Neutrino Non-Standard Interaction Phenomenology

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NTN Workshop

Fermilab

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- Jointly with the OSU group of K.S. Babu.
- Funding was used to host an **NTN NSI Workshop** at WashU (May 2019) and for travel exchange between WashU, OSU and Fermilab.

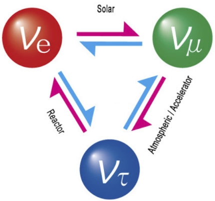
Main Products:

1. P. S. B. Dev, K. S. Babu, P. B. Denton, P. A. N. Machado *et al.*, "Neutrino Non-Standard Interactions: A Status Report," SciPost Phys. Proc. **2**, 001 (2019).
2. K. S. Babu, P. S. B. Dev, S. Jana and A. Thapa, "Non-Standard Interactions in Radiative Neutrino Mass Models," JHEP **03**, 006 (2020).
3. K. S. Babu, P. S. B. Dev, S. Jana and Y. Sui, "Zee-Burst: A New Probe of Neutrino Nonstandard Interactions at IceCube," Phys. Rev. Lett. **124**, 041805 (2020).
4. A. de Gouvêa, P. S. B. Dev, B. Dutta, T. Ghosh, T. Han and Y. Zhang, "Leptonic Scalars at the LHC," JHEP **07**, 142 (2020).
5. K. S. Babu, G. Chauhan and P. S. B. Dev, "Neutrino nonstandard interactions via light scalars in the Earth, Sun, supernovae, and the early Universe," Phys. Rev. D **101**, 095029 (2020).
6. P. S. B. Dev, W. Rodejohann, X. J. Xu and Y. Zhang, "MUonE sensitivity to new physics explanations of the muon anomalous magnetic moment," JHEP **05**, 053 (2020).
7. Z. Chacko, P. S. B. Dev, R. N. Mohapatra and A. Thapa, "Predictive Dirac and Majorana Neutrino Mass Textures from $SU(6)$ Grand Unified Theories," Phys. Rev. D **102**, 035020 (2020).
8. K. S. Babu, P. S. B. Dev, S. Jana and A. Thapa, "Unified framework for B-anomalies, muon $g-2$ and neutrino masses," JHEP **03**, 179 (2021).
9. S. S. Chatterjee, P. S. B. Dev and P. A. N. Machado, "Impact of improved energy resolution on DUNE sensitivity to neutrino non-standard interactions," JHEP **08**, 163 (2021).

Follow-up Products:

1. P. S. B. Dev, B. Dutta, T. Ghosh, T. Han, H. Qin and Y. Zhang, "Leptonic scalars and collider signatures in a UV-complete model," JHEP **03**, 068 (2022).
2. K. S. Babu, P. S. B. Dev and S. Jana, "Probing neutrino mass models through resonances at neutrino telescopes," Int. J. Mod. Phys. A **37**, 2230003 (2022).

Why Non-Standard Interactions (NSI)?



Neutrino Oscillations $\Longrightarrow$ Nonzero Neutrino Mass $\Longrightarrow$ BSM Physics

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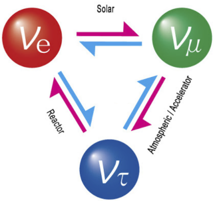
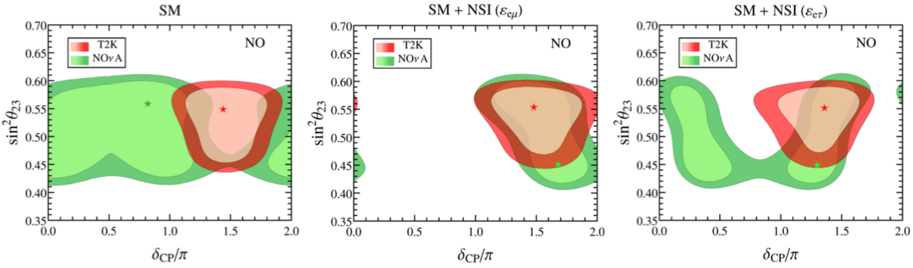


Neutrino Oscillations $\Longrightarrow$ Nonzero Neutrino Mass $\Longrightarrow$ BSM Physics

- Must introduce new fermions, scalars and/or gauge bosons – **messengers of neutrino mass physics**.
- New couplings involving neutrinos – **inevitably lead to NSI** at some level.
- Potentially observable effects in neutrino production, propagation, and/or detection.
- Relevant for all kinds of neutrinos (accelerator, reactor, atmospheric, solar, supernova, astrophysical, cosmic).
- **Search for NSI is complementary to the direct search for new physics at the LHC.**
- At the very least, could serve as a foil for the standard 3-neutrino oscillation scheme.

  [Liao, Marfatia, Whisnant (PRD '16); Masud, Mehta (PRD '16); Agarwalla, Chatterjee, Palazzo (PLB '16); Deepthi, Goswami, Nath (PRD '17); Capozzi, Chatterjee, Palazzo (PRL '20); Esteban, Gonzalez-Garcia, Maltoni '20; Bakhti, Rajaee (PRD '21)]

T2K-NOνA Anomaly



[Chatterjee, Palazzo, 2008.04161 (PRL '21)]

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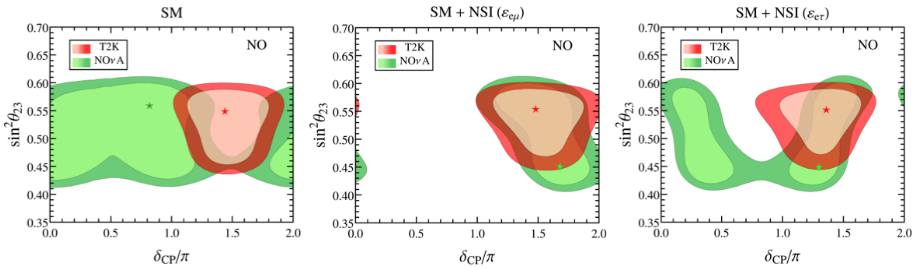

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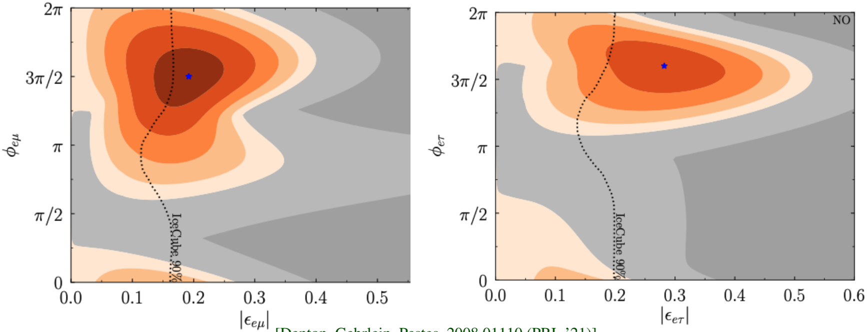
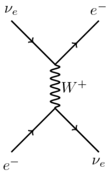
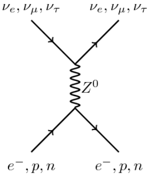


[Denton, Gehrlein, Pestes, 2008.01110 (PRL '21)]

Standard Neutrino Interactions with Matter





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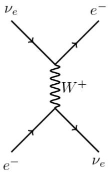
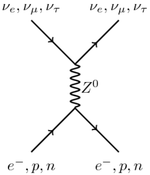




- Effective potential for coherent forward scattering:

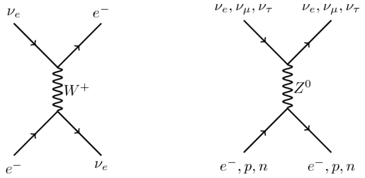
$$V_{\rm CC} = \sqrt{2} G_F N_e = (3.8 \times 10^{-14} \text{eV}) \left(\frac{\rho}{\text{gm/cm}^3} \right) \left(\frac{Y_e}{0.5} \right) .$$

- Time evolution governed by Schrödinger equation:

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

where E is the neutrino energy, $M = U\,\text{diag}(m_1, m_2, m_3) U^T$ is the neutrino mass matrix and $V = \text{diag}(V_{\rm CC}, 0, 0)$.

Standard Neutrino Interactions with Matter



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- Probability of oscillation over a length L:

$$P(\nu_\alpha \to \nu_\beta) = \left| \langle \nu_\beta | e^{-iHL} | \nu_\alpha \rangle \right|^2 \simeq \sin^2 2\theta_M \sin^2 \left(\frac{\Delta m_M^2 L}{4E} \right) .$$

Non-Standard Neutrino Interactions with Matter

[Wolfenstein (PRD '78)]

$$\boxed{\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}G_F \sum_{f,X,\alpha,\beta} \varepsilon_{\alpha\beta}^{fX} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_X f)}\,, \text{ with } X = L, R, \text{ and } f \in \{e, u, d\}.$$

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- Only vector part is relevant:

$$\varepsilon_{\alpha\beta} = \sum_{f\in\{e,u,d\}} \frac{N_f}{N_e} \varepsilon_{\alpha\beta}^{fV} = \varepsilon_{\alpha\beta}^{eV} + \frac{N_p}{N_e}(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}) + \frac{N_n}{N_e}(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV})$$

$$= \varepsilon_{\alpha\beta}^{eV} + (2 + Y_n)\varepsilon_{\alpha\beta}^{uV} + (1 + 2Y_n)\varepsilon_{\alpha\beta}^{dV}$$

with $\varepsilon_{\alpha\beta}^{fV} = \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$ and $Y_n = N_n/N_e$.

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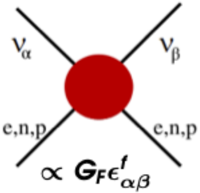
with $\varepsilon_{\alpha\beta}^{fV} = \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$ and $Y_n = N_n/N_e$.

- Leads to extra matter effect in propagation:

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

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



Current Constraints*

[Farzan, Tortola, 1710.09360 (Front. Phys. '18)]

	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

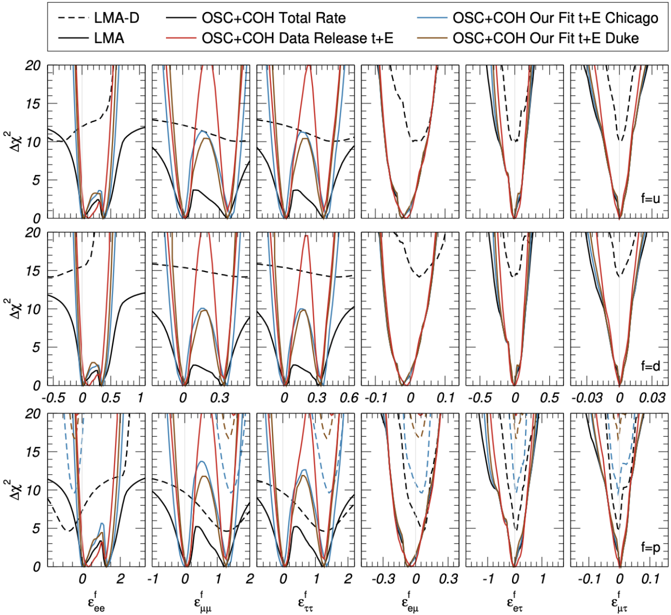
(Flavor-diagonal)

	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

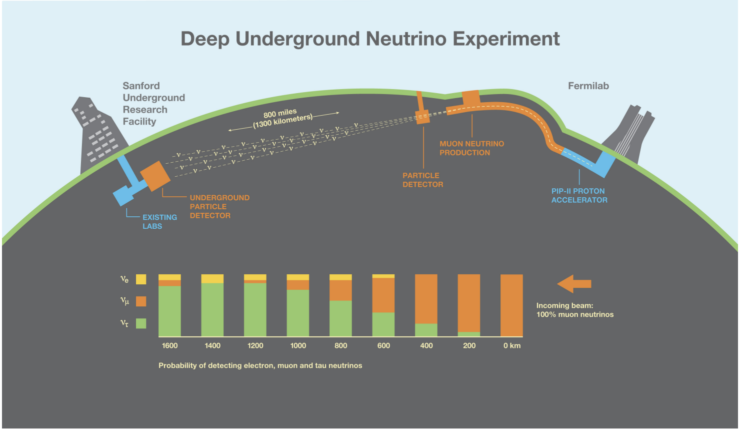
(Flavor-changing)

* Conditions apply

Global Fit



[Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.09109 (JHEP '20); see also Dutta *et al.*, 2002.03066 (JHEP '20)]

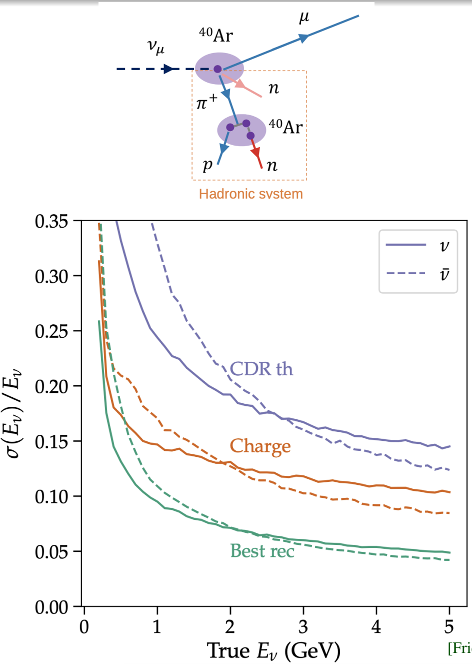


- Long baseline.
- Huge statistics.
- Well-understood beam.

Good sensitivity to matter NSI

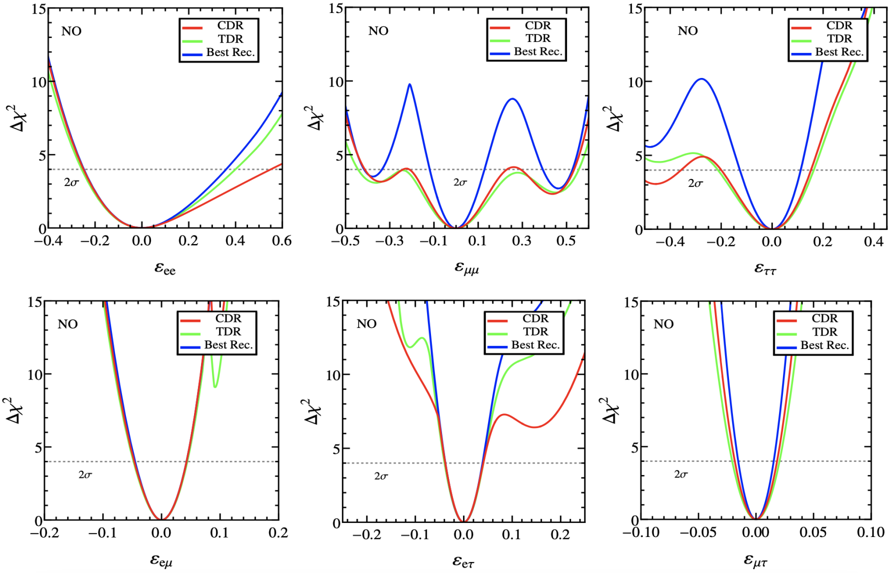
[de Gouvêa, Kelly (NPB ’16); Coloma (JHEP ’16); Blennow *et al.* (JHEP ’16); Liao, Marfatia, Whisnant (JHEP ’17)]

Improved Energy Resolution



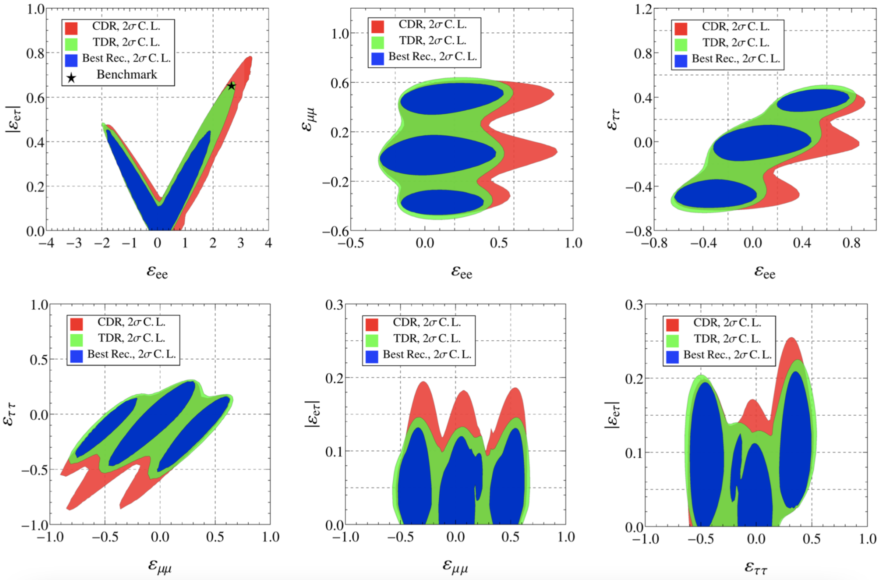
[Friedland, Li, 1811.06159 (PRD '19)]

Improved DUNE Sensitivity to NSI



[Chatterjee, BD, Machado, 2106.04597 (JHEP '21)]

Breaking Degeneracies



[Chatterjee, BD, Machado, 2106.04597 (JHEP '21)]

NSI Model Building

- In the standard parametrization, NSI is a dimension-6 operator:

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

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

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

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- Moreover, it breaks $SU(2)_L$ gauge symmetry explicitly.
- Restoring gauge invariance in a UV-complete model will in general impose stringent constraints on NSI. [Gavela, Hernandez, Ota, Winter (PRD '09); Biggio, Blennow, Fernandez-Martinez (JHEP '09)]

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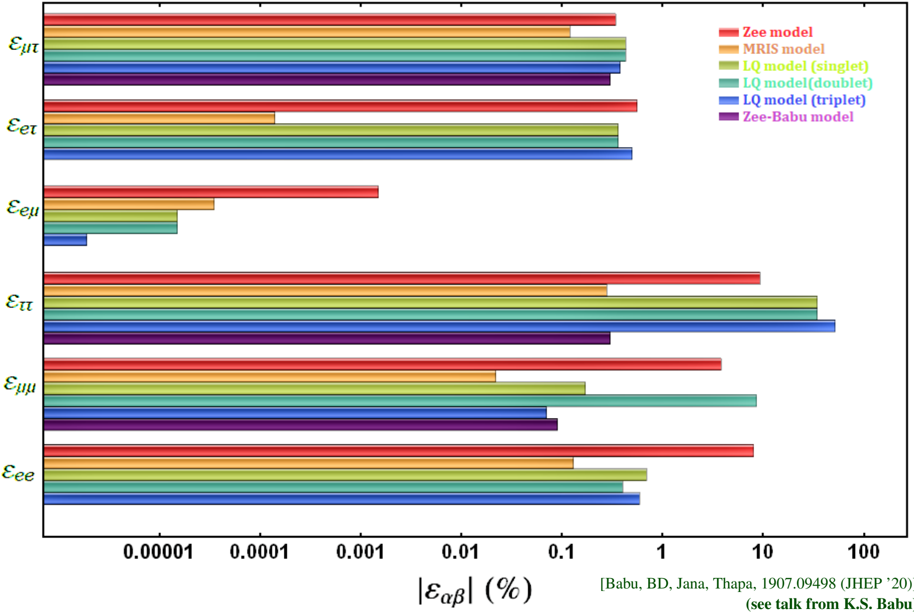
- Restoring gauge invariance in a UV-complete model will in general impose stringent constraints on NSI. [Gavela, Hernandez, Ota, Winter (PRD '09); Biggio, Blennow, Fernandez-Martinez (JHEP '09)]
- Specifically, if there is an operator of the form $\frac{1}{\Lambda^2}(\bar{\nu}_\alpha\gamma^\mu P_L \nu_\beta)(\bar{\ell}_\gamma\gamma_\mu P_L \ell_\delta)$, it must be part of the more general form $\frac{1}{\Lambda^2}(\bar{L}_\alpha\gamma^\mu L_\beta)(\bar{L}_\gamma\gamma_\mu L_\delta)$.
- Severely constrained by rare LFV processes like $\mu \to 3e$, viz. ${\rm BR}(\mu \to 3e) < 10^{-12}$ implies $\varepsilon^{ee}_{e\mu} < 10^{-6}$.
- **Are there realistic UV-complete models having large NSI?**
- Important in order to understand which sort of physics the neutrino experimental program is actually probing when model-independent NSI constraints are presented.

NSI in Radiative Neutrino Models



[Babu, BD, Jana, Thapa, 1907.09498 (JHEP '20)]

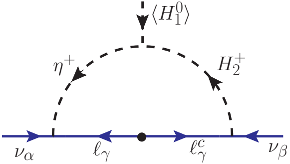
(see talk from K.S. Babu)

Essentially covers all NSI possibilities with heavy mediators (with mass $\gg E_\nu$).

An Example: Zee Model

[Zee (PLB '80)]

$$-\mathcal{L}_Y \supset f_{\alpha\beta} L^i_\alpha L^j_\beta \epsilon_{ij} \eta^+ + \widetilde{Y}_{\alpha\beta} \widetilde{H}^i_1 L^j_\alpha \ell^c_\beta \epsilon_{ij} + Y_{\alpha\beta} \widetilde{H}^i_2 L^j_\alpha \ell^c_\beta \epsilon_{ij} + \text{H.c.}$$



$$\boxed{M_\nu = \kappa \left(f M_\ell Y + Y^T M_\ell f^T \right)}$$

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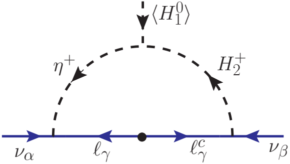

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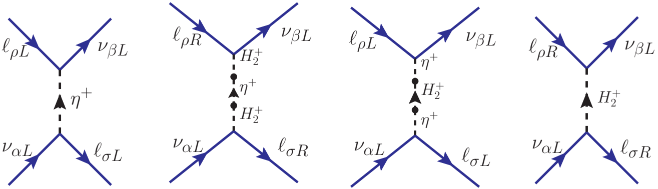
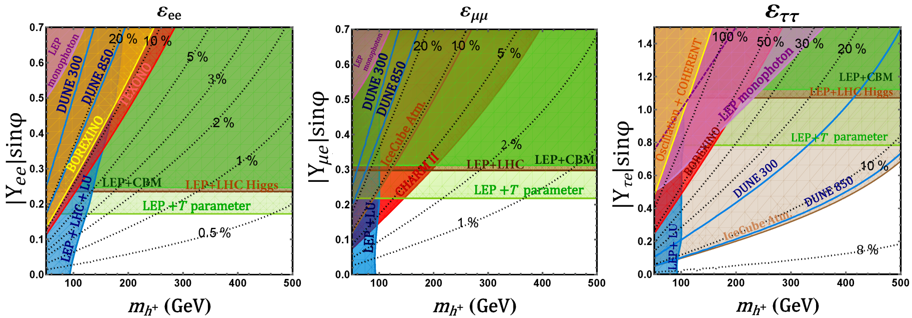


(small) (small)

$$\varepsilon_{\alpha\beta} \equiv \varepsilon^{(h^+)}_{\alpha\beta} + \varepsilon^{(H^+)}_{\alpha\beta} = \frac{1}{4\sqrt{2} G_F} Y_{\alpha e} Y^\star_{\beta e} \left(\frac{\sin^2\varphi}{m^2_{h^+}} + \frac{\cos^2\varphi}{m^2_{H^+}} \right)$$

NSI Predictions in the Zee Model

[Babu, BD, Jana, Thapa, 1907.09498 (JHEP '20)]



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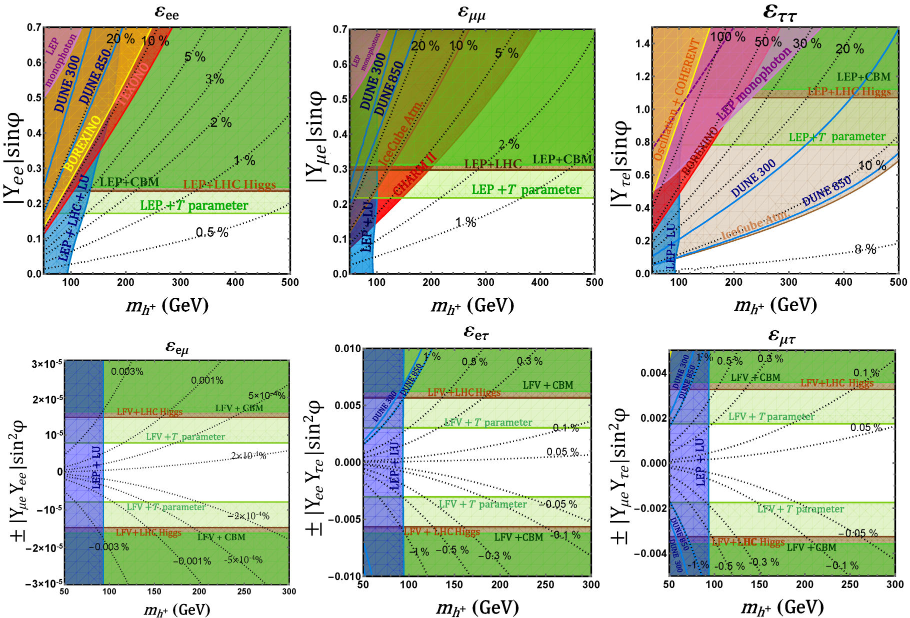
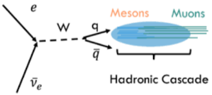


NSI with Ultra High Energy Neutrinos



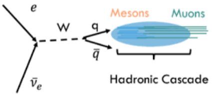
[Glashow (Phys. Rev. '60)]

Glashow resonance

$$E_\nu = \frac{m_W^2}{2m_e} = 6.3 \text{ PeV}$$

Observed by IceCube

[Nature **591**, 220 (2021)]



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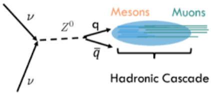
Observed by IceCube

[Nature **591**, 220 (2021)]



[Weiler (PRL '82)]

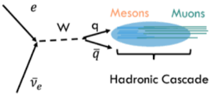
Z-burst

$$E_\nu = \frac{m_Z^2}{2m_\nu} > 10^{14} \text{ GeV}$$

Beyond GZK cutoff

Unlikely to be seen

NSI with Ultra High Energy Neutrinos



[Glashow (Phys. Rev. '60)]

Glashow resonance

$$E_\nu = \frac{m_W^2}{2m_e} = 6.3 \text{ PeV}$$

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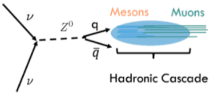

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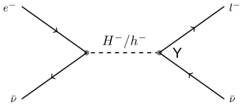

[Babu, BD, Jana, Sui (PRL '20)]

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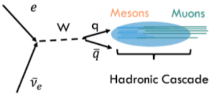

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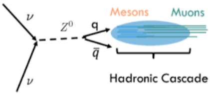

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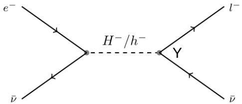

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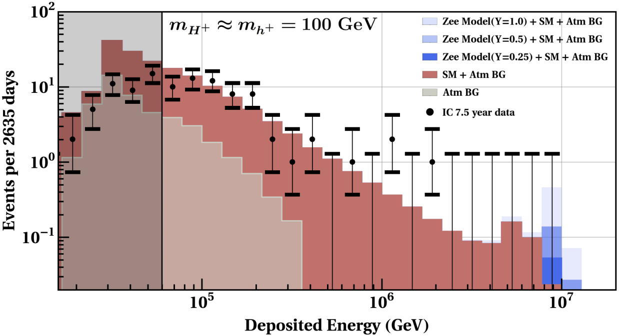
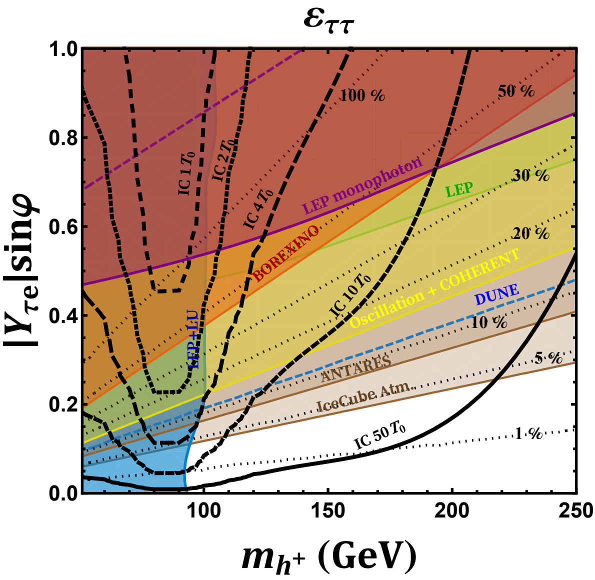


A New Probe of NSI

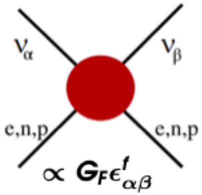


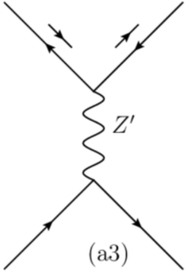
[Babu, BD, Jana, Sui, 1908.02779 (PRL '20); Babu, BD, Jana, 2202.06975 (IJMPA '22)]

- The EFT argument does not work.
- Possible to avoid cLFV constraints with light mediators.
- An explicit example with $(B-L)_3$ flavored light Z'. [Babu, Friedland, Machado, Mocioiu, 1705.01822 (JHEP '17)]
- Large diagonal $\varepsilon_{\tau\tau}$ up to $\sim 50\%$.
- How about large off-diagonal NSI?
- In general, for light Z',

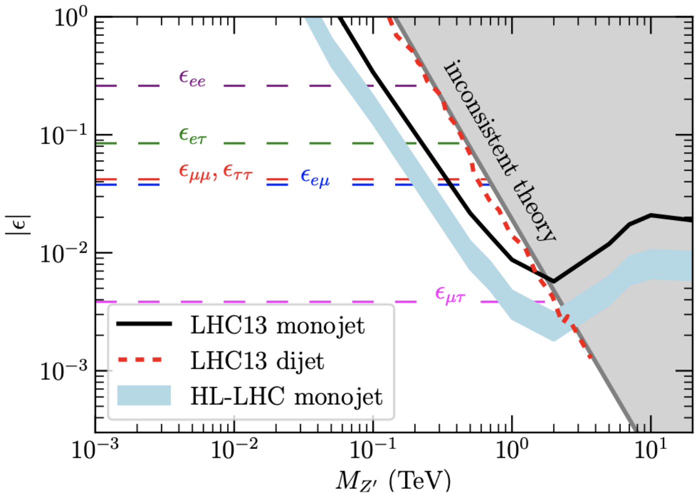
$$\varepsilon^f_{\alpha\beta} = \frac{g_f (g_\nu)_{\alpha\beta}}{2\sqrt{2} G_F m^2_{Z'}}$$

- An explicit example violating the Schwartz inequality, i.e. $|\varepsilon^f_{\alpha\beta}| > |\varepsilon^f_{\alpha\alpha}\varepsilon^f_{\beta\beta}|^{1/2}$, with $U(1)' \times Z_2$. [Farzan, 1912.09408 (PLB '20)]





LHC versus Oscillation Experiments



[Babu,Gonçalves, Jana, Machado, 2003.03383 (PLB ’21);

see also Friedland, Graesser, Shoemaker, Vecchi (PLB ’12); Franzosi, Frandsen, Shoemaker (PRD ’15); Liu, Sun, Gao (JHEP ’21)]

Going beyond Vector NSI

- NSI induced by a neutral scalar mediator:

$$\mathcal{L}_{\rm eff}^{S} = \frac{y_f y_{\alpha\beta}}{m_\phi^2}(\bar{\nu}_\alpha \nu_\beta)(\bar{f} f)\,.$$

- Cannot be Fierzed into a vector current, so does not contribute to matter potential.
- Appears as a medium-dependent correction to the neutrino mass.

  [Ge, Parke (PRL '19); Smirnov, Xu (JHEP '19)]
- Need $G_{\rm eff} \equiv y_f y_{\alpha\beta}/m_\phi^2 \sim 10^{10} G_F$ to have any observable effect. Possible only for a sufficiently light scalar mediator.

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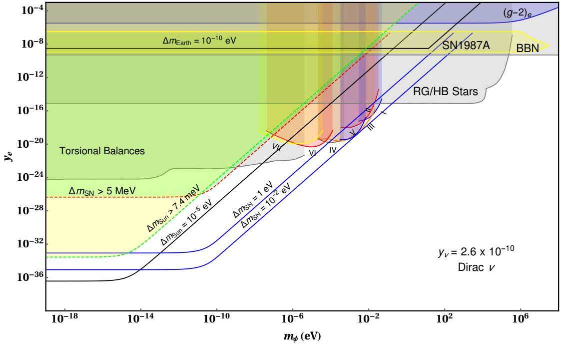
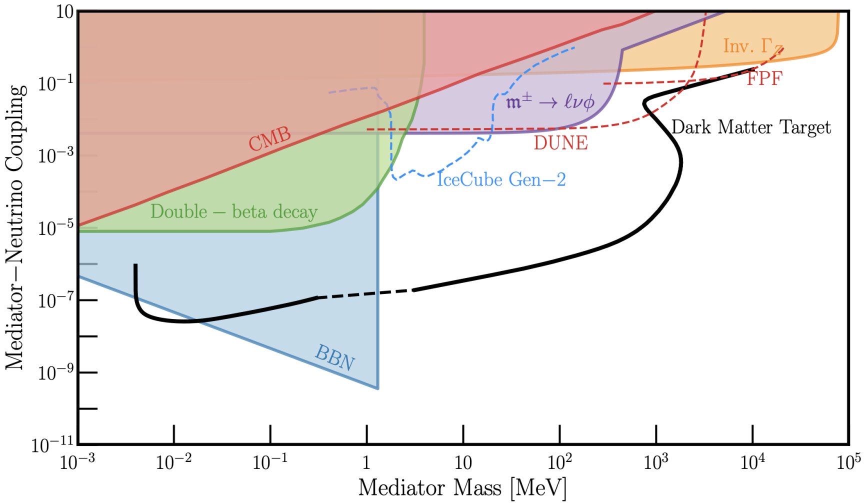


[Babu, Chauhan, BD, 1912.13488 (PRD '20)]

Non-Standard Neutrino Self-Interactions



[Berryman *et al.*, Snowmass White Paper 2203.01955]

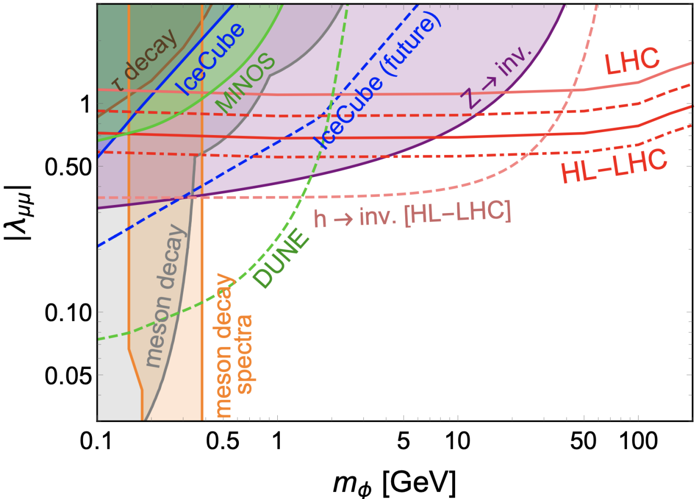
Can also lead to novel features in UHE neutrino spectrum.

[Ioka, Murase (PTEP '14); Ng, Beacom (PRD '14); Cherry, Friedland, Shoemaker '14; Esteban, Pandey, Brdar, Beacom (PRD '21)]

Leptonic Scalar

$$\mathcal{L} \supset \frac{1}{2}\lambda_{\alpha\beta}\phi\nu_\alpha\nu_\beta$$

[Berryman, de Gouvêa, Kelly, Zhang (PRD '18); Kelly, Zhang (PRD '19); Blinov, Kelly, Krnjaic, McDermott (PRL '19)]



Distinct LHC signatures [de Gouvêa, BD, Dutta, Ghosh, Han, Zhang (JHEP '20); BD, Dutta, Ghosh, Han, Qin, Zhang (JHEP '22)]

Conclusion

- NSI at some level is inevitable in BSM scenarios for neutrino mass generation.
- Searches for NSI are complementary to the direct searches for new physics at the LHC.
- Possible to achieve observable NSI in realistic, UV-complete models.
- Heavy mediator case is now exhausted.
- Light mediator case still being explored.
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Thank You.

Acknowledgments

Need a better NTN logo!