Non-Standard Neutrino Interactions and PMNS Non-Unitarity

Enrique Fernández-Martínez

inνisiblesPlus elusiνes

νProbes

Introduction: NSI

Generic new physics affecting ν oscillations can be parameterized as 4-fermion Non-Standard Interactions:

Production or detection of a ν_β associated to a l_α

$$2\sqrt{2}G_F\varepsilon_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L l_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R} f'\right)$$

So that $$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}|\nu_\beta\rangle$$

$$\pi \rightarrow \mu + \nu_\beta \qquad n + \nu_\beta \rightarrow p + l_\alpha$$

Y. Grossman hep-ph/9507344

Direct bounds on prod/det NSI

$$2\sqrt{2}G_F\varepsilon^{ud}_{\alpha\beta}\left(\bar{l}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{u}\gamma_\mu P_{L,R}d\right)$$

$$2\sqrt{2}G_F\varepsilon^{\mu e}_{\alpha\beta}\left(\bar{\mu}\gamma^\mu P_L\nu_\beta\right)\left(\bar{\nu}_\alpha\gamma_\mu P_L e\right)$$

$$\left|\varepsilon^{ud}\right| < \begin{pmatrix} 0.041 & 0.025 & 0.041 \\ 0.026 & 0.078 & 0.013 \\ 0.12 & 0.013 & 0.13 \end{pmatrix}$$

$$\left|\varepsilon^{\mu e}\right| < \begin{pmatrix} 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \end{pmatrix}$$

90% CL

bounds order $\sim 10^{-2}$

C. Biggio, M. Blennow and EFM 0907.0097

Introduction: NSI

Non-Standard ν scattering off matter can also be parameterized as 4-fermion Non-Standard Interactions:

$$2\sqrt{2}G_F\varepsilon^m_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f\right)$$

so that $$\tilde{V}_{\mathrm{MSW}} = a_{\mathrm{CC}}\begin{pmatrix} 1+\varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} \end{pmatrix}$$

$\nu_\alpha \longrightarrow \nu_\beta$ in matter $f = e, u, d$

Direct bounds on matter NSI

If matter NSI are uncorrelated to production and detection direct bounds are mainly from ν scattering off e and nuclei

$$2\sqrt{2}G_F \varepsilon^m_{\alpha\beta}\left(\bar{\nu}_\beta \gamma^\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R} f\right)$$

$$|\varepsilon^e_m| < \begin{pmatrix} 0.14 & 0.1 & 0.44 \\ 0.1 & 0.03 & 0.1 \\ 0.44 & 0.1 & 0.5 \end{pmatrix} \quad |\varepsilon^u_m| < \begin{pmatrix} 1 & 0.05 & 0.5 \\ 0.05 & 0.008 & 0.05 \\ 0.5 & 0.05 & 3 \end{pmatrix} \quad |\varepsilon^d_m| < \begin{pmatrix} 0.6 & 0.05 & 0.5 \\ 0.05 & 0.015 & 0.05 \\ 0.5 & 0.05 & 6 \end{pmatrix}$$

90% CL

Rather weak bounds…

…can they be saturated avoiding additional constraints?

S. Davidson, C. Peña garay, N. Rius and A. Santamaria hep-ph/0302093

J. Barranco, O. G. Miranda, C. A. Moura and J. W. F. Valle hep-ph/0512195

J. Barranco, O. G. Miranda, C. A. Moura and J. W. F. Valle 0711.0698

C. Biggio, M. Blennow and EFM 0902.0607

Oscillation bounds on matter NSI

And from oscillations…

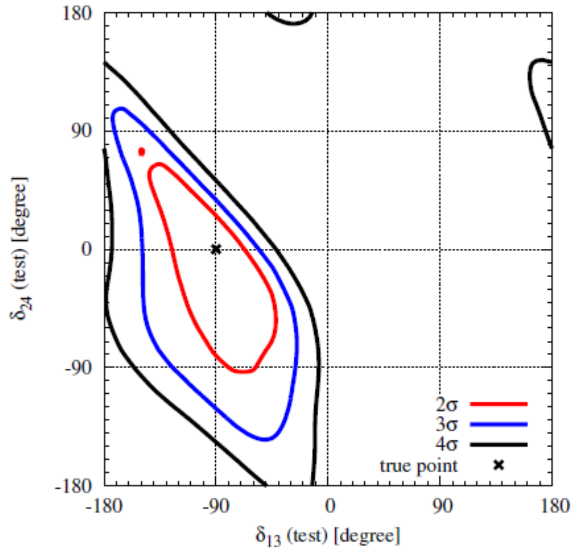
See also P. Coloma, P. B. Denton, M.C. Gonzalez-Garcia, M. Maltoni and T. Schwetz 1701.04828 for comprehensive combintion of oscillations+scattering bounds

		90% CL	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus\ [-1.19, -0.81]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$+0.310$	$[+0.02, +0.51]$	$\oplus\ [-1.17, -1.03]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.01, +0.03]$
$\varepsilon^d_{e\mu}$	-0.023	$[-0.09, +0.04]$	$[-0.09, +0.08]$
$\varepsilon^d_{e\tau}$	$+0.023$	$[-0.13, +0.14]$	$[-0.13, +0.14]$
$\varepsilon^d_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$

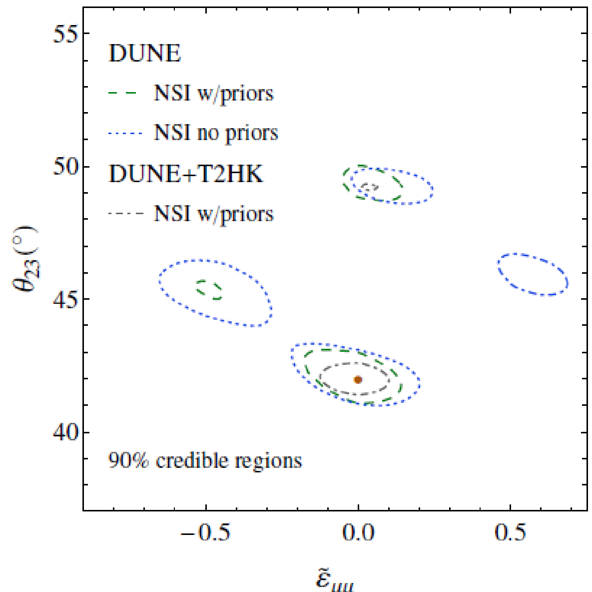
M.C. Gonzalez-Garcia and M. Maltoni 1307.3092

…can they be saturated avoiding additional constraints?

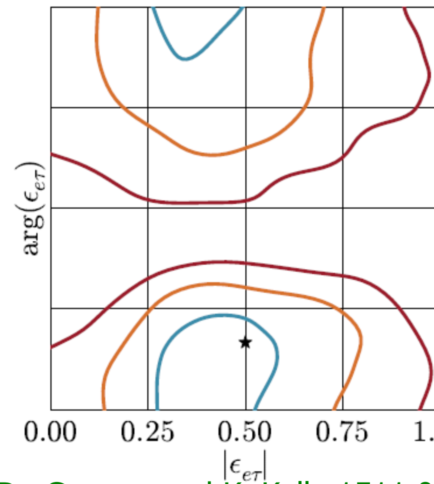
Striking potential signals in oscillations



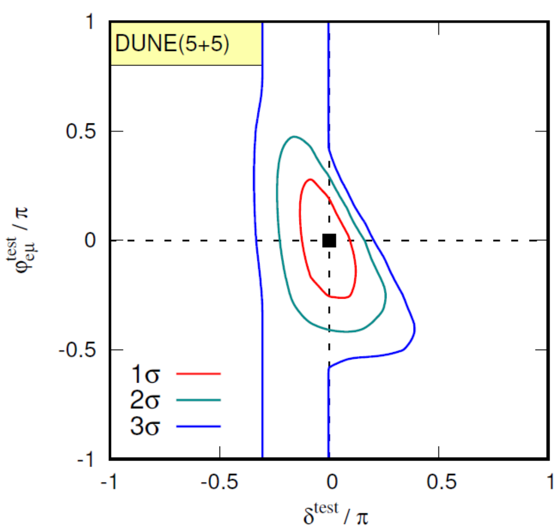
D. Dutta, R. Gandhi, B. Kayser, M. Masud, S. Prakash 1607.02152



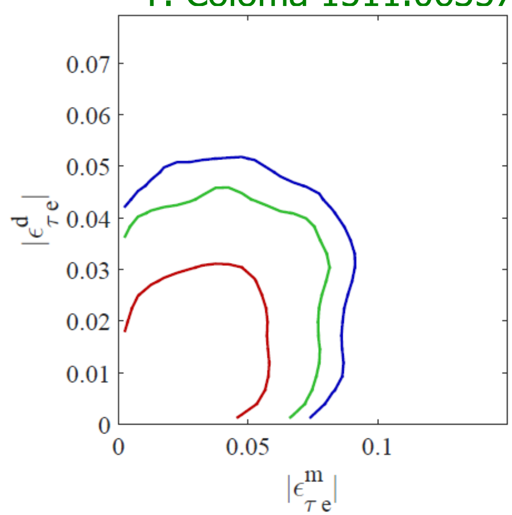
P. Coloma 1511.06357



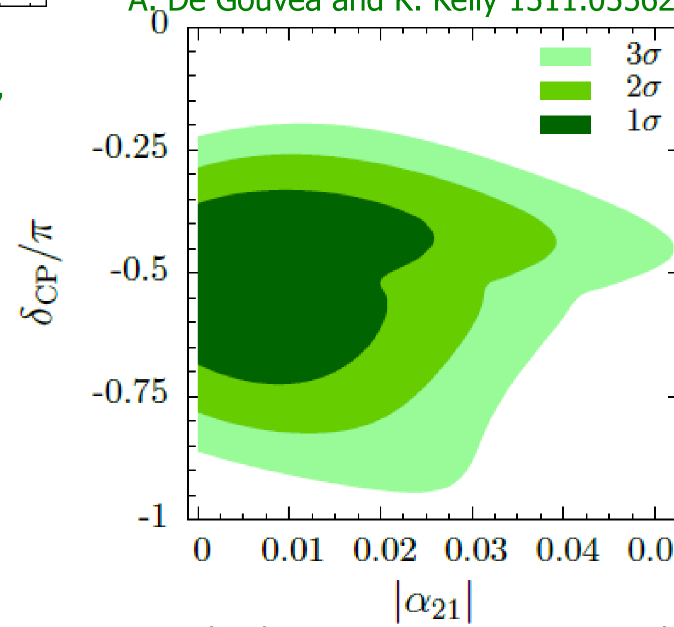
A. De Gouvea and K. Kelly 1511.05562



M. Masud and P. Mehta 1603.01380



M. Blennow, S. Choubey, T. Ohlsson, D. Pramanik and S. Raut, 1606.08851



F. J. Escrihuela, D. V. Forero, O. G. Miranda, M. Tórtola and J. W. F. Valle 1612.07377

Gauge invariance

However $2\sqrt{2}G_F\varepsilon^m_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f\right)$

is related to $2\sqrt{2}G_F\varepsilon^m_{\alpha\beta}\left(\bar{l}_\beta\gamma^\mu P_L l_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f\right)$

by gauge invariance and very strong bounds exist

$$\varepsilon^m_{e\mu} < \sim 10^{-6}$$

$$\varepsilon^m_{e\tau} < \sim 10^{-4}$$

$$\varepsilon^m_{\mu\tau} < \sim 10^{-4}$$

$\mu \to e\,\gamma$
$\mu \to e$ in nuclei
τ decays

S. Bergmann et al. hep-ph/0004049
Z. Berezhiani and A. Rossi hep-ph/0111147
S. Antusch, M. Blennow, EFM and T. Ota, 1005.0756

Large NSI?

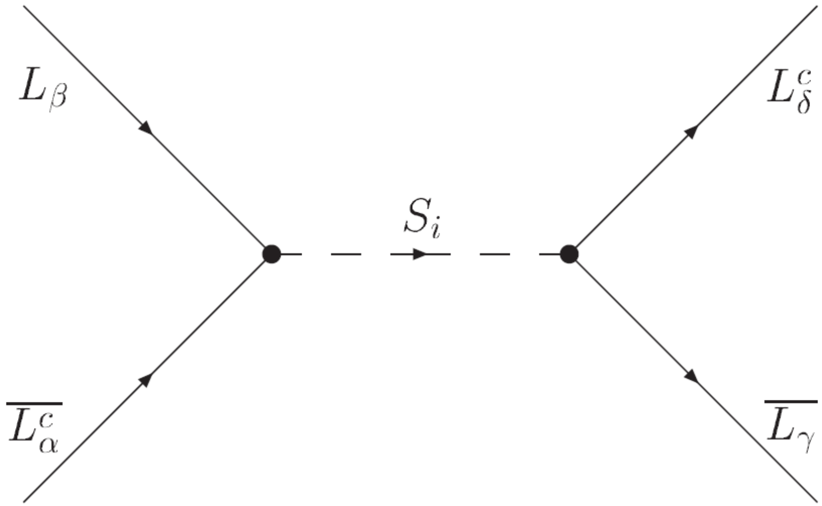
Search for gauge invariant SM extensions satisfying:

- Matter NSI are generated at tree level by integrating out heavy fields
- 4-charged fermion ops not generated at the same level
- No cancellations between diagrams with different messenger particles to avoid constraints
- The Higgs Mechanism is responsible for EWSB

S. Antusch, J. Baumann and EFM 0807.1003
B. Gavela, D. Hernández, T. Ota and W. Winter 0809.3451

Large NSI?

At d=6 only one direct possibility: charged scalar singlet



Present in Zee model or R-parity violating SUSY

$$\mathcal{L}^S_{int} = -\lambda^i_{\alpha\beta}\overline{L^c_\alpha} i\sigma_2 L_\beta S_i + \text{H.c.} = \lambda^i_{\alpha\beta} S_i (\overline{\ell^c_\alpha} P_L \nu_\beta - \overline{\ell^c_\beta} P_L \nu_\alpha) + \text{H.c.}$$

$$\mathcal{L}^{d=6,as}_{NSI} = c^{d=6,as}_{\alpha\beta\gamma\delta}\left(\overline{L^c_\alpha} i\sigma_2 L_\beta\right)\left(\overline{L_\gamma} i\sigma_2 L^c_\delta\right) \qquad \varepsilon^{m,e_L}_{\alpha\beta} = \sum_i \frac{\lambda^i_{e\beta}\lambda^{i*}_{e\alpha}}{\sqrt{2} G_F m^2_{S_i}}$$

M. Bilenky and A. Santamaria hep-ph/9310302

Large NSI?

Since $\lambda_{\alpha\beta} = -\lambda_{\beta\alpha}$ only $\varepsilon_{\mu\mu}$, $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau} \neq 0$

Very constrained:

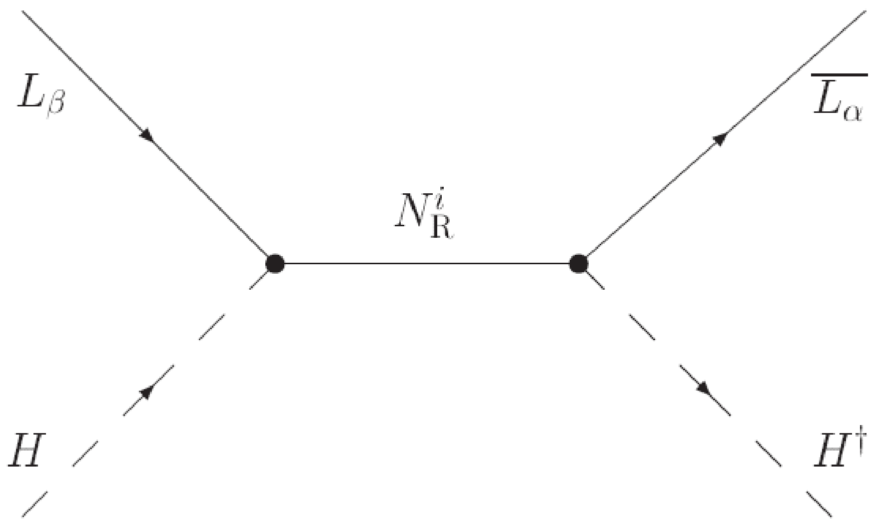
$$
\begin{aligned}
|\varepsilon^{m,e_\mathrm{L}}_{\mu\mu}| &< 8.2 \cdot 10^{-4} \\
|\varepsilon^{m,e_\mathrm{L}}_{\tau\tau}| &< 8.4 \cdot 10^{-3} \\
|\varepsilon^{m,e_\mathrm{L}}_{\mu\tau}| &< 1.9 \cdot 10^{-3}
\end{aligned}
$$

$\mu \to e\,\gamma$
μ decays
τ decays
CKM unitarity

F. Cuypers and S. Davidson hep-ph/9310302
S. Antusch, J. Baumann and EFM 0807.1003

Large NSI?

At d=6 indirect way: fermion singlets



Masses

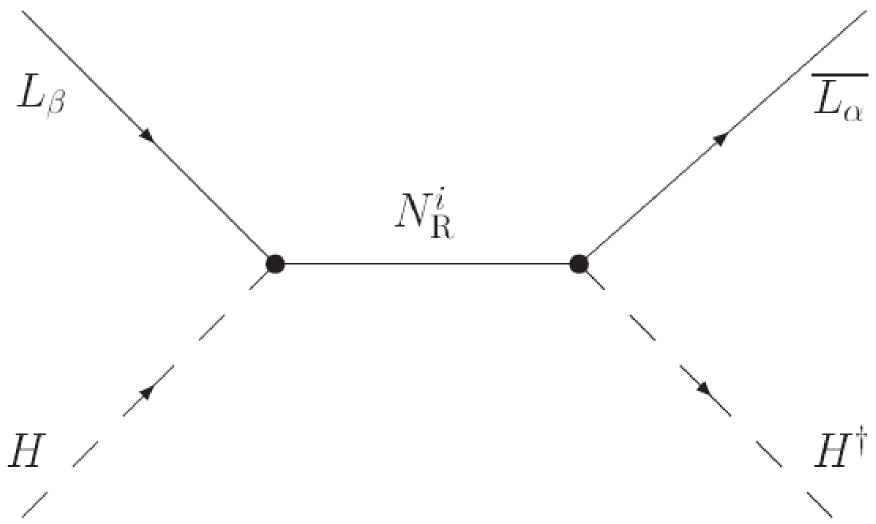
$$Y_N^t \frac{1}{M_N} Y_N \left(\overline{L_\beta^c} i\sigma_2 H\right)\left(H^t i\sigma_2 L_\alpha\right) \xrightarrow[\langle H\rangle = \frac{v}{\sqrt{2}}]{\text{SSB}} m_\nu \overline{\nu}_\beta^c \nu_\alpha$$

$$m_\nu = Y_N^t \frac{v^2}{2M_N} Y_N$$

Weinberg 1879

Large NSI?

At d=6 indirect way: fermion singlets



$$Y_N^\dagger \frac{1}{M_N^2} Y_N \left(\overline{L}_\beta i\sigma_2 H^*\right) i\partial\!\!\!/ \left(H^t i\sigma_2 L_\alpha\right) \xrightarrow[\langle H \rangle = \frac{v}{\sqrt{2}}]{\text{SSB}}$$

Mixing

$$\eta \overline{\nu}_\beta i\partial\!\!\!/ \nu_\alpha$$

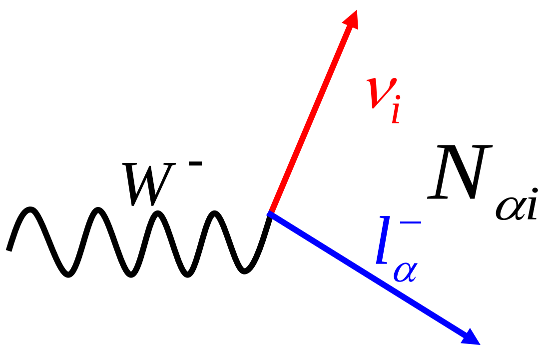
$$\eta = Y_N^t \frac{v^2}{2M_N^2} Y_N$$

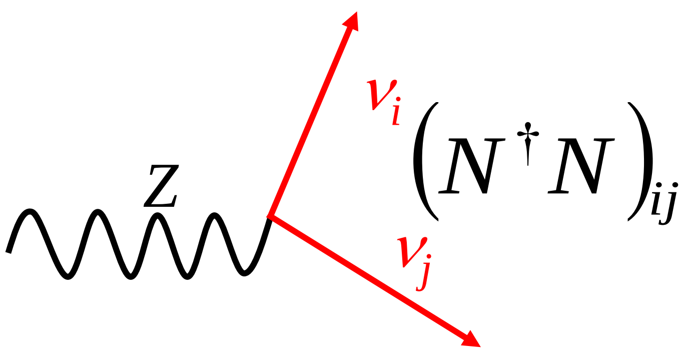
A. Broncano, M. B. Gavela and E. Jenkins hep-ph/0210192

Probing the Seesaw: Non-Unitarity

$$U^T \begin{pmatrix} 0 & m_D \\ m_D^t & M_N \end{pmatrix} U = \begin{pmatrix} N^t & X^t \\ \Theta^t & Y^t \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^t & M_N \end{pmatrix} \begin{pmatrix} N & \Theta \\ X & Y \end{pmatrix} = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

The 3×3 submatrix N of active neutrinos will not be unitary



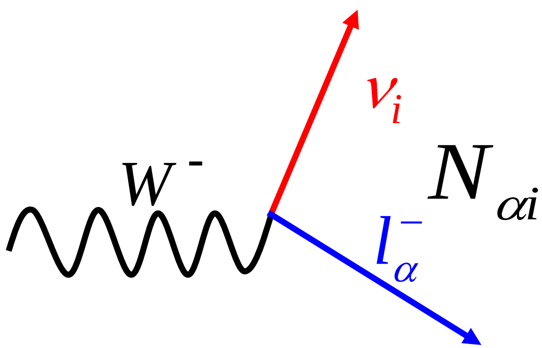


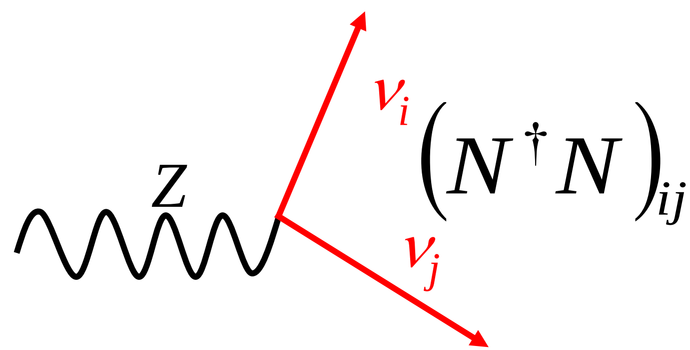
Effects in weak interactions…

Probing the Seesaw: Non-Unitarity

$$U^T \begin{pmatrix} 0 & m_D \\ m_D^t & M_N \end{pmatrix} U = \begin{pmatrix} N^t & X^t \\ \Theta^t & Y^t \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^t & M_N \end{pmatrix} \begin{pmatrix} N & \Theta \\ X & Y \end{pmatrix} = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

The 3×3 submatrix N of active neutrinos will not be unitary





Effects in weak interactions…

When the W and Z are integrated out to obtain the Fermi theory NSI are recovered!

Probing the Seesaw: Non-Unitarity

In general $N = (1-\eta)\cdot U$ with η Hermitian and U Unitary

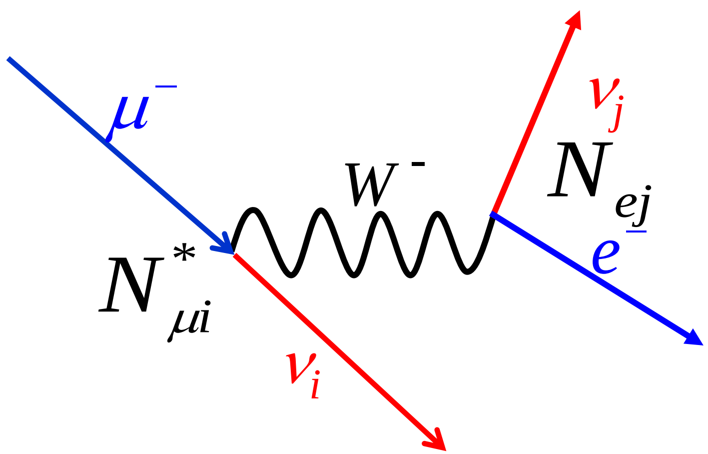
For a Seesaw $\eta = \dfrac{\Theta\Theta^\dagger}{2}$ with $\Theta \approx m_{\mathrm{D}}^\dagger M_N^{-1}$ the heavy-active mixing

Probing the Seesaw: Non-Unitarity

In general $N = (1-\eta)\cdot U$ with η Hermitian and U Unitary

For a Seesaw $\eta = \frac{\Theta\Theta^{\dagger}}{2}$ with $\Theta \approx m_{\mathrm{D}}^{\dagger} M_N^{-1}$ the heavy-active mixing

G_F from μ decay is affected!



$$G_\mu = G_F \left(NN^{\dagger}\right)_{ee} \left(NN^{\dagger}\right)_{\mu\mu}$$

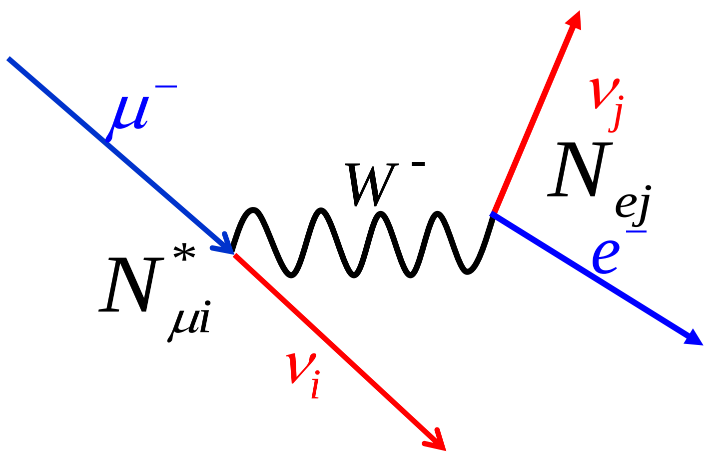
$$G_\mu = G_F \left(1 - \eta_{ee} - \eta_{\mu\mu}\right)$$

Probing the Seesaw: Non-Unitarity

In general $N = (1-\eta)\cdot U$ with η Hermitian and U Unitary

For a Seesaw $\eta = \dfrac{\Theta\Theta^\dagger}{2}$ with $\Theta \approx m_D^\dagger M_N^{-1}$ the heavy-active mixing

G_F from μ decay is affected!



$$G_\mu = G_F \left(NN^\dagger\right)_{ee}\left(NN^\dagger\right)_{\mu\mu}$$
$$G_\mu = G_F \left(1-\eta_{ee}-\eta_{\mu\mu}\right)$$

But $G_F = \dfrac{\alpha\pi M_Z^2}{\sqrt{2}M_W^2\left(M_Z^2-M_W^2\right)}$

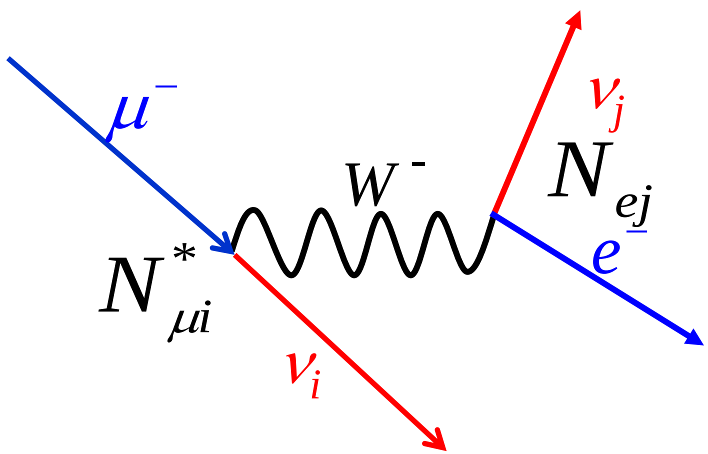
Agree at the ~per mille level

Probing the Seesaw: Non-Unitarity

In general $N = (1-\eta)\cdot U$ with η Hermitian and U Unitary

For a Seesaw $\eta = \dfrac{\Theta\Theta^\dagger}{2}$ with $\Theta \approx m_{\mathrm{D}}^\dagger M_N^{-1}$ the heavy-active mixing

G_F from μ decay is affected!



$$\mathrm{G}_\mu = G_F\left(NN^\dagger\right)_{ee}\left(NN^\dagger\right)_{\mu\mu}$$
$$\mathrm{G}_\mu = G_F\left(1-\eta_{ee}-\eta_{\mu\mu}\right)$$

But $G_F = \dfrac{\alpha\pi M_Z^2}{\sqrt{2}M_W^2\left(M_Z^2 - M_W^2\right)}$

Agree at the ~per mille level

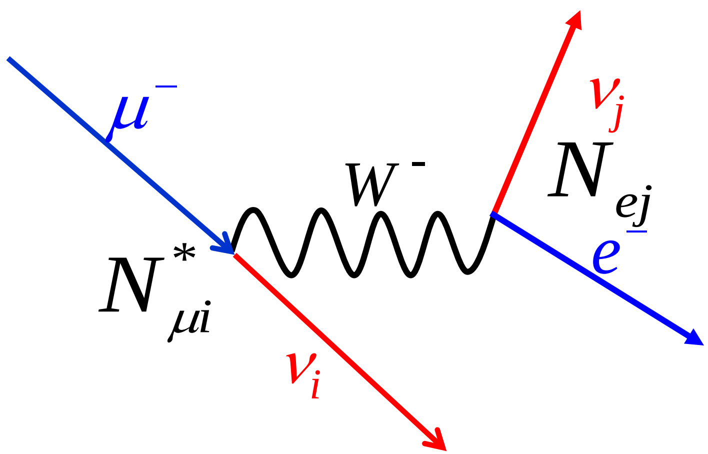
Measurements of s_W^2 or tests of CKM unitarity from β and K decay also constrain G_F

Probing the Seesaw: Non-Unitarity

In general $N = (1-\eta)\cdot U$ with η Hermitian and U Unitary

For a Seesaw $\eta = \dfrac{\Theta\Theta^{\dagger}}{2}$ with $\Theta \approx m_{\mathrm{D}}^{\dagger} M_N^{-1}$ the heavy-active mixing

G_F from μ decay is affected!



$$\mathrm{G}_{\mu} = G_F \left(NN^{\dagger}\right)_{ee} \left(NN^{\dagger}\right)_{\mu\mu}$$

$$\mathrm{G}_{\mu} = G_F \left(1-\eta_{ee}-\eta_{\mu\mu}\right)$$

But $G_F = \dfrac{\alpha\pi M_Z^2}{\sqrt{2}M_W^2\left(M_Z^2 - M_W^2\right)}$

Agree at the ~per mille level

Measurements of s_W^2 or tests of CKM unitarity from β and K decay also constrain G_F

Lepton weak universality from π, K and τ decay ratios

LVF processes from the loss of the GIM cancellation...

Probing the Seesaw: Non-Unitarity

Recent bounds from a global fit to flavour and Electroweak precision data (28 observables considered)

$$|\eta_{\alpha\beta}| \leq \begin{pmatrix} 1.3\cdot 10^{-3} & 1.2\cdot 10^{-5} & 1.4\cdot 10^{-3} \\ 1.2\cdot 10^{-5} & 2.0\cdot 10^{-4} & 6.0\cdot 10^{-4} \\ 1.4\cdot 10^{-3} & 6.0\cdot 10^{-4} & 2.8\cdot 10^{-3} \end{pmatrix}$$

EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1605.08774
See also (incomplete list!) P. Langaker and D. London 1988
S. M. Bilenky and C. Giunti hep-ph/9211269
E. Nardi, E. Roulet and D. Tommasini hep-ph/9503228
D. Tommasini, G. Barenboim, J. Bernabeu and C. Jarlskog hep-ph/9503228
S. Antusch, C. Biggio, EFM, B. Gavela and J. López Pavón hep-ph/0607020
S. Antusch, J. Baumann and EFM 0807.1003
D. V. Forero, S. Morisi, M. Tortola, and J. W. F. Valle 1107.6009
S. Antusch and O. Fischer 1407.6607
F.J. Escrihuela, D.V. Forero, O.G. Miranda, M. Tórtola, J.W.F. Valle 1612.07377

Probing the Seesaw: Non-Unitarity

Or $N = (1-\alpha)\cdot U_{PMNS}$ with $(1-\alpha) = U_{36}U_{26}U_{16}U_{35}U_{25}U_{15}U_{34}U_{24}U_{14}$

$$\alpha \simeq \begin{pmatrix} \frac{1}{2}\left(s_{14}^2+s_{15}^2+s_{16}^2\right) & 0 & 0 \\ \hat{s}_{14}\hat{s}_{24}^* + \hat{s}_{15}\hat{s}_{25}^* + \hat{s}_{16}\hat{s}_{26}^* & \frac{1}{2}\left(s_{24}^2+s_{25}^2+s_{26}^2\right) & 0 \\ \hat{s}_{14}\hat{s}_{34}^* + \hat{s}_{15}\hat{s}_{35}^* + \hat{s}_{16}\hat{s}_{36}^* & \hat{s}_{24}\hat{s}_{34}^* + \hat{s}_{25}\hat{s}_{35}^* + \hat{s}_{26}\hat{s}_{36}^* & \frac{1}{2}\left(s_{34}^2+s_{35}^2+s_{36}^2\right) \end{pmatrix}$$

Triangular structure more convinient for oscillations

Z.-z. Xing 0709.2220 and 1110.0083.
F. J. Escrihuela, D. V. Forero, O. G. Miranda, M. Tortola, and J. W. F. Valle 1503.08879.

Probing the Seesaw: Non-Unitarity

Or $N = (1-\alpha)\cdot U_{PMNS}$ with $(1-\alpha) = U_{36}U_{26}U_{16}U_{35}U_{25}U_{15}U_{34}U_{24}U_{14}$

$$\alpha \simeq \begin{pmatrix} \frac{1}{2}\left(s_{14}^2 + s_{15}^2 + s_{16}^2\right) & 0 & 0 \\ \hat{s}_{14}\hat{s}_{24}^* + \hat{s}_{15}\hat{s}_{25}^* + \hat{s}_{16}\hat{s}_{26}^* & \frac{1}{2}\left(s_{24}^2 + s_{25}^2 + s_{26}^2\right) & 0 \\ \hat{s}_{14}\hat{s}_{34}^* + \hat{s}_{15}\hat{s}_{35}^* + \hat{s}_{16}\hat{s}_{36}^* & \hat{s}_{24}\hat{s}_{34}^* + \hat{s}_{25}\hat{s}_{35}^* + \hat{s}_{26}\hat{s}_{36}^* & \frac{1}{2}\left(s_{34}^2 + s_{35}^2 + s_{36}^2\right) \end{pmatrix}$$

Triangular structure more convinient for oscillations

Z.-z. Xing 0709.2220 and 1110.0083.

F. J. Escrihuela, D. V. Forero, O. G. Miranda, M. Tortola, and J. W. F. Valle 1503.08879.

Dictionary

$$\begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix} = \begin{pmatrix} \eta_{ee} & 0 & 0 \\ 2\eta_{e\mu}^* & \eta_{\mu\mu} & 0 \\ 2\eta_{e\tau}^* & 2\eta_{\mu\tau}^* & \eta_{\tau\tau} \end{pmatrix}$$

$$\epsilon_{\beta\alpha}^{s*} = \epsilon_{\alpha\beta}^{d} = -\alpha_{\alpha\beta}$$

$$\epsilon_{ee} = -\alpha_{ee} \qquad \epsilon_{\mu\mu} = \alpha_{\mu\mu} \qquad \epsilon_{\tau\tau} = \alpha_{\tau\tau}$$

$$\epsilon_{e\mu} = \frac{1}{2}\alpha_{\mu e}^* \qquad \epsilon_{e\tau} = \frac{1}{2}\alpha_{\tau e}^* \qquad \epsilon_{\mu\tau} = \frac{1}{2}\alpha_{\tau\mu}^*$$

M. Blennow, P.Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1609.08637

Can we escape these bounds?

In F.J. Escrihuela, D.V. Forero, O.G. Miranda, M. Tórtola, J.W.F. Valle 1612.07377 bounds from charged lepton flavour and precision EW tests are quoted separately from short baseline oscillation searches.

	One parameter (1 d.o.f.)		All parameters 6 d.o.f.	
	90% C.L.	3σ	90% C.L.	3σ
	Neutrinos + charged leptons			
α_{11}	0.9974	0.9963	0.9961	0.9952
α_{22}	0.9994	0.9991	0.9990	0.9987
α_{33}	0.9988	0.9976	0.9973	0.9961
$\|\alpha_{21}\|$	1.7×10^{-3}	2.5×10^{-3}	2.6×10^{-3}	4.0×10^{-3}
$\|\alpha_{31}\|$	2.0×10^{-3}	4.4×10^{-3}	5.0×10^{-3}	7.0×10^{-3}
$\|\alpha_{32}\|$	1.1×10^{-3}	2.0×10^{-3}	2.4×10^{-3}	3.4×10^{-3}
	Neutrinos only			
$\|\alpha_{21}\|$	2.6×10^{-2}	3.6×10^{-2}	-	-
$\|\alpha_{32}\|$	1.5×10^{-2}	2.0×10^{-2}	-	-

Interesting suggestion: there might be a cancellation with some other source of new physics in the first set not present in the second.

The first set is more model-dependent and the second more robust?

Can we escape these bounds?

In F.J. Escrihuela, D.V. Forero, O.G. Miranda, M. Tórtola, J.W.F. Valle 1612.07377 bounds from charged lepton flavour and precision EW tests are quoted separately from short baseline oscillation searches.

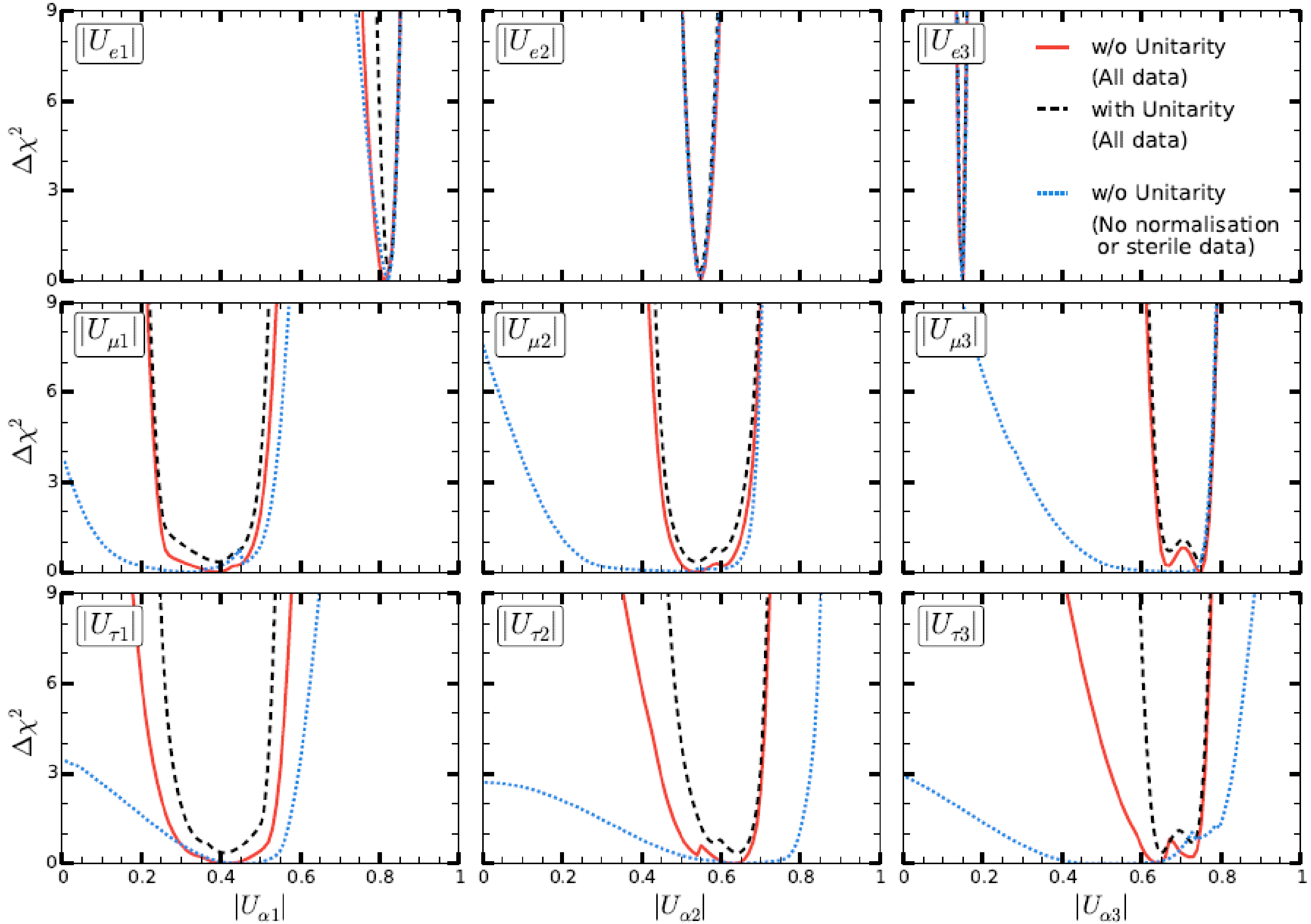
	One parameter (1 d.o.f.)		All parameters 6 d.o.f.	
	90% C.L.	3σ	90% C.L.	3σ
Neutrinos + charged leptons				
α_{11}	0.9974	0.9963	0.9961	0.9952
α_{22}	0.9994	0.9991	0.9990	0.9987
α_{33}	0.9988	0.9976	0.9973	0.9961
$\lvert\alpha_{21}\rvert$	1.7×10^{-3}	2.5×10^{-3}	2.6×10^{-3}	4.0×10^{-3}
$\lvert\alpha_{31}\rvert$	2.0×10^{-3}	4.4×10^{-3}	5.0×10^{-3}	7.0×10^{-3}
$\lvert\alpha_{32}\rvert$	1.1×10^{-3}	2.0×10^{-3}	2.4×10^{-3}	3.4×10^{-3}
Neutrinos only				
$\lvert\alpha_{21}\rvert$	2.6×10^{-2}	3.6×10^{-2}	-	-
$\lvert\alpha_{32}\rvert$	1.5×10^{-2}	2.0×10^{-2}	-	-

Personally, I find it difficult: Main bounds from first set come from μ, π, β, K and τ decays. These are the same processes to produce and detect ν. If they are cancelled by new physics, prod and det NSI cancelling the NU effects also in oscillations should be induced.

Ideas for discussion?

A different possibility: Steriles

For very light (< keV) extra neutrinos these strong constraints are lost and ν oscillations are our best probe of this scale.



S. Parke and M. Ross-Lonergan arXiv:1508.05095

Steriles vs NU

	"Non-Unitarity" $(m > \text{EW})$	"Light steriles" $\Delta m^2 \gtrsim 100\ \text{eV}^2$	$\Delta m^2 \sim 0.1 - 1\ \text{eV}^2$
α_{ee}	$1.3 \cdot 10^{-3}$ [44]	$2.4 \cdot 10^{-2}$ [46]	$1.0 \cdot 10^{-2}$ [46]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$ [44]	$2.2 \cdot 10^{-2}$ [47]	$1.4 \cdot 10^{-2}$ [48]
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$ [44]	$1.0 \cdot 10^{-1}$ [47]	$1.0 \cdot 10^{-1}$ [47]
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$ [44]	$2.5 \cdot 10^{-2}$ [49]	$1.7 \cdot 10^{-2}$
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$ [44]	$6.9 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$ [44]	$1.2 \cdot 10^{-2}$ [50]	$5.3 \cdot 10^{-2}$

EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1605.08774
M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1609.08637

Steriles vs NU

$$U = \begin{pmatrix} N & \Theta \\ X & Y \end{pmatrix}$$

"Heavy ν" Non-Unitarity

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

Steriles vs NU

$$U = \begin{pmatrix} N & \Theta \\ X & Y \end{pmatrix}$$

"Heavy ν" Non-Unitarity

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

"Light ν" Steriles

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}} + \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{IJ} L}{2E}} + \sum_{i,J} N_{\beta i} N^*_{\alpha i} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{iJ} L}{2E}}$$

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

Steriles vs NU

$$U = \begin{pmatrix} N & \Theta \\ X & Y \end{pmatrix}$$

"Heavy ν" Non-Unitarity

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

"Light ν" Steriles

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

$$+ \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{IJ} L}{2E}}$$

$$\xcancel{+ \sum_{i,J} N_{\beta i} N^*_{\alpha i} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{iJ} L}{2E}}}$$

If $\frac{\Delta m^2_{iJ} L}{E} >> 1$ oscillations too fast to resolve and only see average effect

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

Steriles vs NU

$$U = \begin{pmatrix} N & \Theta \\ X & Y \end{pmatrix}$$

"Heavy ν" Non-Unitarity

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

"Light ν" Steriles

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

$$+ \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{IJ} L}{2E}}$$

At leading order "heavy" non-unitarity and avergaed-out "light" steriles have the same impact in oscillations

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

Conclusions

- Gauge invariance applied to NSI imply very strong bounds. Possible ways out:
  - EFT not applicable (light mediators) see Yasaman next!
  - Cancellation between different NSI mediators (finetuning)
- Non-Unitarity a type of NSI, very motivated by Seesaw! But strong constraints from flavour and EW precission. Ways out:
  - Low energy non-Unitarity (averaged out steriles!)
  - Cancellations?? Seems hard since its the same process
- Other ideas?

Abstract submission ends in a couple of weeks!
Very few neutrino asbtracts!!!