Going NuTs

over the short-baseline anomalies

Kevin J. Kelly, CERN

IFT NuTs Workshop, 2nd June 2022

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[2111.10359] & [2204.09130] with many great collaborators

Outline

- How did we get here?
  - Anomalies and additional neutrino states

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  - Interpretation in four-neutrino framework

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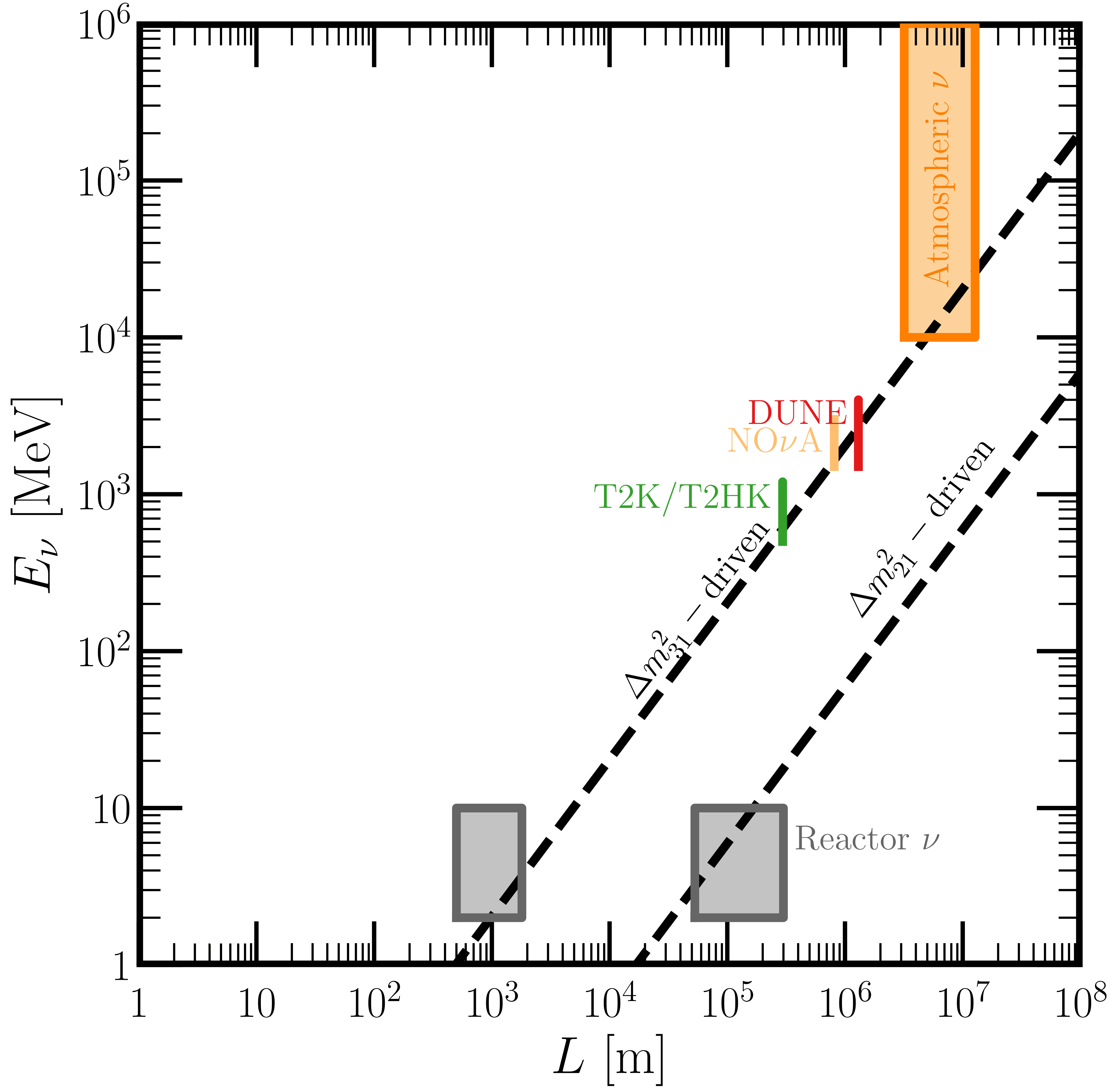
- The latest & greatest results
  - Interpretation in four-neutrino framework
- Beyond the sterile neutrino picture
  - Testable new-physics in current & upcoming experiments

Where do we measure oscillations?



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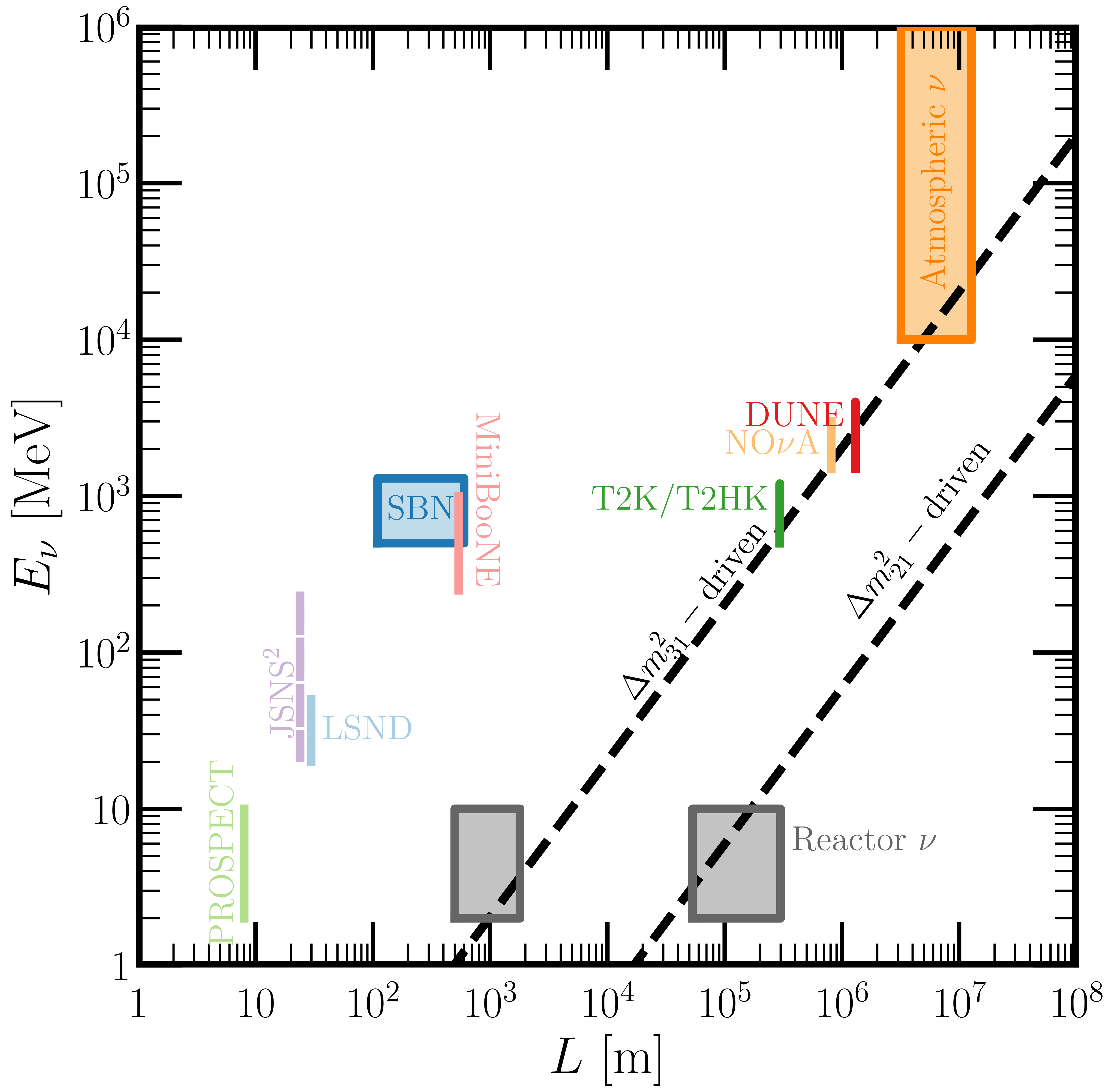
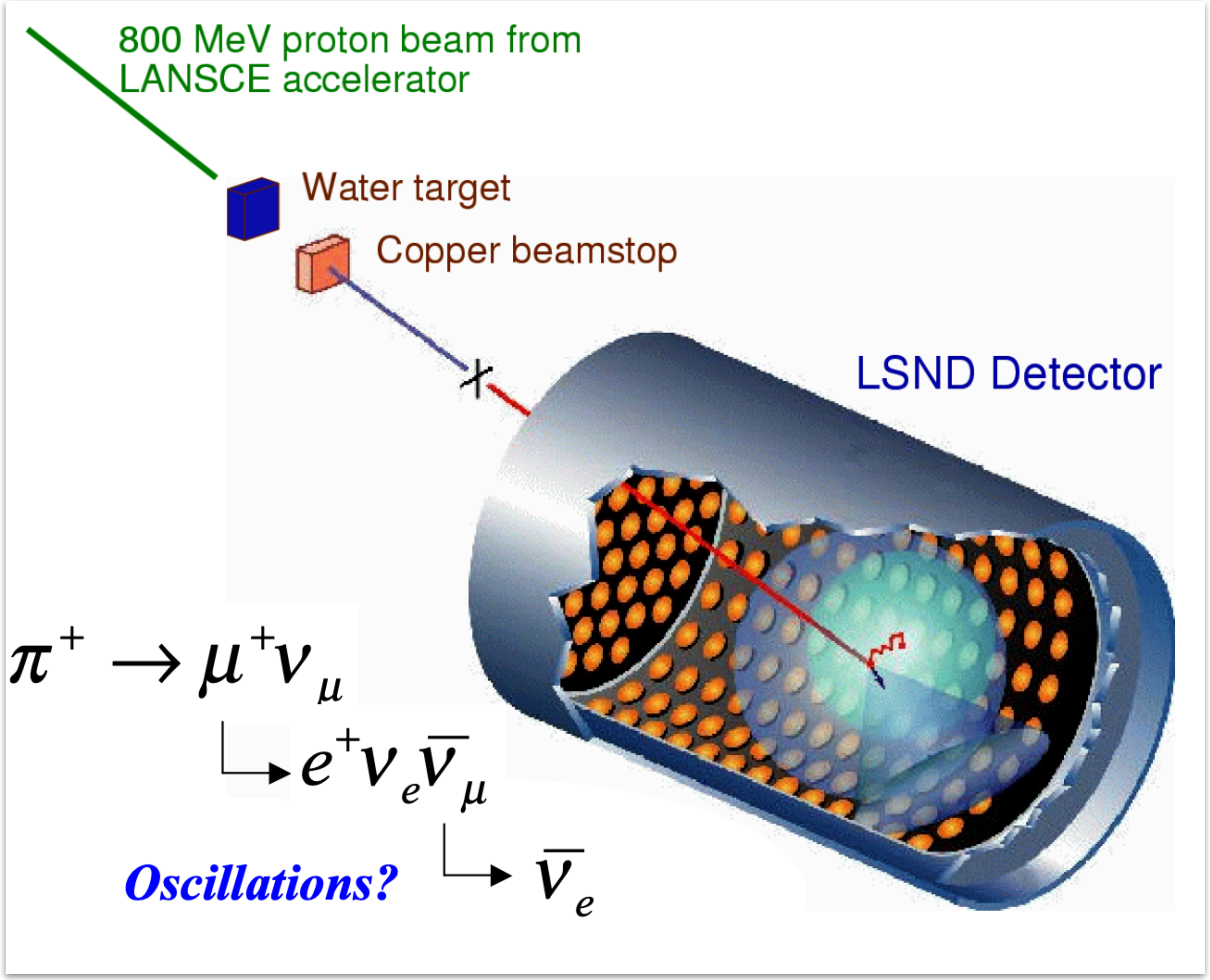


Liquid Scintillator Neutrino Detector (LSND)



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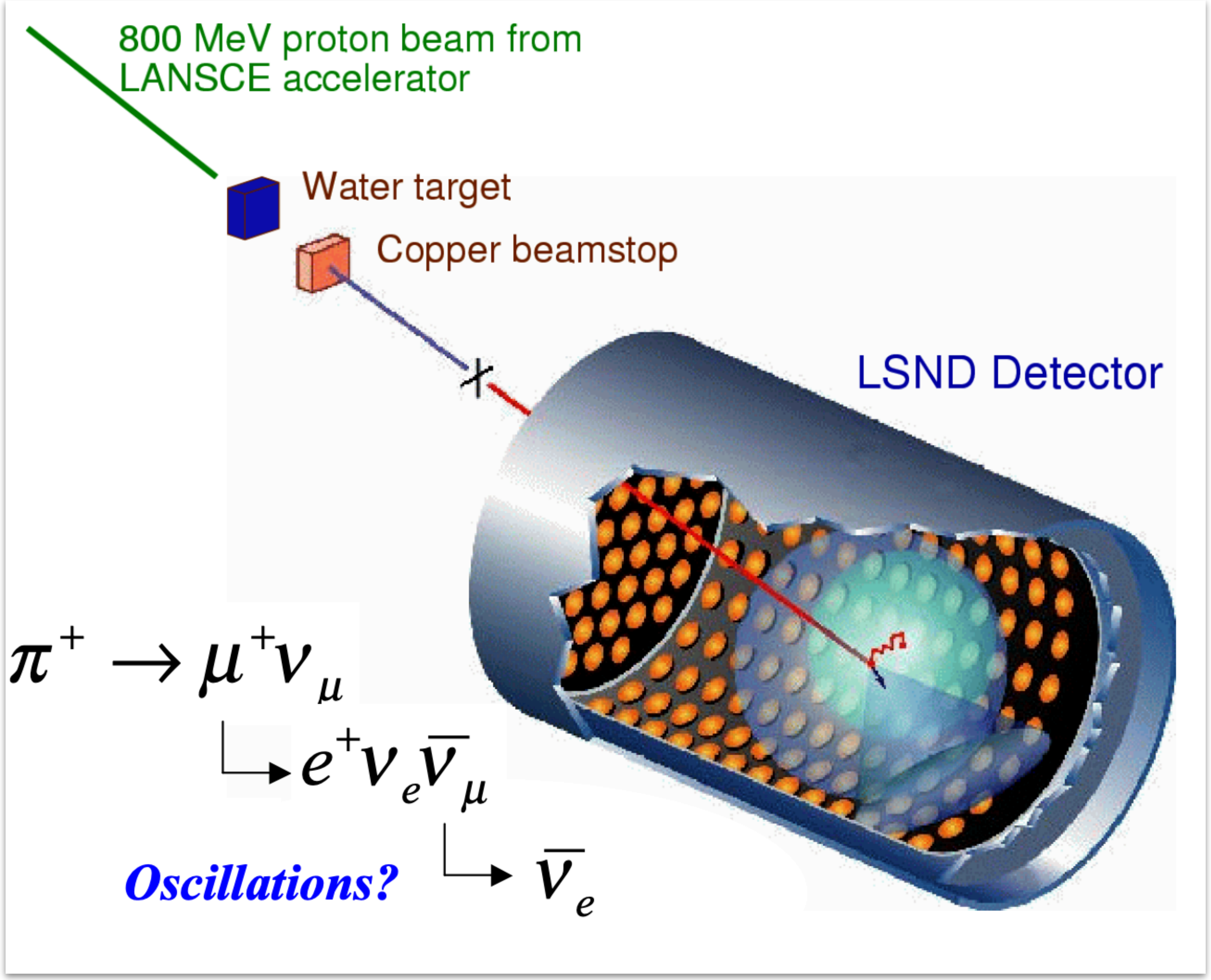
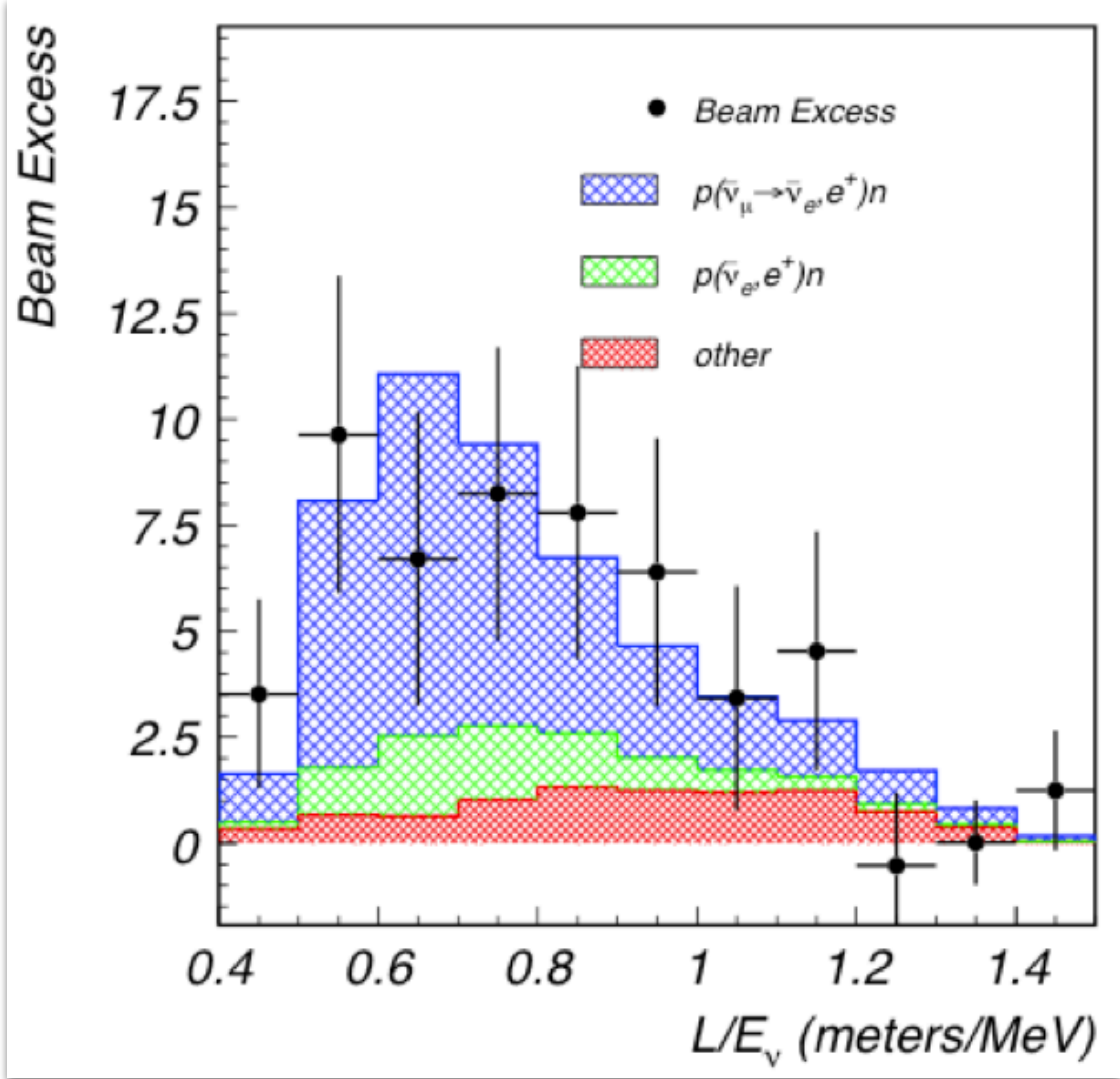


$\overline{\nu}_\mu \to \overline{\nu}_e?$



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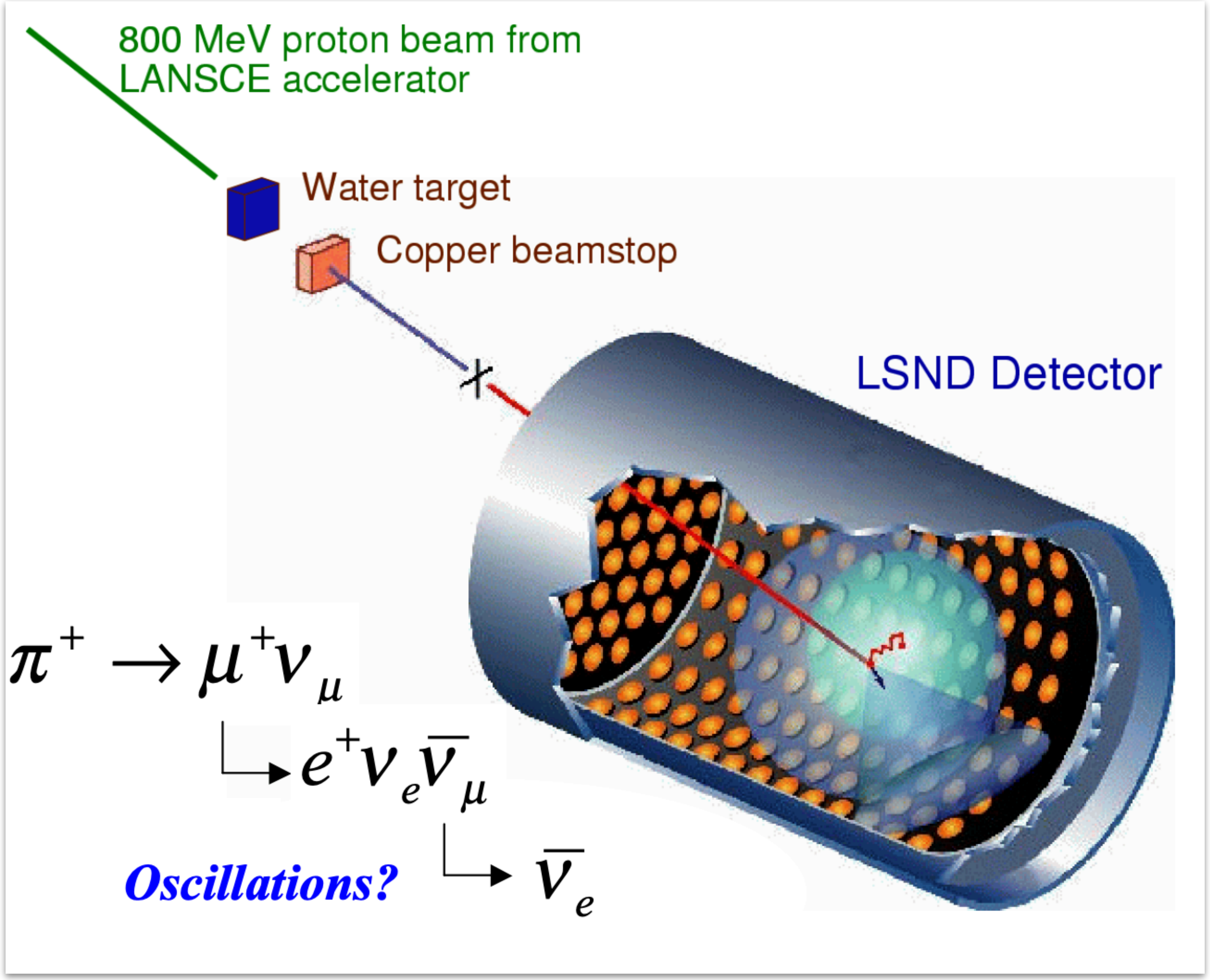
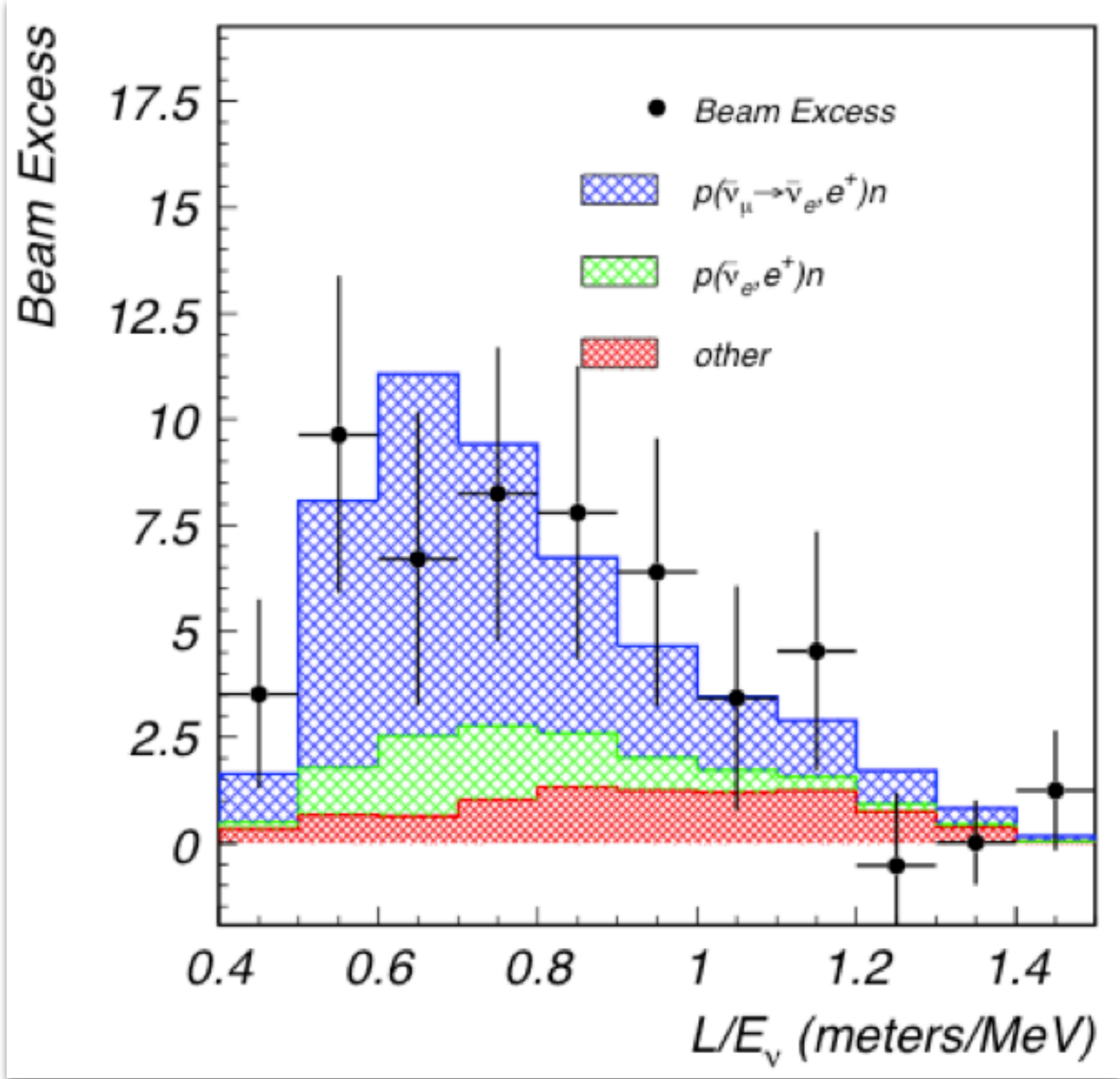


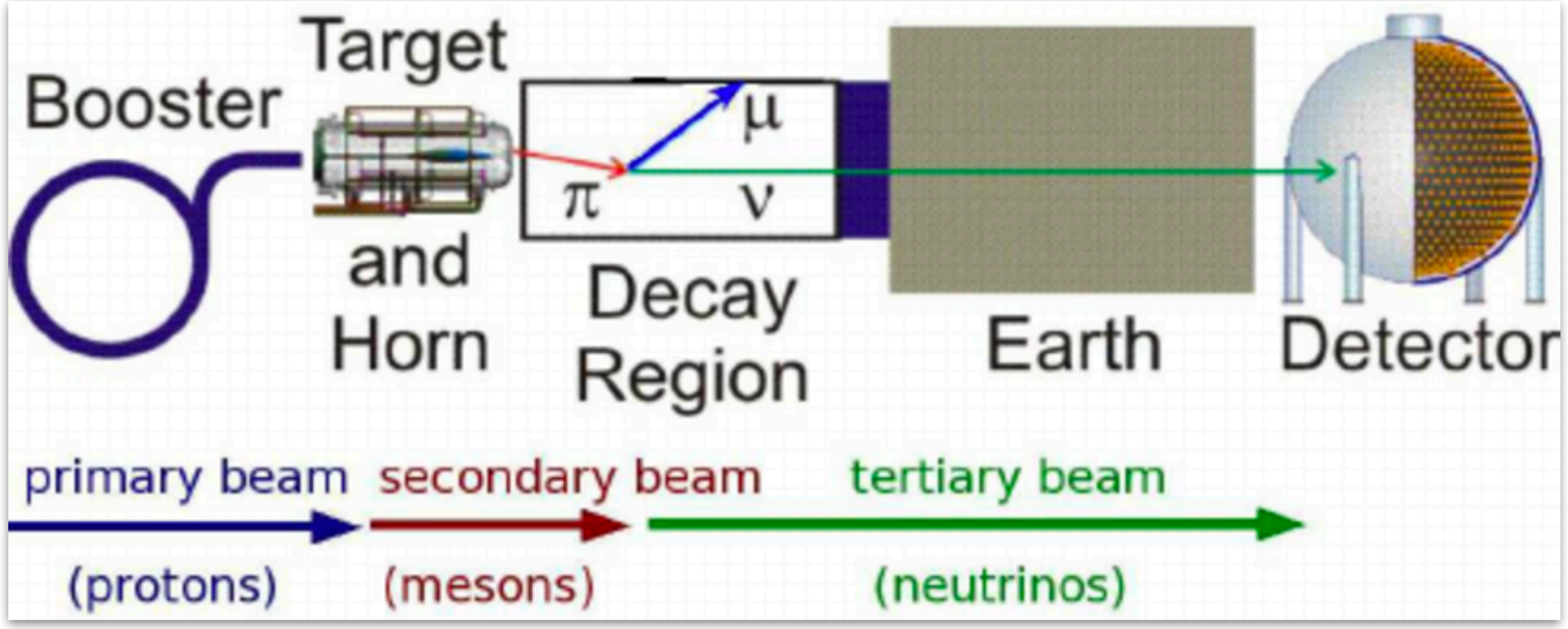


Neutrinos (mostly) from pion/muon decay-at-rest — O(30) MeV, roughly 50 meter baseline length.

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

MiniBooNE

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



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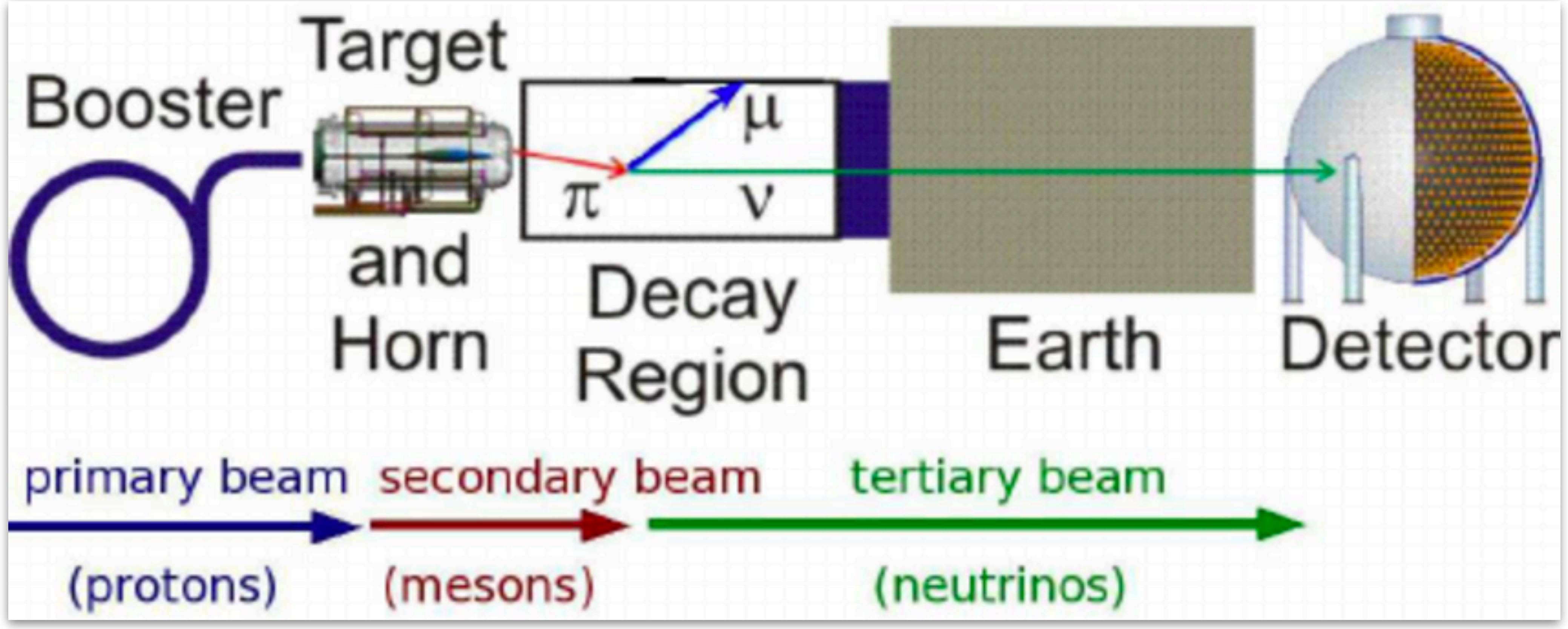

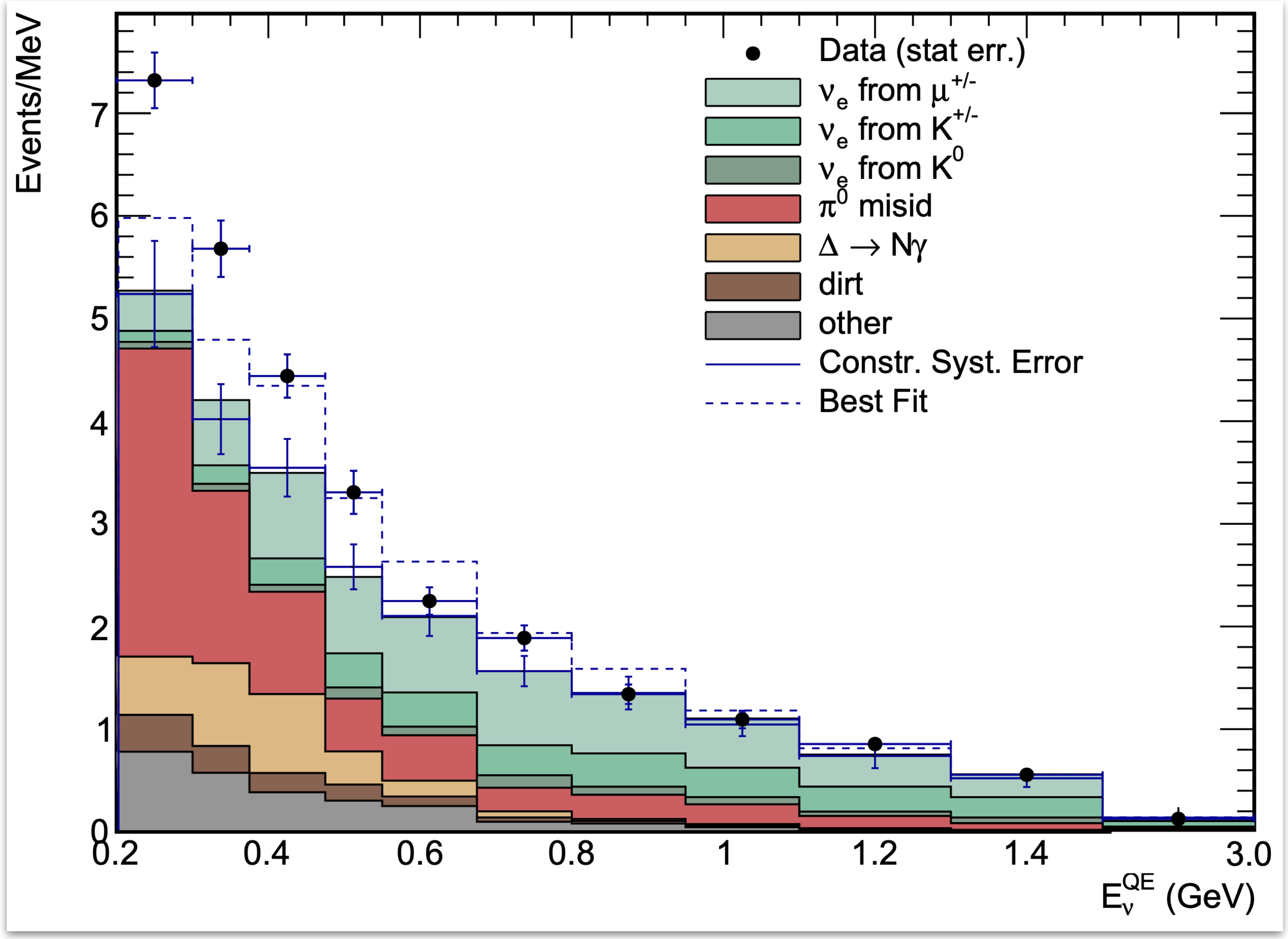

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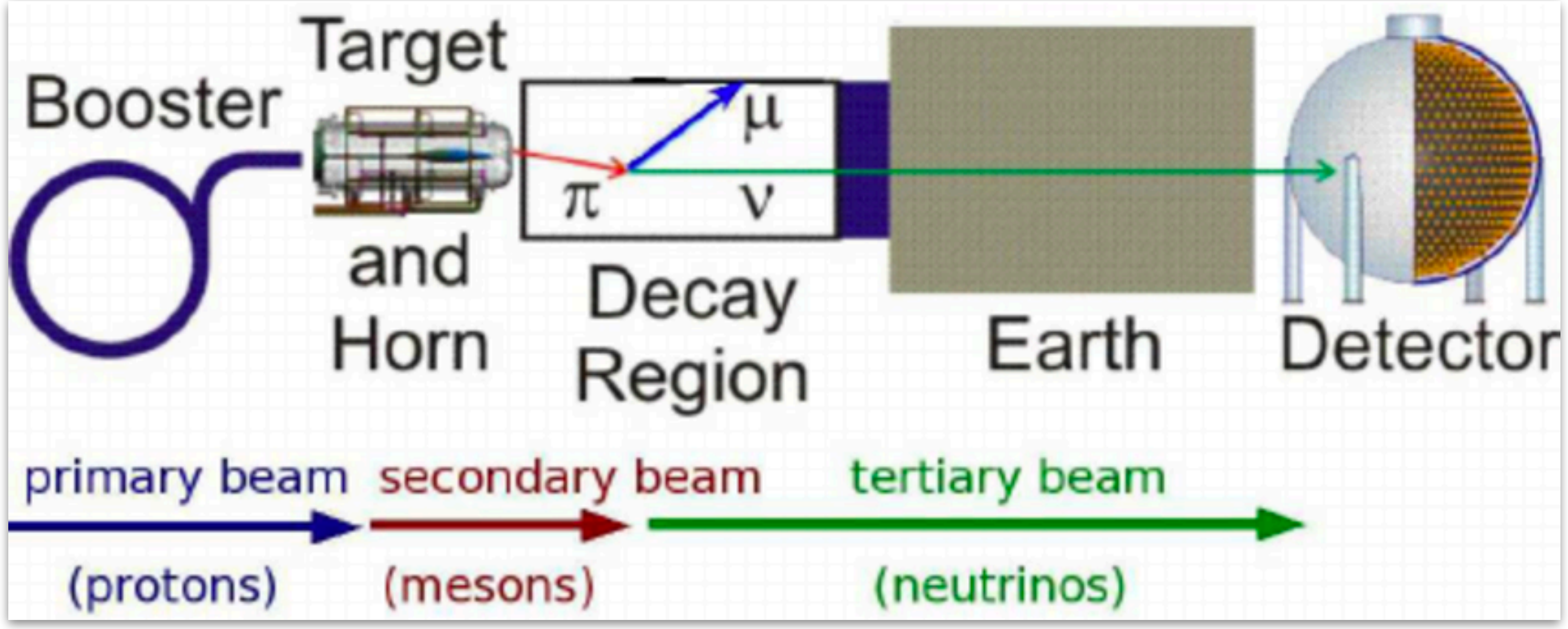
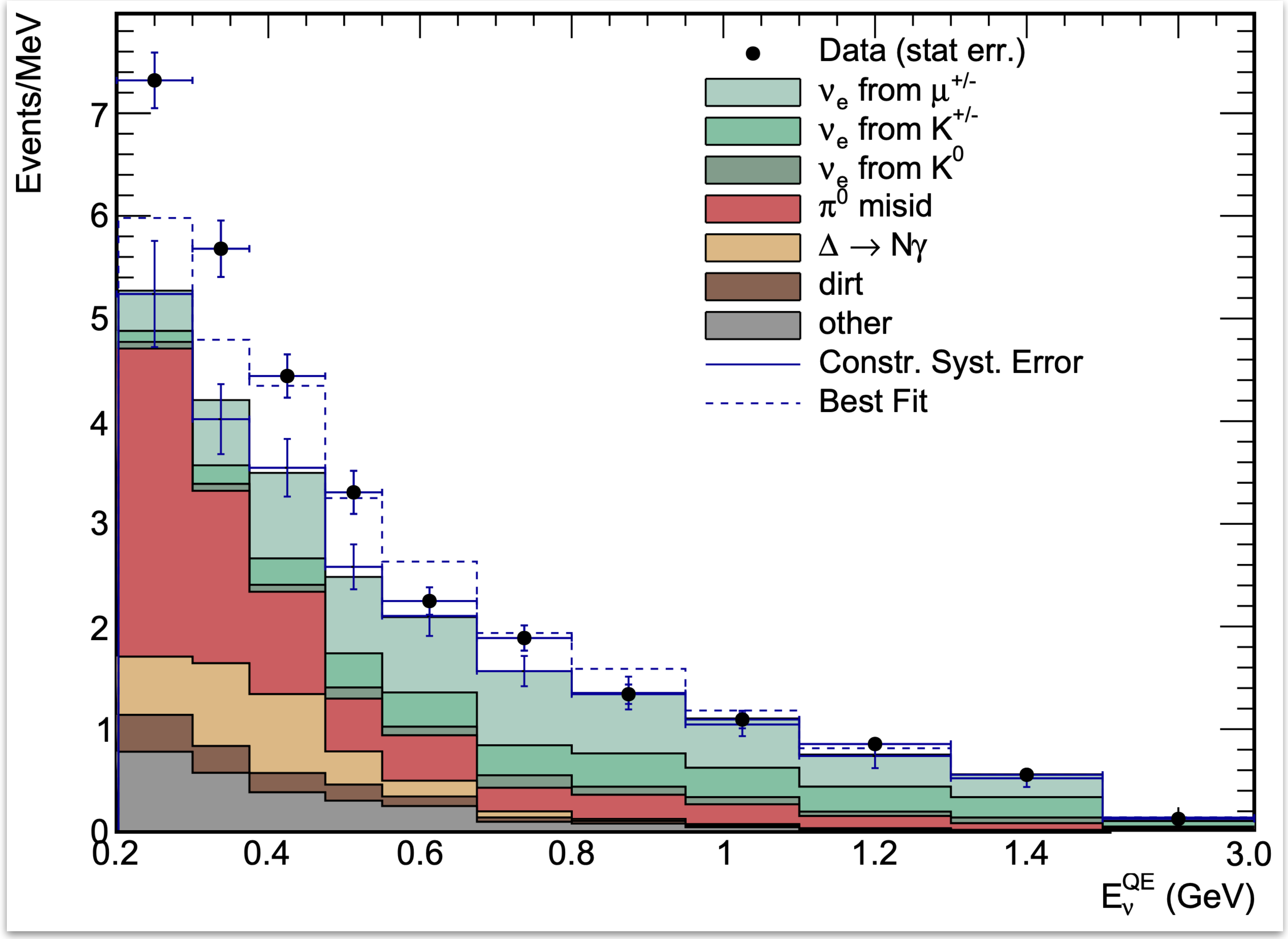
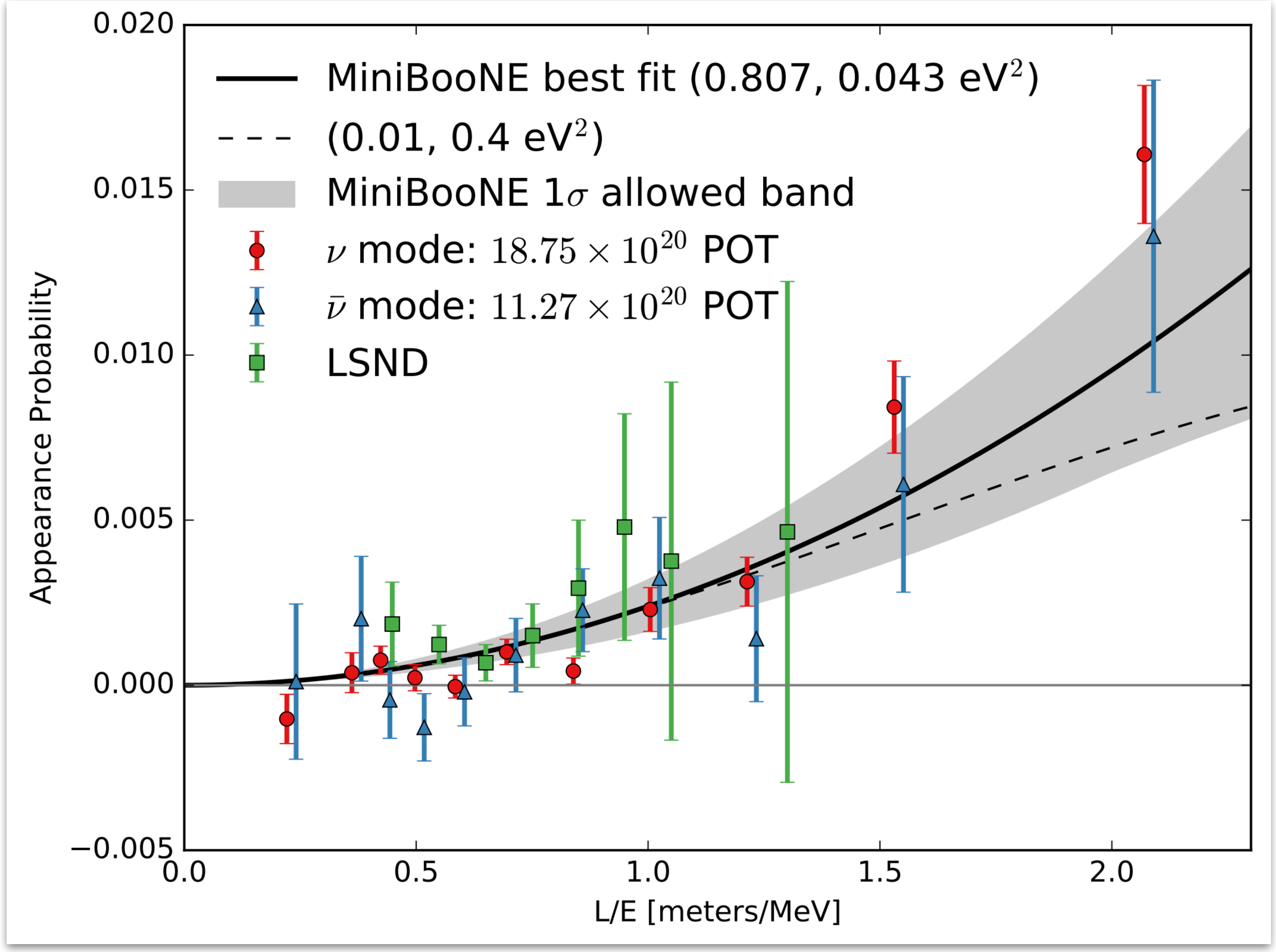


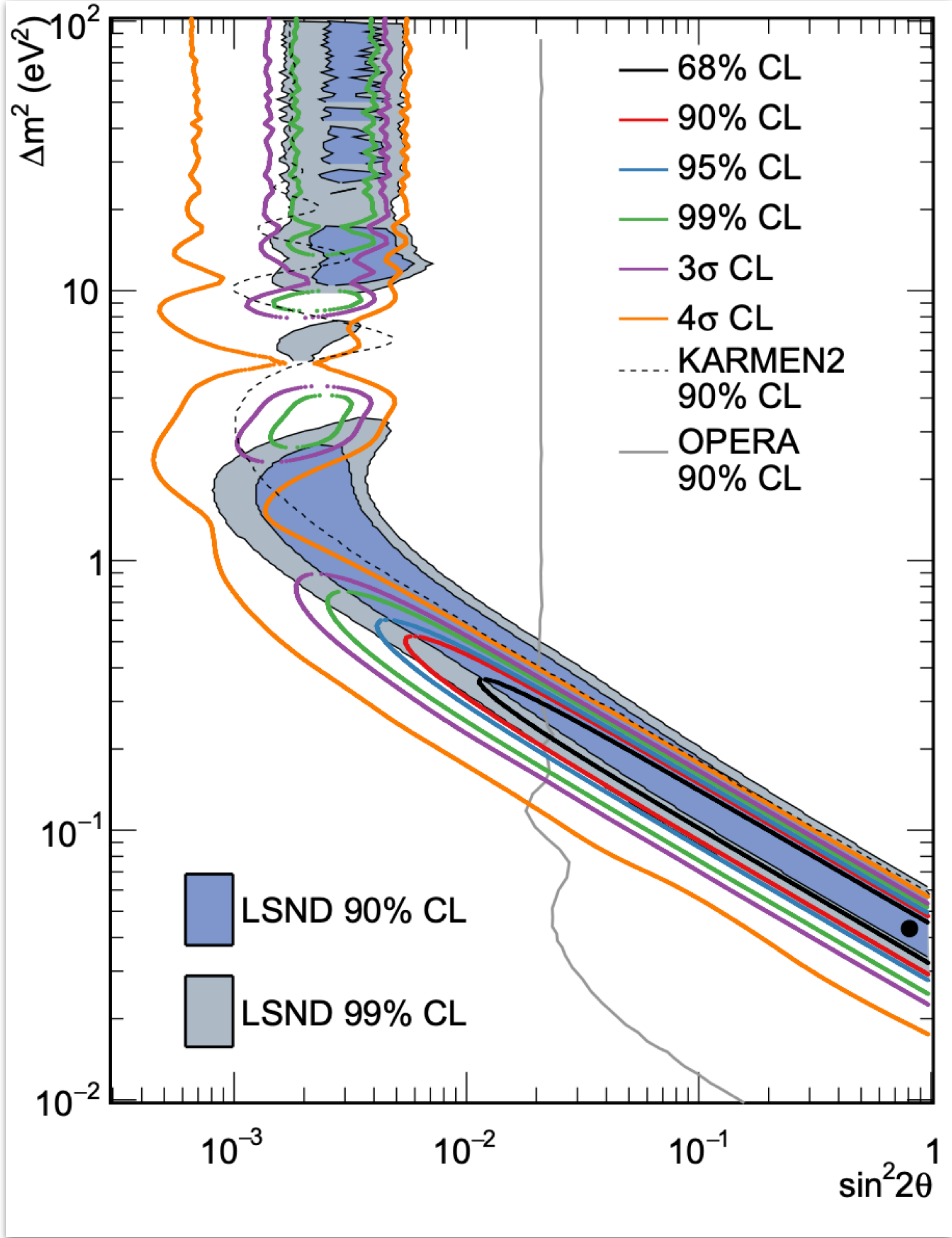
$$\nu_\mu \to \nu_e \text{ AND } \overline{\nu}_\mu \to \overline{\nu}_e?$$

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

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

- 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.

Electron-Neutrino Disappearance?

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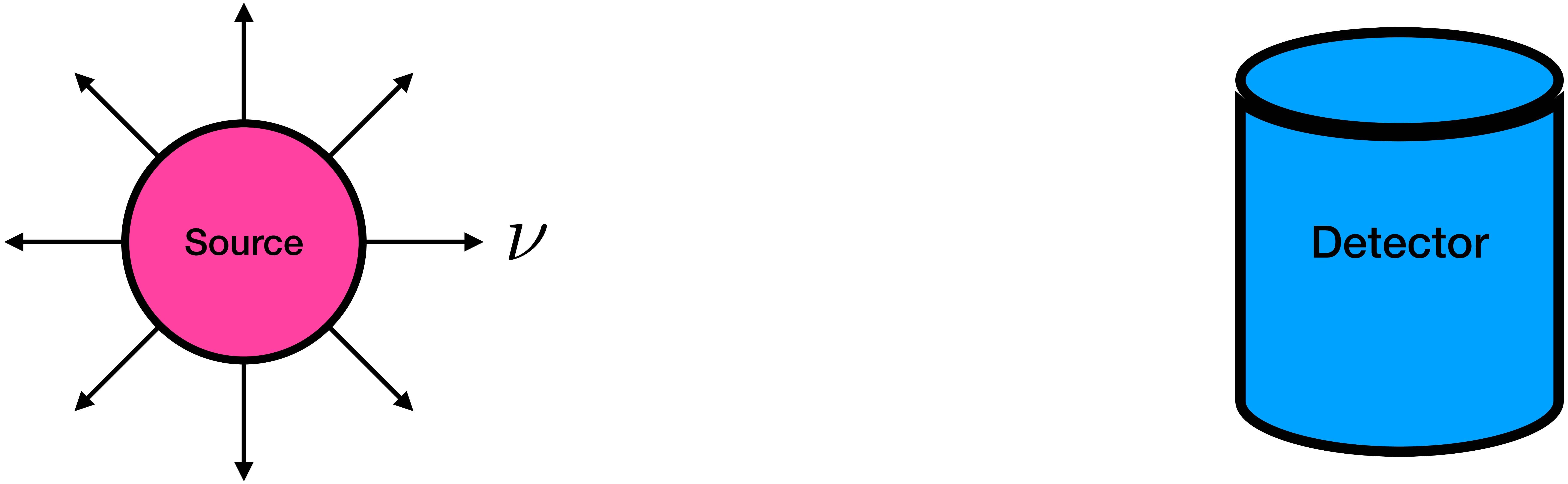
Much, much more information?

Patrick H.’s seminar on Monday

Key Challenge: Flux Uncertainties

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



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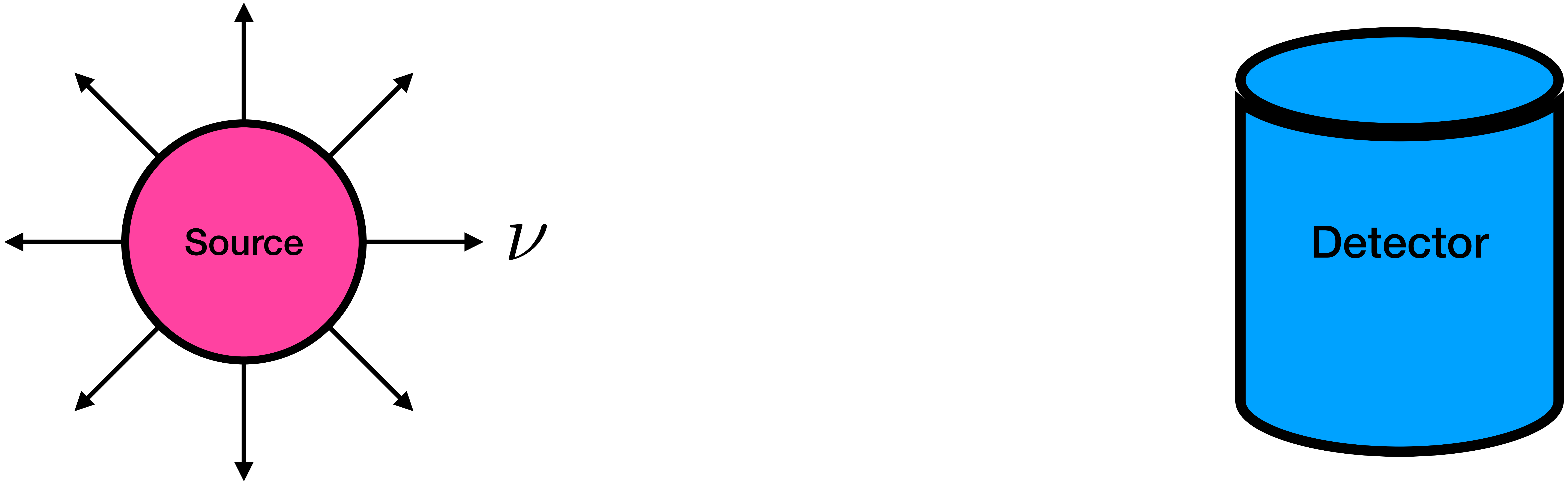
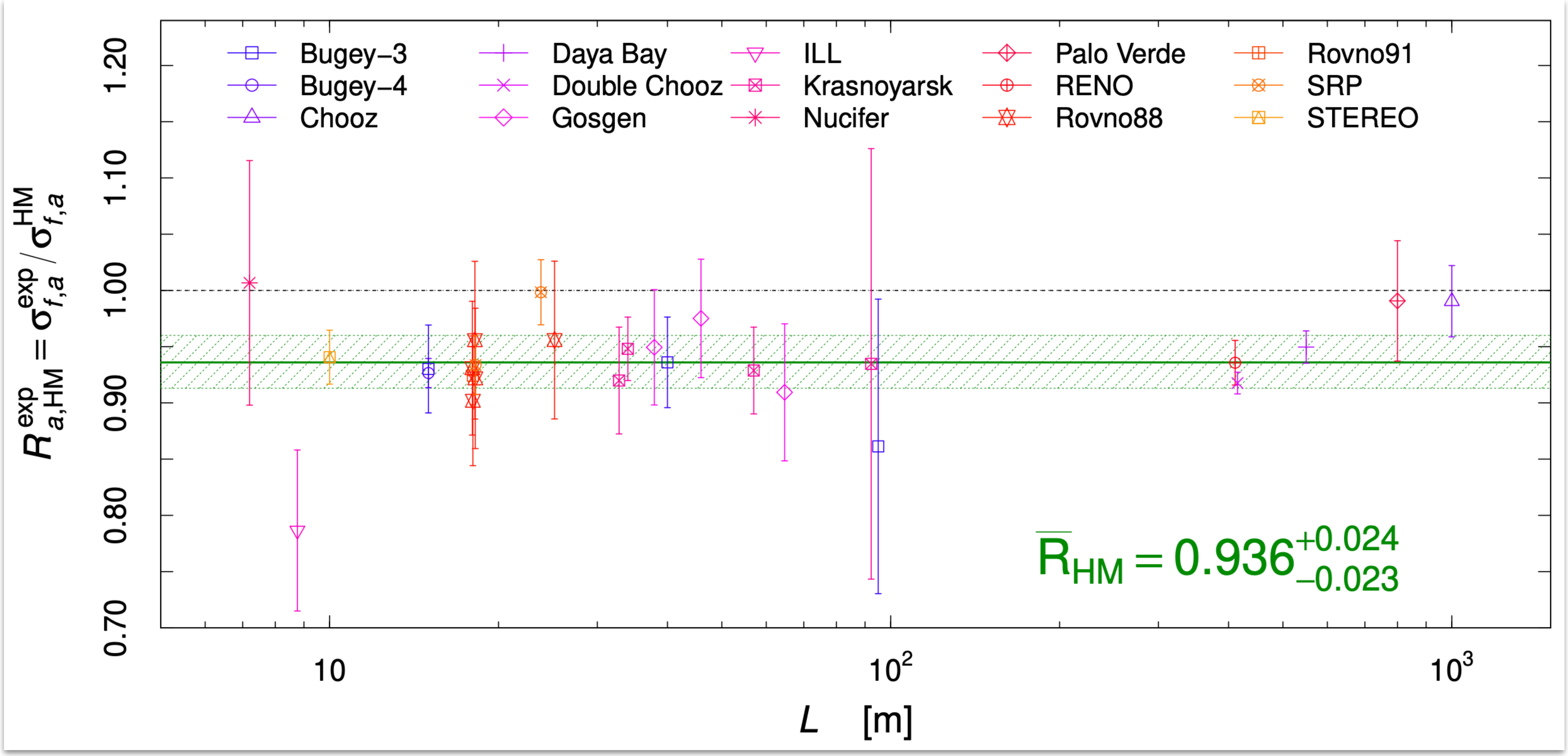


Experiments measure *rates* (product of flux, cross section, and oscillation probability), not probability directly. Constraints on the mixing angle will therefore be limited by uncertainties on fluxes, cross sections, etc.

The Reactor Antineutrino (Rate) Anomaly

Giunti et al, [2110.06820]



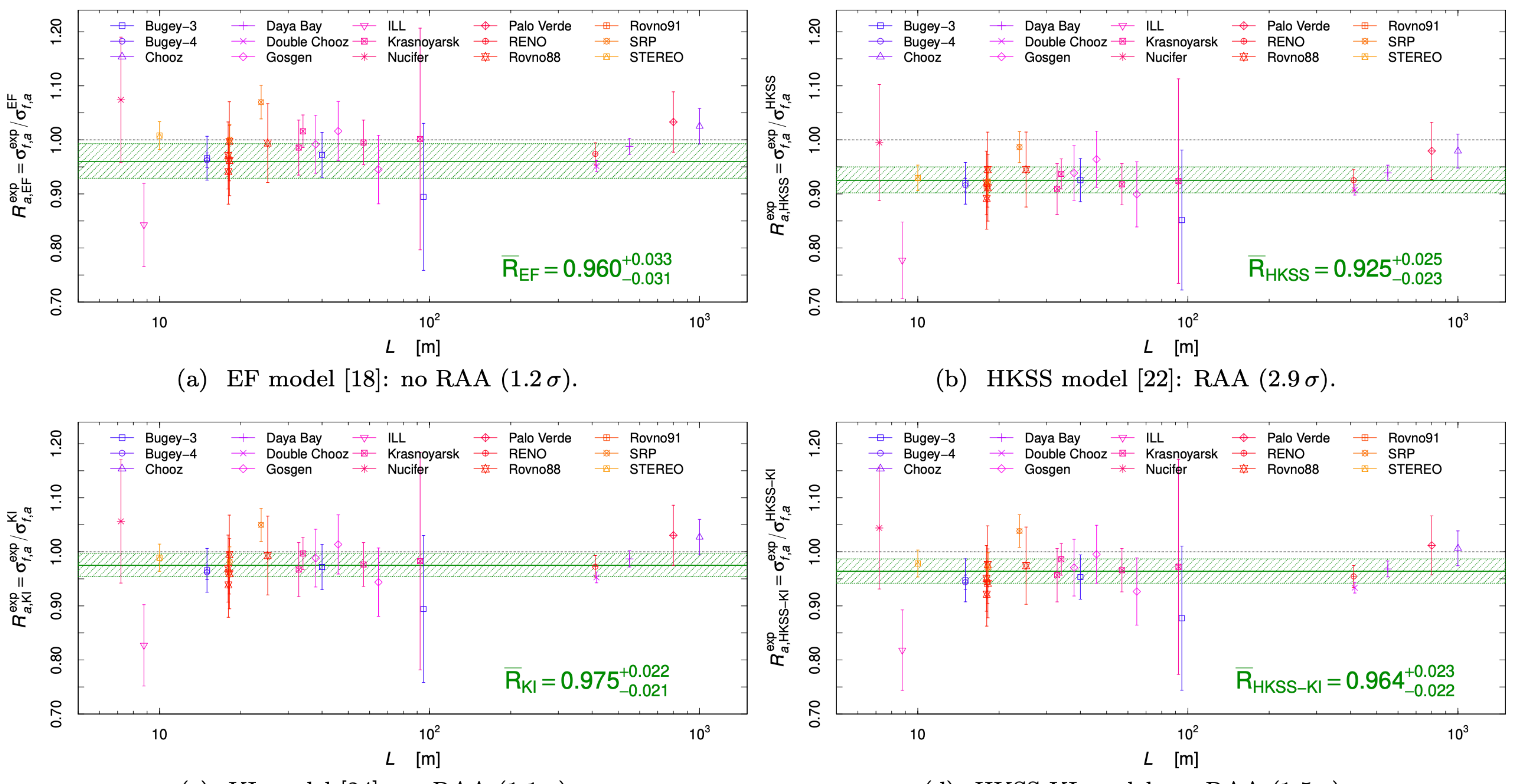
Using flux predictions from Mueller et al [1101.2663] and Huber [1106.0687] — significant rate deficit across many baselines.

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

(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 ($2.9\,\sigma$).

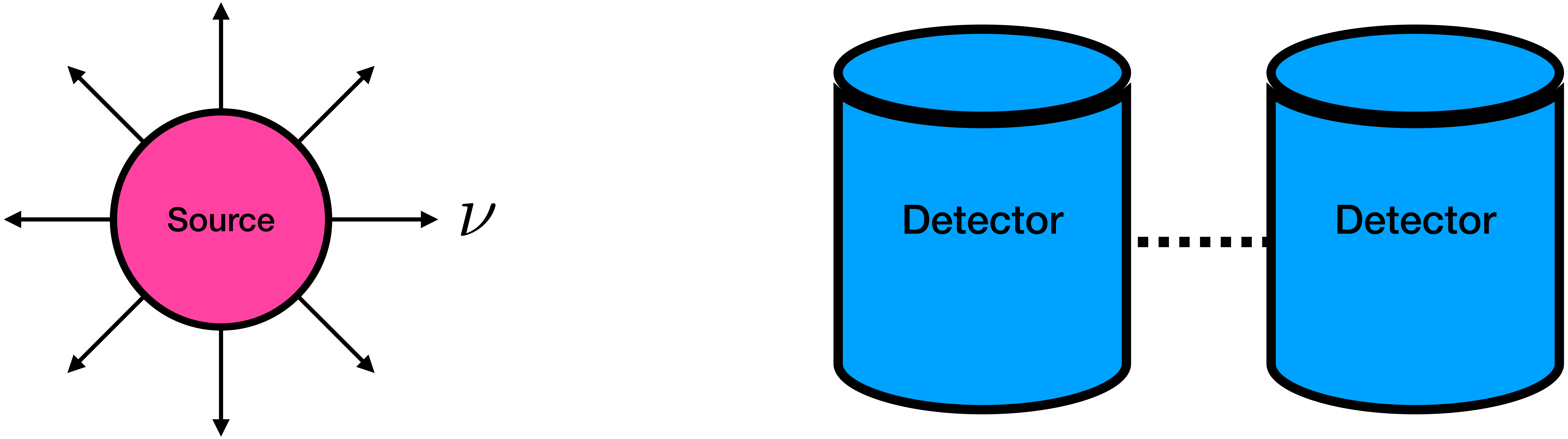
(c) KI model [24]: no RAA ($1.1\,\sigma$).

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

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

Avoiding Uncertainties

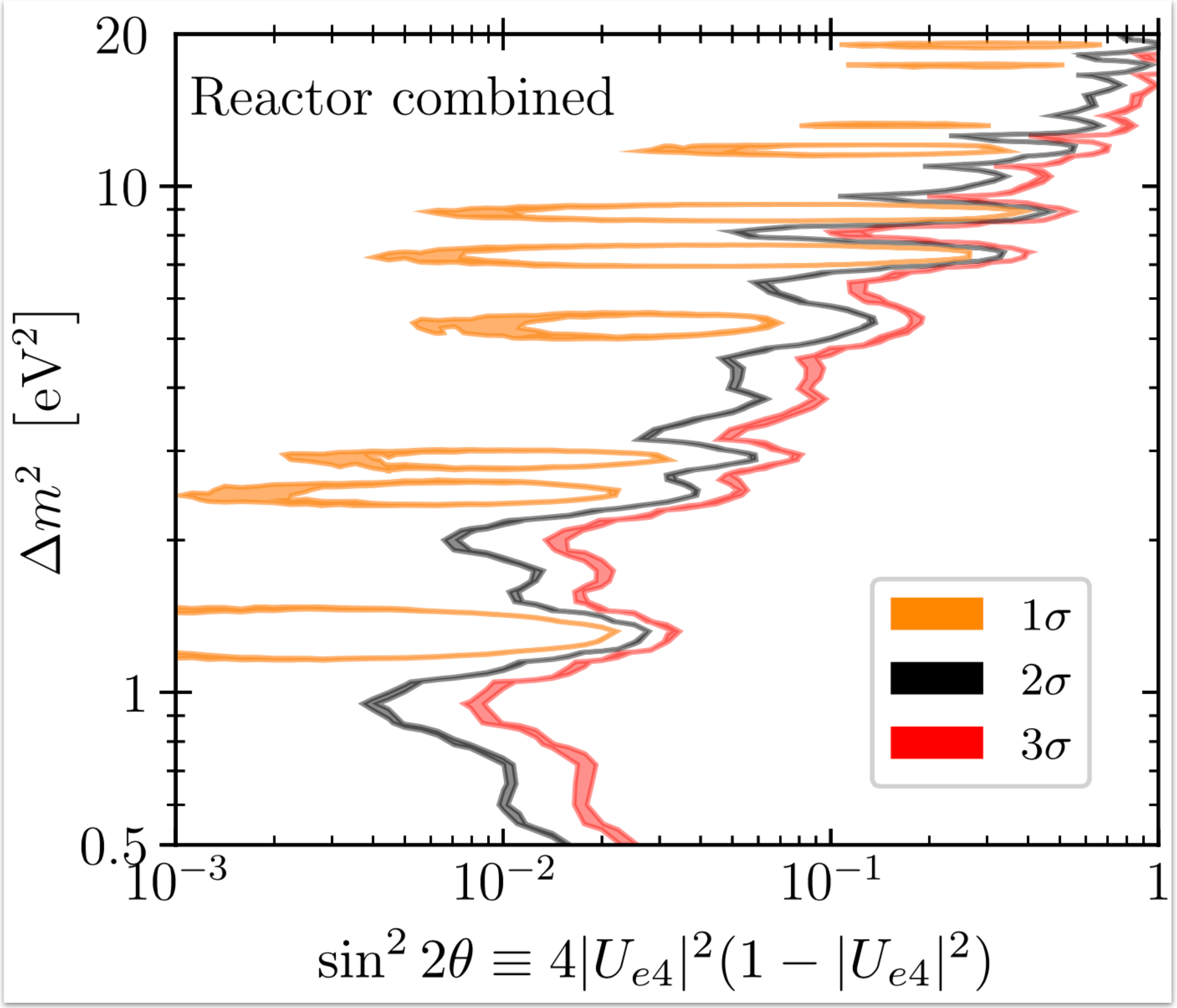
$$P\left(\nu_\alpha \rightarrow \nu_\alpha\right) = 1 - 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$



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

Reactor Global Picture

Berryman et al, [2111.12530]



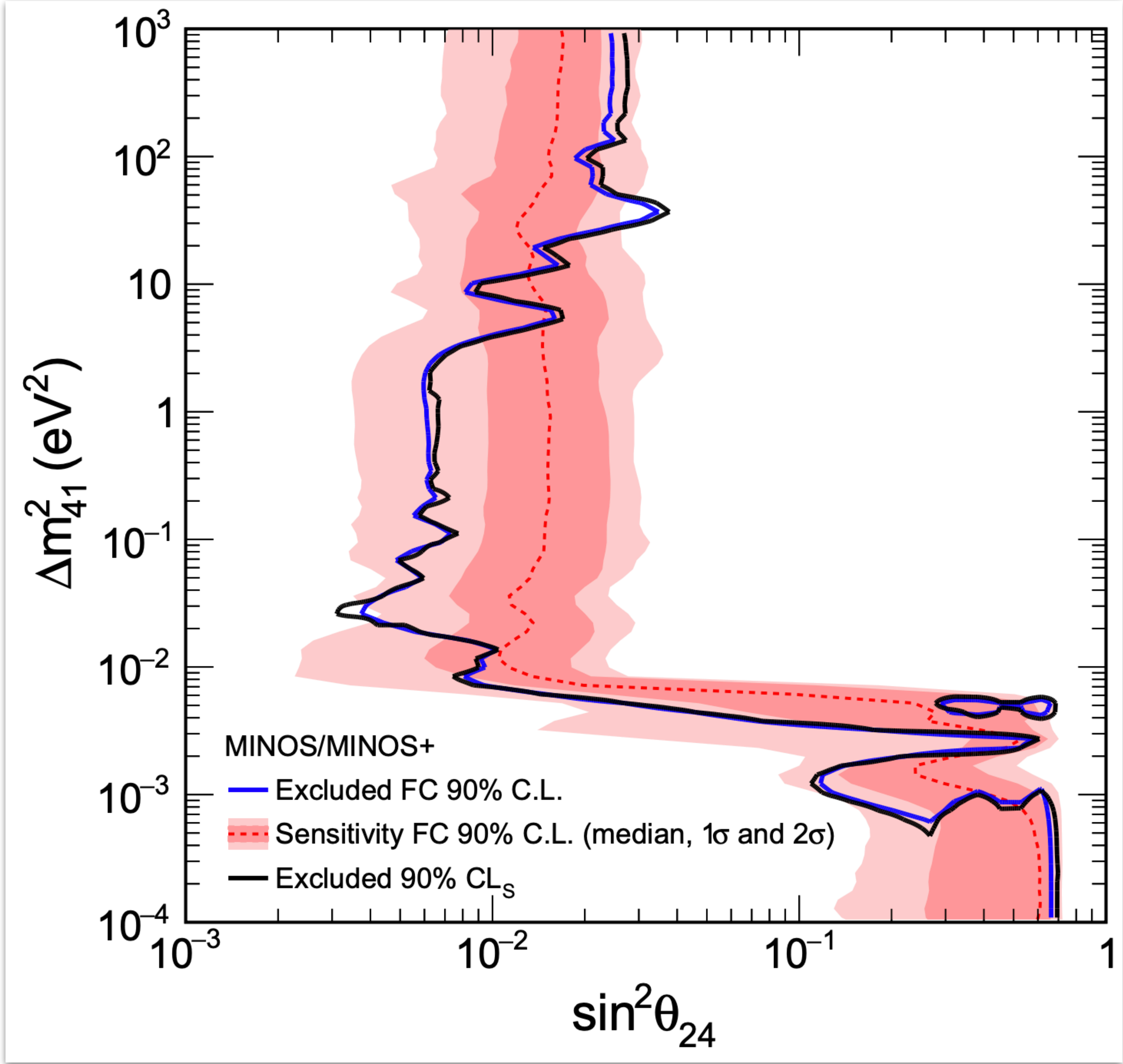
PROSPECT
STEREO
DANSS
Neutrino 4
NEOS

No significant* deviation from expectation!

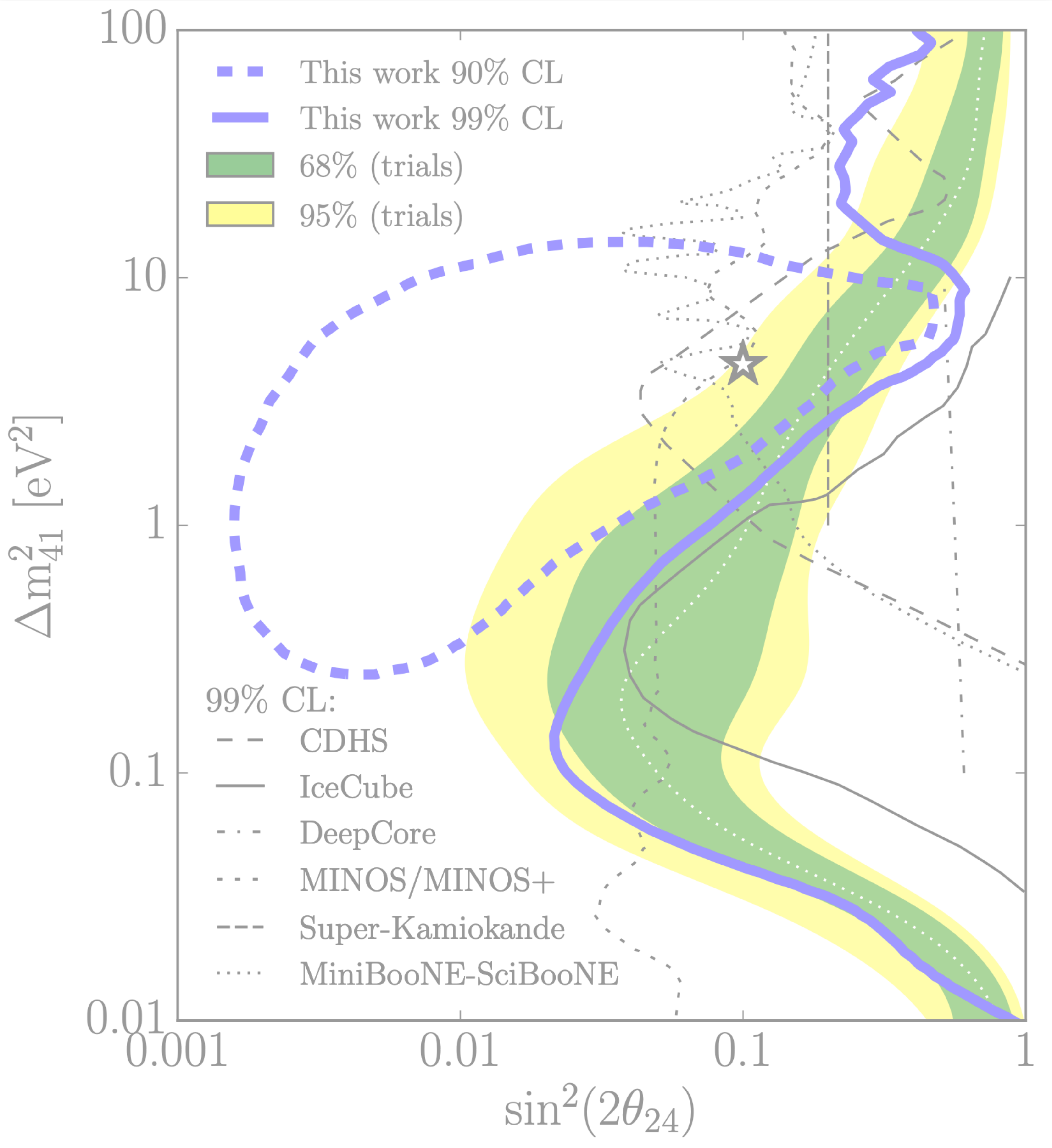
Muon-Neutrino Disappearance?

MINOS + IceCube

MINOS/MINOS+, [2002.00301]



IceCube Collaboration, [2005.12942]



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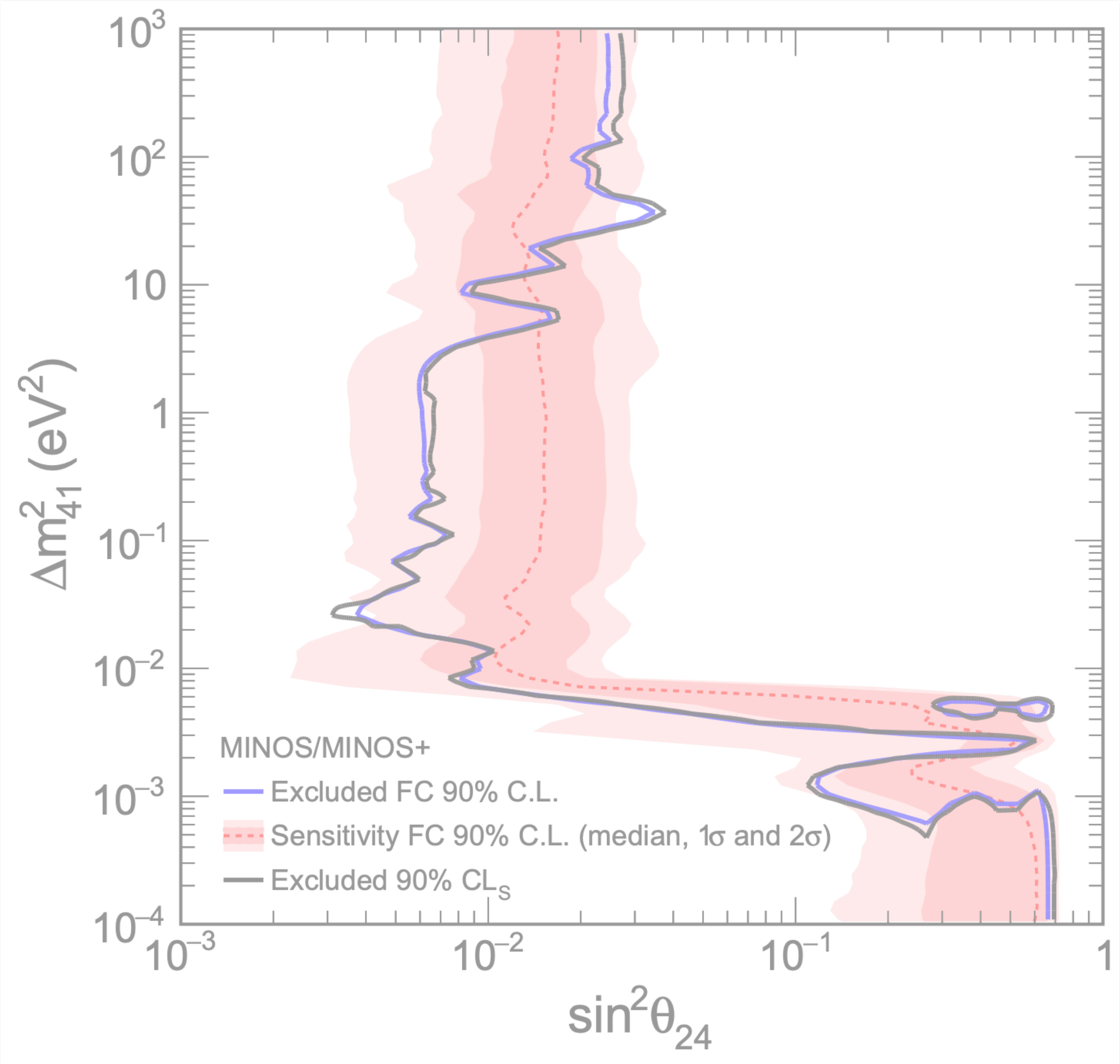

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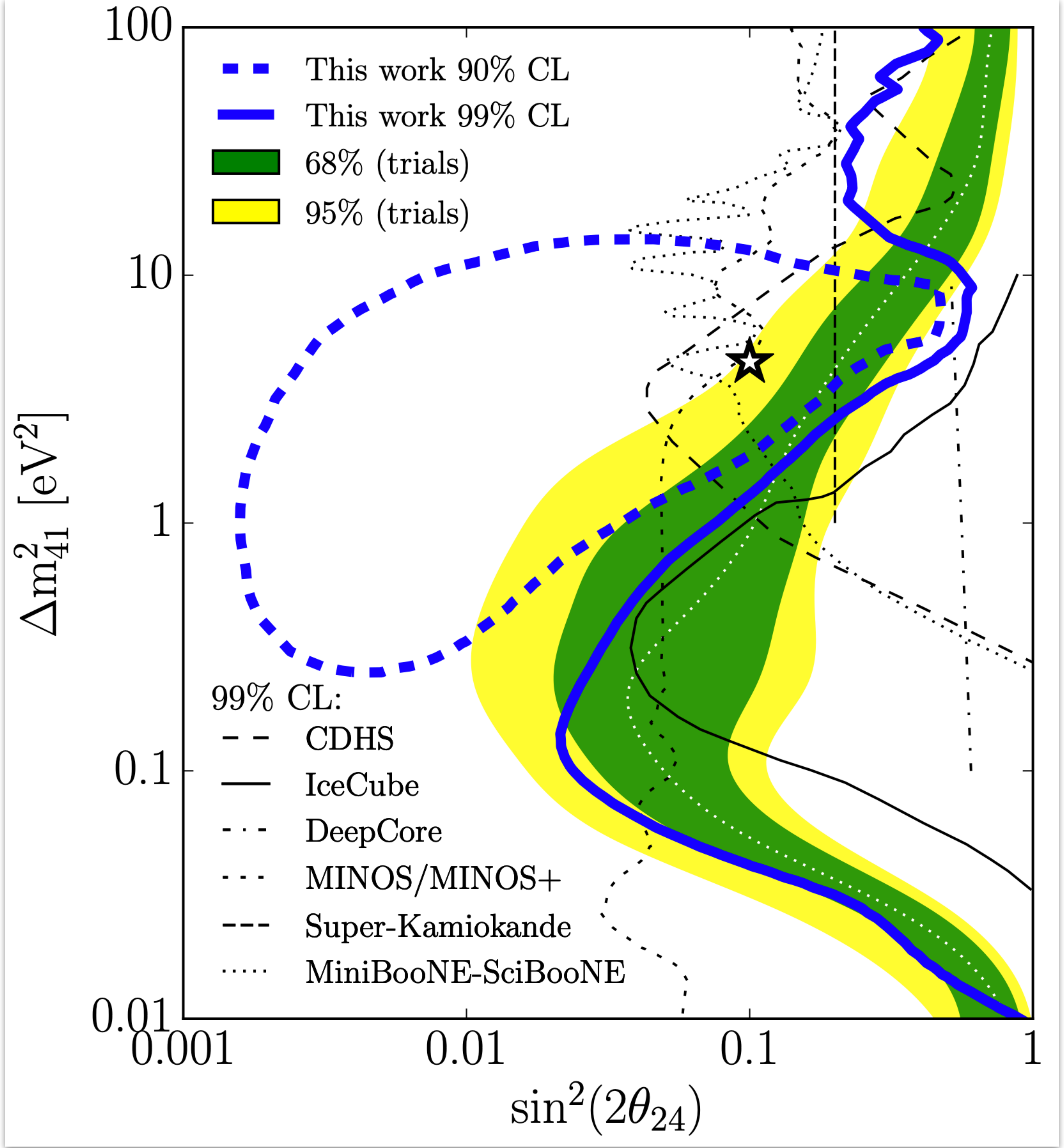
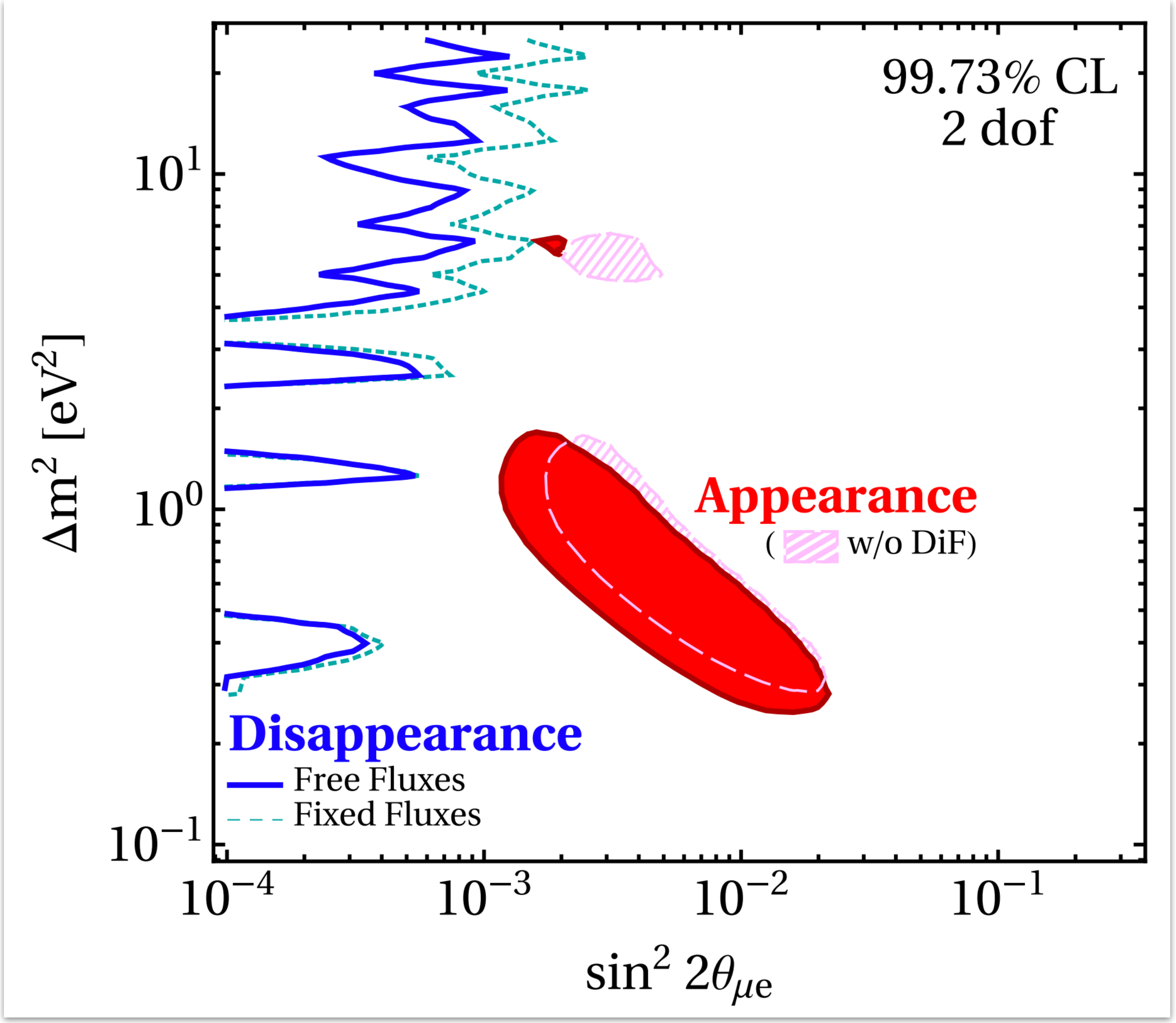
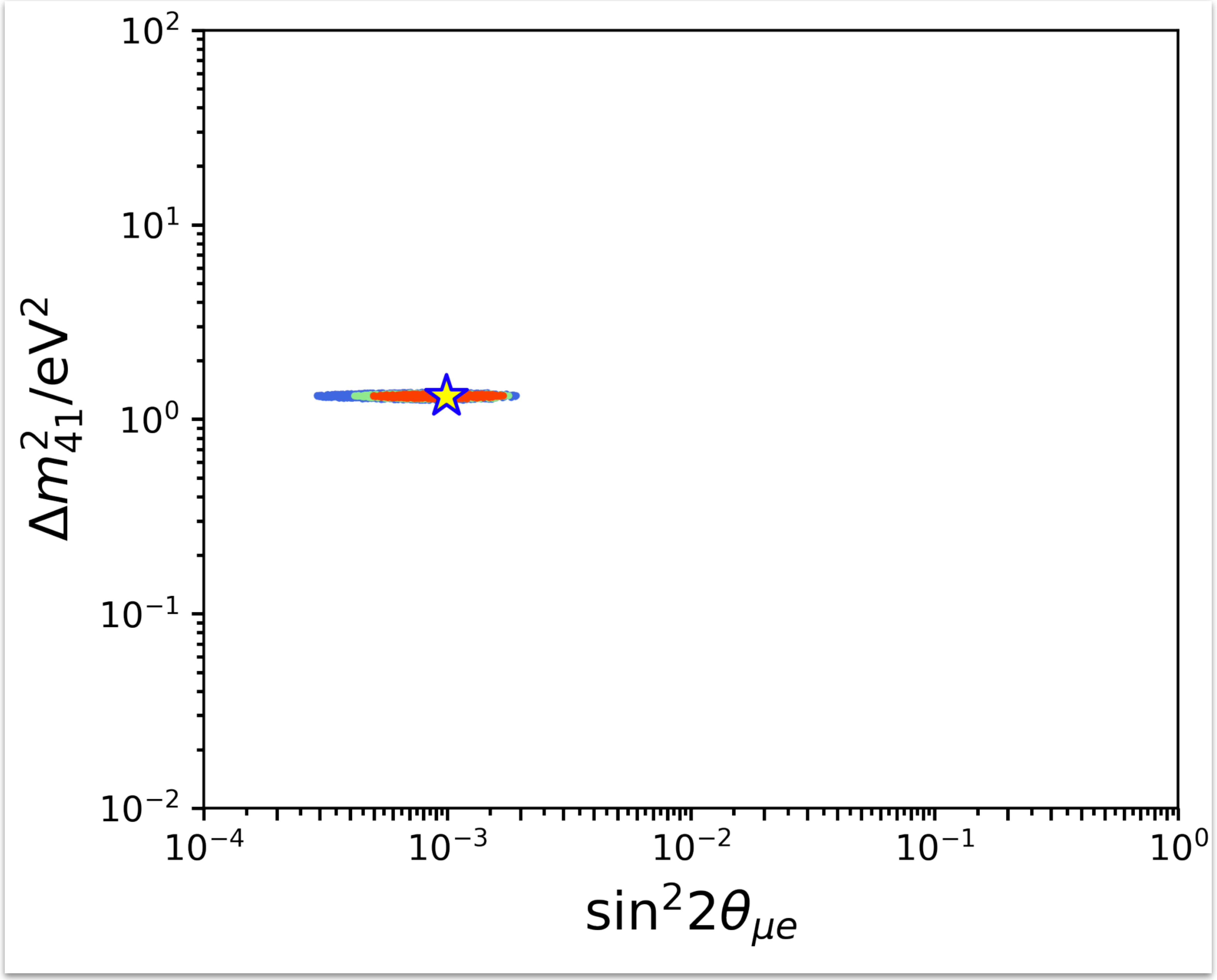


Sterile Neutrino Global Fits ca 2019



Dentler et al, [1803.10661]

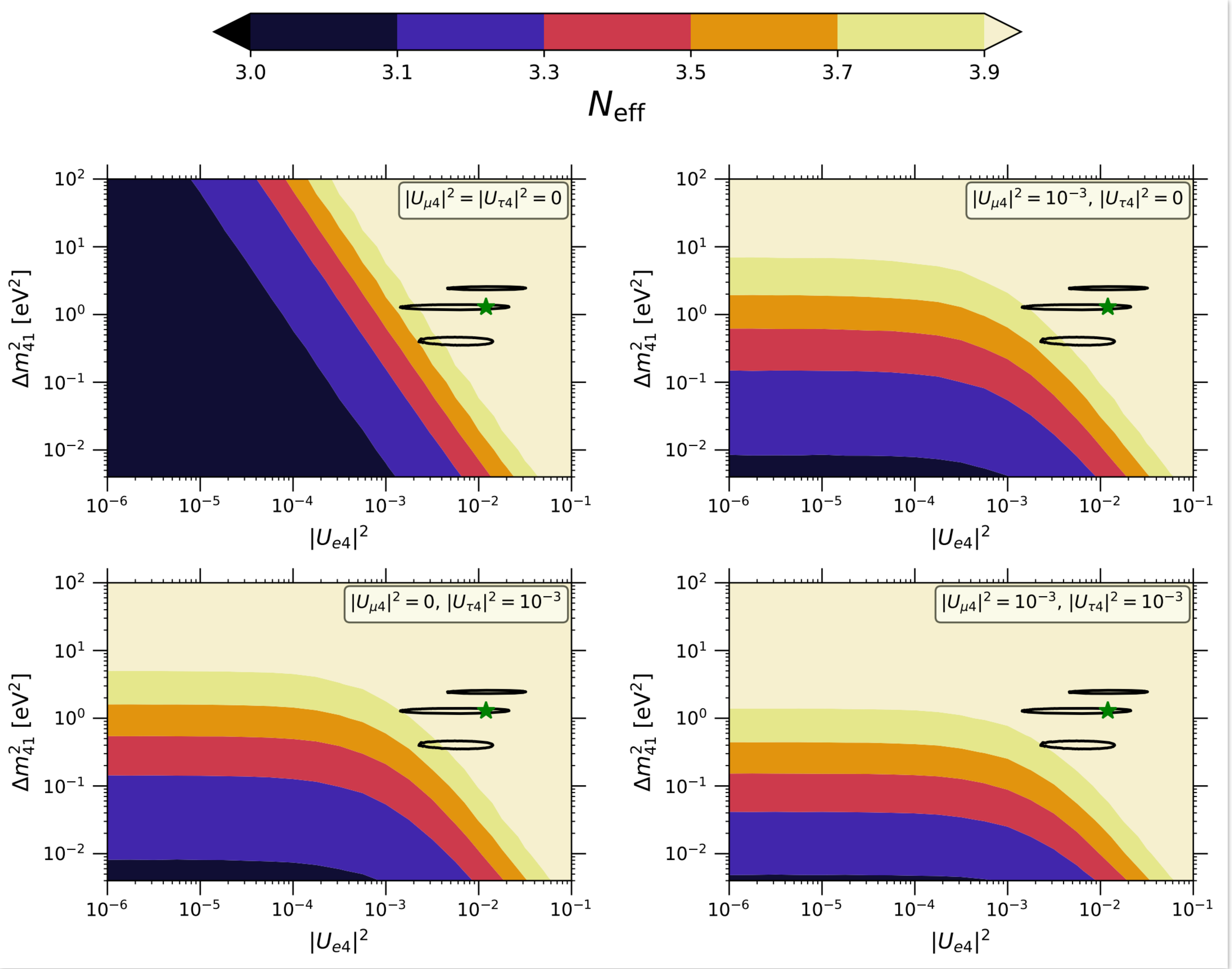


Diaz et al, [1906.00045]

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.



My thoughts in 2019?

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Let’s wait and see what happens next.

Interlude: T2K & NOvA

T2K, NOvA, and their (mild) tension

As we heard from Michele, 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]

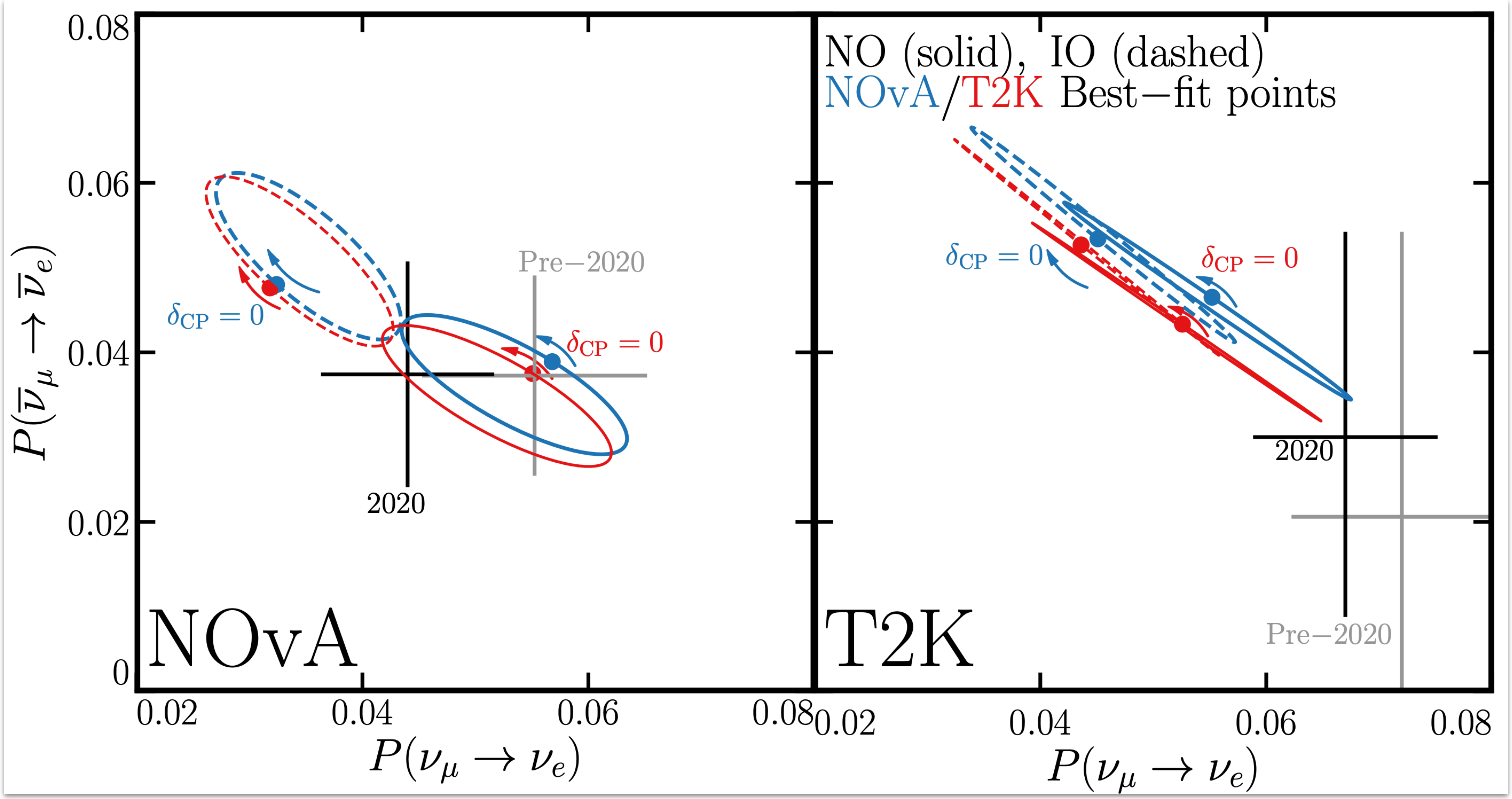
3ν		$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2_{31}/10^{-3}$ eV^2	δ_{CP}	χ^2	$\Delta\chi^2_{NO,IO}$
T2K	NO	0.022	0.56	2.52	4.58	66.82	1.48
	IO	0.022	0.56	−2.41	4.71	68.19	
NOvA	NO	0.022	0.58	2.52	2.34	43.40	0.14
	IO	0.022	0.57	−2.41	4.78	43.55	
Joint	NO	0.022	0.57	2.51	3.67	115.58	−3.76
	IO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



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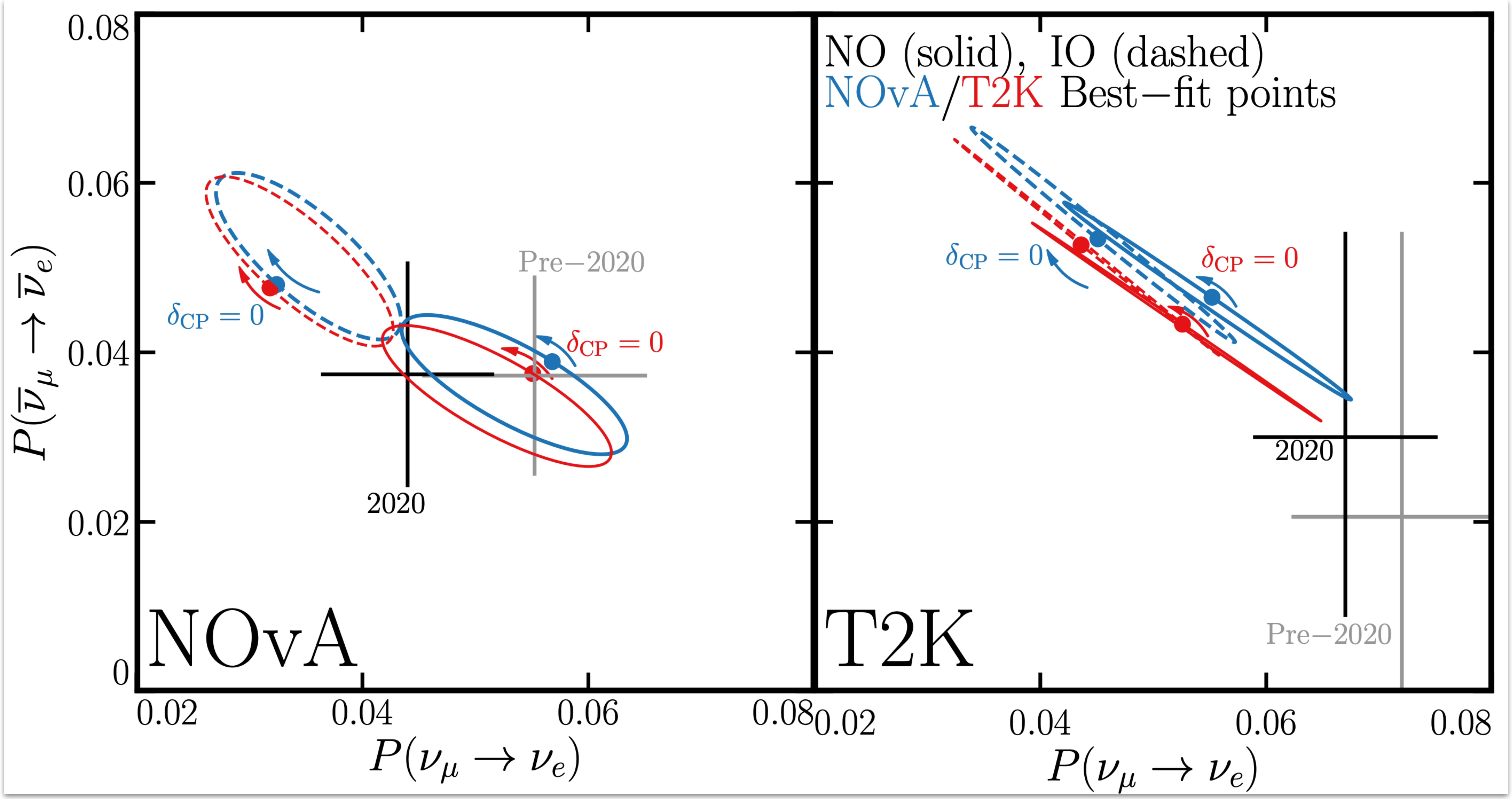

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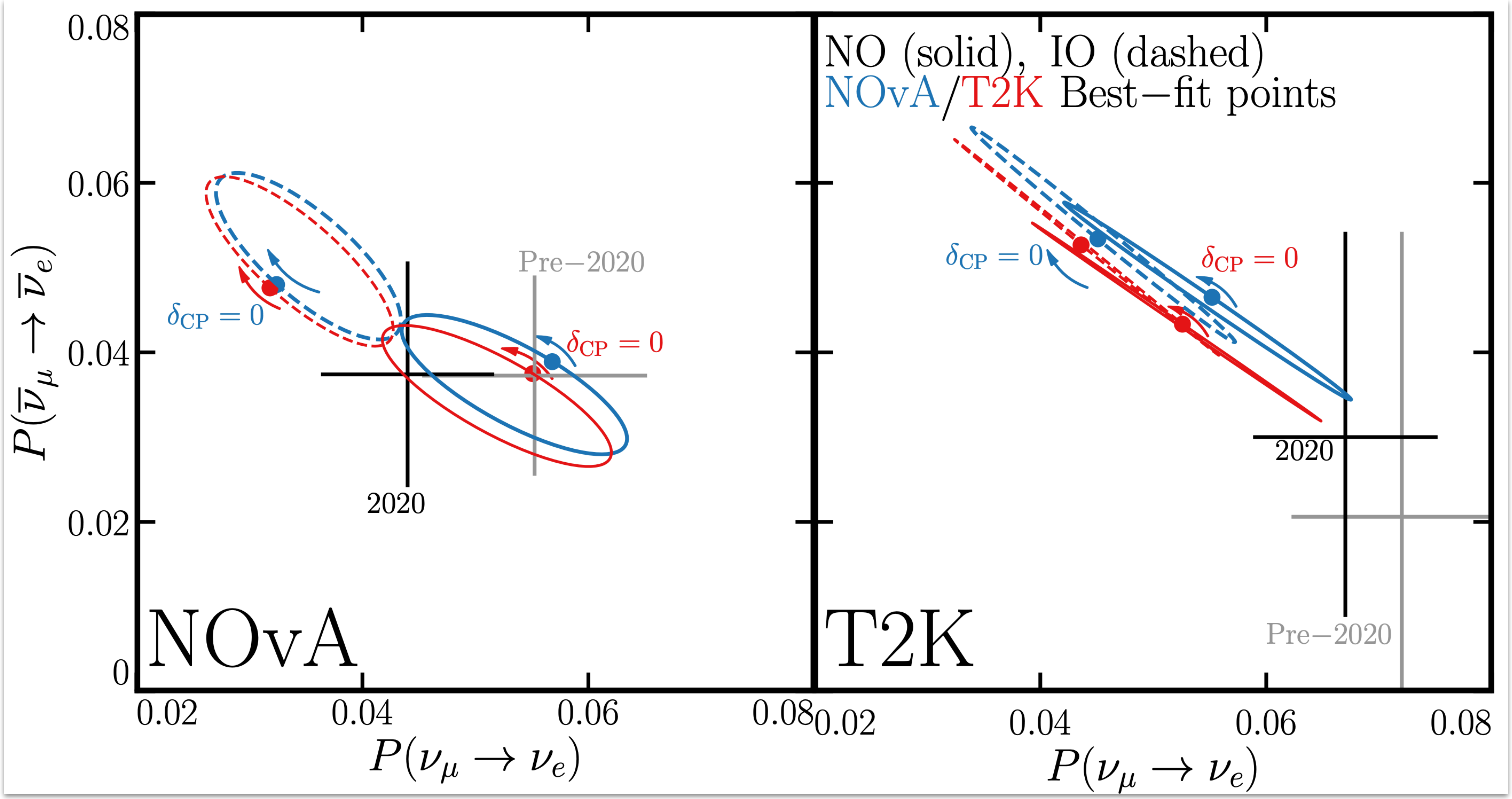

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Could this be ameliorated by a sterile neutrino with small muon mixing, large-ish electron mixing?

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
$\Delta m^2_{4l}/$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

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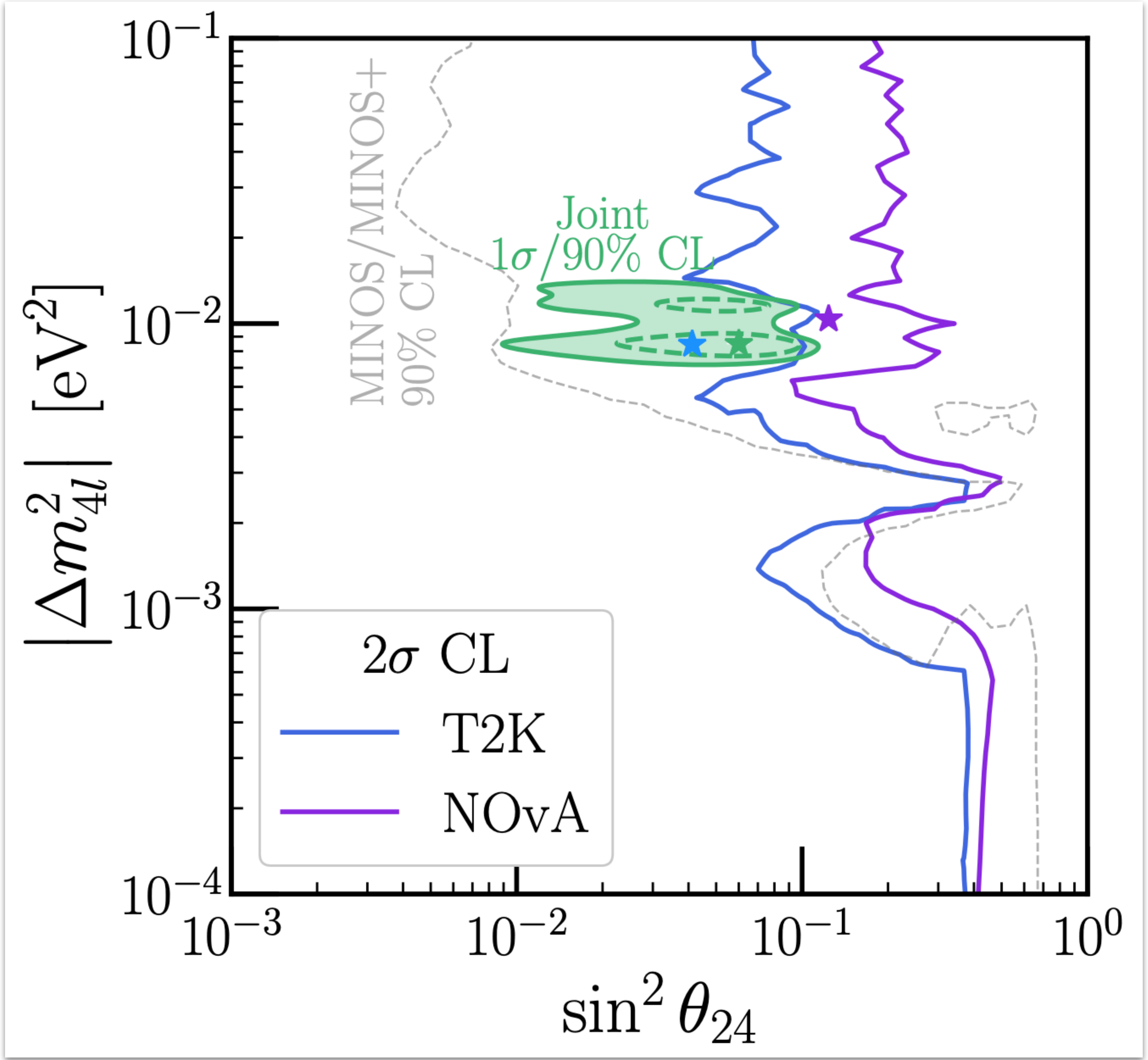
Preferred Parameter Space



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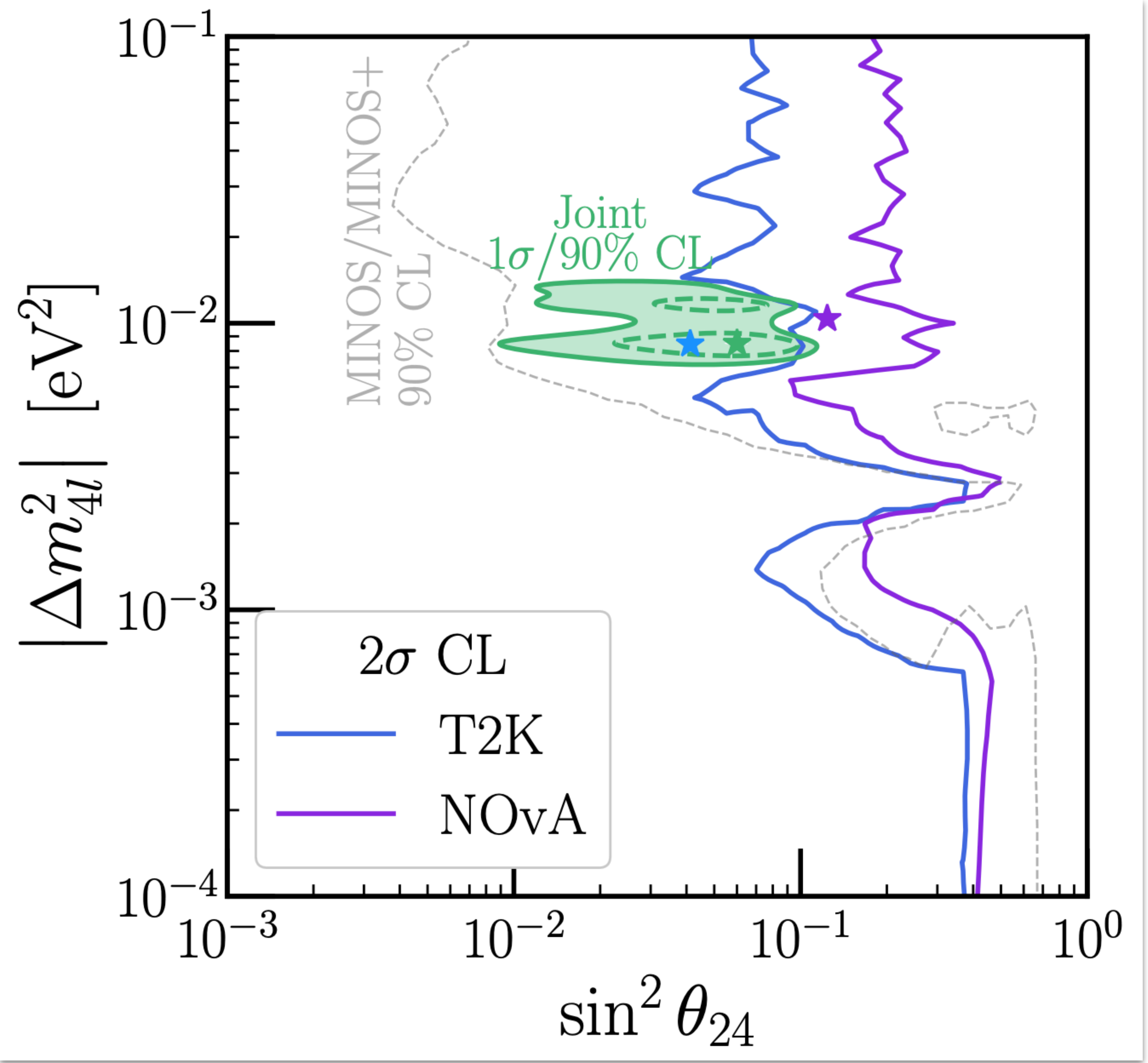
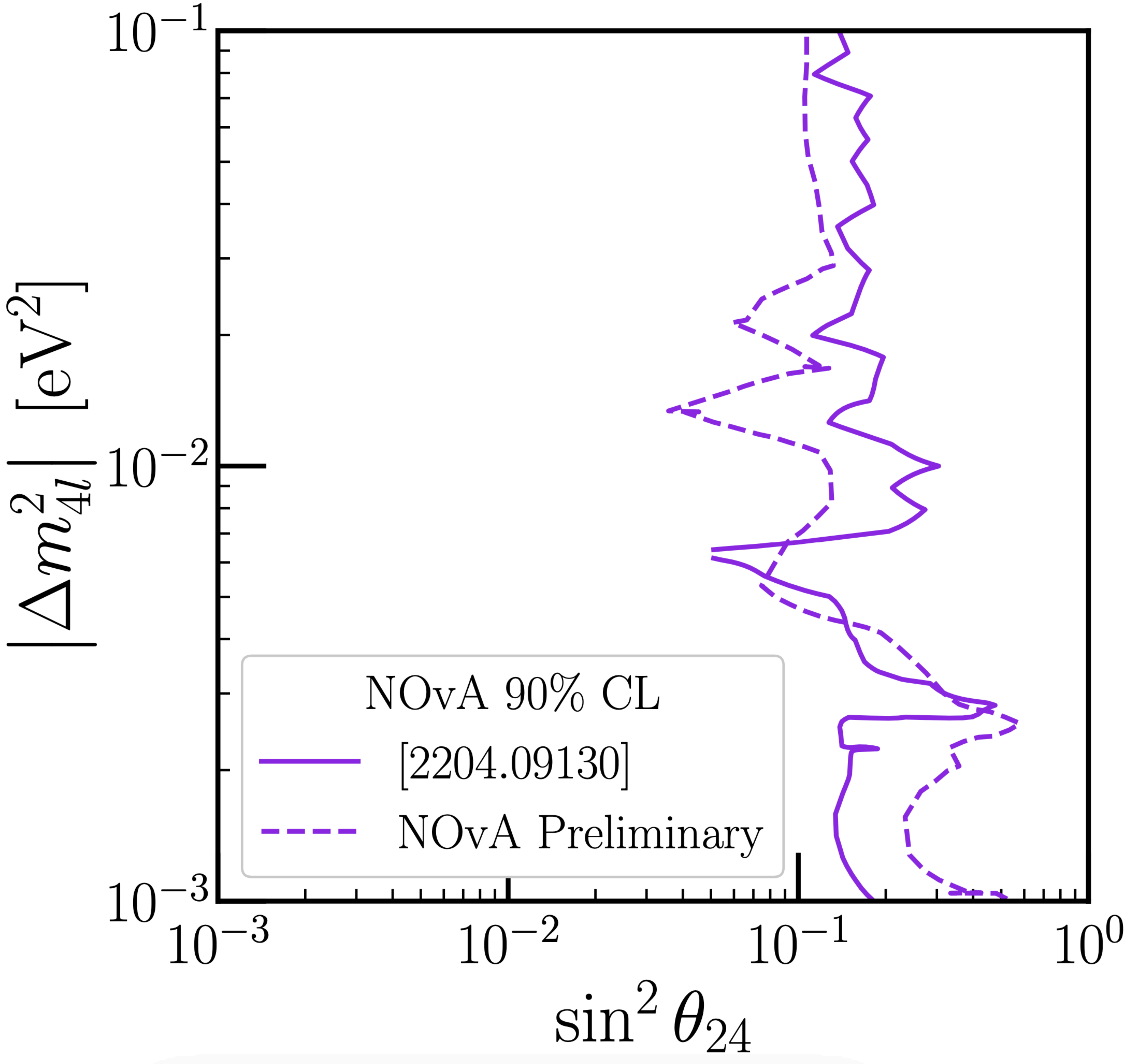




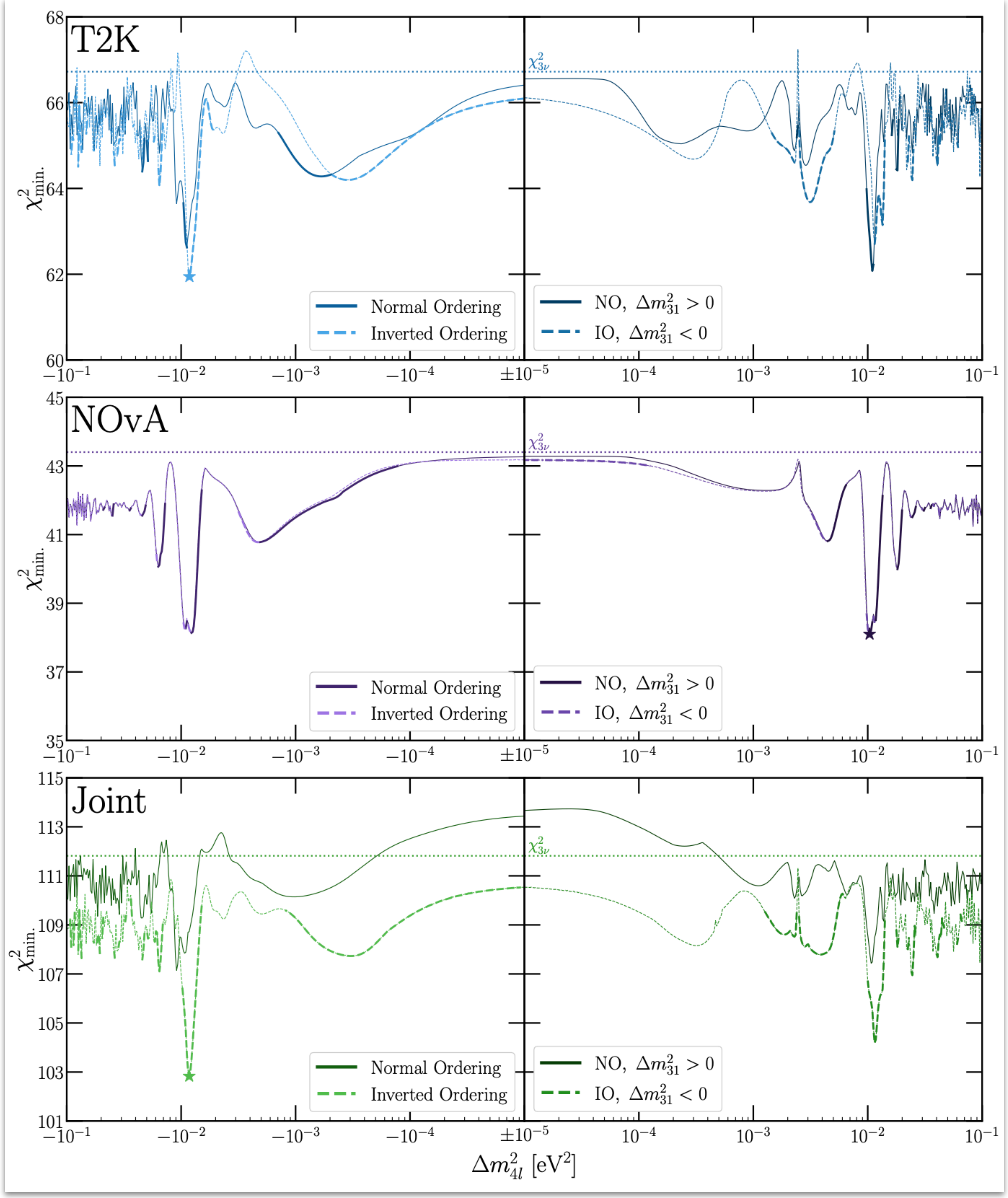
de Gouvêa et al, [2204.09130]

From NOvA's Neutrino2022 Talk Yesterday — 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.

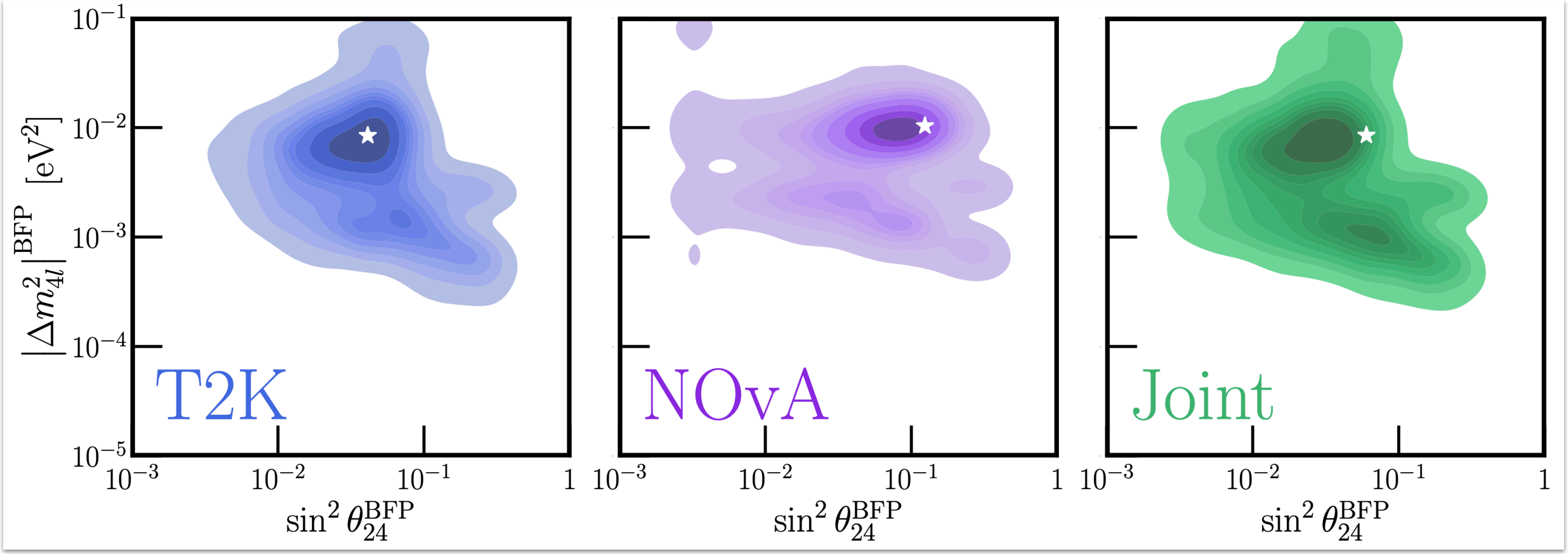
Are we simply absorbing statistical fluctuations in this new oscillation length?



de Gouvêa et al, [2204.09130]

Yes. (probably.)

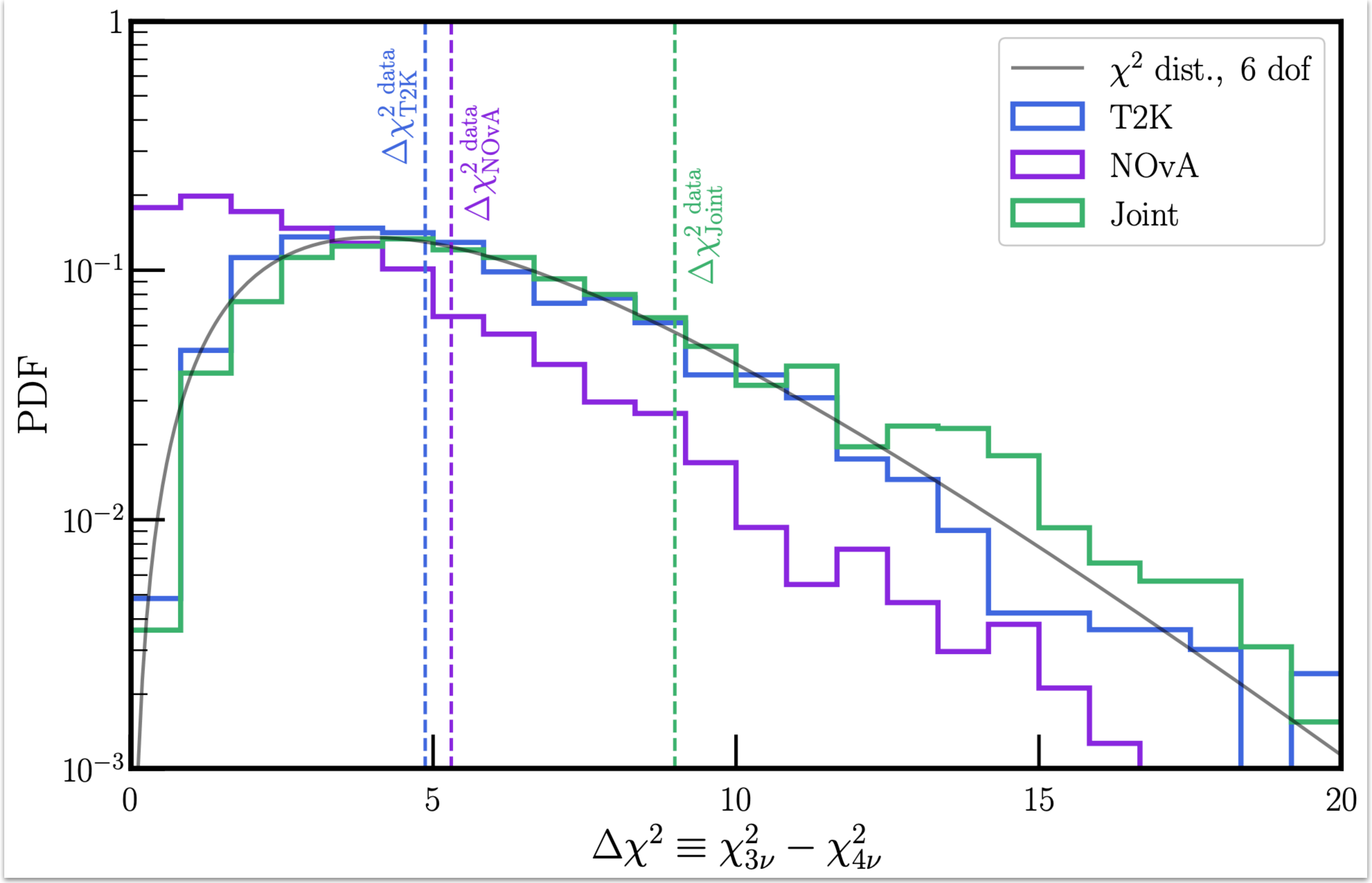
de Gouvêa et al, [2204.09130]



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]

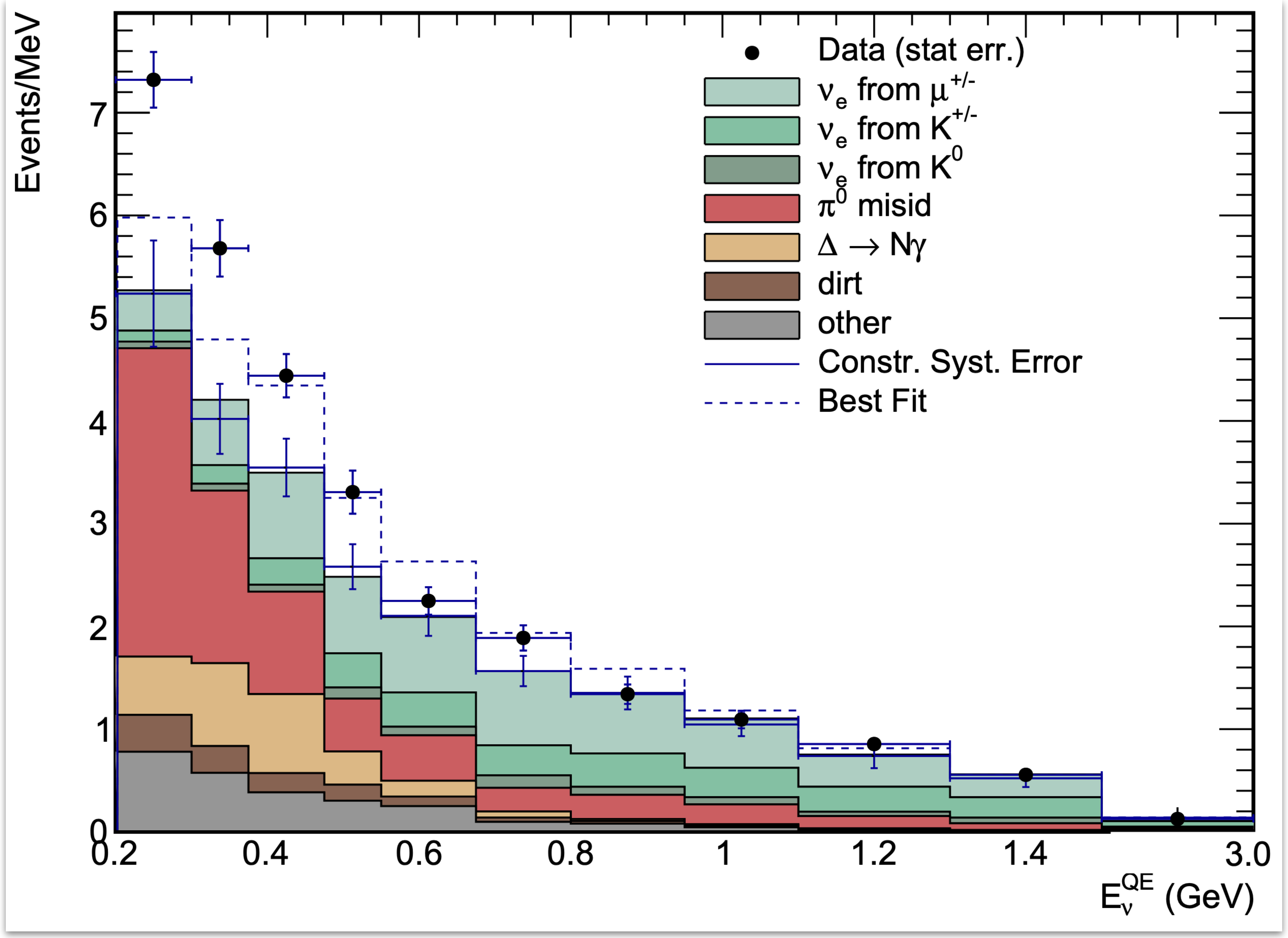


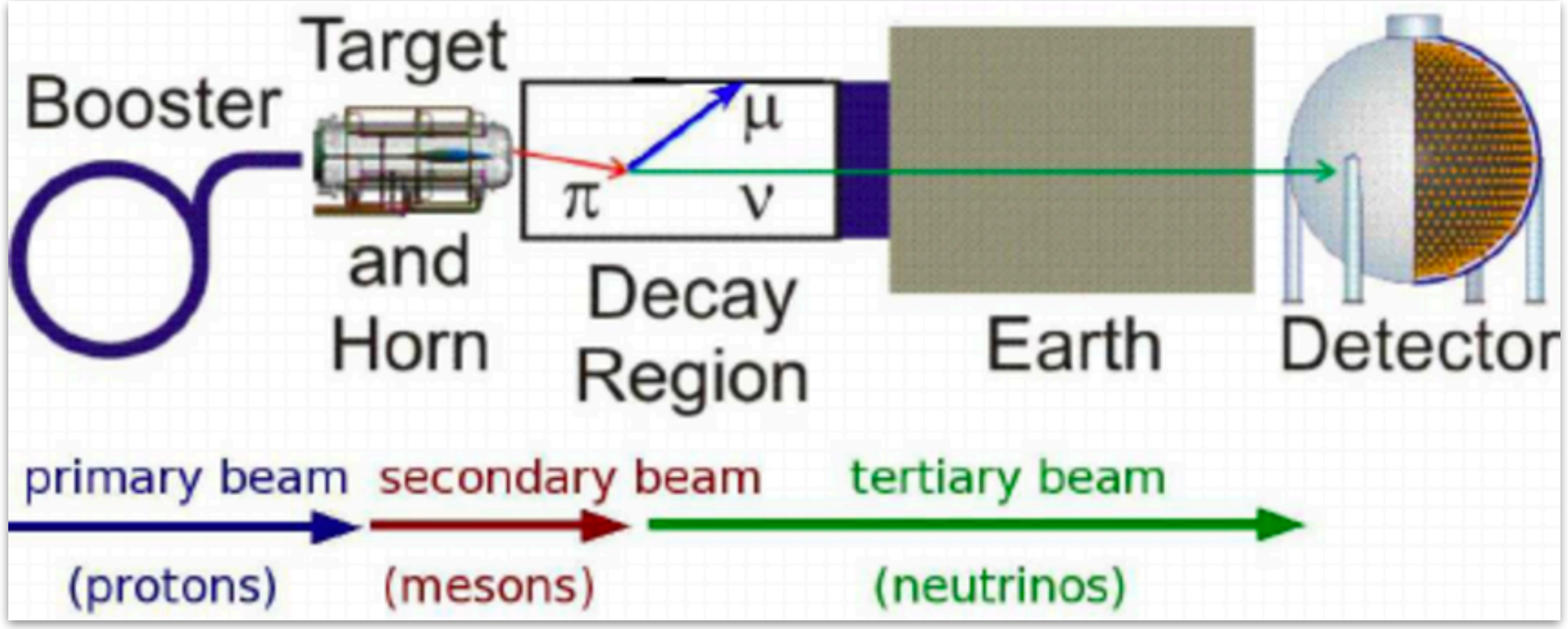
Accounting for this means that the $\Delta\chi^2$ preference of 8.99 that we observe only translates to a significance of approximately 0.22σ.

Recent Experimental Results

—MicroBooNE

The Challenge of MiniBooNE



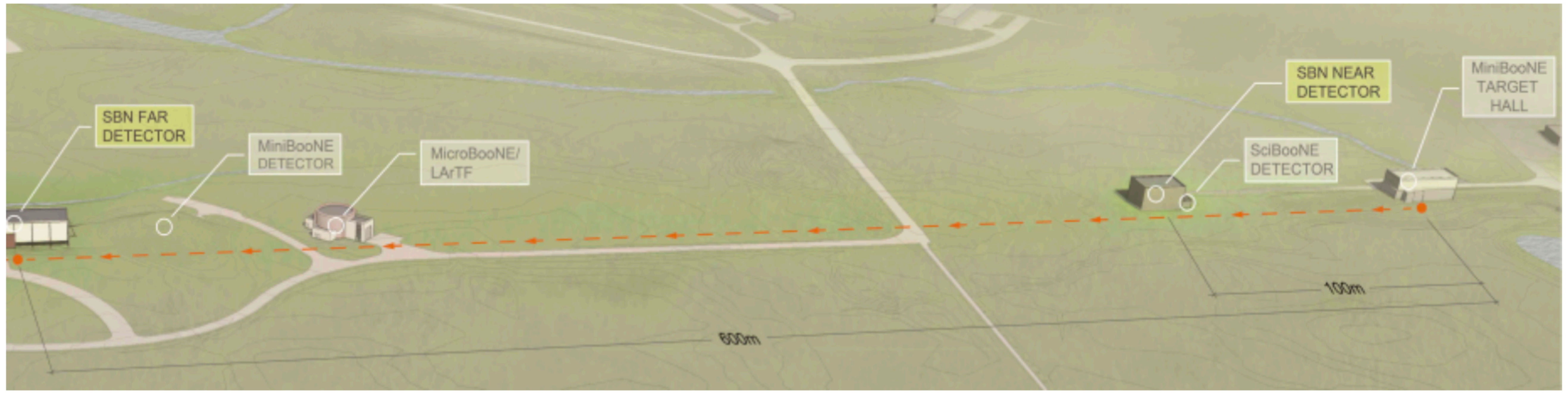


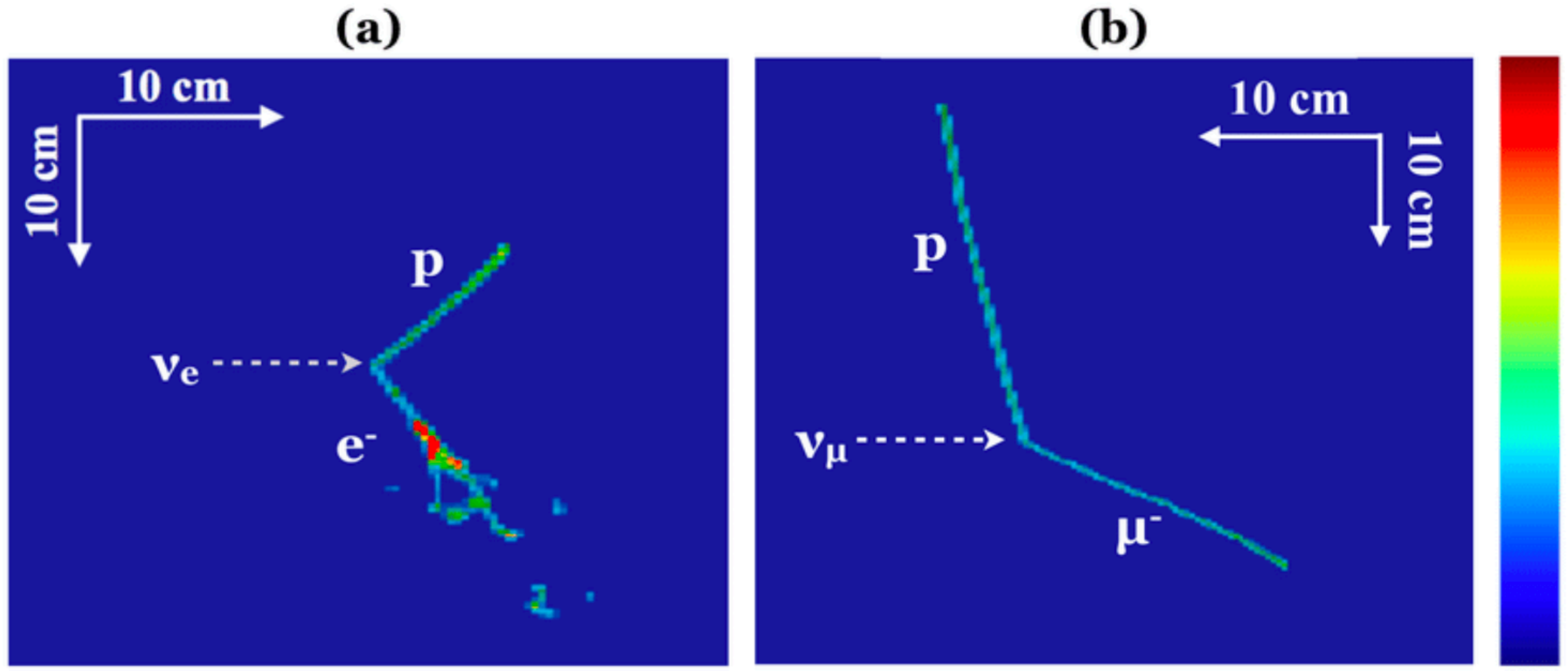
Cherenkov signatures in MiniBooNE are unable to distinguish between photons, electrons, and multiple-electron signatures.

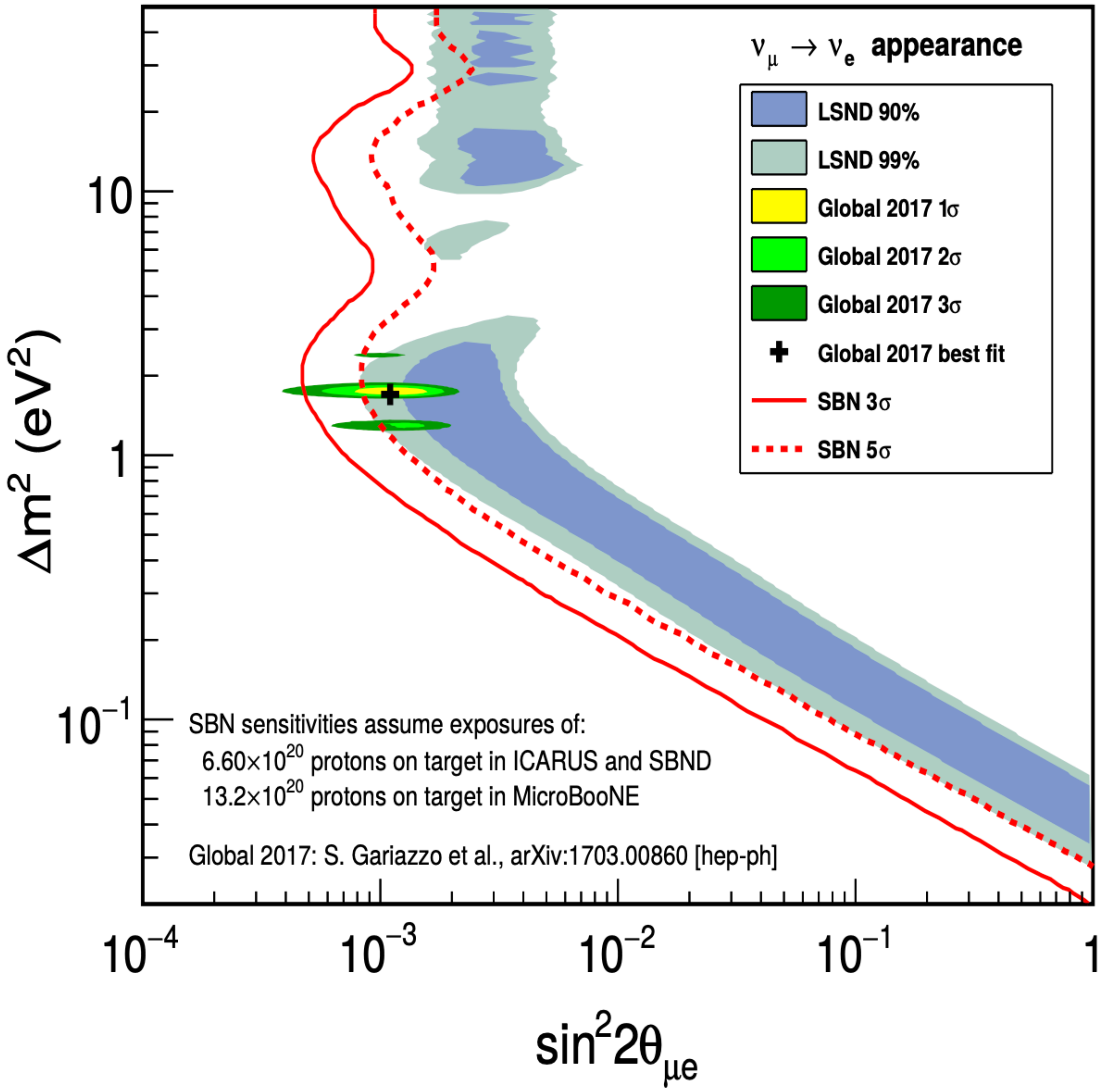
The SBN Programme

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

(Courtesy of Ivan Esteban)

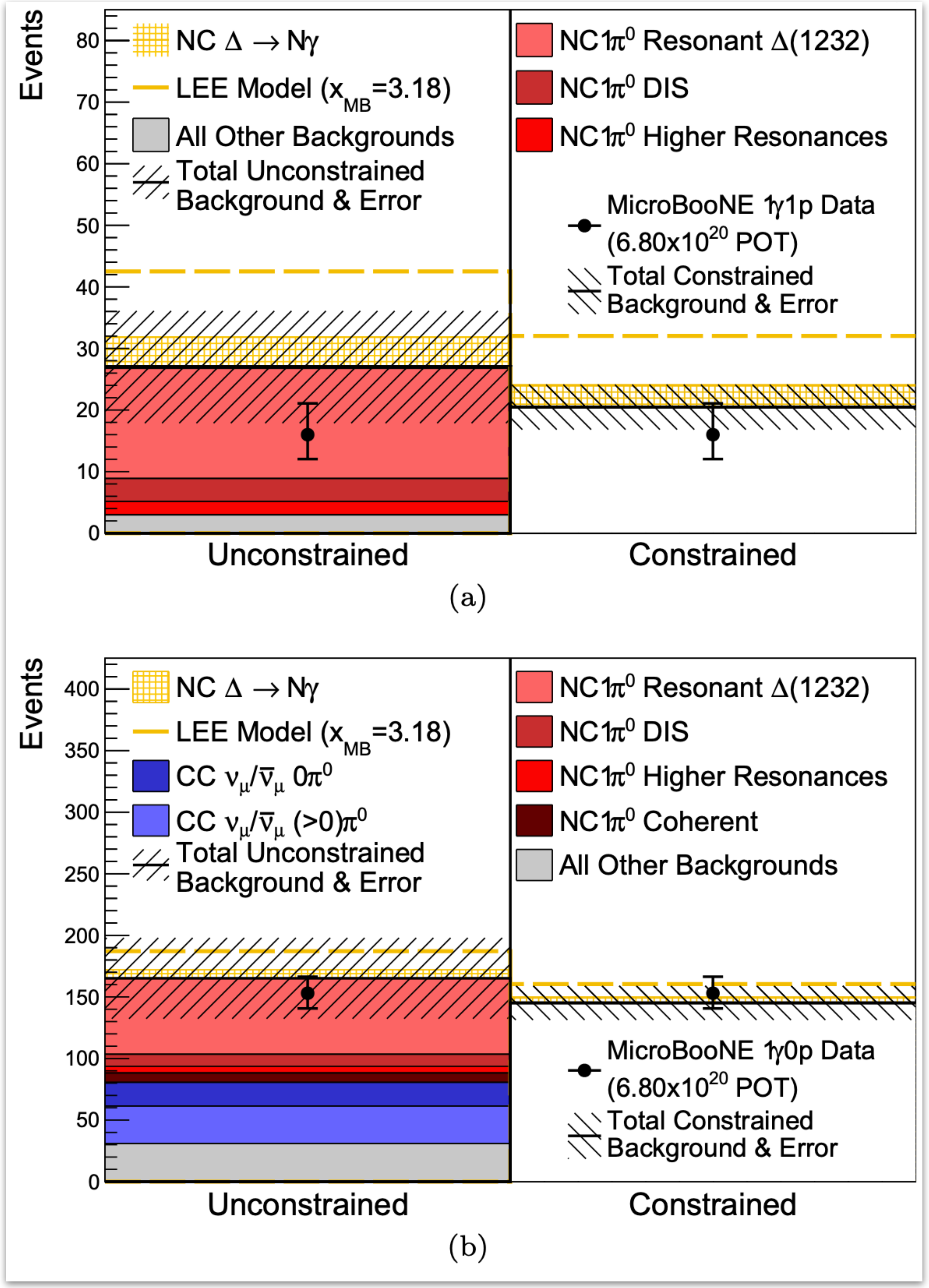






Liquid Argon Time Projection Chambers — “Colored Bubble Chambers”

MicroBooNE Photon Analysis

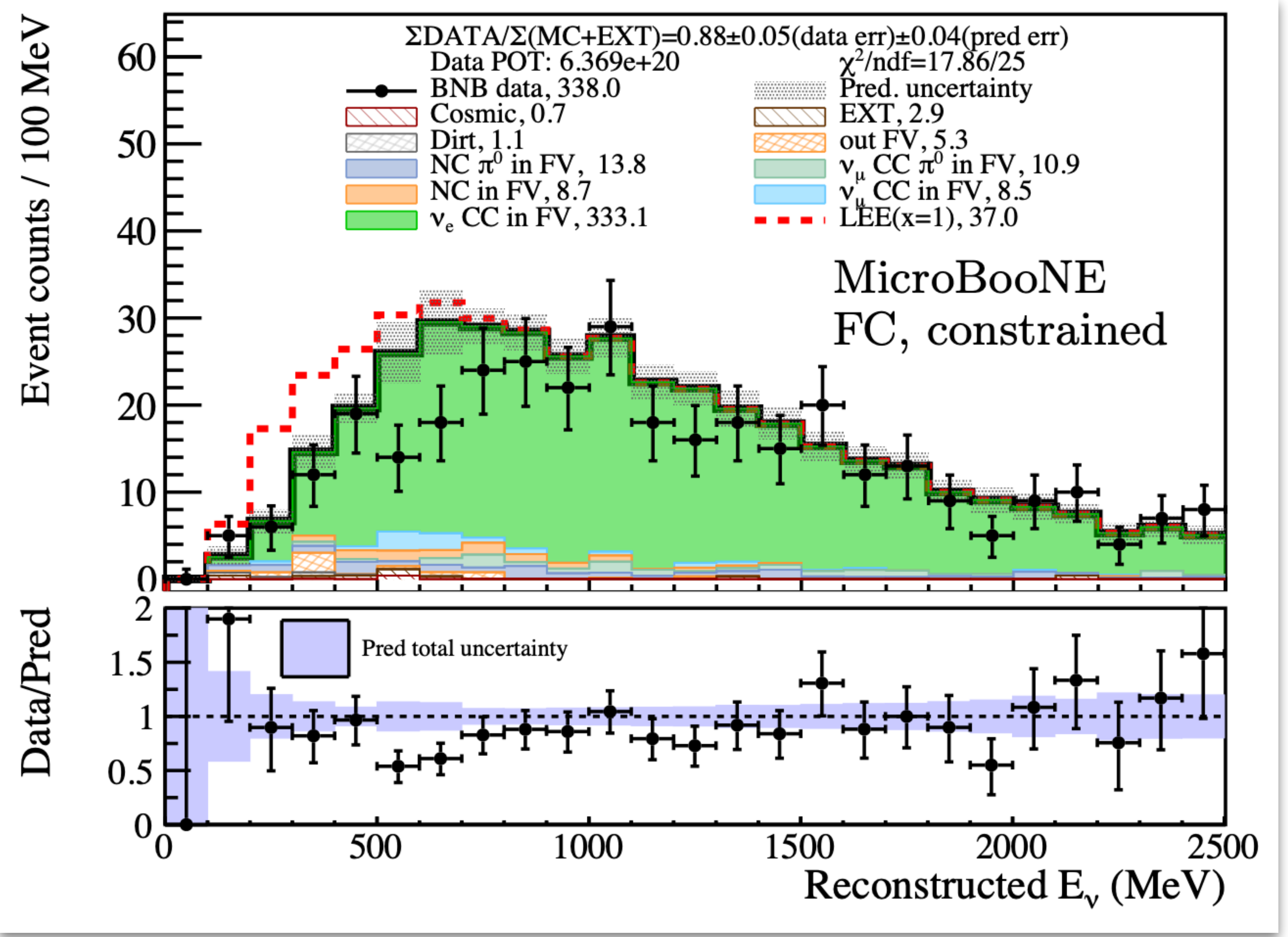


MicroBooNE Collaboration, [2110.00409]

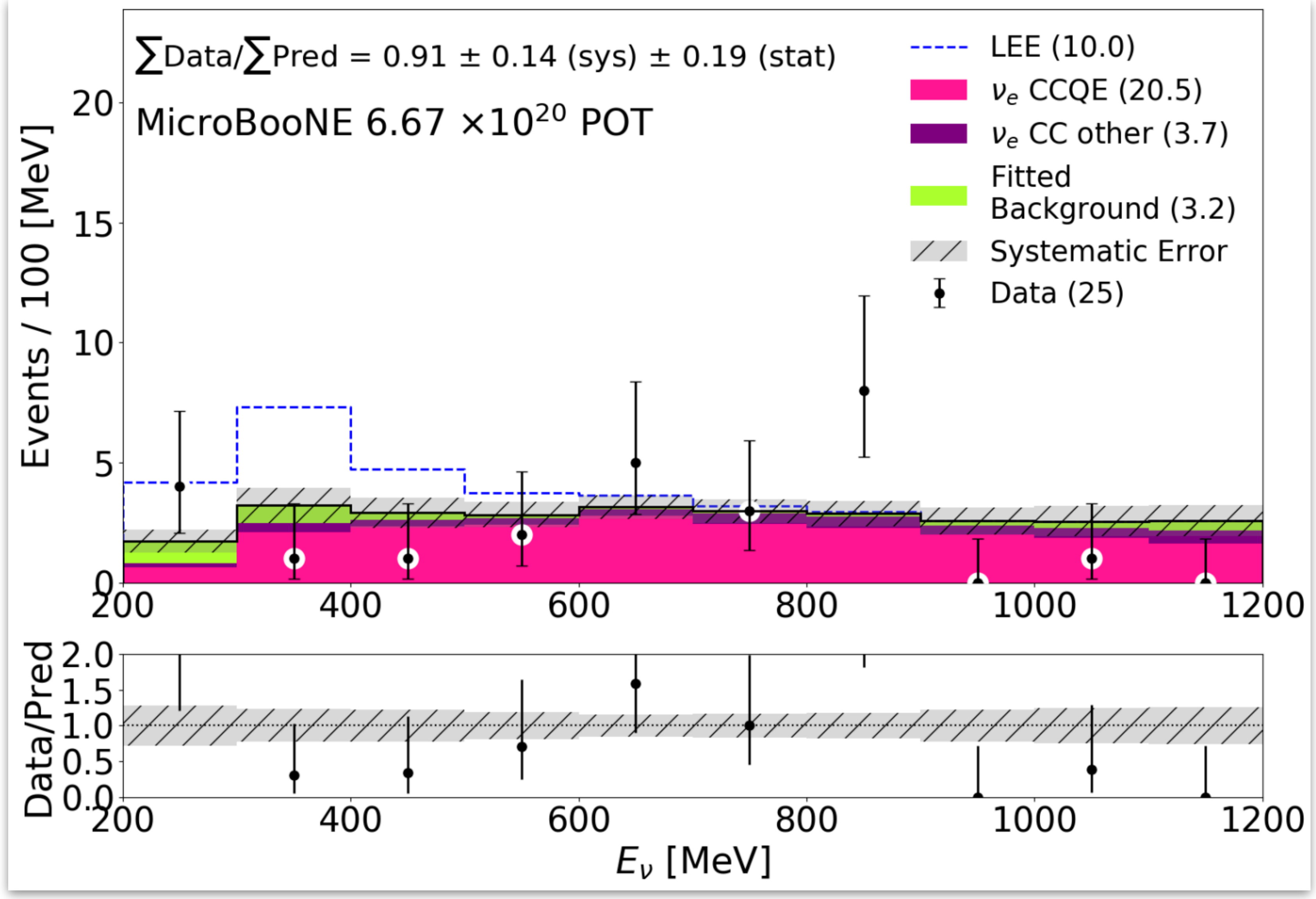
MicroBooNE disfavors the $\Delta \to N\gamma$ explanation of the MiniBooNE anomaly at 94.8% CL.

MicroBooNE Electron Analyses

“Inclusive” [2110.13978]



“CCQE” [2110.14080]



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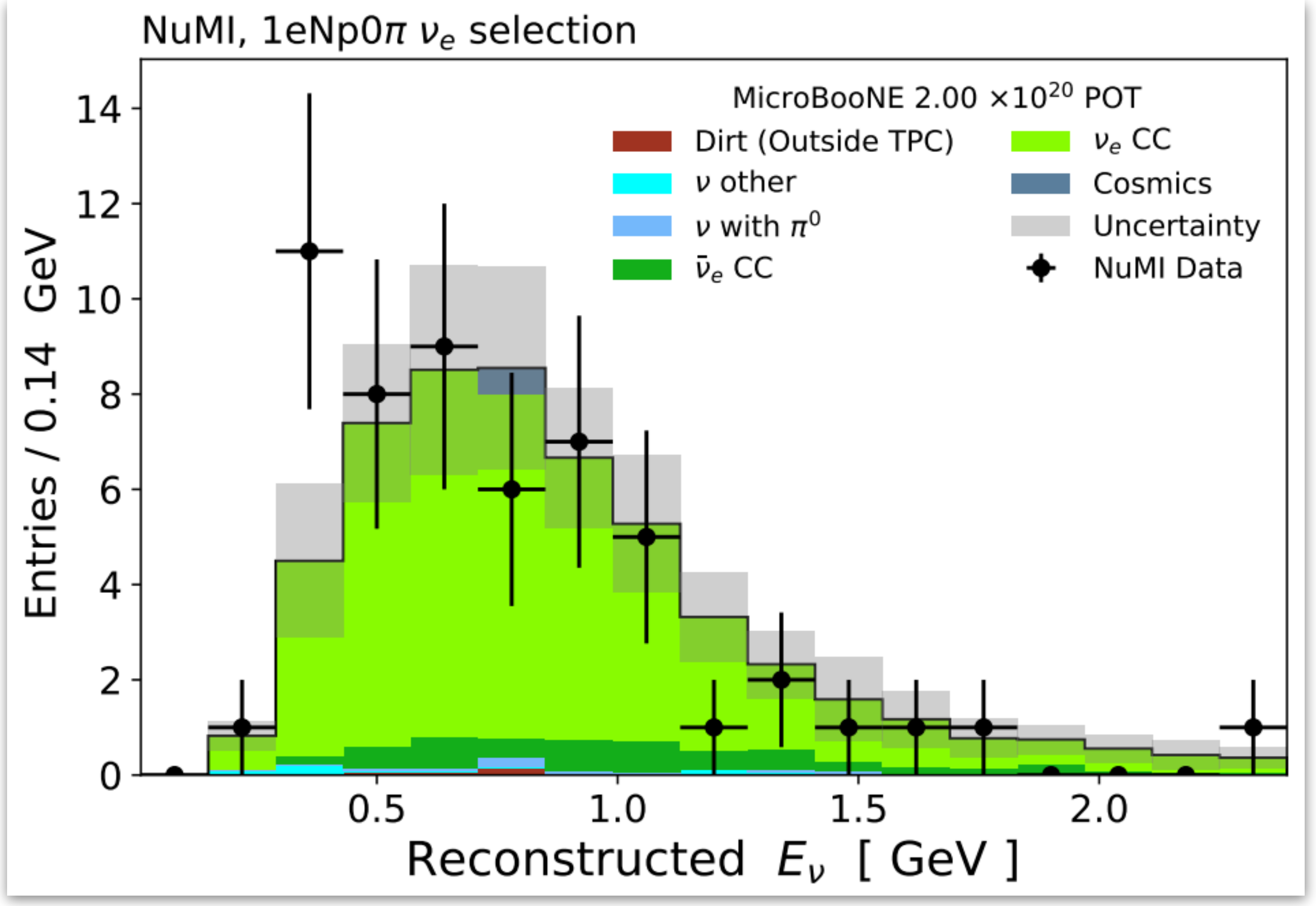

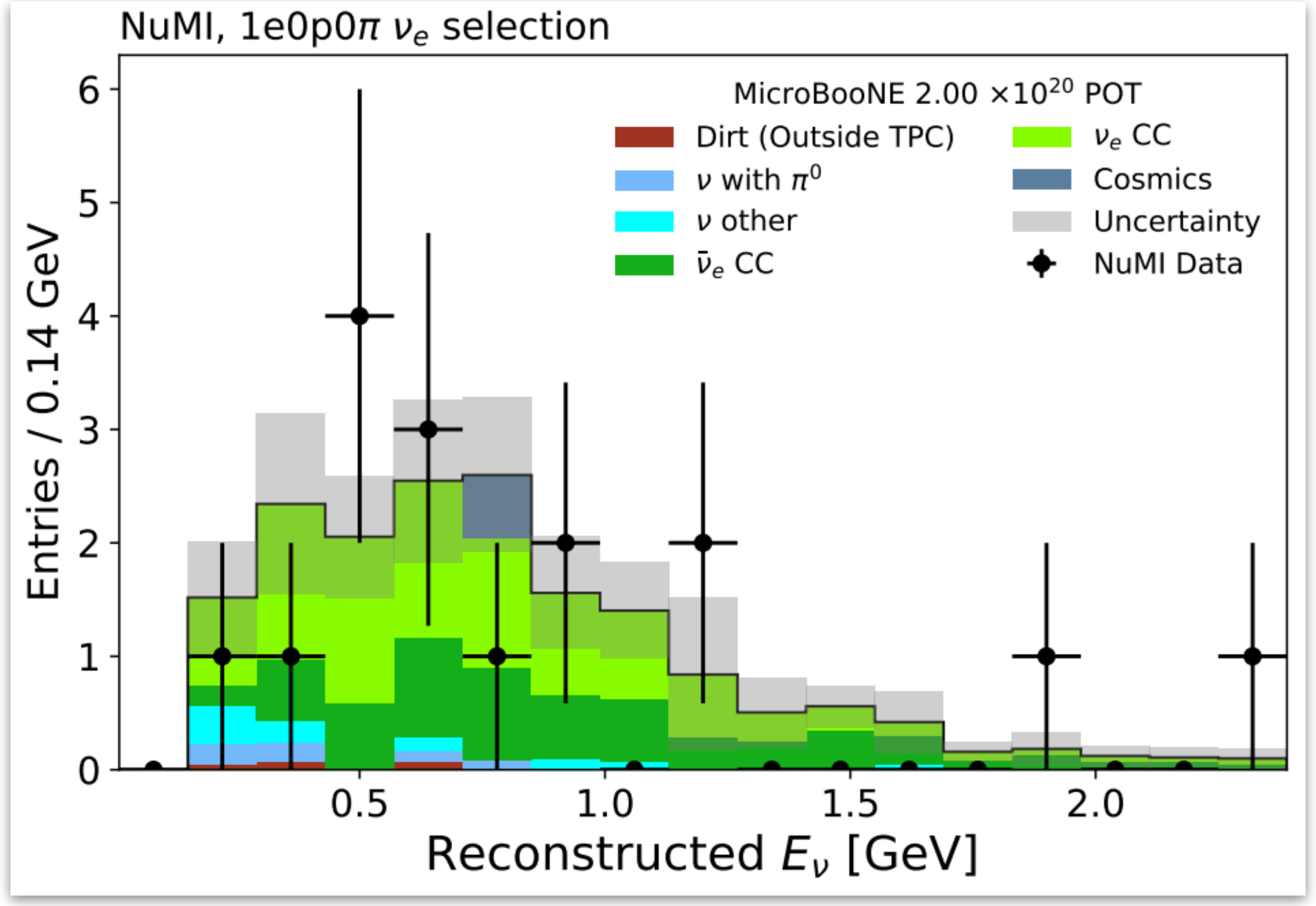

MicroBooNE Electron Analyses

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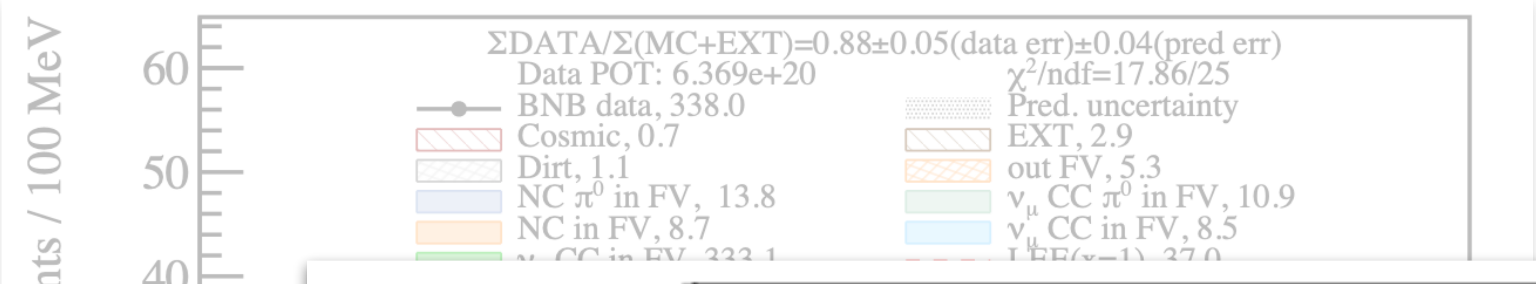

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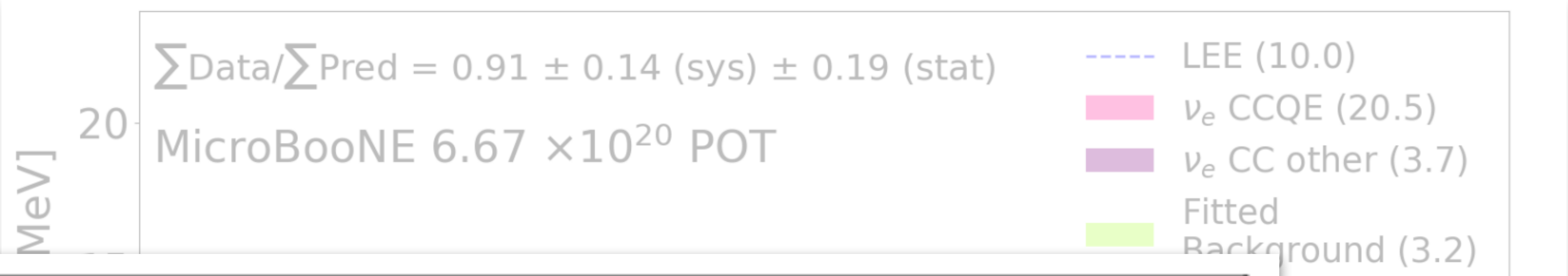

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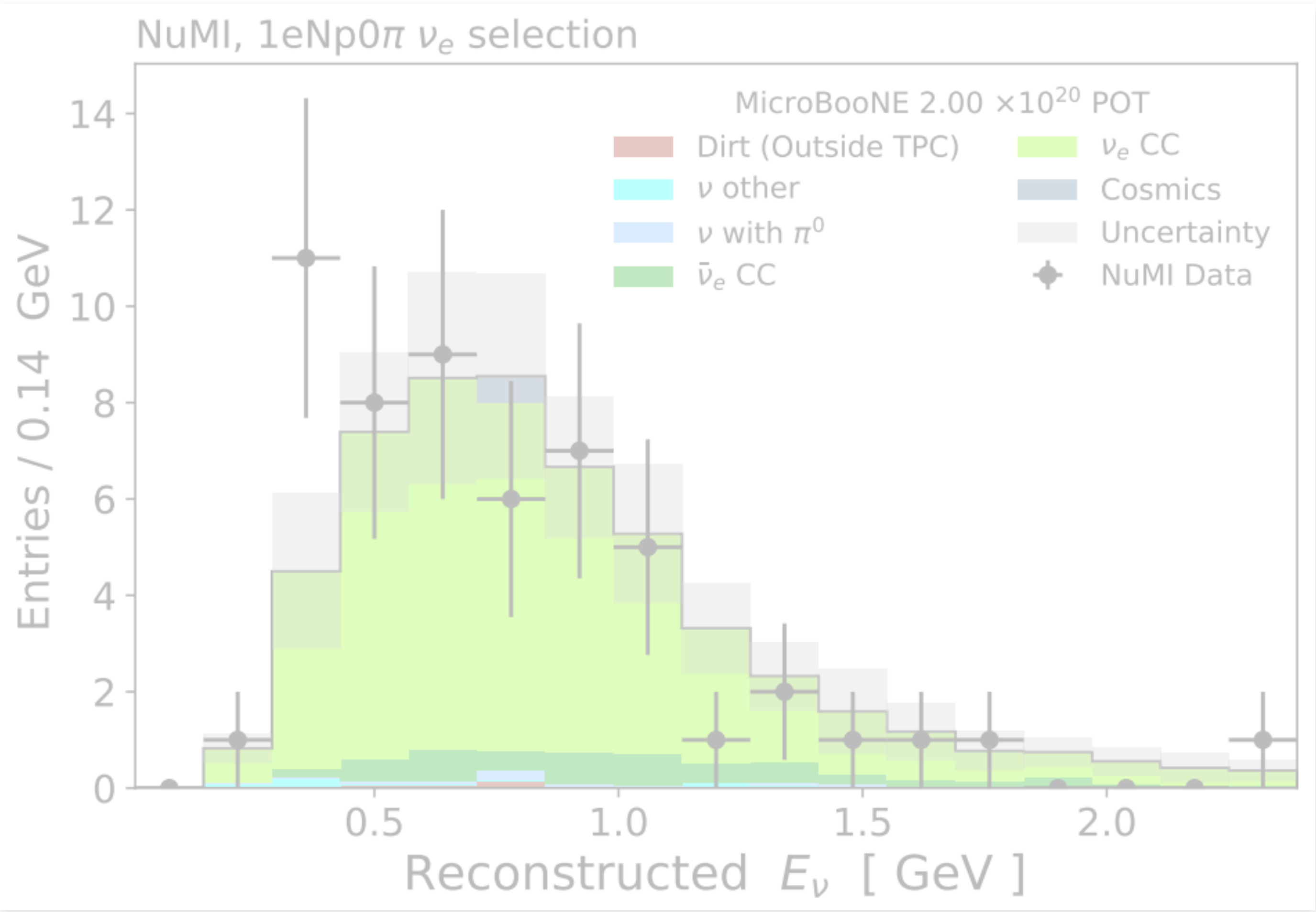
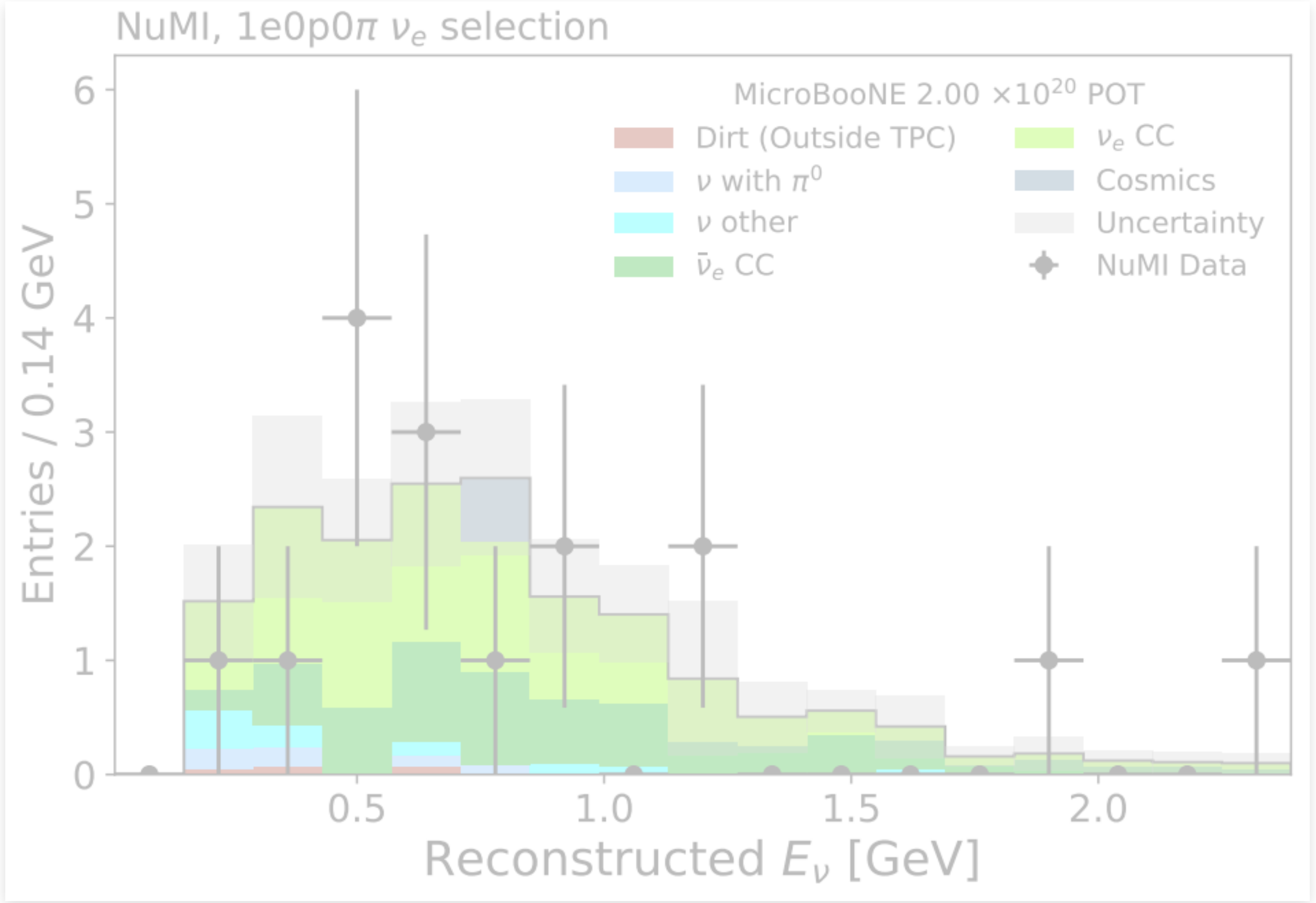
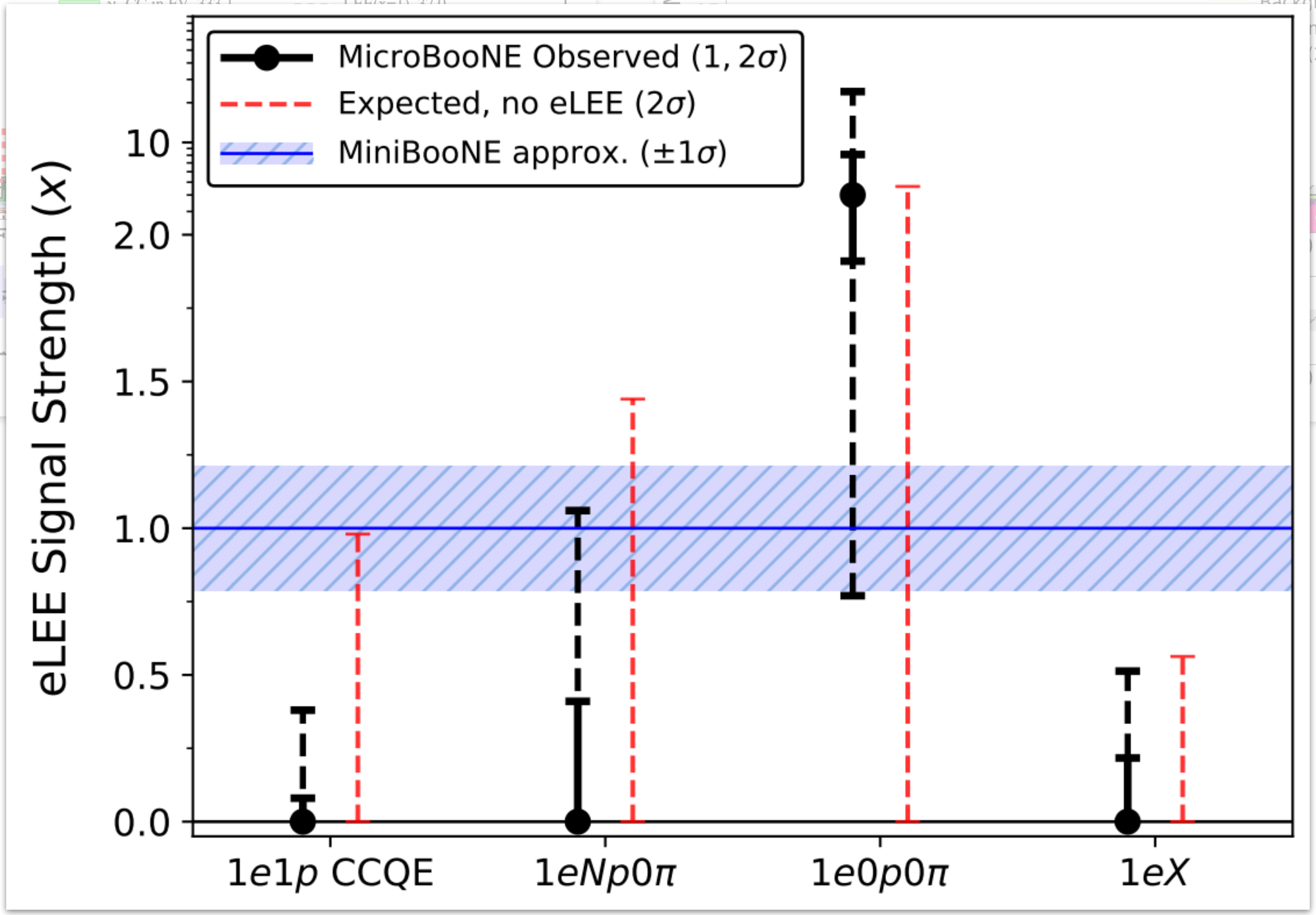


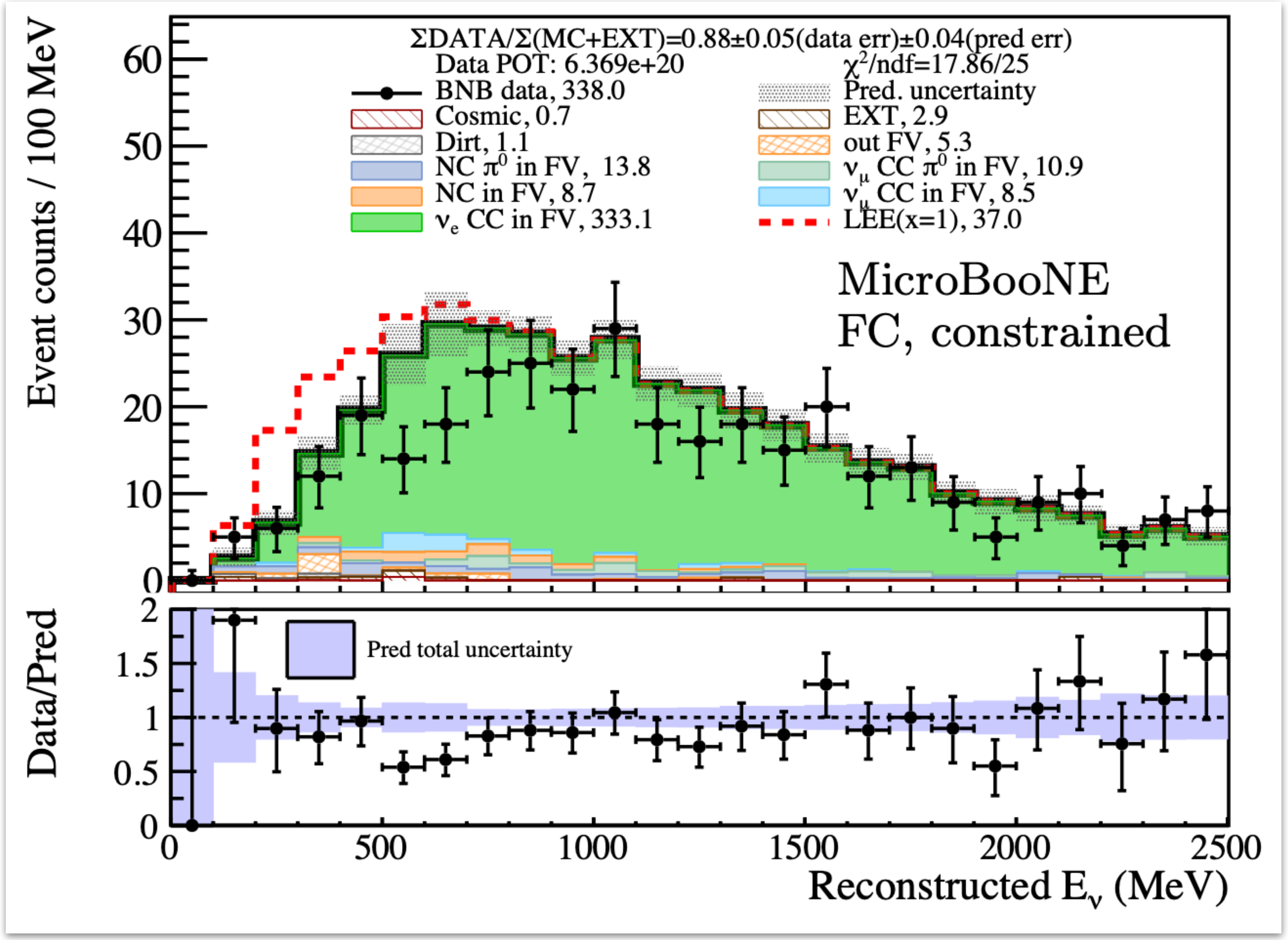




Discussion of all Results [2110.14054]

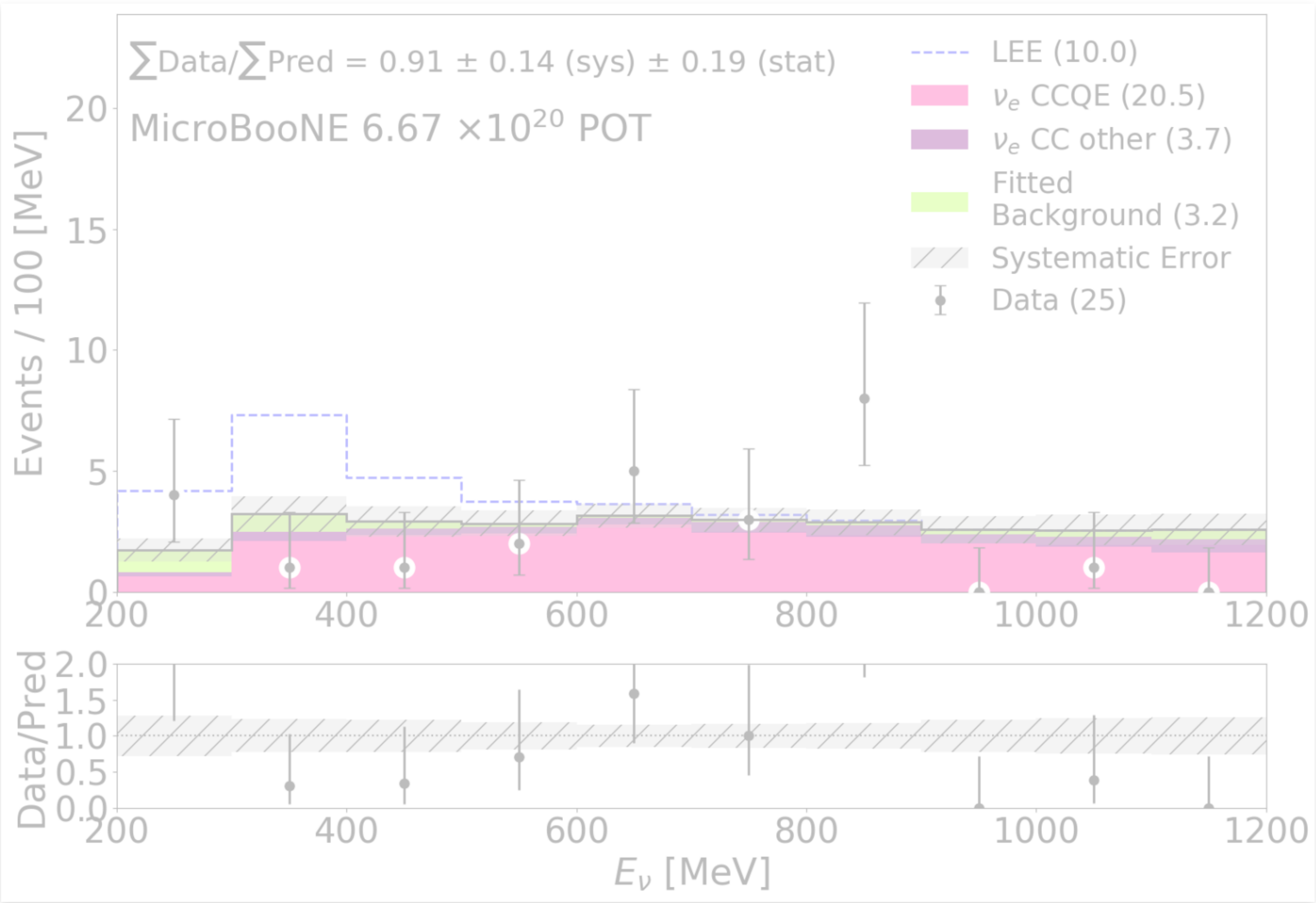
Complementarity of Inclusive/CCQE

"Inclusive" [2110.13978]



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

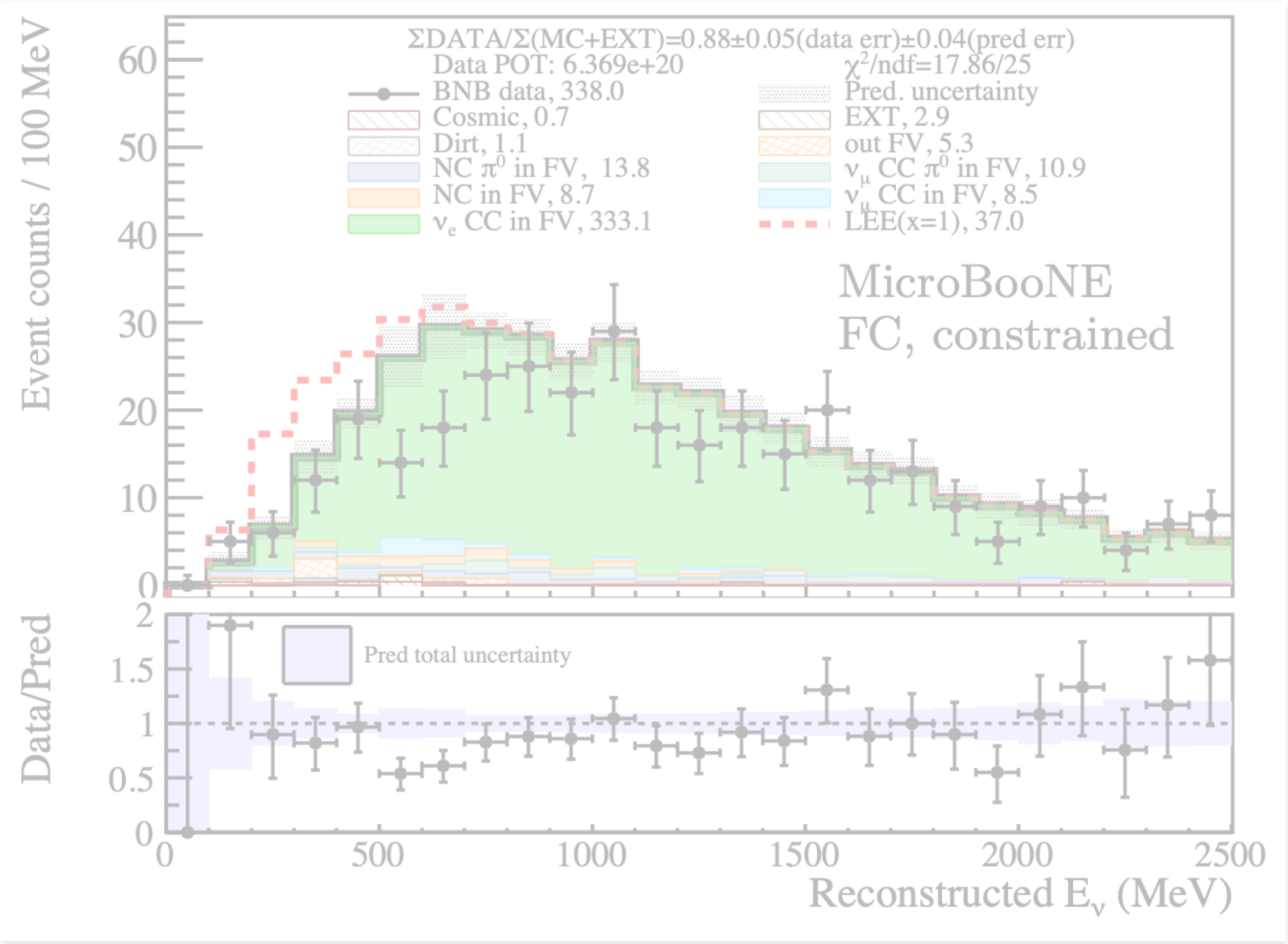
"CCQE" [2110.14080]



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

Complementarity of Inclusive/CCQE

"Inclusive" [2110.13978]



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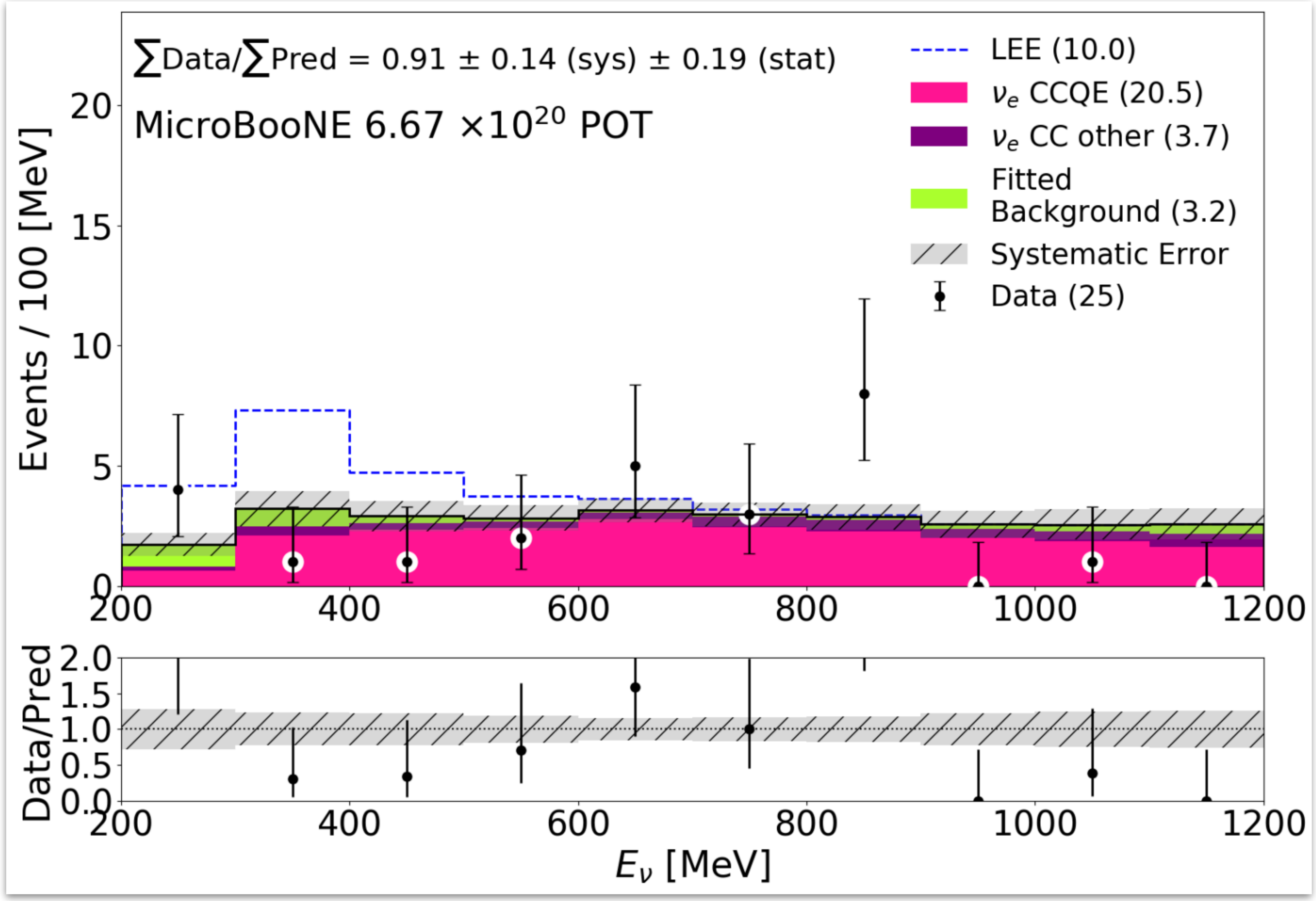

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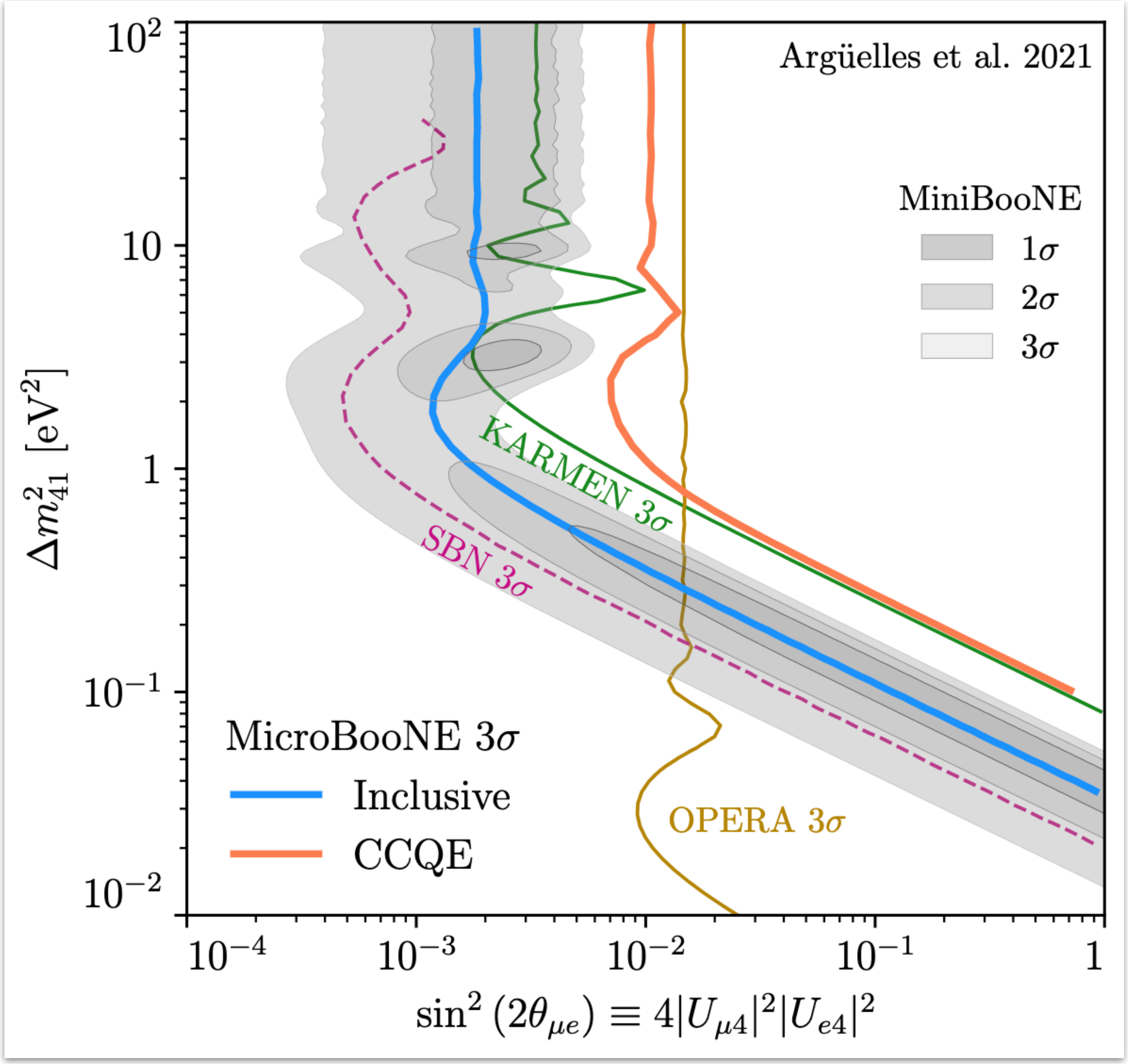
MicroBooNE and Sterile Neutrinos

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



Argüelles, KJK, et al, [2111.10359]

MicroBooNE and Sterile Neutrinos

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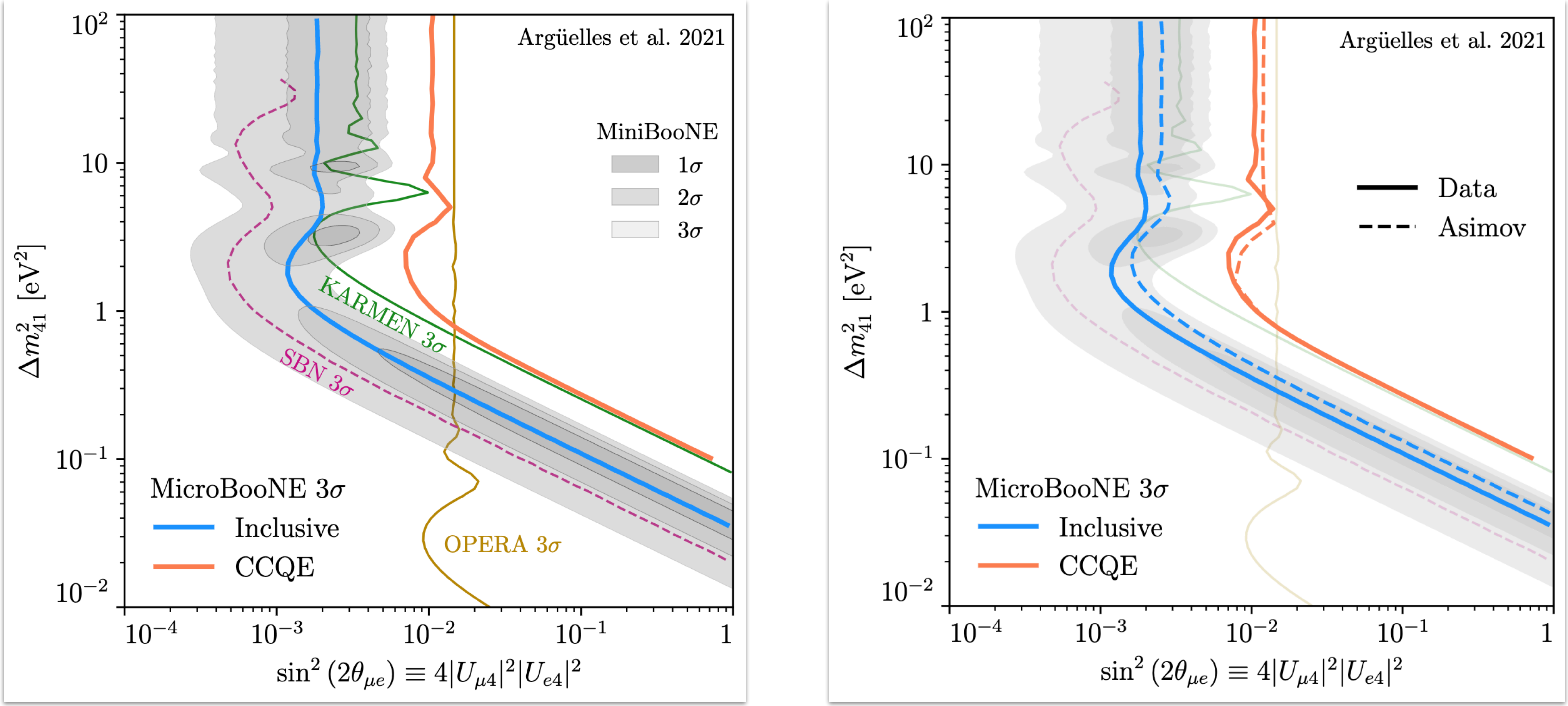

Argüelles, KJK, et al, [2111.10359]

Complete 3+1 Neutrino Framework

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

Complete 3+1 Neutrino Framework

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

Complete 3+1 Neutrino Framework

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

Anomalous appearance *requires* disappearance!

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

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

Complete 3+1 Neutrino Framework

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

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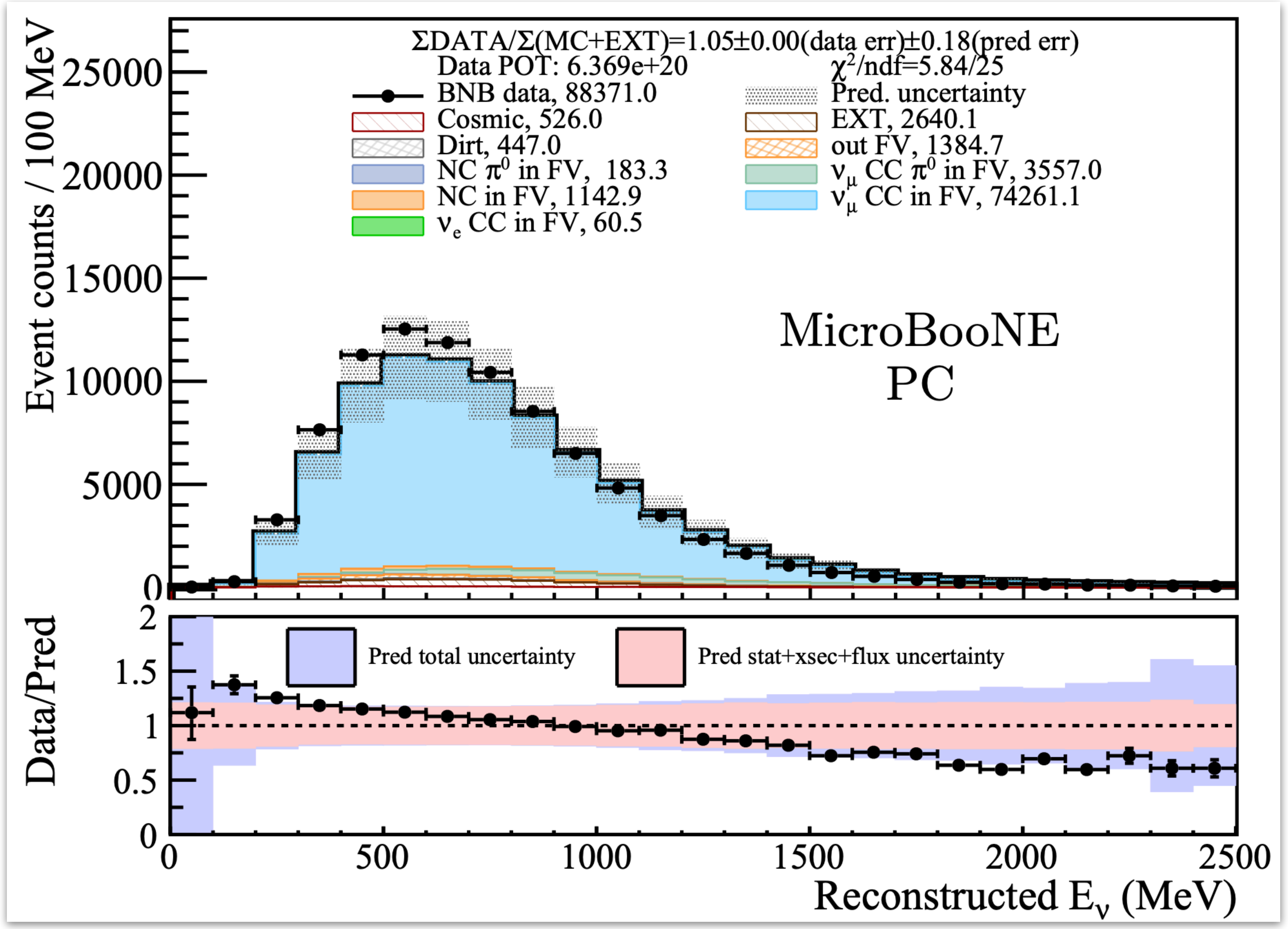
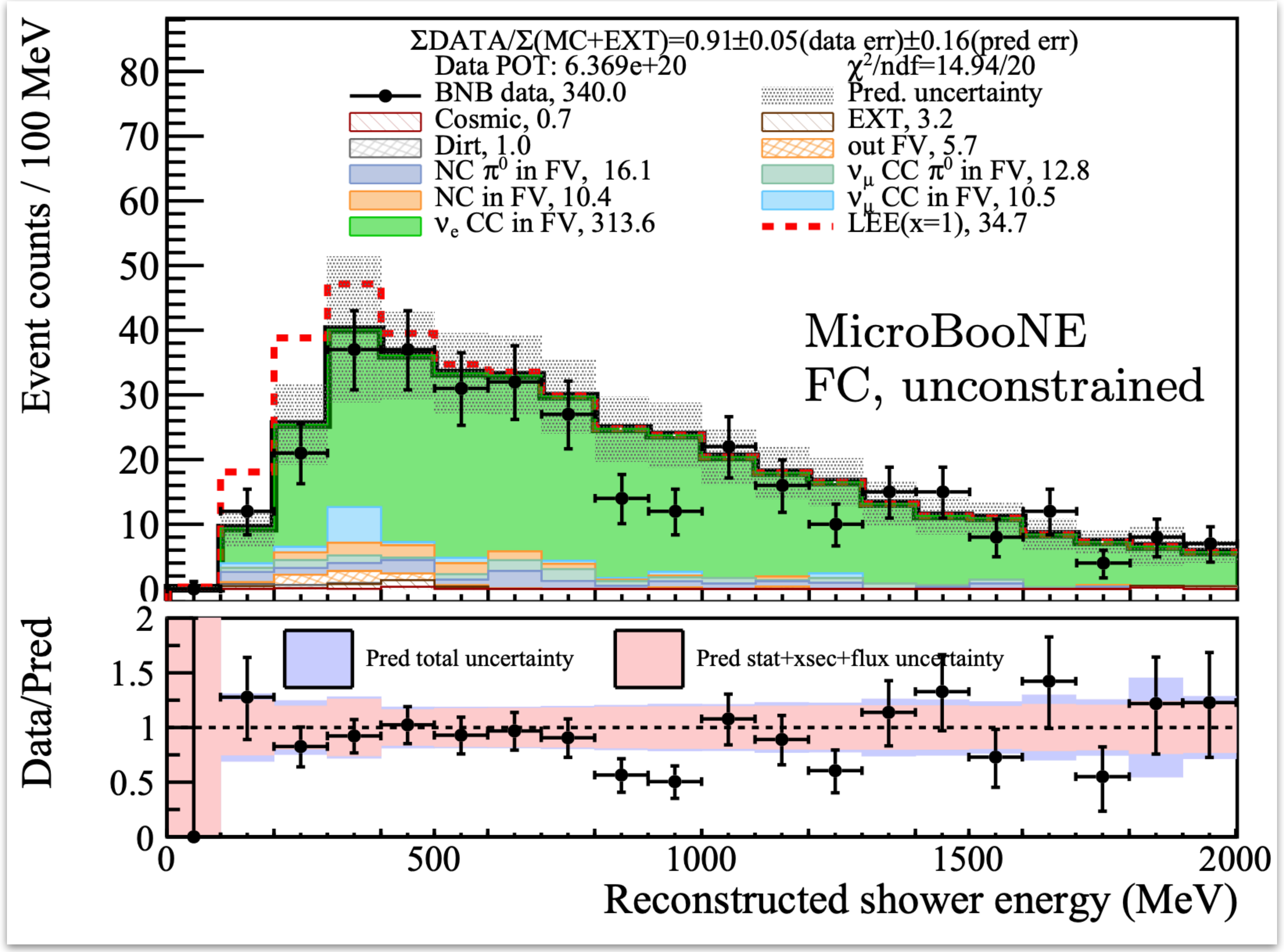
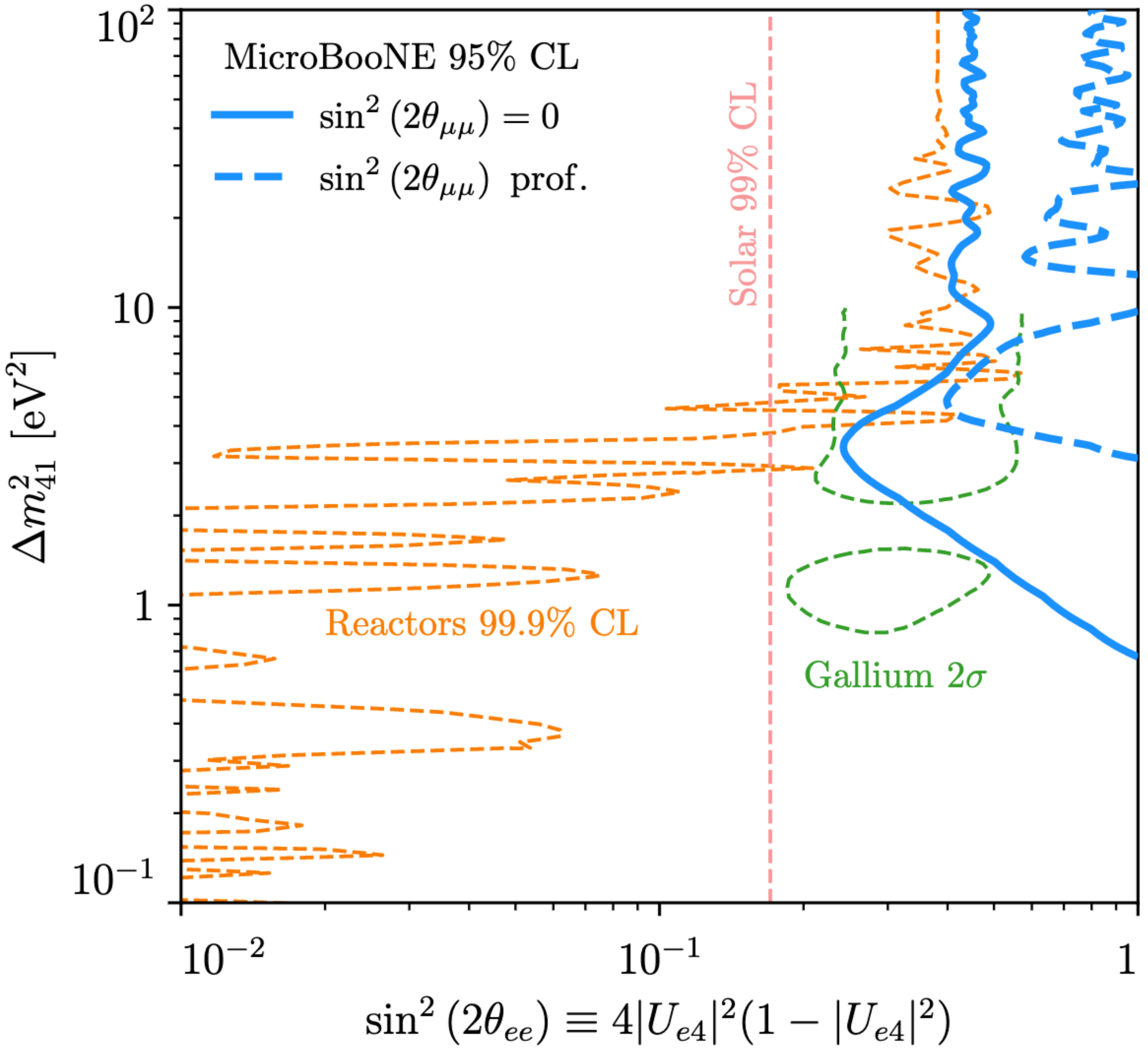


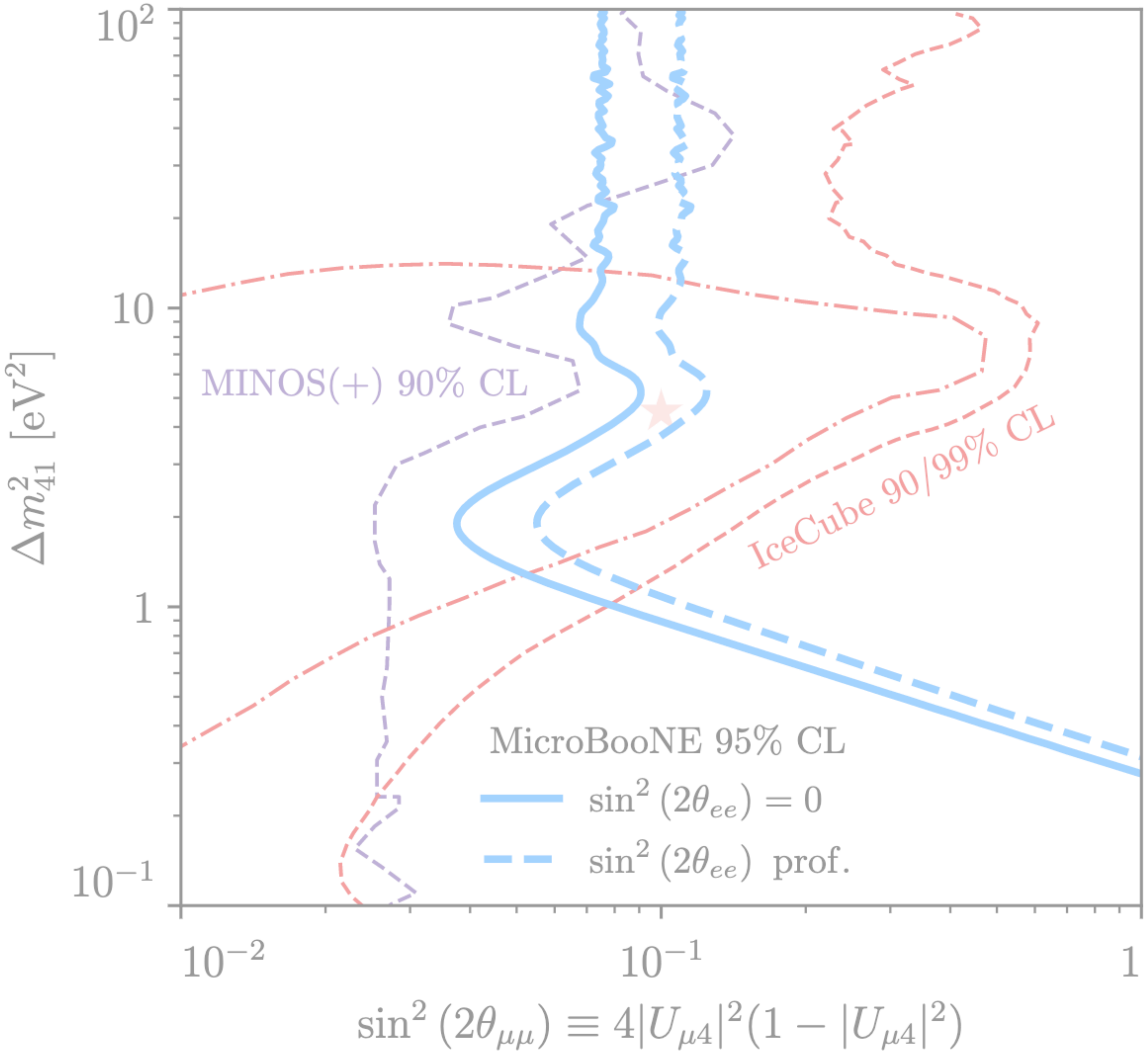


MicroBooNE, [2110.13978]

Four-Flavor Results

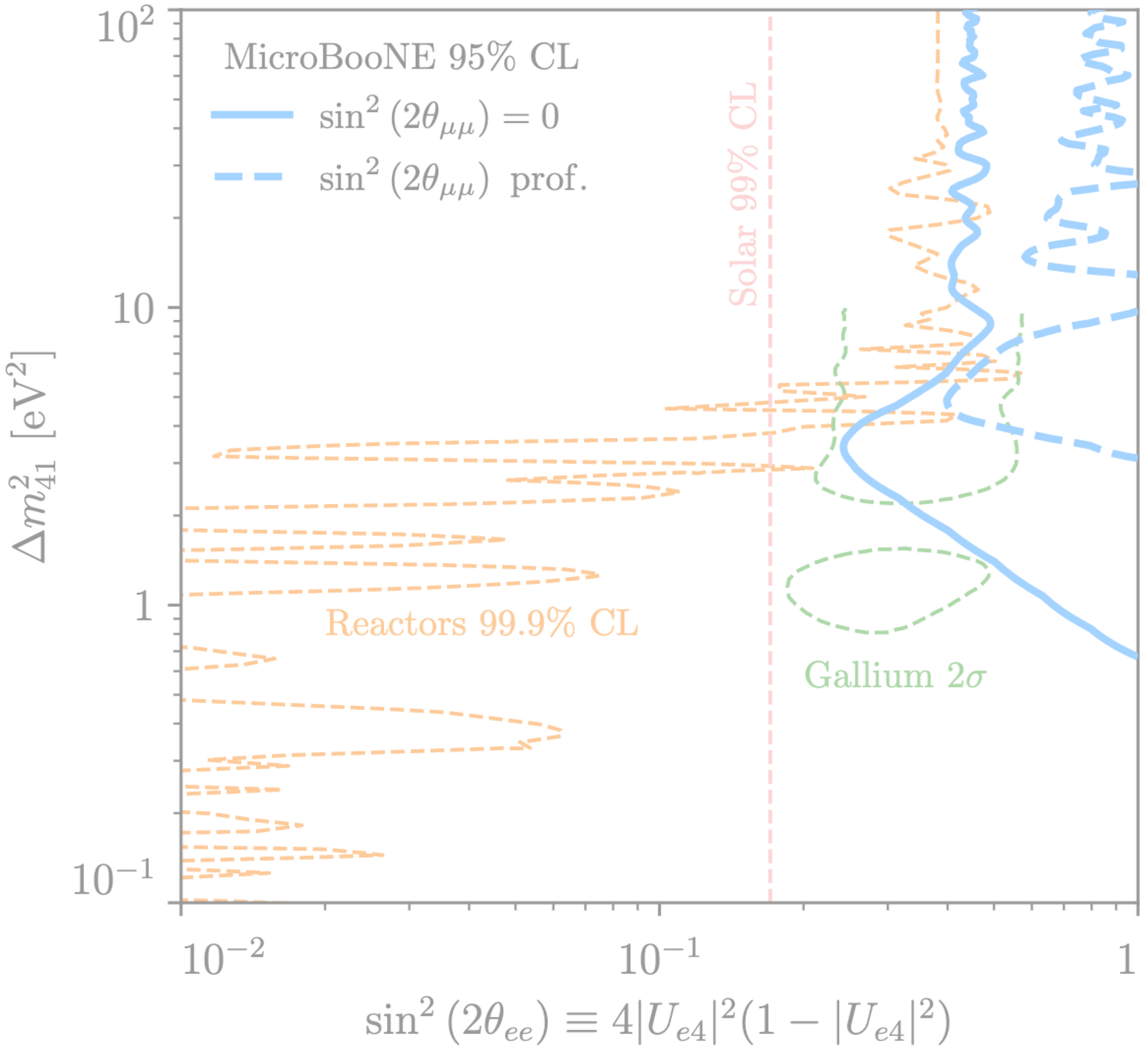


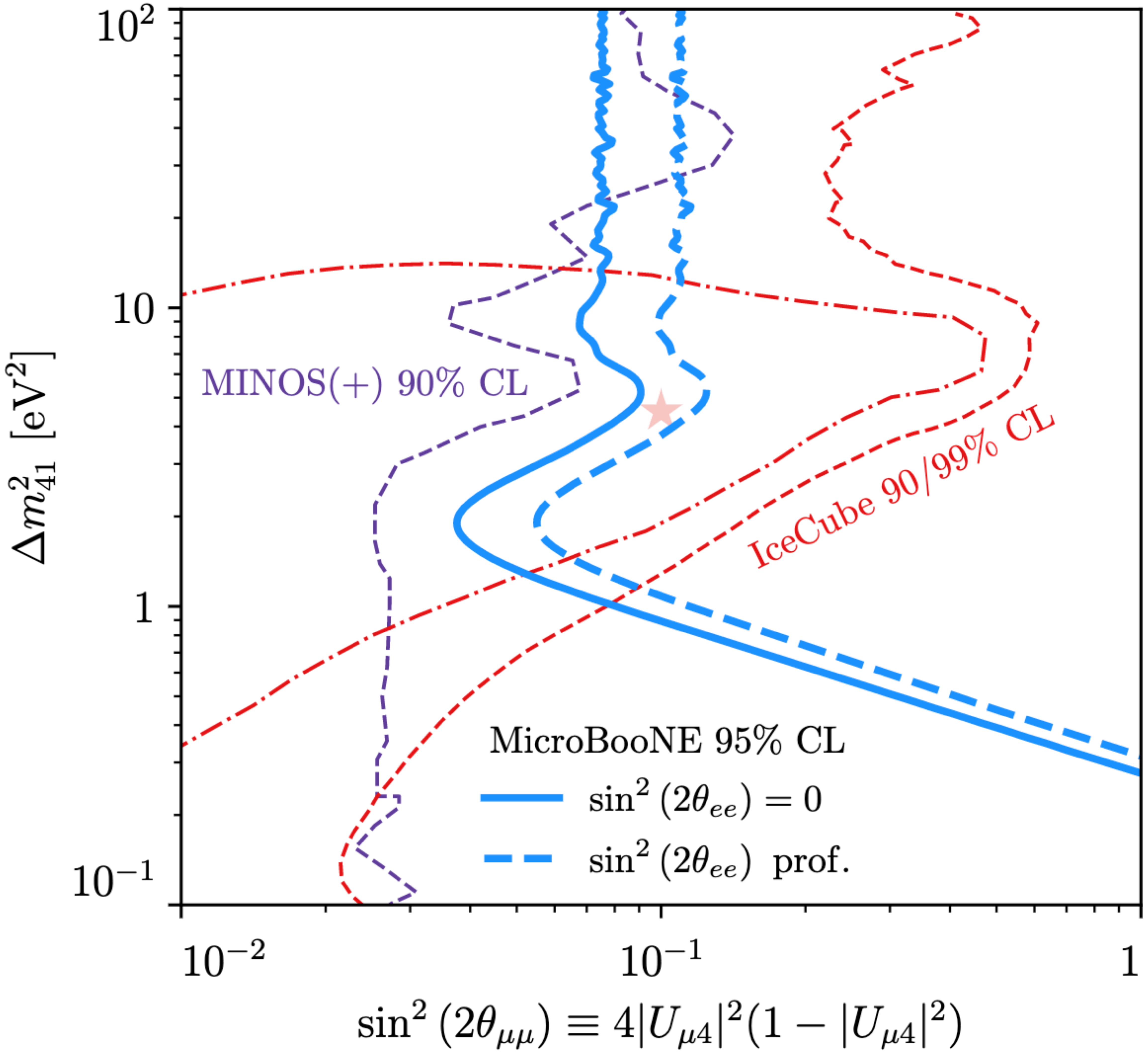
Argüelles et al, [2111.10359]



Four-Flavor Results

Argüelles et al, [2111.10359]

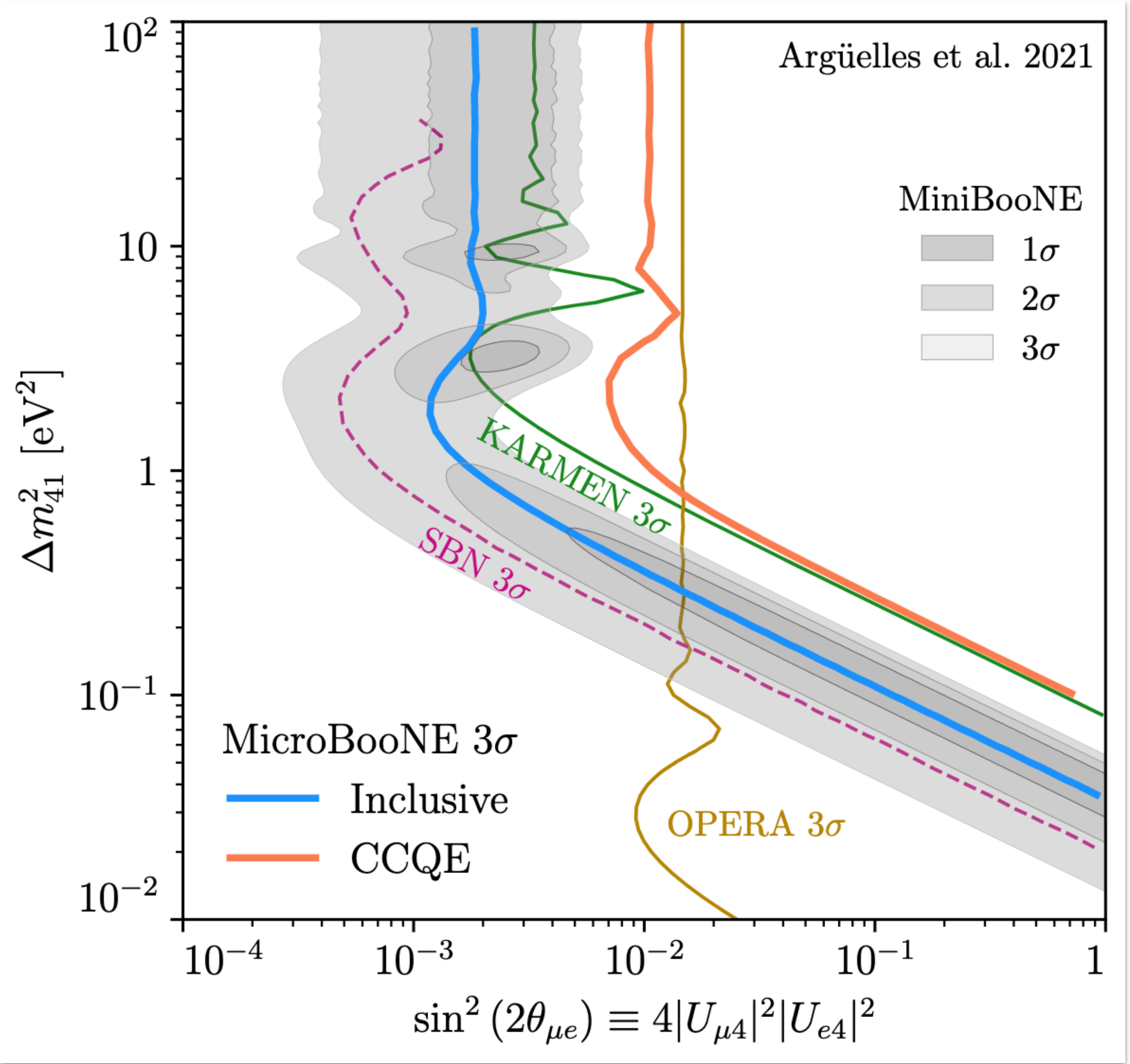




Four-Flavor, Appearance

[2111.10359]

Profiling over unseen mixing angle, how does sensitivity change?

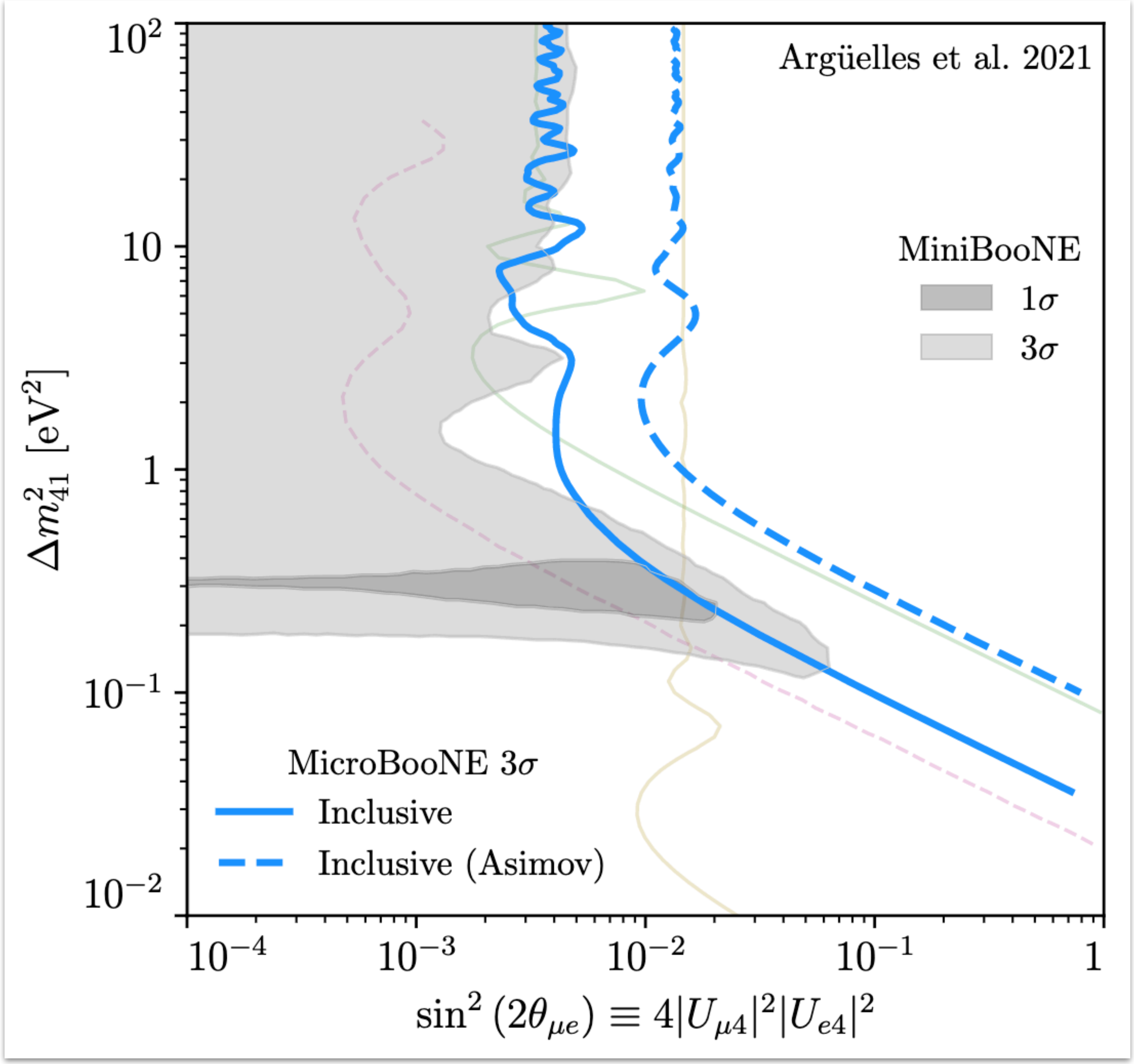


Four-Flavor, Appearance

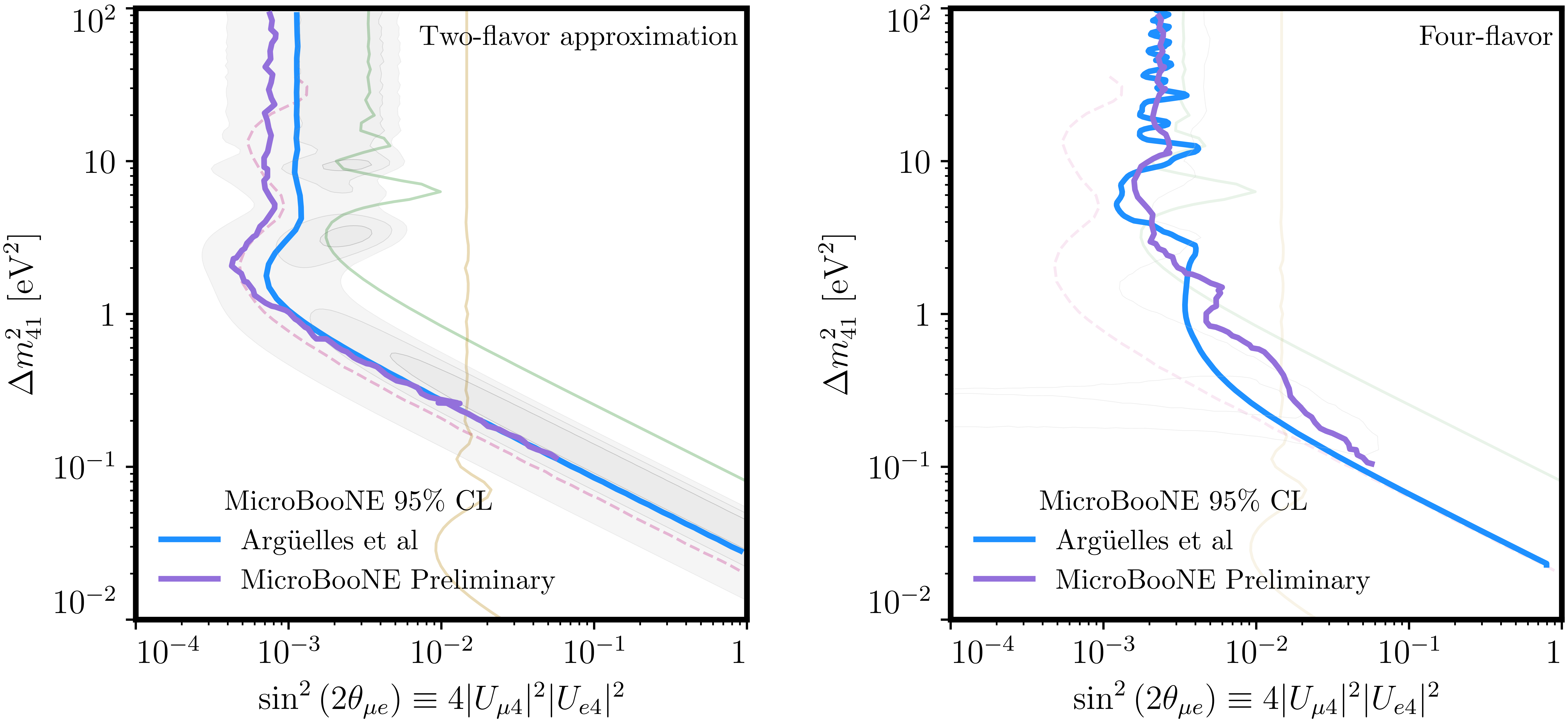
[2111.10359]

Profiling over unseen mixing angle, how does sensitivity change?

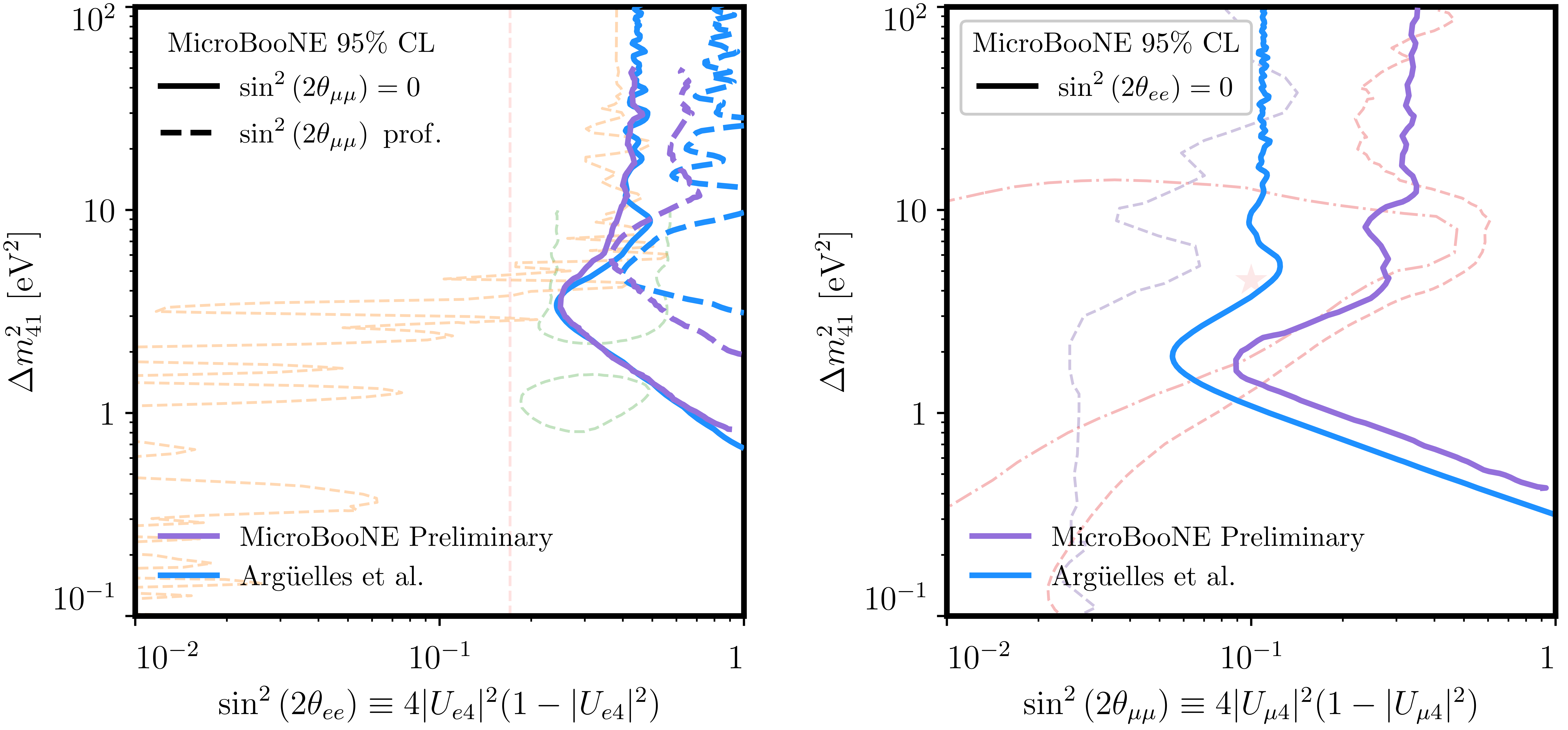
For better or worse, opens up parameter space for consistency between MiniBooNE and MicroBooNE — the MiniBooNE anomaly persists…



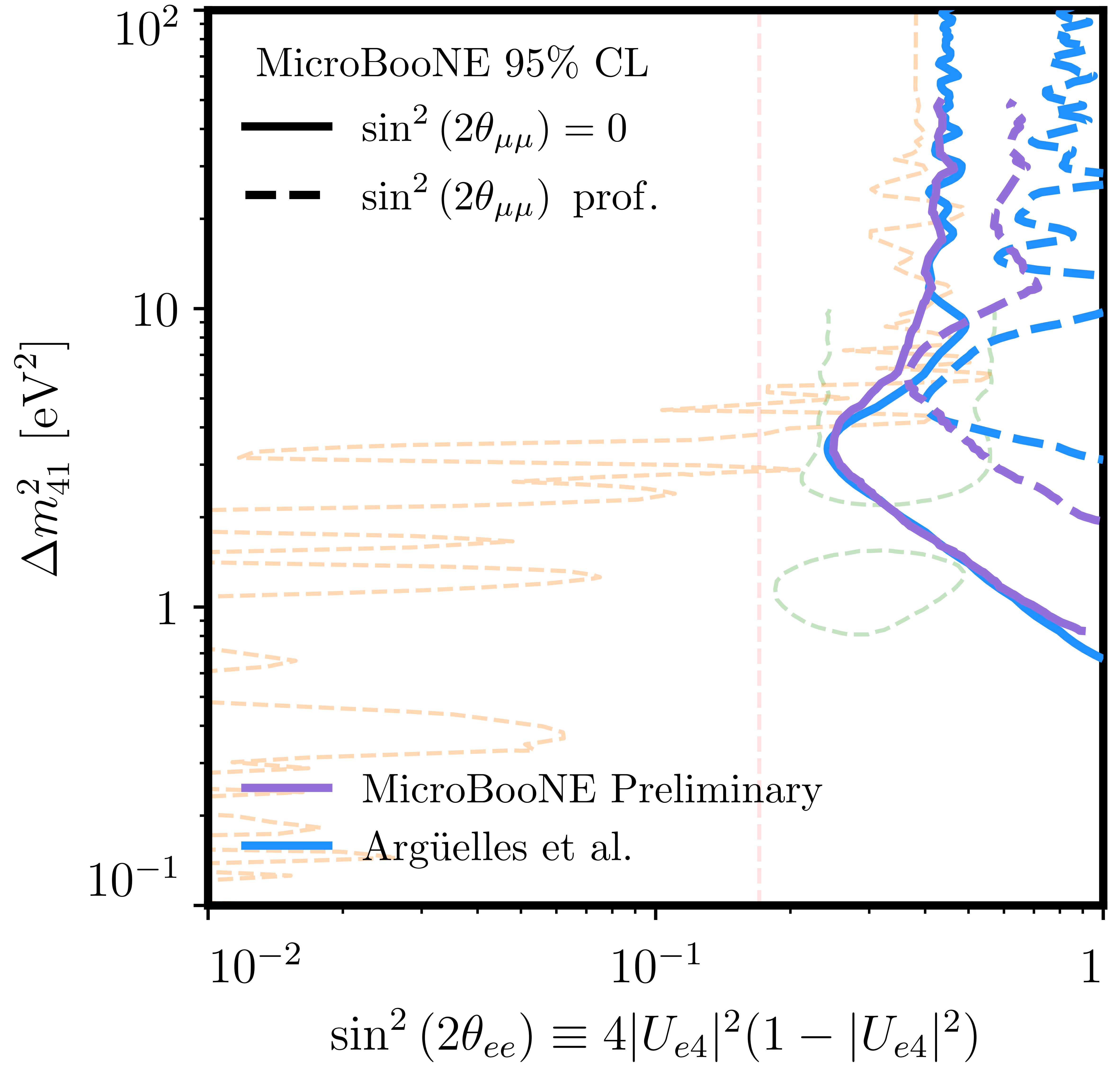
Neutrino2022 Comparisons

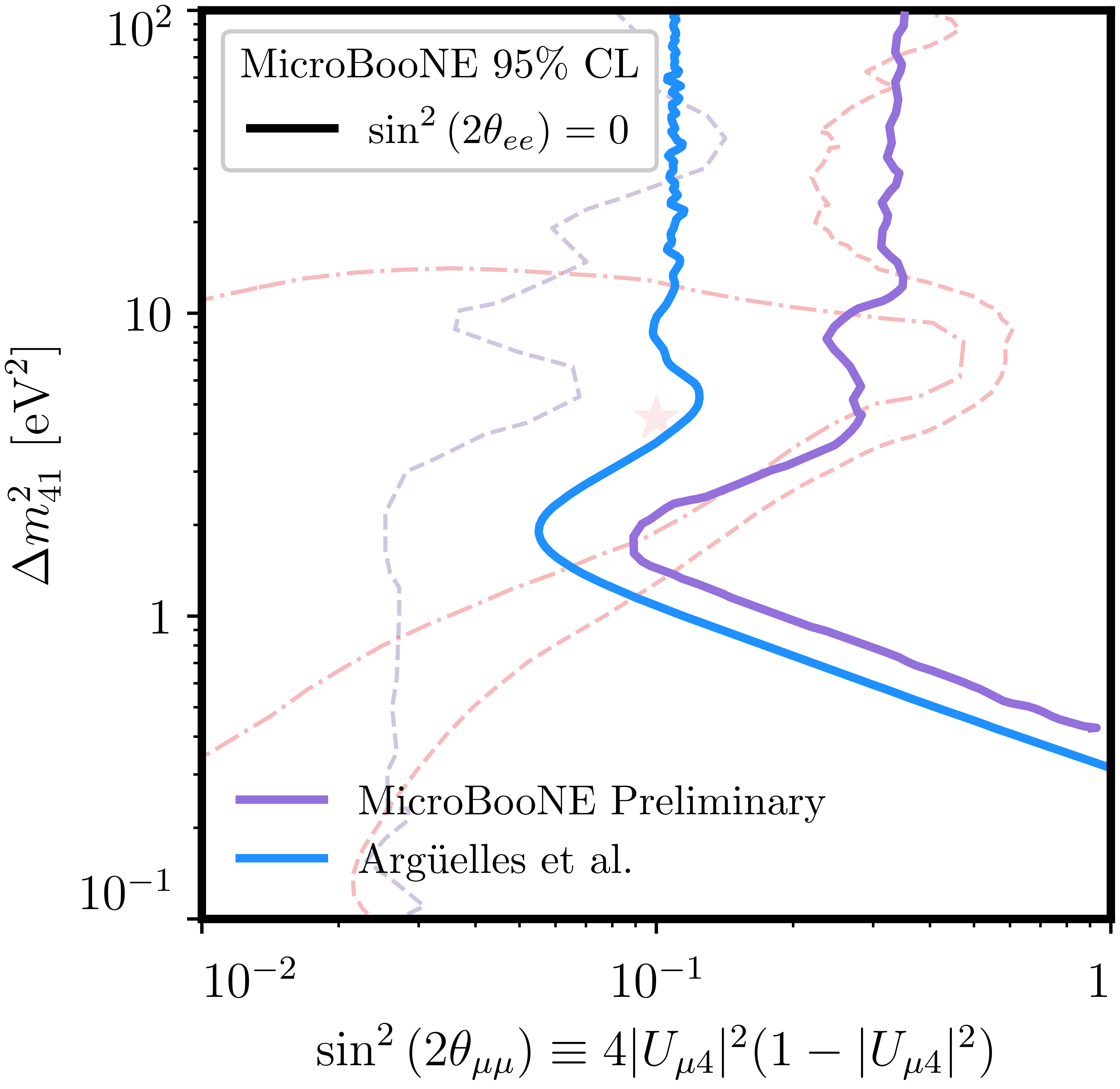


Neutrino2022 Comparisons



Neutrino2022 Comparisons



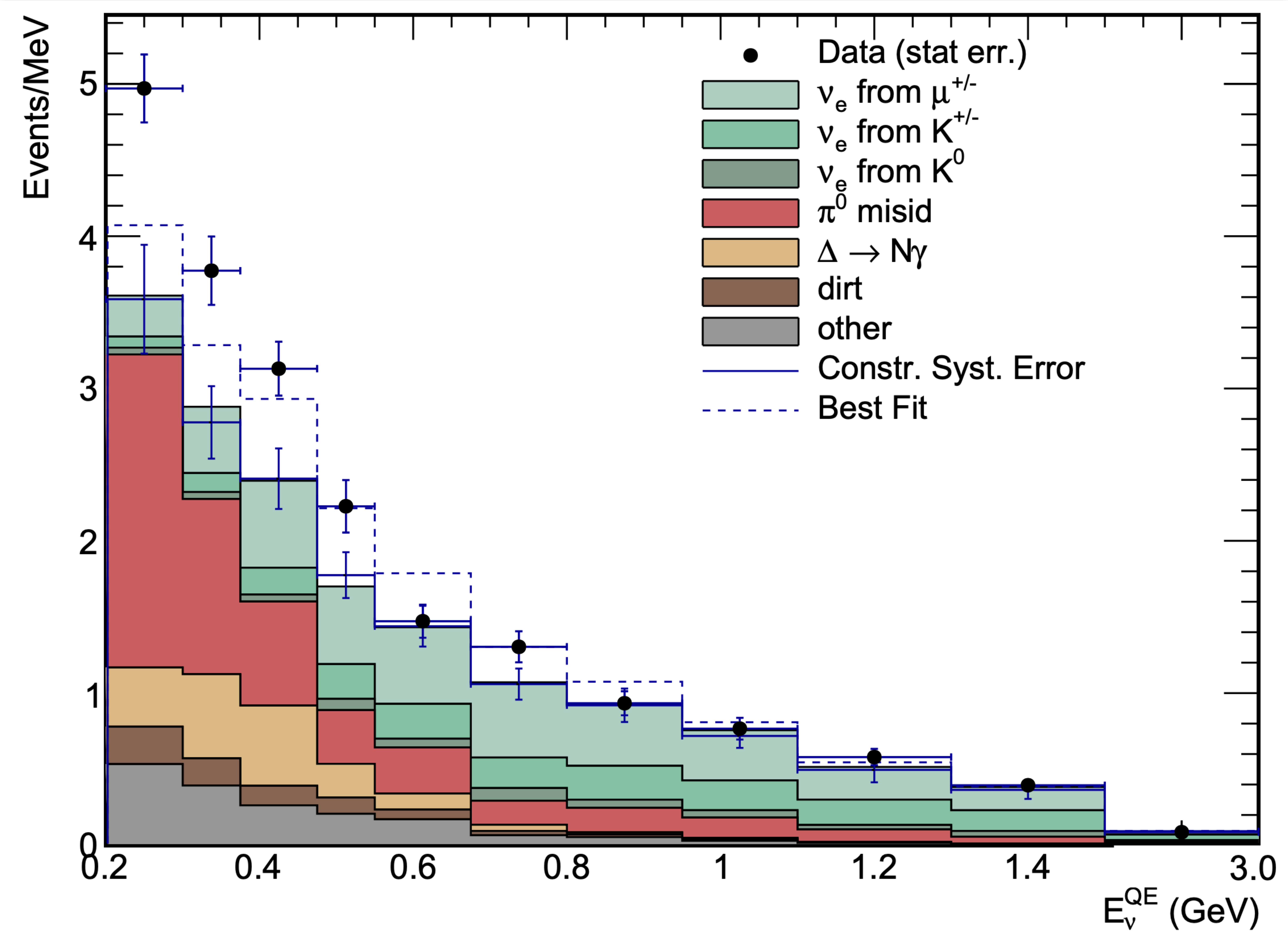


We *think* we understand the differences between our/MicroBooNE's results. Feel free to ask me offline.

Beyond Sterile Neutrinos

Other Electron-Neutrino Explanations?

Electron-like events in MiniBooNE



MiniBooNE Collaboration [1805.12028]

Laundry List of Explanations

From M. Hostert's talk yesterday

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

Table of explanations of the short-baseline anomalies

See K. Kelly's talk tomorrow

Category	Model	Signature	Anomalies: LSND	MiniBooNE	Reactors	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	$\nu A \to NA$, $N \to \nu e^+e^-$ or $N \to \nu\gamma\gamma$	✓	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \to NA$, $N \to \nu\gamma$	✓	✓	✗	✗	[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]

To be tested

These mostly involve production of new particles in the detector.

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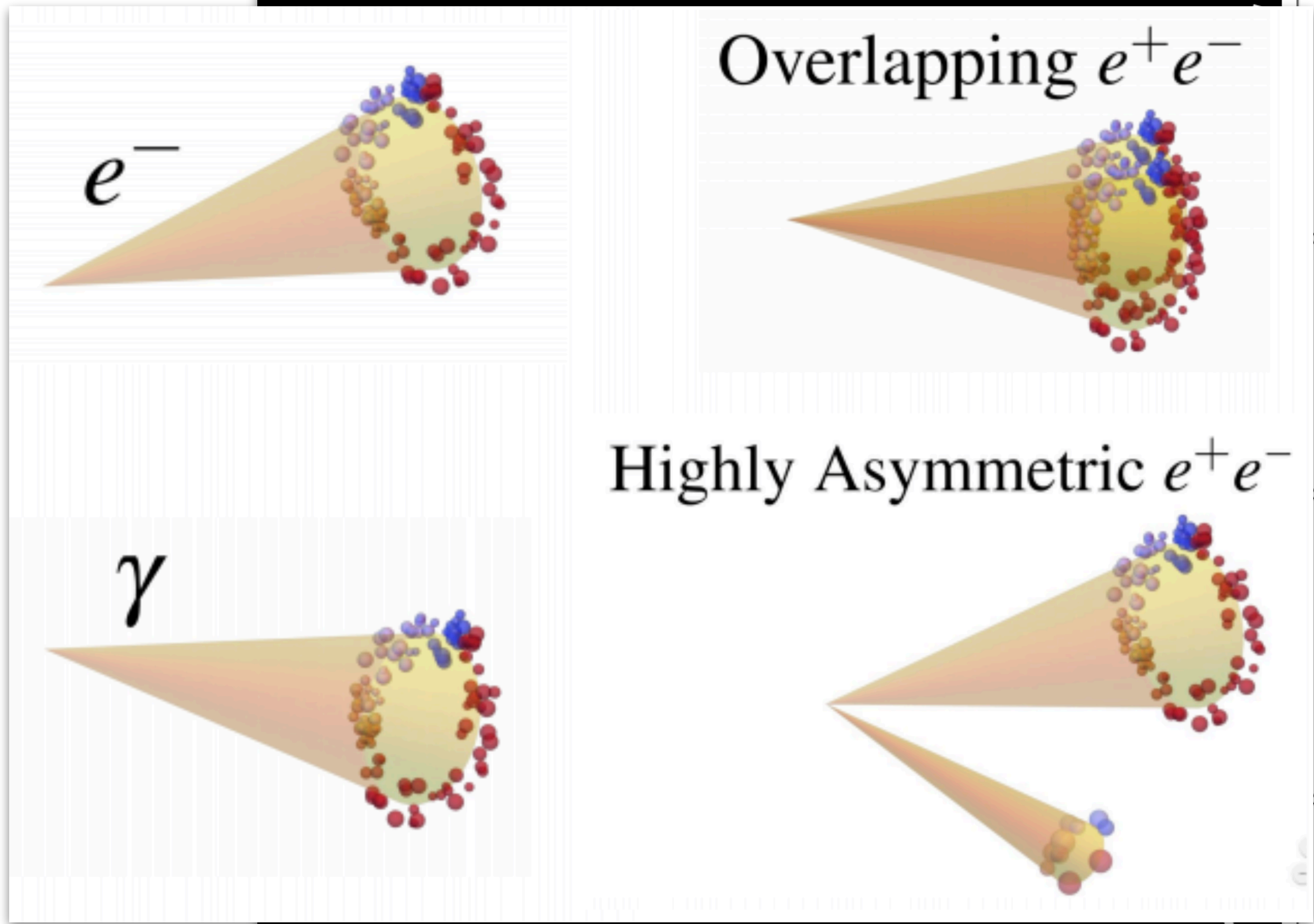

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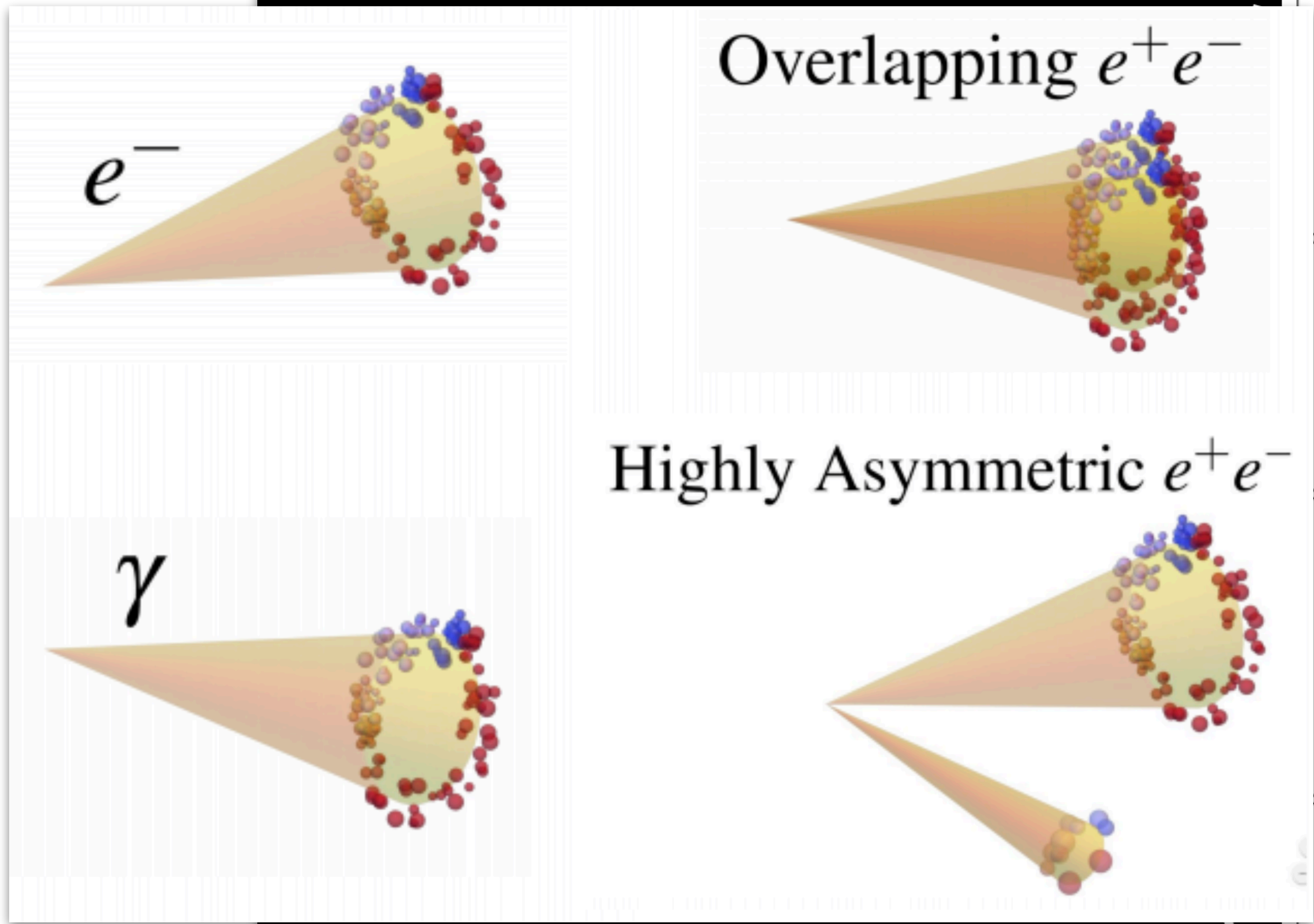

A nice, model-independent approach? Brdar et al, [2007.14411]
An "Altarelli Cocktail" of backgrounds in MiniBooNE? Brdar and Kopp, [2109.08157]
Want to discuss more about MiniBooNE background challenges? Come find me after the talk!

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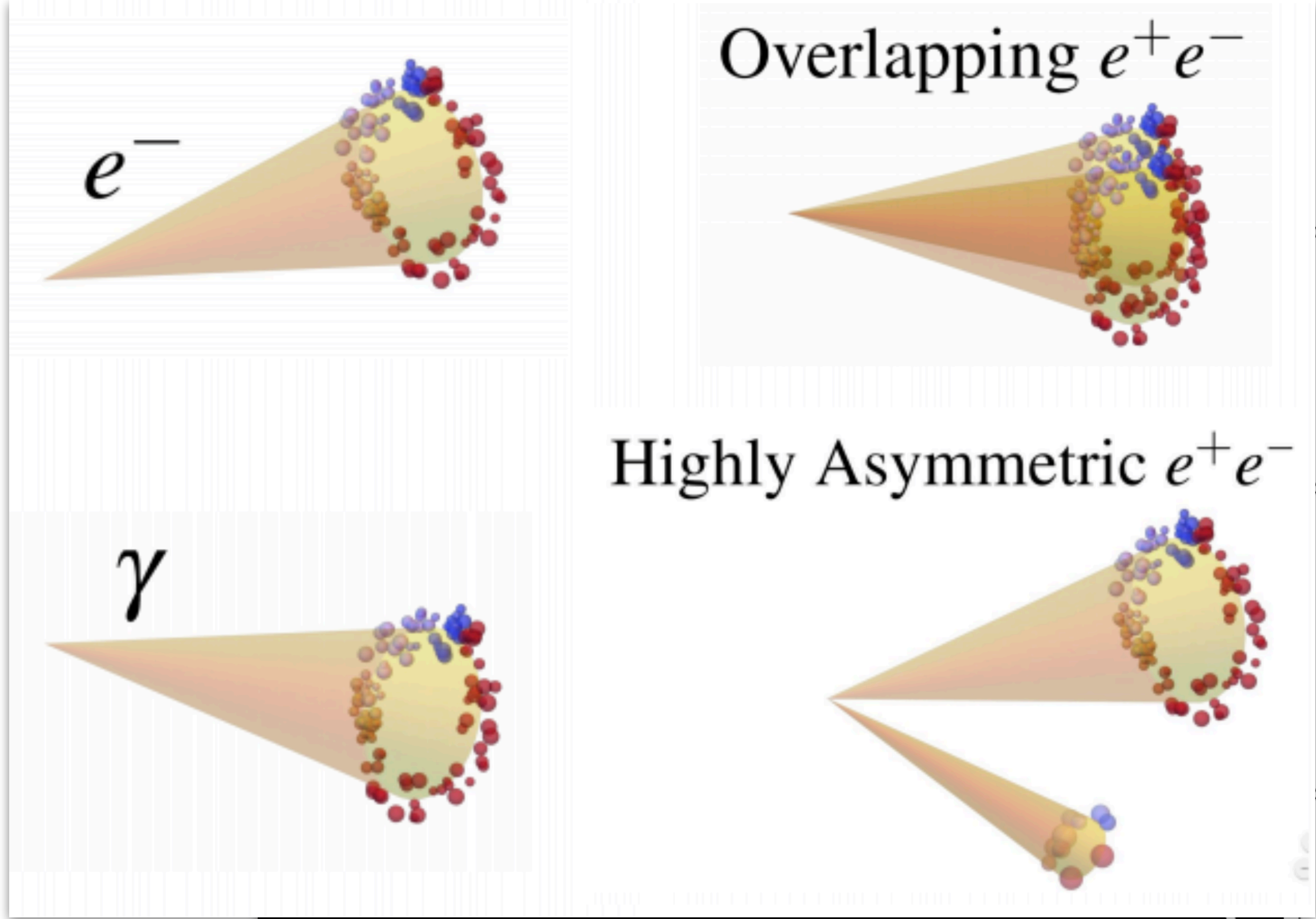
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \to N A$, $N \to \nu e^+ e^-$ 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]
Want to discuss more about MiniBooNE background challenges? Come find me after the talk!

Visibly Decaying Sterile Neutrinos

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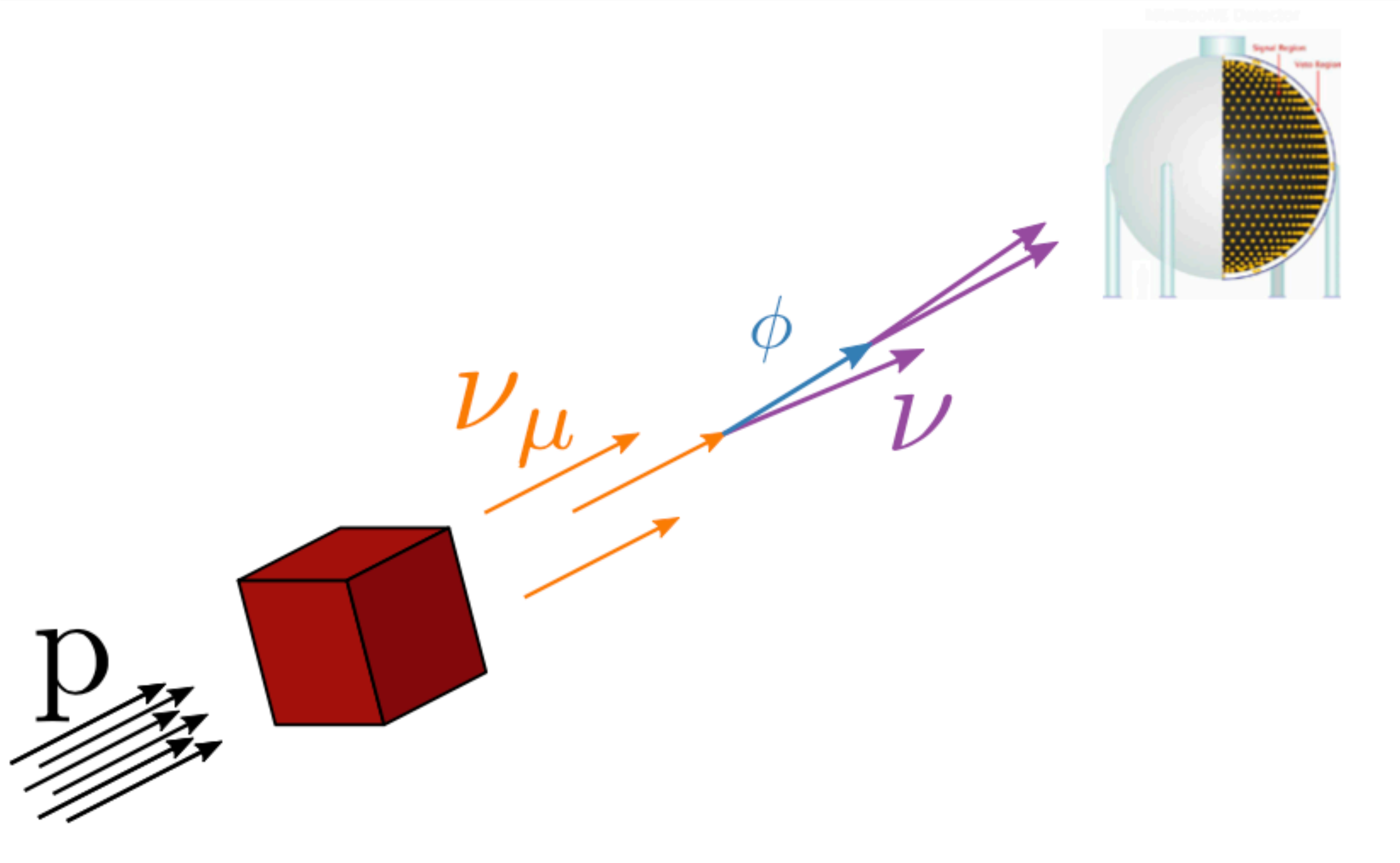

Decaying Sterile Neutrino Hypothesis —
Dentler et al, [1911.01427], de Gouvêa et al, [1911.01447]

Visibly Decaying Sterile Neutrinos

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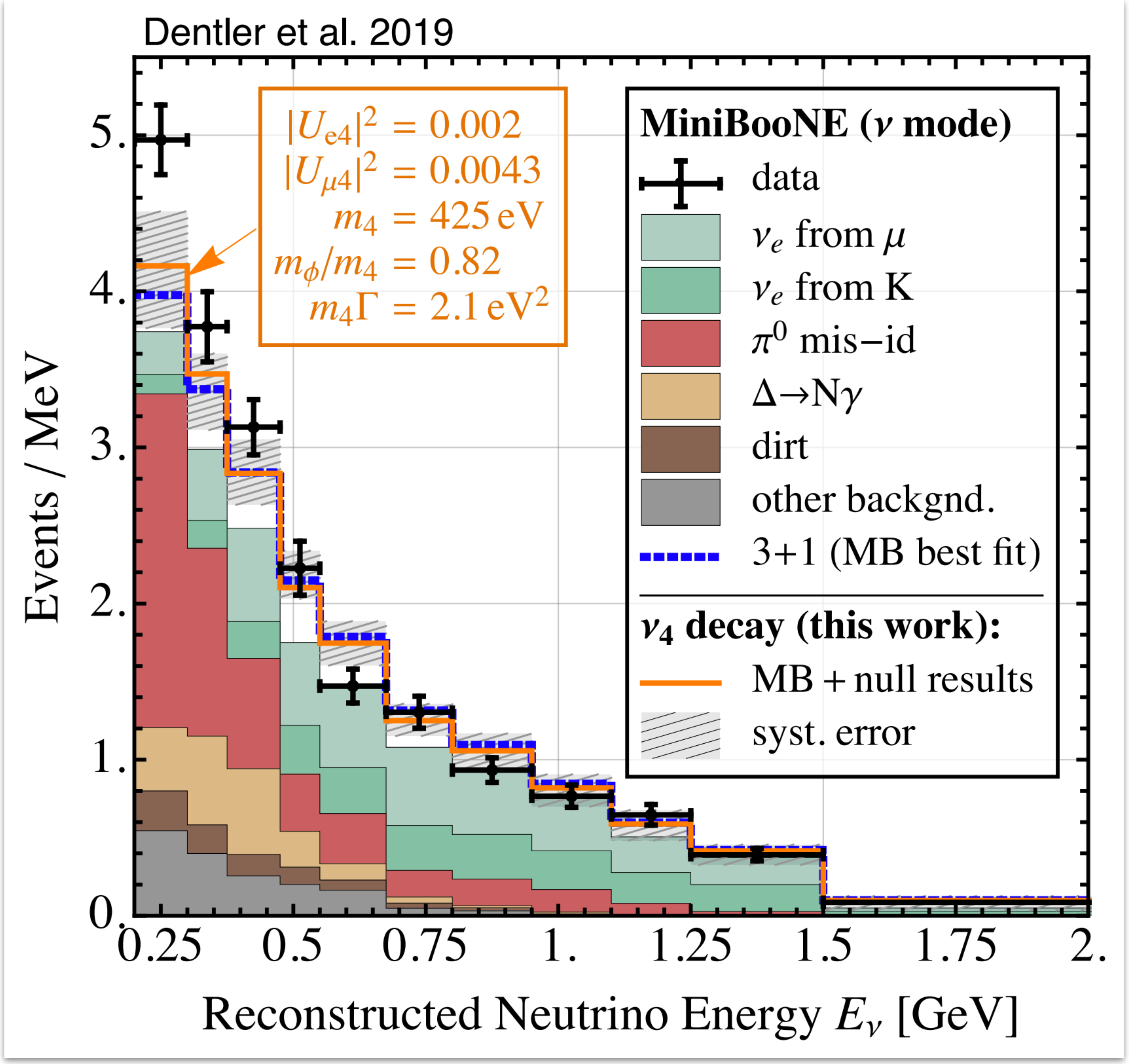

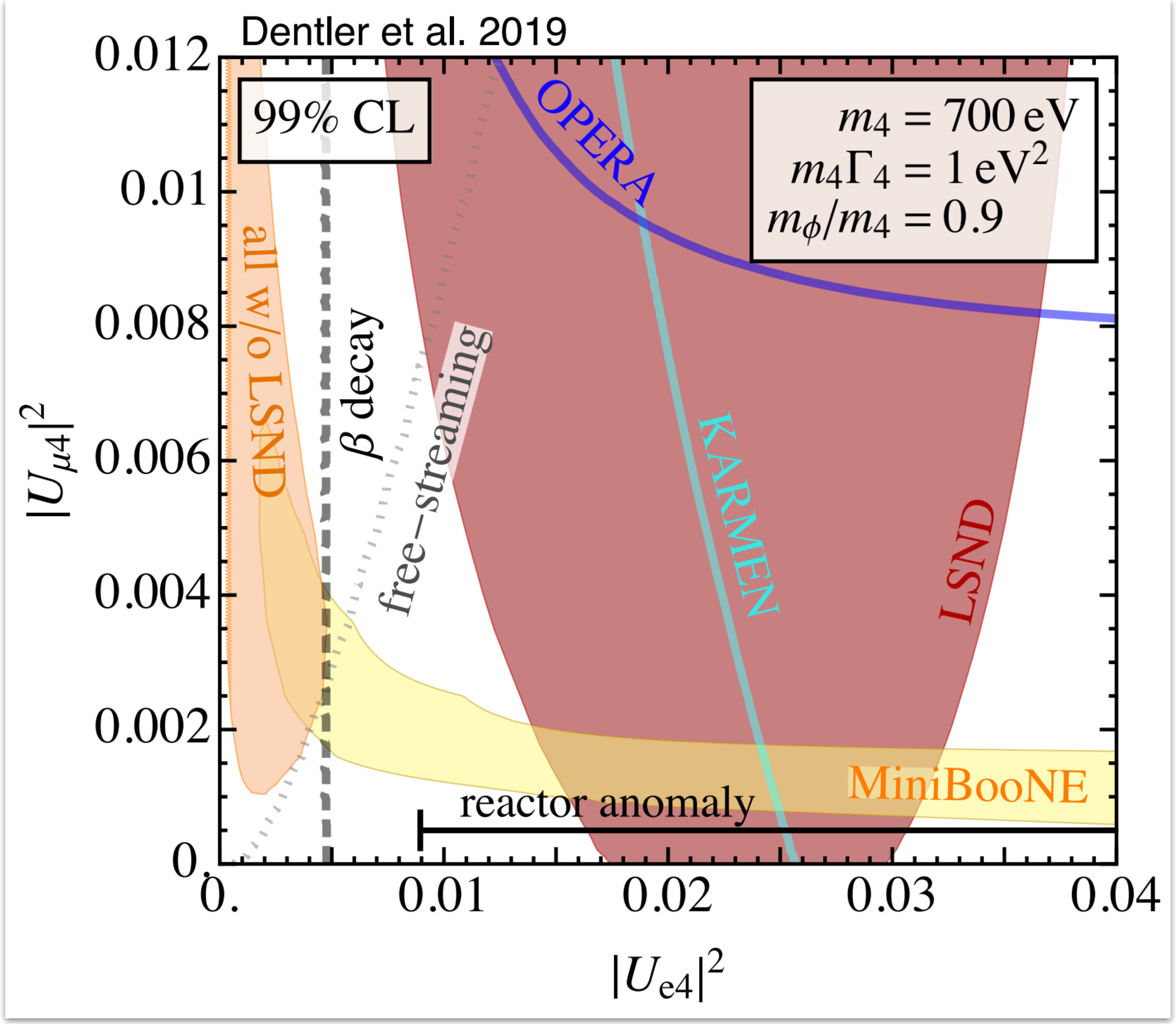

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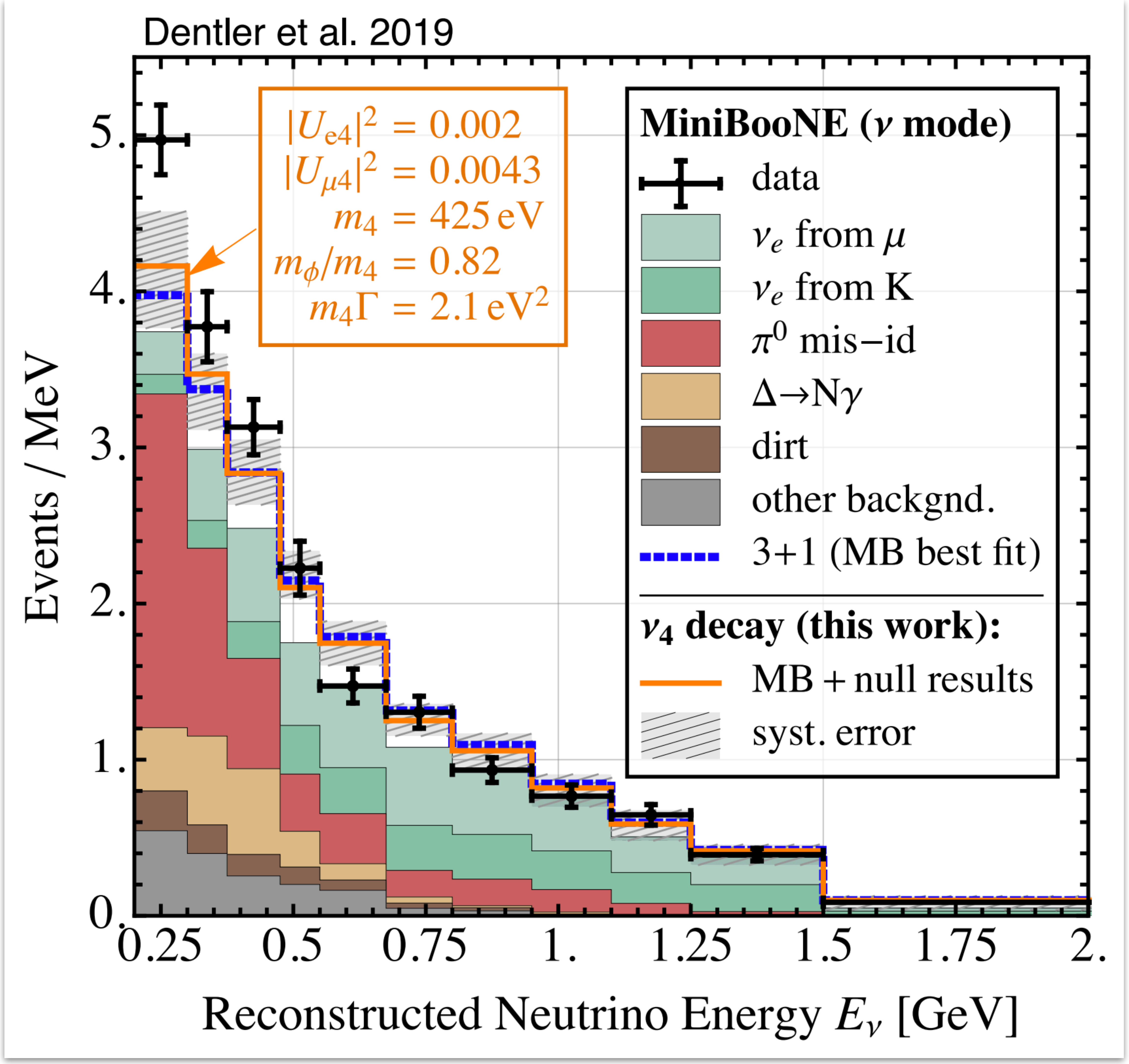
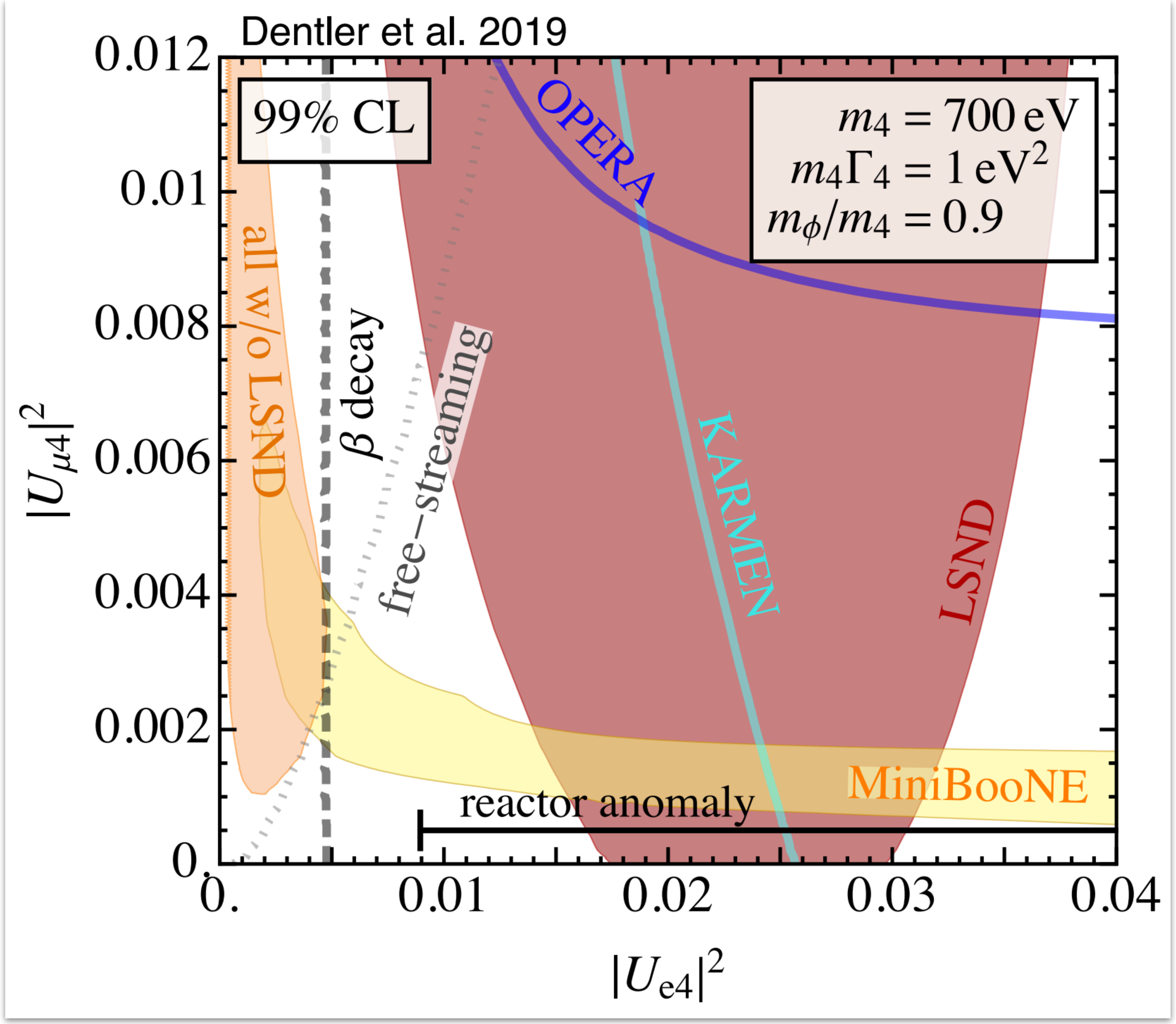
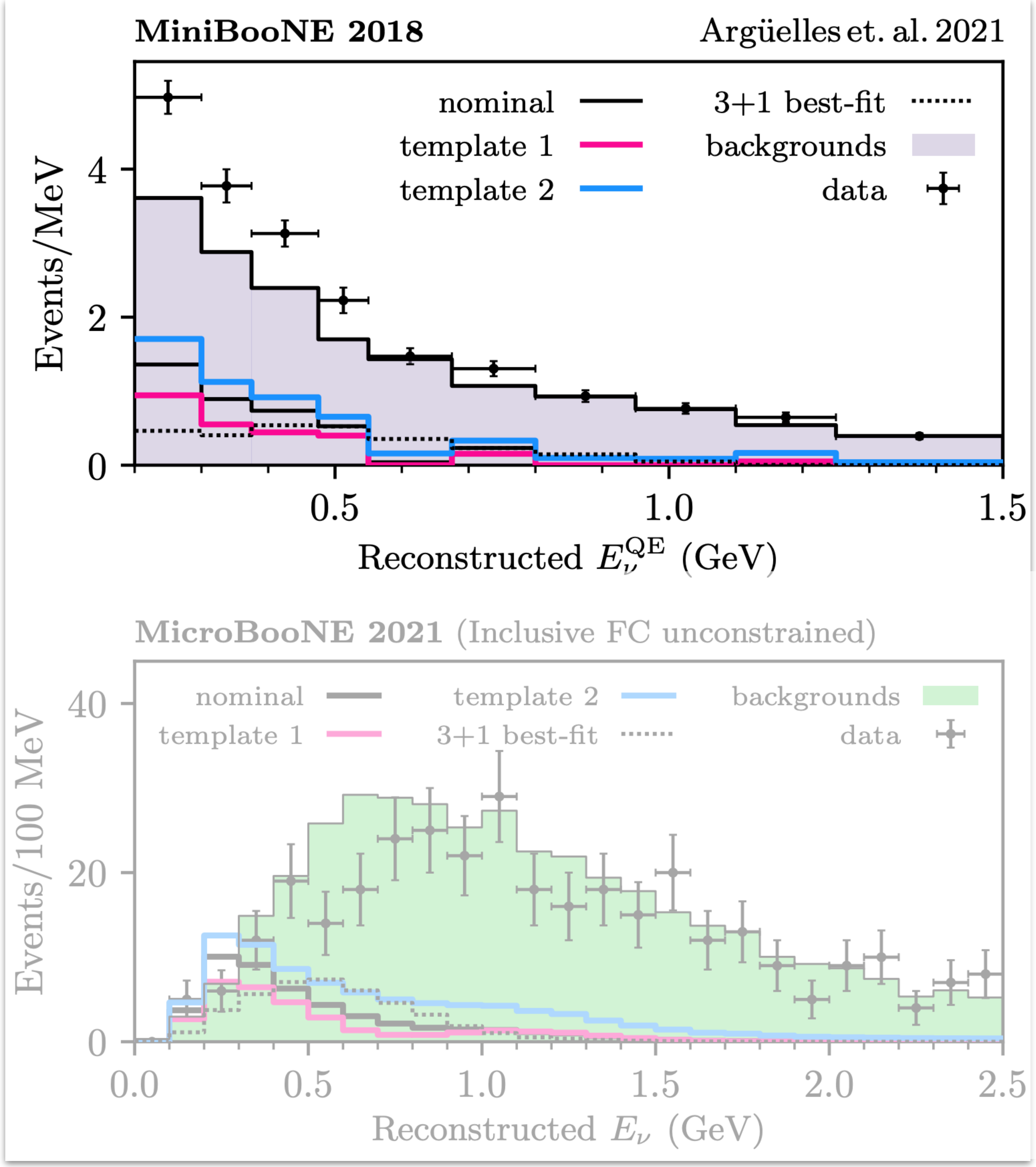




However, this model predicts **anti**neutrinos coming from solar neutrinos decaying, which is strongly constrained — Hostert & Pospelov [2008.11851]

Can MicroBooNE say anything about this, and other models?



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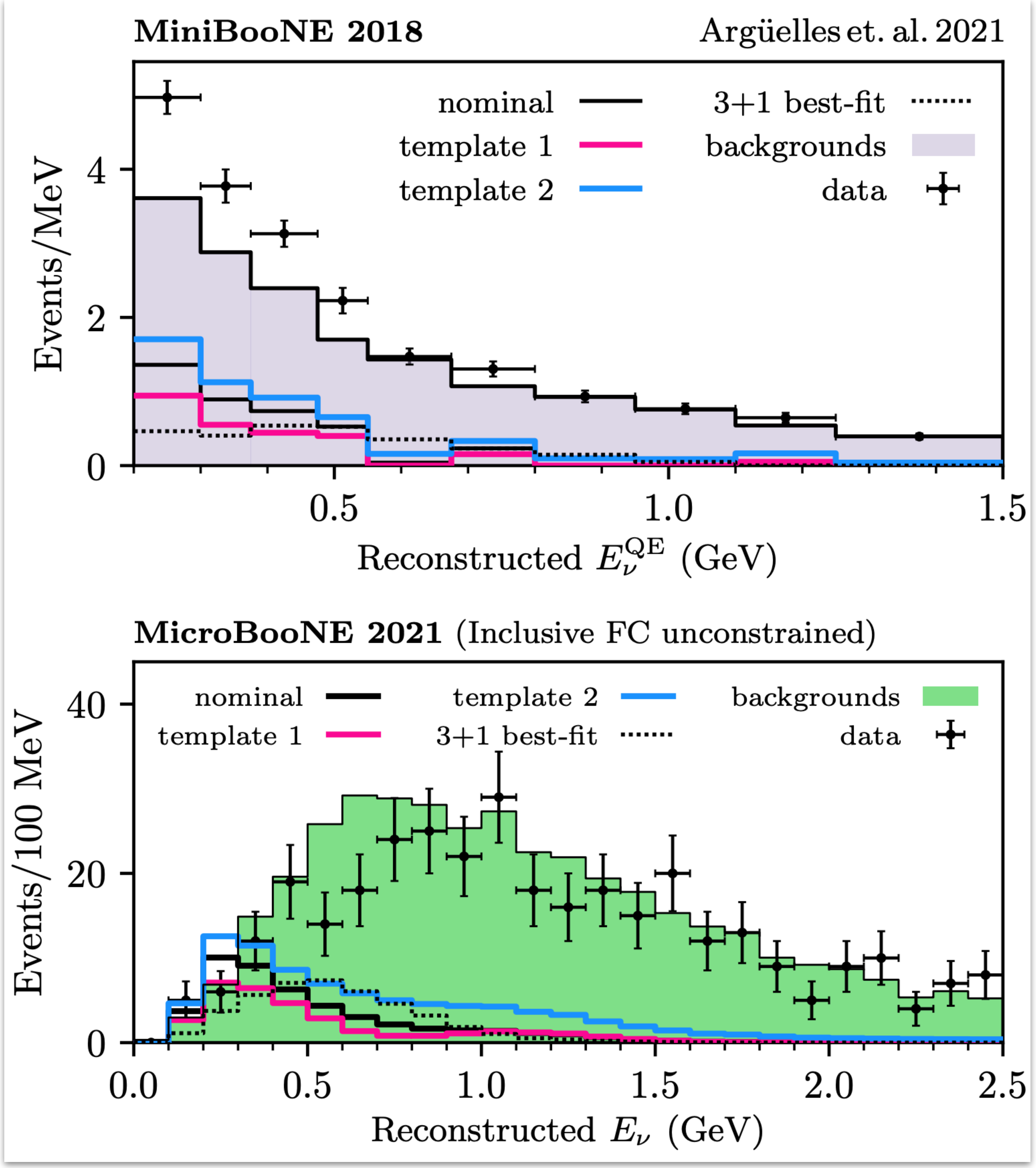

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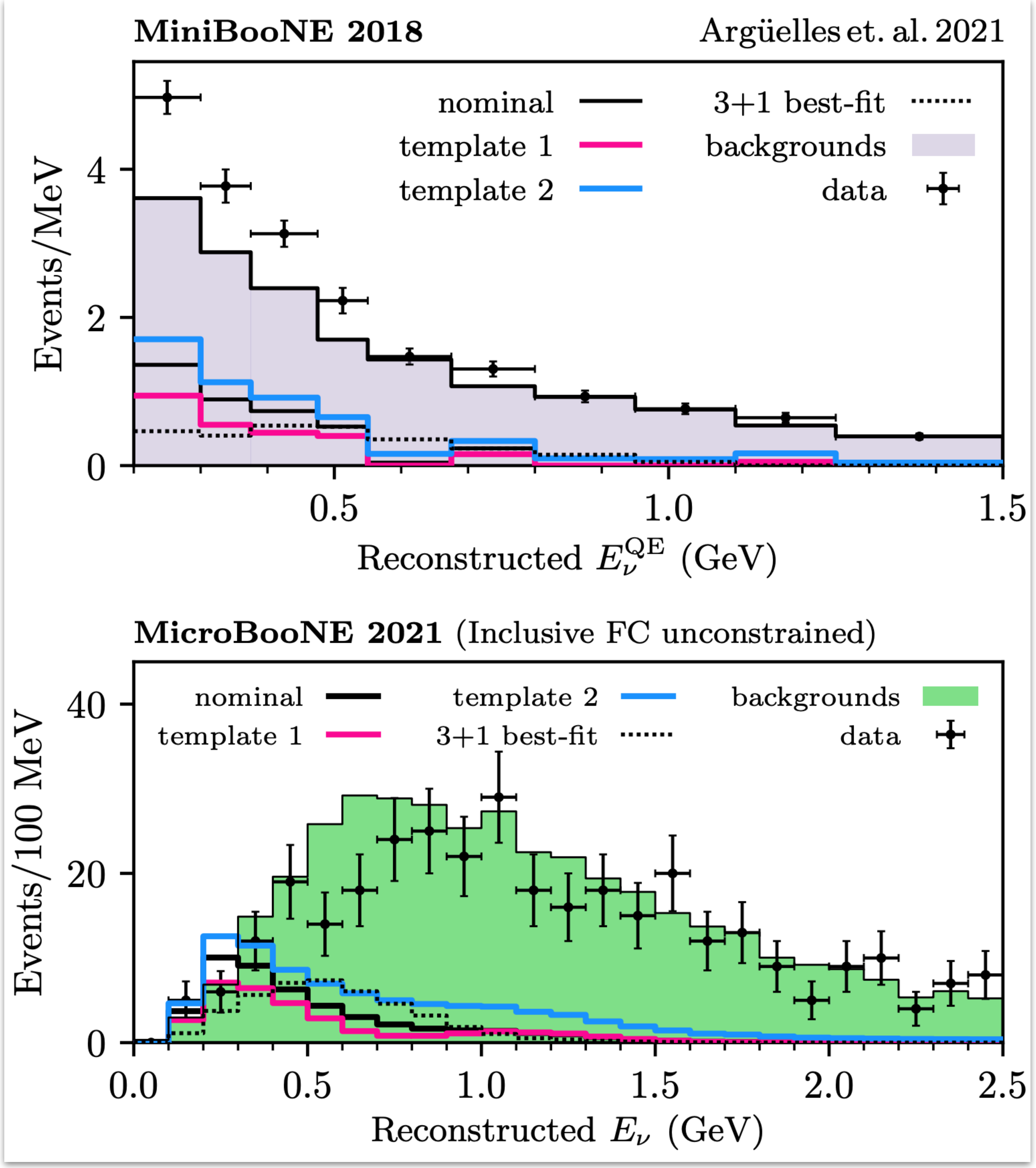

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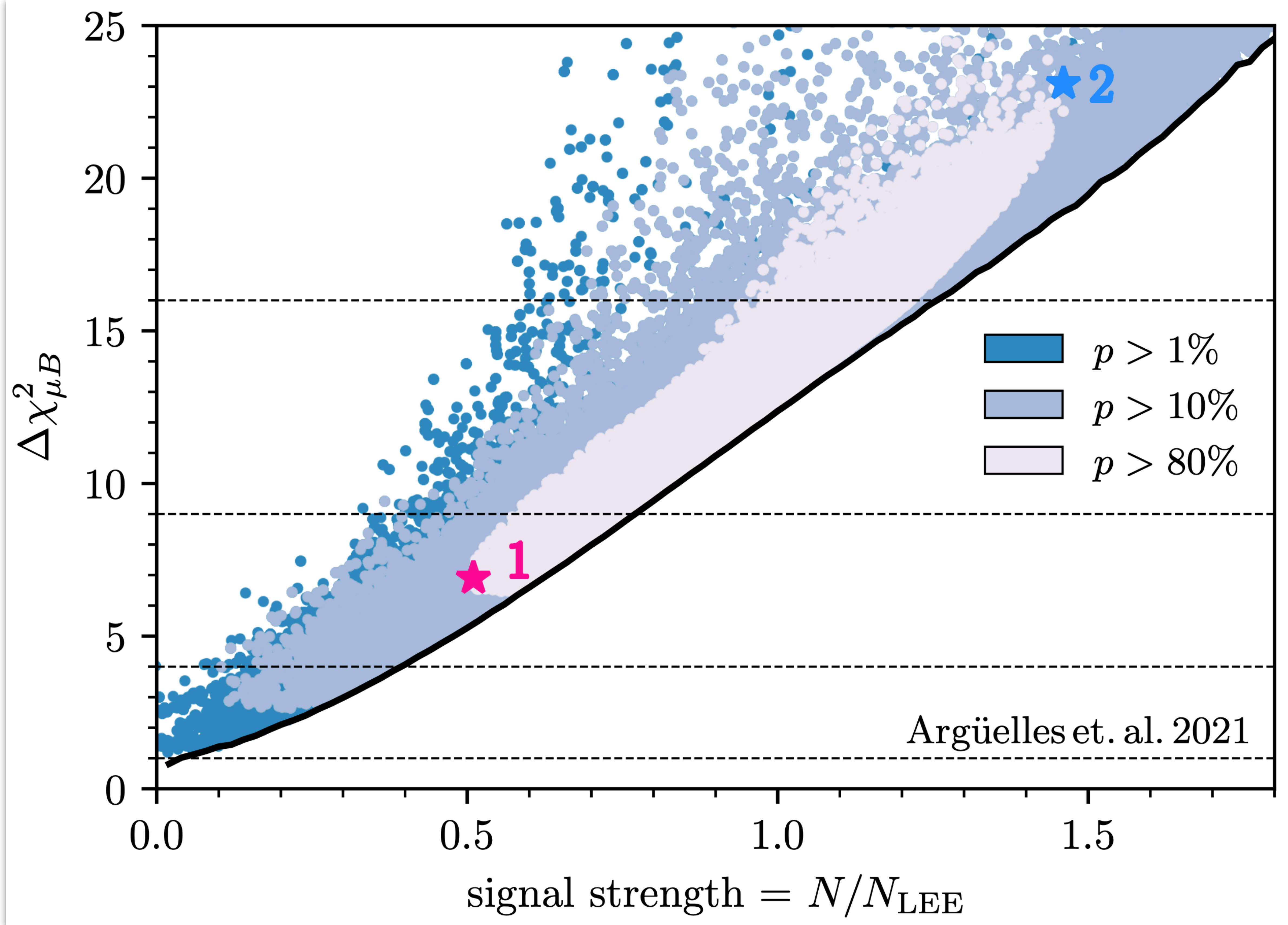

- Plenty of electron-neutrino templates that fit MiniBooNE well that MicroBooNE hasn't (yet) ruled out significantly — are any of these spectra predicted in a new-physics model?

Neutrino Facilities as Beam-Dumps

Berryman, KJK et al, [1912.07622]

Beyond searching for explanations of the MiniBooNE + LSND excesses, upcoming neutrino near-detector facilities are excellent places to search for new-physics processes, if thought of as beam-dump facilities.

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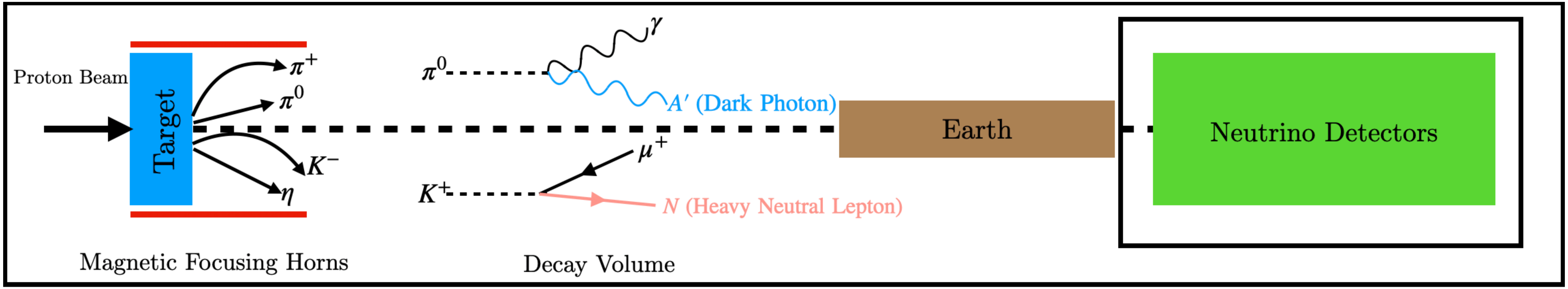

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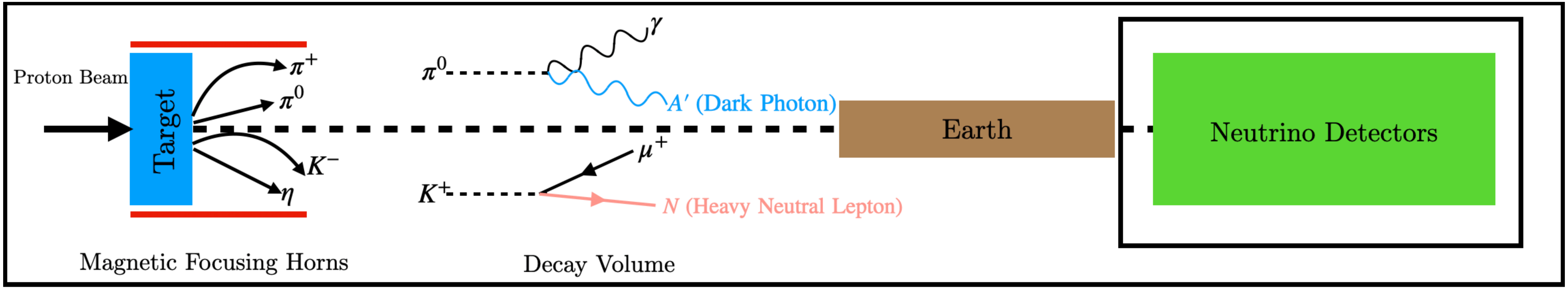

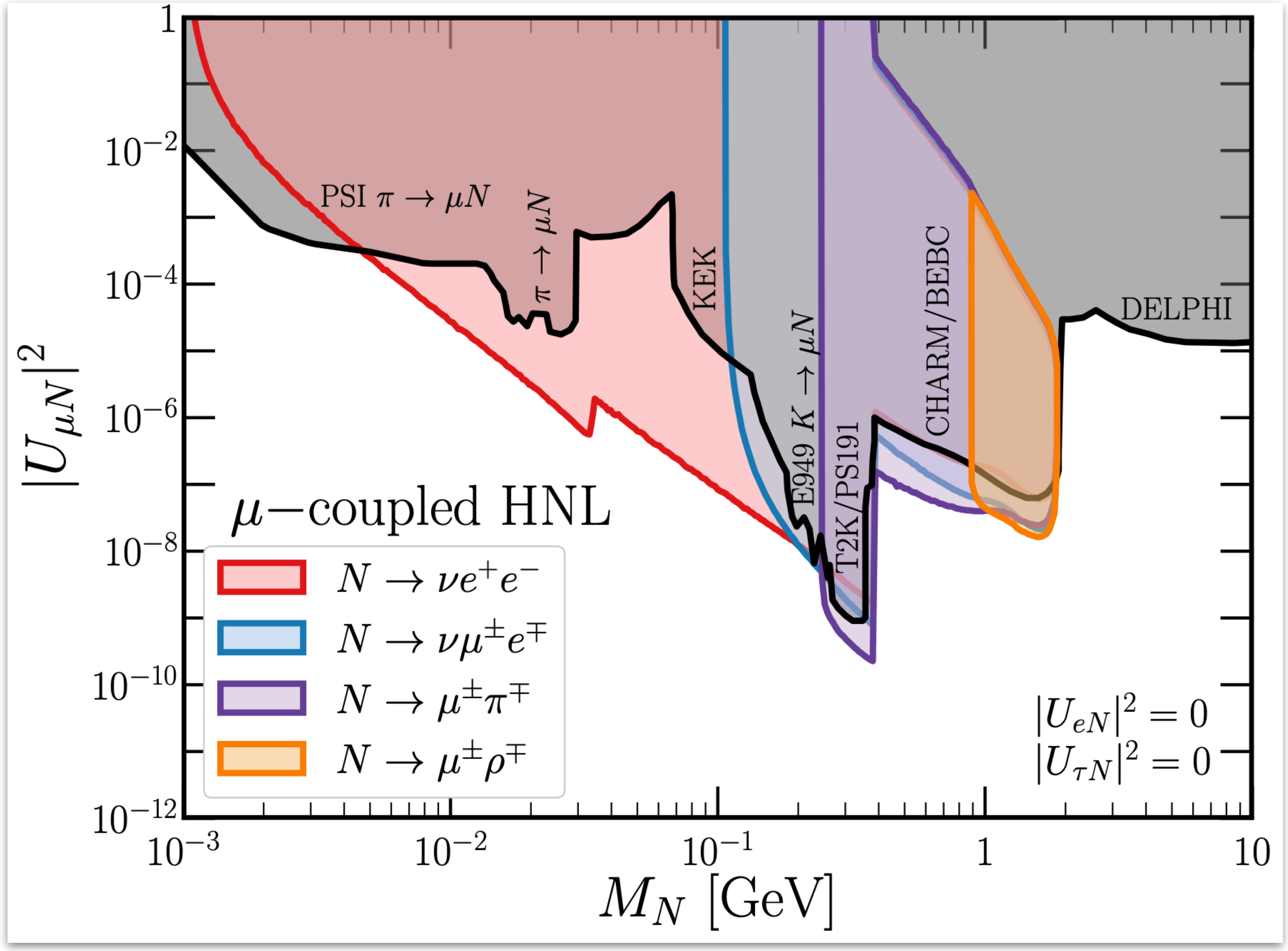

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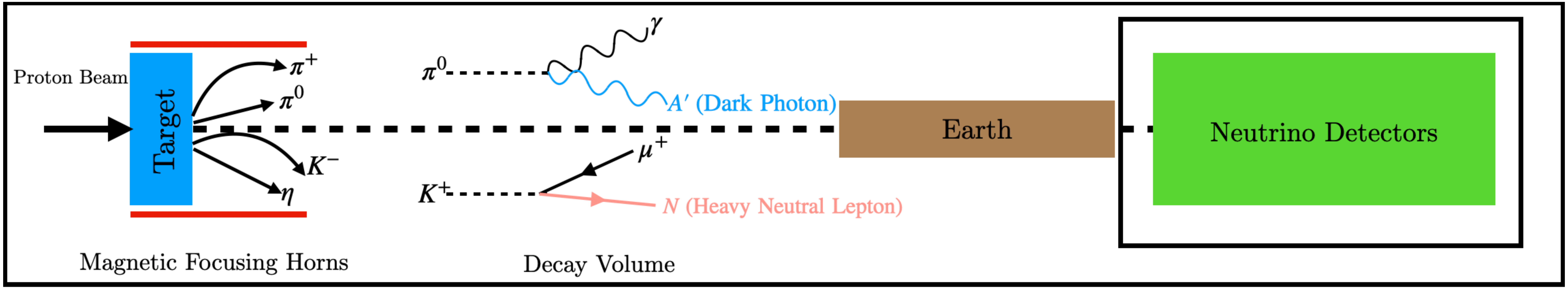

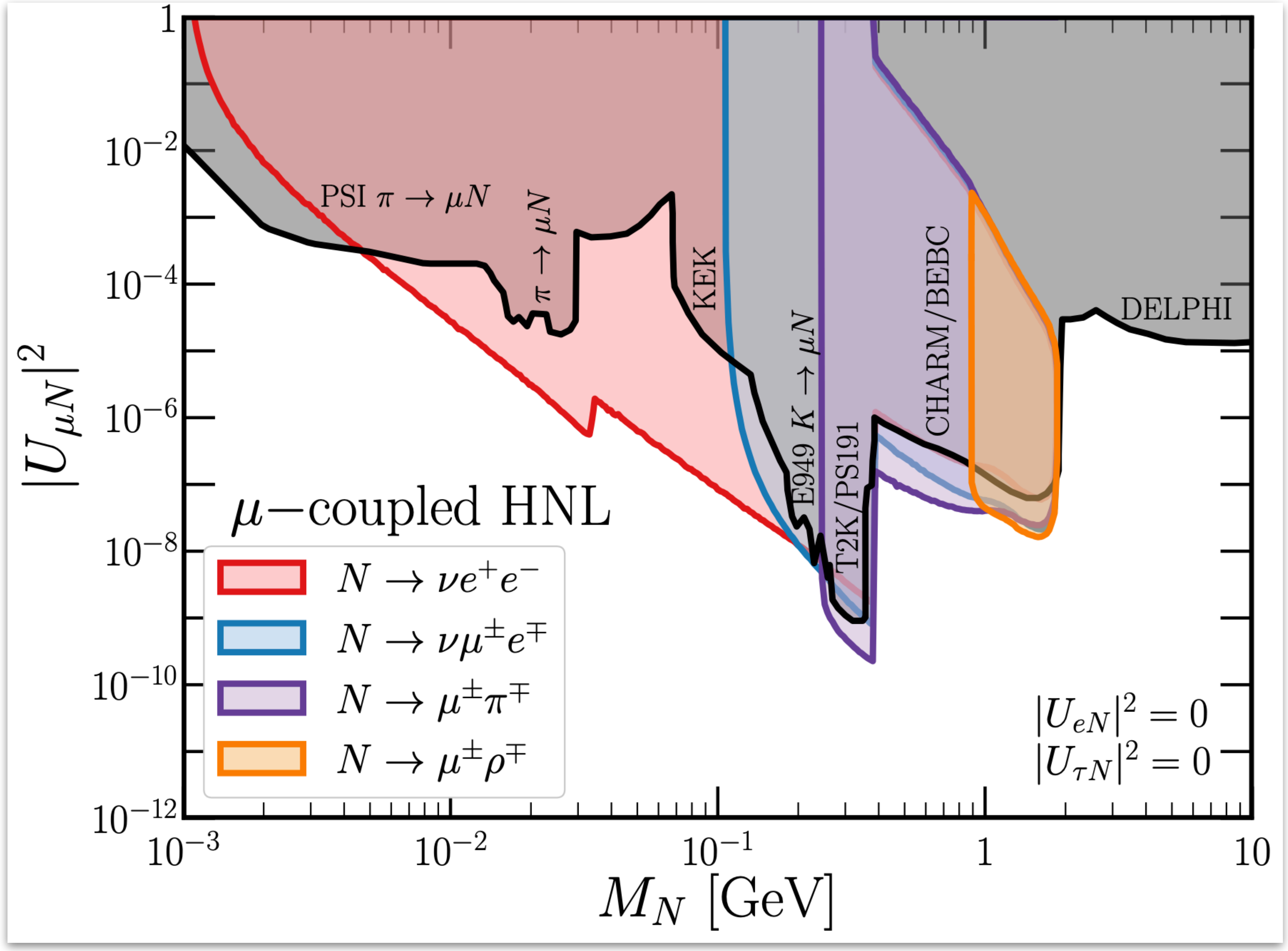

Types of new-physics that can be tested in this context:

- Heavy Neutral Leptons
- Dark Photons
- Dark Higgs Bosons
- Axions/Axion-Like Particles
- Light Dark Matter scattering
- …

An *incomplete* list of references:
[1912.07622], [1905.00284], [2007.03701], [2102.03383], [2106.00568], [1909.11670], [2106.06548], [2011.05995], [2011.07054], [1903.10505], [2108.03262], [2106.04584], [2104.07681], [2106.13684]

Takeaways

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.
- Some fun with hints in the T2K/NOvA tension, but (likely) nothing to take too seriously.
- 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!
- Other testable explanations of previous anomalies remain possibilities, and data to come soon will shed light on the situation!

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Thank you!