Can Neutrino Oscillations Probe New Lepton Number Violating Physics?

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Retrospective

‘Neutrino-Antineutrino’ Oscillations

- Gell-Mann and Pais: $K^0 - \bar{K}^0$ oscillations (1955)

$\sim$ QCD-produced $(K^0, \bar{K}^0)$ superpositions of mass eigenstates $(K_1^0,\ K_2^0)$

$\sim$ Strangeness violating weak interactions: $K^0 \rightleftarrows \bar{K}^0$

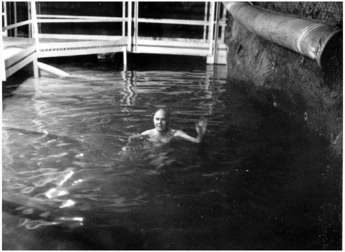
- Pontecorvo: $\nu - \bar{\nu}$ oscillations (1957, before ν_μ)

$\sim$ Introduce ν_R: Dirac + Majorana mass term

$\sim$ Weak-produced ν_L superpositions of Majorana mass eigenstates (ν_1, ν_2)

$\sim$ L violating (LNV) mass: $\nu_L \rightleftarrows \nu_R^C$

$\sim$ ν_R sterile: Reines and Cowan observe deficit
ν_R interact: rumoured Davis signal

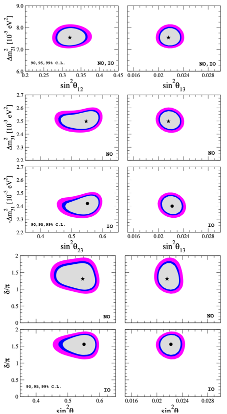


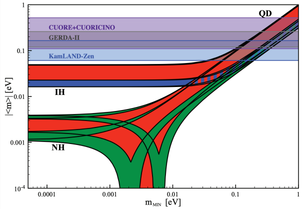
Current Standing

1. Global oscillation fits: Δm^2_{21}, $|\Delta m^2_{31}|$, θ_{12}, θ_{23} and θ_{13}
   - $\Rightarrow$ Strong preference for CP violating phase $\delta \in [\pi, 2\pi]$
   - $\Rightarrow$ 3σ support for normal ordering (NO)

2. Massive ν kinematics: KATRIN (m_0) and cosmology ($\sum m_\nu$)

3. Probes sensitive to L:
   - $\Rightarrow$ $0\nu\beta\beta$
   - $\Rightarrow$ Meson decays
   - $\Rightarrow$ $\mu^- - e^+$ conversion in nuclei





Question: Could an *oscillation* process sensitive to charge (therefore L) be a probe of LNV physics?

Framework

Oscillations in QFT

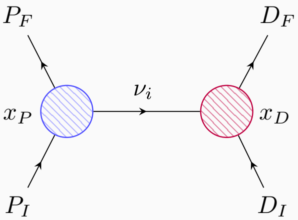
- In QFT, rate of oscillation process: $\Gamma_{\nu_\alpha \to \nu_\beta} \propto \left| \mathcal{A}_{\nu_\alpha \to \nu_\beta}(T, \mathbf{L}) \right|^2 = \left| \sum_i \mathcal{A}_i \right|^2$

$\Rightarrow$ The S-matrix element written as sum over propagating mass eigenestates ν_i:

$$\mathcal{A}_i = \int \frac{d^4 q}{(2\pi)^4} \; \mathcal{M}_D \; \frac{\not{q} + m_i}{q^2 - m_i^2 + i\epsilon} \; \mathcal{M}_P \; e^{-iq\cdot(x_D - x_P)}$$

- SM $(V - A)$ currents at production and detection, require $\mathcal{L}_P = \mathcal{L}_D^\dagger$. Then for negative helicity ν

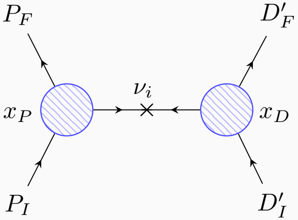
$\Rightarrow \mathcal{A}_i^{LR} \propto U_{\alpha i}^* U_{\beta i} P_L(\not{q} + m_i) P_R \propto \boxed{U_{\alpha i}^* U_{\beta i} (2E_{\mathbf{q}})}$



Oscillations of Majorana Fermions in QFT

- If ν Majorana, possible to show that $\mathcal{L}_P = \mathcal{L}_D$ gives a finite $\mathcal{A}_i$ using Majorana Feynman rules
- For both positive and negative helicity ν

$\Rightarrow \mathcal{A}_i^{RR} \propto U^*_{\alpha i} U^*_{\beta i} P_R(\not{q} + m_i) P_R \propto \boxed{U^*_{\alpha i} U^*_{\beta i} m_i}$



Consequences:

1. Same-sign ℓ_α, ℓ_β at production and detection, $|\Delta L| = 2$
2. $\mathcal{A}_i^{RR} \propto U^*_{\alpha i} U^*_{\beta i}$, sensitive to Majorana phases
3. $\mathcal{A}_i^{RR} \propto \frac{m_i}{(2E_{\mathbf{q}})} \mathcal{A}_i^{LR}$, highly suppressed

What would be the effect of a non $(V - A)$ current at production or detection?

LNV Non-Standard Interactions

- Introduce a four-fermion non-standard interaction (NSI) term:

$$\mathcal{L}_{P,D} = -\frac{G_F}{\sqrt{2}} \sum_{\rho,\sigma} \varepsilon^{(\rho,\sigma)} \left(\bar{\nu}\ \Gamma_\rho\ \ell\right) \left(\bar{d}\ \Gamma_\sigma\ u\right) + \text{h.c.}$$

- Γ_ρ, Γ_σ $\Rightarrow$ Any allowed combination of S, V, T, P, A
- Define $\varepsilon_{\beta\alpha}^{(\rho,\sigma)} \equiv \sum_i U_{\alpha i}\gamma_{\beta i}^{(\rho,\sigma)}$ $\Rightarrow$ ε in 'flavour' basis, γ in 'mass' basis
- $\Gamma_\rho \propto P_L$ (P_R) $\Rightarrow$ LNC (LNV)

$\Rightarrow$ Focus on combination $\varepsilon^{\mathrm{NSI}} \equiv \varepsilon^{(V+A, V\pm A)}$

$\Rightarrow$ $V+A$ leptonic current at detection lifts the $\frac{m_i^2}{(2E_{\mathbf{q}})^2}$ suppression

- Equivalent to EFT picture with $d = 6$ operators constructed from SM fields below EW scale

$\Delta L = 0 + \text{H.c.}$		$\lvert\Delta L\rvert = 2 + \text{H.c.}$	
$\mathcal{O}_{\nu edu}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^{\mu}e_{Lr})(\bar{d}_{Ls}\gamma_{\mu}u_{Lt})$	$\mathcal{O}_{\nu edu}^{S,LL}$	$(\nu_{Lp}^{T}Ce_{Lr})(\bar{d}_{Rs}u_{Lt})$
$\mathcal{O}_{\nu edu}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^{\mu}e_{Lr})(\bar{d}_{Rs}\gamma_{\mu}u_{Rt})$	$\mathcal{O}_{\nu edu}^{T,LL}$	$(\nu_{Lp}^{T}C\sigma^{\mu\nu}e_{Lr})(\bar{d}_{Rs}\sigma_{\mu\nu}u_{Lt})$
$\mathcal{O}_{\nu edu}^{S,RR}$	$(\bar{\nu}_{Lp}e_{Rr})(\bar{d}_{Ls}u_{Rt})$	$\mathcal{O}_{\nu edu}^{S,LR}$	$(\nu_{Lp}^{T}Ce_{Lr})(\bar{d}_{Ls}u_{Rt})$
$\mathcal{O}_{\nu edu}^{T,RR}$	$(\bar{\nu}_{Lp}\sigma^{\mu\nu}e_{Rr})(\bar{d}_{Ls}\sigma_{\mu\nu}u_{Rt})$	$\mathcal{O}_{\nu edu}^{V,RL}$	$(\nu_{Lp}^{T}C\gamma^{\mu}e_{Rr})(\bar{d}_{Ls}\gamma_{\mu}u_{Lt})$
$\mathcal{O}_{\nu edu}^{S,RL}$	$(\bar{\nu}_{Lp}e_{Rr})(\bar{d}_{Rs}u_{Lt})$	$\mathcal{O}_{\nu edu}^{V,RR}$	$(\nu_{Lp}^{T}C\gamma^{\mu}e_{Rr})(\bar{d}_{Rs}\gamma_{\mu}u_{Rt})$

[Jenkins, Manohar, Stoffer '18]

$$L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij} \quad \longrightarrow \quad \frac{v}{\sqrt{2}}(\nu_L^T C\gamma^{\mu}\ell_R)(\bar{d}_L\gamma_{\mu}u_R)$$

Non-Standard Oscillation Formula I

- In the QFT framework, NSI oscillation probability for '$\nu_\alpha \to \bar{\nu}_\beta$':

$$P^{\mathrm{NSI}}_{\nu_\alpha \to \overline{\nu}_\beta} = N_\alpha \left| \sum_i^3 U^*_{\alpha i}\, \gamma_{\beta i}\; e^{-i \frac{m_i^2}{2E_{\mathbf{q}}} L} \right|^2 \propto \sum_\lambda F^{\{\alpha\}}_\lambda (L, E_{\mathbf{q}})\, \varepsilon^2_{\beta\lambda} + \sum_{\lambda<\lambda'} G^{\{\alpha\}}_{\lambda\lambda'} (L, E_{\mathbf{q}})\, \varepsilon_{\beta\lambda}\varepsilon_{\beta\lambda'}$$

$\Rightarrow$ $\lambda, \lambda' = (e, \mu, \tau)$

$\Rightarrow$ N_α a normalisation factor ensuring $\sum_\beta \left(P_{\nu_\alpha \to \nu_\beta} + P^{\mathrm{NSI}}_{\nu_\alpha \to \overline{\nu}_\beta} \right) = 1$

$$\Rightarrow F^{\{\alpha\}}_\lambda (L, E_{\mathbf{q}}) = \sum_i |U_{\alpha i}|^2 |U_{\lambda i}|^2 + 2\,\mathrm{Re} \left\{ \sum_{i<j} U^*_{\alpha i} U_{\alpha j} U^*_{\lambda i} U_{\lambda j} e^{-i \frac{\Delta m^2_{ij}}{2E_{\mathbf{q}}} L} \right\}$$

$$G^{\{\alpha\}}_{\lambda\lambda'} (L, E_{\mathbf{q}}) = 2\,\mathrm{Re} \left\{ \sum_i |U_{\alpha i}|^2 U^*_{\lambda i} U_{\lambda' i} \right\} + 2\,\mathrm{Re} \left\{ \sum_{i<j} U^*_{\alpha i} U_{\alpha j} \left(U^*_{\lambda i} U_{\lambda' j} + U^*_{\lambda' i} U_{\lambda j} \right) e^{-i \frac{\Delta m^2_{ij}}{2E_{\mathbf{q}}} L} \right\}$$

Non-Standard Oscillation Formula II

- $P^{\mathrm{NSI}}_{\nu_\alpha \to \overline{\nu}_\beta}$ sensitive to $\varepsilon_{\beta e}$, $\varepsilon_{\beta\mu}$, $\varepsilon_{\beta\tau}$

$\Rightarrow$ In this framework even for zero distance, $F_\lambda^{(\alpha)} \neq 0$ for $\lambda \neq \alpha$

$$F_\lambda^{\{\alpha\}}\,(L=0) = \sum_i |U_{\alpha i}|^2\,|U_{\lambda i}|^2 \;\;,\quad G_{\lambda\lambda'}^{\{\alpha\}}\,(L=0) = 2\,\mathrm{Re}\left\{\sum_i |U_{\alpha i}|^2\, U^*_{\lambda i} U_{\lambda' i}\right\}$$

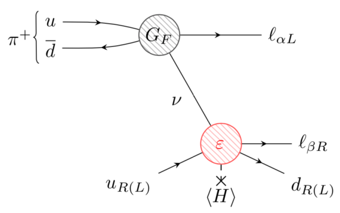
$$\varepsilon^{\mathrm{NSI}} = \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{\mu e} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau e} & \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} \end{pmatrix}$$

- $\nu_\alpha \to \bar{\nu}_e$ or LNV process with ingoing/outgoing $\ell_\alpha^\pm e^\pm$ ($0\nu\beta\beta$, $\mu^- - e^+$)
- $\nu_\alpha \to \bar{\nu}_\mu$ or LNV process with ingoing/outgoing $\ell_\alpha^\pm \mu^\pm$ ($K^+ \to \pi^-\mu^+\mu^+$, $\mu^- - e^+$)
- LNV process with ingoing/outgoing $\ell_\alpha^\pm \tau^\pm$ ($\tau^- \to \mu^+\pi^-\pi^-$)

Oscillation Analysis and Results

MINOS

- **MINOS** experiment (2005–2016): magnetised far detector determined $\ell_\beta^\pm$ from track curvature
- Measured the ratio



$$R_{\mu\mu} \equiv \frac{N_{\mu^+}}{N_{\mu^-}} = \frac{\Gamma_{\nu_\mu \to \overline{\nu}_\mu} + \Gamma_{\overline{\nu}_\mu \to \overline{\nu}_\mu}}{\Gamma_{\nu_\mu \to \nu_\mu} + \Gamma_{\overline{\nu}_\mu \to \nu_\mu}}$$

$\Rightarrow$ Rate for NSI process: $\Gamma_{\nu_\mu \to \overline{\nu}_\mu} = \int dE \, \frac{d\Gamma_{\nu_\mu}}{dE} \cdot P^{\mathrm{NSI}}_{\nu_\mu \to \overline{\nu}_\mu} \cdot \sigma_{\overline{\nu}_\mu}$

- Upper bound of $S_{\mu\mu} = (R_{\mu\mu} - \text{background}) < 0.026 \Rightarrow$ Upper bound on $\varepsilon_{\mu\lambda}$

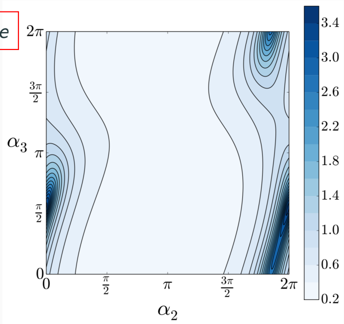
Plan:

1. $|\Delta m^2_{31}| \gg \Delta m^2_{21}$, so use 2ν approximation: $\lambda = \mu, \tau$ (backup)
2. Generalise to 3ν case: $\lambda = e, \mu, \tau$

MINOS - Three Neutrino Phase Dependence

$$U = R_{23} W_{13} R_{12}$$
$$\times \,\mathrm{diag}(1, e^{i\frac{\alpha_2}{2}}, e^{i\frac{\alpha_3}{2}})$$

$\varepsilon_{\mu e}$



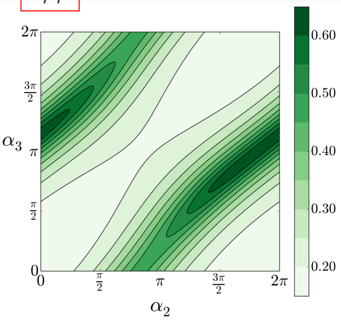
$|\varepsilon_{\mu e}| \lesssim 3.5$

$|\varepsilon_{\mu\mu}| \lesssim 0.6$

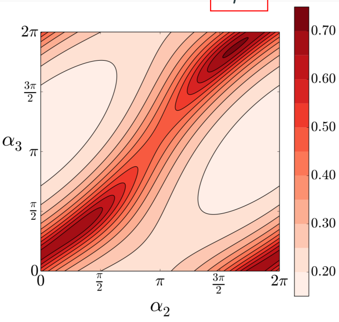
$|\varepsilon_{\mu\tau}| \lesssim 0.7$

See rough dependence of $\varepsilon_{\mu\mu}$ and $\varepsilon_{\mu\tau}$ bounds on $\eta \sim (\alpha_3 - \alpha_2)/2$

$\varepsilon_{\mu\mu}$



$\varepsilon_{\mu\tau}$



KamLAND

- **KamLAND** experiment: initially confirmed the LMA solution to solar ν problem

$\Rightarrow$ Recently searched for $\bar{\nu}_e$ descendant from ^{8}B solar ν_e $\Rightarrow$ NSI at detection

- Assume ν_e oscillate to an incoherent mixture of $(\nu_e, \nu_\mu, \nu_\tau)$

$\Rightarrow$ No dependence on (α_2, α_3) and

$$P^{\rm NSI}_{\nu_e \to \bar{\nu}_e} \to \sum_\lambda P^{\rm eff}_{\nu_e \to \nu_\lambda} |\varepsilon_{e\lambda}|^2$$

$\Rightarrow$ $P^{\rm eff}_{\nu_e \to \nu_\lambda}$ the adiabatic transition probability (valid for $E_\nu \gtrsim 2$ MeV in LMA solution)

- **KamLAND** gives an upper bound $S_{ee} = (R_{ee} - \text{background}) < 2.8 \cdot 10^{-4}$

$$|\varepsilon_{ee}| \lesssim 0.017 \;, \quad |\varepsilon_{e\mu}| \lesssim 0.017 \;, \quad |\varepsilon_{e\tau}| \lesssim 0.015$$

Conventional LNV Probes

Neutrinoless Double Beta Decay (Long-Range Mechanism)

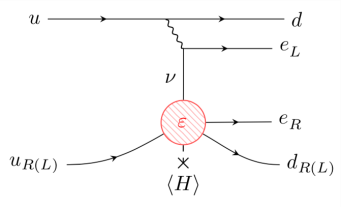
- $(V+A)$ leptonic current $\Rightarrow$ In our framework the $0\nu\beta\beta$ half-life becomes

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = \frac{C_{mm}}{m_e^2}\left|\sum_i^3 U_{ei}^2 m_i\right|^2 + C_{\gamma\gamma}\left|\sum_i^3 U_{ei}\gamma_{ei}^*\right|^2 + C_{m\gamma}\,\mathrm{Re}\left\{\sum_{i,j}^3 U_{ei}^2 m_i U_{ej}^*\gamma_{ej}\right\}$$

C_{mm}, $C_{\gamma\gamma}$, $C_{m\gamma}$ products of NMEs and electron phase space integrals (calculated Muto *et. al* '89)

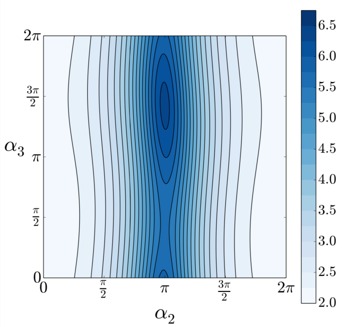
- Use $T_{1/2}^{0\nu\beta\beta}(^{76}\mathrm{Ge}) > 5.3 \times 10^{25}$ y (**GERDA-II**)
- Take NO: $m_1 = 0$ eV, $m_2 = \sqrt{\Delta m_{21}^2}, m_3 = \sqrt{\Delta m_{31}^2}$

$\Rightarrow$ Upper bounds on $|\varepsilon_{ee}|$ and also $|\varepsilon_{e\mu}|$, $|\varepsilon_{e\tau}|$ (zero-distance) as function of (α_2, α_3)



Neutrinoless Double Beta Decay - Phase Dependence

ε_{ee}



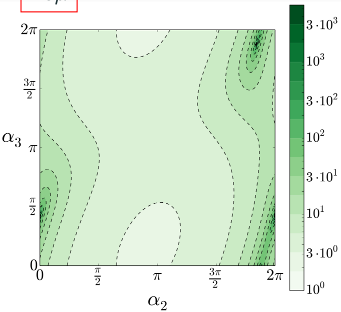
$$U = R_{23} W_{13} R_{12} \times \mathrm{diag}(1, e^{i\frac{\alpha_2}{2}}, e^{i\frac{\alpha_3}{2}})$$

$|\varepsilon_{ee}| \lesssim 6.3 \times 10^{-9}$

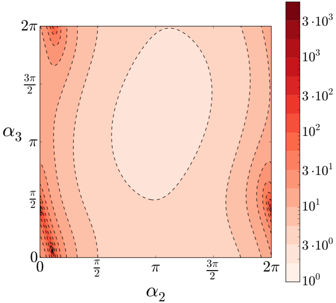
$|\varepsilon_{e\mu}|$ – Unbounded

$|\varepsilon_{e\tau}|$ – Unbounded

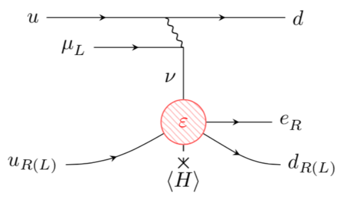
$\varepsilon_{e\mu}$



$\varepsilon_{e\tau}$



Muon to Positron Conversion in Nuclei



- **LFNV** $\mu^- - e^+$ conversion process (proposed by Pontecorvo) $\Rightarrow$ Probe of LNV in the μe sector

$\Rightarrow$ Future LFV searches (PRISM/Mu2e) can search for his channel

$\Rightarrow$ More sensitive than $K^+ \to \pi^- \mu^+ \mu^+$

- In our framework (not including $|(M_\nu)_{e\mu}|^2$ contribution)

$$R_{\mu e} \approx \left| \sum_i \left(U^*_{ei} \gamma_{\mu i} + U^*_{\mu i} \gamma_{ei} \right) \right|^2 \frac{G_F^2}{2} \frac{Q^6}{q^2} \lesssim 10^{-11} \quad \textbf{(SINDRUM-II)}$$

($q \approx 100$ MeV, $Q \approx 15.6$ MeV)

- Constraints are $\boxed{|\varepsilon_{\mu\lambda}| \lesssim \mathcal{O}(10^4)}$, only improving to $\mathcal{O}(10^2)$ in future

$\Rightarrow$ Implied effective operator scale $\Lambda \sim \frac{1}{\sqrt{|\varepsilon_{\mu\lambda}| G_F}} \sim 3$ GeV (EFT barely valid)

Results Summary

NSI coefficient	Previous upper bound	Process	LBL upper bound	LBL experiment
$\lvert\varepsilon_{ee}\rvert$	$2.1 \times 10^{-9} - 6.3 \times 10^{-9}$		0.017	
$\lvert\varepsilon_{e\mu}\rvert$	$2.9 \times 10^{-9} - \infty$	$0\nu\beta\beta$ (^{76}Ge)	0.017	KamLAND
$\lvert\varepsilon_{e\tau}\rvert$	$2.6 \times 10^{-9} - \infty$		0.015	
$\lvert\varepsilon_{\mu e}\rvert$	$\sim 4 \times 10^{3} - 1 \times 10^{4}$		$0.22 - 3.47$	
$\lvert\varepsilon_{\mu\mu}\rvert$	$\sim 6 \times 10^{3} - \infty$	$\mu^- - e^+$	$0.16 - 0.63$	MINOS
$\lvert\varepsilon_{\mu\tau}\rvert$	$\sim 5 \times 10^{3} - \infty$		$0.16 - 0.71$	

- Above: Upper bounds on **LNV NSI** coefficients

⇒ $0\nu\beta\beta$ provides most stringent e-sector constraints

⇒ For finely-tuned (α_2, α_3) values **KamLAND** more constraining for $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$

⇒ Conversely, **MINOS** provides most stringent μ-sector constraints

⇒ Most constraining microscopic process ($\mu^- - e^+$ rather than $K^+ \to \pi^- \mu^+ \mu^+$) is $\mathcal{O}(10^3)$ worse and stretches EFT approach

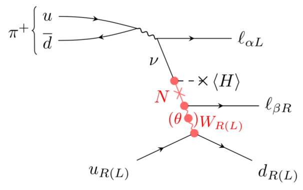
Comments and Future Work I

Assumptions

- Most recent global fit values of oscillation parameters and δ in NO
- Idealised picture of oscillations in QFT
- Simplistic treatment of solar neutrinos

Future Work

- Let oscillation parameters vary along with $\varepsilon^{\mathrm{NSI}}$
- Technical details of LNV NSI impact on matter oscillations
- Constraints on $\varepsilon^{\mathrm{NSI}}$ $\Rightarrow$ constraints on given model, e.g. sterile neutrinos



Conclusions

- An oscillation experiment ND or FD sensitive to the charge of outgoing $\ell_\beta^\pm$
  $\Rightarrow$ probe of LNV physics

- E.g. $(V+A)$ leptonic current at detection aleviates the $\left(\frac{m_i}{2E_{\mathbf{q}}}\right)^2$ suppression of a Majorana ν

$\Rightarrow$ In the associated low energy EFT a modified mixing $U_{\alpha i} \to \gamma_{\alpha i}$ results in a modified oscillation probability $P^{\mathrm{NSI}}_{\nu_\alpha \to \bar{\nu}_\beta}$

$\Rightarrow$ Oscillations a testing ground for the off-diagonal flavour structure of $\varepsilon^{\mathrm{NSI}}$

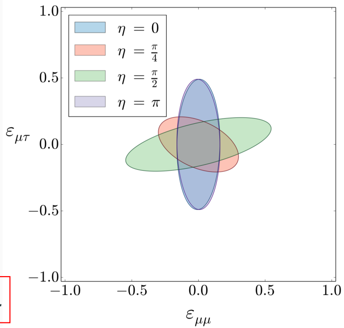
- **KamLAND** only provides better constraints in the e-sector than $0\nu\beta\beta$ for finely-tuned (α_2, α_3). **MINOS**, however, provides the most stringent μ-sector constraints

Thanks for listening, any questions?

Backup

MINOS - Two Neutrino Results

$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta e^{i\eta} \\ \sin\vartheta e^{-i\eta} & \cos\vartheta \end{pmatrix}$$



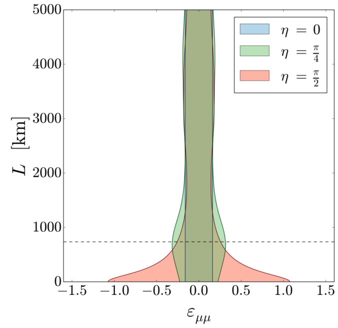
$\varepsilon_{\mu\mu} - \varepsilon_{\mu\tau}$

For $\eta = 0$:

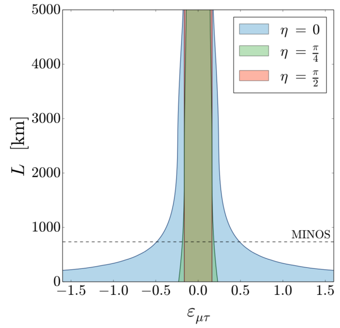
$P^{\rm NSI}_{\nu_\mu \to \bar\nu_\mu} = P_{\nu_\mu \to \nu_\mu} |\varepsilon_{\mu\mu}|^2$

$P^{\rm NSI}_{\nu_\mu \to \bar\nu_\mu} = P_{\nu_\mu \to \nu_\tau} |\varepsilon_{\mu\tau}|^2$

$\varepsilon_{\mu\mu} - L$

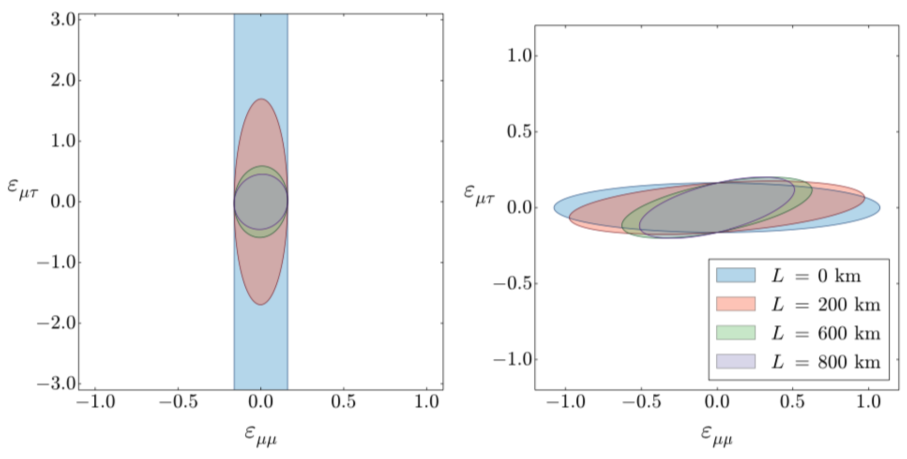


$\varepsilon_{\mu\tau} - L$

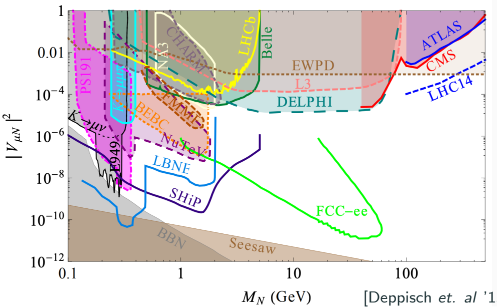


MINOS - More Plots

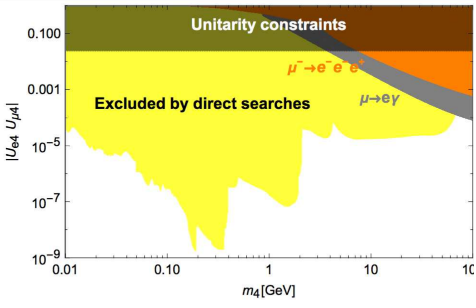
- Allowed regions in $(\varepsilon_{\mu\mu}, \varepsilon_{\mu\tau})$ for different baselines:

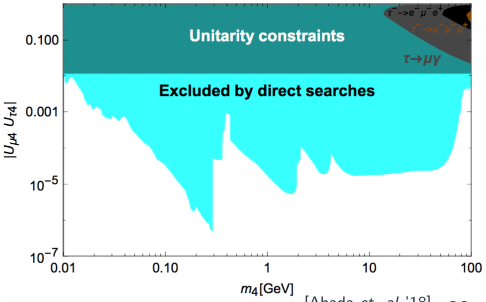


Comments and Future Work II



[Deppisch *et. al* '15]





[Abada *et. al* '18]