NSI and Neutrino Mass Models at DUNE

Bhupal Dev

Washington University in St. Louis

with S. K. Agarwalla (IOP) and S. S. Chatterjee (Durham), arXiv: 1812.xxxxx

Physics Opportunities in the Near DUNE Detector Hall (PONDD)

Fermilab

December 4, 2018

Outline

- Neutrino NSI
- Near-detector Effects
- Current Constraints
- DUNE Projections
- Models for (Large) NSI
- Conclusion

Neutrino Non-standard Interactions (NSI)

- Unknown couplings involving neutrinos.
- E.g. Yukawa, gauge, higher spin particles, higher-dimensional operators.
- Many neutrino mass models naturally lead to NSI at some level.
- Potentially observable effects in neutrino oscillation experiments.

Neutrino Non-standard Interactions (NSI)

- Unknown couplings involving neutrinos.
- E.g. Yukawa, gauge, higher spin particles, higher-dimensional operators.
- Many neutrino mass models naturally lead to NSI at some level.
- Potentially observable effects in neutrino oscillation experiments.
- In principle, could exist in the neutrino production, propagation, and detection processes.
- Relevant for accelerator, reactor, atmospheric, solar and supernova neutrinos.
- Search for NSI is complementary to the direct search for new physics at the LHC.
- $\mathcal{O}(1000)$ papers/reviews on NSI effects. A representative sample: Ribeiro, Minakata, Nunokawa, Uchinami, Zukanovich-Funchal '07; Antusch, Baumann, Fernandez-Martinez '08; Gavela, Hernandez, Ota, Winter '08; Kopp, Machado, Parke '10; Ohlsson '12; Miranda, Nunokawa '15; Masud, Mehta '16; Liao, Marfatia, Whisnant '16; Agarwalla, Chatterjee, Palazzo '16; de Gouvea, Kelly '16; Coloma, Schwetz '16; Stapleford, Vaananen, Kneller, McLaughlin, Shapiro '16; Farzan, Tortola '17; Salvado, Mena, Palomares-Ruiz, Rius '17; Gonzalez-Garcia, Maltoni, Perez-Gonzalez, Zukanovich Funchal '18

Standard 3-flavor Case

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}}_{\text{weak eigenstates}} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{\text{PMNS mixing matrix}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}_{\text{mass eigenstates}}$$

Standard 3-flavor Case

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}}_{\text{weak eigenstates}} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{\text{PMNS mixing matrix}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}_{\text{mass eigenstates}}$$

- Time evolution governed by Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[\frac{MM^\dagger}{2E} + V(t)\right]\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \equiv H\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix},$$

where E is the neutrino energy, $M = U\,\mathrm{diag}(m_1, m_2, m_3)U^T$ is the neutrino mass matrix and $V = (A, 0, 0)$ with $A = \sqrt{2}G_F N_e$ is the effective matter potential induced by CC interaction with electrons.

Standard 3-flavor Case

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}}_{\text{weak eigenstates}} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{\text{PMNS mixing matrix}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}_{\text{mass eigenstates}}$$

- Time evolution governed by Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[\frac{MM^\dagger}{2E} + V(t)\right]\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \equiv H\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix},$$

  where E is the neutrino energy, $M = U\,\mathrm{diag}(m_1, m_2, m_3)U^T$ is the neutrino mass matrix and $V = (A, 0, 0)$ with $A = \sqrt{2}G_F N_e$ is the effective matter potential induced by CC interaction with electrons.

- Probability of oscillation over a length L:

$$P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta | e^{-iHL} | \nu_\alpha \rangle\right|^2$$

Introducing NSI

- In a model-independent set up, usually parametrized by a dimension-6, four-fermion operator.
- Two types: NC and CC.

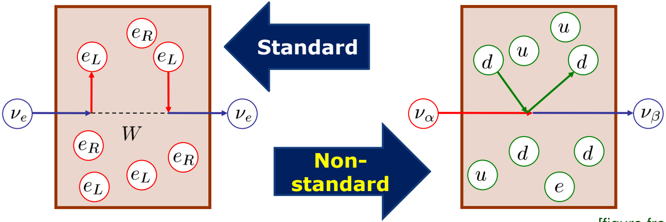
Introducing NSI

- In a model-independent set up, usually parametrized by a dimension-6, four-fermion operator.
- Two types: NC and CC.
- **NC NSI** [Wolfenstein '78]: $\boxed{\mathcal{L}_{\text{NSI}}^{\text{NC}} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{fX} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu P_X f)}$

  with $X = L, R$. Leads to extra matter effect in propagation:

$$P(\nu_\alpha \to \nu_\beta) = \left| \langle \nu_\beta | e^{-i(H+V_{\text{NSI}})L} | \nu_\alpha \rangle \right|^2 ,$$

$$\text{where } V_{\text{NSI}} = \sqrt{2} G_F N_e \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$



[figure from T. Ohlsson]

Non-standard Oscillation

$$i\frac{d}{dL}\begin{pmatrix}\nu_e\\ \nu_\tau\end{pmatrix} = \left[\frac{1}{2E}U\begin{pmatrix}0 & 0\\ 0 & \Delta m^2\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\tau}\\ \epsilon_{e\tau} & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\tau\end{pmatrix}$$

$$\boxed{P(\nu_e \to \nu_\tau) = \sin^2 2\theta_M \ \sin^2\left(\frac{\Delta m_M^2 L}{4E}\right)}$$

$$\left(\frac{\Delta m_M^2}{2EA}\right)^2 \equiv \left(\frac{\Delta m^2}{2EA}\cos 2\theta - (1+\epsilon_{ee}-\epsilon_{\tau\tau})\right)^2 + \left(\frac{\Delta m^2}{2EA}\sin 2\theta + 2\epsilon_{e\tau}\right)^2$$

$$\sin 2\theta_M \equiv \frac{\Delta m^2 \sin 2\theta + 4EA\epsilon_{e\tau}}{\Delta m_M^2}$$

CC NSI

$$\boxed{\mathcal{L}_{\rm NSI}^{\rm CC} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{ff'X}(\bar{\nu}_\alpha\gamma^\mu P_L\ell_\beta)(\bar{f}'\gamma_\mu P_X f)}$$

[Grossman '95]

- Flavor mixture states at source and detection.

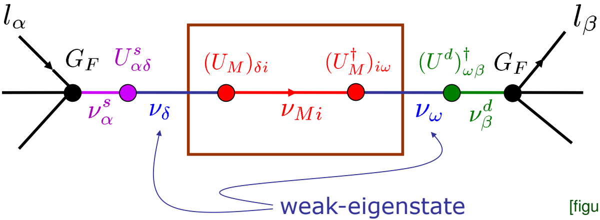
$$P(\nu_\alpha \to \nu_\beta) = \left|\langle\nu_\beta^{\rm d}|e^{-iHL}|\nu_\alpha^{\rm s}\rangle\right|^2$$

- Source NSI (in pion decay):

$$|\nu_\alpha^{\rm s}\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}^{\rm s}|\nu_\beta\rangle\,, \quad \text{e.g. } \pi^+ \xrightarrow{\varepsilon_{e\mu}^{\rm s}} \mu^+\nu_e$$

- Detection NSI (in neutrino-nucleon scattering):

$$\langle\nu_\alpha^{\rm d}| = \langle\nu_\alpha| + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}^{\rm s}\langle\nu_\beta|\,, \quad \text{e.g. } \nu_\tau n \xrightarrow{\varepsilon_{e\tau}^{\rm d}} e^- p$$



[figure from T. Ohlsson]

Interesting Near-Detector Physics

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_i [U^s U_M]_{\alpha i} \exp\left(i \frac{(\Delta m_M^2)_{i1} L}{4E} \right) [U^d U_M]^\dagger_{i\beta} \right|^2$$

$\boxed{\text{Zero-distance effect}}$ [Langacker, London '88]

- In the 2-flavor case,

$$\frac{\Delta m^2 L}{4E} \to 0 \Rightarrow P(\nu_e \to \nu_\mu) \to \left(\epsilon^s_{e\mu} - \epsilon^d_{e\mu} \right)^2$$

Interesting Near-Detector Physics

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_i [U^s U_M]_{\alpha i} \exp\left(i \frac{(\Delta m_M^2)_{i1} L}{4E} \right) [U^d U_M]^\dagger_{i\beta} \right|^2$$

Zero-distance effect [Langacker, London '88]

- In the 2-flavor case,

$$\frac{\Delta m^2 L}{4E} \to 0 \Rightarrow P(\nu_e \to \nu_\mu) \to \left(\epsilon^s_{e\mu} - \epsilon^d_{e\mu} \right)^2$$

- 3-flavor case: [Meloni, Ohlsson, Winter, Zhang '09]

$$\begin{aligned} P(\nu^{\rm s}_\alpha \to \nu^{\rm d}_\beta; L) &= \left| \sum_{\gamma,\delta,i} \left(1+\varepsilon^{\rm d}\right)_{\gamma\beta} \left(1+\varepsilon^{\rm s}\right)_{\alpha\delta} U_{\delta i} U^*_{\gamma i}\, {\rm e}^{-{\rm i}\frac{m_i^2 L}{2E}} \right|^2 \\ &= \sum_{i,j} \mathcal{J}^i_{\alpha\beta} \mathcal{J}^{j*}_{\alpha\beta} - 4 \sum_{i>j} {\rm Re}(\mathcal{J}^i_{\alpha\beta} \mathcal{J}^{j*}_{\alpha\beta}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E} \right) \\ &+ 2 \sum_{i>j} {\rm Im}(\mathcal{J}^i_{\alpha\beta} \mathcal{J}^{j*}_{\alpha\beta}) \sin\left(\frac{\Delta m^2_{ij} L}{2E} \right) , \end{aligned}$$

where

$$\mathcal{J}^i_{\alpha\beta} = U^*_{\alpha i} U_{\beta i} + \sum_\gamma \varepsilon^{\rm s}_{\alpha\gamma} U^*_{\gamma i} U_{\beta i} + \sum_\gamma \varepsilon^{\rm d}_{\gamma\beta} U^*_{\alpha i} U_{\gamma i} + \sum_{\gamma,\delta} \varepsilon^{\rm s}_{\alpha\gamma} \varepsilon^{\rm d}_{\delta\beta} U^*_{\gamma i} U_{\delta i} .$$

Current Constraints (Flavor Diagonal NC NSI)

[Farzan, Tortola '17]

	90% C.L. range	origin
		NSI with quarks
ϵ_{ee}^{dL}	$[-0.3, 0.3]$	CHARM
ϵ_{ee}^{dR}	$[-0.6, 0.5]$	CHARM
$\epsilon_{\mu\mu}^{dV}$	$[-0.042, 0.042]$	atmospheric + accelerator
$\epsilon_{\mu\mu}^{uV}$	$[-0.044, 0.044]$	atmospheric + accelerator
$\epsilon_{\mu\mu}^{dA}$	$[-0.072, 0.057]$	atmospheric + accelerator
$\epsilon_{\mu\mu}^{uA}$	$[-0.094, 0.14]$	atmospheric + accelerator
$\epsilon_{\tau\tau}^{dV}$	$[-0.075, 0.33]$	oscillation data + COHERENT
$\epsilon_{\tau\tau}^{uV}$	$[-0.09, 0.38]$	oscillation data + COHERENT
$\epsilon_{\tau\tau}^{qV}$	$[-0.037, 0.037]$	atmospheric
		NSI with electrons
ϵ_{ee}^{eL}	$[-0.021, 0.052]$	solar + KamLAND
ϵ_{ee}^{eR}	$[-0.07, 0.08]$	TEXONO
$\epsilon_{\mu\mu}^{eL}$, $\epsilon_{\mu\mu}^{eR}$	$[-0.03, 0.03]$	reactor + accelerator
$\epsilon_{\tau\tau}^{eL}$	$[-0.12, 0.06]$	solar + KamLAND
$\epsilon_{\tau\tau}^{eR}$	$[-0.98, 0.23]$ [-0.25, 0.43]	solar + KamLAND and Borexino reactor + accelerator
$\epsilon_{\tau\tau}^{eV}$	$[-0.11, 0.11]$	atmospheric

Current Constraints (Flavor Changing NC NSI)

[Farzan, Tortola '17]

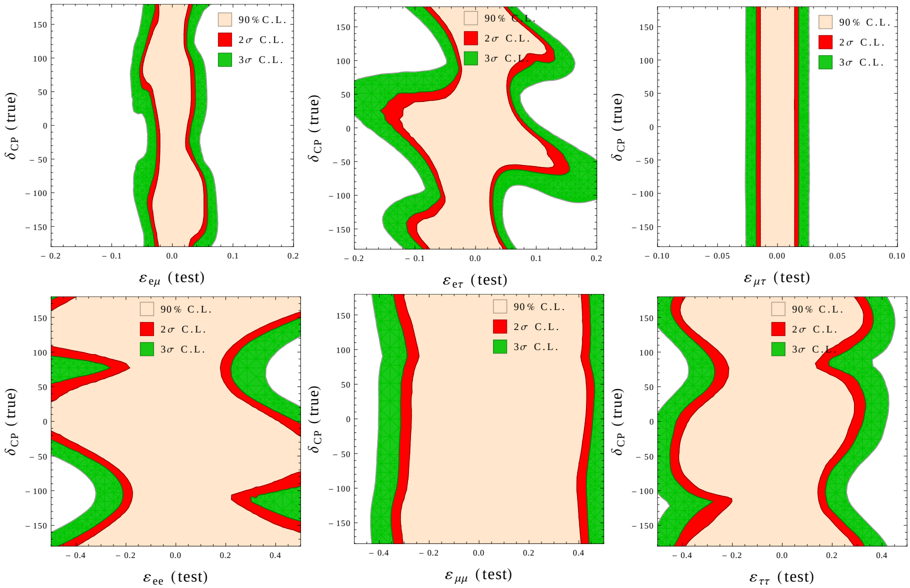
	90% C.L. range	origin
	NSI with quarks	
$\epsilon_{e\mu}^{qL}$	$[-0.023, 0.023]$	accelerator
$\epsilon_{e\mu}^{qR}$	$[-0.036, 0.036]$	accelerator
$\epsilon_{e\mu}^{uV}$	$[-0.073, 0.044]$	oscillation data + COHERENT
$\epsilon_{e\mu}^{dV}$	$[-0.07, 0.04]$	oscillation data + COHERENT
$\epsilon_{e\tau}^{qL}$, $\epsilon_{e\tau}^{qR}$	$[-0.5, 0.5]$	CHARM
$\epsilon_{e\tau}^{uV}$	$[-0.15, 0.13]$	oscillation data + COHERENT
$\epsilon_{e\tau}^{dV}$	$[-0.13, 0.12]$	oscillation data + COHERENT
$\epsilon_{\mu\tau}^{qL}$	$[-0.023, 0.023]$	accelerator
$\epsilon_{\mu\tau}^{qR}$	$[-0.036, 0.036]$	accelerator
$\epsilon_{\mu\tau}^{qV}$	$[-0.006, 0.0054]$	IceCube
$\epsilon_{\mu\tau}^{qA}$	$[-0.039, 0.039]$	atmospheric + accelerator
	NSI with electrons	
$\epsilon_{e\mu}^{eL}$, $\epsilon_{e\mu}^{eR}$	$[-0.13, 0.13]$	reactor + accelerator
$\epsilon_{e\tau}^{eL}$	$[-0.33, 0.33]$	reactor + accelerator
$\epsilon_{e\tau}^{eR}$	$[-0.28, -0.05]$ & $[0.05, 0.28]$ [-0.19, 0.19]	reactor + accelerator TEXONO
$\epsilon_{\mu\tau}^{eL}$, $\epsilon_{\mu\tau}^{eR}$	$[-0.10, 0.10]$	reactor + accelerator
$\epsilon_{\mu\tau}^{eV}$	$[-0.018, 0.016]$	IceCube

Current Constraints (CC NSI)

[Farzan, Tortola '17]

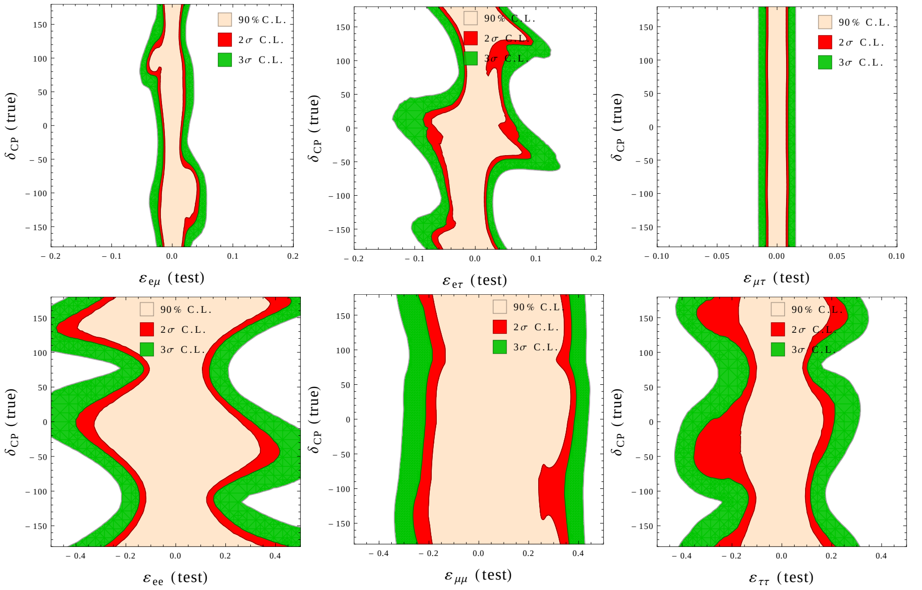
	90% C.L. range	origin
		semileptonic NSI
ϵ_{ee}^{udP}	$[-0.015, 0.015]$	Daya Bay
$\epsilon_{e\mu}^{udL}$	$[-0.026, 0.026]$	NOMAD
$\epsilon_{e\mu}^{udR}$	$[-0.037, 0.037]$	NOMAD
$\epsilon_{\tau e}^{udL}$	$[-0.087, 0.087]$	NOMAD
$\epsilon_{\tau e}^{udR}$	$[-0.12, 0.12]$	NOMAD
$\epsilon_{\tau\mu}^{udL}$	$[-0.013, 0.013]$	NOMAD
$\epsilon_{\tau\mu}^{udR}$	$[-0.018, 0.018]$	NOMAD
		purely leptonic NSI
$\epsilon_{\alpha e}^{\mu eL}$, $\epsilon_{\alpha e}^{\mu eR}$	$[-0.025, 0.025]$	KARMEN
$\epsilon_{\alpha\beta}^{\mu eL}$, $\epsilon_{\alpha\beta}^{\mu eR}$	$[-0.030, 0.030]$	kinematic G_F

DUNE Sensitivity (with 300 kt.MW.yr exposure)



[Agarwalla, BD, Chatterjee (in prep.)]

DUNE Sensitivity (with 850 kt.MW.yr exposure)



[Agarwalla, BD, Chatterjee (in prep.)]

DUNE Projected Limits (90% CL)

NSI Parameter	300 kt.MW.yr	850 kt.MW.yr
$\varepsilon_{e\mu}$	$-0.025 \rightarrow +0.052$	$-0.017 \rightarrow +0.04$
$\varepsilon_{e\tau}$	$-0.055 \rightarrow +0.023$	$-0.042 \rightarrow +0.012$
$\varepsilon_{\mu\tau}$	$-0.015 \rightarrow +0.013$	$-0.01 \rightarrow +0.01$
ε_{ee}	$-0.185 \rightarrow +0.38$	$-0.13 \rightarrow +0.185$
$\varepsilon_{\mu\mu}$	$-0.29 \rightarrow +0.39$	$-0.192 \rightarrow +0.24$
$\varepsilon_{\tau\tau}$	$-0.36 \rightarrow +0.145$	$-0.12 \rightarrow +0.095$

[Agarwalla, BD, Chatterjee (in prep.)]

NSI Model Building

- The dimension-6 operator

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2} G_F \varepsilon^{fX}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu P_X f)$$

  implies that $\boxed{\varepsilon_{\alpha\beta} \sim \frac{m_W^2}{\Lambda^2}}$.

- If new physics scale $\Lambda \sim 1\ (10)$ TeV, then $\varepsilon_{\alpha\beta} \sim 10^{-2}\ (10^{-4})$.

NSI Model Building

- The dimension-6 operator

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2} G_F \varepsilon^{fX}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu P_X f)$$

  implies that $\boxed{\varepsilon_{\alpha\beta} \sim \frac{m_W^2}{\Lambda^2}}$.
- If new physics scale $\Lambda \sim 1$ (10) TeV, then $\varepsilon_{\alpha\beta} \sim 10^{-2}$ (10^{-4}).
- Non-renormalizable, not gauge-invariant. Breaks $SU(2)_L$ gauge symmetry explicitly.
- In general, BSM theories must respect the SM gauge invariance, which implies stringent constraints on NSI.

NSI Model Building

- The dimension-6 operator

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F\varepsilon^{fX}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_X f)$$

  implies that $\boxed{\varepsilon_{\alpha\beta} \sim \frac{m_W^2}{\Lambda^2}}$.
- If new physics scale $\Lambda \sim 1$ (10) TeV, then $\varepsilon_{\alpha\beta} \sim 10^{-2}$ (10^{-4}).
- Non-renormalizable, not gauge-invariant. Breaks $SU(2)_L$ gauge symmetry explicitly.
- In general, BSM theories must respect the SM gauge invariance, which implies stringent constraints on NSI.
- Specifically, if there is an operator of the form $\frac{1}{\Lambda^2}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{\ell}_\gamma\gamma_\mu P_L\ell_\delta)$, it must be part of the more general form $\frac{1}{\Lambda^2}(\bar{L}_\alpha\gamma^\mu L_\beta)(\bar{L}_\gamma\gamma_\mu L_\delta)$.
- This involves four charged leptons and is severely constrained by rare LFV processes like $\mu \to 3e$.
- $\mathrm{BR}(\mu \to 3e) < 10^{-12}$ implies $\varepsilon^{ee}_{e\mu} < 10^{-6}$.

A Concrete Example

- Type-II seesaw: SM+ a scalar triplet $\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$ [Schechter, Valle '80]

$$\mathcal{L}_\Delta = Y_{\alpha\beta}\, L^T_{\alpha L}\, C\, i\sigma_2\, \Delta\, L_{\beta L} + \lambda_\phi\, \phi^T\, i\sigma_2\, \Delta^\dagger \phi + \text{h.c.},$$

$$\mathcal{L}_Y = Y_{\alpha\beta}\left[\Delta^0\, \overline{\nu^C_{\alpha R}}\, \nu_{\beta L} - \frac{1}{\sqrt{2}}\Delta^+ \left(\overline{\ell^C_{\alpha R}}\, \nu_{\beta L} + \overline{\nu^C_{\alpha R}}\, \ell_{\beta L}\right) - \Delta^{++}\, \overline{\ell^C_{\alpha R}}\, \ell_{\beta L}\right] + \text{h.c.}$$

A Concrete Example

- Type-II seesaw: SM+ a scalar triplet $\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$ [Schechter, Valle '80]

$$\mathcal{L}_\Delta = Y_{\alpha\beta}\, L^T_{\alpha L}\, C\, i\sigma_2\, \Delta\, L_{\beta L} + \lambda_\phi\, \phi^T\, i\sigma_2\, \Delta^\dagger \phi + \text{h.c.},$$

$$\mathcal{L}_Y = Y_{\alpha\beta} \left[\Delta^0\, \overline{\nu^C_{\alpha R}}\, \nu_{\beta L} - \frac{1}{\sqrt{2}} \Delta^+ \left(\overline{\ell^C_{\alpha R}}\, \nu_{\beta L} + \overline{\nu^C_{\alpha R}}\, \ell_{\beta L} \right) - \Delta^{++}\, \overline{\ell^C_{\alpha R}}\, \ell_{\beta L} \right] + \text{h.c.}$$

- Integrating out the triplet scalars (with mass M_Δ),

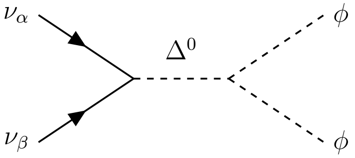
$$\mathcal{L}^m_\nu = \frac{Y_{\alpha\beta}\, \lambda_\phi\, v^2}{M^2_\Delta} \left(\overline{\nu^C_{\alpha R}}\, \nu_{\beta L} \right) = -\frac{1}{2}\, (m_\nu)_{\alpha\beta}\, \overline{\nu^C_{\alpha R}}\, \nu_{\beta L},$$

$$\mathcal{L}_{\text{NSI}} = \frac{Y_{\sigma\beta}\, Y^\dagger_{\alpha\rho}}{M^2_\Delta} \left(\overline{\nu_{\alpha L}}\, \gamma_\mu\, \nu_{\beta L} \right) \left(\overline{\ell_{\rho L}}\, \gamma^\mu\, \ell_{\sigma L} \right),$$

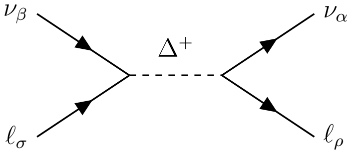
- Leads to the NSI parameters

$$\varepsilon^{\rho\sigma}_{\alpha\beta} = -\frac{M^2_\Delta}{8\sqrt{2}\, G_F\, v^4\, \lambda^2_\phi}\, (m_\nu)_{\sigma\beta}\, (m^\dagger_\nu)_{\alpha\rho},$$

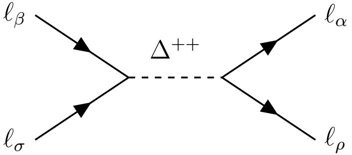
Triplet Higgs Model



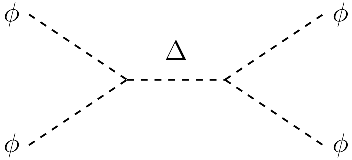
(a) Light neutrino Majorana mass term



(b) Light neutrino matter NSI



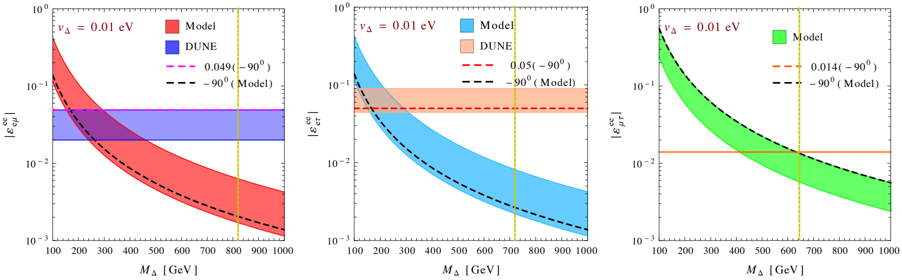
(c) Four-lepton NSI



(d) SM Higgs self-coupling

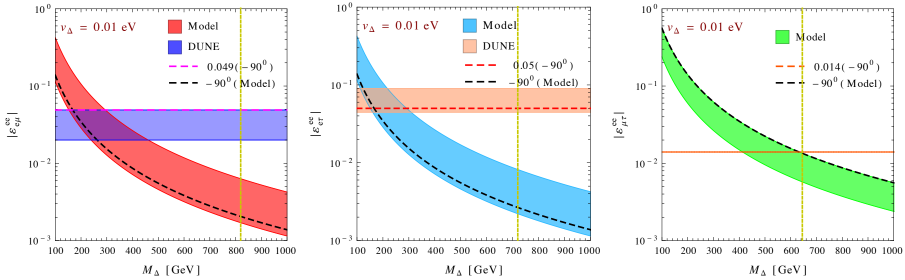
DUNE Sensitivity

[Agarwalla, BD, Chatterjee (in prep.)]



DUNE Sensitivity

[Agarwalla, BD, Chatterjee (in prep.)]



Decay	Constraint on	Bound
$\mu^- \to e^- e^+ e^-$	$\lvert\varepsilon^{e\mu}_{ee}\rvert$	3.5×10^{-7}
$\tau^- \to e^- e^+ e^-$	$\lvert\varepsilon^{e\tau}_{ee}\rvert$	1.4×10^{-4}
$\tau^- \to \mu^- \mu^+ \mu^-$	$\lvert\varepsilon^{\mu\tau}_{\mu\mu}\rvert$	1.2×10^{-4}
$\tau^- \to e^- \mu^+ e^-$	$\lvert\varepsilon^{e\tau}_{e\mu}\rvert$	1.0×10^{-4}
$\tau^- \to \mu^- e^+ \mu^-$	$\lvert\varepsilon^{\mu\tau}_{\mu e}\rvert$	1.0×10^{-4}
$\tau^- \to e^- \mu^+ \mu^-$	$\lvert\varepsilon^{e\tau}_{\mu\mu}\rvert$	1.0×10^{-4}
$\tau^- \to e^- e^+ \mu^-$	$\lvert\varepsilon^{e\tau}_{\mu e}\rvert$	9.9×10^{-5}
$\mu^- \to e^- \gamma$	$\lvert\sum_\alpha \varepsilon^{e\mu}_{\alpha\alpha}\rvert$	2.6×10^{-5}
$\tau^- \to e^- \gamma$	$\lvert\sum_\alpha \varepsilon^{e\tau}_{\alpha\alpha}\rvert$	1.8×10^{-2}
$\tau^- \to \mu^- \gamma$	$\lvert\sum_\alpha \varepsilon^{\mu\tau}_{\alpha\alpha}\rvert$	2.0×10^{-4}
$\mu^+ e^- \to \mu^- e^+$	$\lvert\varepsilon^{\mu e}_{\mu e}\rvert$	3.0×10^{-3}

[Huitu, Karkkainen, Maalampi, Vihonen '17]

Singlet Seesaw

- SM+singlet fermions. Includes type-I seesaw and variants, such as linear, inverse and generalized seesaw.
- Take the inverse seesaw example (which allows large active-sterile neutrino mixing) with two sets of singlets ν_R and S. [Mohapatra, Valle '86]

$$-\mathcal{L}_{\mathrm{m}} = \overline{\nu_{\mathrm{L}}} M_{\mathrm{D}} \nu_{\mathrm{R}} + \overline{S} M_{\mathrm{R}} \nu_{\mathrm{R}} + \frac{1}{2} \overline{S} \mu S^c + \mathrm{H.c.}$$

LNV: tiny

9x9 ν-mass matrix: $\{\nu_L, \nu_R^c, S^c\}$

$$\boxed{M_\nu = \begin{pmatrix} 0 & M_{\mathrm{D}} & 0 \\ M_{\mathrm{D}}^T & 0 & M_{\mathrm{R}}^T \\ 0 & M_{\mathrm{R}} & \mu \end{pmatrix}}$$

Light neutrino mass matrix:

$$\boxed{m_\nu \simeq M_{\mathrm{D}} M_{\mathrm{R}}^{-1} \mu (M_{\mathrm{R}}^T)^{-1} M_{\mathrm{D}}^T = F \mu F^T}$$

Non-unitarity and NSI

$$-\mathcal{L} = \frac{g}{\sqrt{2}} W_\mu^+ \left(\sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U_{\ell m}^* \, \overline{\nu_m} \gamma^\mu P_L \ell + \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V_{\ell m'}^* \, \overline{N_{m'}^c} \gamma^\mu P_L \ell \right) + \text{h.c.}$$
$$+ \frac{g}{2\cos\theta_W} Z_\mu \left(\sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U_{\ell m}^* \, \overline{\nu_m} \gamma^\mu P_L \, \nu_\ell + \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V_{\ell m'}^* \, \overline{N_{m'}^c} \gamma^\mu P_L \, \nu_\ell \right) + \text{h.c}$$

Non-unitarity and NSI

$$
\begin{aligned}
-\mathcal{L} = {} & \frac{g}{\sqrt{2}} W^+_\mu \left(\sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U^*_{\ell m} \, \overline{\nu_m} \gamma^\mu P_L \ell + \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V^*_{\ell m'} \, \overline{N^c_{m'}} \gamma^\mu P_L \ell \right) + \text{h.c.} \\
& + \frac{g}{2\cos\theta_W} Z_\mu \left(\sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U^*_{\ell m} \, \overline{\nu_m} \gamma^\mu P_L \, \nu_\ell + \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V^*_{\ell m'} \, \overline{N^c_{m'}} \gamma^\mu P_L \, \nu_\ell \right) + \text{h.c}
\end{aligned}
$$

- Non-unitarity: $U \simeq \left(1 - \frac{\varepsilon}{2}\right) U_{\text{PMNS}}$, where $\varepsilon = FF^\dagger$ is the NSI parameter and

$$
F = M_D M_R^{-1} \sim \begin{cases} \left(\frac{m_\nu}{M_R}\right)^{1/2} & \text{(type-I)} \\ \left(\frac{m_\nu}{\mu}\right)^{1/2} & \text{(inverse)} \end{cases}
$$

[BD, Mohapatra '09]

Non-unitarity and NSI

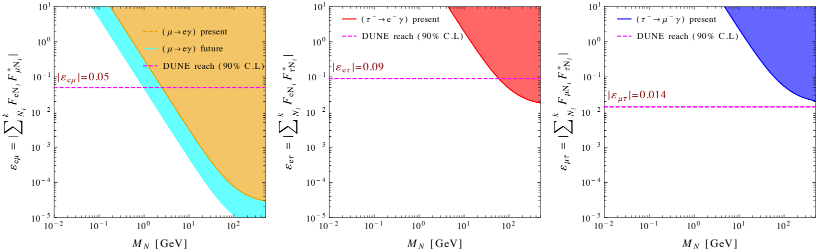
$$-\mathcal{L} = \frac{g}{\sqrt{2}} W_\mu^+ \left(\sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U_{\ell m}^* \, \overline{\nu_m} \gamma^\mu P_L \ell + \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V_{\ell m'}^* \, \overline{N_{m'}^c} \gamma^\mu P_L \ell \right) + \text{h.c.}$$

$$+ \frac{g}{2\cos\theta_W} Z_\mu \left(\sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U_{\ell m}^* \, \overline{\nu_m} \gamma^\mu P_L \, \nu_\ell + \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V_{\ell m'}^* \, \overline{N_{m'}^c} \gamma^\mu P_L \, \nu_\ell \right) + \text{h.c}$$

- Non-unitarity: $U \simeq \left(1 - \frac{\varepsilon}{2}\right) U_{\rm PMNS}$, where $\varepsilon = FF^\dagger$ is the NSI parameter and

$$F = M_D M_R^{-1} \sim \begin{cases} \left(\frac{m_\nu}{M_R}\right)^{1/2} & \text{(type-I)} \\ \left(\frac{m_\nu}{\mu}\right)^{1/2} & \text{(inverse)} \end{cases}$$

[BD, Mohapatra '09]

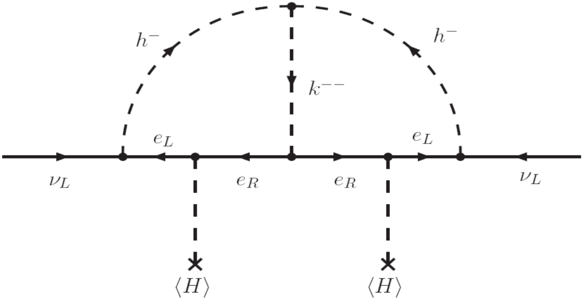


[Agarwalla, BD, Chatterjee (in prep.)]

Zee-Babu Model

[Zee '85, '86; Babu '88]

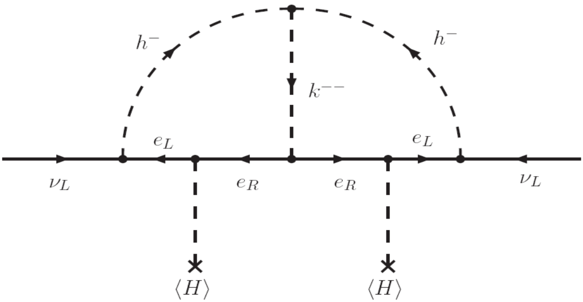
$$\mathcal{L} = \mathcal{L}_{\rm SM} + f_{\alpha\beta} L^T_{\rm L\alpha} C i\sigma_2 L_{\rm L\beta} h^+ + g_{\alpha\beta} \overline{e^c_\alpha} e_\beta k^{++} - \mu h^- h^- k^{++} + \text{h.c.} + V_H \,,$$

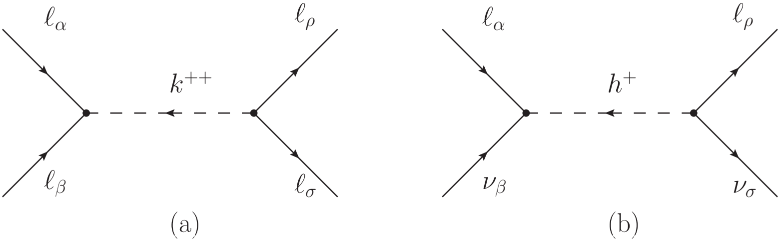


Zee-Babu Model

[Zee '85, '86; Babu '88]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + f_{\alpha\beta} L^T_{{\rm L}\alpha} C {\rm i}\sigma_2 L_{{\rm L}\beta} h^+ + g_{\alpha\beta} \overline{e^c_\alpha} e_\beta k^{++} - \mu h^- h^- k^{++} + {\rm h.c.} + V_H \,,$$

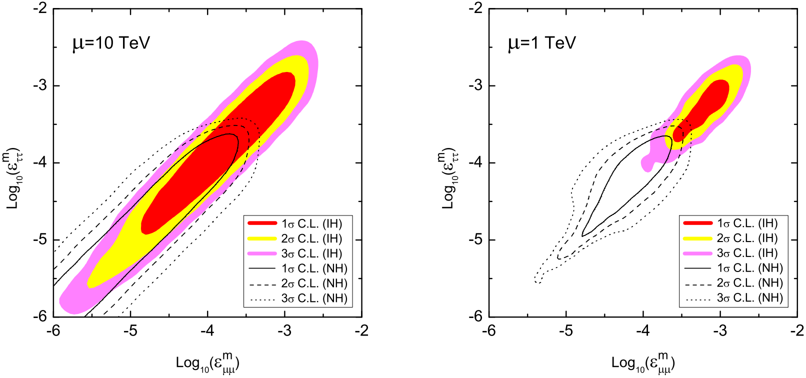




NSI in Zee-Babu Model

$$\varepsilon^m_{\alpha\beta} = \varepsilon^{ee}_{\alpha\beta} = \frac{f_{e\beta} f^*_{e\alpha}}{\sqrt{2} G_F m_h^2} \simeq \frac{4 f_{e\beta} f^*_{e\alpha}}{g_W^2} \frac{m_W^2}{m_h^2} \propto \frac{m_W^2}{m_h^2} \,,$$

$$\varepsilon^s_{\mu\tau} = \varepsilon^{e\mu}_{\tau e} = \frac{f_{\mu e} f^*_{e\tau}}{\sqrt{2} G_F m_h^2} \simeq \frac{4 f_{\mu e} f^*_{e\tau}}{g_W^2} \frac{m_W^2}{m_h^2} \propto \frac{m_W^2}{m_h^2} \,,$$

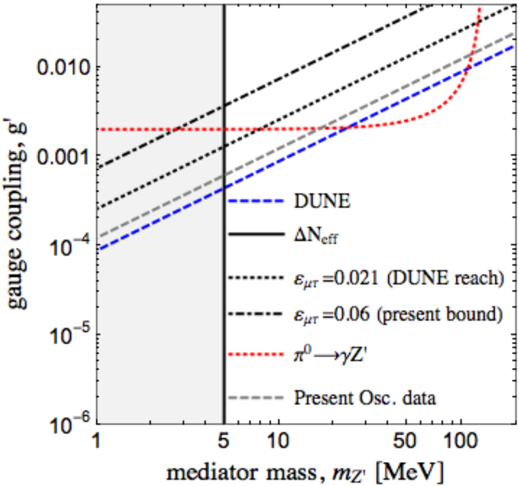


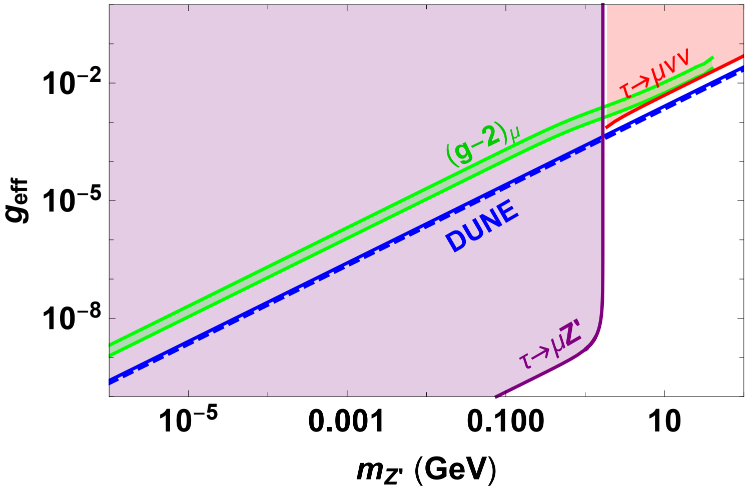
[Ohlsson, Schwetz, Zhang '09]

NSI from Extra $U(1)$

- Based on $SU(2)_L \times U(1)_Y \times U(1)'$. [Farzan, Shoemaker '15; Babu, Friedland, Machado, Mocioiu '17]

$$\varepsilon_{\alpha\beta}^{ff'} = \frac{g_{ff'} g_{\nu_\alpha \nu_\beta}}{2\sqrt{2} G_F m_{Z'}^2} \quad \text{(regardless of the } Z' \text{ mass)}$$





[Altmannshofer, Chen, BD, Soni '16; Agarwalla, BD, Chatterjee (in prep.)]

Conclusion

- NSI could be responsible for neutrino flavor transitions either at the source/detector (CC) or during propagation through matter (NC).
- Interesting near-detector physics.
- NSIs are inevitable in many neutrino mass models.
- In a realistic model, difficult (but not impossible) to avoid the stringent LFV bounds and simultaneously entertain observable NSI.
- Search for NSI at DUNE will be complementary to the direct searches for new physics at the LHC.

Conclusion

- NSI could be responsible for neutrino flavor transitions either at the source/detector (CC) or during propagation through matter (NC).
- Interesting near-detector physics.
- NSIs are inevitable in many neutrino mass models.
- In a realistic model, difficult (but not impossible) to avoid the stringent LFV bounds and simultaneously entertain observable NSI.
- Search for NSI at DUNE will be complementary to the direct searches for new physics at the LHC.

Thank You.