Short-Baseline Tau Appearance

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Workshop on Future Short-Baseline Neutrino Experiments

Fermilab

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Outline

1. Basics of τ-appearance via oscillations;
2. Current bounds;
3. Expectations – Generic;
4. Expectations – Model;
5. Do we learn anything from a negative result?

Throughout, I will assume we are testing the hypothesis that the SBL anomalies are evidence for new neutrino states with masses around 1 eV.

I will also concentrate on $\nu_\mu \to \nu_\tau$ oscillation unless otherwise noted. Most of the time, the same argument goes for $\nu_e \to \nu_\tau$.

Some basics

- The idea is to look for ν_τ in a ν_μ/ν_e beam. For most beams, the ν_τ contamination is completely negligible (unless the energies are really high).
- Signal is τ-appearance. Kinematics requires $E_\nu > 3.5$ GeV.
- I am not going to discuss how one looks for τ. Ideas include (i) to identify the τ production point and the $\tau \to \mu$ decay vertex by searching for kinks (a la DONUT/OPERA), (ii) to study the p_T distribution of muons in the detector (a la NOMAD). μ from $\tau \to \mu$ have larger p_T.

Current Bounds:

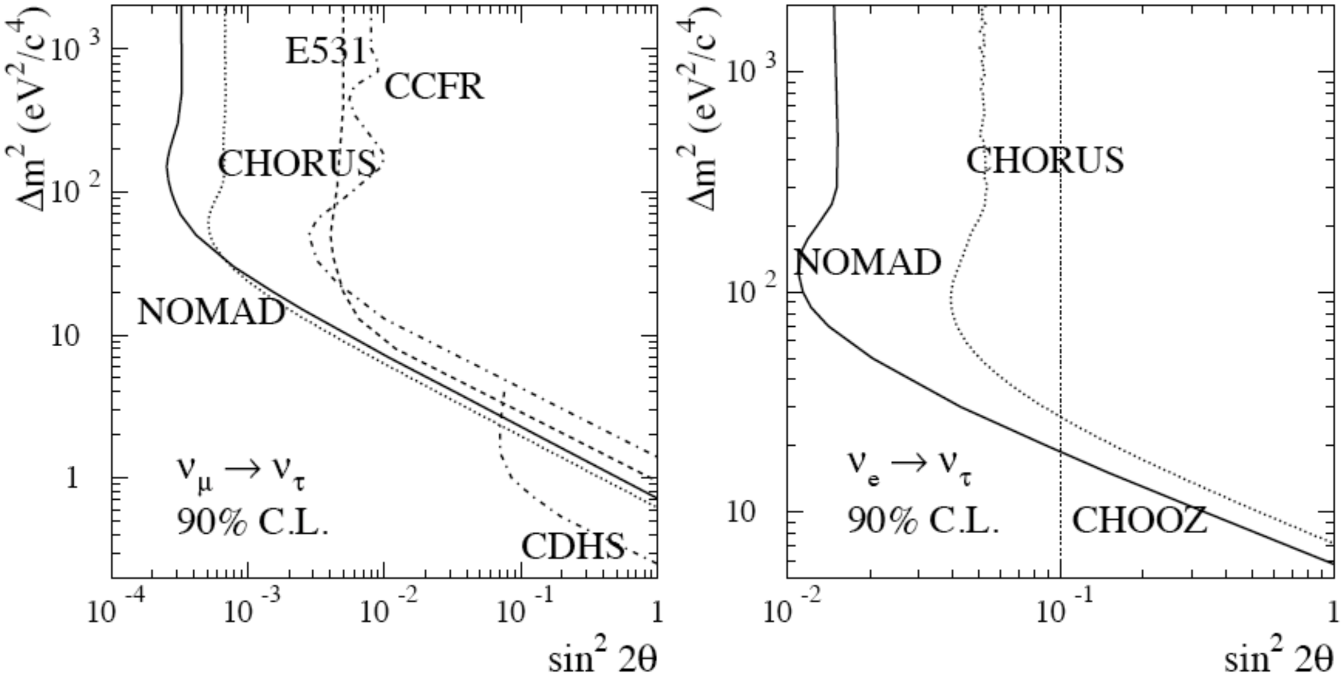
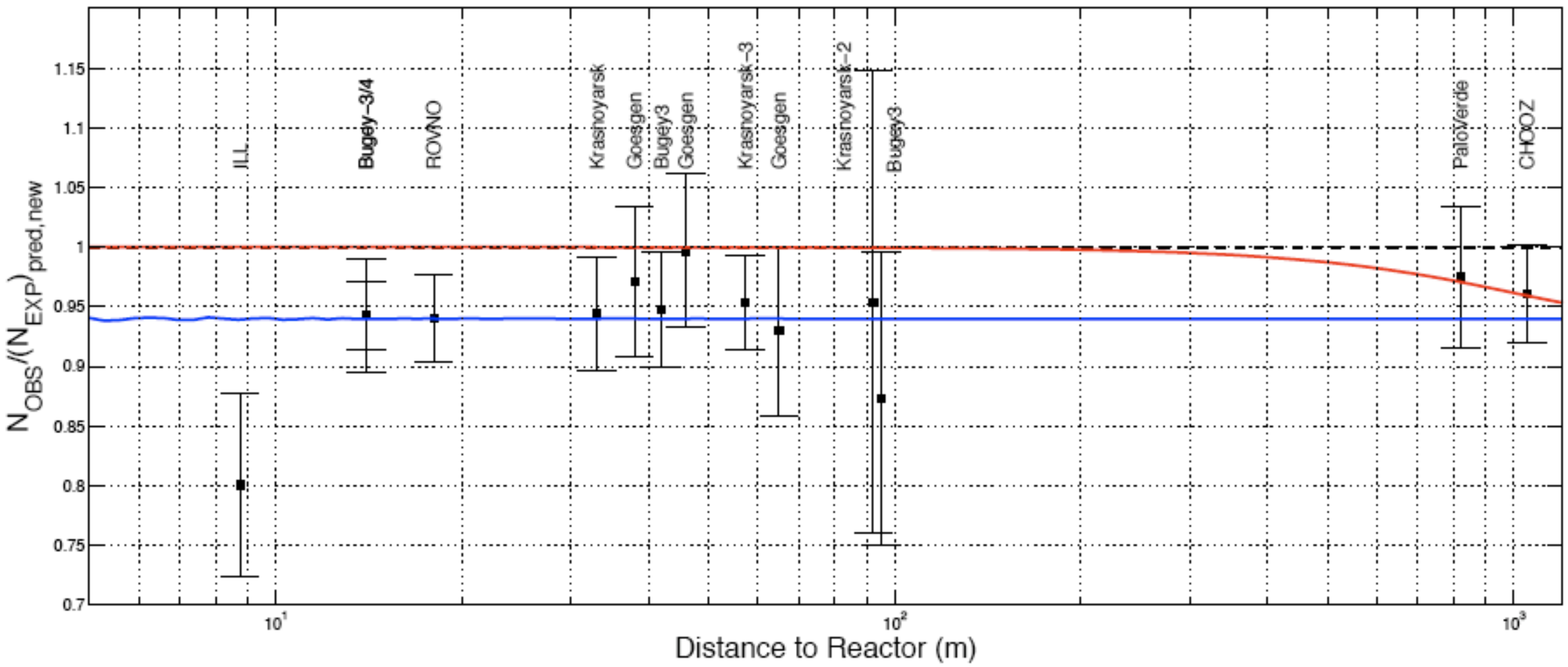
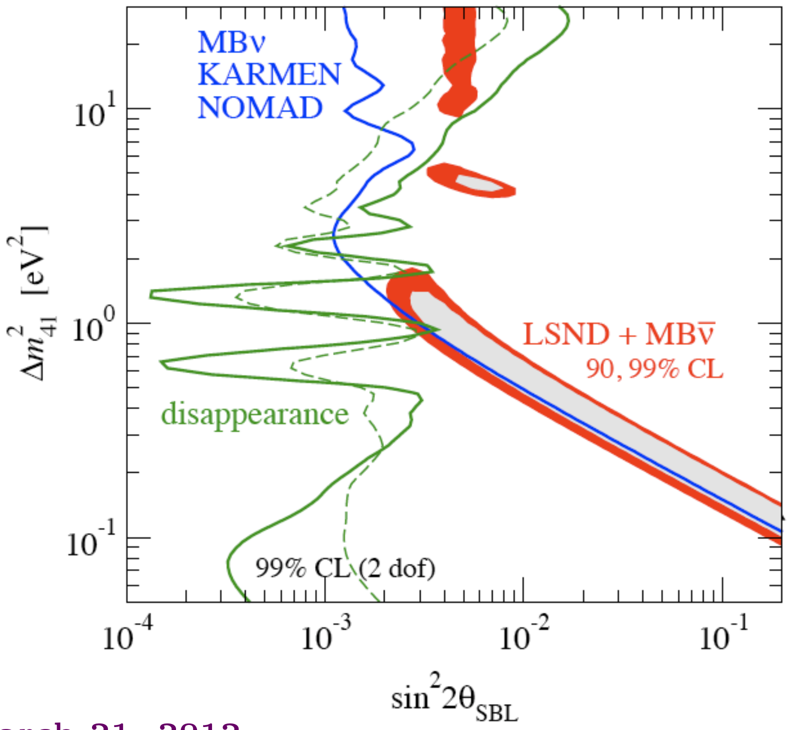


Fig. 14. Contours outlining a 90 % CL region in the $\Delta m^2 - \sin^2 2\theta$ plane for the two-family oscillation scenario. The NOMAD $\nu_\mu \rightarrow \nu_\tau$ (left) and $\nu_e \rightarrow \nu_\tau$ (right) curves are shown as solid lines, together with the limits published by other experiments [20–24]

Lowering this to the 1 eV^2 domain: For $L = 1$ km and $E = 5$ GeV, the new oscillation phase is around 0.25. $\sin^2 0.25 \sim 0.06$. Not too small. And it scales like $(L/E)^2$. Larger L helps quickly.

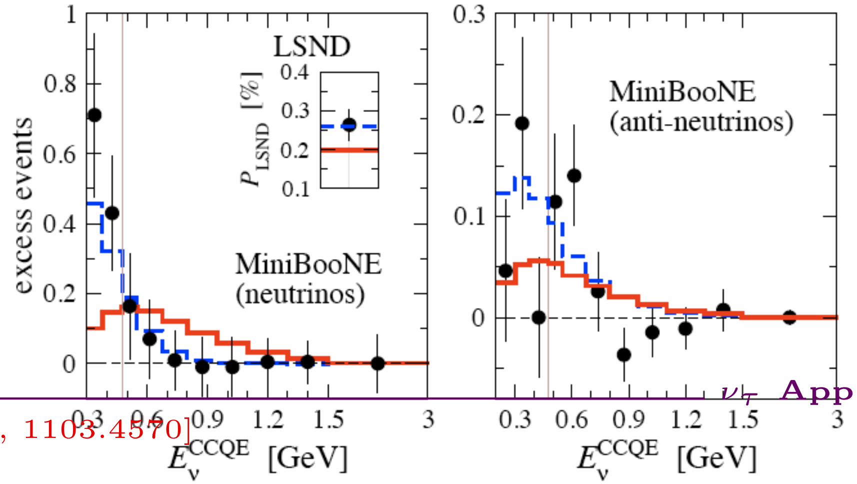


More Room For New Neutrinos?



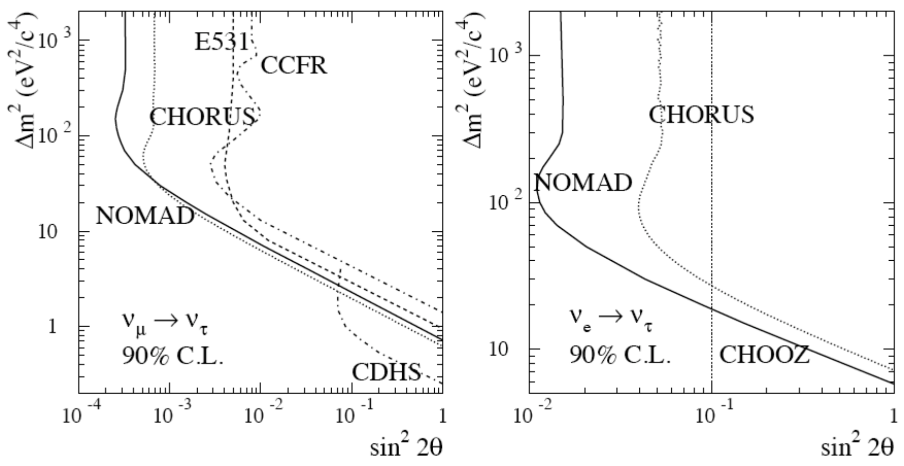
	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

Table II: Parameter values and χ^2 at the global best fit points for 3+2 and 1+3+1 oscillations (Δm^2's in eV^2).



'igure 3: Global constraints on sterile neutrinos in the 3+1
.odel. We show the allowed regions at 90% and 99% CL from

[Kopp,Maltoni,Schwetz, 1103.4570]



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$$P_{\mu\tau} \sim \sin^2 2\theta_{\mu\tau} \sin^2\left(\frac{\Delta m^2_4 L}{4E}\right), \sin^2 2\theta_{\mu\tau} = 4|U_{\mu 4}|^2|U_{\tau 4}|^2 \Rightarrow |U_{\mu 4}|^2 \sim 0.02.$$

KEY QUESTION: What is $U_{\tau 4}$?

Generically, we would assume $|U_{\tau 4}| \sim |U_{e4}|, |U_{\mu 4}|$. This is what happens for the all the known elements of the leptonic mixing matrix! If this is the case, we expect…

$$\sin^2 2\theta_{\mu\tau} \sim 10^{-3}$$

i.e., "lowering" (in Δm^2) NOMAD's curve by around one order of magnitude.

The Seesaw Lagrangian

A simple[a], renormalizable Lagrangian that allows for neutrino masses is

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

where N_i ($i = 1, 2, n$) are SM gauge singlet fermions.

$\mathcal{L}_\nu$ is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, $\mathcal{L}_\nu$ describes, besides all other SM degrees of freedom, $3+n$ Majorana fermions: $3+n$ **neutrinos.**

[a] Only requires the introduction of two or more fermionic degrees of freedom, no new interactions or symmetries.

More Details:

$$m_\nu = \begin{pmatrix} 0 & \lambda v \\ (\lambda v)^t & M \end{pmatrix},$$

M is diagonal, and all its eigenvalues are real and positive. The charged lepton mass matrix also diagonal, real, and positive.

To leading order in $(\lambda v)M^{-1}$, the three lightest neutrino mass eigenvalues are given by the eigenvalues of

$$m_a = \lambda v M^{-1} (\lambda v)^t,$$

where m_a is the mostly active neutrino mass matrix, while the heavy sterile neutrino masses coincide with the eigenvalues of M.

$(3+n)\times(3+n)$ mixing matrix U $[U^t m_\nu U = \mathrm{diag}(m_1, m_2, m_3, m_4, m_5, \ldots)]$ is

$$U = \left(\begin{array}{cc} V & \Theta \\ -\Theta^\dagger V & 1_{n\times n}\end{array}\right),$$

where V is the active neutrino mixing matrix (MNS matrix)

$$V^t m_a V = \mathrm{diag}(m_1, m_2, m_3),$$

and the matrix that governs active–sterile mixing is

$$\Theta = (\lambda v)^* M^{-1}.$$

One can solve for the Yukawa couplings and re-express

$$\Theta = V\sqrt{\mathrm{diag}(m_1, m_2, m_3)}R^\dagger M^{-1/2},$$

where R is a complex orthogonal matrix $RR^t = 1$.

Concrete Example: 2 right-handed neutrinos [AdG, W-C Huang, arXiv:1110.6122]

$$X_{\rm normal} = \begin{pmatrix} 0.23e^{i\phi} & 0.1e^{i\delta} \\ (0.25-0.02e^{-i\delta})e^{i\phi} & 0.70 \\ -(0.25+0.02e^{-i\delta})e^{i\phi} & 0.70 \end{pmatrix} \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix}$$

$$X_{\rm inverted} = \begin{pmatrix} 0.83e^{i\psi} & 0.55 \\ -(0.39+0.06e^{-i\delta})e^{i\psi} & 0.59-0.04e^{-i\delta} \\ (0.39-0.06e^{-i\delta})e^{i\psi} & -0.59-0.04e^{-i\delta} \end{pmatrix} \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix}$$

$$\zeta \in C$$

where

$$X_{\rm normal\ (inverted)} = \Theta\sqrt{\frac{m_{\rm heavy}}{m_3\ (m_2)}}$$

Some Relevant Examples: [AdG, W-C Huang, arXiv:1110.6122]

$\zeta = 3/4\pi + i$, $\delta = 6/5\pi$, $\phi = \pi/2$ and a normal mass hierarchy,

$$X_{\rm normal} = \left(\begin{array}{cc} 0.41e^{-0.66i} & 0.45e^{1.03i} \\ 0.62e^{2.67i} & 0.61e^{-2.62i} \\ 1.27e^{2.44i} & 1.26e^{-2.41i} \end{array} \right).$$

$\zeta = 2/3\pi + 0.3i$, $\delta = 0$, $\psi = \pi/2$, and an inverted mass hierarchy,

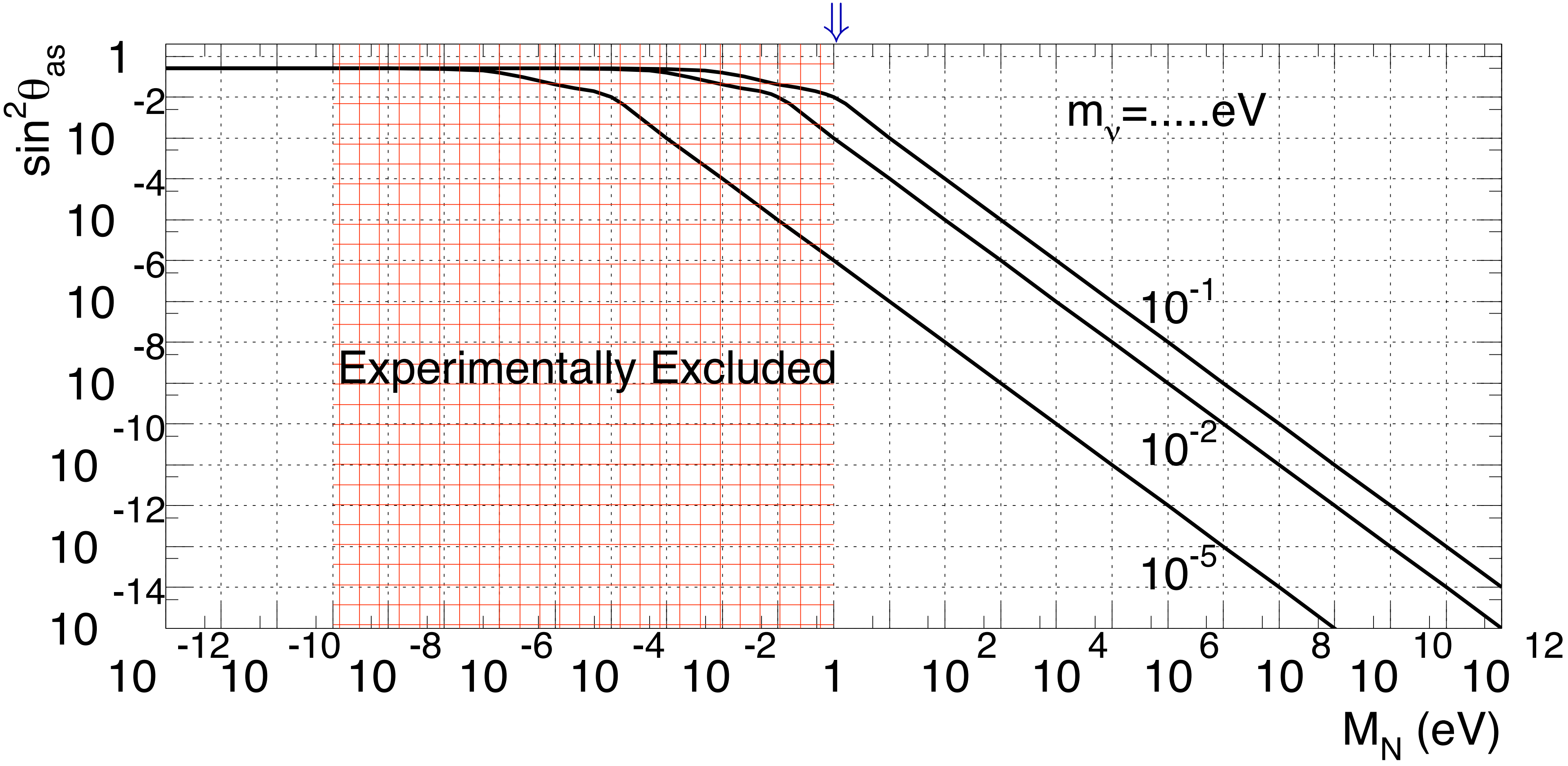
$$X_{\rm inverted} = \left(\begin{array}{cc} 0.44e^{-2.24i} & 0.62e^{1.83i} \\ 0.69e^{2.66i} & 0.66e^{-2.14i} \\ 0.71e^{-0.39i} & 0.60e^{0.89i} \end{array} \right).$$

both accommodate 3+2 fit for $m_4^2 = 0.5$ eV^2 and $m_5^2 = 0.9$ eV^2.Furthermore, $|U_{\tau 4}|$ and $|U_{\tau 5}|$ are completely fixed. No more free parameters. They are also both larger than (or at least as large as $|U_{\mu 4}|$ and $|U_{\mu 5}|$).

$\nu_\mu \to \nu_\tau$ MUST be observed if this is the origin of the two mostly sterile neutrinos.

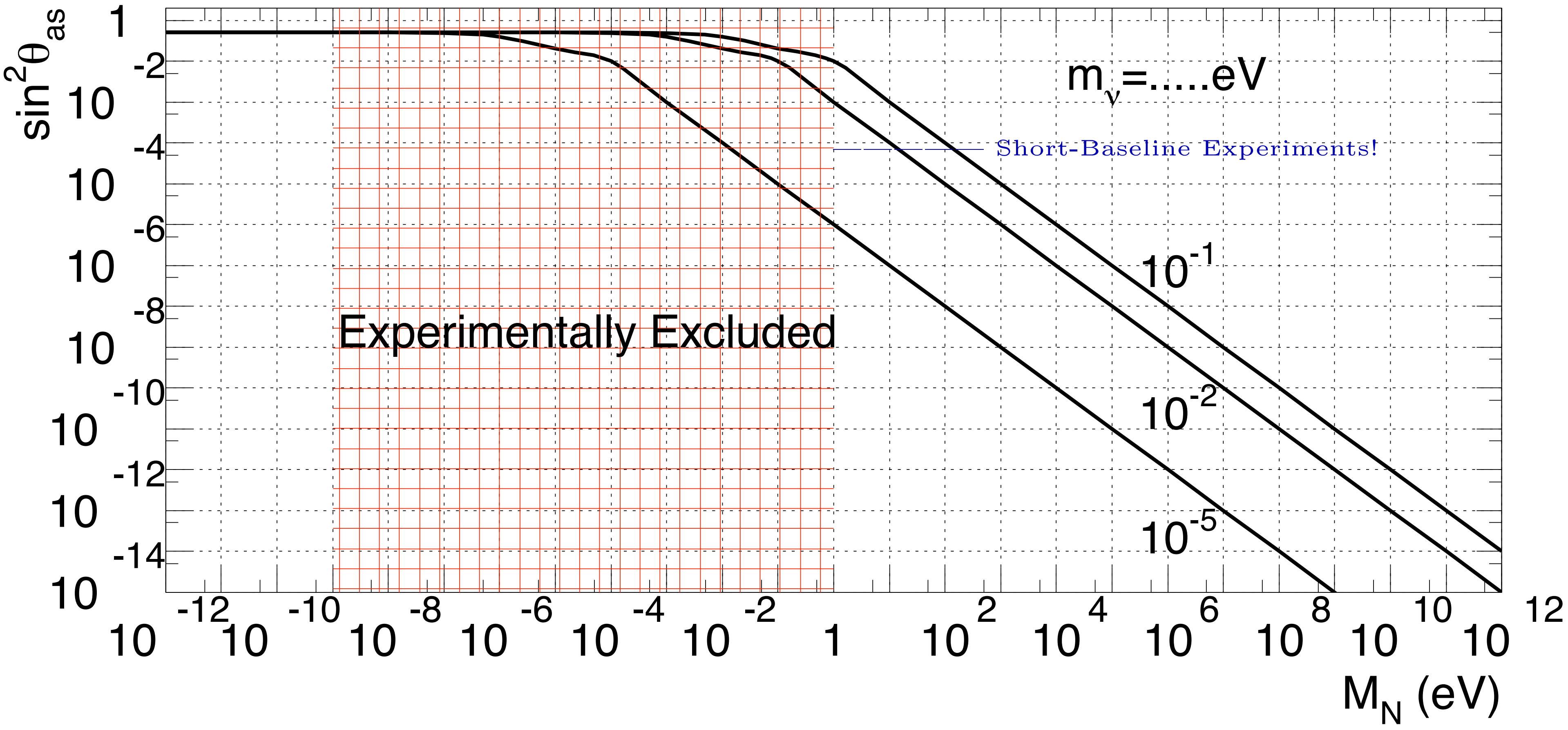
Constraining the Seesaw Lagrangian

[rough upper bound, see Donini et al, arXiv:1106.0064]

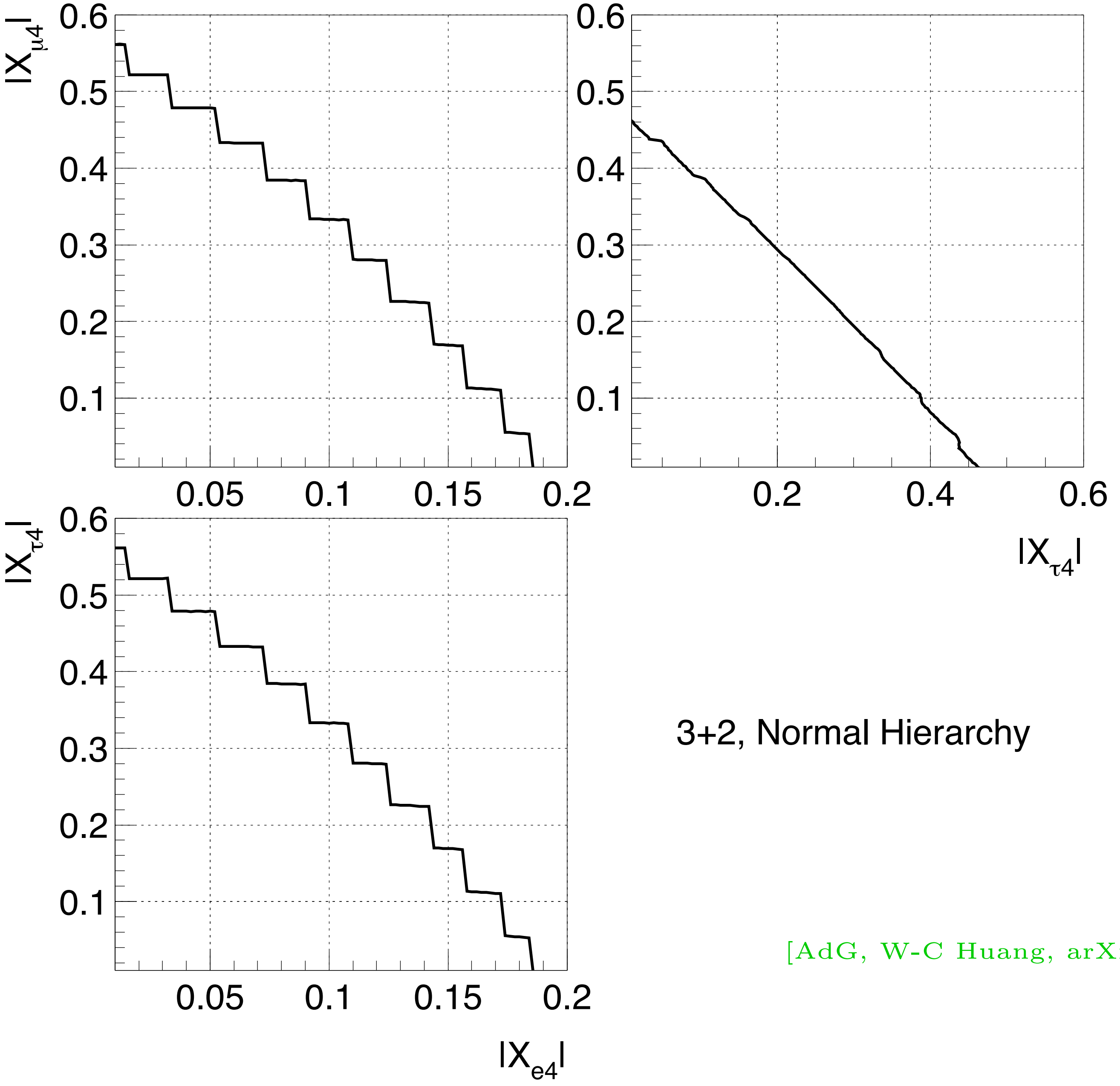


[AdG, Huang, Jenkins, arXiv:0906.1611]

Can we improve our sensitivity?



[AdG, Huang, Jenkins, arXiv:0906.1611]



3+2, Normal Hierarchy

[AdG, W-C Huang, arXiv:1110.6122]

Making Predictions, for an inverted mass hierarchy, $m_4 = 1$ eV($\ll m_5$)

- ν_e disappearance with an associated effective mixing angle $\sin^2 2\vartheta_{ee} > 0.02$. An interesting new proposal to closely expose the Daya Bay detectors to a strong β-emitting source would be sensitive to $\sin^2 2\vartheta_{ee} > 0.04$;

- ν_μ disappearance with an associated effective mixing angle $\sin^2 2\vartheta_{\mu\mu} > 0.07$, very close to the most recent MINOS lower bound;

- $\nu_\mu \leftrightarrow \nu_e$ transitions with an associated effective mixing angle $\sin^2 \vartheta_{e\mu} > 0.0004$;

- $\nu_\mu \leftrightarrow \nu_\tau$ transitions with an associated effective mixing angle $\sin^2 \vartheta_{\mu\tau} > 0.001$. A $\nu_\mu \to \nu_\tau$ appearance search sensitive to probabilities larger than 0.1% for a mass-squared difference of 1 eV^2 would definitively rule out $m_4 = 1$ eV if the neutrino mass hierarchy is inverted.

CONCLUSIONS

1. If oscillations are behind the SBL anomalies, it is generically expected that τ appearance should occur with an effective mixing angle that is similar to that for $\nu_\mu \to \nu_e$;
2. Of course, there remains the logical possibility that the new neutrino states have very small τ-components, e.g. $|U_{\mu 4}|^2 \ll 0.01$.
3. I presented a very simple scenario where the existence of mostly sterile neutrinos is related to the origin of neutrino masses. The scenario is quite predictive and, if the SBL anomalies have indeed run into these states, τ-appearance must happen at the part-per-mille level;
4. If one ignores the SBL anomalies, SBL τ-appearance searches will play an integral part as far as testing whether the seesaw scale is below 10 eV.