Impact of NSI on sterile neutrino searches at IceCube

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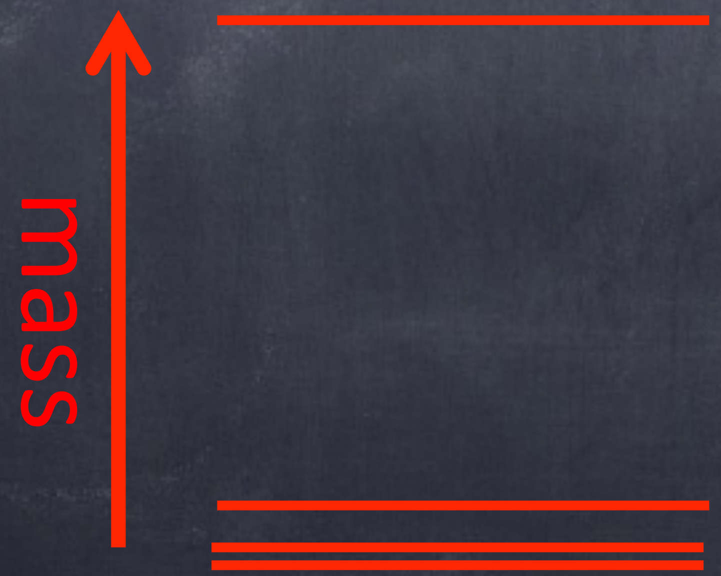
LSND

$$\bar{\nu}_\mu \to \bar{\nu}_e$$

Baseline: 30 m

Maximum energy: 53 MeV

$$L/E \sim 1 \text{ km/GeV} \quad \Longrightarrow \quad \Delta m^2 \sim 1 \text{ eV}^2$$



MiniBooNE

$\nu_\mu \to \nu_e \qquad \bar{\nu}_\mu \to \bar{\nu}_e$

Baseline: 500 m

Average energy: 800 MeV

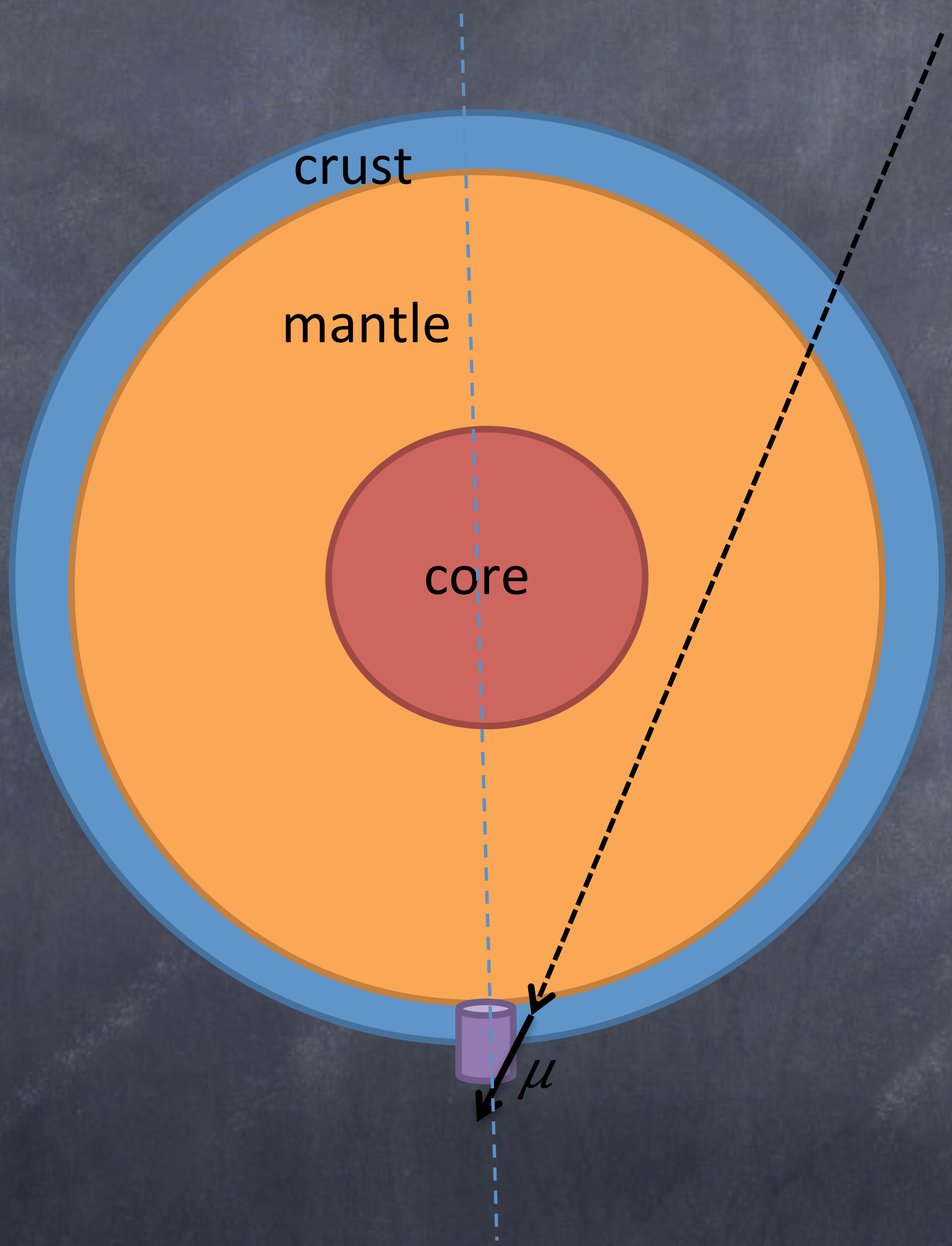
$$L/E \sim 1 \text{ km/GeV} \implies \Delta m^2 \sim 1 \,\text{eV}^2$$

LSND+MiniBooNE anomaly has 6.1 sigma significance

Oscillation amplitude from global analysis:

$$\sin^2 2\theta_{14} \sin^2 \theta_{24} \sim 0.1 \sin^2 \theta_{24}$$

IceCube



Focus on (anti)muon neutrino survival probabilities

Resonant 3+1 atmospheric neutrino oscillations

Oscillation maximum in vacuum: $\frac{\Delta m^2}{\mathrm{eV}^2} \frac{L}{10^3\ \mathrm{km}} \frac{\mathrm{TeV}}{E} \sim 1$

Resonance condition in earth matter:

$$\Delta m^2_{41} \cos 2\theta_{24} \simeq \mp 1\ \mathrm{eV}^2\ \frac{E}{5\ \mathrm{TeV}}$$

Resonance occurs in antineutrino channel

Nonstandard interactions in matter

$$\mathcal{L}_{\rm NSI} = 2\sqrt{2} G_F \epsilon^{fC}_{\alpha\beta} [\overline{\nu_\alpha}\gamma^\rho P_L \nu_\beta][\bar{f}\gamma_\rho P_C f] + \text{h.c.}$$

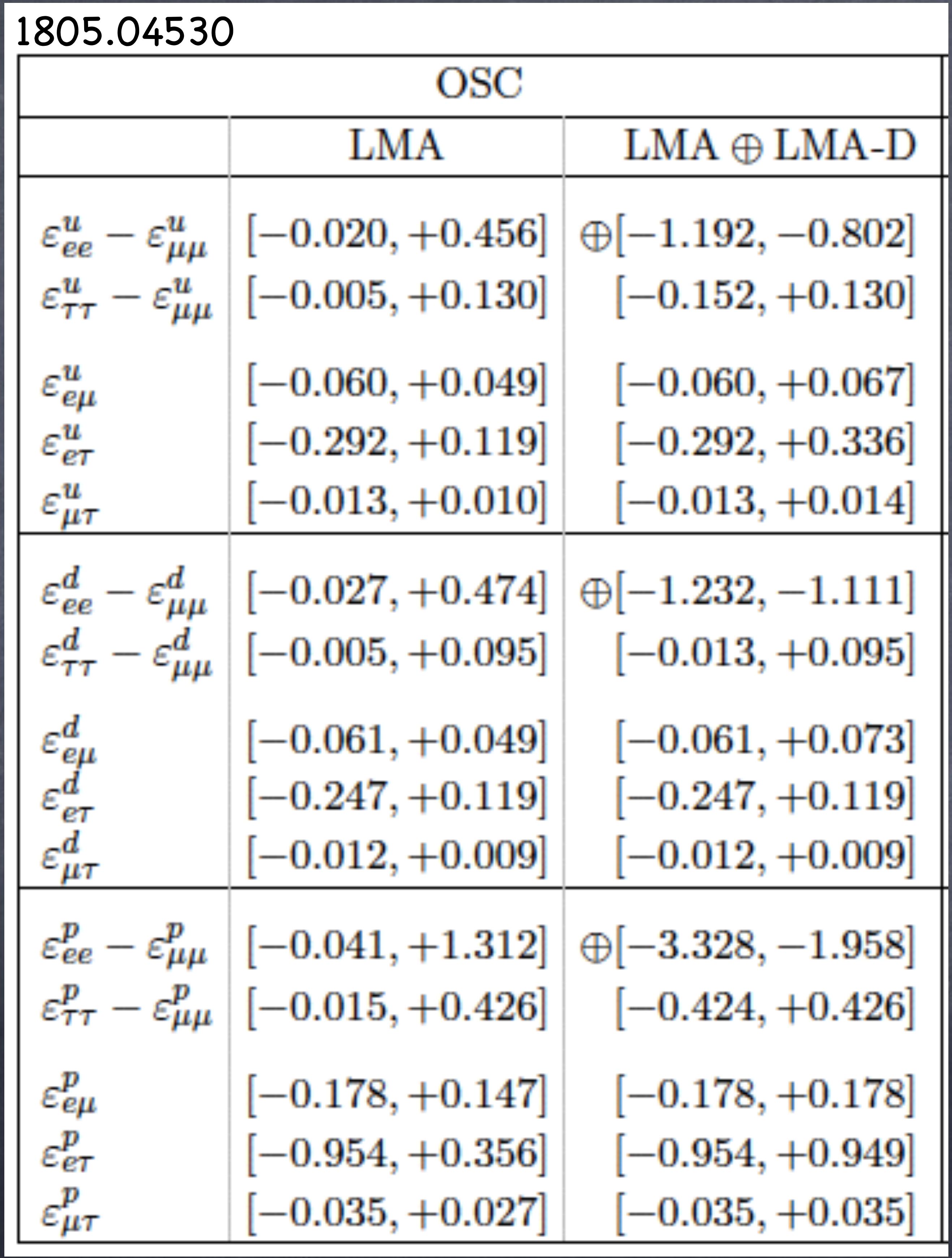
$$\alpha, \beta = e, \mu, \tau, \quad C = L, R, \quad f = u, d, e$$

$$\epsilon_{\alpha\beta} \equiv \sum_{f,C} \epsilon^{fC}_{\alpha\beta} \frac{N_f}{N_e}$$

On earth $N_u = N_d = 3N_e$

- Model independent bounds from neutrino oscillation data allow large diagonal NSI parameters with O(1) differences between them

- COHERENT bounds obtained using contact approx don't apply for mediators lighter than 50 MeV



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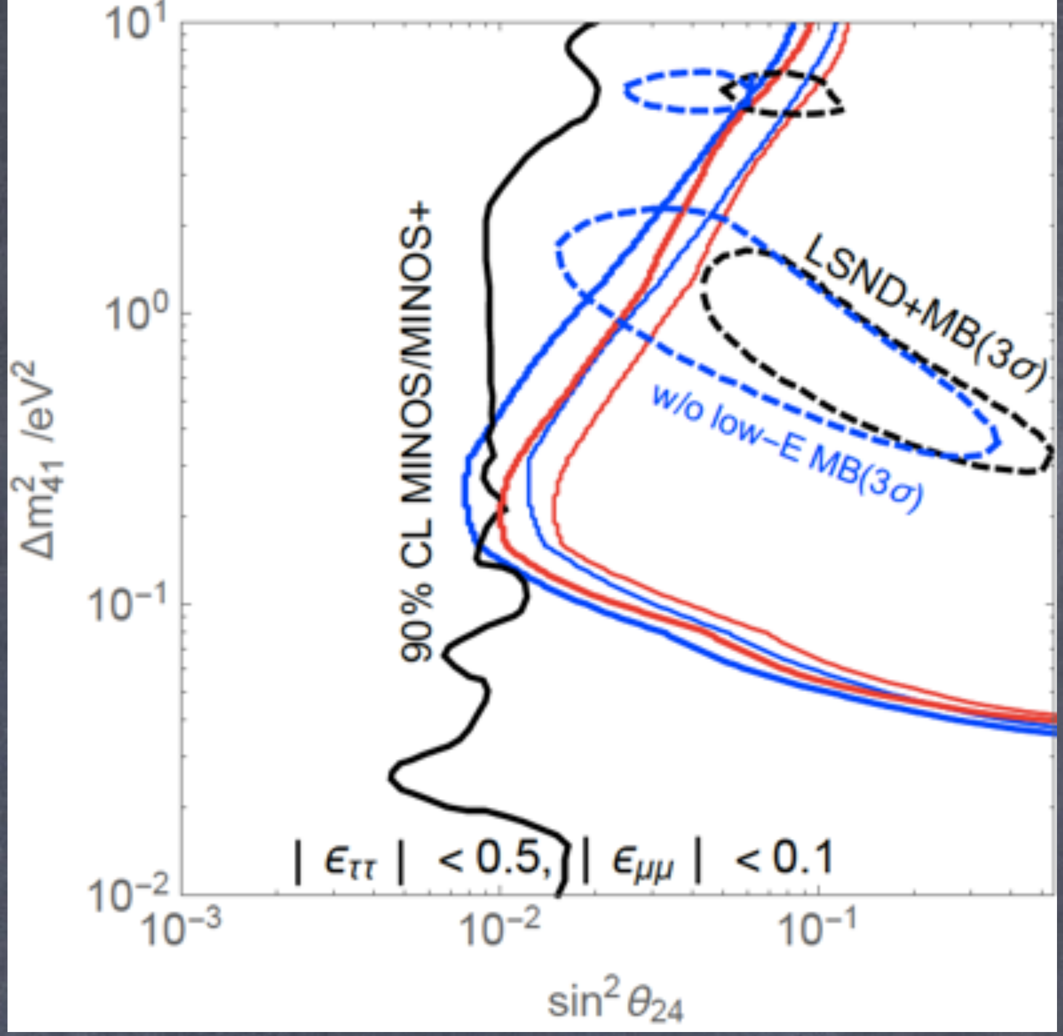
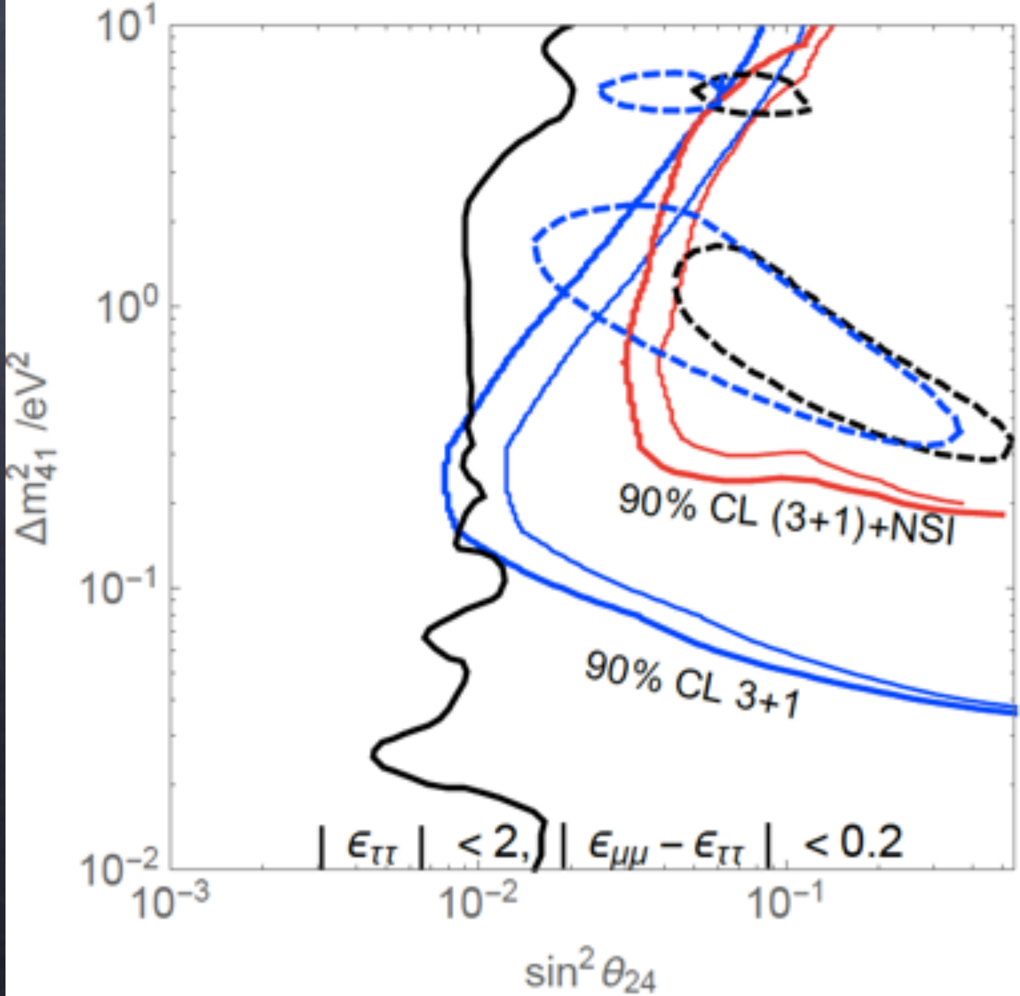
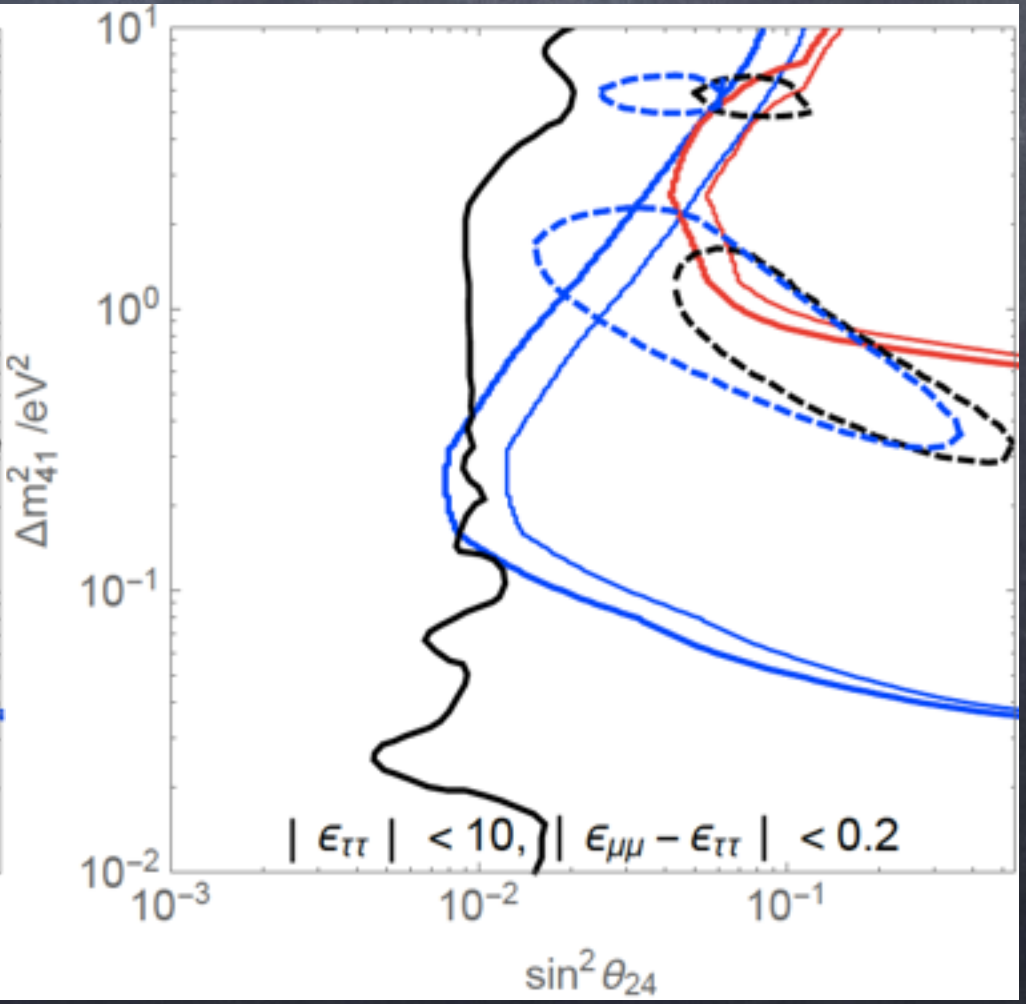
	OSC	
	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.005, +0.130]$	$[-0.152, +0.130]$
$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.067]$
$\varepsilon^u_{e\tau}$	$[-0.292, +0.119]$	$[-0.292, +0.336]$
$\varepsilon^u_{\mu\tau}$	$[-0.013, +0.010]$	$[-0.013, +0.014]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$[-0.027, +0.474]$	$\oplus[-1.232, -1.111]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$[-0.005, +0.095]$	$[-0.013, +0.095]$
$\varepsilon^d_{e\mu}$	$[-0.061, +0.049]$	$[-0.061, +0.073]$
$\varepsilon^d_{e\tau}$	$[-0.247, +0.119]$	$[-0.247, +0.119]$
$\varepsilon^d_{\mu\tau}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$
$\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$	$[-0.041, +1.312]$	$\oplus[-3.328, -1.958]$
$\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$	$[-0.015, +0.426]$	$[-0.424, +0.426]$
$\varepsilon^p_{e\mu}$	$[-0.178, +0.147]$	$[-0.178, +0.178]$
$\varepsilon^p_{e\tau}$	$[-0.954, +0.356]$	$[-0.954, +0.949]$
$\varepsilon^p_{\mu\tau}$	$[-0.035, +0.027]$	$[-0.035, +0.035]$

Bottomline:



Adapted from 1602.08766, 1703.00860, 1710.06488, 1803.10661





Simplifications

- For E > 500 GeV, electron flavor can be neglected
- Mass splittings between active neutrinos negligible
- Assume all phases in the mixing matrix are zero
- Assume all NSI parameters are real

3+1 oscillations with NSI

$$H = \frac{\Delta m_{41}^2}{2E_\nu}\left[\begin{pmatrix} 0 & s_{24}s_{34} & s_{24}c_{34} \\ s_{24}s_{34} & s_{34}^2 & s_{34}c_{34} \\ s_{24}c_{34} & s_{34}c_{34} & c_{34}^2 \end{pmatrix} + \hat{A}\begin{pmatrix} \epsilon_{\mu\mu} & \epsilon_{\mu\tau} & 0 \\ \epsilon_{\mu\tau} & \epsilon_{\tau\tau} & 0 \\ 0 & 0 & \kappa \end{pmatrix}\right] + \mathcal{O}(s_{14}^2, s_{24}^2)$$

$$\hat{A} = \frac{2\sqrt{2}G_F N_e E_\nu}{\Delta m_{41}^2} \qquad \kappa = \frac{N_n}{2N_e} \simeq 0.5$$

Special case: If the submatrix of NSI parameters is proportional to the identity, the NSI interaction can be attributed entirely to the sterile neutrino

3+1 oscillations with NSI

$$P_{\nu_\mu\nu_\mu} = 1 - 4\sum_{j<k} |U'_{\mu j}|^2 |U'_{\mu k}|^2 \sin^2(\lambda_k - \lambda_j)\frac{\Delta m^2_{41} L}{4E_\nu} \qquad j = 1, 2, 3$$

For $|\epsilon_{\mu\tau}|,\ |\epsilon_{\tau\tau} - \epsilon_{\mu\mu}|,\ s_{24} \ll 1,$

$$U'_{\mu 1} \simeq 1$$

$$U'_{\mu 2} \simeq \frac{2[s_{24}\sin(\theta_{34} - \xi) + \epsilon_{\mu\tau}\hat{A}\cos\xi]}{\lambda_2 - \lambda_1}$$

$$U'_{\mu 3} \simeq \frac{2[s_{24}\cos(\theta_{34} - \xi) + \epsilon_{\mu\tau}\hat{A}\sin\xi]}{\lambda_3 - \lambda_1}$$

$$\xi = \frac{1}{2}\arctan\frac{\sin 2\theta_{34}}{\cos 2\theta_{34} + (\kappa - \epsilon_{\tau\tau})\hat{A}}$$

$$\lambda_1 \simeq 0$$

$$\lambda_{2,3} \simeq \frac{1}{2}\left[1 + (\kappa - \epsilon_{\tau\tau})\hat{A} \mp \sqrt{1 + 2\cos 2\theta_{34}(\kappa - \epsilon_{\tau\tau})\hat{A} + (\kappa - \epsilon_{\tau\tau})^2\hat{A}^2}\right]$$

For antineutrinos, $\hat{A} \to -\hat{A}$

Notes and expectations

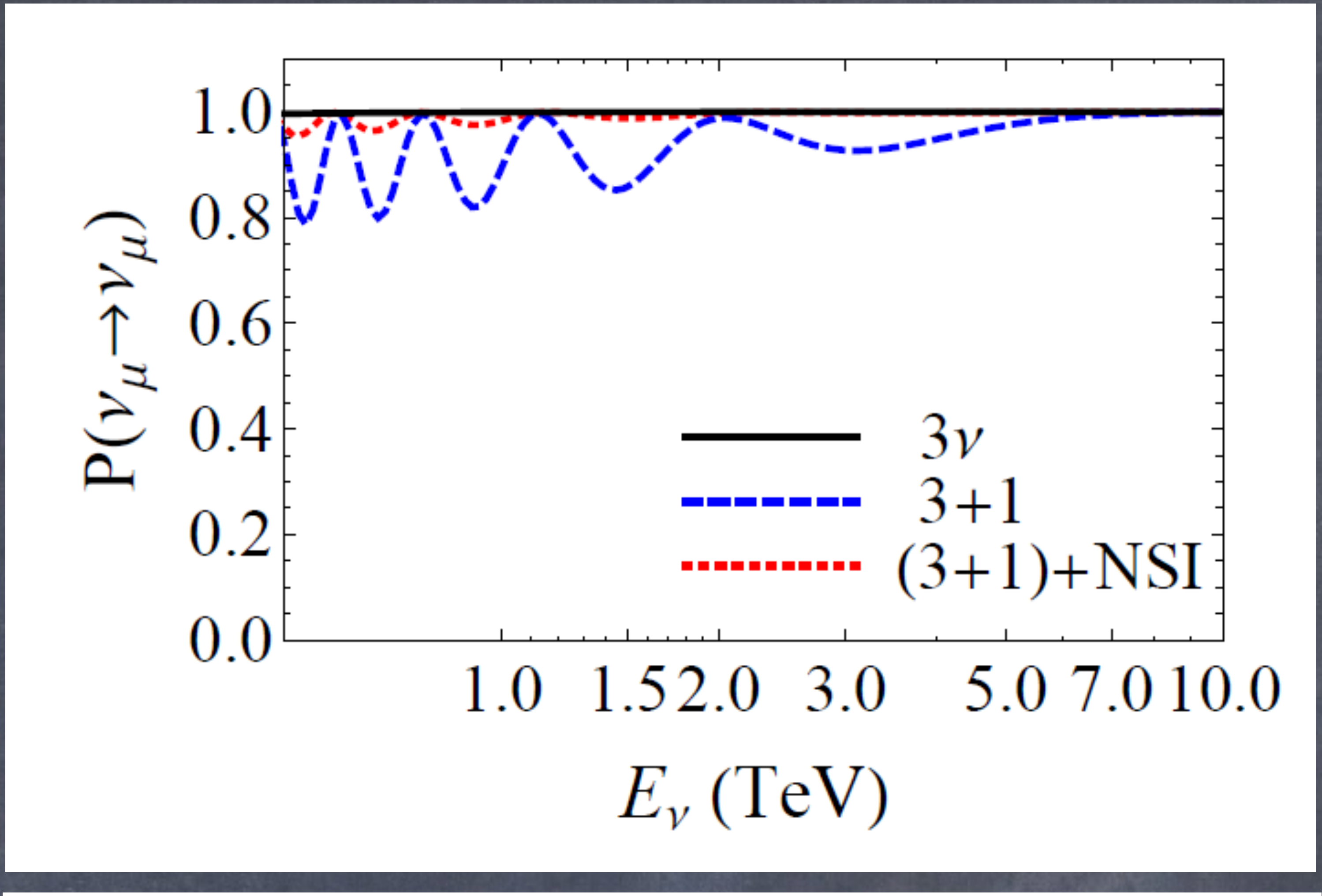
- IC data are consistent with 3-neutrino oscillations, for which survival probability is unity above 500 GeV
- Deviations from unity will be mainly governed by mixing matrix elements, not oscillation frequencies
- $\therefore \epsilon_{\mu\tau}$ will be constrained to be close to 0
- Large values of $\epsilon_{\tau\tau}$ suppress the mixing matrix elements, and will be consistent with IC data

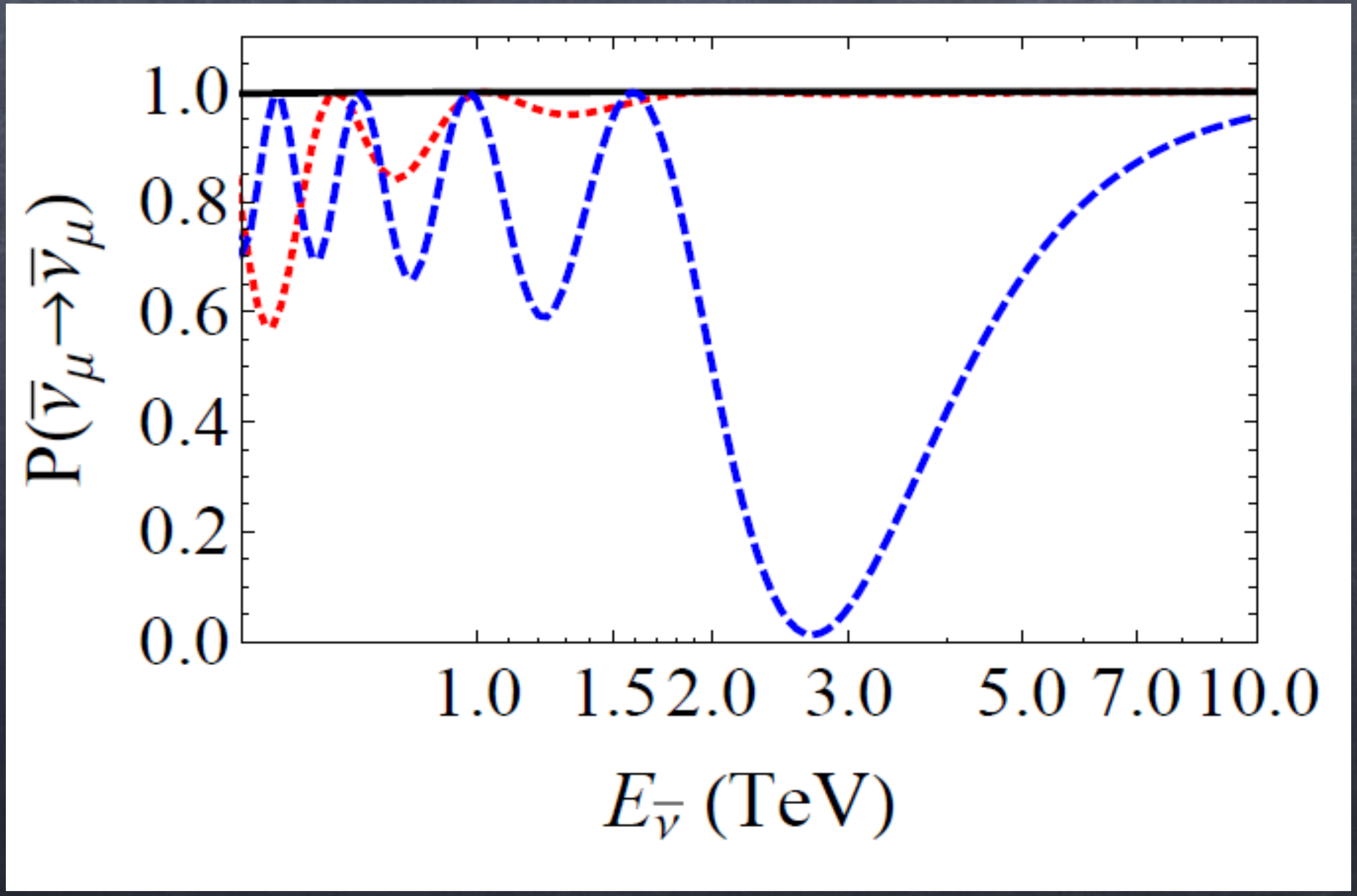
$$\Delta m^2_{41} = 0.63 \text{ eV}^2$$

$$\sin^2 2\theta_{24} = 0.25$$

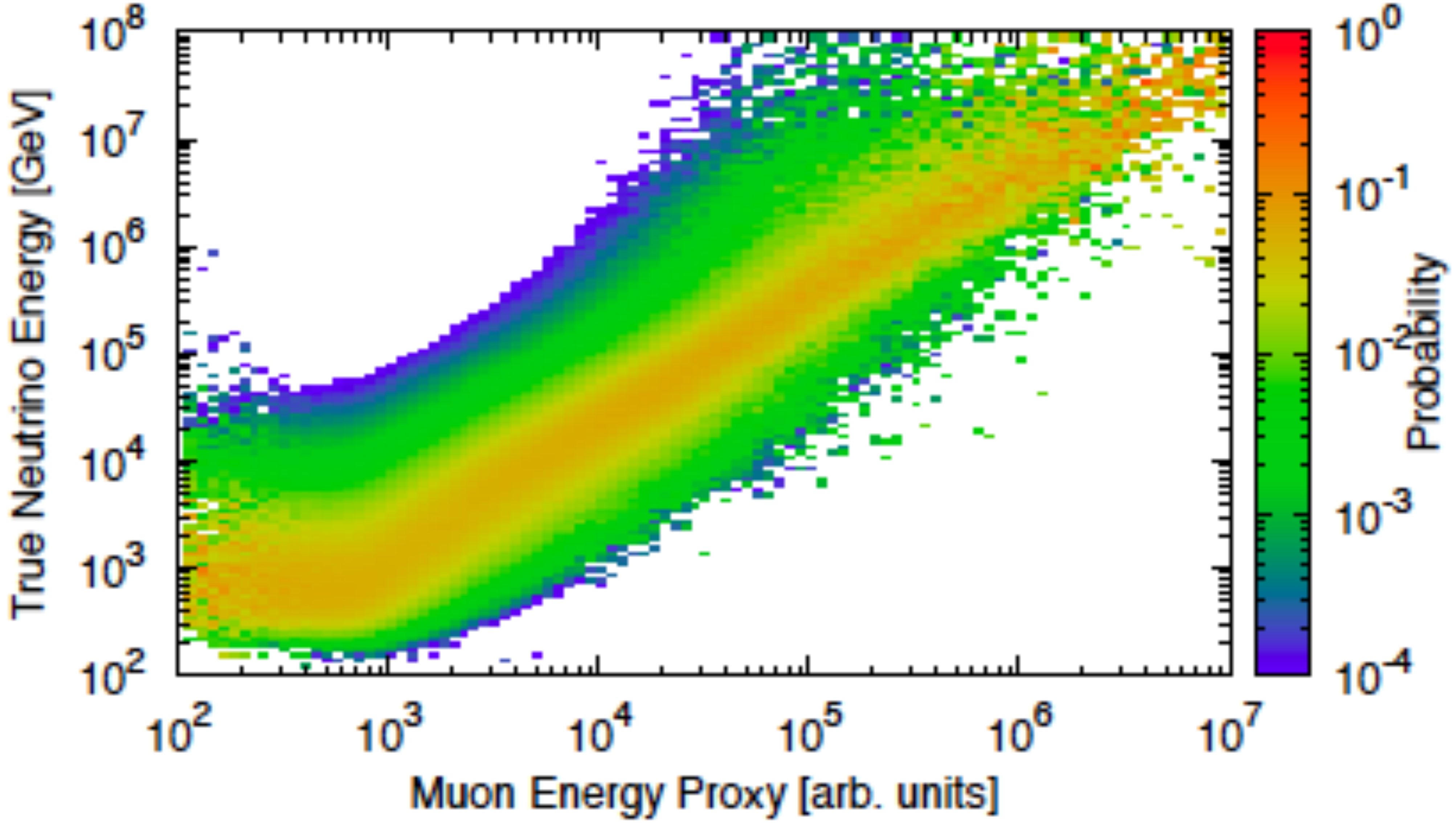
$$\epsilon_{\mu\mu} = -6.26$$

$$\epsilon_{\tau\tau} = -6.4$$





Muon energy proxy



(b) Distribution of energy proxy values arising from different true neutrino energies.

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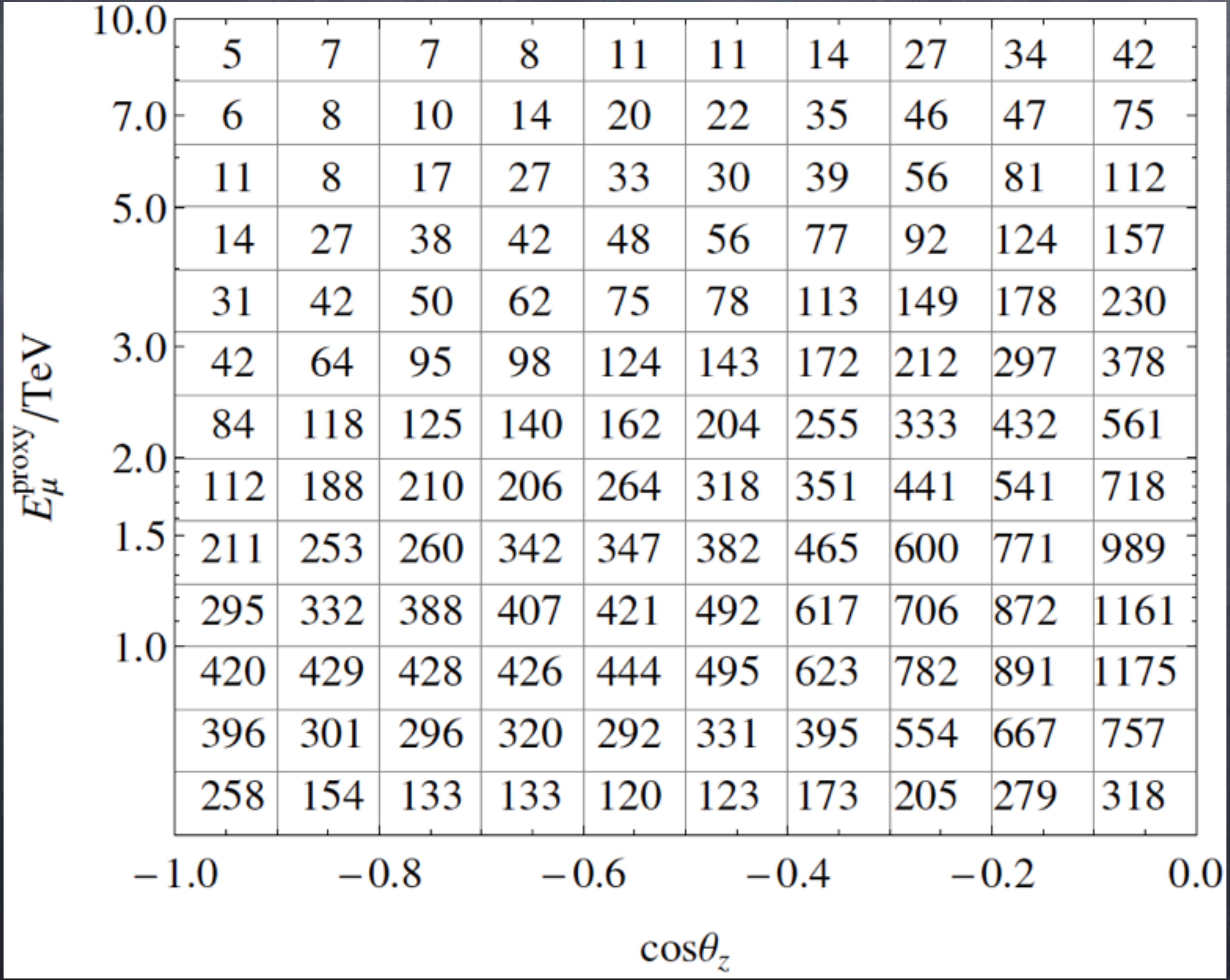
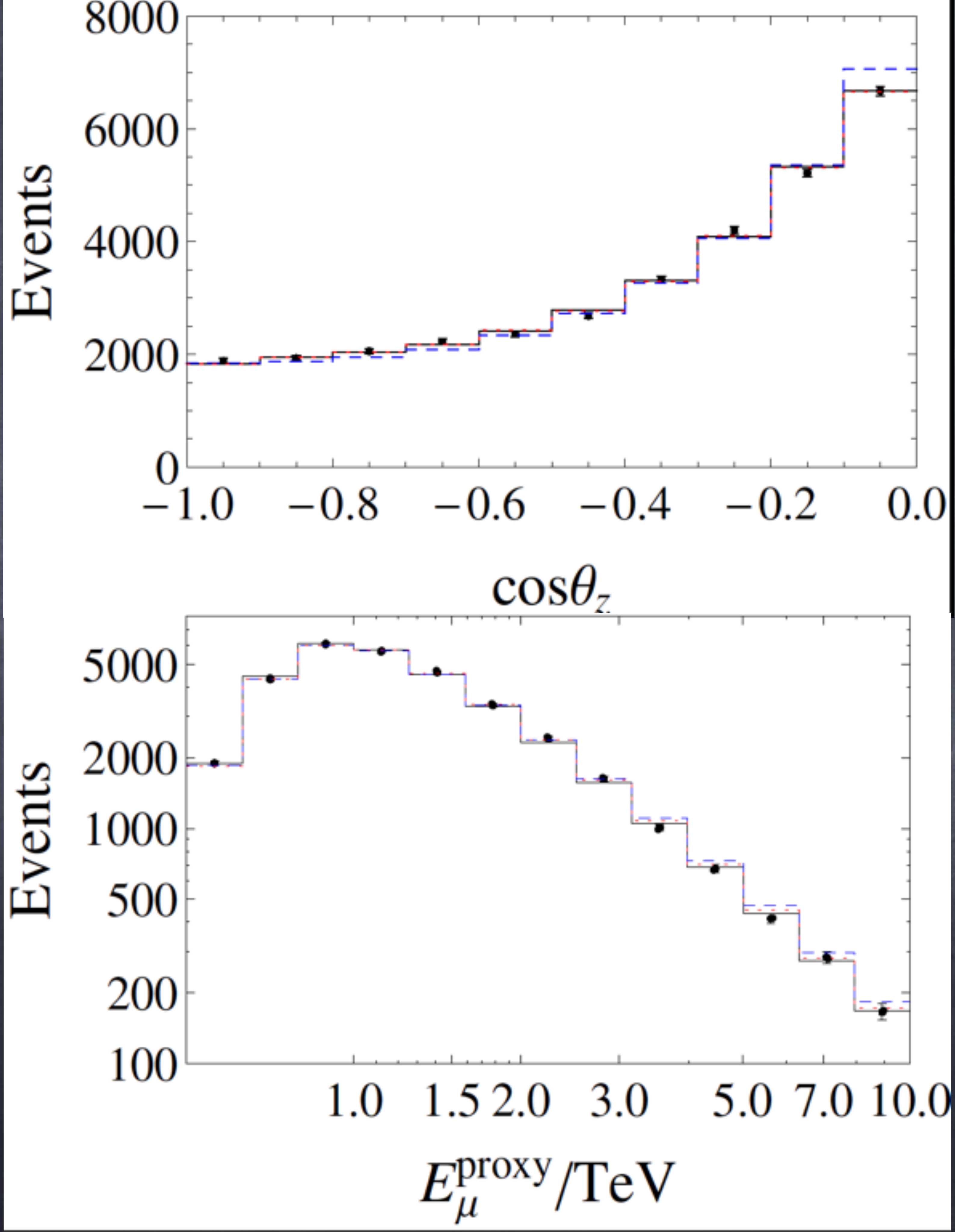
Although the energy loss observed in the detector is only loosely connected to the true neutrino energy, it is a useful statistical tool

2-year IceCube upgoing atmospheric data



5	7	7	8	11	11	14	27	34	42
6	8	10	14	20	22	35	46	47	75
11	8	17	27	33	30	39	56	81	112
14	27	38	42	48	56	77	92	124	157
31	42	50	62	75	78	113	149	178	230
42	64	95	98	124	143	172	212	297	378
84	118	125	140	162	204	255	333	432	561
112	188	210	206	264	318	351	441	541	718
211	253	260	342	347	382	465	600	771	989
295	332	388	407	421	492	617	706	872	1161
420	429	428	426	444	495	623	782	891	1175
396	301	296	320	292	331	395	554	667	757
258	154	133	133	120	123	173	205	279	318


8000
6000
4000
2000
0
Events
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
$\cos\theta_z$
5000
2000
1000
500
200
100
Events
1.0
1.5
2.0
3.0
5.0
7.0
10.0
E_μ^{proxy}/TeV

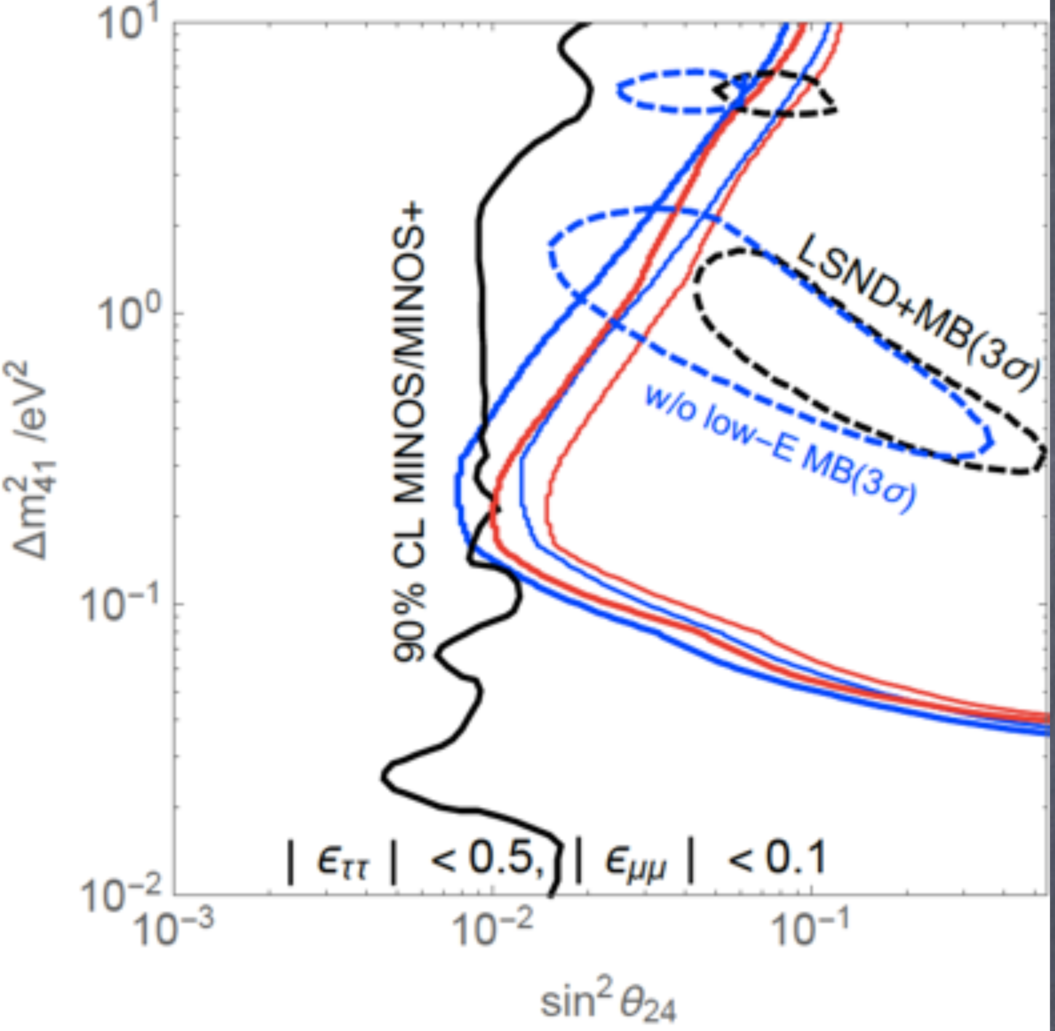
Analysis

Fix

- $\sin^2\theta_{14} = 0.01$ (best fit to reactor neutrino disappearance data) since IC is not sensitive to this parameter
- $\theta_{34} = 0$ to weaken the IC signal (i.e. relax the exclusion)
- $\epsilon_{\mu\tau} = 0$ to weaken the IC signal

Marginalize over atmospheric flux normalization, $\epsilon_{\mu\mu}$, $\epsilon_{\tau\tau}$ for each point in the $(\sin^2 2\theta_{24}, \Delta m^2_{41})$ plane

Results:



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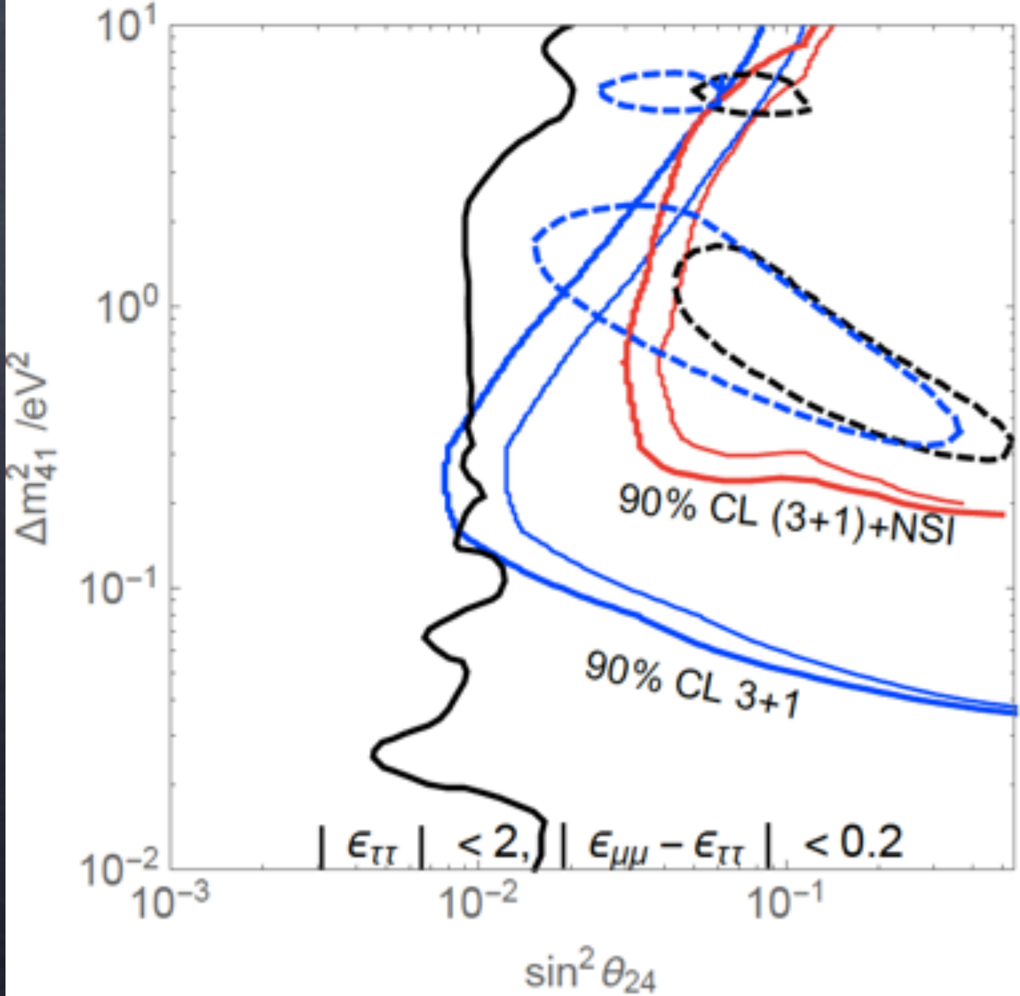
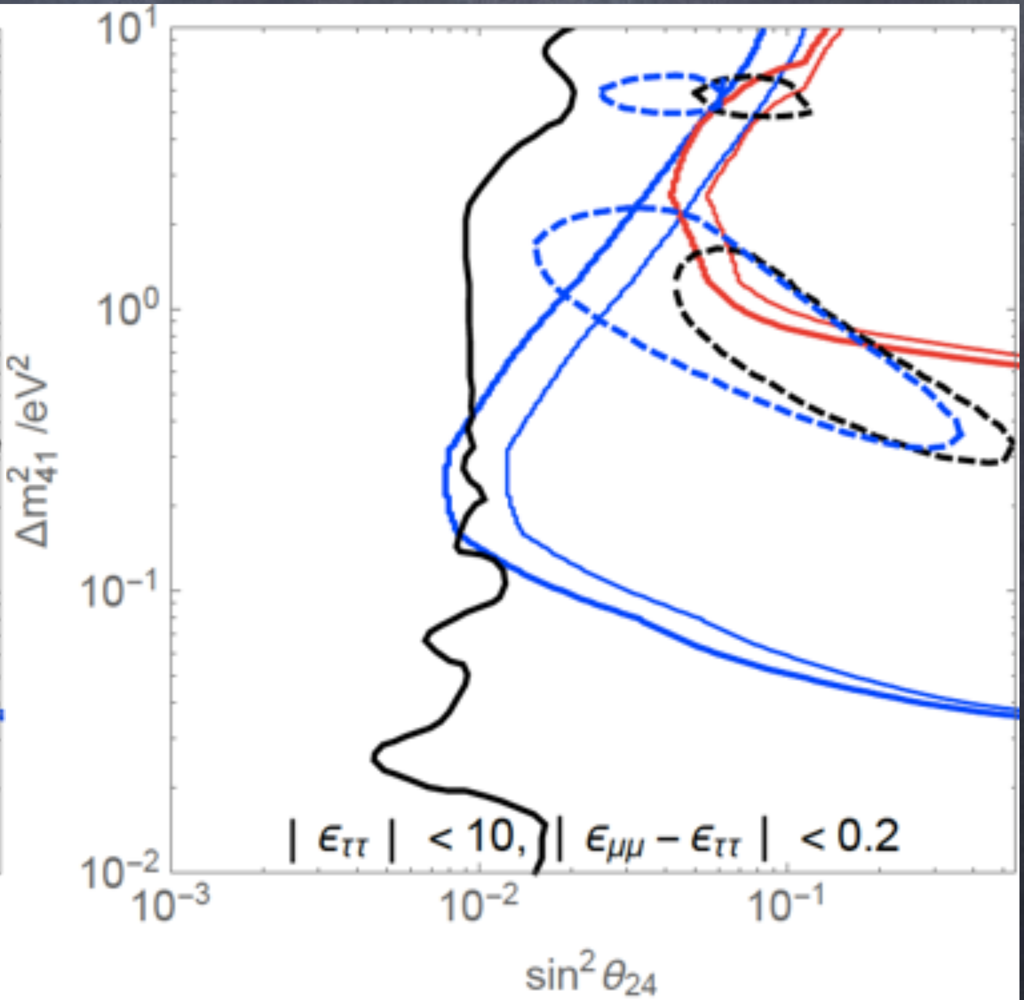
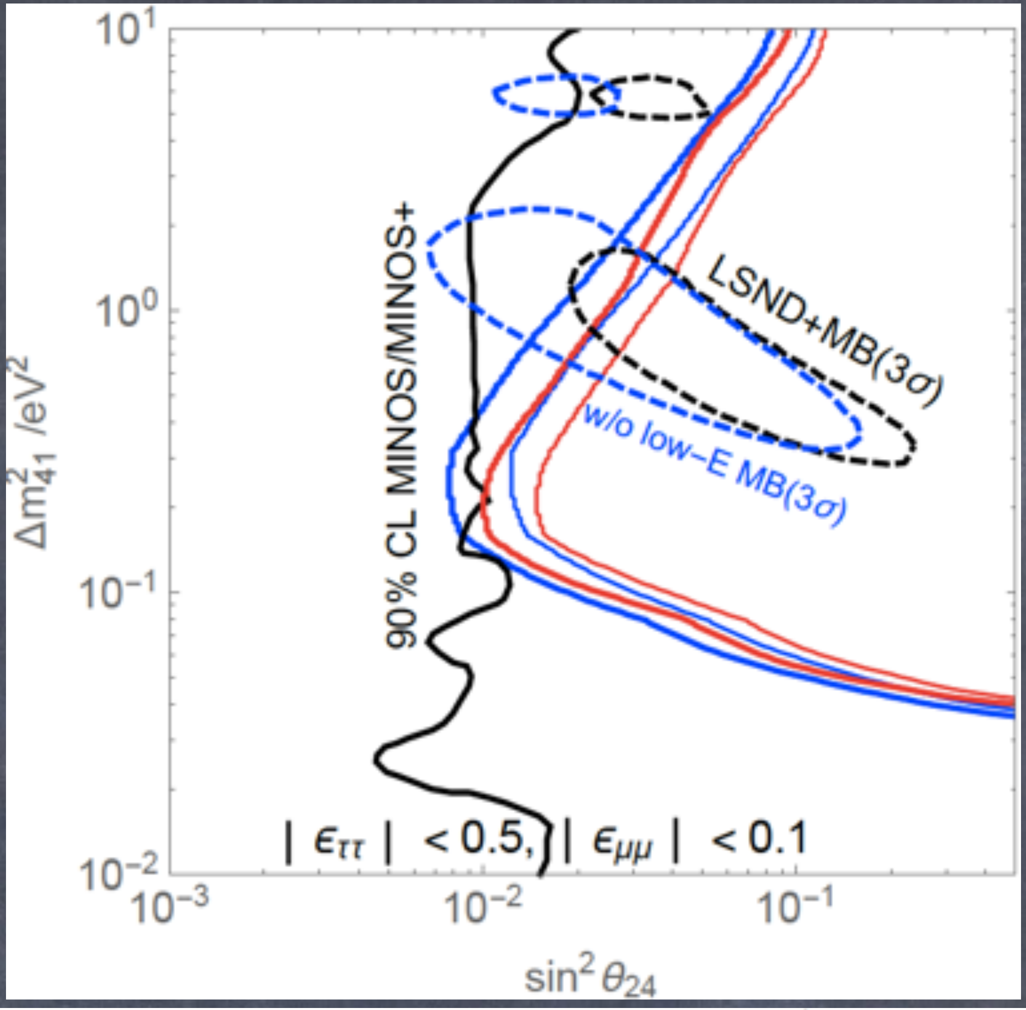




$\sin^2\theta_{14} = 0.023$



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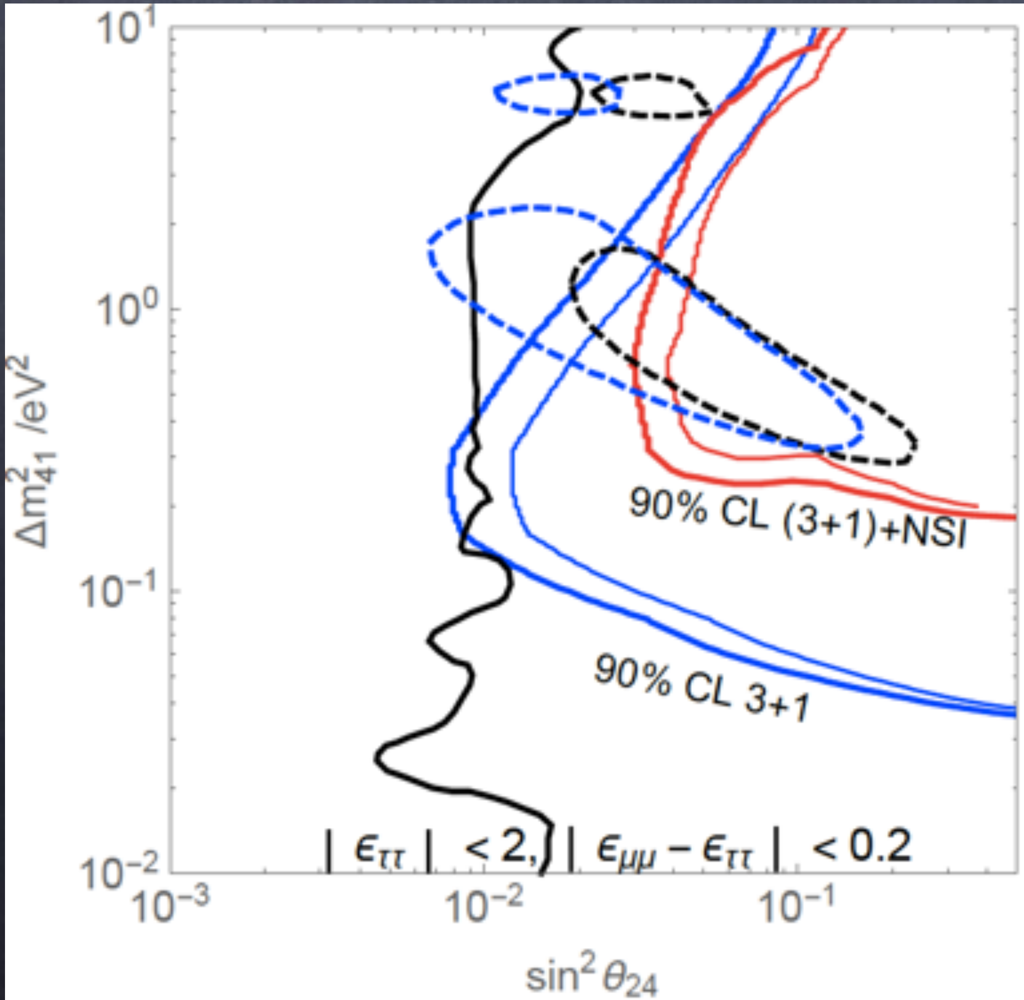

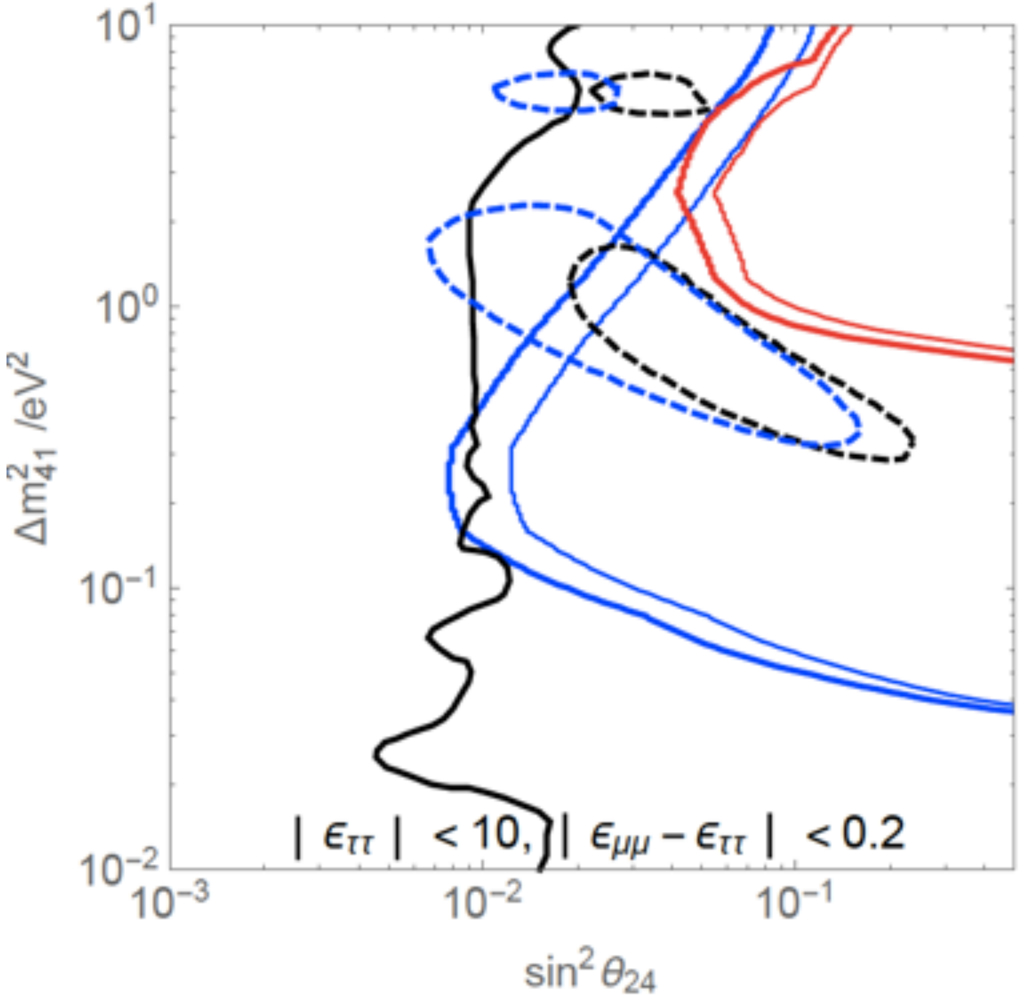

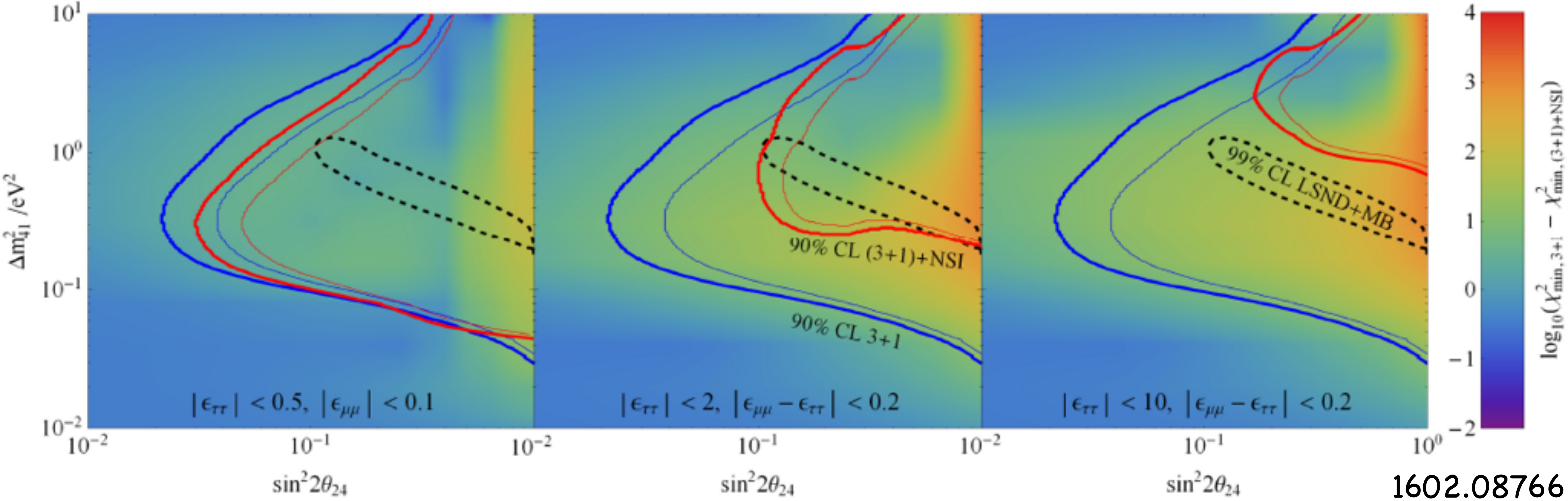

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The shading shows the effect of NSI on 3+1 oscillations

Summary

- 3+1 model for LSND/MiniBooNE anomaly excluded by 2-year IceCube atmospheric neutrino data at more than 99% C.L.

- LSND/MiniBooNE is consistent with IceCube in a (3+1)+NSI model if the NSI parameters only obey model-independent bounds

- NSI can be attributed entirely to sterile neutrino

- Can survive MINOS/MINOS+ bound only if systematics underestimated a la 1803.11488