The MiniBooNE Anomaly

Kevin J. Kelly, CERN (with help from Ivan Esteban, OSU, and Joachim Kopp, JGU Mainz/CERN)
Mini SBN-TH Workshop, 13 December, 2021

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Outline

- MiniBooNE (and other) anomalies 101
  - Sterile-neutrino Interpretation

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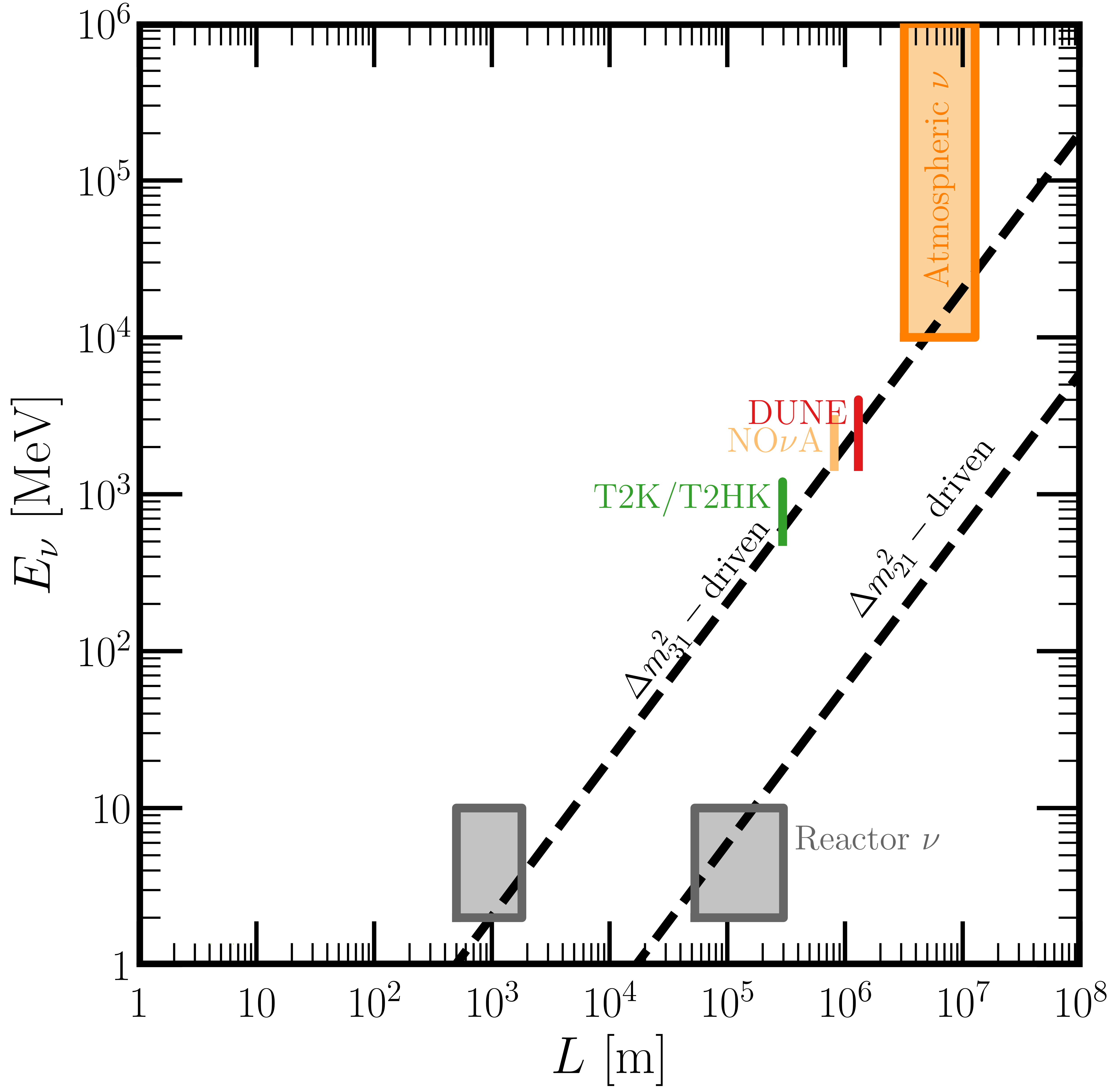
- MiniBooNE Anomaly 301
  - Other new-physics explanations for MiniBooNE et al?

An incomplete set of oscillation experiments



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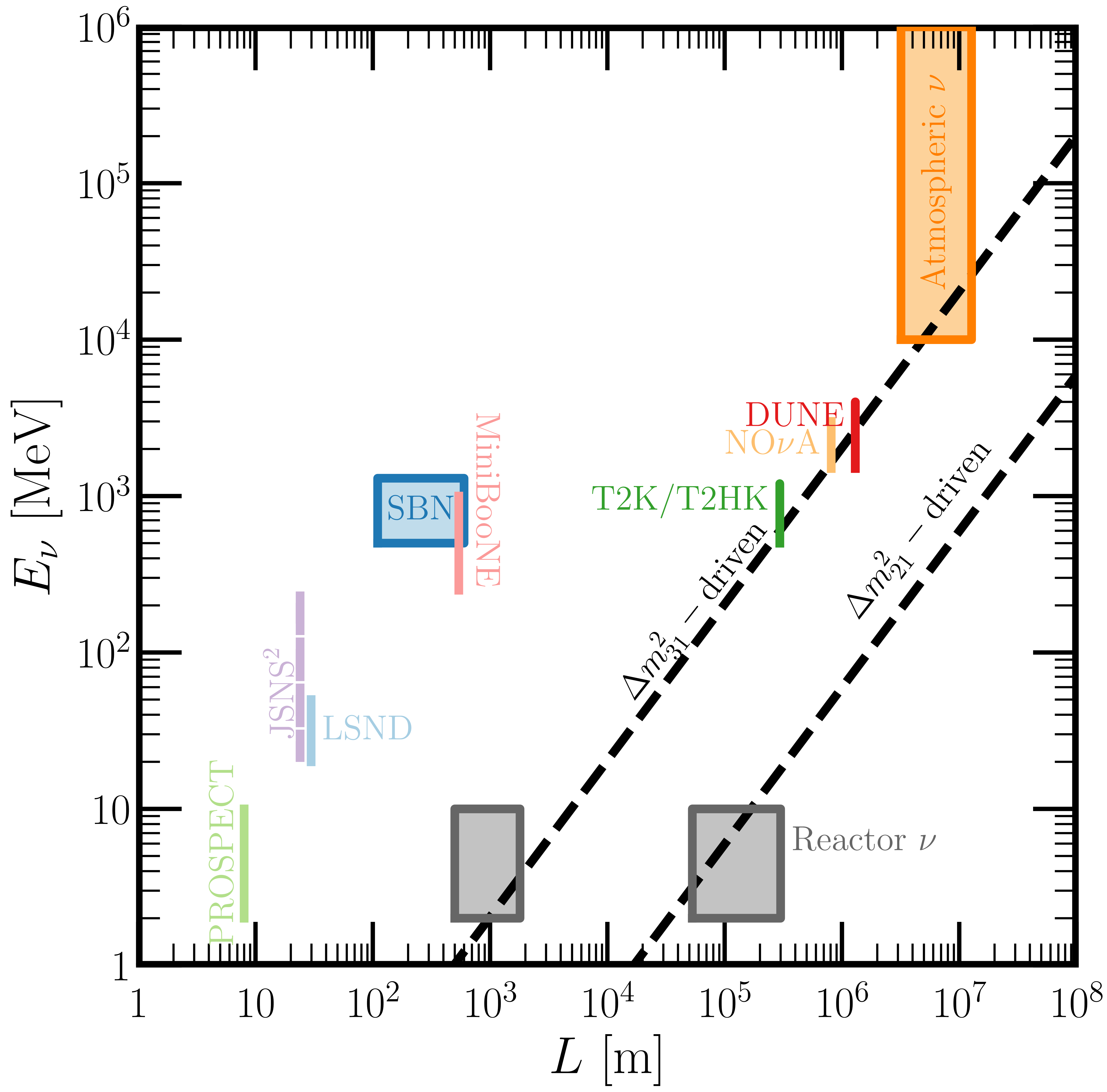
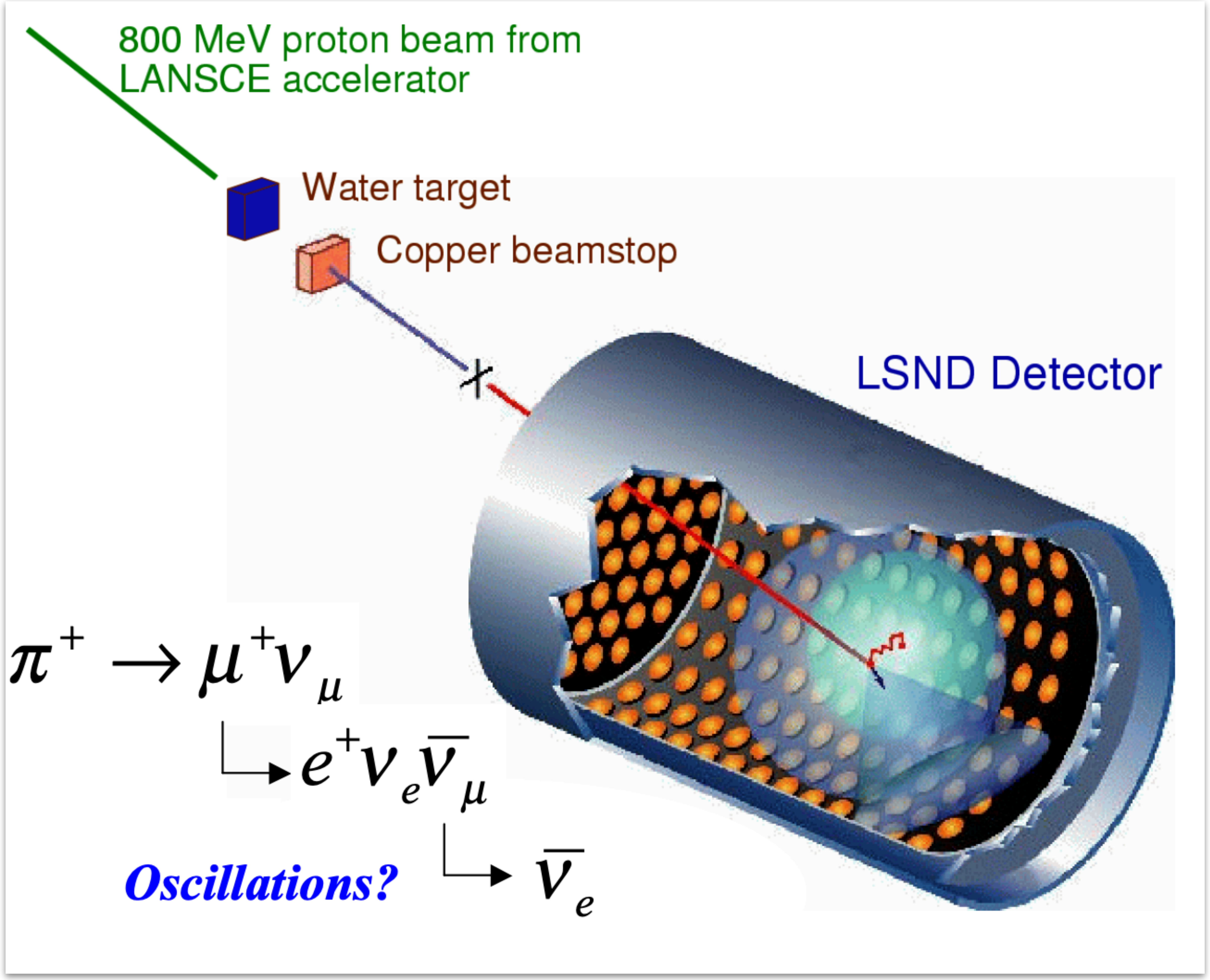


Liquid Scintillator Neutrino Detector (LSND)



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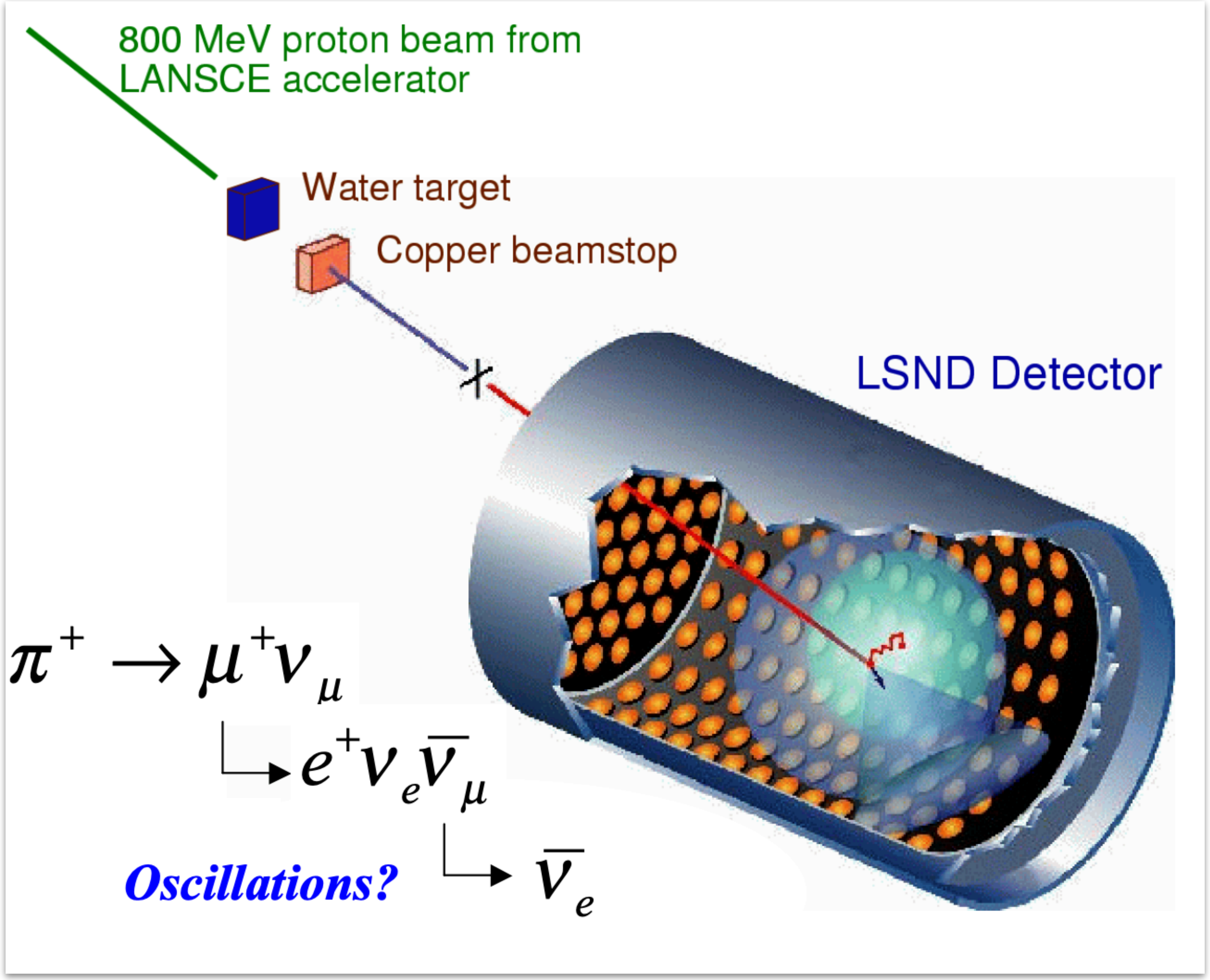
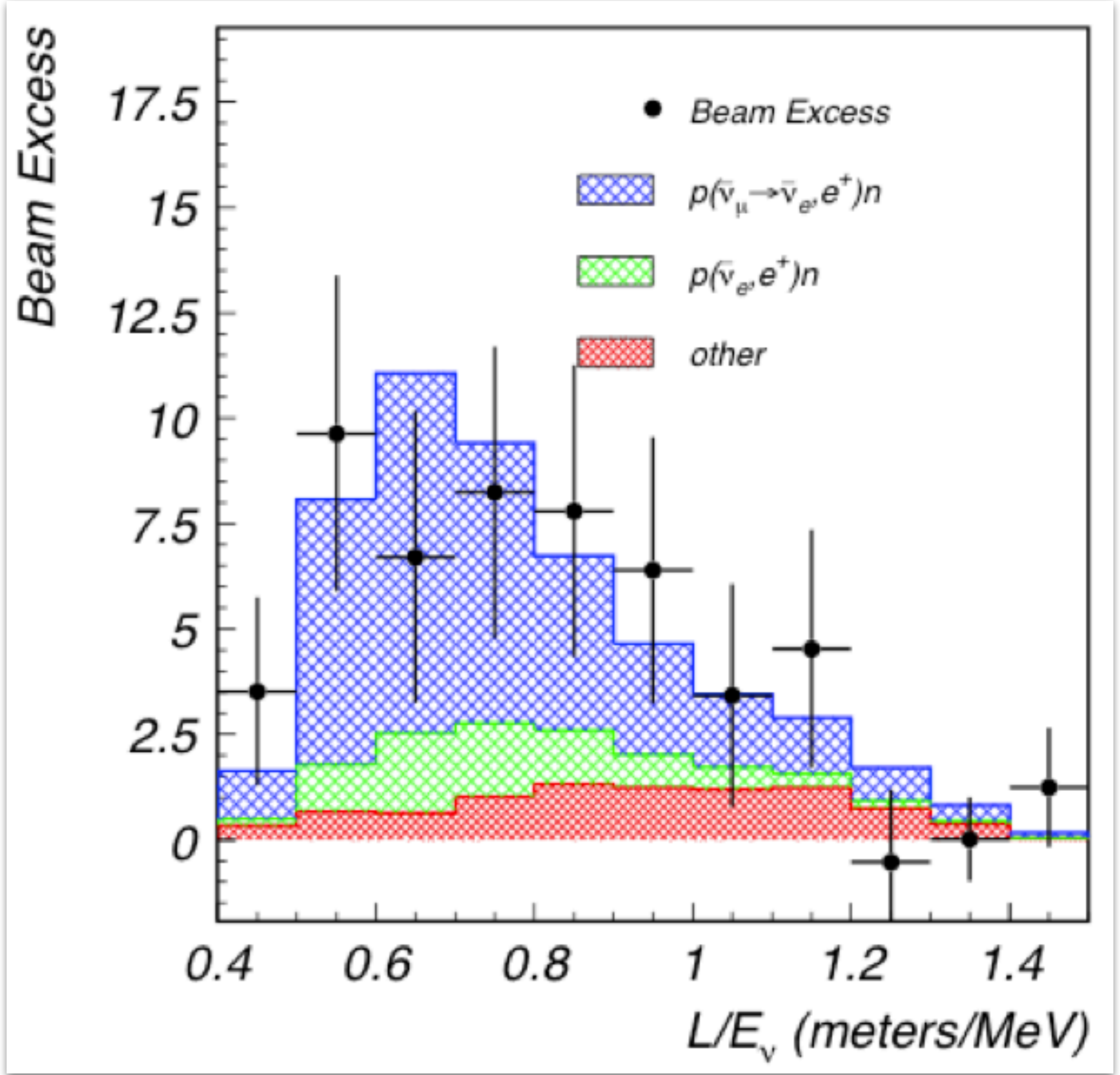


$\overline{\nu}_\mu \rightarrow \overline{\nu}_e?$



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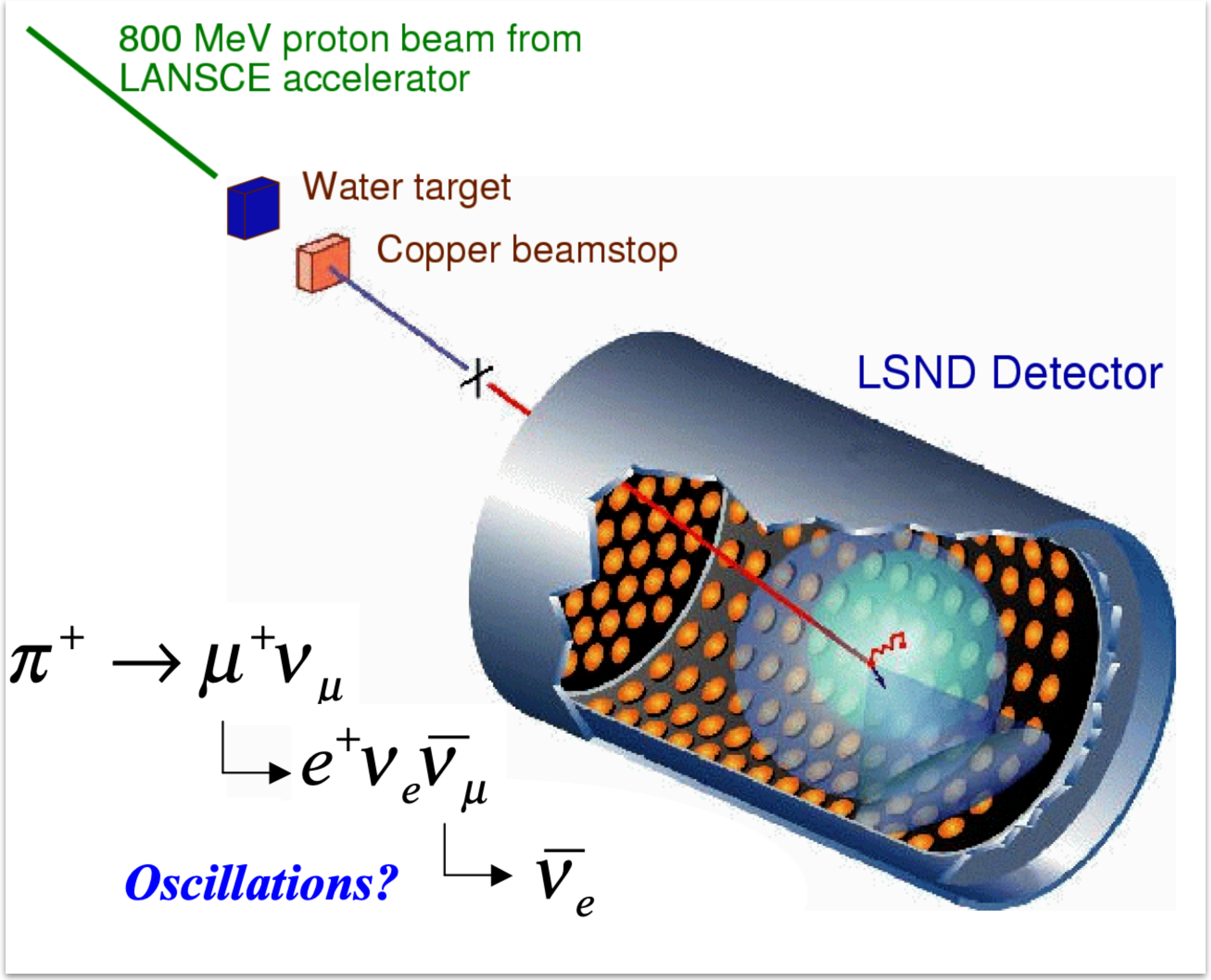

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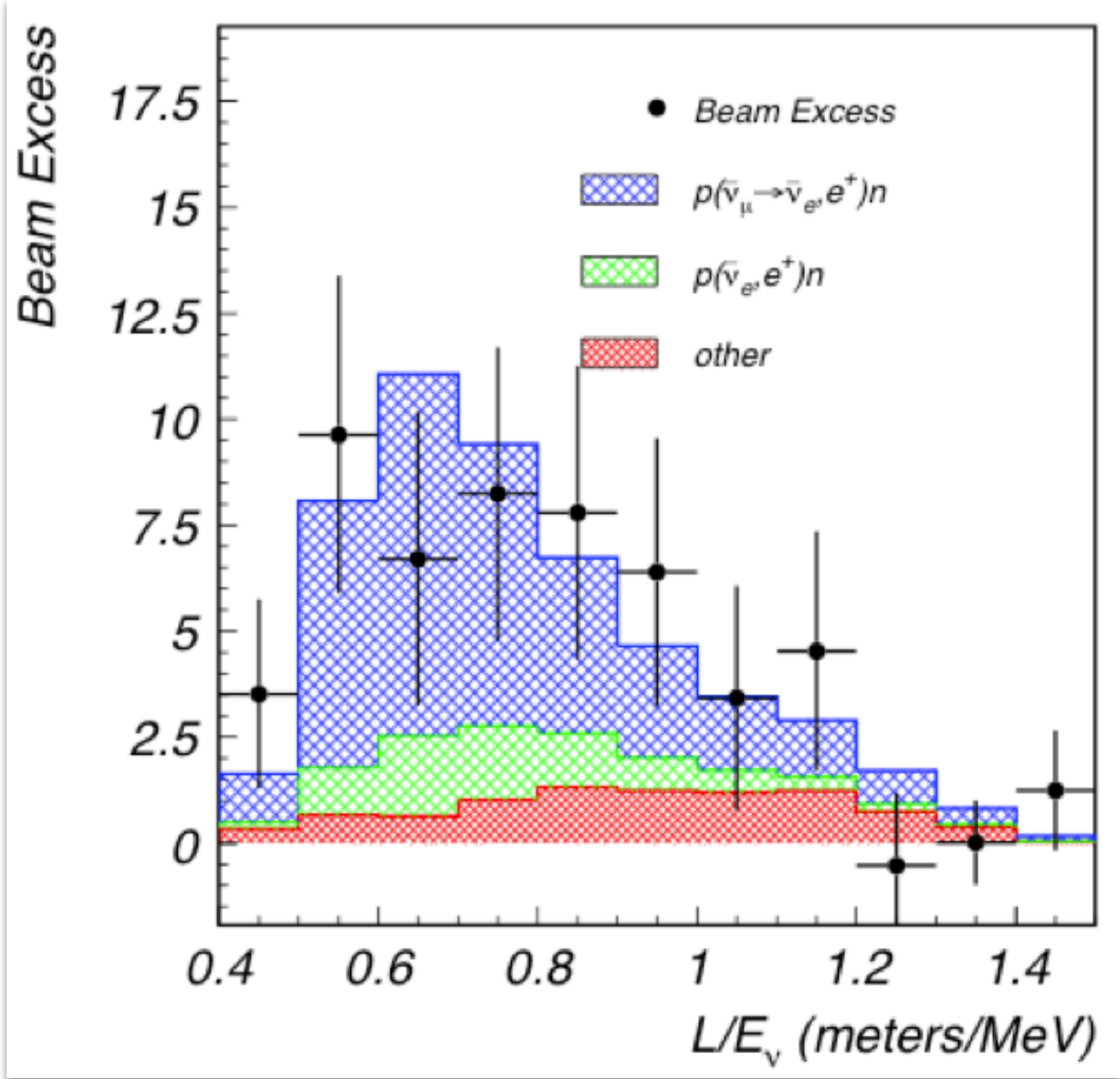
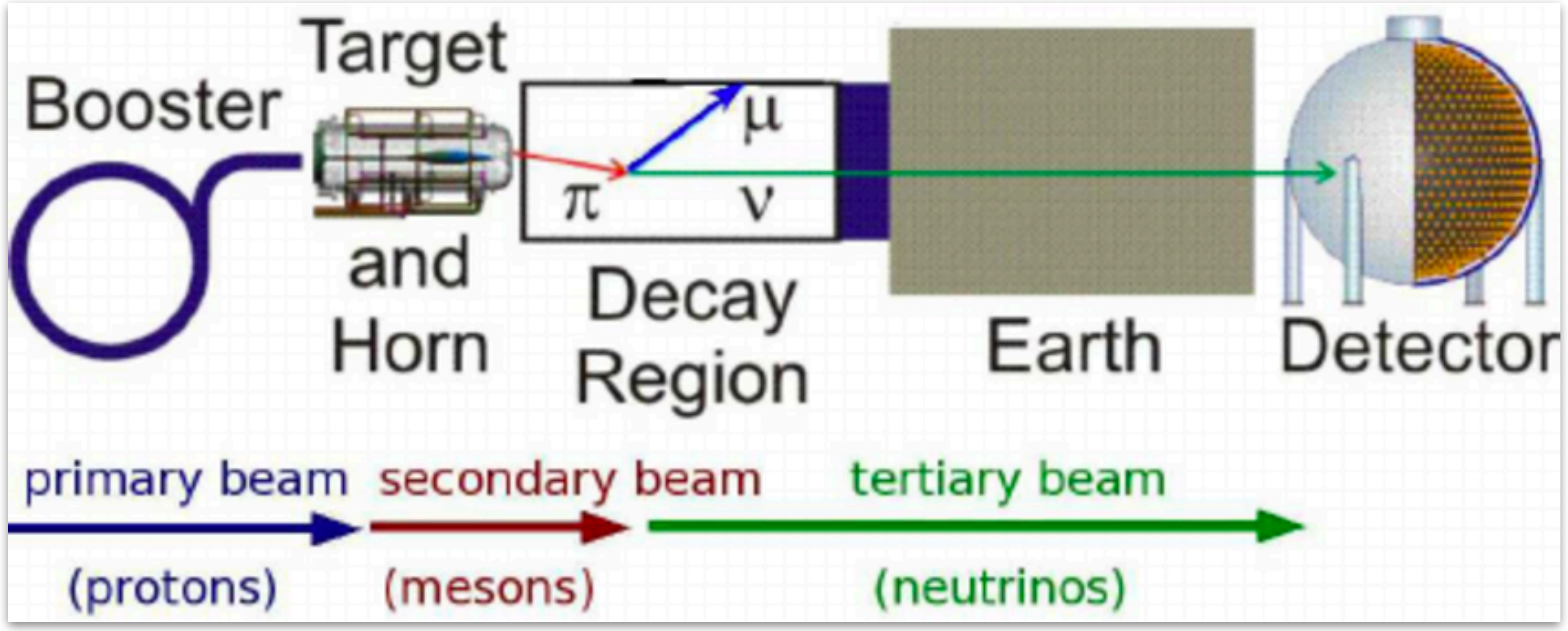


Neutrinos (mostly) from pion/muon decay-at-rest — O(30) MeV, roughly 50 meter baseline length.

Observed excess — $87.9 \pm 22.4 \pm 6.0 \longrightarrow P\left(\overline{\nu}_\mu \rightarrow \overline{\nu}_e\right) \approx 2.6 \times 10^{-3}$

MiniBooNE

Designed to test the LSND anomaly — very different L, E, but similar L/E



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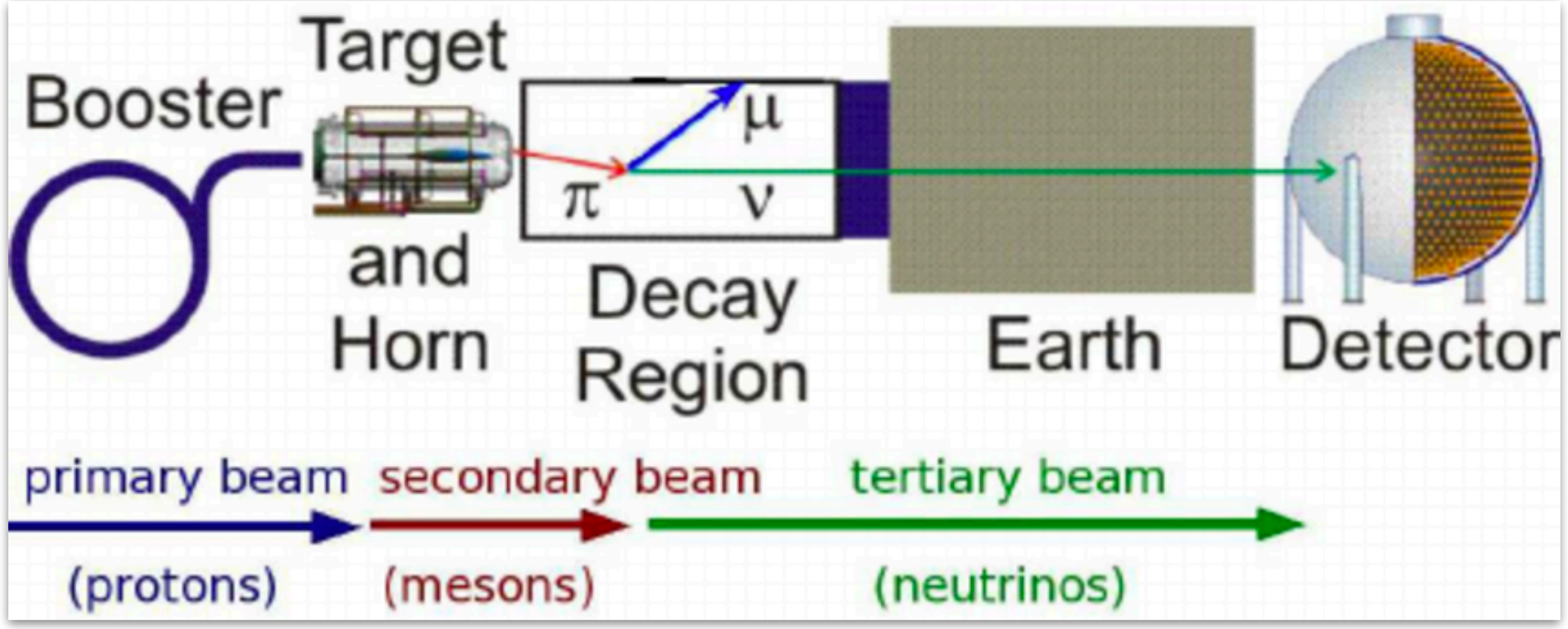

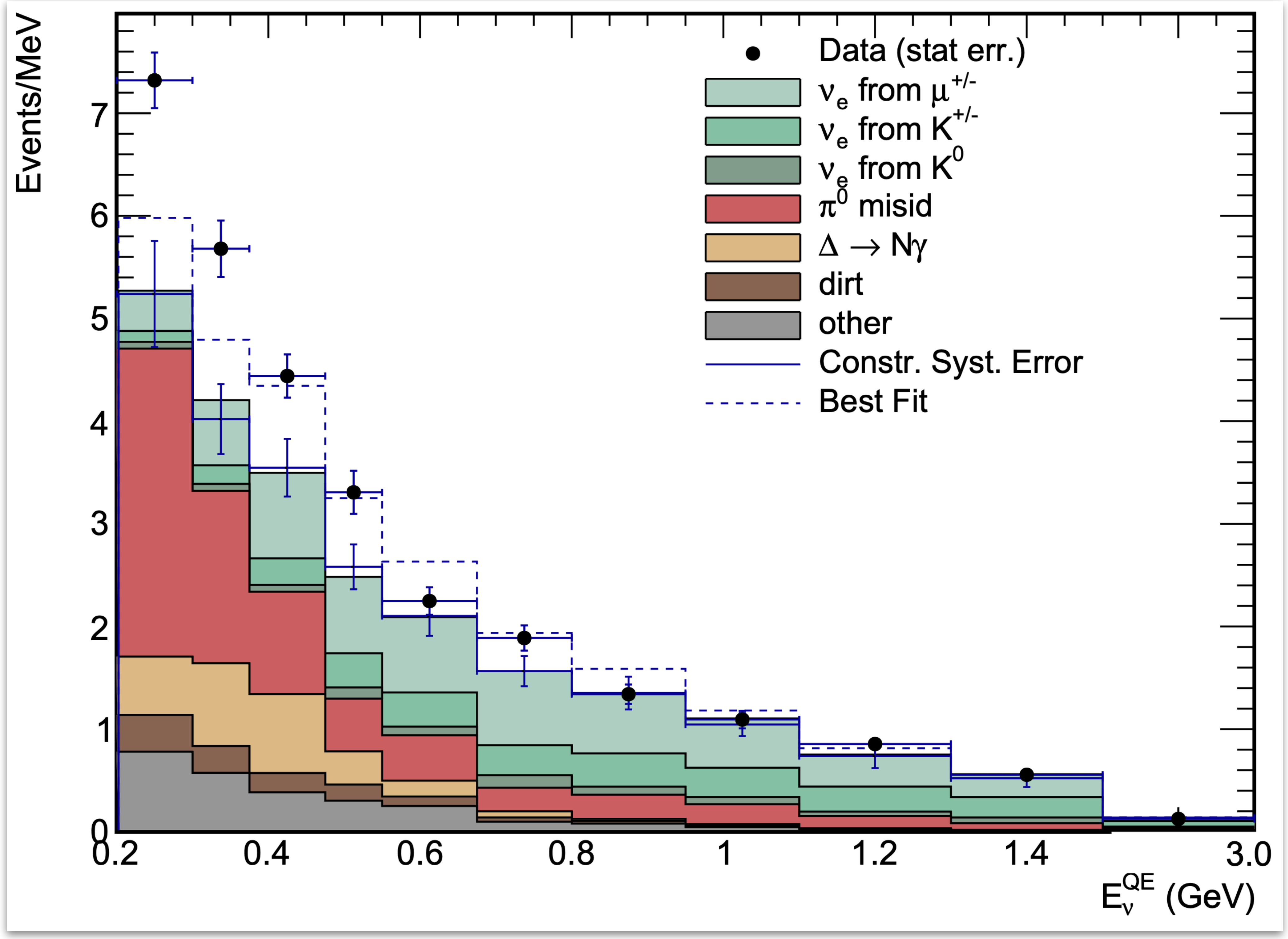

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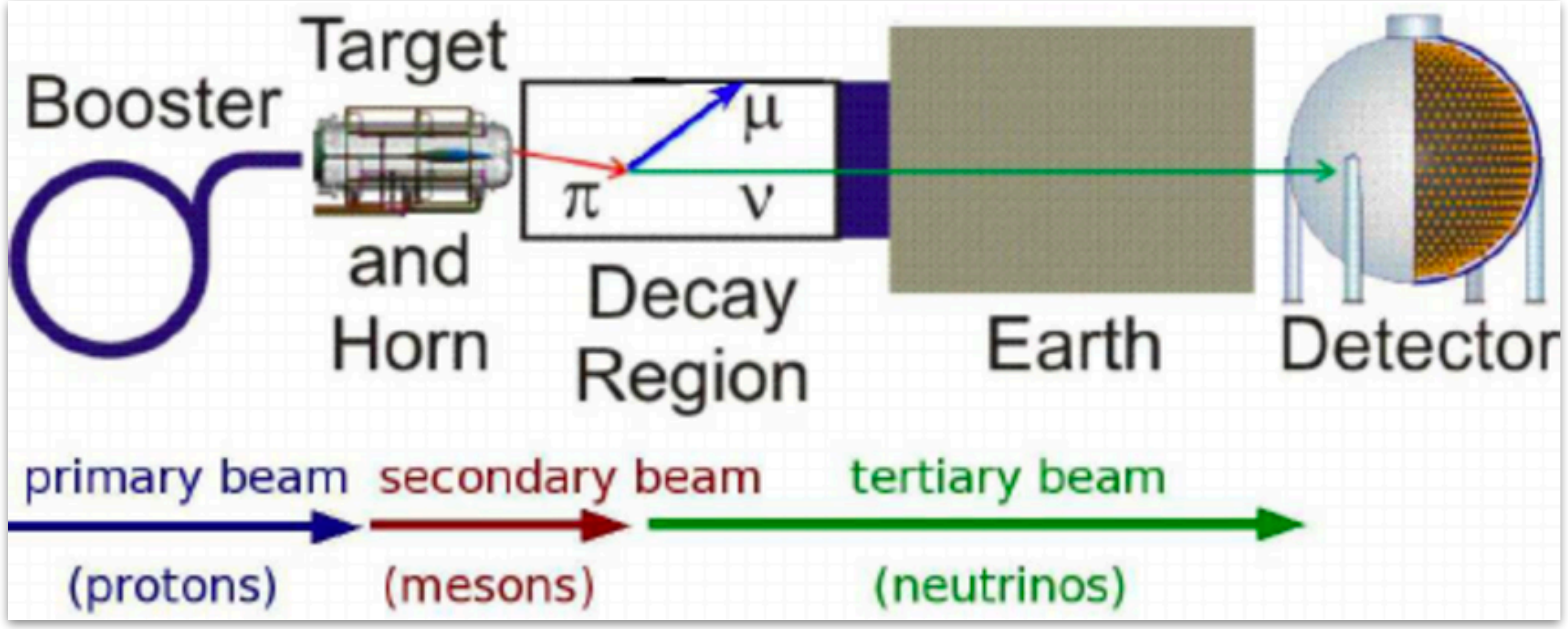
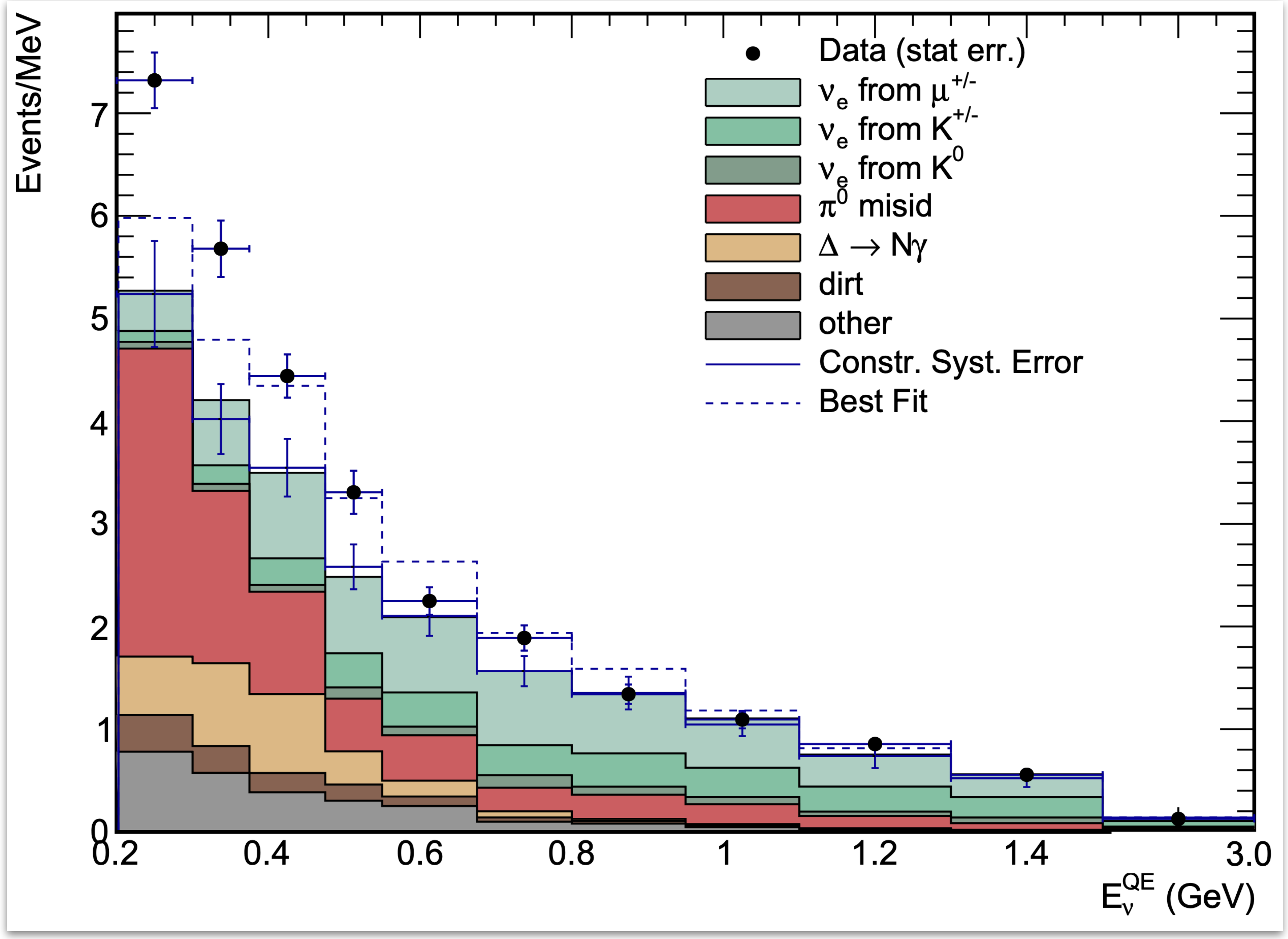
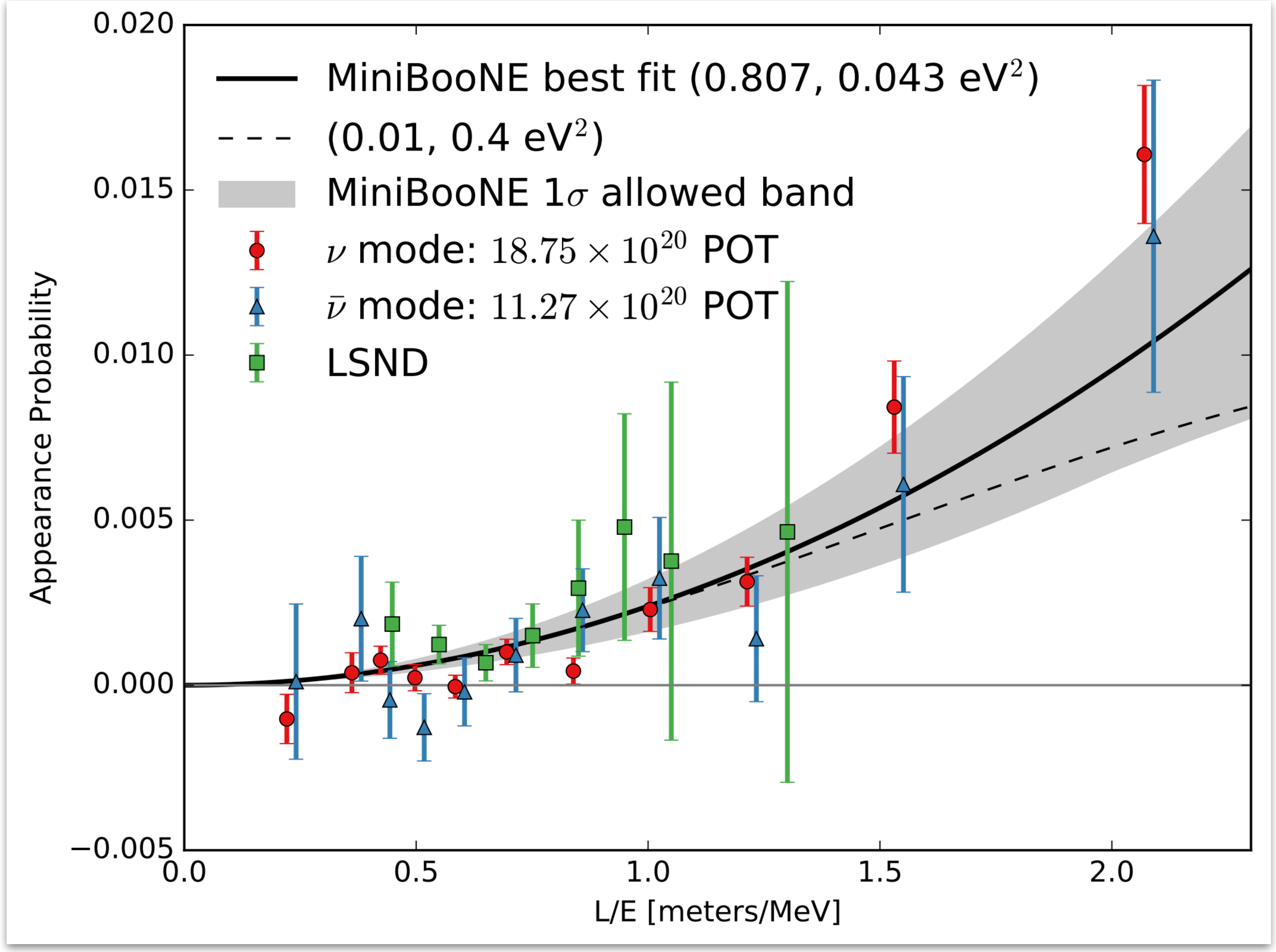


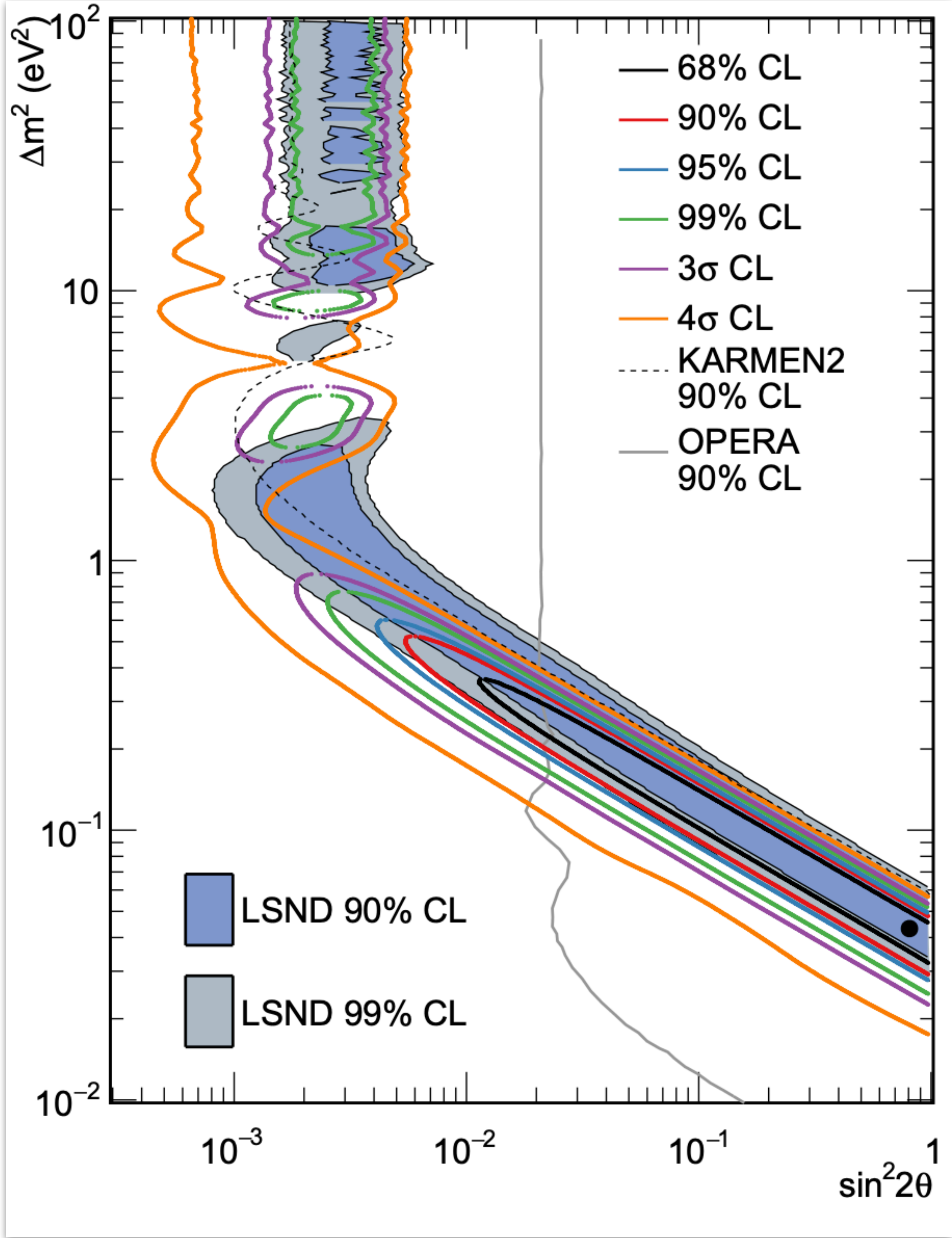
$$\nu_\mu \to \nu_e \text{ AND } \overline{\nu}_\mu \to \overline{\nu}_e?$$

MiniBooNE Collab., [2006.16883]





Anomalous Appearance — Fourth Neutrino



MiniBooNE Collab., [2006.16883]

IF coming from oscillations, the results from LSND and MiniBooNE require a new mass eigenstate around the eV scale.

Combined with the observed invisible width of the Z-boson (LEP), any additional light neutrino(s) must be sterile — gauge singlets.

Invoking a New (sterile) Neutrino

$$P\left(\nu_{\mu} \to \nu_{e}\right) = \sin^{2}\left(2\theta_{\mu e}\right)\sin^{2}\left(\frac{\Delta m_{41}^{2} L}{4E_{\nu}}\right)$$

- Add in a new (fourth) neutrino mass eigenstate with a significantly larger mass than the three “light” ones. This extends the Leptonic mixing matrix to 4x4 instead of 3x3.

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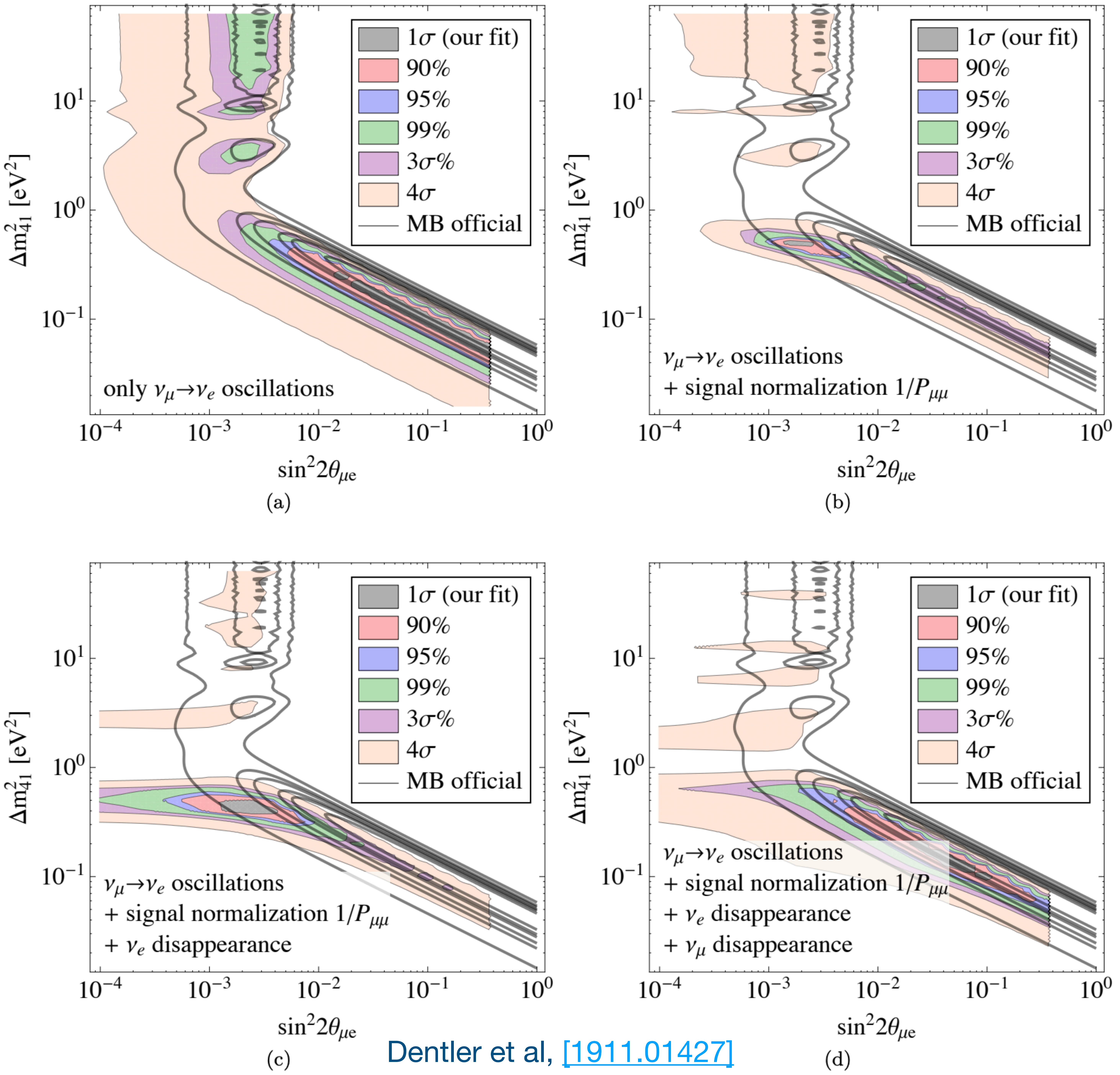
$$\sin^{2}\left(2\theta_{\mu e}\right) \equiv 4\left|U_{e4}\right|^{2}\left|U_{\mu 4}\right|^{2}$$

- Electron-neutrino appearance is driven by a product of the new matrix elements. Each of these being non-zero predicts electron-neutrino **and** muon-neutrino disappearance at the same neutrino energy/distance.

Consistency in MiniBooNE with four flavours

Two important features overlooked in "simple" appearance assumptions:

- Expectation of appearance signal is predicted based on muon-neutrino background observation (which is modified if muon neutrinos are disappearing) — panel (a) to panel (b).
- Expectation of intrinsic electron- and muon-neutrino backgrounds should be modified if those backgrounds can oscillate — panels (c) and (d).

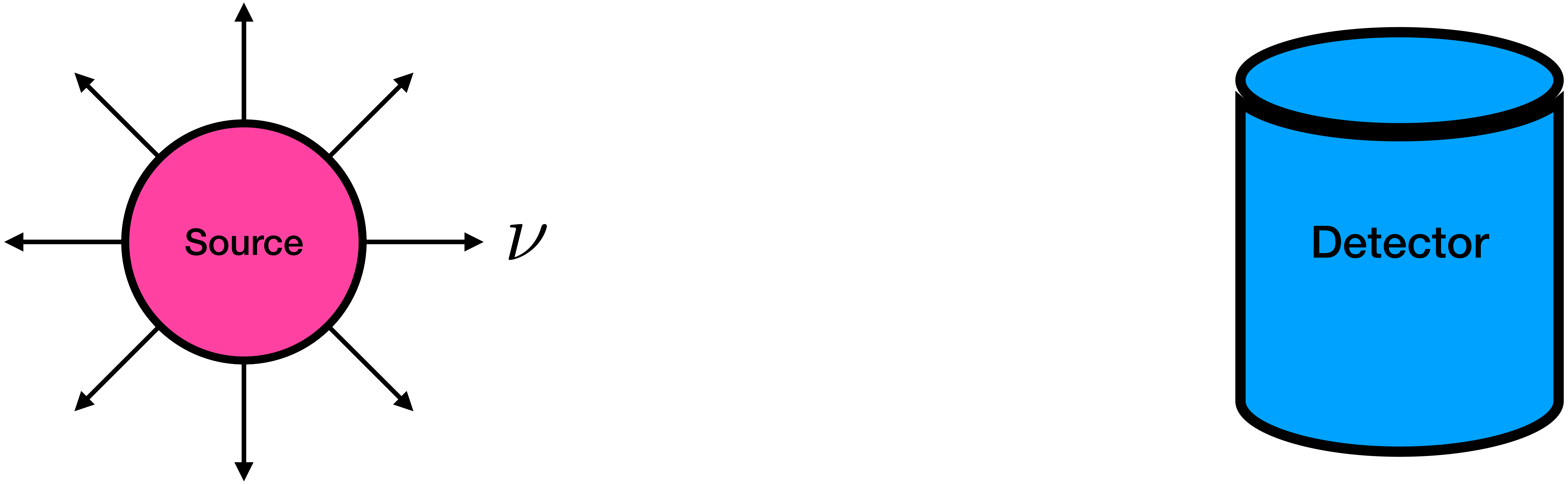


Dentler et al, [1911.01427]

Electron-Neutrino Disappearance?

Key Challenge: Flux Uncertainties

$$P\left(\nu_\alpha \rightarrow \nu_\alpha\right) = 1 - 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E_\nu}\right)$$



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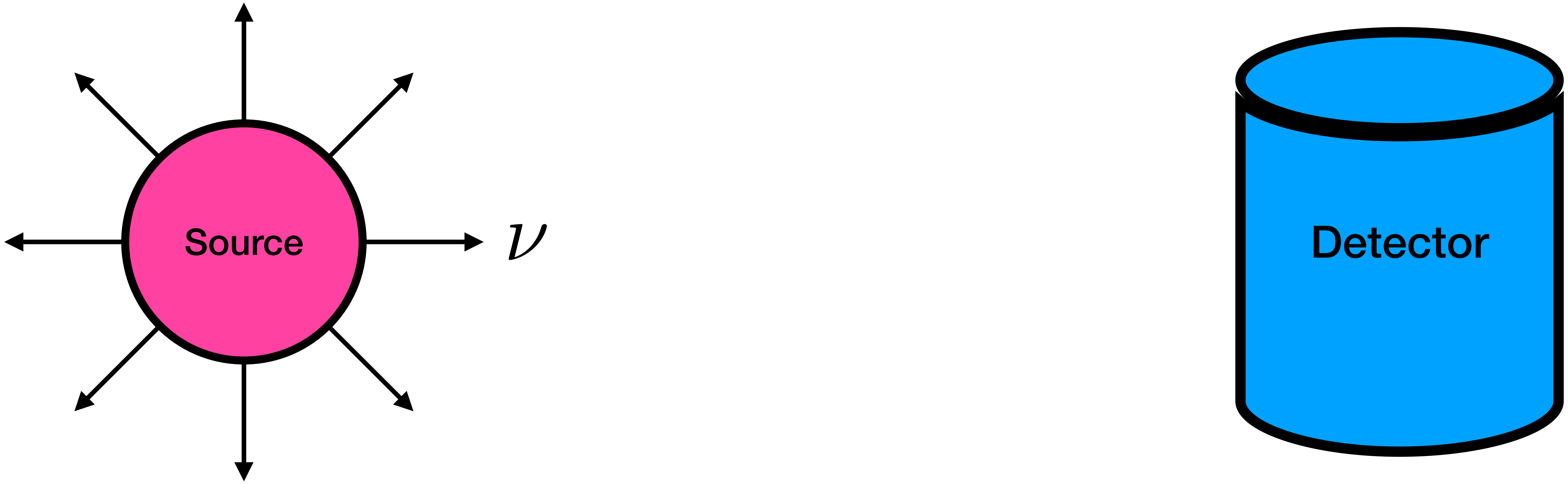
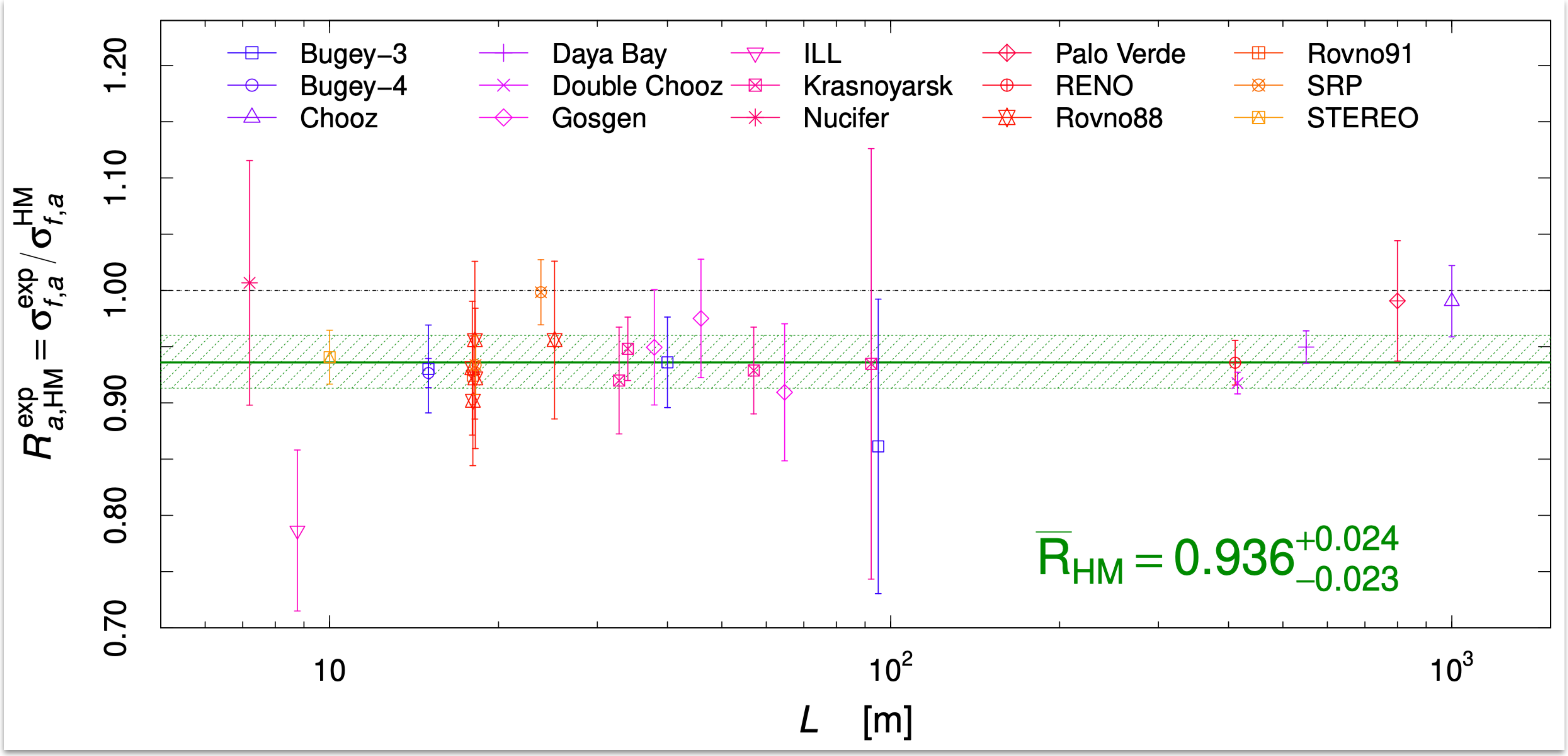


Experiments measure *rates* (product of flux, cross section, and oscillation probability), not probability directly. Constraints on the mixing angle will therefore be limited by uncertainties on fluxes, cross sections, etc.

The Reactor Antineutrino (Rate) Anomaly

Giunti et al, [2110.06820]



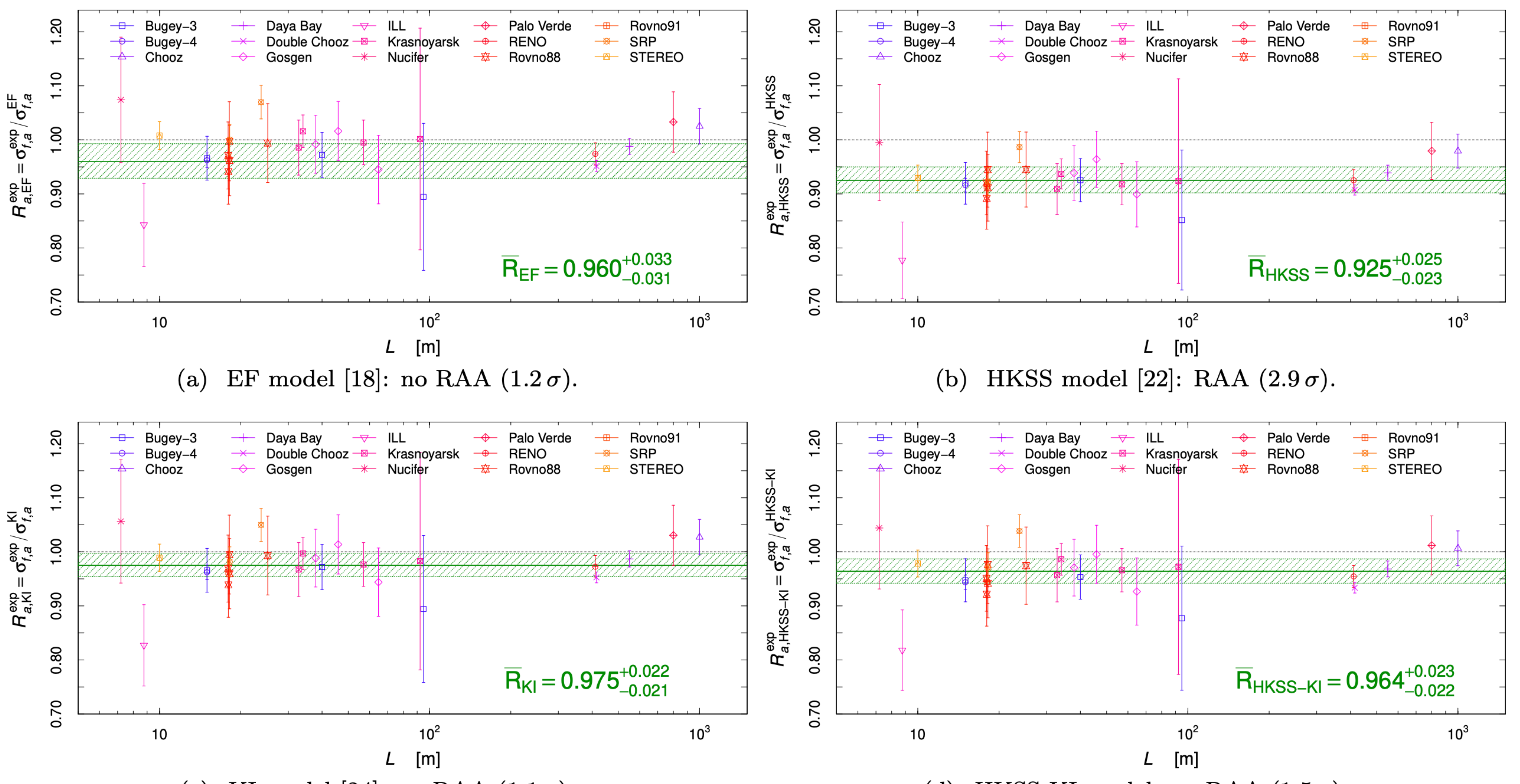
Using flux predictions from Mueller et al [1101.2663] and Huber [1106.0687] — significant rate deficit across many baselines.

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) \to 1 - 2|U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$

(large mass-squared splitting)

Flux Re-evaluations

Giunti et al, [2110.06820]



(a) EF model [18]: no RAA ($1.2\,\sigma$).

(b) HKSS model [22]: RAA ($2.9\,\sigma$).

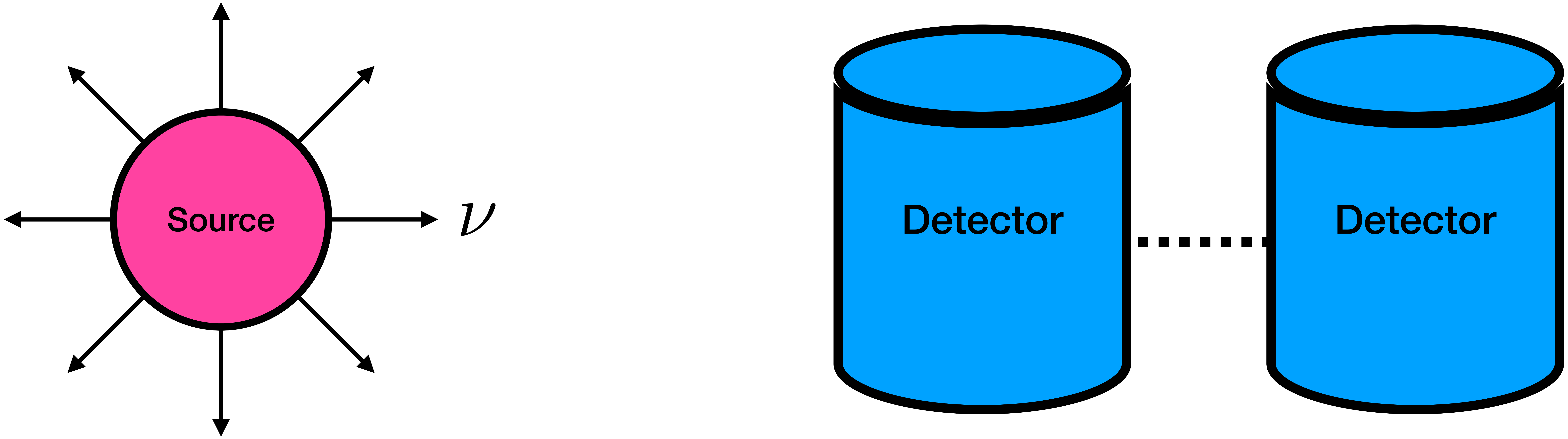
(c) KI model [24]: no RAA ($1.1\,\sigma$).

(d) HKSS-KI model: no RAA ($1.5\,\sigma$).

Overall rate anomaly seems to have vanished — larger predicted-flux uncertainties, etc.

Avoiding Uncertainties

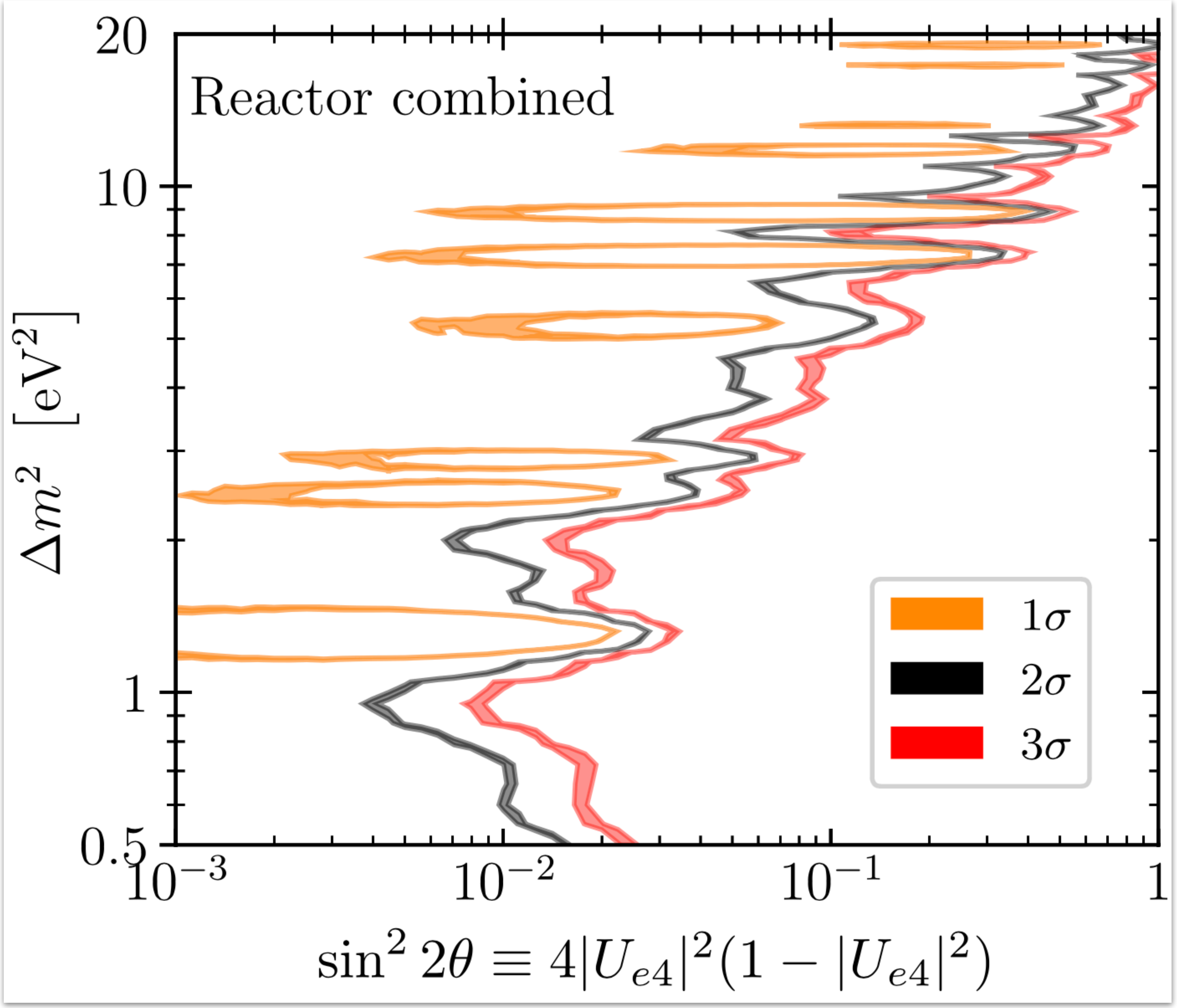
$$P\left(\nu_\alpha \rightarrow \nu_\alpha\right) = 1 - 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$



Make and compare measurements at a variety of distances — movable source, movable detector, segmented detector…

Reactor Global Picture

Berryman et al, [2111.12530]



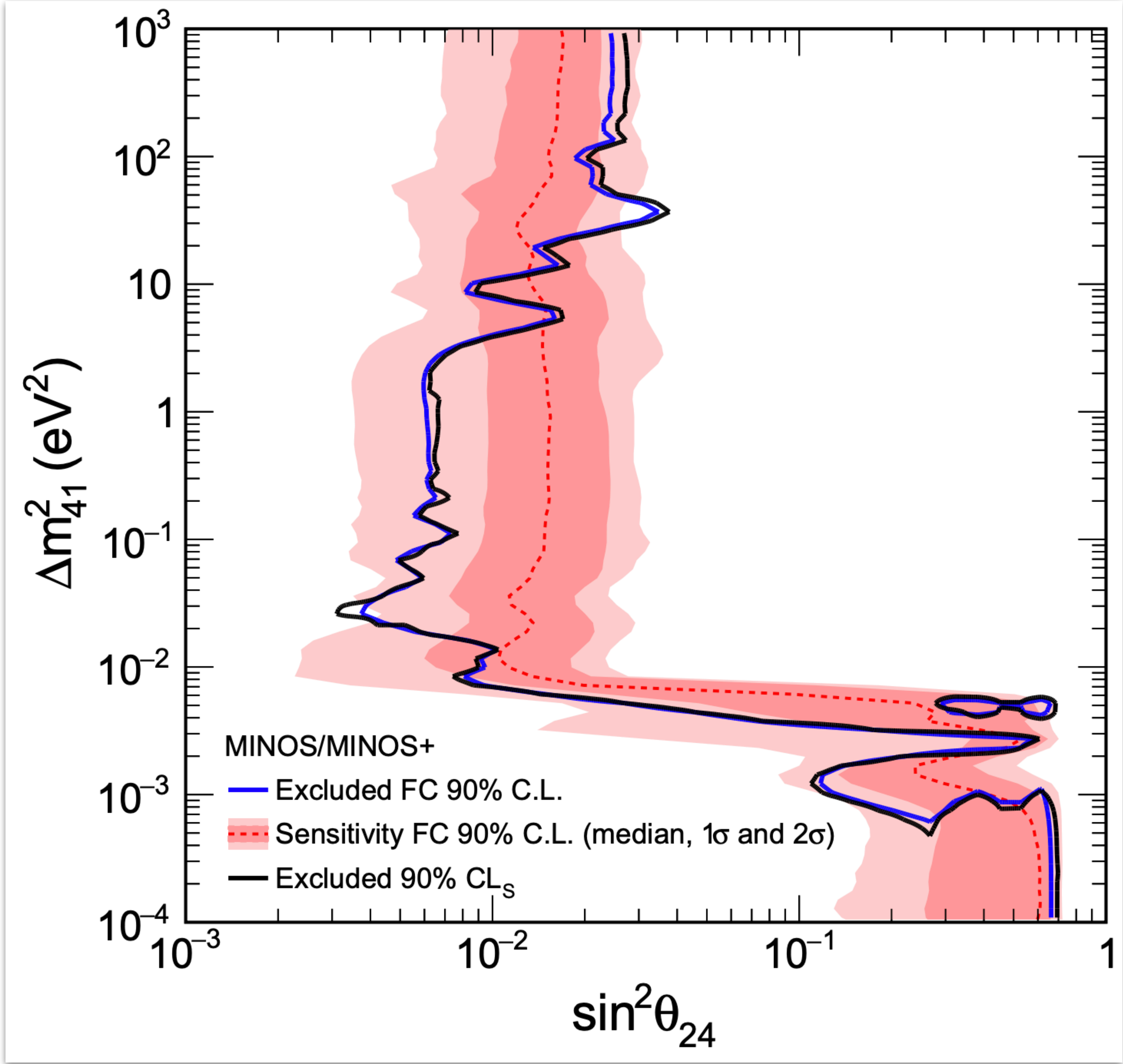
PROSPECT
STEREO
DANSS
Neutrino 4
NEOS

No significant* deviation from expectation!

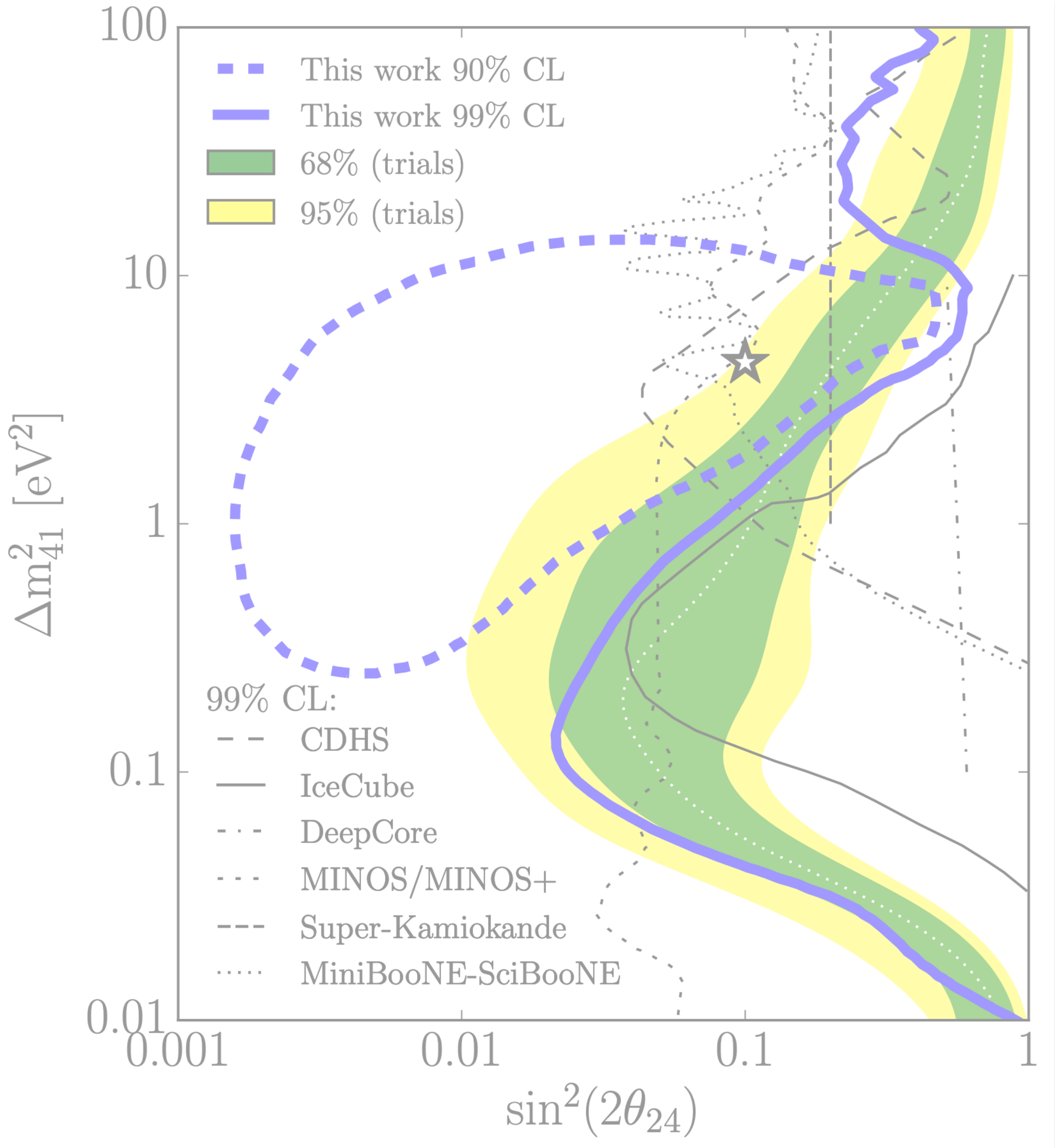
Muon-Neutrino Disappearance?

MINOS + IceCube

MINOS/MINOS+, [2002.00301]



IceCube Collaboration, [2005.12942]



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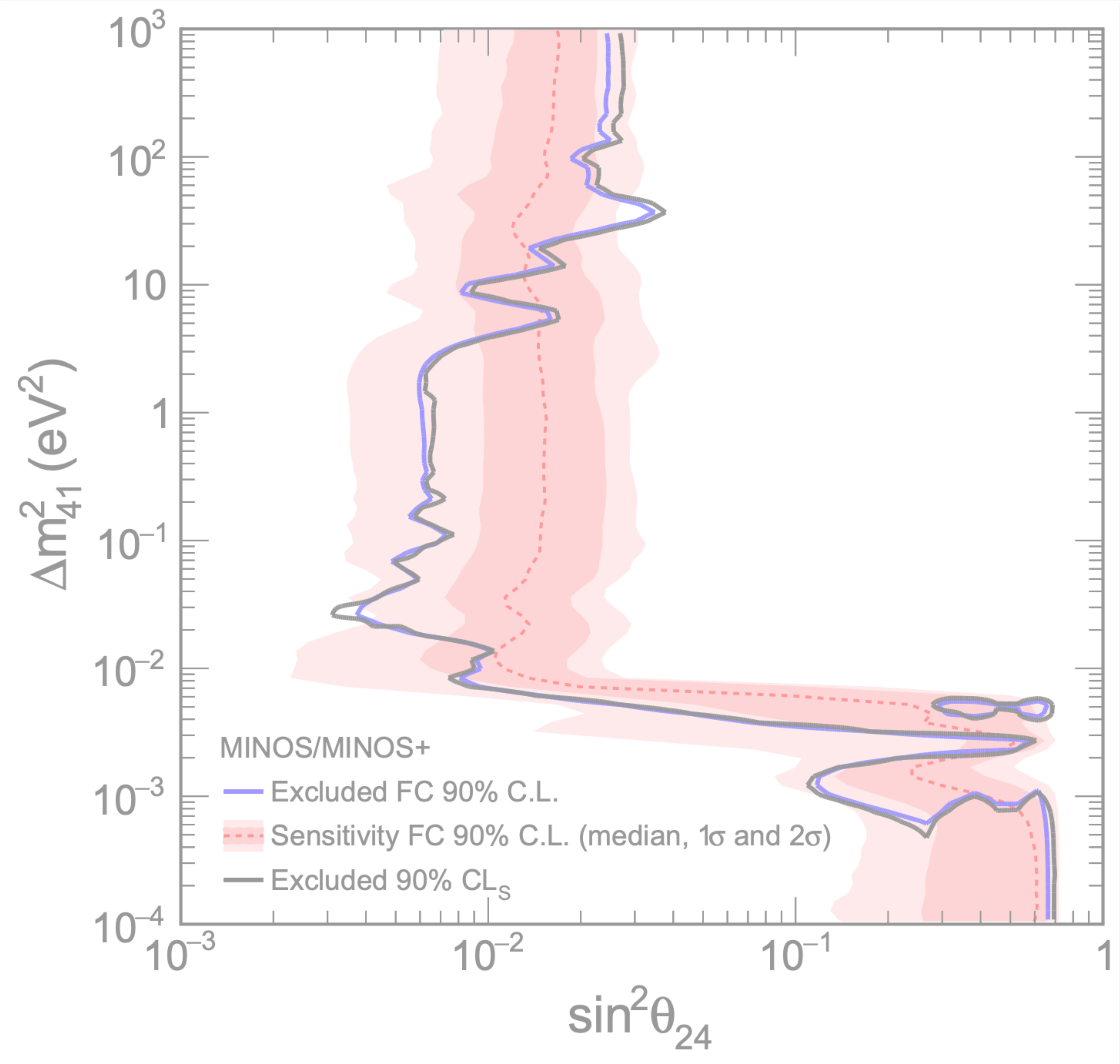

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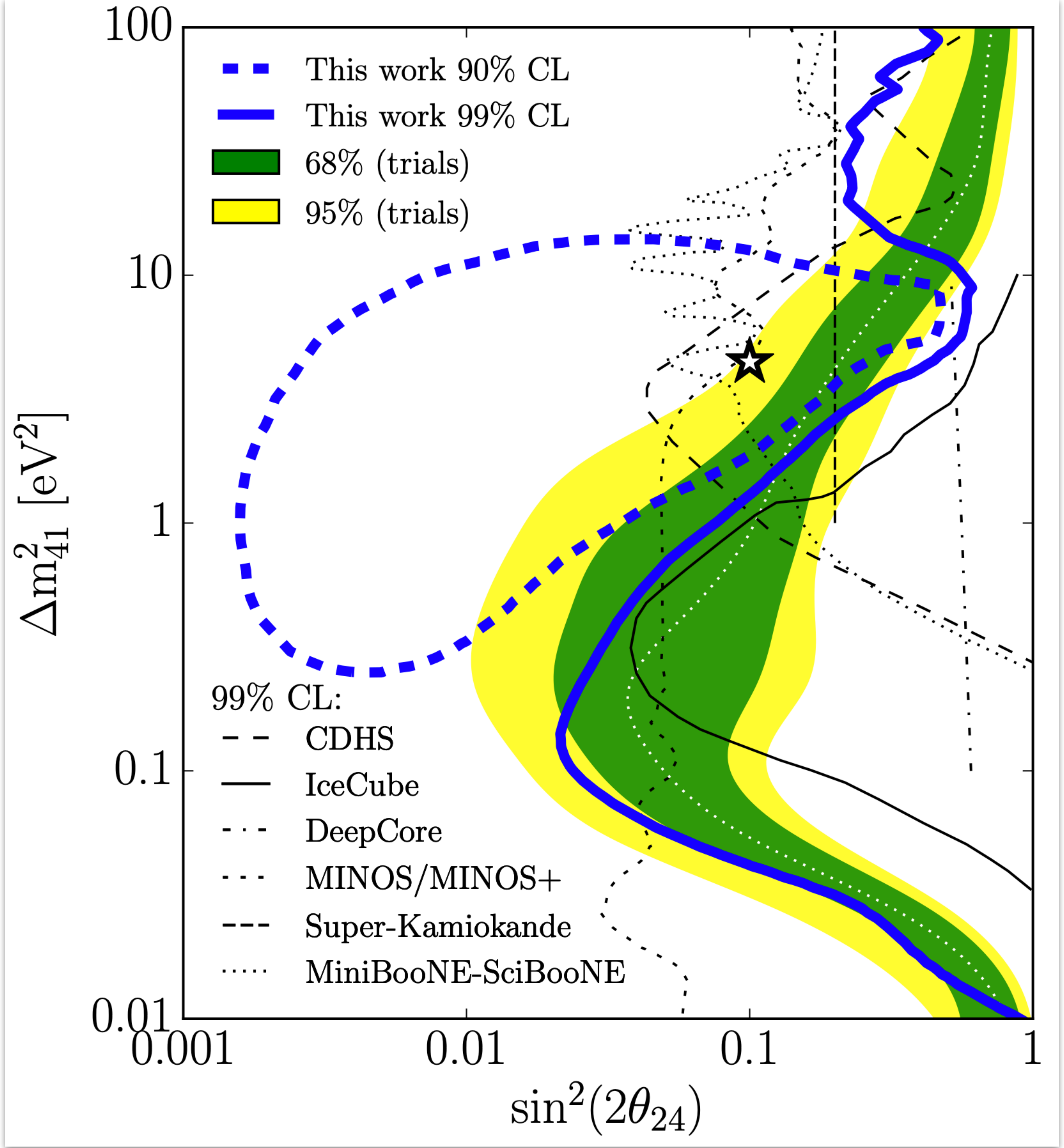
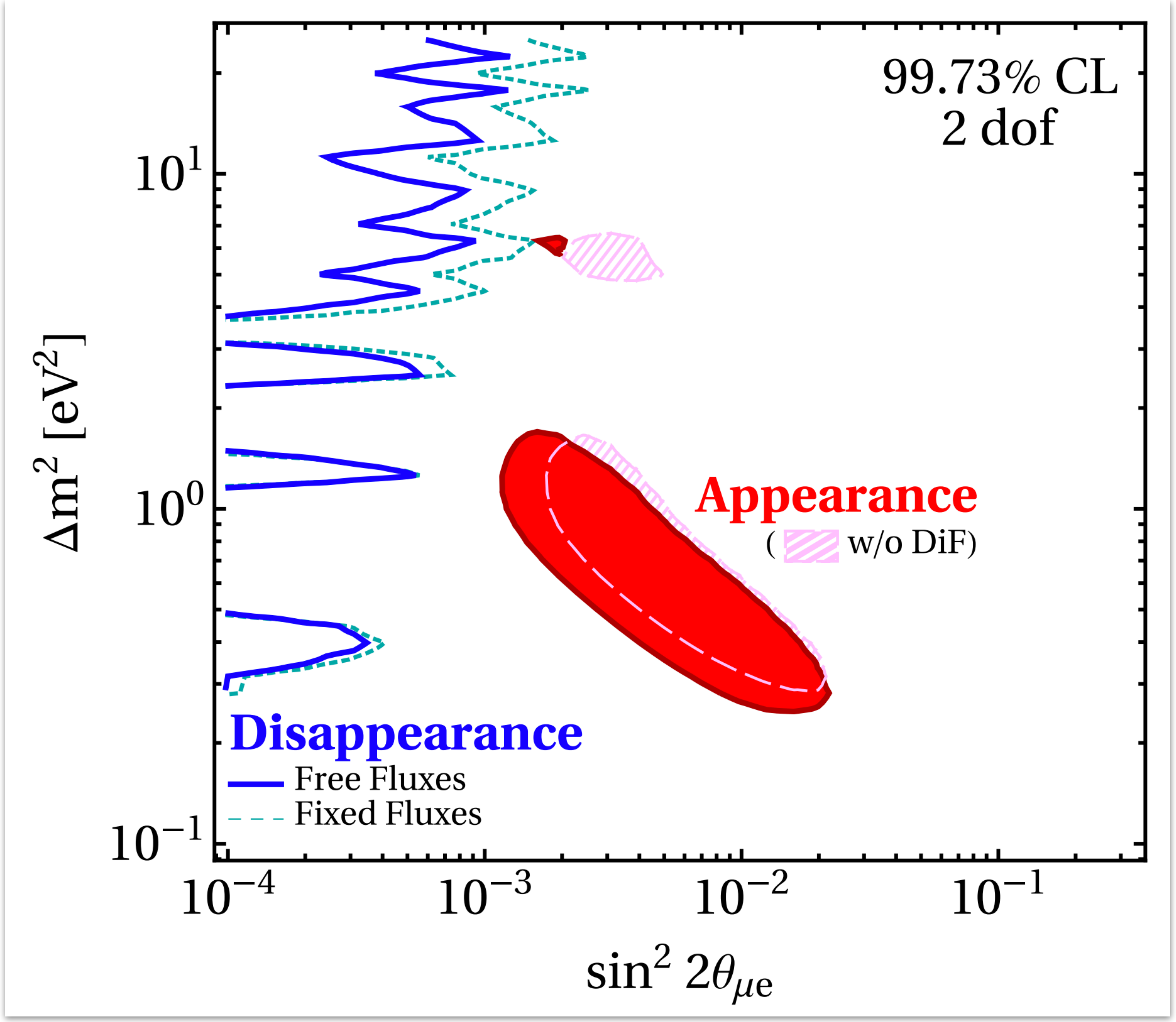
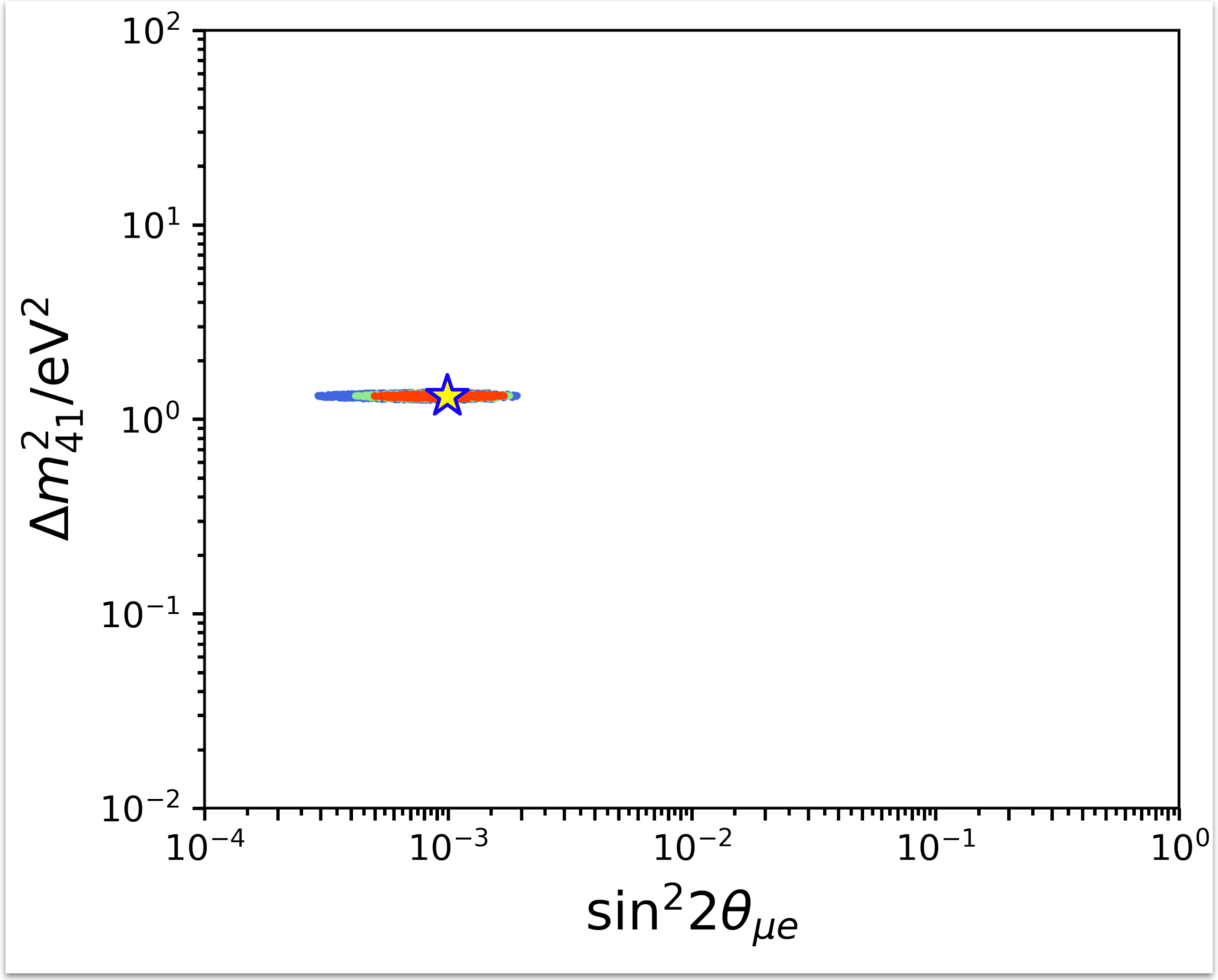


Sterile Neutrino Global Fits ca 2019



Dentler et al, [1803.10661]



Diaz et al, [1906.00045]

MiniBooNE Excess Characteristics

Excess with respect to Neutrino* Energy

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MiniBooNE Collab., [2006.16883]

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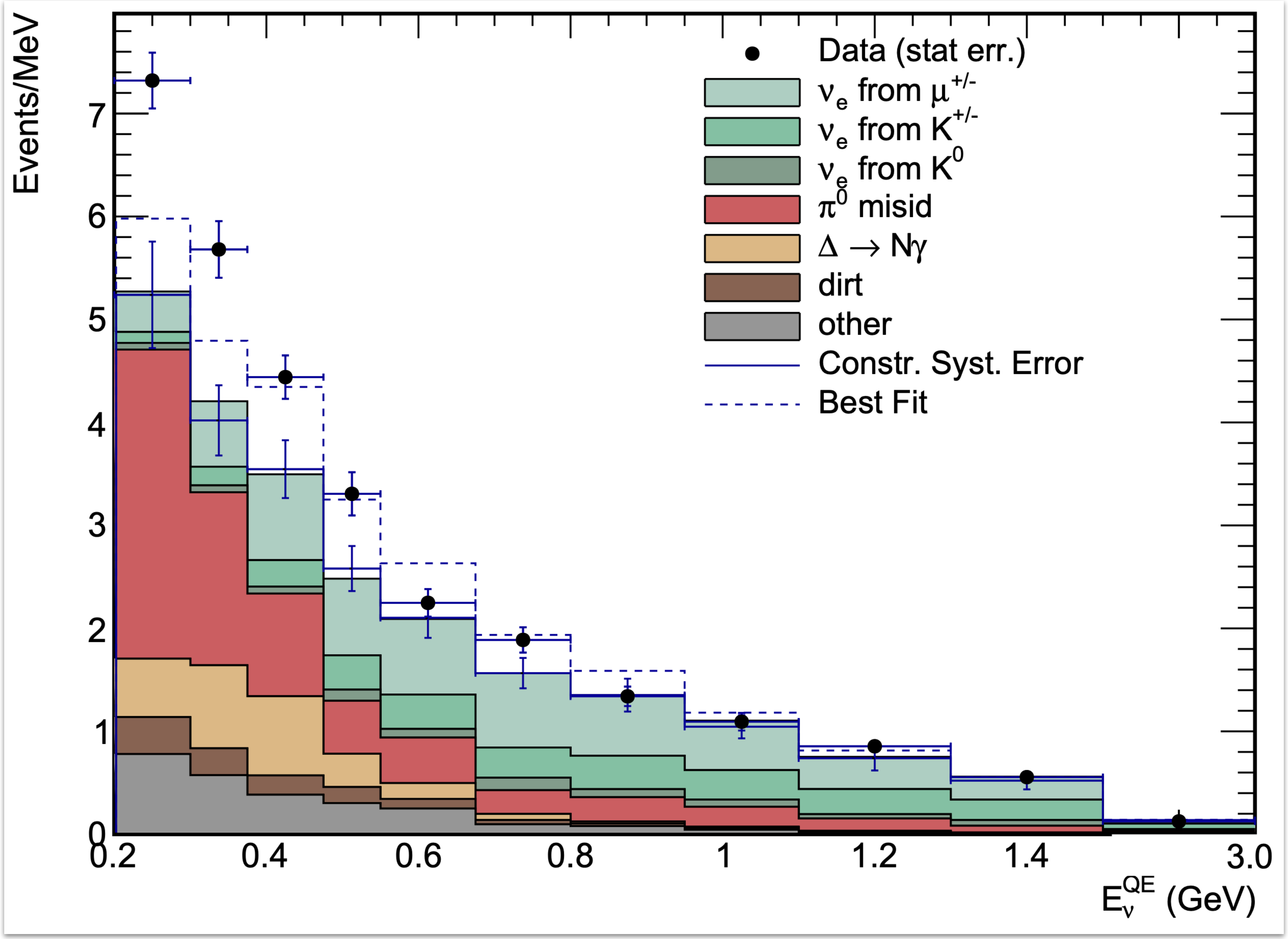
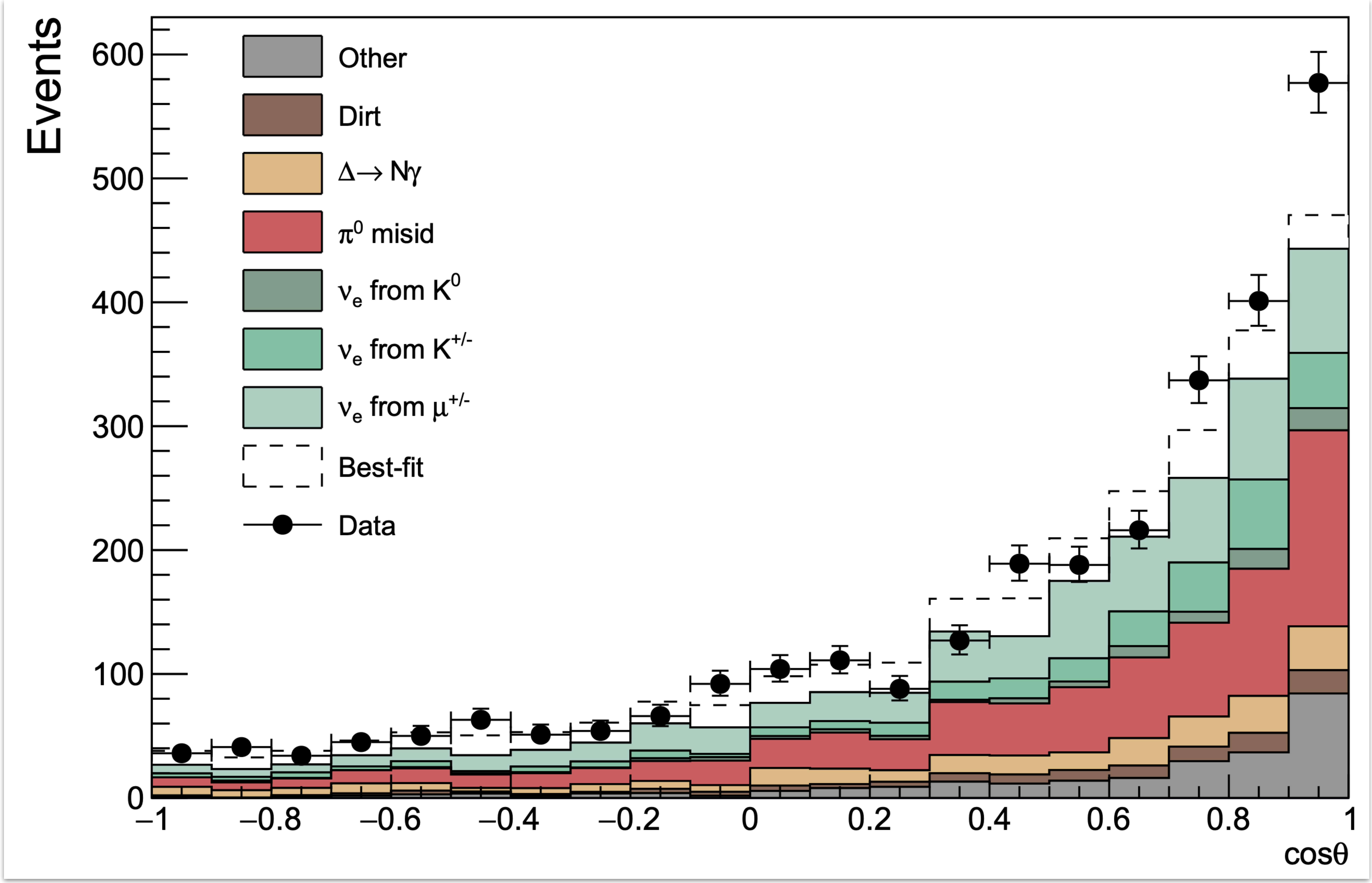


MiniBooNE Collab., [2006.16883]

Excess with respect to Outgoing Lepton Direction



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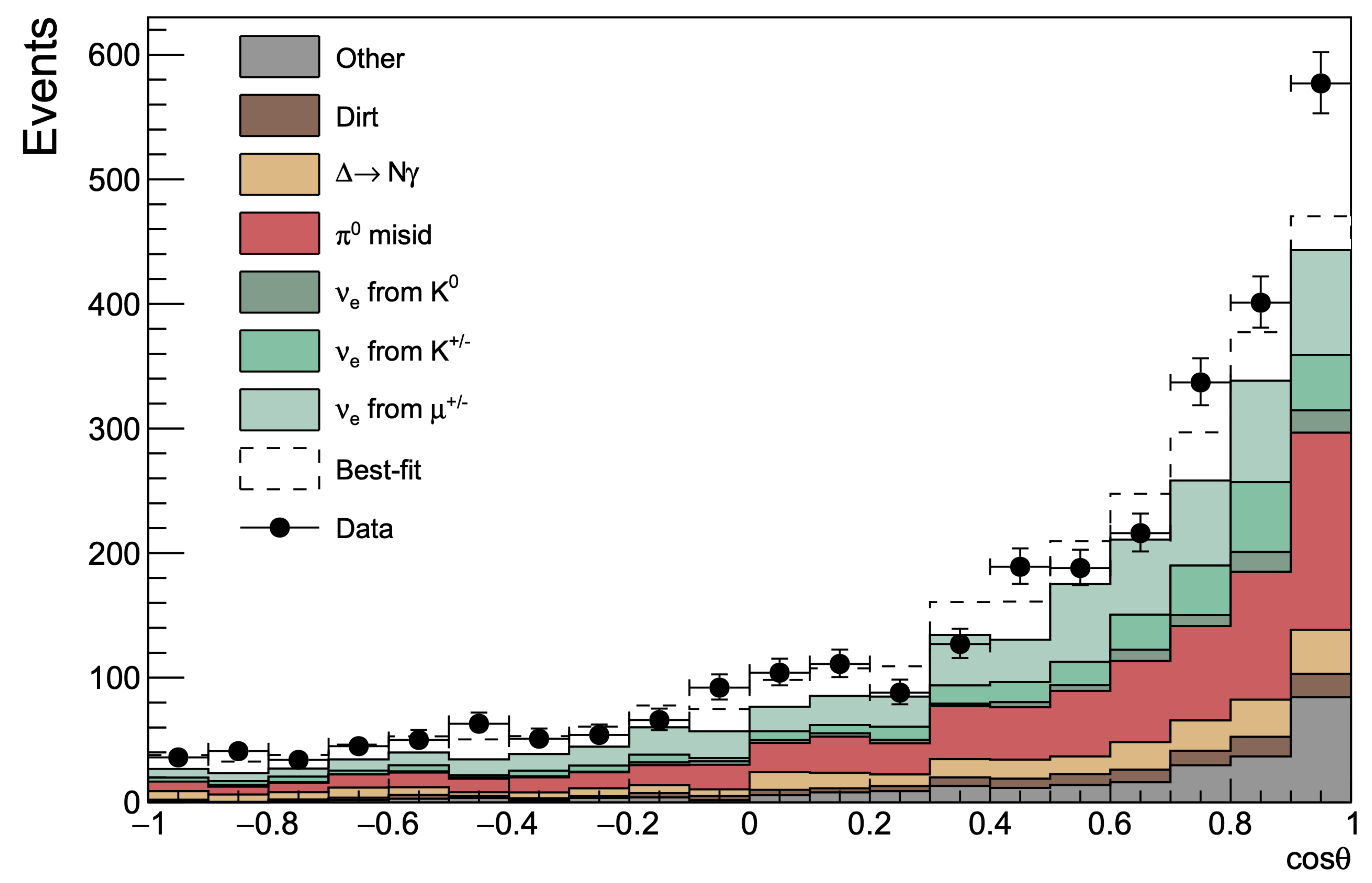
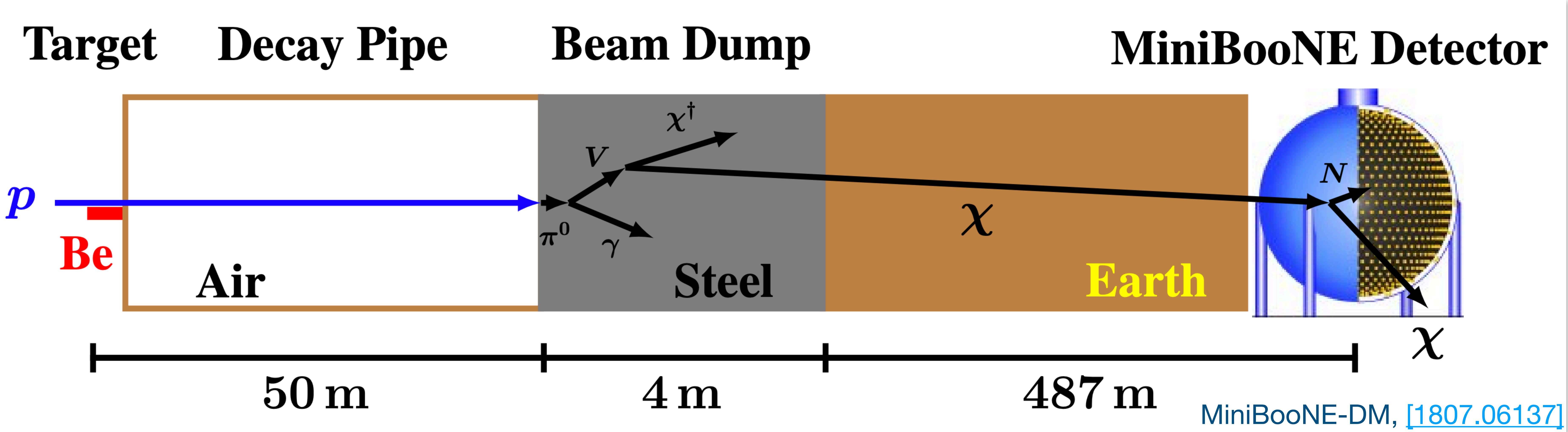


MiniBooNE Collab., [2006.16883]

MiniBooNE-DM Operation



MiniBooNE-DM, [1807.06137]

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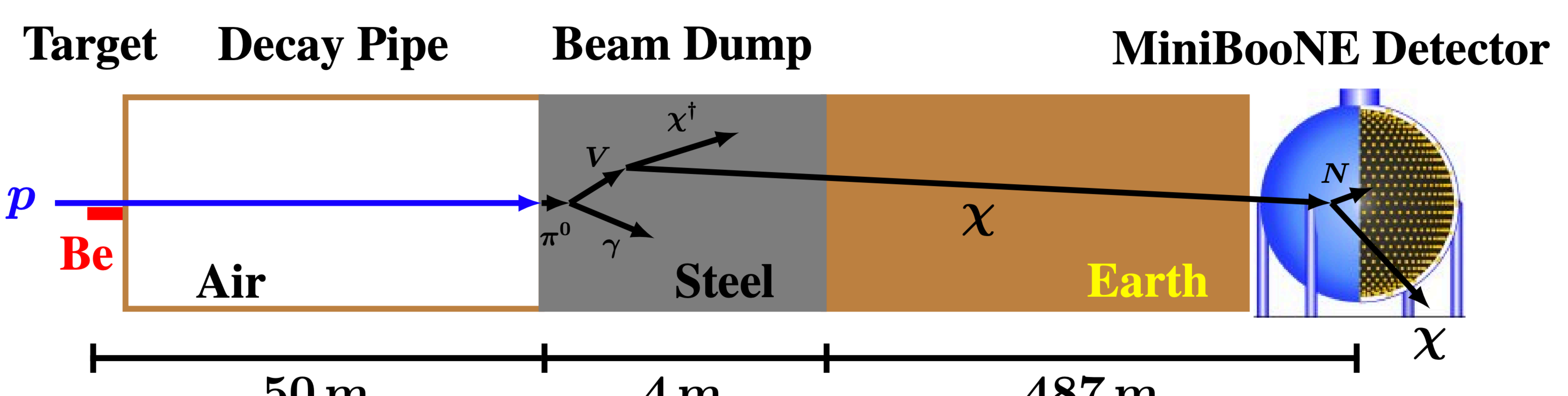

MiniBooNE-DM, [1807.06137]

No Excess Observed!

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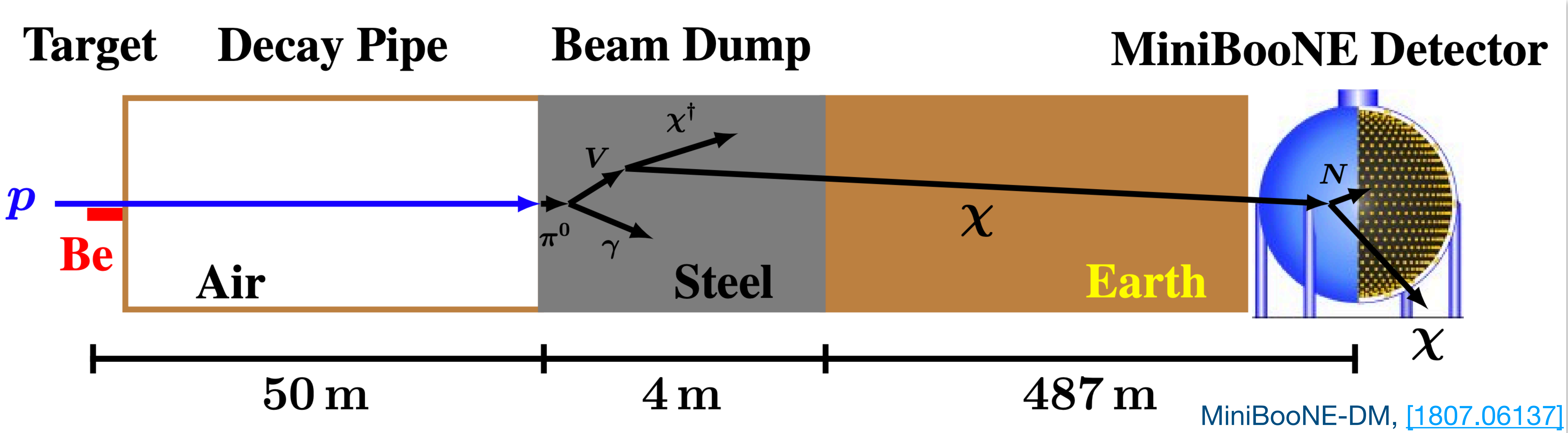
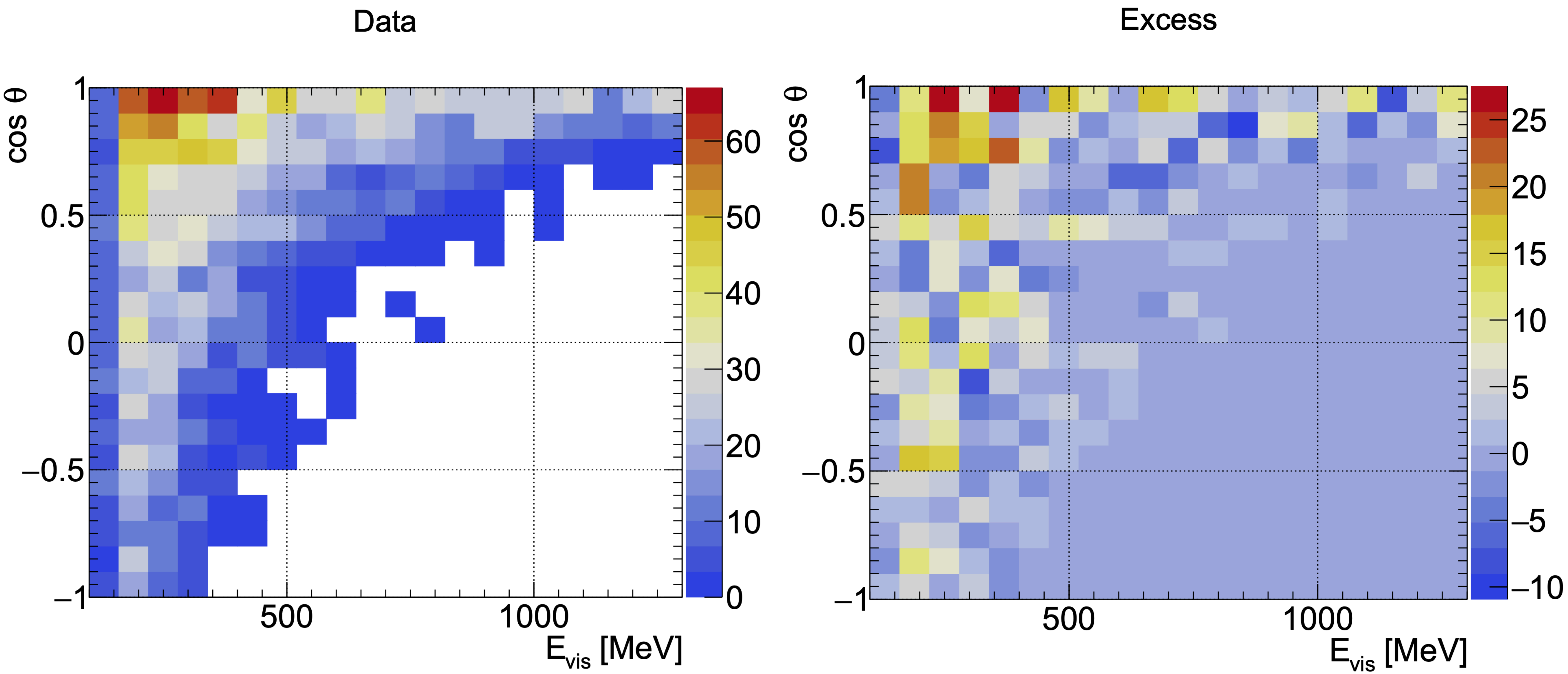


MiniBooNE-DM, [1807.06137]

No Excess Observed!

Combined with angular/energy distributions, allows for one to exclude a significant subset of new-physics explanations for the LEE. This includes explanations that arise from neutral meson decays, continuum processes, etc. See Jordan et al, [1810.07185] for more.

Two-Dimensional Distributions



Does this excess follow the expectation from your favorite new-physics explanation?

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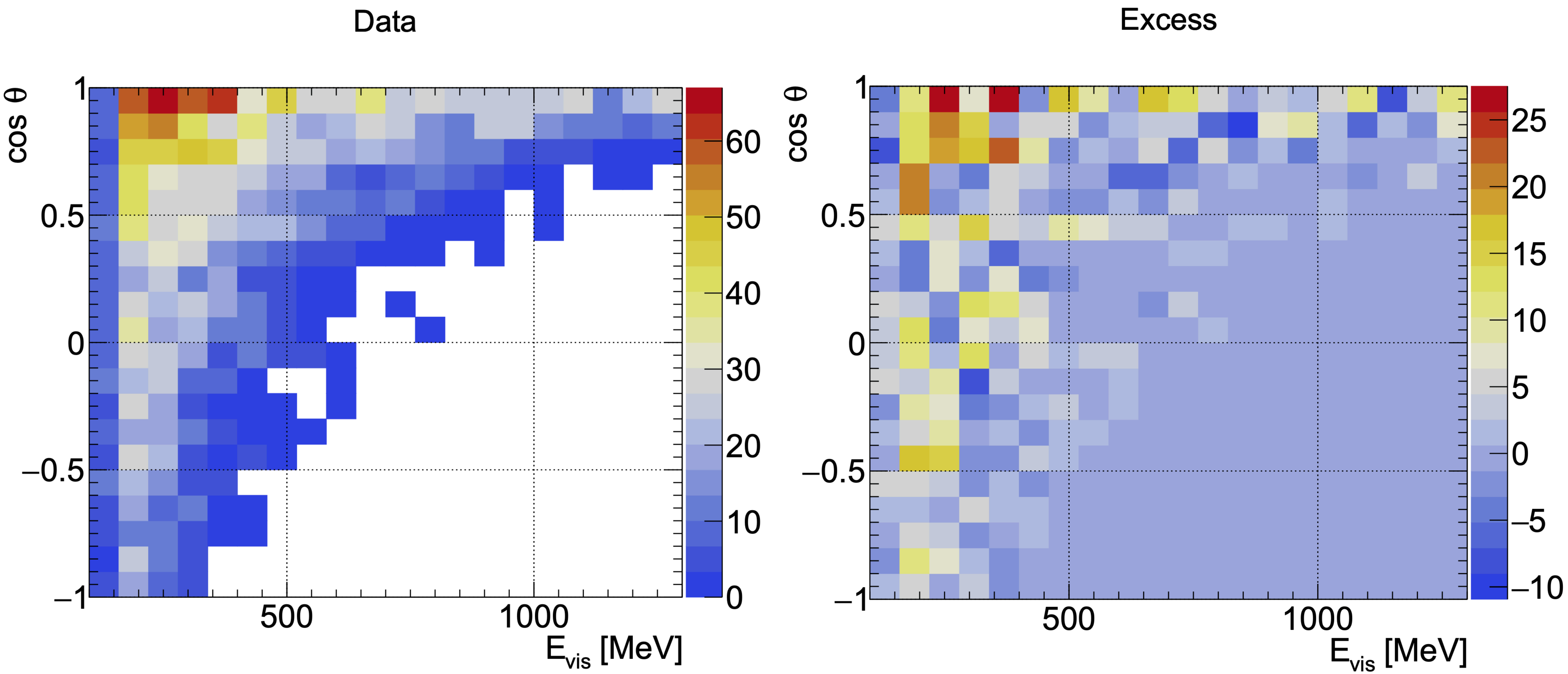

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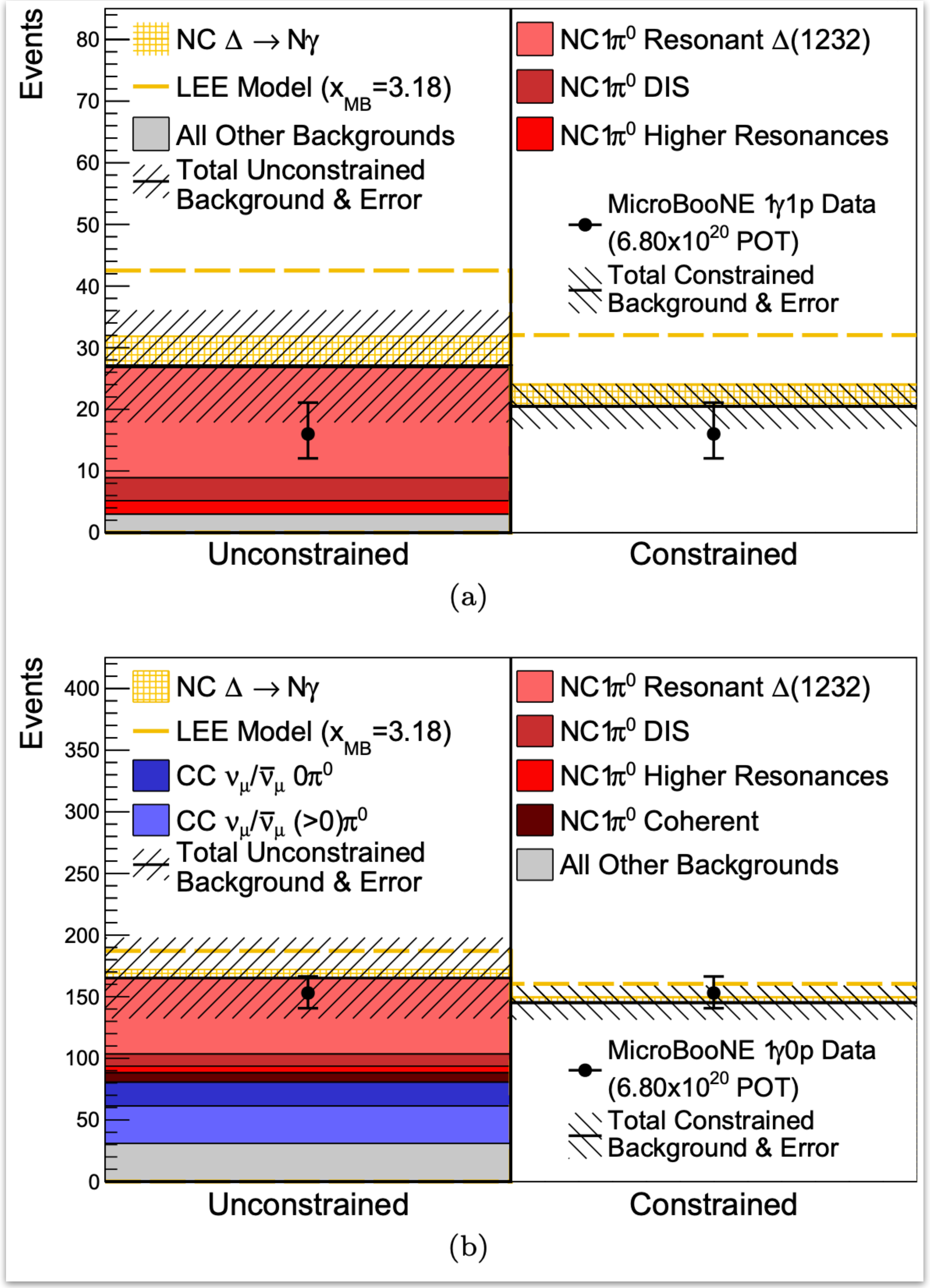
Recent Experimental Results

—MicroBooNE

MicroBooNE Photon Analysis

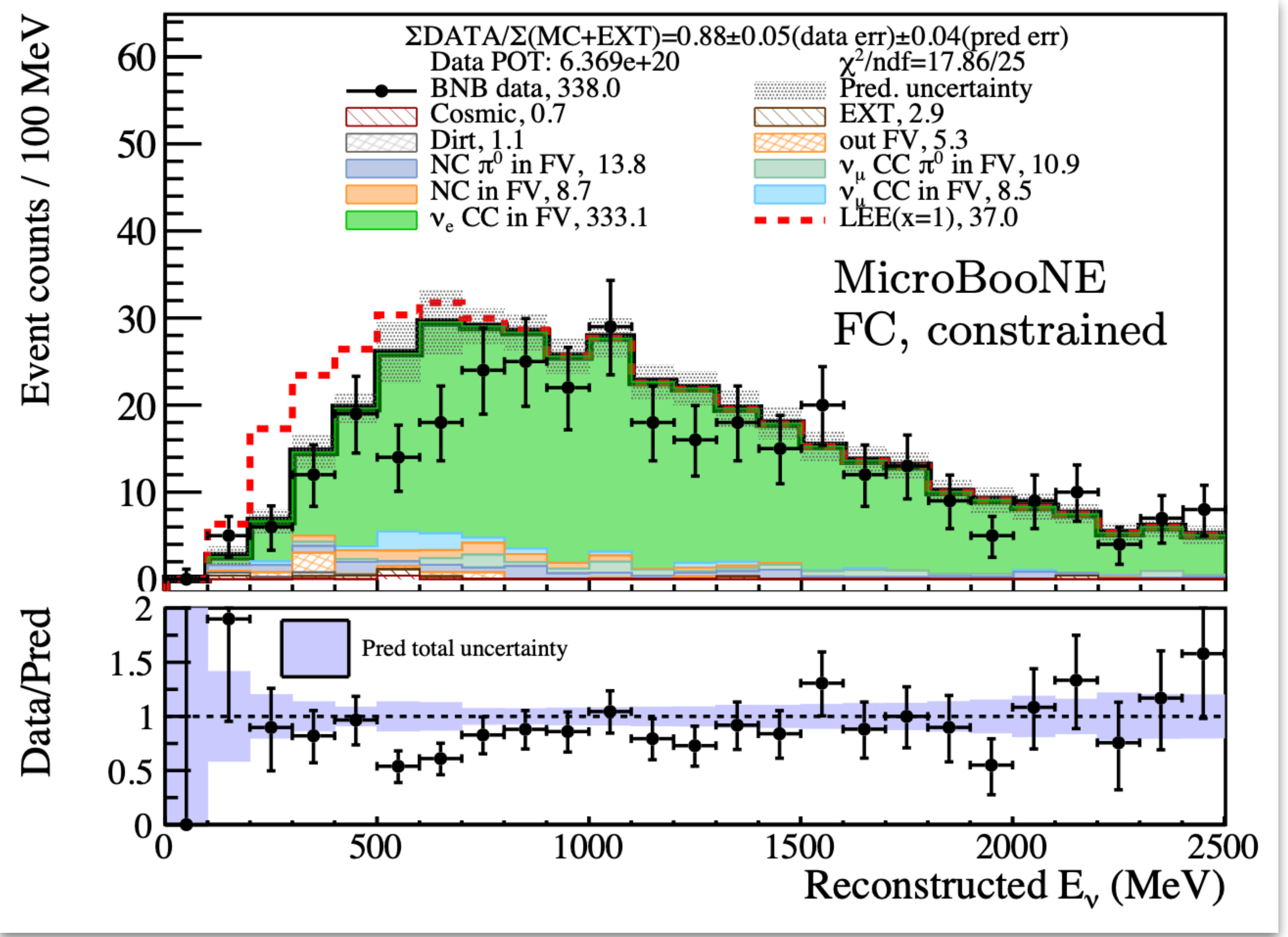


MicroBooNE Collaboration, [2110.00409]

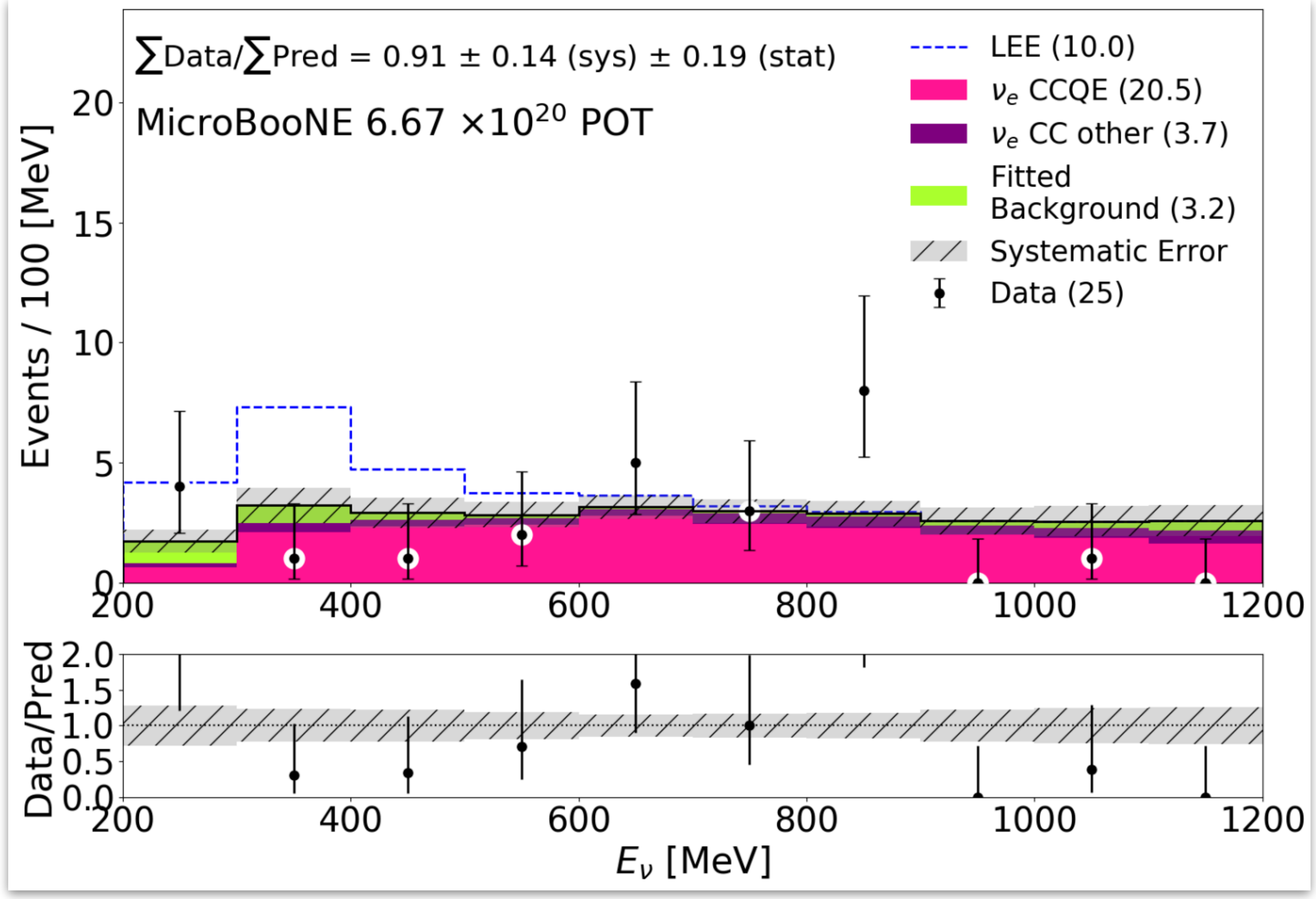
MicroBooNE disfavors the $\Delta \to N\gamma$ explanation of the MiniBooNE anomaly at 94.8% CL.

MicroBooNE Electron Analyses

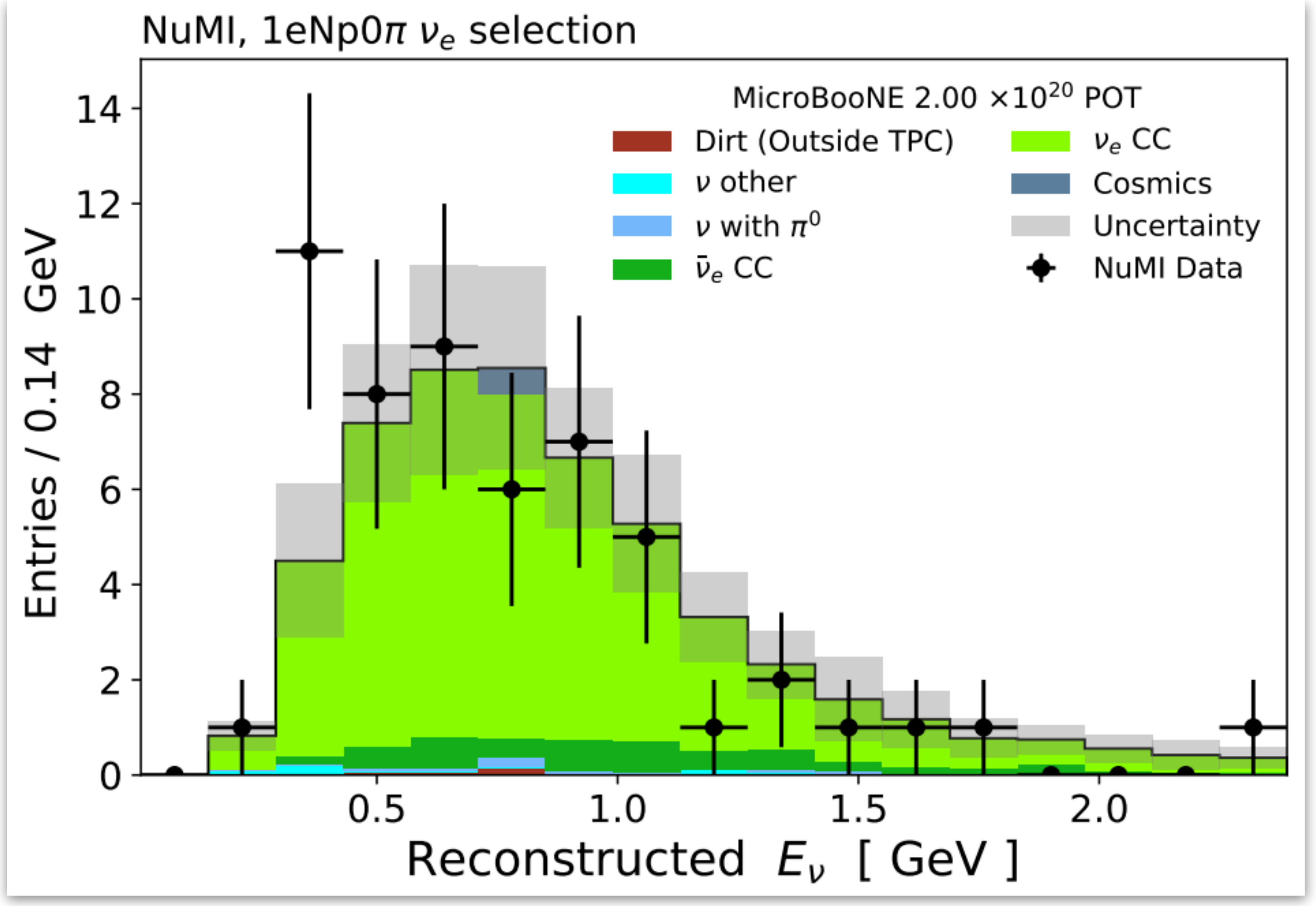
“Inclusive” [2110.13978]

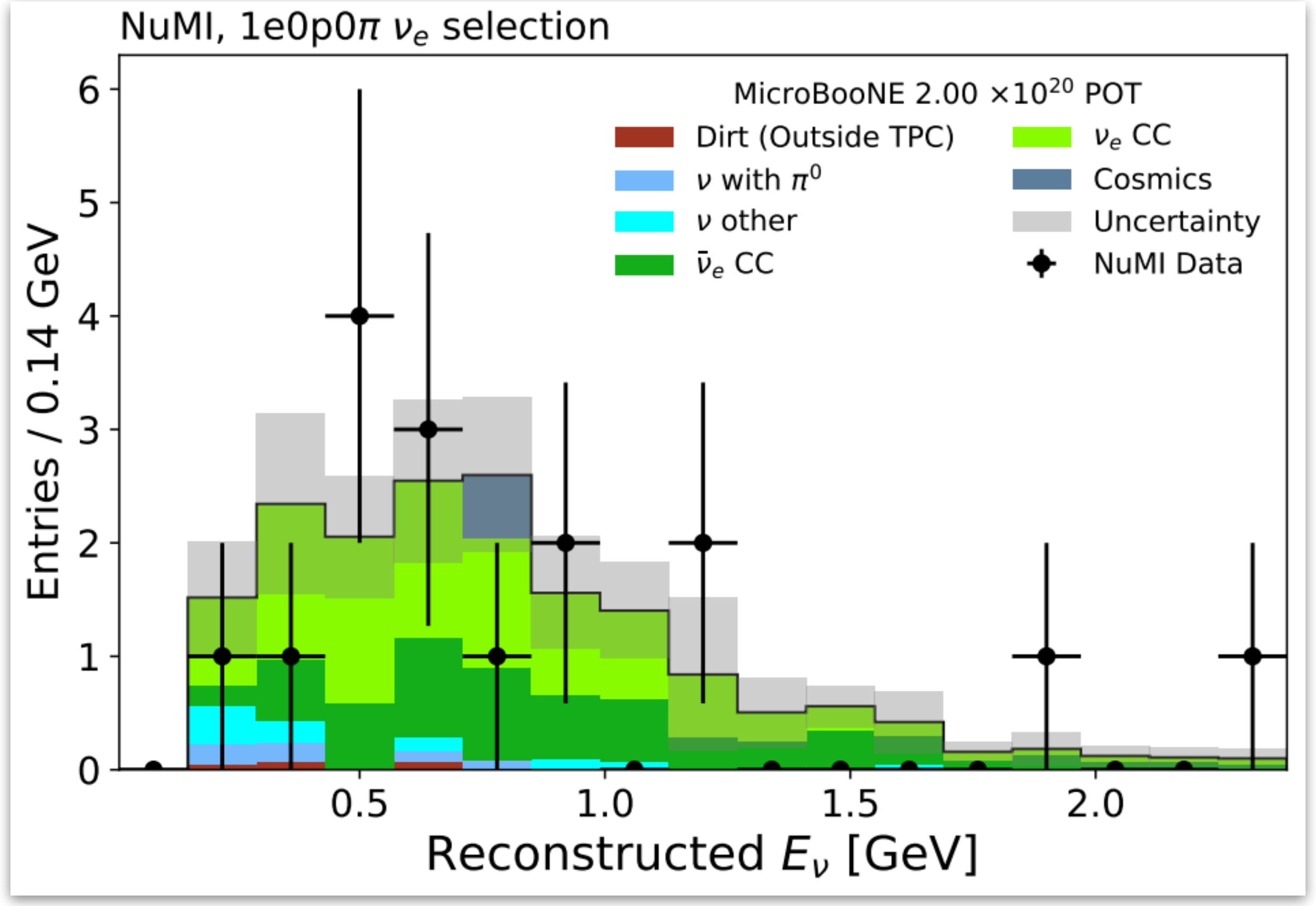


“CCQE” [2110.14080]



“Pionless” [2110.14065]





MicroBooNE Electron Analyses

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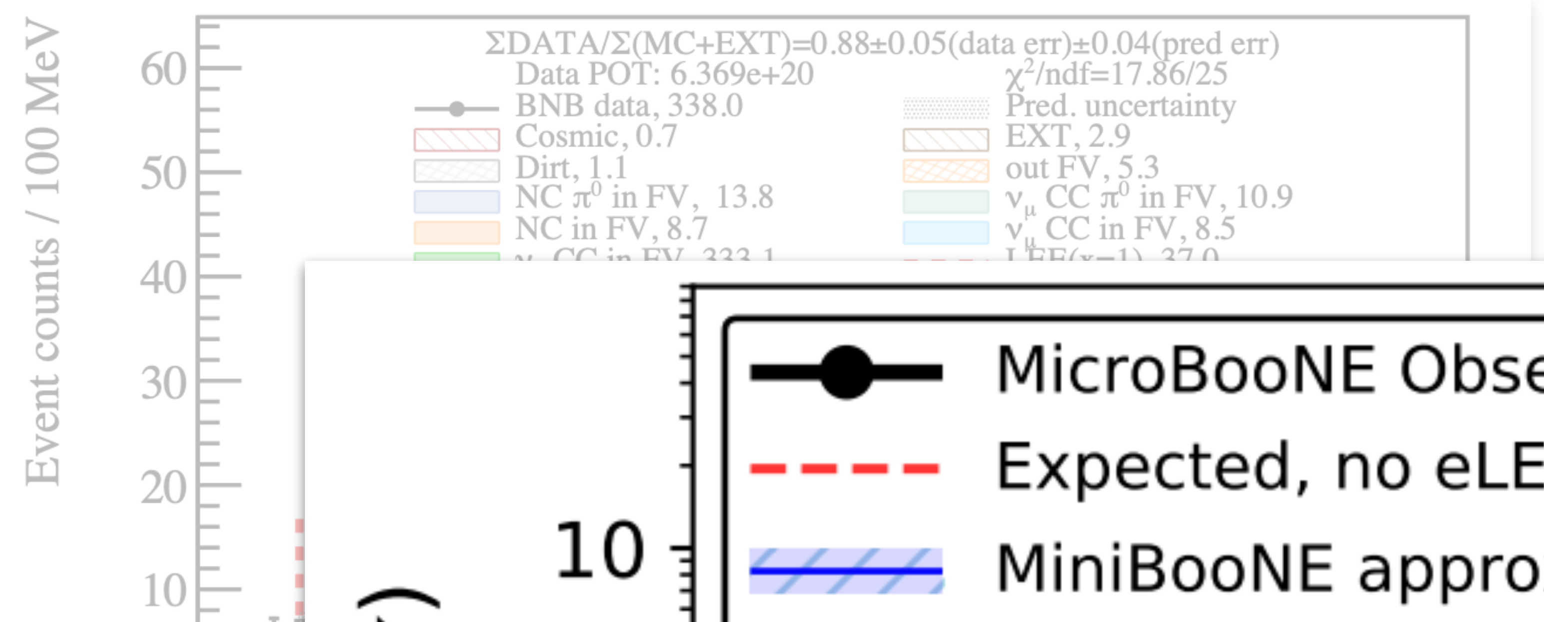

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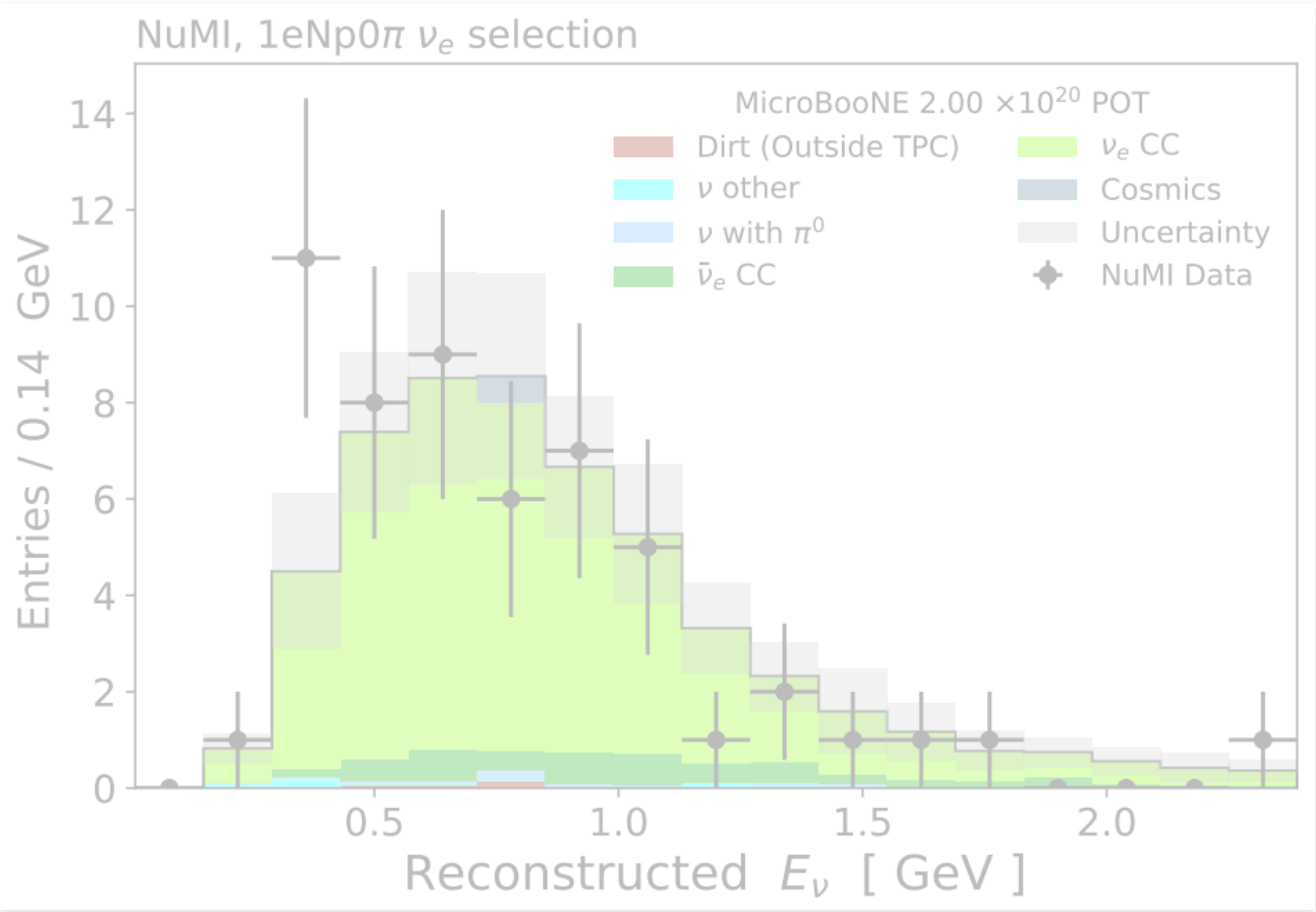
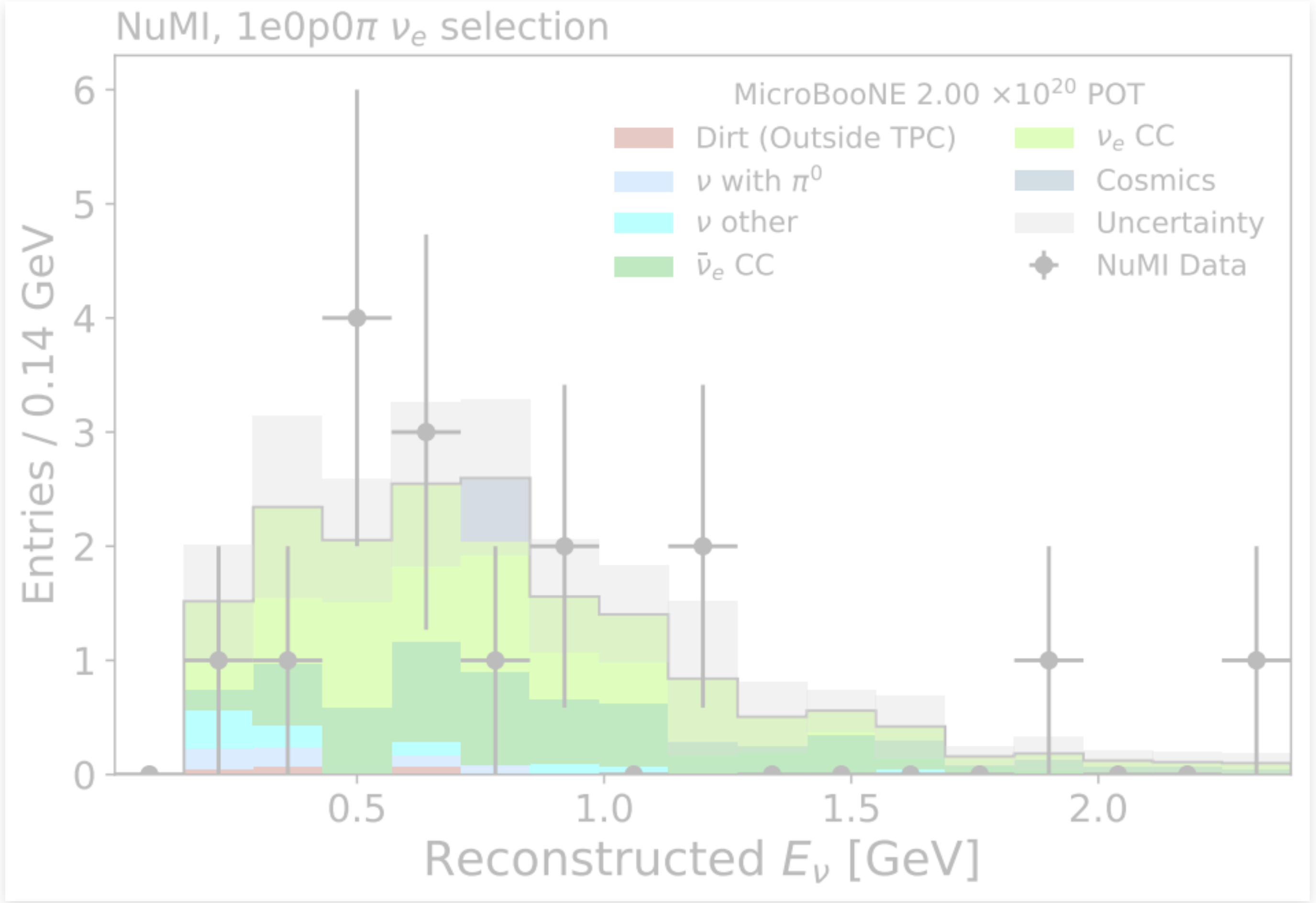
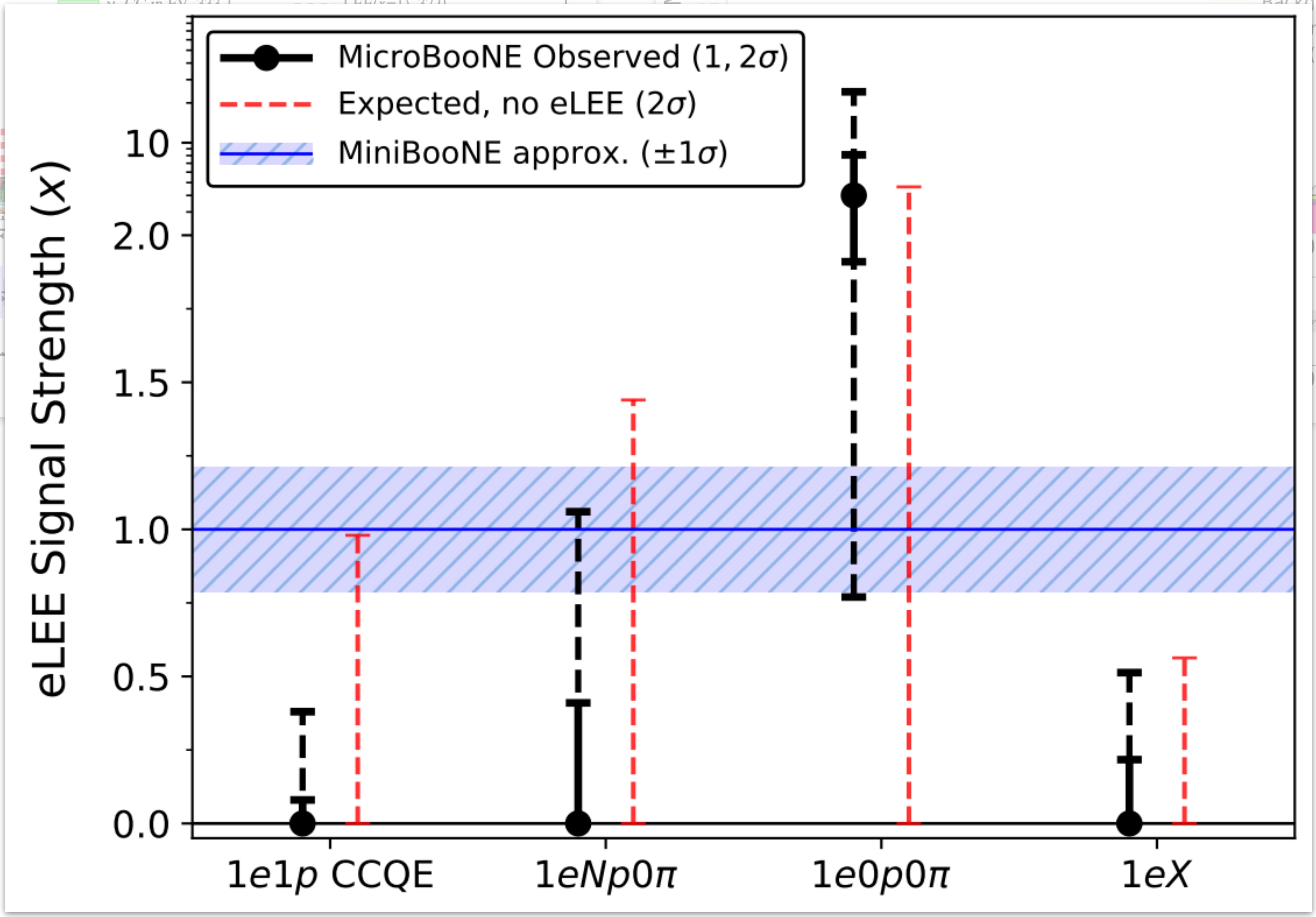


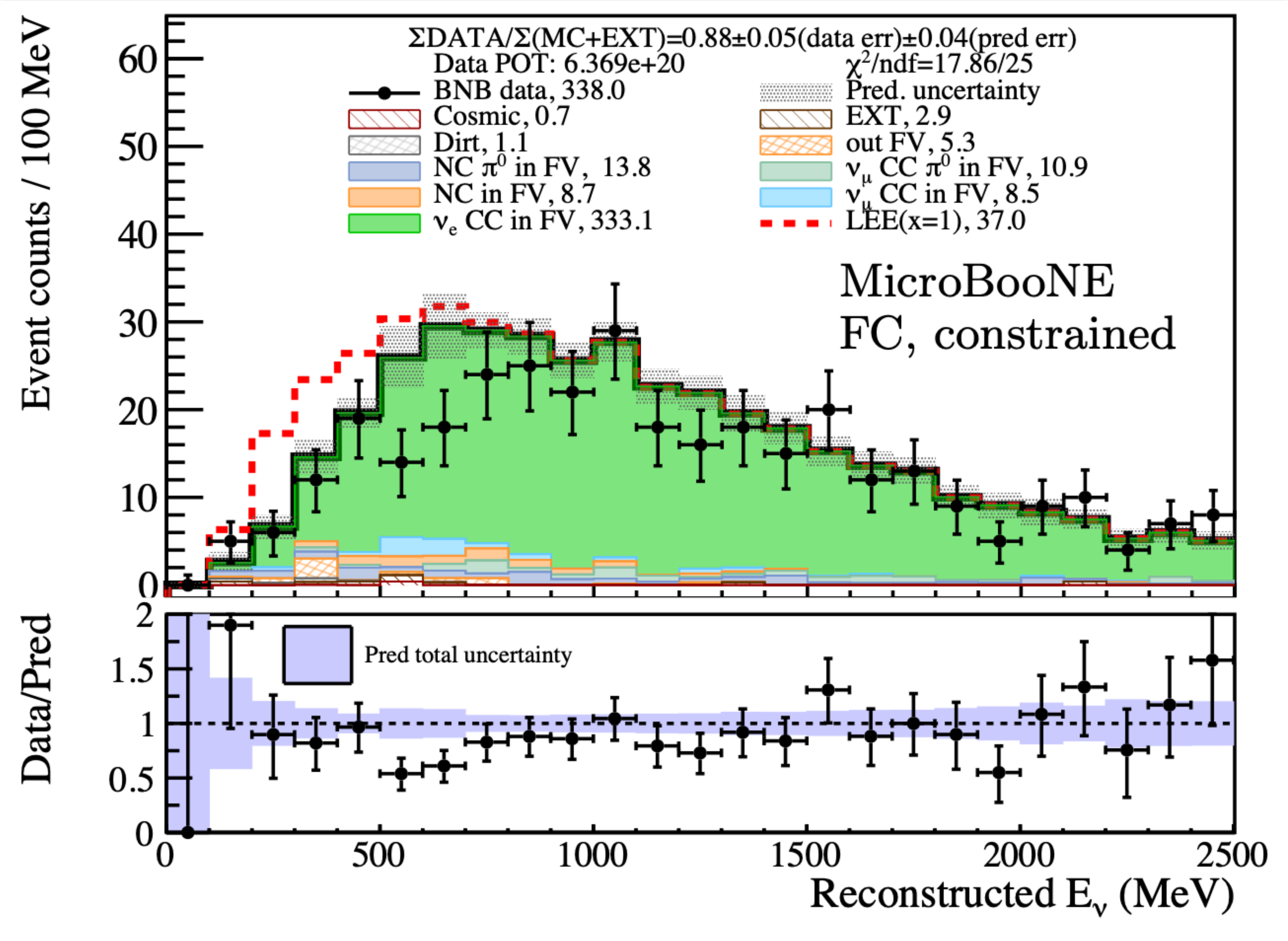




Discussion of all Results [2110.14054]

Complementarity of Inclusive/CCQE

"Inclusive" [2110.13978]



- Large electron-neutrino and muon-neutrino (not shown) samples.
- Large (expected) excess from muon-neutrino to electron-neutrino oscillation

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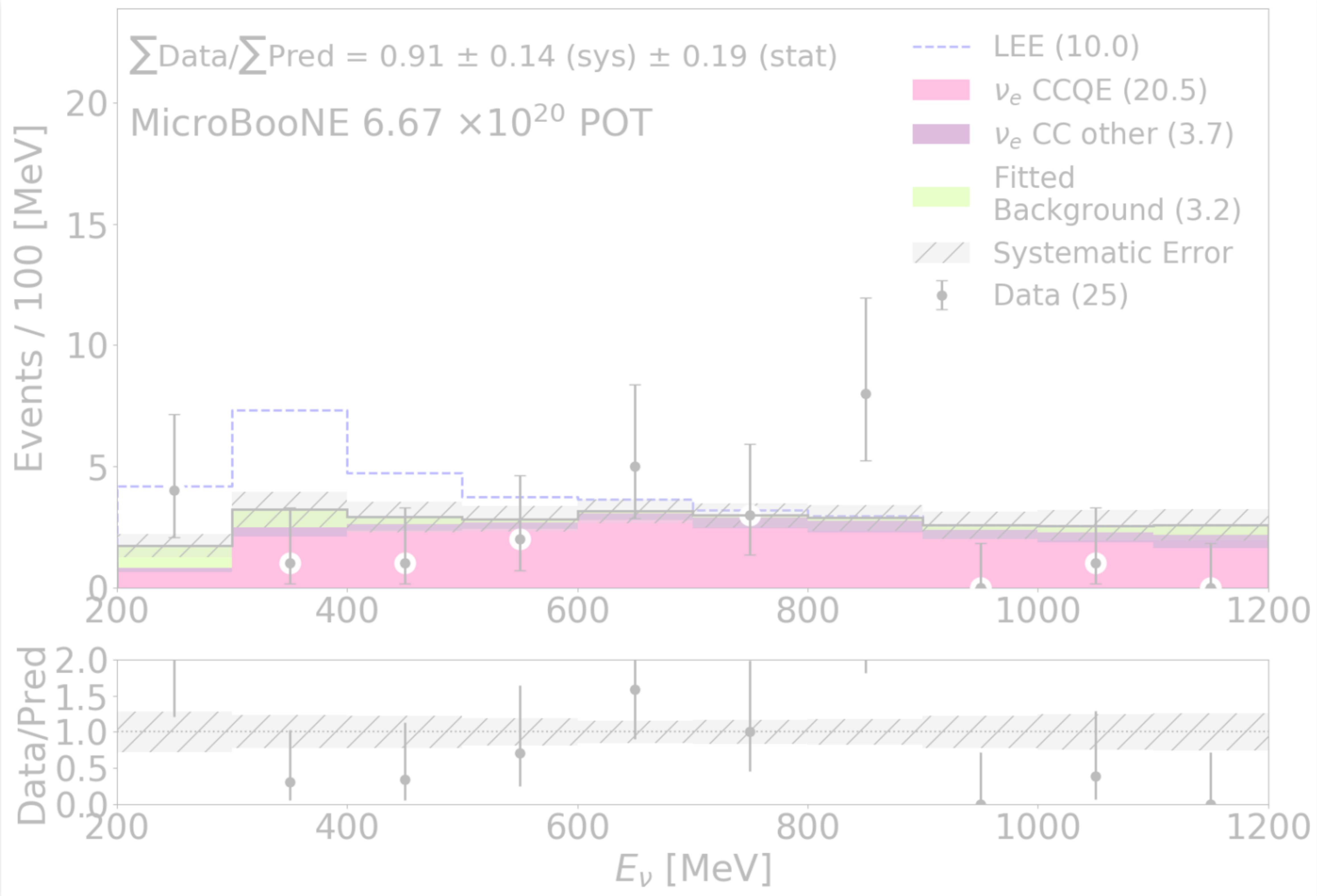

- Very pure sample, low background expectations.
- Expected excess from muon-neutrino to electron-neutrino oscillation is (relatively) large

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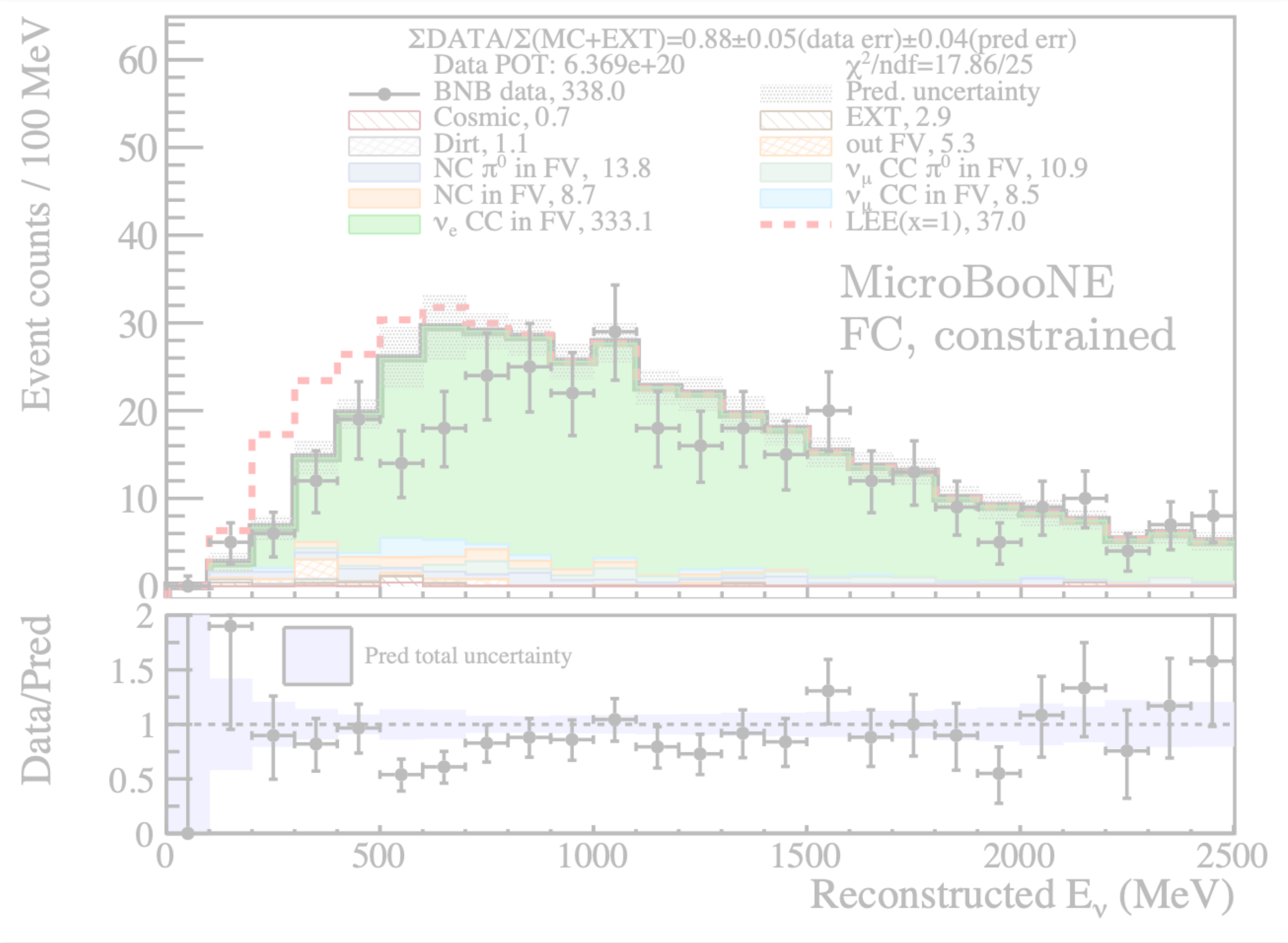

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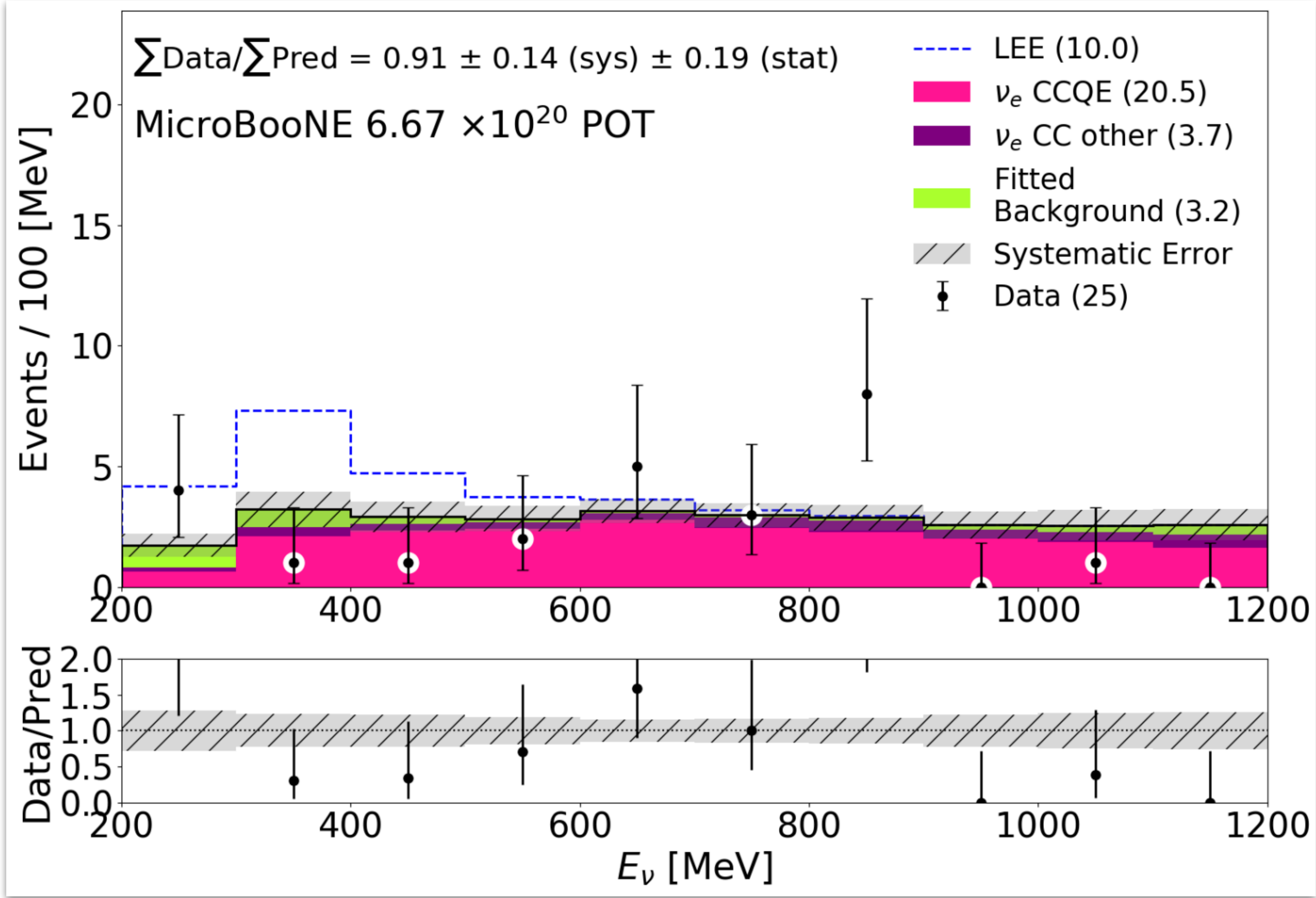

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MicroBooNE and Sterile Neutrinos

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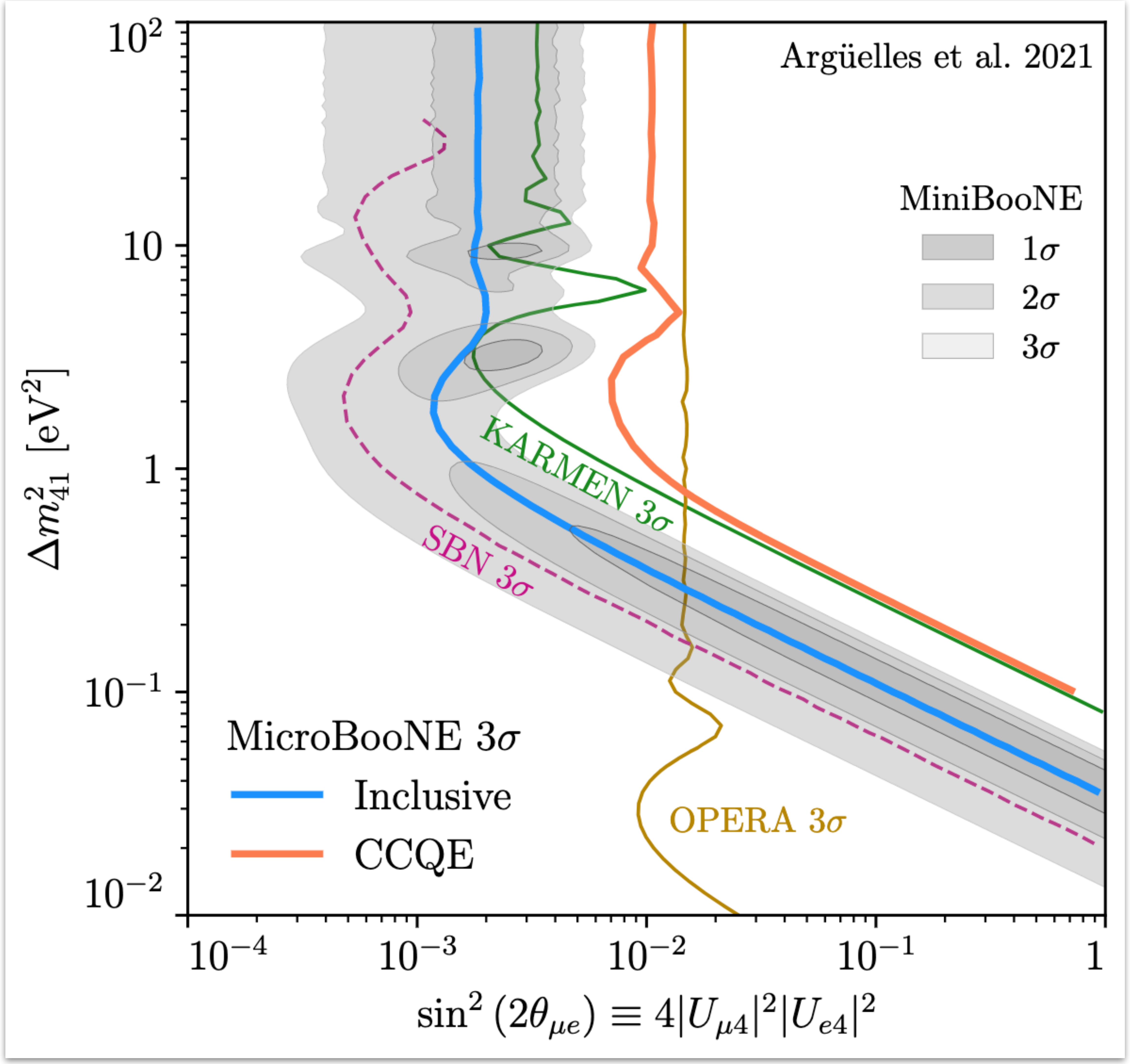

Argüelles, KJK, et al, [2111.10359]

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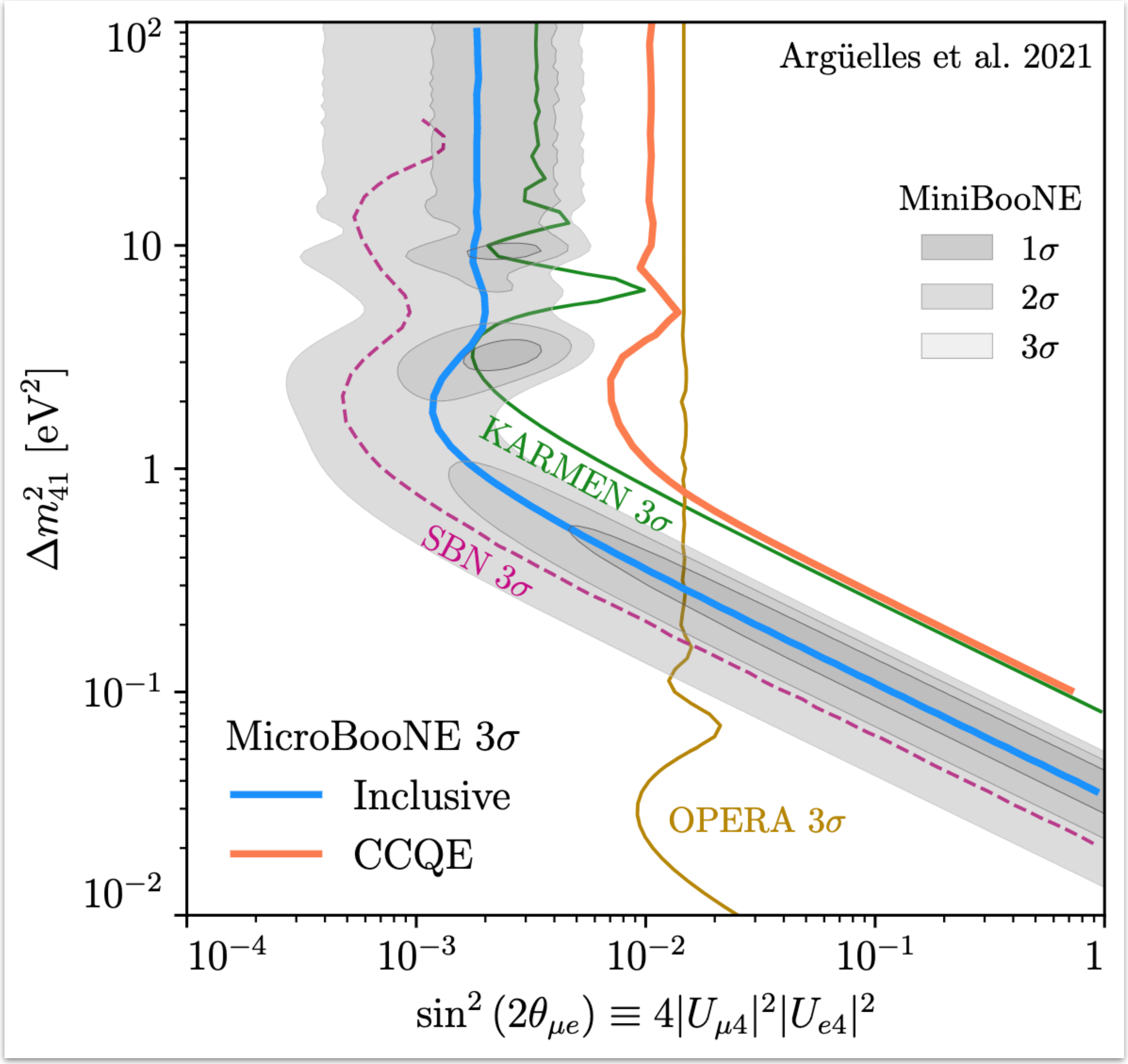

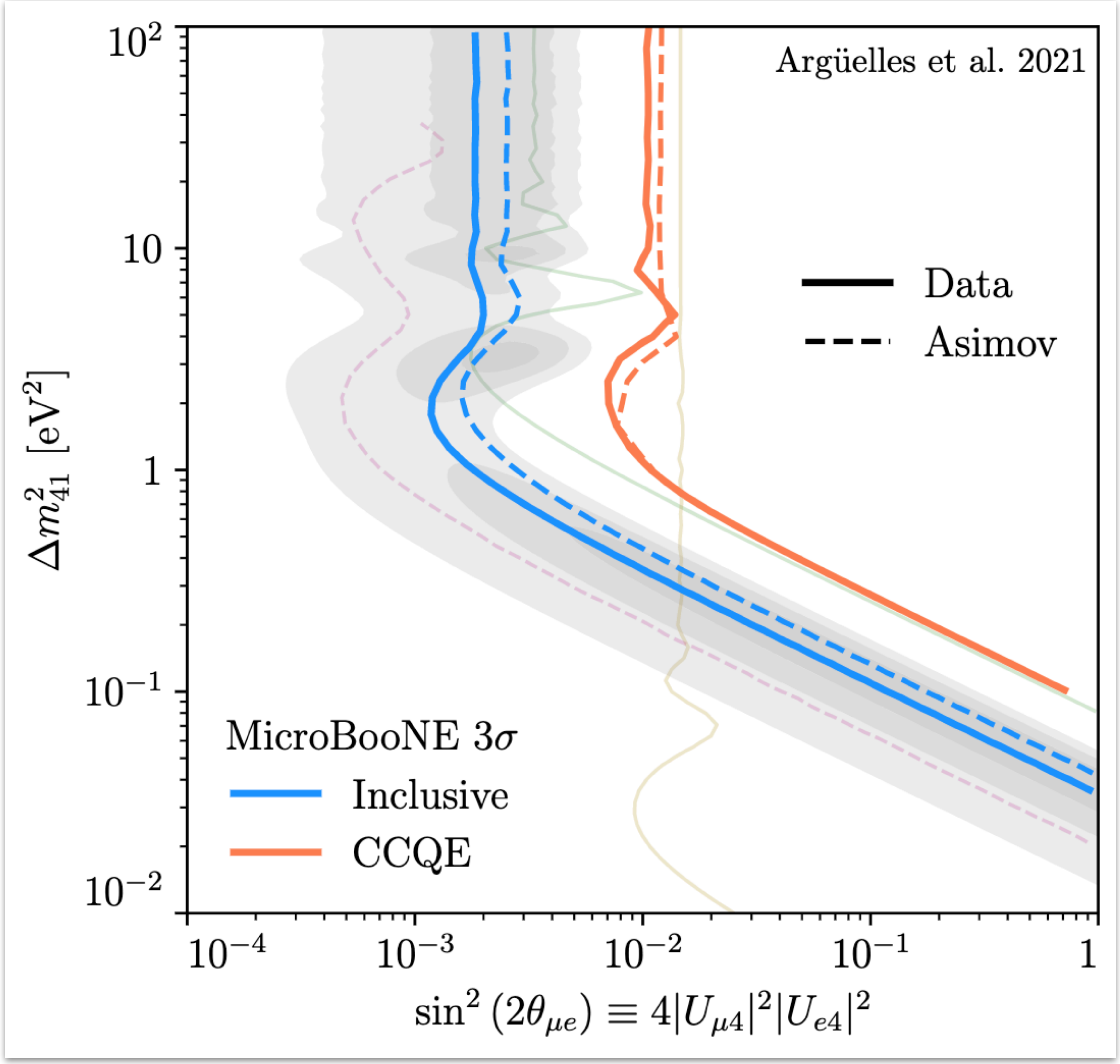

Argüelles, KJK, et al, [2111.10359]

Complete 3+1 Neutrino Framework

$$P\left(\nu_{\mu} \rightarrow \nu_{e}\right) = \sin^{2}\left(2\theta_{\mu e}\right)\sin^{2}\left(\frac{\Delta m_{41}^{2} L}{4E_{\nu}}\right)$$

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

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Anomalous appearance *requires* disappearance!

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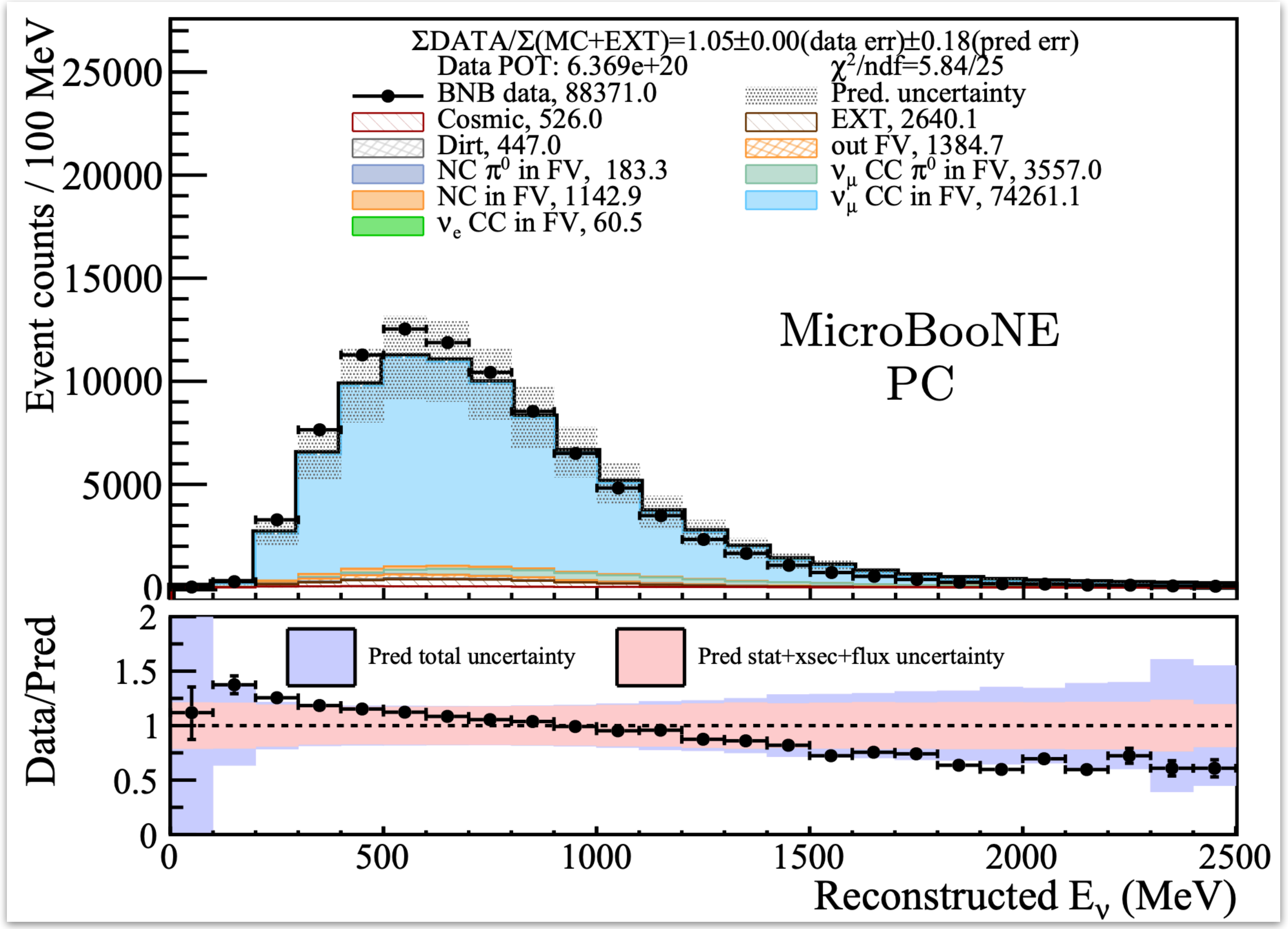
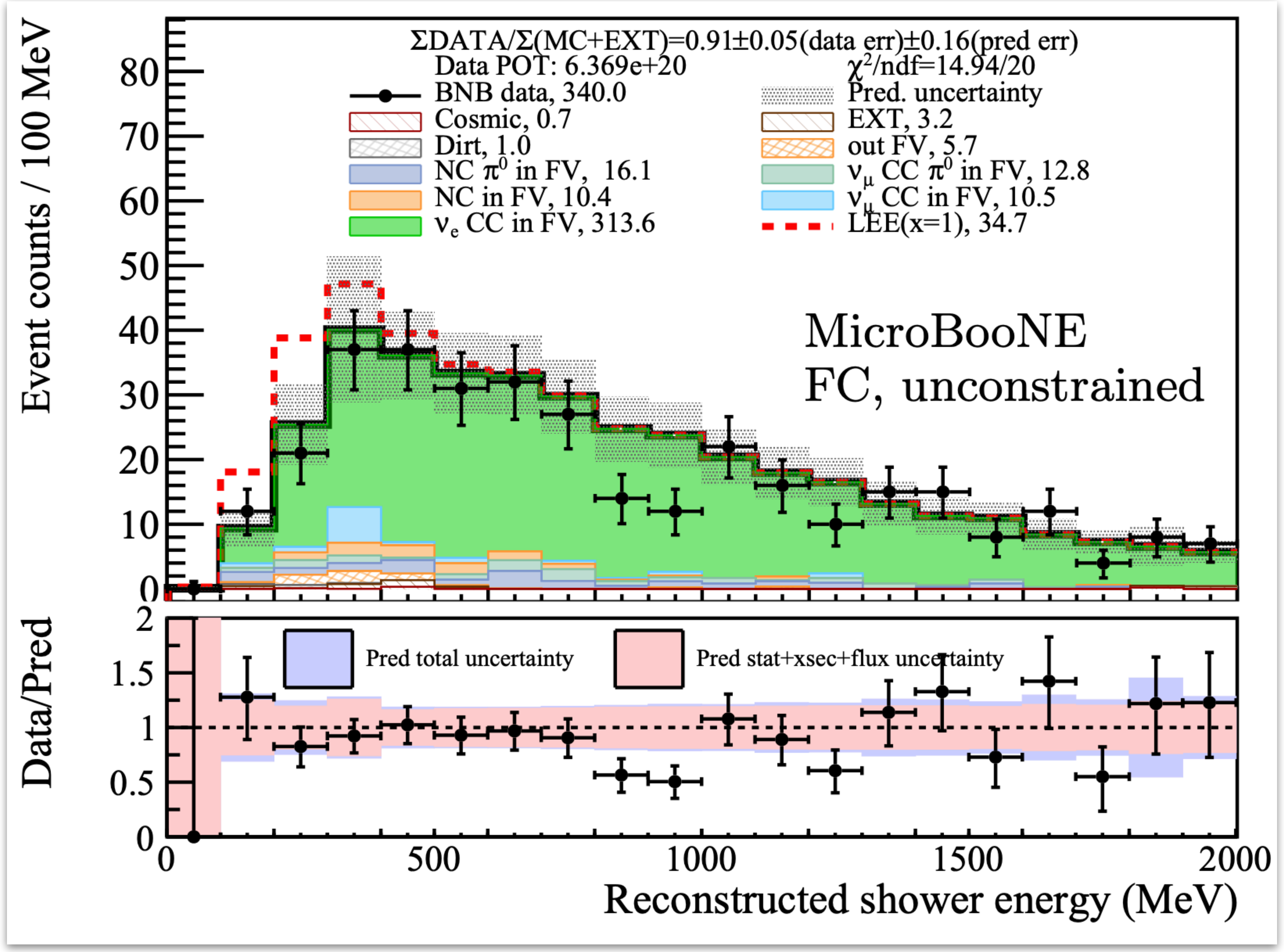
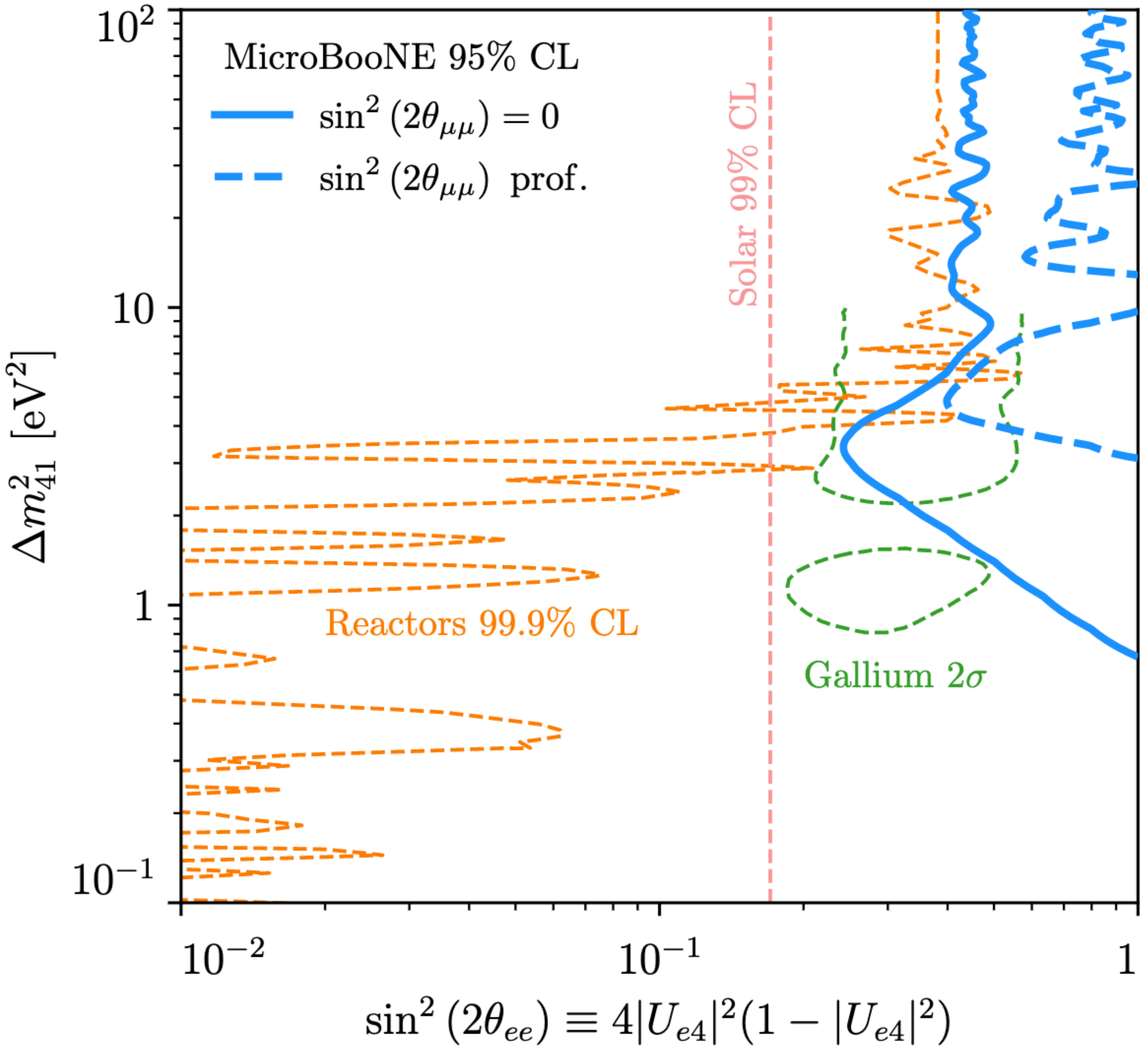




MicroBooNE, [2110.13978]

Four-Flavor Results



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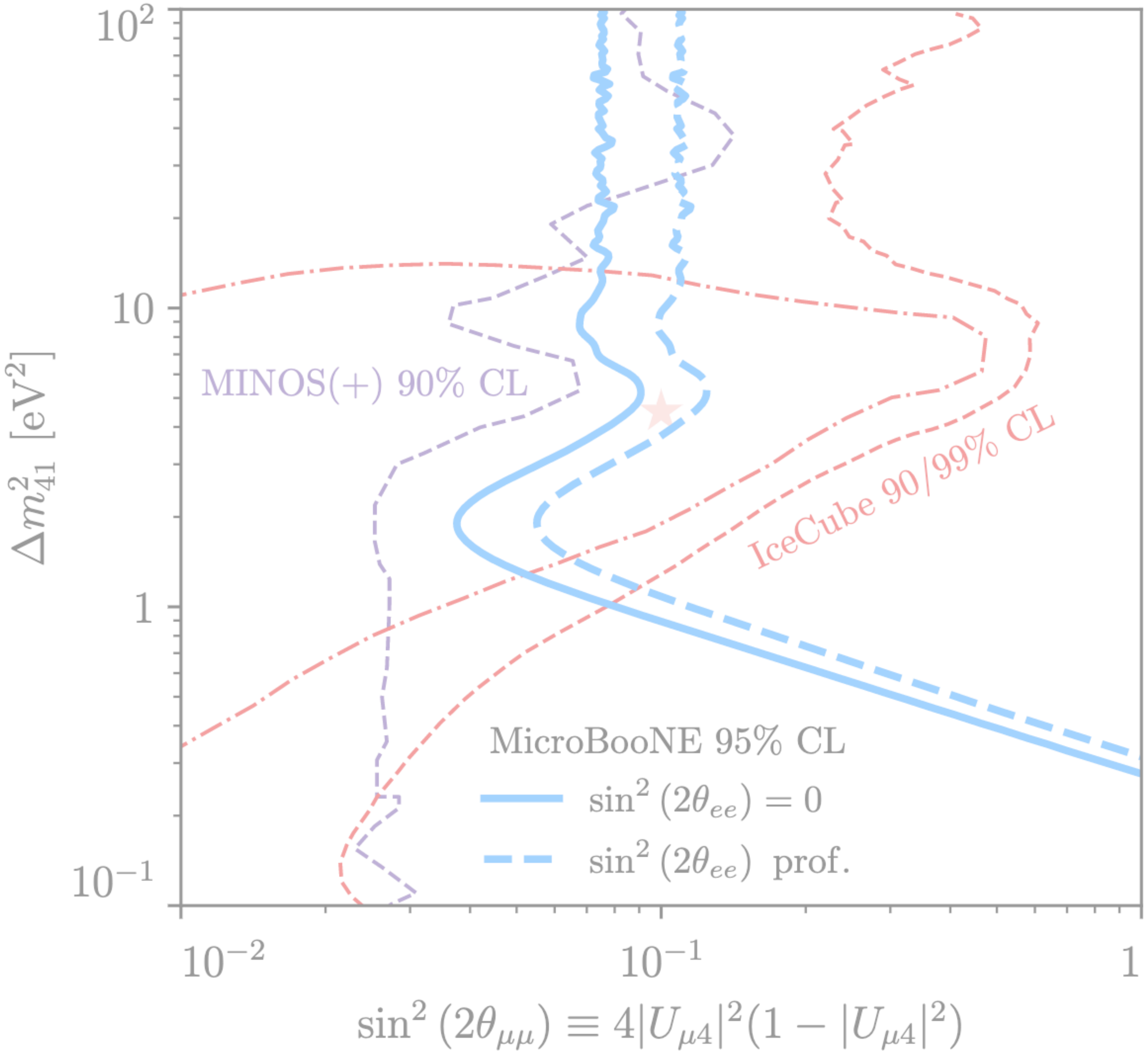

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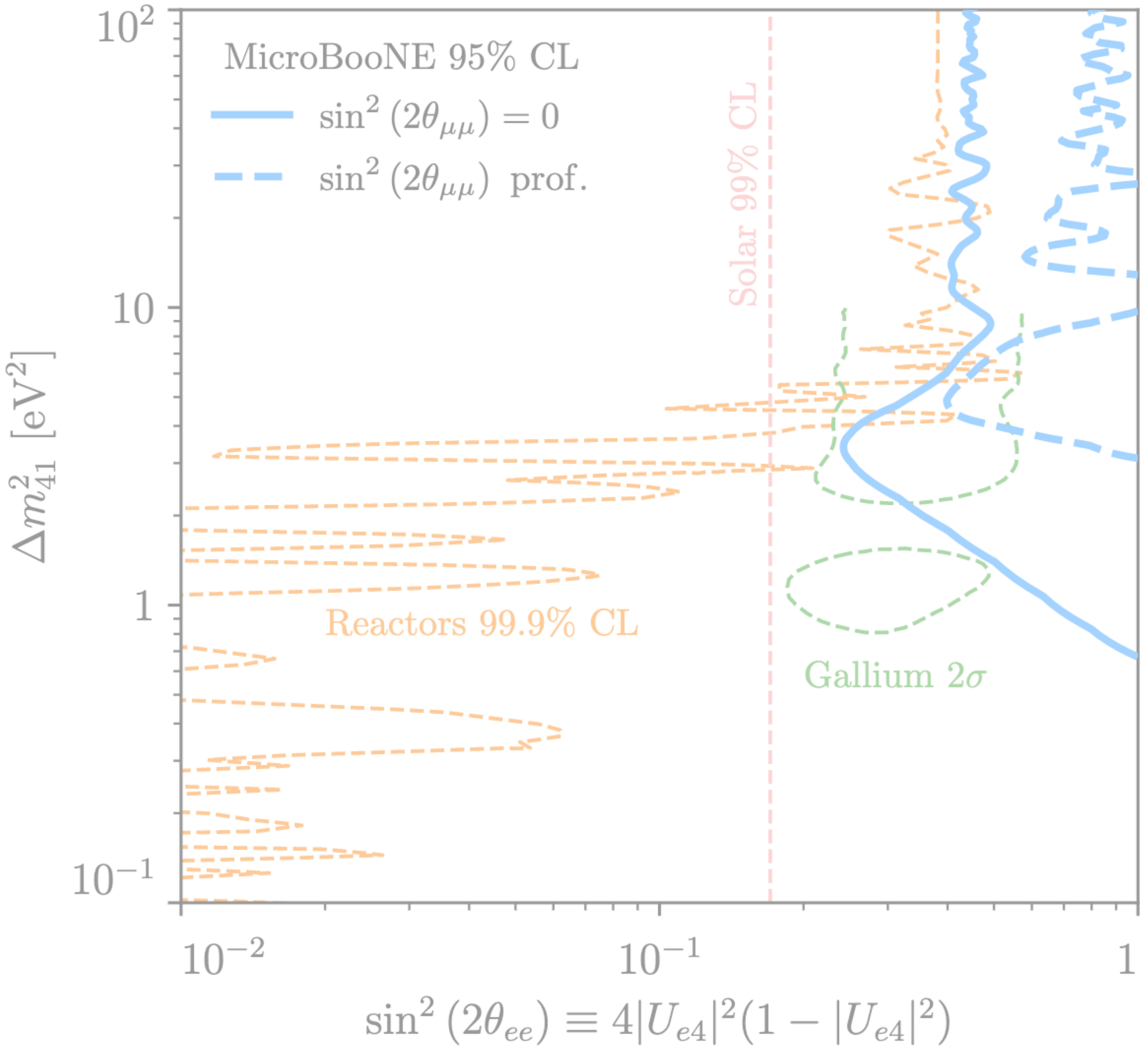
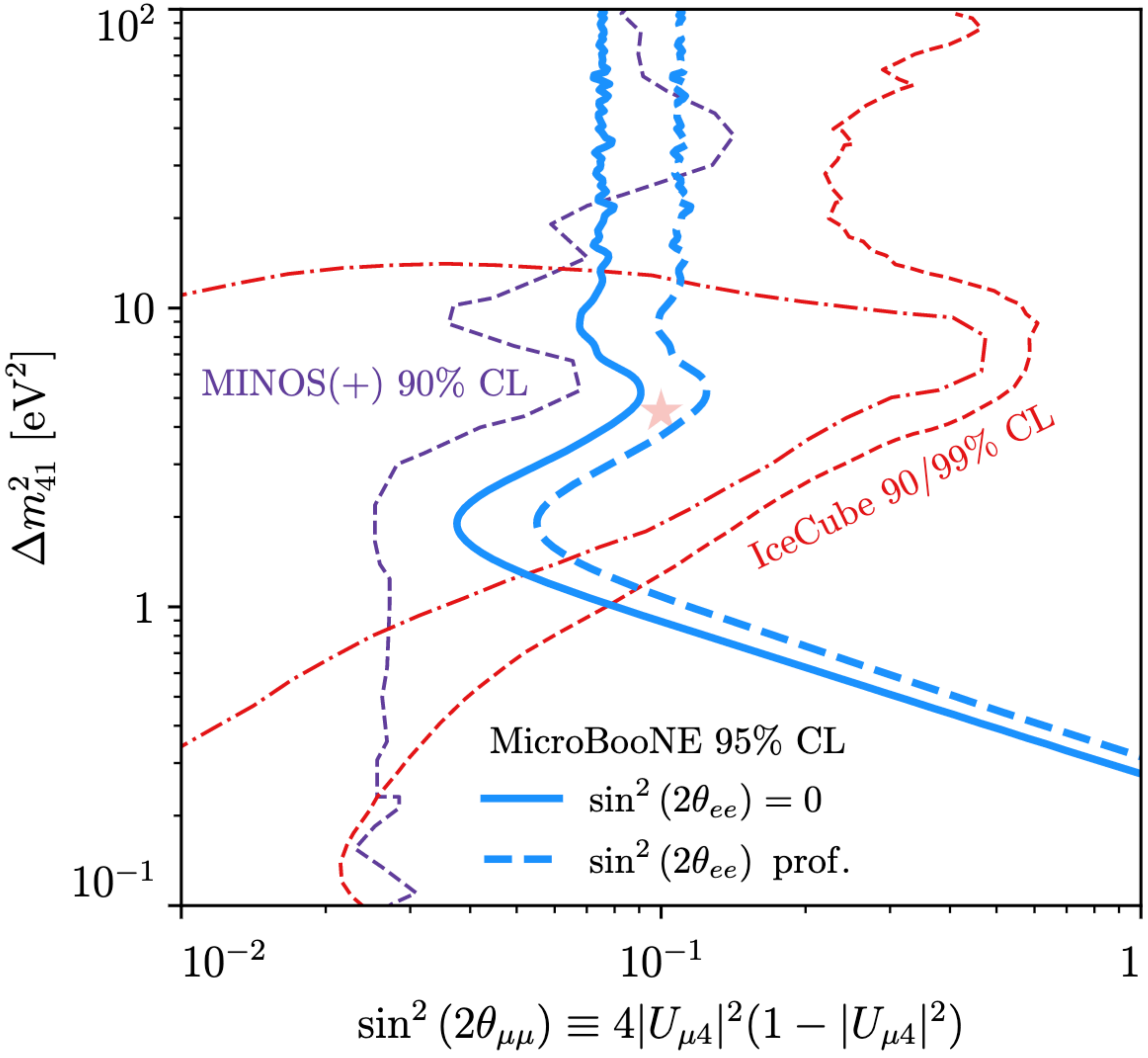
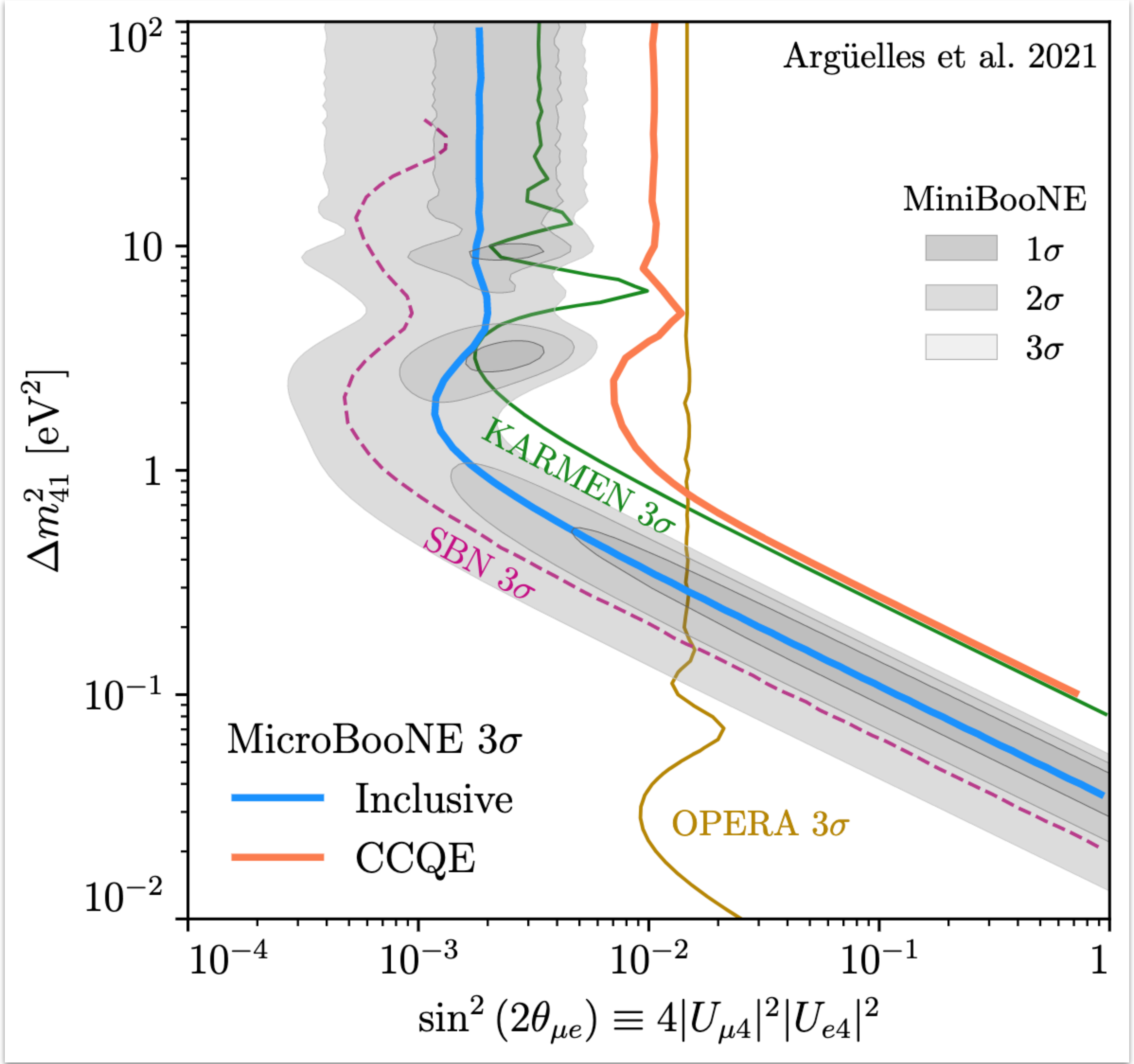




Four-Flavor, Appearance

[2111.10359]

Profiling over unseen mixing angle, how does sensitivity change?



Four-Flavor, Appearance

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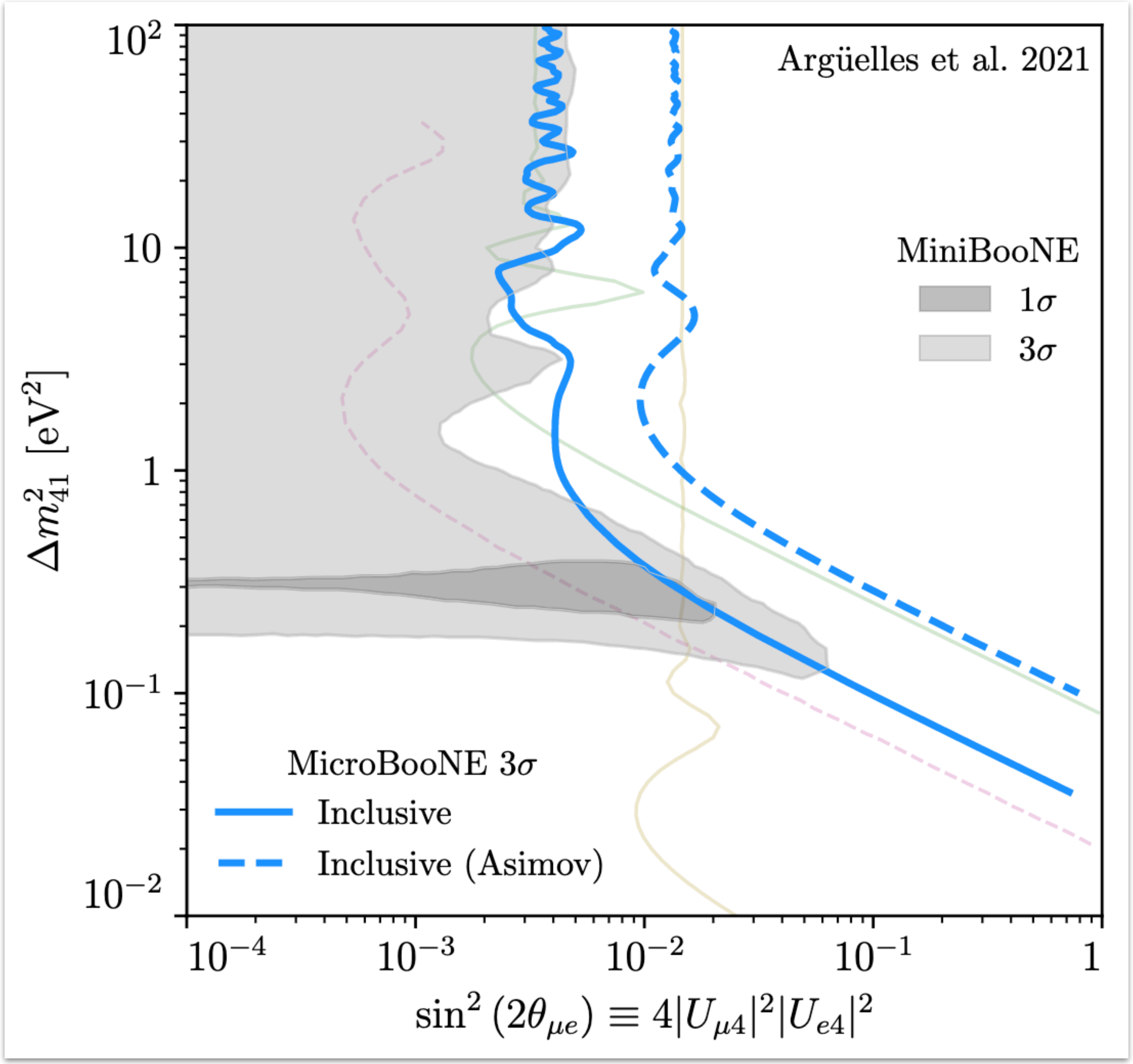
For better or worse, opens up parameter space for consistency between MiniBooNE and MicroBooNE — the MiniBooNE anomaly persists…



Beyond Sterile Neutrinos

Model-Building Explanations of LSND and/or MiniBooNE

From Pedro Machado, Neutrino2020

New signatures:

Gninenko 1107.0279 — No LSND

Heavy neutrino O(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916, Arguelles et al 1812.08768

Heavy neutrino O(1-100MeV), light Z', decay — No LSND

Oscillations+:

Asaadi et al 1712.08019

Resonant matter effect — UV challenge

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eV steriles and extra dimensional shortcuts — not clear

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Steriles + NCNSI + CCNSI — Baroque

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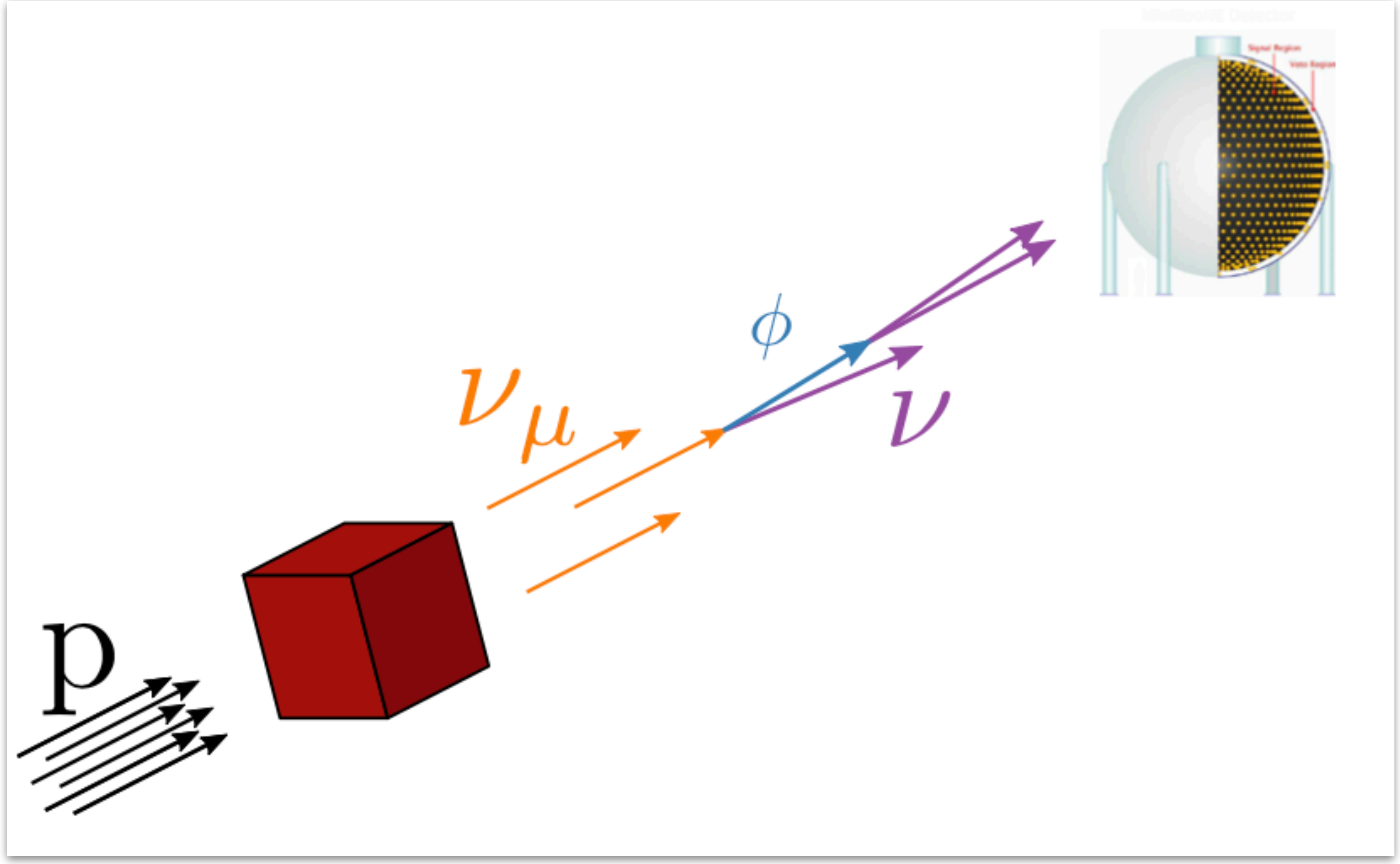

Decaying Sterile Neutrino Hypothesis —
Dentler et al, [1911.01427], de Gouvêa et al, [1911.01447]

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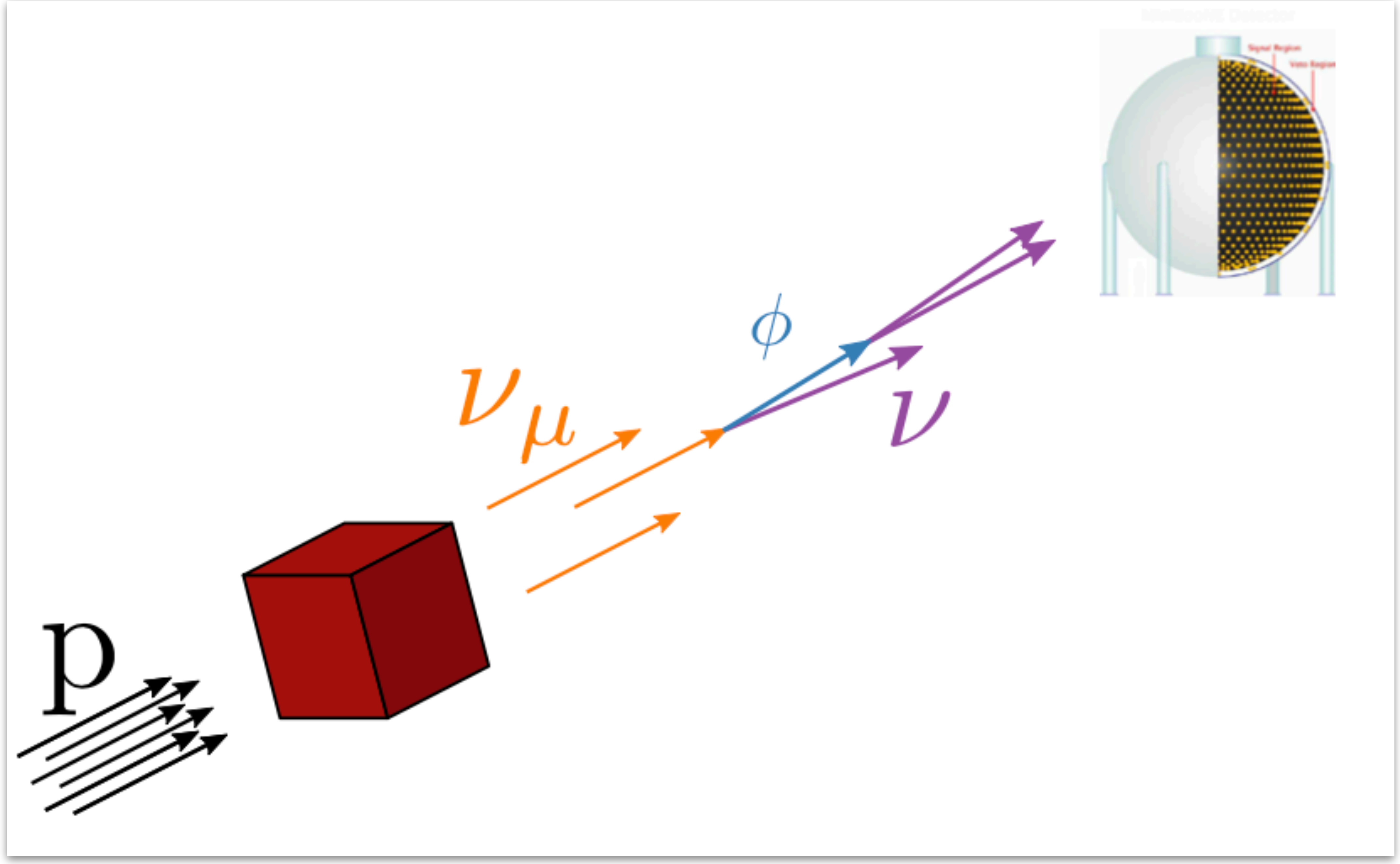

Decaying Sterile Neutrino Hypothesis —
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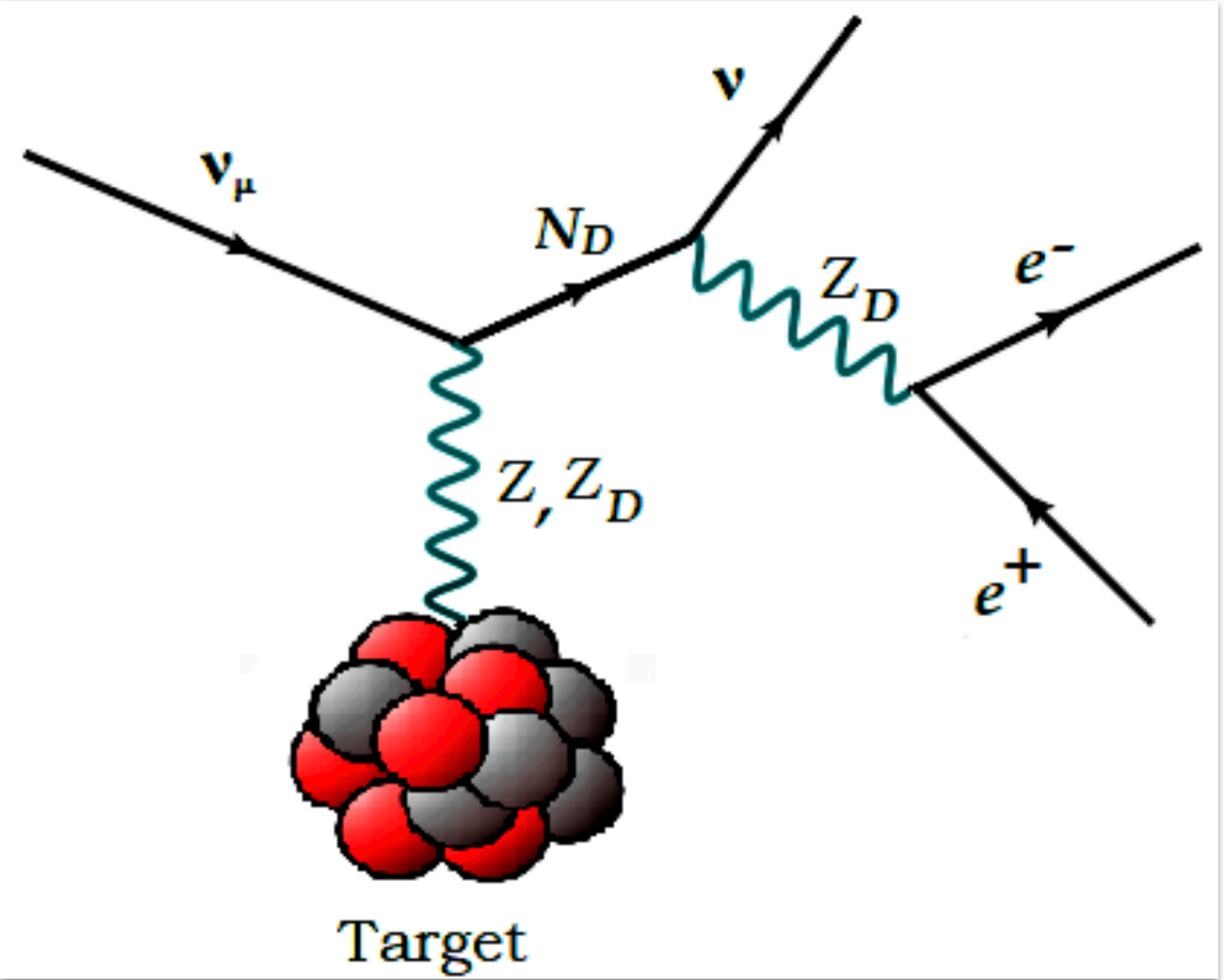
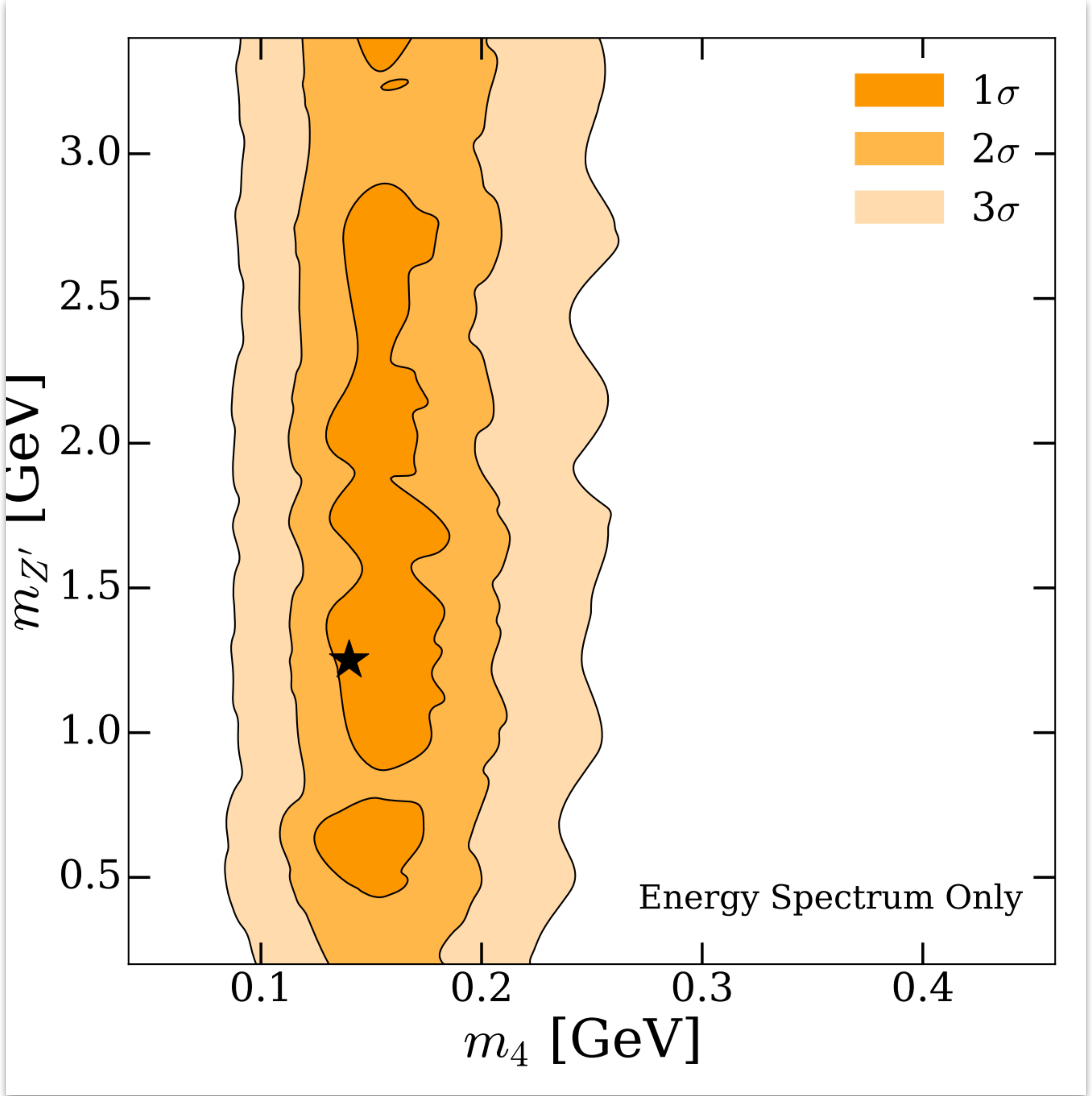
A nice, model-independent approach? Brdar et al, [2007.14411]
An "Altarelli Cocktail" of backgrounds in MiniBooNE? Brdar and Kopp, [2109.08157]

“Dark” Neutrinos

Bertuzzo et al [1807.09877]

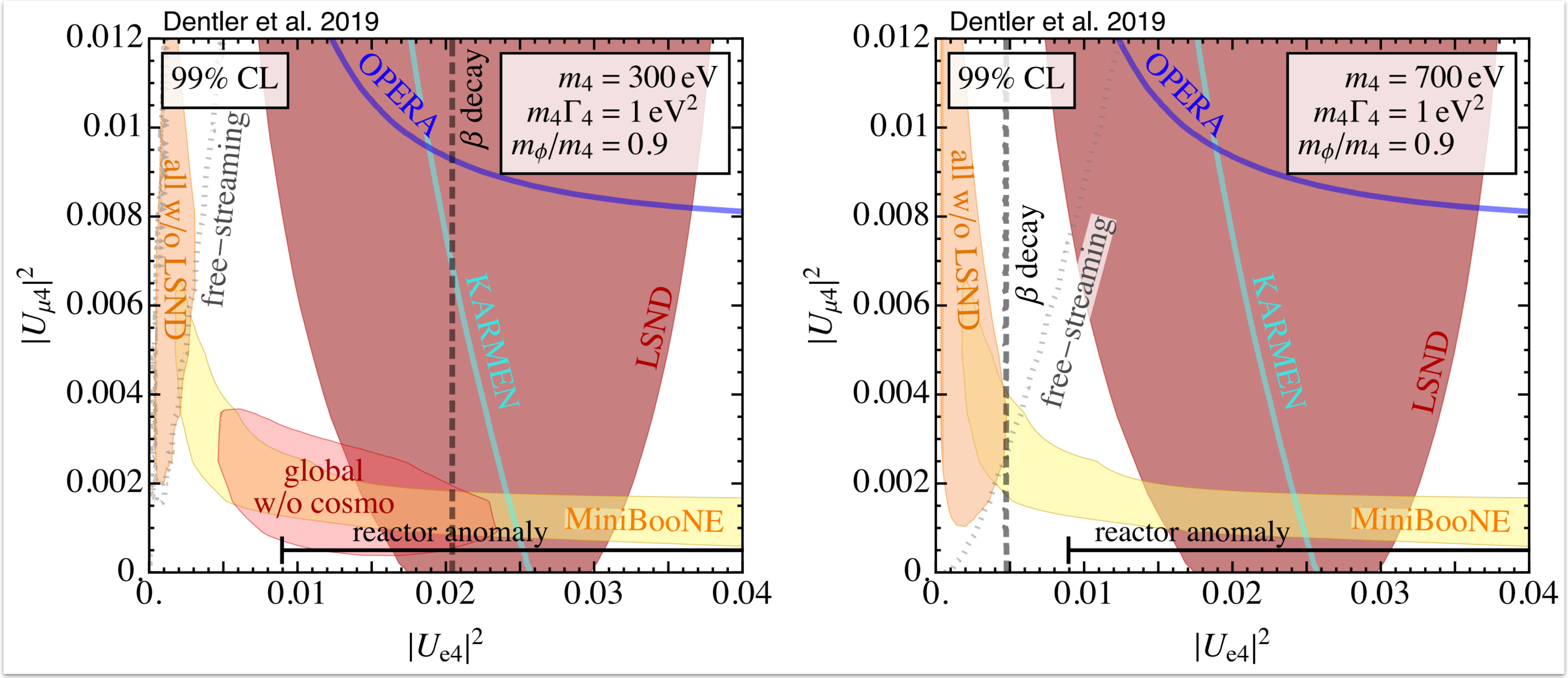


Ballett et al [1808.02915]



Idea: MiniBooNE is actually observing *di-electron* signals from new-physics contributions and can’t tell this apart from a standard electron-neutrino signature. Logical next-step test for MicroBooNE after their single-photon and single-electron analyses.

Decaying Sterile Neutrinos



Challenging to explain MiniBooNE, LSND, Cosmology, and negative results simultaneously.

Global-fit region constrained by decaying *solar* neutrinos as well — Hostert and Pospelov, [2008.11851]

Takeaways

Conclusions

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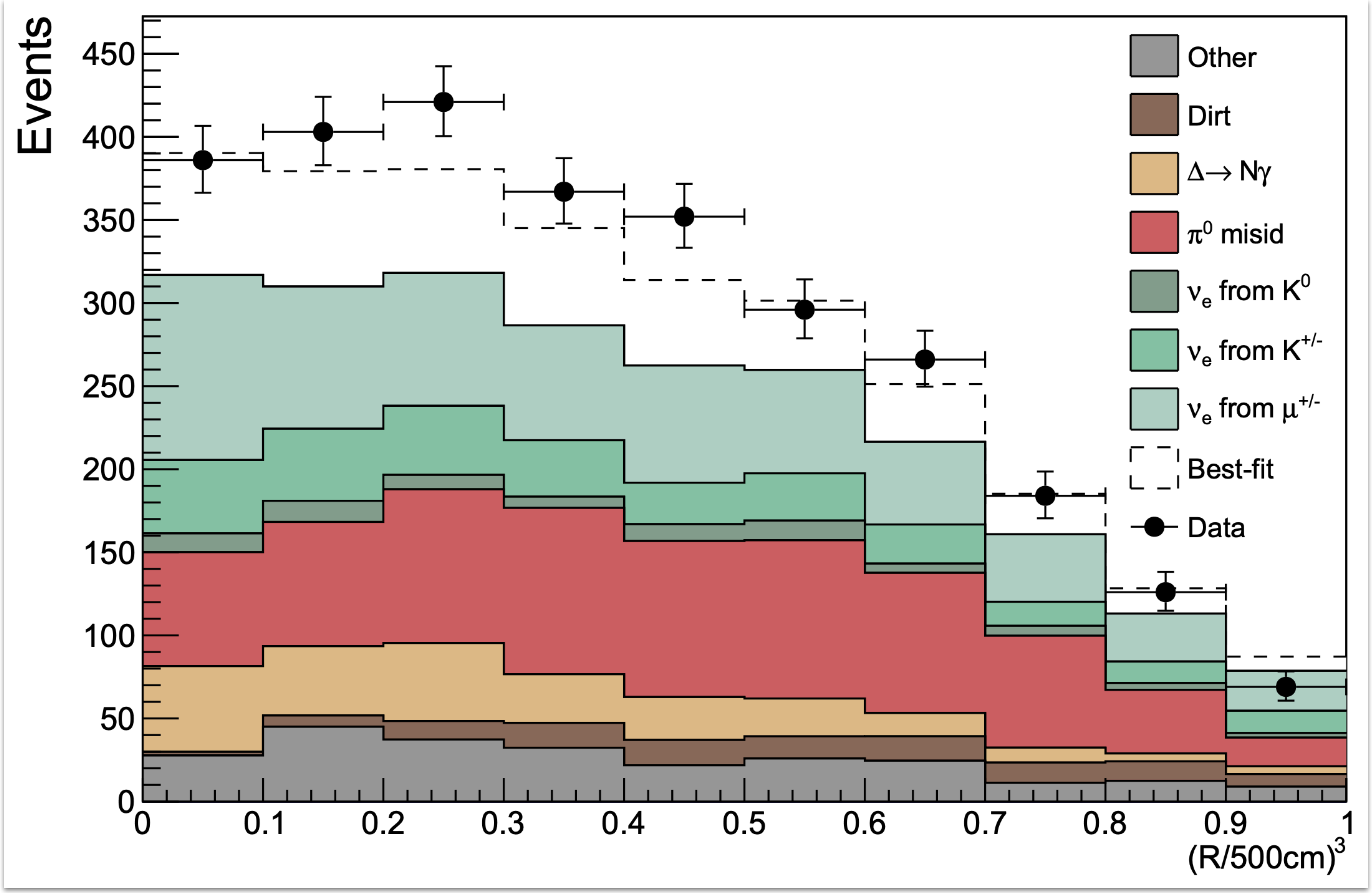
Thank you!

Backup Slides

More MiniBooNE Distributions — Position



More MiniBooNE Distributions — Time