MiniBooNE Anomaly

Status and (B)SM

Kevin J. Kelly, Texas A&M University

PITT PACC νTools, 15th Dec., 2022

kjkelly@tamu.edu

[2111.10359] & [2210.08021] with many great collaborators

Outline

- Neutrino anomalies and vanilla sterile neutrinos

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- MicroBooNE weighs in

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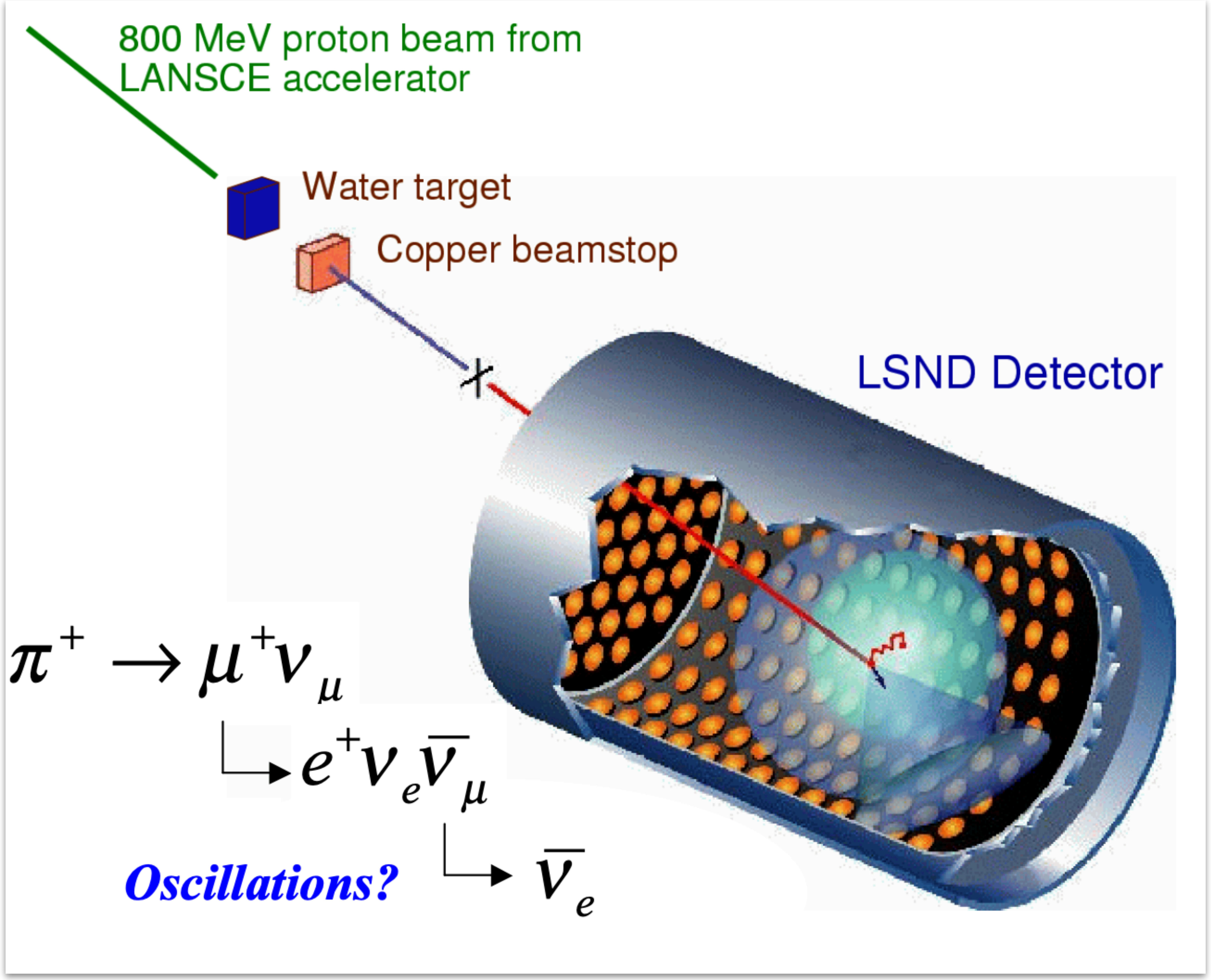
- Neutrino anomalies and vanilla sterile neutrinos
- MicroBooNE weighs in
- But wait, there’s more!

Liquid Scintillator Neutrino Detector (LSND)



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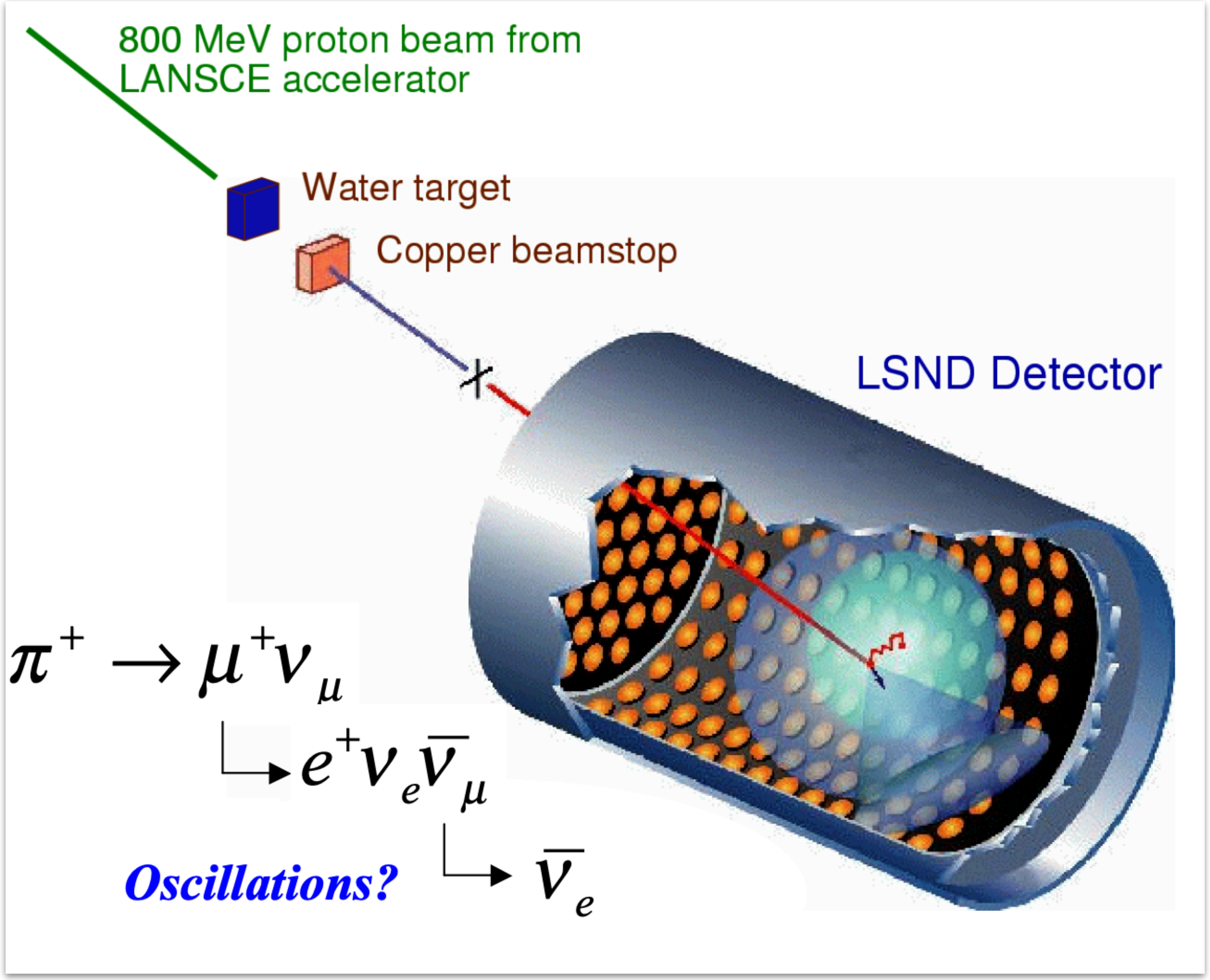
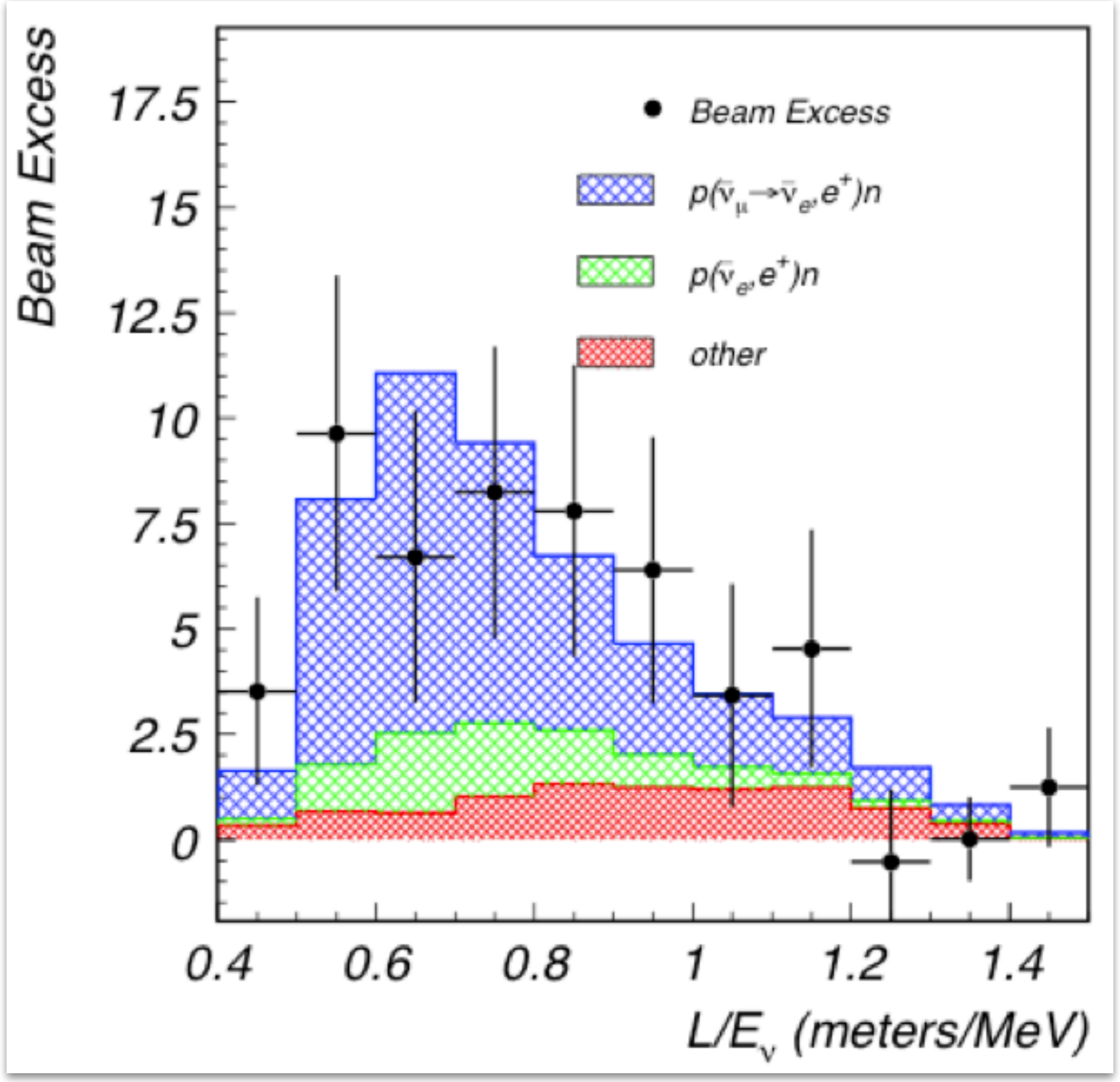


$\overline{\nu}_\mu \rightarrow \overline{\nu}_e?$



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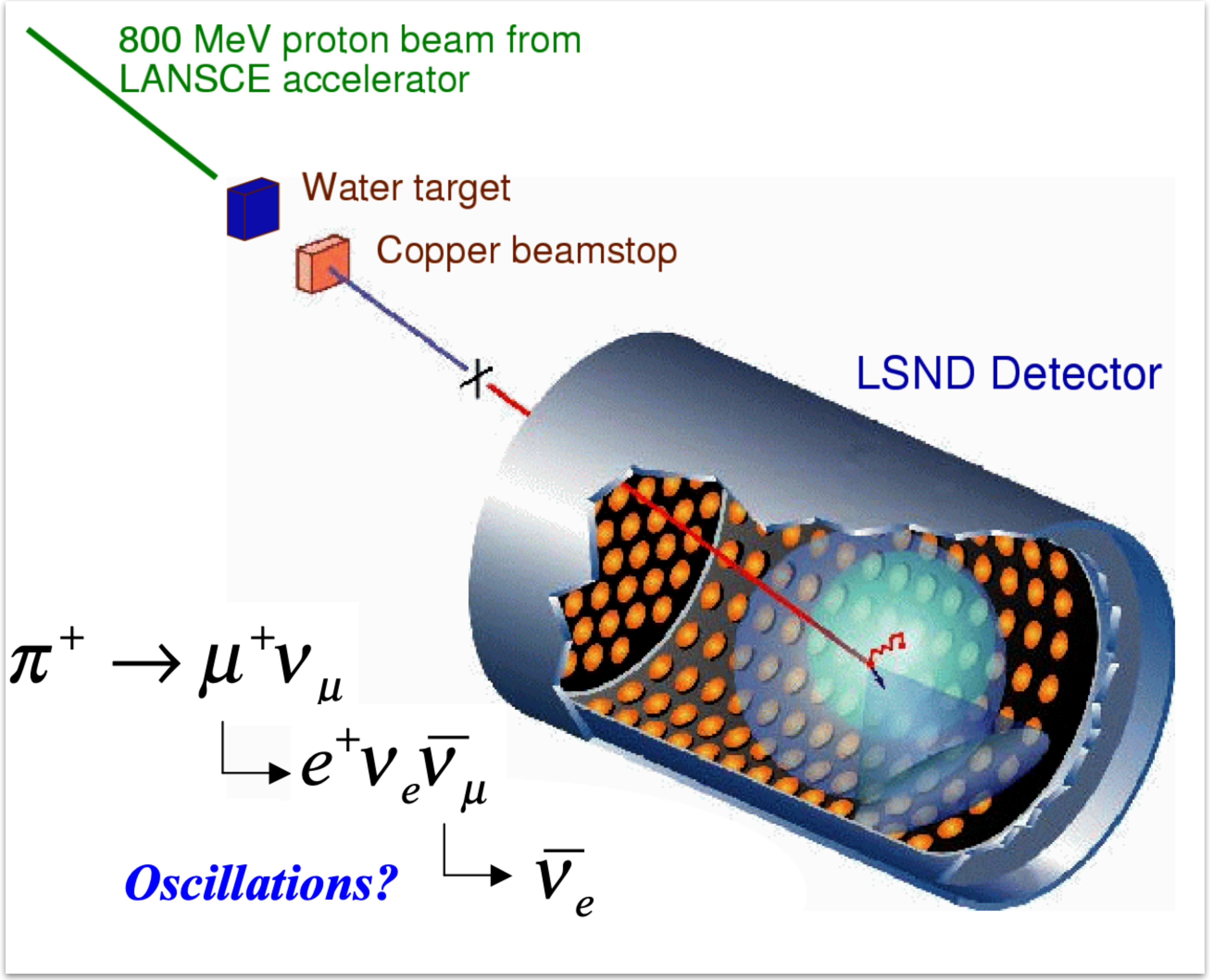

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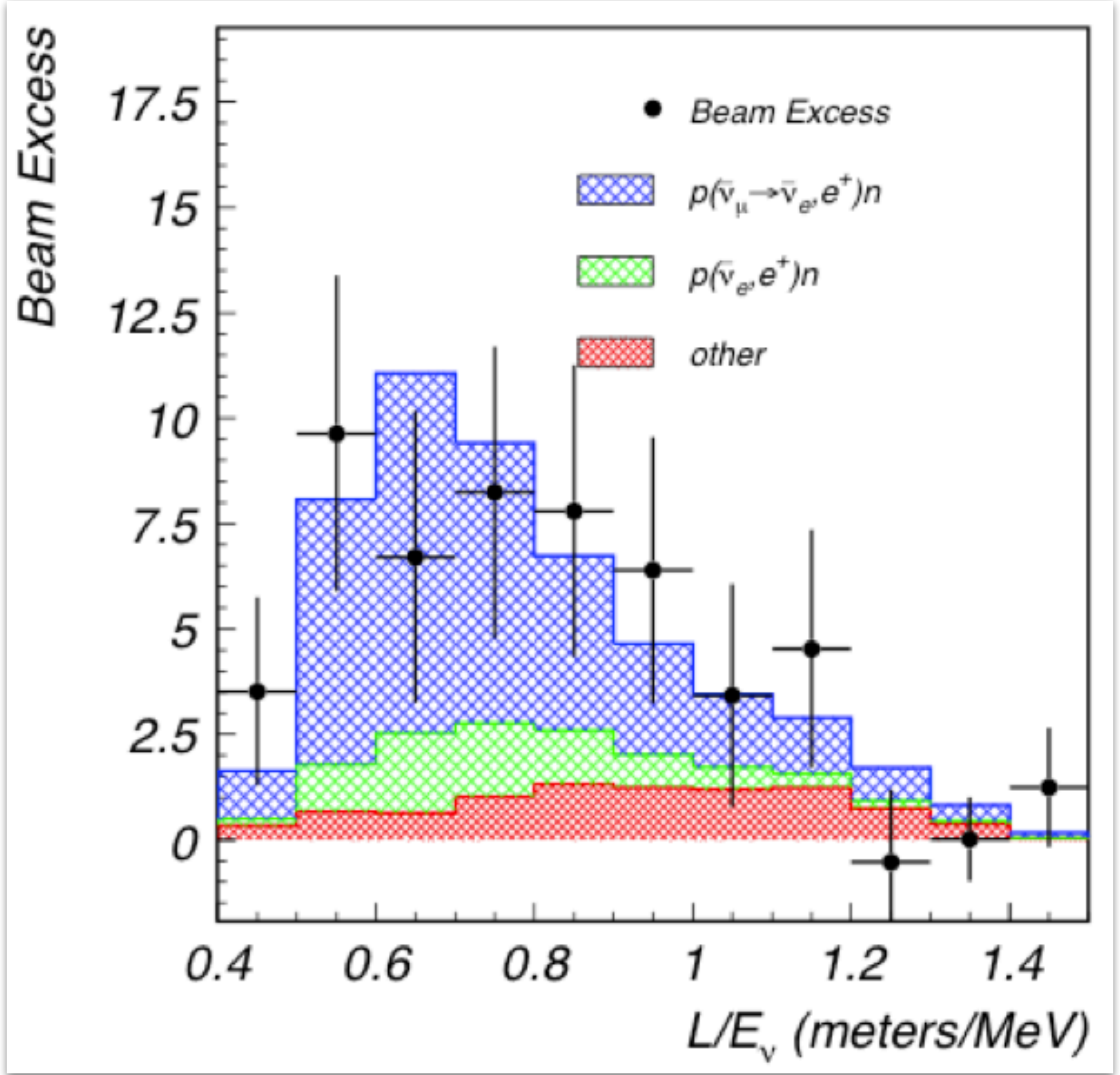
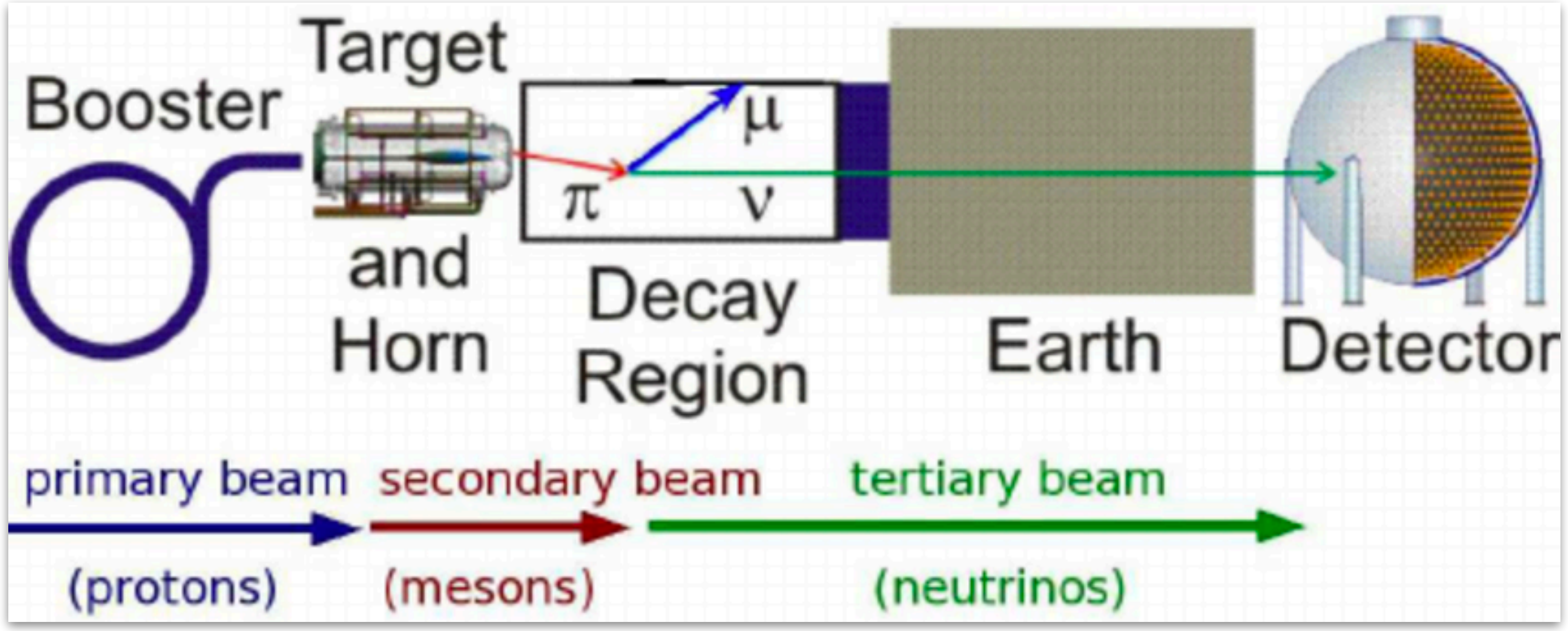


Neutrinos (mostly) from pion/muon decay-at-rest — O(30) MeV, roughly 50 meter baseline length.

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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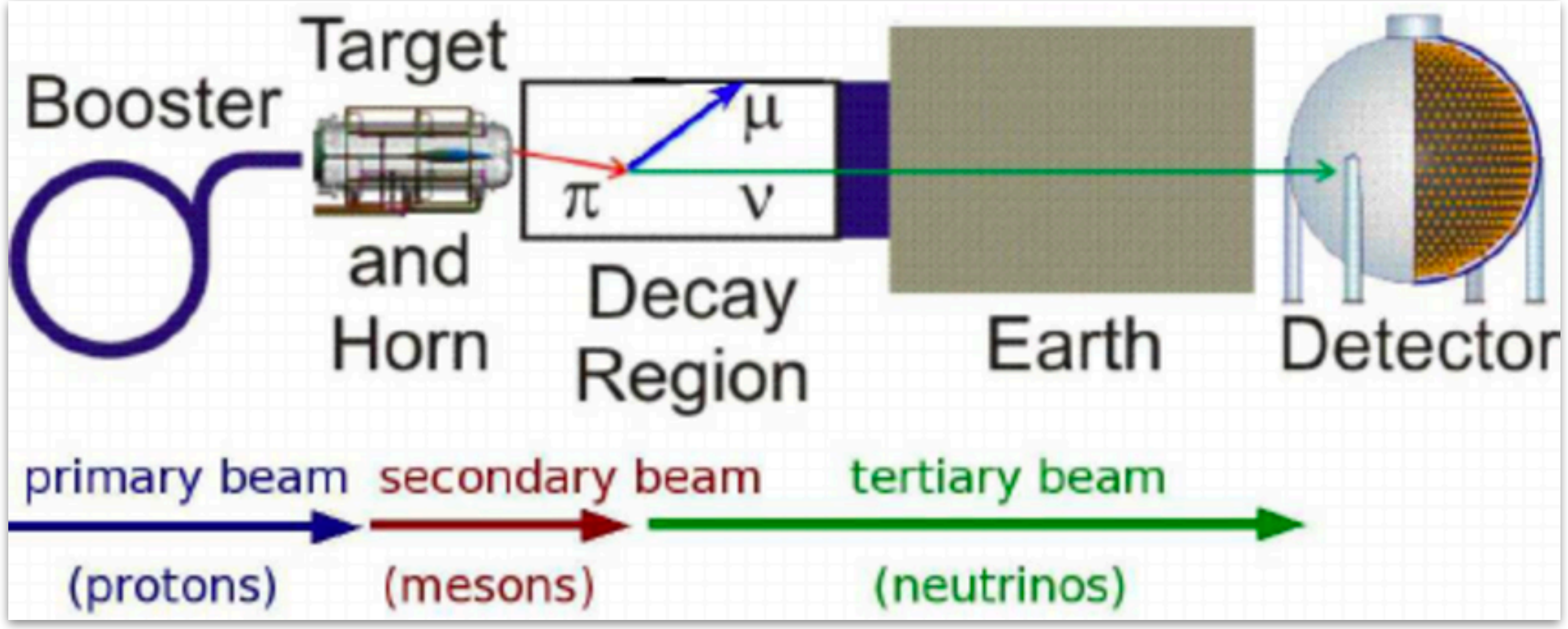

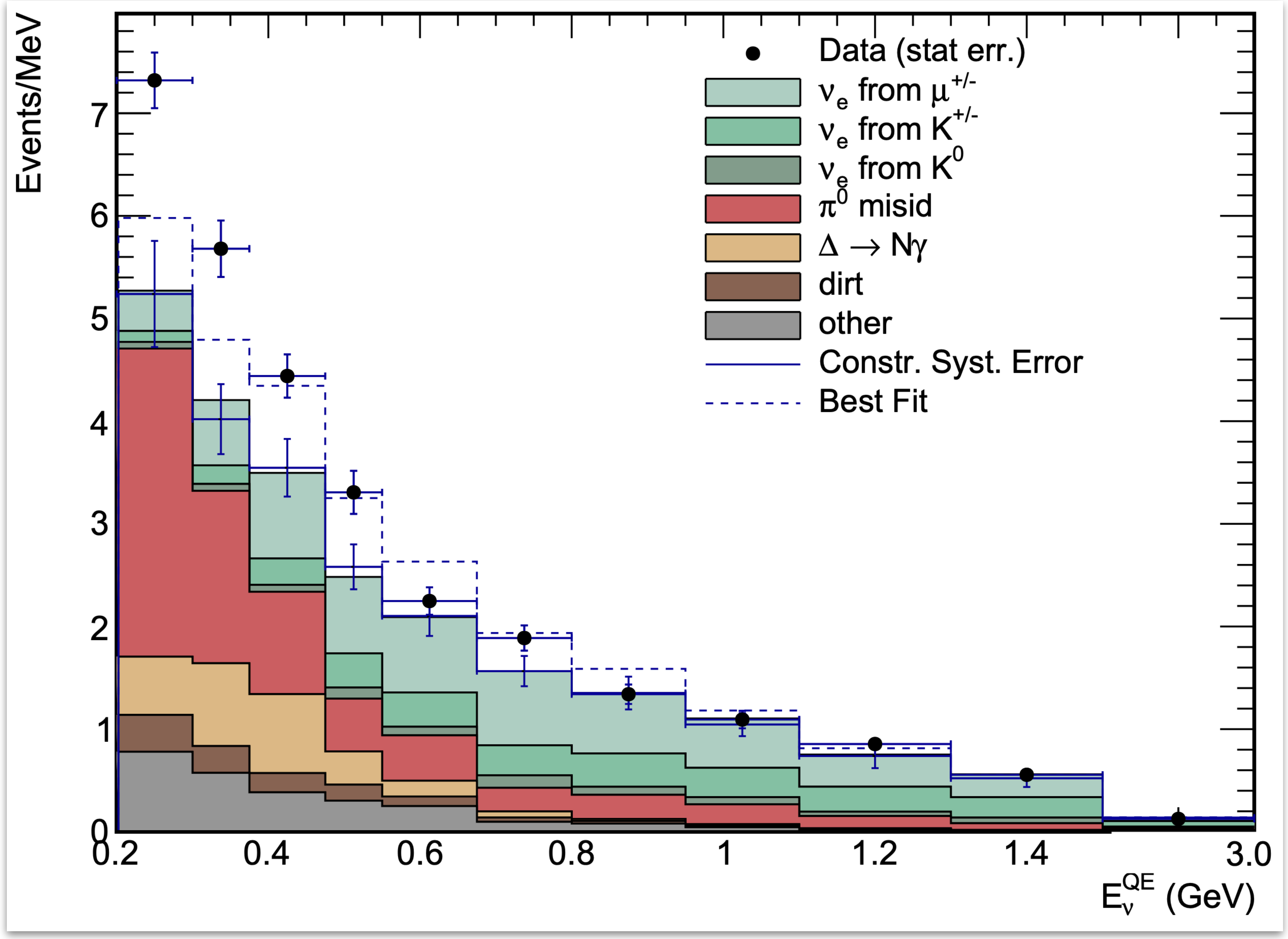

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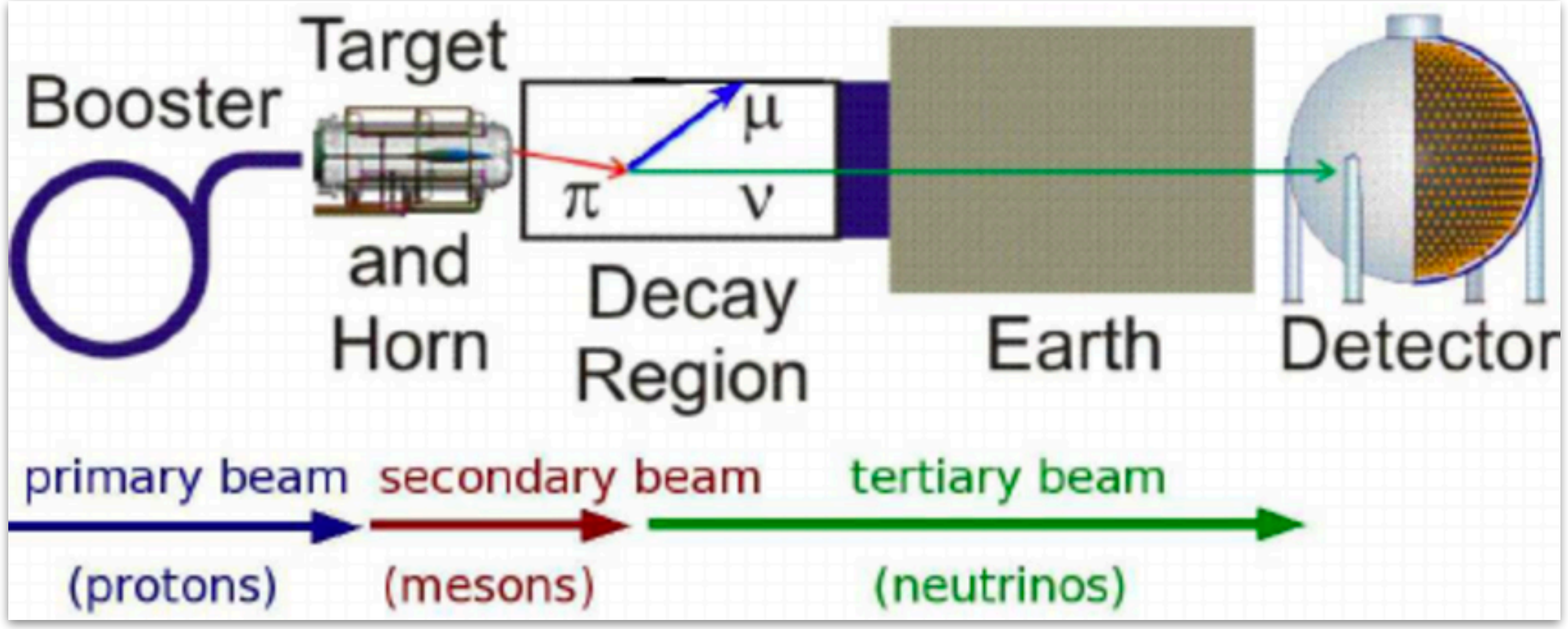
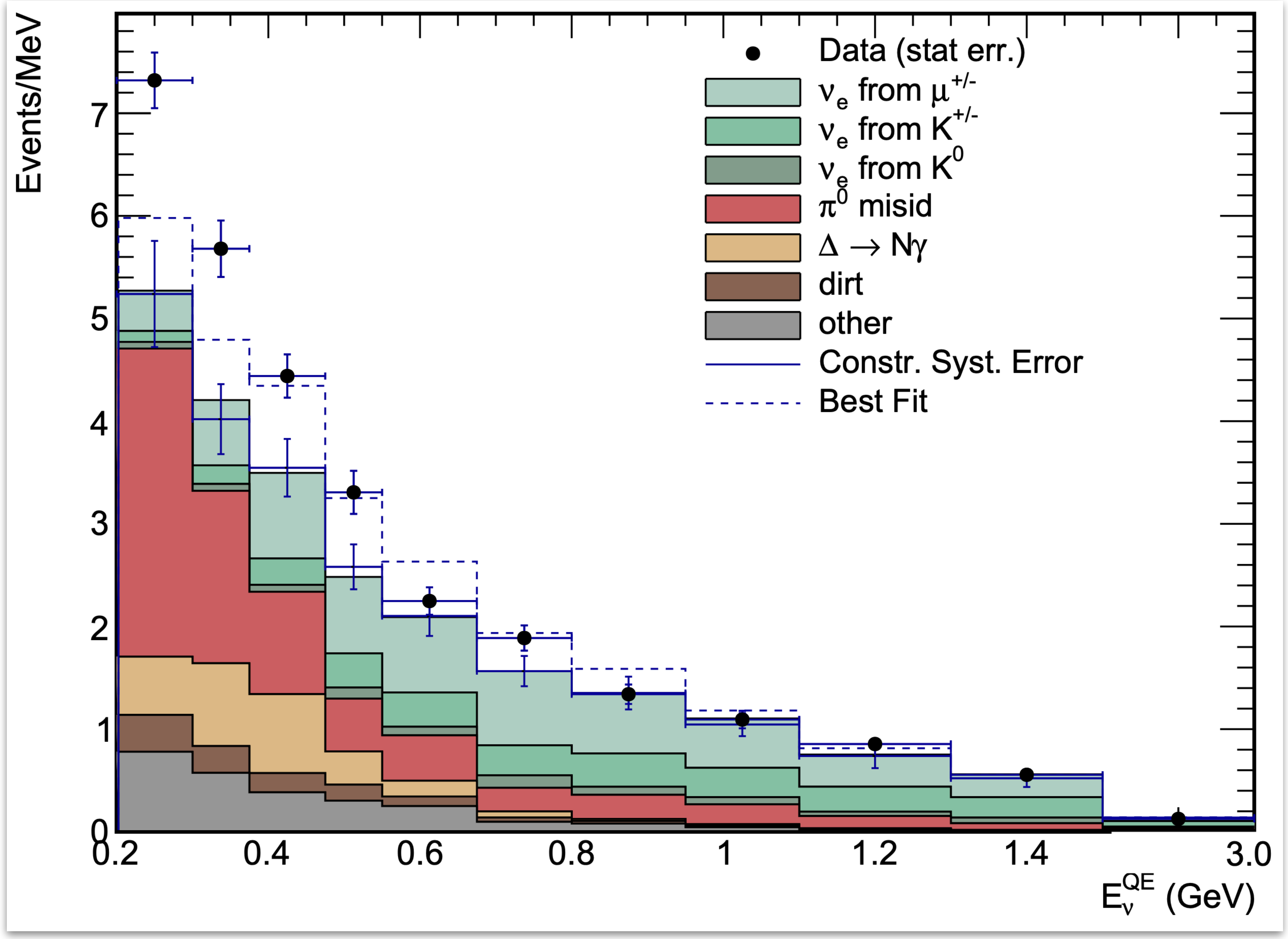
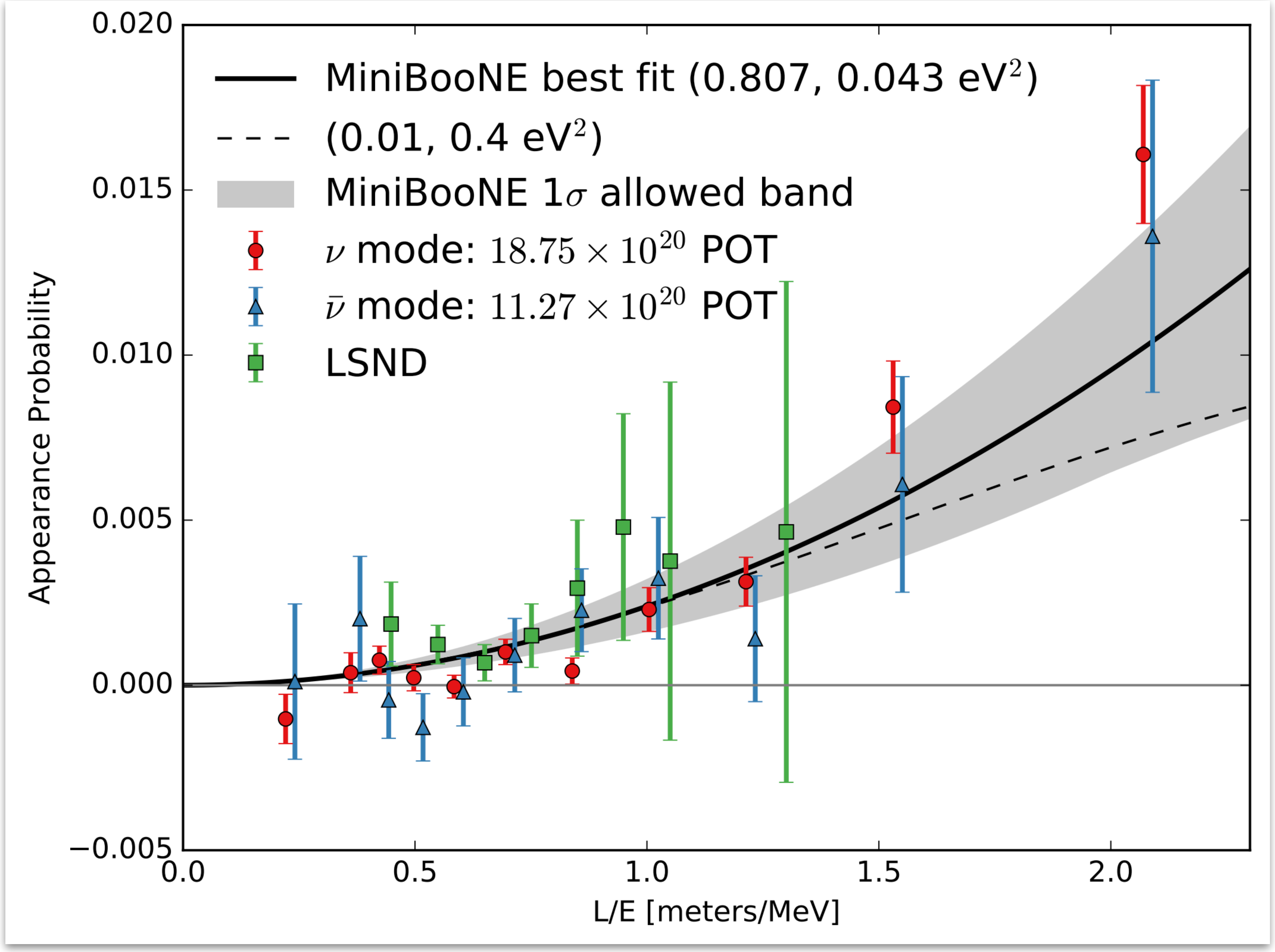


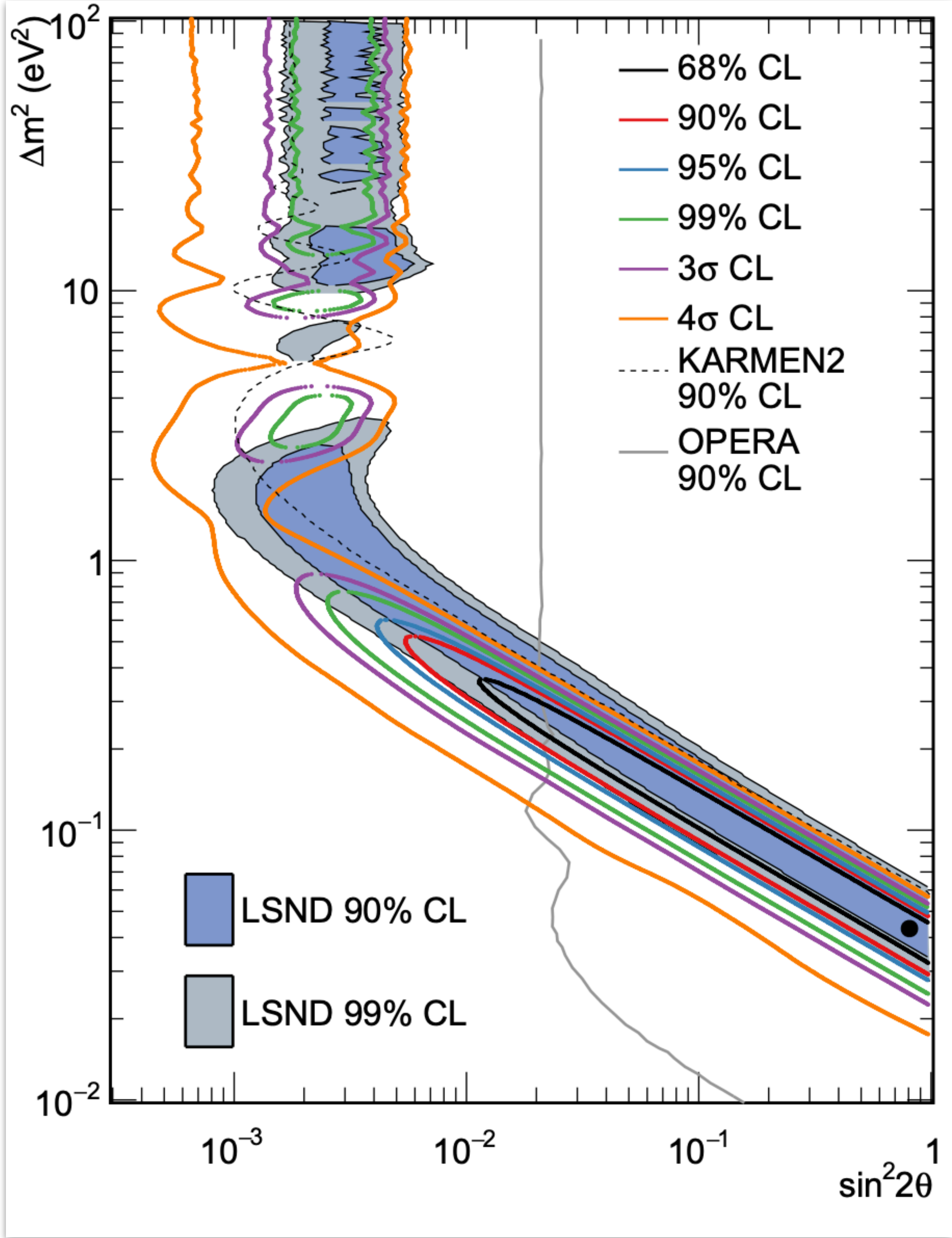
$$\nu_\mu \to \nu_e \text{ AND } \bar{\nu}_\mu \to \bar{\nu}_e?$$

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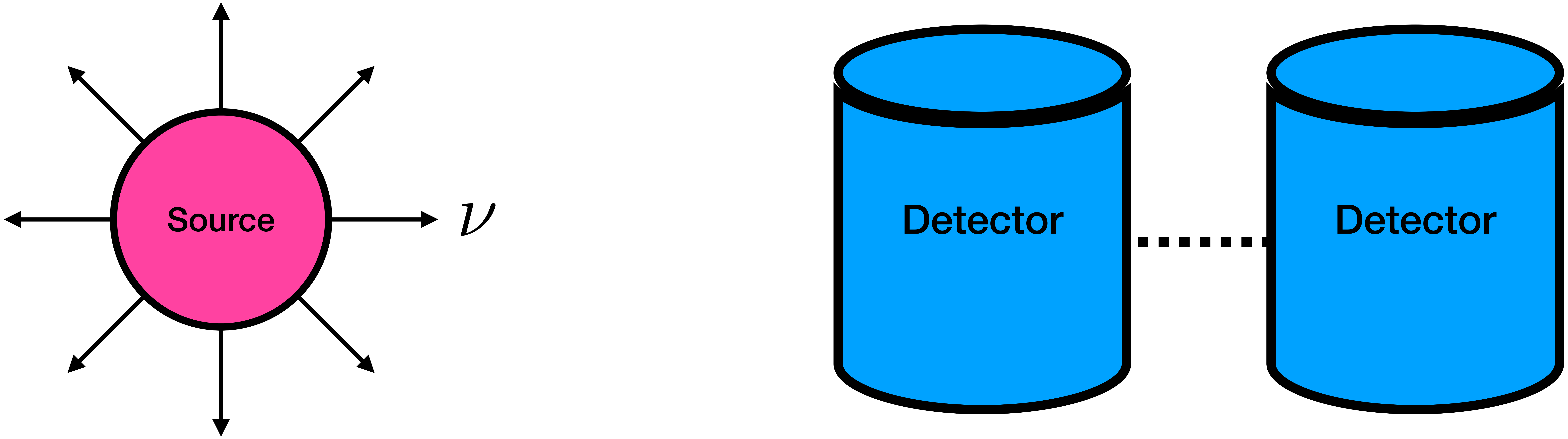
$$\sin^2\left(2\theta_{\mu e}\right) \equiv 4\left|U_{e4}\right|^2\left|U_{\mu 4}\right|^2$$

- 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?

Avoiding Uncertainties in Reactor Measurements

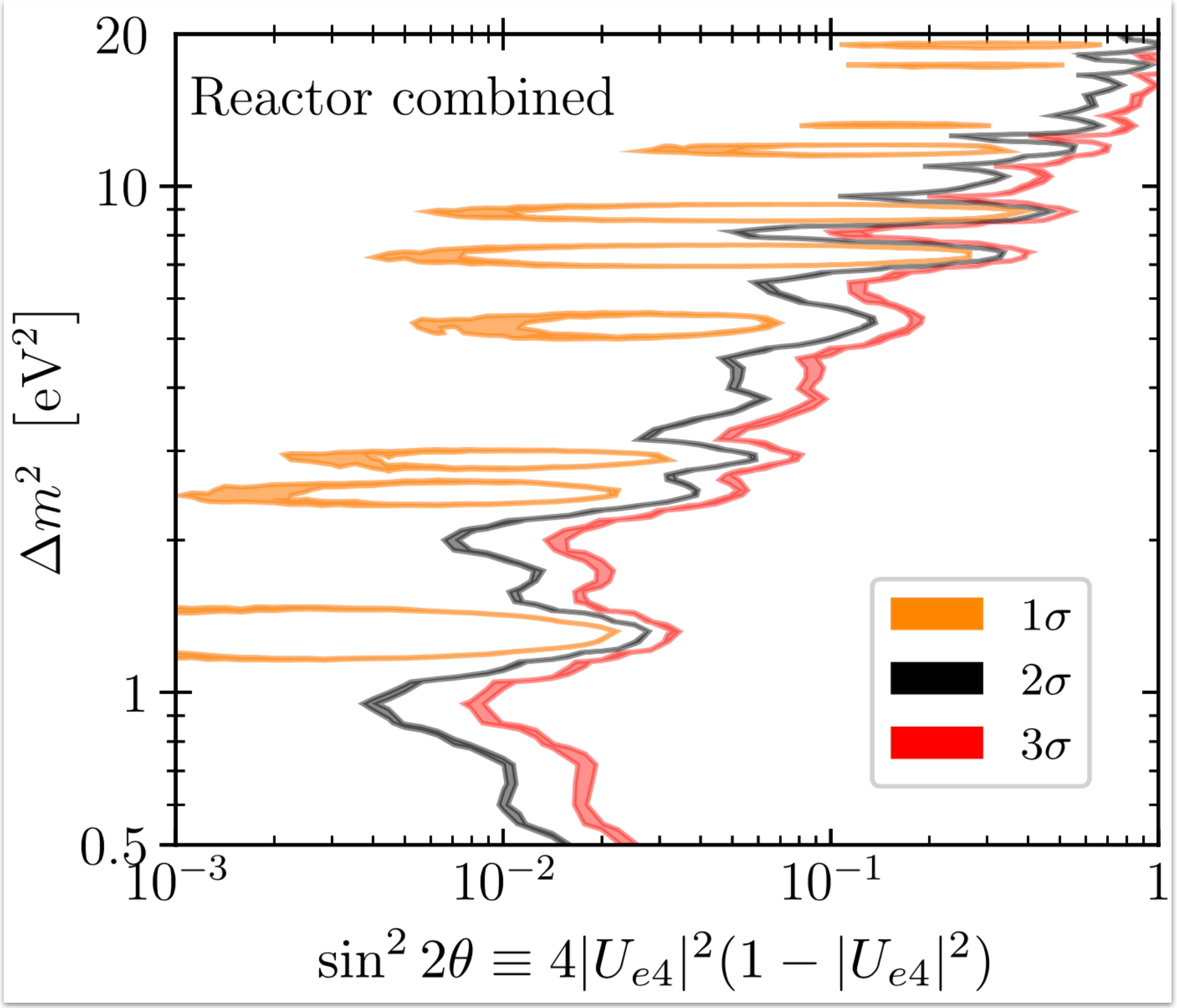
$$P\left(\nu_\alpha \to \nu_\alpha\right) = 1 - 4|U_{\alpha 4}|^2\left(1 - |U_{\alpha 4}|^2\right)\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$



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

Reactor Global Picture

Berryman et al, [2111.12530]



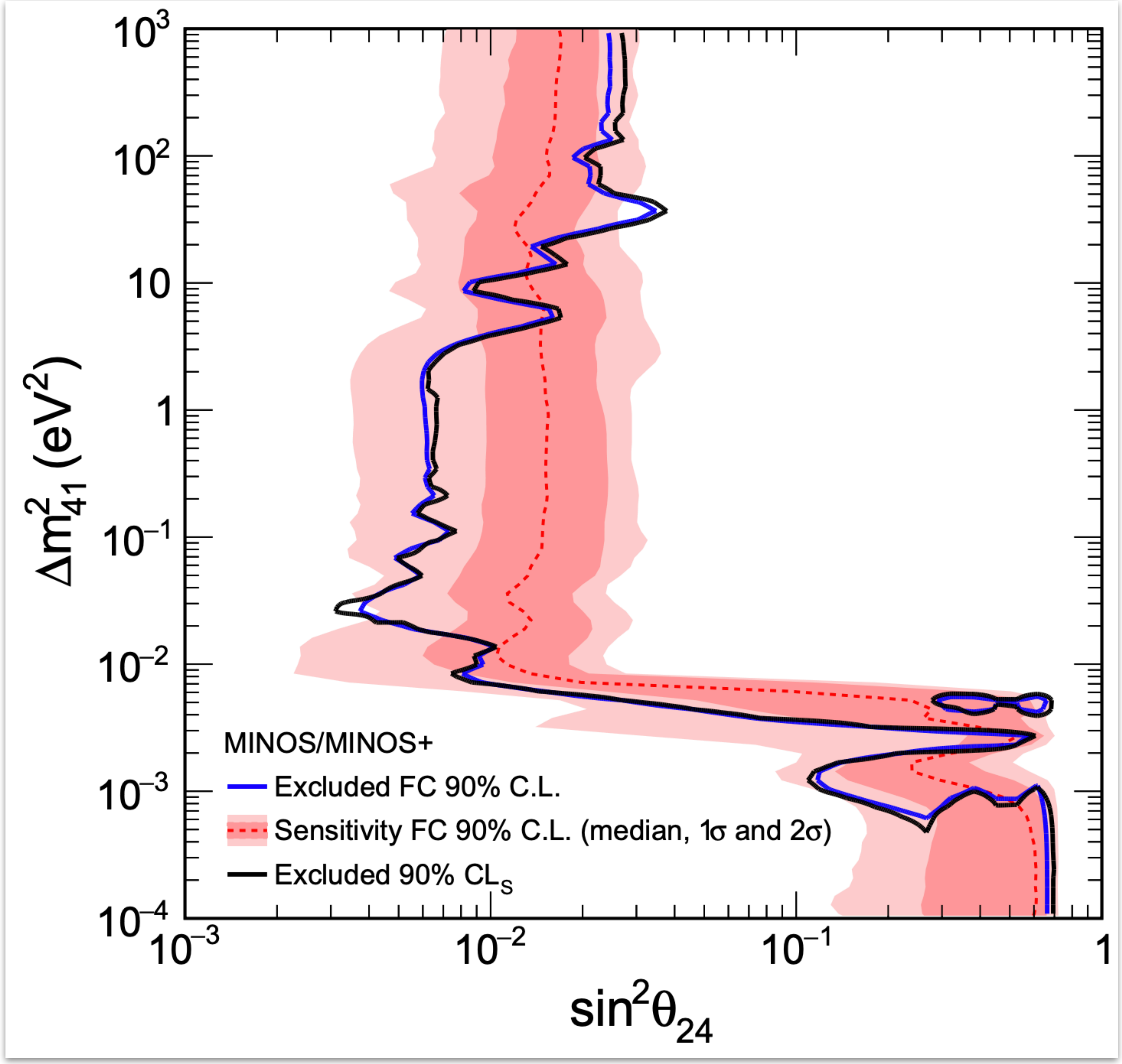
PROSPECT
STEREO
DANSS
Neutrino 4
NEOS

No significant* deviation from expectation!

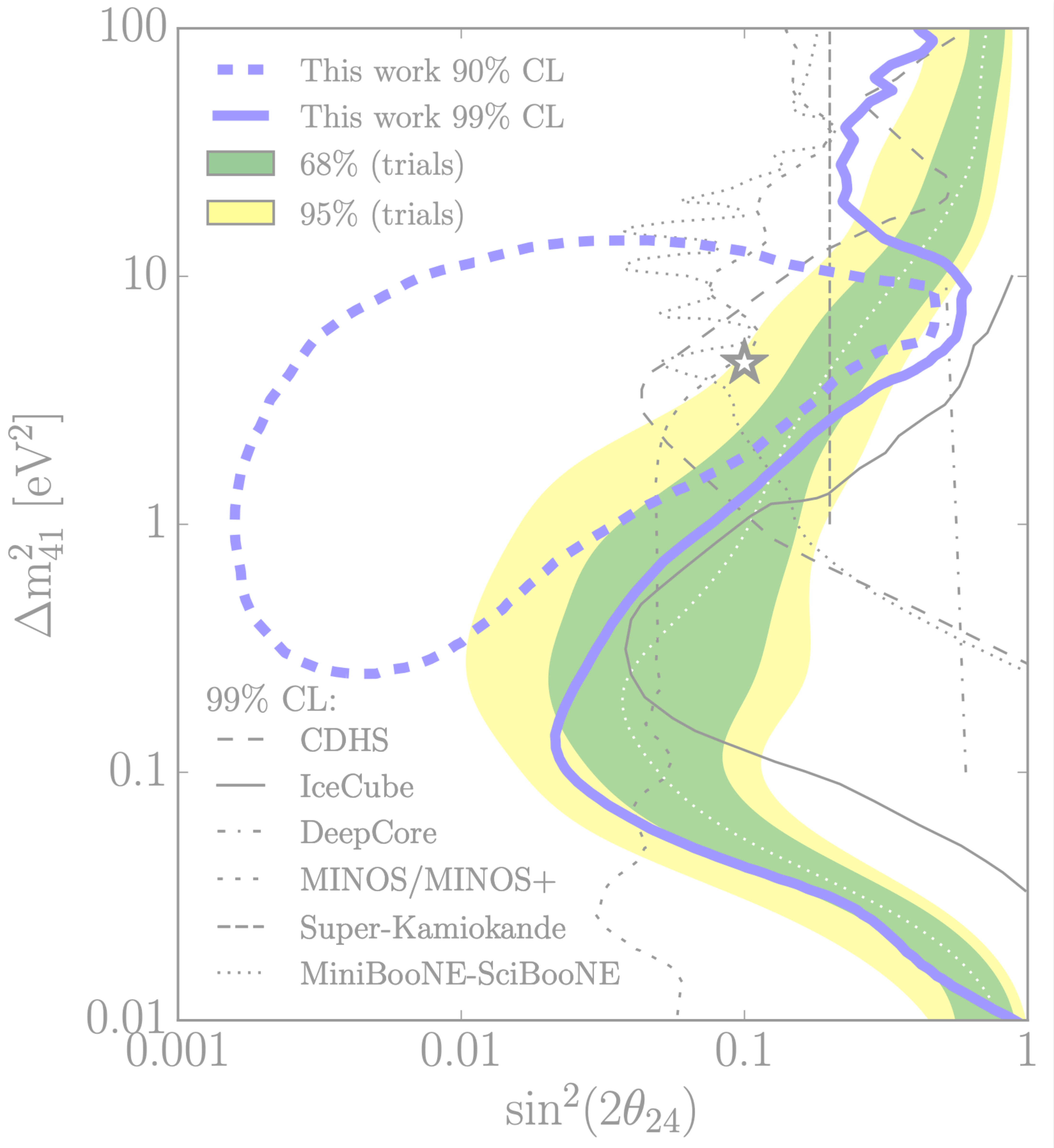
Muon-Neutrino Disappearance?

MINOS + IceCube

MINOS/MINOS+, [2002.00301]



IceCube Collaboration, [2005.12942]



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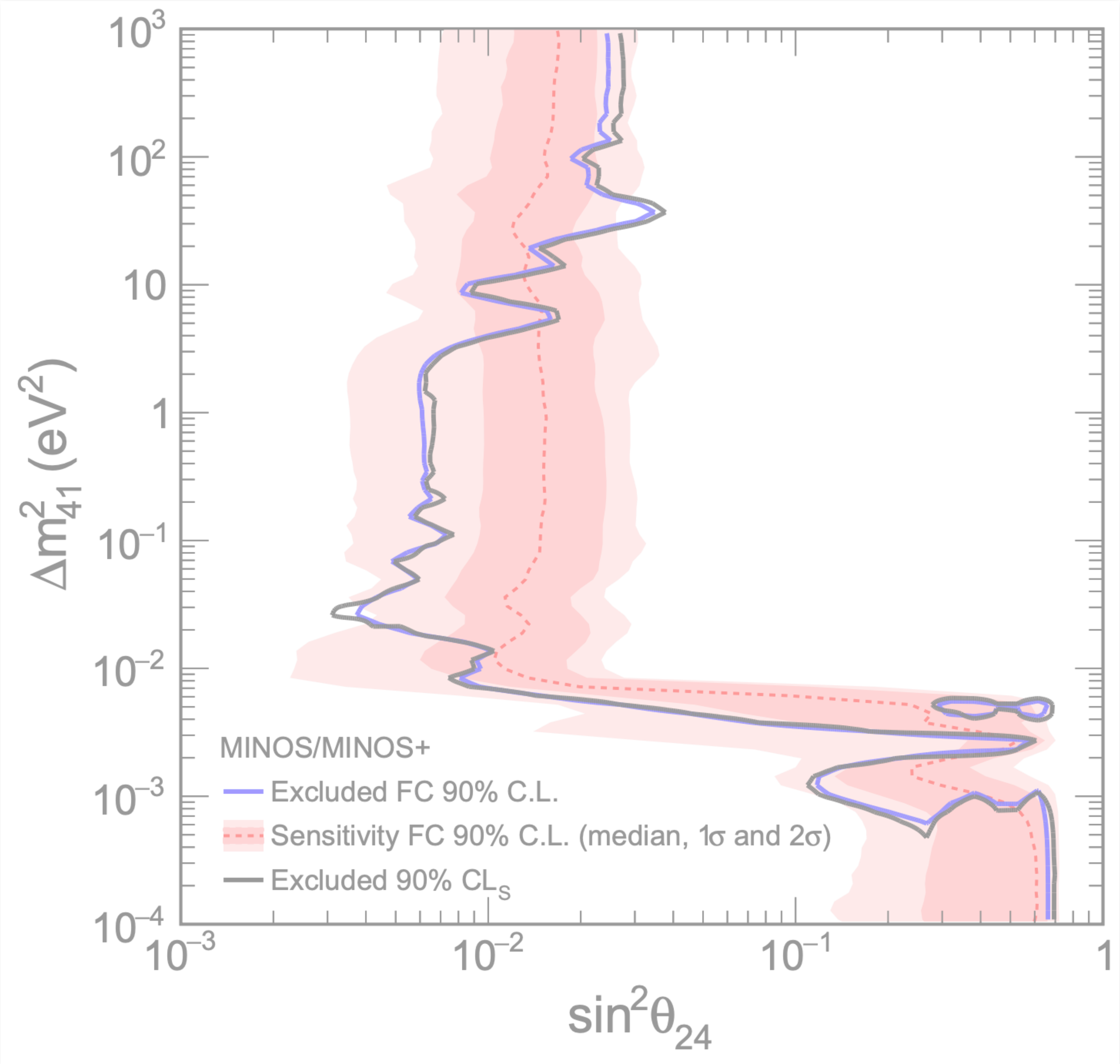

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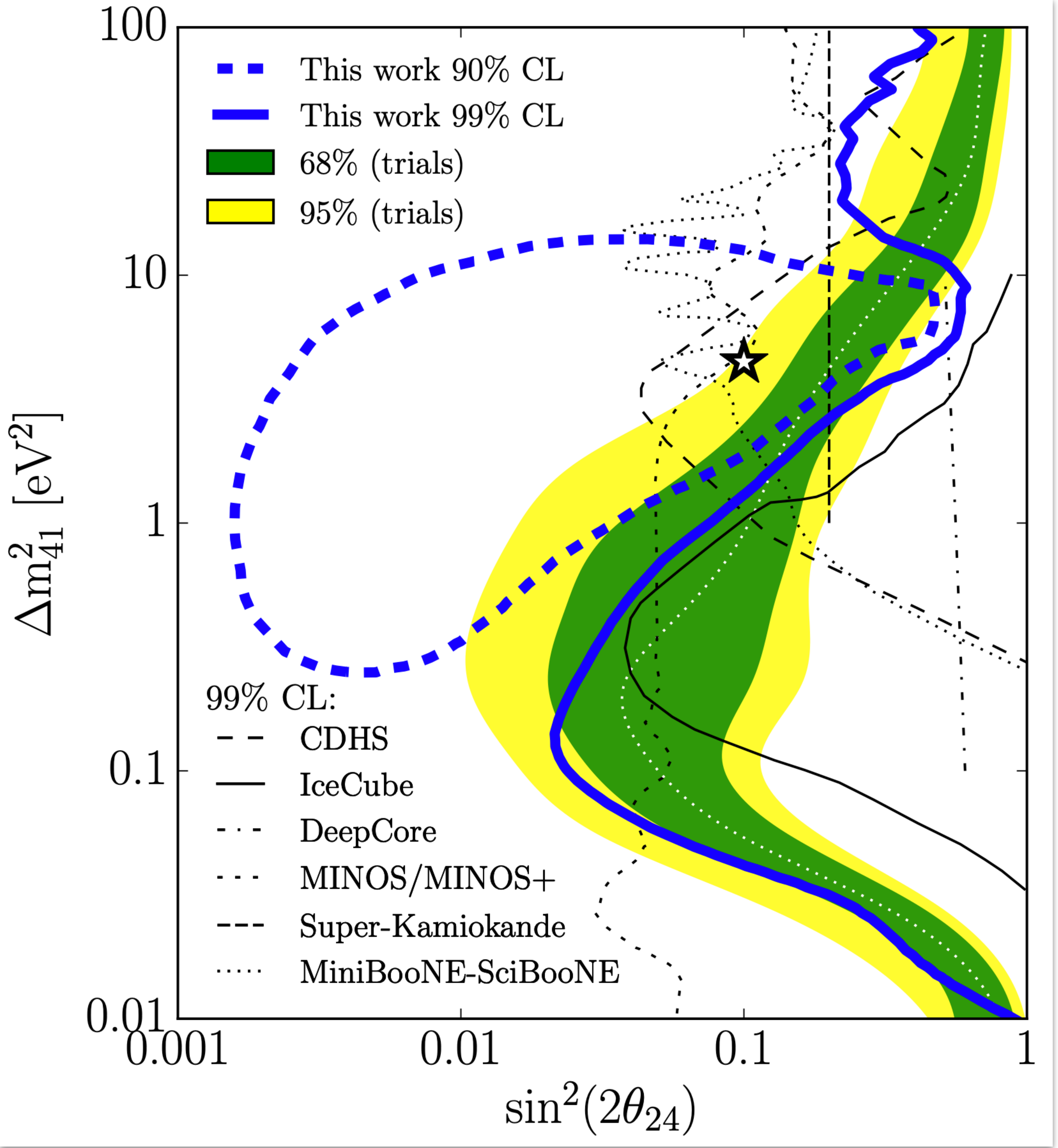
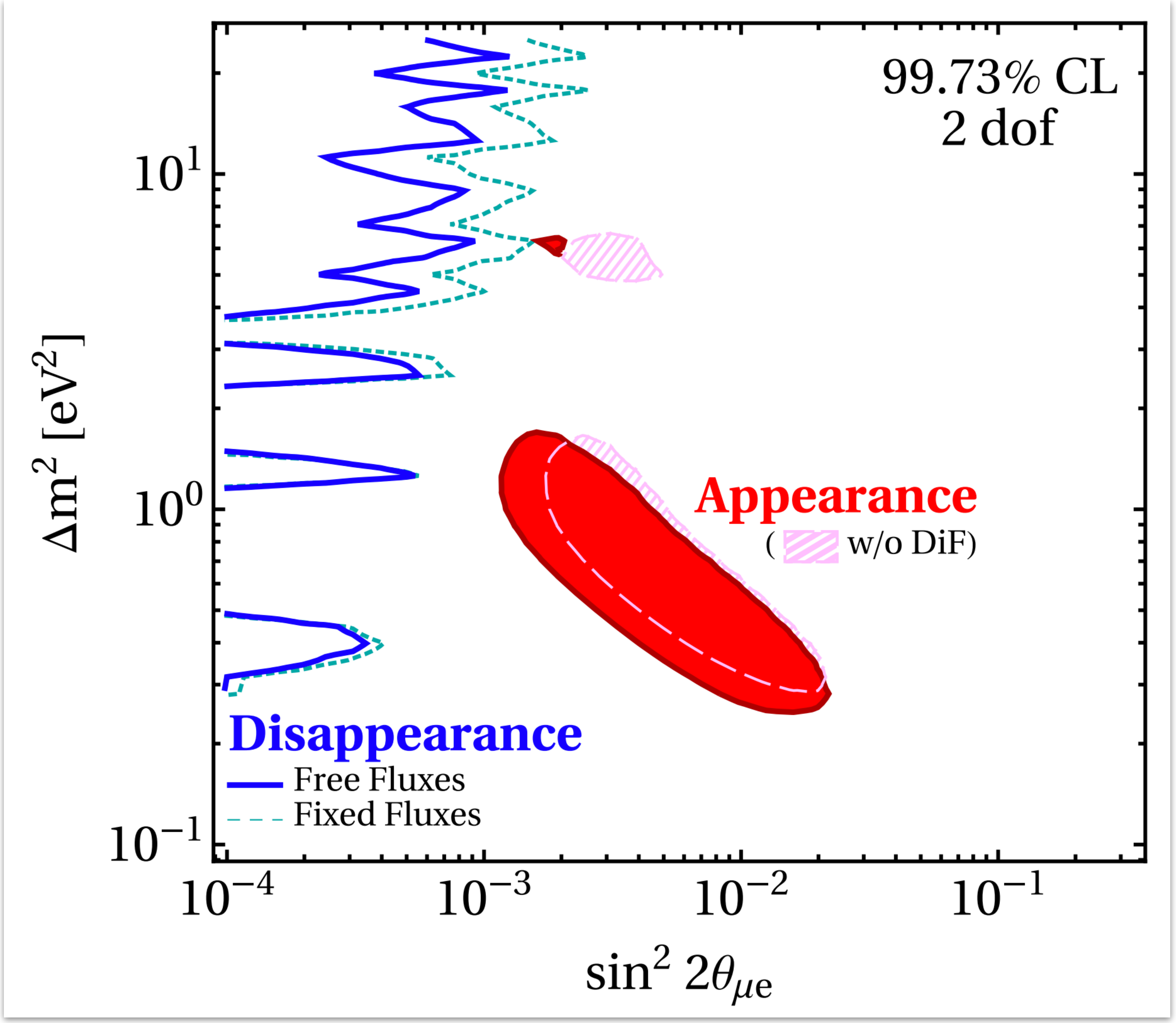
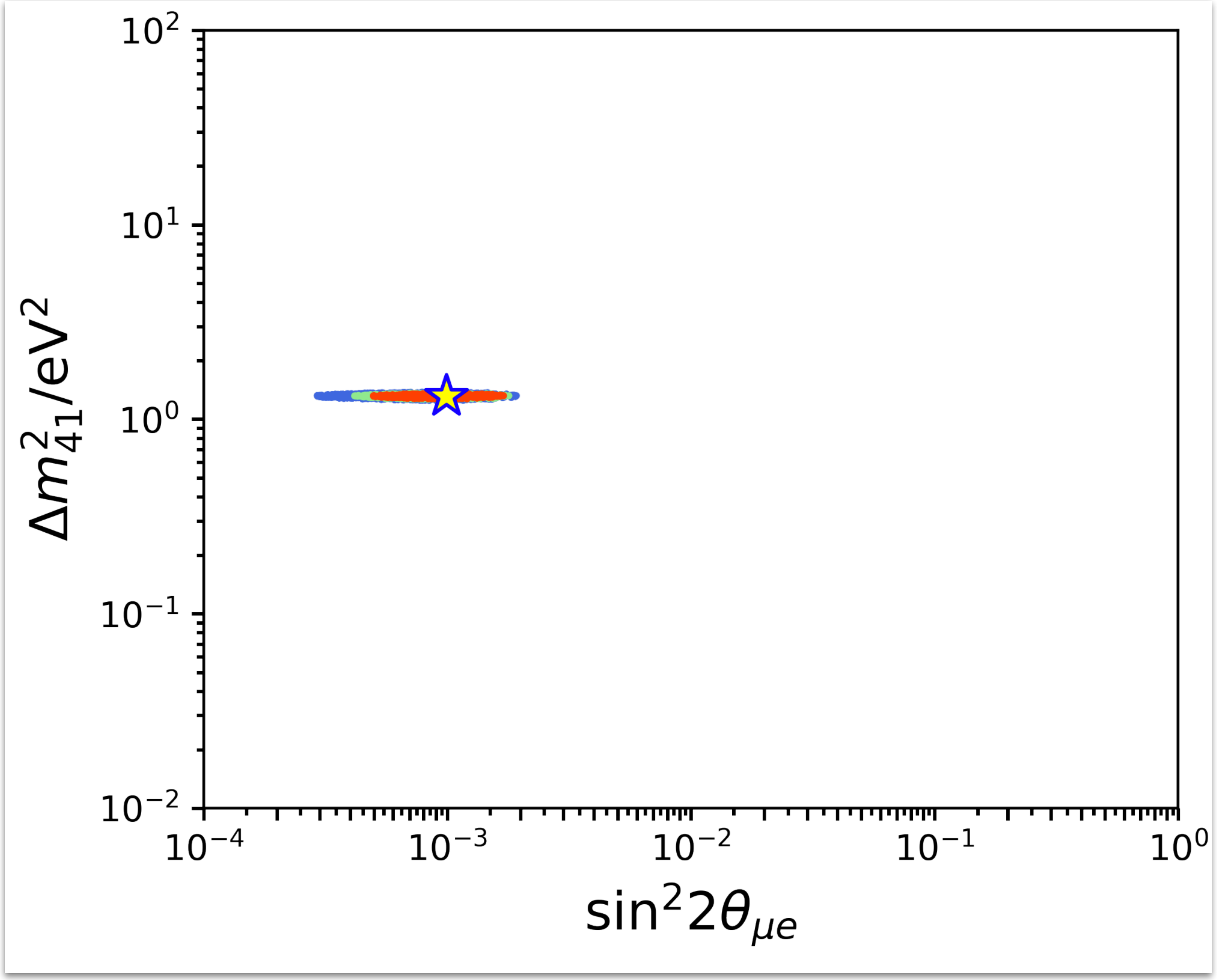


Sterile Neutrino Global Fits ca 2019

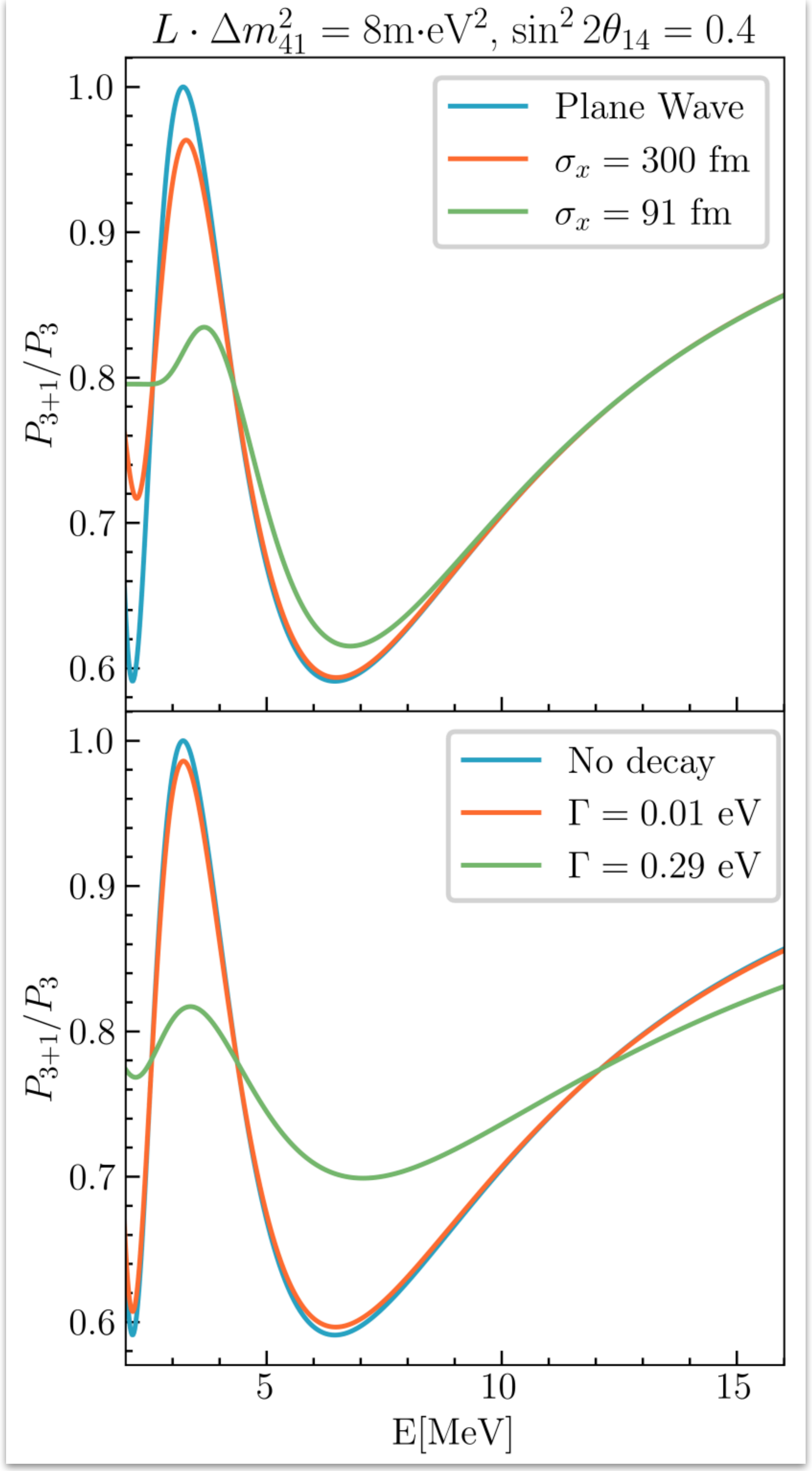


Dentler et al, [1803.10661]



Diaz et al, [1906.00045]

How to Alleviate This?



Tension between null results (reactor spectral measurements…) and positive ones (LSND + MiniBooNE) can be relieved a bit by allowing for either non-infinite neutrino wave-packets or allowing the fourth neutrino to decay.

$4.9\sigma \rightarrow 3.6\sigma$ (WP)

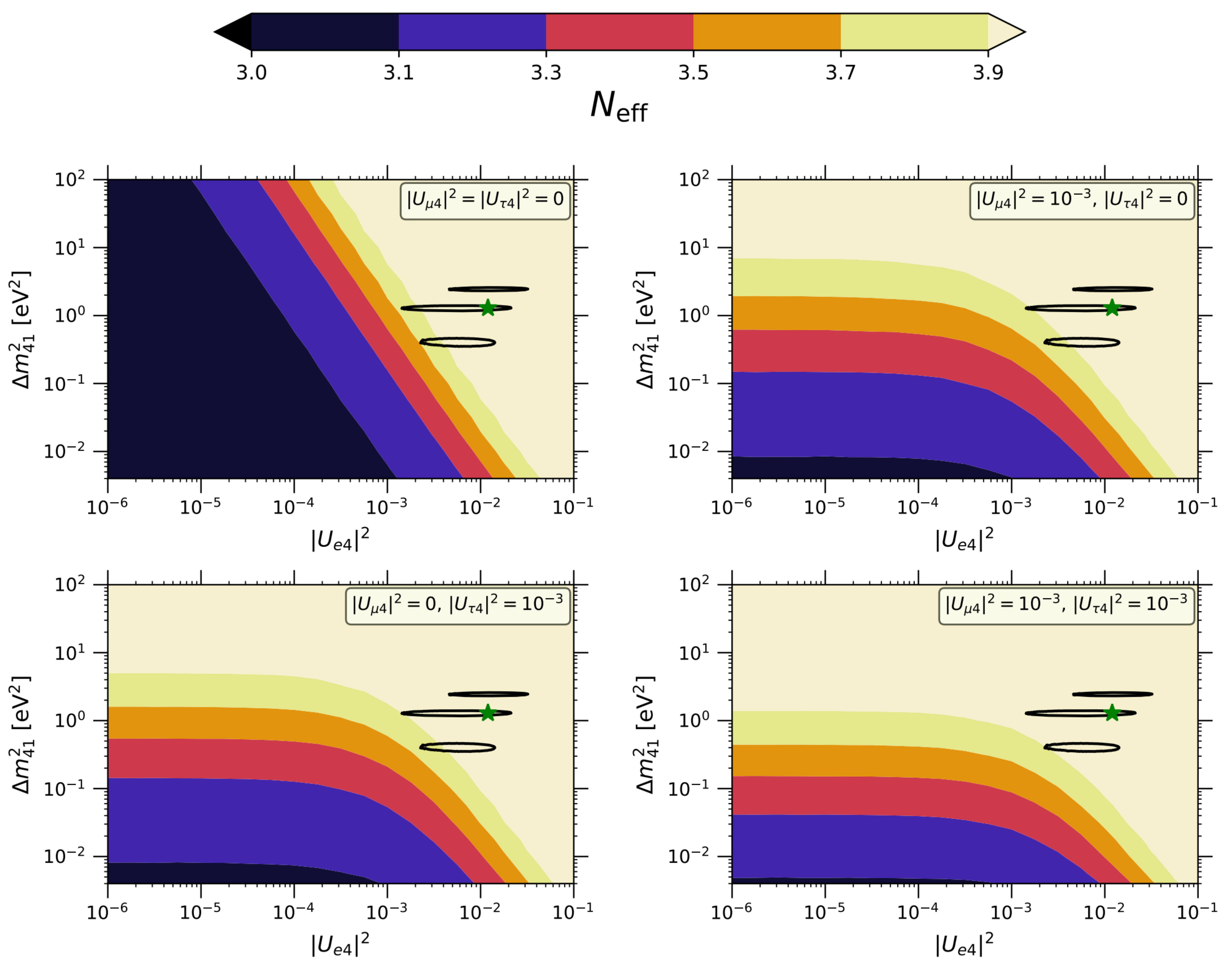
$4.9\sigma \rightarrow 3.7\sigma$ (Decay)

Hardin et al, [2211.02610] (see also Argüelles et al [2201.05108])

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.



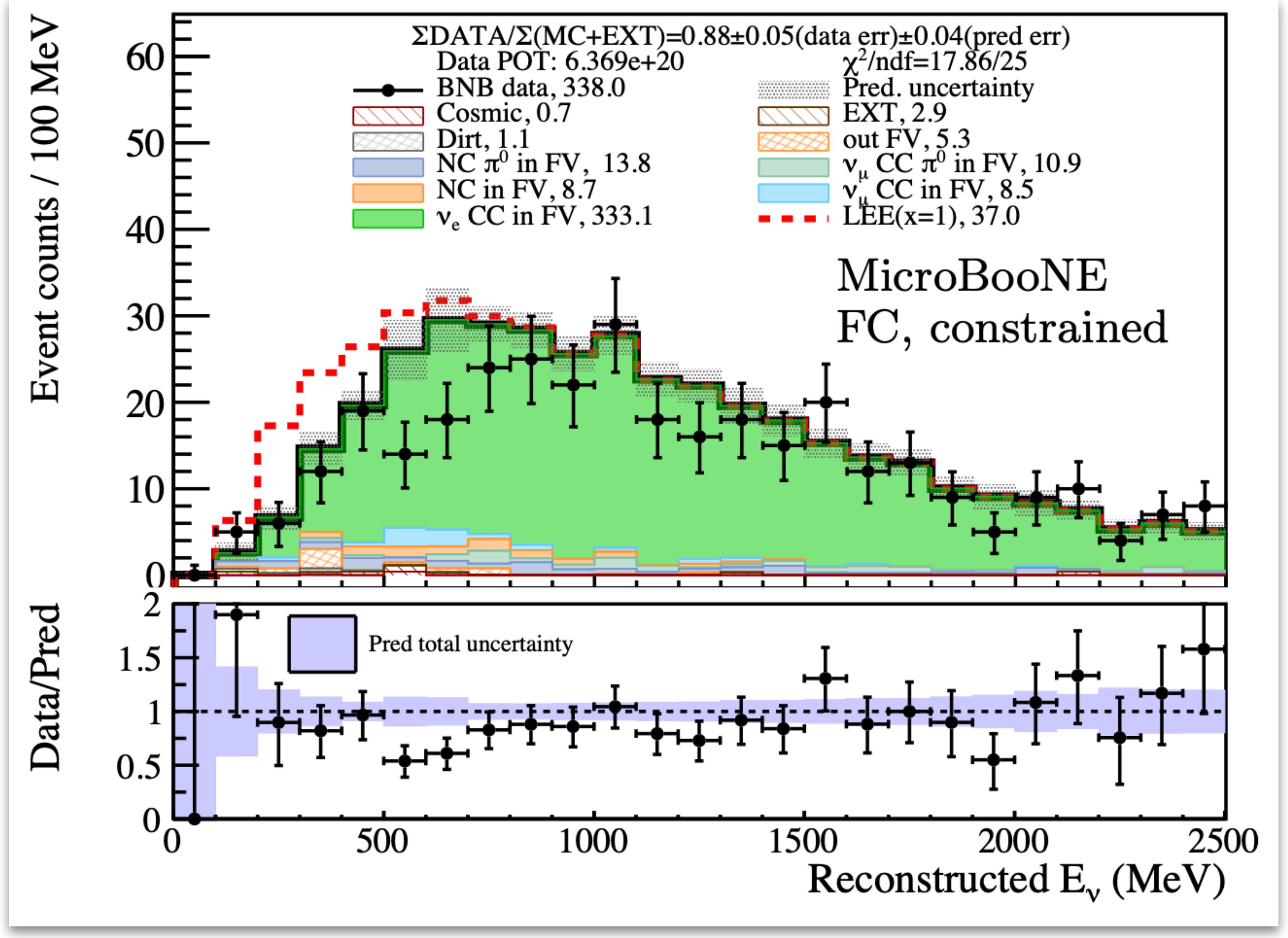
Recent Experimental Results

—MicroBooNE

MicroBooNE Electron Analyses

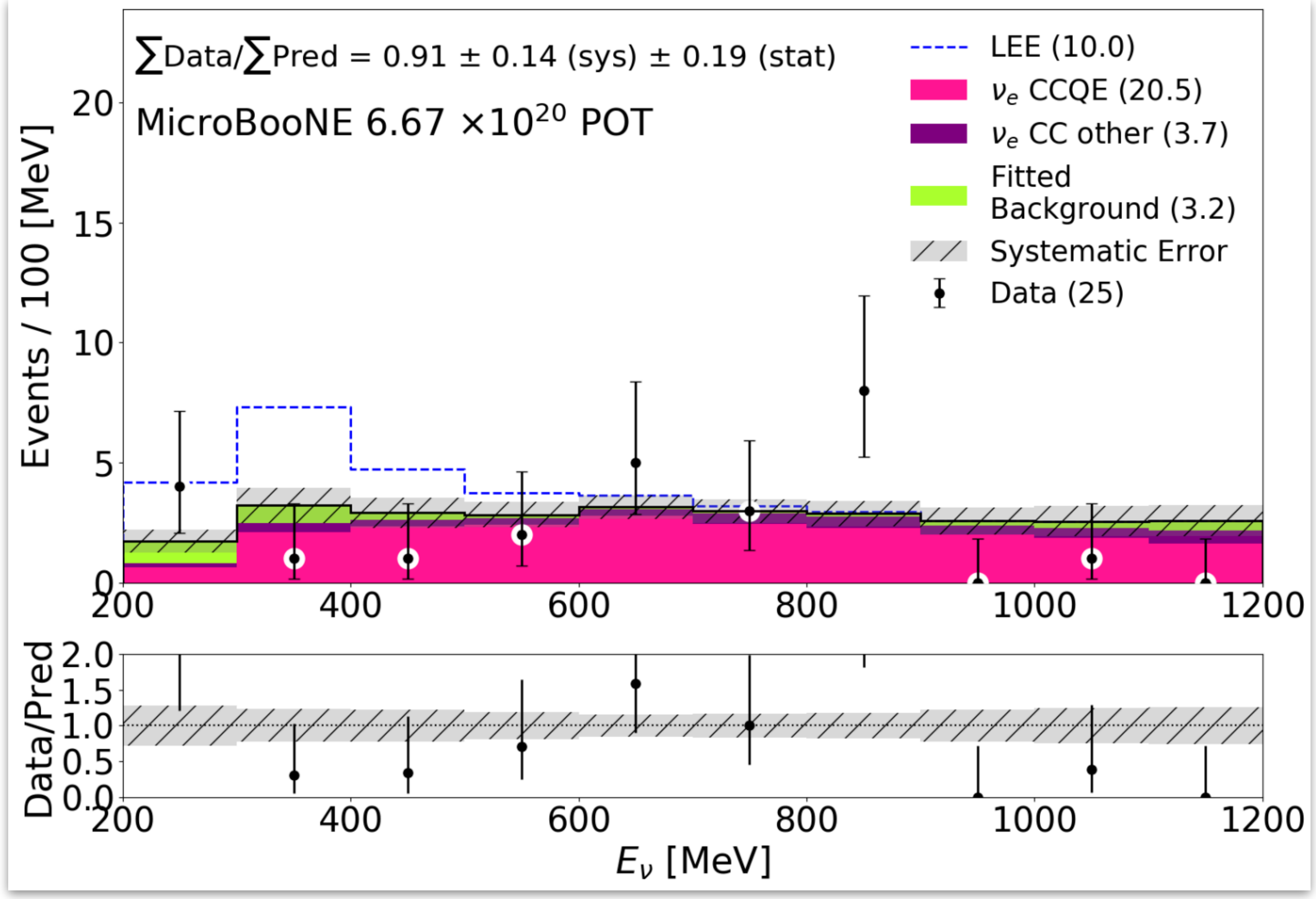
“Inclusive”

[2110.13978]



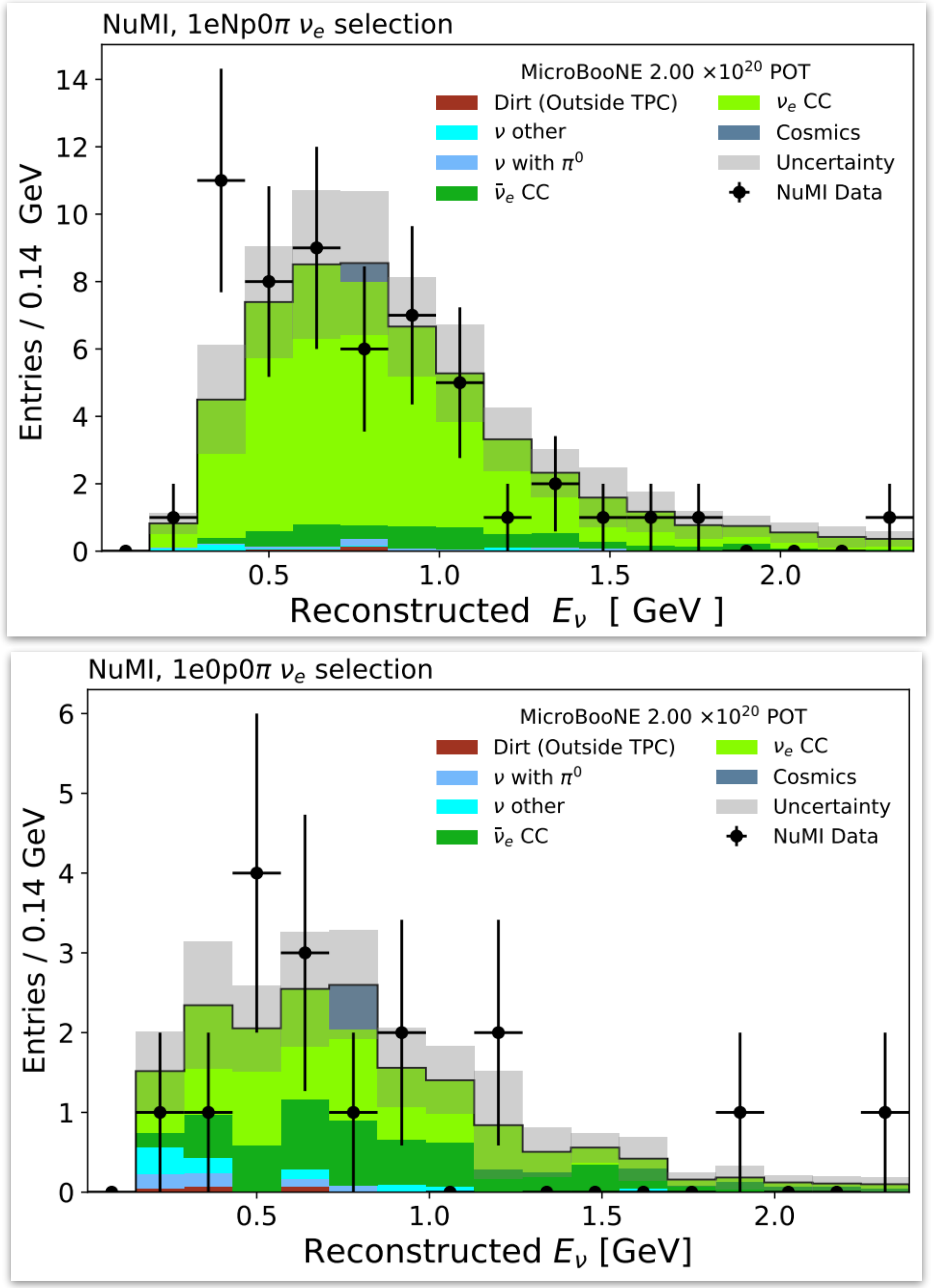
“CCQE”

[2110.14080]



“Pionless”

[2110.14065]



MicroBooNE Electron Analyses

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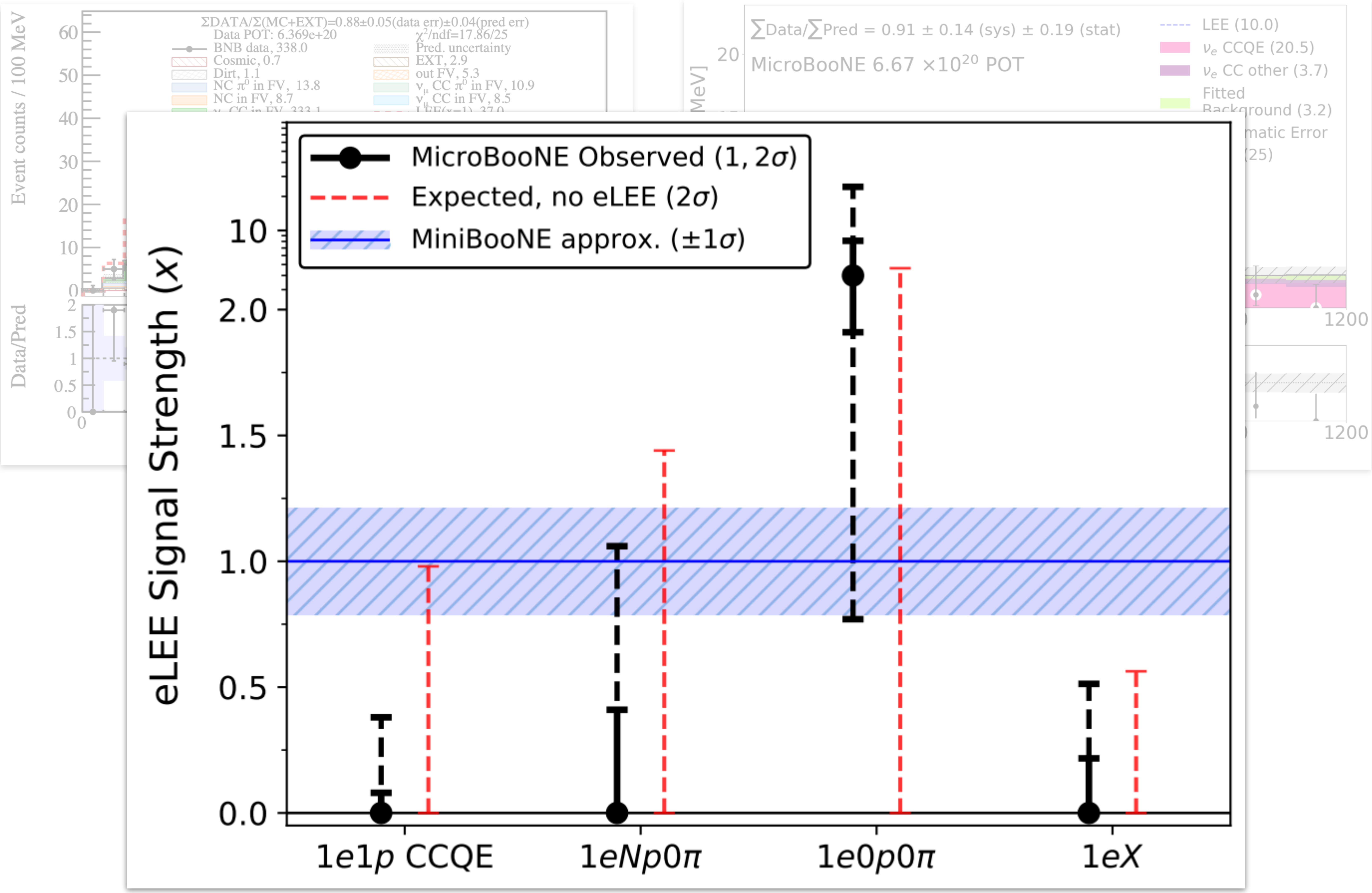
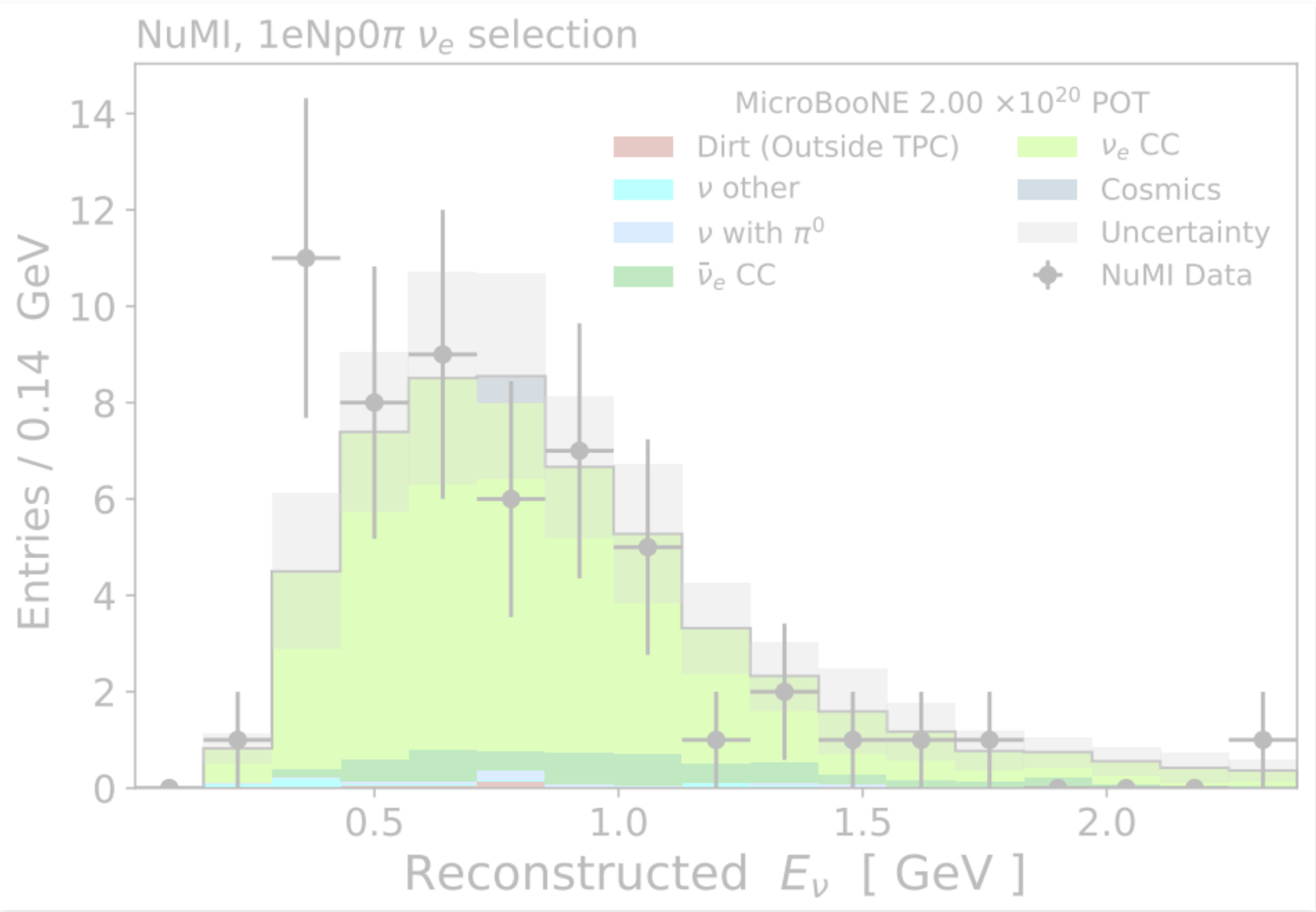
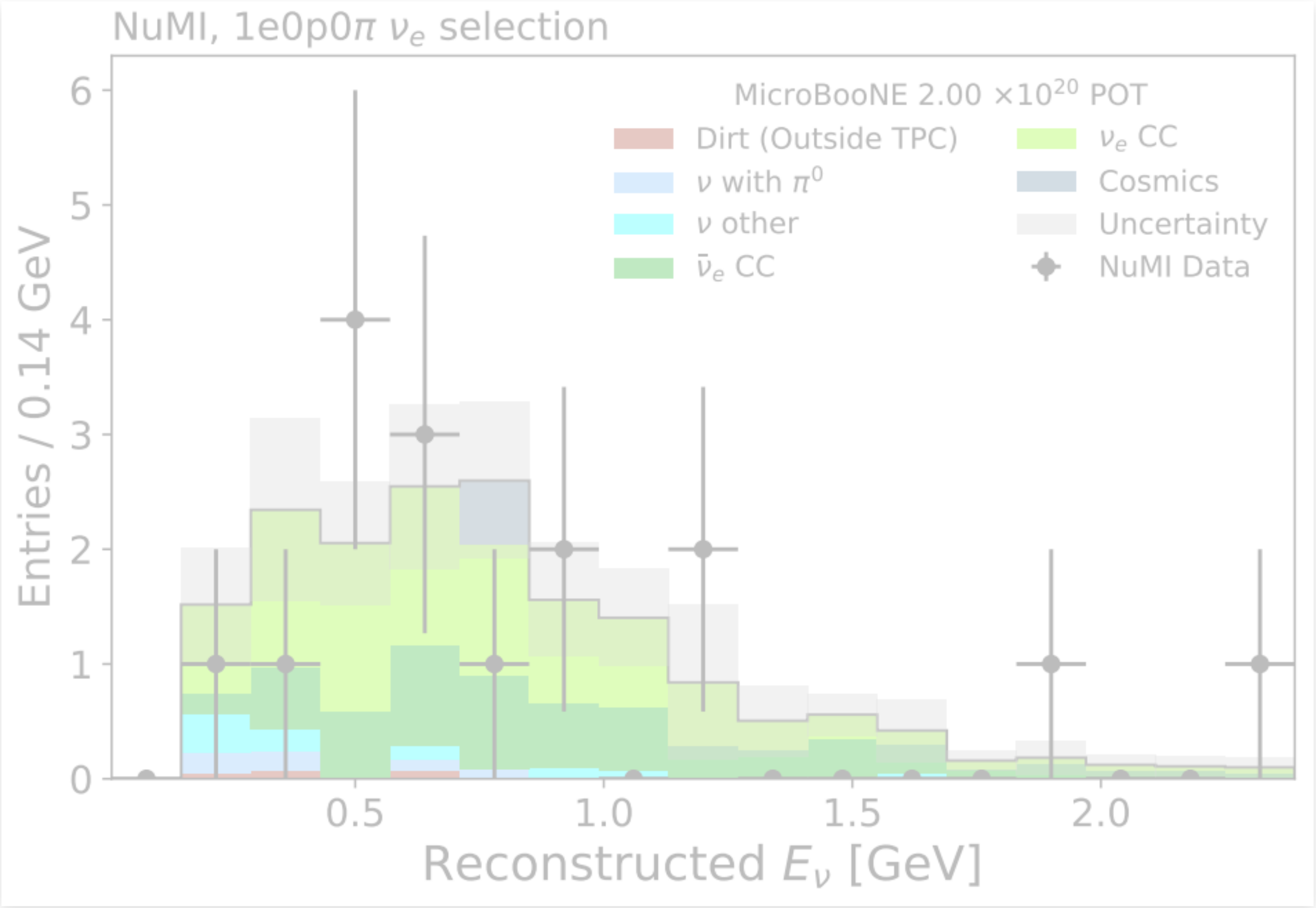


Discussion of all Results [2110.14054]

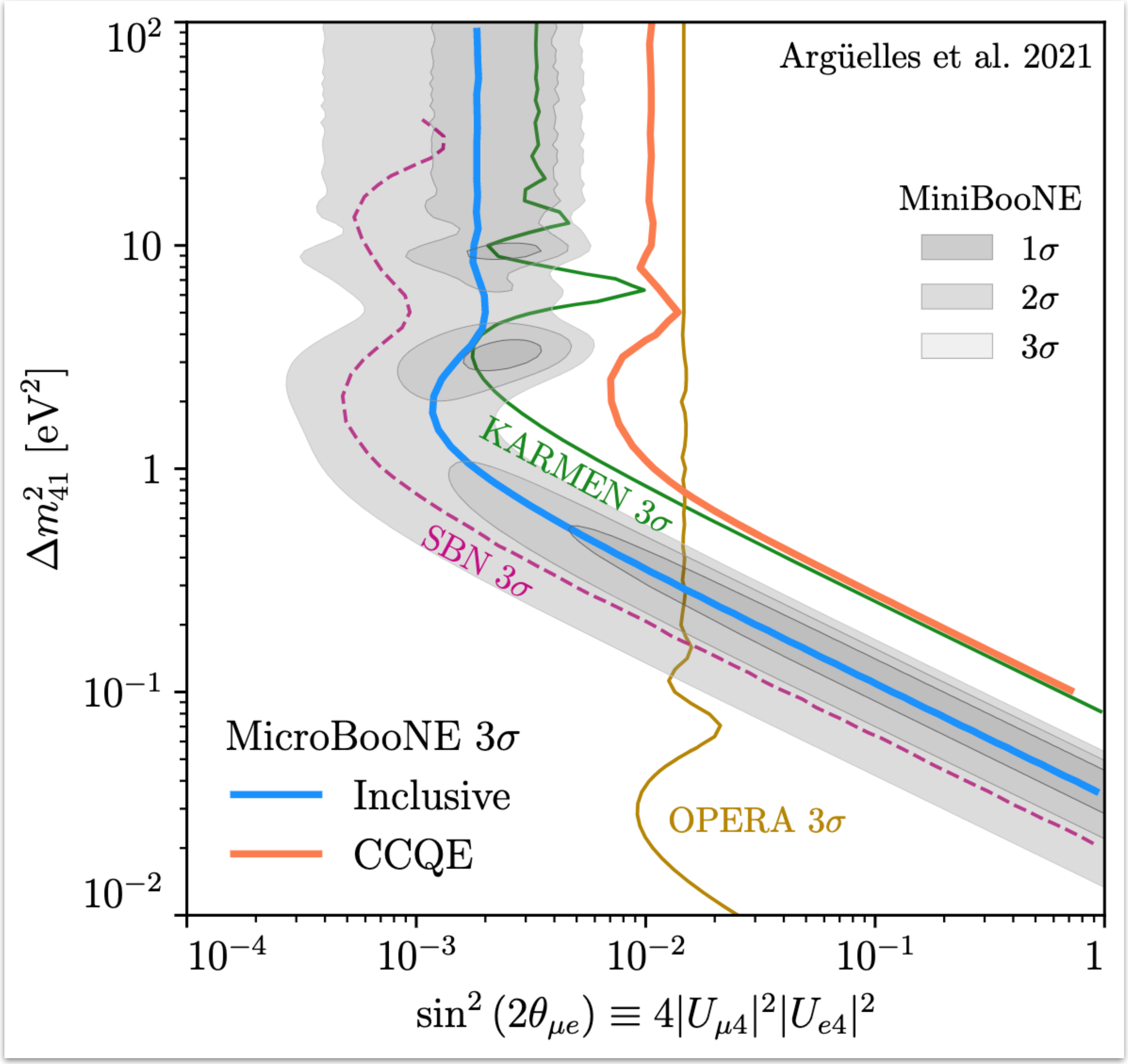
"Pionless" [2110.14065]





MicroBooNE and Sterile Neutrinos

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



Argüelles, KJK, et al, [2111.10359]

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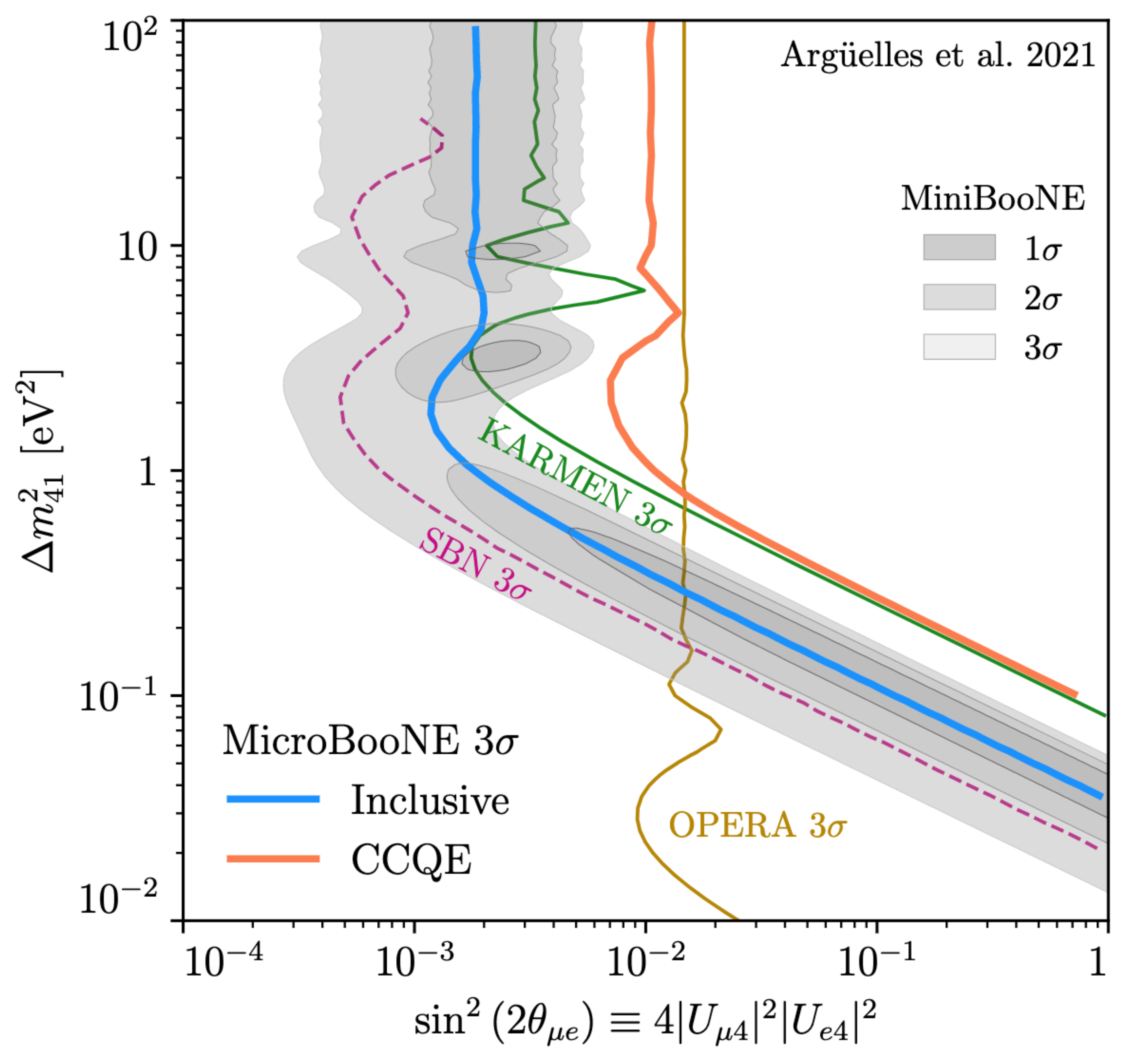

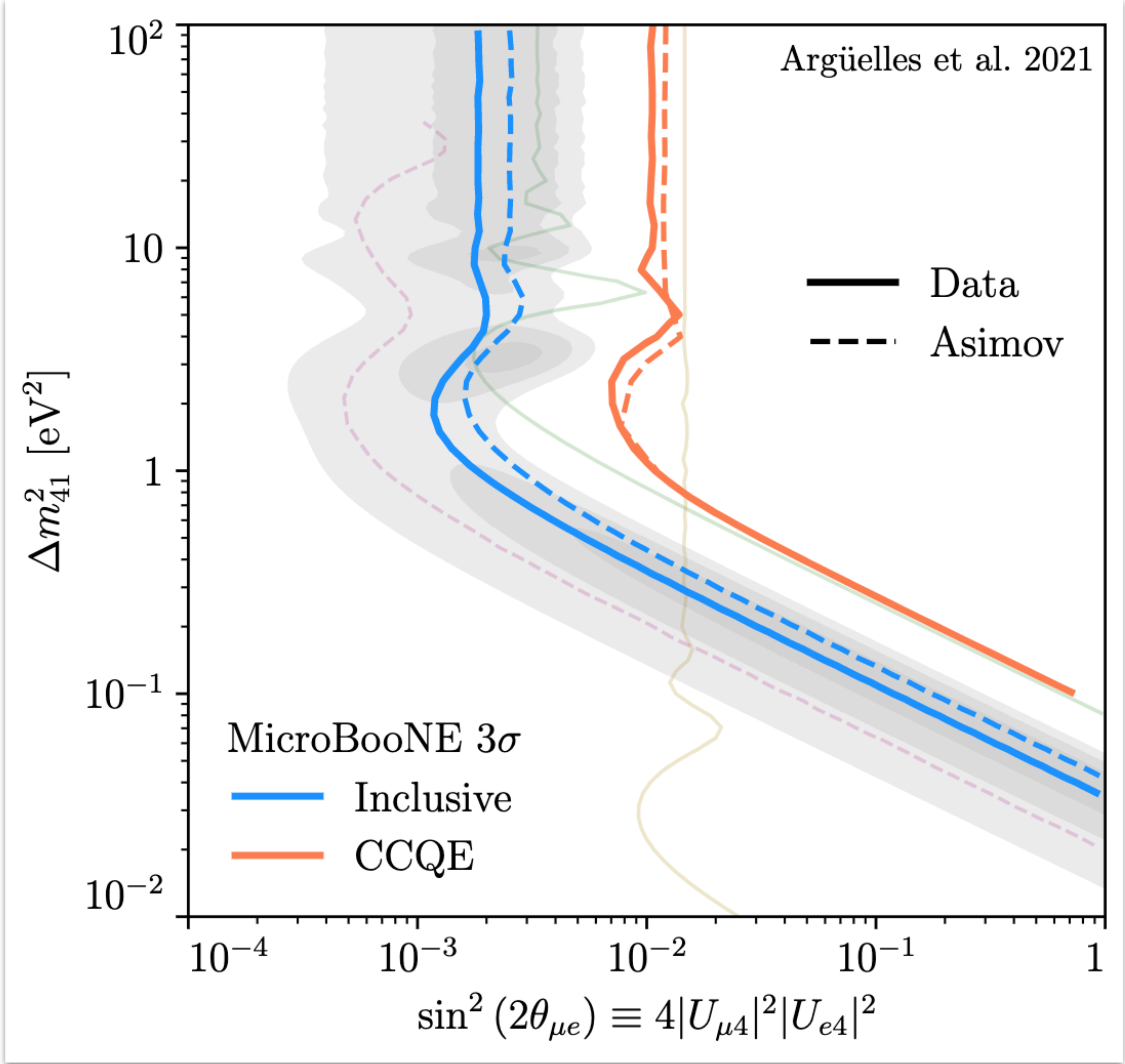

Argüelles, KJK, et al, [2111.10359]

Complete 3+1 Neutrino Framework

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

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

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Anomalous appearance *requires* disappearance!

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

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

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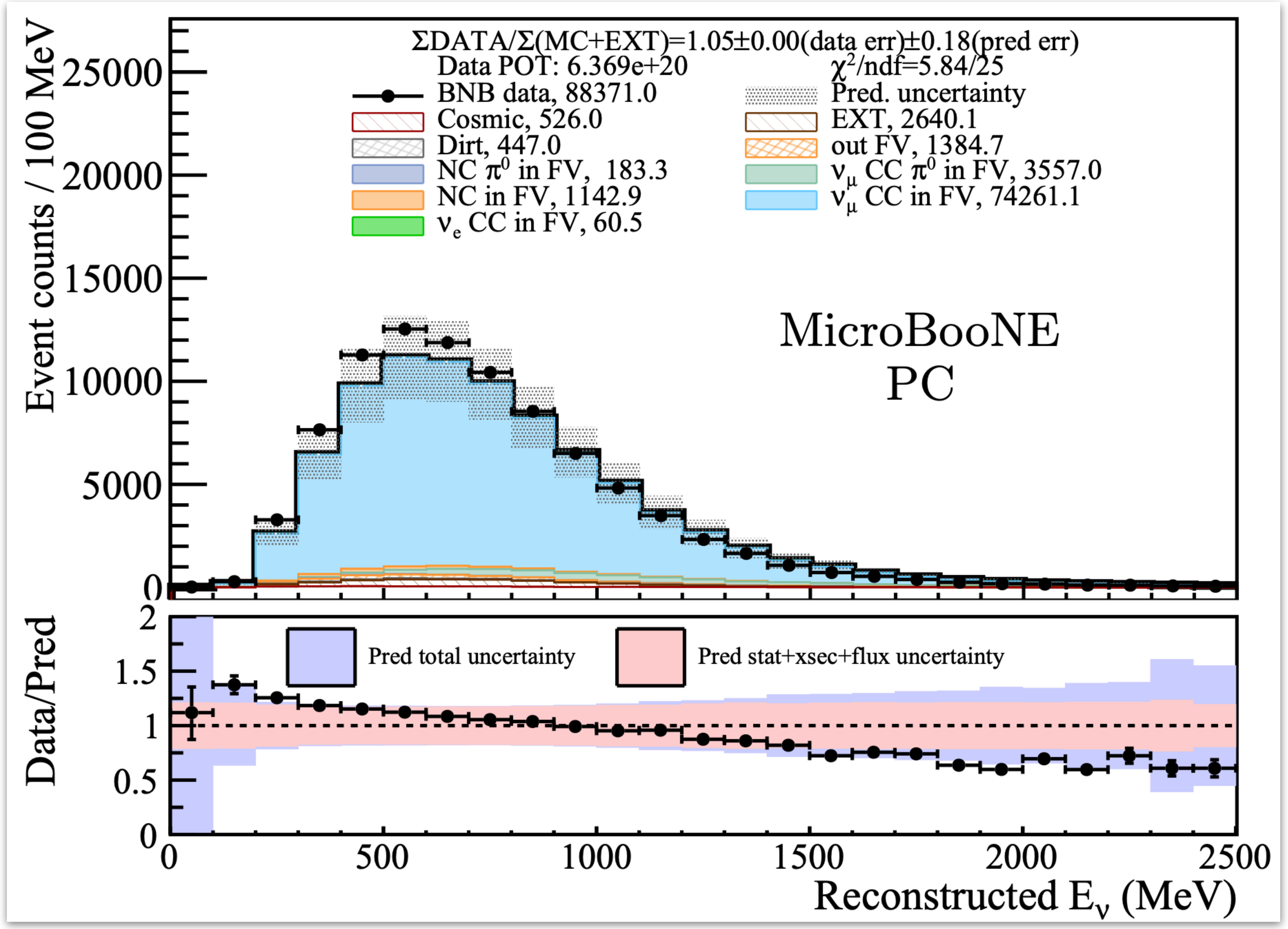

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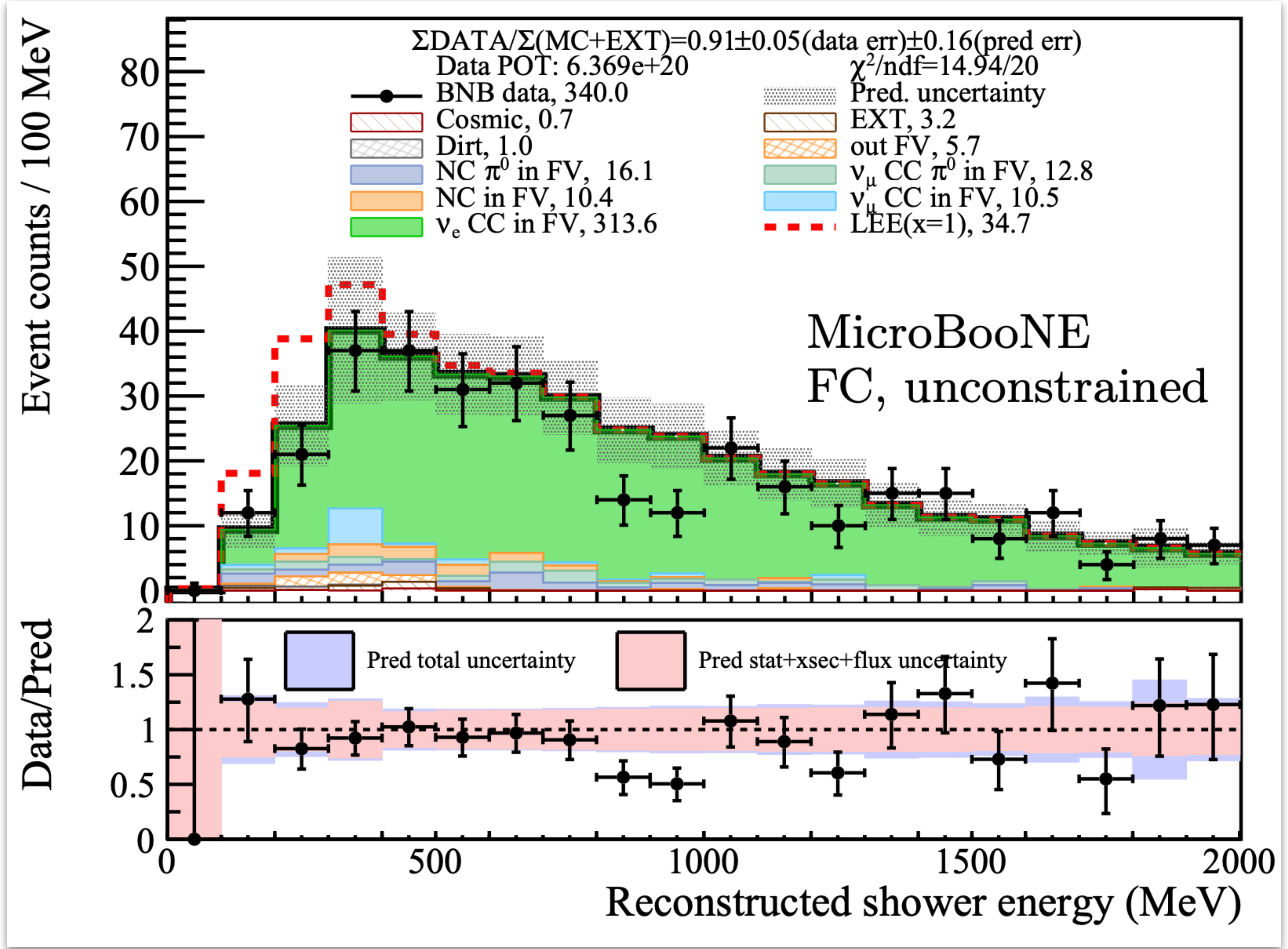
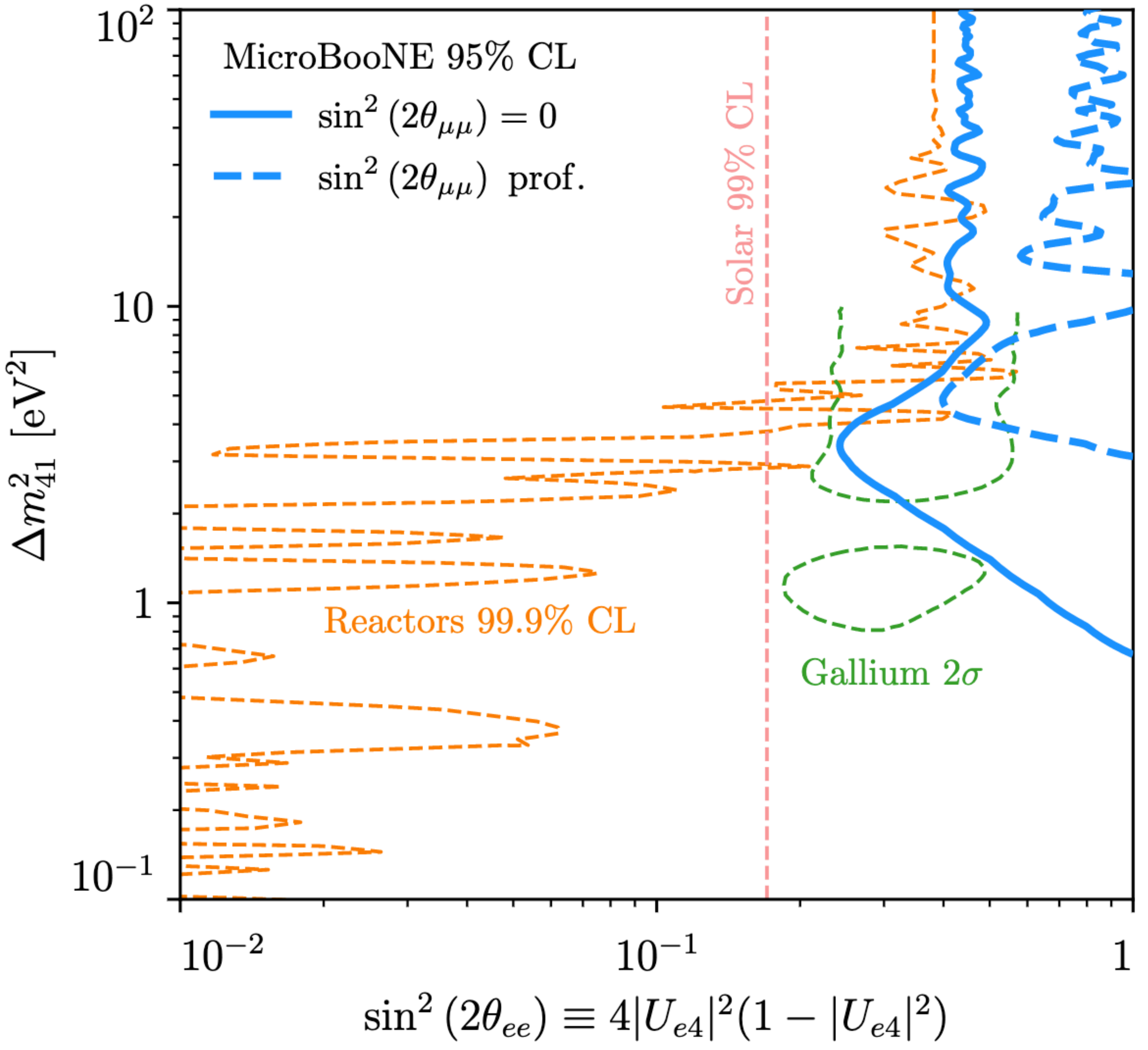
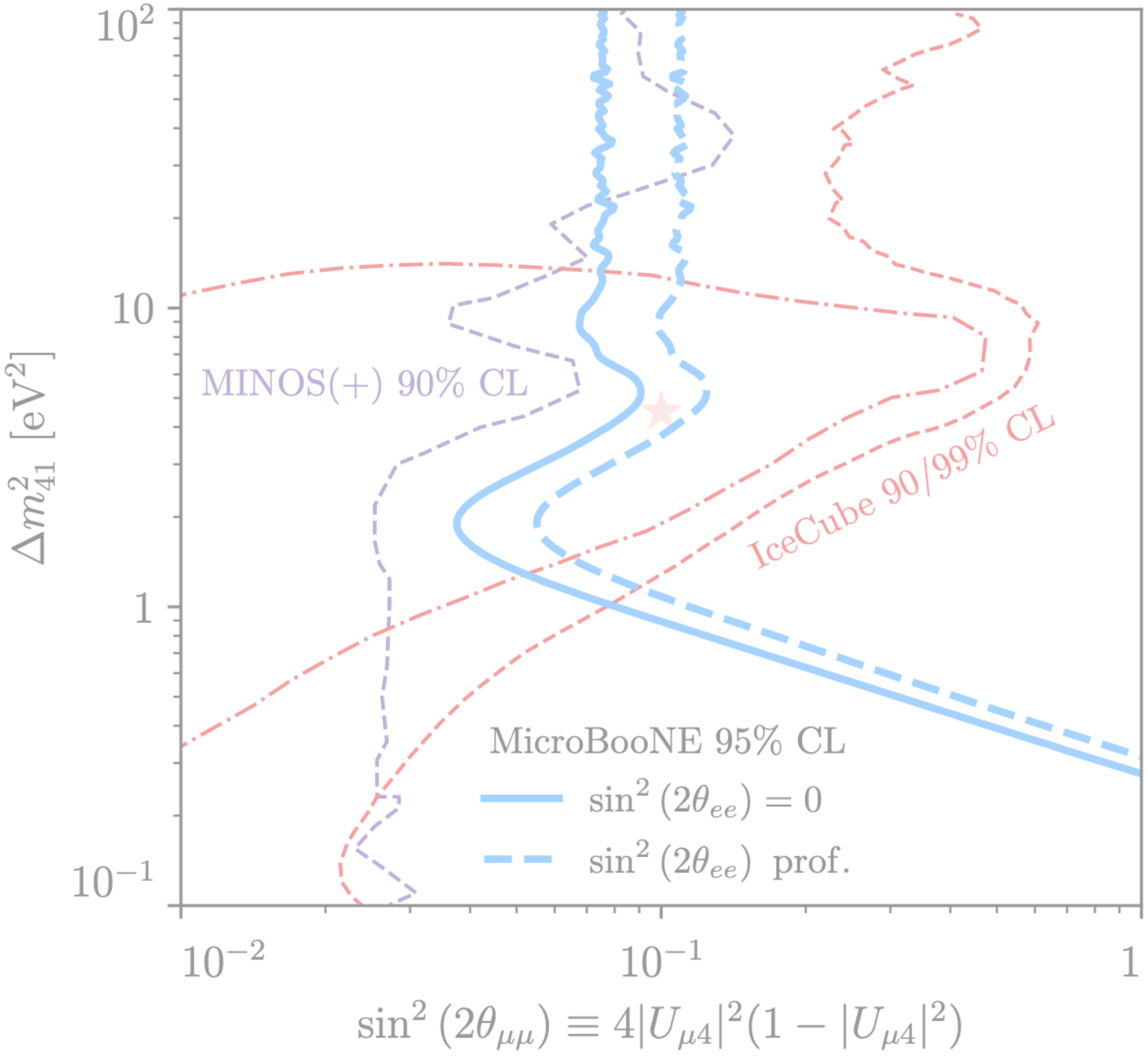


MicroBooNE, [2110.13978]

Four-Flavor Results

Argüelles et al, [2111.10359]





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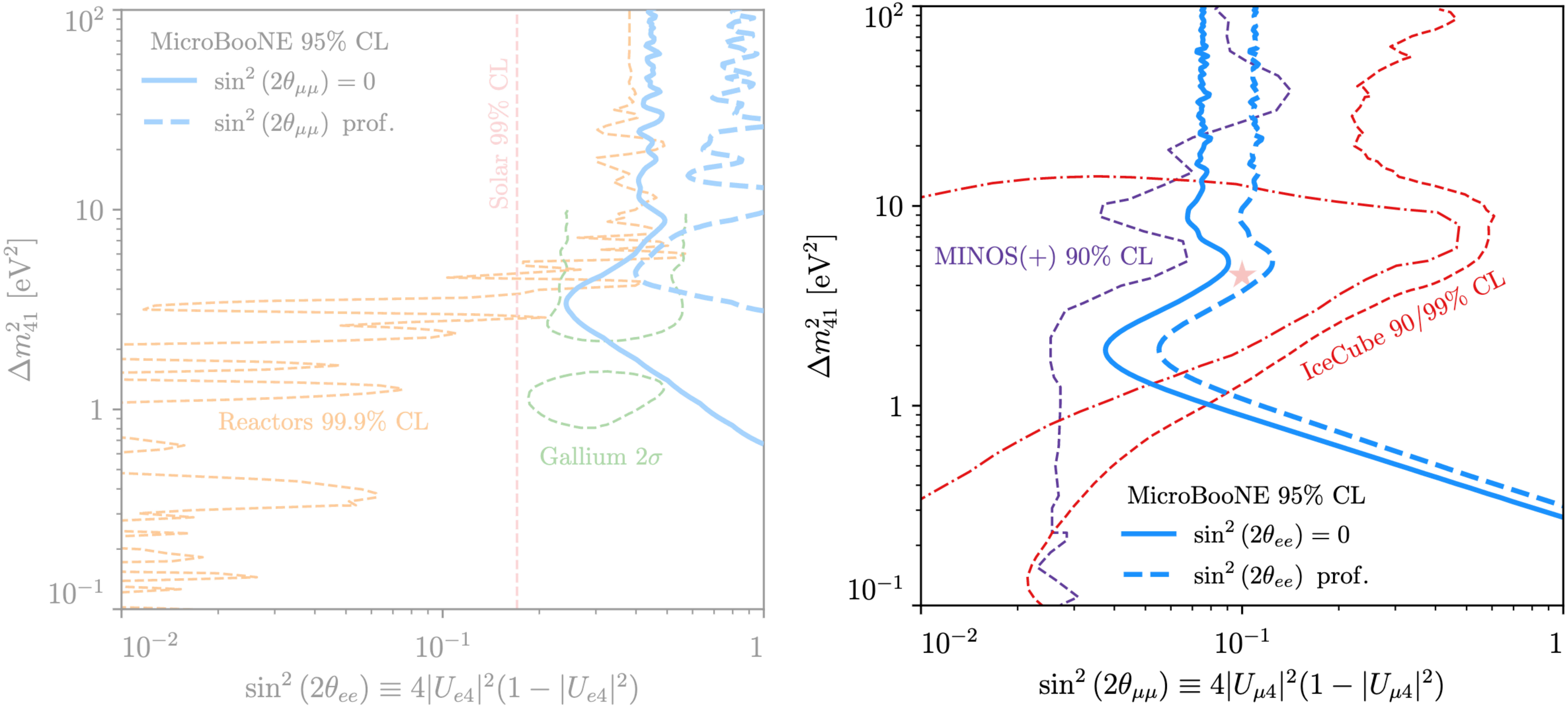
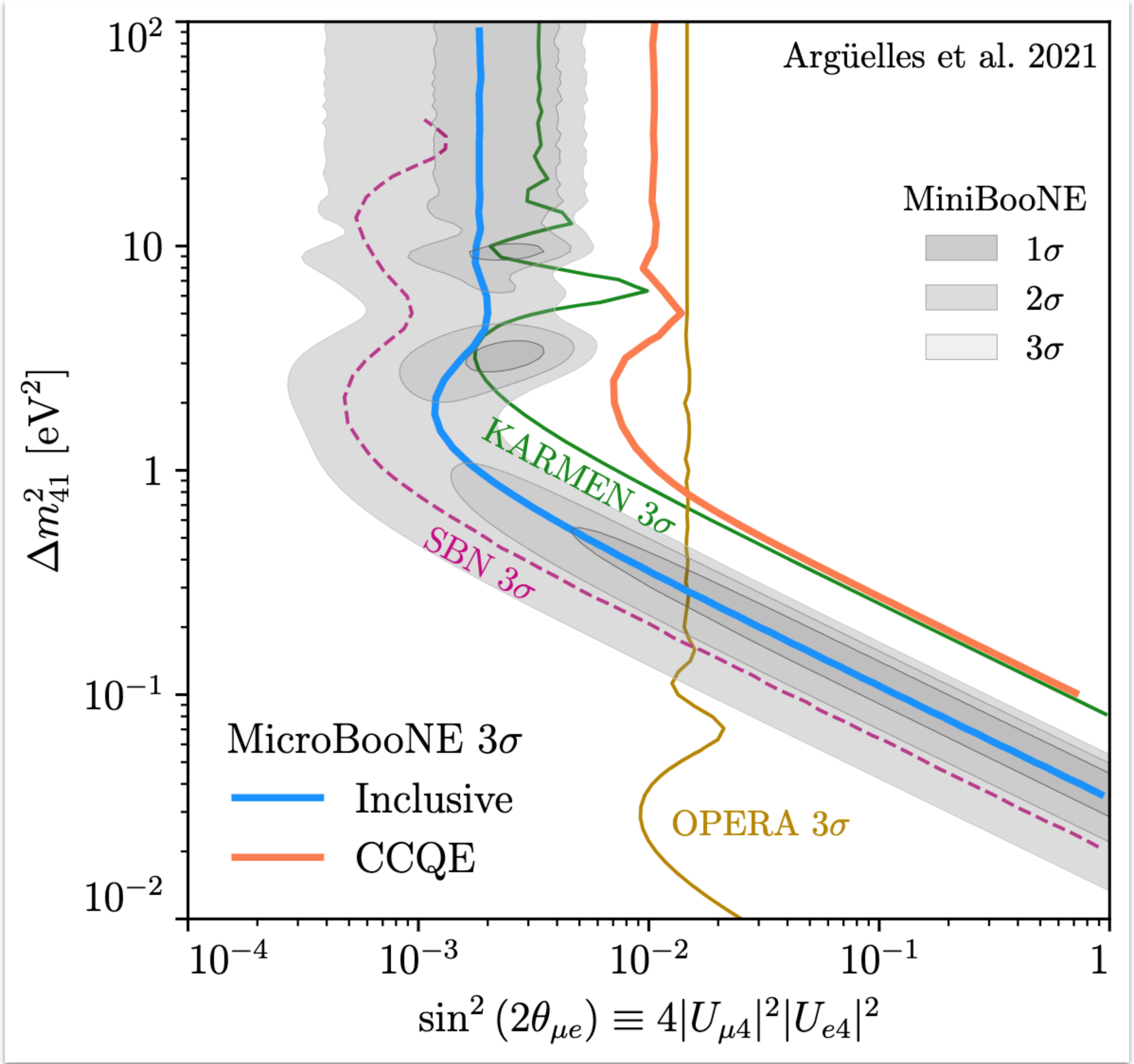


Four-Flavor, Appearance

[2111.10359]

Profiling over unseen mixing angle, how does sensitivity change?

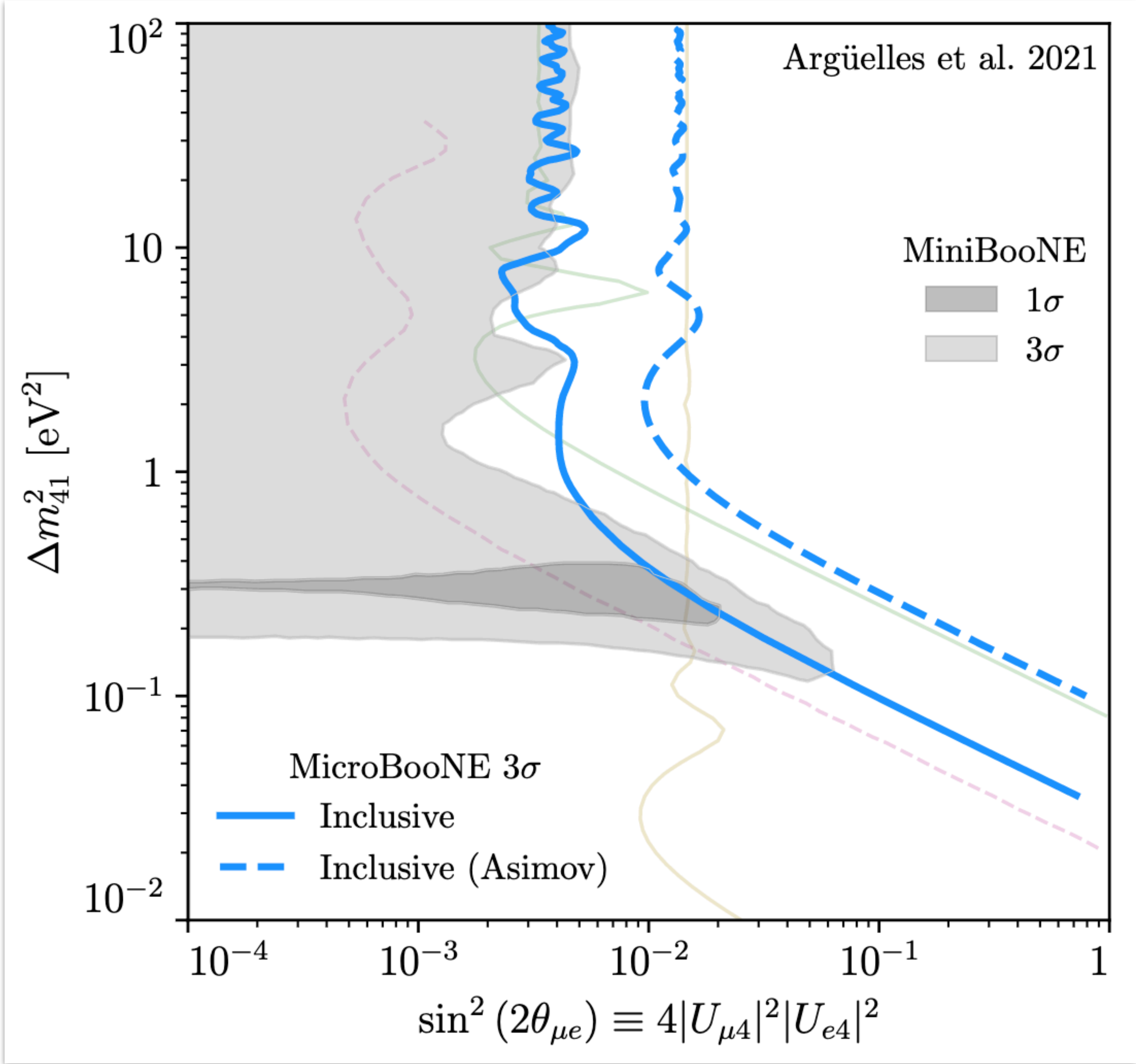


Four-Flavor, Appearance

[2111.10359]

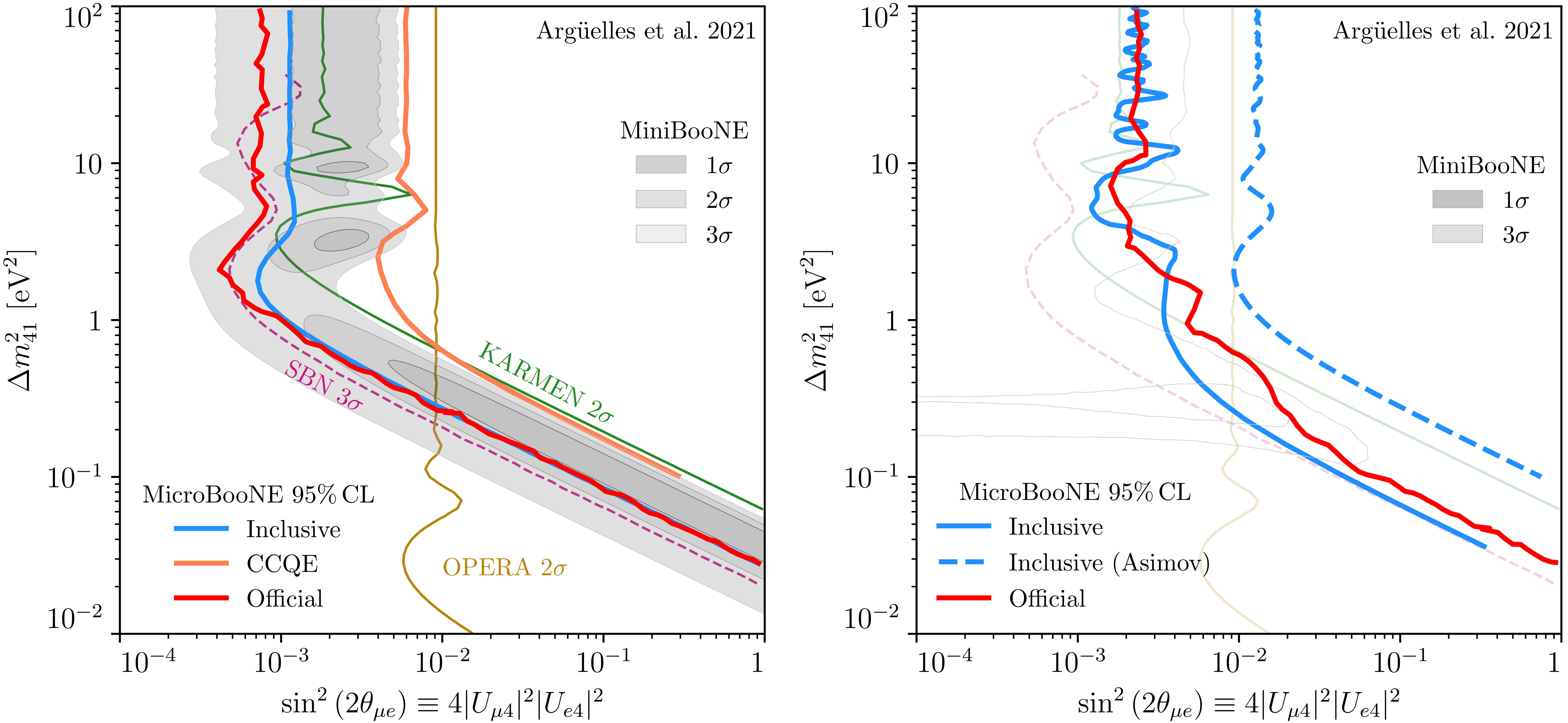
Profiling over unseen mixing angle, how does sensitivity change?

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



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

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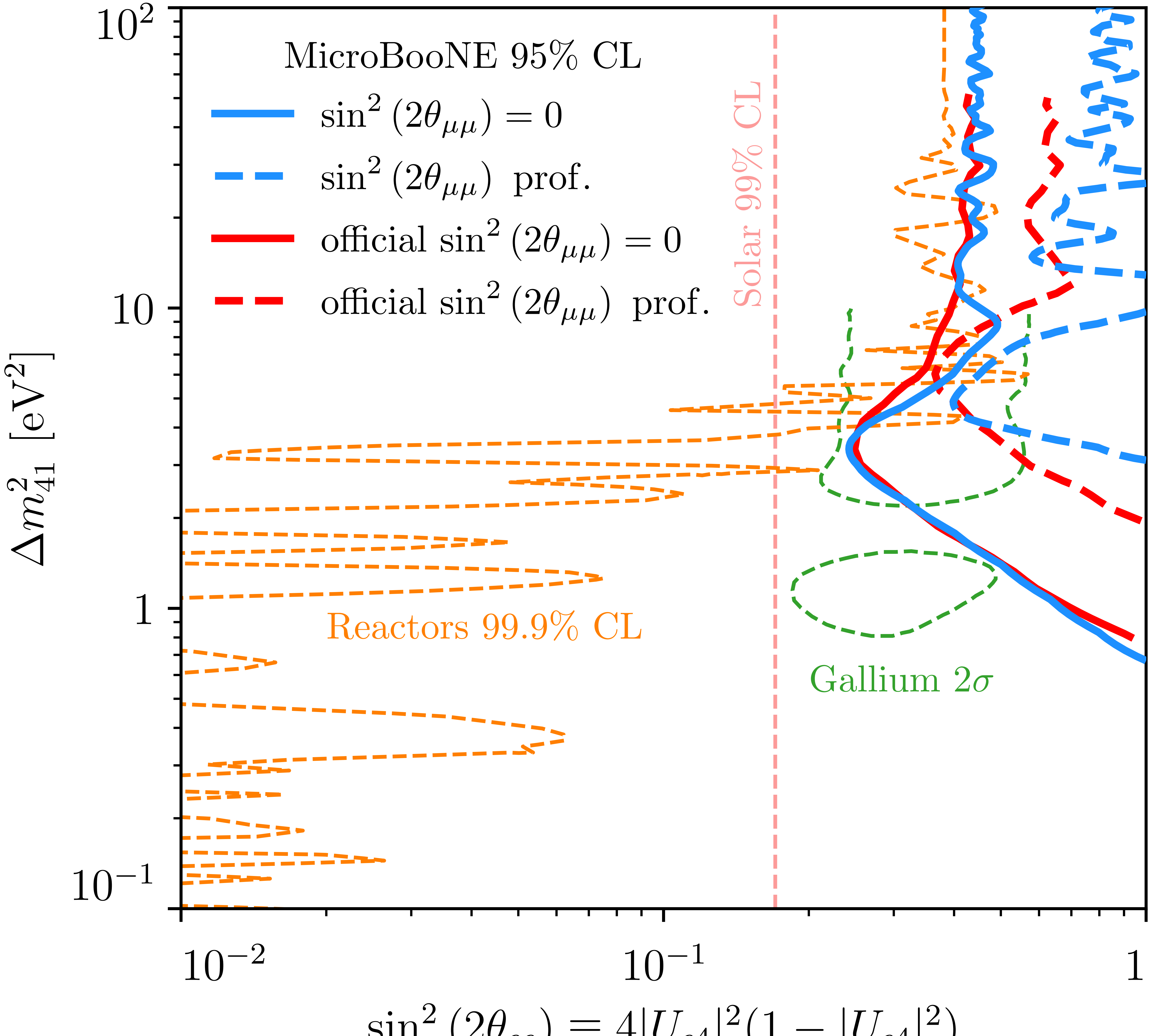
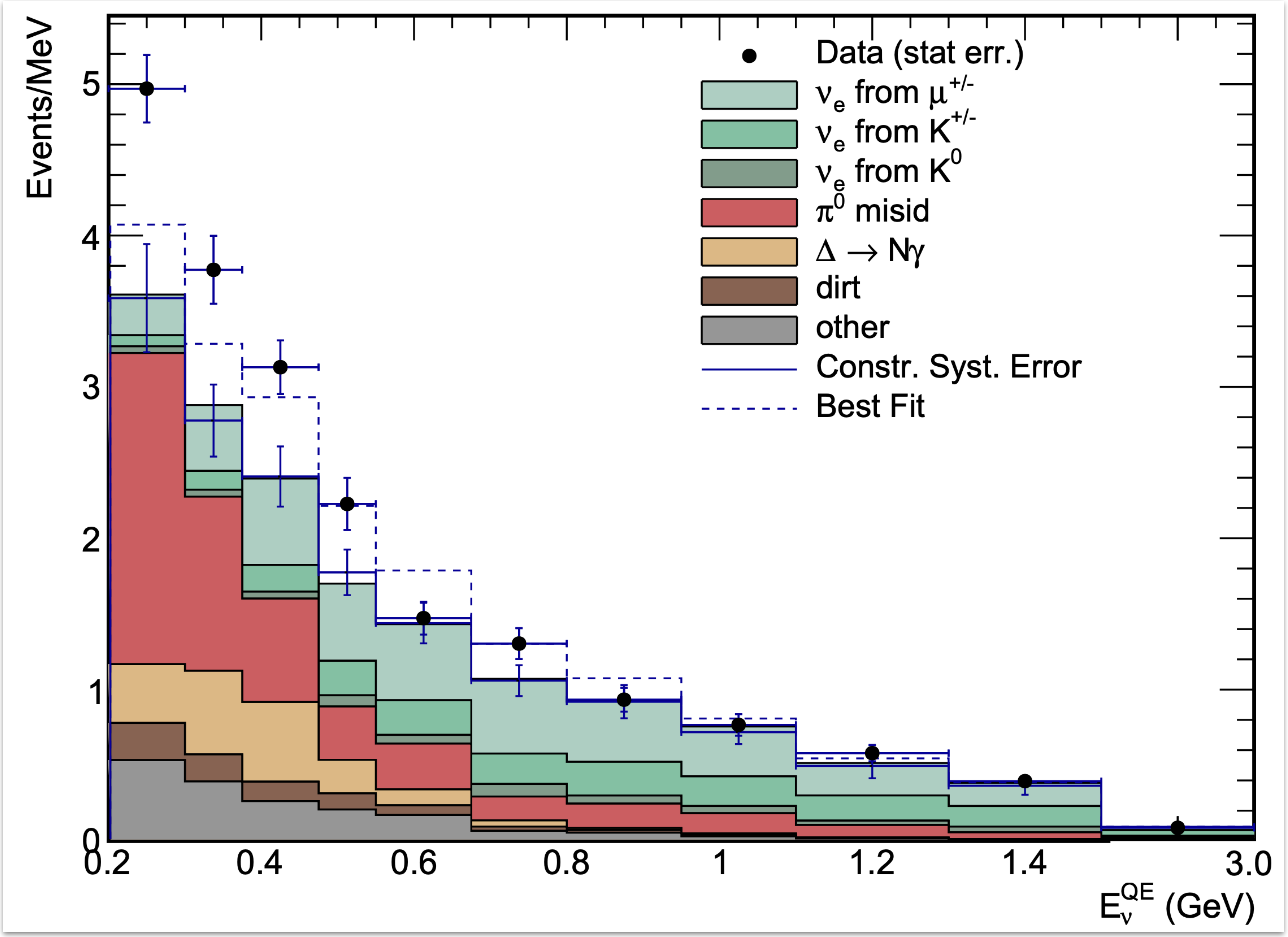


Beyond Sterile Neutrinos

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	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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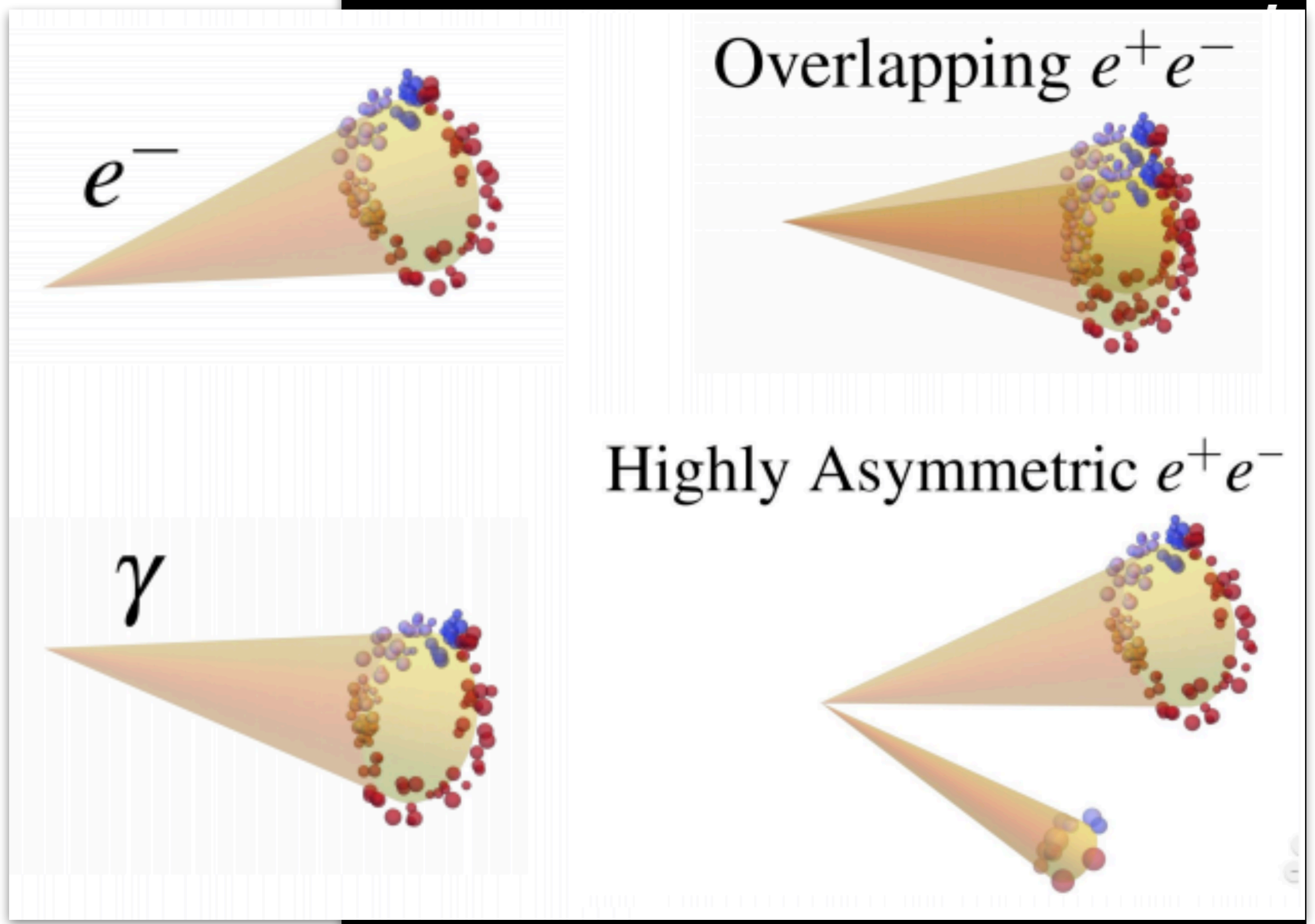

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Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	✓	✗	✗	✗	[174, 175, 274]
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Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[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]

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]
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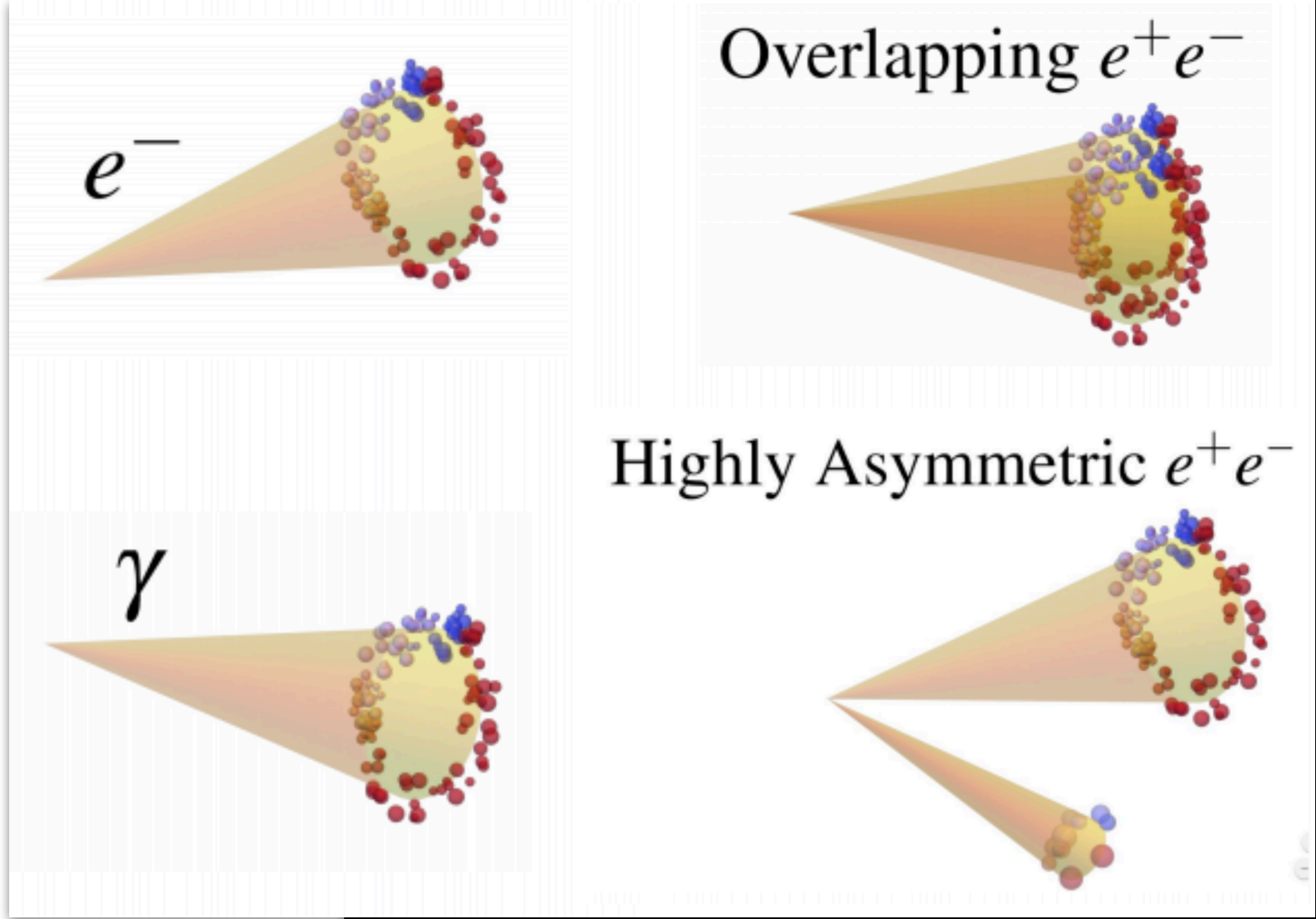
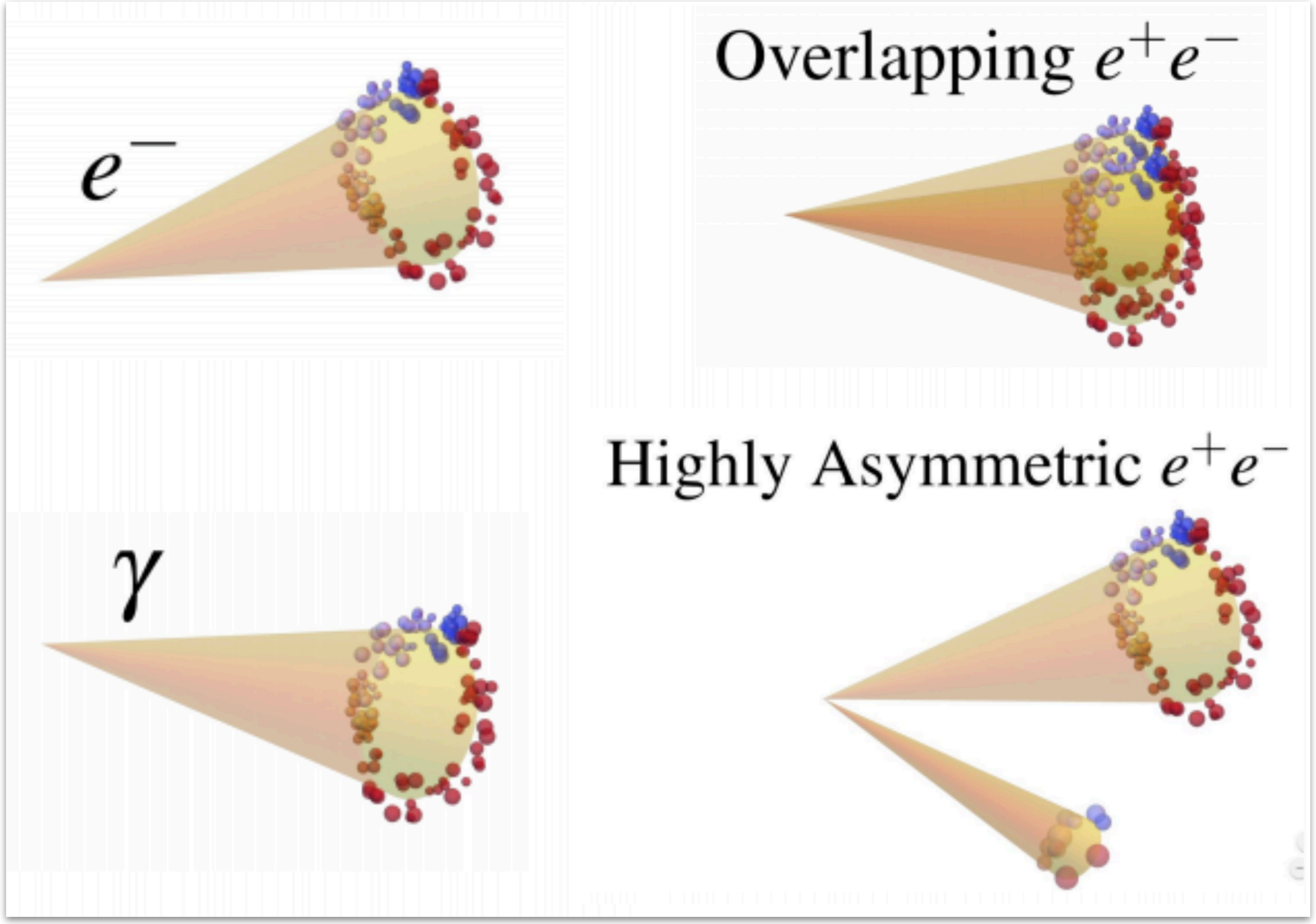


Lots of talks yesterday/today/tomorrow about a number of these BSM searches in a variety of detectors. Personally, I'm excited to see how these more exotic searches' analyses develop over time.

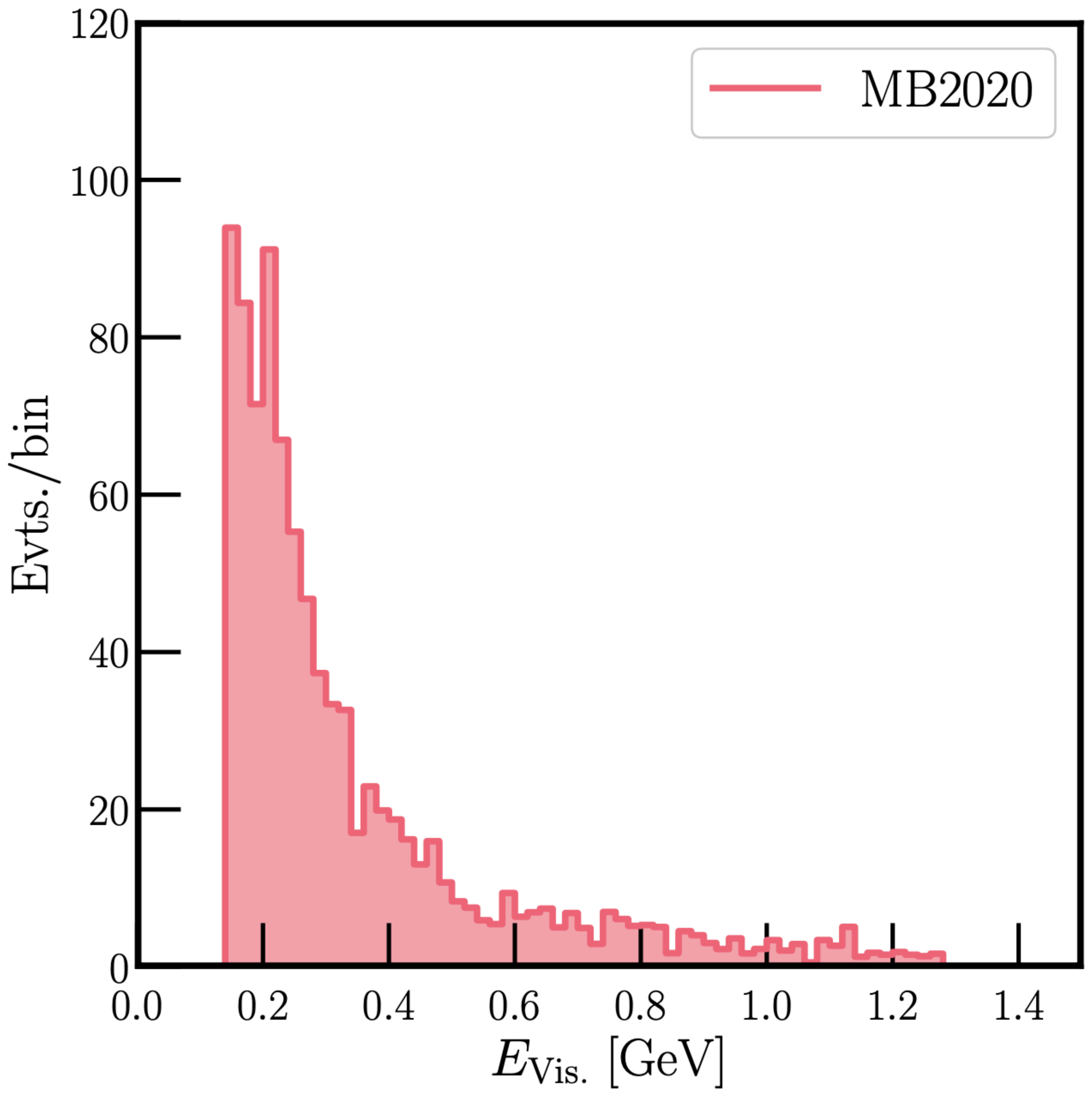
What about (Non-B)SM?



- Overlapping/asymmetric electron/positron pairs look like a single-electron shower in MiniBooNE, and do to overlapping/asymmetric photon pairs.
- Huge source of these? Neutral-current single-π^0 scattering in MiniBooNE. Particularly problematic for low-energy pion showers.

Looking at many MiniBooNE Backgrounds in a SM context: Brdar & Kopp, [2109.08157]

How does MiniBooNE treat NCπ^0 Events?



MiniBooNE likelihood-based background rate, courtesy of MB MC.

- Our goal: come up with a "phenomenological" set of cuts that yields the same distribution as quoted by MiniBooNE, depending on main kinematic quantities of the shower:
  - Opening angle of the two highest-energy photons in an event.
  - Asymmetry (maximum energy divided by total energy) in the shower.

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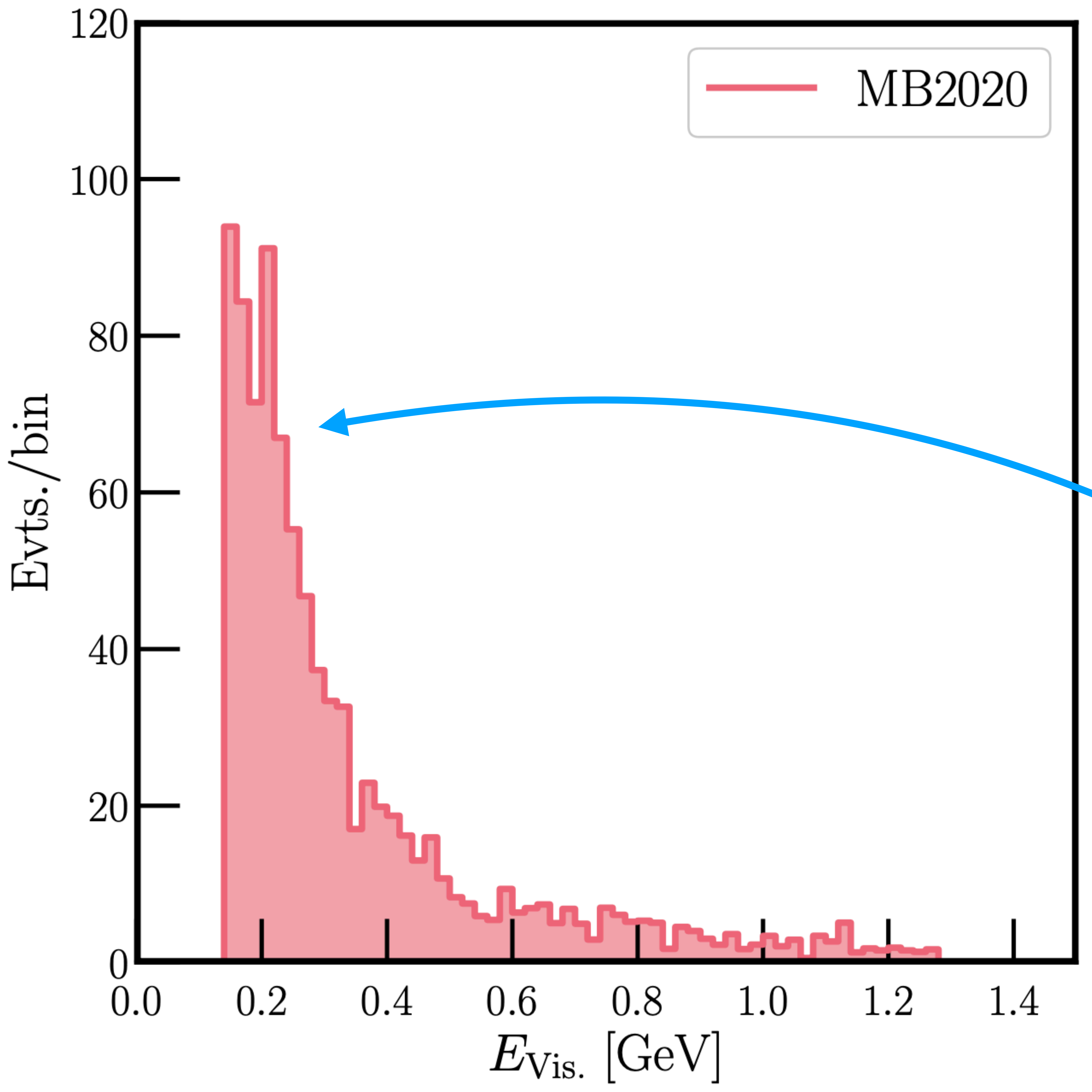

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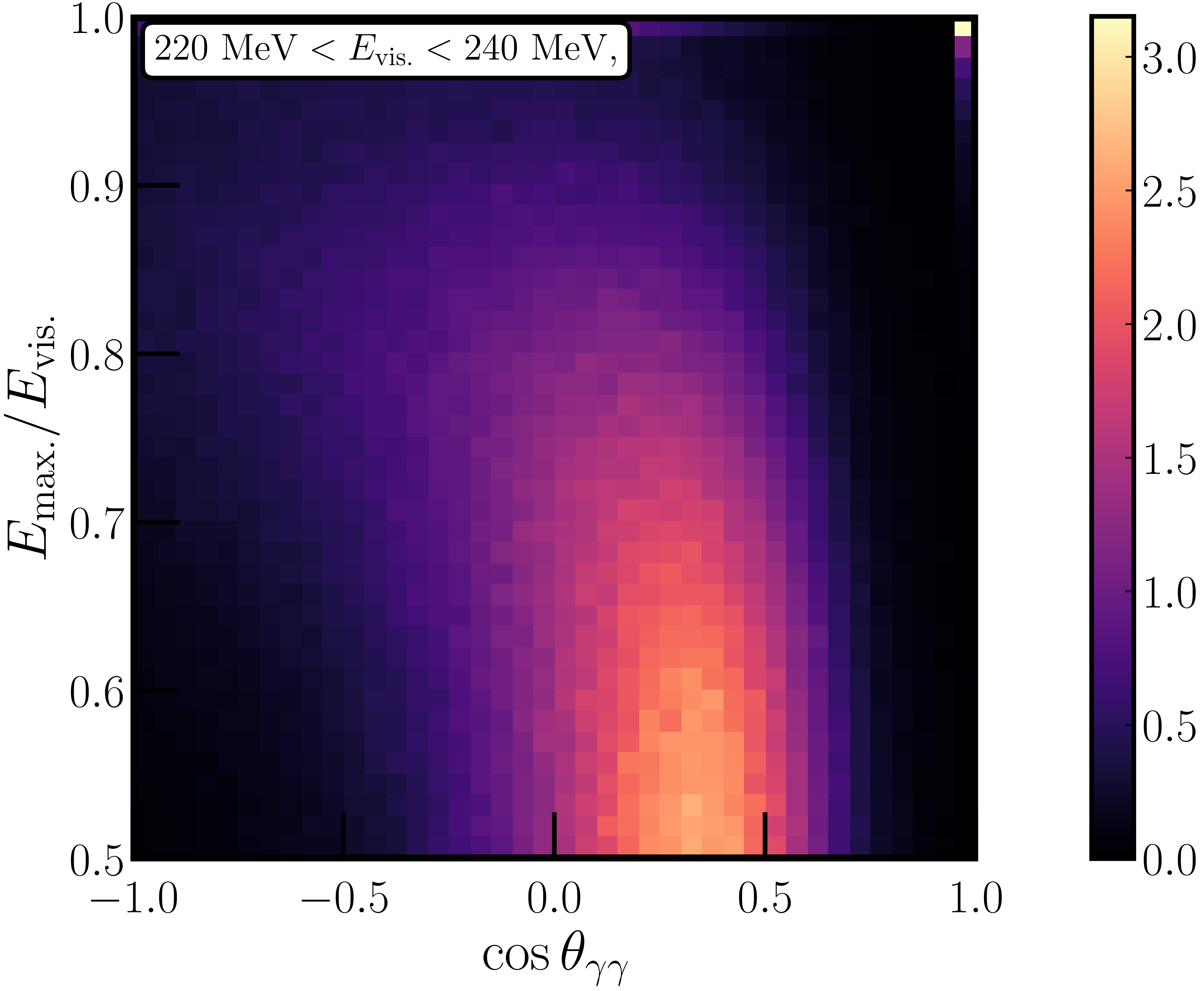
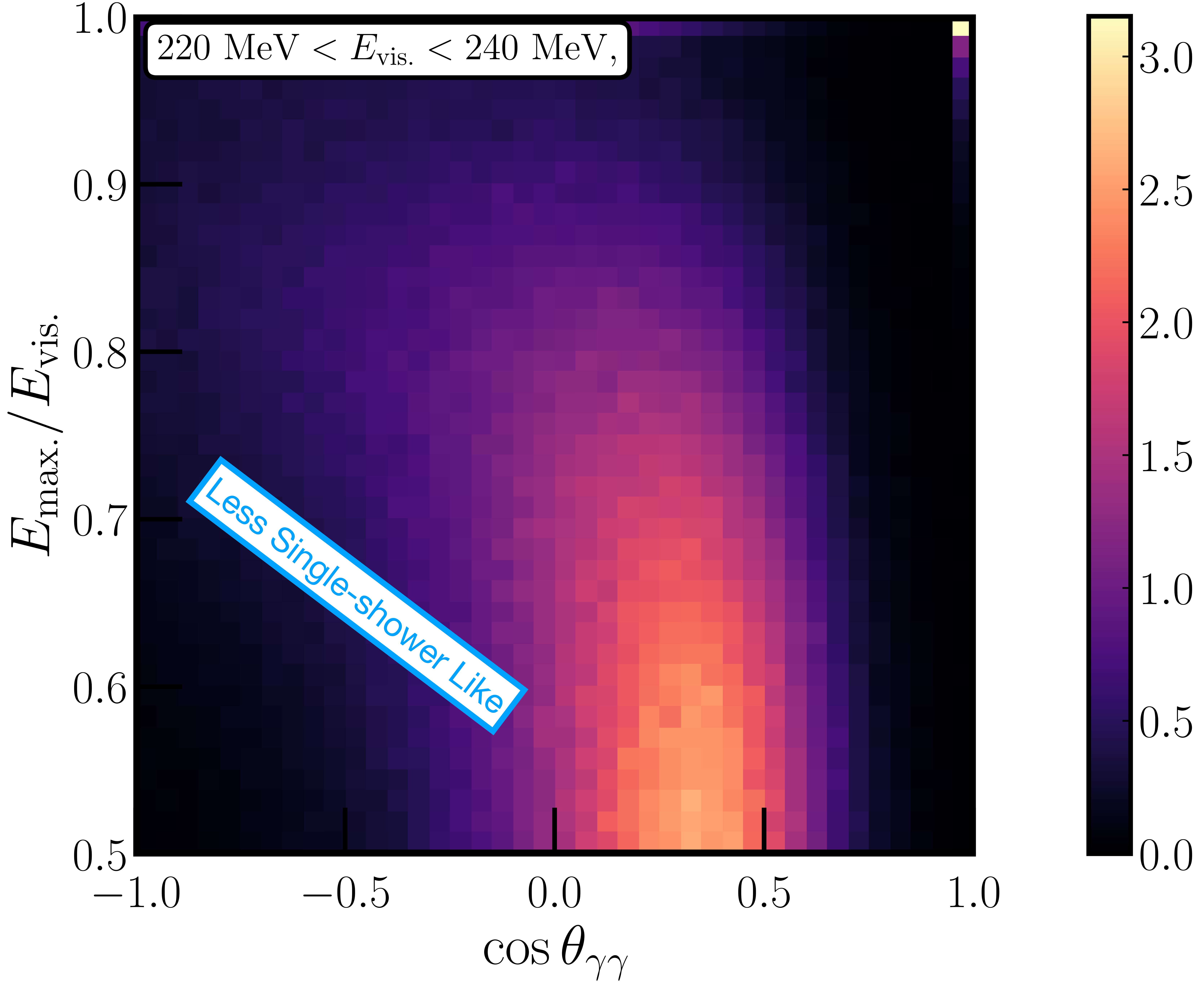
Let's pick one of these bins and look at *all* events from NUANCE in that energy range.



220 MeV < $E_{\mathrm{vis.}}$ < 240 MeV,
$E_{\mathrm{max.}}/E_{\mathrm{vis.}}$
1.0
0.9
0.8
0.7
0.6
0.5
−1.0
−0.5
0.0
0.5
1.0
$\cos\theta_{\gamma\gamma}$
3.0
2.5
2.0
1.5
1.0
0.5
0.0



220 MeV < $E_{\text{vis.}}$ < 240 MeV,
Less Single-shower Like
$E_{\text{max.}}/E_{\text{vis.}}$
$\cos\theta_{\gamma\gamma}$
1.0
0.9
0.8
0.7
0.6
0.5
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3.0
2.5
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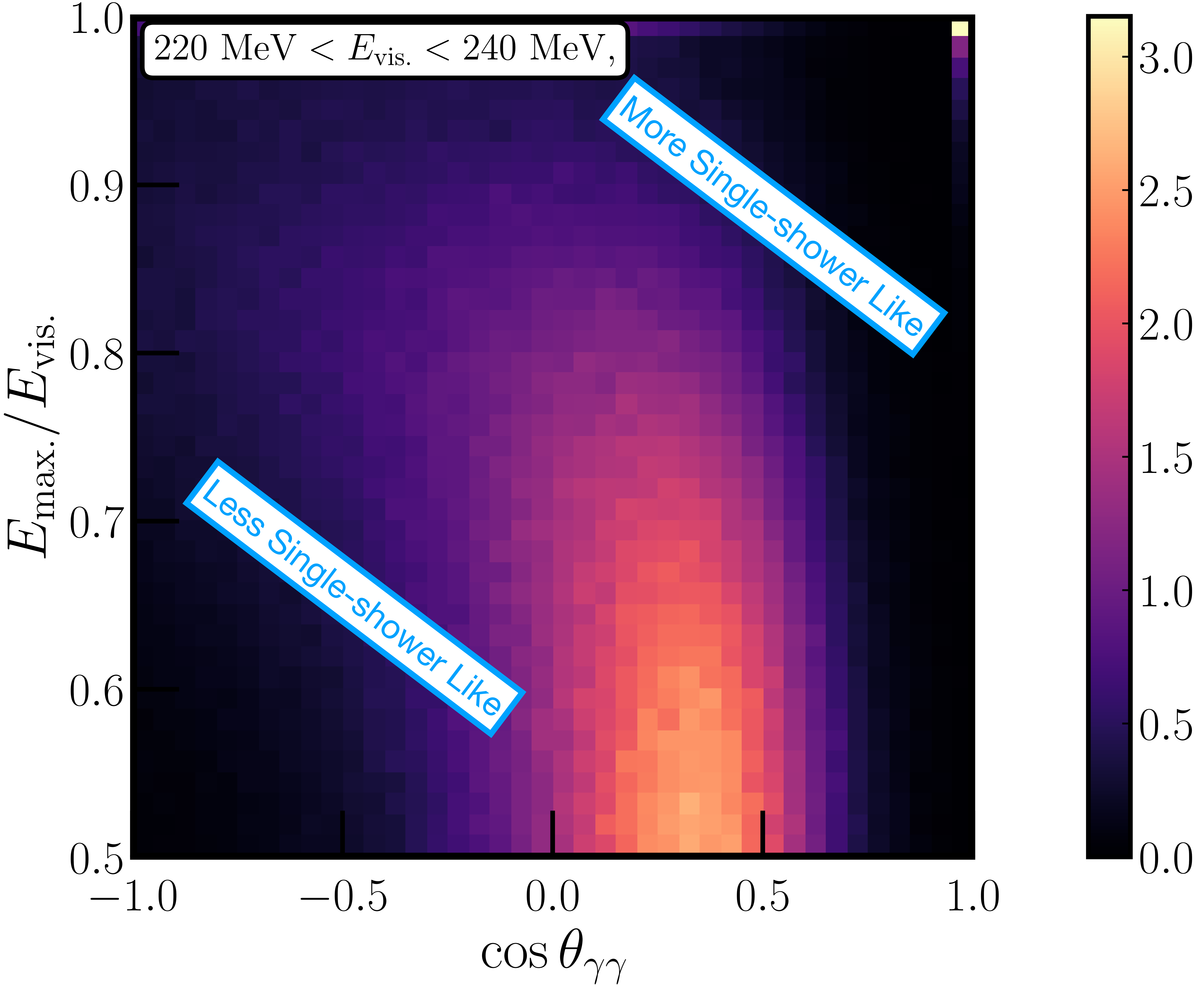

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1.5
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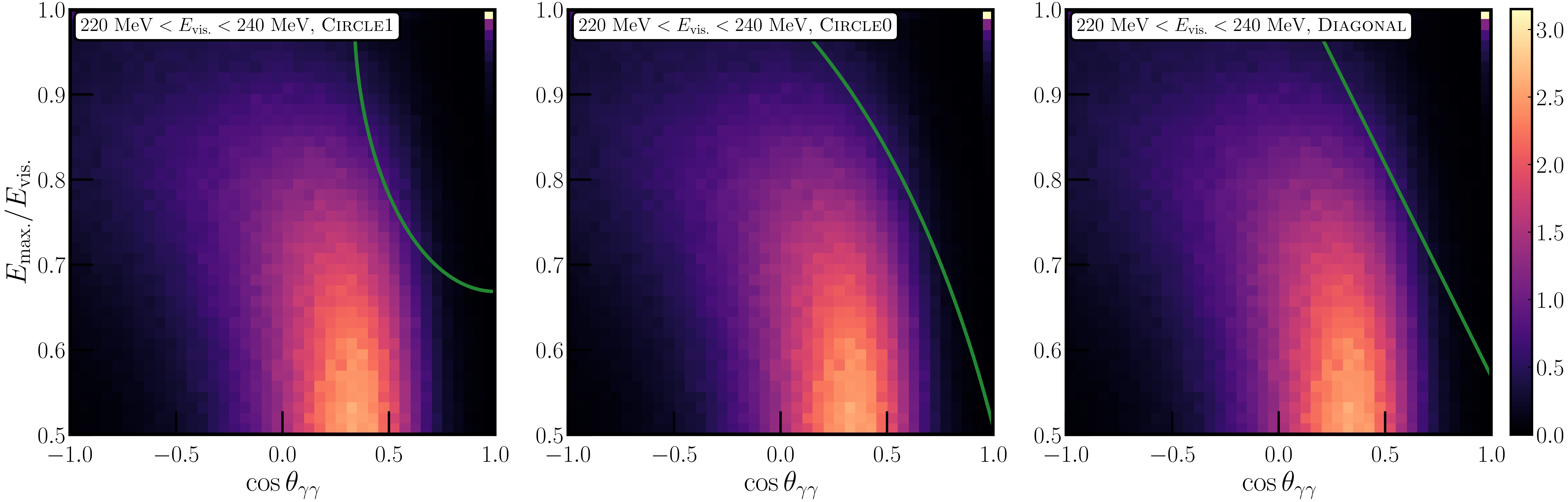
Opening Angle/Asymmetry Distributions

Three different cut prescriptions, each as a function of visible energy — These will (by definition) get us accepted distributions that match MiniBooNE's with respect to $E_{\rm vis.}$



Kelly, Kopp [2210.08021]

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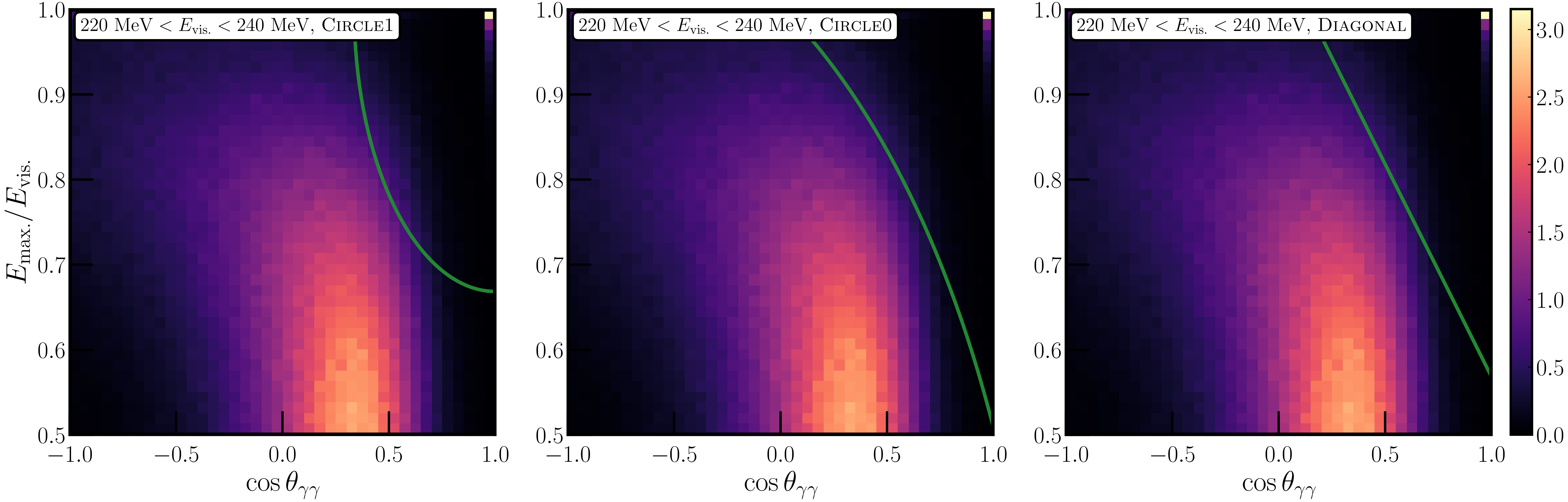
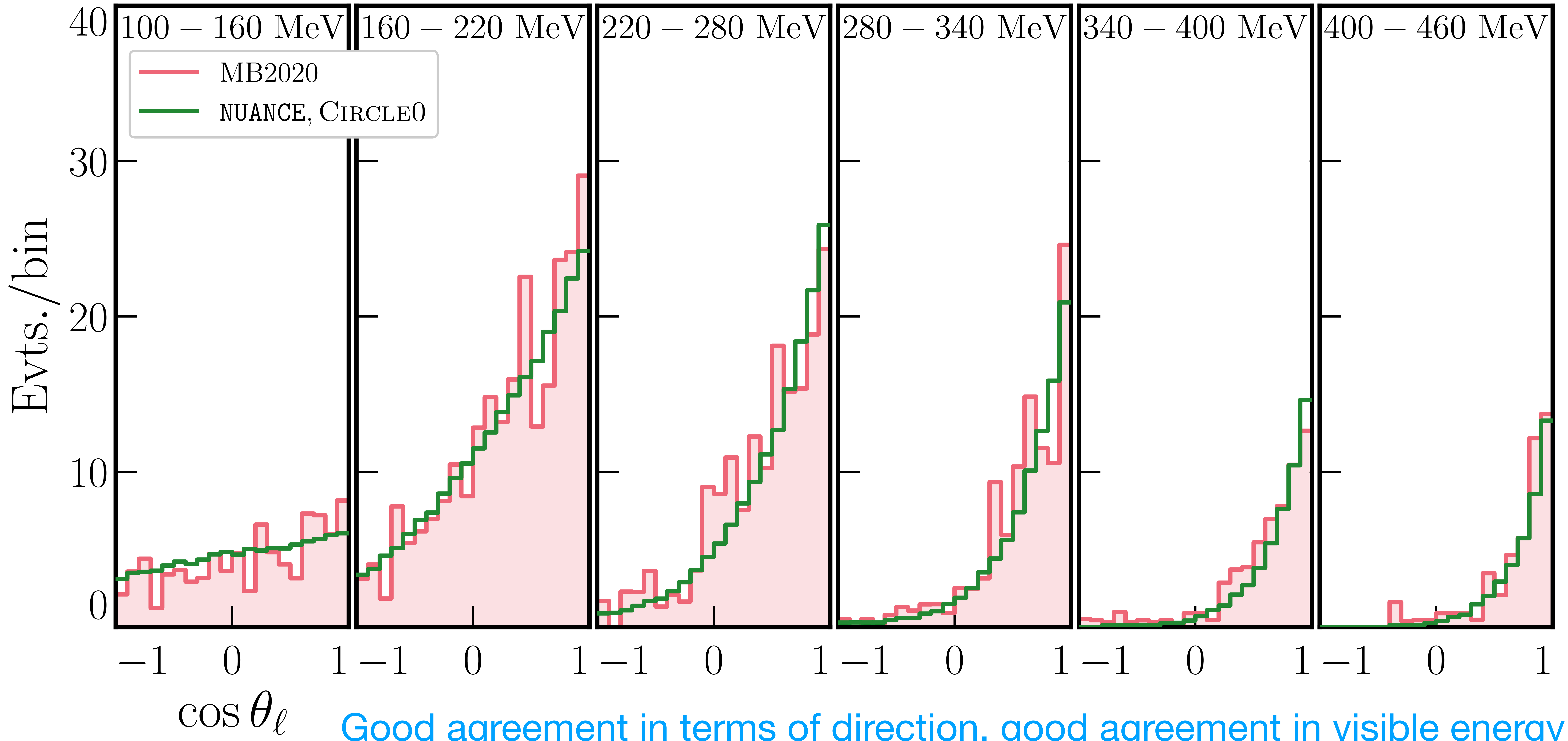


How do our post-cut distributions compare to theirs with respect to other observables?

Kelly, Kopp [2210.08021]

Our Results

Kelly, Kopp [2210.08021]



Good agreement in terms of direction, good agreement in visible energy (by construction) — leads to good agreement as a function of $E_\nu^{\rm QE}$

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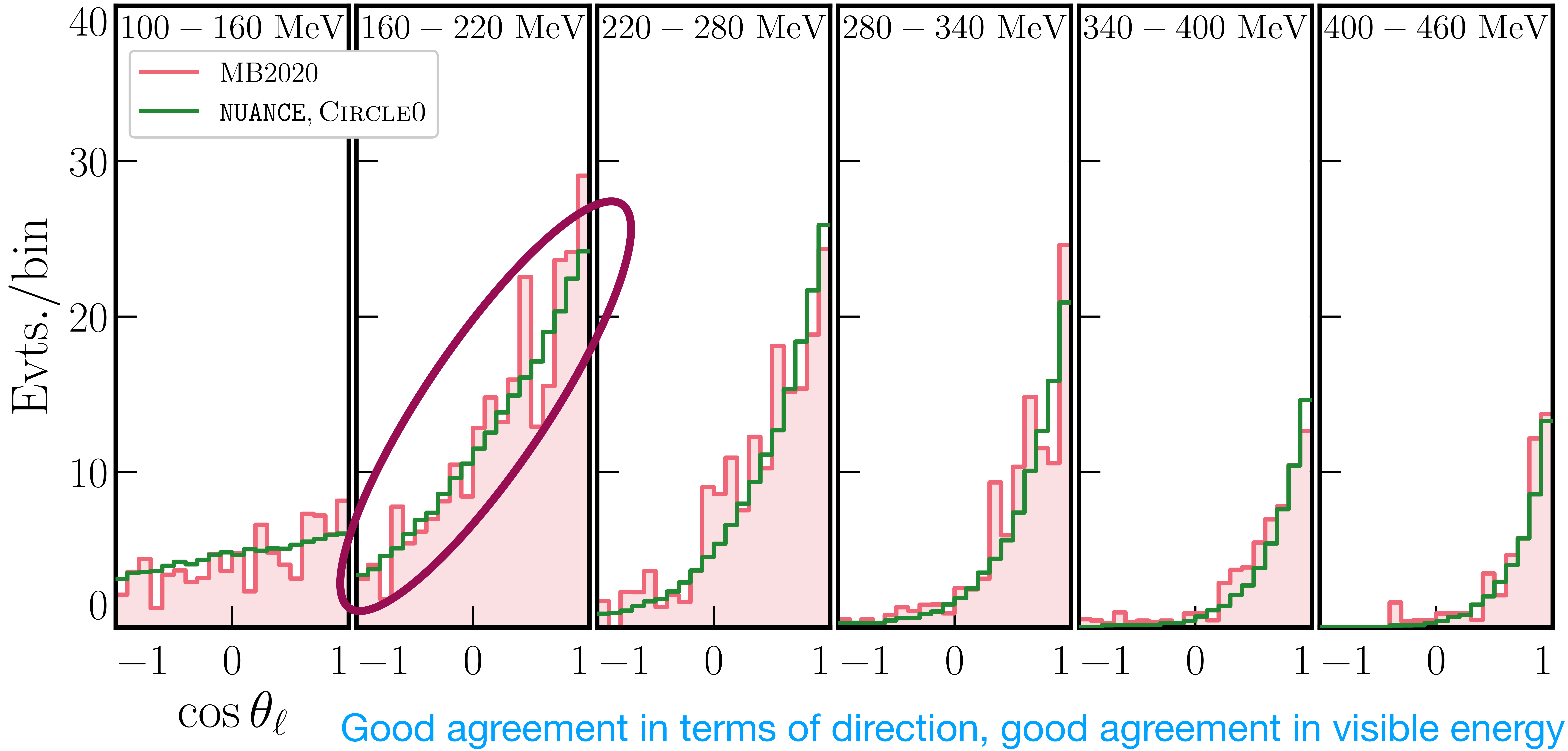
Kelly, Kopp [2210.08021]



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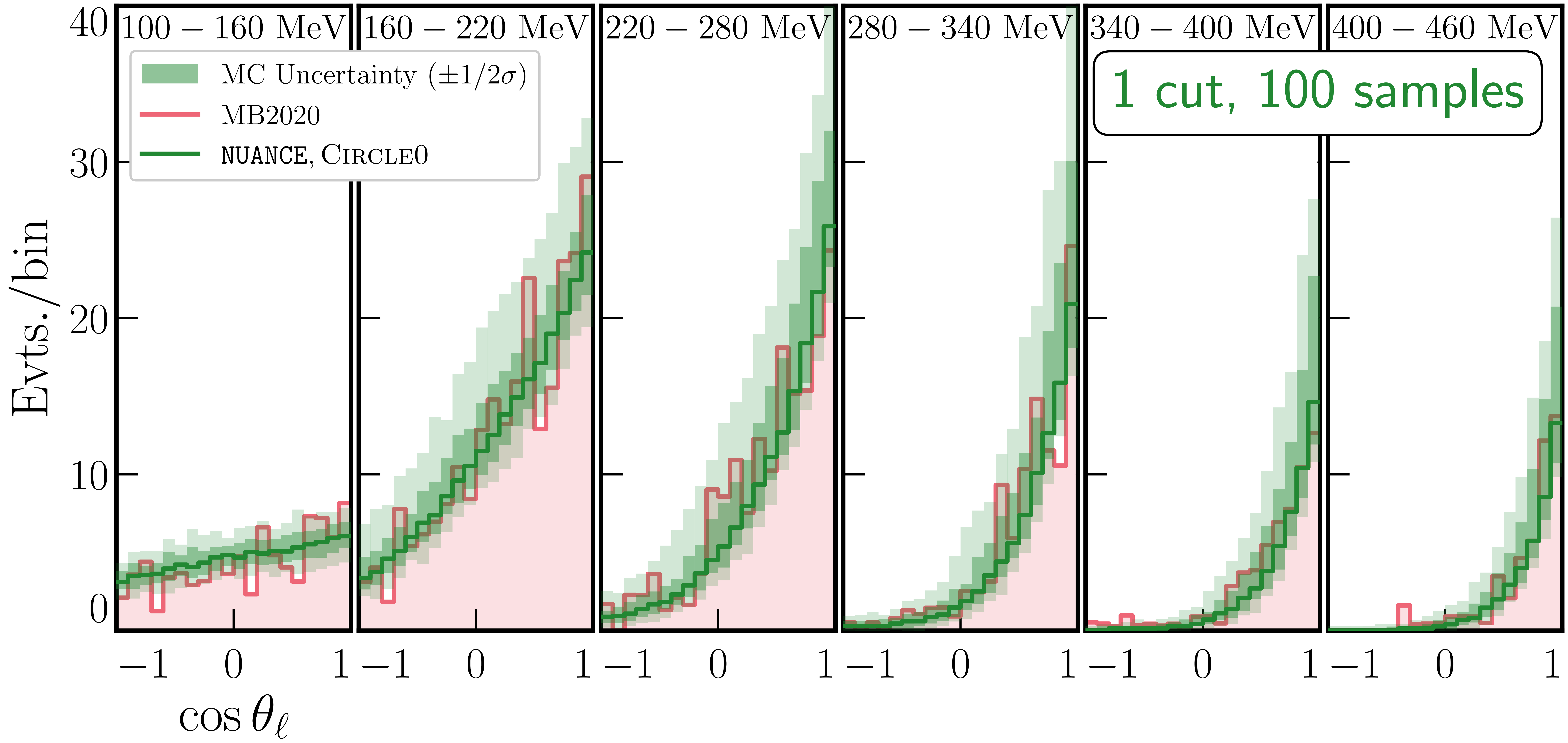

Comparable bin-to-bin jitter when we analyze our MC in smaller sub-samples, each with comparable statistics to MB's analysis.

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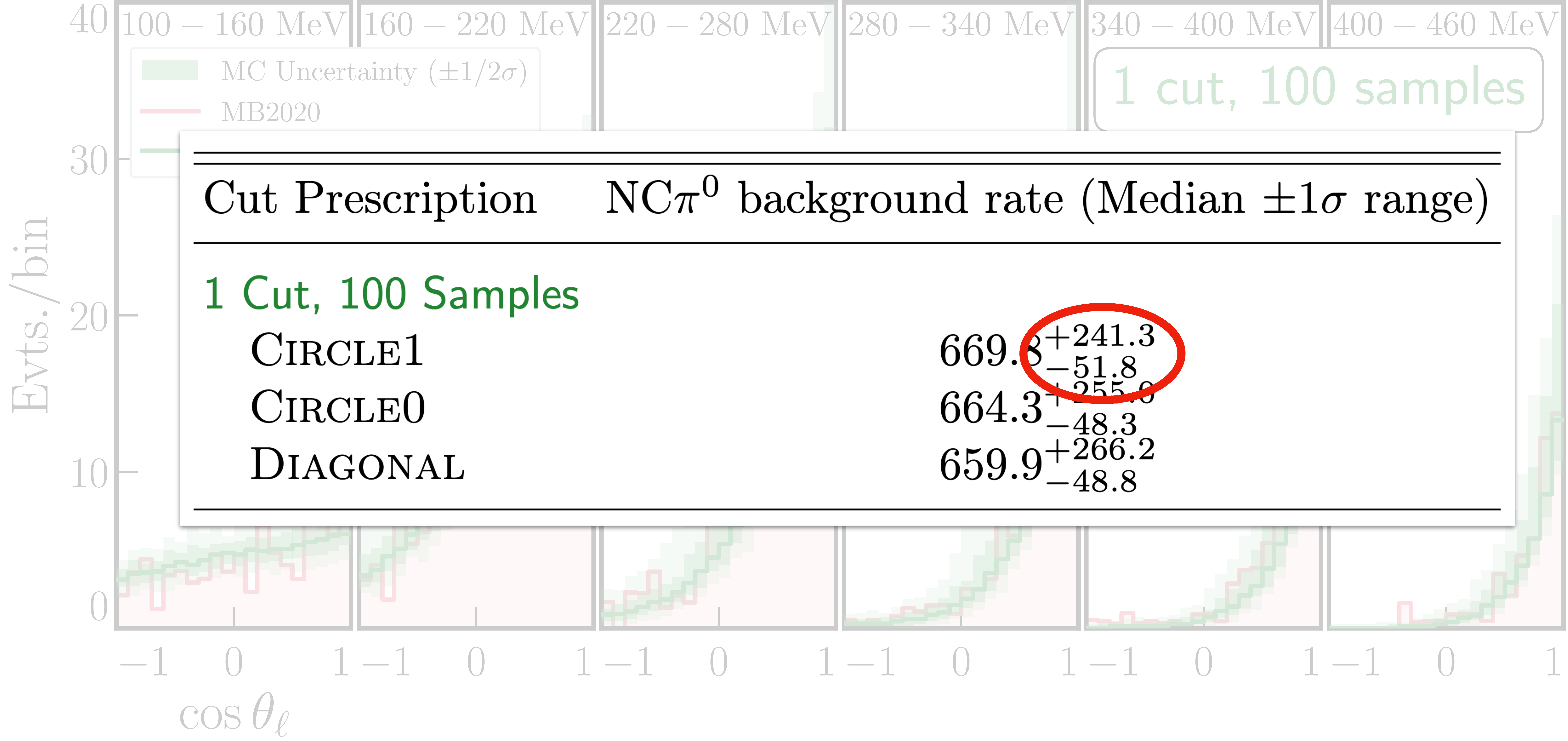


Cut Prescription	$NC\pi^0$ background rate (Median $\pm 1\sigma$ range)
1 Cut, 100 Samples	
Circle1	$669.8^{+241.3}_{-51.8}$
Circle0	$664.3^{+255.0}_{-48.3}$
Diagonal	$659.9^{+266.2}_{-48.8}$

Comparable bin-to-bin jitter when we analyze our MC in smaller sub-samples, each with comparable statistics to MB's analysis.

Determining cuts based on MC Subsamples

Green: Cuts derived based on our long, 100x NUANCE Sample

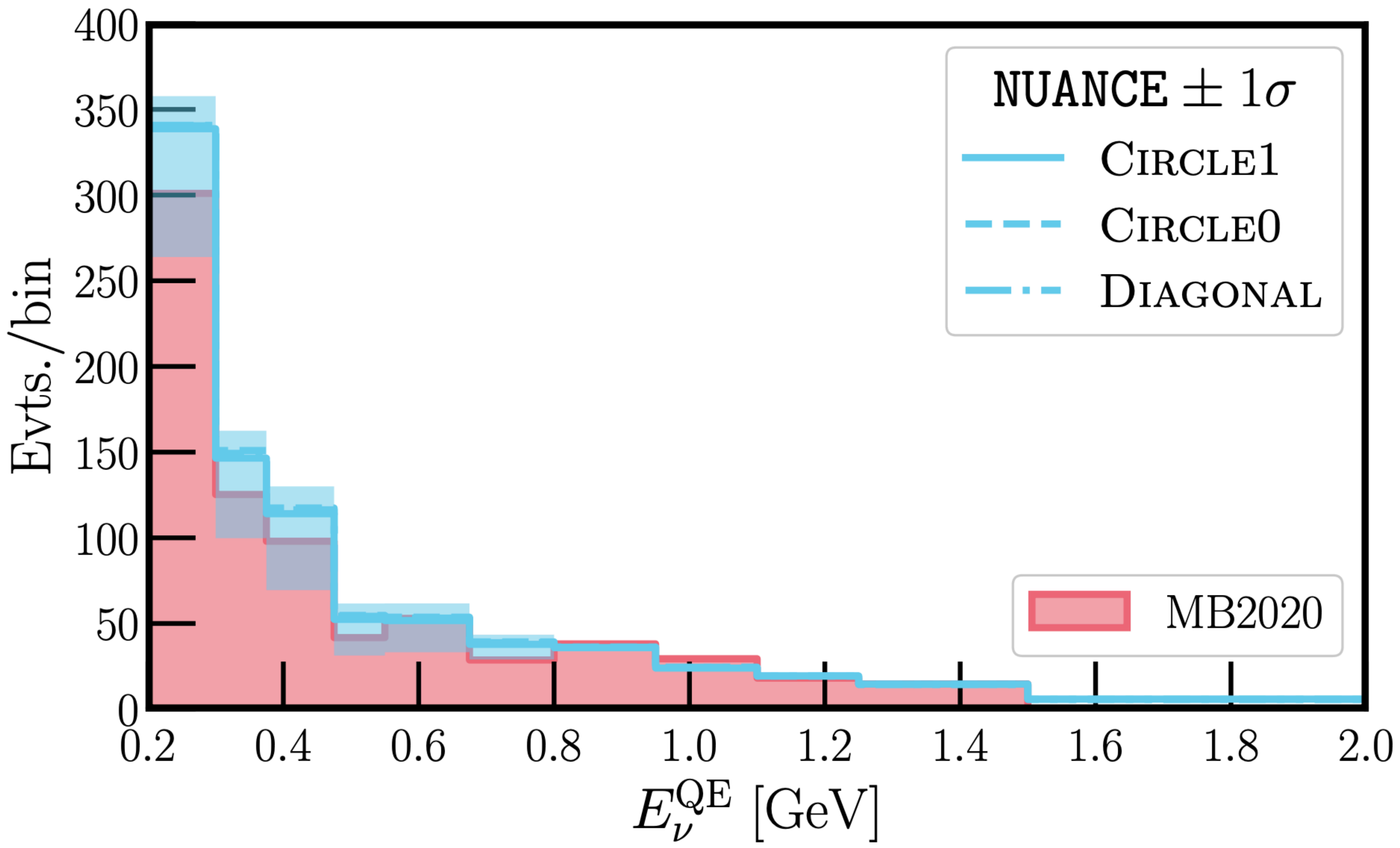
Determining cuts based on MC Subsamples

Green: Cuts derived based on our long, 100x NUANCE Sample

Blue: Different cuts, each derived based on a MiniBooNE-sized MC Sample

Correcting for this Effect?

Kelly, Kopp [2210.08021]

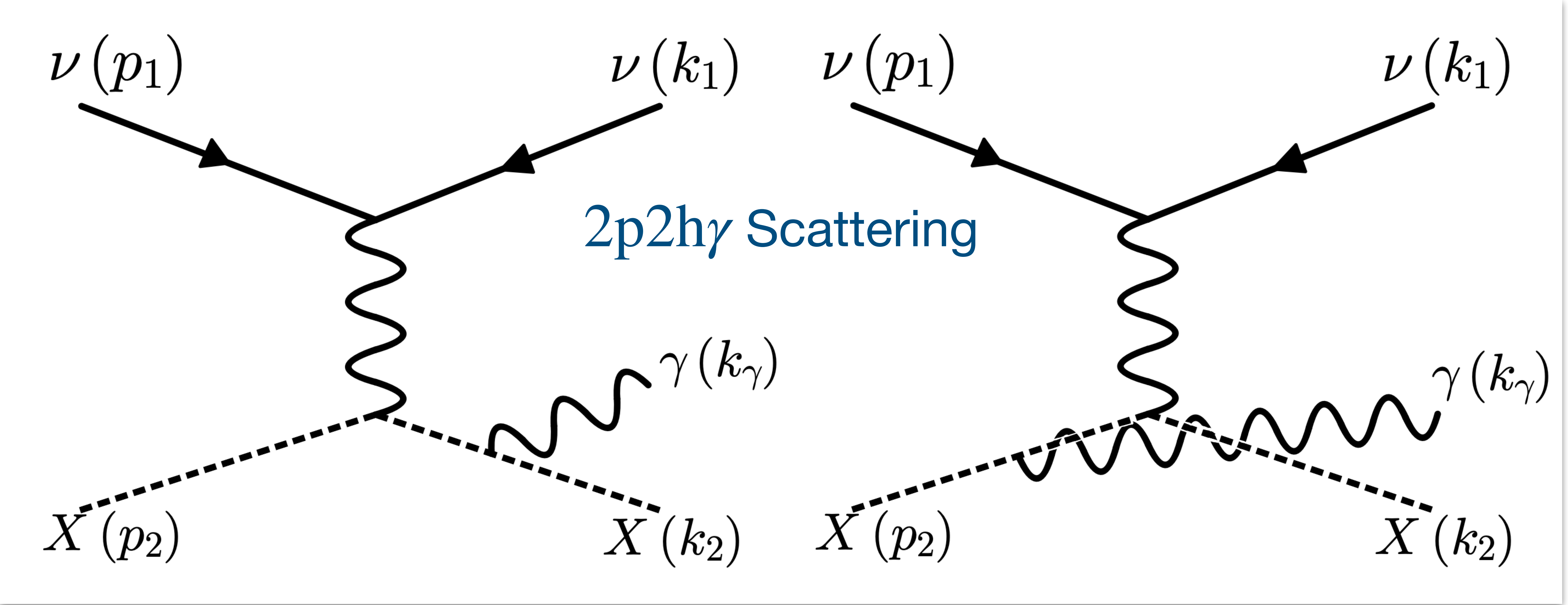


We've tried our approaches of correcting for this effect, asking "if MiniBooNE considered 100x larger MC statistics, what would their NCπ^0 background estimate be?"

Overall, we estimate that this effect could yield ~100 additional background events to MiniBooNE's LEE search, reducing the excess's significance by ~1σ.

Other Single/Double Photon Effects?

Kelly, Kopp [2210.08021]



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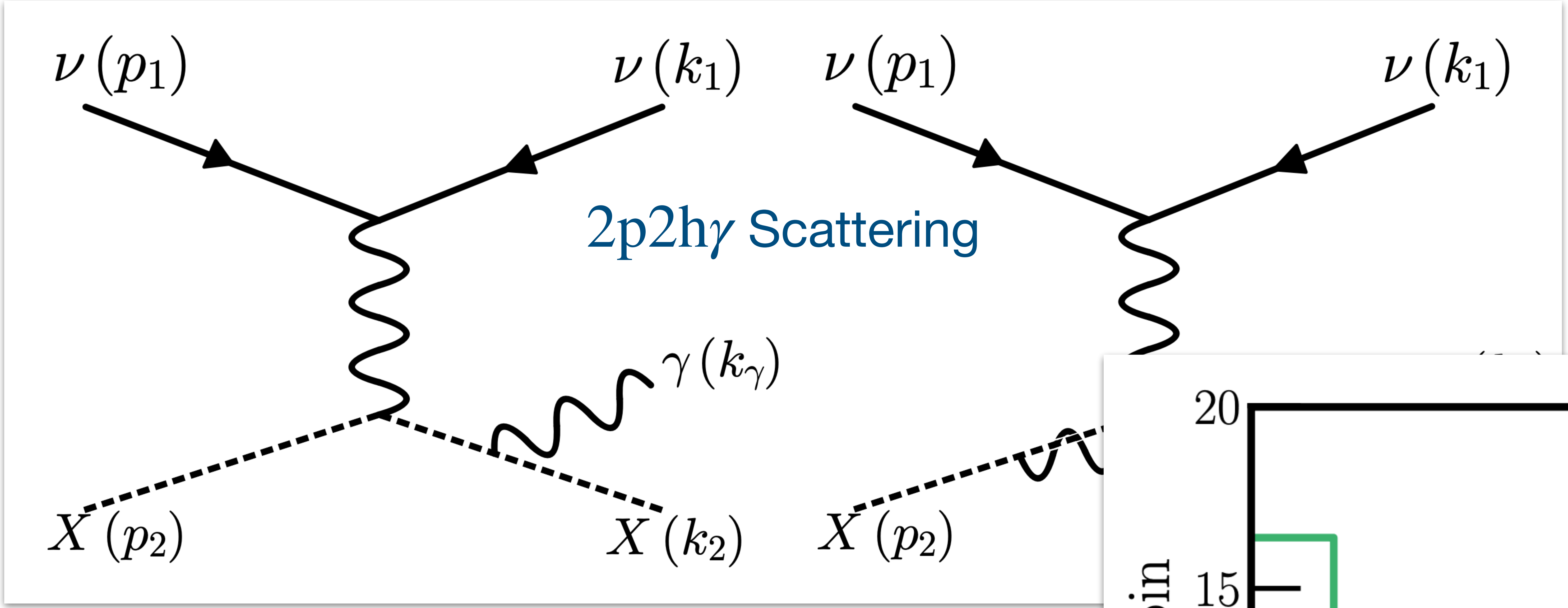

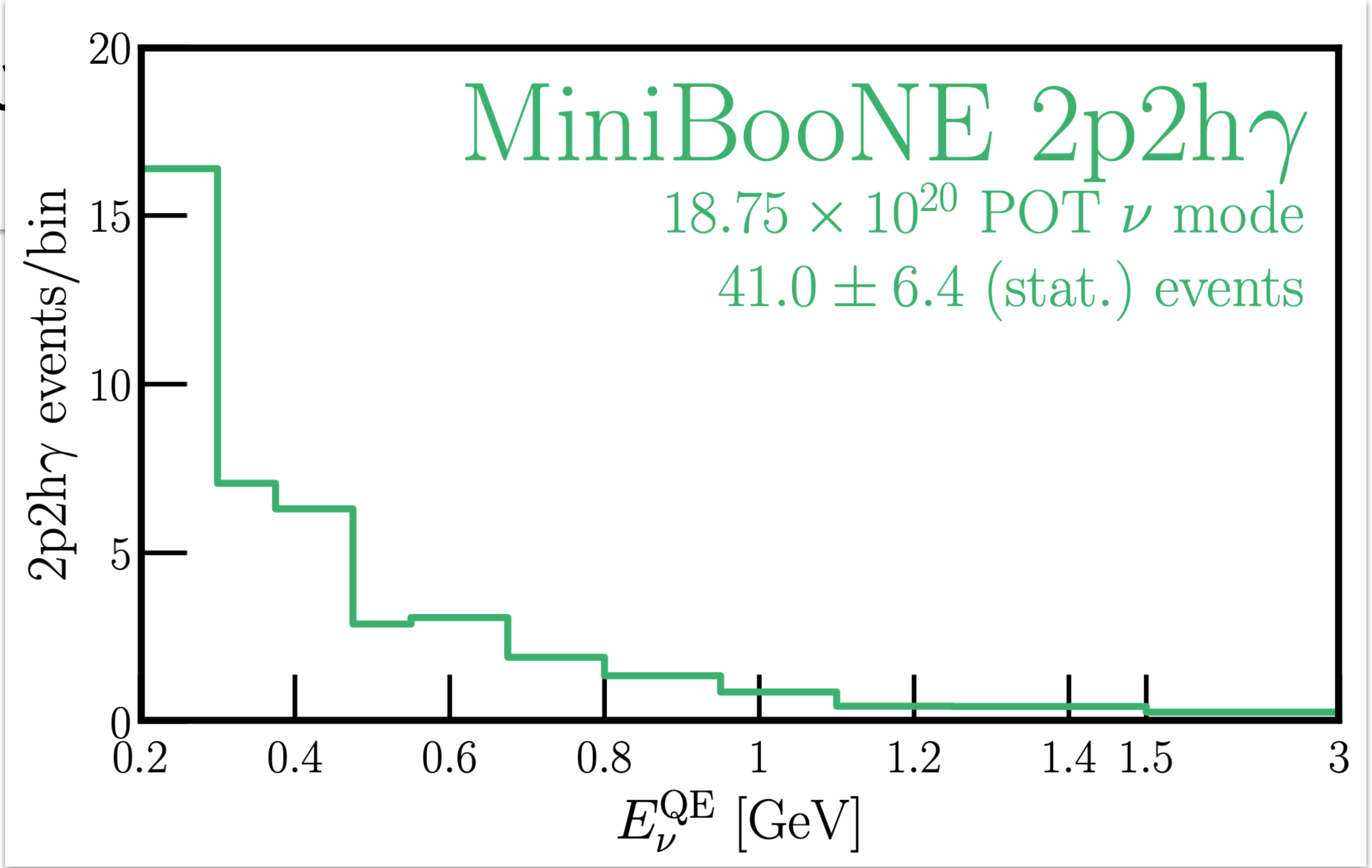

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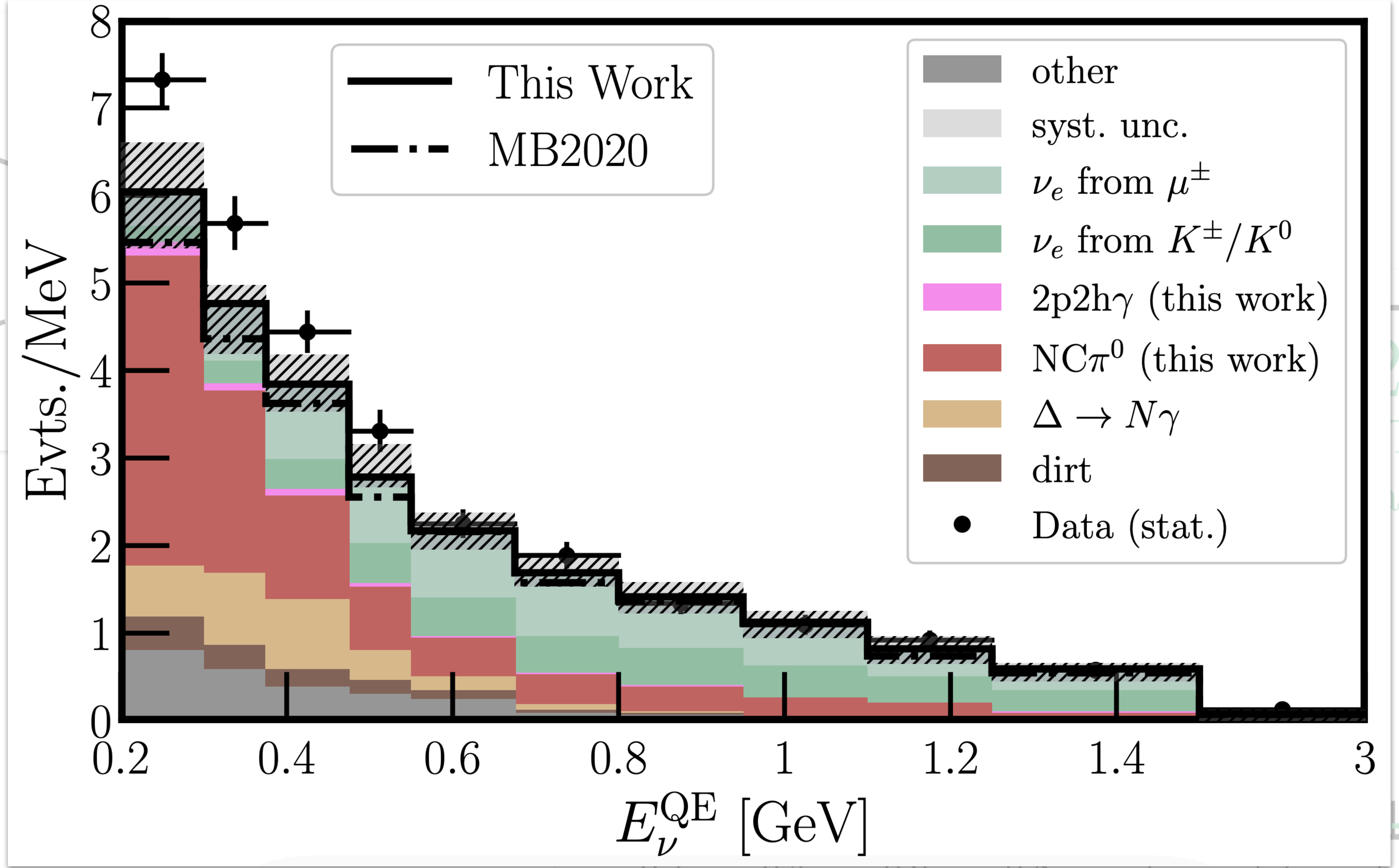

Our estimate of the updated MB Significance: $\sim 3\sigma$

Takeaways

Conclusions

- Despite strong statistical significance for appearance at LSND and MiniBooNE, there is still great tension between these and other sterile neutrino search results.

- Various BSM scenarios can accommodate/solve these tensions with varying success, and the current/near-term slate of experiments is *very* powerful for testing these hypotheses.

- MicroBooNE has begun searches for anomalous ν_e appearance. No hints yet, though constraints aren't quite ruling out MiniBooNE yet either.

- Perhaps it's time to take a deep dive in some MiniBooNE SM contributions, like Neutral-Current Single-Pion signatures. What can the SBN detectors add to this discussion?

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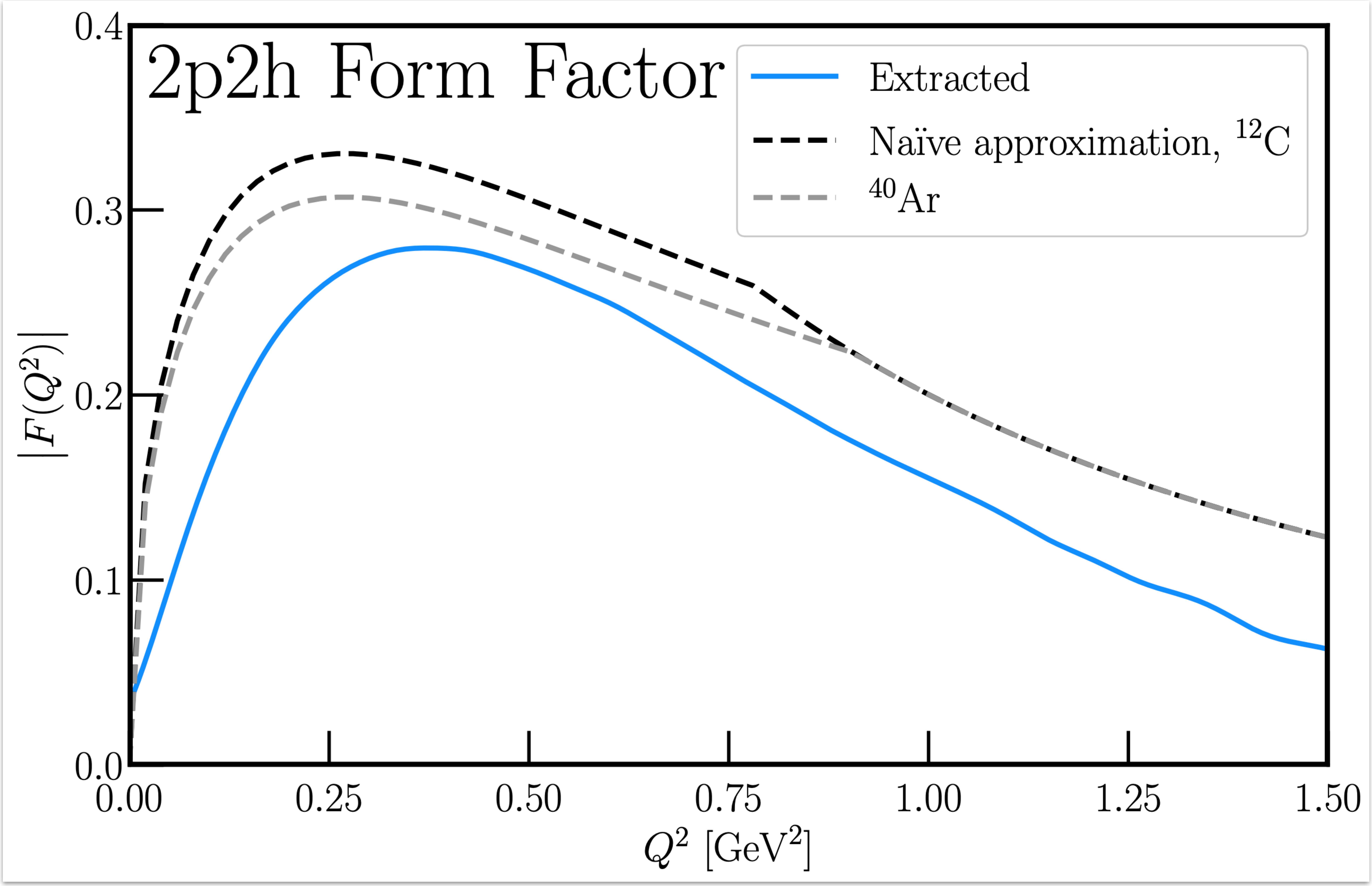
Thank you!

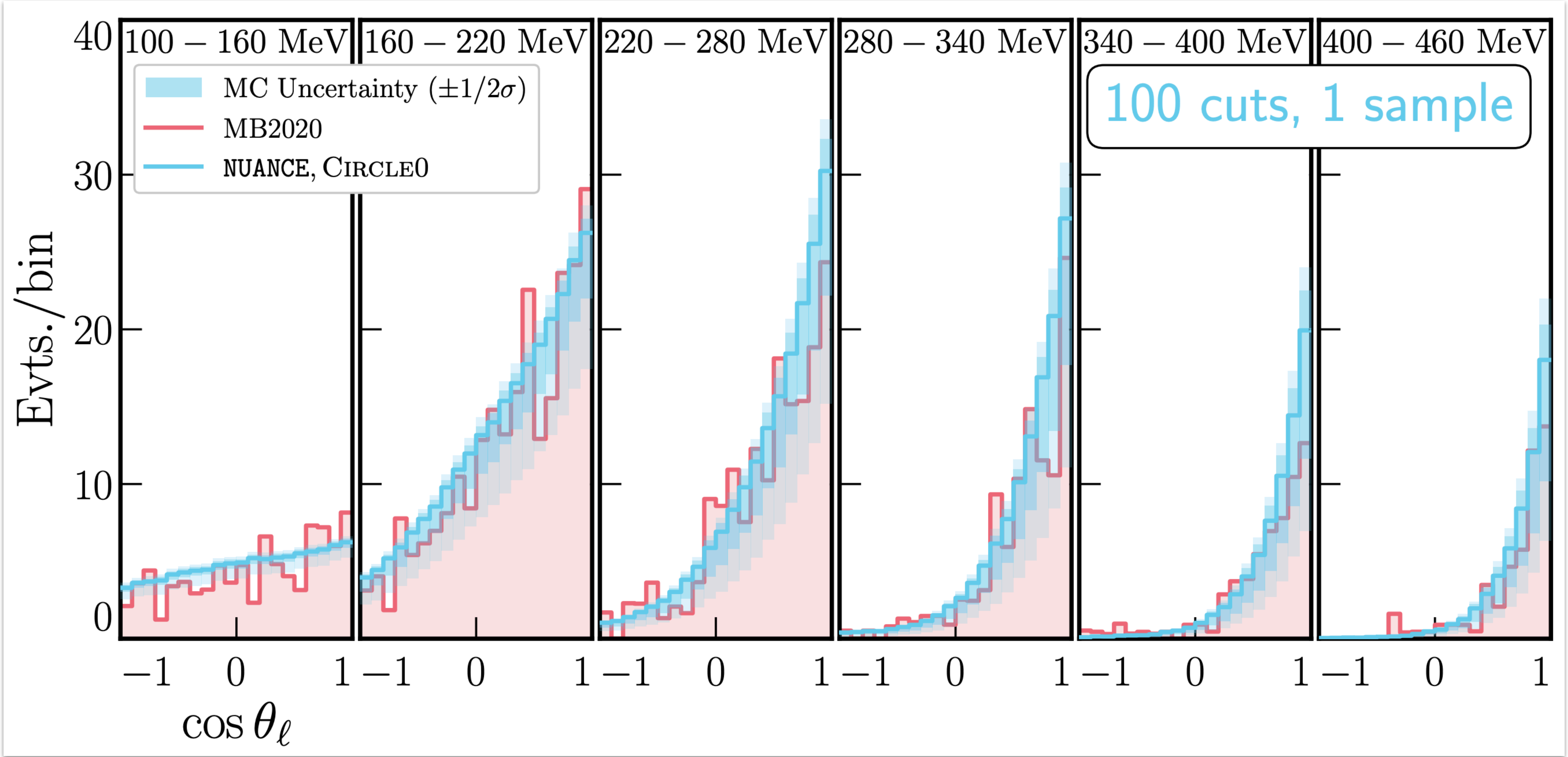
Backup

Form Factor for 2p2h Scattering

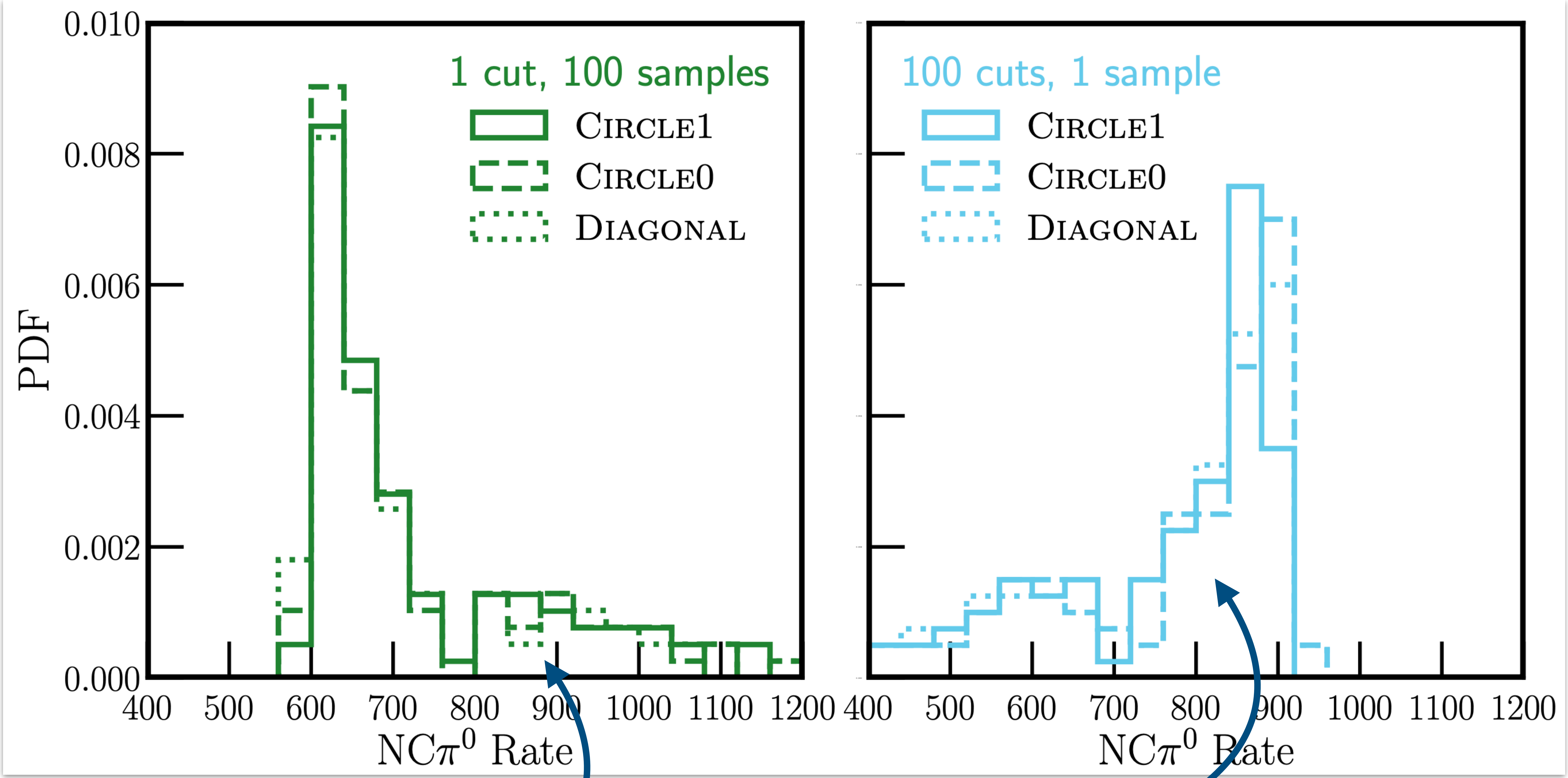


2p2hγ Events at SBN

MiniBooNE "Slices" In Alternate Strategy



NCπ^0 Event Rates



Spread of distribution: Important for estimating MC Statistical Uncertainty

Median of distribution: Important for estimating impact of small MC Statistics for MiniBooNE