Recent Developments Regarding the MiniBooNE Anomaly

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NuFACT 2023: Working Group 5

NuFACT 2023
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Outline

- Overview of the MiniBooNE anomaly
- A $\overline{\nu}_e$-based explanation
- A neutrissimo-based explanation

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MeV-scale heavy neutral lepton with a transition magnetic moment coupling to active neutrinos

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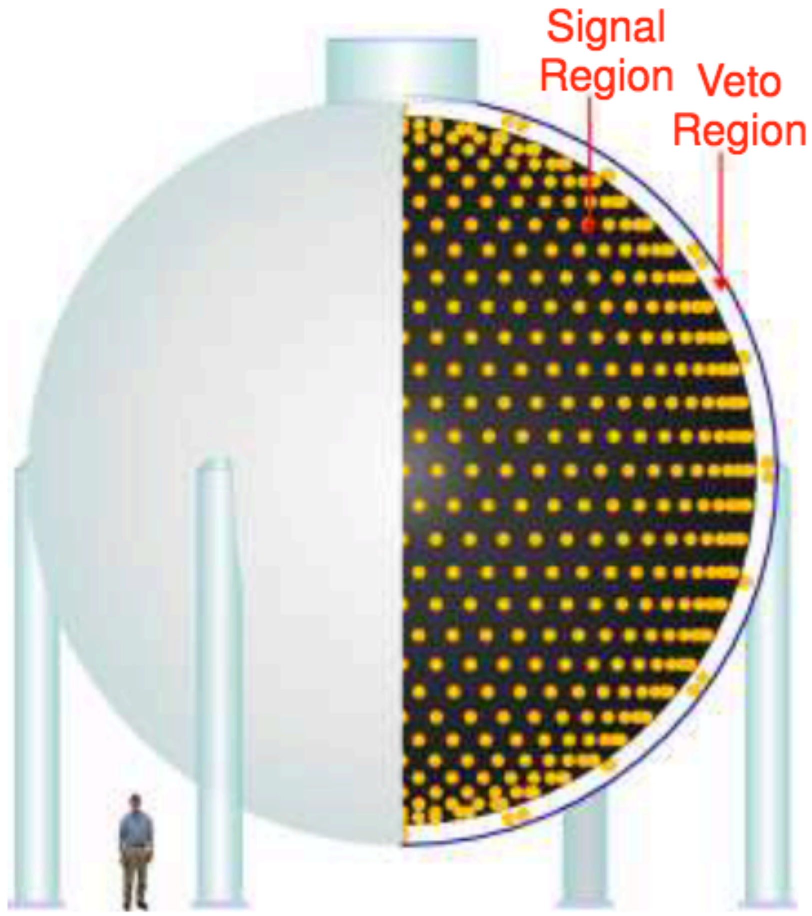
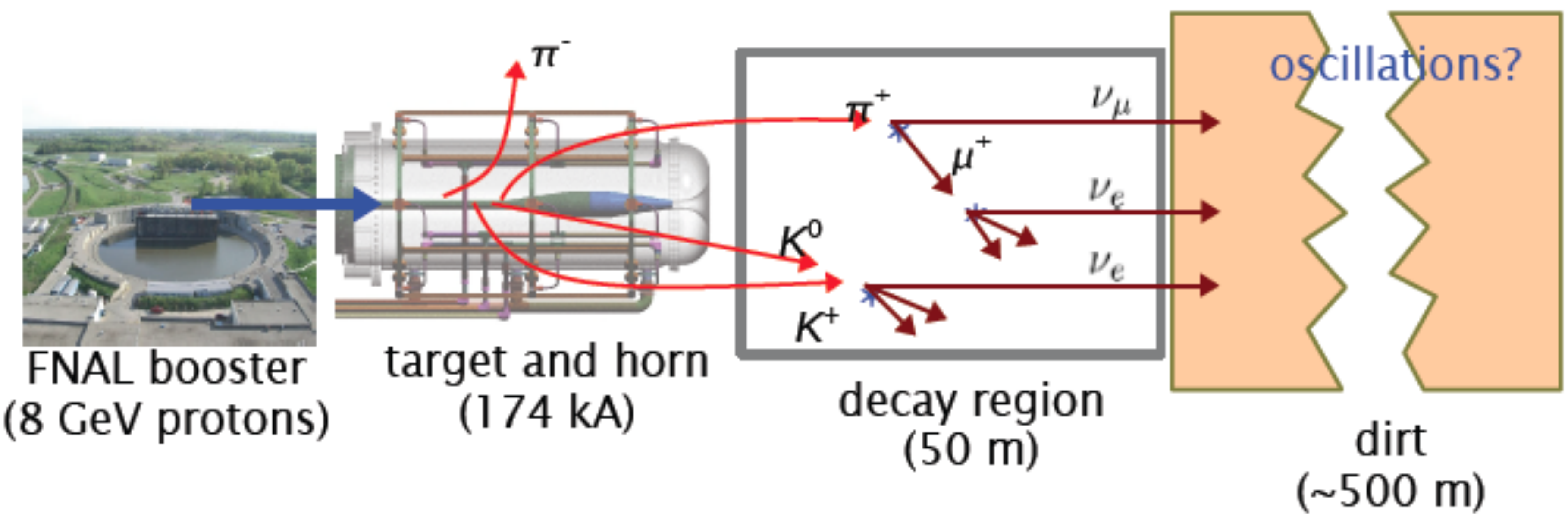
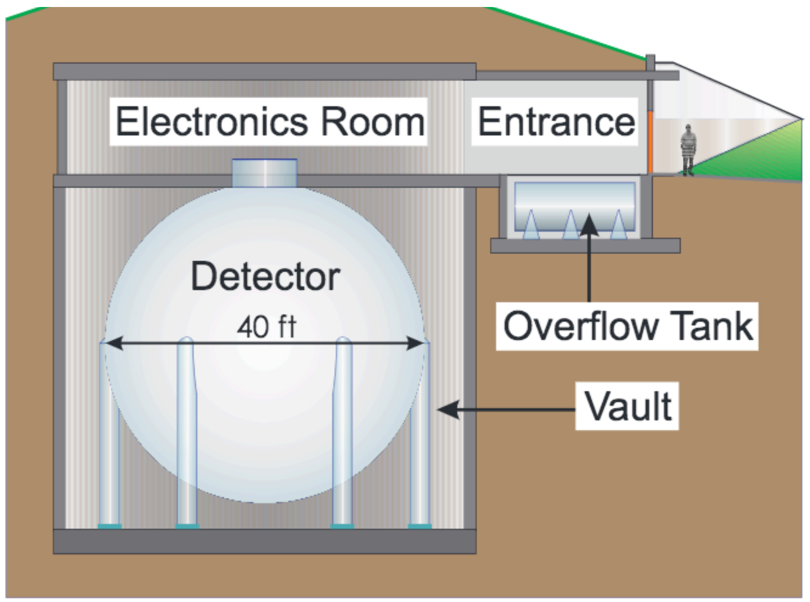
- <u>**Overview of the MiniBooNE anomaly**</u>
- A $\overline{\nu}_e$-based explanation
- A neutrissimo-based explanation

The MiniBooNE Experiment

- 800-ton CH_2 Cherenkov detector
- Situated along Fermilab's Booster Neutrino Beam
- ~540 m from the beryllium target
- Took data from 2002—2019

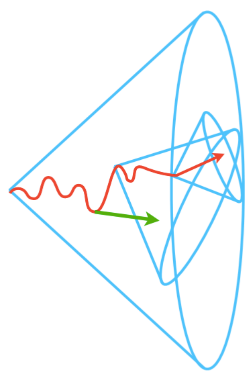


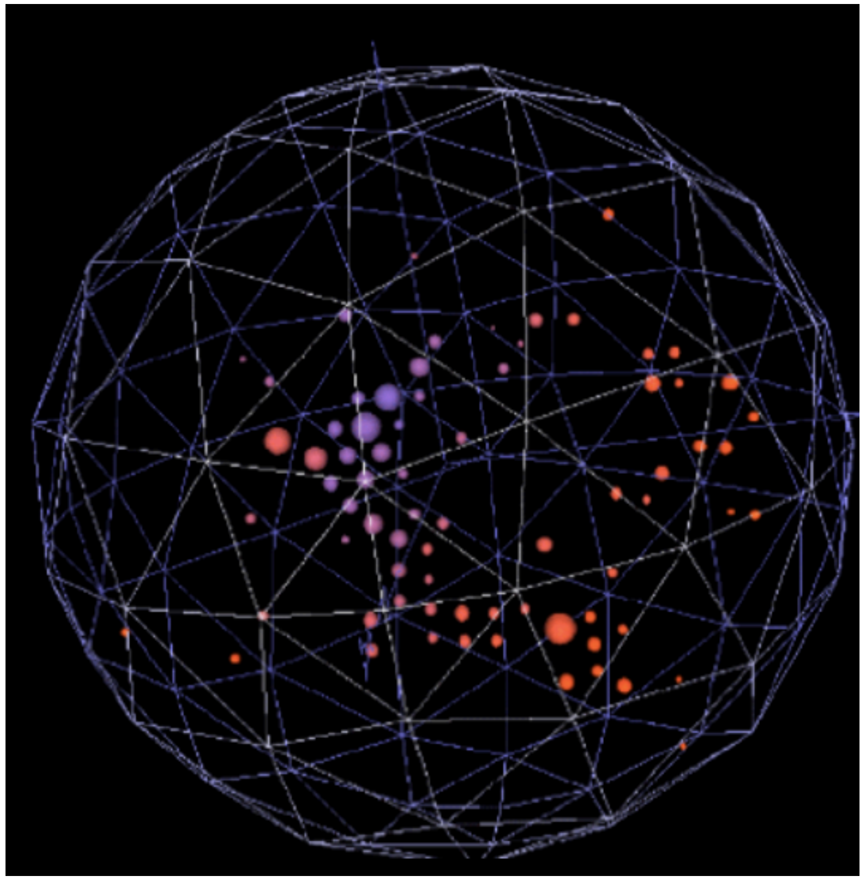




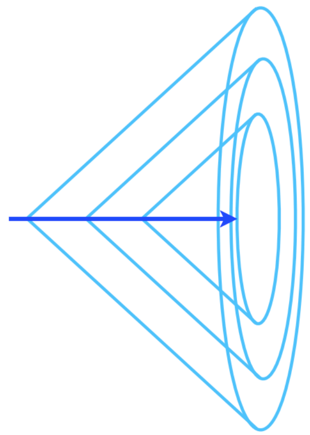
Particle ID @ MiniBooNE

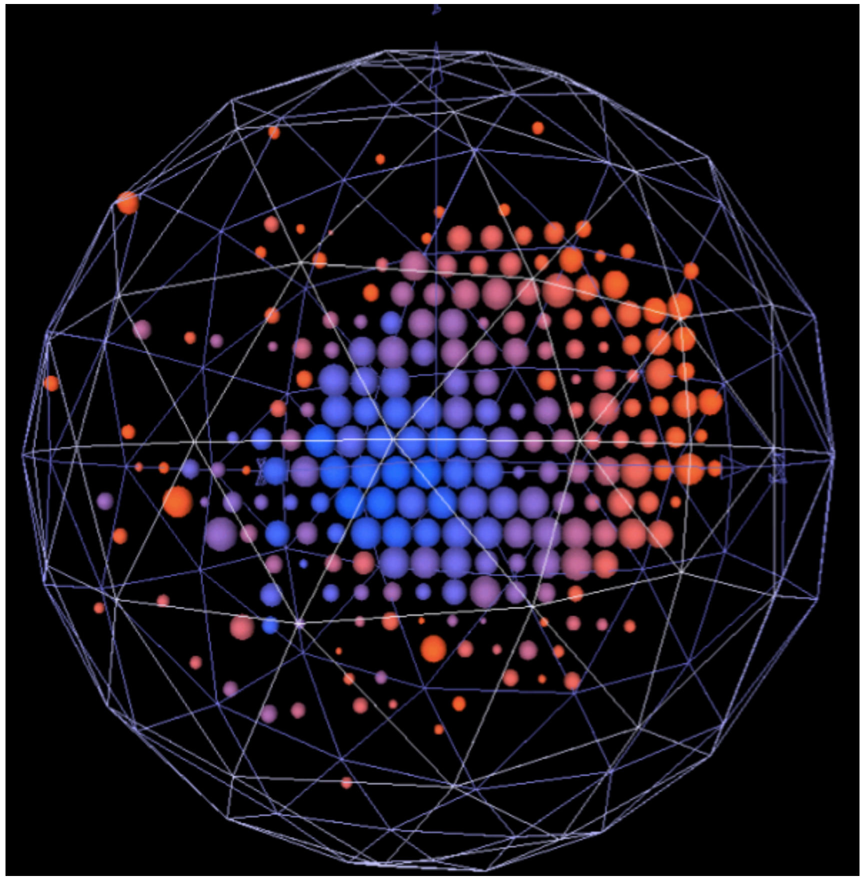
Electrons: "fuzzy" rings from multiple scattering



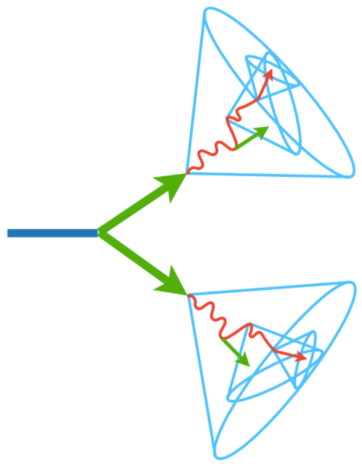


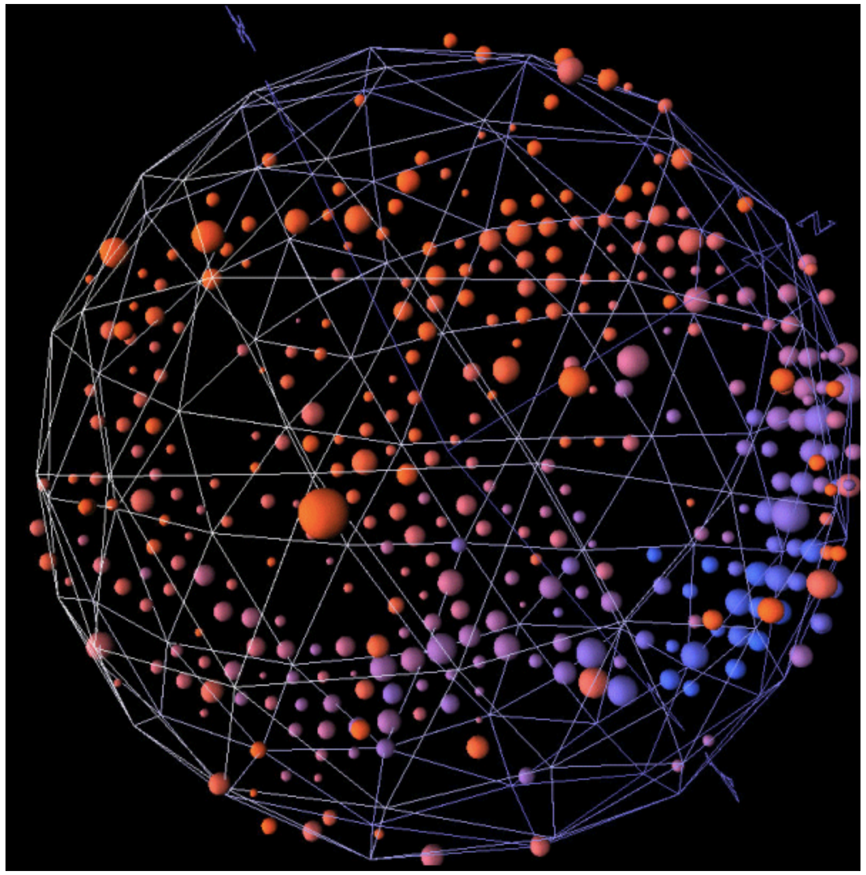
Muons: "clean" rings from long, straight tracks





Neutral Pions: two rings from decay to two photons





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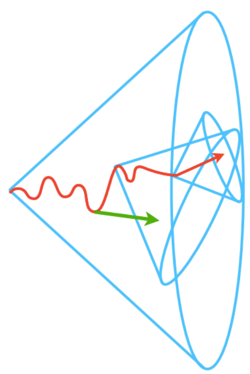
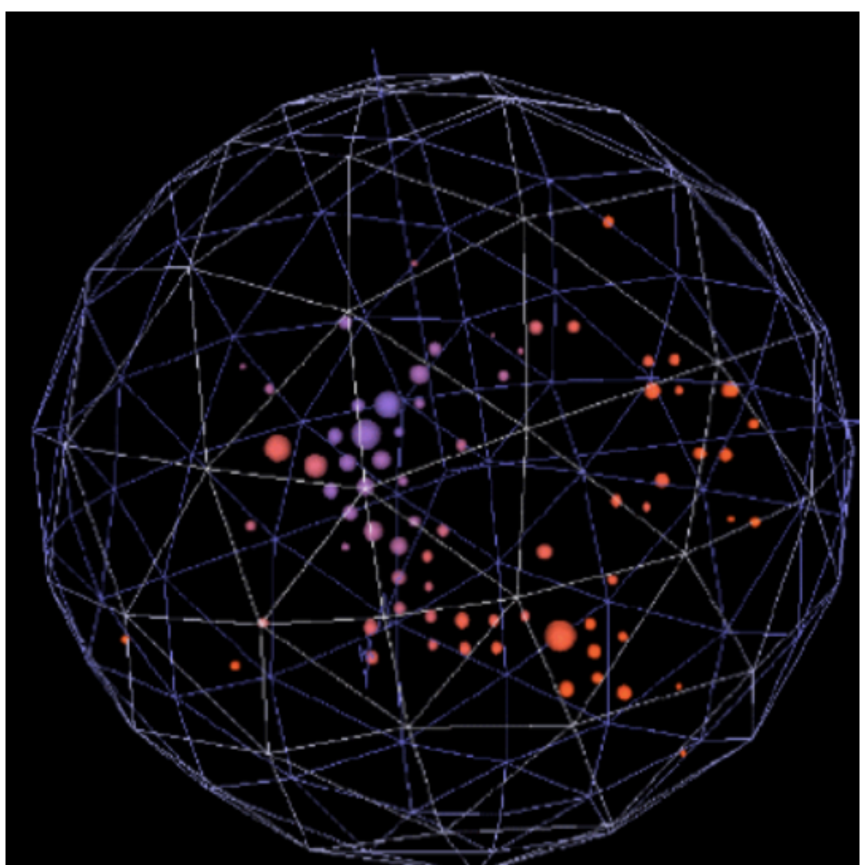
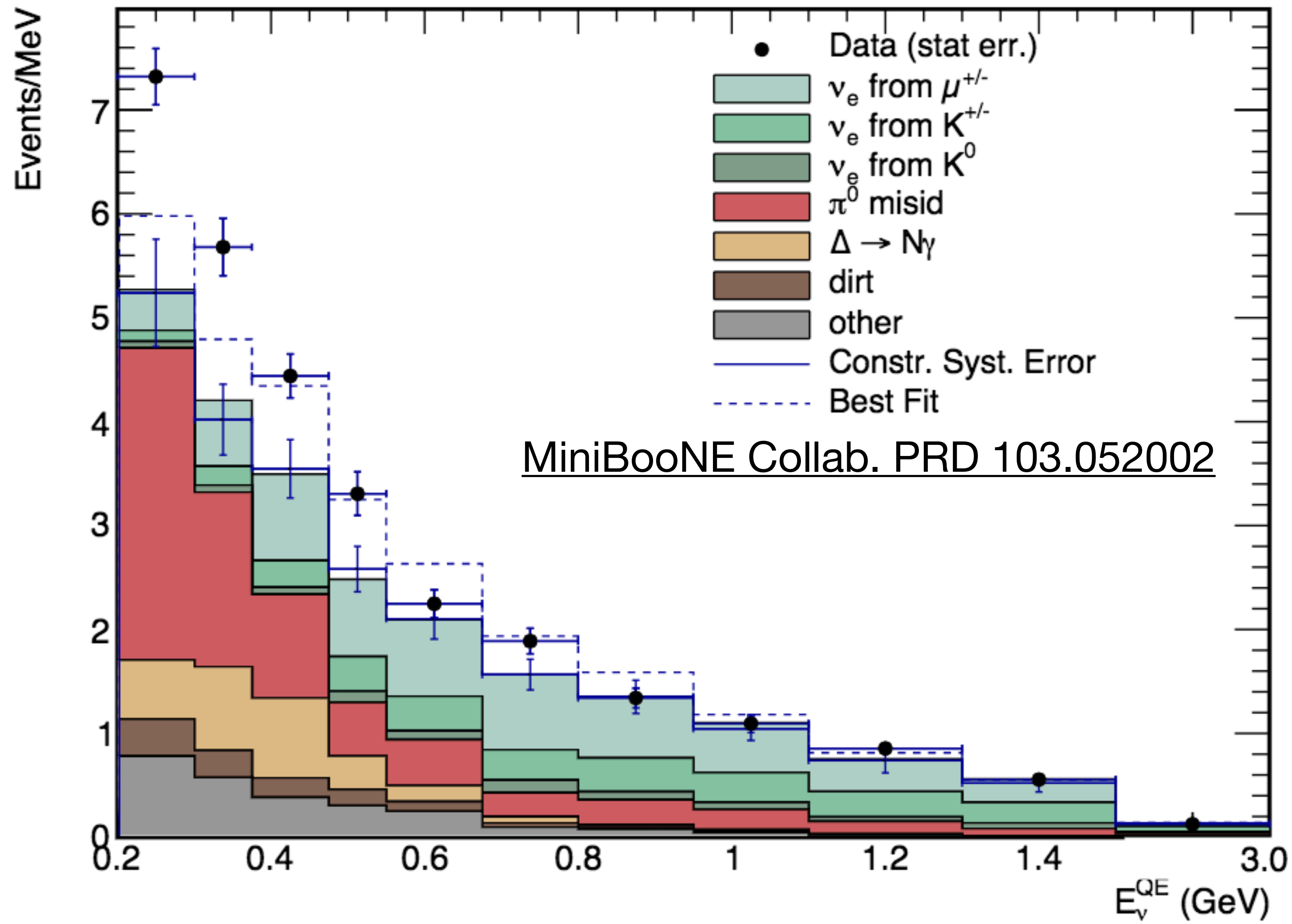




4.8σ low-energy excess (LEE) of electron-like events



The MiniBooNE LEE

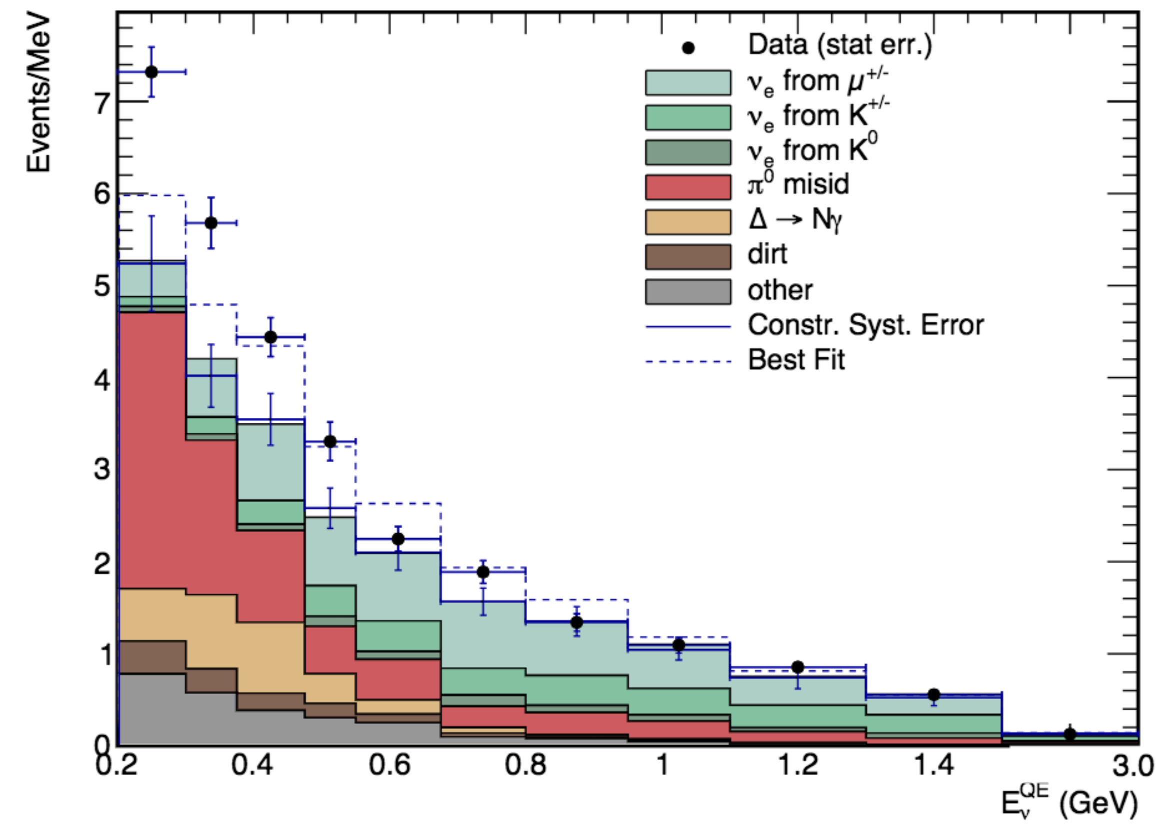
Cherenkov limitations:

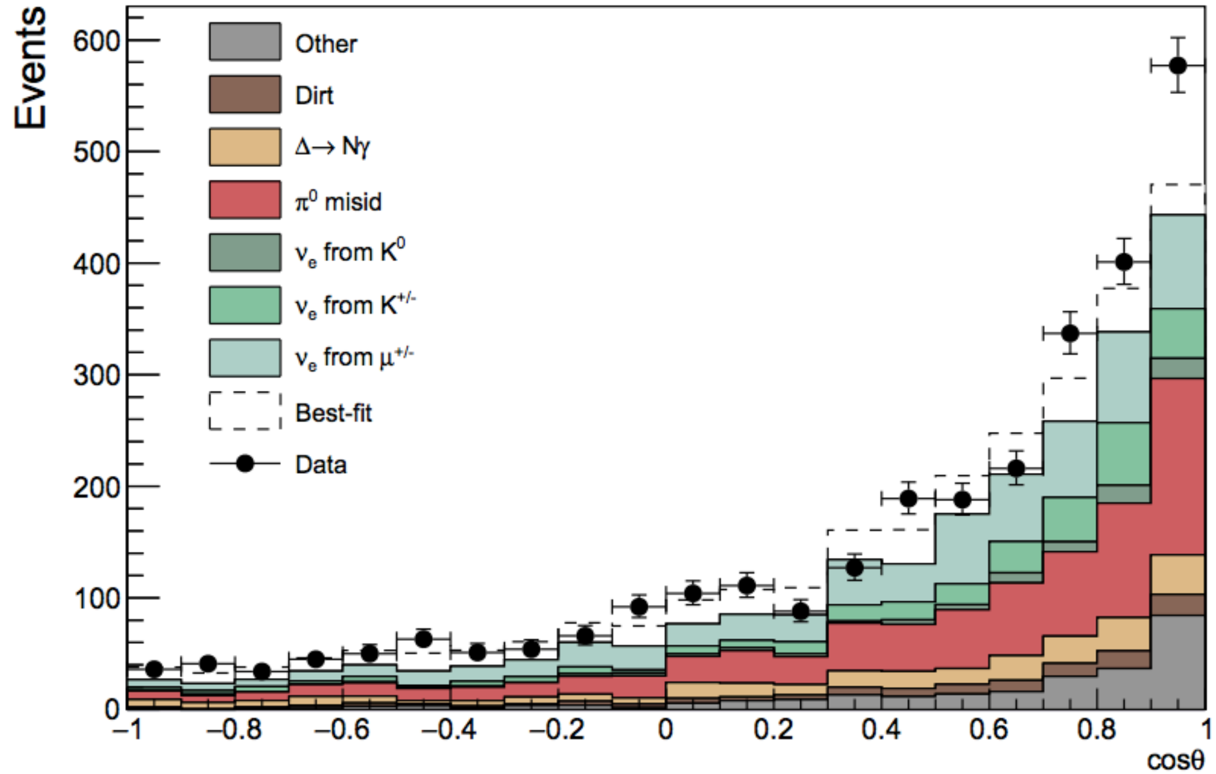
- Electrons/photons indistinguishable
- No hadronic information

The excess could be…

1. True electron neutrinos?
2. Mis-modeled photon background?
3. More exotic new physics?

MiniBooNE Collab. PRD 103.052002





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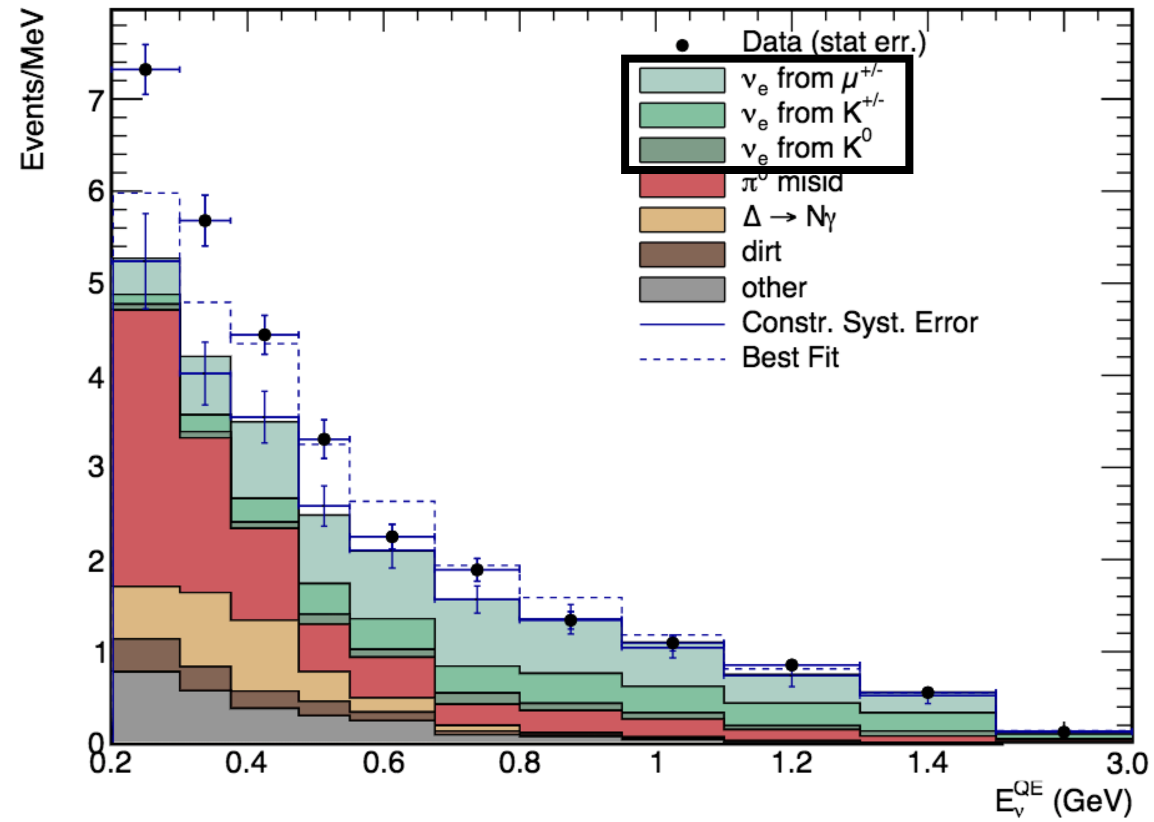

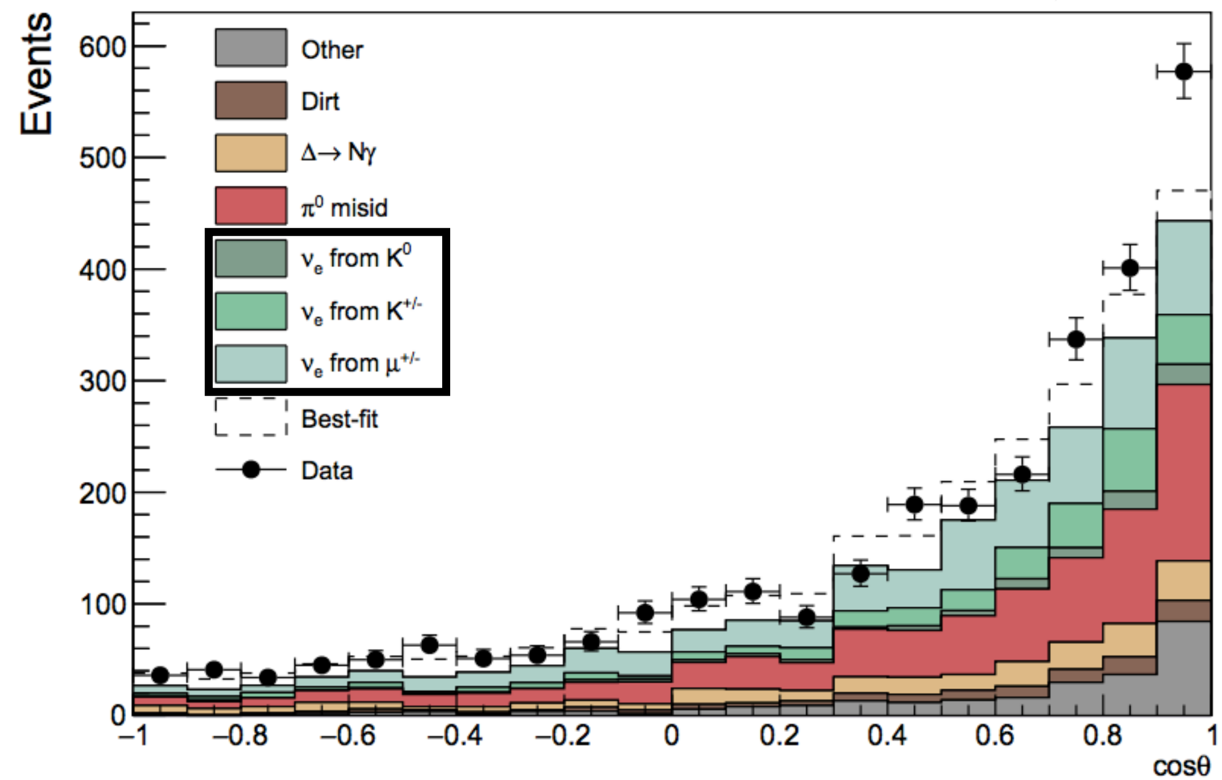

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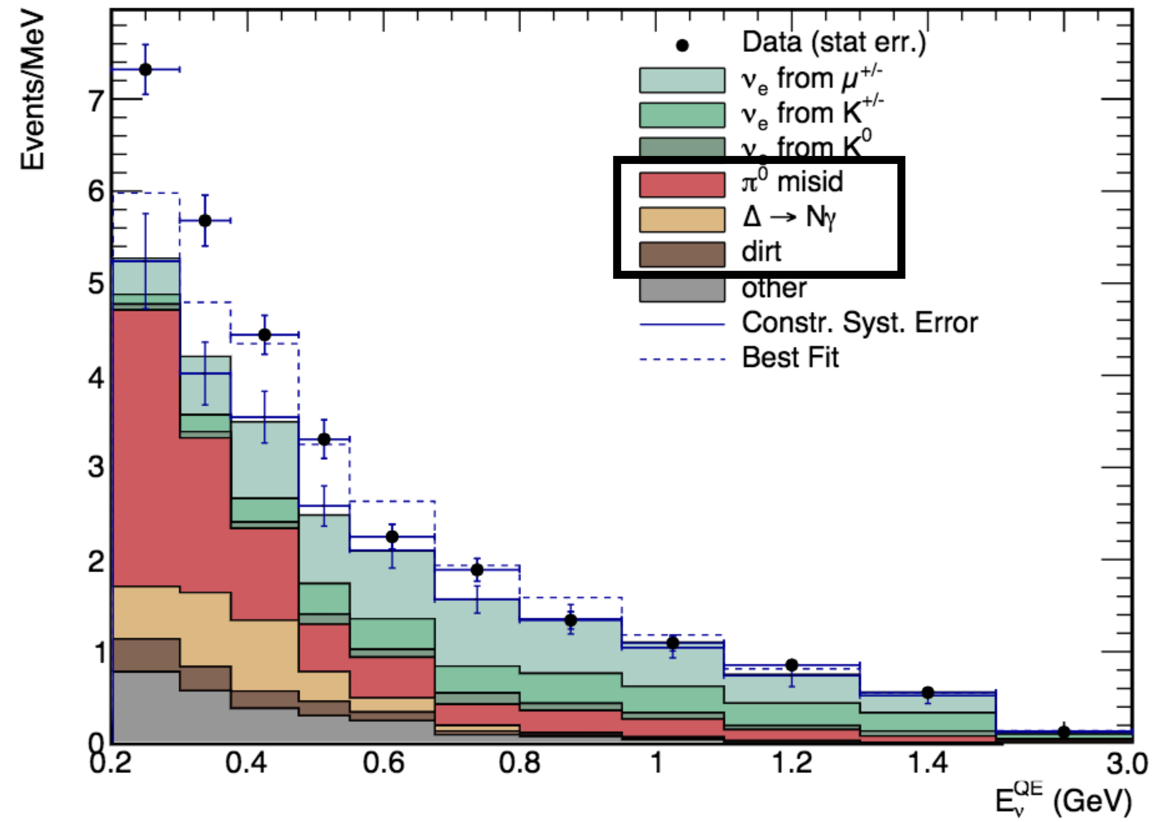

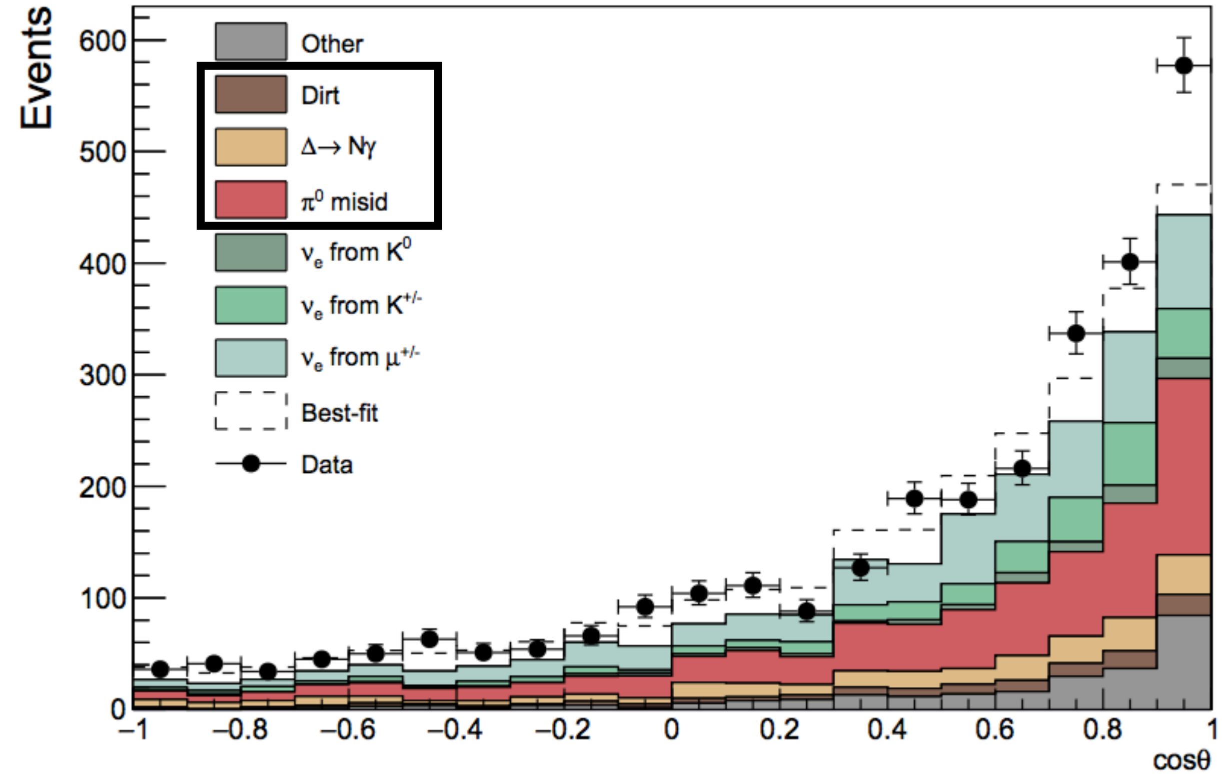

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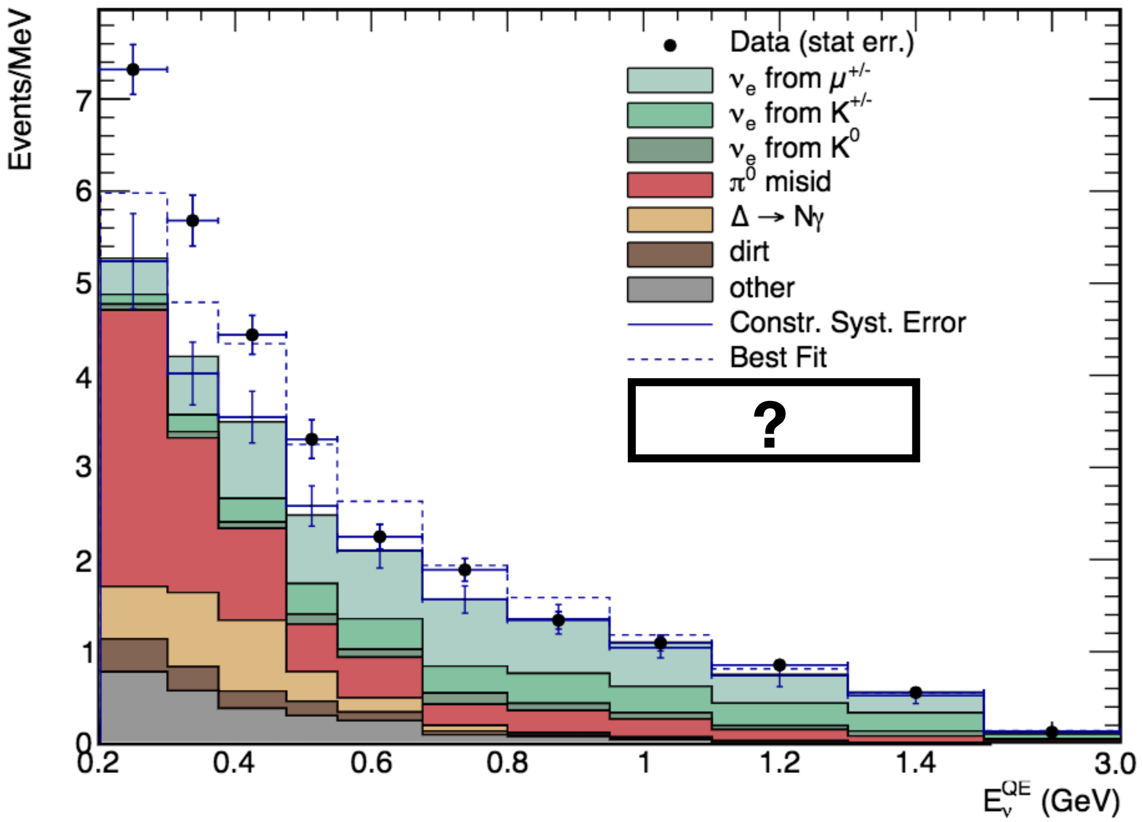
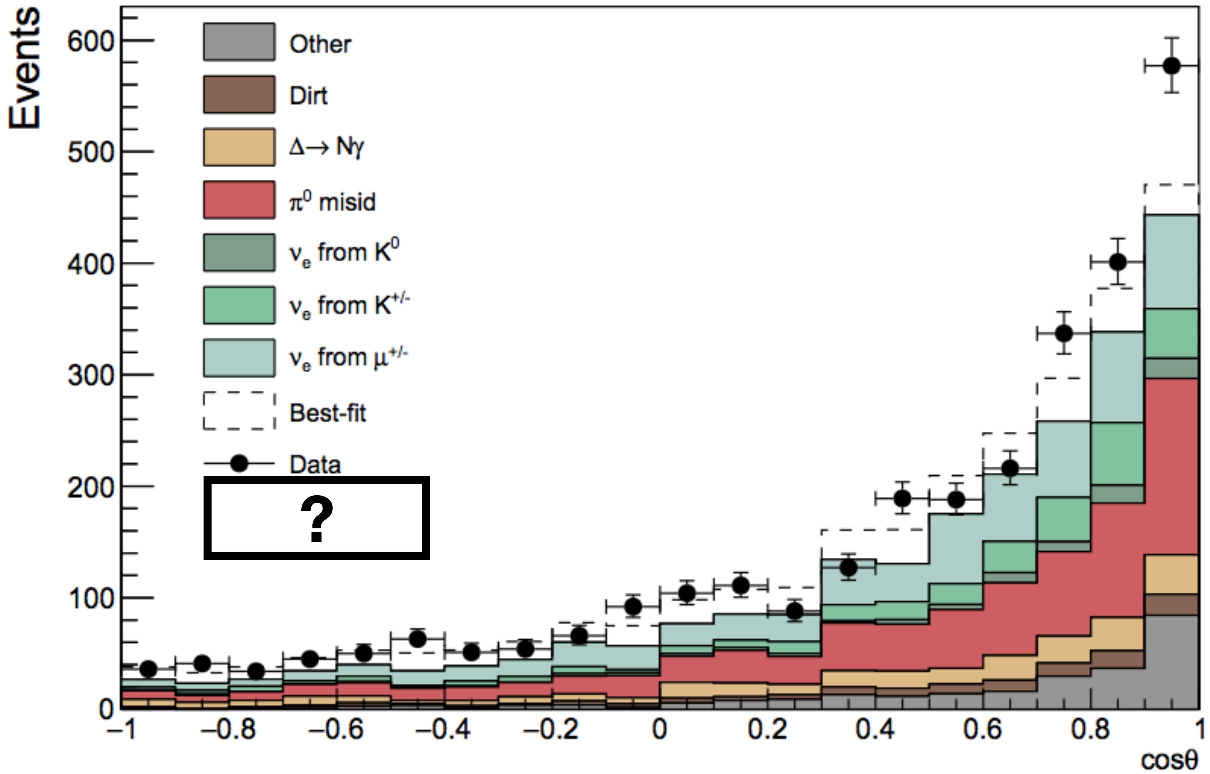
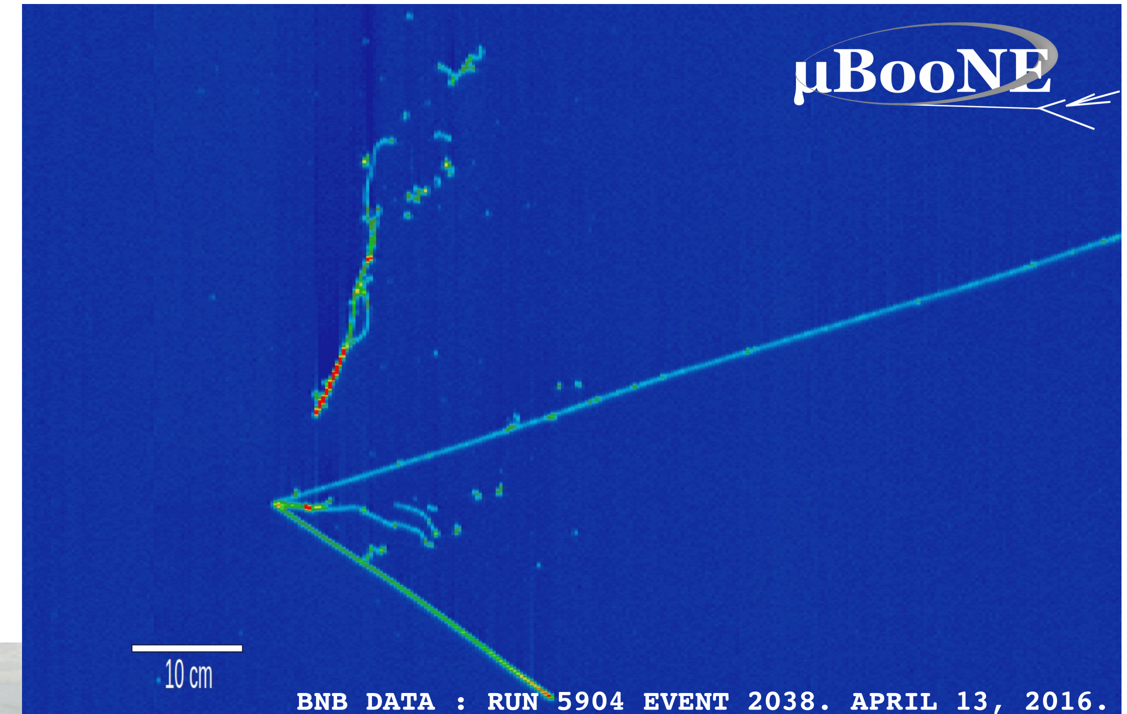
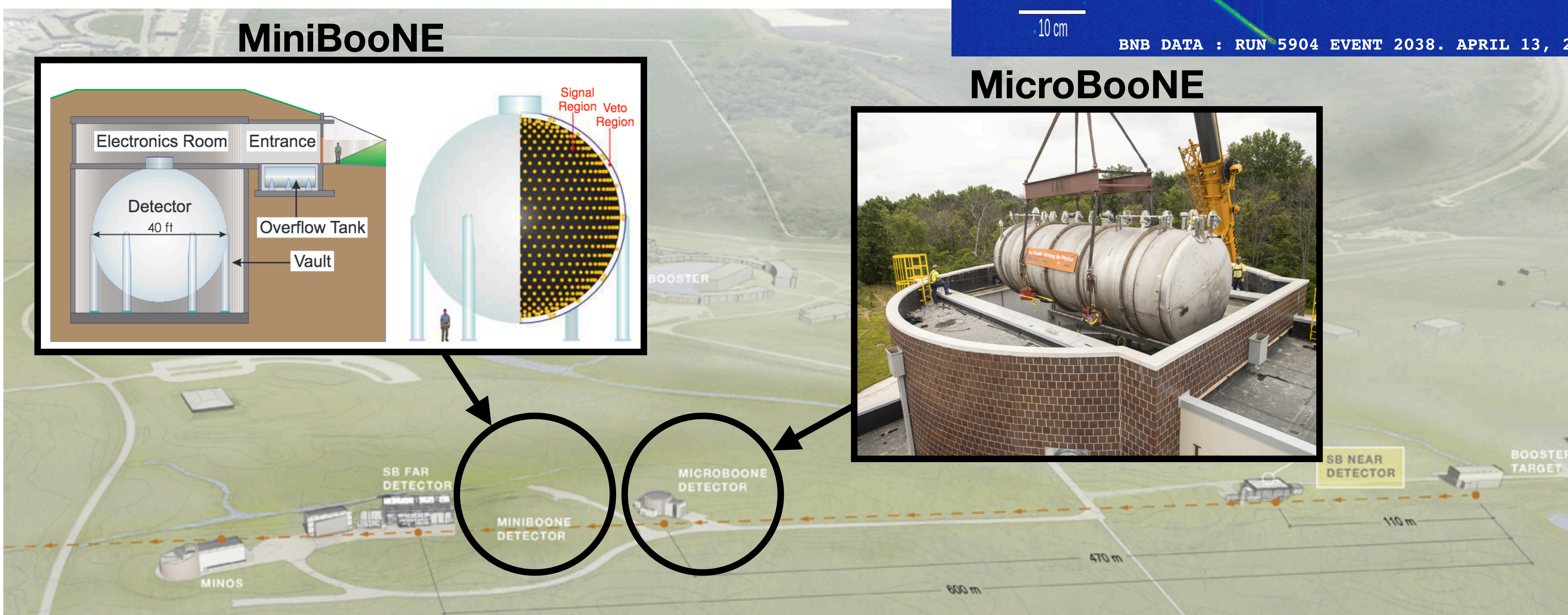




The MicroBooNE Experiment

- Designed to directly address the MiniBooNE anomaly using a liquid argon time projection chamber (LArTPC)
- Sits ~70 m upstream of MiniBooNE along the BNB

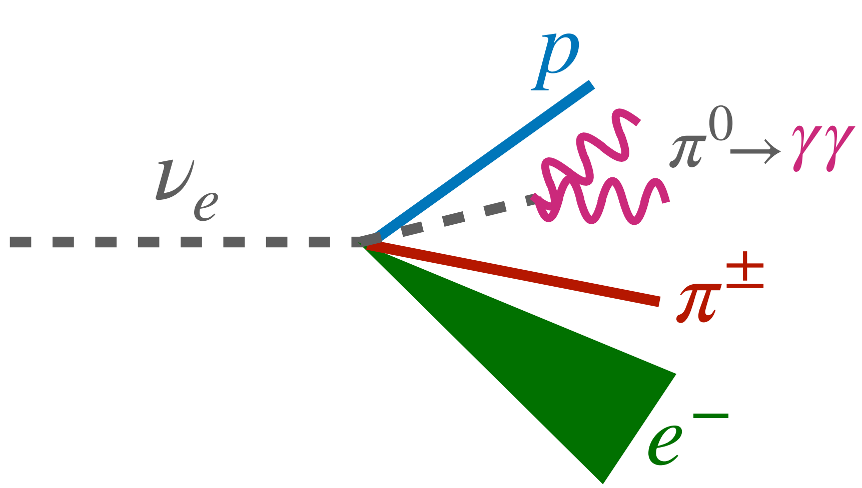




The MicroBooNE ν_e Analyses

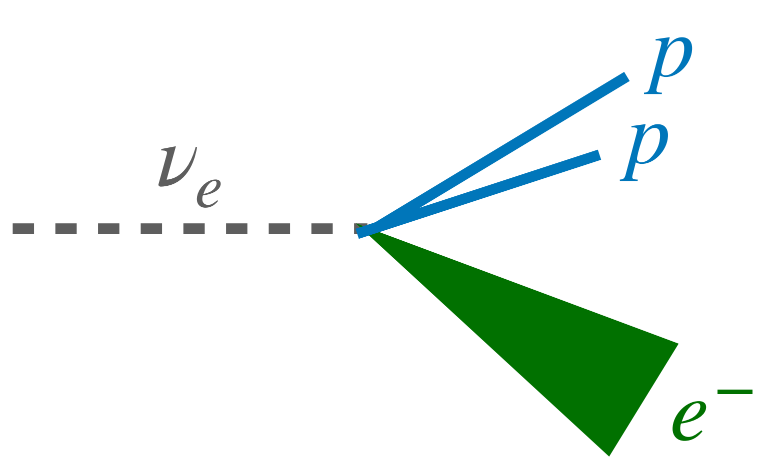
The Inclusive Analysis

- Searched for ν_e CC interactions with anything in the final state (1eX)
- Used the WireCell LArTPC reconstruction algorithm



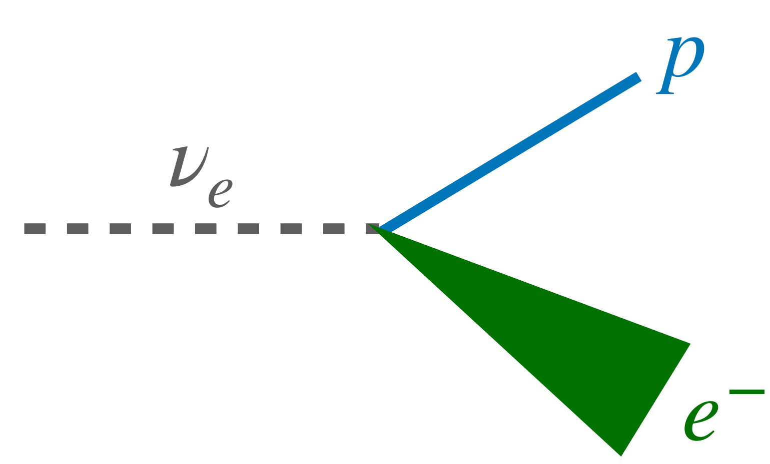
The MiniBooNE-Like Analysis

- Searched for ν_e CC interactions with no pions in the final state (1eXp0π)
- Used the Pandora LArTPC reconstruction algorithm



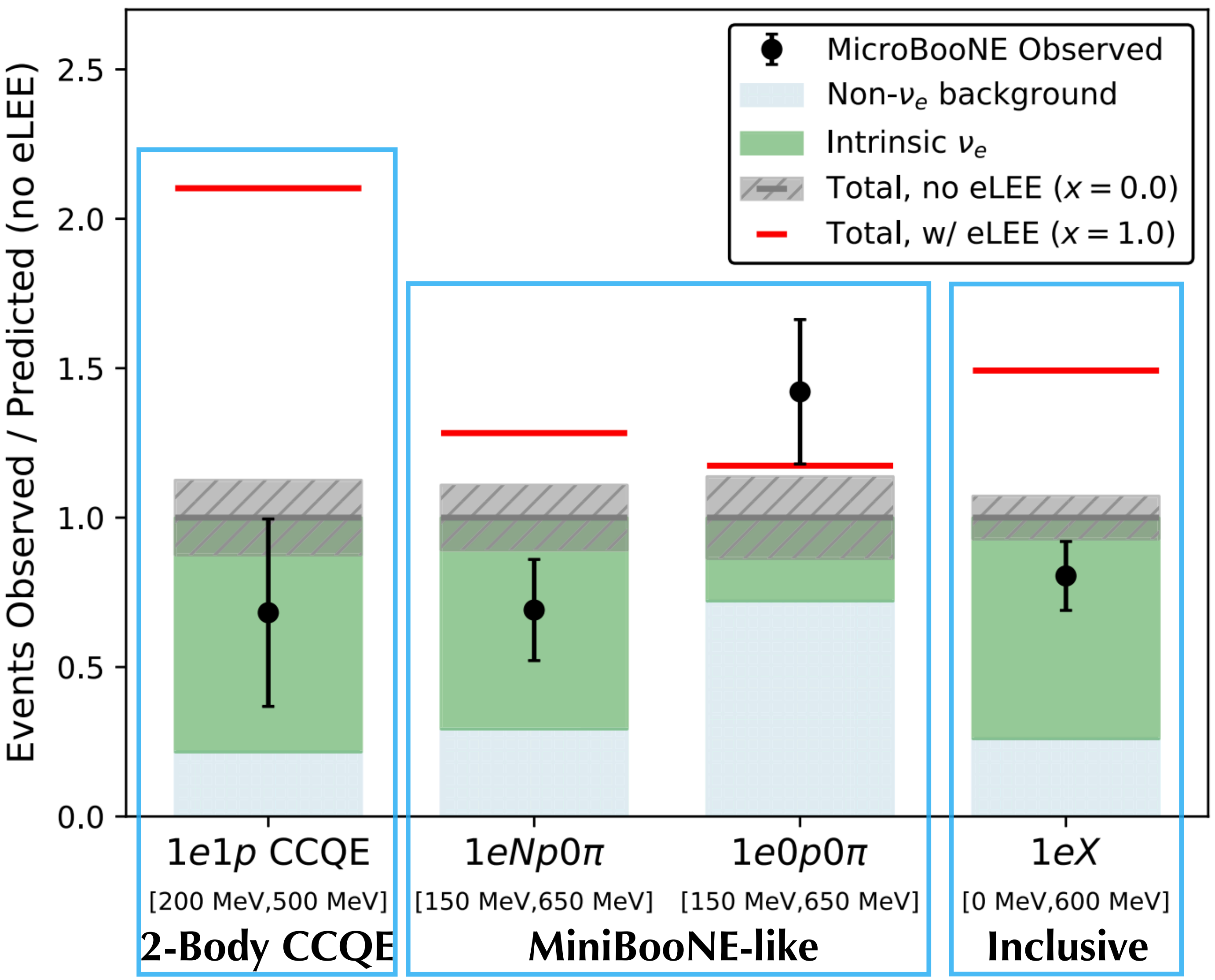
The Two-Body CCQE Analysis (incl. NK)

- Searched for ν_e CCQE interactions with one proton and one electron in the final state (1e1p)
- Used custom LArTPC-based deep learning algorithms



MicroBooNE's ν_e Results

- Initial MicroBooNE data suggest the excess is not primarily due to low-energy ν_e CC interactions



Final fit results

	1e1p CCQE	$1eNp0\pi$	$1e0p0\pi$	$1eX$
E_ν (MeV)	200-1200	150-1550	150-1550	0-2500
$p\ (\chi^2_{x=0})$	1.4×10^{-2}	0.18	0.13	0.85
$p\ (\Delta\chi^2 < \text{obs.})$, w/ eLEE	1.6×10^{-4}	2.1×10^{-2}	0.93	9.0×10^{-5}

Generic MiniBooNE-like excess of ν_e interactions ruled out at the 3σ confidence level

MicroBooNE Collab. PRL 128, 241801

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Antineutrinos at MiniBooNE

- The MicroBooNE results severely disfavor the hypothesis that the MiniBooNE LEE comes entirely from an excess of ν_e interactions
- Do they say the same about an excess of $\bar{\nu}_e$ interactions?

M. Hostert

C. Argüelles

Implications of MicroBooNE's low sensitivity to electron antineutrino interactions in the search for the MiniBooNE excess

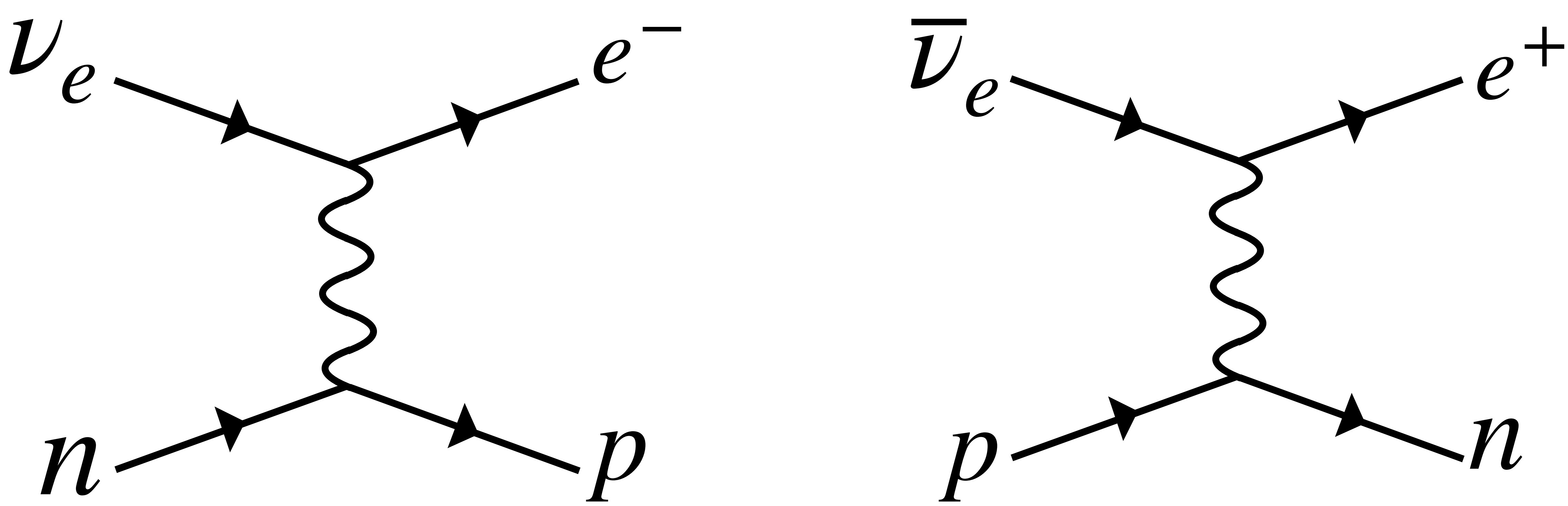
N. W. Kamp, M. Hostert, C. A. Argüelles, J. M. Conrad, and M. H. Shaevitz
Phys. Rev. D **107**, 092002 – Published 3 May 2023

J. Conrad

M. Shaevitz

Antineutrinos at MiniBooNE

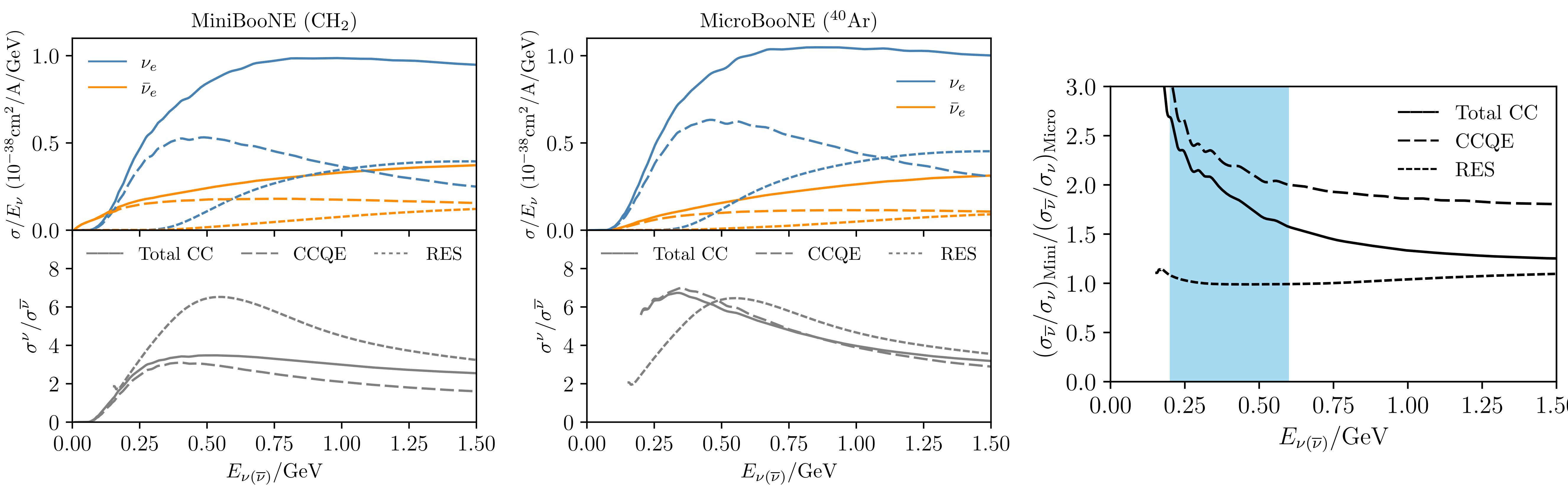
- The $\overline{\nu}_e$ CCQE cross section tends to be suppressed compared to the ν_e CCQE cross section
- This comes from interference between the vector and axial form factors as well as differences in the number of available nucleon targets and their binding energy



Kamp+ PRD 107, 092002 (2023)

Antineutrinos at MiniBooNE

- Binding energy differences between protons and neutrons are much larger in argon compared to carbon
- This is because argon has a neutron-rich nucleus, while the carbon nucleus is isoscalar

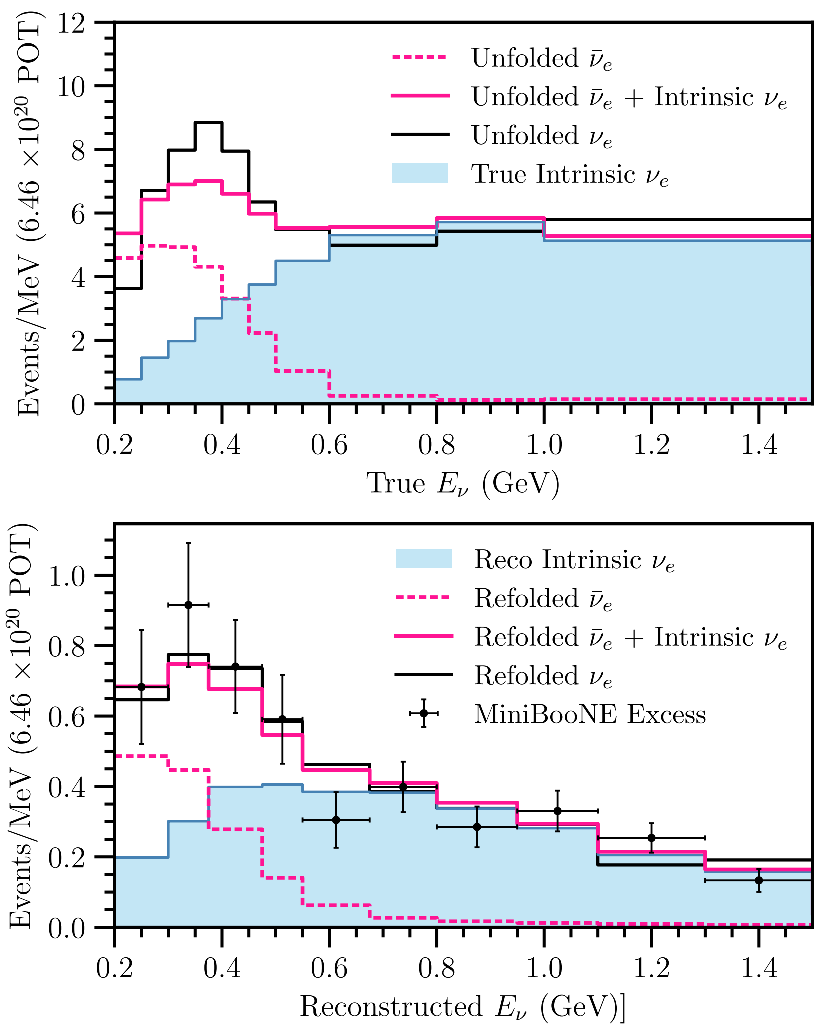


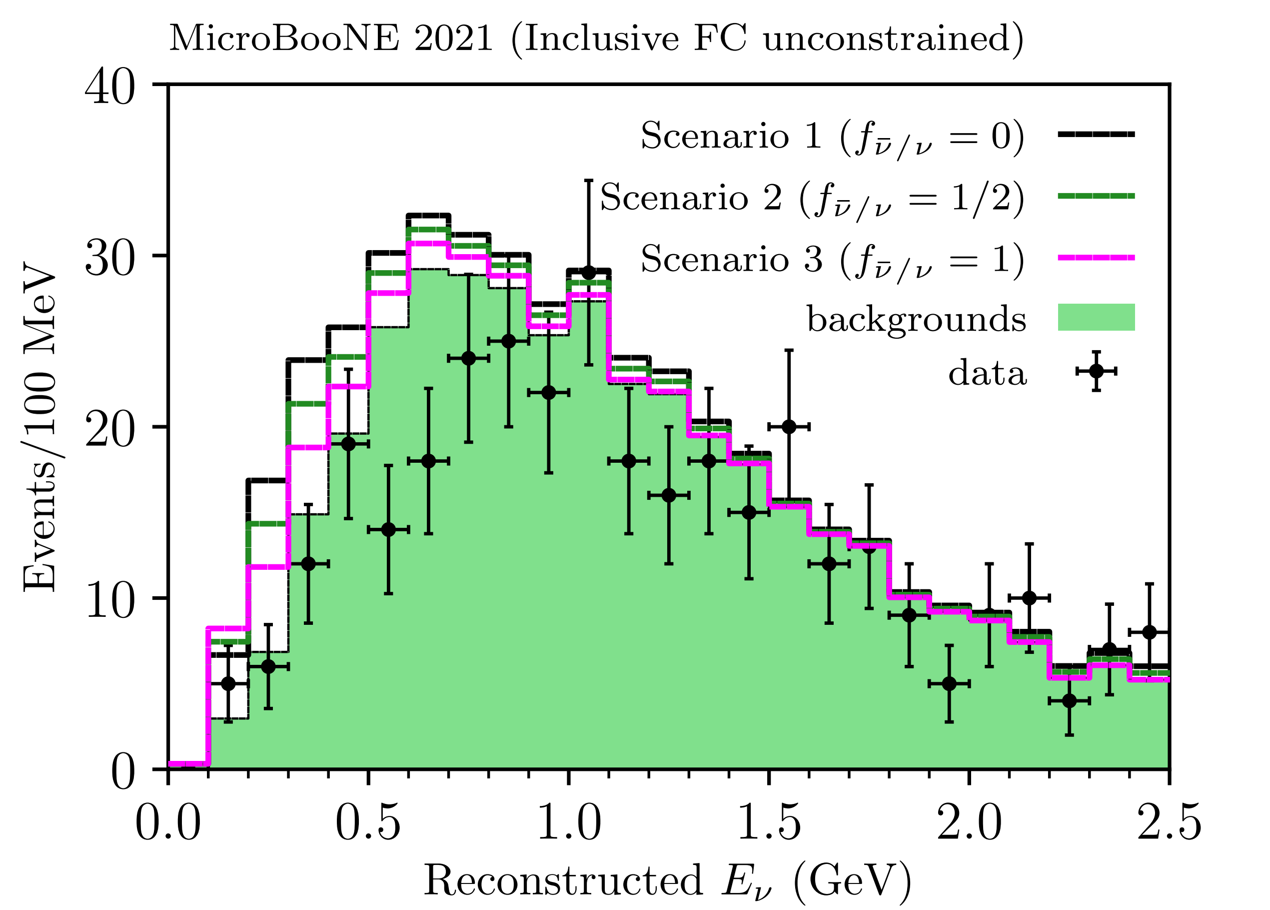
Cross sections from GENIE v3.02.00 (Alvarez-Ruso+ 2021)

Kamp+ PRD 107, 092002 (2023)

Antineutrinos at MiniBooNE

- We unfold the MiniBooNE data under an assumption that the excess comes entirely from $\bar{\nu}_e$ CCQE interactions
- This unfolded $\bar{\nu}_e$ prediction is then propagated to the MicroBooNE inclusive analysis





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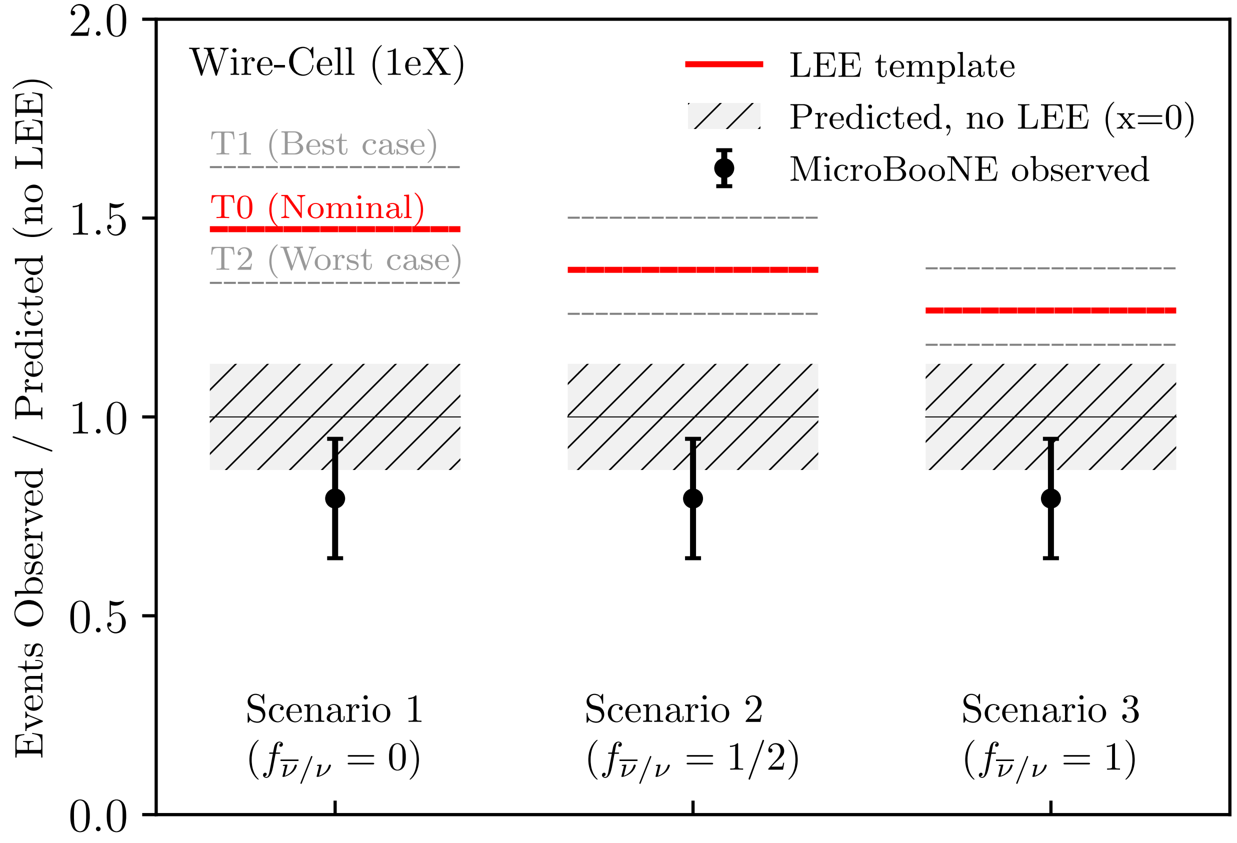
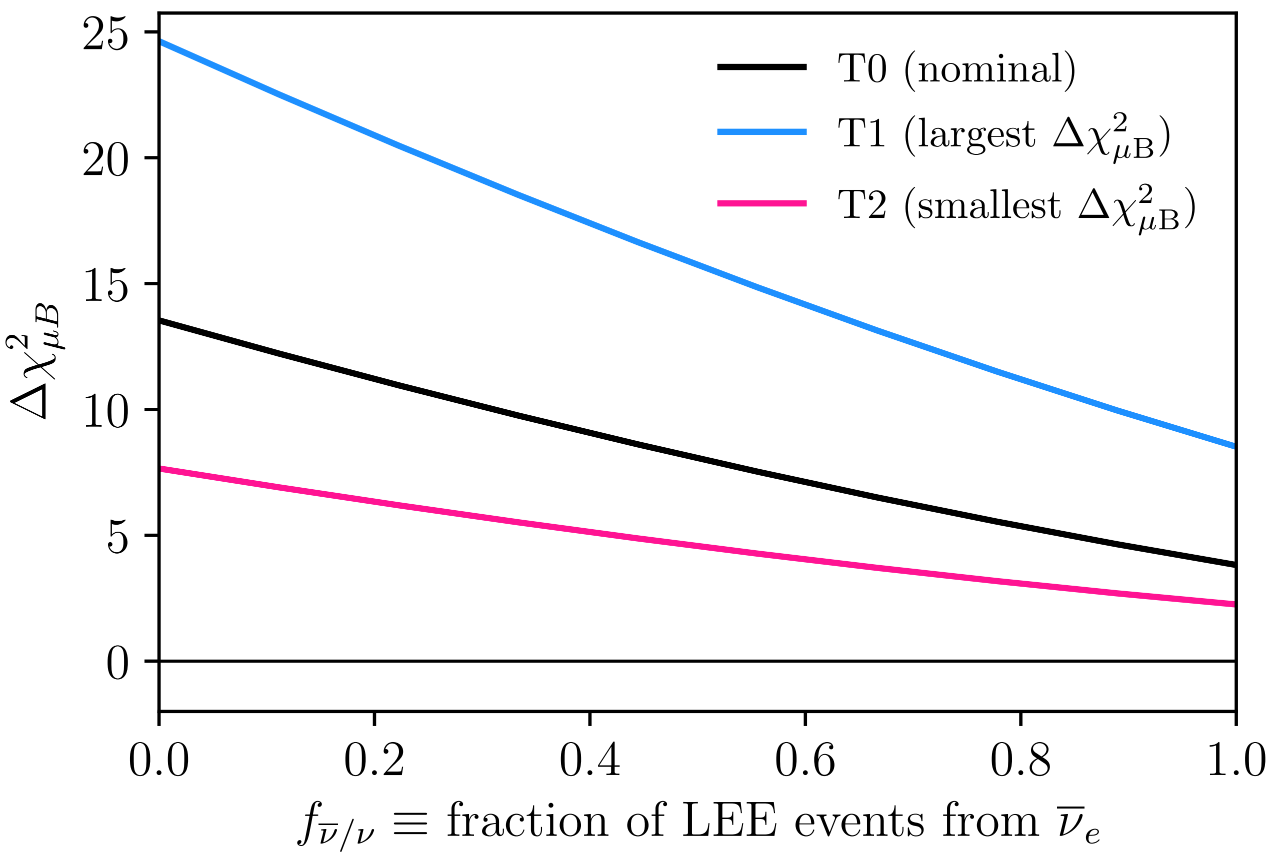
Antineutrinos at MiniBooNE

- We repeat the statistical tests from the official MicroBooNE ν_e analyses

MicroBooNE exclusion power diminishes as more of the excess is attributed to $\overline{\nu}_e$ interactions



MicroBooNE data are consistent at the 2σ confidence level with the entire MiniBooNE LEE coming from $\overline{\nu}_e$ interactions



Kamp+ PRD 107, 092002 (2023)

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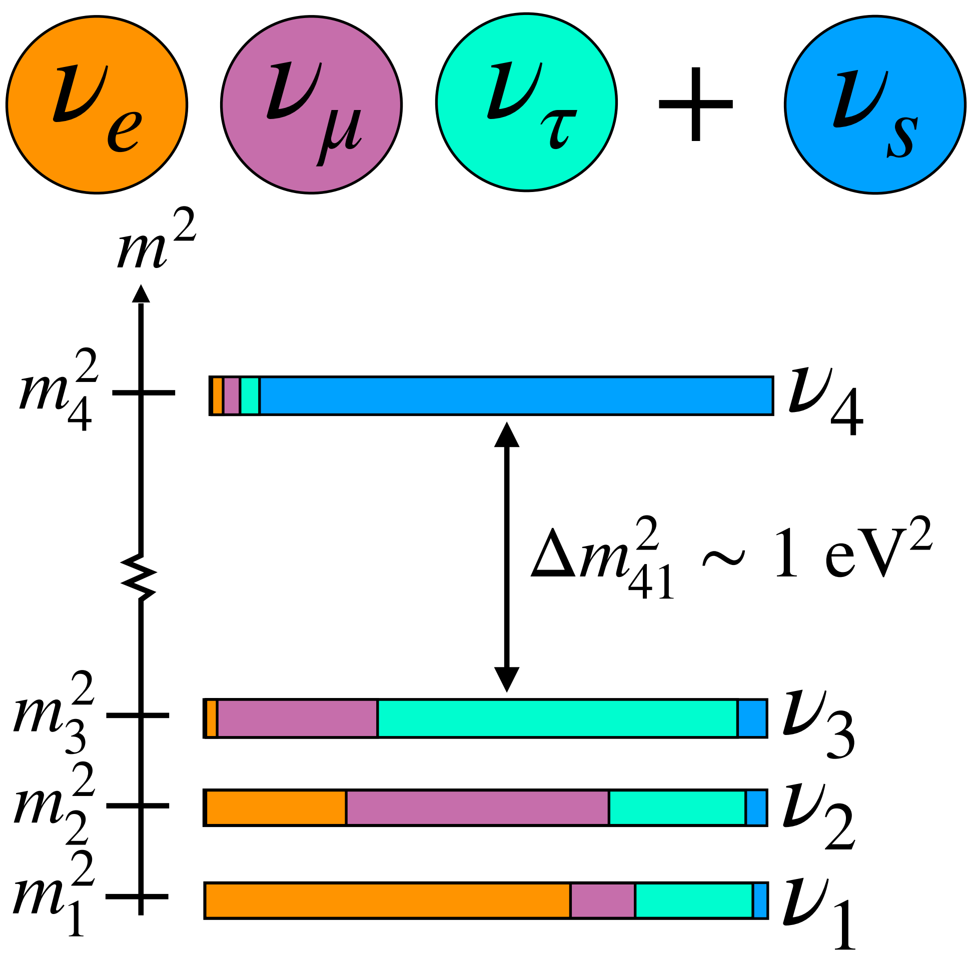
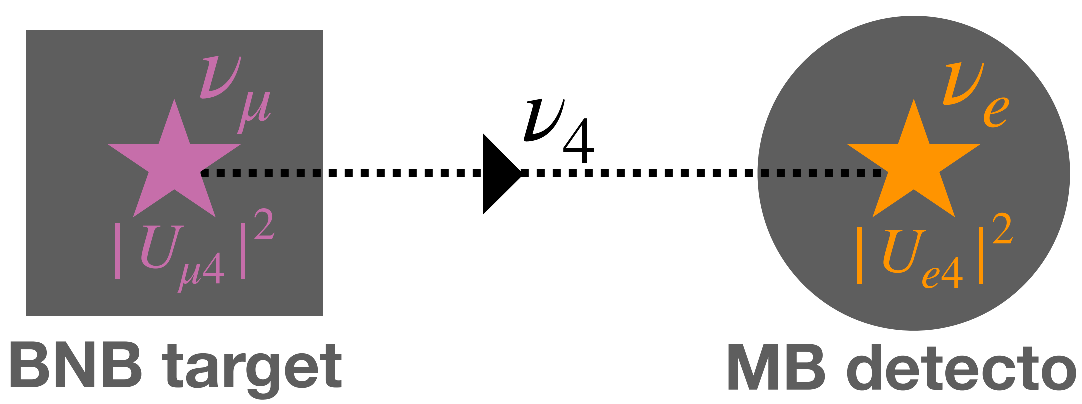
MeV-scale heavy neutral lepton with a transition magnetic moment coupling to active neutrinos

The 3+1 Hypothesis

- We first introduce the most common beyond-the-SM interpretation of MiniBooNE: the eV-scale sterile neutrino



$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{\mu 1} & U_{\tau 1} & U_{s1}\\ U_{e2} & U_{\mu 2} & U_{\tau 2} & U_{s2}\\ U_{e3} & U_{\mu 3} & U_{\tau 3} & U_{s3}\\ U_{e4} & U_{\mu 4} & U_{\tau 4} & U_{s4}\end{bmatrix} \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{bmatrix}$$



$$P(\nu_\mu \to \nu_e) = 4\,\underline{|U_{e4}|^2}\,\underline{|U_{\mu 4}|^2}\sin^2\left(1.27\Delta m_{41}^2 \frac{L}{E}\right)$$

3+1 Model Tension

$$P(\nu_\mu \to \nu_e) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$ **SBL Accelerator**

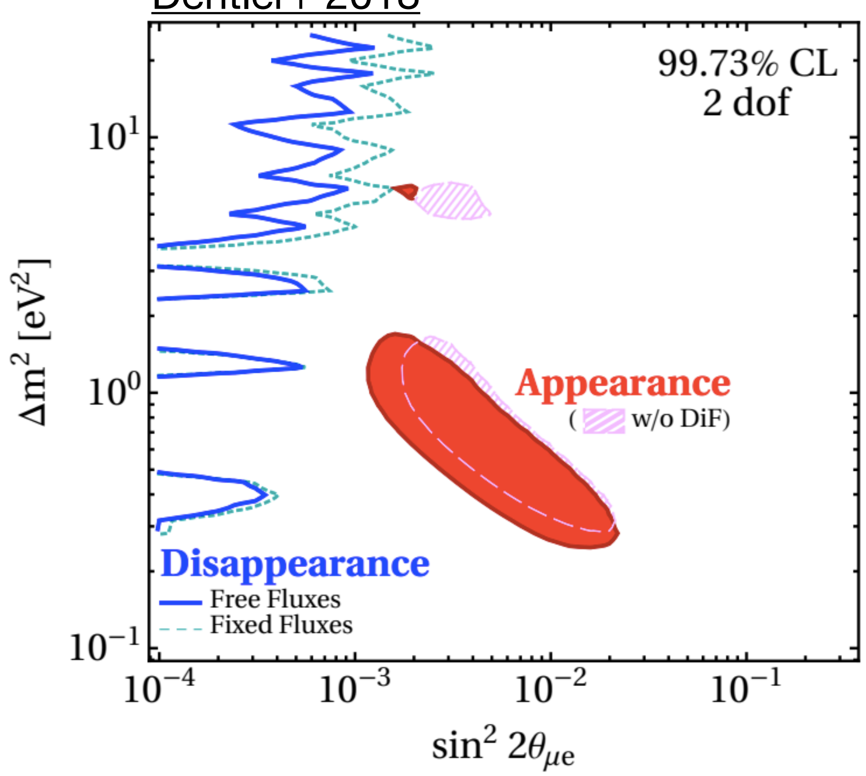
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$ **LBL Accelerator/Atmospheric**

$$P(\nu_e \to \nu_e) = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$ **SBL Reactor/Gallium**

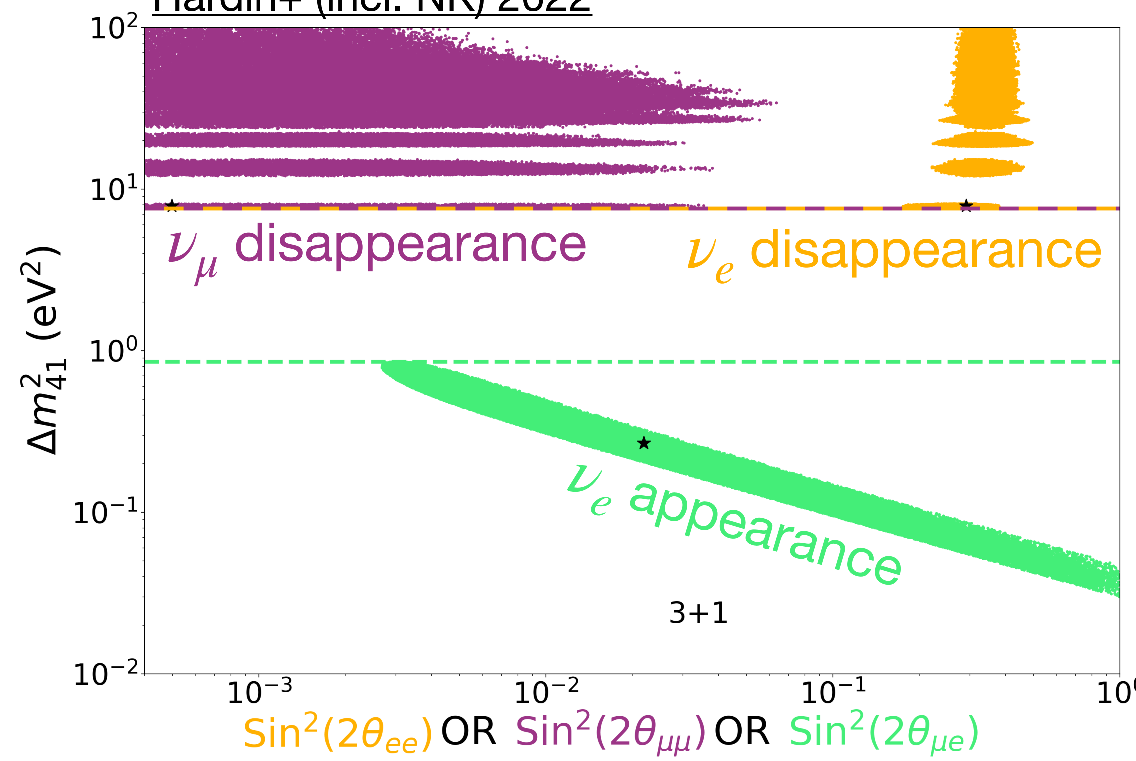
Lack of muon neutrino disappearance* in tension with electron neutrino appearance/disappearance anomalies

*up to some IceCube hints

Dentler+ 2018



Hardin+ (incl. NK) 2022

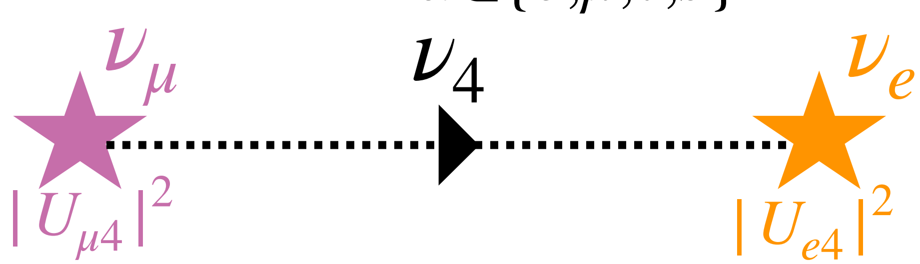


The Mixed Model

- MiniBooNE drives the tension in sterile neutrino global fits [1,2]
- To address this, we consider a mixed model consisting of:

(1) an eV-scale sterile neutrino

$$\nu_{i\in\{1,2,3,4\}} = \sum_{\alpha\in\{e,\mu,\tau,s\}} U_{i\alpha}\nu_\alpha$$

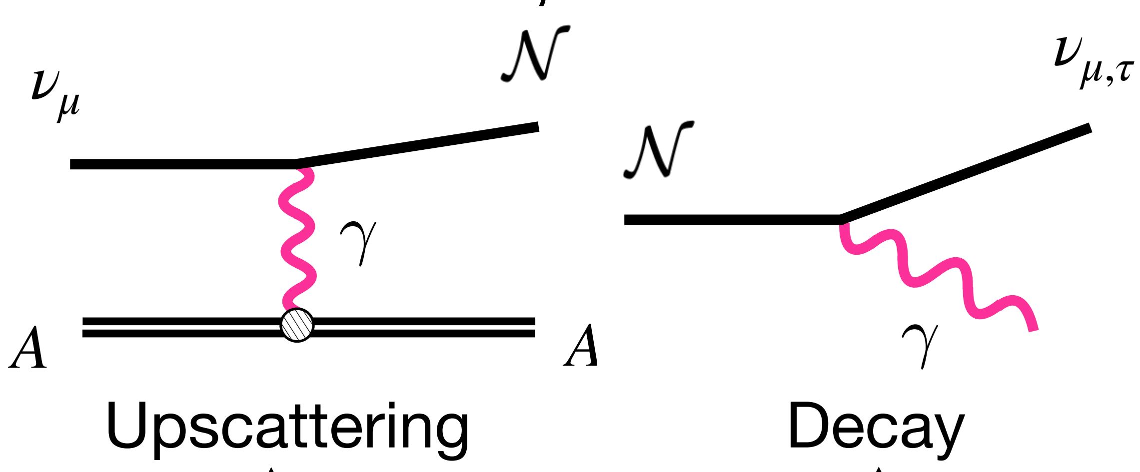


$$P(\nu_\mu \to \nu_e) = 4|U_{e4}|^2|U_{\mu4}|^2\sin^2\left(1.27\Delta m^2\frac{L}{E}\right)$$

$\oplus$

(2) an MeV-scale HNL or "Neutrissimo"

$$\mathscr{L}_{\text{eff}} \supset d_{\alpha\mathcal{N}}\overline{\nu_\alpha}\sigma_{\mu\nu}F^{\mu\nu}\mathcal{N}_R + \text{h.c.}$$



These new interactions can explain the bulk of the MiniBooNE Excess, relieving tension in sterile neutrino global fits [2,3]

[1] Hardin+ 2211.02610
[2] Vergani+ PRD 104, 095005
[3] Kamp+ PRD 107, 055009

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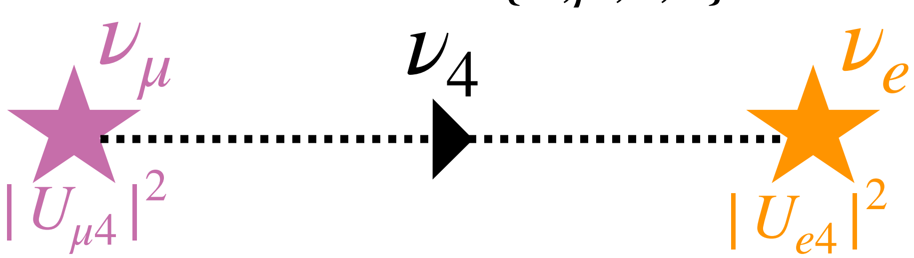

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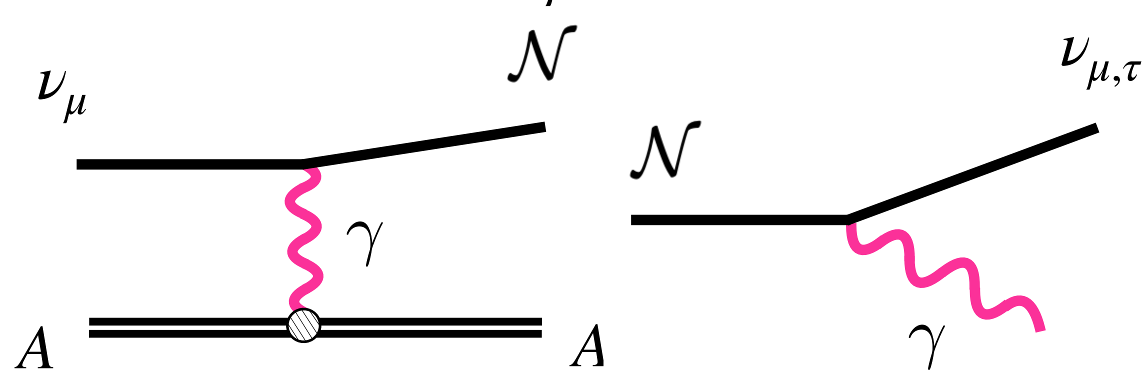
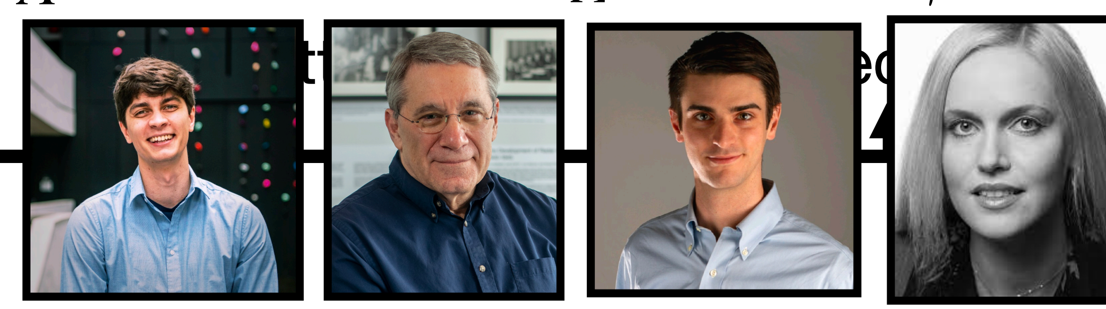


Explaining the MiniBooNE excess through a mixed model of neutrino oscillation and decay

S. Vergani, N. W. Kamp, A. Diaz, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. A. Uchida
Phys. Rev. D **104**, 095005 – Published 8 November 2021

Dipole-coupled heavy-neutral-lepton explanations of the MiniBooNE excess including constraints from MINERvA data

N. W. Kamp, M. Hostert, A. Schneider, S. Vergani, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. A. Uchida
Phys. Rev. D **107**, 055009 – Published 9 March 2023



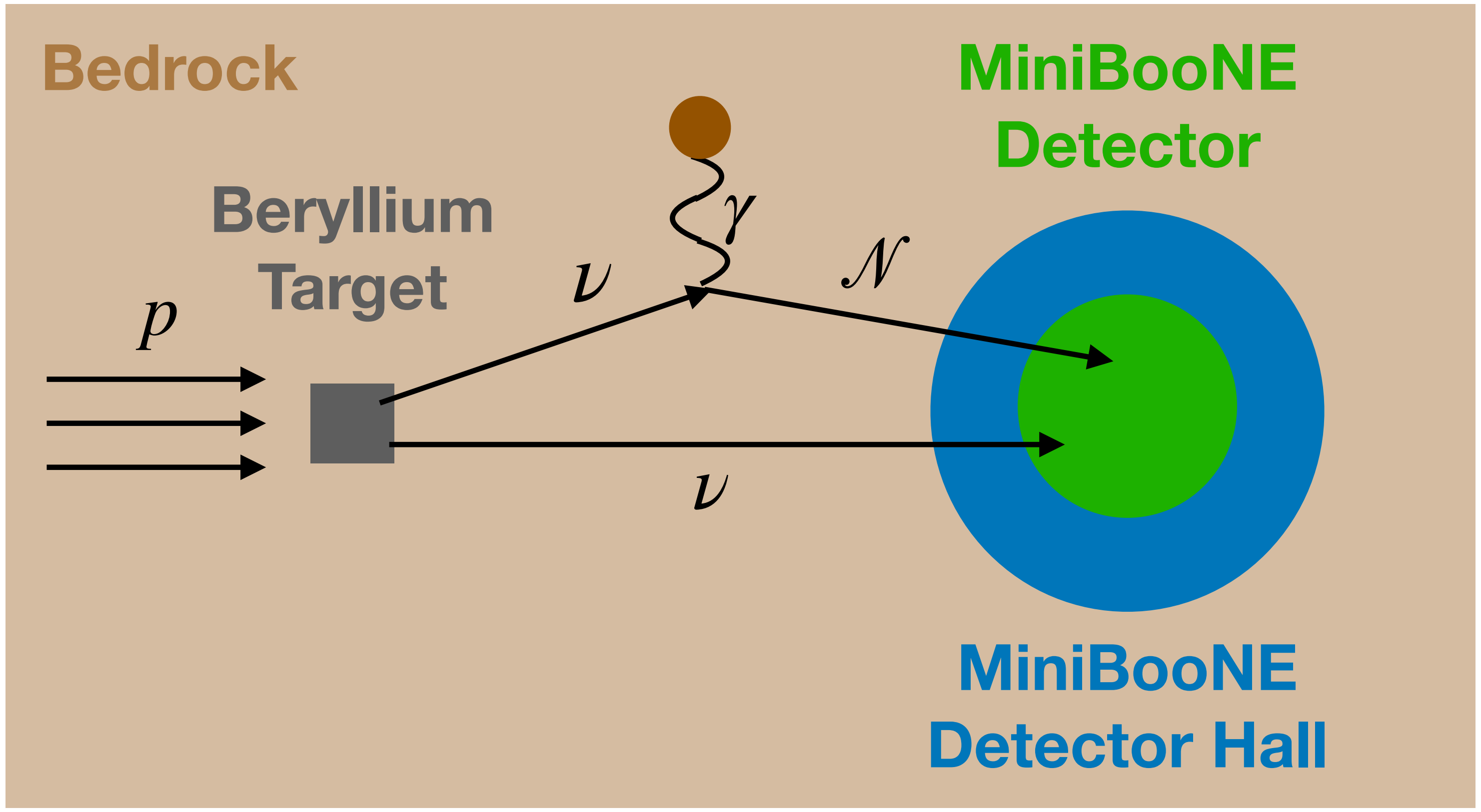
M. Hostert | M. Shaevitz | A. Schneider | M. Uchida

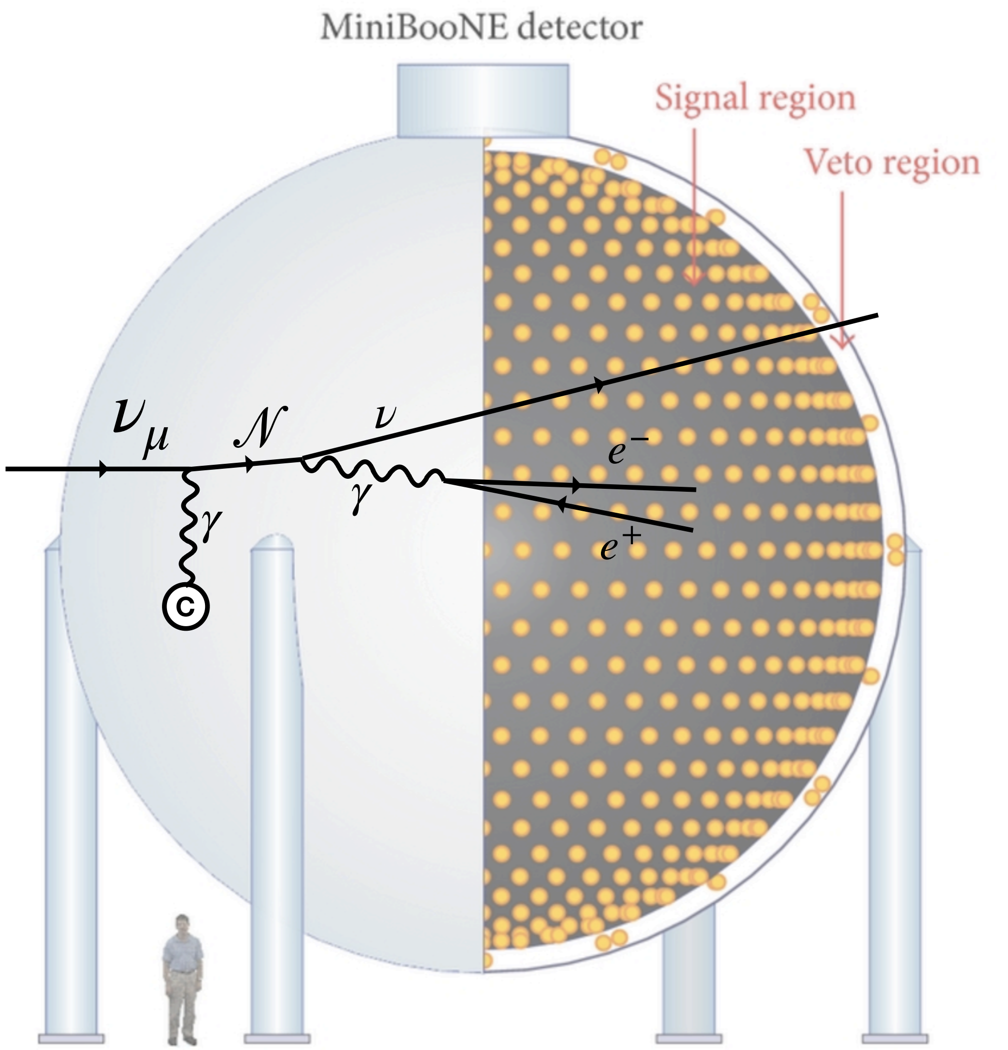
C. Argüelles | S. Vergani | J. Conrad | A. Diaz

Mixed Model Fit Strategy

1. Perform a global sterile neutrino fit without MiniBooNE to fix the sterile neutrino parameters [1]

2. Simulate neutrissimo uspcattering and decay in MiniBooNE using the public LeptonInjector software package [2]

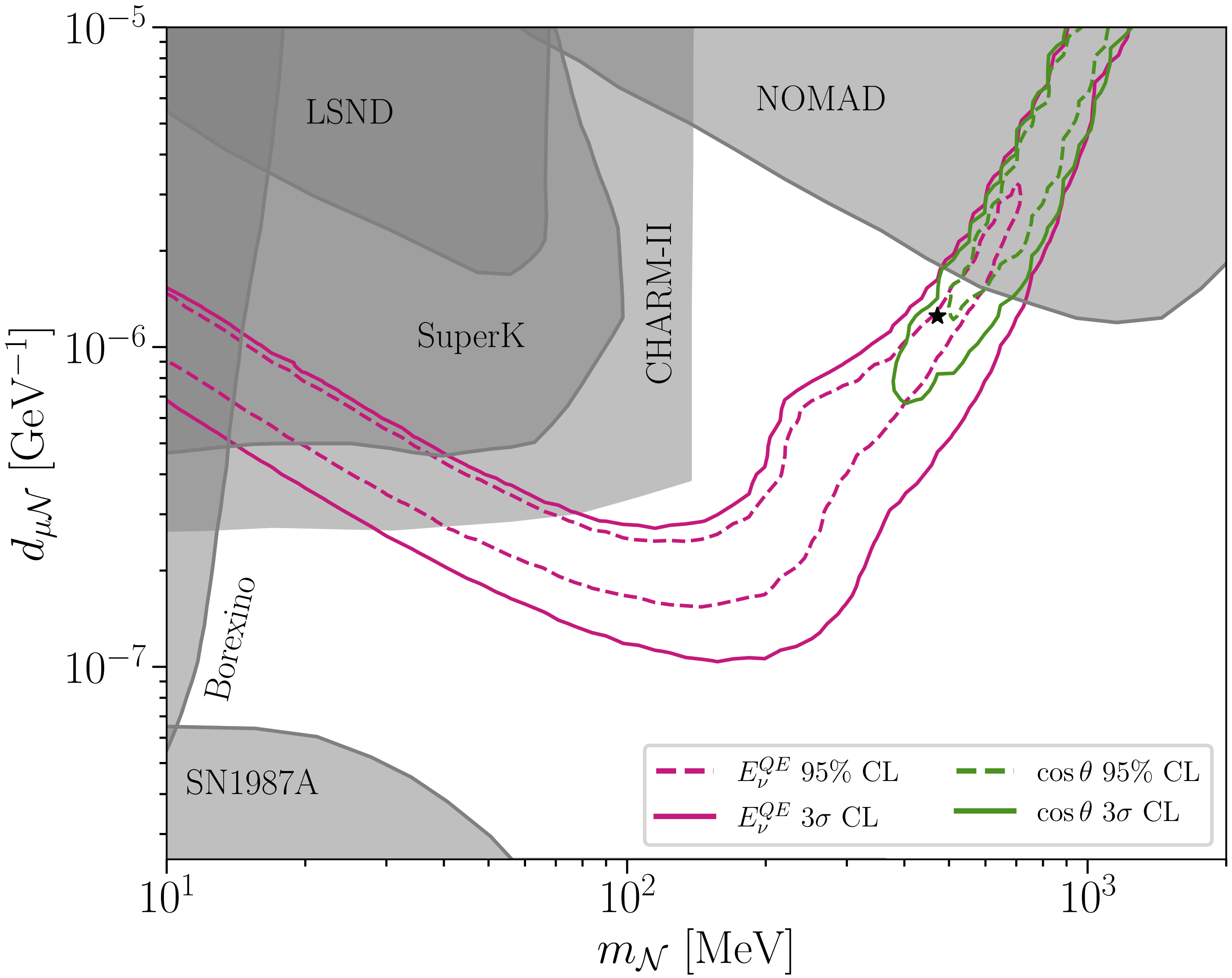


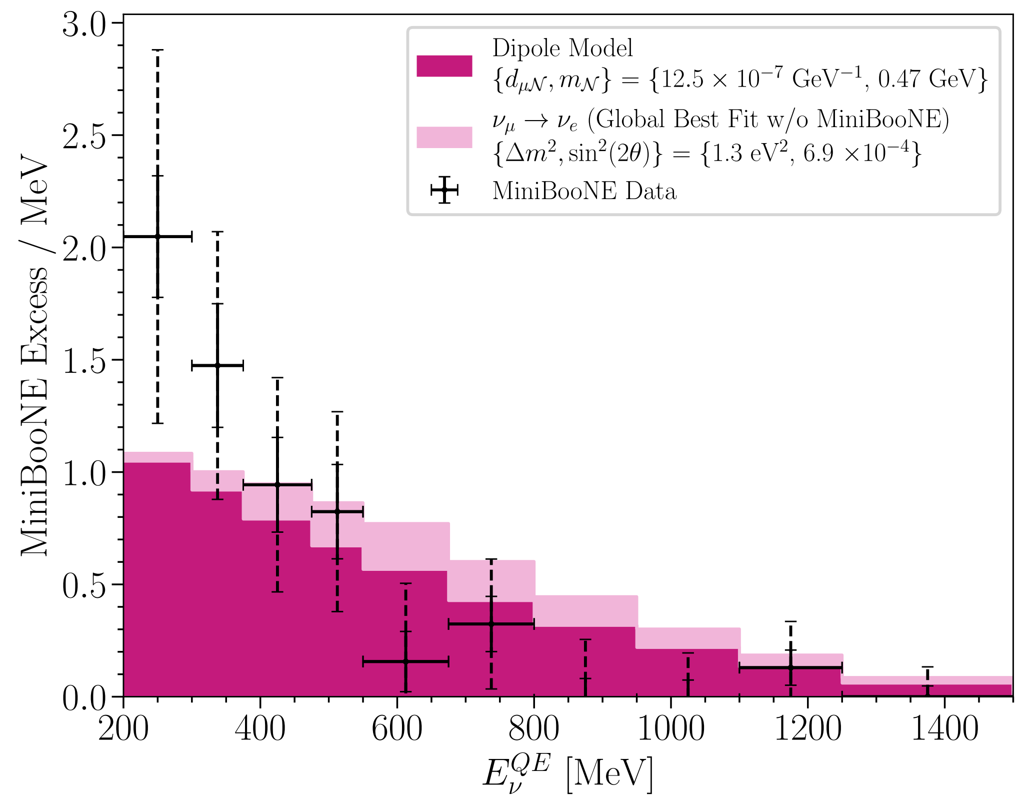


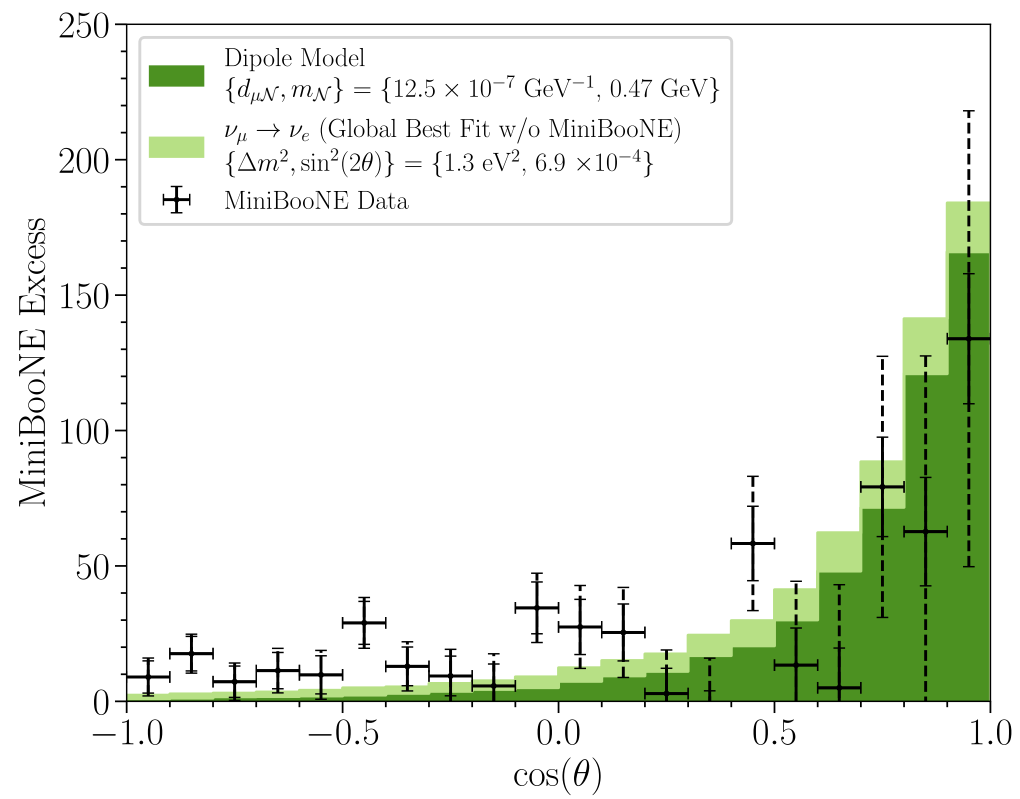
[1] Vergani+ PRD 104, 095005

[2] github.com/Harvard-Neutrino/LeptonInjector

Neutrissimos @ MiniBooNE





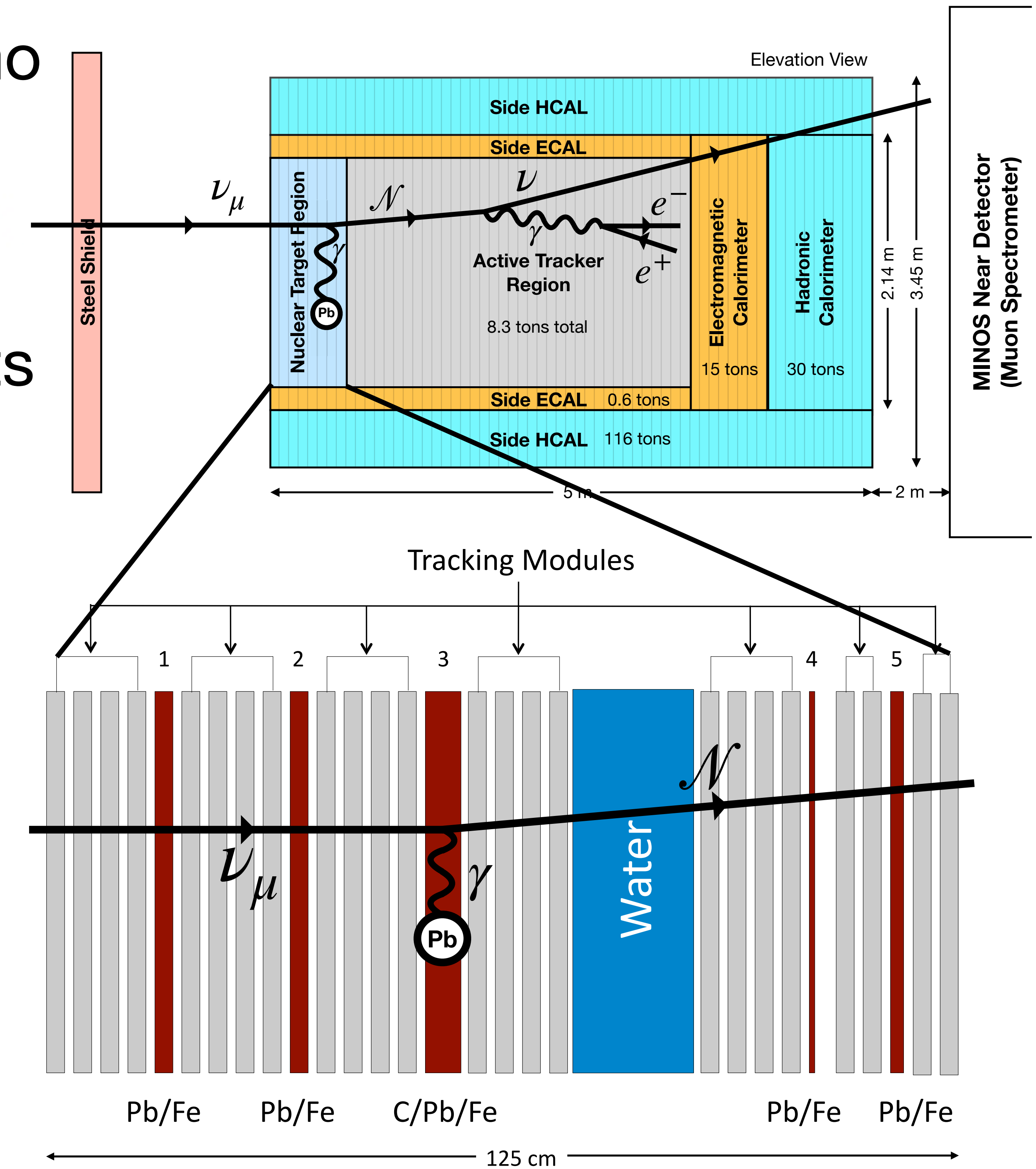


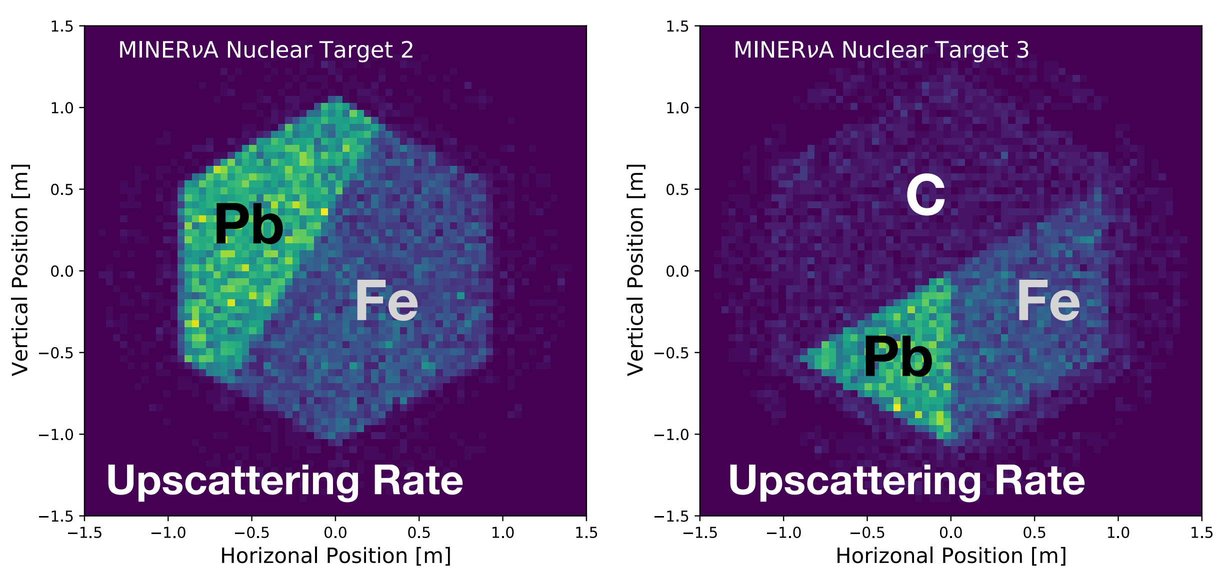
Energy and angular distributions prefer different regions of parameter space, but allowed regions overlap at the 95% CL

Kamp+ PRD 107, 055009

Neutrissimos @ MINERvA

- Single showers from neutrissimo decays would show up as a high dE/dx background in MINERvA neutrino-electron elastic scattering measurements
- We simulate upscattering and decay in a realistic MINERvA detector using LeptonInjector





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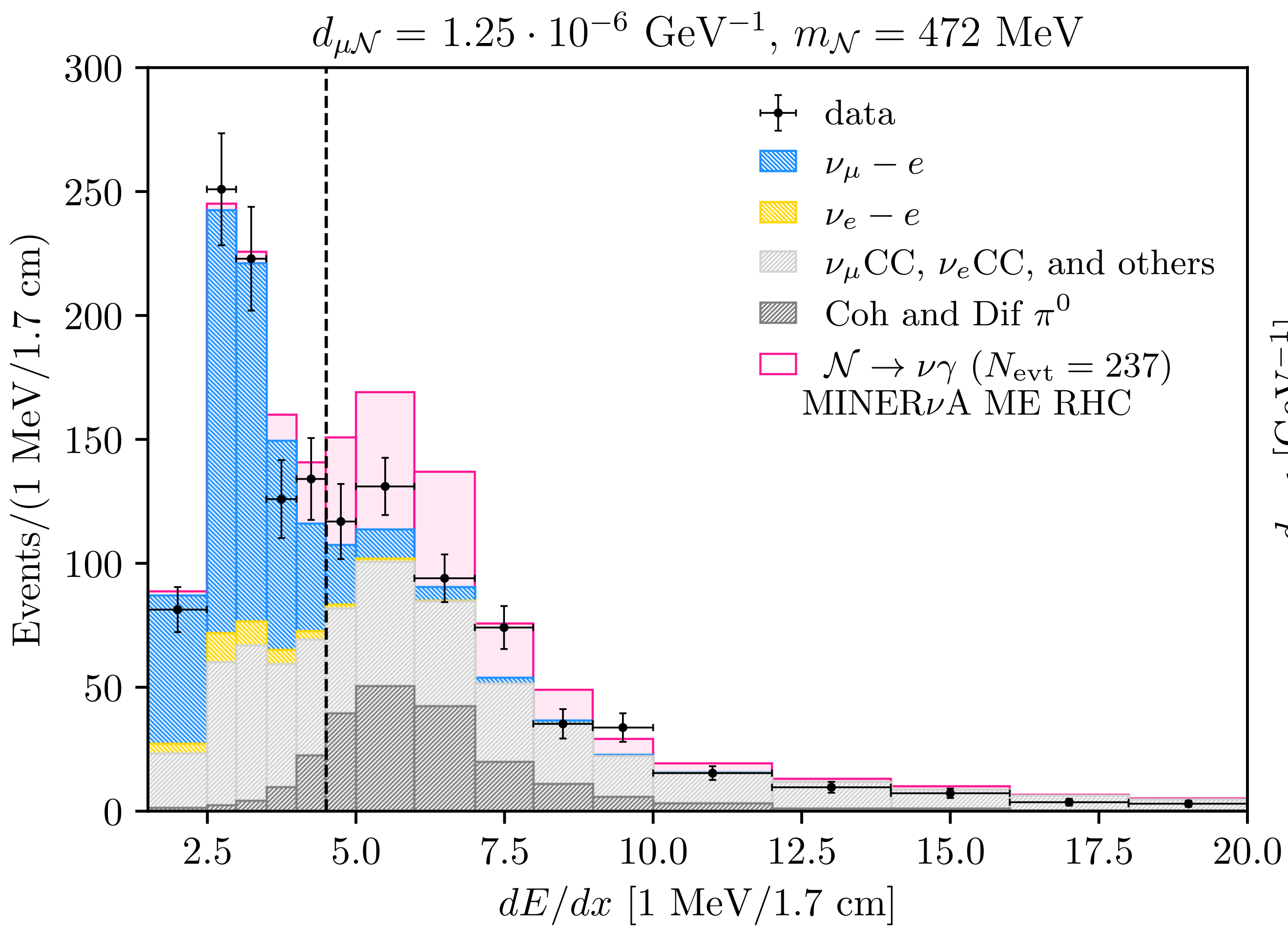
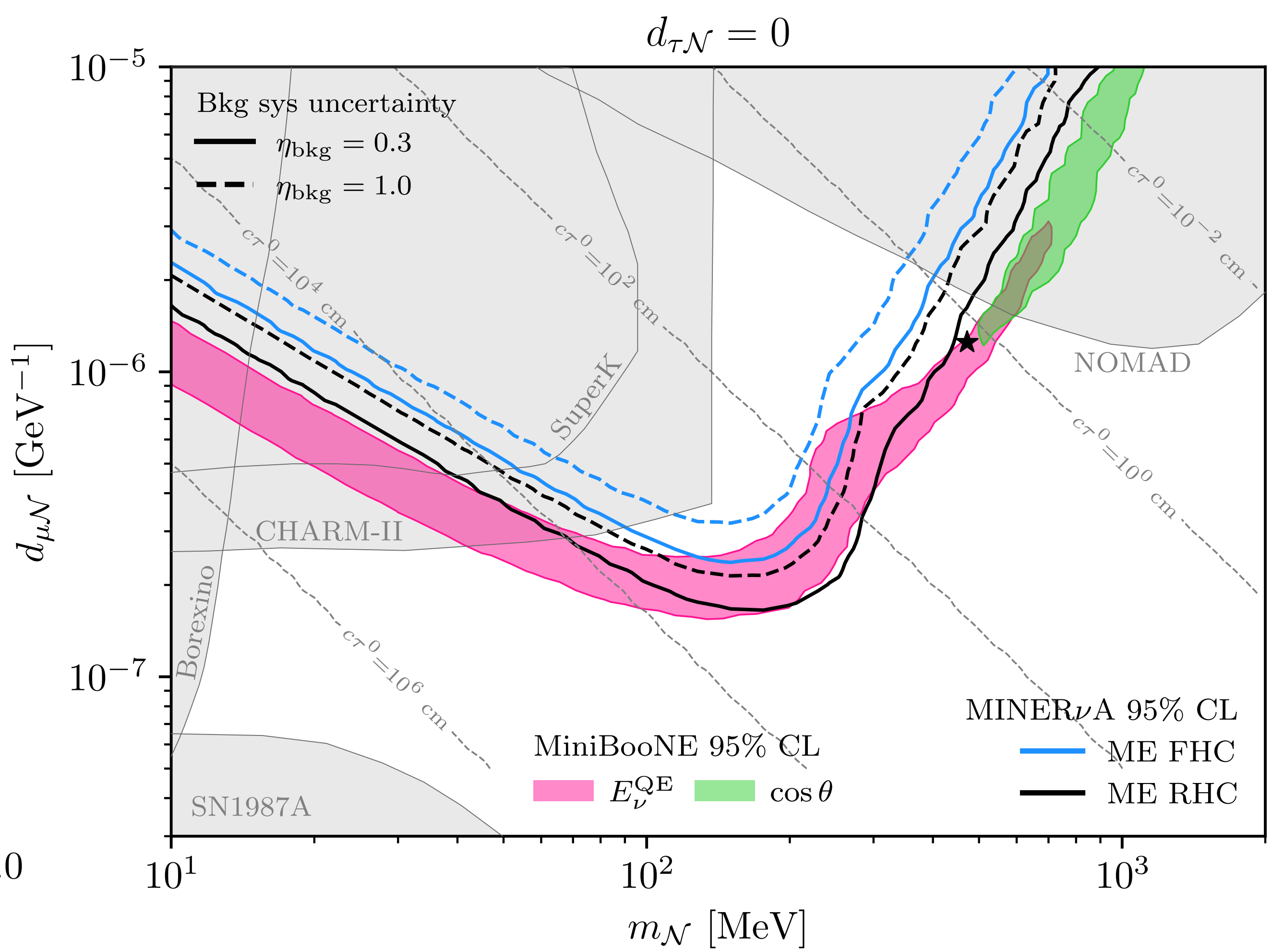
MINERvA Constraints

- Use the high dE/dx sideband region to set constraints
- Most stringent MINERvA constraints do not rule out the MiniBooNE-preferred region at the 95% CL





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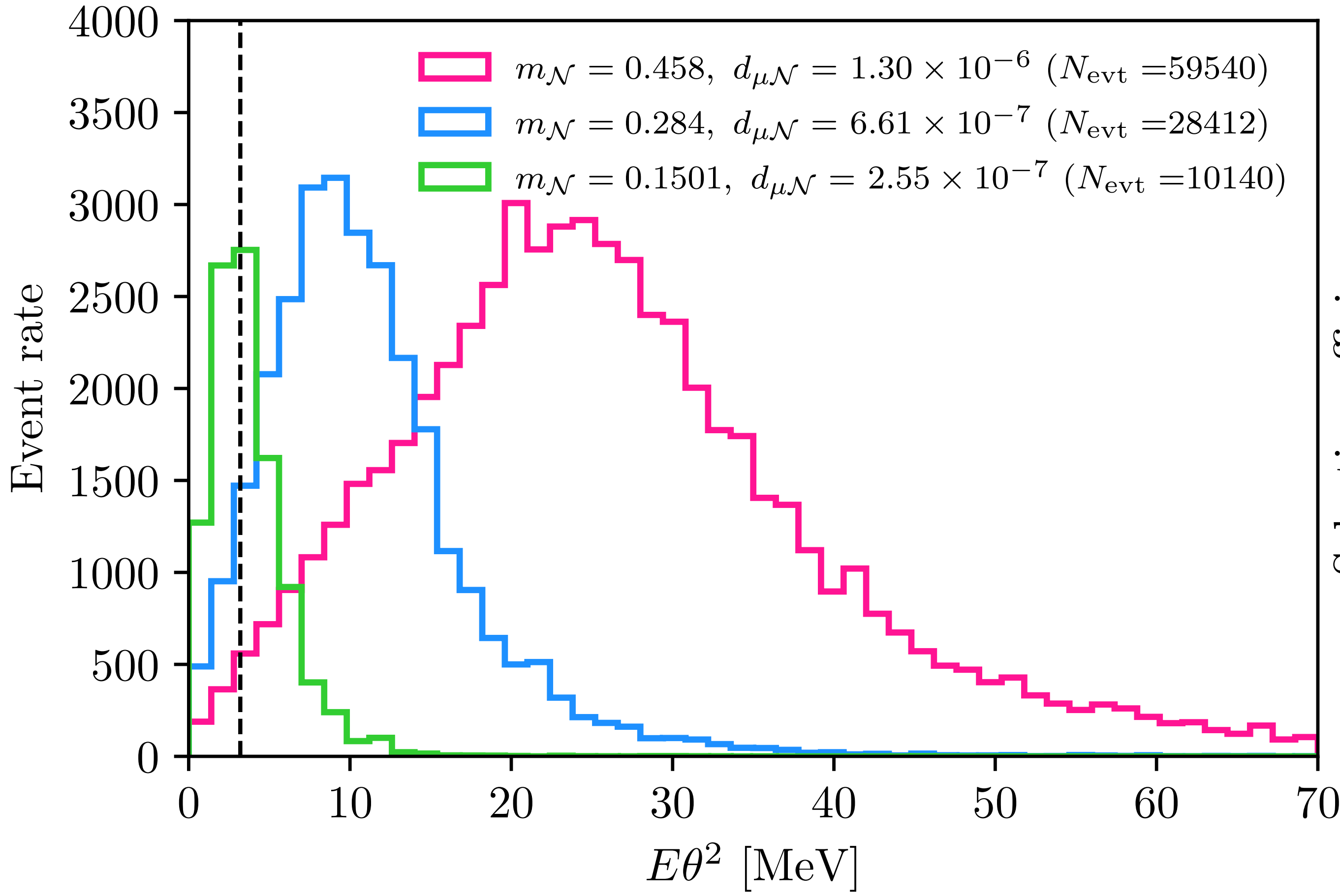
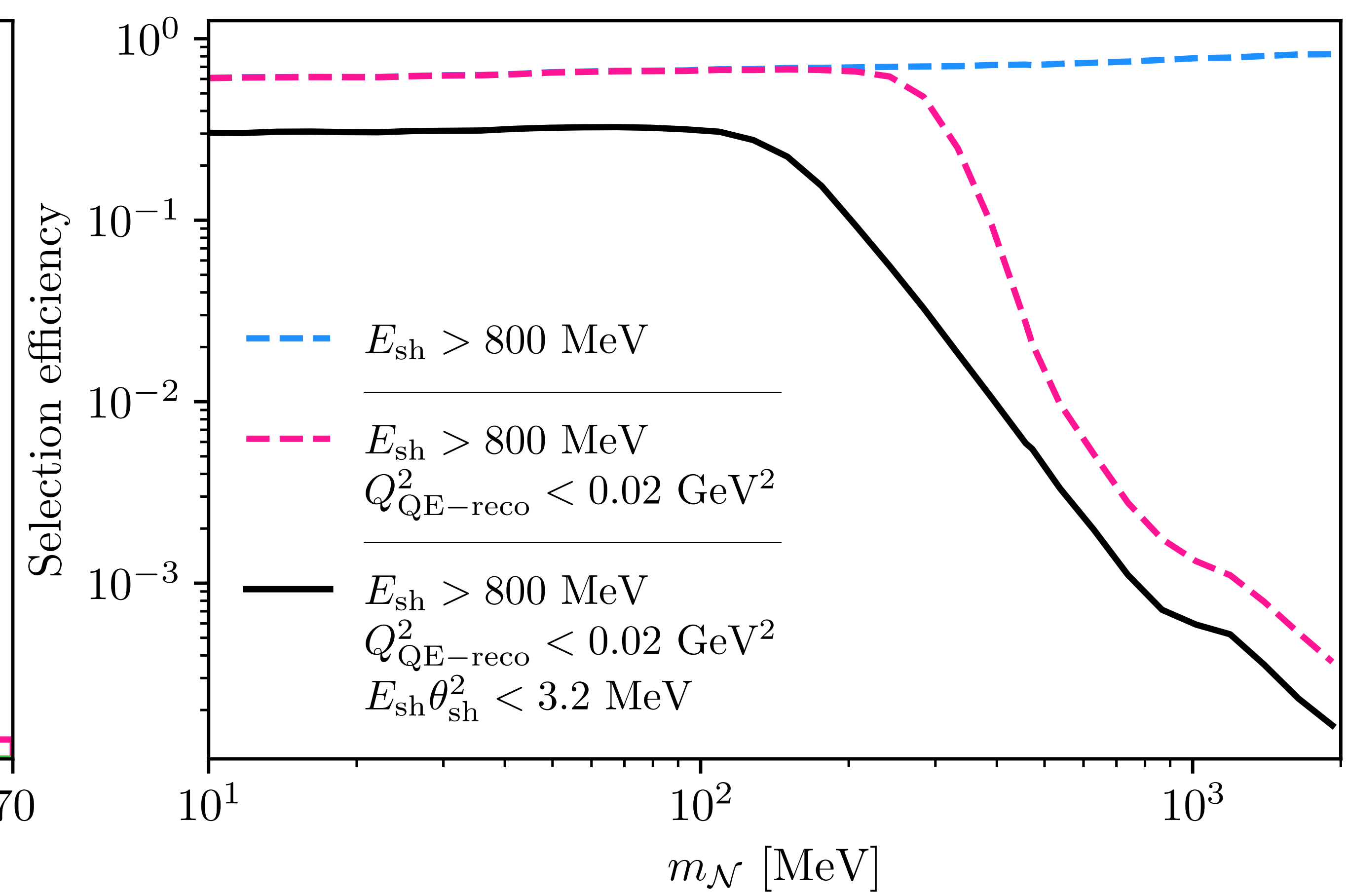
MINERvA Constraints

- The selection cuts in MINERvA's elastic scattering analysis reject most of the neutrissimo decays
- Before any cuts, MINERvA should see ~10^4-10^5 photons from this model for the MiniBooNE parameters of interest





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MINERvA Constraints

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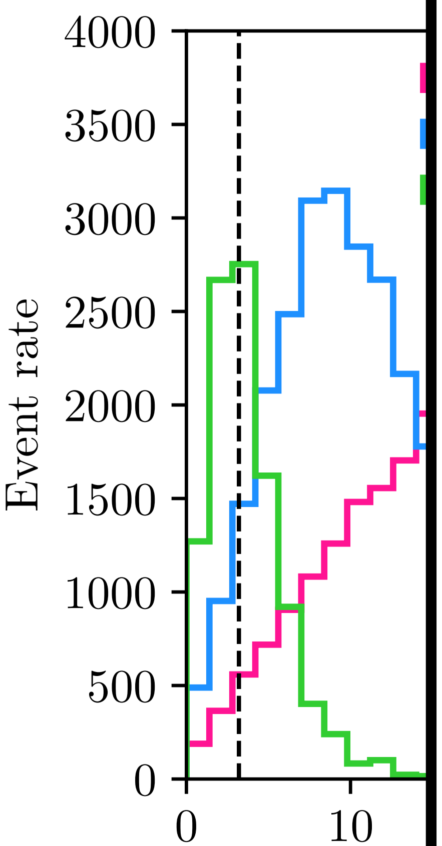
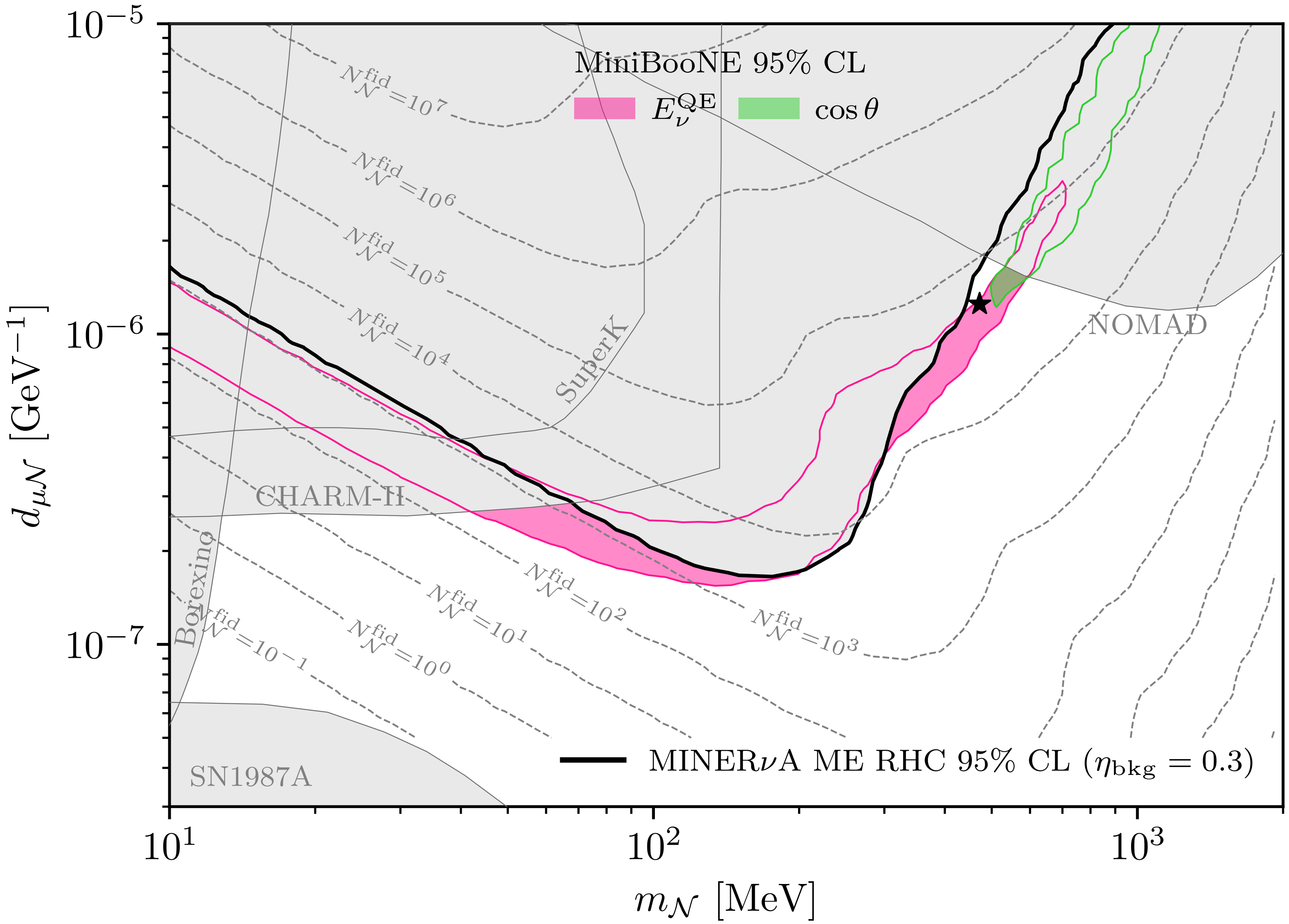
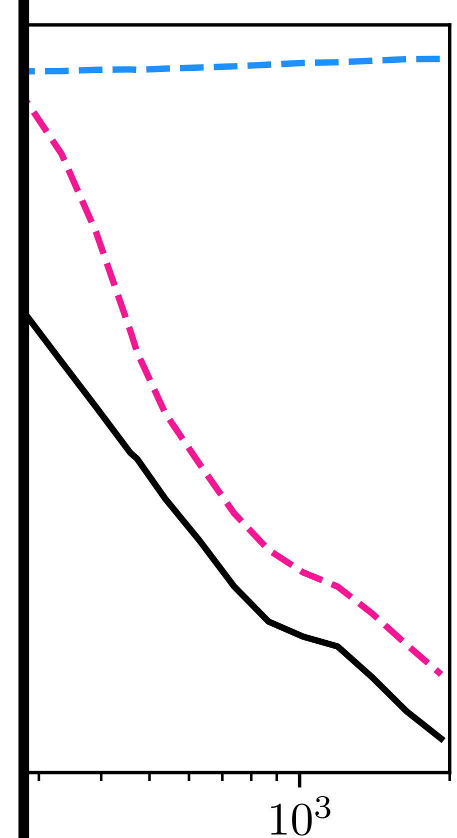




A dedicated MINERvA analysis should be able to make a definitive statement regarding dipole-portal explanations of the MiniBooNE excess!



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Conclusion

- The 4.8σ low-energy excess of electron-like events observed by MiniBooNE remains unexplained
- MicroBooNE results disfavor a ν_e-based explanation of the entire excess
- The same MicroBooNE results are, however, consistent with a $\bar{\nu}_e$-based explanation at the 2σ confidence level
- A mixed model comprised of an eV-scale sterile neutrino and an MeV-scale neutrissimo can explain the MiniBooNE excess while avoiding the internal tension observed in sterile neutrino global fits

Thank you!