Investigating DUNE oscillations sensitivity to sterile Pseudo-Dirac Neutrinos

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Open problems in particle physics

Origin of neutrino masses

Baryon asymmetry of the Universe

Nature of dark matter

Hierarchy problem

Strong CP problem

Flavor puzzle

Call for new physics

What we know

Origin of neutrino masses

- **In the SM neutrinos are massless**
- **Neutrino oscillations tell us that they must have a mass**

$$\Delta m^2_{21} \simeq 7.4 \times 10^{-5}\ \mathrm{eV}^2 \qquad |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

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What we do not know

- **Are neutrinos Dirac or Majorana?**
- **What is the mechanism that generate neutrino masses?**
- **Do we have normal or inverted ordering?**
- **Is there CP violation in the leptonic sector?**

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Future long baseline oscillation experiments (T2HK, DUNE)

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What we do not know

- Are neutrinos Dirac or Majorana?
- What is the mechanism that generate neutrino masses?

How much can these experiments tell us?

- Do we have normal or inverted ordering?
- Is there CP violation in the leptonic sector?

Future long baseline oscillation experiments (T2HK, DUNE)

How do we give mass to neutrinos?

ΔL conserved

Higgs mechanism

$$m_\nu \sim y_\nu \frac{v}{\sqrt{2}}$$

$y_\nu < 6.5 \cdot 10^{-13}$

Why so small?

ΔL largely violated

High scale See-saw

$$m_\nu \sim \frac{y_\nu^2 v^2}{M}$$

If $y_\nu^2 \sim O(1) \rightarrow M \sim 10^{11}\mathrm{GeV},$

If $y_\nu^2 \sim O(y_e^2) \rightarrow M \sim 1\mathrm{GeV},$

Schechter and Valle 1980; Mohapatra and Senjanovic 1979; Minkowski 1977; Gell-Mann, Ramond and Slansky 1979; Yanagida 1980

ΔL approximately conserved

Low scale see-saw

$$m_\nu \sim \frac{v^2}{M^2}\mu$$

$\mu \ll 1$

Symmetry protected scenarios

Mohapatra, & Valle 1986 ; Akhmedov, Lindner, Schnapka, and Valle 1996; Gonzalez-Garcia and Valle 1989; Gavela, Hambye, Hernandez 2009; Bernabéu, Santamaria, Vidal, Mendez, and Valle 1987; Mohapatra 1986

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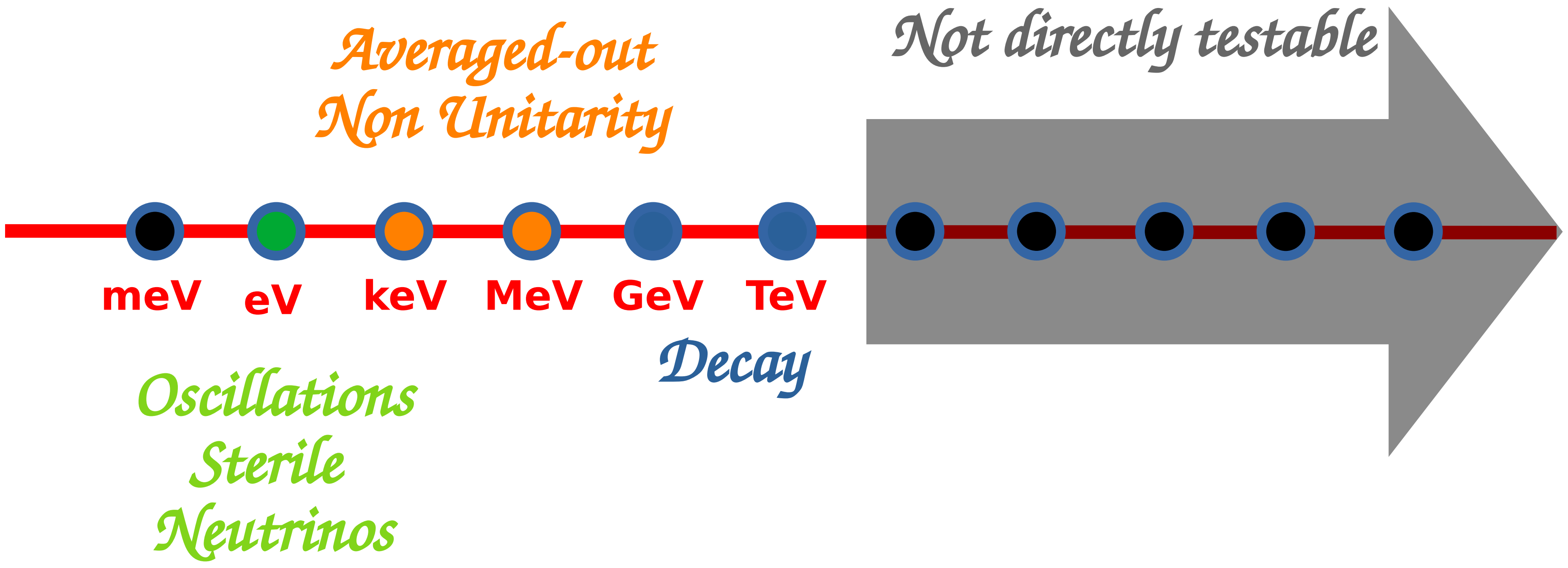
How do we give mass to neutrinos?

New Physics scale M



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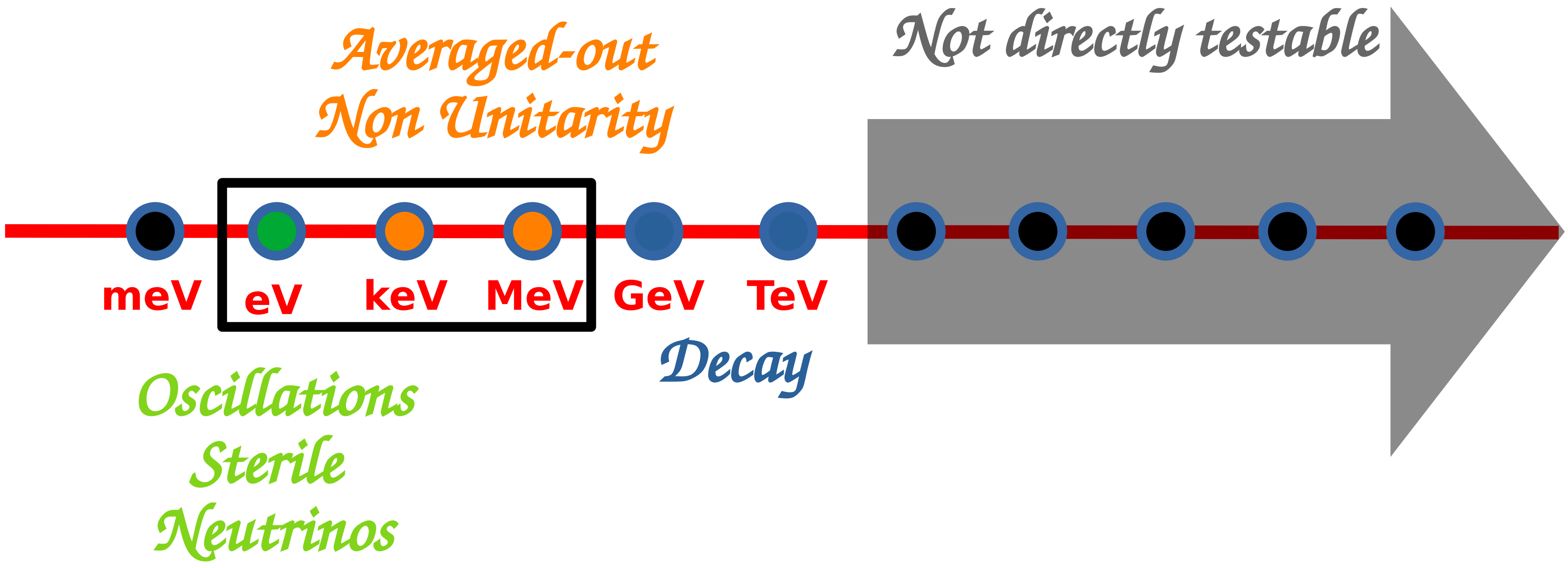


This work

LISS Model

We add two new neutrinos to the SM particle content

N_R^1 $\quad$ N_R^2

$L = 1$ $\quad$ $L = -1$

$$\mathcal{L} \supset -\left(Y_\alpha \, \bar{\ell}_\alpha \, \tilde{\phi} \, N_R^1 + \underline{\epsilon \, Y'_\alpha \, \bar{\ell}_\alpha \, \tilde{\phi} \, N_R^2} + \frac{\Lambda}{2} \, \bar{N}_R^{1c} \, N_R^2 + \underline{\frac{\mu}{2} \, \bar{N}_R^{2c} \, N_R^2} \right) + \mathrm{h.c.}$$

Sources of lepton number violation

$$\mathrm{M} = \begin{pmatrix} \mathbf{0} & \mathbf{Y} v & \epsilon \, \mathbf{Y}' v \\ \mathbf{Y}^T v & 0 & \Lambda \\ \epsilon \, \mathbf{Y}'^T v & \Lambda & \mu \end{pmatrix}$$

Linear-inverse seesaw (LISS) = Linear seesaw + Inverse seesaw

$$|Yv|\,, |\epsilon Y'v|, |\mu| \ll \Lambda$$

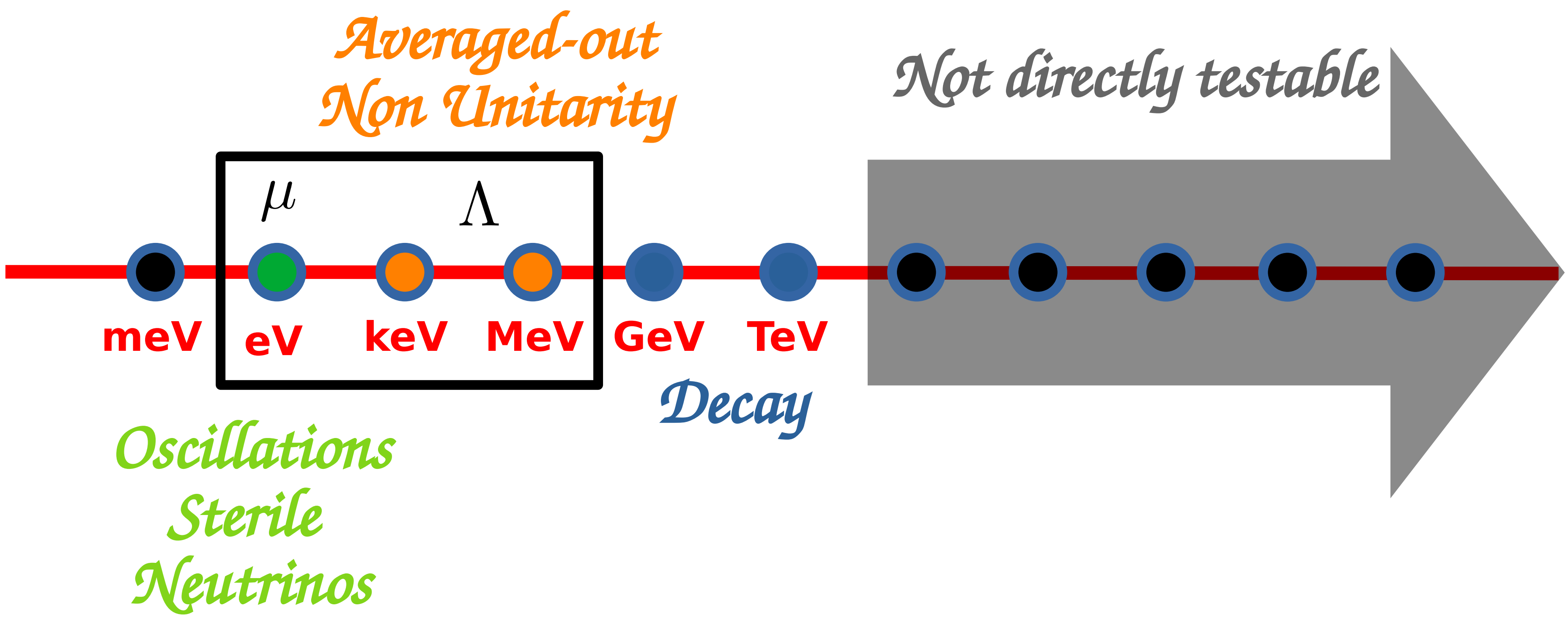
$$\mathrm{U}_B^T M_{\mathrm{LISS}} U_B = \begin{pmatrix} m_{\mathrm{light}}^{3\times3} & 0_{3\times1} & 0_{3\times1} \\ 0_{1\times3} & \multicolumn{2}{c}{\multirow{2}{*}{$M_{\mathrm{heavy}}^{2\times2}$}} \\ 0_{1\times3} & & \end{pmatrix}$$

$$m_\nu \equiv m_{\mathrm{light}} \simeq \frac{1}{\Lambda}\left(\mu\,\frac{Y_N Y_N^T v^2}{\Lambda} - \left(\epsilon v^2 \mathrm{Y}_N Y_N'^T + \epsilon v^2 \mathrm{Y}_N' Y_N^T\right)\right)$$

$$\mathrm{M}_{\mathrm{heavy}} \simeq \begin{pmatrix} 0 & \Lambda \\ \Lambda & \mu \end{pmatrix} \qquad\qquad m_{4,5} \simeq \Lambda \pm \frac{1}{2}|\mu|$$

The two heavy neutrinos form a pseudo-Dirac pair

LISS Phenomenology



$\mu \qquad \Delta m^2_{54} \sim (1\text{–}10)\ \text{eV}^2,$

This work $\quad \Lambda \qquad \Delta m^2_{41},\ \Delta m^2_{51} \sim (1\ \text{keV}^2\text{–}1\ \text{MeV}^2).$

Oscillation phenomenology of the LISS model

PMNS

$$
U=\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & U_{\mu5} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & U_{\tau5} \\
U_{s1,1} & U_{s1,2} & U_{s1,3} & U_{s1,4} & U_{s1,5} \\
U_{s2,1} & U_{s2,2} & U_{s2,3} & U_{s2,4} & U_{s2,5}
\end{pmatrix}.
$$

$$
H = \frac{1}{2E} U \,\mathrm{diag}\left(m_1^2, m_2^2, m_3^2, m_4^2, m_5^2\right) U^\dagger + \mathrm{diag}\left(V_{\mathrm{NC}} + V_{\mathrm{CC}}, V_{\mathrm{NC}}, V_{\mathrm{NC}}, 0, 0\right)
$$

$$
P_{\nu_\beta \to \nu_\alpha}(t) = |\langle \nu_\alpha | \exp(-iHt) | \nu_\beta \rangle|^2 = \left| \sum_{k=1}^{5} \tilde{U}_{\alpha k} \tilde{U}^*_{\beta k} e^{-i\lambda_k t} \right|^2
$$

$$
\begin{aligned}
P_{\nu_\beta \to \nu_\alpha}(t) = & \sum_{k=1}^{5} \left|\tilde{U}_{\alpha k}\right|^2 \left|\tilde{U}_{\beta k}\right|^2 \\
& + 2 \sum_{k>j} \left\{ \Re\left[\tilde{U}_{\alpha k} \tilde{U}^*_{\beta k} \tilde{U}^*_{\alpha j} \tilde{U}_{\beta j}\right] \cos\left[(\lambda_k - \lambda_j)\, t\right] \right. \\
& \left. - \Im\left[\tilde{U}_{\alpha k} \tilde{U}^*_{\beta k} \tilde{U}^*_{\alpha j} \tilde{U}_{\beta j}\right] \sin\left[(\lambda_k - \lambda_j)\, t\right] \right\}
\end{aligned}
$$

At short baselines

$$\sin^2\frac{\Delta_{41}}{2}, \sin^2\frac{\Delta_{51}}{2} \to \frac{1}{2}$$

Constructive interference

$$P^{\rm ND}_{\nu_\alpha\to\nu_\alpha} = 1 - 4\left|U_{\alpha 4}\right|^2\left(1-\left|U_{\alpha 4}\right|^2\right)\sin^2\frac{\Delta_{41}}{2} - 4\left|U_{\alpha 5}\right|^2\left(1-\left|U_{\alpha 5}\right|^2\right)\sin^2\frac{\Delta_{51}}{2}$$
$$+ 4\left|U_{\alpha 4}\right|^2\left|U_{\alpha 5}\right|^2\left(\sin^2\frac{\Delta_{41}}{2} + \sin^2\frac{\Delta_{51}}{2} - \sin^2\frac{\Delta_{41}-\Delta_{51}}{2}\right)$$

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$$+ 4\left|U_{\alpha4}\right|^2\left|U_{\alpha5}\right|^2\left(\sin^2\frac{\Delta_{41}}{2}+\sin^2\frac{\Delta_{51}}{2}-\sin^2\frac{\Delta_{41}-\Delta_{51}}{2}\right)$$

Destructive interference

$$P^{\rm ND}_{\nu_\alpha\to\nu_\beta} = 4\left|U_{\alpha4}\right|^2\left|U_{\beta4}\right|^2\sin^2\frac{\Delta_{41}}{2} + 4\left|U_{\alpha5}\right|^2\left|U_{\beta5}\right|^2\sin^2\frac{\Delta_{51}}{2}$$
$$+ 4\,{\rm Re}\left[U_{\alpha4}U_{\alpha5}U^*_{\beta4}U^*_{\beta5}\right]\left(\sin^2\frac{\Delta_{41}}{2}+\sin^2\frac{\Delta_{51}}{2}-\sin^2\frac{\Delta_{41}-\Delta_{51}}{2}\right)$$

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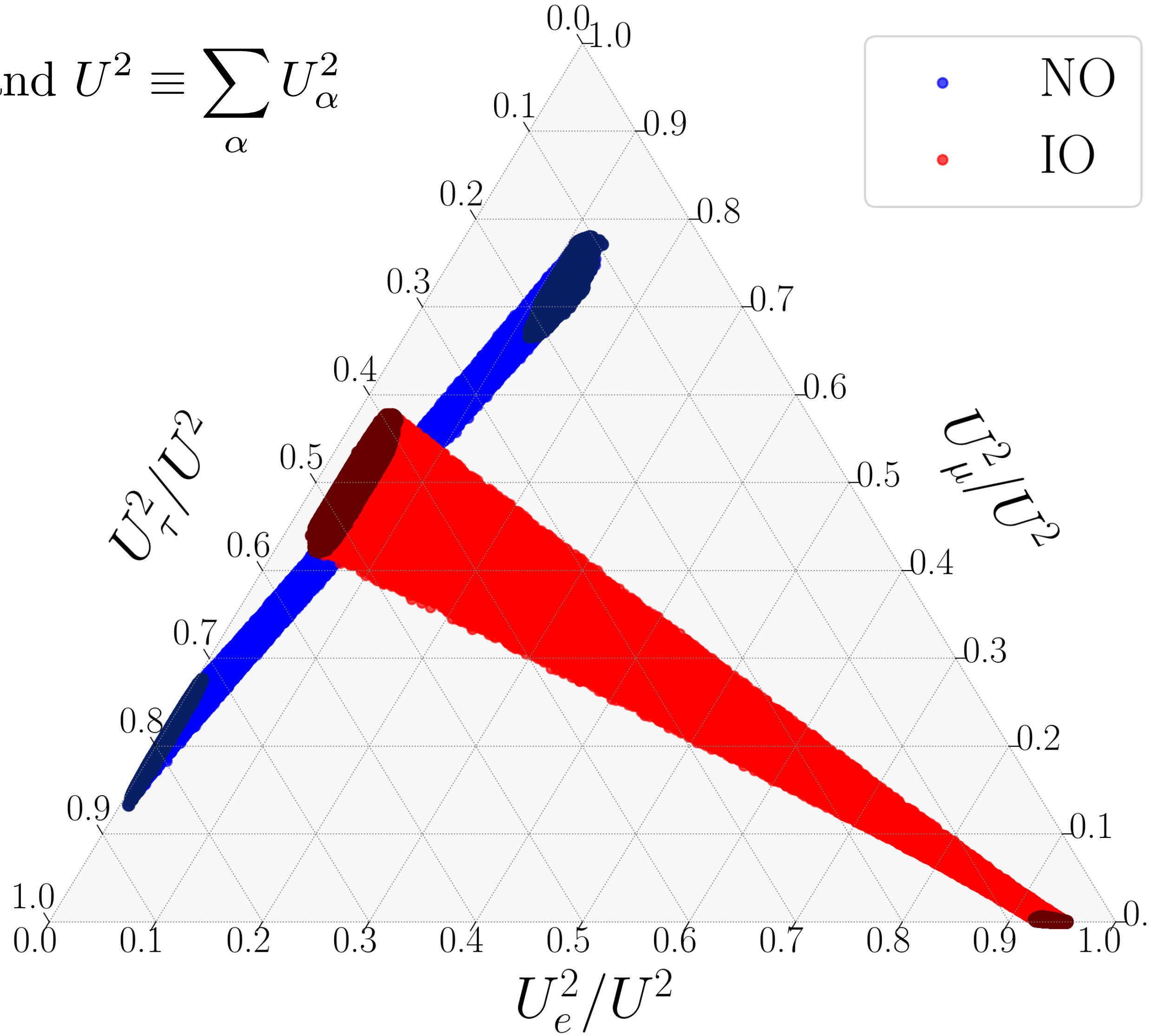
Low mass	Resonant	High mass
Averaged-out Non Unitarity	Oscillations Sterile Neutrinos	Averaged-out Non Unitarity
$\Delta m^2_{54} < 1{\rm eV}^2$	$1{\rm eV}^2 < \Delta m^2_{54} < 70-100{\rm eV}^2$	$\Delta m^2_{54} > 100{\rm eV}^2$

Flavor structure

$$U_\alpha^2 \equiv U_{\alpha 4}^2 + U_{\alpha 5}^2 \text{ and } U^2 \equiv \sum_\alpha U_\alpha^2$$



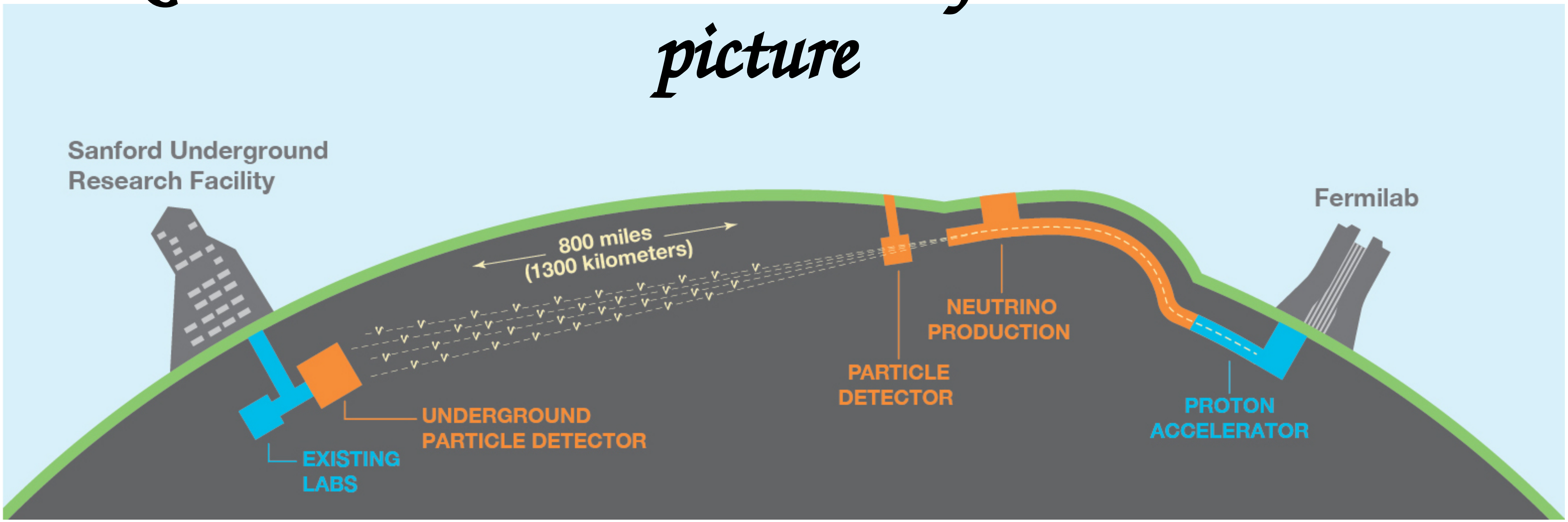
$$U^{\text{PMNS}} = \begin{pmatrix} 0.801 \to 0.842 & 0.519 \to 0.580 & 0.142 \to 0.155 \\ 0.248 \to 0.505 & 0.473 \to 0.682 & 0.649 \to 0.764 \\ 0.270 \to 0.521 & 0.483 \to 0.690 & 0.628 \to 0.746 \end{pmatrix}$$

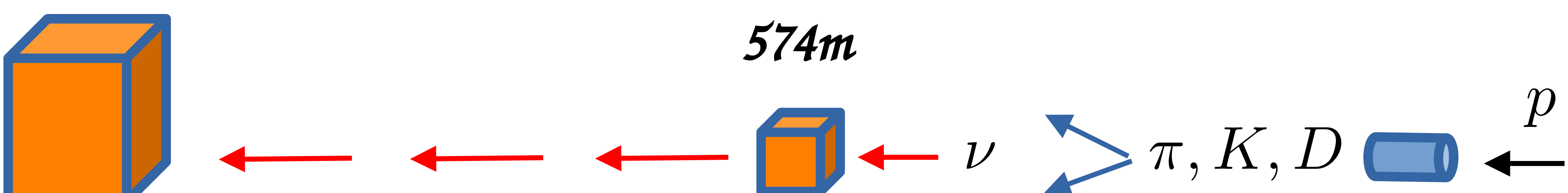
$$\Delta m_{21}^2 \simeq 7.4 \times 10^{-5} \text{ eV}^2$$

$$|\Delta m_{31}^2| \simeq 2.5 \times 10^{-3} \text{ eV}^2$$

DUNE

DUNE will test the robustness of the three-neutrino picture





Results

Disappearance channels

$$\sin^2\frac{\Delta_{41}}{2}, \sin^2\frac{\Delta_{51}}{2} \to \frac{1}{2}$$

Constructive interference

$$P^{\rm ND}_{\nu_\alpha\to\nu_\alpha} = 1 - 4\left|U_{\alpha 4}\right|^2\left(1-\left|U_{\alpha 4}\right|^2\right)\sin^2\frac{\Delta_{41}}{2} - 4\left|U_{\alpha 5}\right|^2\left(1-\left|U_{\alpha 5}\right|^2\right)\sin^2\frac{\Delta_{51}}{2}$$
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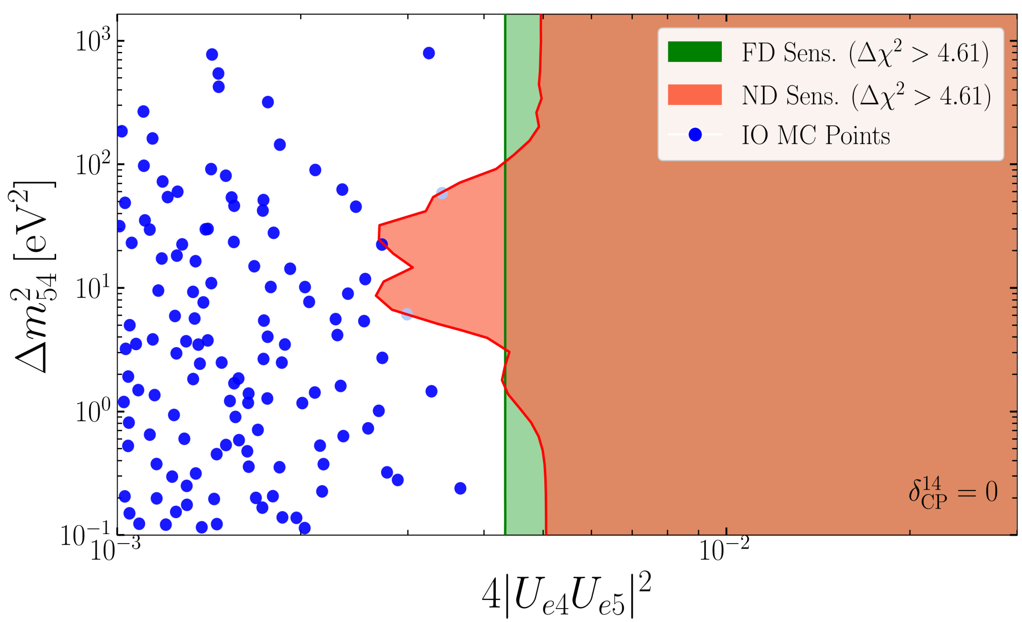
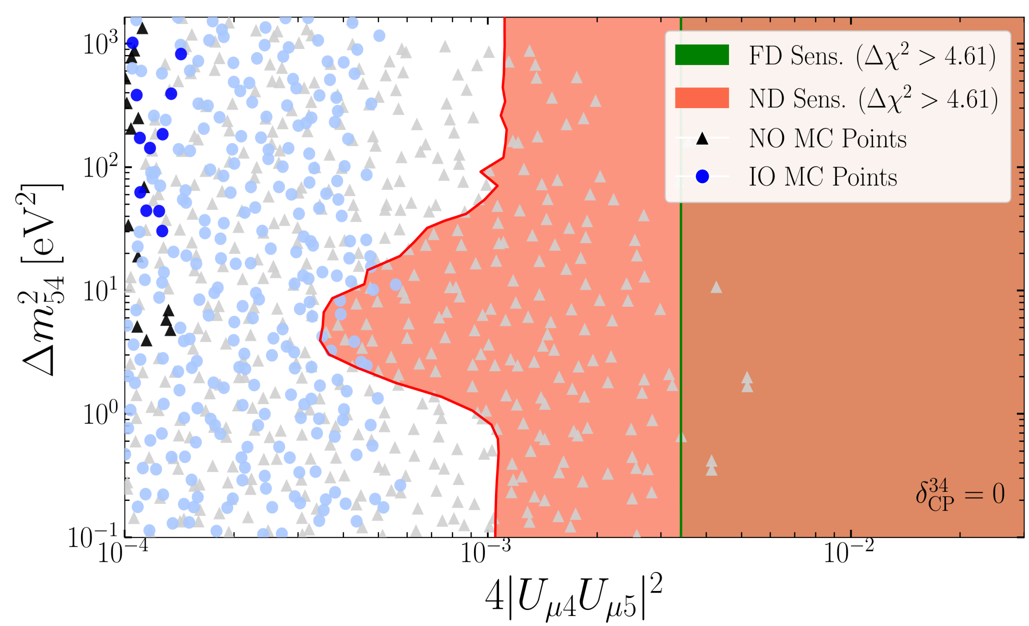
$\nu_e \to \nu_e$



$\nu_\mu \to \nu_\mu$



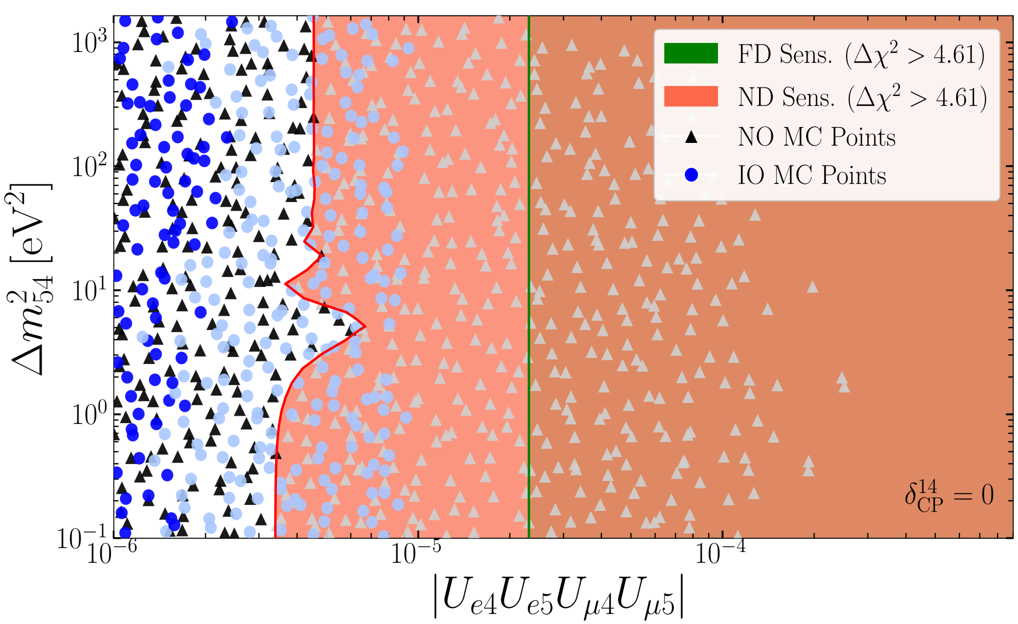
Appearance channels

Destructive interference

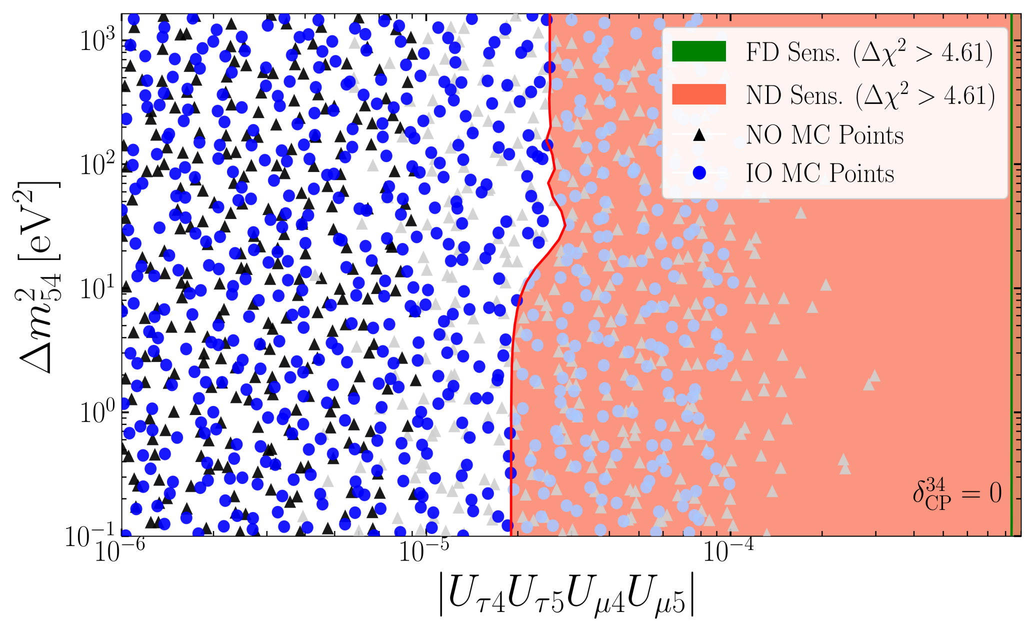
$$\sin^2\frac{\Delta_{41}}{2}, \sin^2\frac{\Delta_{51}}{2} \to \frac{1}{2}$$

$$P_{\nu_\alpha\to\nu_\beta} = 4\,|U_{\alpha4}|^2\,|U_{\beta4}|^2 \sin^2\frac{\Delta_{41}}{2} + 4\,|U_{\alpha5}|^2\,|U_{\beta5}|^2 \sin^2\frac{\Delta_{51}}{2}$$
$$+ 4\,\mathrm{Re}\left[U_{\alpha4}U_{\alpha5}U^*_{\beta4}U^*_{\beta5}\right]\left(\sin^2\frac{\Delta_{41}}{2} + \sin^2\frac{\Delta_{51}}{2} - \sin^2\frac{\Delta_{41}-\Delta_{51}}{2}\right)$$

$\nu_\mu \to \nu_e$



$\nu_\mu \to \nu_\tau$



How do we compare with current experiments?

Parameter	Channel	Current (90% C.L.)	DUNE expected (90% C.L.)
$4\|U_{e4}U_{e5}\|^2$	ν_e DIS	0.00036 LM [90] 0.00036 R [90] 0.00036 HM [90]	0.0043 LM 0.0027 R 0.0043 HM
$4\|U_{\mu 4}U_{\mu 5}\|^2$	ν_μ DIS	0.00076 LM [91] 0.00076 R [91] 0.00076 HM [91]	0.0011 LM 0.00035 R 0.0011 HM
$\|U_{e4}U_{e5}U_{\mu 4}U_{\mu 5}\|$	ν_e APP	0.00011 LM [92] < 0.00014 R [92] 0.00014 HM [92]	$3.4 \cdot 10^{-6}$ LM $8.2 \cdot 10^{-6}$ R $4.6 \cdot 10^{-6}$ HM
$\|U_{\tau 4}U_{\tau 5}U_{\mu 4}U_{\mu 5}\|$	ν_τ APP	$2.7 \cdot 10^{-5}$ LM [92] $< 3.6 \cdot 10^{-5}$ R [92] $3.6 \cdot 10^{-5}$ HM [92]	$1.9 \cdot 10^{-5}$ LM $3.0 \cdot 10^{-5}$ R $2.5 \cdot 10^{-5}$ HM

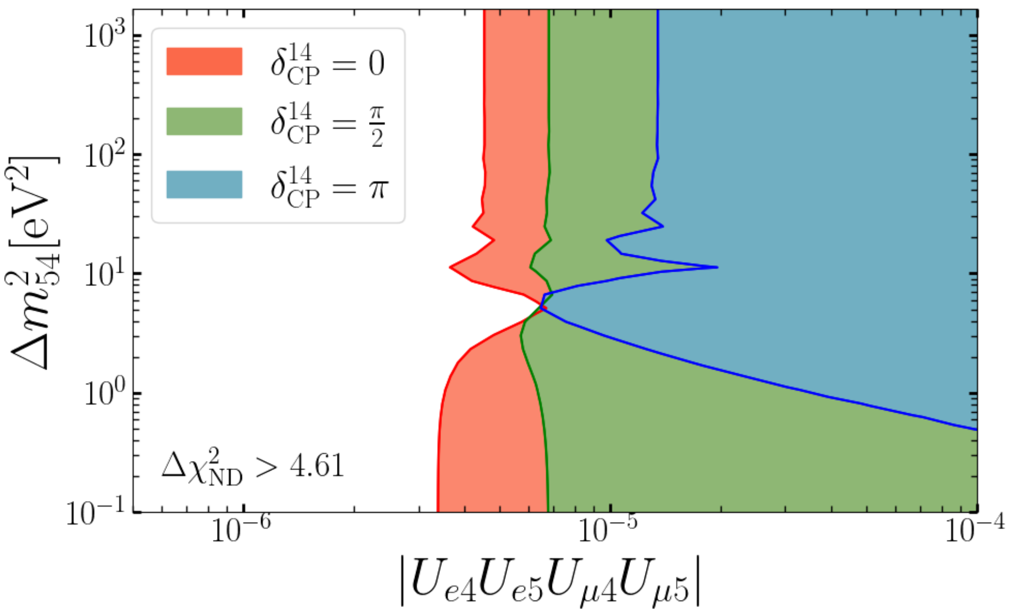
Dune does better than current bounds

Effect of CP violating phases

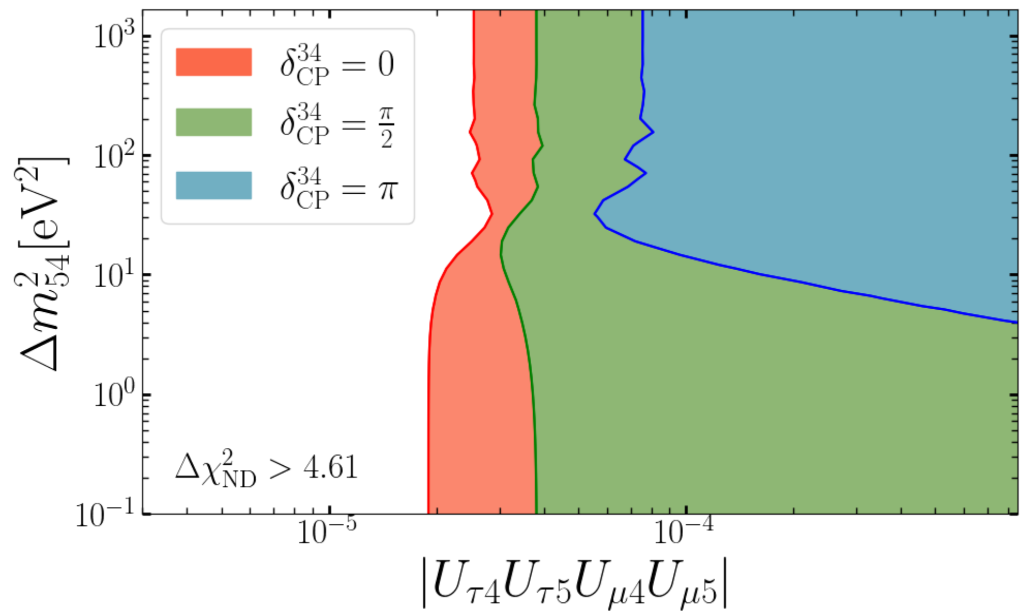
$\theta = U_{\alpha i}$

$$P_{\nu_\mu \to \nu_e} \simeq 4\theta^4 \left[1 + \frac{1}{2}\cos\delta_{14} + \frac{1}{2}\cos\left(\Delta_{54} + \delta_{14}\right) + \mathcal{O}\left(\theta^2\right)\right]$$

$\nu_\mu \to \nu_e$



$\nu_\mu \to \nu_\tau$



$$P_{\nu_\mu \to \nu_\tau} \simeq 4\theta^4 \left[1 + \frac{1}{2}\cos\delta_{34} + \frac{1}{2}\cos\left(\Delta_{54} + \delta_{34}\right) + \mathcal{O}\left(\theta^2\right)\right]$$

Conclusions

- The Linear Inverse Seesaw (LISS) model provides a viable framework for generating neutrino masses consistent with current oscillation data.

- In certain regions of the LISS parameter space, neutrino oscillation experiments currently set the most stringent constraints.

- Future experiments such as DUNE are expected to provide leading constraints on the LISS model, in the regions of parameter space where oscillation effects are accessible.

Thank you

Back-up

$$U = R_{45}R_{35}R_{25}R_{15}R_{34}R_{24}R_{14}R_{23}R_{13}R_{12}\,\mathrm{diag}\left(1, e^{i\varphi_2}, e^{i\varphi_3}, e^{i\varphi_4}, e^{i\varphi_5}\right),$$

$$\mathrm{R}_{14} = \begin{pmatrix} \cos\theta_{14} & 0 & 0 & \sin\theta_{14}e^{-i\delta_{14}} & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ -\sin\theta_{14}e^{i\delta_{14}} & 0 & 0 & \cos\theta_{14} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}.$$

$$U_{e4} = e^{-i(\delta_{14}-\varphi_4)}\,\cos\theta_{15}\,\sin\theta_{14},$$

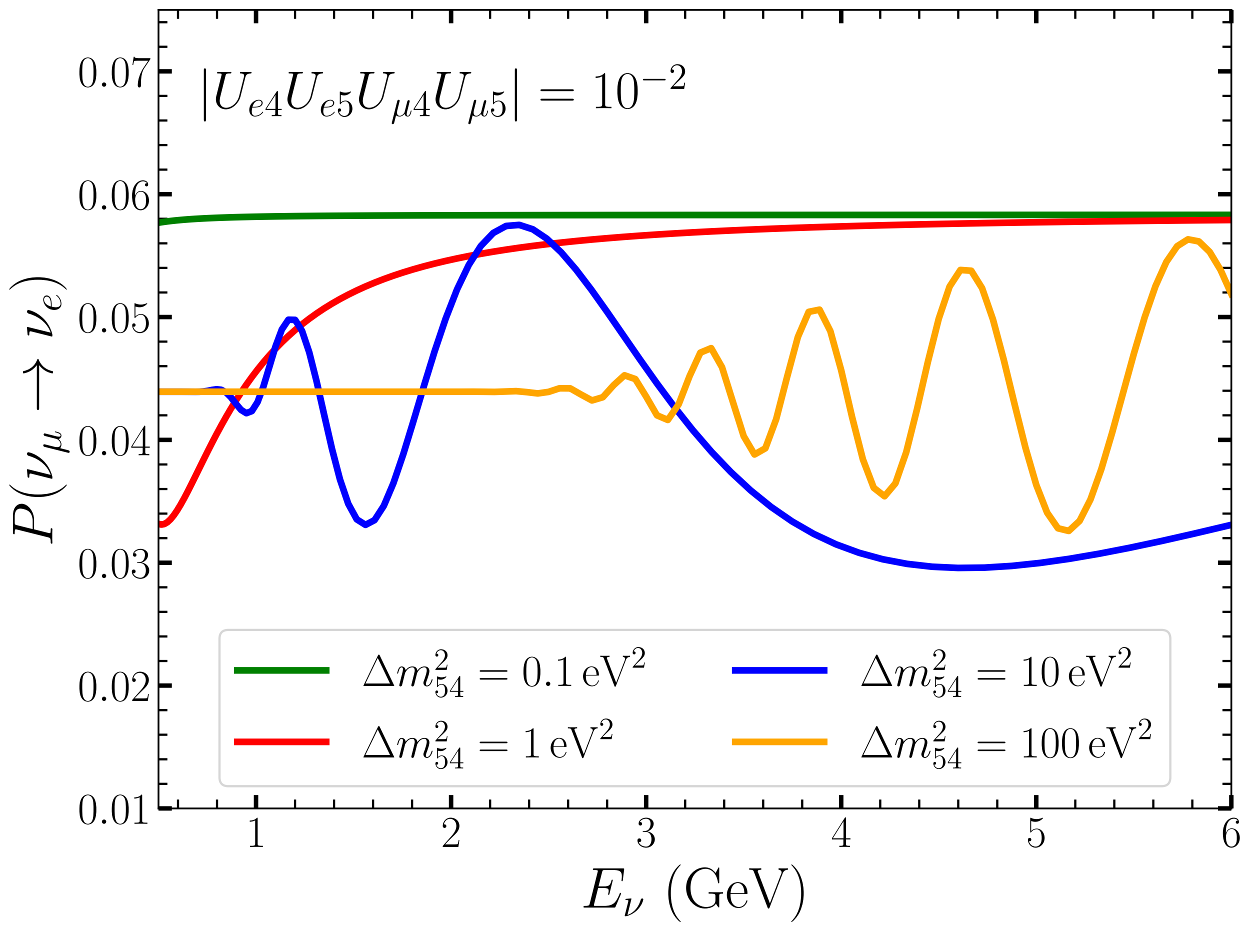
$$U_{e5} = e^{-i(\delta_{15}-\varphi_5)}\,\sin\theta_{15},$$

$$U_{\mu 4} = e^{i\varphi_4}\Big[\cos\theta_{14}\,\cos\theta_{25}\,\sin\theta_{24} - e^{-i(\delta_{14}-\delta_{15}+\delta_{25})}\,\sin\theta_{14}\,\sin\theta_{15}\,\sin\theta_{25}\Big],$$

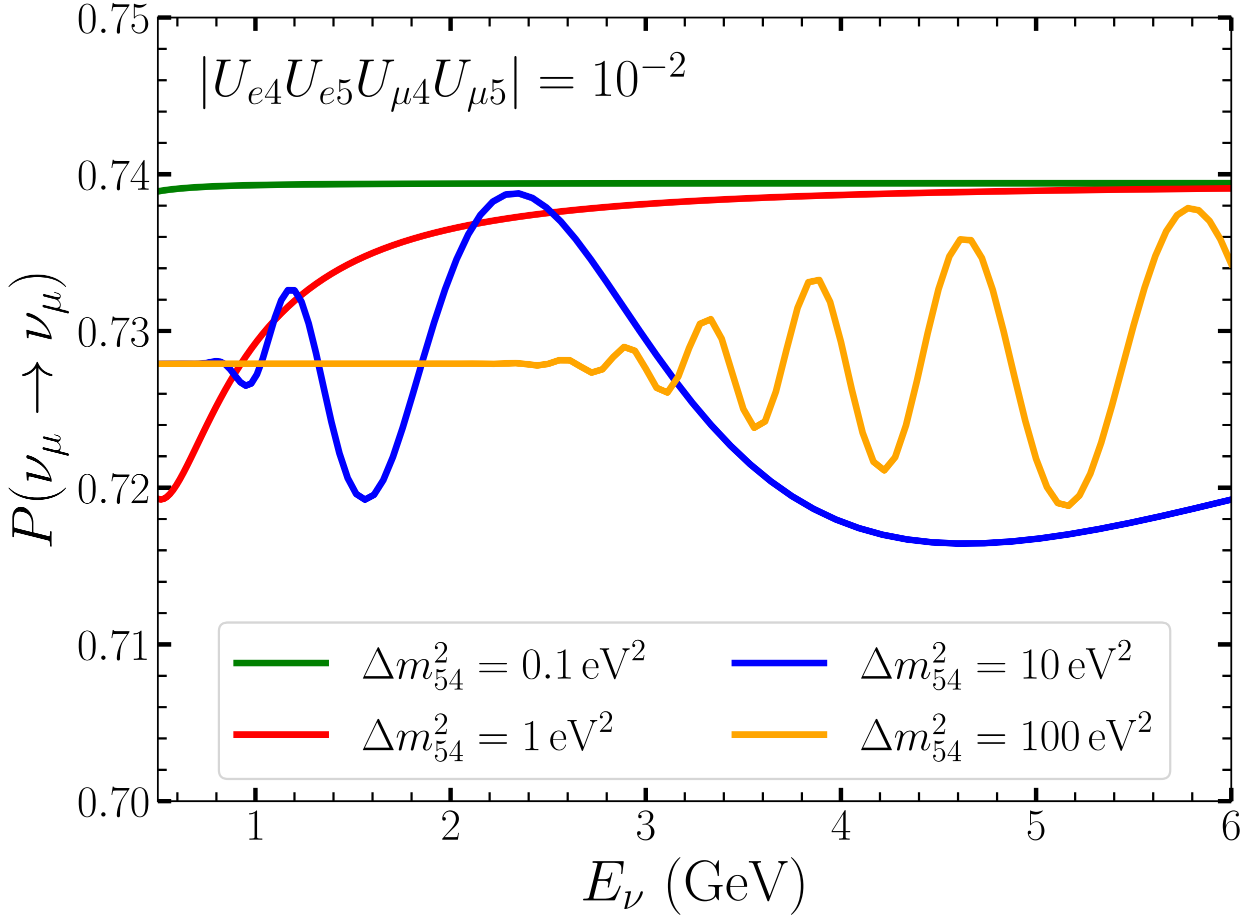
$$U_{\mu 5} = e^{-i(\delta_{25}-\varphi_5)}\,\cos\theta_{15}\,\sin\theta_{25},$$

$$\begin{aligned} U_{\tau 4} = e^{-i(\delta_{14}+\delta_{34}+\delta_{35}-\varphi_4)}\Big[& e^{i(\delta_{14}+\delta_{35})}\cos\theta_{14}\,\cos\theta_{24}\,\cos\theta_{35}\,\sin\theta_{34} \\ & - e^{i(\delta_{15}+\delta_{34})}\cos\theta_{25}\,\sin\theta_{14}\,\sin\theta_{15}\,\sin\theta_{35} \\ & - e^{i(\delta_{14}+\delta_{25}+\delta_{34})}\cos\theta_{14}\,\sin\theta_{24}\,\sin\theta_{25}\,\sin\theta_{35}\Big], \end{aligned}$$

$$U_{\tau 5} = e^{-i(\delta_{35}-\varphi_5)}\,\cos\theta_{15}\,\cos\theta_{25}\,\sin\theta_{35}.$$



$|U_{e4}U_{e5}U_{\mu4}U_{\mu5}| = 10^{-2}$
0.07
0.06
0.05
0.04
0.03
0.02
0.01
$P(\nu_\mu \to \nu_e)$
1
2
3
4
5
6
E_ν (GeV)
$\Delta m^2_{54} = 0.1\,\mathrm{eV}^2$
$\Delta m^2_{54} = 10\,\mathrm{eV}^2$
$\Delta m^2_{54} = 1\,\mathrm{eV}^2$
$\Delta m^2_{54} = 100\,\mathrm{eV}^2$



$|U_{e4}U_{e5}U_{\mu4}U_{\mu5}| = 10^{-2}$
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$\Delta m^2_{54} = 1\,\mathrm{eV}^2$
$\Delta m^2_{54} = 100\,\mathrm{eV}^2$
$P(\nu_\mu \to \nu_\mu)$
E_ν (GeV)
0.75
0.74
0.73
0.72
0.71
0.70
1
2
3
4
5
6