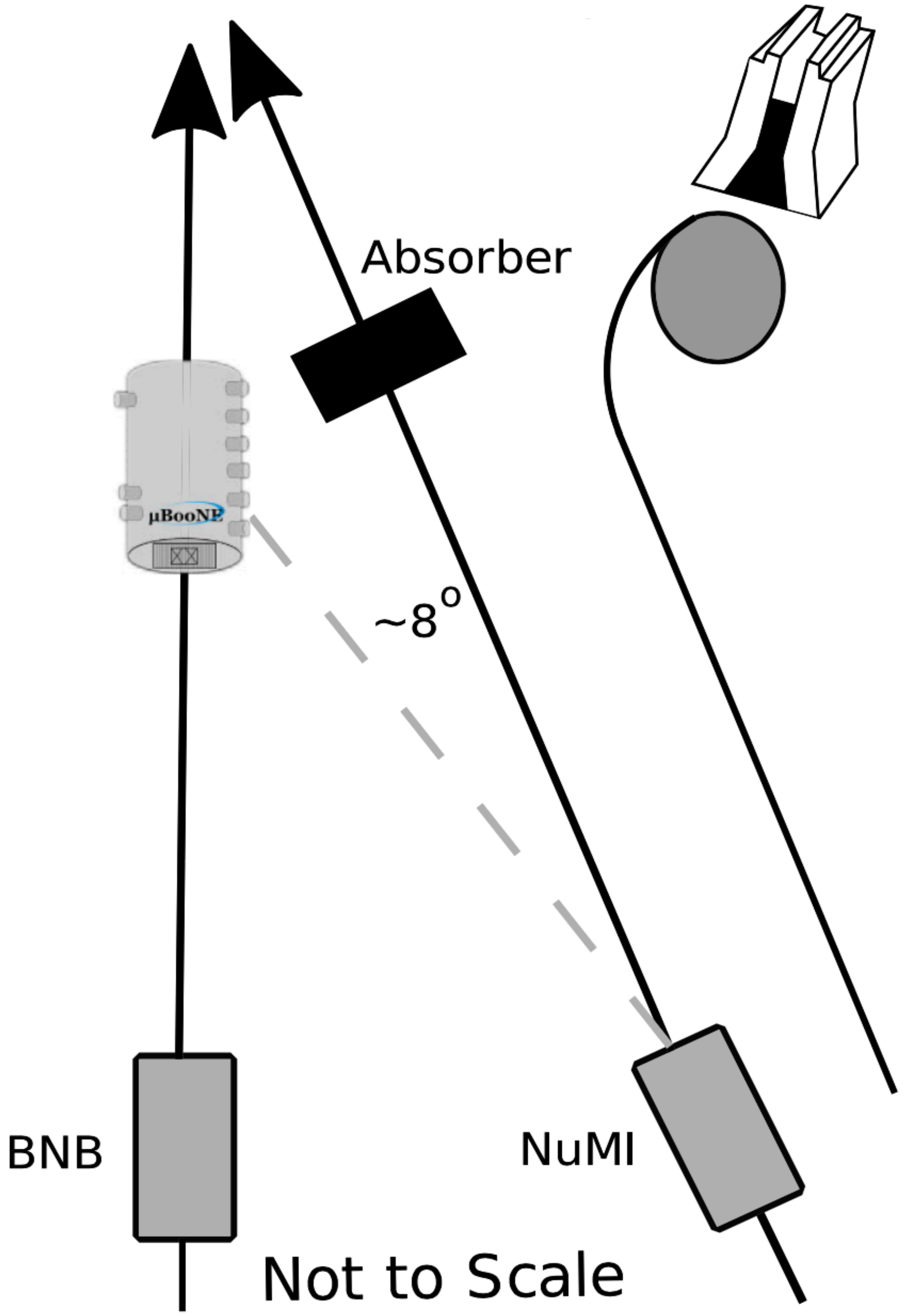


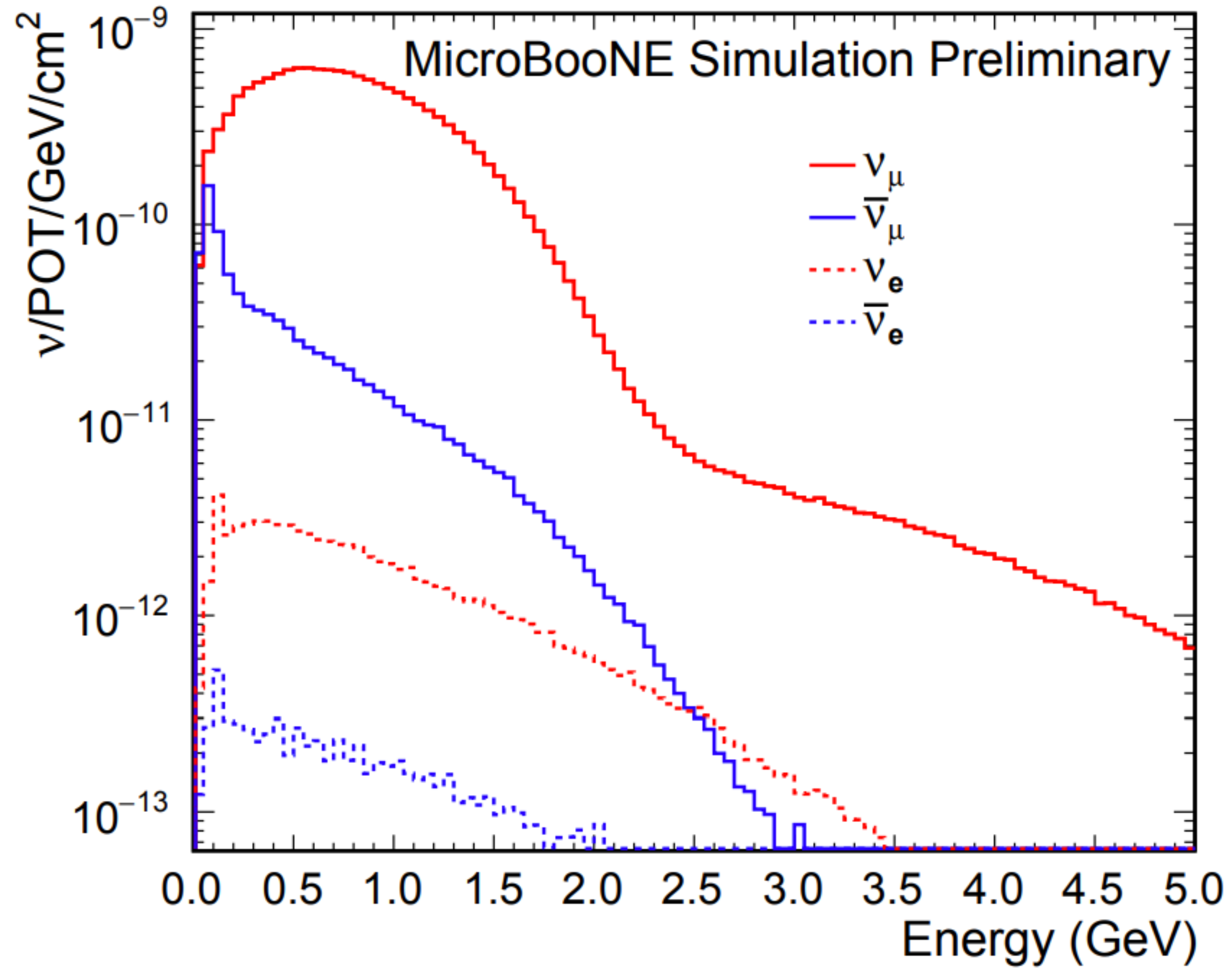


- Reinterpret LEE ν_e analysis under 3+1 sterile neutrino oscillation framework
  - Simultaneously analyze ν_e appearance and disappearance channels
- MicroBooNE's first 3+1 sterile neutrino search
  - Inclusive ν_e selection using BNB data showed consistency with the 3ν hypothesis.
  - Partially excluded the allowed regions.

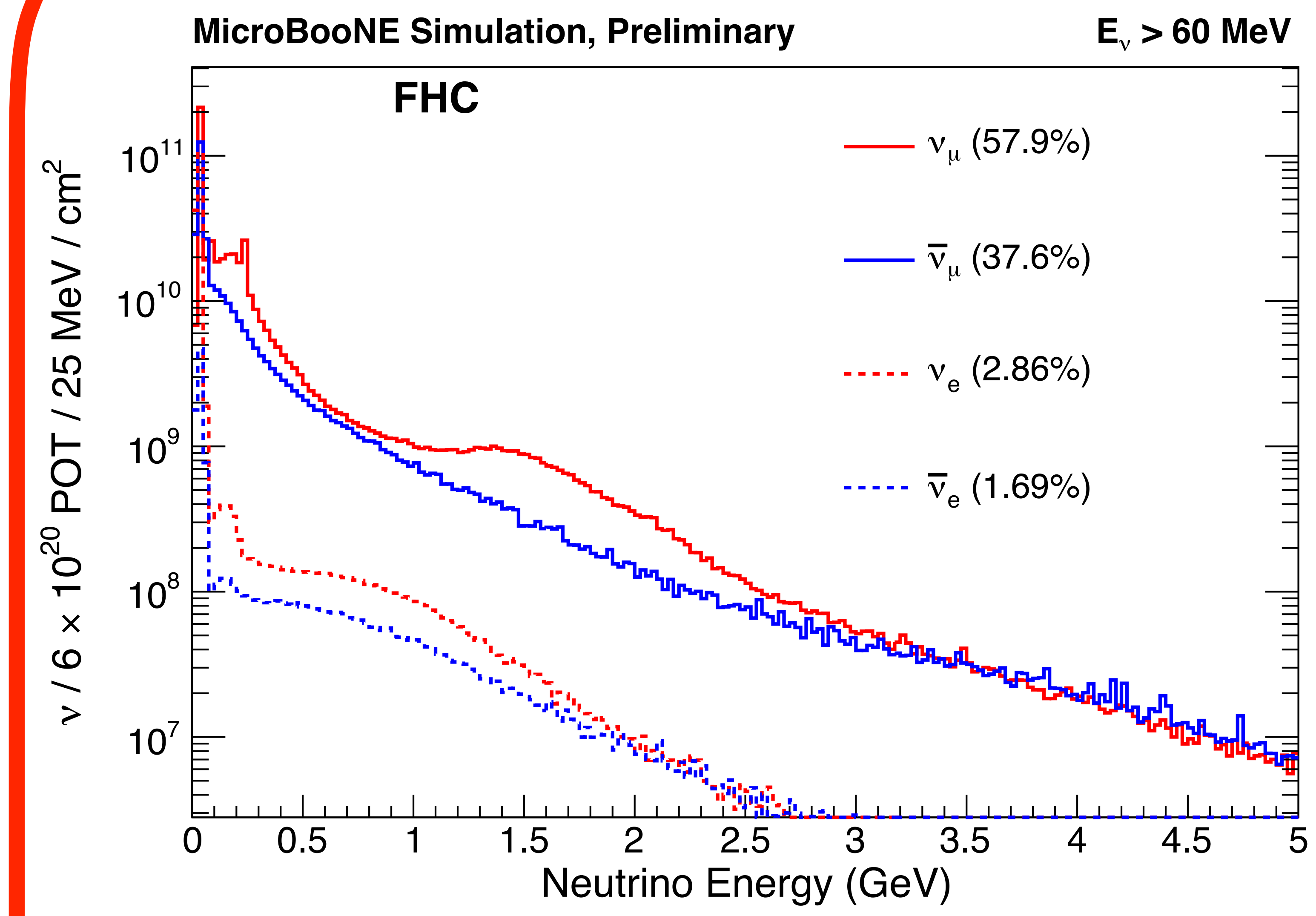
Phys. Rev. Lett. 130, 011801 (2023)

BNB and NuMI at MicroBooNE



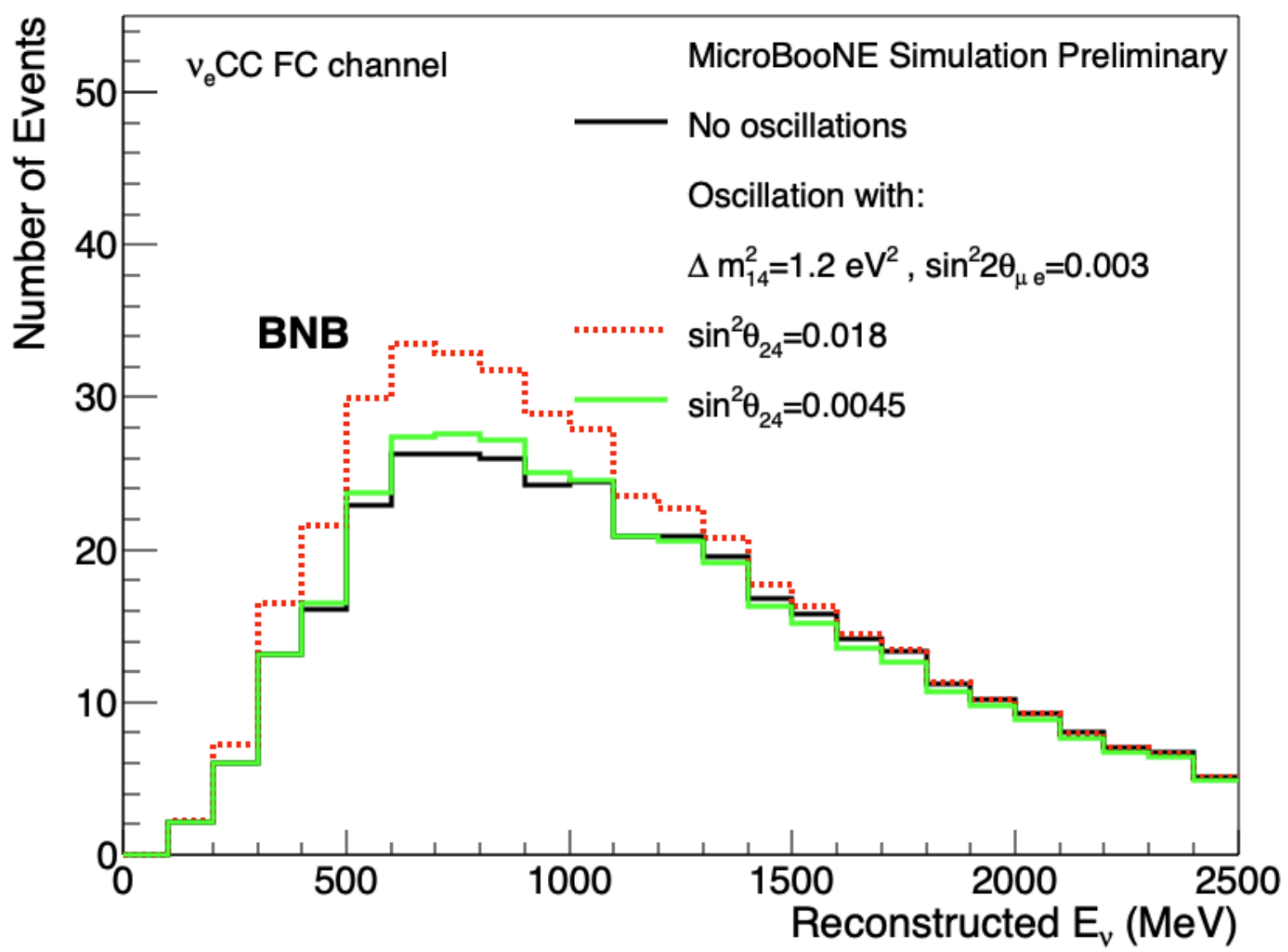


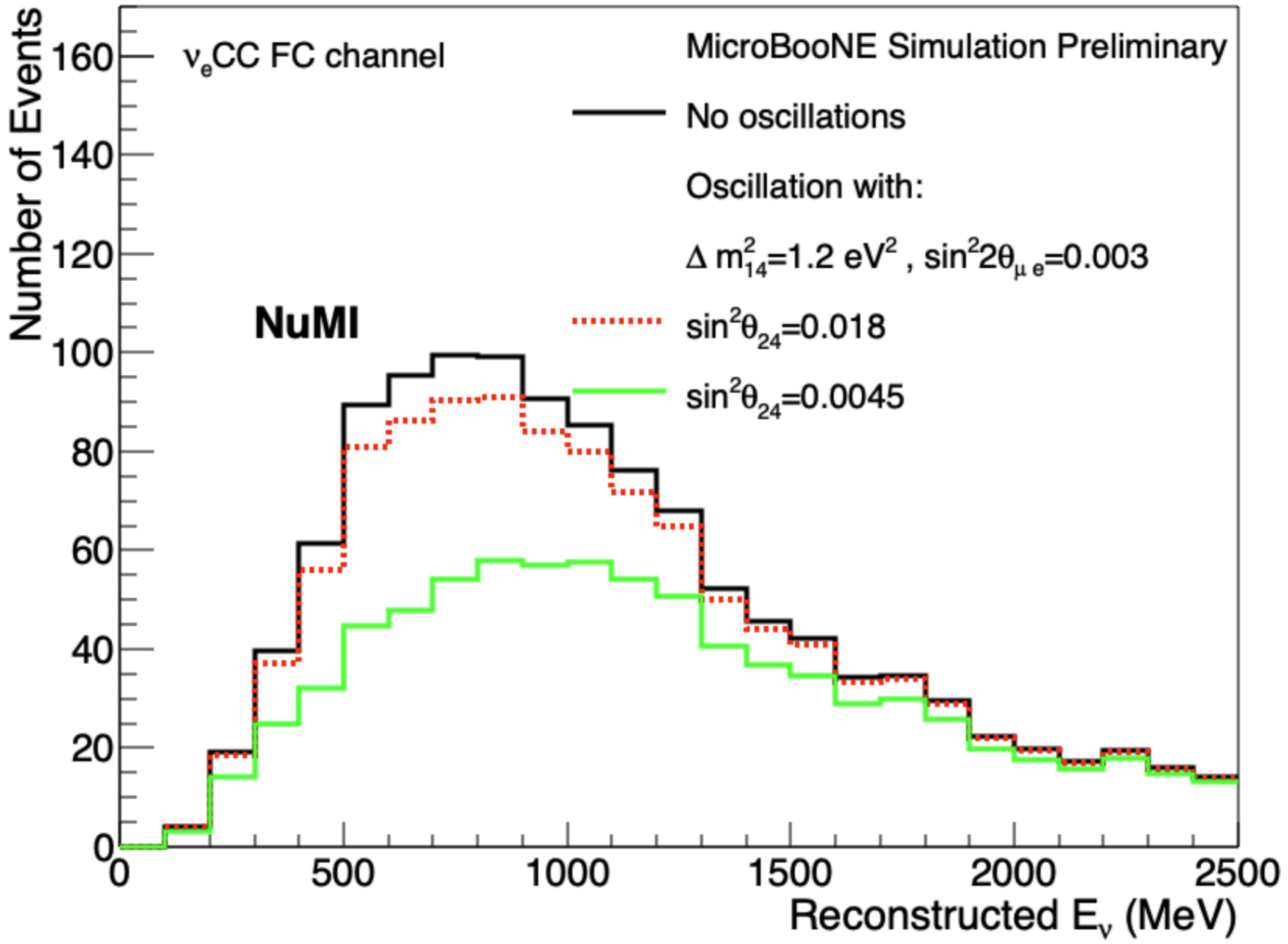
BNB:
- on-axis
- 99.5% ν_μ / 0.5% ν_e
- 470 meter baseline

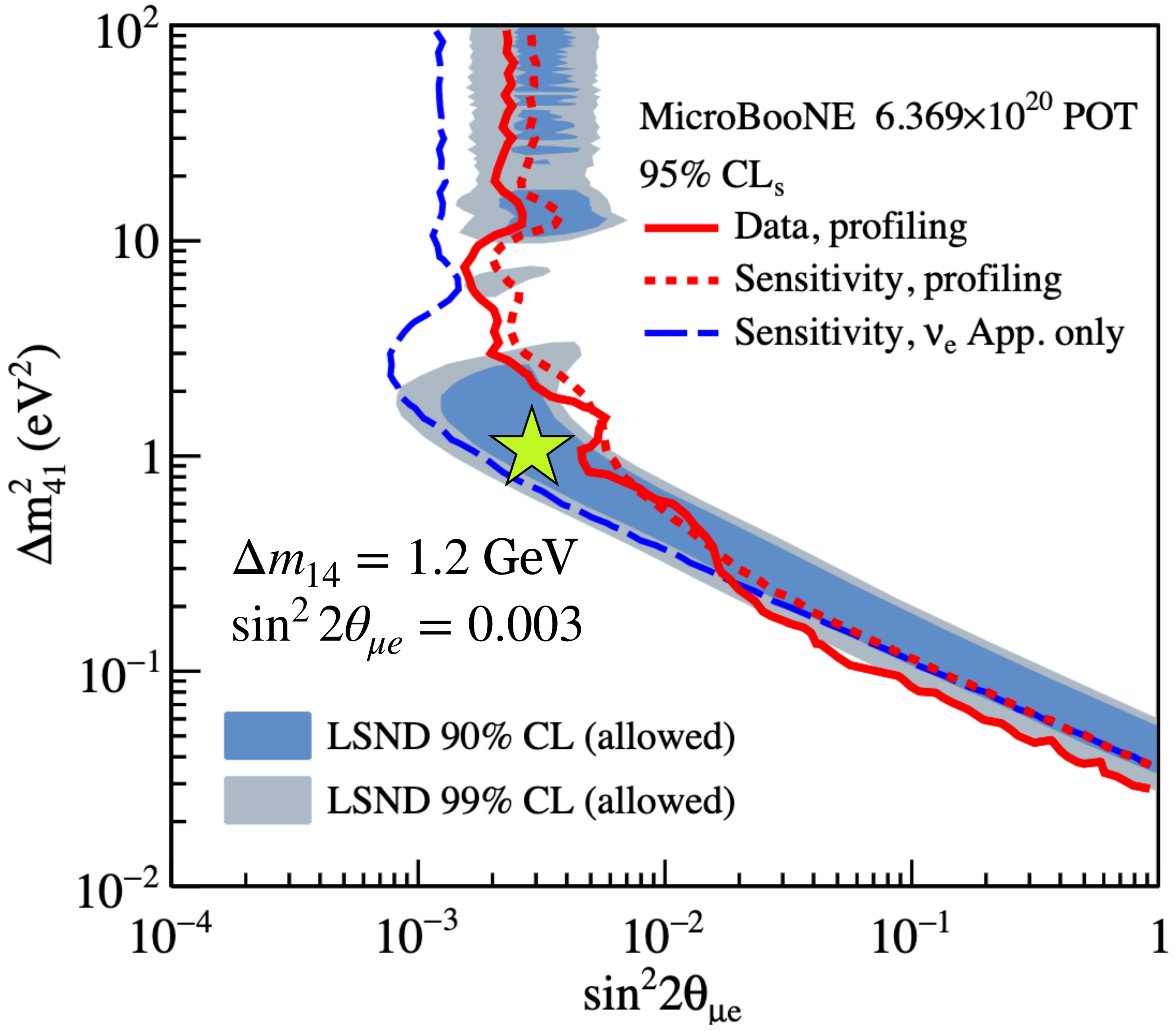


NuMI:
- 8° off-axis
- 95% ν_μ / 5% ν_e
- comparable ν and $\bar{\nu}$
- Flux from target and absorber

3+1 Degeneracy Breaking: BNB + NuMI

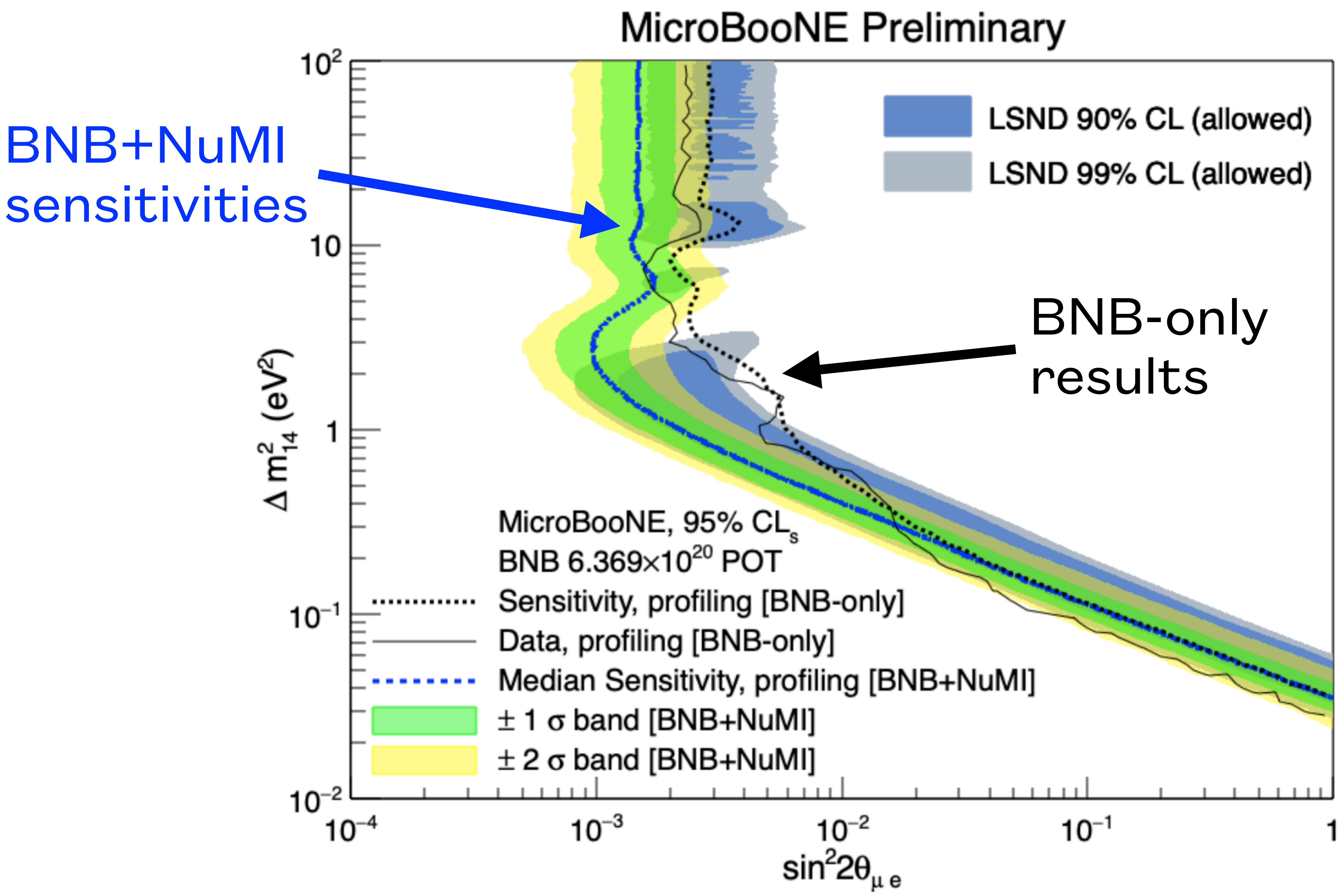


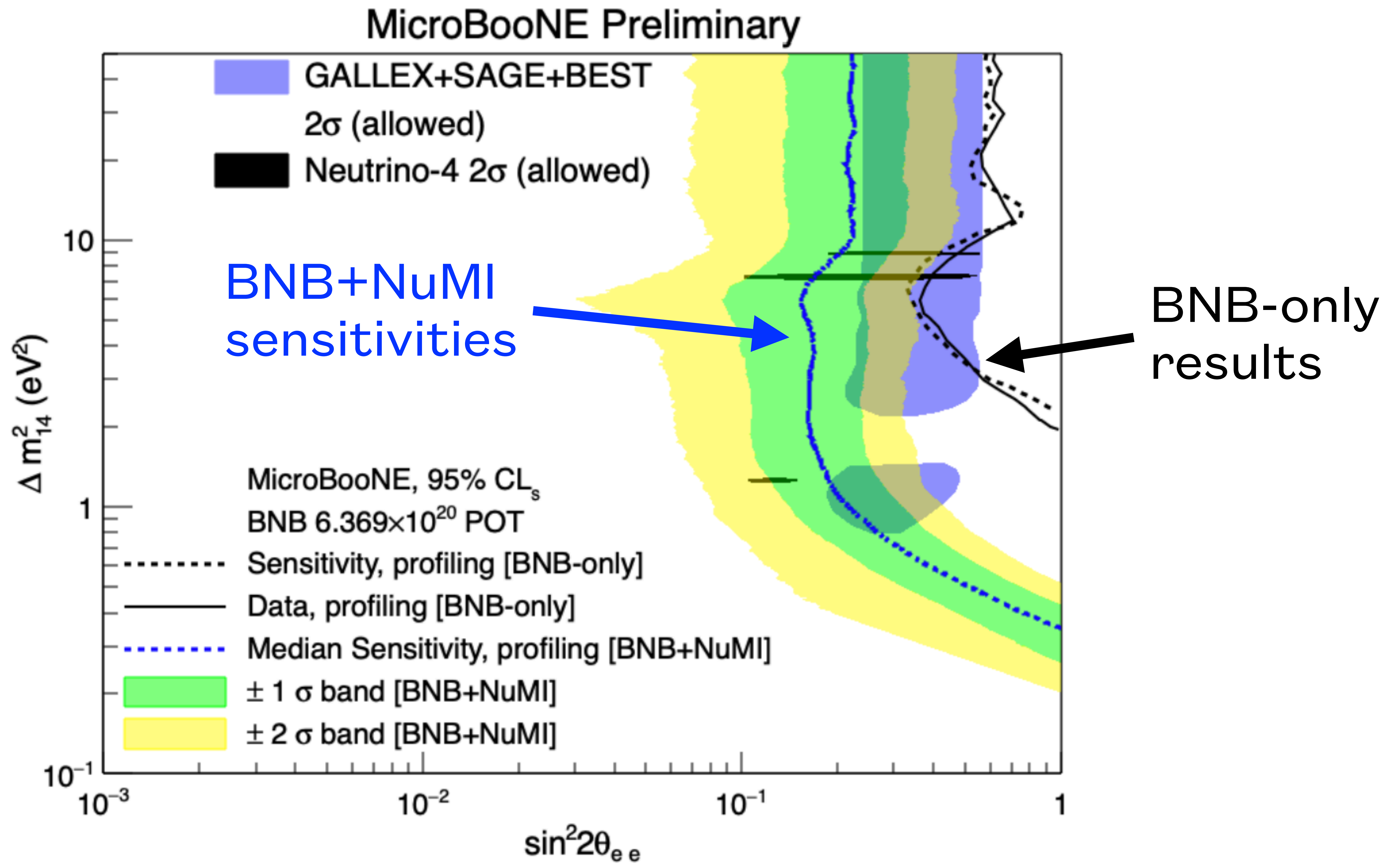




- 3+1 degeneracy: ν_e disappearance cancels $\nu_\mu \rightarrow \nu_e$ appearance
  - Degeneracy depends on the ratio of intrinsic rate ν_μ/ν_e — in BNB ~ 200, in NuMI ~ 25.
  - For the same mixing angles, a large effect in NuMI would be observed. NuMI can break the degeneracy!

3+1 Sensitivity Improvement: BNB + NuMI





- Joint 3+1 analysis with BNB + NuMI significantly improves the sensitivity!
  - The sensitivity covers the majority of the LSND and the Gallium allowed regions.

(More details in MICROBOONE-NOTE-1129-PUB for updated NuMI flux and MICROBOONE-NOTE-1132-PUB for dual-beam 3+1 analysis)

- Stay tuned for upcoming results from this analysis!

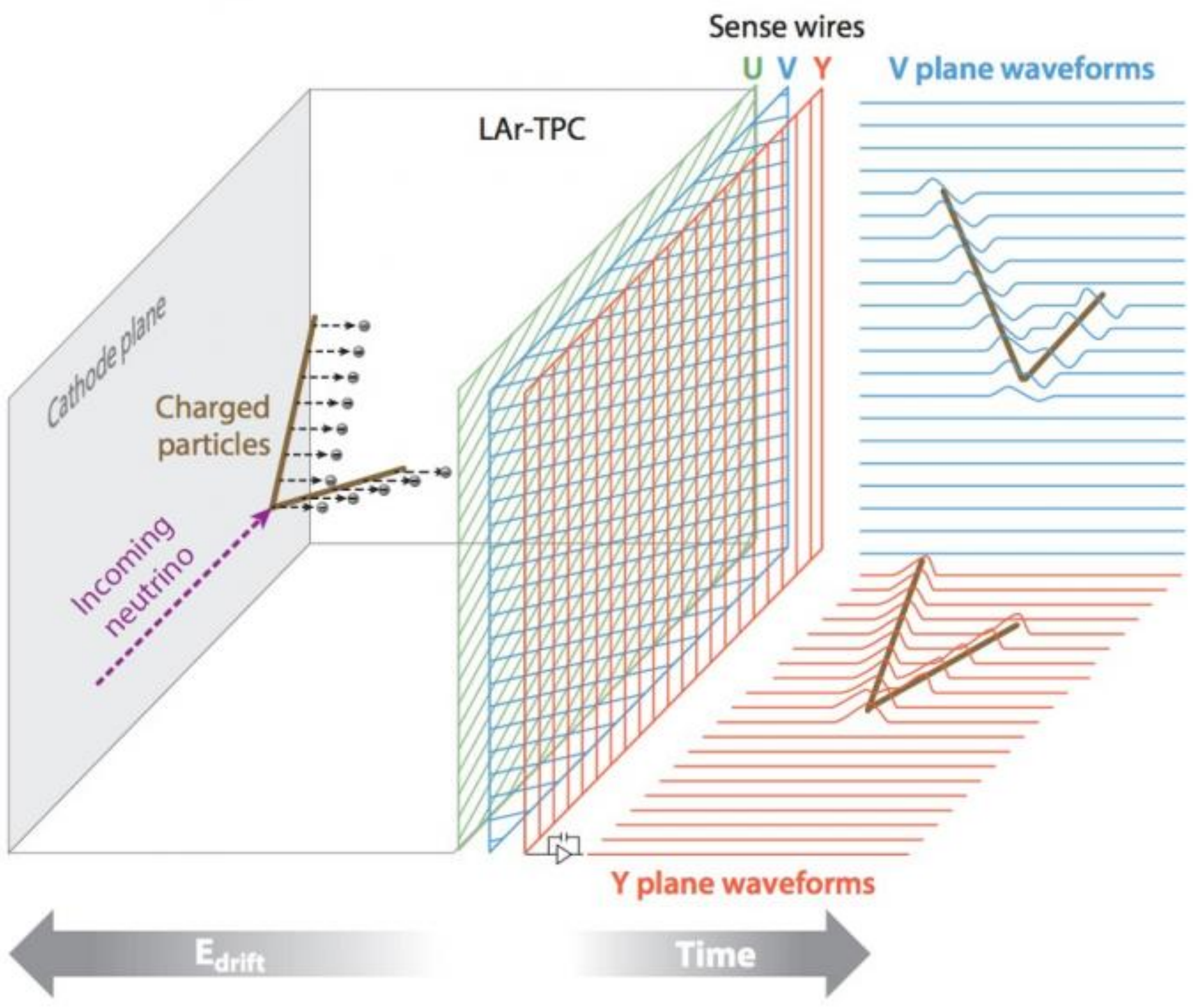
Summary

- The MicroBooNE experiment was designed to investigate the nature of the low energy excess observed by MiniBooNE.
- The first full-dataset ν_e LEE analysis results, with updates in signal models and sideband constraints, are presented, excluding the ν_e-like excess at > 99% CL.
- A novel "Dual-Beam" 3+1 sterile neutrino search provides significantly improved sensitivity in 3+1 interpretation of the short-baseline anomalies, with results coming soon.
- Focusing on other LEE interpretations in single-photon and e+e- topologies!

Thank you!

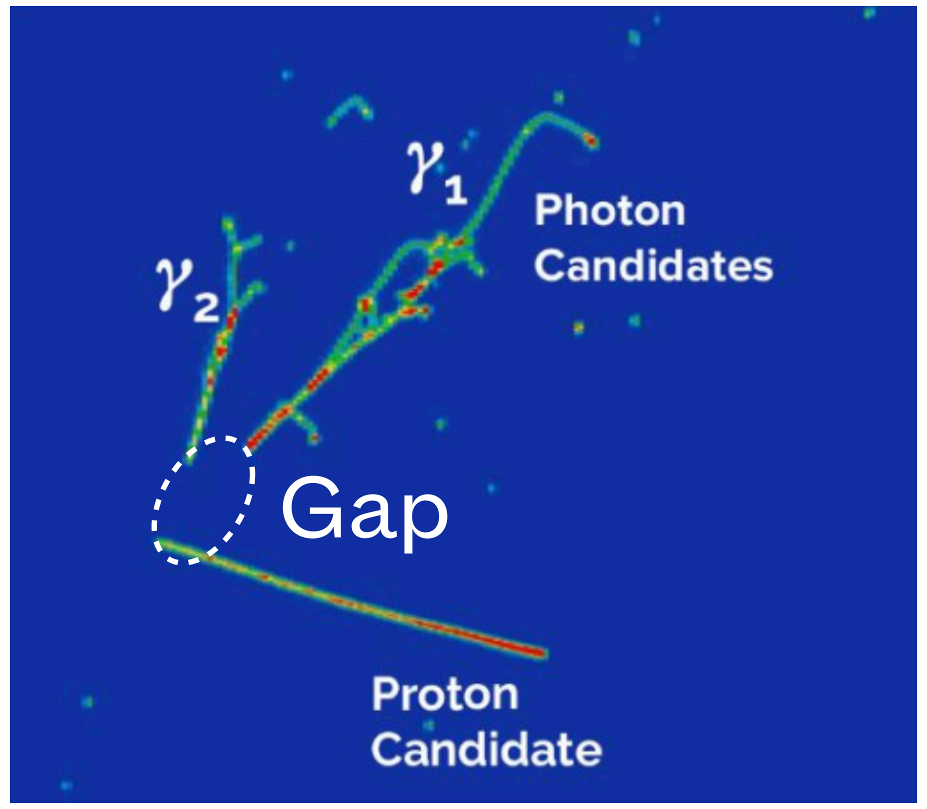
Backup

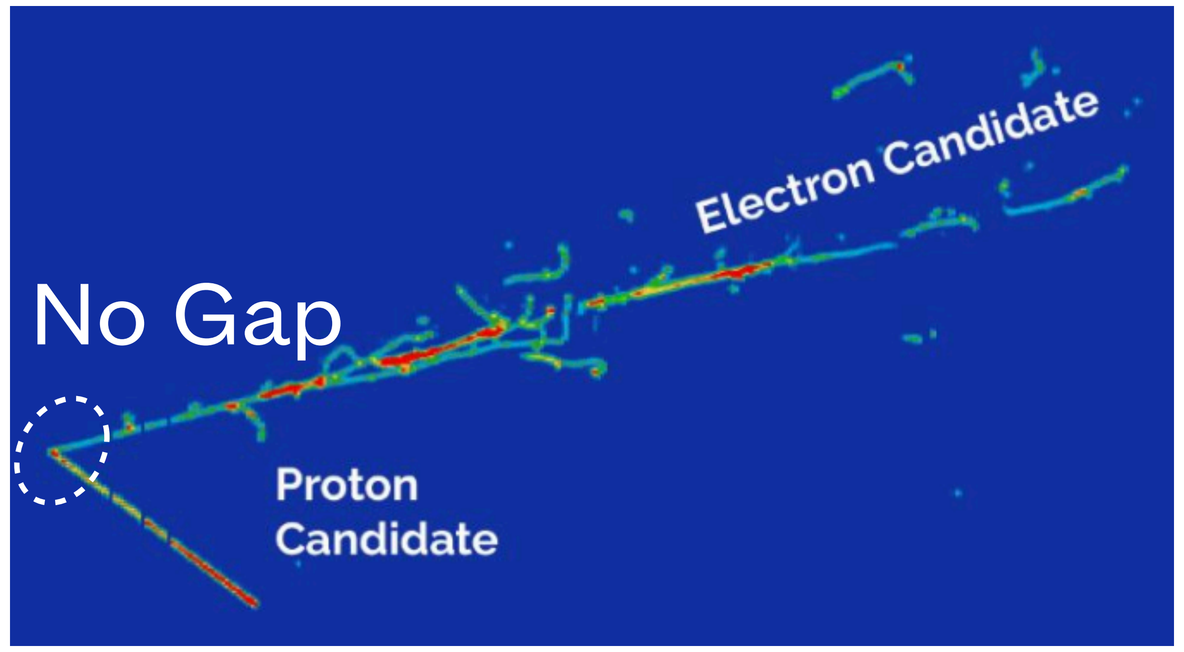
LArTPC Detector



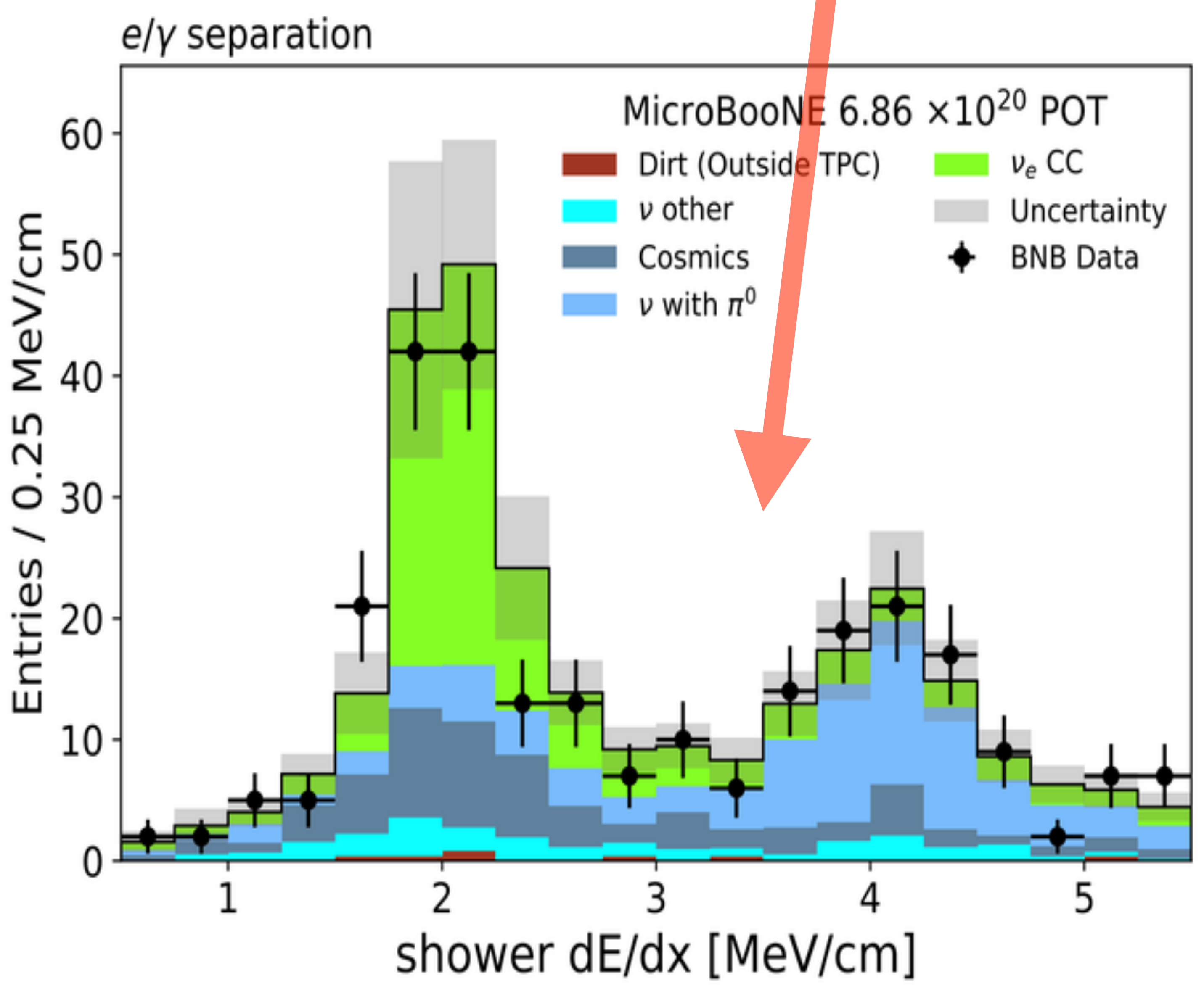
- Charged particles ionize the argon atoms and create free electrons, that drift toward the 3-wire planes under an external E-field and induce signals on the wires.
- Light flashes (photons) are detected by PMTs behind the wire planes, giving the interaction timing information.

- MicroBooNE's LArTPC is powerful in electron-photon separation.
  - Millimeter spatial resolution and calorimetry.





electrons - 1 MIP
vs.
photons - 2 MIP



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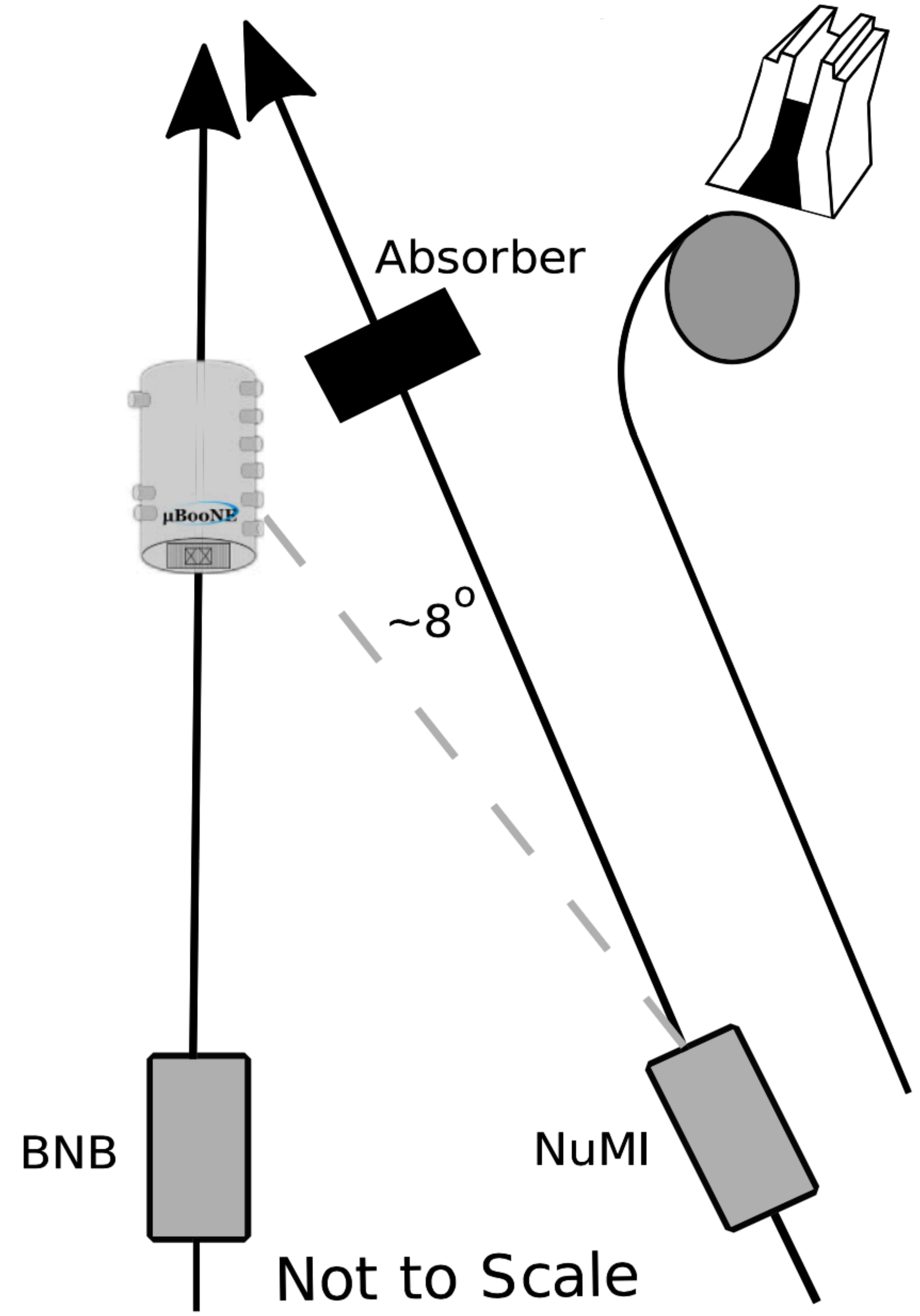

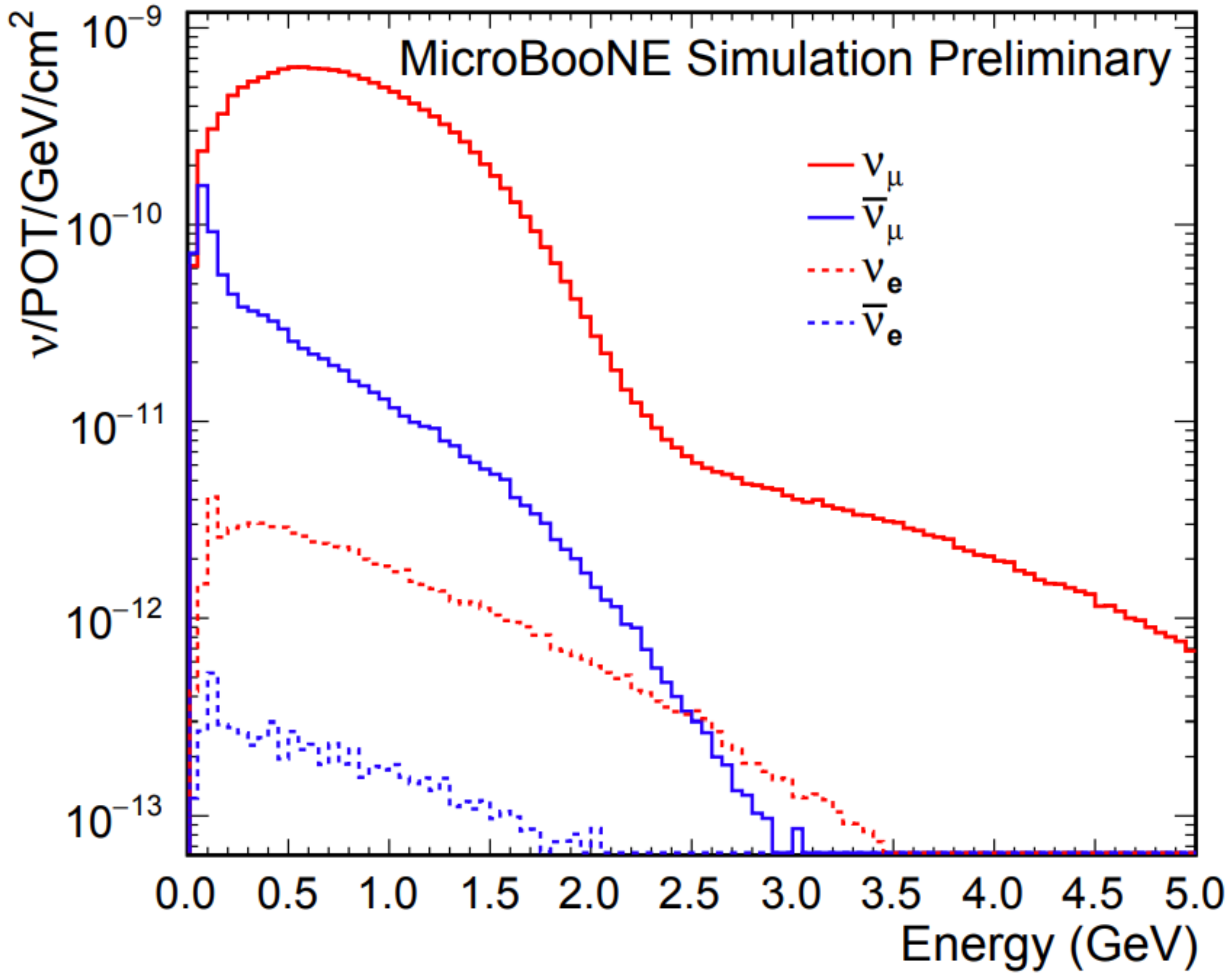

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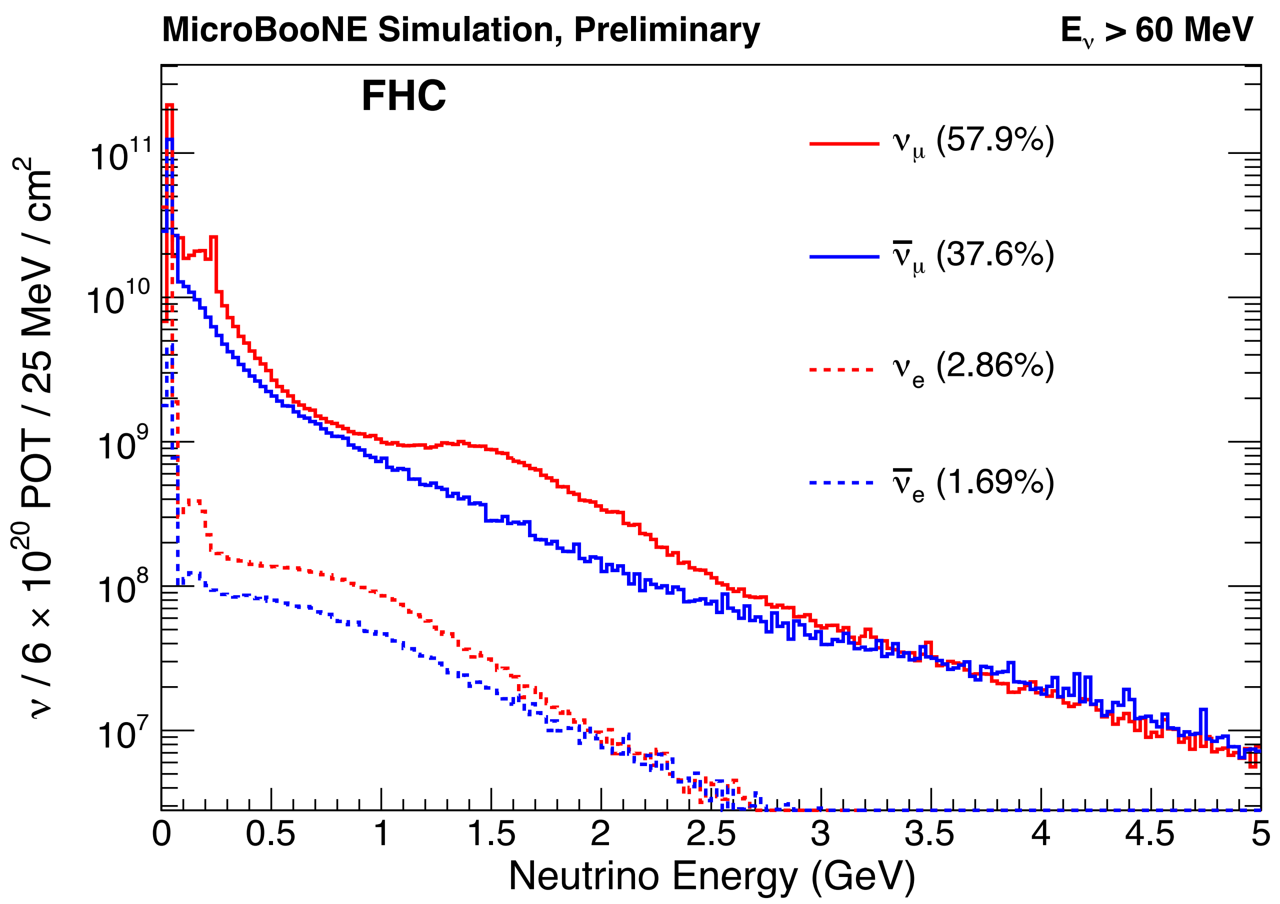

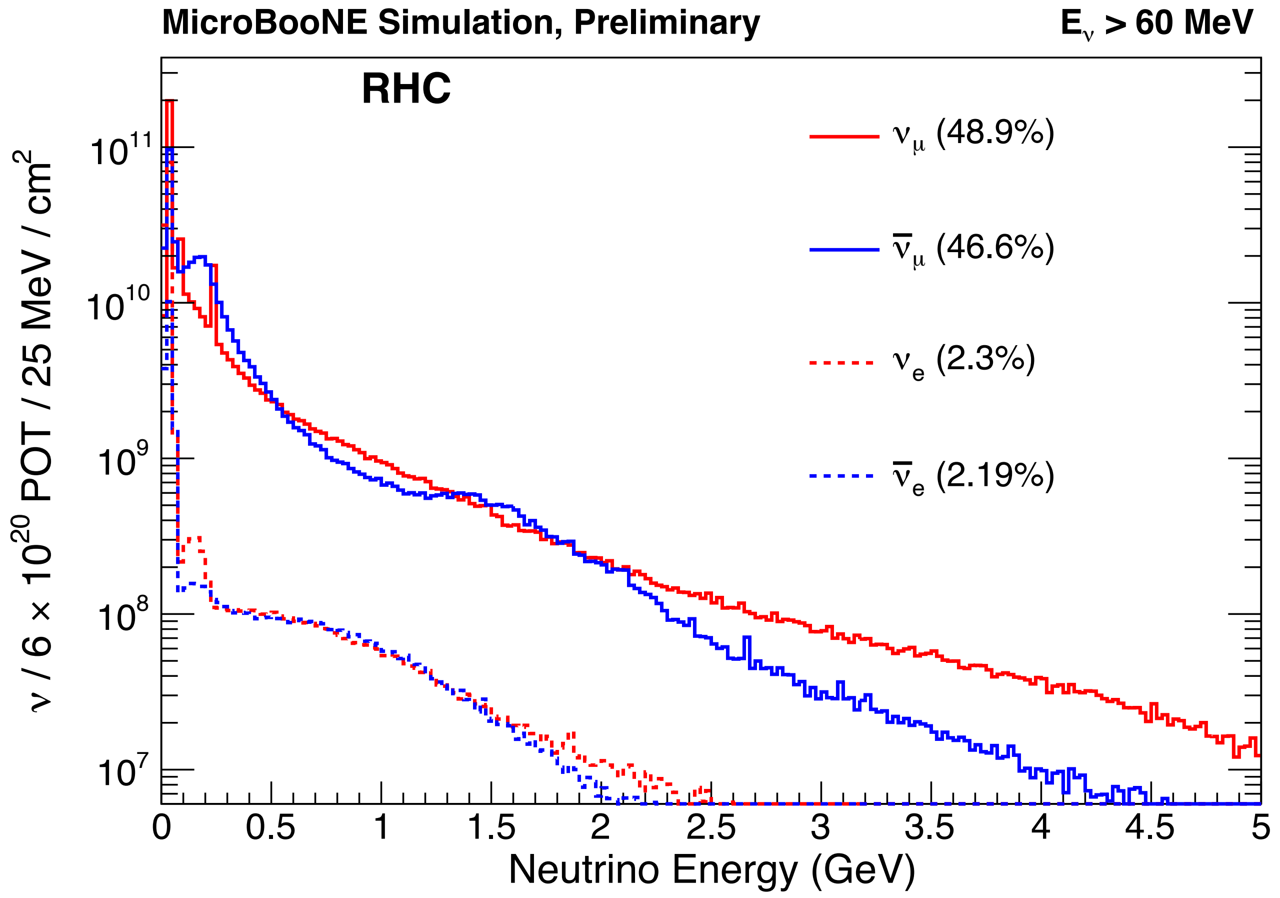

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