Light Sterile Neutrinos

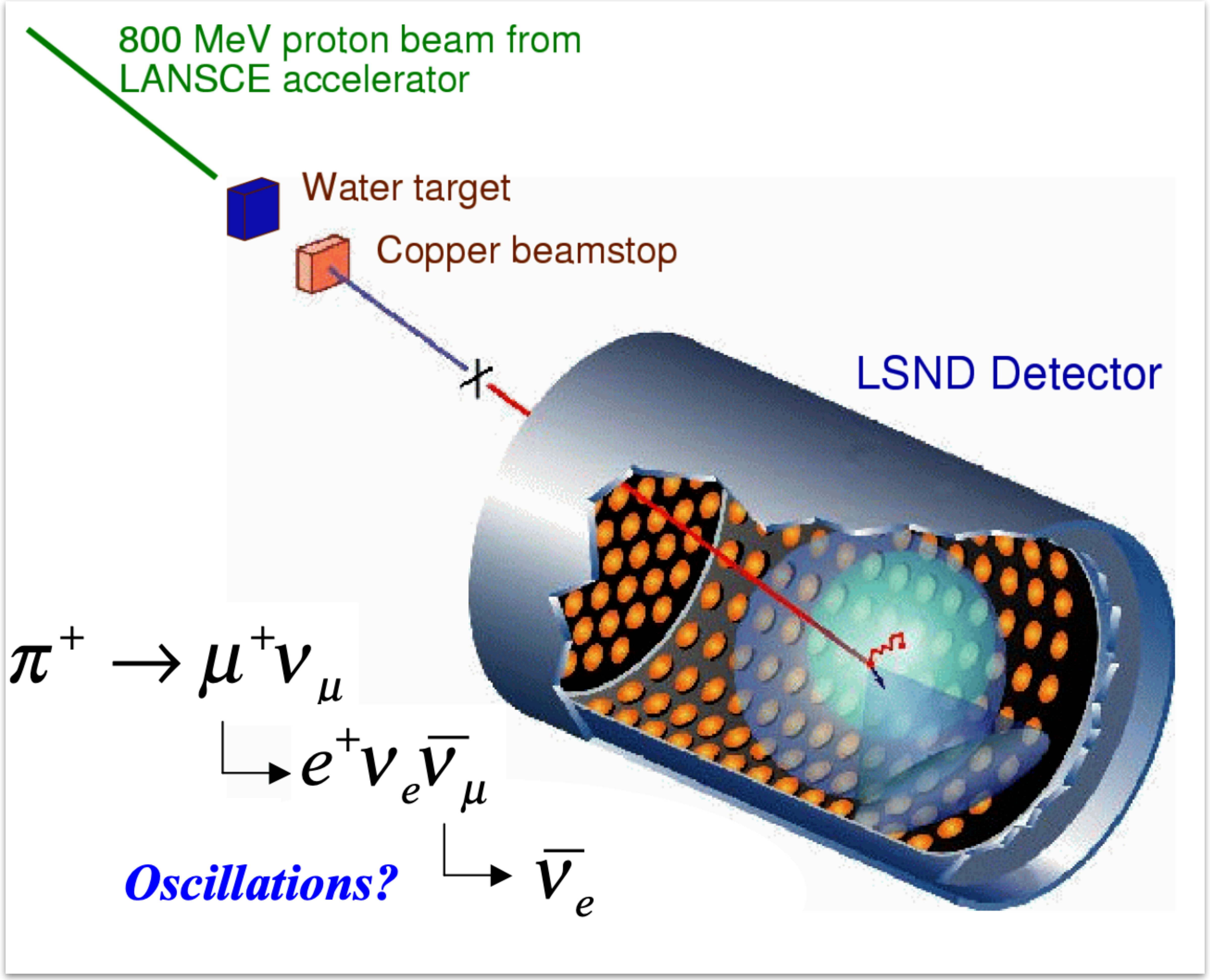
at Neutrino Oscillation Experiments

Kevin J. Kelly, Texas A&M University
WIN 2023 — 7th July, 2023
kjkelly@tamu.edu
[2111.10359] & [2204.09130] with many great collaborators

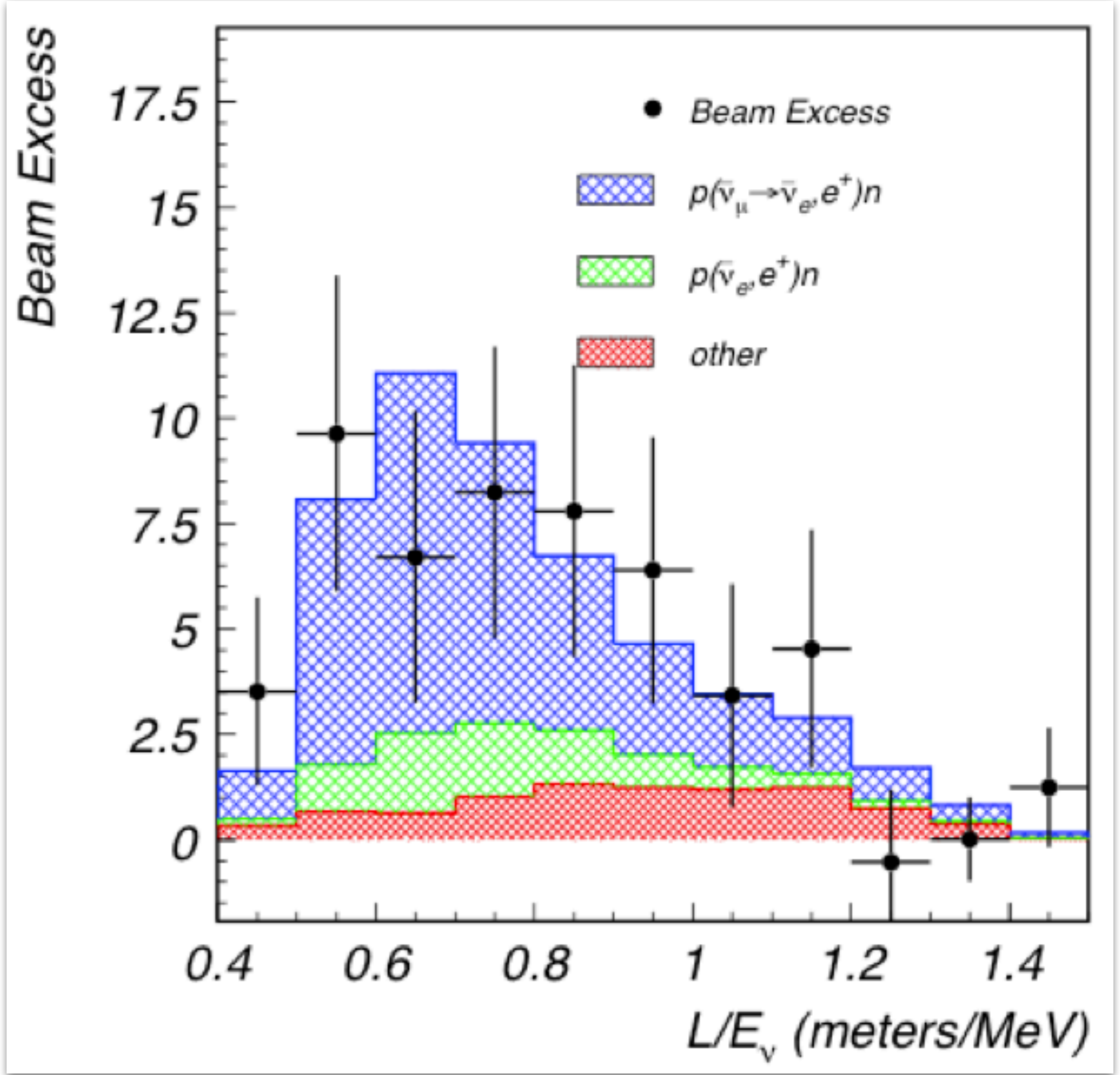
Outline

- How did we get here?
  - Short-baseline anomalies
- The latest & greatest results
  - Four-neutrino framework — T2K, NOvA, MicroBooNE…?
- Beyond the sterile neutrino picture
  - Testable new-physics in current & upcoming experiments

Liquid Scintillator Neutrino Detector (LSND)



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

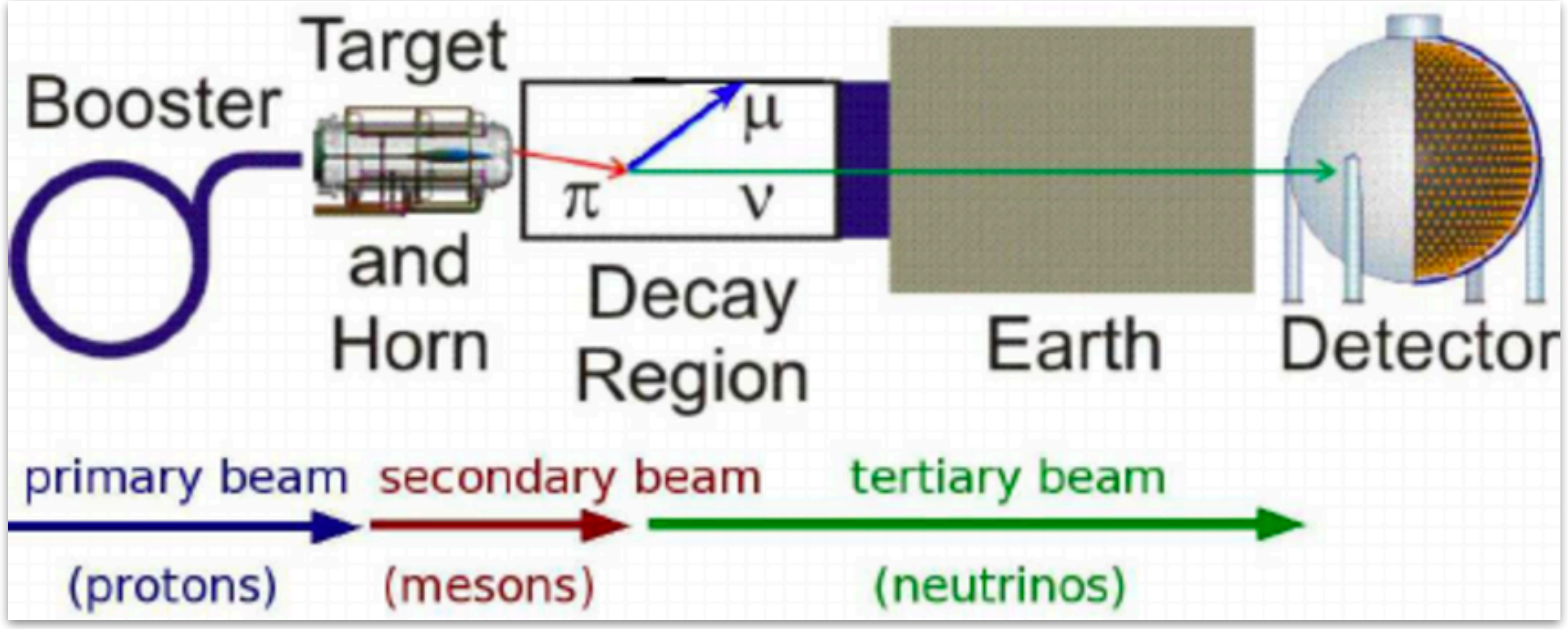


Neutrinos (mostly) from pion/muon decay-at-rest — O(30) MeV, roughly 50 meter baseline length.

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

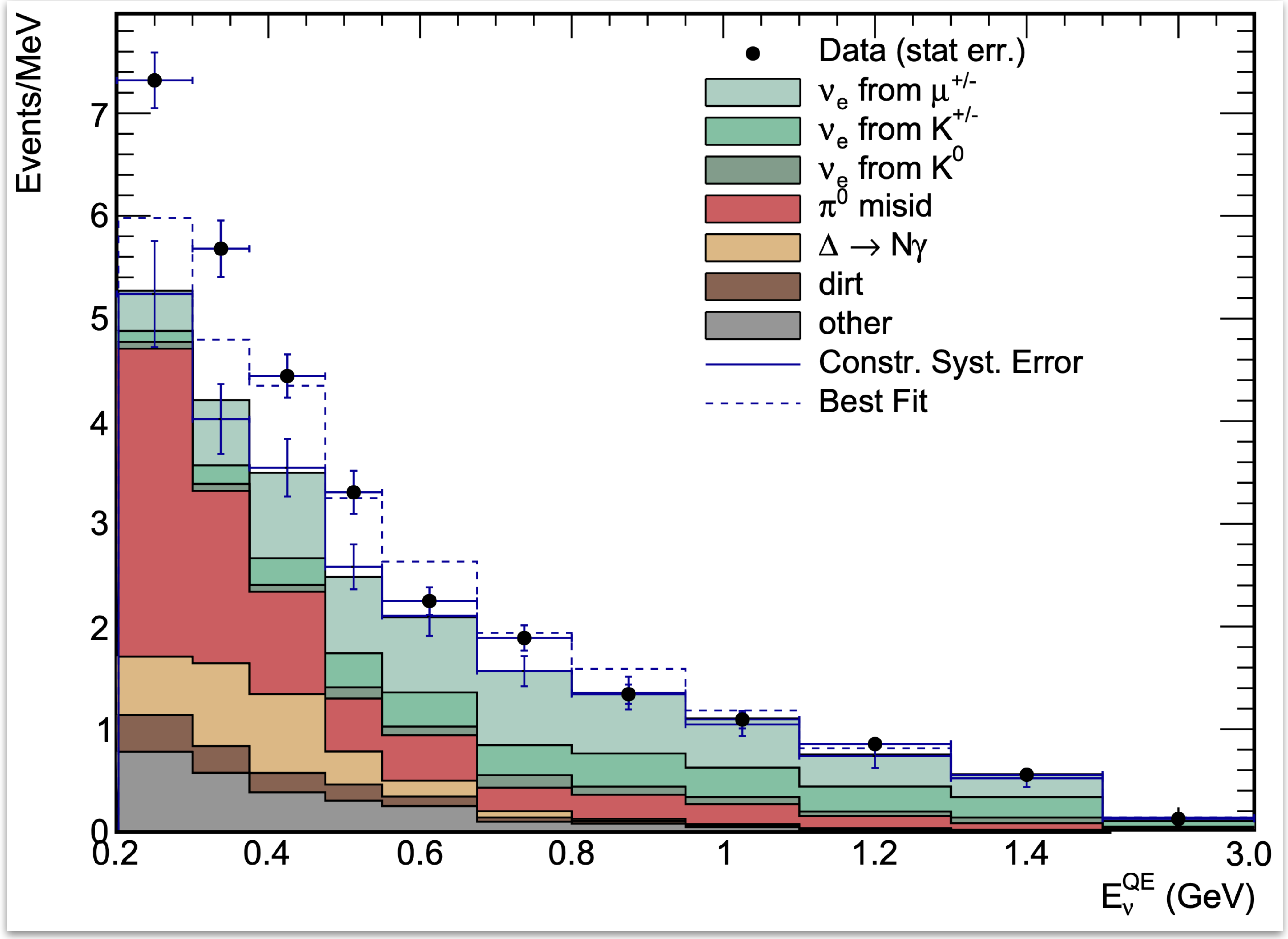
MiniBooNE

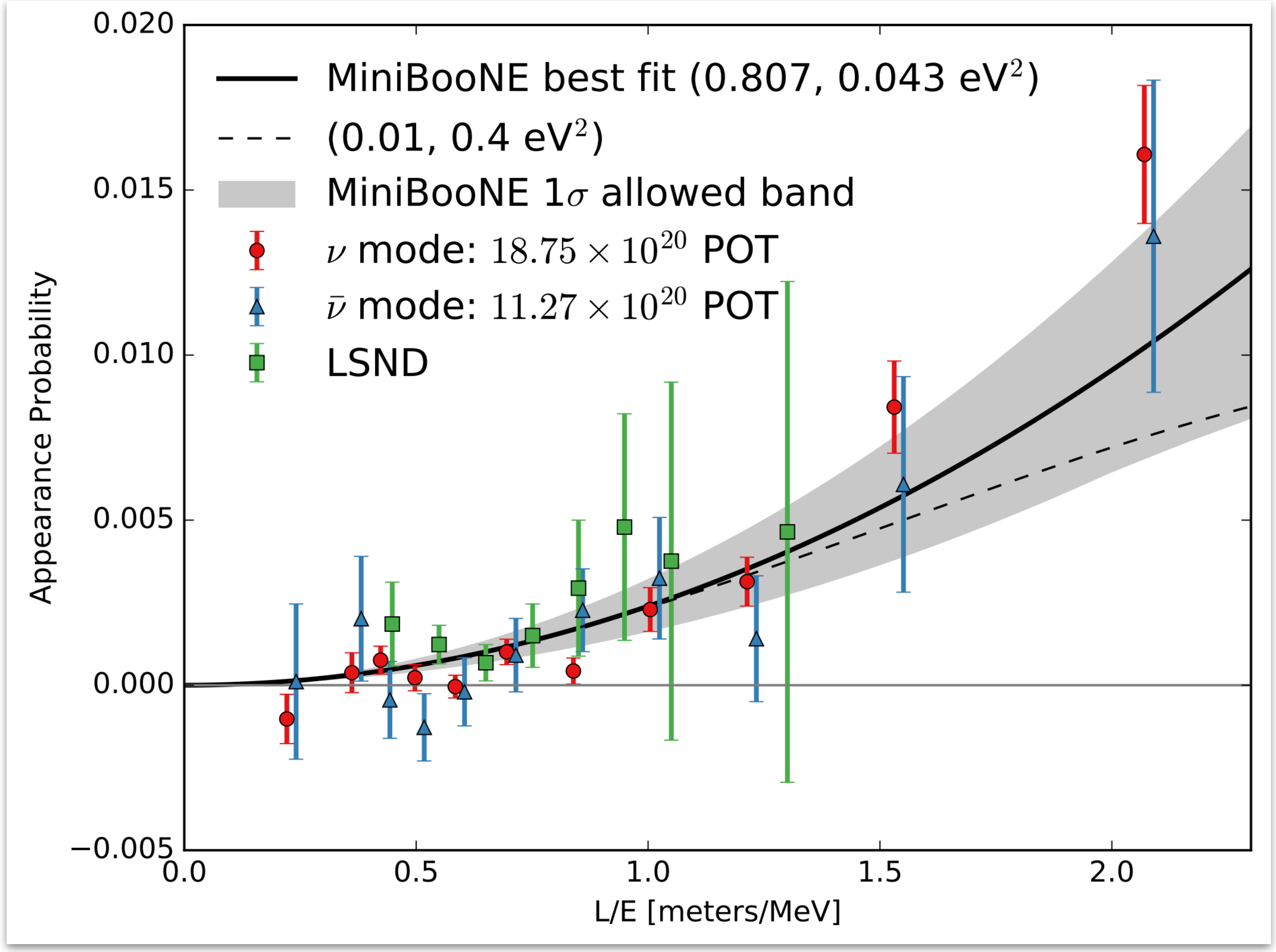
Designed to test the LSND anomaly — very different L, E, but similar L/E



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

MiniBooNE Collab., [2006.16883]





Consequences of Invoking a light (sterile) Neutrino

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

- 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.

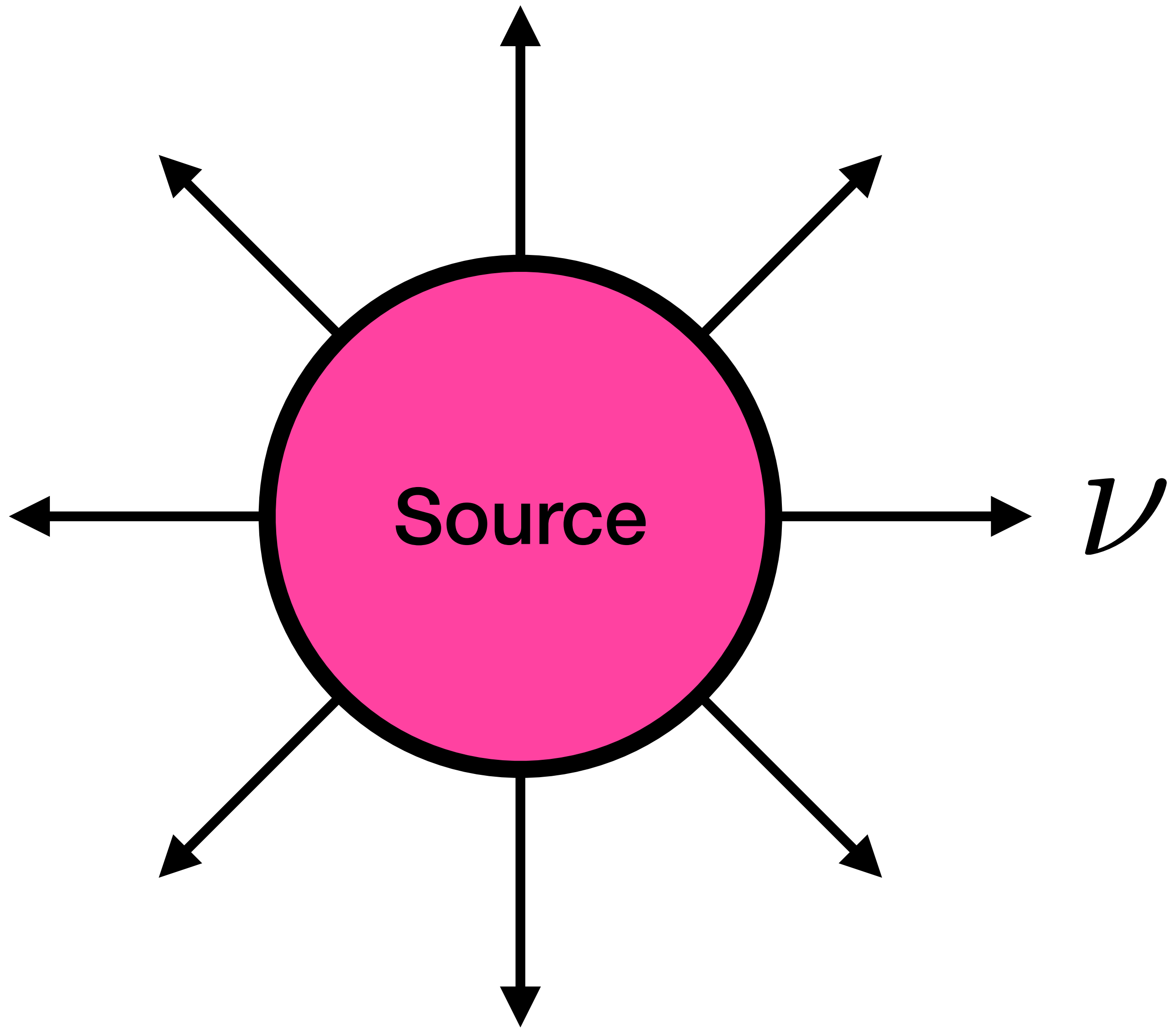
$$\sin^2\left(2\theta_{\mu e}\right) \equiv 4\left|U_{e4}\right|^2\left|U_{\mu 4}\right|^2$$

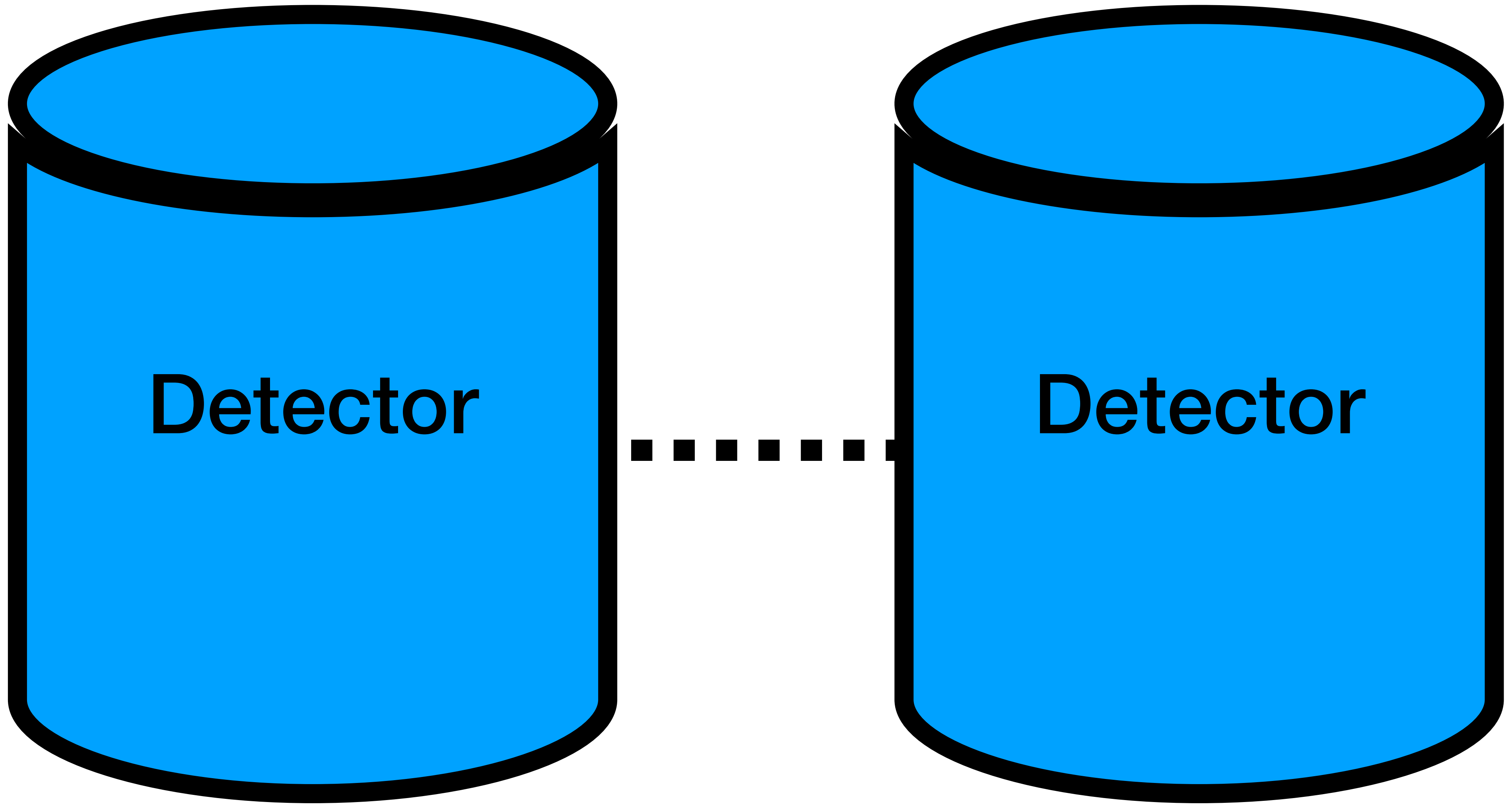
- Electron-neutrino appearance is driven by a product of the new matrix elements. Each of these being non-zero predicts electron-neutrino **and** muon-neutrino disappearance at the same neutrino energy/distance.

Electron-Neutrino Disappearance?

Avoiding Uncertainties in Electron Antineutrino Disappearance

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



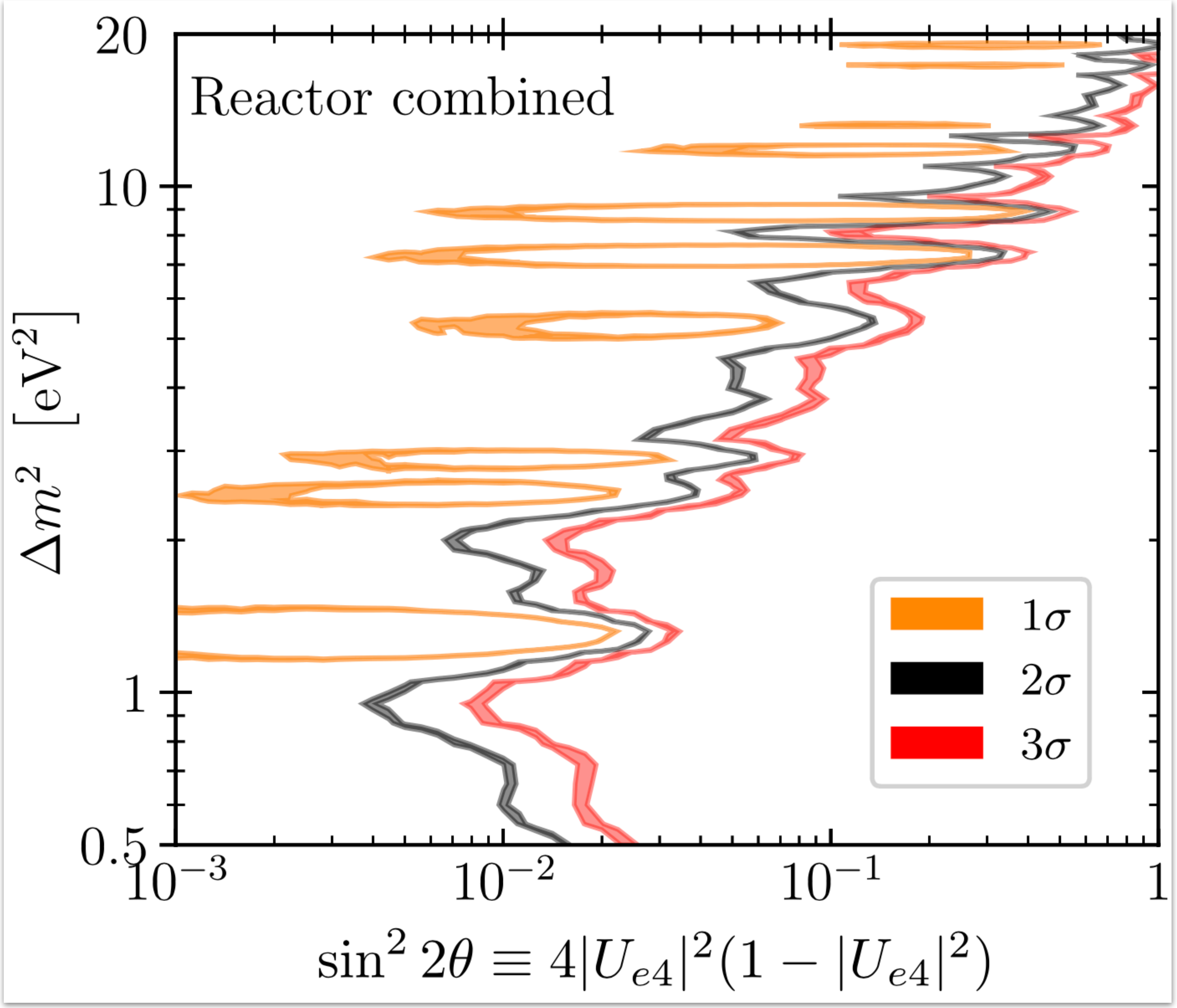


Experiments measure *rates* (product of flux, cross section, and oscillation probability), not probability directly. Constraints on the mixing angle will therefore be limited by uncertainties on fluxes, cross sections, etc.

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

Reactor Global Picture

Berryman et al, [2111.12530]



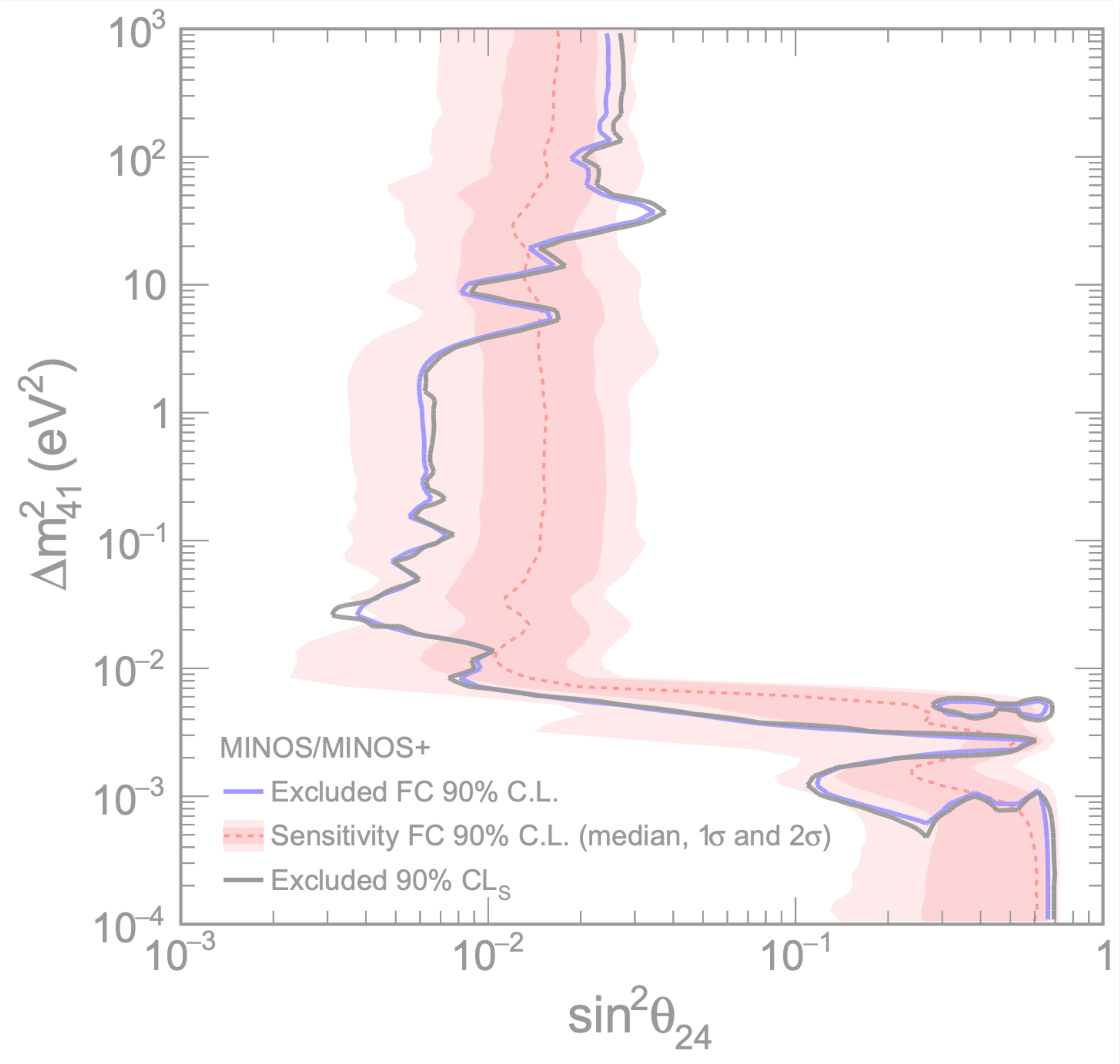
PROSPECT
STEREO
DANSS
Neutrino 4
NEOS

No significant* deviation from expectation!

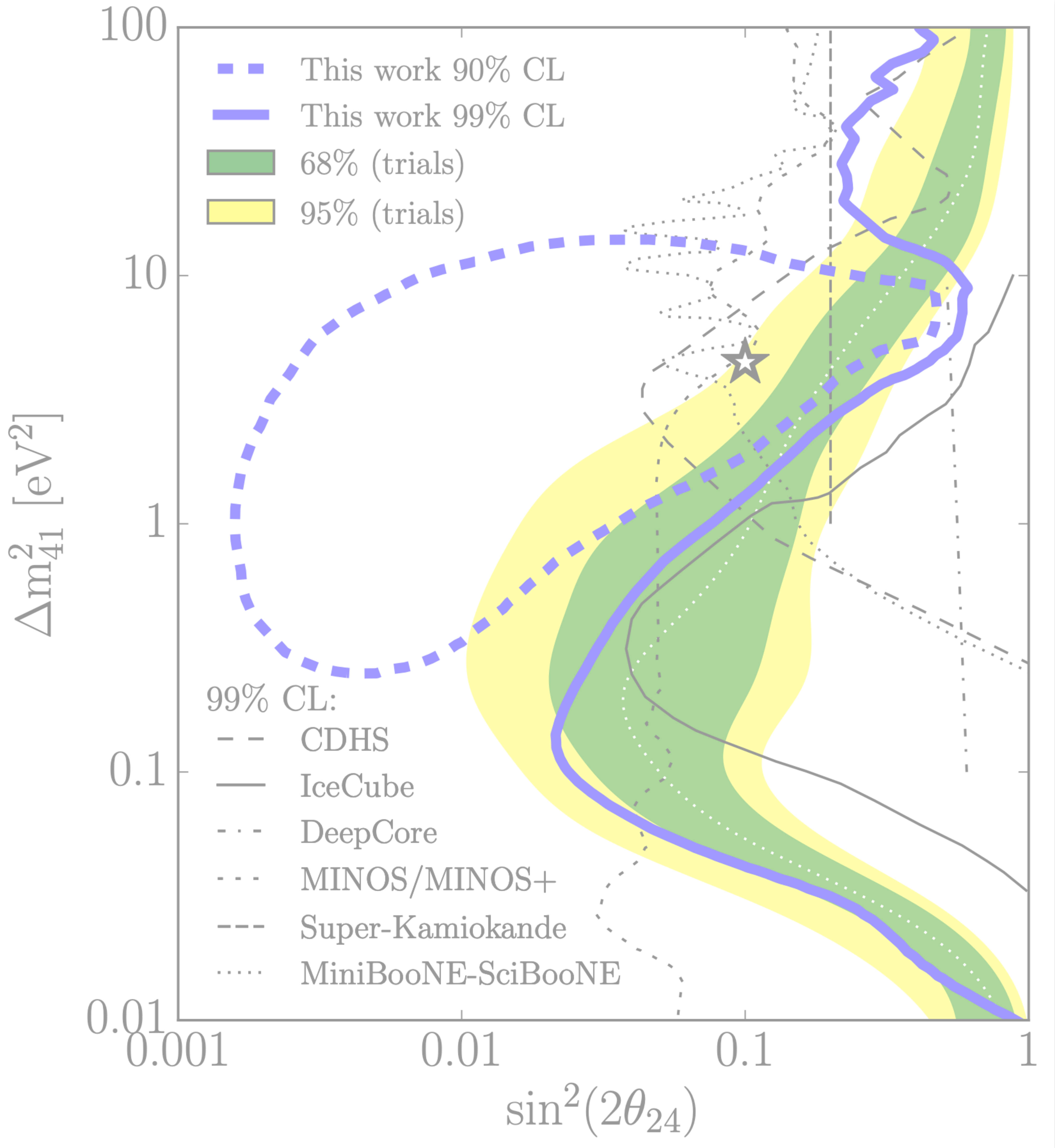
Muon-Neutrino Disappearance?

MINOS + IceCube

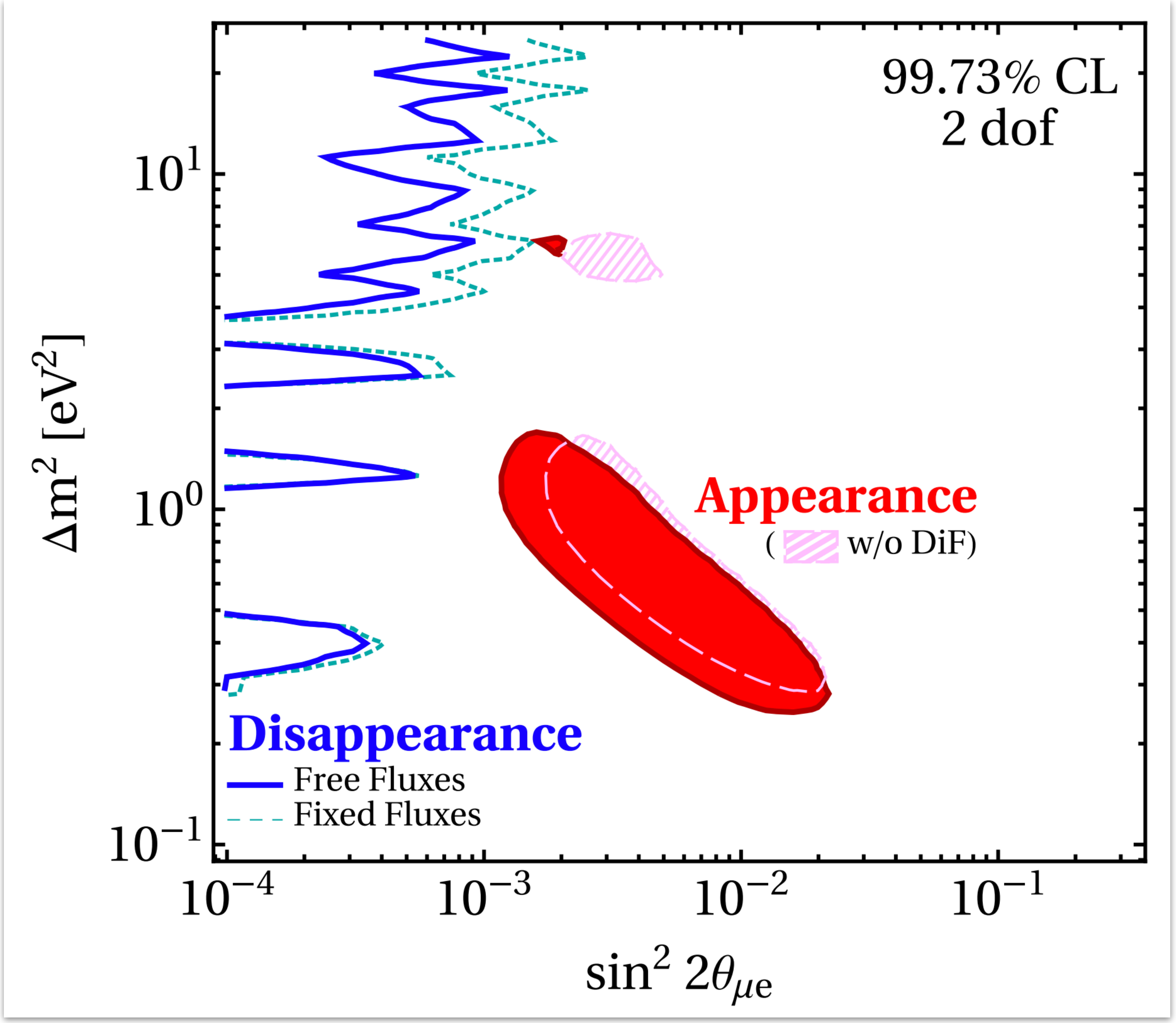
MINOS/MINOS+, [2002.00301]



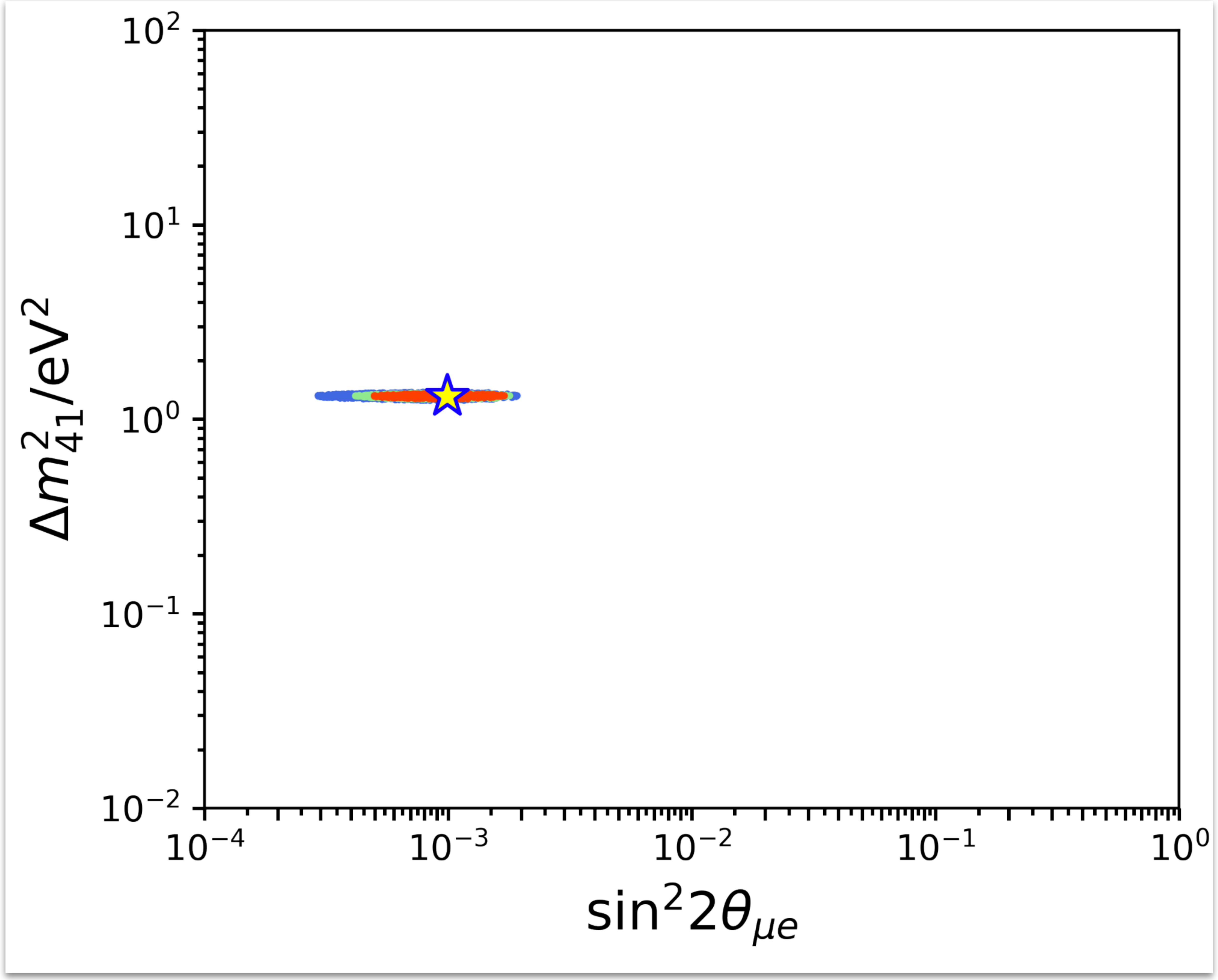
IceCube Collaboration, [2005.12942]



Sterile Neutrino Global Fits ca 2019



Dentler et al, [1803.10661]

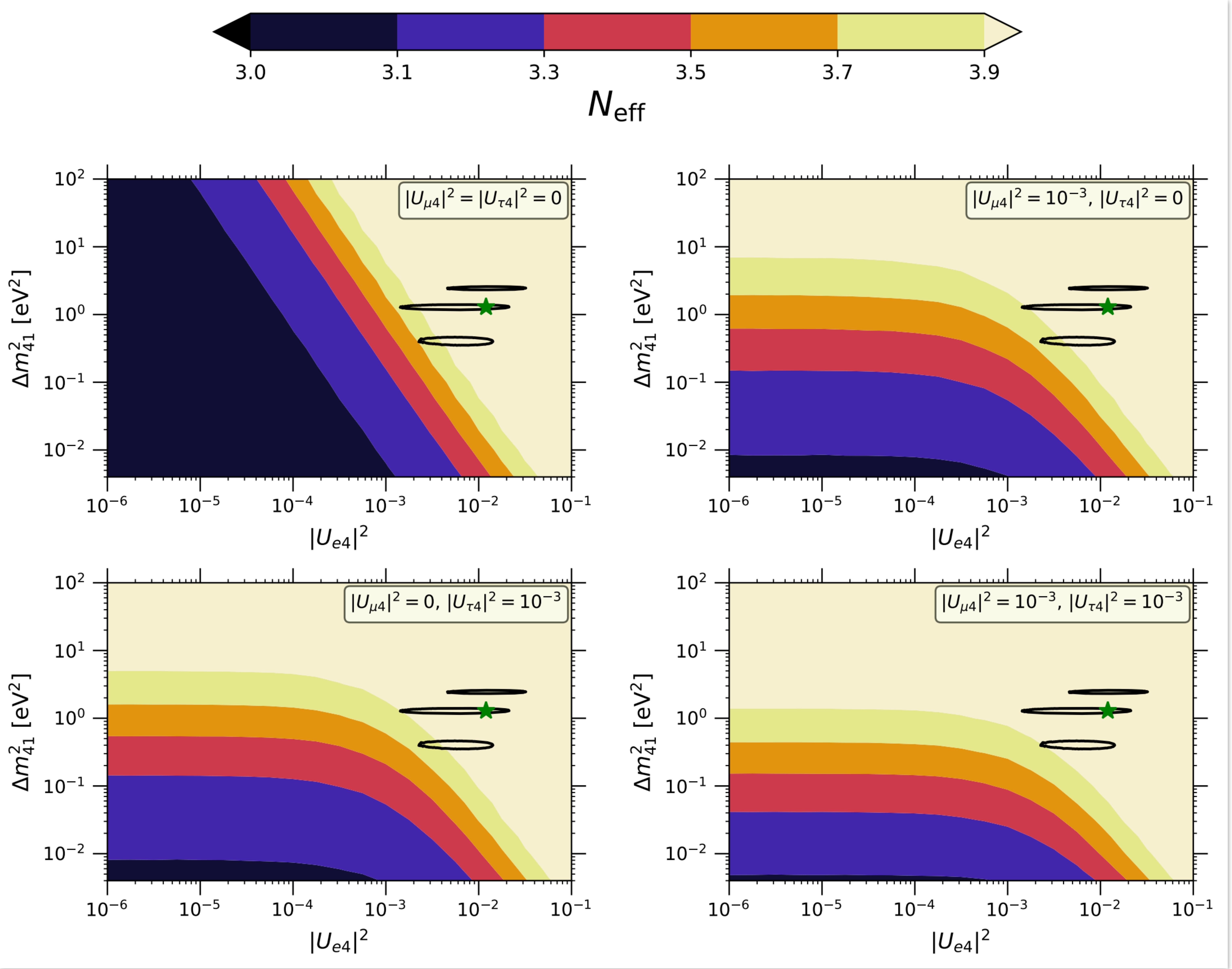


Diaz et al, [1906.00045]

Sterile Neutrinos & Cosmology

Gariazzo et al, [1905.11290]

A new, eV-scale massive fermion that mixes (even with small mixing angles) with the SM neutrinos will be thermalized in the early universe. Cosmological probes (precision measurements of Big-Bang Nucleosynthesis and the Cosmic Microwave Background) are highly sensitive to the number of relativistic species.



Interlude: T2K & NOvA

T2K, NOvA, and their (mild) tension

There is a small tension between NOvA and T2K's latest data, in terms of electron (anti)neutrino appearance.

de Gouvêa et al, [2204.09130]

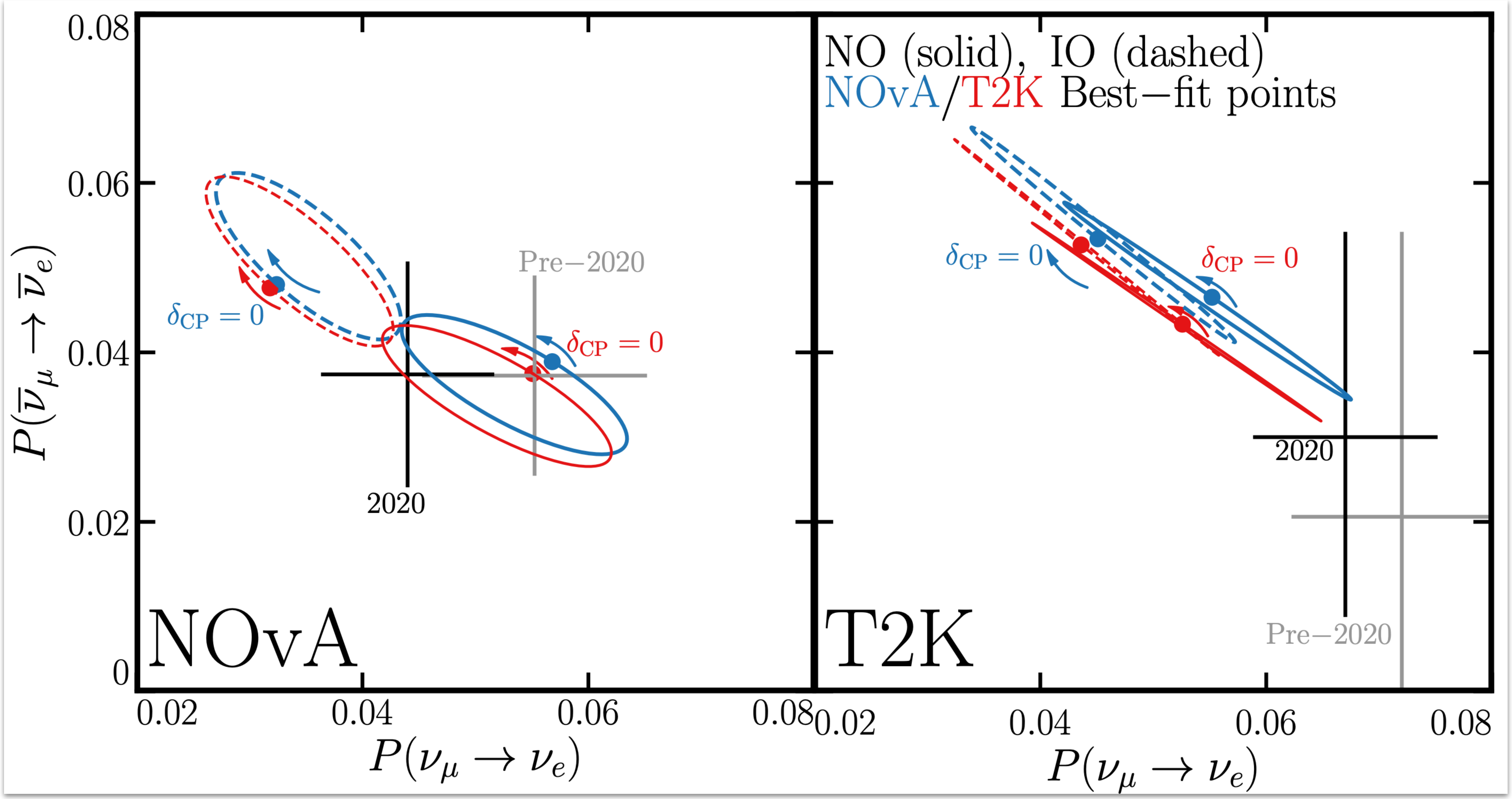
3ν		$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2_{31}/10^{-3}\ \mathrm{eV}^2$	δ_{CP}	χ^2	$\Delta\chi^2_{\mathrm{NO,IO}}$
T2K	NO	0.022	0.56	2.52	4.58	66.82	1.48
	IO	0.022	0.56	−2.41	4.71	68.19	
NOvA	NO	0.022	0.58	2.52	2.34	43.40	0.14
	IO	0.022	0.57	−2.41	4.78	43.55	
Joint	NO	0.022	0.57	2.51	3.67	115.58	−3.76
	IO	0.022	0.57	−2.41	4.72	111.82	

One way to lift the tension? Inverted Mass Ordering (IO) instead of Normal (NO)

Another possibility? NSIs in NOvA, no significant matter effect in T2K: Denton et al [2008.01110], Chatterjee & Palazzo [2008.04161]

Where's the Tension?

KJK et al, [2007.08526]



Vaguely speaking, T2K & NOvA agree in terms of muon neutrino disappearance, but not the appearance channels.

Could this be ameliorated by a sterile neutrino with small muon mixing, large-ish electron mixing?

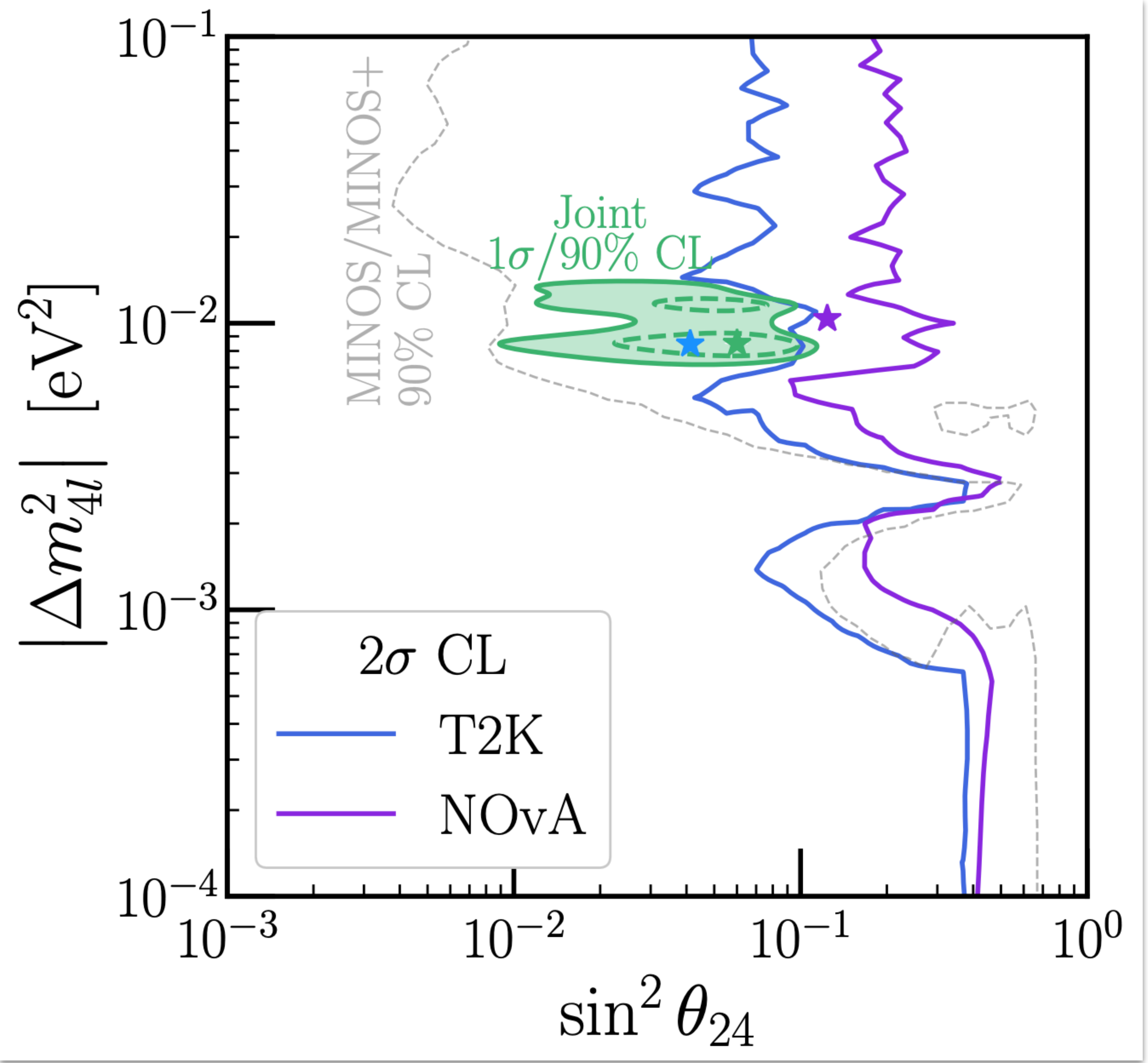
Short answer, yes!

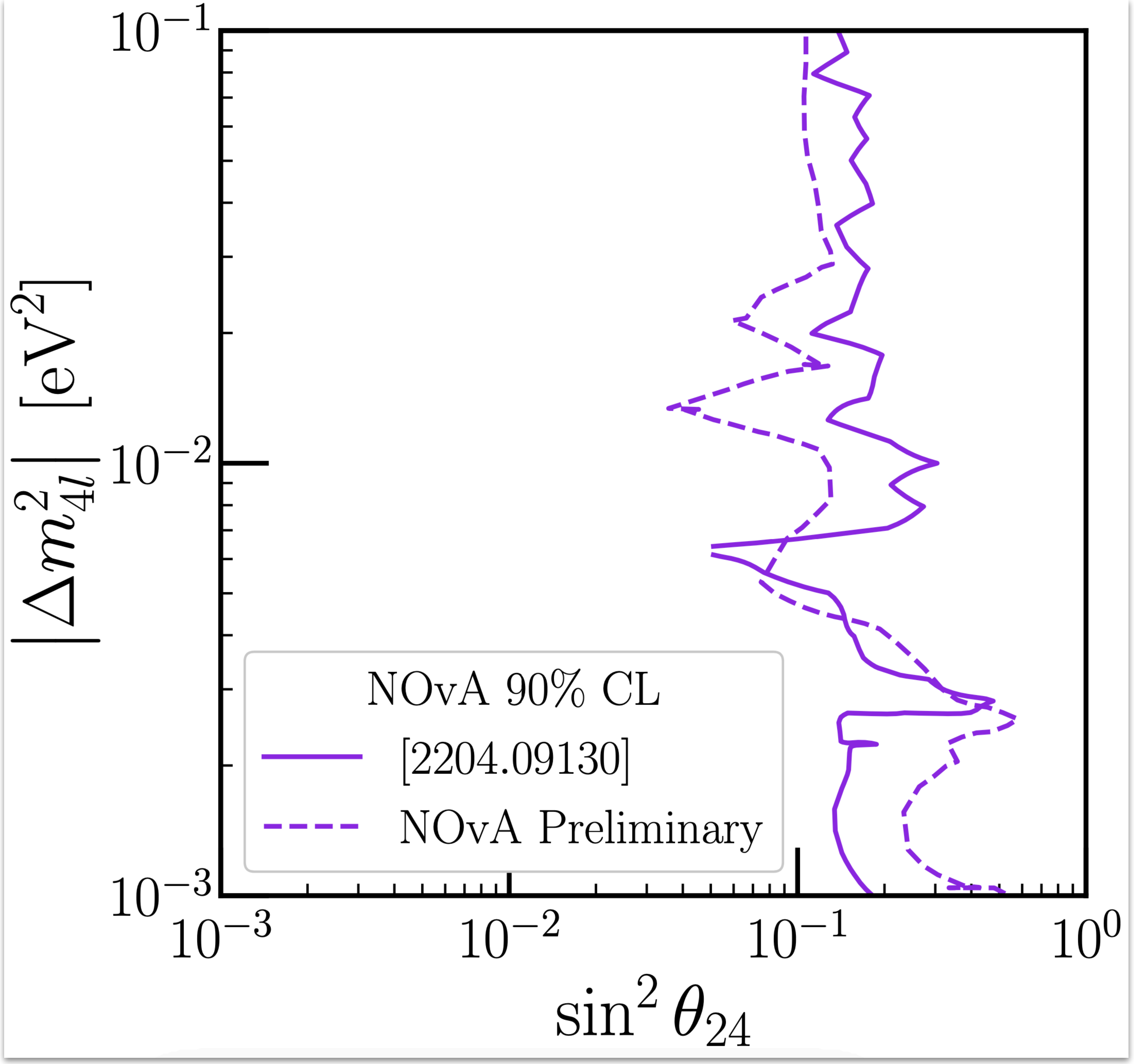
de Gouvêa et al, [2204.09130]

4ν	T2K	NOvA	Joint
$\sin^2\theta_{13}$	0.024	0.022	0.023
$\sin^2\theta_{23}$	0.43	0.44	0.43
$\Delta m^2_{31}/10^{-3}$ eV^2	-2.39	2.43	-2.39
δ_{CP}	4.41	0.00	4.46
$\sin^2\theta_{14}$	7.8×10^{-2}	6.9×10^{-3}	4.3×10^{-2}
$\sin^2\theta_{24}$	4.1×10^{-2}	1.2×10^{-1}	6.0×10^{-2}
$\sin^2\theta_{34}$	0.78	0.29	0.37
$\Delta m^2_{4l}/\mathrm{eV}^2$	-8.5×10^{-3}	1.0×10^{-2}	-8.5×10^{-3}
δ_{14}	1.82	3.51	4.88
δ_{24}	2.64	3.15	5.89
$\chi^2_{4\nu}$	61.95	38.10	102.83
Ordering	$m_4 < m_3 < m_1 < m_2$	$m_1 < m_2 < m_3 < m_4$	$m_4 < m_3 < m_1 < m_2$
$\chi^2_{3\nu} - \chi^2_{4\nu}$	4.87	5.30	8.99

Significant improvement to the combined T2K + NOvA fit when a fourth neutrino is included!

Preferred Parameter Space





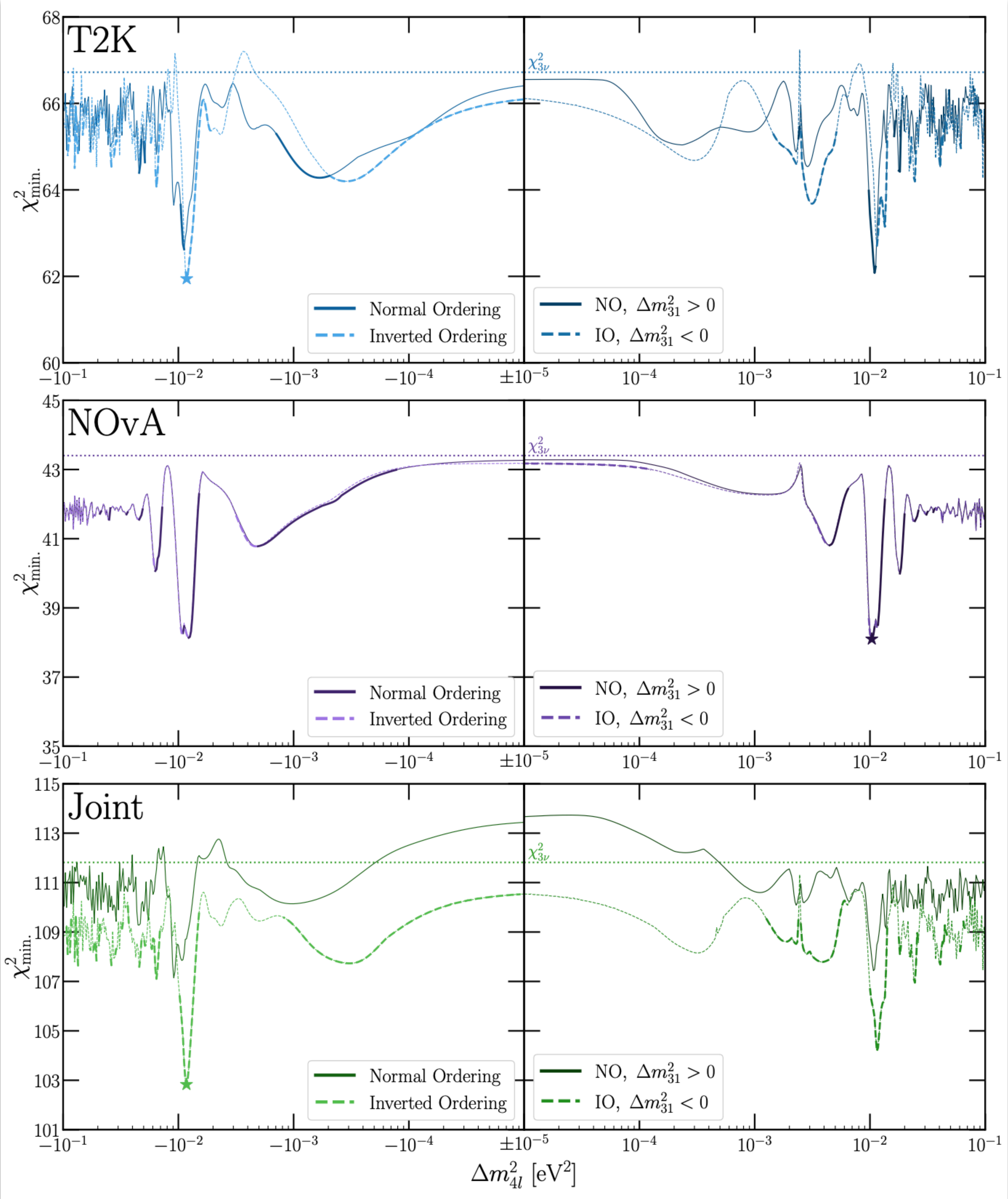
de Gouvêa et al, [2204.09130]

From NOvA's Neutrino2022 Talk — different datasets, broad agreement!

Any Caveats to Declare?

Even though T2K/NOvA show no strong preference for a fourth neutrino on their own, every fit we perform finds (some) preference when the new mass-squared splitting is on the order of 10^{-2} eV^2. For both experiments, with this new mass-squared spitting and their energy binning, individual bins will see significant oscillations across their bin widths.

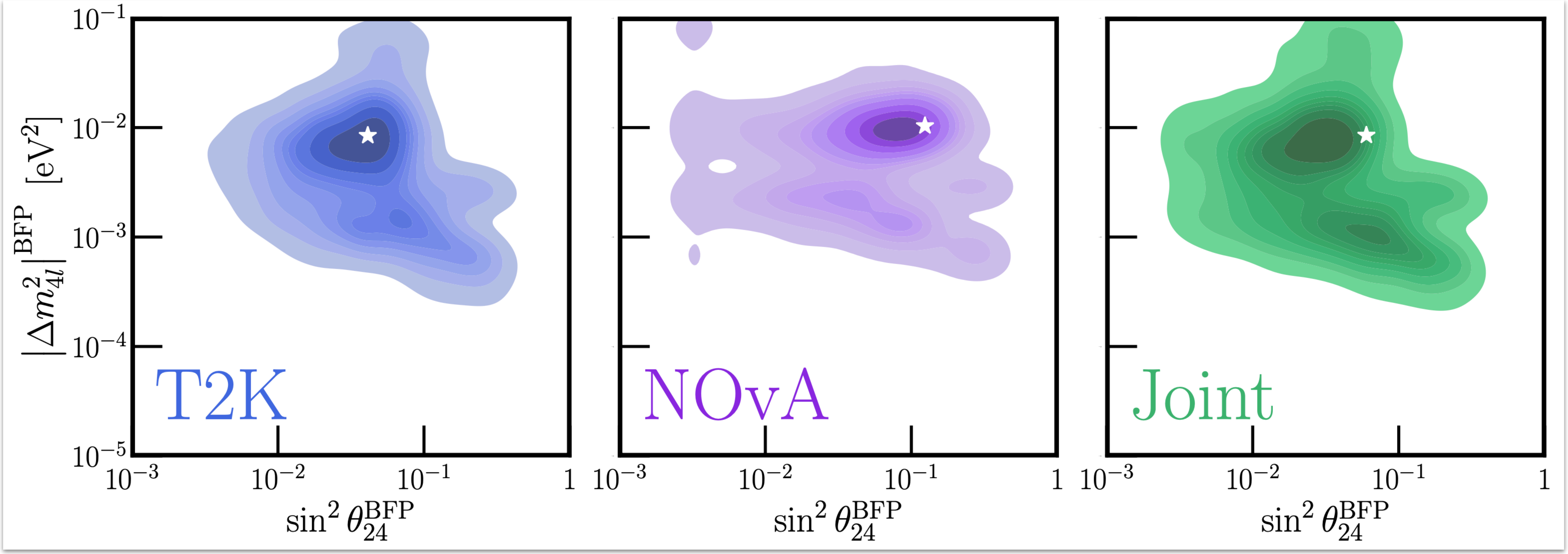
Are we simply absorbing statistical fluctuations in this new oscillation length?



de Gouvêa et al, [2204.09130]

Yes. (probably.)

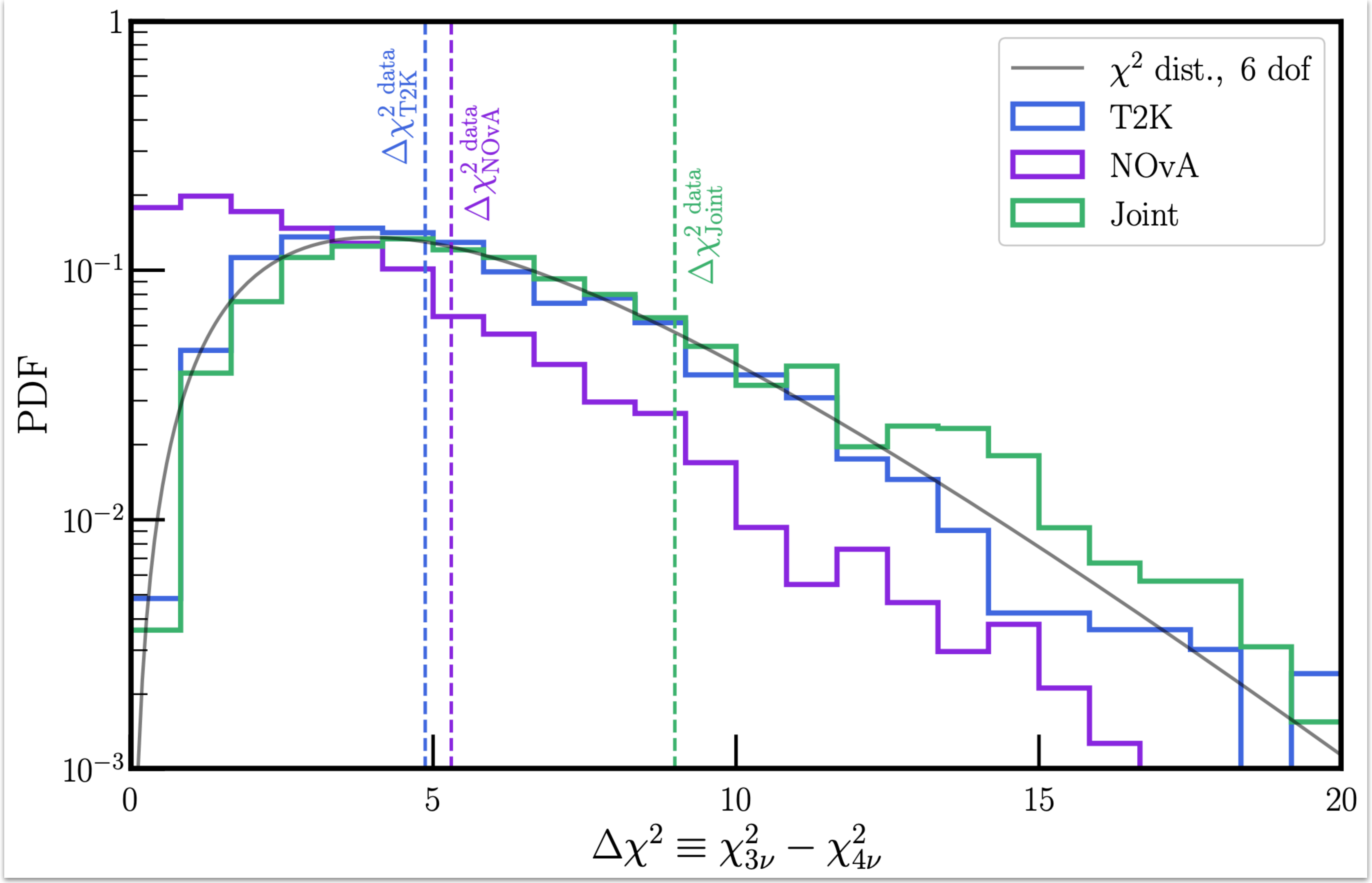
de Gouvêa et al, [2204.09130]



Simulate data according to three-neutrino hypothesis, including statistical fluctuations, and fit to four-neutrino hypothesis. Where do these fits end up? White stars are our best-fit points to the observed data.

How big of a Fake Preference?

de Gouvêa et al, [2204.09130]

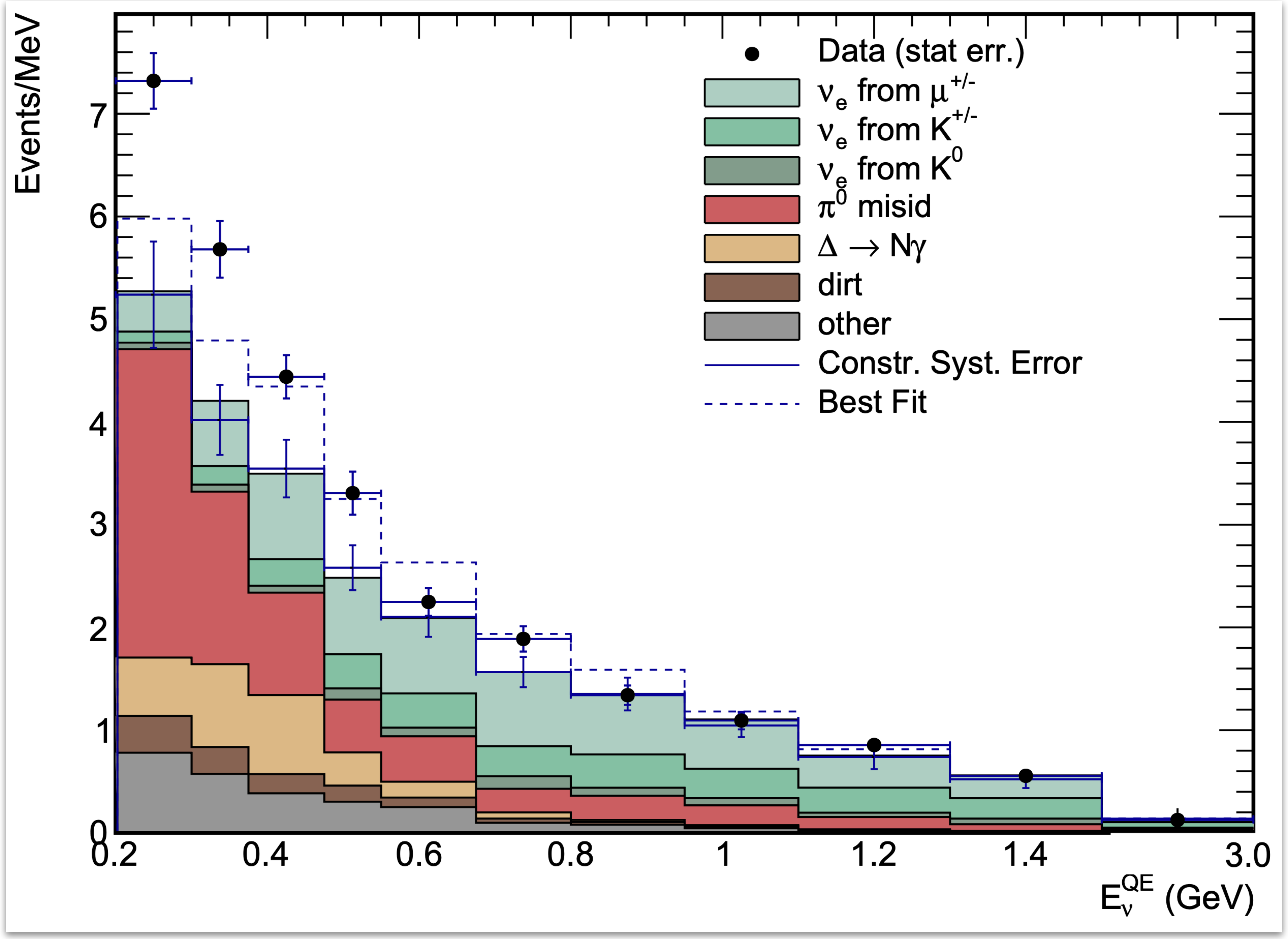


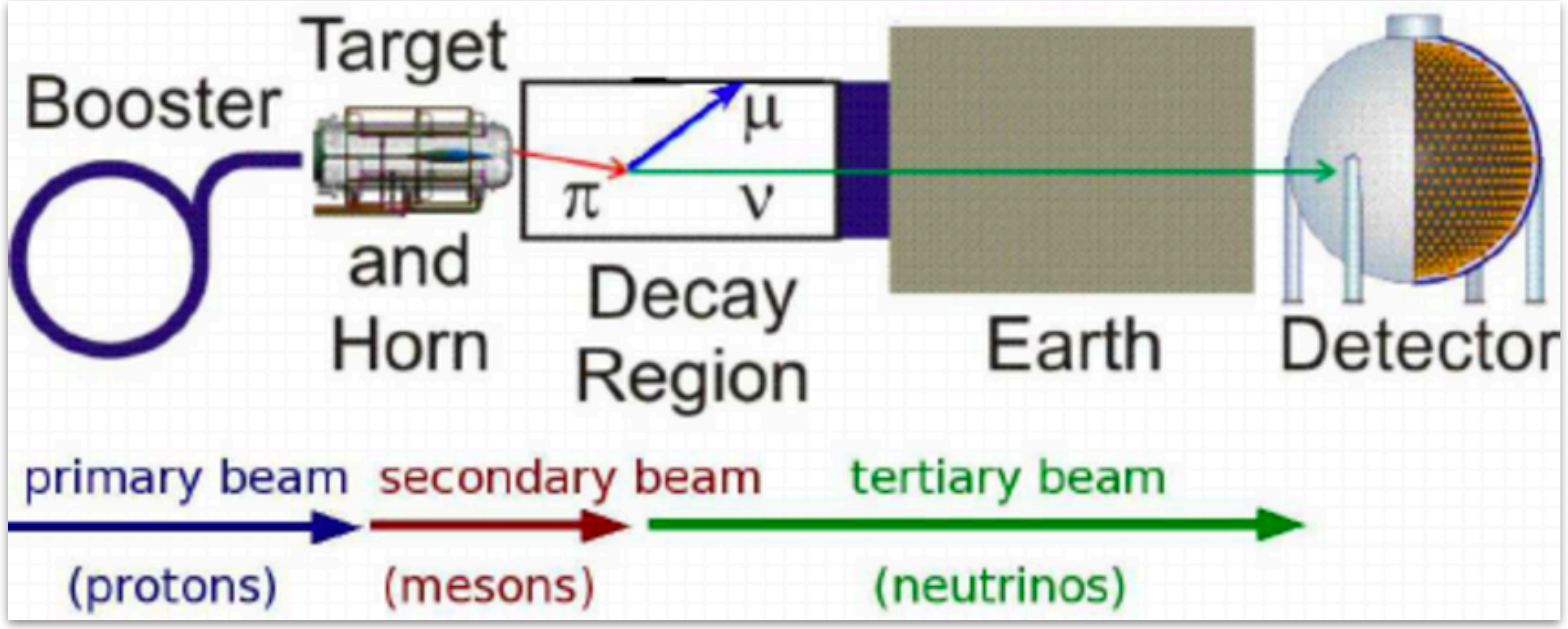
Accounting for this means that the $\Delta\chi^2$ preference of 8.99 that we observe only translates to a significance of approximately 0.22σ.

Recent Experimental Results

—MicroBooNE

The Challenge of MiniBooNE



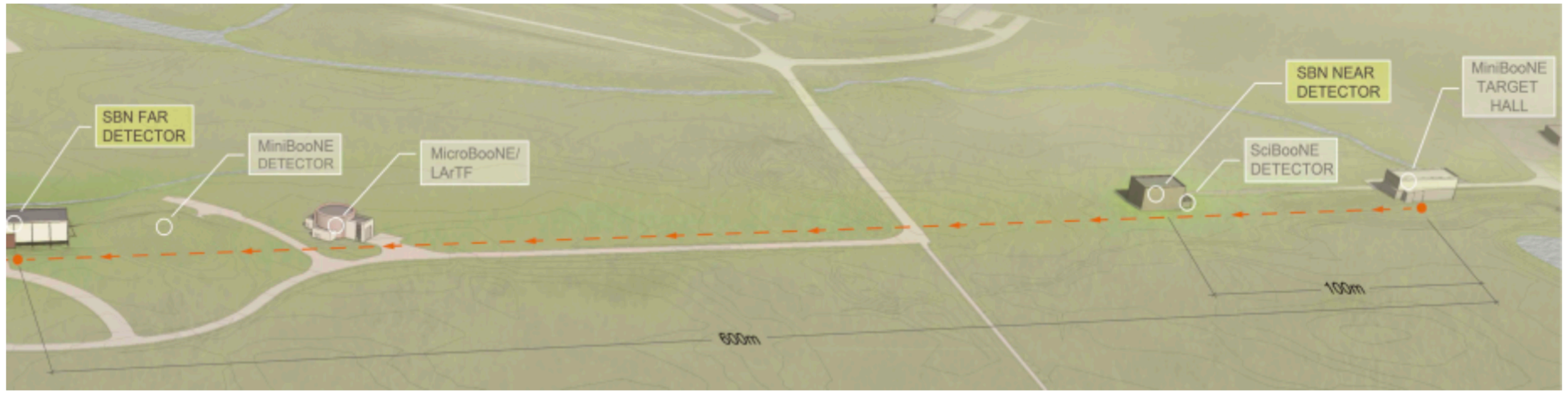


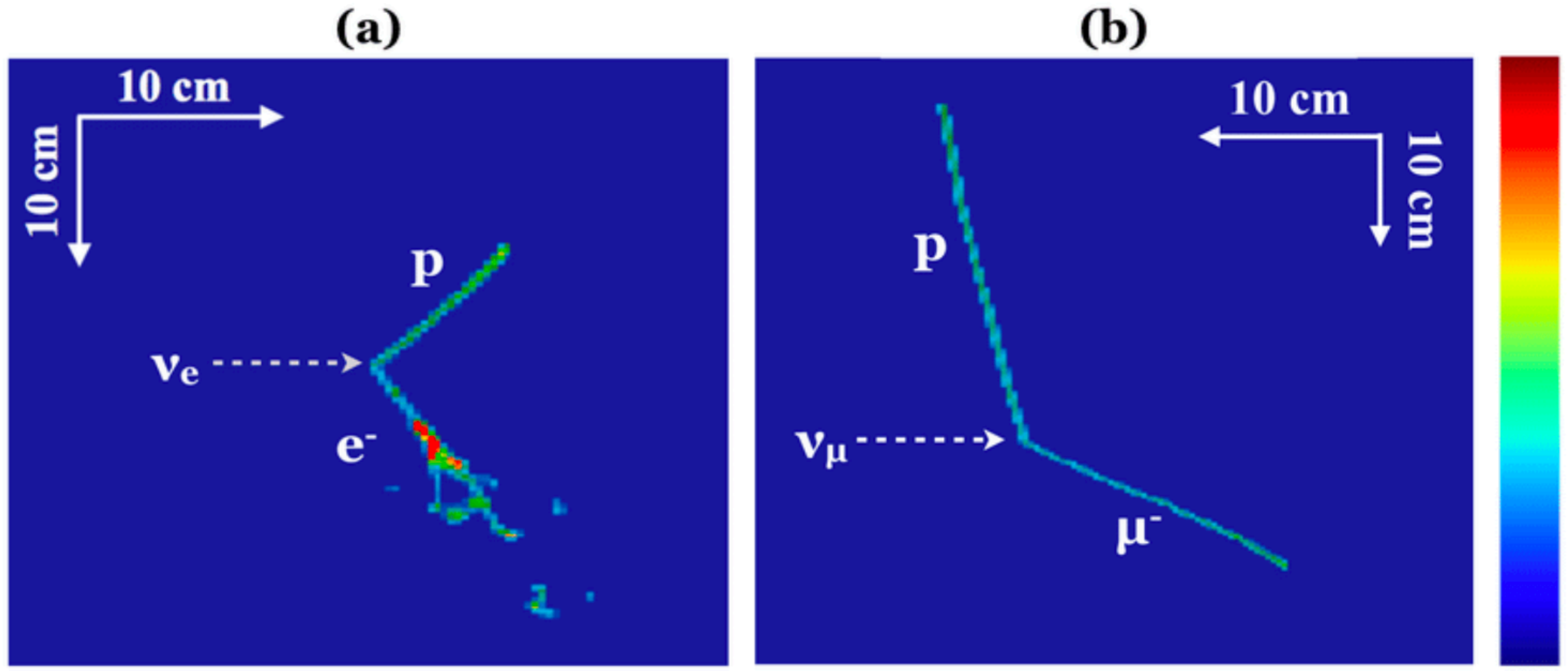
Cherenkov signatures in MiniBooNE are unable to distinguish between photons, electrons, and multiple-electron signatures.

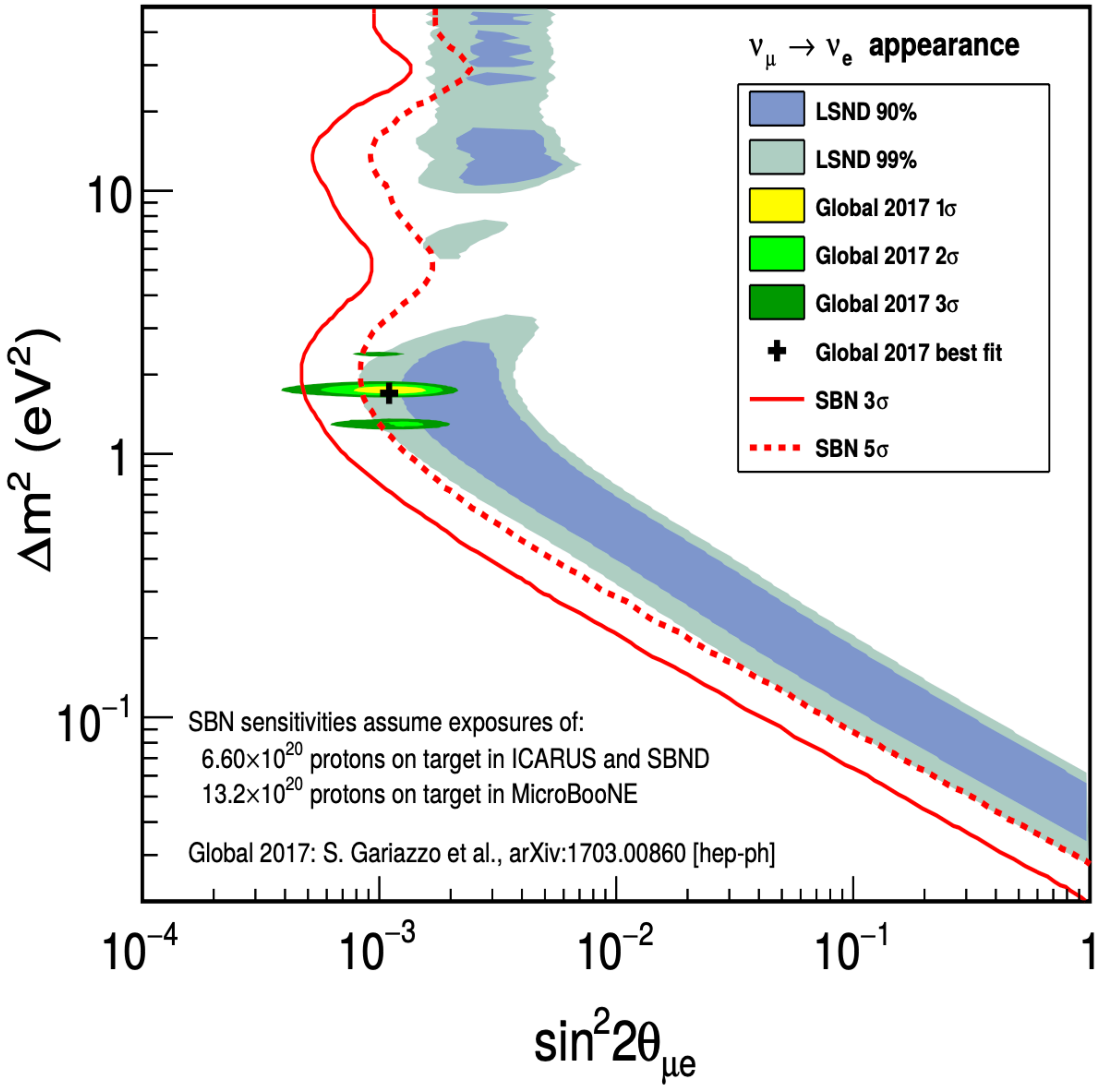
The SBN Programme

Let's solve this **once and for all**!

(Courtesy of Ivan Esteban)

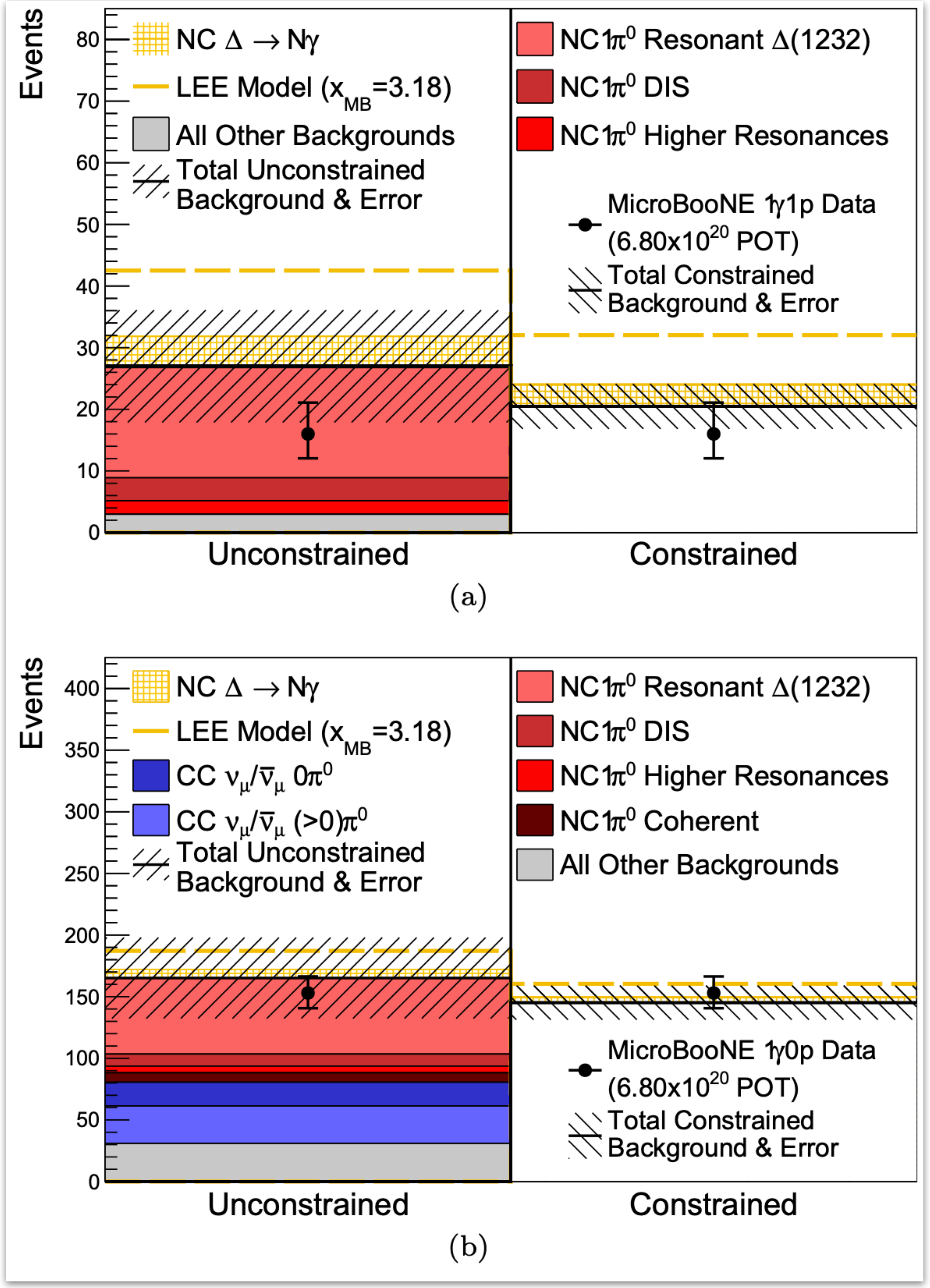






Liquid Argon Time Projection Chambers — “Colored Bubble Chambers”

MicroBooNE Photon Analysis

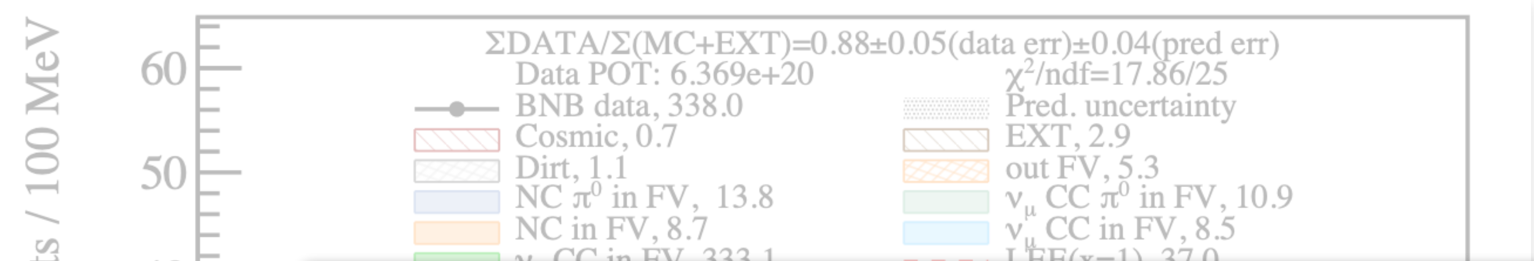


MicroBooNE Collaboration, [2110.00409]

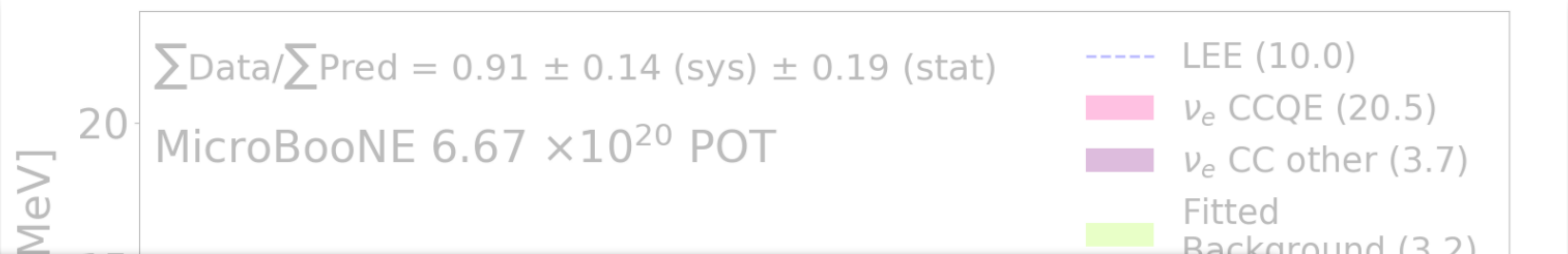
MicroBooNE disfavors the $\Delta \to N\gamma$ explanation of the MiniBooNE anomaly at 94.8% CL.

MicroBooNE Electron Analyses

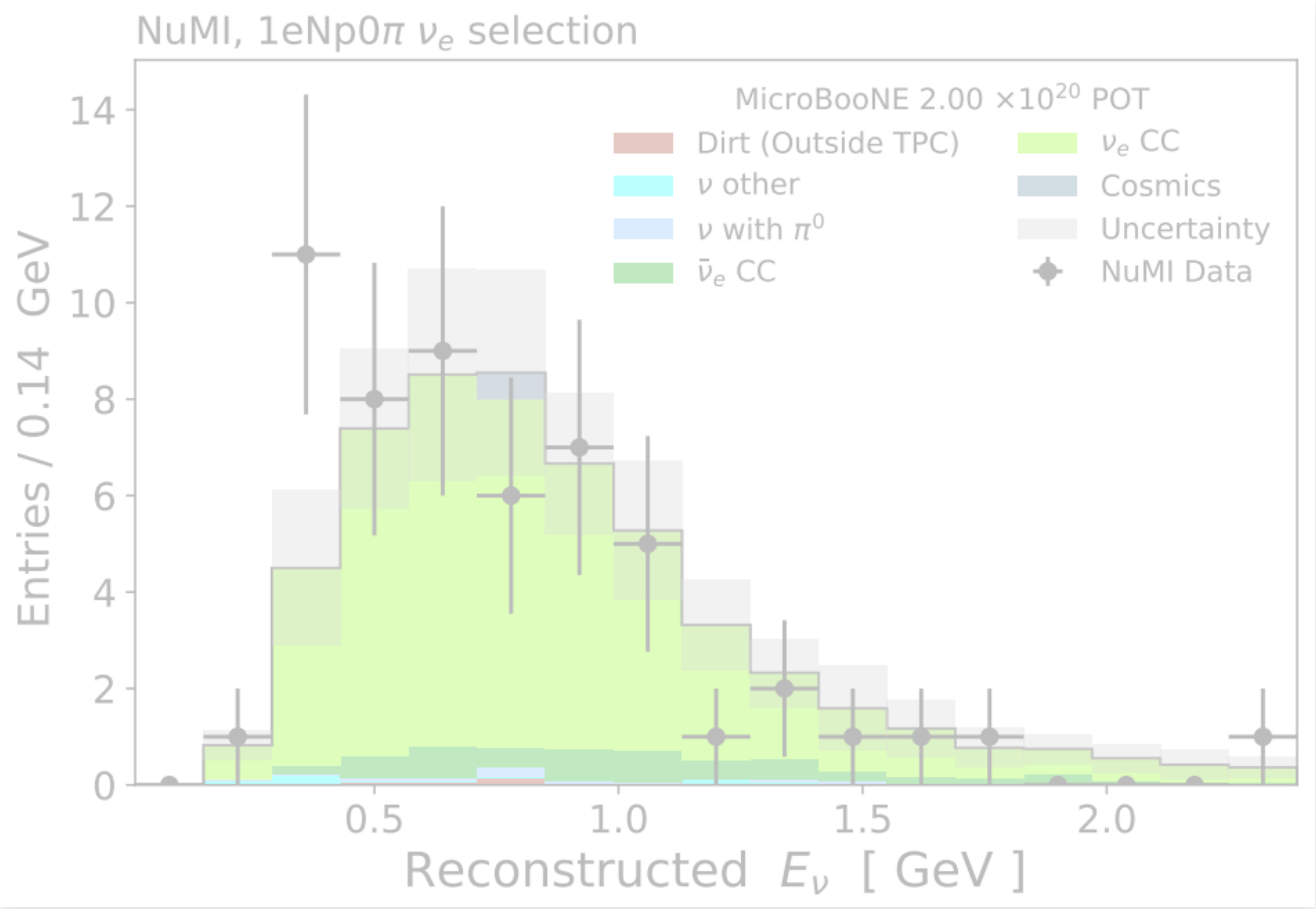
"Inclusive" [2110.13978]

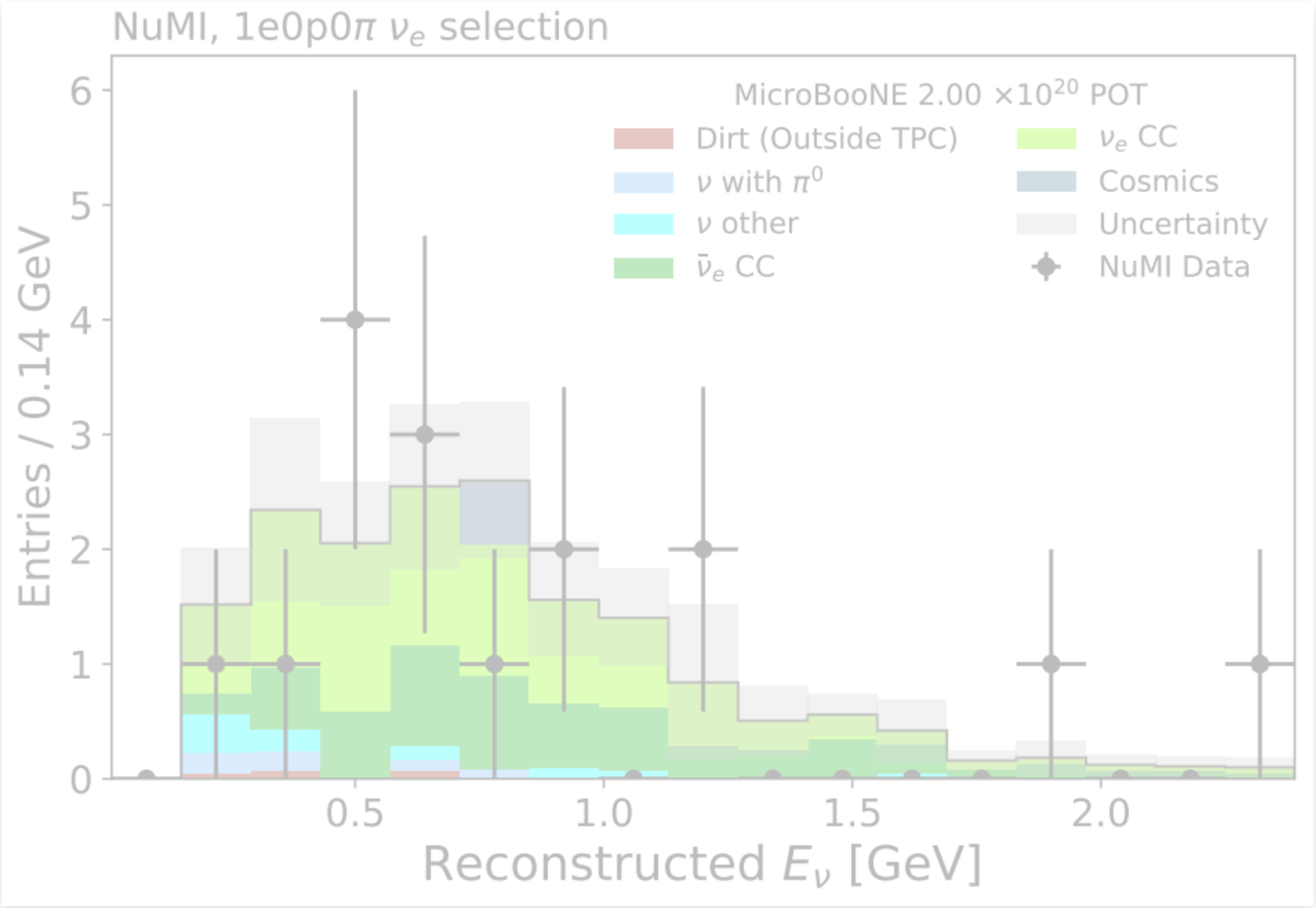


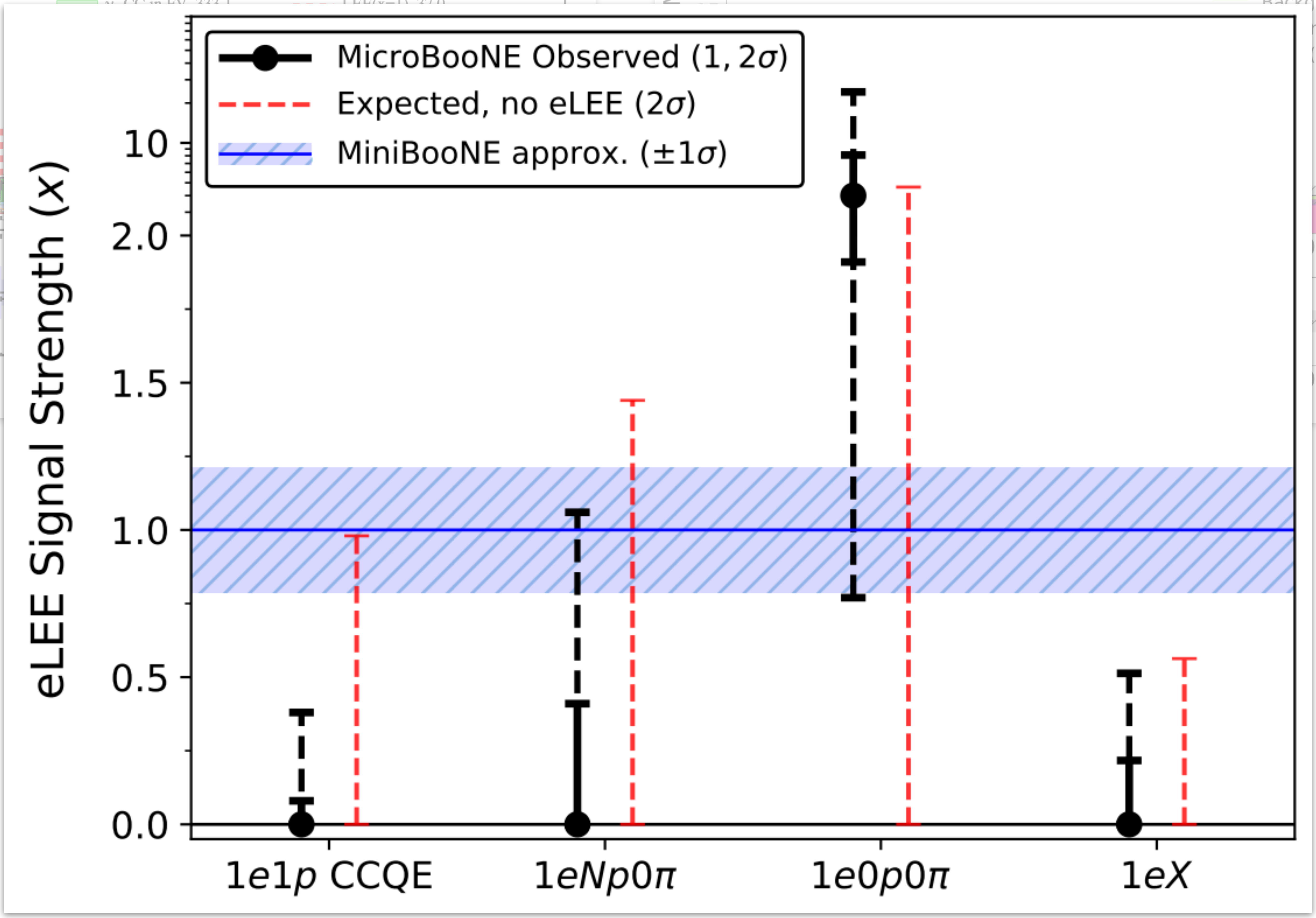
"CCQE" [2110.14080]



"Pionless" [2110.14065]



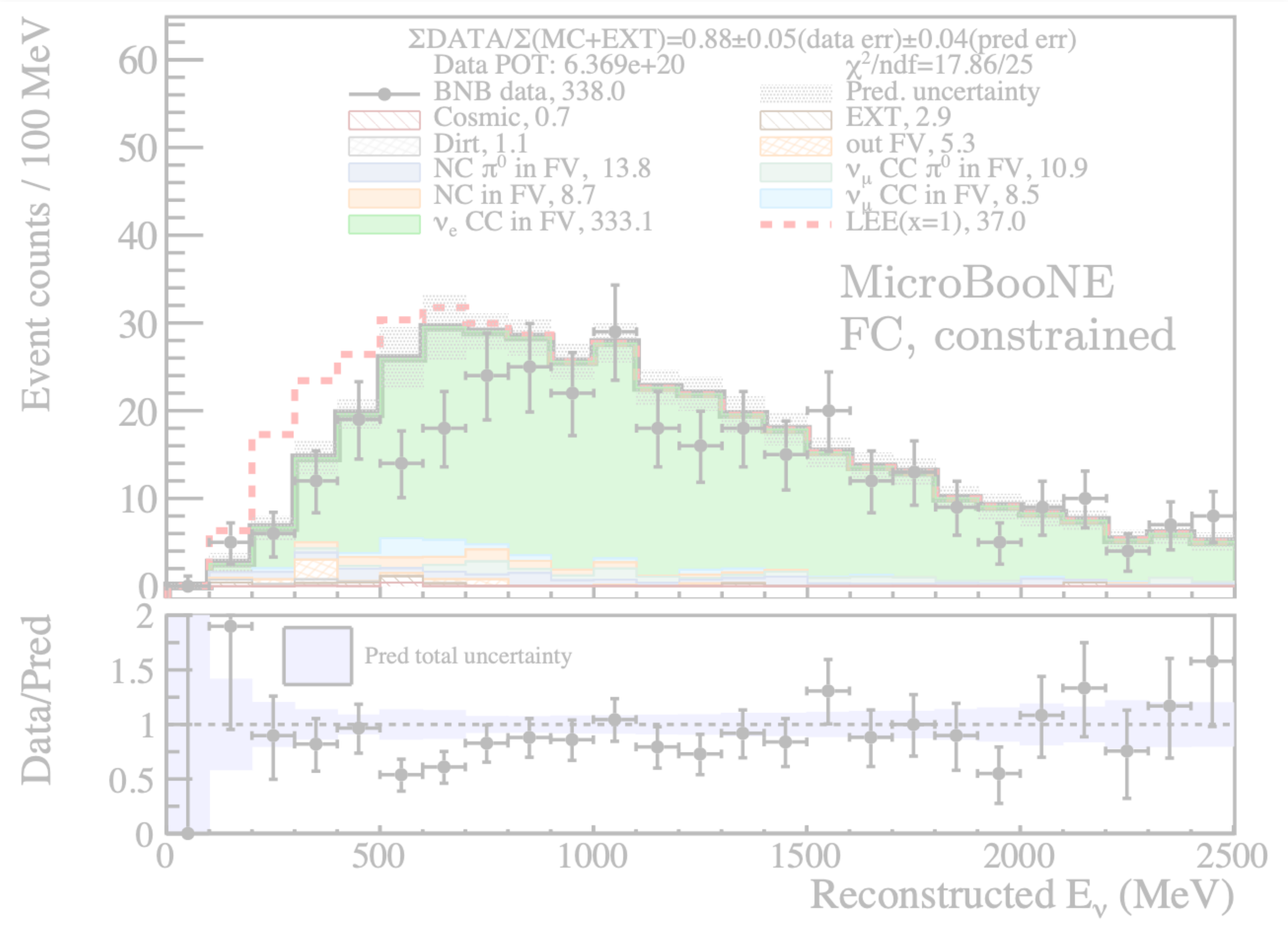




Discussion of all Results [2110.14054]

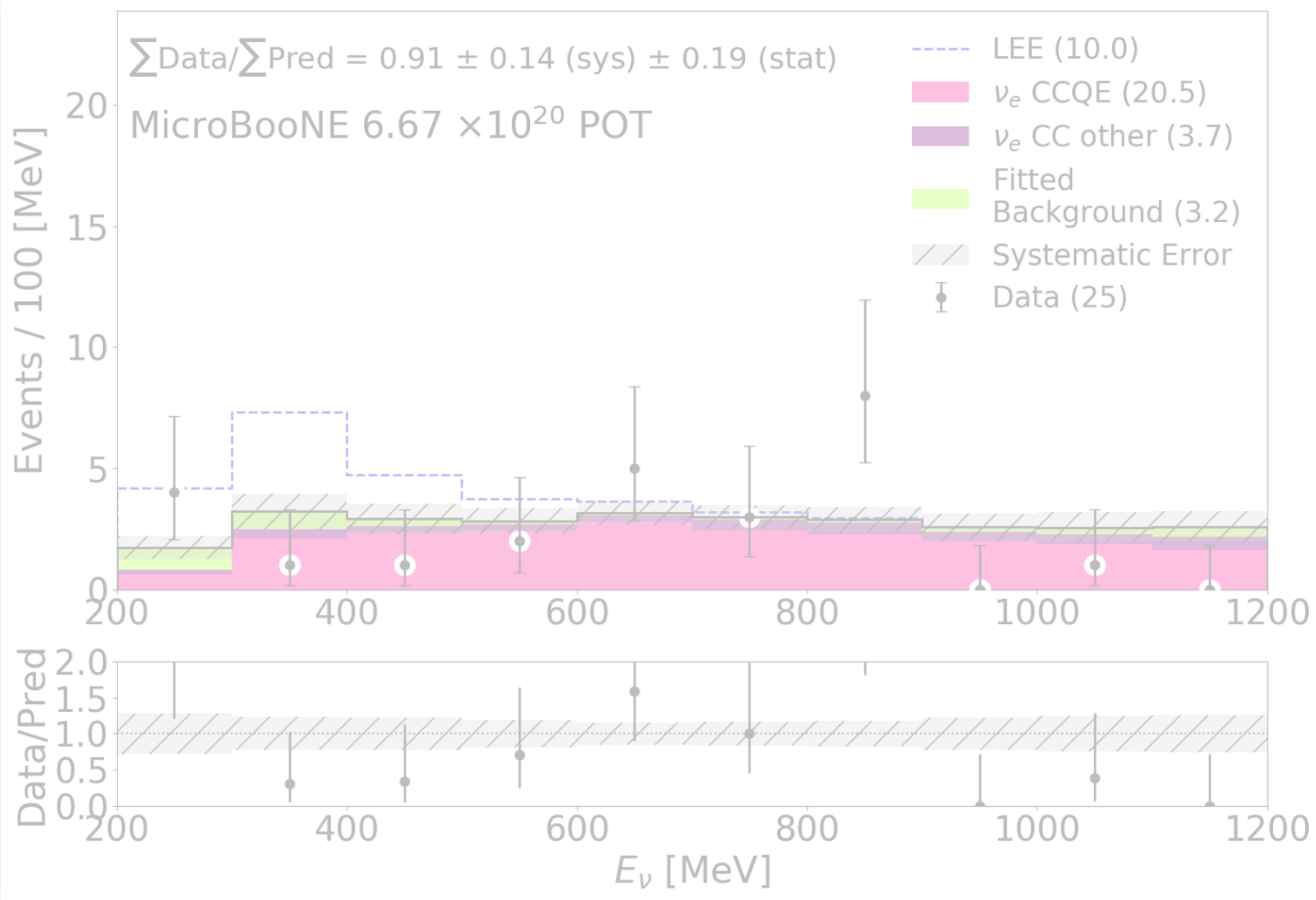
Complementarity of Inclusive/CCQE

"Inclusive" [2110.13978]



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

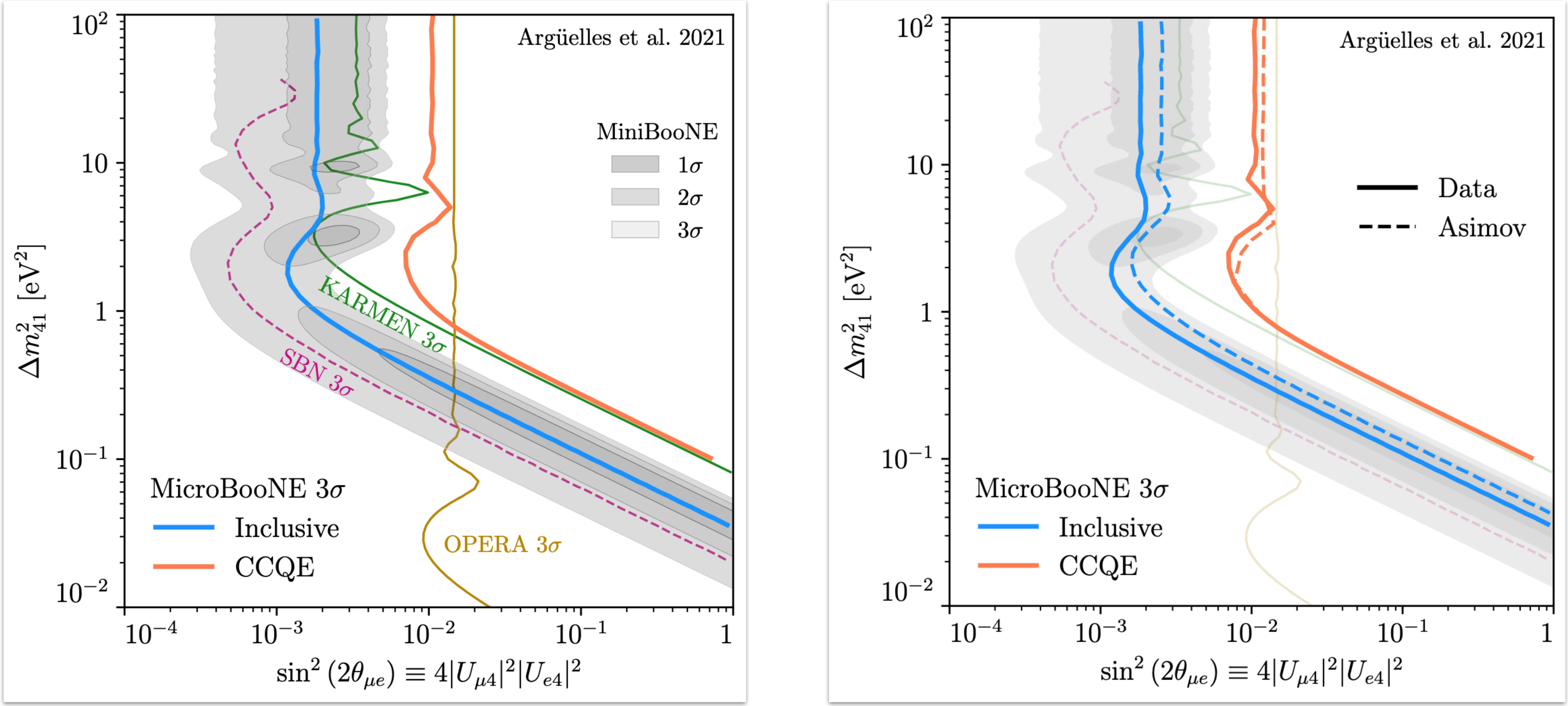
"CCQE" [2110.14080]



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

MicroBooNE and Sterile Neutrinos

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



Argüelles, KJK, et al, [2111.10359]

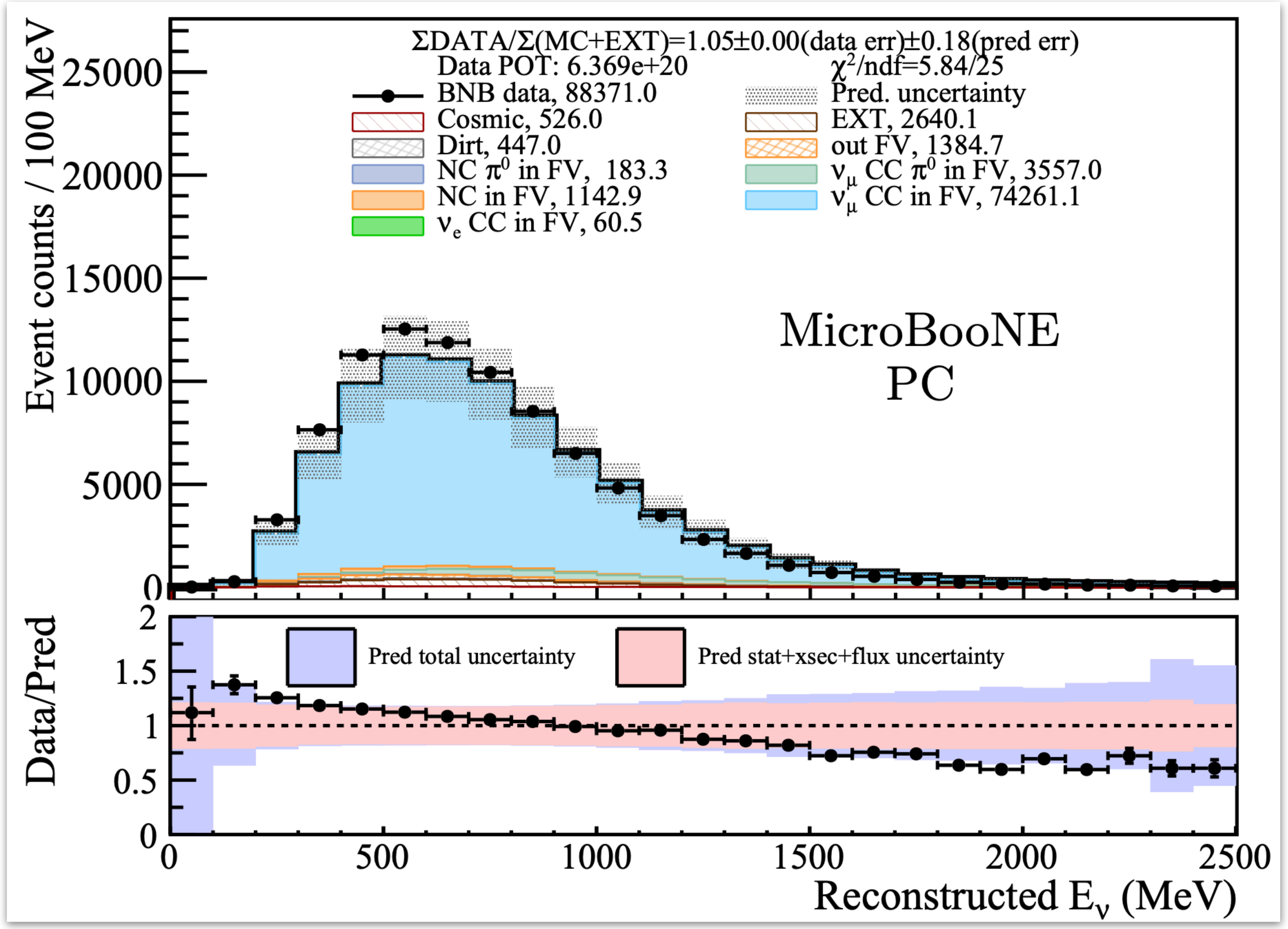
Complete 3+1 Neutrino Framework

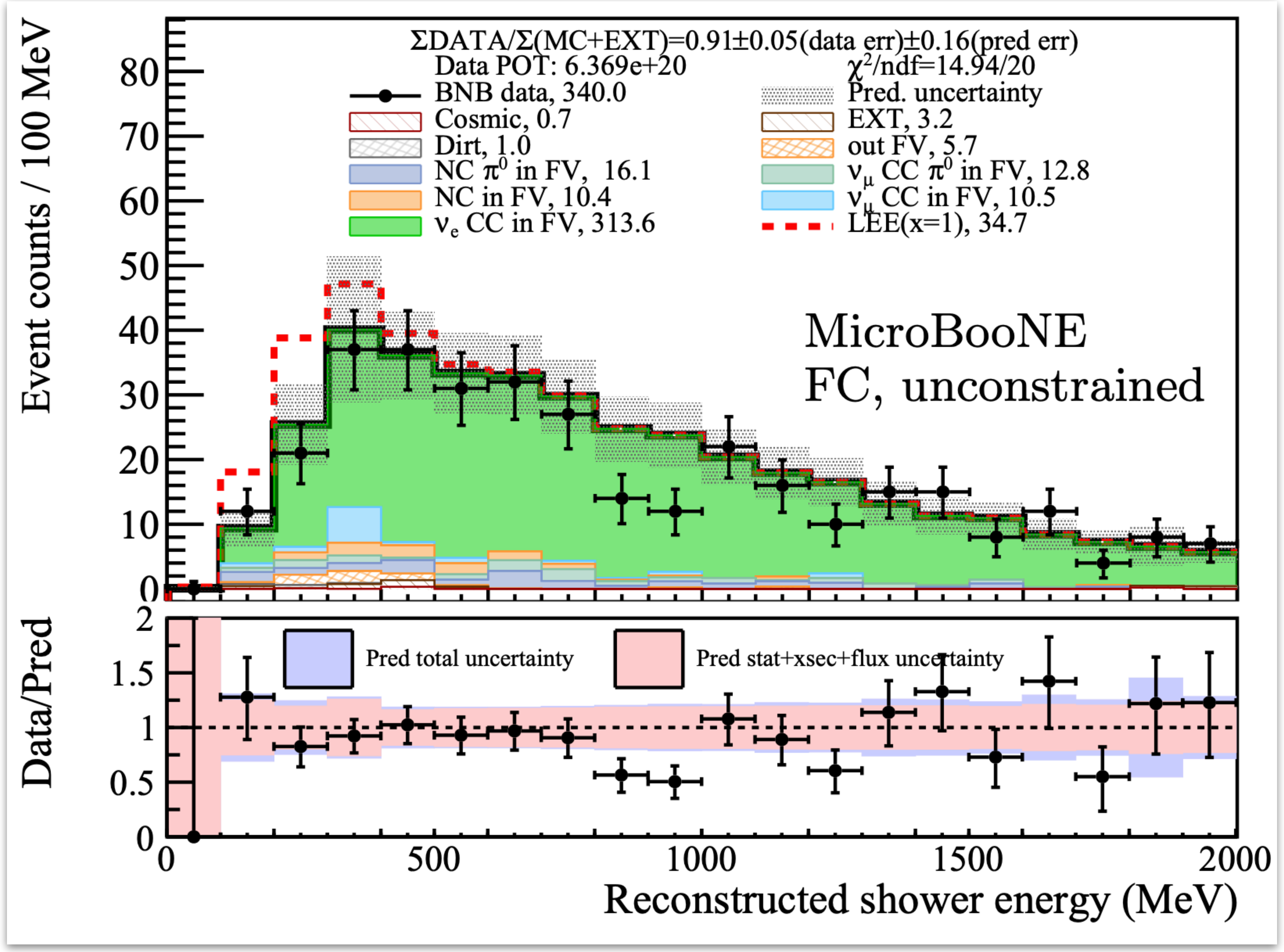
$$P\left(\nu_\mu \to \nu_e\right) = 4|U_{\mu4}|^2|U_{e4}|^2\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

Anomalous appearance *requires* disappearance!

$$P\left(\nu_\mu \to \nu_\mu\right) = 4|U_{\mu4}|^2\left(1-|U_{\mu4}|^2\right)\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

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

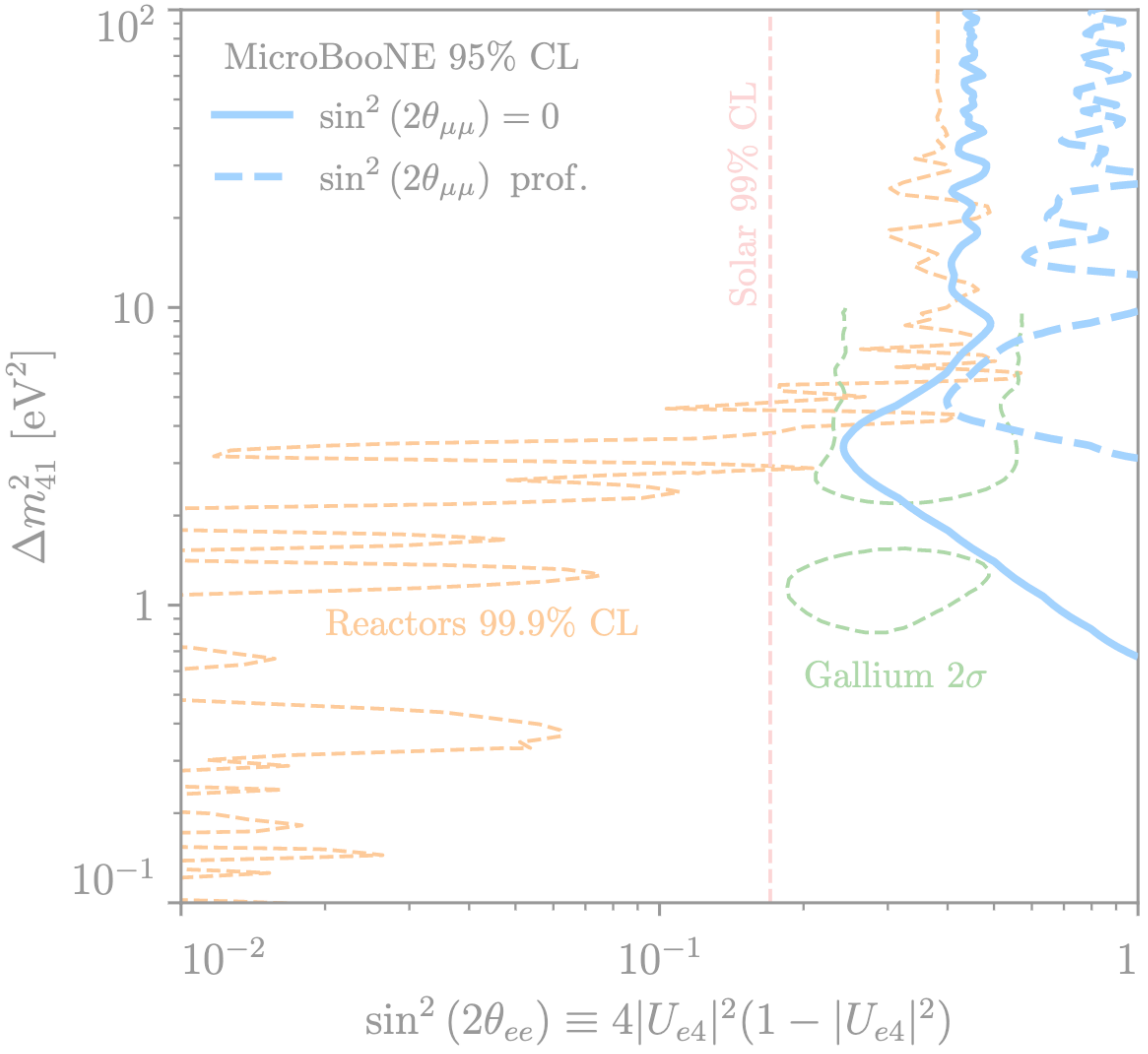


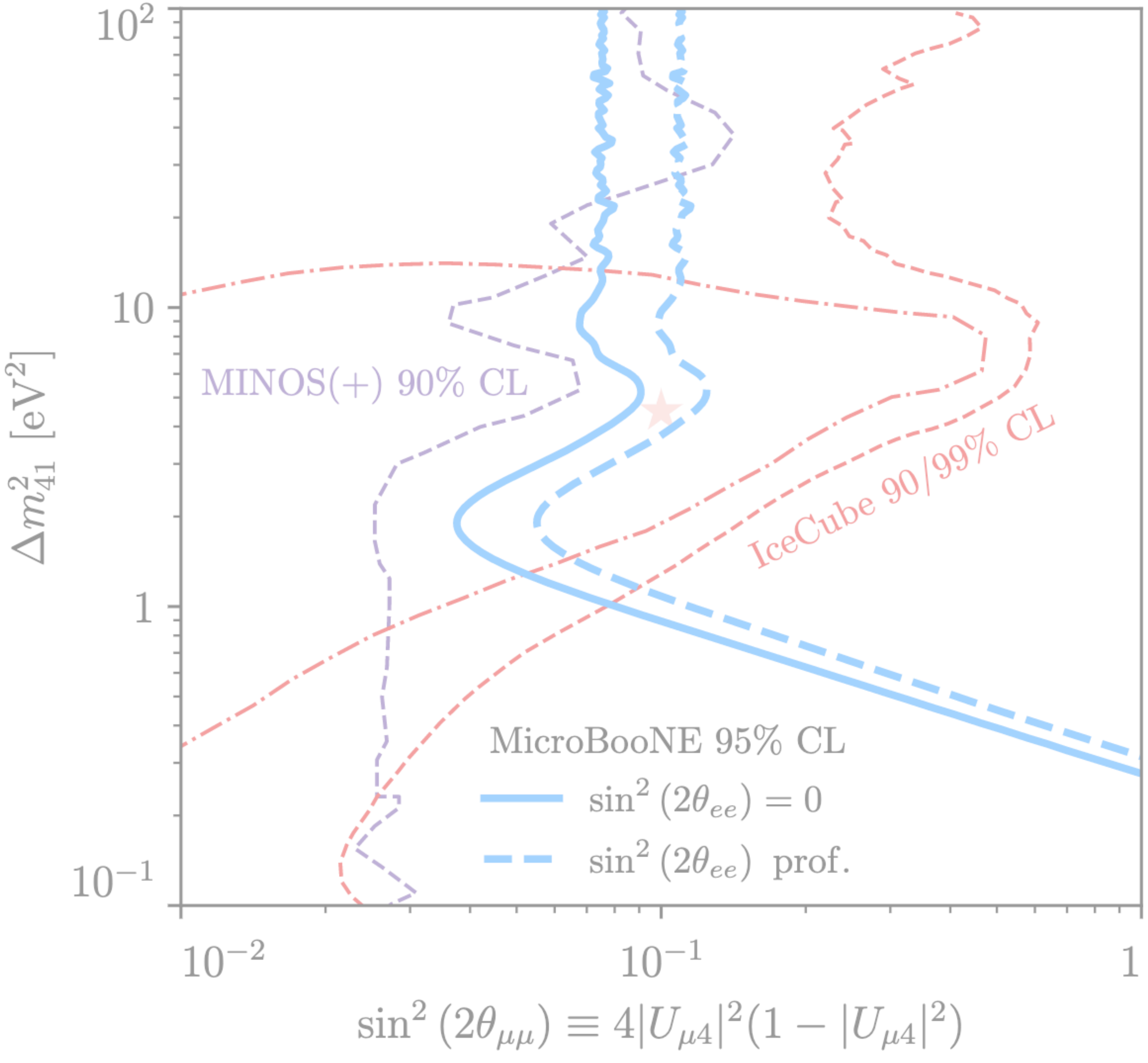


MicroBooNE, [2110.13978]

Four-Flavor Results

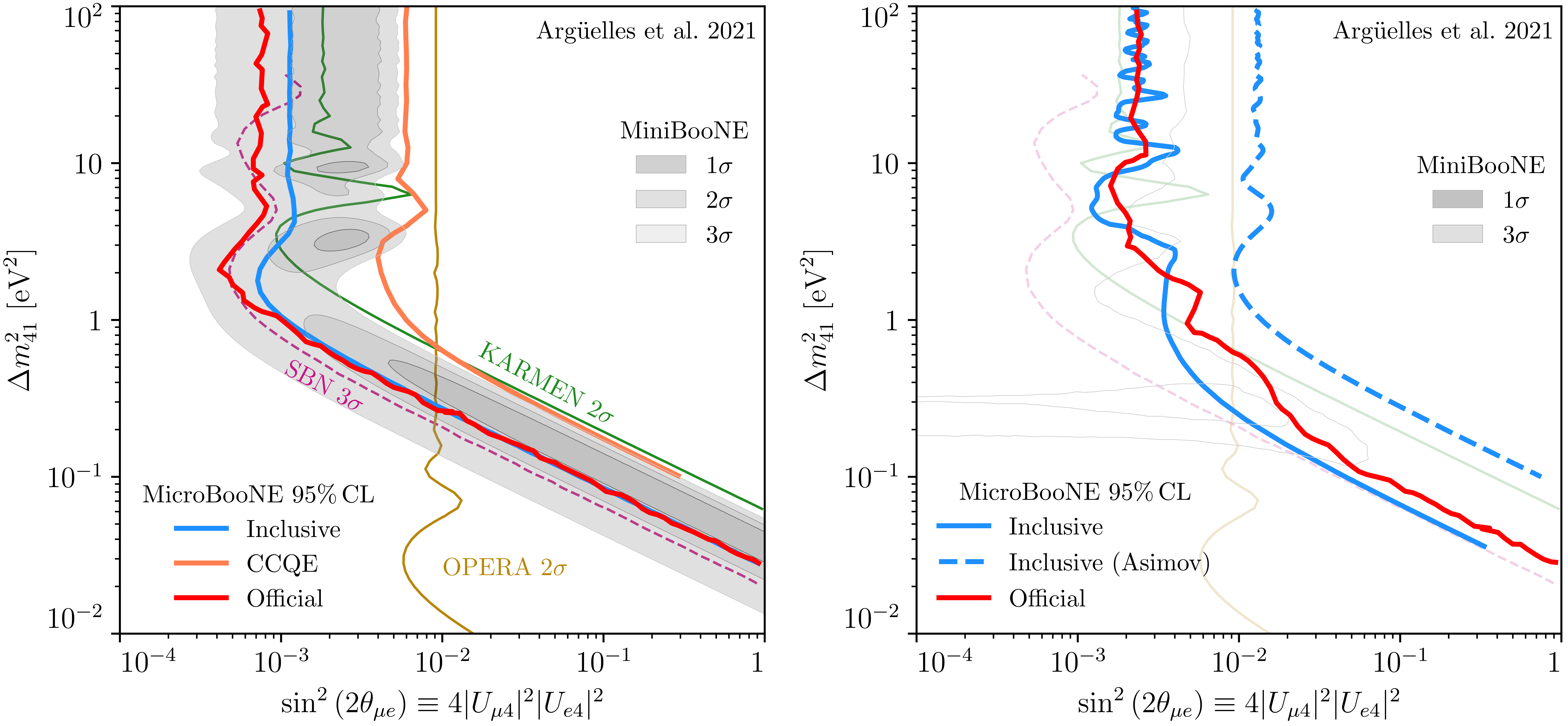
Argüelles et al, [2111.10359]





MicroBooNE Official Comparisons

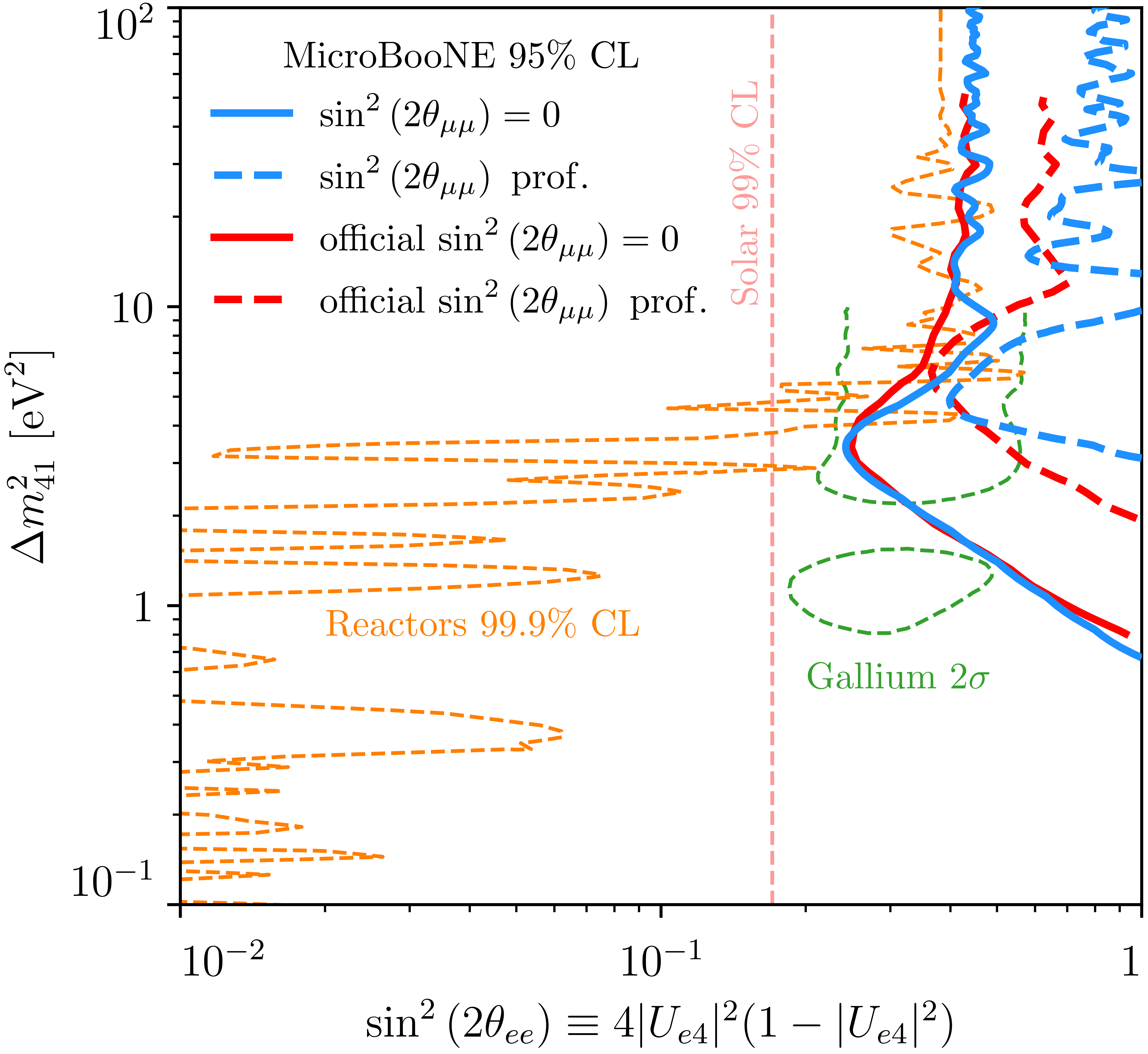
MicroBooNE: [2210.10216]



We *think* we understand the differences between our/MicroBooNE's results. Feel free to ask me offline.

MicroBooNE Official Comparisons

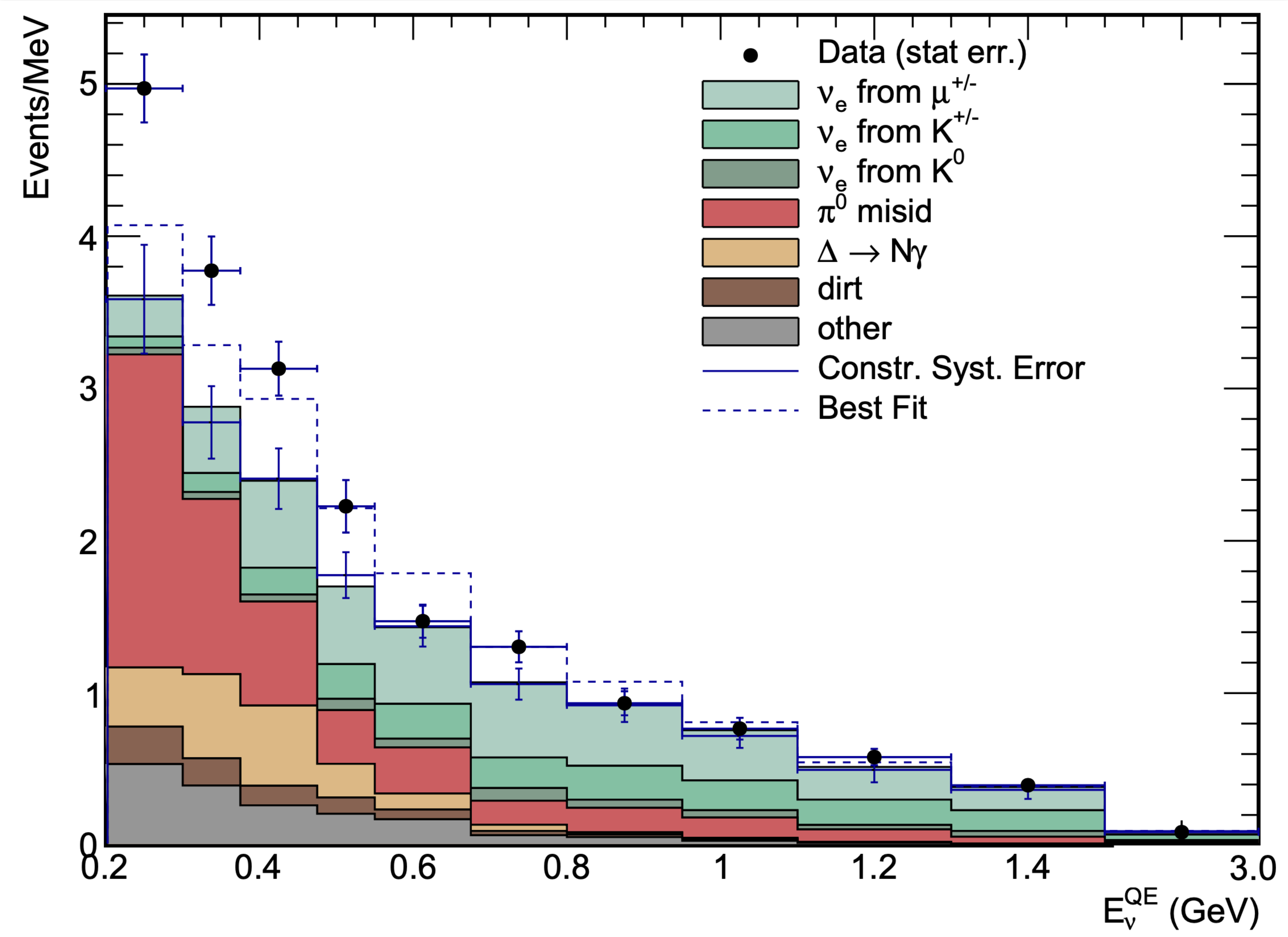
MicroBooNE: [2210.10216]



Beyond Sterile Neutrinos

Other Electron-Neutrino Explanations?

Electron-like events in MiniBooNE



MiniBooNE Collaboration [1805.12028]

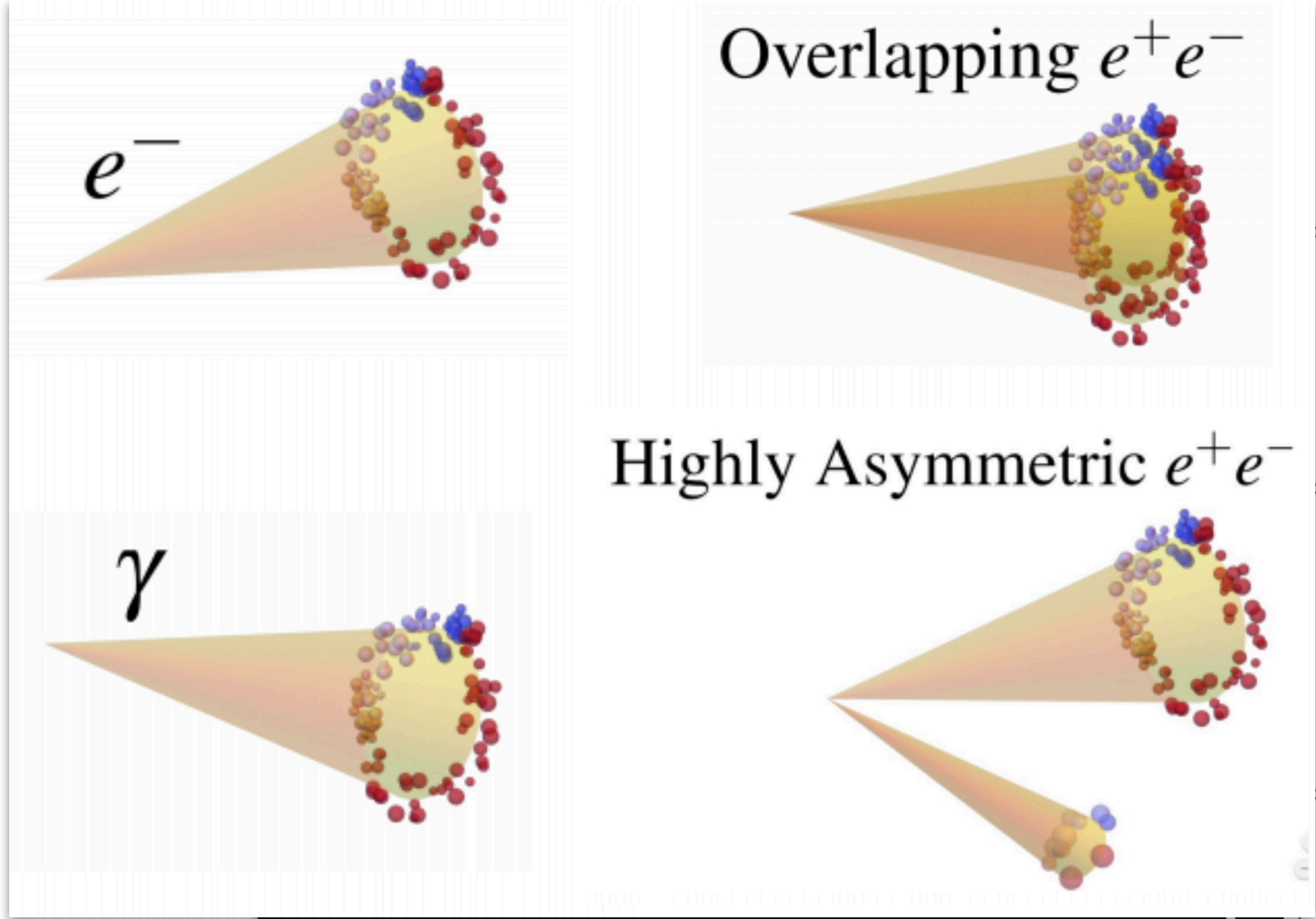
Laundry List of Explanations

From M. Hostert

NF02 White Paper: arXiv:2203.07323. Questions (and complaints) → *mhostert@pitp.com*

Table of explanations of the short-baseline anomalies

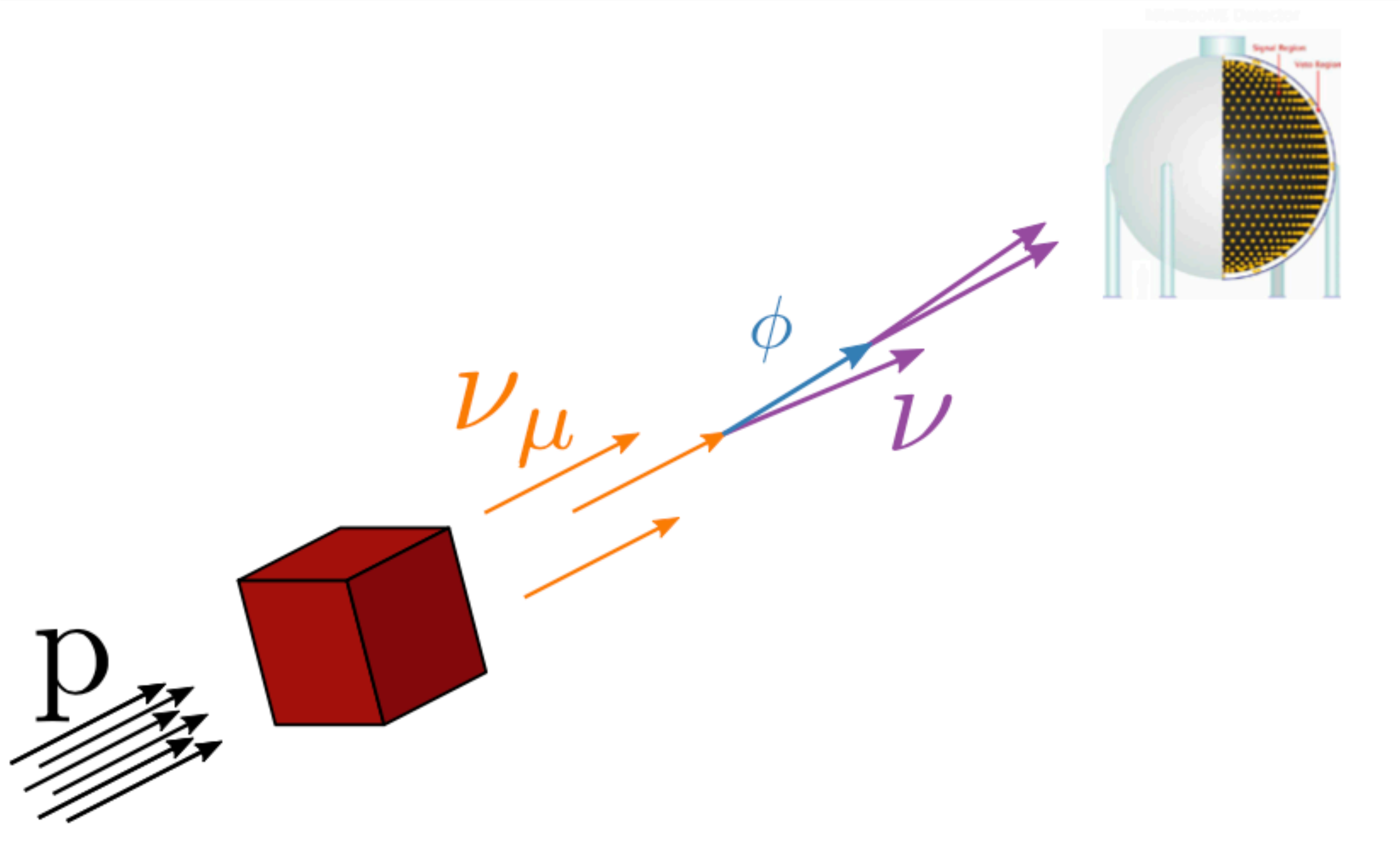
Category	Model	Signature	Anomalies: LSND	Anomalies: MiniBooNE	Anomalies: Reactors	Anomalies: Sources	References
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \to \phi \nu_e$	✓	✓	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \to N A$, $N \to \nu e^+ e^-$ or $N \to \nu\gamma\gamma$	✓	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \to N A$, $N \to \nu\gamma$	✓	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or e^+e^-	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]



A nice, model-independent approach? Brdar et al, [2007.14411]

An “Altarelli Cocktail” of backgrounds in MiniBooNE? Brdar and Kopp, [2109.08157]

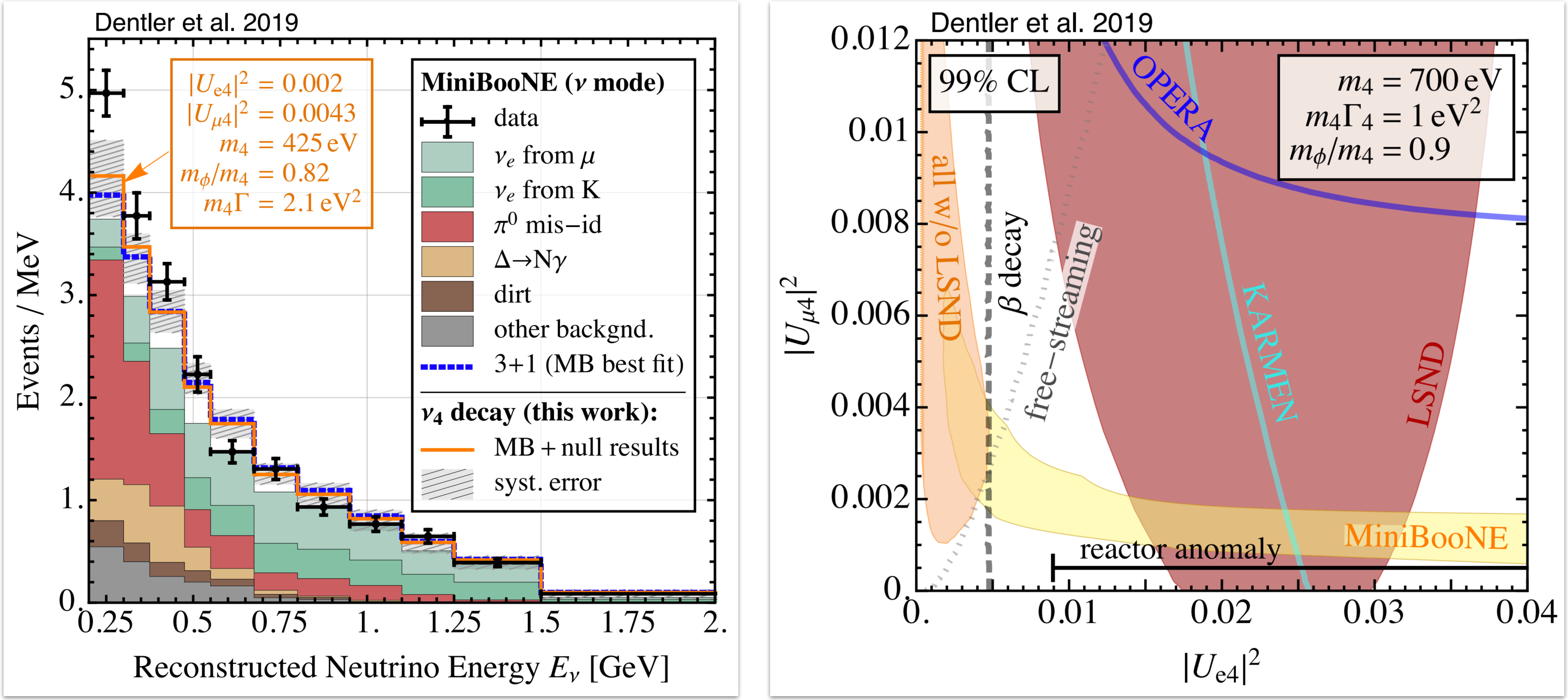
Visibly Decaying Sterile Neutrinos



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

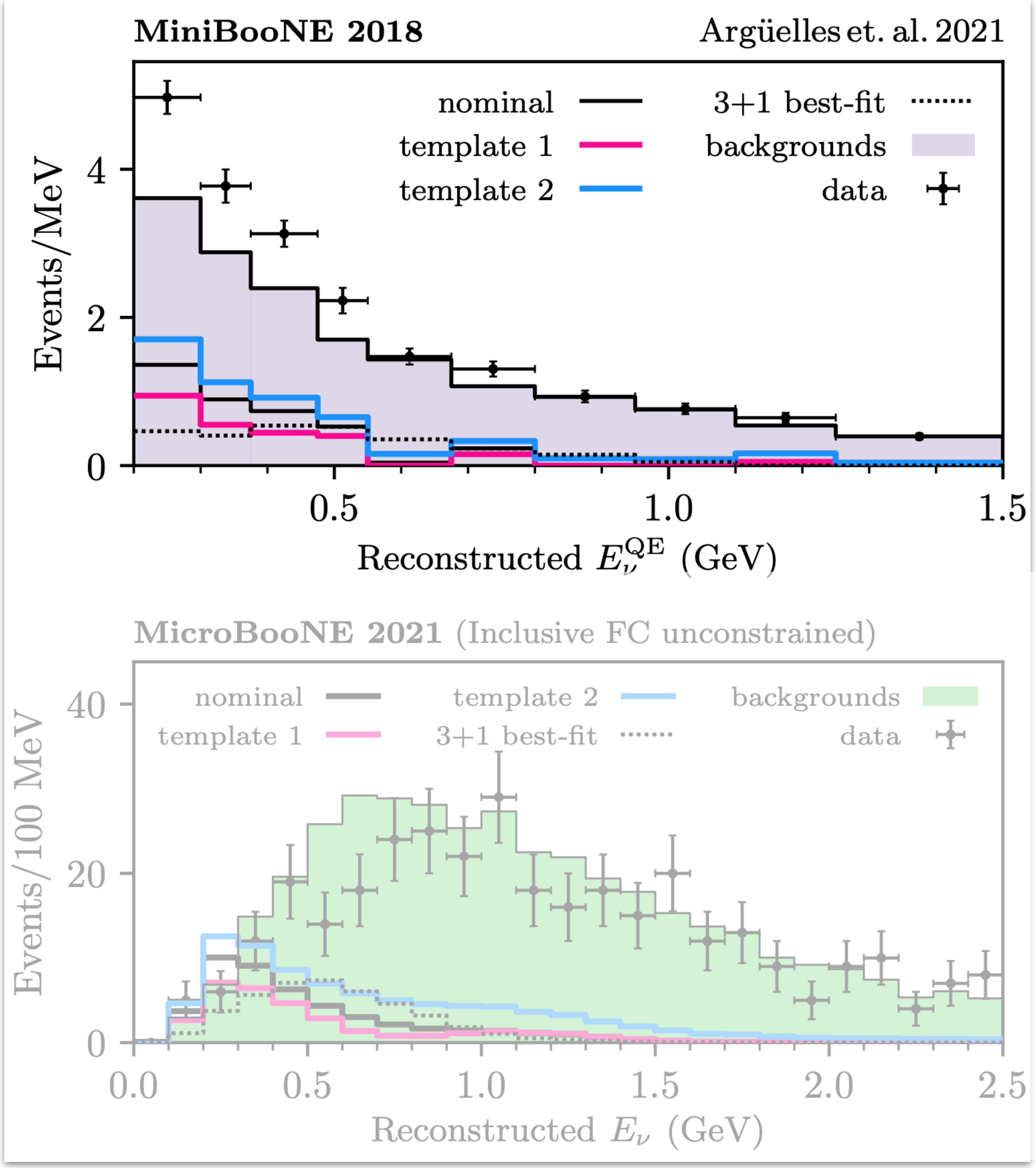
Visibly Decaying Sterile Neutrinos

Dentler et al [1911.01427]

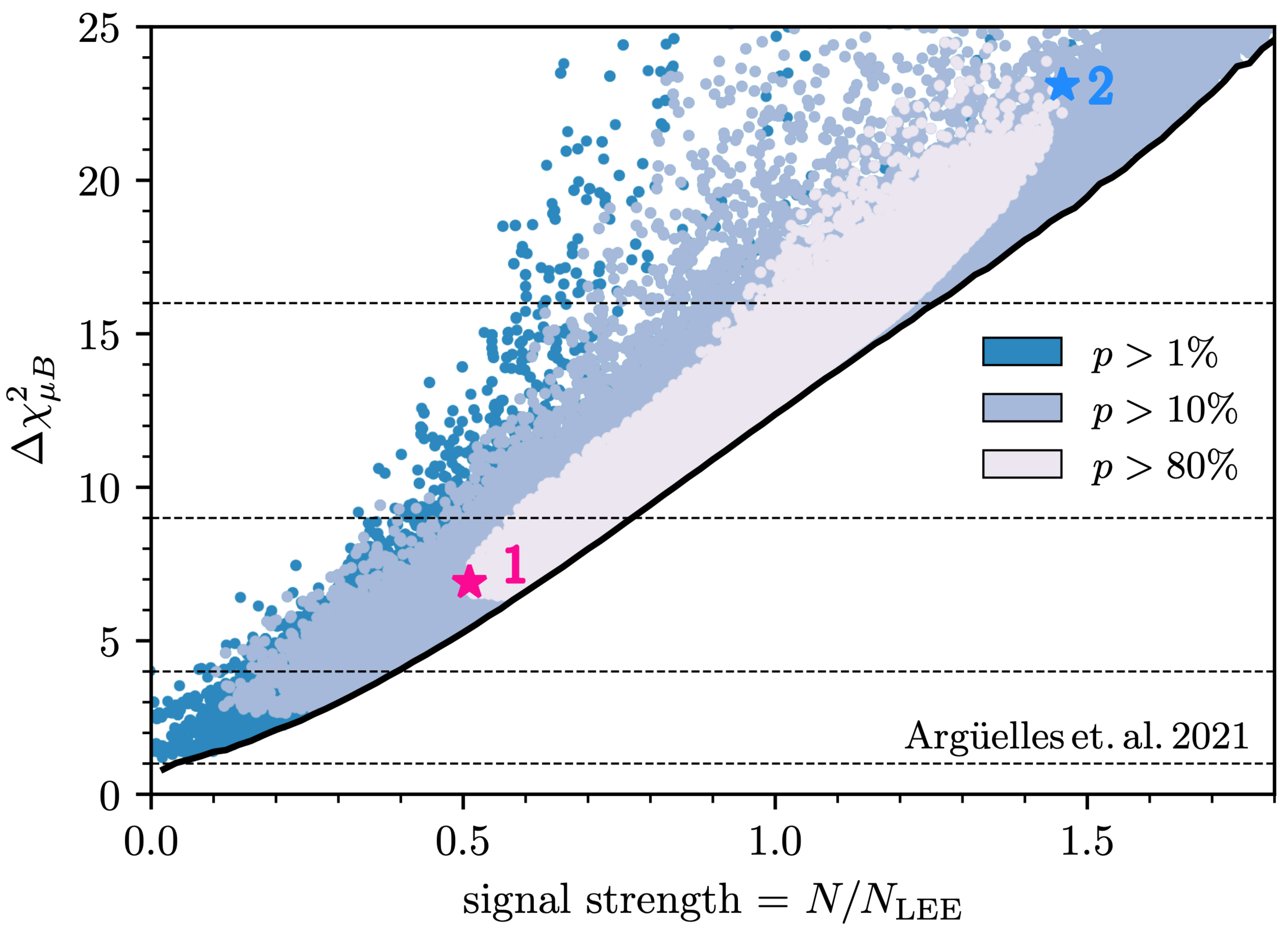


However, this model predicts **anti**neutrinos coming from solar neutrinos decaying, which is strongly constrained — Hostert & Pospelov [2008.11851]

Can MicroBooNE say anything about this, and other models?



[2111.10359]



- Plenty of electron-neutrino templates that fit MiniBooNE well that MicroBooNE hasn't (yet) ruled out significantly — are any of these spectra predicted in a new-physics model?

Conclusions

- The MiniBooNE and LSND anomalies (and some other results) have fueled interest in sterile neutrino searches for nearly two decades.
- Tensions between appearance-type and disappearance-type searches lead to inconclusive results.
- Long-baseline tensions provide an interesting ground to explore light sterile, though more data is certainly needed.
- MicroBooNE's recent results have begun to test MiniBooNE's results comprehensively.
    - The lack of electron-type signature puts a strong constraint on sterile-neutrino parameter space, but the work is not done yet!
- Still hope to be had — upcoming neutrino experiments are BSM factories (hopefully)!

Thank you!