

The Current State of Neutrino Theory

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ν Flavor Oscillations are a Fact

Neutrino oscillation experiments have revealed that **neutrinos change flavor** after propagating a finite distance. The rate of change depends on the neutrino energy E_ν and the baseline L . The evidence is overwhelming.

- $\nu_\mu \rightarrow \nu_\tau$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ — atmospheric and accelerator experiments;
- $\nu_e \rightarrow \nu_{\mu,\tau}$ — solar experiments;
- $\bar{\nu}_e \rightarrow \bar{\nu}_{\text{other}}$ — reactor experiments;
- $\nu_\mu \rightarrow \nu_{\text{other}}$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_{\text{other}}$ — atmospheric and accelerator expts;
- $\nu_\mu \rightarrow \nu_e$ — accelerator experiments.

The simplest and **only satisfactory** explanation of **all** this data is that neutrinos have distinct masses, and mix.

Phenomenological Understanding of Neutrino Masses & Mixing

(The Standard Massive Neutrino Paradigm)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Definition of neutrino mass eigenstates (who are ν_1, ν_2, ν_3):

- $m_1^2 < m_2^2$ $\Delta m_{13}^2 < 0$ – Inverted Mass Hierarchy
- $m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$ $\Delta m_{13}^2 > 0$ – Normal Mass Hierarchy

$$\tan^2 \theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2 \theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin \theta_{13} e^{-i\delta}$$

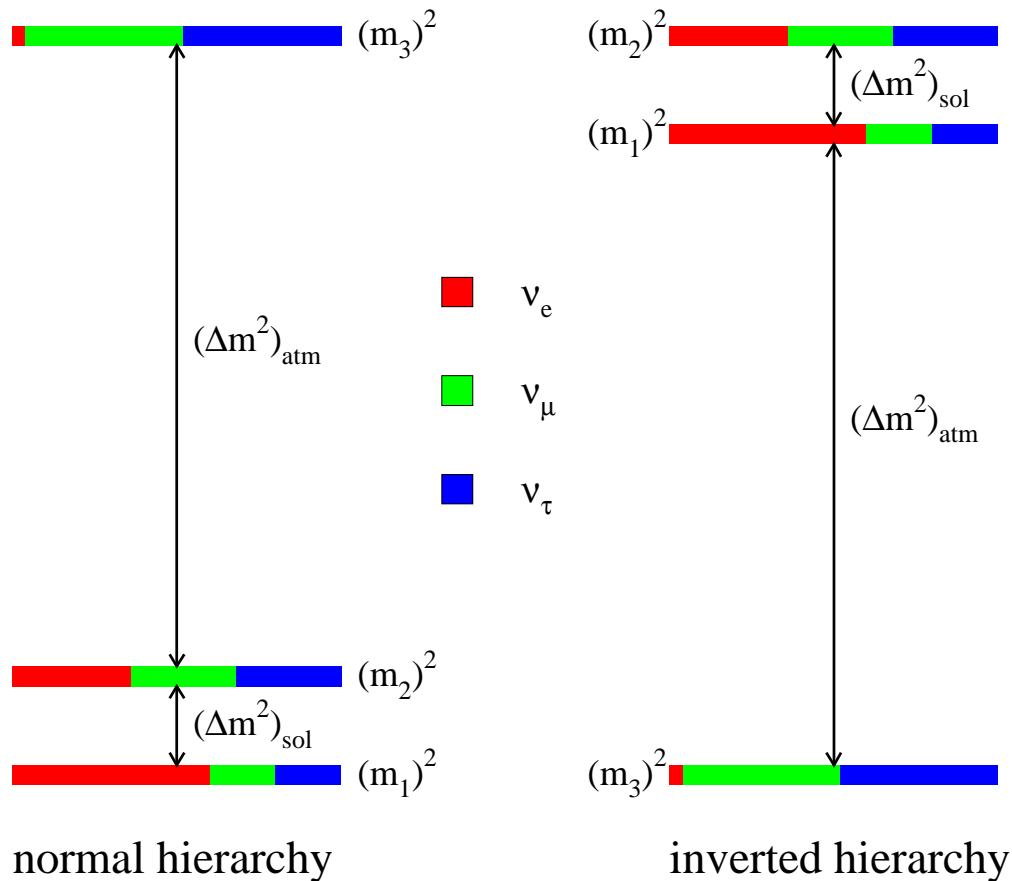
Three Flavor Mixing Hypothesis Fits All* Data Really Well.

parameter	best fit $\pm 1\sigma$	2σ	3σ
$\Delta m_{21}^2 [10^{-5} \text{eV}^2]$	7.62 ± 0.19	7.27–8.01	7.12–8.20
$\Delta m_{31}^2 [10^{-3} \text{eV}^2]$	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	$2.34 - 2.69$ $-(2.25 - 2.59)$	$2.26 - 2.77$ $-(2.15 - 2.68)$
$\sin^2 \theta_{12}$	$0.320^{+0.015}_{-0.017}$	0.29–0.35	0.27–0.37
$\sin^2 \theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$	$0.41\text{--}0.62$ $0.42\text{--}0.62$	$0.39\text{--}0.64$
$\sin^2 \theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$	$0.019\text{--}0.033$ $0.020\text{--}0.034$	$0.015\text{--}0.036$ $0.016\text{--}0.037$
δ	$(0.83^{+0.54}_{-0.64}) \pi$ $0.07\pi^a$	$0 - 2\pi$	$0 - 2\pi$

* Modulo short-baseline anomalies.

[Forero, Tórtola, Valle, 1205.4018]

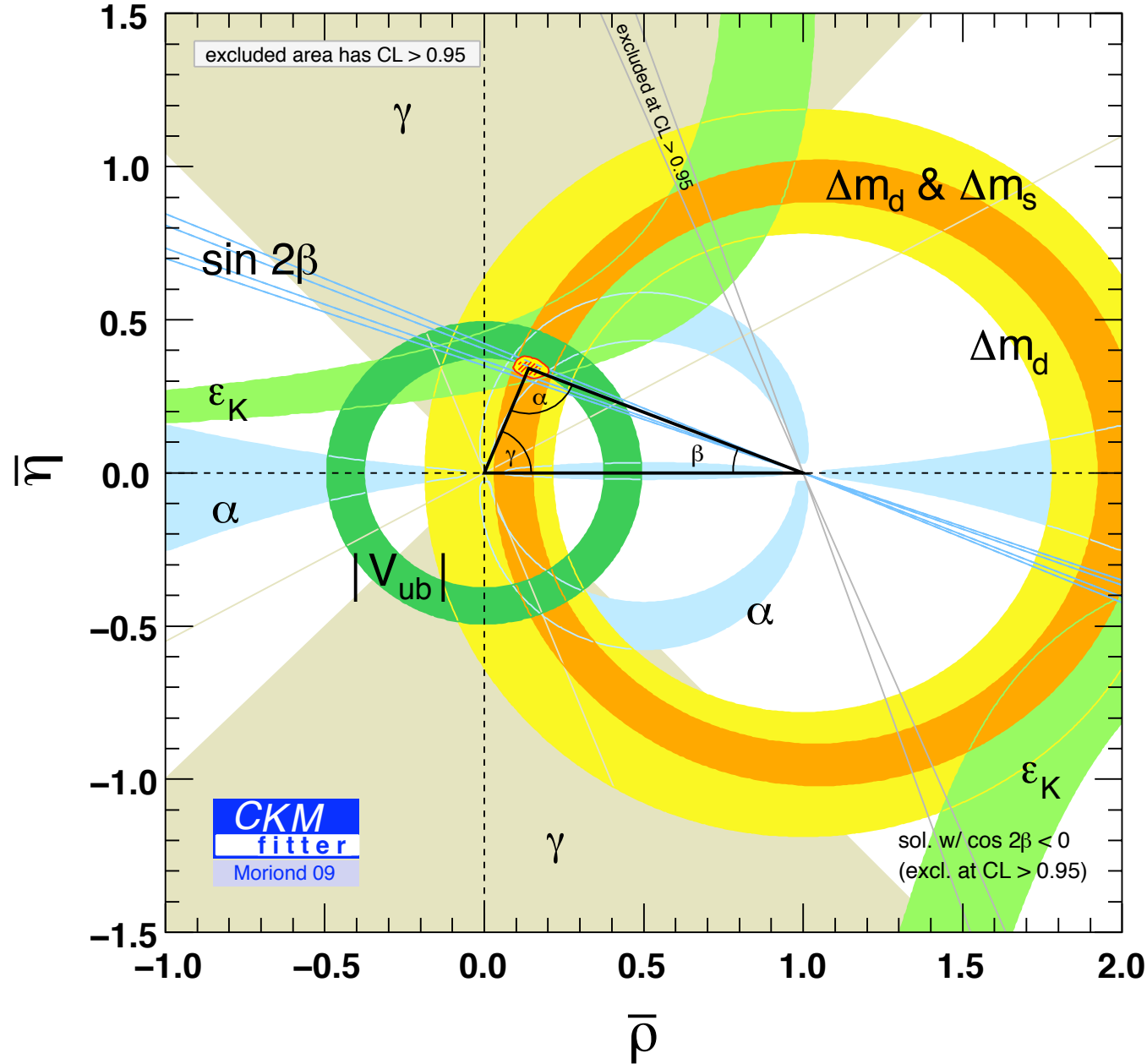
What We Know We Don't Know: Missing Oscillation Parameters



- What is the ν_e component of ν_3 ? ($\theta_{13} \neq 0!$)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$)
- Is ν_3 mostly ν_μ or ν_τ ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m_{13}^2 > 0$?)

\Rightarrow All of the above can “only” be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)



We need to do this in the lepton sector!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

What we have **really measured** (very roughly):

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu2}|^2 + |U_{\tau2}|^2$ – solar data;
- $|U_{e2}|^2 |U_{e1}|^2$ – KamLAND;
- $|U_{\mu3}|^2 (1 - |U_{\mu3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2 (1 - |U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{e3}|^2 |U_{\mu3}|^2$ (upper bound \rightarrow hint) – MINOS, T2K.

We still have a ways to go!

Not all is well(?): The Short Baseline Anomalies

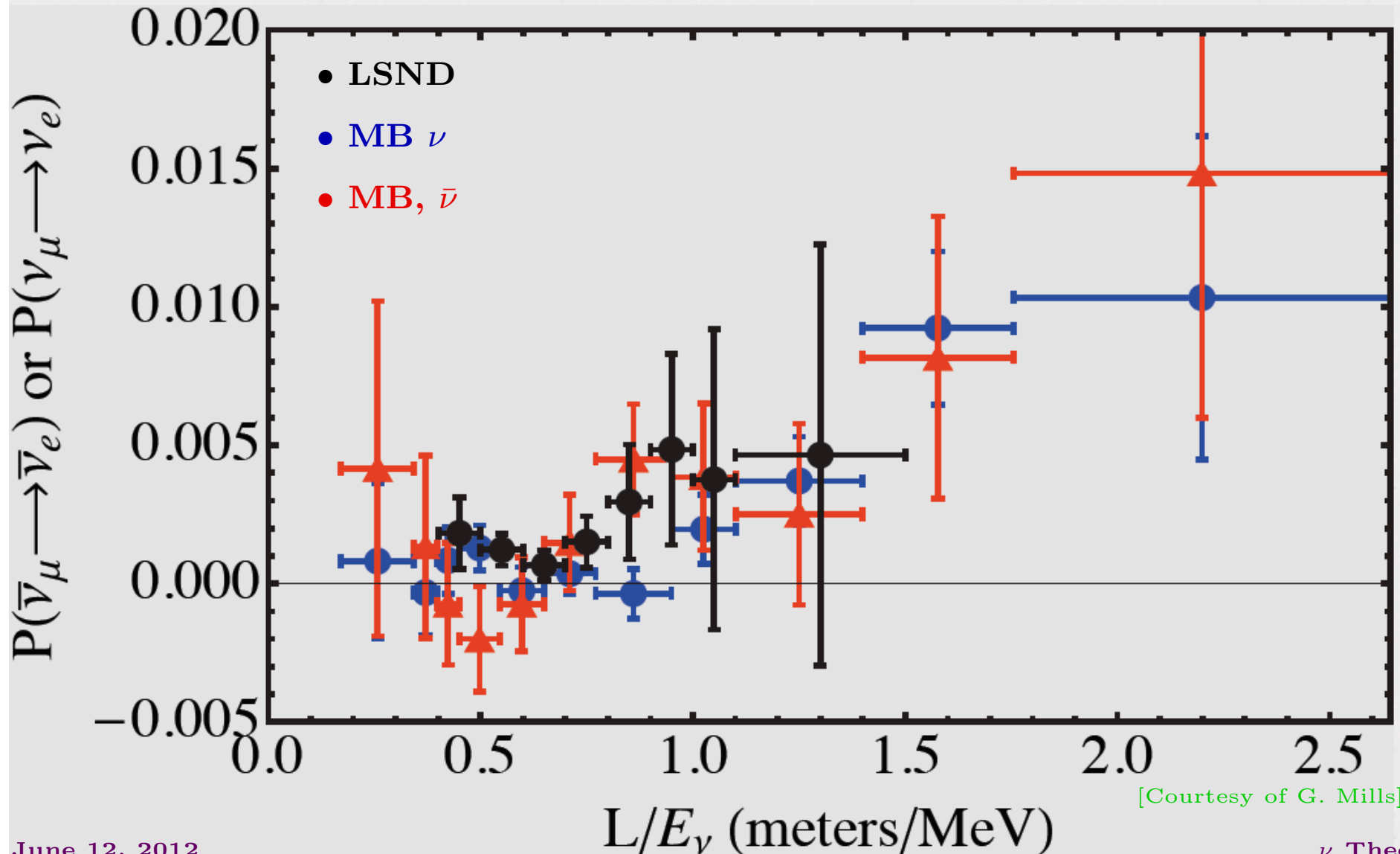
[also see MiniBooNE talk tomorrow]

Different data sets, sensitive to L/E values small enough that the known oscillation frequencies do not have “time” to operate, point to unexpected neutrino behavior. These include

- $\nu_\mu \rightarrow \nu_e$ appearance — LSND, MiniBooNE;
- $\nu_e \rightarrow \nu_{\text{other}}$ disappearance — radioactive sources;
- $\bar{\nu}_e \rightarrow \bar{\nu}_{\text{other}}$ disappearance — reactor experiments.

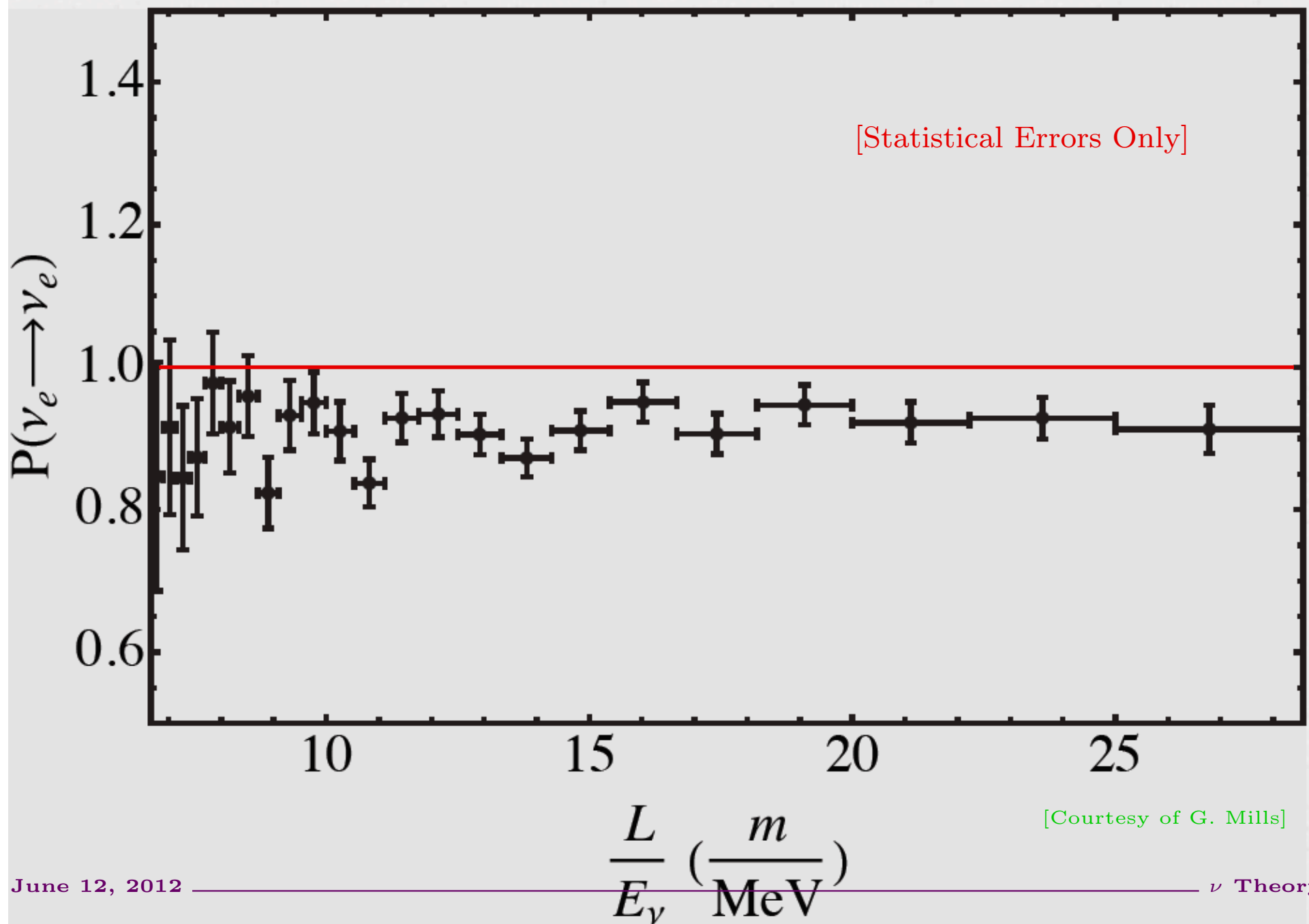
None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here...

MiniBooNE & LSND

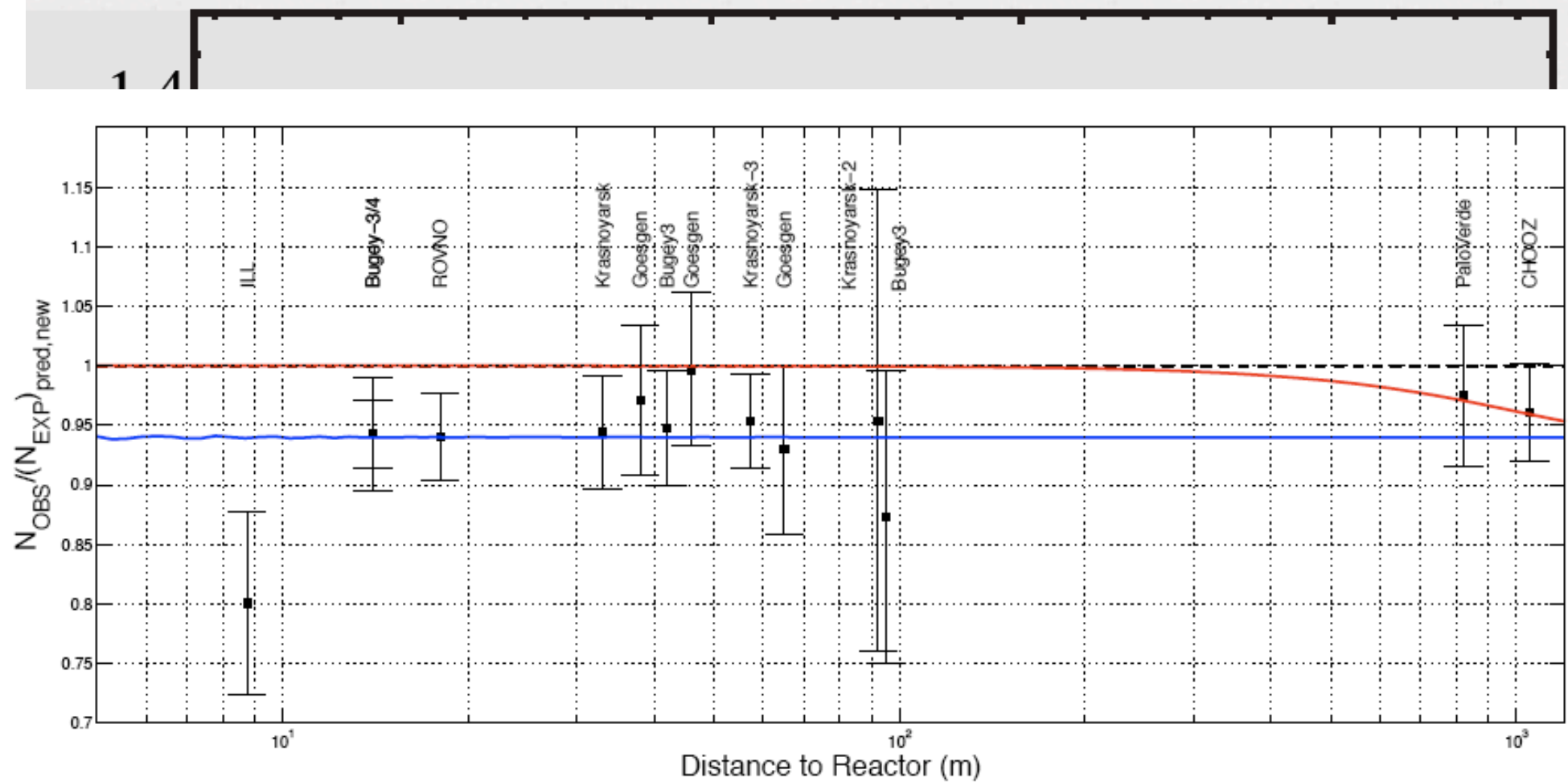


[Courtesy of G. Mills]

Bugey 40 m



Bugey 40 m



10

15

20

25

$$\frac{L}{E_\nu} \left(\frac{m}{\text{MeV}} \right)$$

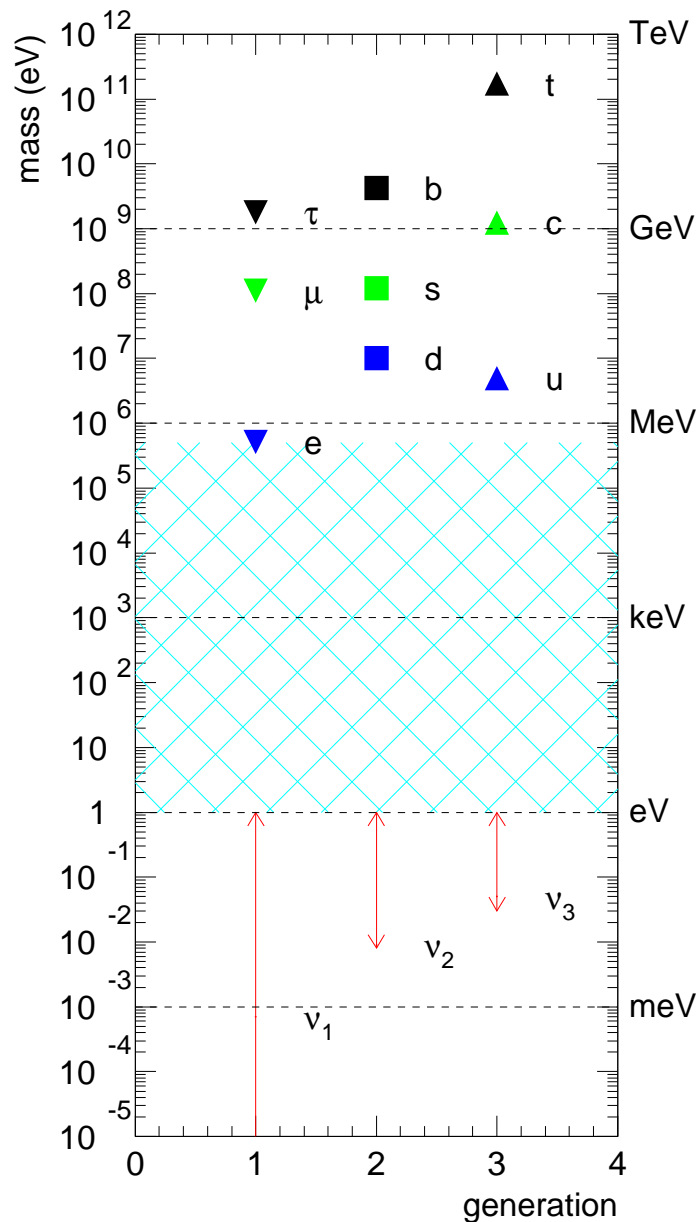
What is Going on Here?

- Are these “anomalies” related?
- Is this neutrino oscillations, other new physics, or something else?
- Are these related to the origin of neutrino masses and lepton mixing?
- How do clear this up **definitively**?

Need new clever experiments, of the short-baseline type!

Observable wish list:

- ν_μ disappearance (and antineutrino);
- ν_e disappearance (and antineutrino);
- $\nu_\mu \leftrightarrow \nu_e$ appearance;
- $\nu_{\mu,e} \rightarrow \nu_\tau$ appearance.



What We Are Trying To Understand:

⇐ **NEUTRINOS HAVE TINY MASSES**

⇓ **LEPTON MIXING IS “WEIRD”** ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

What is the New Standard Model? [ν SM]

The short answer is – WE DON'T KNOW. Not enough available info!

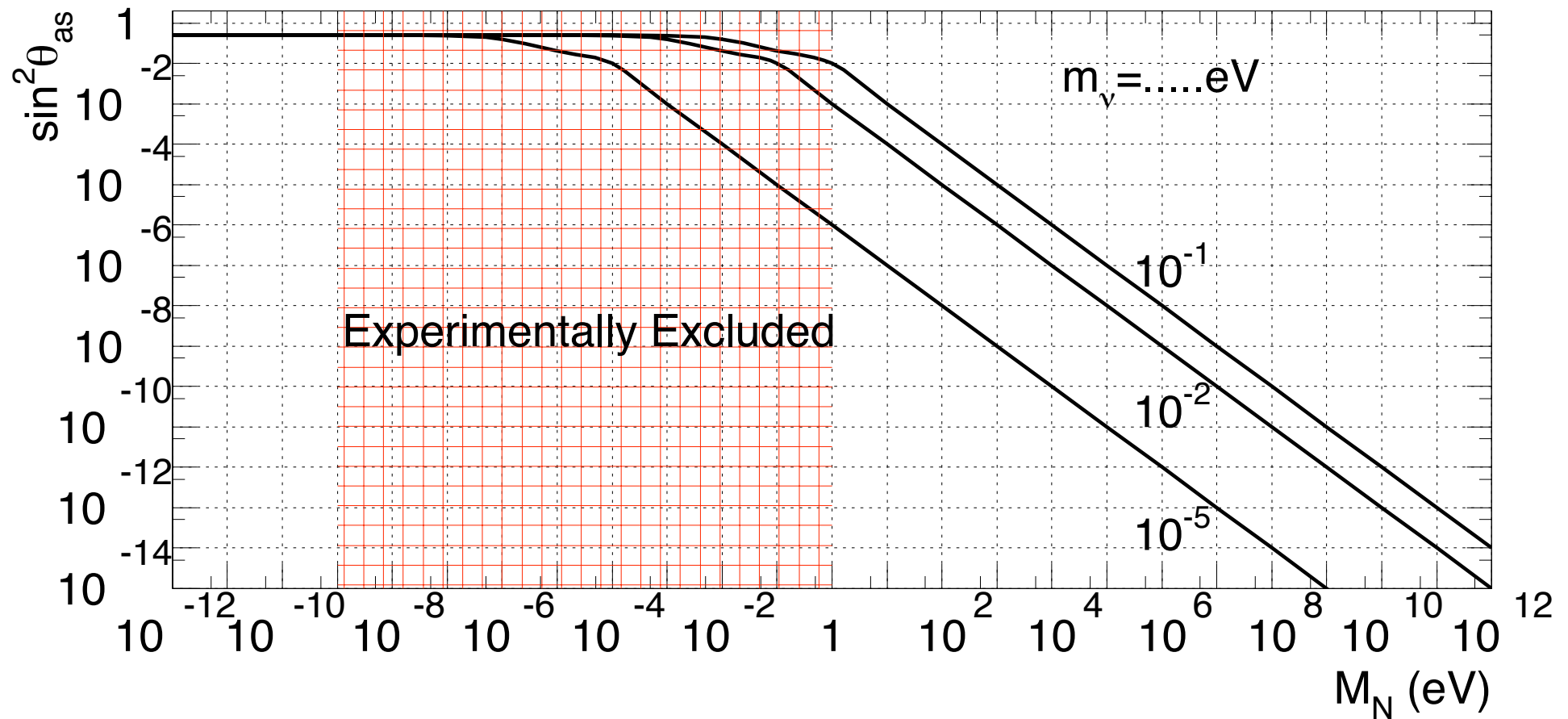


Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the ν SM candidates can do. [are they falsifiable?, are they “simple”?, do they address other outstanding problems in physics?, etc]

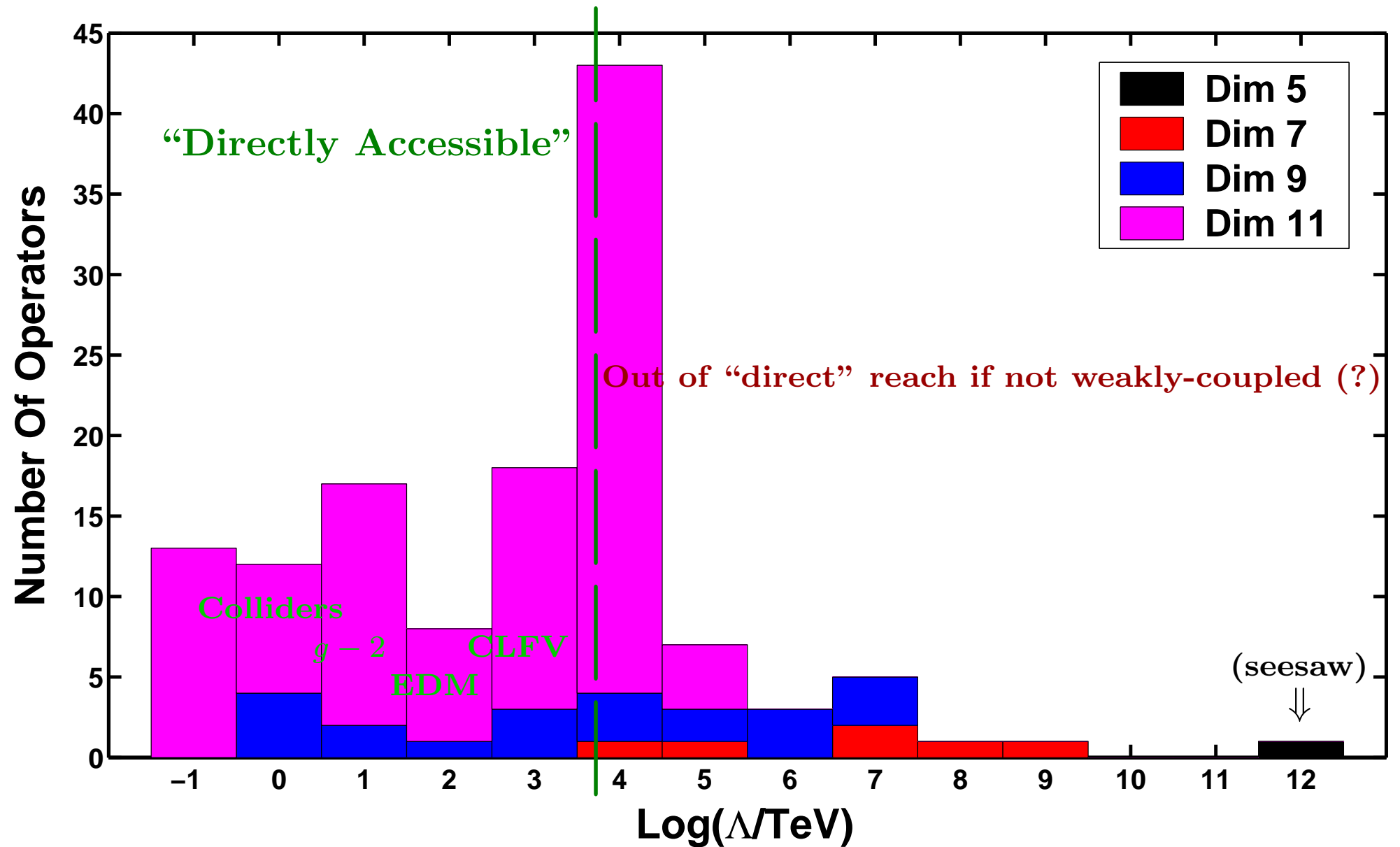
We need more experimental input.

Our “Best” Model: the Seesaw Lagrangian

Model parameters virtually unconstrained. Good news: different right-handed neutrino masses M_N yield very different phenomenology



[AdG, Huang, Jenkins, arXiv:0906.1611]



Understanding Fermion Mixing

The other puzzling phenomenon uncovered by the neutrino data is the fact that **Neutrino Mixing is Strange**. What does this mean?

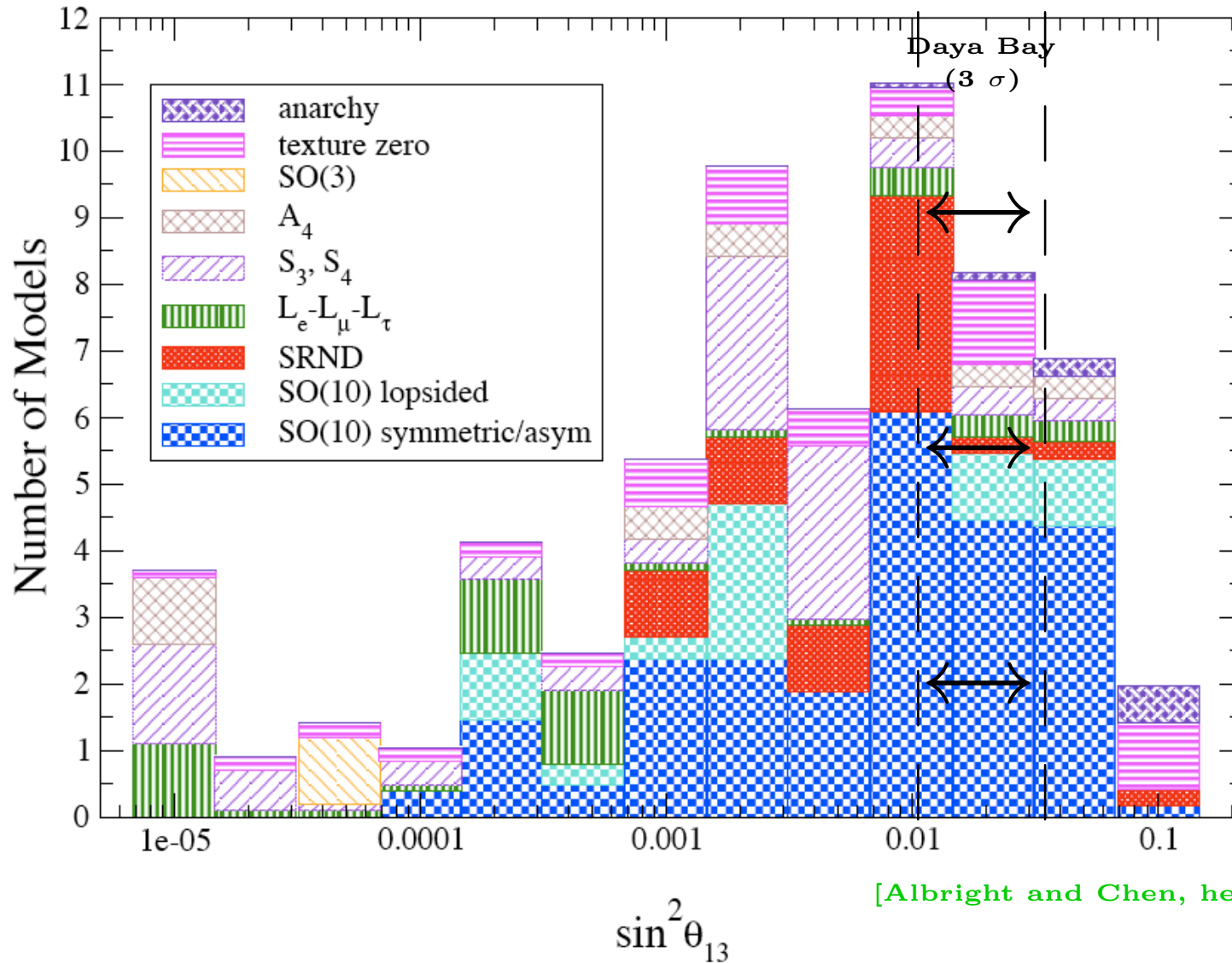
It means that lepton mixing is very different from quark mixing:

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

$[|(V_{MNS})_{e3}| < 0.2]$

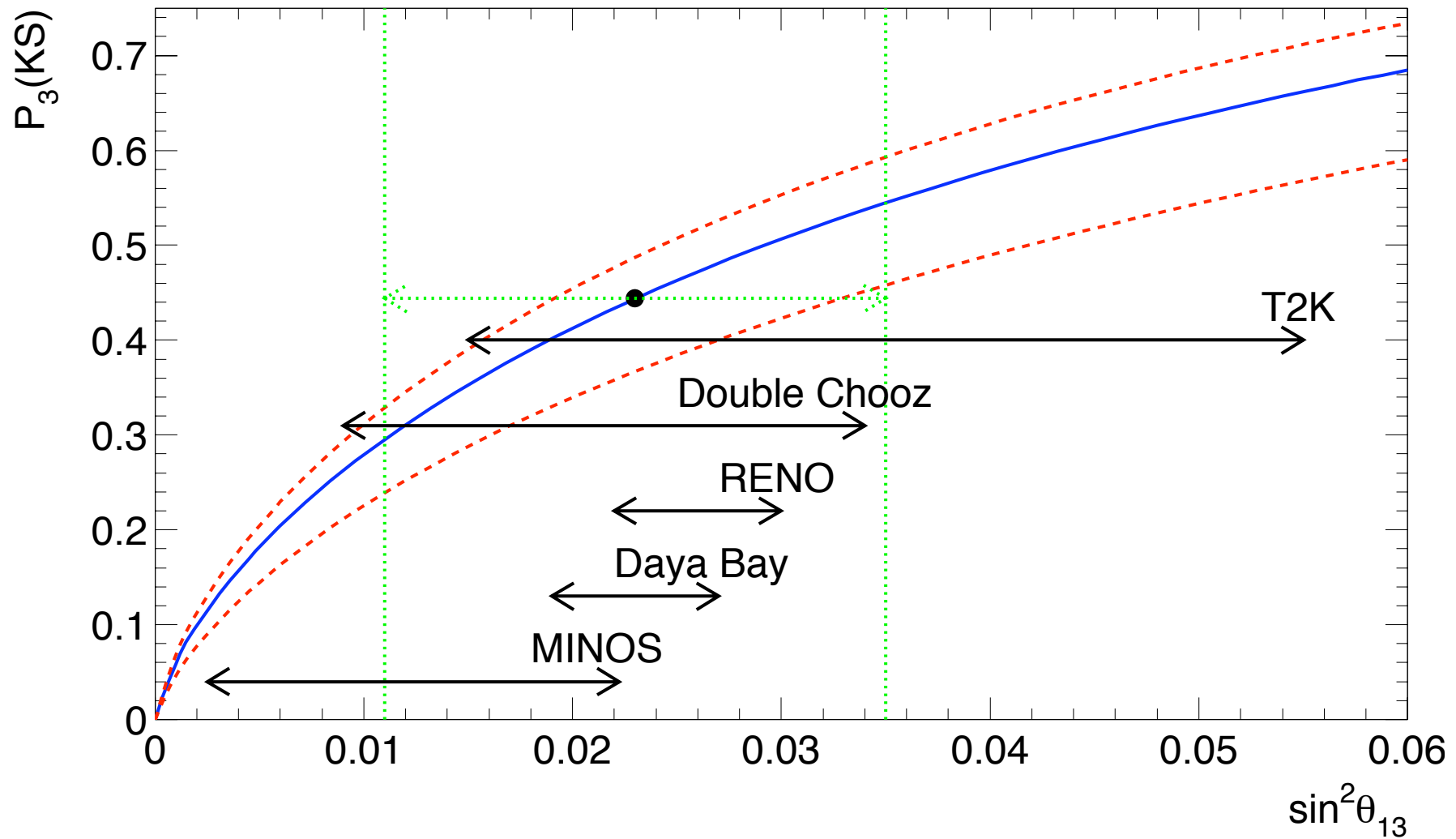
WHY?

They certainly look VERY different, but which one would you label as “strange”?



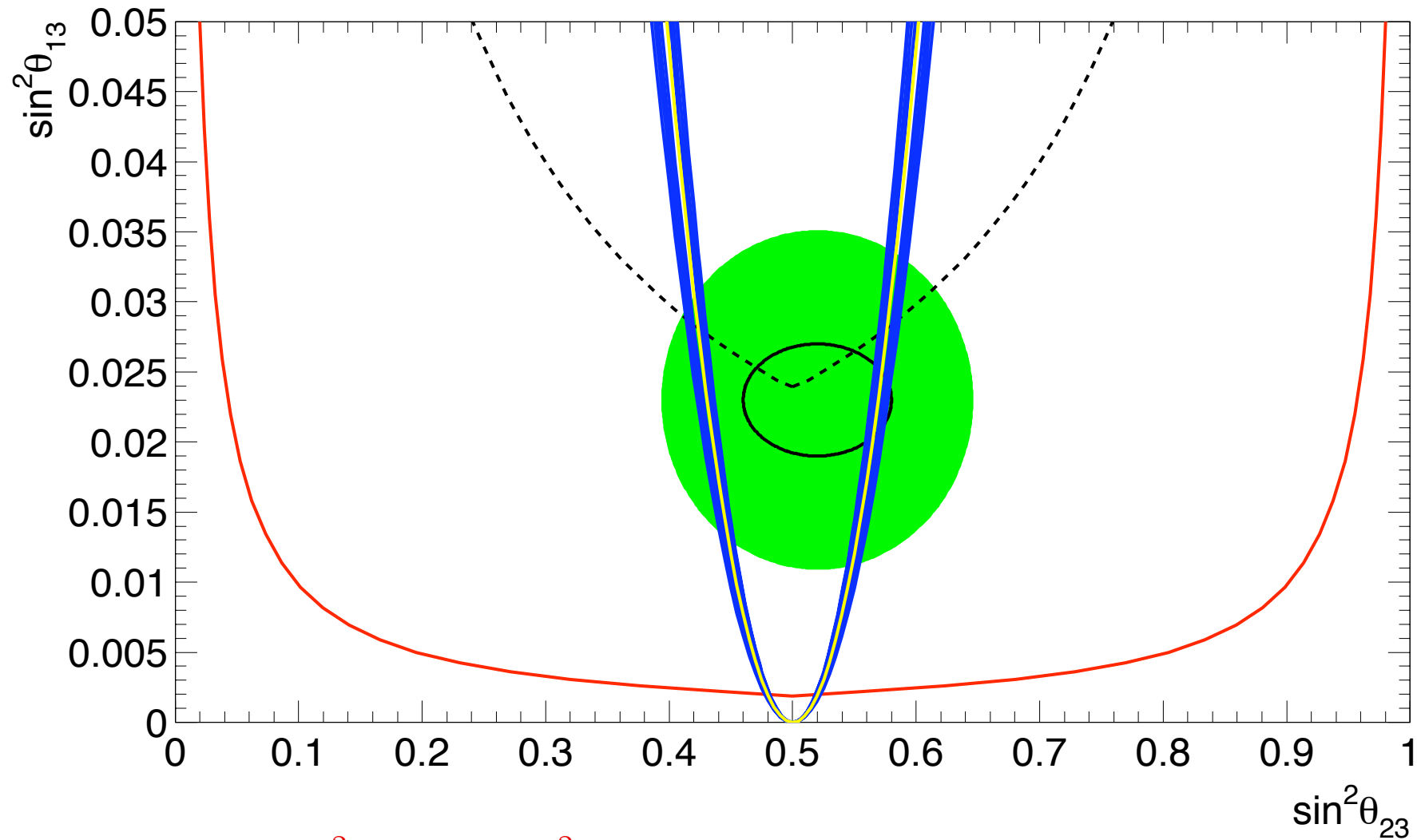
“Left-Over” Predictions: δ , mass-hierarchy, $\cos 2\theta_{23}$

Neutrino Mixing Anarchy: Alive and Kicking!



[AdG, Murayama, 1204.1249]

Anarchy vs. Order — more precision required!



Order: $\sin^2 \theta_{13} = C \cos^2 2\theta_{23}$, $C \in [0.8, 1.2]$

[AdG, Murayama, 1204.1249]

How Do We Learn More?

In order to learn more, we need more information. Any new data and/or idea is welcome, including

- searches for charged lepton flavor violation;
($\mu \rightarrow e\gamma$, $\mu \rightarrow e$ -conversion in nuclei, etc)
- searches for lepton number violation;
(neutrinoless double beta decay, etc)
- neutrino oscillation experiments;
(Daya Bay, NO ν A, etc)
- searches for fermion electric/magnetic dipole moments
(electron edm, muon $g - 2$, etc);

- precision studies of neutrino – matter interactions;
(Miner ν a, MicroBooNE, etc)
- collider experiments:
(LHC, etc)
 - *Can* we “see” the physics responsible for neutrino masses at the LHC?
– YES!
Must we see it? – NO, but we won’t find out until we try!
 - we need to understand the physics at the TeV scale before we can really understand the physics behind neutrino masses (is there low-energy SUSY?, etc).

CONCLUSIONS

1. We know very little about the new physics uncovered by neutrino oscillations, e.g.,
 - It could be renormalizable \rightarrow “boring” Dirac neutrinos.
 - It could be due to Physics at absurdly high energy scales $M \gg 1$ TeV \rightarrow high energy seesaw. How can we ever convince ourselves that this is correct?
 - It could be due to very light new physics \rightarrow low energy seesaw.
Prediction: new light propagating degrees of freedom – sterile neutrinos.
2. We still don’t understand the pattern of lepton mixing, but anarchical hypothesis works great. Can one do better? (θ_{23} , quarks, ...)
3. We need to definitively resolve the short-baseline anomalies. It could be good-old Standard Model physics, but we may be in the process of uncovering something very interesting.
4. We need more experimental data!

Backup Slides . . .



The “Holy Grail” of Neutrino Oscillations – CP Violation

In the **old Standard Model**, there is only one^a source of CP-invariance violation:

⇒ The complex phase in V_{CKM} , the quark mixing matrix.

Indeed, as far as we have been able to test, all CP-invariance violating phenomena agree with the CKM paradigm:

- ϵ_K ;
- ϵ'_K ;
- $\sin 2\beta$;
- etc.

Neutrino masses and lepton mixing provide strong reason to believe that other sources of CP-invariance violation exist.

^amodulo the QCD θ -parameter, which will be “willed away” as usual.

CP-invariance Violation in Neutrino Oscillations

The most promising approach to studying CP-violation in the leptonic sector seems to be to compare $P(\nu_\mu \rightarrow \nu_e)$ versus $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$.

The amplitude for $\nu_\mu \rightarrow \nu_e$ transitions can be written as

$$A_{\mu e} = U_{e2}^* U_{\mu 2} (e^{i\Delta_{12}} - 1) + U_{e3}^* U_{\mu 3} (e^{i\Delta_{13}} - 1)$$

where $\Delta_{1i} = \frac{\Delta m_{1i}^2 L}{2E}$, $i = 2, 3$.

The amplitude for the CP-conjugate process can be written as

$$\bar{A}_{\mu e} = U_{e2} U_{\mu 2}^* (e^{i\Delta_{12}} - 1) + U_{e3} U_{\mu 3}^* (e^{i\Delta_{13}} - 1).$$

[remember: according to unitarity, $U_{e1} U_{\mu 1}^* = -U_{e2} U_{\mu 2}^* - U_{e3} U_{\mu 3}^*$]

In general, $|A|^2 \neq |\bar{A}|^2$ (CP-invariance violated) as long as:

- Nontrivial “Weak” Phases: $\arg(U_{ei}^* U_{\mu i}) \rightarrow \delta \neq 0, \pi$;
- Nontrivial “Strong” Phases: $\Delta_{12}, \Delta_{13} \rightarrow L \neq 0$;
- Because of Unitarity, we need all $|U_{\alpha i}| \neq 0 \rightarrow$ three generations.

All of these can be satisfied, with a little luck: given that two of the three mixing angles are known to be large, **we need** $|U_{e3}| \neq 0$. ✓

[see LBNE talk tomorrow]

More Room For New Neutrinos (?)

[Kopp,Maltoni,Schwetz, 1103.4570]

	LSND+MB($\bar{\nu}$) vs rest appearance vs disapp.			
	old	new	old	new
$\chi^2_{\text{PG},3+2}/\text{dof}$	25.1/5	19.9/5	19.9/4	14.7/4
PG ₃₊₂	10^{-4}	0.13%	5×10^{-4}	0.53%
$\chi^2_{\text{PG},1+3+1}/\text{dof}$	19.6/5	16.0/5	14.4/4	10.6/4
PG ₁₊₃₊₁	0.14%	0.7%	0.6%	3%

Table III: Compatibility of data sets [23] for 3+2 and 1+3+1 oscillations using old and new reactor fluxes.

data, although in this case the fit is slightly worse than a fit to appearance data only (dashed histograms). Note that MiniBooNE observes an event excess in the lower part of the spectrum. This excess can be explained if only appearance data are considered, but not in the global analysis including disappearance searches [8]. Therefore, we follow [19] and assume an alternative explanation for this excess, e.g. [25]. In Tab. III we show the compatibility of the LSND/MiniBooNE($\bar{\nu}$) signal with the rest of the data, as well as the compatibility of appearance and disappearance searches using the PG test from [23].

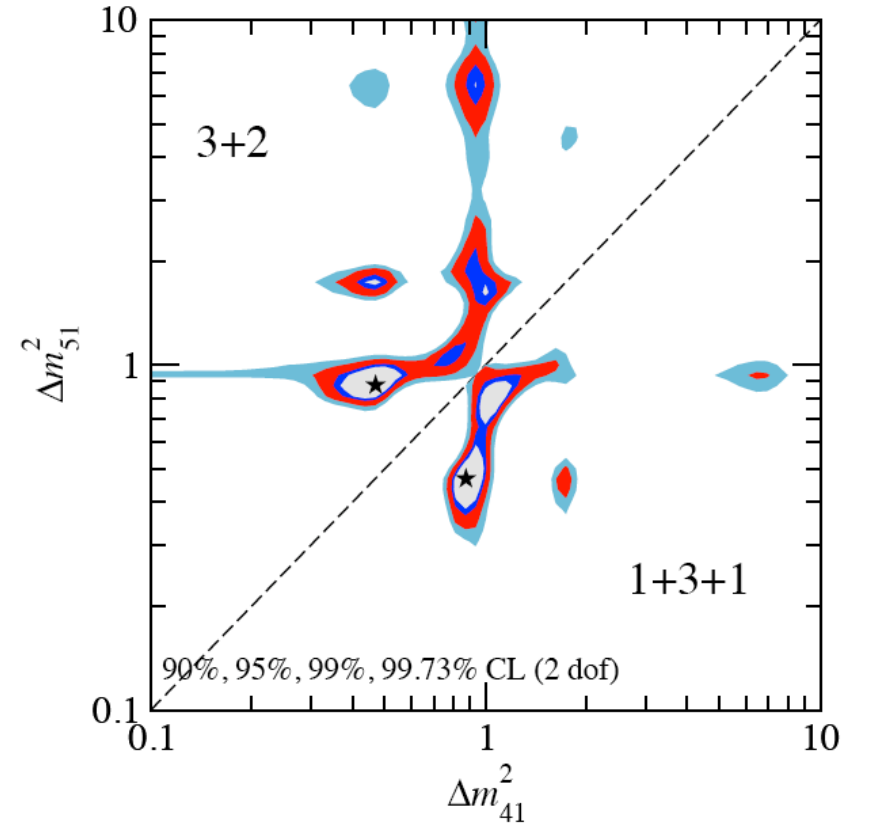


Figure 5: The globally preferred regions for the neutrino mass squared differences Δm^2_{41} and Δm^2_{51} in the 3+2 (upper left) and 1+3+1 (lower right) scenarios.

Options include:

- modify SM Higgs sector (e.g. Higgs triplet) and/or
- modify SM particle content (e.g. $SU(2)_L$ Triplet or Singlet) and/or
- modify SM gauge structure and/or
- supersymmetrize the SM and add R-parity violation and/or
- augment the number of space-time dimensions and/or
- etc

Important: different options \rightarrow different phenomenological consequences

(Almost) All We Know About Solar Neutrinos

