Theoretical Overview of Neutrino Oscillations

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NNN25

Neutrino Oscillation Is Well Established

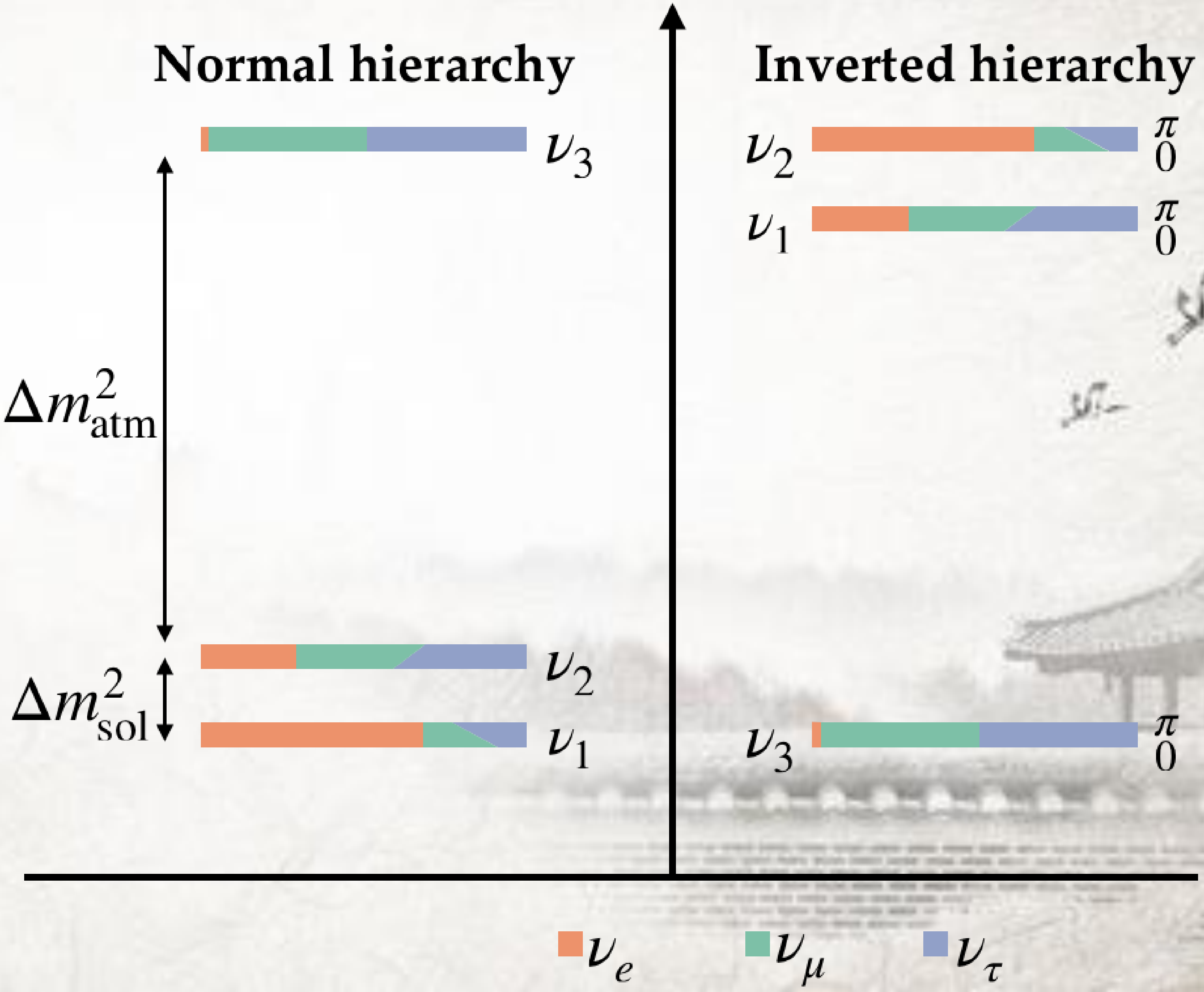
The standard neutrino oscillation paradigm

PMNS mixing matrix:

$\theta_{12}, \theta_{13}, \theta_{23}, \delta_{\rm CP}$

Mass-square differences:
$\Delta m^2_{21}, \Delta m^2_{32}$,

mass ordering



Neutrino Oscillation Is Well Established

The framework

Vacuum oscillation

Mixing:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

Free propagation:

$$|\nu_i(t)\rangle = e^{-i\,E_i\,t}|\nu_i(0)\rangle$$

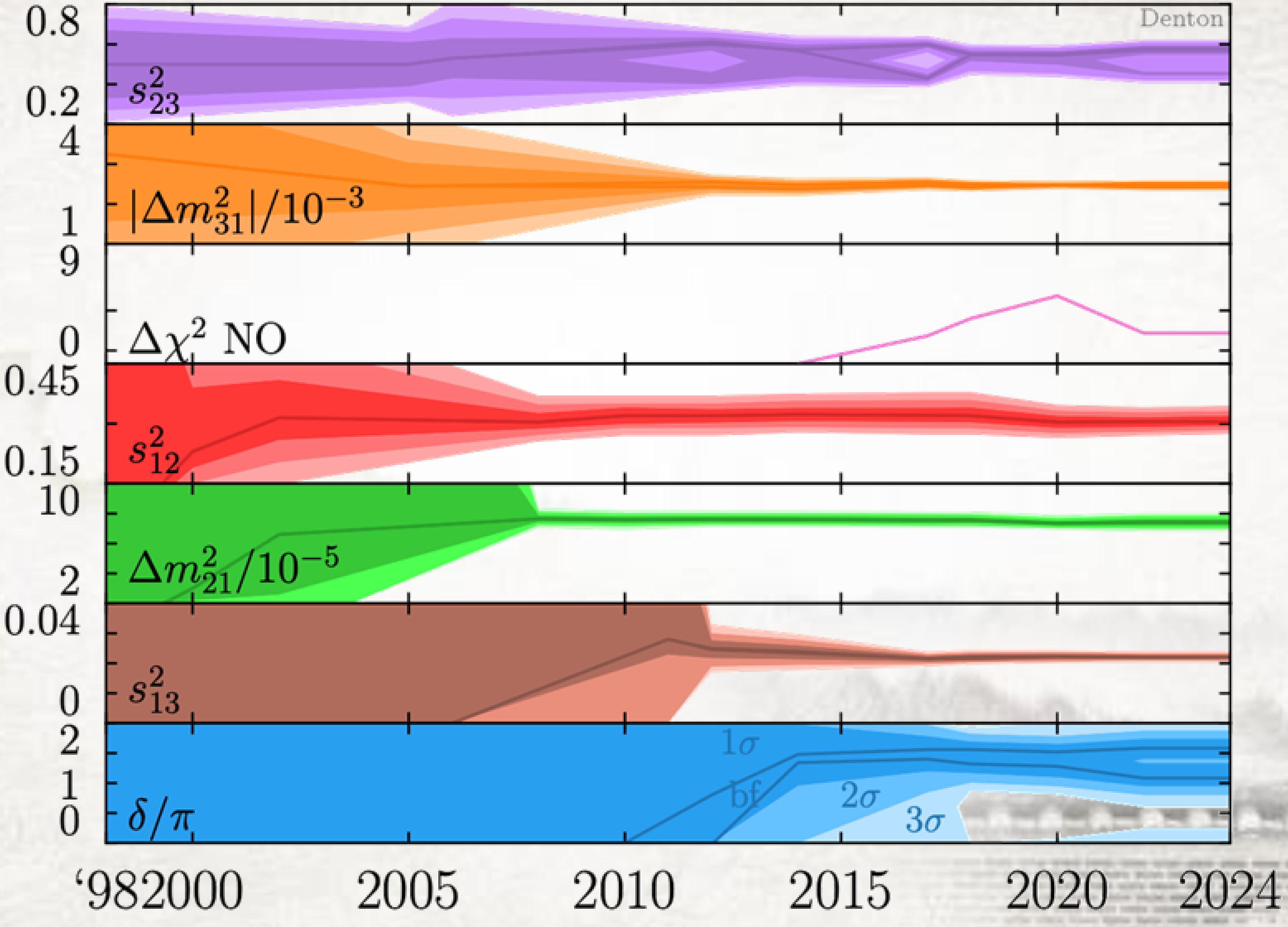
Matter effect

$$H_{\mathrm{matter}} = H_{\mathrm{vacuum}} + V_{\mathrm{matter}}$$

Mater potential is in flavor basis, e.g., ν_e propagating in a constant electron density

This framework is tested across neutrino energies, baselines, and flavors

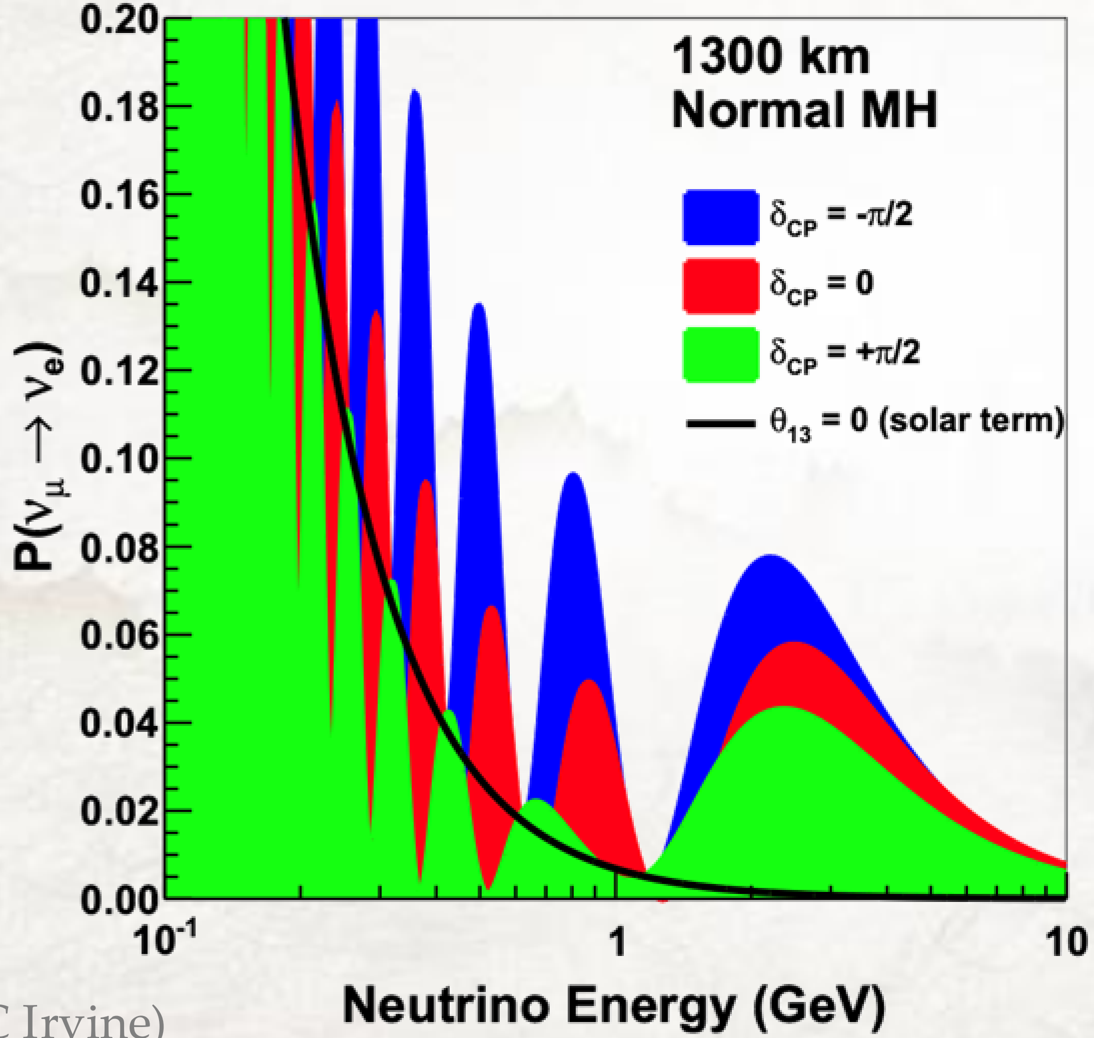
Progress Could Be Summarized As Follows



Denton, 25

THE Known Unknows

CP violating phase δ_{CP}, mass ordering, θ_{23} octant



DUNE CDR vol 2

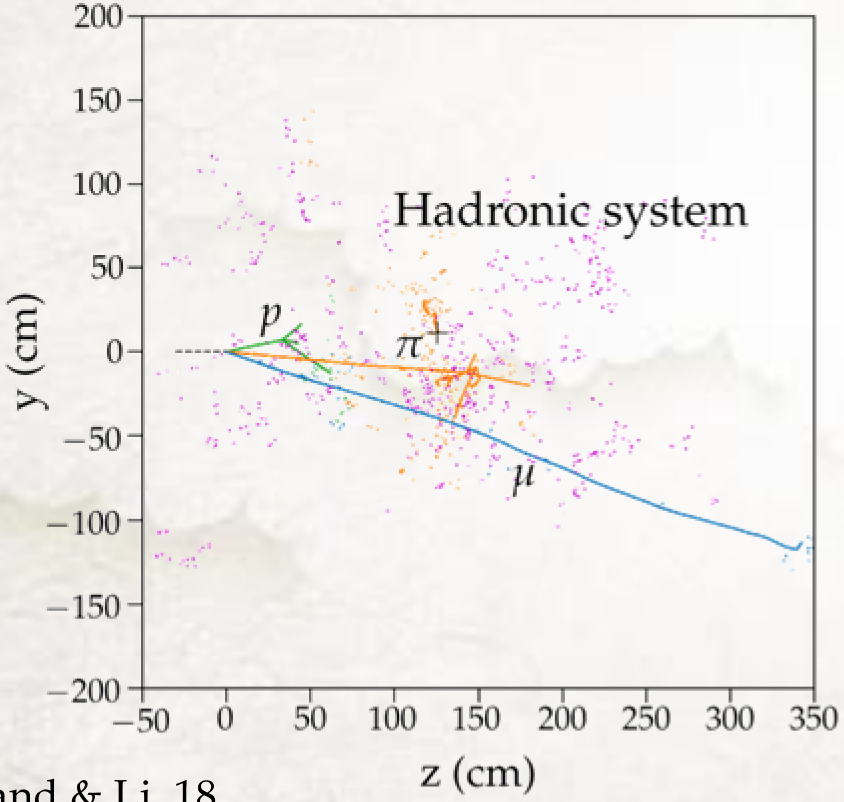
DUNE oscillation probabilities as an example

Subtle effects!

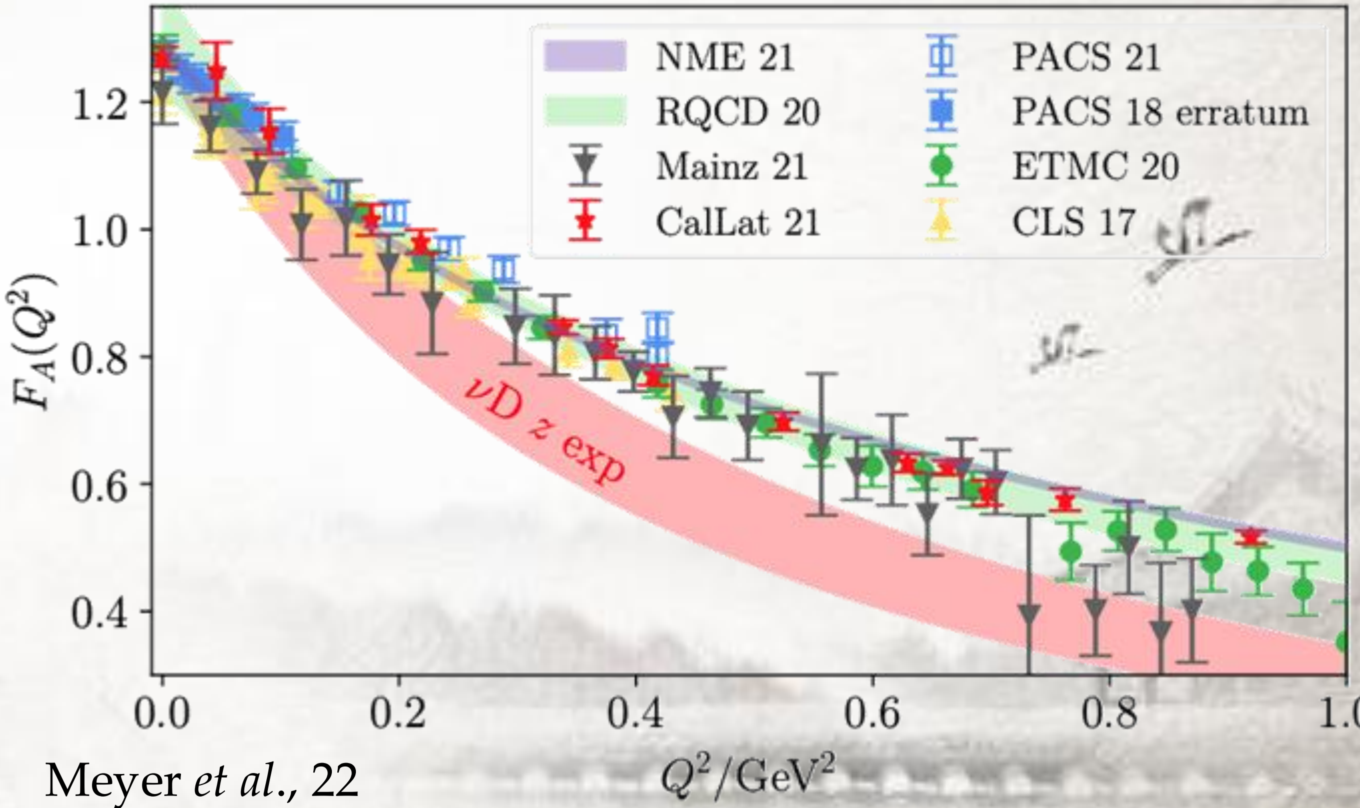
Requires precise measurements, large statistics, and controlled systematics

Important Theoretical Efforts: ν-A Cross Sections

Understanding neutrino-nucleus scattering cross sections in GeV range, for long-baseline experiments



Friedland & Li, 18

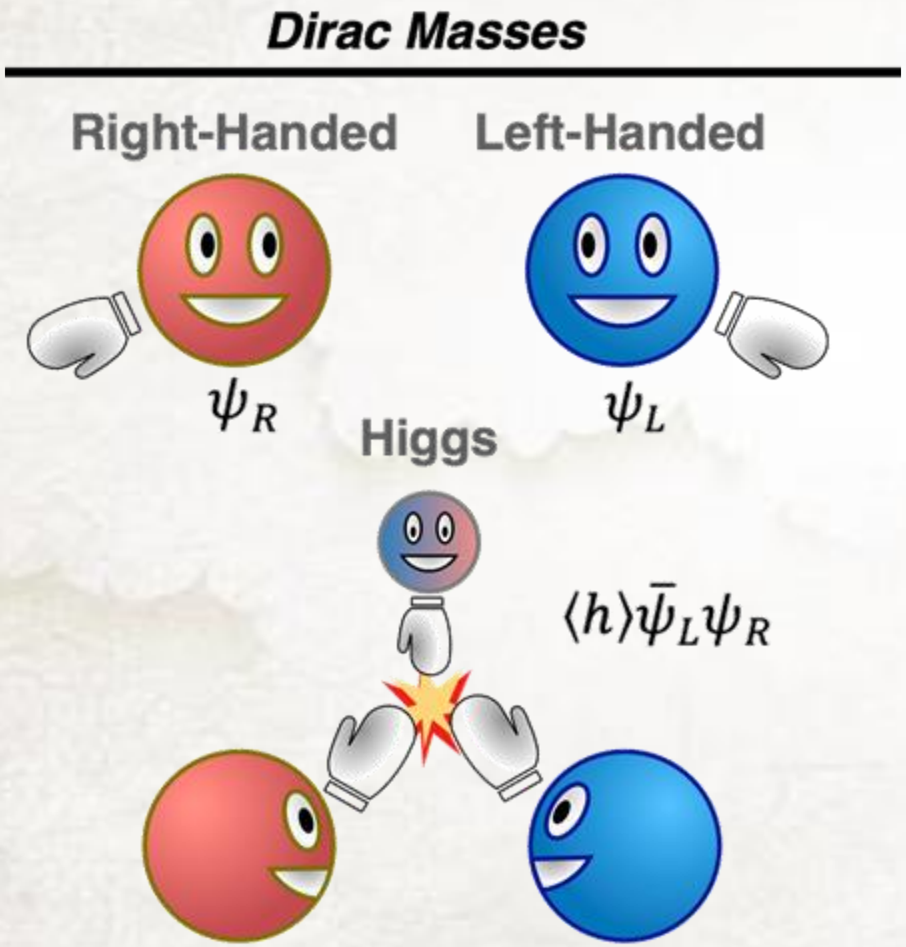


Meyer *et al.*, 22

Super difficult problem, lots of ongoing efforts!

More Known Unknows

What gives neutrino mass?



In Standard Model:
We cannot have: $m\overline{\nu_L}\nu_L$

The most obvious field to add:
gauge singlet $\boldsymbol{\nu_R}$

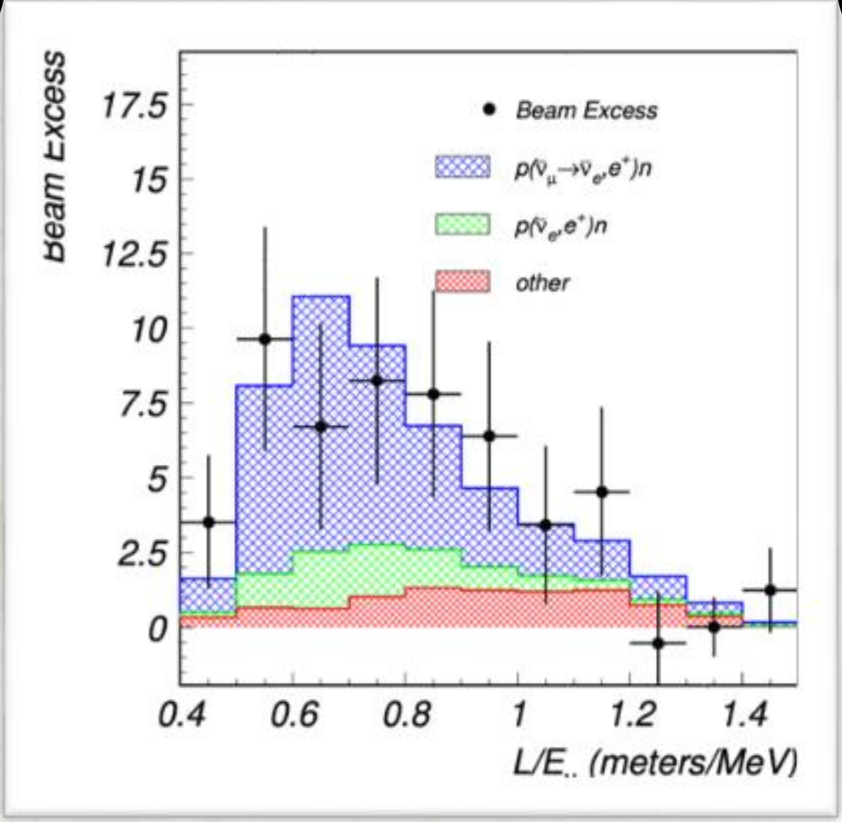
So that we can have $m\,\overline{\nu_L}\,\nu_R$
This also gives us M $\overline{\nu_R^C}\,\nu_R$, which we can test in $0\nu\beta\beta$ exp

Figure credit: S. Ellis

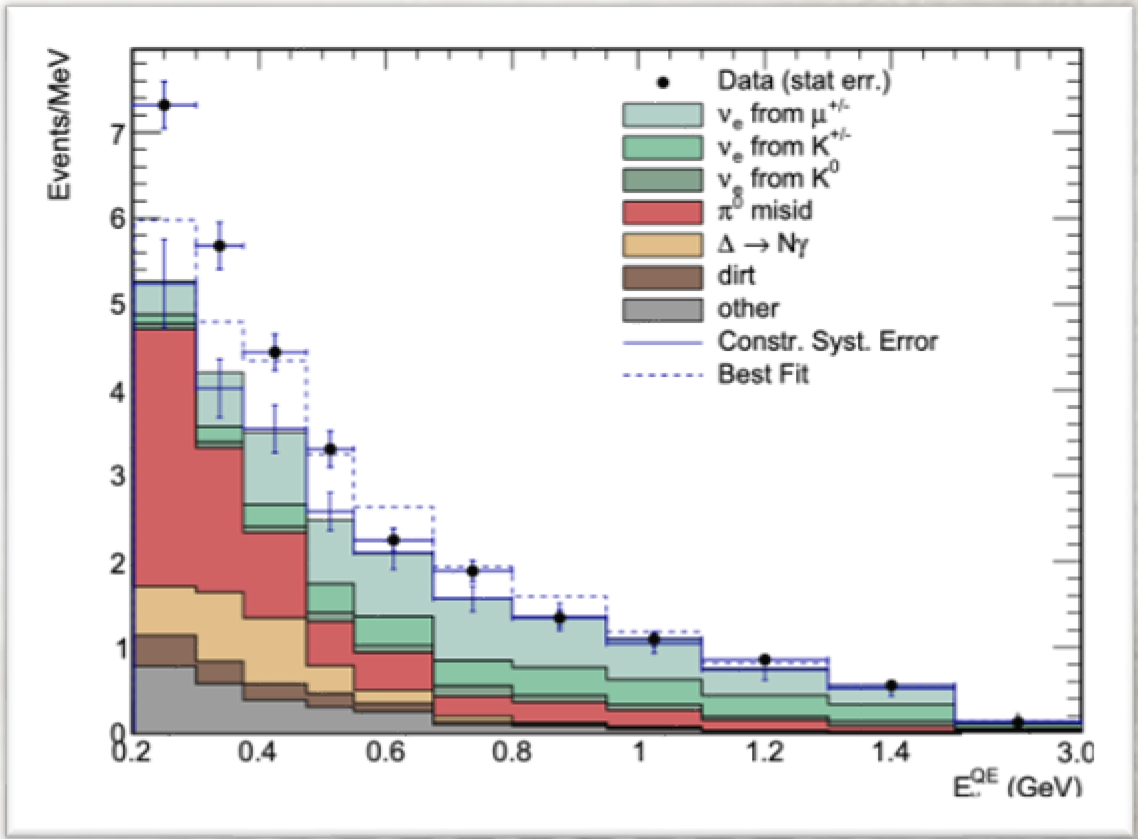
Light Steriles: Sterile Neutrinos

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = (4 * 4 \text{ unitary Matrix}) \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$

$$P_{\alpha\beta} = \sin^2(2\theta)\ \sin^2(\frac{\Delta m^2\ L}{4E})$$



LSND, 00



MiniBooNE, 20

Extremely active area!

Heavy Steriles: Non-Unitarity of PMNS Matrix

Heavy states cannot be directly produced and observed

The observable is the non-unitarity of the 3*3 matrix

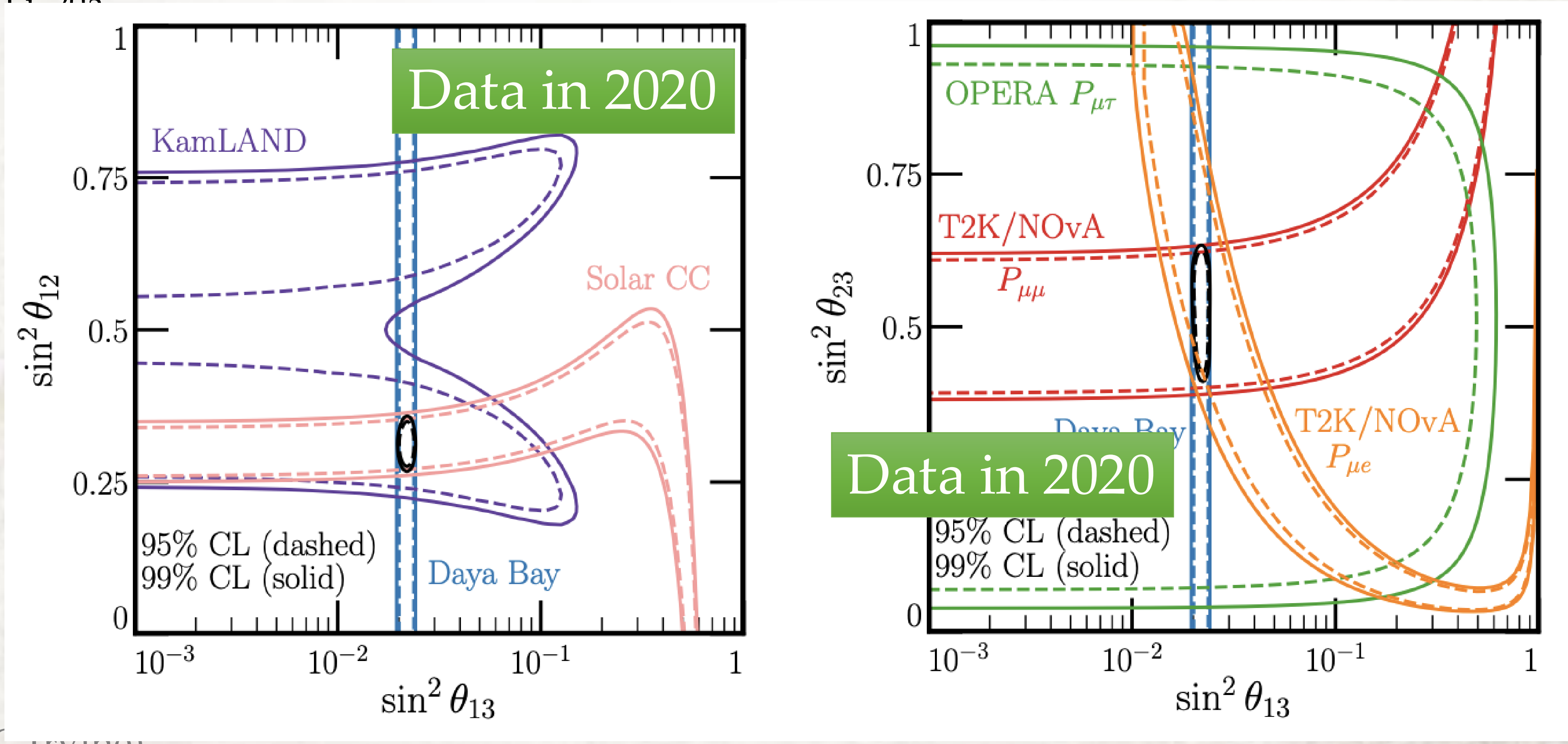
$$U_{\text{PMNS}} \neq \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric   Reactor/Interference   Solar

Testing Unitarity

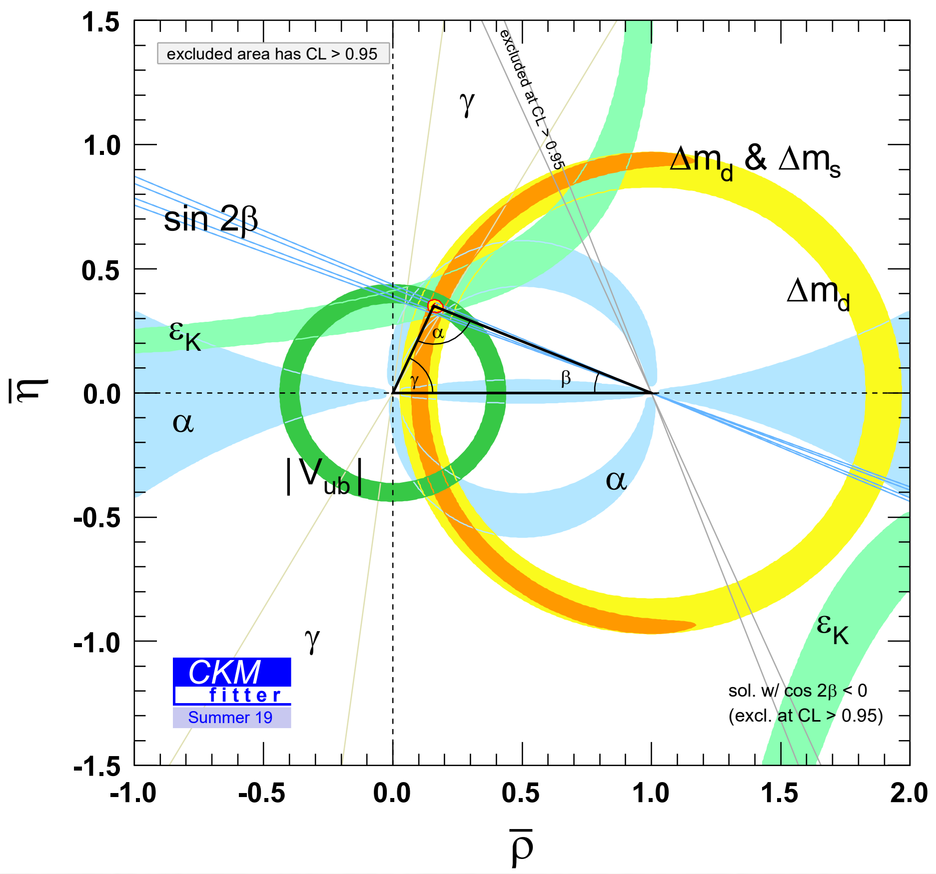
Consistency checks --- lines should intercept at the true point if our assumptions of unitarity are valid

Ellis, Kelly, Li 20...



Testing Unitarity --- Unitarity Triangles

Consistency checks --- lines should intercept at the true point if our assumptions of unitarity are valid



$$U_{e1}U_{\mu 1}^{*} + U_{e2}U_{\mu 2}^{*} + U_{e3}U_{\mu 3}^{*} = 0$$

$$\rho_{e\mu} + i\,\eta_{e\mu} \equiv -\frac{U_{e1}U_{\mu 1}^{*}}{U_{e3}U_{\mu 3}^{*}}$$

Testing Unitarity --- Leptonic Unitarity Triangles

Ellis, Kelly, Li, 20b

Current data

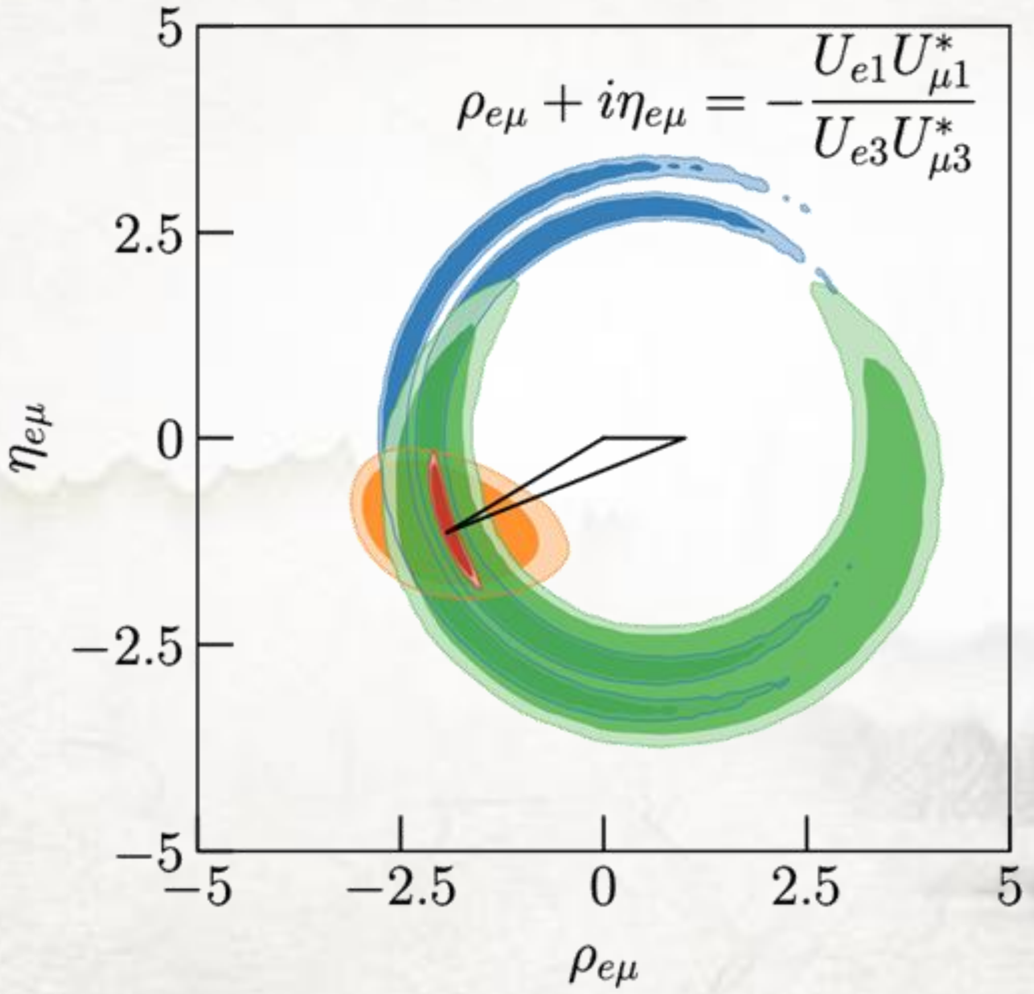
Future data:

Disappearance

$\nu_\alpha \to \nu_\alpha$

Appearance

$\nu_\alpha \to \nu_\beta$



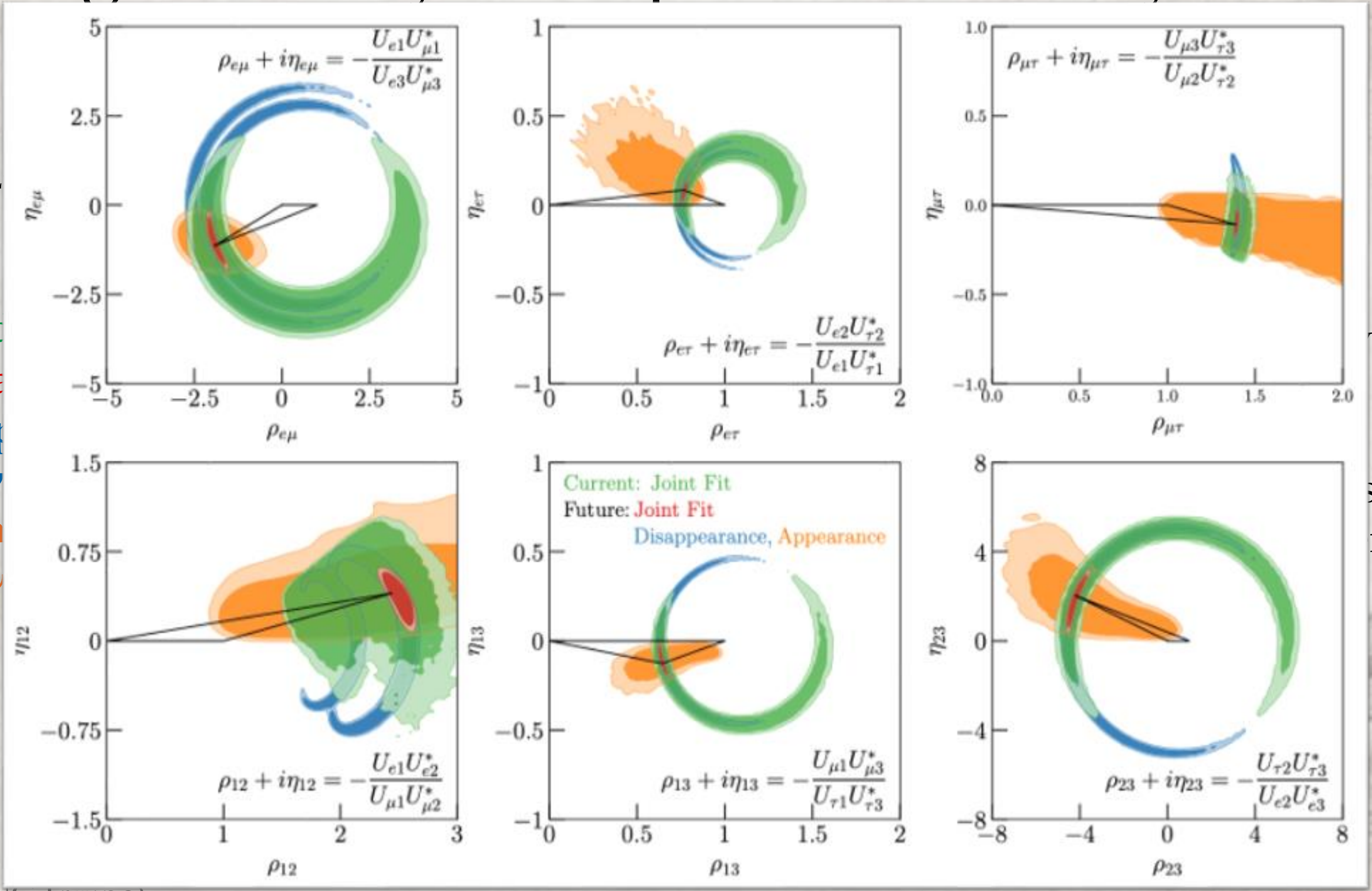
Currently No Sensitivity to CPV

Future:

- Appearance vs. Disappearance
- Only One Measurement of δ_{CP}

Testing Unitarity --- Leptonic Unitarity Triangles

Ellis, Kelly, L



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ment of δ_{CP}

Theory of Oscillation --- Is It Solved?

No! My personal favorite example: decoherence

We never question this:

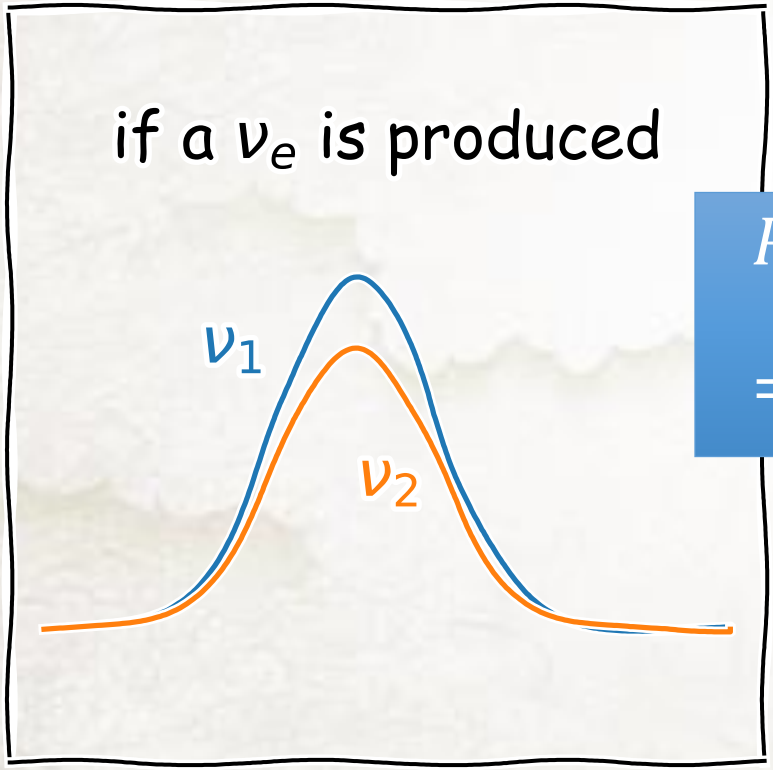
$$P_{\alpha\beta} = \sin^2(2\theta)\ \sin^2(\frac{\Delta m^2\, L}{4E})$$ 2-flavor vacuum oscillation

But, there is an alternative prediction!

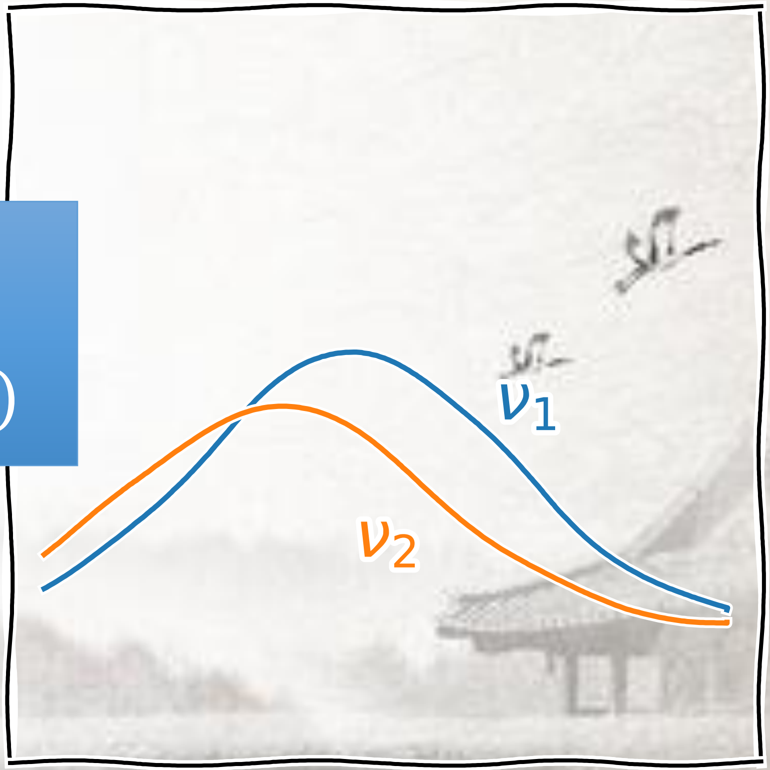
$$P_{\alpha\beta} = \sin^2(2\theta)\ \left\{\frac{1}{2} - \frac{1}{2}\cos\left(\frac{\Delta m^2\, L}{2E}\right) e^{-\frac{L^2}{L_{\mathrm{coh}}^2} - \cdots}\right\}$$ 2-flavor vacuum oscillation

Quantum Decoherence of Neutrinos

Important assumption: neutrino wave packets are coherent



$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

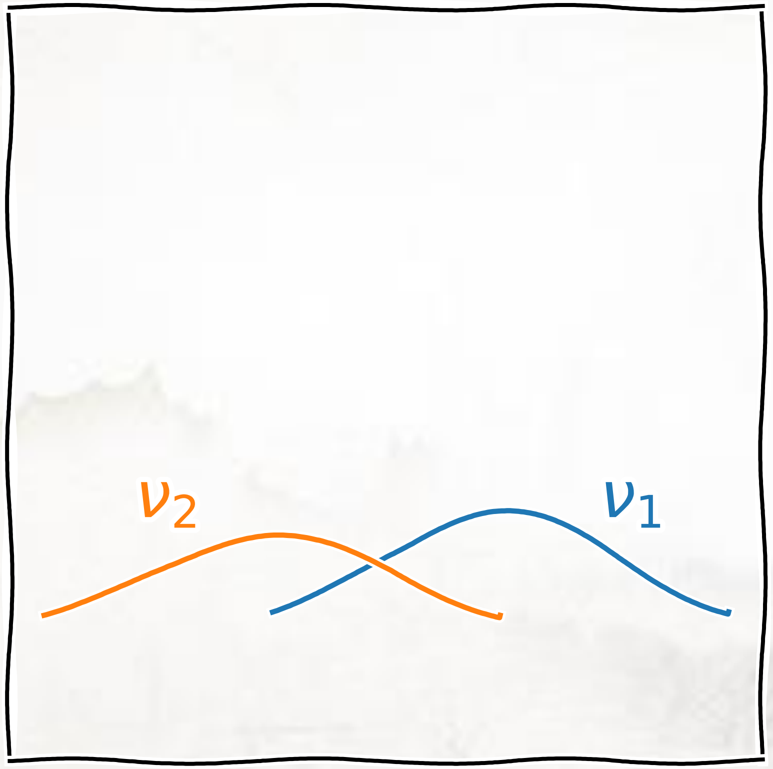


Coherence: wave packets cannot be too separated

Quantum Decoherence of Neutrinos

What if the neutrino wave packets are no longer coherent?

After propagation over a *long* distance



$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\left[\frac{1}{2} - \frac{1}{2}\cos\left(\frac{\Delta m^2 L}{2E}\right) e^{-L^2/L_{\text{coh}}^2}\right]$$

Predicts observable differences

Can This Be Experimentally Tested?

Before: unlikely. Experimental baselines L $\ll L_{coh}$

Now…

Impact of Wave Packet Separation in Low-Energy Sterile Neutrino Searches

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(Dated: March 13, 2023)

Light sterile neutrinos have been motivated by anomalies observed in short-baseline neutrino experiments. Among them, radioactive-source and reactor experiments have provided evidence and constraints, respectively, for electron neutrino disappearance compatible with an eV-scale neutrino. The results from these observations are seemingly in conflict. This paper brings into focus the assumption that the neutrino wave packet can be approximated as a plane wave, which is adopted in all analyses of such experiments. We demonstrate that the damping of oscillation due to decoherence effects, *e.g.*, a finite wave packet size, solves the tension between these electron-flavor observations and constraints.

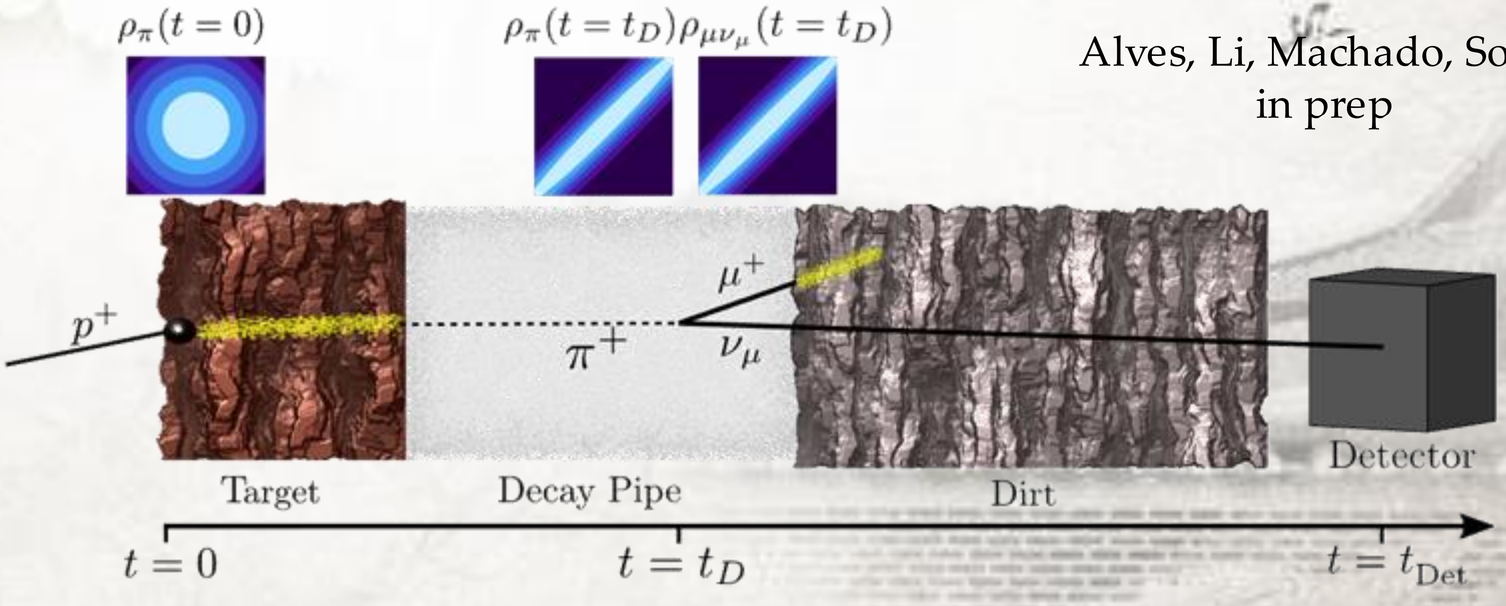
How Can We Test Decoherence Predictions?

The issue: $$L_{\text{coh}} = \frac{4\sqrt{2}\, E_\nu^2\, \sigma_x}{|\Delta m^2|}$$ σ_x: the wave packet size of neutrinos

We cannot make predictions and test decoherence effects with experimental data because we do not know what σ_x is.

Alves, Li, Machado, Song, in prep

Our attempts: computing σ_x for accelerator neutrinos using open quantum system approach



Conclusions

1. Neutrino oscillation is well established and tested
2. Plenty of known unknowns, we will hear about the progress at NNN!
3. Still unresolved issues with neutrino oscillation formalism, e.g., decoherence
4. Not discussed: limitations of oscillation physics, absolute mass, Dirac vs. Majorana, we will also hear about them at NNN!

Extras!

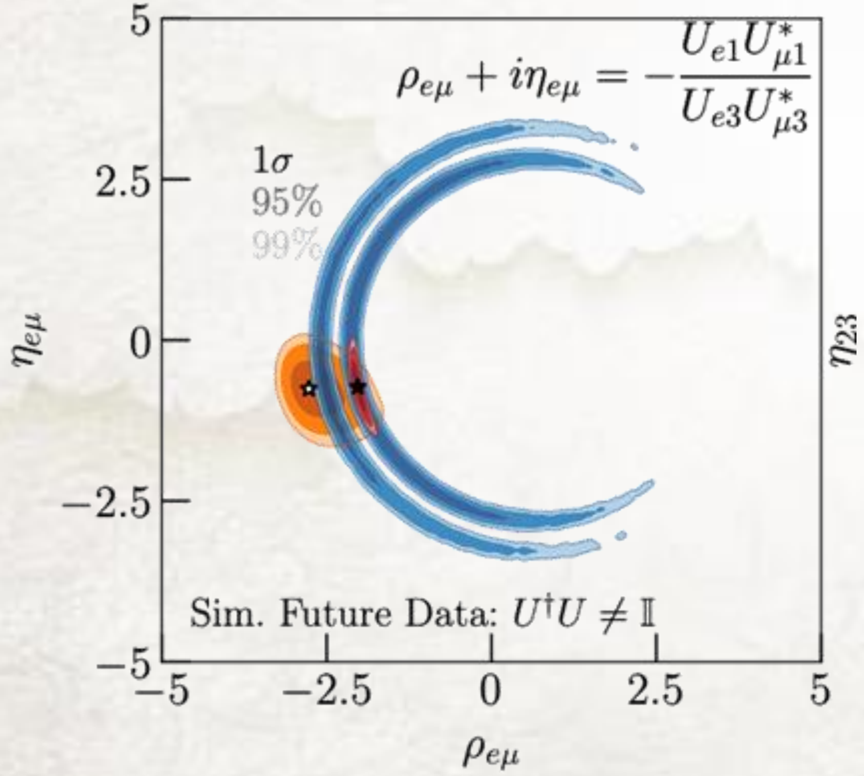
Triangles as Tests of Unitarity

Injected Non-Unitarity

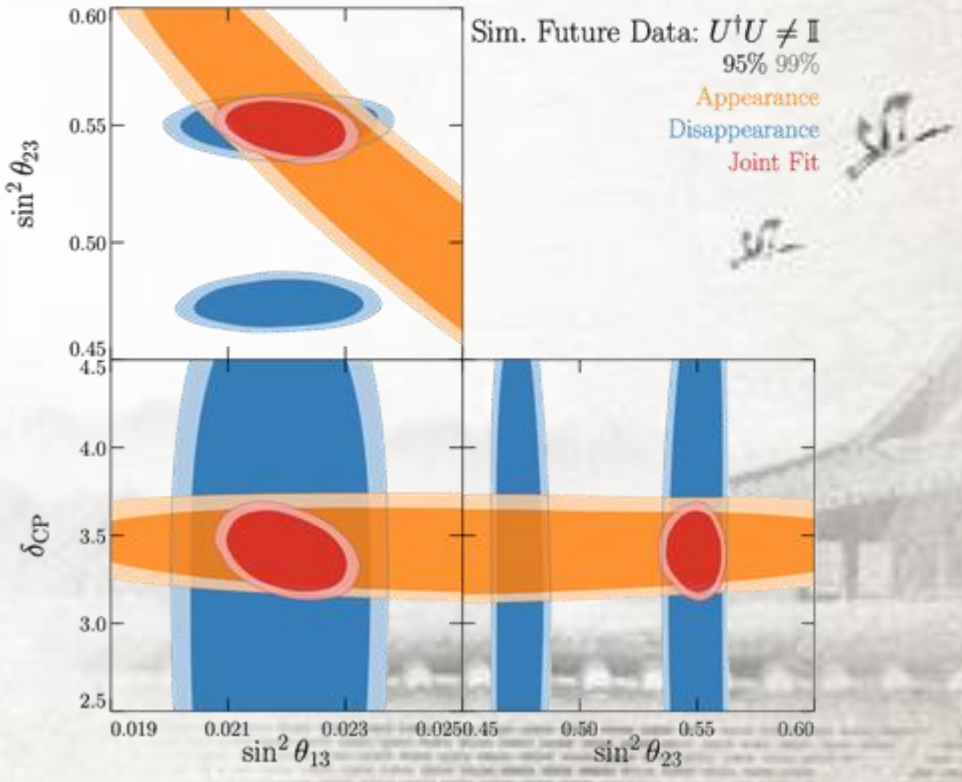
$$U_{e1}U_{\mu1}^* + U_{e2}U_{\mu2}^* + U_{e3}U_{\mu3}^* = 0.01 + 0.04i$$

Ellis, Kelly, Li, 20b

Tension in Triangle



No Tension in Standard Approach



Advocating for Experiments to Separately Analyze Appearance and Disappearance Data