

Problematic Pion-Induced Photons at MiniBooNE

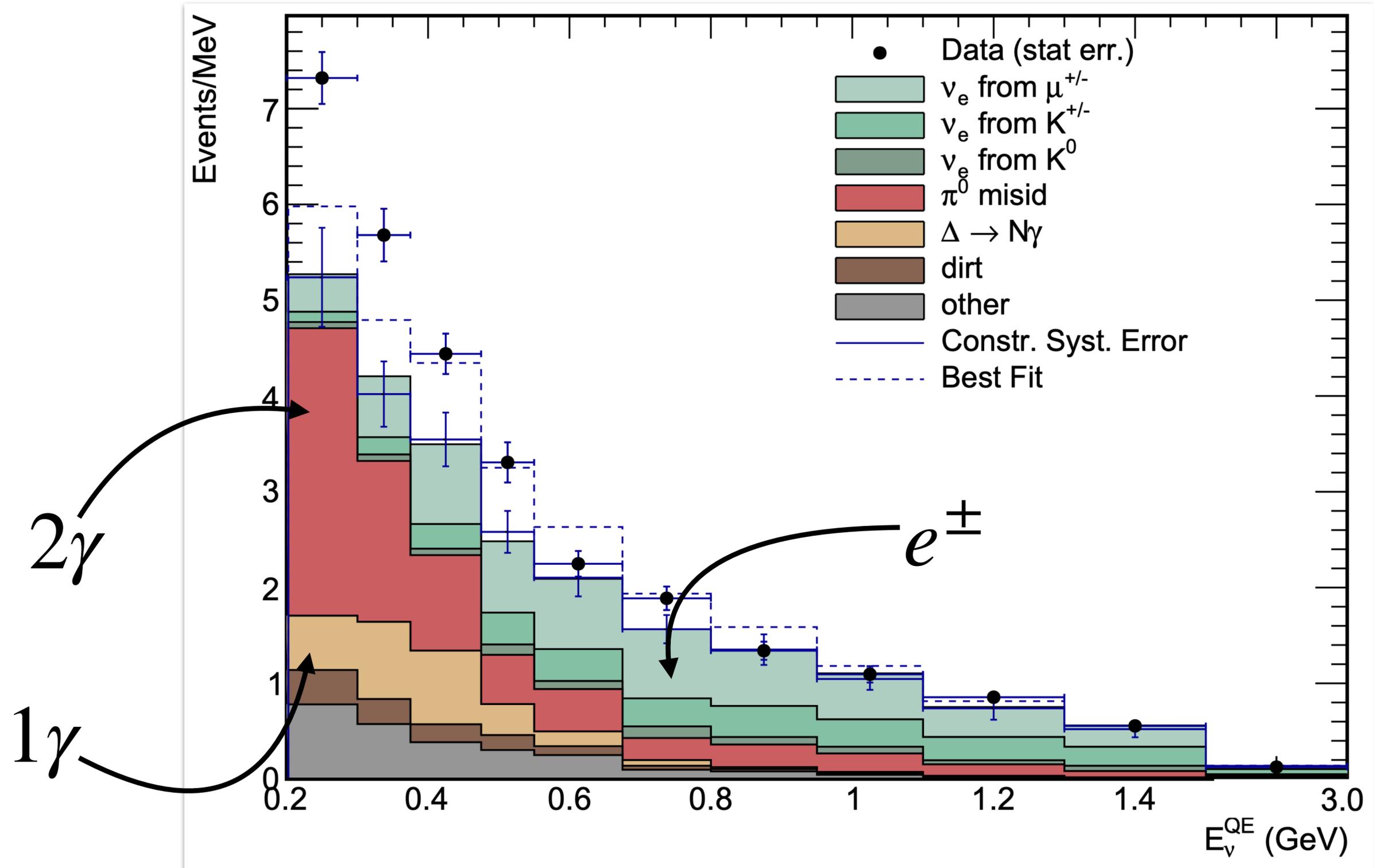
Kevin J. Kelly, Texas A&M University
CERN Neutrino Platform Pheno Week, 16th March 2023

kjkelly@tamu.edu

[\[2210.08021\]](#) with J. Kopp & [\[2111.10359\]](#) with many great collaborators

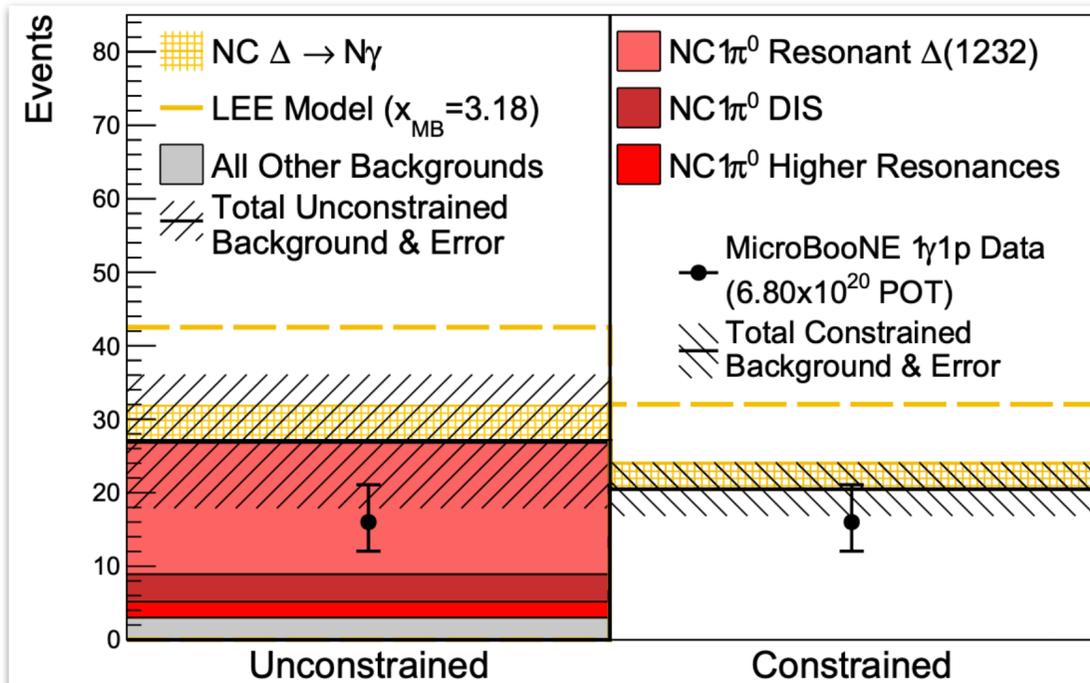
The MiniBooNE Excess

Electron-like events in MiniBooNE

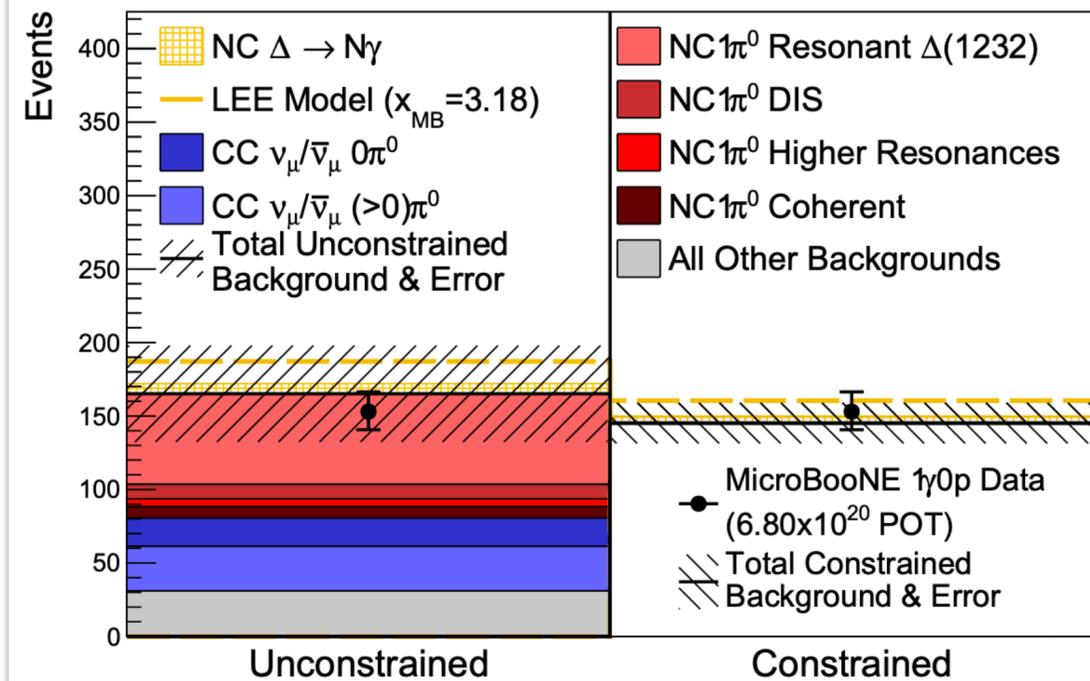


Aside: MicroBooNE

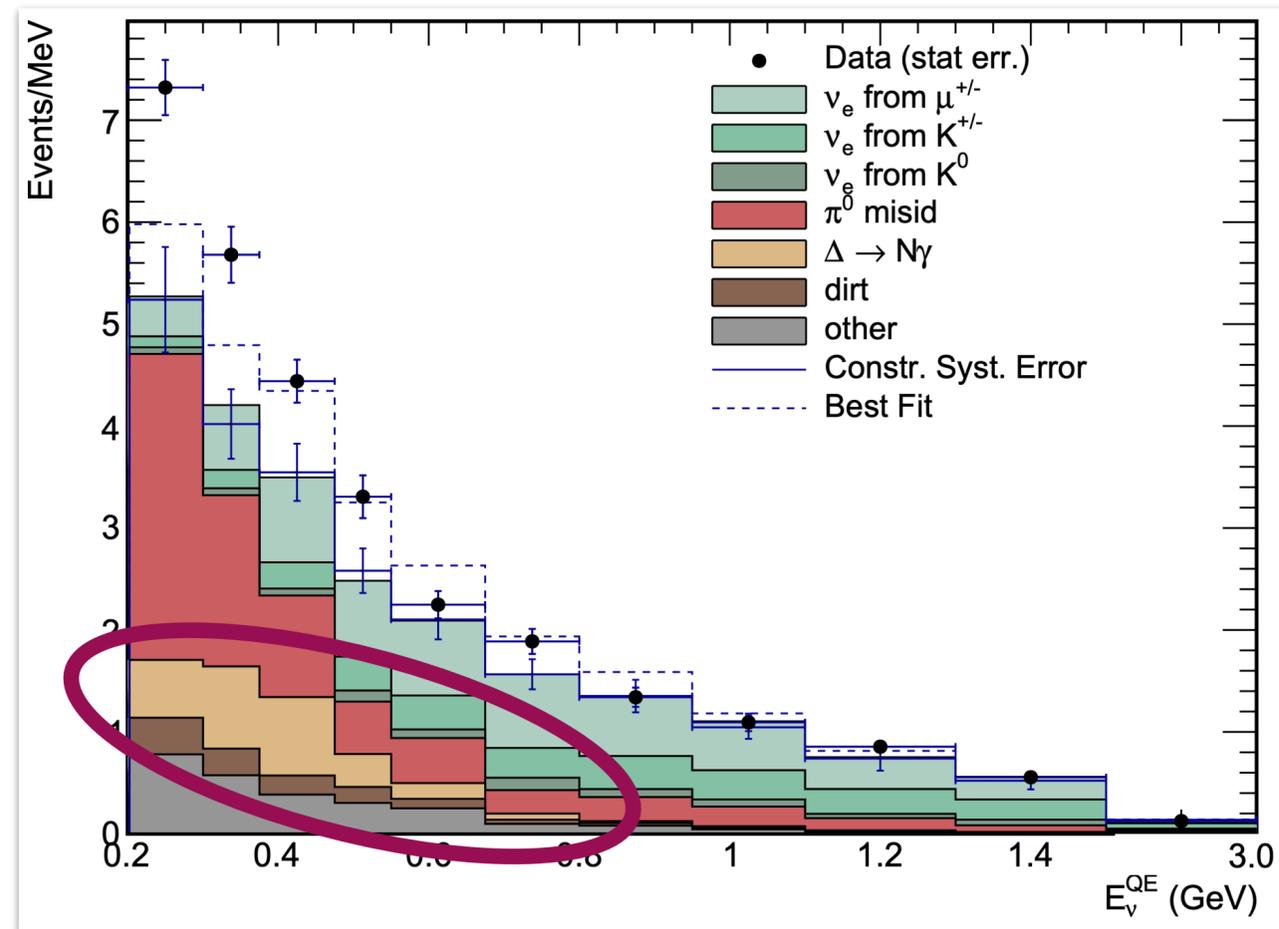
MicroBooNE $\Delta \rightarrow N\gamma$ Analysis



(a)



(b)

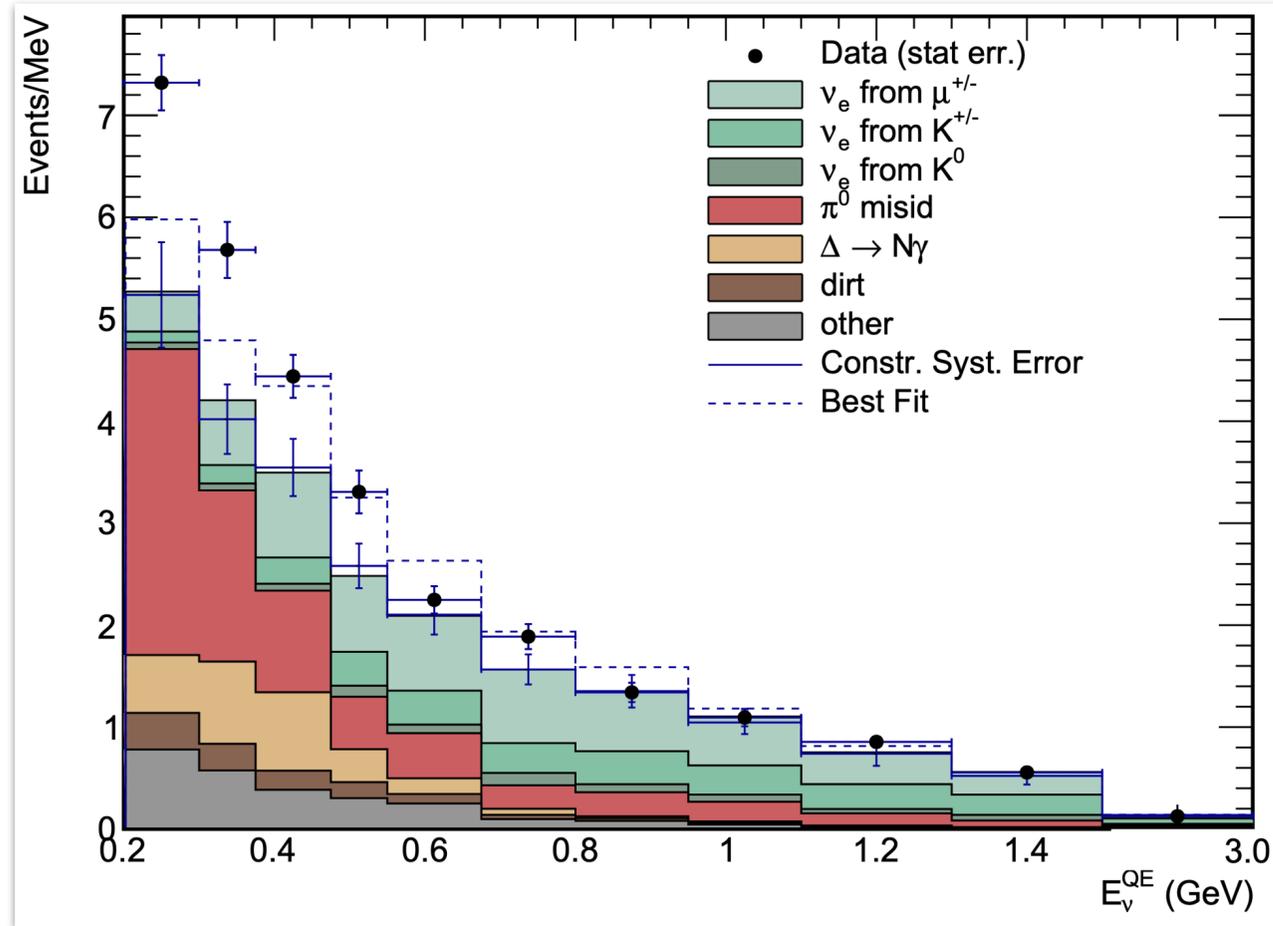


MicroBooNE disfavors the $\Delta \rightarrow N\gamma$ explanation of the MiniBooNE anomaly at 94.8% CL.

MicroBooNE $\nu_\mu \rightarrow \nu_e$ Analyses

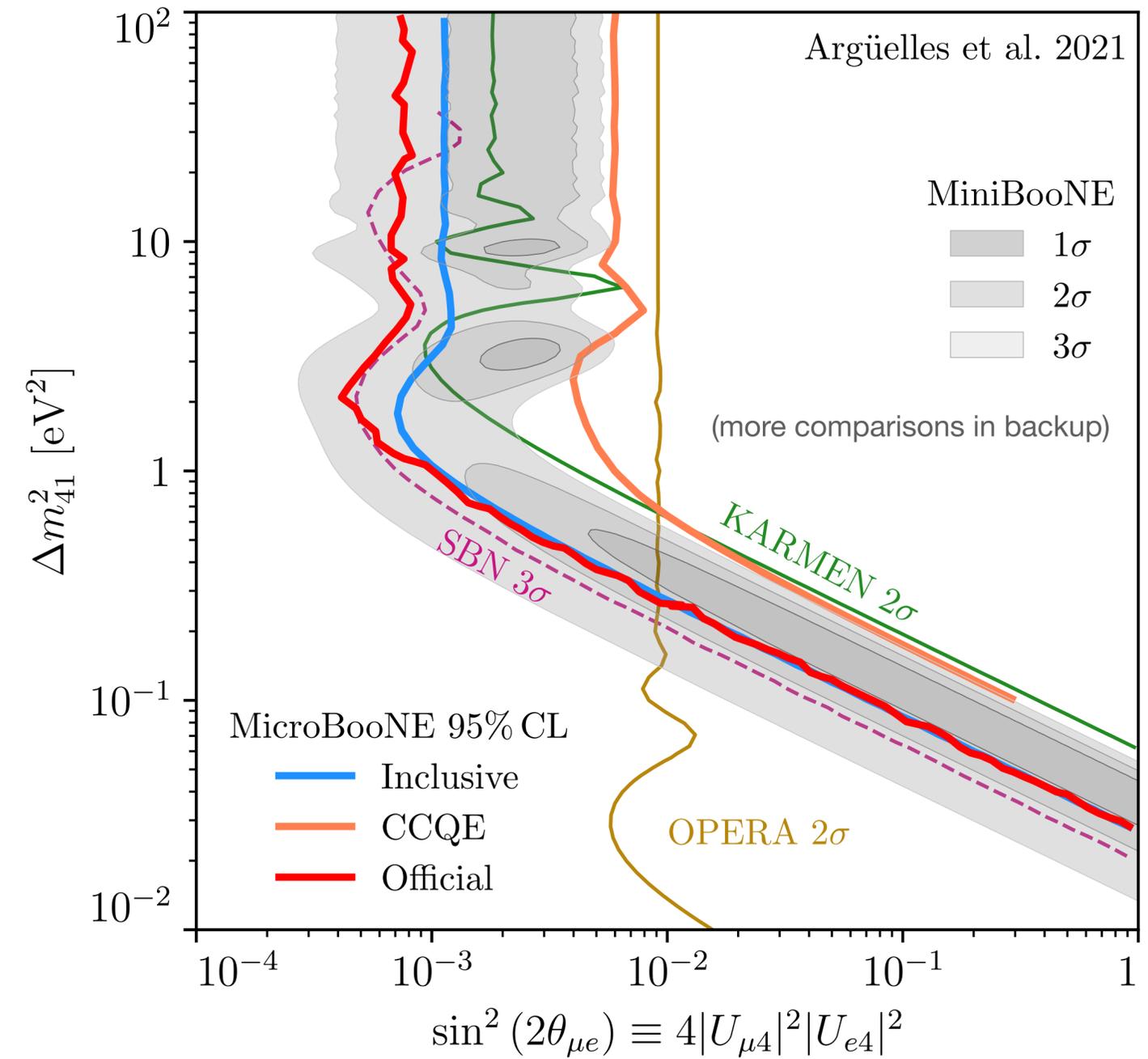
Pheno: Argüelles, Esteban, Hostert, KJK, Kopp, Machado, Martinez-Soler, Perez-Gonzalez, [\[2111.10359\]](#)

MicroBooNE Official [\[2210.10216\]](#)



Circa October 2021, MicroBooNE began looking at ν_e explanations of the MiniBooNE excess (summary given in [\[2110.14054\]](#)).

Different channels disfavor this explanation at the $\sim 2\sigma$ level.



Electron *antineutrinos* instead? Kamp, Hostert, Argüelles, Conrad, Shaevitz [\[2301.12573\]](#)

Beyond the Sterile Neutrino Picture?

From M. Hostert

NF02 White Paper: [arXiv:2203.07323](https://arxiv.org/abs/2203.07323). Questions (and complaints) → mhostert@pitp.com

Table of explanations of the short-baseline anomalies

Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
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	$\nu_4 \rightarrow \phi \nu_e$	✓	✓	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \rightarrow \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \rightarrow \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \rightarrow e^+ \nu_\alpha \bar{\nu}_e$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \rightarrow e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \rightarrow \nu \gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \rightarrow \nu (X \rightarrow e^+ e^-)$ or $N \rightarrow \nu (X \rightarrow \gamma \gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu e^+ e^-$ or $N \rightarrow \nu \gamma \gamma$	✓	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu \gamma$	✓	✓	✗	✗	[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.

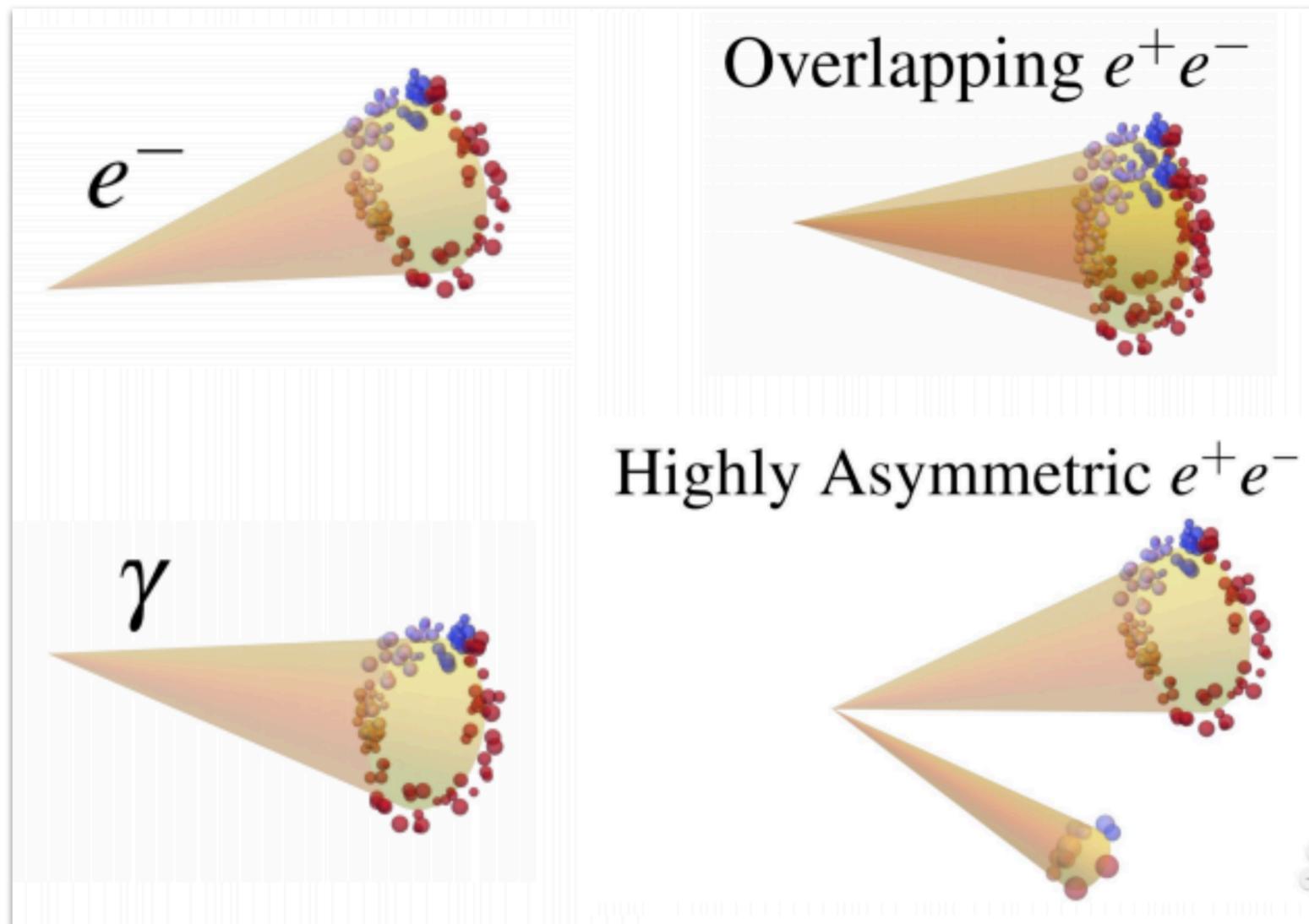
A nice, model-independent approach? Brdar et al, [\[2007.14411\]](https://arxiv.org/abs/2007.14411)

An “Altarelli Cocktail” of backgrounds in MiniBooNE? Brdar and Kopp, [\[2109.08157\]](https://arxiv.org/abs/2109.08157)

Recent work regarding the Gallium Anomaly? Giant et al, [\[2212.09722\]](https://arxiv.org/abs/2212.09722), Brdar et al, [\[2303.05528\]](https://arxiv.org/abs/2303.05528)

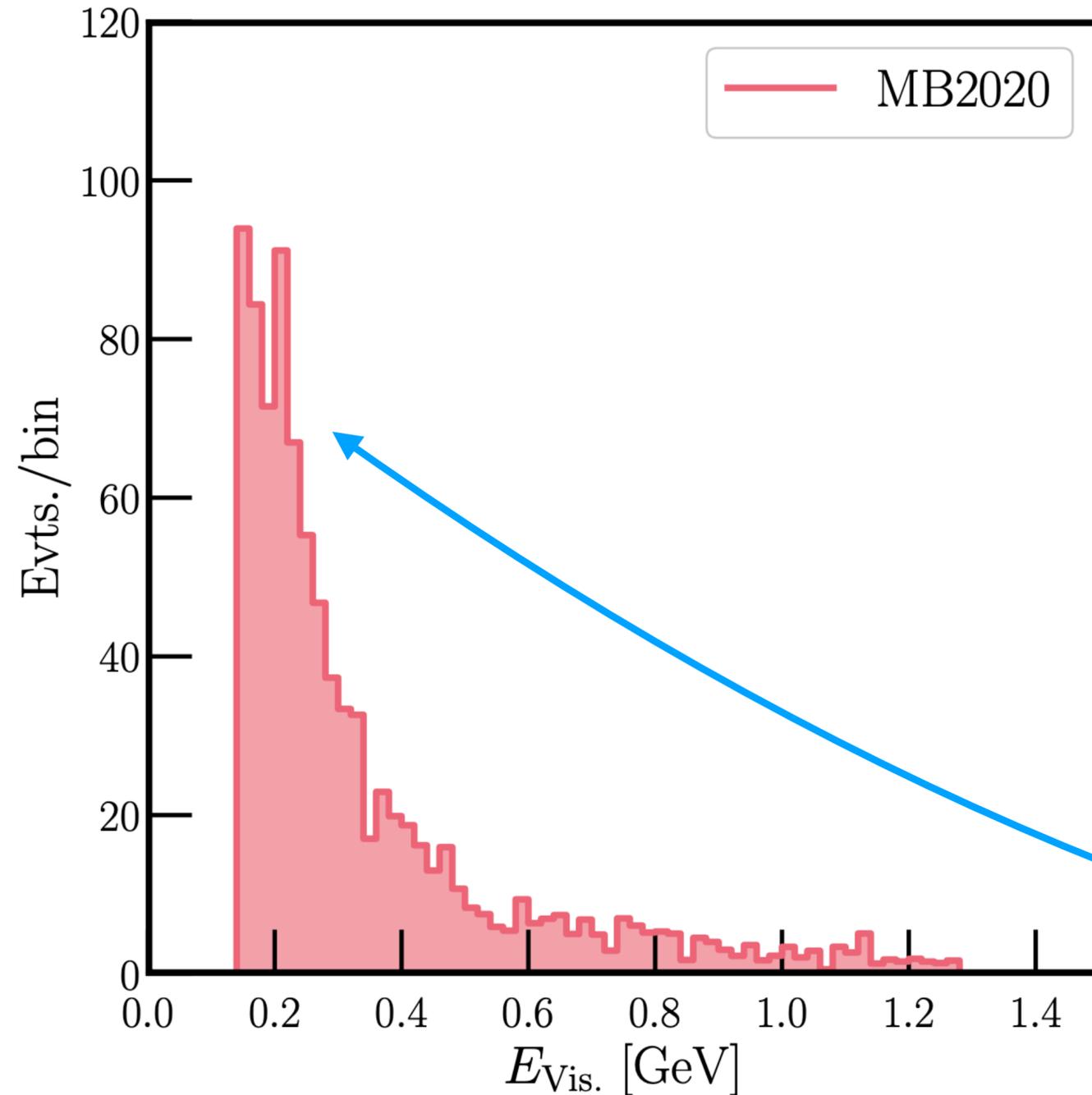
Back to MiniBooNE

Neutral Pions in MiniBooNE



- 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.

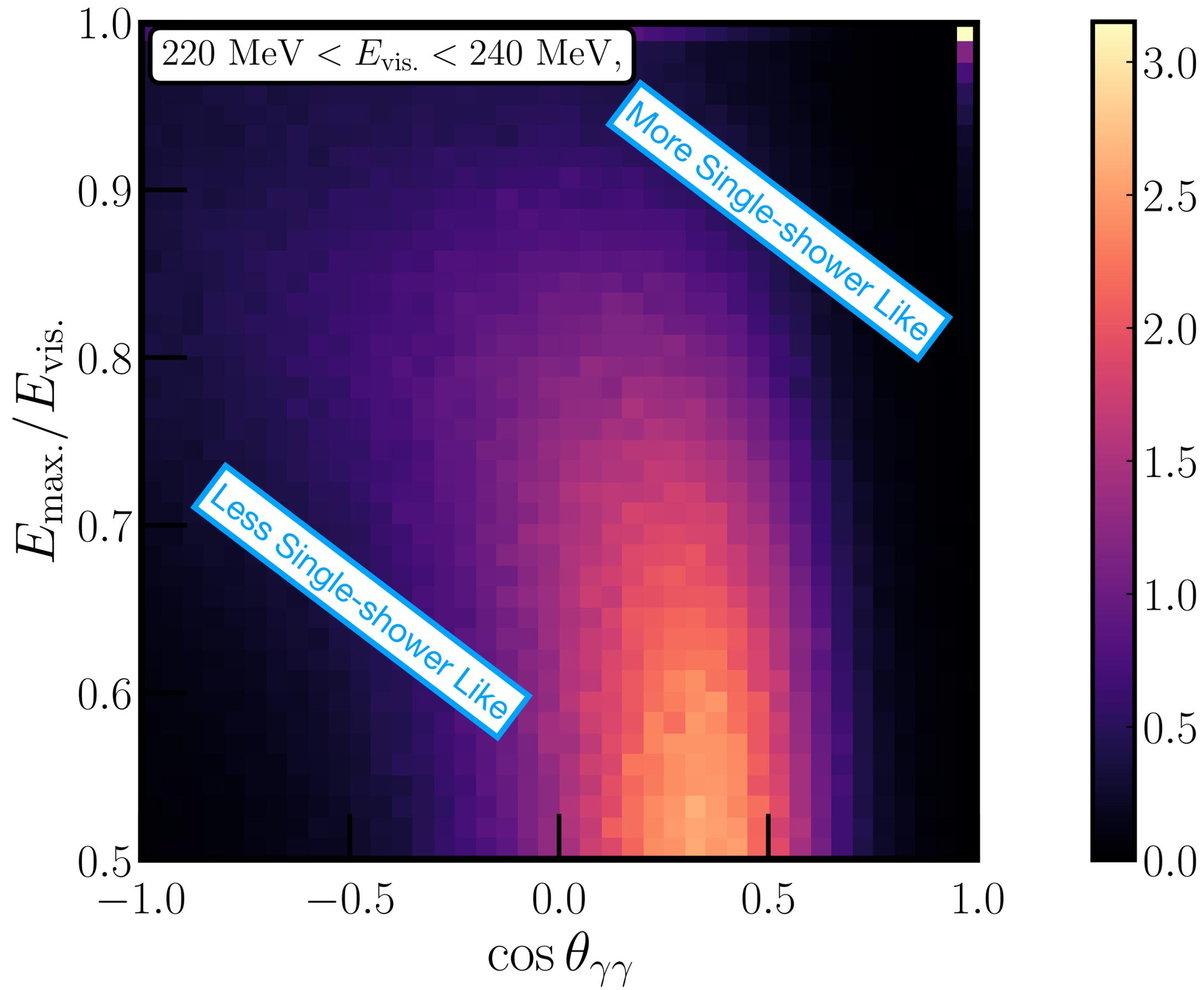
How does MiniBooNE treat $\text{NC}\pi^0$ Events?



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

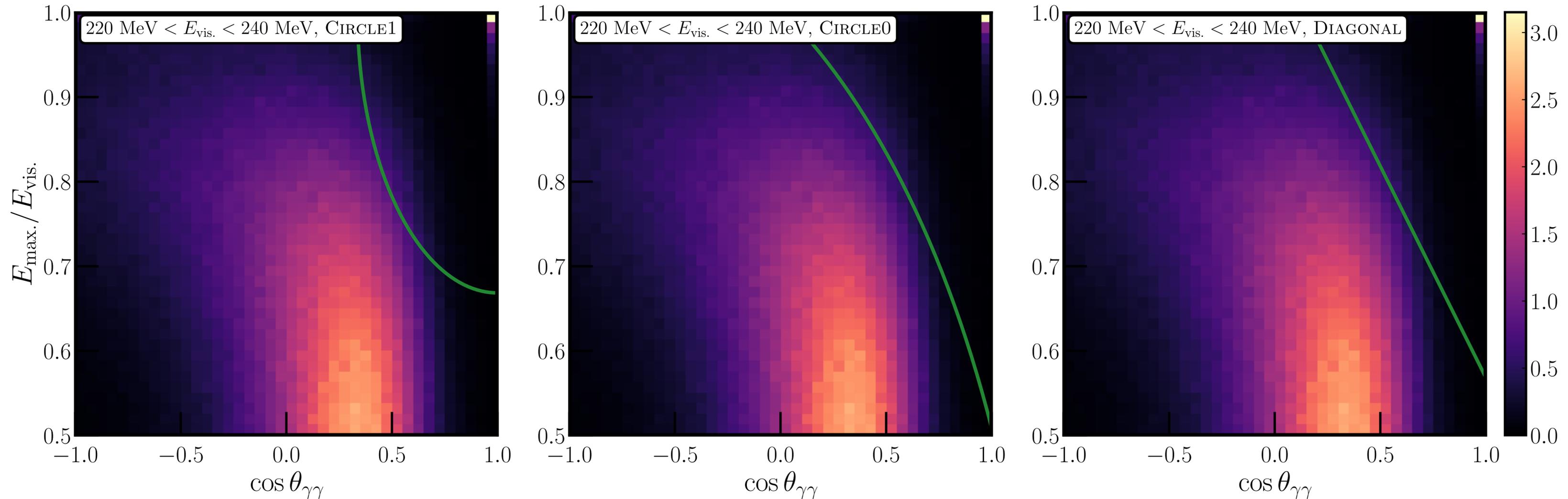
- Our goal: come up with a “phenomenological” set of cuts that yields the same distribution as quoted by MiniBooNE, depending on main kinematic quantities of the shower:
 - Opening angle of the two highest-energy photons in an event.
 - Asymmetry (maximum energy divided by total energy) in the shower.

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



Opening Angle/Asymmetry Distributions

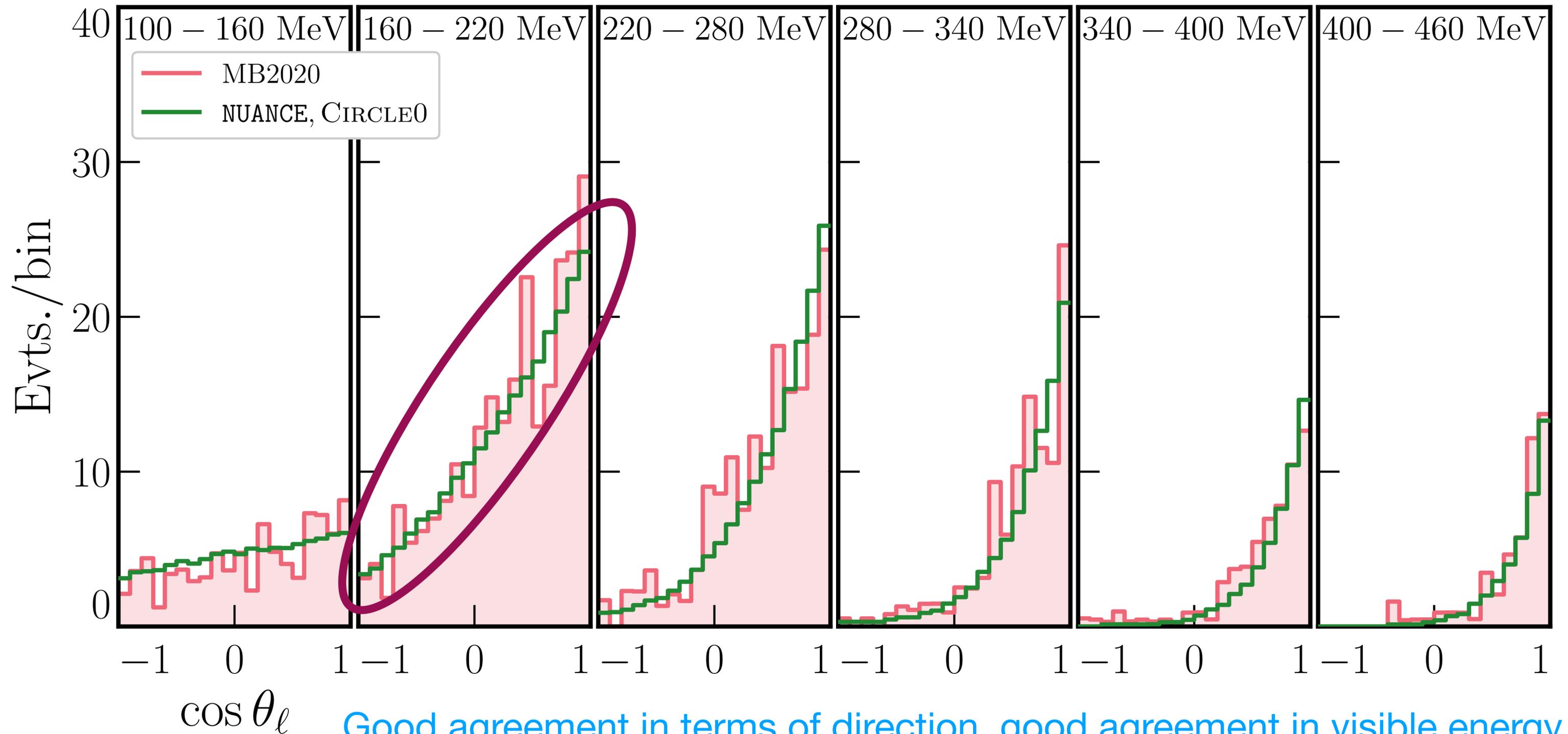
Three different cut prescriptions, each as a function of visible energy — These will (by definition) get us accepted distributions that match MiniBooNE's with respect to $E_{\text{vis.}}$.



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

Our Results

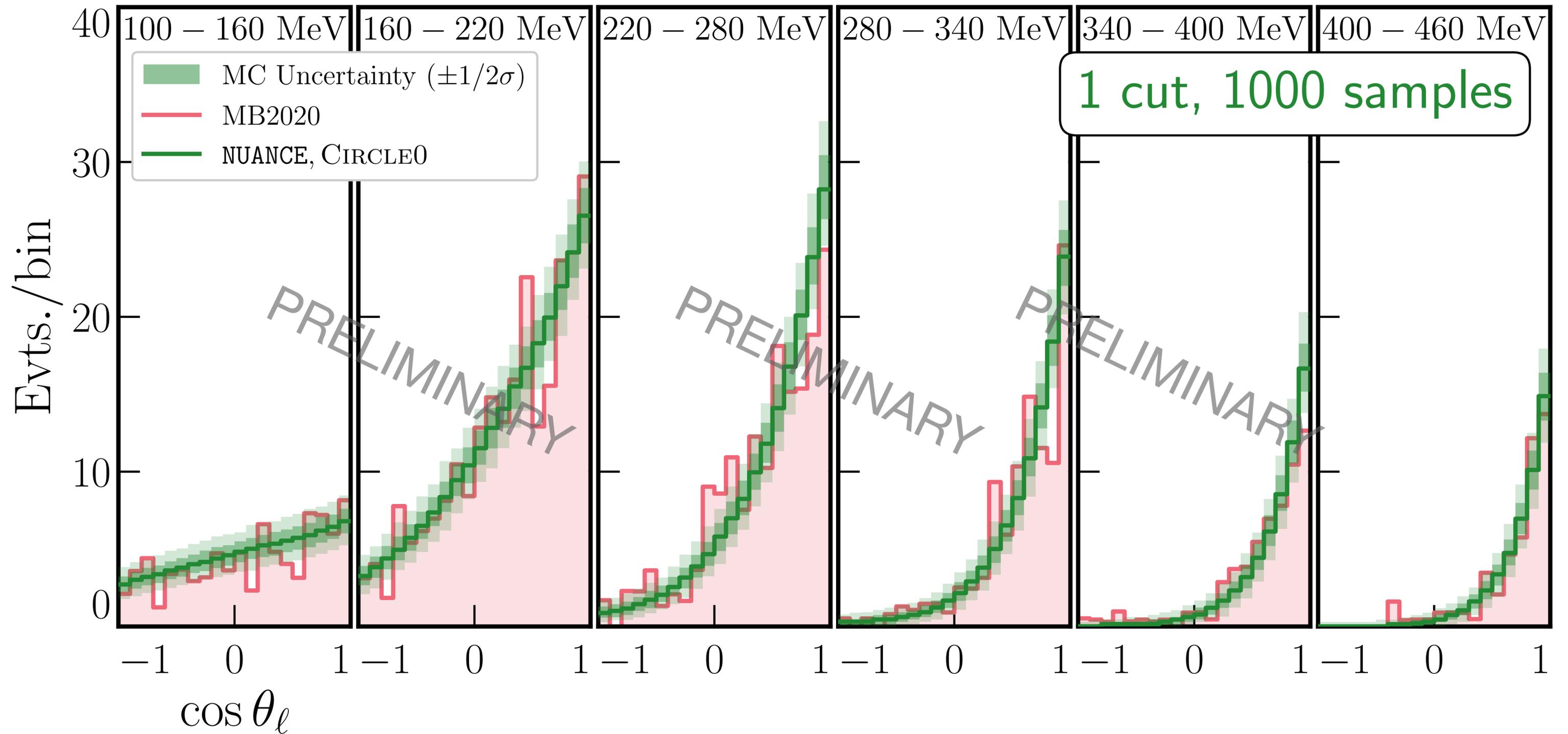
Kelly, Kopp [\[2210.08021\]](#)



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

Our Results

Kelly, Kopp — in-progress update to [\[2210.08021\]](#)



Updated analysis compared to v1 on arXiv, more updates to follow.

Challenge with $\pi^0 \rightarrow \gamma\gamma$

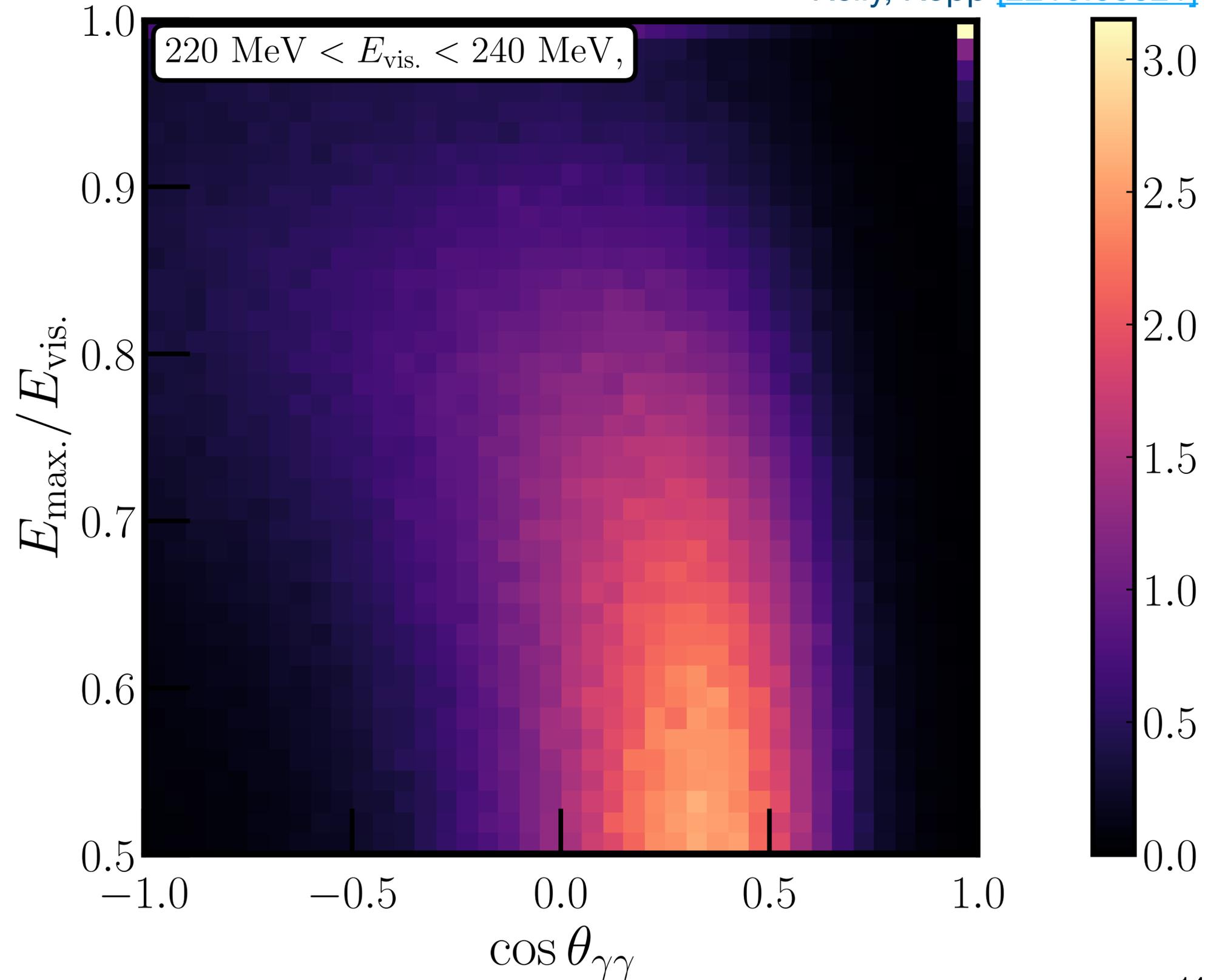
Kelly, Kopp [\[2210.08021\]](#)

- Distributions as a function of opening angle/asymmetry depend significantly on resolution assumptions.

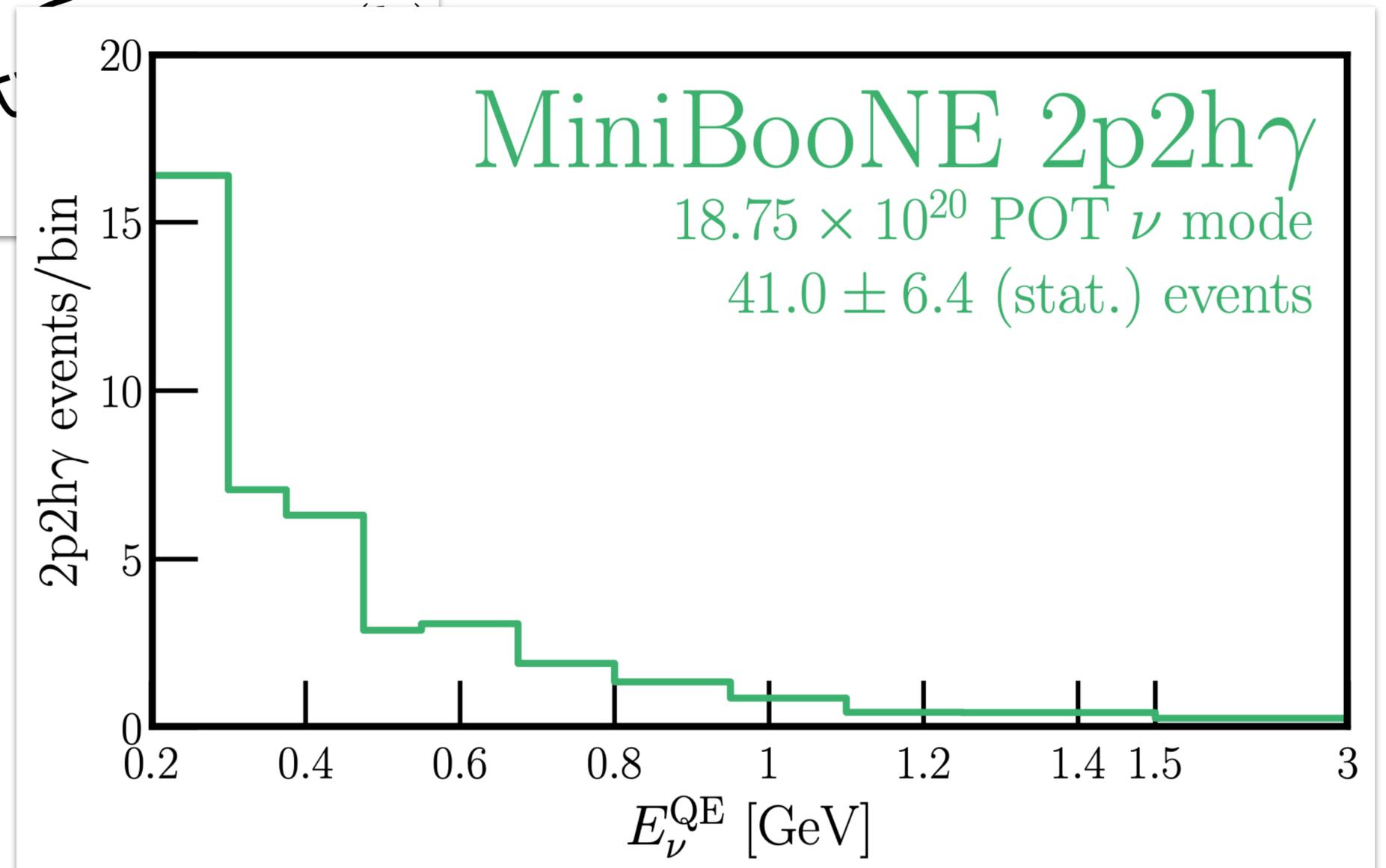
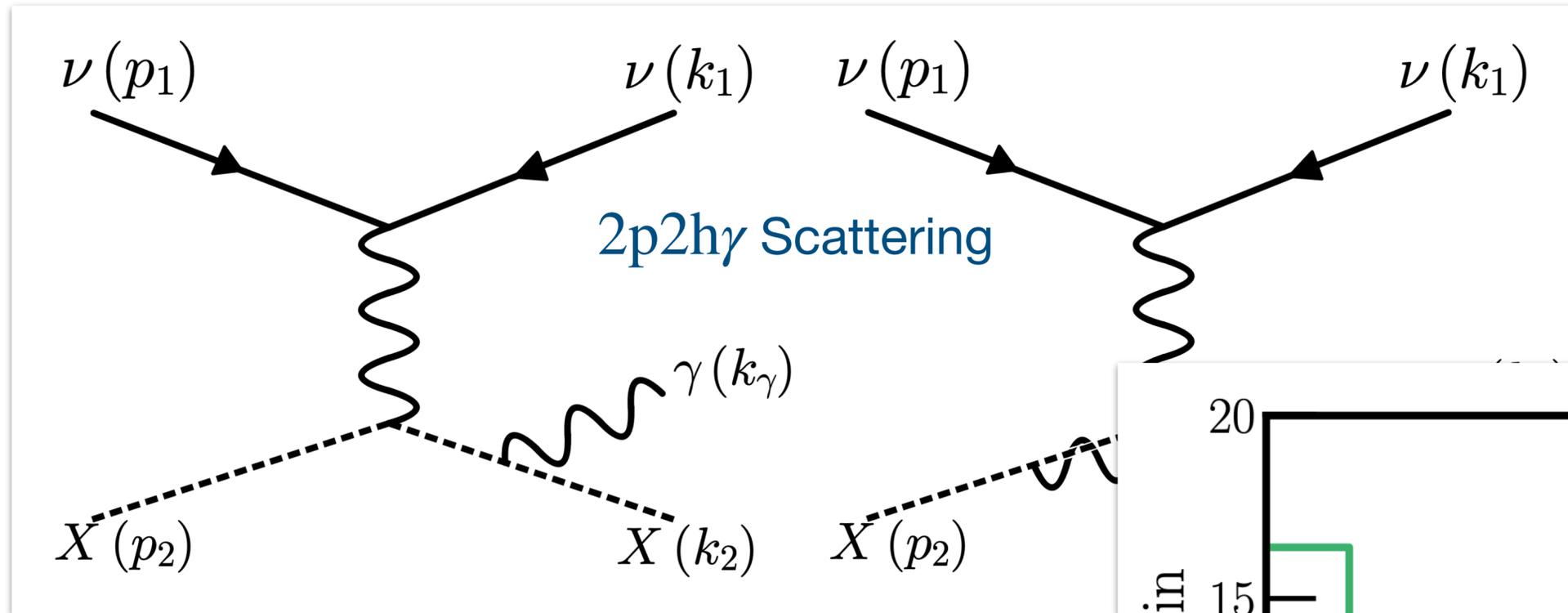
$$\left(\frac{\sigma_{E_\gamma}}{E_\gamma}\right)^2 = \left(\frac{0.08}{\sqrt{E_\gamma/\text{GeV}}}\right)^2 + \left(\frac{0.024}{E_\gamma/\text{GeV}}\right)^2$$

$$\sigma_{\theta_\gamma} = 10^\circ$$

- Could biases in these resolutions (especially for low photon/pion energies) relative to MC expectations lead to some observed excess?

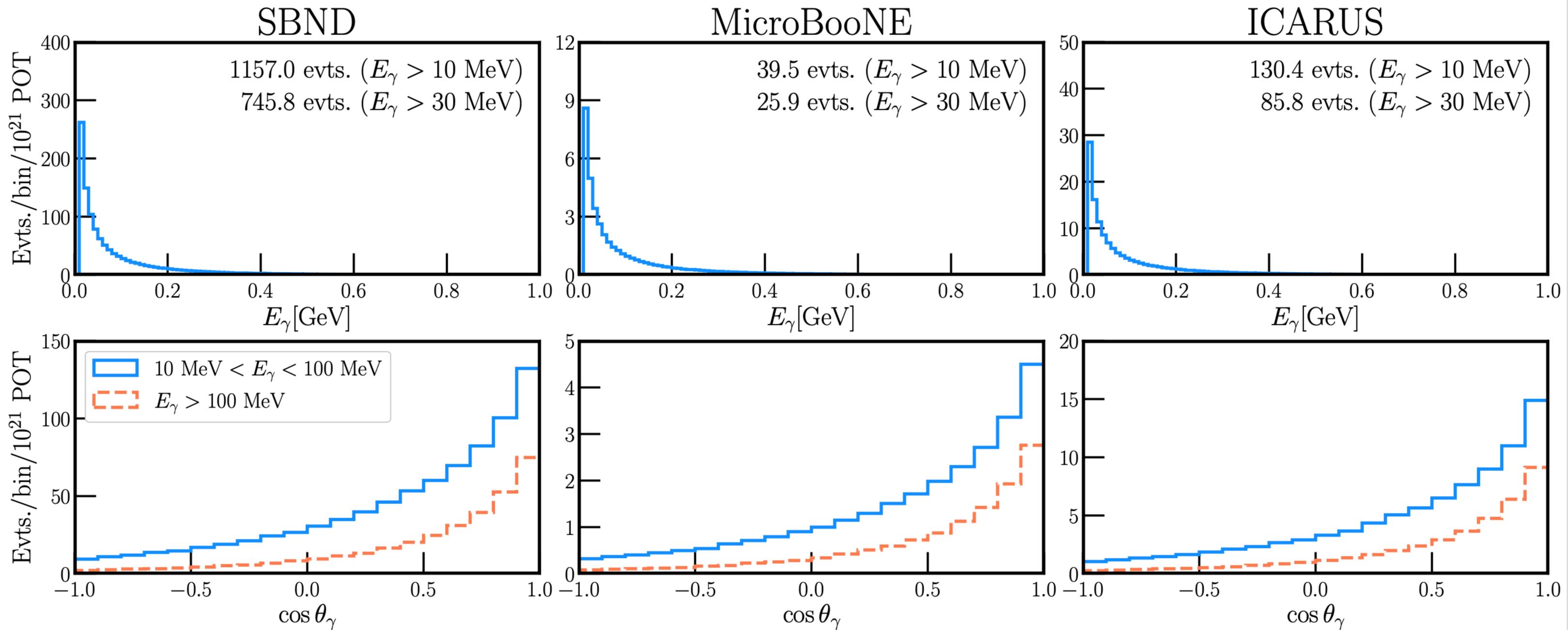


Other Single/Double Photon Effects?



2p2h γ Events at SBN

Kelly, Kopp [\[2210.08021\]](#)



Takeaways

Conclusions

- The MiniBooNE excess has withstood great scrutiny for years now, and various contributions to the background expectation are now being explored in even greater detail.
- There's still more to understand about MiniBooNE, including the neutral-current single-pion contribution to its background.
- 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)!

Backup

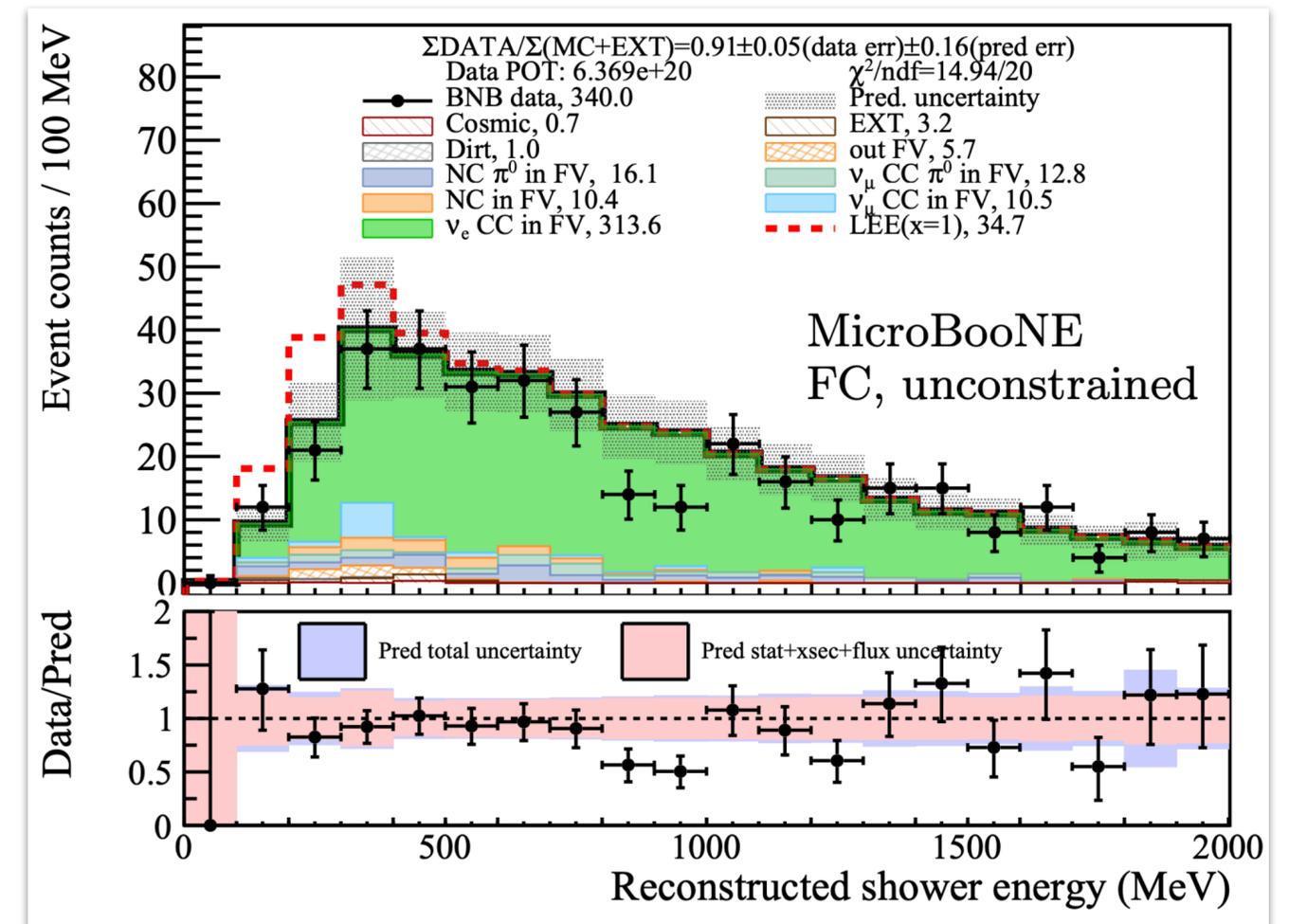
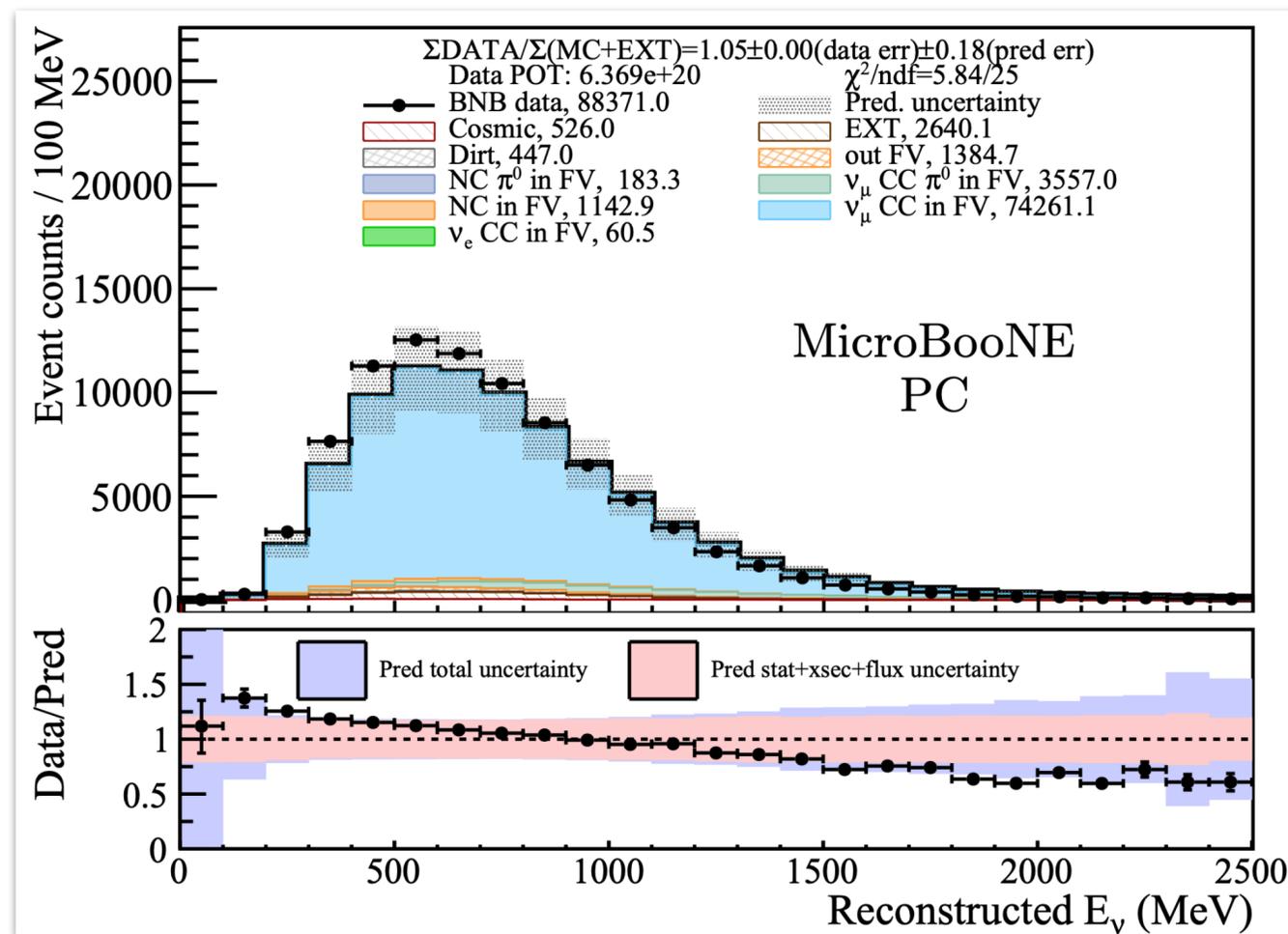
Complete 3+1 Neutrino Framework

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

Anomalous appearance *requires* disappearance!

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

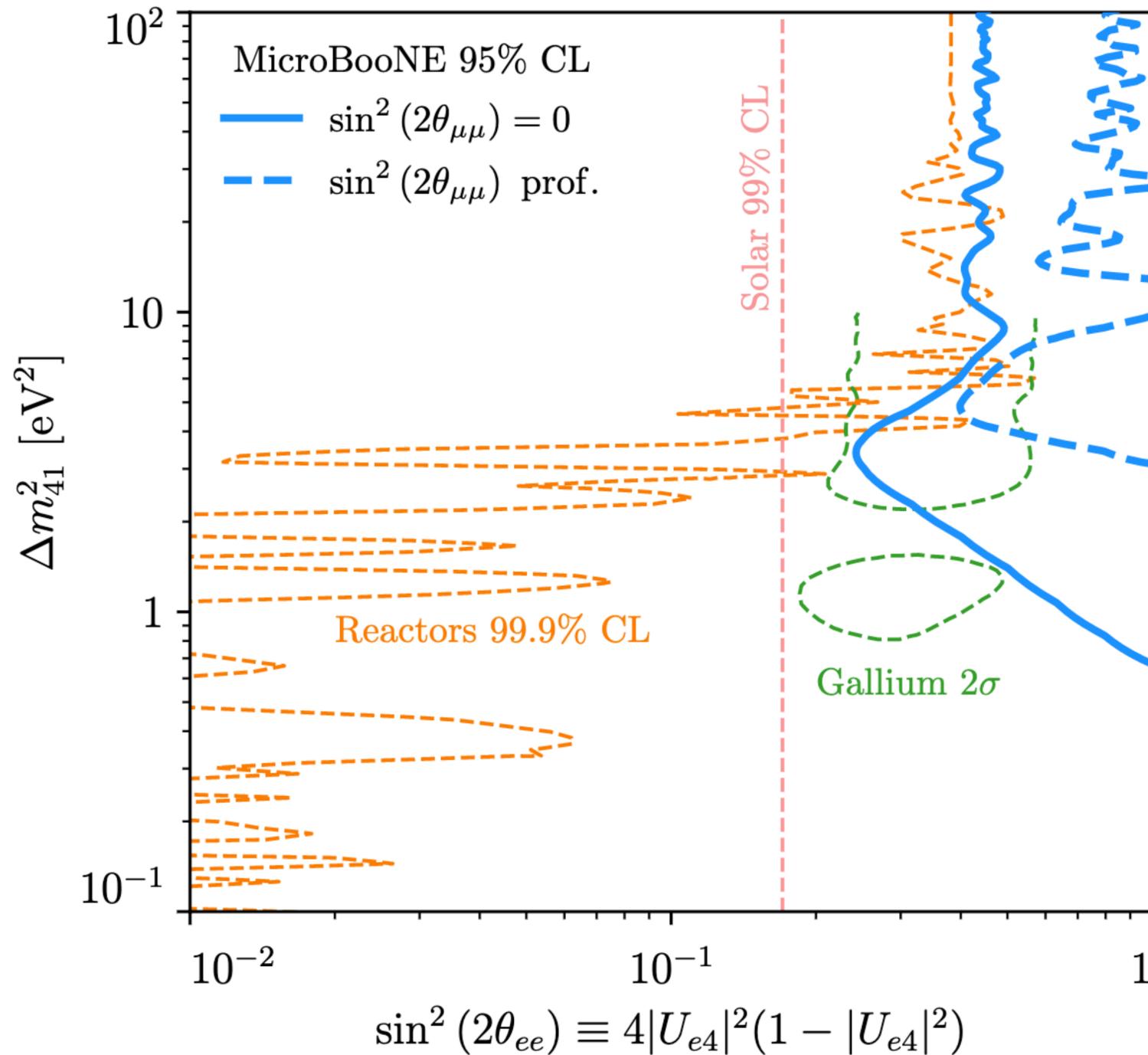
$$P(\nu_e \rightarrow \nu_e) = 4|U_{e 4}|^2(1 - |U_{e 4}|^2) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E_\nu}\right)$$



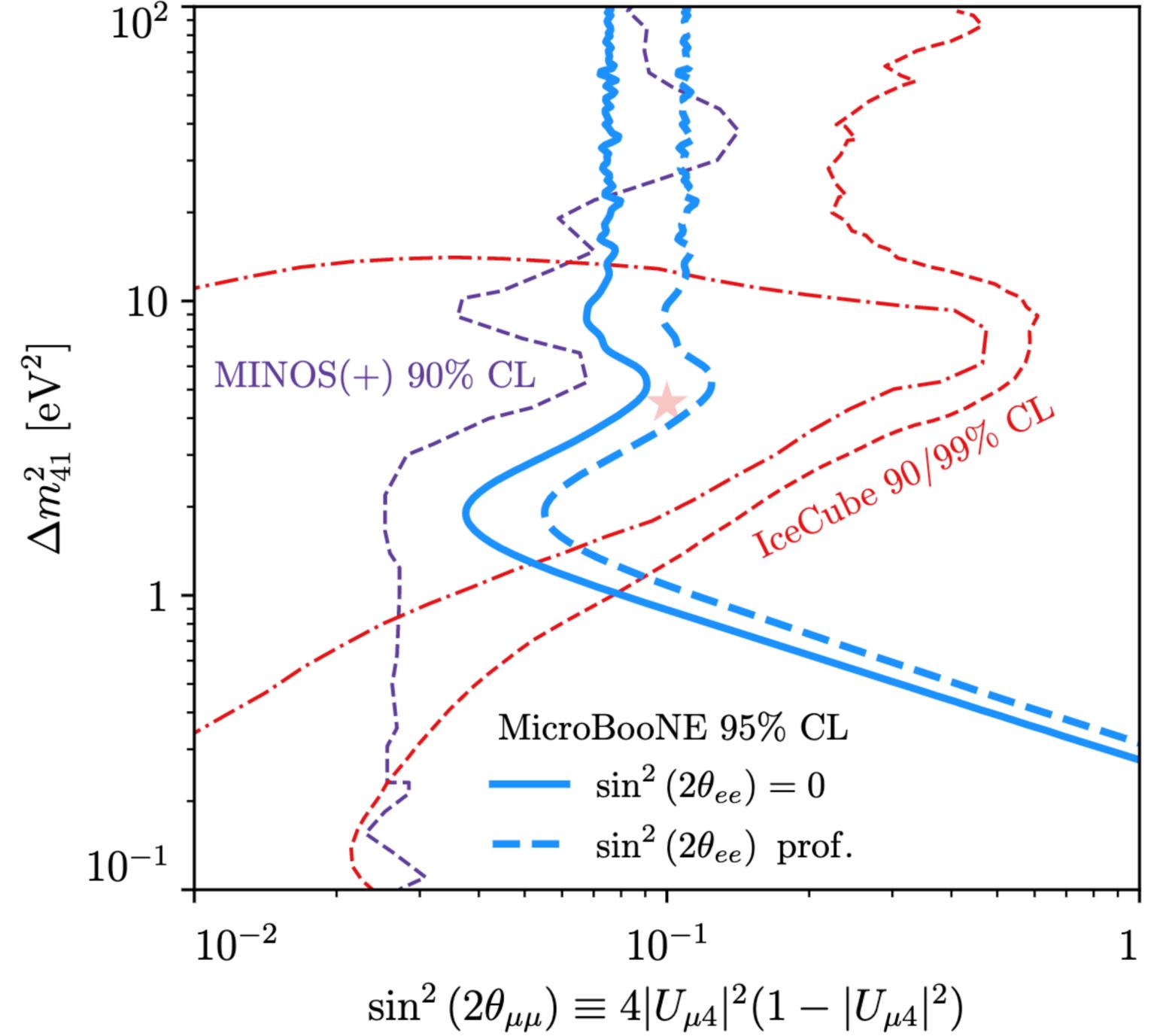
MicroBooNE, [2110.13978]

MicroBooNE ν_e Four-Flavor Results

Argüelles et al, [2111.10359]



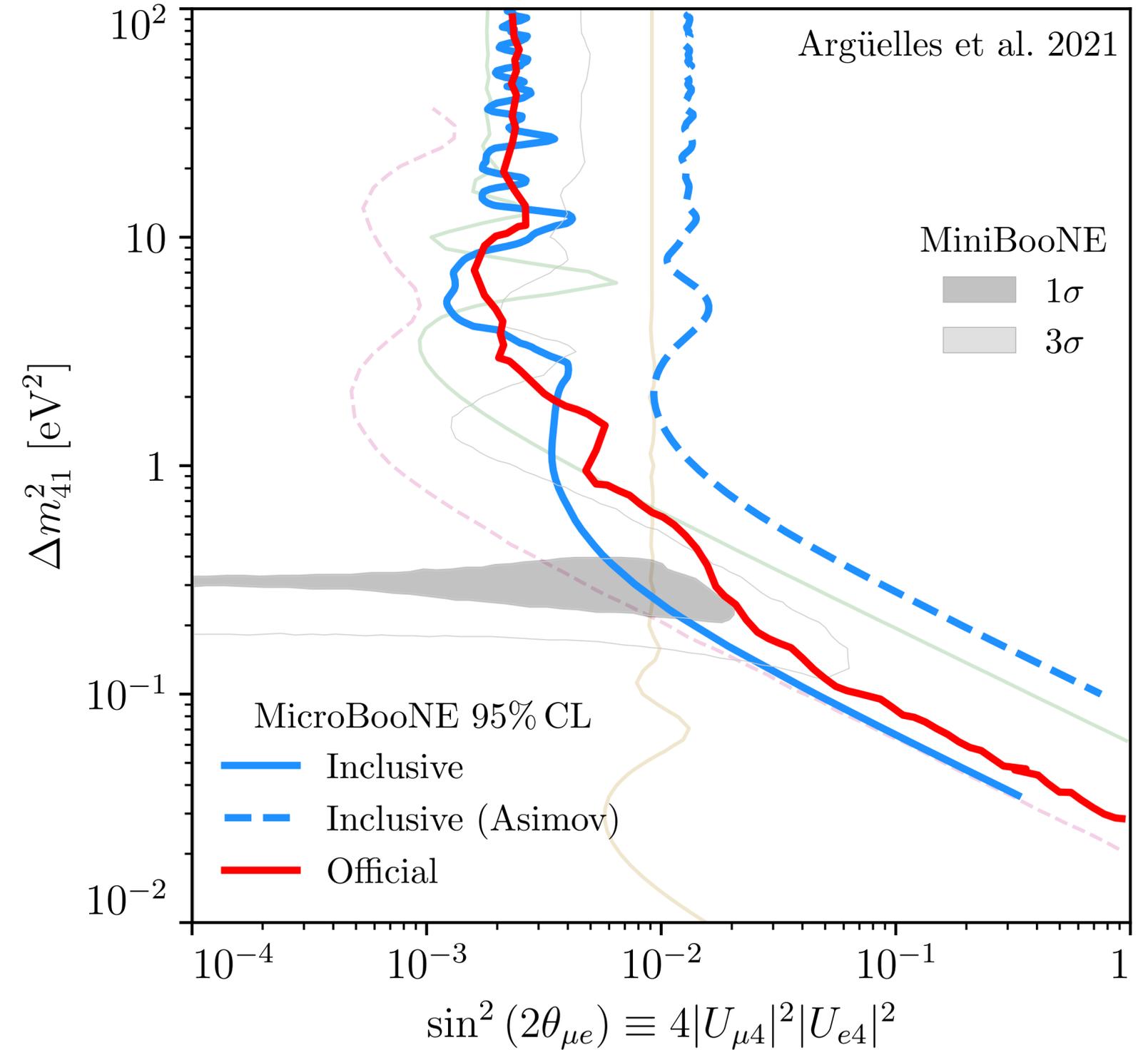
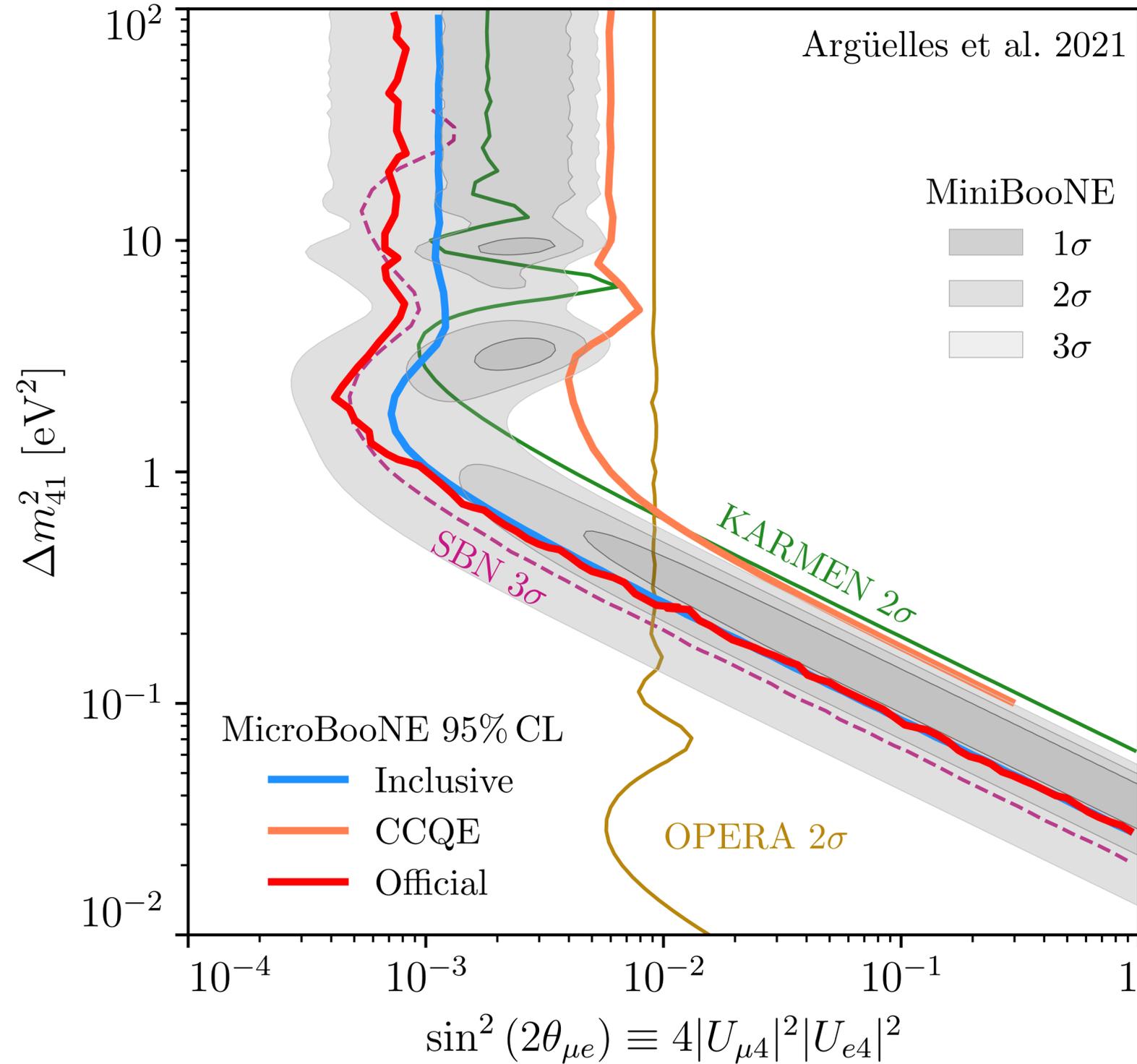
$$P(\nu_e \rightarrow \nu_e) = 4|U_{e4}|^2(1 - |U_{e4}|^2) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E_\nu}\right)$$



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

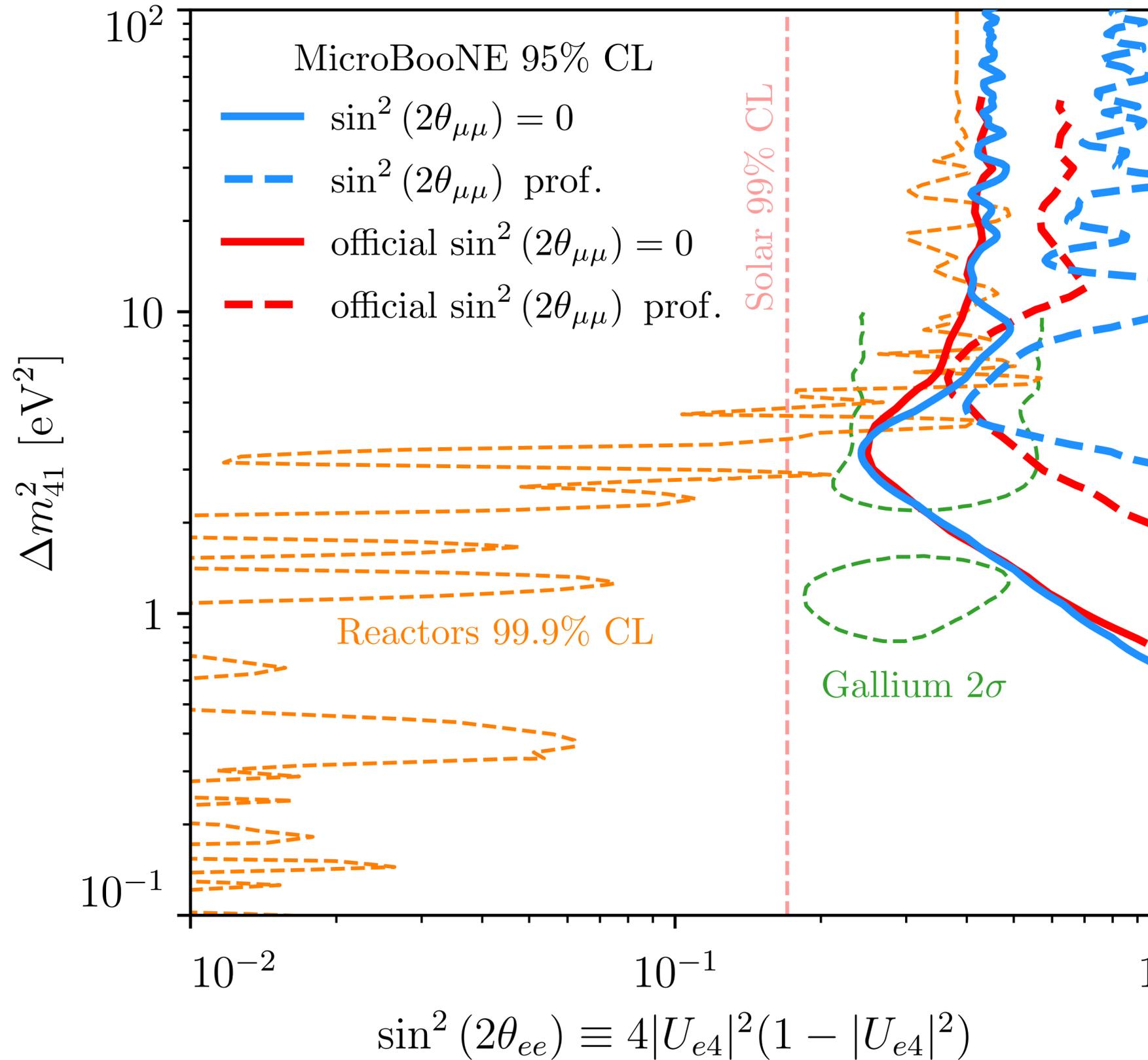
Full Comparisons with MicroBooNE

MicroBooNE: [\[2210.10216\]](https://arxiv.org/abs/2210.10216)



Full Comparisons with MicroBooNE (2)

MicroBooNE: [\[2210.10216\]](https://arxiv.org/abs/2210.10216)



Form Factor for 2p2h Scattering

