WashU

McDONNELL CENTER FOR THE SPACE SCIENCES

Neutrino Non-Standard Interactions (NSI)

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EuCAPT
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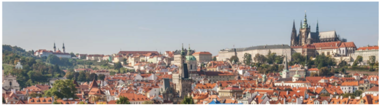

September 19, 2024

Outline

- **Lecture 1:** NSI Basics
  - Why care about NSI?
  - Review of SI and matter effect
  - Wolfenstein parametrization of (vector) NSI
  - NSI in propagation (NC), production and detection (CC)
  - Current status and future prospects of NSI constraints
  - Possible hint of NSI in oscillation data?

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- **Lecture 2:** NSI Model Building and Phenomenology
- **Lecture 3:** Beyond ε – Scalar NSI, NSSI, Neutrino-DM interactions, ...

References

- $\mathcal{O}(500)$ papers on NSI.
- Apologies if your favorite paper(s) not cited here.
- Reviews:

  - T. Ohlsson, Rept. Prog. Phys. **76**, 044201 (2013) [arXiv:1209.2710].
  - O. G. Miranda and H. Nunokawa, New J. Phys. **17**, no.9, 095002 (2015) [arXiv:1505.06254].
  - Y. Farzan and M. Tortola, Front. in Phys. **6**, 10 (2018) [arXiv:1710.09360].
  - P. S. B. Dev *et al.*, SciPost Phys. Proc. **2**, 001 (2019) [arXiv:1907.00991].
  - S. K. Agarwalla *et al.*, Snowmass LOI (2022).

Why Non-Standard Interactions?

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

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- Must introduce new fermions, scalars and/or gauge bosons – **messengers of neutrino mass physics**.
- New couplings involving neutrinos – **inevitably lead to NSI**.
- Potentially observable effects in neutrino production, propagation, and/or detection.
- Relevant for all kinds of neutrinos (accelerator, reactor, atmospheric, solar, supernova, astrophysical, cosmic).

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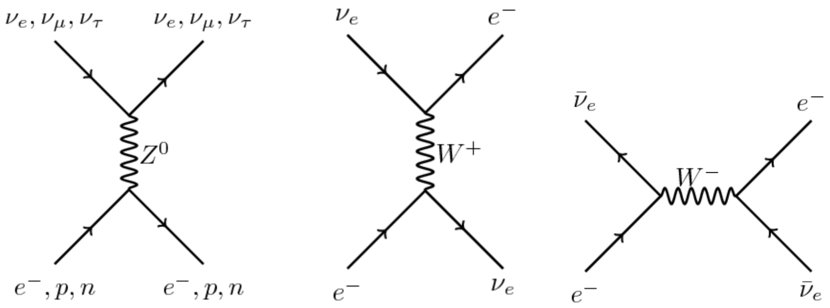
- Potentially observable effects in neutrino production, propagation, and/or detection.
- Relevant for all kinds of neutrinos (accelerator, reactor, atmospheric, solar, supernova, astrophysical, cosmic).
- **Complementary to direct search for new physics at the LHC.**
- At the very least, could serve as a foil for the standard 3-neutrino oscillation scheme.
- **Better understanding of NSI is crucial for correct interpretation of oscillation data.**
- Potential hints of NSI in recent T2K/NOνA data.

Standard Neutrino Interactions with Matter



$$\mathcal{H}_Z = \frac{G_F}{\sqrt{2}} J_Z^\mu J_{Z_\mu}^\dagger \,, \text{where } J_Z^\mu = \sum_{i=\ell,\nu_\ell,u,d} \overline{\psi}_i \gamma^\mu \left[I_i^3 (1-\gamma_5) - 2Q_i \sin^2\theta_W \right] \psi_i \,,$$

$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}} J_W^\mu J_{W_\mu}^\dagger \,, \text{where } J_W^\mu = \bar{e}\gamma^\mu (1-\gamma_5)\nu_e \,.$$

Effective Matter Potential

Type of reaction	Matter potential
V_Z^n	$\mp G_F N_n/\sqrt{2}$
V_Z^p	$\pm G_F(1-4\sin^2\theta_W)N_p/\sqrt{2}$
V_Z^e	$\mp G_F(1-4\sin^2\theta_W)N_e/\sqrt{2}$
V_W^e	$\pm\sqrt{2}G_F N_e$

[For a derivation, see e.g., J. Linder, hep-ph/0504264]

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[For a derivation, see e.g., J. Linder, hep-ph/0504264]

- Upper (Lower) sign is for neutrino (antineutrino).
- In an electrically neutral medium ($N_e = N_p$), $V_Z^e + V_Z^p = 0$.
- V_Z^n is diagonal in neutrino flavor, and gives an overall phase shift, which is of no physical significance in oscillations.
- Effective neutrino matter potential induced by Earth:

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

Oscillation Probability

- 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, $M = U\,\mathrm{diag}(m_1, m_2, m_3)U^T$ is the neutrino mass matrix and $V = \mathrm{diag}(V_{\mathrm{CC}}, 0, 0)$.

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- Probability of oscillation over a length L (in the 2-flavor limit):

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

where
$$\tan 2\theta_M = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A},$$
$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2},$$
$$A = 2EV_{\mathrm{CC}}.$$

Neutral Current NSI

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

with $X = L, R$, and $f \in \{e, u, d\}$. [L. Wolfenstein, PRD '78)]

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- Only vector part is relevant (axial-vector part is spin-dependent):

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

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

with $\varepsilon_{\alpha\beta}^{fV} = \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$ and $Y_n = N_n/N_e \simeq 1$ for Earth.

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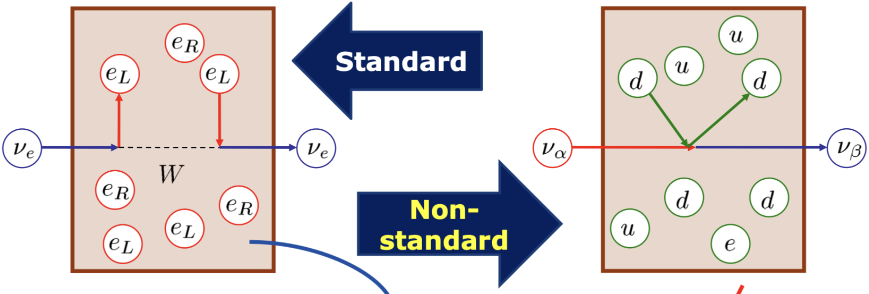
  with $\varepsilon_{\alpha\beta}^{fV} = \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$ and $Y_n = N_n/N_e \simeq 1$ for Earth.

- Leads to extra matter effect in propagation:

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

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

What does NSI do?



$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

[figure adapted from T. Ohlsson]

Induces non-standard oscillations during propagation

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

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

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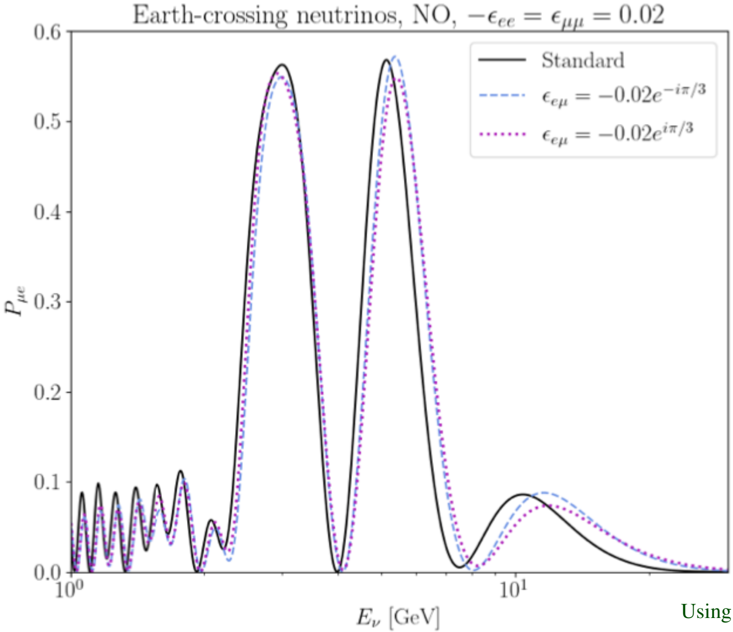
$$P(\nu_e \to \nu_\tau) = \sin^2 2\theta_M \, \sin^2\left(\frac{\Delta m^2_M L}{4E}\right)$$

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

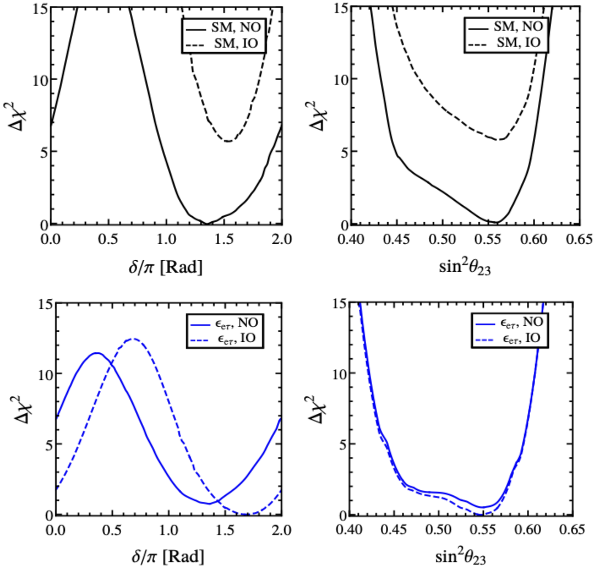
$$\sin 2\theta_M \equiv \frac{\Delta m^2 \sin 2\theta + 4EA\epsilon_{e\tau}}{\Delta m^2_M}$$

Modifies standard oscillation probabilities



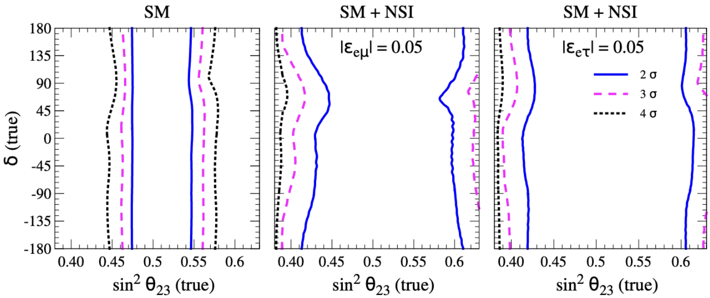
Using NuProbe

Can obscure mass-ordering determination



[Capozzi, Chatterjee, Palazzo 1908.06992 (PRL)]

Can degrade octant and δ_{CP} discovery potential



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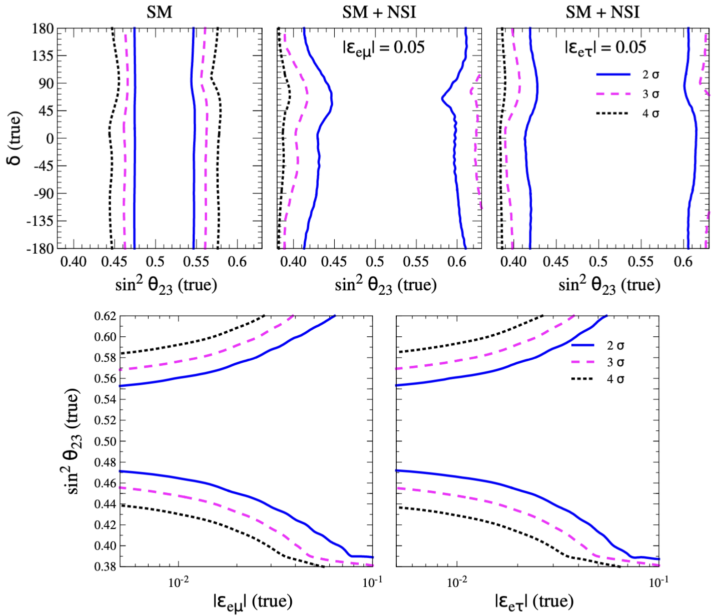


[Agarwalla, Chatterjee, Palazzo 1607.01745]

Charged Current NSI

[Y. Grossman, hep-ph/9507344]

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

- Flavor mixture states at source and detection.

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

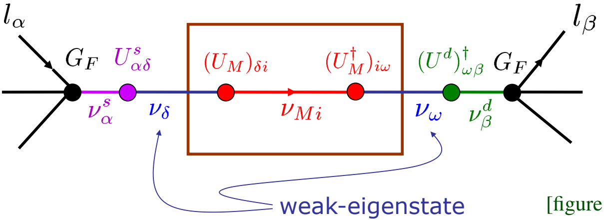
- Source NSI (e.g. in pion decay):

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

- Detection NSI (e.g. in neutrino-nucleon scattering):

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

Interesting Near-Detector Physics



[figure from T. Ohlsson]

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

Zero-distance effect [Langacker, London (PRD '88)]

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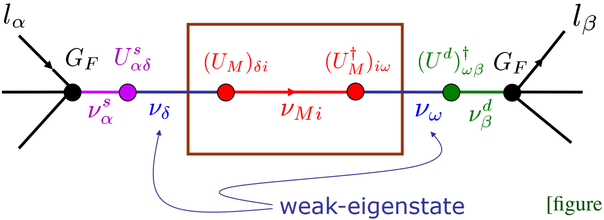

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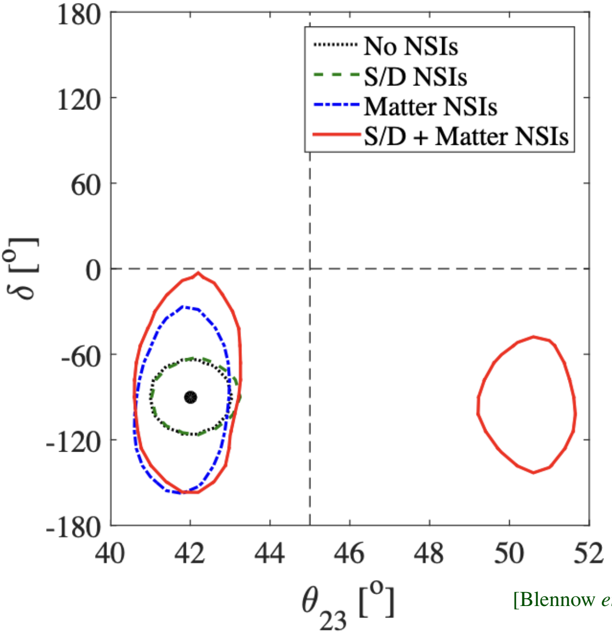
Zero-distance effect [Langacker, London (PRD '88)]

- In the 2-flavor case,

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

- Can in principle be probed with a near detector close to the source (e.g., ESSνSB), assuming that the neutrino fluxes at source are well-known.

CC+NC NSI can make things worse!



[Blennow *et al* 1606.08851]

Current Constraints* on NC NSI

[Farzan, Tortola 1710.09360]

	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

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$\epsilon_{\tau\tau}^{eV}$	$[-0.11, 0.11]$	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 (one at a time, some constraints do not apply to light mediators)

Current Constraints* on CC NSI

[Farzan, Tortola 1710.09360]

	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

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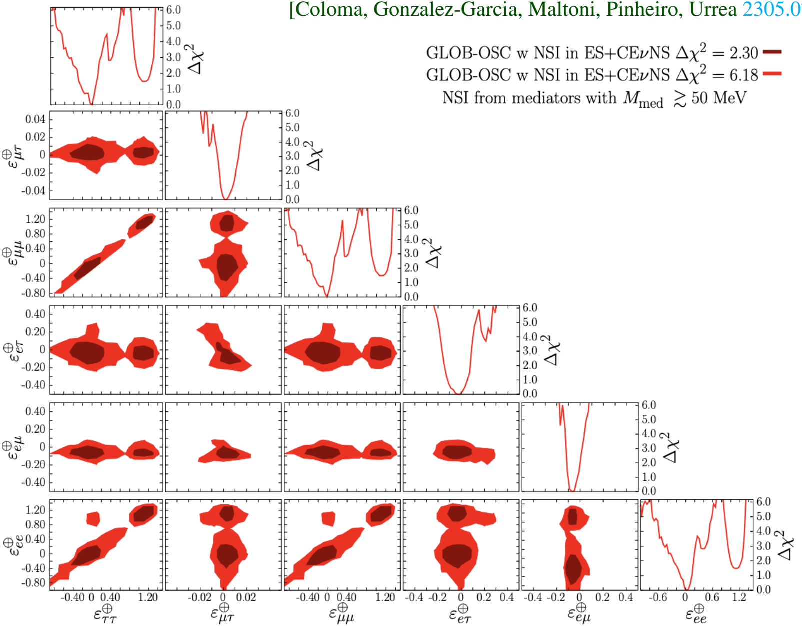
$\epsilon_{e\mu}^{udL}$	$[-0.026, 0.026]$	NOMAD
$\epsilon_{e\mu}^{udR}$	$[-0.037, 0.037]$	NOMAD
$\epsilon_{\tau e}^{udL}$	$[-0.087, 0.087]$	NOMAD
$\epsilon_{\tau e}^{udR}$	$[-0.12, 0.12]$	NOMAD
$\epsilon_{\tau\mu}^{udL}$	$[-0.013, 0.013]$	NOMAD
$\epsilon_{\tau\mu}^{udR}$	$[-0.018, 0.018]$	NOMAD
		purely 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

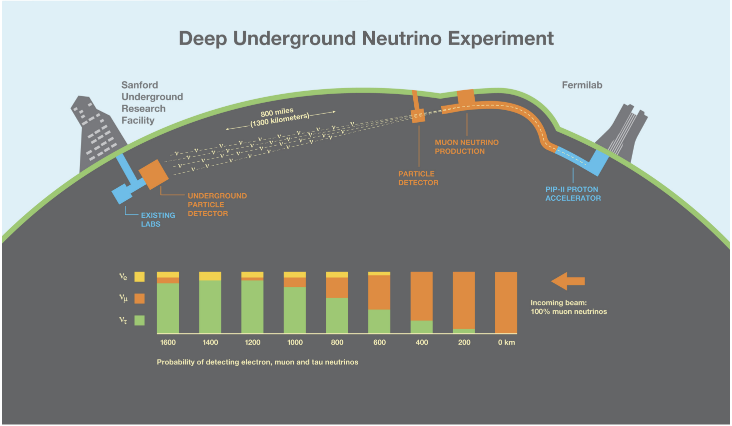
- From model-building perspective, getting ‘large’ CC NSI is more difficult than NC NSI.
- In some models (with purely leptonic NSI), CC and NC NSI are correlated by Fierz transformation.
- We will mostly focus on NC NSI (unless otherwise specified).

Global Fit

[Coloma, Gonzalez-Garcia, Maltoni, Pinheiro, Urrea 2305.07698]



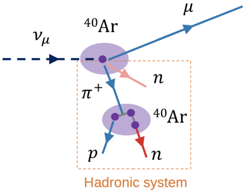
Future Prospects at DUNE



- Long baseline, huge statistics, intense & well-characterized beam.
- Excellent sensitivity to matter NSI.

[de Gouvêa, Kelly 1511.05562; Coloma 1511.06357; Blennow *et al.* 1606.08851; Liao, Marfatia, Whisnant 1612.01443; Chatterjee *et al* 1809.09313; Han *et al* 1910.03272]

Improved Energy Resolution



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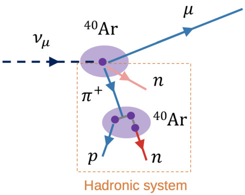

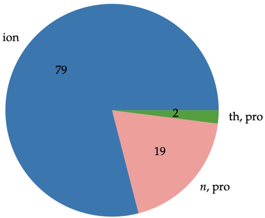

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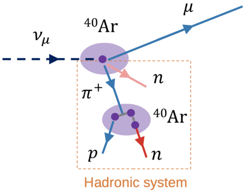
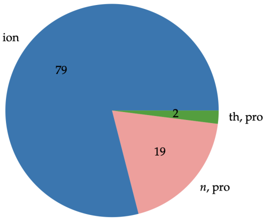
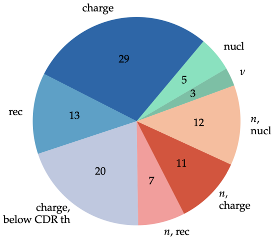
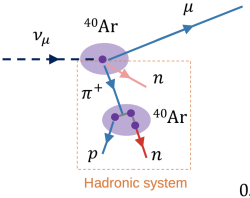
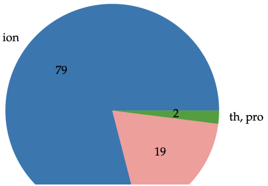


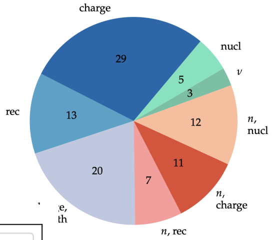


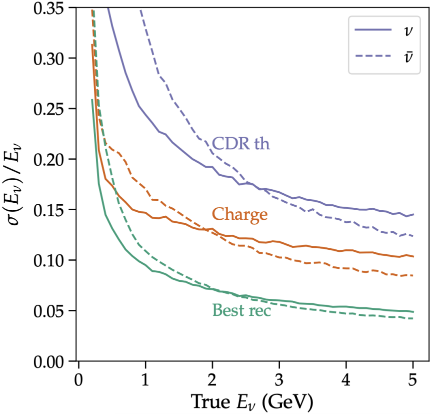


Improved Energy Resolution



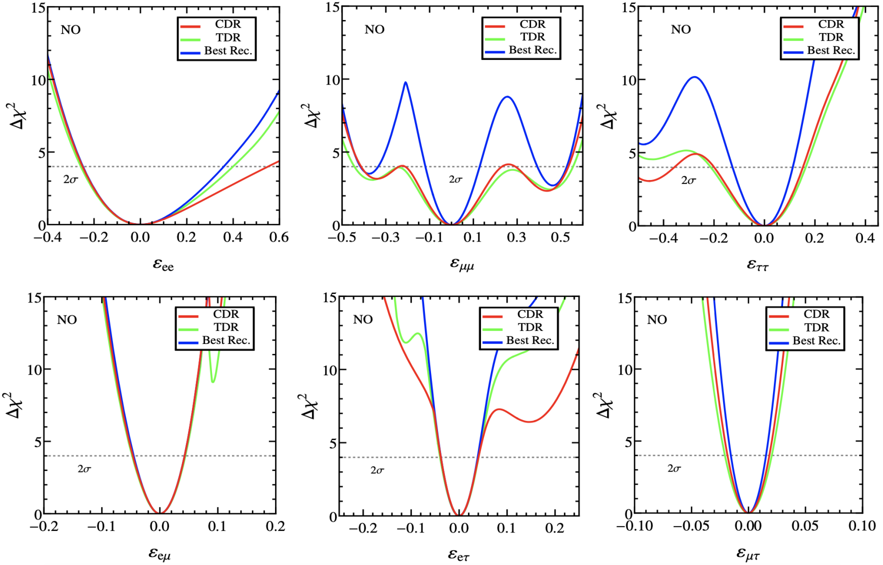






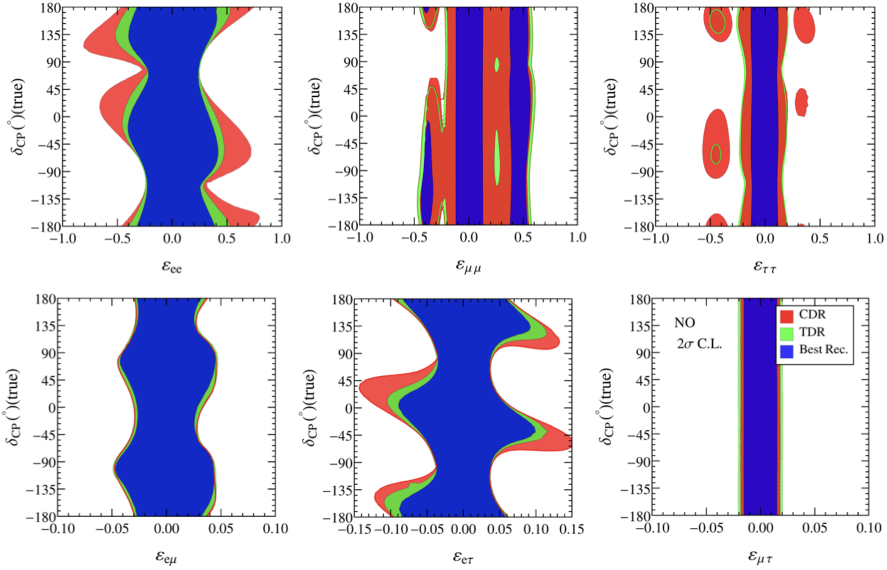
[Friedland, Li 1811.06159]

Improved DUNE Sensitivity to NSI



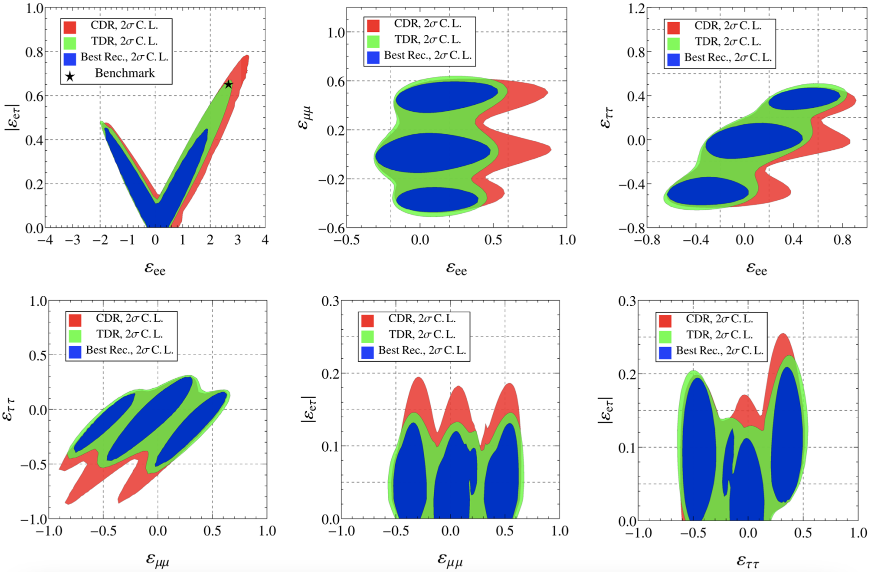
[Chatterjee, BD, Machado 2106.04597]

Dependence on δ_{CP}



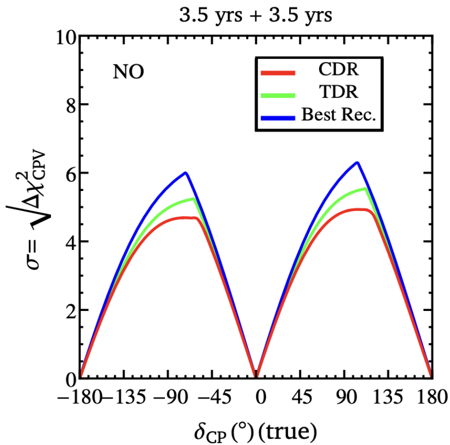
[Chatterjee, BD, Machado 2106.04597]

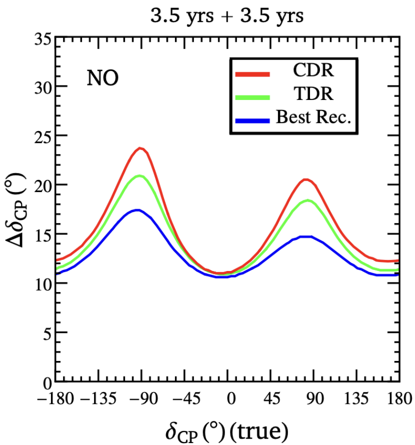
Breaking Degeneracies



[Chatterjee, BD, Machado 2106.04597]

Improved δ_{CP} Sensitivity

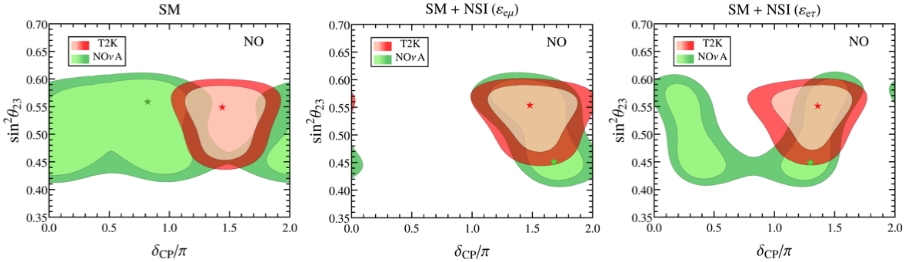




[Chatterjee, BD, Machado 2106.04597;

see also De Romeri, Fernandez-Martinez, Sorel, 1607.00293]

Hint of NSI?



[Chatterjee, Palazzo 2008.04161 (PRL); see also Denton, Gehrlein, Pestes 2008.01110 (PRL)]

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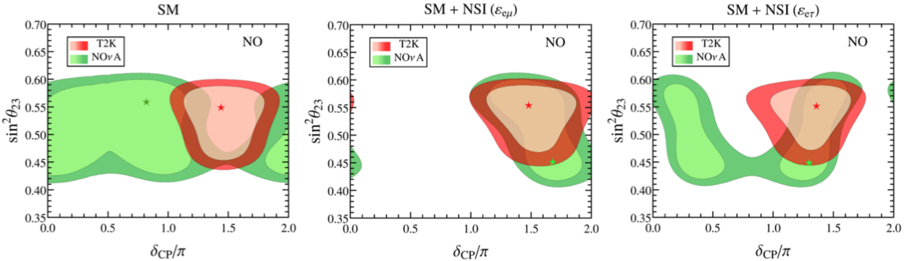
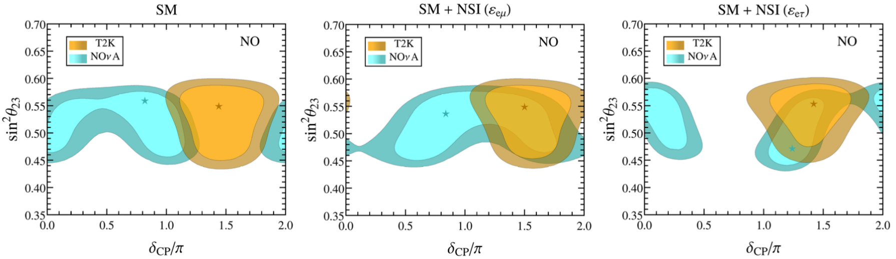


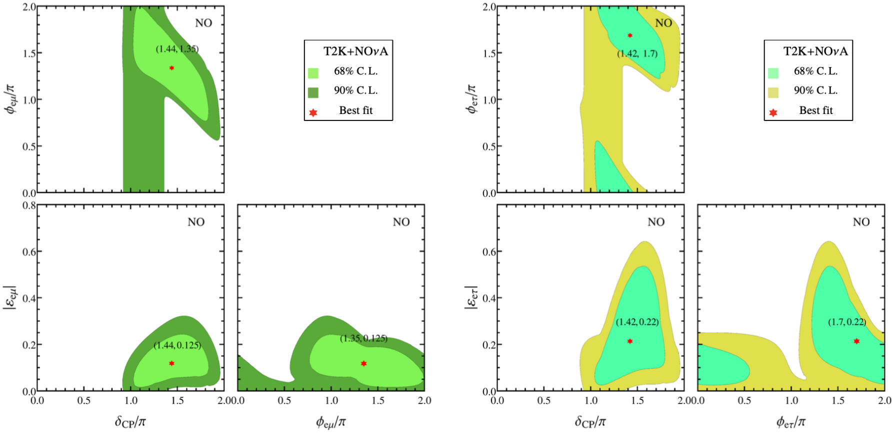
[Chatterjee, Palazzo 2008.04161 (PRL); see also Denton, Gehrlein, Pestes 2008.01110 (PRL)]

T2K-NOνA anomaly persists in 2024 data!



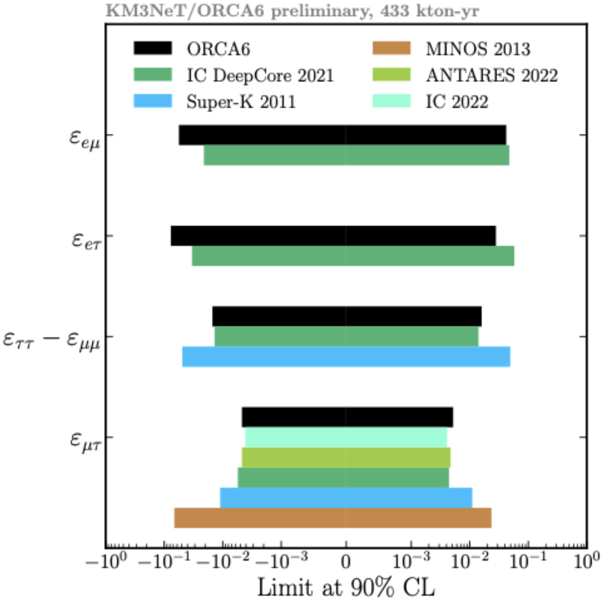
[Chatterjee, Palazzo 2409.10599]

But not conclusive yet!



[Chatterjee, Palazzo 2409.10599]

Strong constraints from IceCube and KM3NeT



[KM3NeT, ICRC 2023; IceCube 2201.03566 (PRL)]

Outline

- **Lecture 1:** NSI Basics
- **Lecture 2:** NSI Model Building and Phenomenology
  - Main challenge
  - EFT approach
  - UV-completion
  - Heavy mediators
  - Light mediators
  - Loop-induced NSI
- **Lecture 3:** Beyond ε – Scalar NSI, NSSI, Neutrino-DM interactions, ...

NSI Model Building

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

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

$$\boxed{\varepsilon_{\alpha\beta} \sim \frac{g_\Lambda^2 m_W^2}{\Lambda^2}}$$

- Two regimes to get 'observable' NSI, i.e. $\varepsilon_{\alpha\beta} \sim \mathcal{O}(1)$:
  - Heavy mediator: $g_\Lambda \sim \mathcal{O}(1)$ and $\Lambda \gtrsim m_W$.
  - Light mediator: $g_\Lambda \ll 1$ and $\Lambda \ll m_W$ such that $g_\Lambda^2/\Lambda^2 \sim \mathcal{O}(G_F)$.

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  - Light mediator: $g_\Lambda \ll 1$ and $\Lambda \ll m_W$ such that $g_\Lambda^2/\Lambda^2 \sim \mathcal{O}(G_F)$.
- EFT approach is valid in *both* cases as long as $q^2 \ll \Lambda^2$.
- Always true for matter NSI, since $q^2 \to 0$ for coherent forward scattering.

Main Challenge

- The NSI operator by itself is not $SU(2)_L$ gauge-invariant.
- Restoring gauge invariance in a renormalizable, UV-complete model will in general impose stringent constraints on NSI.

  [Gavela, Hernandez, Ota, Winter 0809.3451; Biggio, Blennow, Fernandez-Martinez 0907.0097]

Main Challenge

- The NSI operator by itself is not $SU(2)_L$ gauge-invariant.
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  [Gavela, Hernandez, Ota, Winter 0809.3451; Biggio, Blennow, Fernandez-Martinez 0907.0097]
- Consider the leptonic NSI operator of the form

$$\frac{1}{\Lambda^2}(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{\ell}_\gamma \gamma_\mu P_L \ell_\delta).$$

- In a UV-complete theory, 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. $\mathrm{BR}(\mu \to 3e) < 10^{-12}$ implies $\varepsilon^e_{e\mu} \lesssim 10^{-6}$.
- Similar constraints for quark NSI from atomic parity violation, CKM unitarity, etc. [Antusch, Baumann, Fernandez-Martinez 0807.1003]

Why do we care?

- **Are there realistic UV-complete models having observable NSI?**
- Important in order to understand which sort of new physics the neutrino experimental program is actually probing when model-independent NSI constraints are presented.
- Complementarity of neutrino oscillation and scattering experiments with traditional low- and high-energy experiments searching for new physics.

Why do we care?

- **Are there realistic UV-complete models having observable NSI?**
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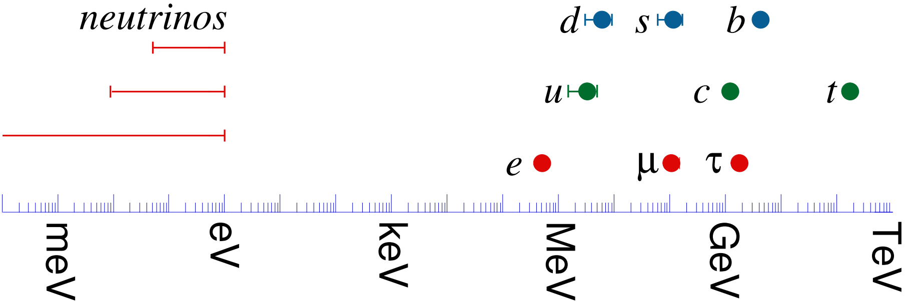
- Complementarity of neutrino oscillation and scattering experiments with traditional low- and high-energy experiments searching for new physics.
- After all, neutrinos are the first (and so far only) ones to give concrete laboratory evidence of new physics.
- **Can we use NSI to probe neutrino mass physics?**
- *Oscillation physics is insensitive to absolute neutrino mass, but not necessarily to the origin of neutrino mass.*

Neutrino Mass Mechanism



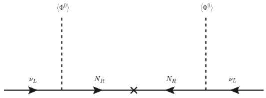
- Simplest solution: Add right-handed neutrinos N.
- Gives Dirac Yukawa term $Y_D \bar{L} H N$+H.c.
- After EWSB, gives Dirac neutrino mass $M_D = Y_D v$.
- But $m_\nu \lesssim 0.1$ eV implies $Y_D \lesssim 10^{-12}$. Possible but ugly!
- **Perhaps something (beautiful) beyond the SM Higgs mechanism?**

Seesaw Mechanism

- One possibility is to break the accidental $B - L$ symmetry of the SM by higher-dimensional operators.
- Lowest-order is dimension-5 Weinberg operator: [Weinberg, PRL '79]

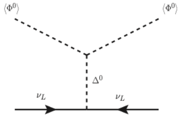
$$\mathcal{O}_1 = \frac{1}{\Lambda} L^i L^j H^k H^l \epsilon_{ik} \epsilon_{jl}.$$

- Only 3 tree-level realizations: [Ma, hep-ph/9805219 (PRL)]



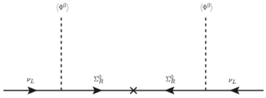
Type-I seesaw

Minkowski (PLB '77); Mohapatra, Senjanovic (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79



Type-II seesaw

Schechter, Valle (PRD '80); Lazarides, Shafi, Wetterich (NPB '81); Mohapatra, Senjanovic (PRD '81)



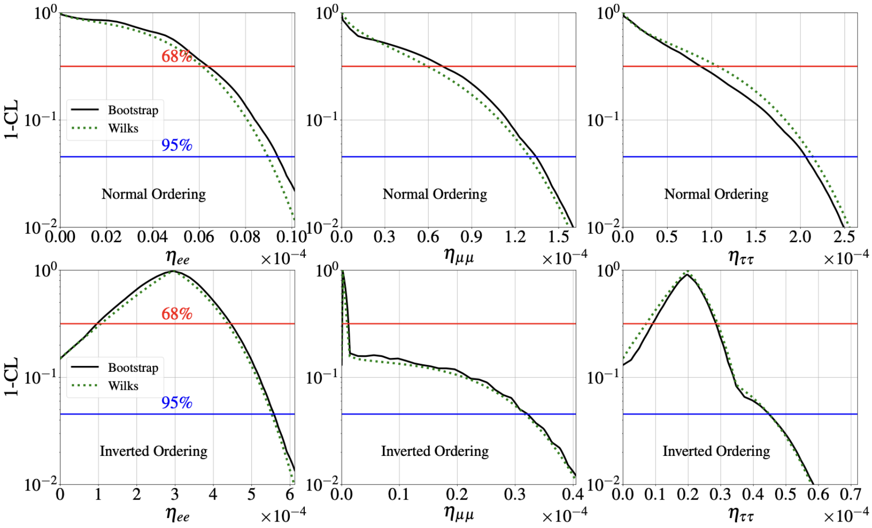
Type-III seesaw

Foot, Lew, He, Joshi (ZPC '89)

NSI in Type-I Seesaw

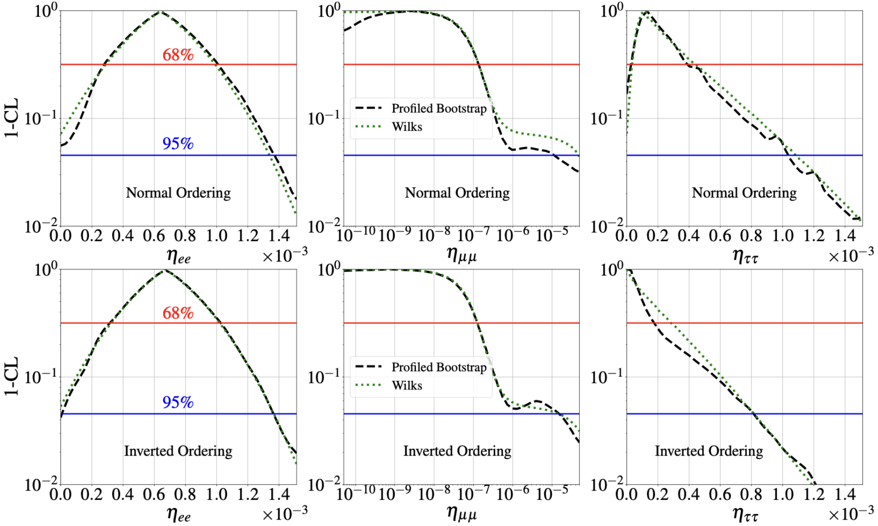
- Related to **non-unitarity** in the neutrino mixing matrix. [Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon 1609.08637]
- The seesaw mass matrix $\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix}$ is diagonalized by a $(3+n) \times (3+n)$ unitarity matrix $\mathcal{U} = \begin{pmatrix} U & R \\ S & V \end{pmatrix}$.
- $U \simeq (1-\eta)U_{\rm PMNS}$ with $\eta = RR^\dagger/2$ and $R \simeq M_D M_N^{-1}$.
- $\varepsilon_{\alpha\beta}$ are identical to $\eta_{\alpha\beta}$ (up to a factor of 2 for the off-diagonals).
- Can also be derived from 'first principles' using the canonical diagonalization of the kinetic term. [Broncano, Gavela, Jenkins hep-ph/0210271]
- Stringent constraints on non-unitarity from EWPD, LFV, CKM unitarity, etc. [Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, hep-ph/0607020; Antusch, Fischer 1407.6607]; Blennow, Fernández-Martínez, Hernández-García, López-Pavón, Marcano, Naredo-Tuero, 2306.01040]

Global Analysis of NSI with 2 RHNs



[Blennow, Fernández-Martínez, Hernández-García, López-Pavón, Marcano, Naredo-Tuero, 2306.01040]

Global Analysis of NSI with 3 RHNs



[Blennow, Fernández-Martínez, Hernández-García, López-Pavón, Marcano, Naredo-Tuero, 2306.01040]

Mild preference for non-zero NSI at 10^{-4} level (in ee and $\tau\tau$) for NO.

NSI in Type-II Seesaw

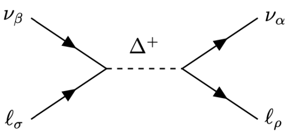
- SM+ a scalar triplet $\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$ [Schechter, Valle '80]

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

- 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

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

NSI in Type-II Seesaw

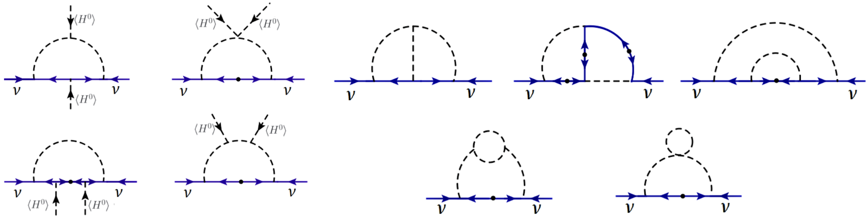
Strongly constrained by cLFV, neutrino mass and lab constraints on Δ^+.

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

[Huitu, Karkkainen, Maalampi, Vihonen 1711.02971]

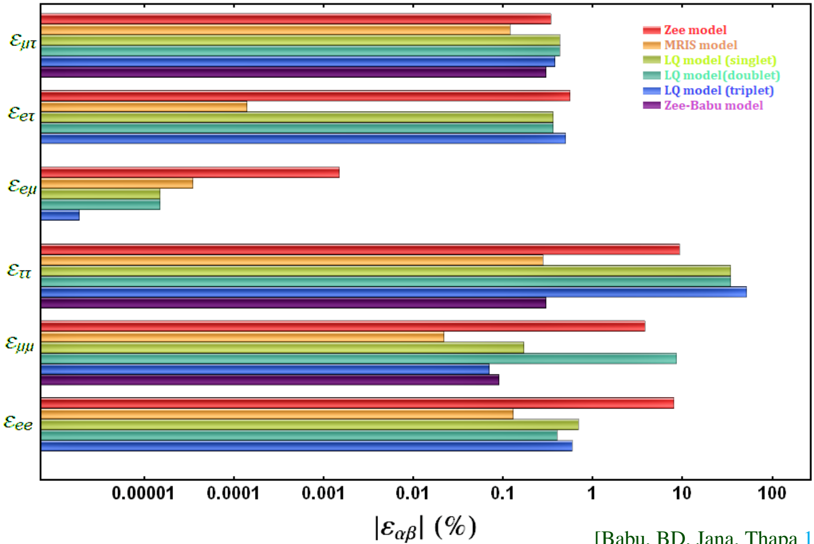
Radiative Neutrino Mass Models

- Attractive alternative to tree-level seesaw.
- In-buit loop (and chiral) suppression factors naturally allows for lower new physics scale.



[Zee (PLB ’80; NPB ’86); Babu (PLB ’88); Cai, Herrero-Garcia, Schmidt, Vicente, Volkas 1706.08524]

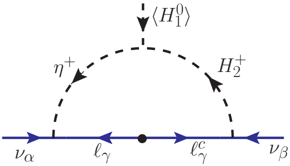
NSI in Radiative Neutrino Models



[Babu, BD, Jana, Thapa 1907.09498]

Essentially covers all NSI possibilities with heavy mediators.

An Example: Zee Model



[Zee (PLB '80)]

$$M_\nu \;=\; \kappa\,(f M_\ell Y + Y^T M_\ell f^T)$$

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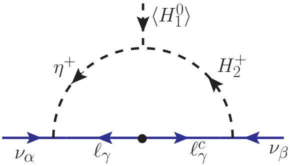

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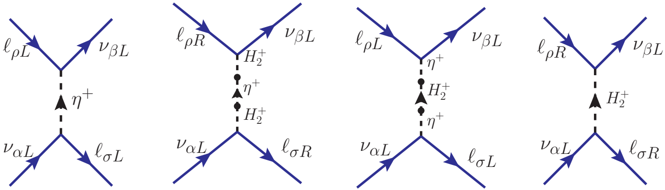
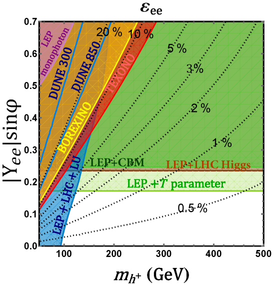


(small) (small)

$$\varepsilon_{\alpha\beta} \;\equiv\; \varepsilon_{\alpha\beta}^{(h^+)} + \varepsilon_{\alpha\beta}^{(H^+)} \;=\; \frac{1}{4\sqrt{2}G_F} Y_{\alpha e} Y_{\beta e}^\star \left(\frac{\sin^2\varphi}{m_{h^+}^2} + \frac{\cos^2\varphi}{m_{H^+}^2} \right)$$

NSI Predictions in the Zee Model

[Babu, BD, Jana, Thapa 1907.09498]



NSI Predictions in the Zee Model

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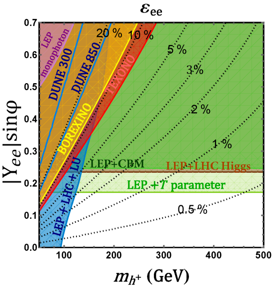

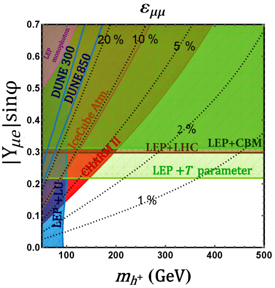

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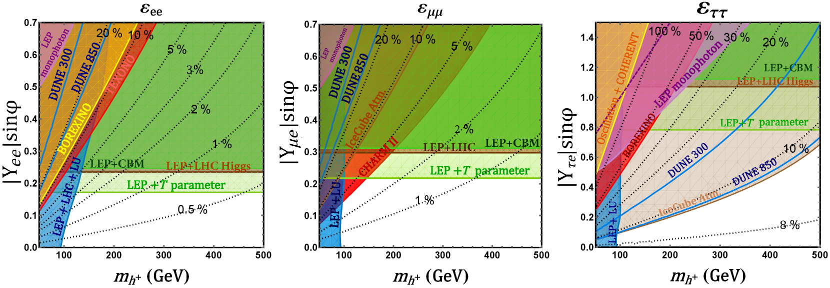

NSI Predictions in the Zee Model

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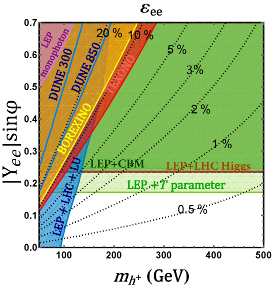
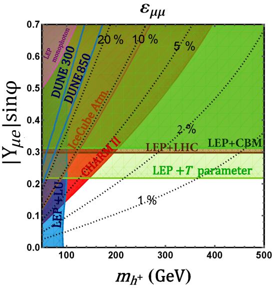
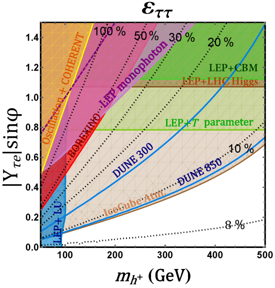
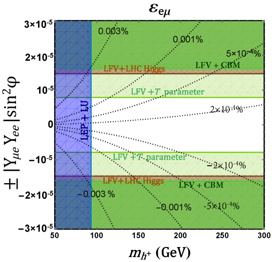


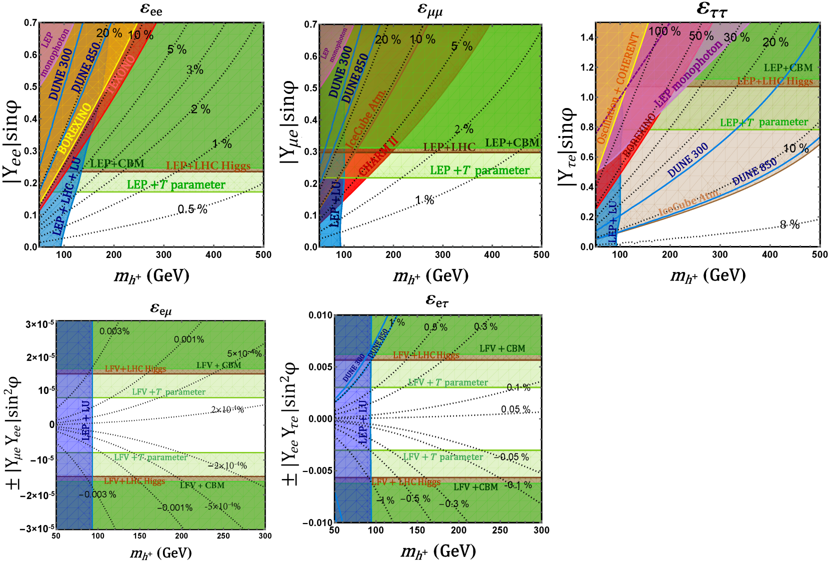






NSI Predictions in the Zee Model

[Babu, BD, Jana, Thapa 1907.09498]



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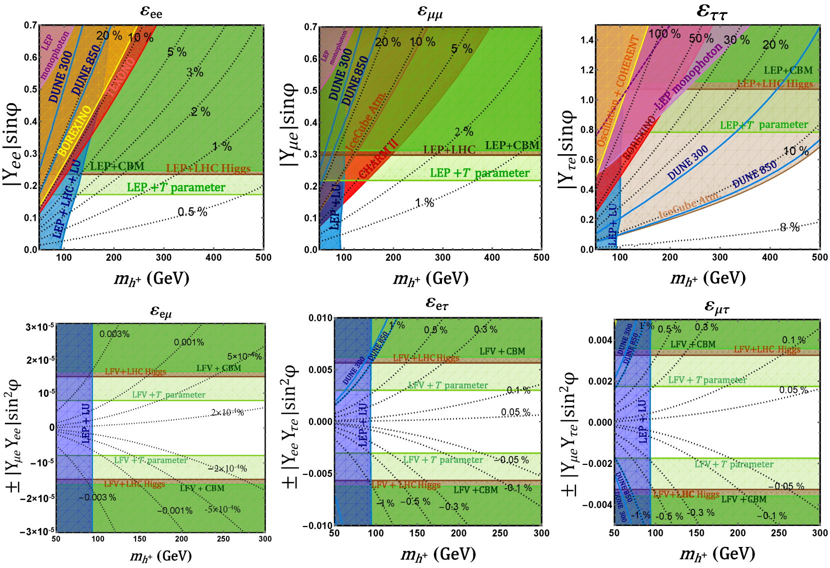
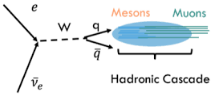


A New Resonance for High Energy Neutrinos



[Glashow (PR ’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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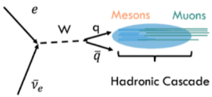

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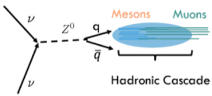

[Weiler (PRL '82)]

Z-burst

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

Beyond GZK cutoff

Unlikely to be seen

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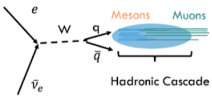

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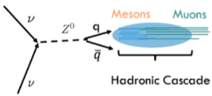

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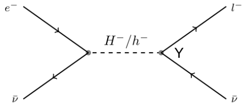

[Babu, BD, Jana, Sui (PRL '20)]

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$$E_\nu = \frac{m_{h^-/H^-}^2}{2m_e} \gtrsim 10 \text{ PeV}$$

Observable (soon!)

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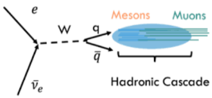

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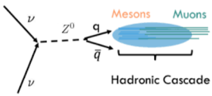

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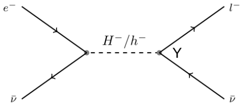

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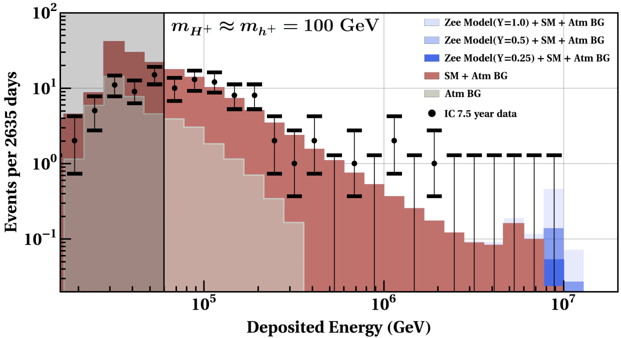
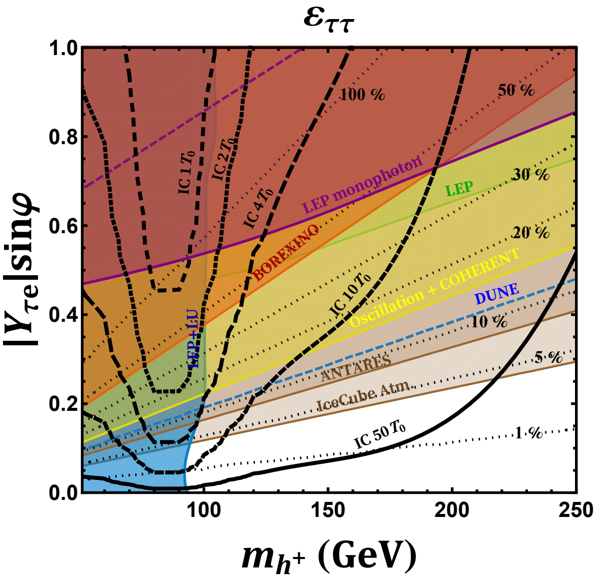


A New Probe of NSI using UHE Neutrinos



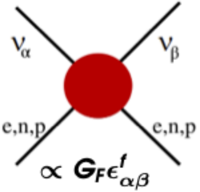
[Babu, BD, Jana, Sui 1908.02779; Babu, BD, Jana 2202.06975]

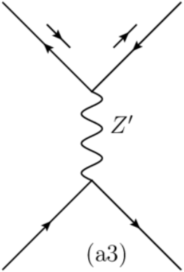
NSI with Light Mediators

- Still lacking a comprehensive UV-complete exploration.
- Possible to avoid cLFV constraints with flavored light mediators.
- An explicit example with $(B-L)_3$ flavored light Z'. [Babu, Friedland, Machado, Mocioiu 1705.01822]
- Large diagonal $\varepsilon_{\tau\tau}$ up to $\sim 50\%$.
- **How about large off-diagonal NSI?**
- In general, for light Z',

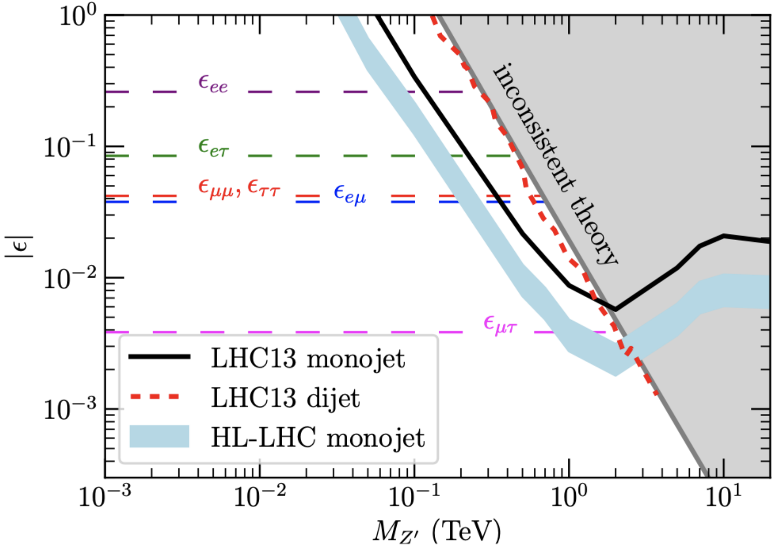
$$\varepsilon^f_{\alpha\beta} = \frac{g_f (g_\nu)_{\alpha\beta}}{2\sqrt{2} G_F m^2_{Z'}}$$

- 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]



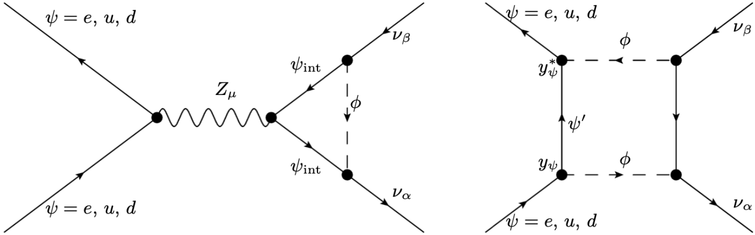


LHC Probe of NSI



[Babu,Gonçalves, Jana, Machado 2003.03383]

Loop-induced NSI



$$\mathcal{L}_{\rm NSI} = \left(\epsilon^{\triangleright}_{\alpha\beta} + \epsilon^{\square}_{\alpha\beta}\right) \frac{G_F}{\sqrt{2}} \overline{\psi}\gamma^\mu\psi\overline{\nu_\alpha}\gamma_\mu P_L \nu_\beta, \quad (\psi = e_L,\ e_R,\ u_L,\ u_R, \cdots),$$

$$\epsilon^{\triangleright}_{\alpha\beta} = -\frac{8g^{(1)}_{\alpha\beta}}{g} Q_Z^{(\psi)} c_W, \qquad \epsilon^{\square}_{\alpha\beta} = \frac{1}{16\pi^2} \frac{\sqrt{2} y_\alpha^* y_\beta |y_\psi|^2}{4 m_\phi^2 G_F}.$$

	ϵ_e^F	$\epsilon_e^\triangleright$	$\epsilon_n^\triangleright$	$\epsilon_p^\triangleright$	$\epsilon_e^\square$	$\epsilon_n^\square$	$\epsilon_p^\square$
model A	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-3})$	0	0
model B	0	$\mathcal{O}(10^{-1})$	$\mathcal{O}(1)$	$\mathcal{O}(10^{-1})$	0	0	0
model C	0	0	0	0	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$

[Bischer, Rodejohann, Xu 1807.08102]

Outline

- **Lecture 1:** NSI Basics
- **Lecture 2:** NSI Model Building and Phenomenology
- **Lecture 3:** Beyond ε
  - Scalar NSI
  - Neutrino Self Interactions
  - Neutrino-DM interactions