Neutrino Non-Standard Interactions (NSI)

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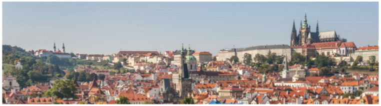

September 19, 2024

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?

$$\boxed{\textbf{Neutrino Oscillations} \Longrightarrow \textbf{Nonzero Neutrino Mass} \Longrightarrow \textbf{BSM Physics}}$$

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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**.
- 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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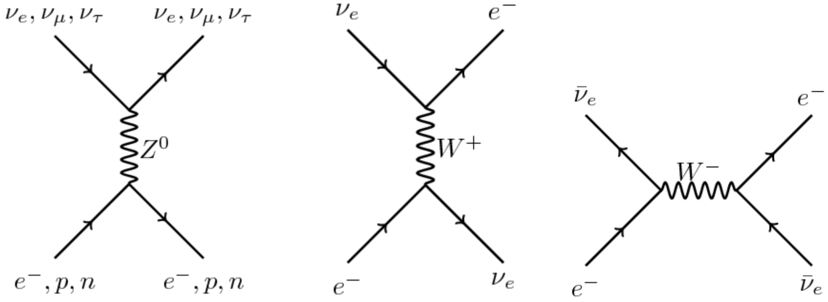
- Relevant for all kinds of neutrinos (accelerator, reactor, atmospheric, solar, supernova, astrophysical, cosmic).
- **Complementary to direct search for new physics at the LHC.**
- At the very least, could serve as a foil for the standard 3-neutrino oscillation scheme.
- **Better understanding of NSI 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:

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

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):

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

$$\text{where} \quad \tan 2\theta_M = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A},$$

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2},$$

$$A = 2EV_{\mathrm{CC}}.$$

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):

$$\begin{aligned}\varepsilon_{\alpha\beta} = \sum_{f\in\{e,u,d\}} \frac{N_f}{N_e}\varepsilon_{\alpha\beta}^{fV} &= \varepsilon_{\alpha\beta}^{eV} + \frac{N_p}{N_e}(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}) + \frac{N_n}{N_e}(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV}) \\ &= \varepsilon_{\alpha\beta}^{eV} + (2 + Y_n)\varepsilon_{\alpha\beta}^{uV} + (1 + 2Y_n)\varepsilon_{\alpha\beta}^{dV}\end{aligned}$$

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

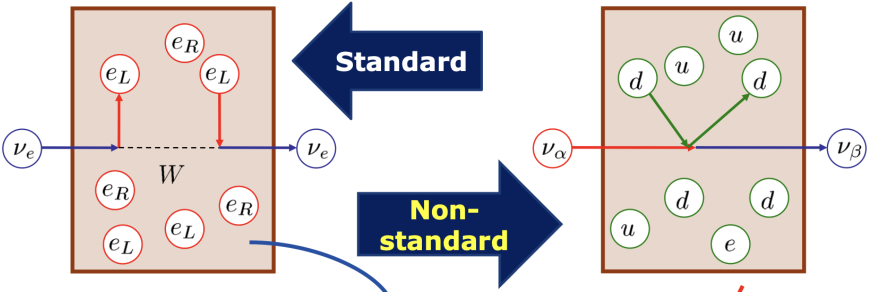
  with $\varepsilon_{\alpha\beta}^{fV} = \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$ and $Y_n = N_n/N_e \simeq 1$ for Earth.

- Leads to extra matter effect in propagation:

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

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

What does NSI do?



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

[figure adapted from T. Ohlsson]

Induces non-standard oscillations during propagation

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

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

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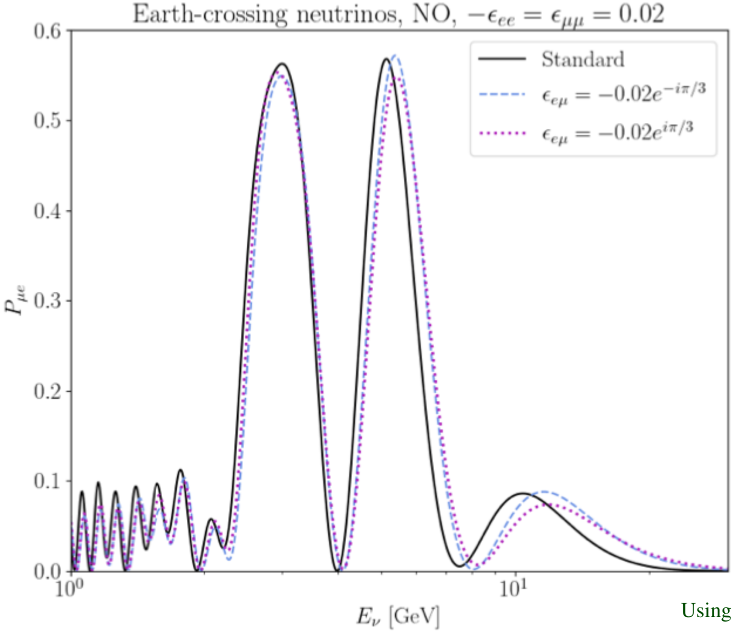
$$\boxed{P(\nu_e \to \nu_\tau) = \sin^2 2\theta_M \, \sin^2\left(\frac{\Delta m_M^2 L}{4E}\right)}$$

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

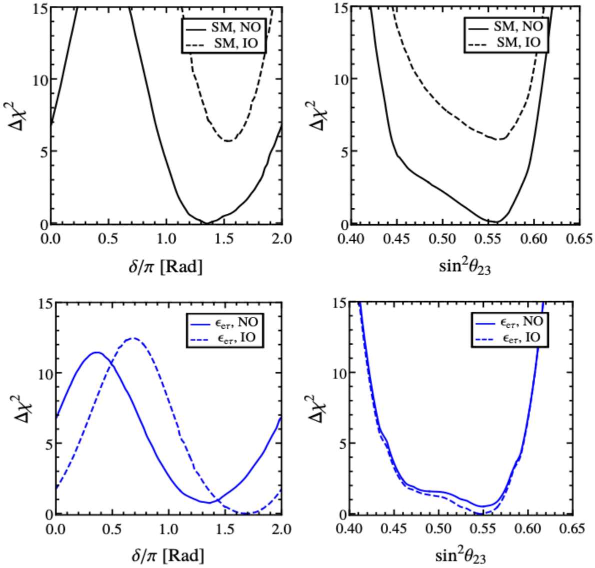
$$\sin 2\theta_M \equiv \frac{\Delta m^2 \sin 2\theta + 4EA\epsilon_{e\tau}}{\Delta m_M^2}$$

Modifies standard oscillation probabilities



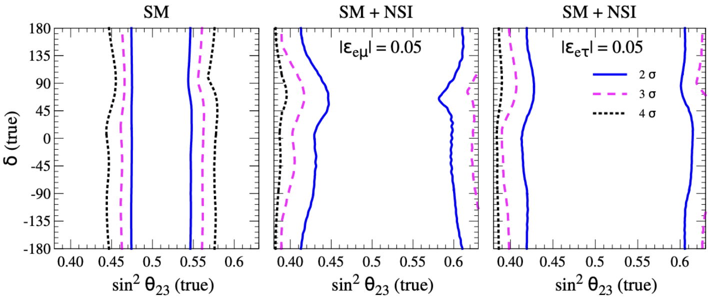
Using `NuProbe`

Can obscure mass-ordering determination



[Capozzi, Chatterjee, Palazzo 1908.06992 (PRL)]

Can degrade octant and δ_{CP} discovery potential



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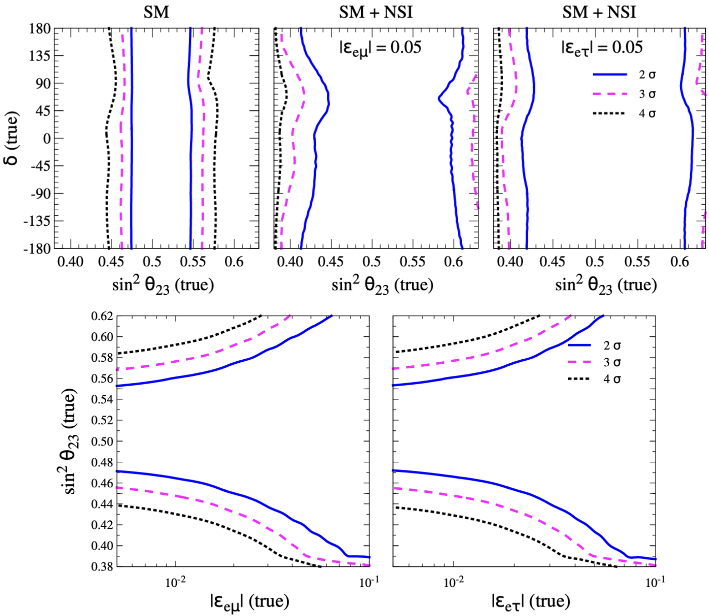


[Agarwalla, Chatterjee, Palazzo 1607.01745]

Charged Current NSI

[Y. Grossman, hep-ph/9507344]

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

- Flavor mixture states at source and detection.

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

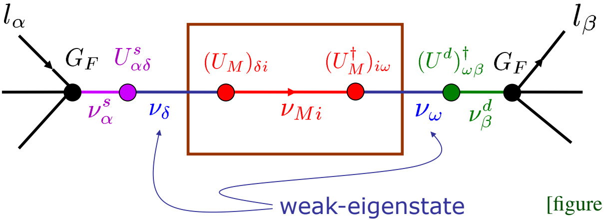
- **Source NSI** (e.g. in pion decay):

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

- **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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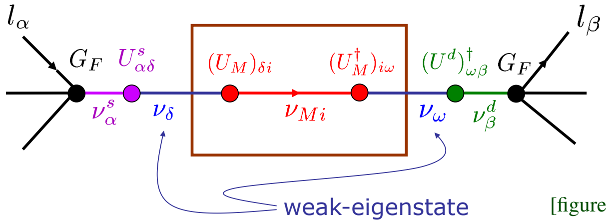

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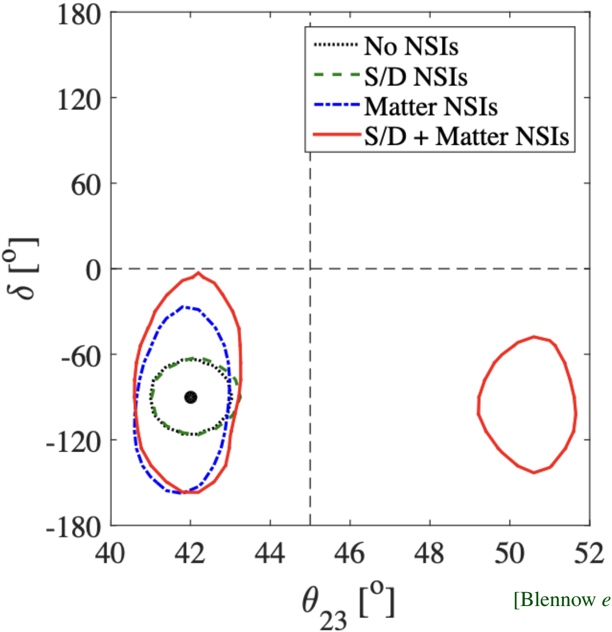
Zero-distance effect [Langacker, London (PRD '88)]

- 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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$\epsilon_{\tau\tau}^{eR}$	$[-0.98, 0.23]$ [-0.25, 0.43]	solar + KamLAND and Borexino reactor + accelerator
$\epsilon_{\tau\tau}^{eV}$	$[-0.11, 0.11]$	atmospheric

(Flavor-diagonal)

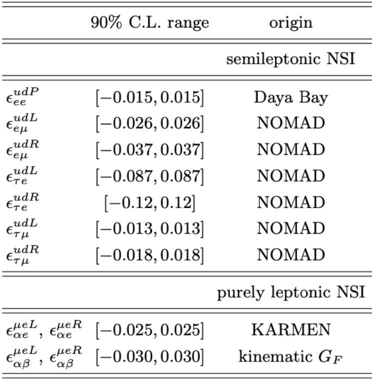
	90% C.L. range	origin
	NSI with quarks	
$\epsilon_{e\mu}^{qL}$	$[-0.023, 0.023]$	accelerator
$\epsilon_{e\mu}^{qR}$	$[-0.036, 0.036]$	accelerator
$\epsilon_{e\mu}^{uV}$	$[-0.073, 0.044]$	oscillation data + COHERENT
$\epsilon_{e\mu}^{dV}$	$[-0.07, 0.04]$	oscillation data + COHERENT
$\epsilon_{e\tau}^{qL}$, $\epsilon_{e\tau}^{qR}$	$[-0.5, 0.5]$	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 (one at a time, some constraints do not apply to light mediators)

Current Constraints* on CC NSI

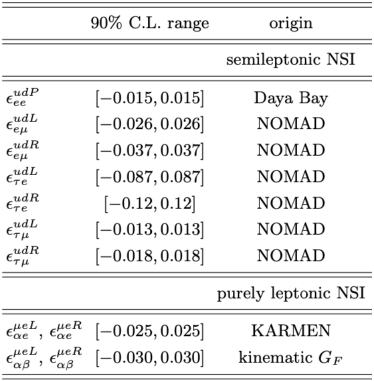
[Farzan, Tortola 1710.09360]



	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
$\epsilon_{\alpha e}^{\mu e L}$, $\epsilon_{\alpha e}^{\mu e R}$	$[-0.025, 0.025]$	KARMEN
$\epsilon_{\alpha\beta}^{\mu e L}$, $\epsilon_{\alpha\beta}^{\mu e R}$	$[-0.030, 0.030]$	kinematic G_F

Current Constraints* on CC NSI

[Farzan, Tortola 1710.09360]



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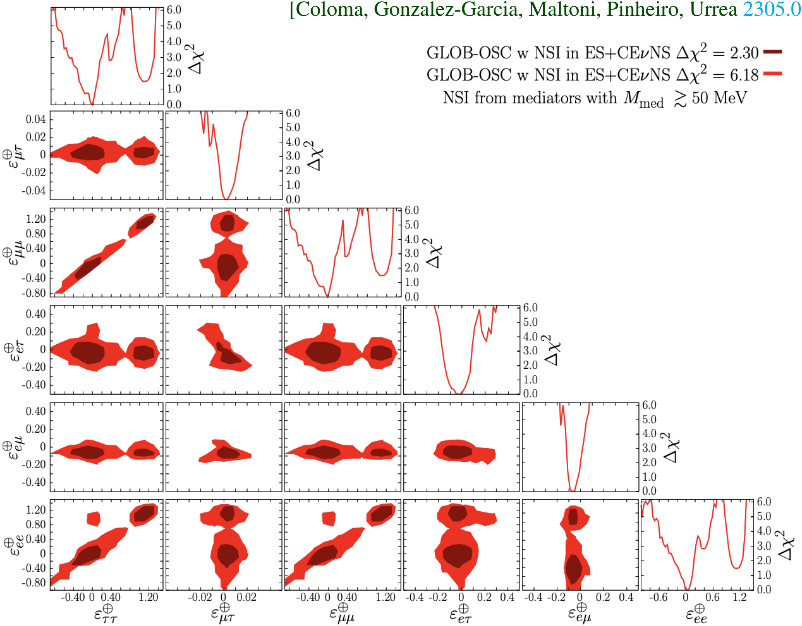
$\epsilon_{e\mu}^{udL}$	$[-0.026, 0.026]$	NOMAD
$\epsilon_{e\mu}^{udR}$	$[-0.037, 0.037]$	NOMAD
$\epsilon_{\tau e}^{udL}$	$[-0.087, 0.087]$	NOMAD
$\epsilon_{\tau e}^{udR}$	$[-0.12, 0.12]$	NOMAD
$\epsilon_{\tau\mu}^{udL}$	$[-0.013, 0.013]$	NOMAD
$\epsilon_{\tau\mu}^{udR}$	$[-0.018, 0.018]$	NOMAD
		purely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

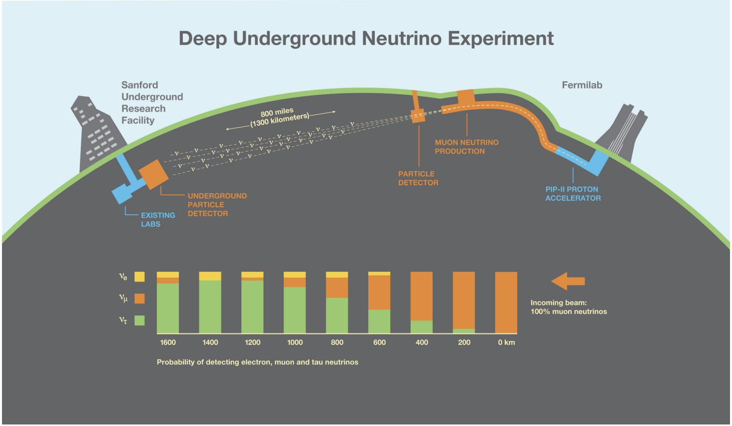
- From model-building perspective, getting ‘large’ CC NSI is more difficult than NC NSI.
- In some models (with purely leptonic NSI), CC and NC NSI are correlated by Fierz transformation.
- We will mostly focus on NC NSI (unless otherwise specified).

Global Fit

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



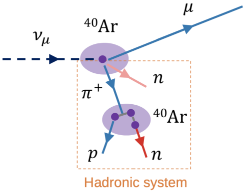
Future Prospects at DUNE



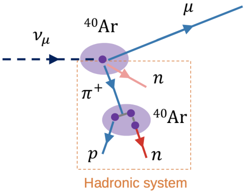
- Long baseline, huge statistics, intense & well-characterized beam.
- Excellent sensitivity to matter NSI.

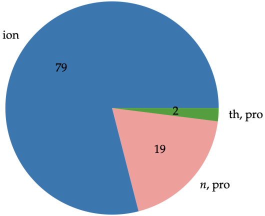
[de Gouvêa, Kelly 1511.05562; Coloma 1511.06357; Blennow *et al.* 1606.08851; Liao, Marfatia, Whisnant 1612.01443; Chatterjee *et al* 1809.09313; Han *et al* 1910.03272]

Improved Energy Resolution

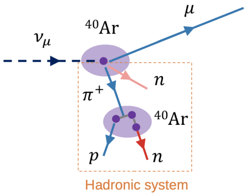


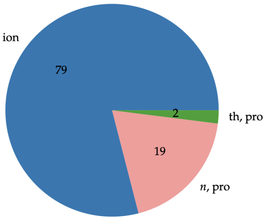
Improved Energy Resolution

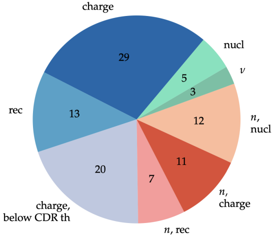




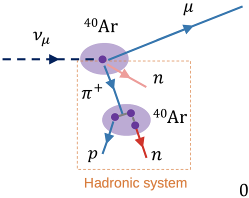
Improved Energy Resolution

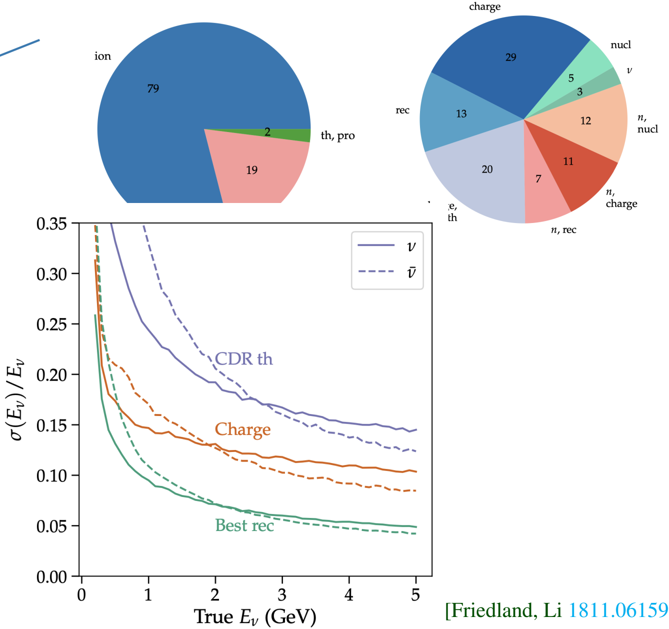






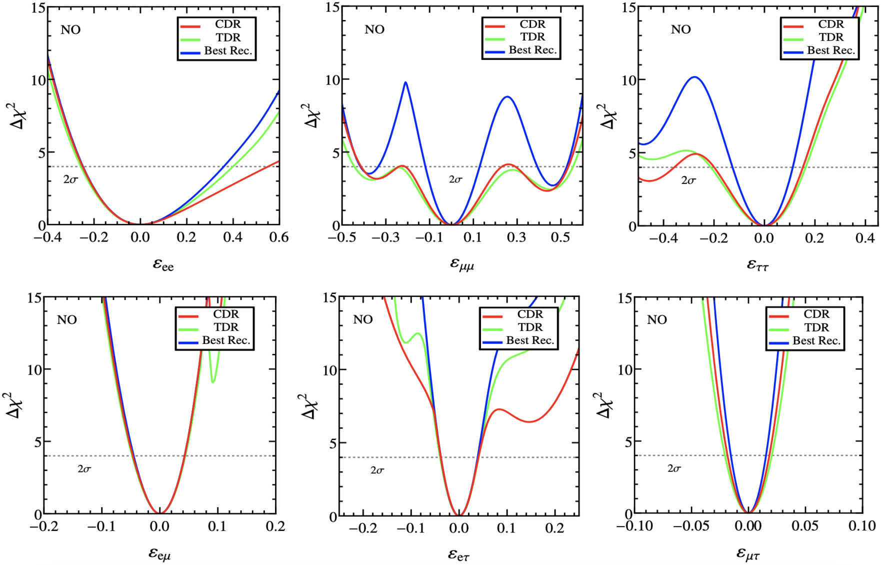
Improved Energy Resolution





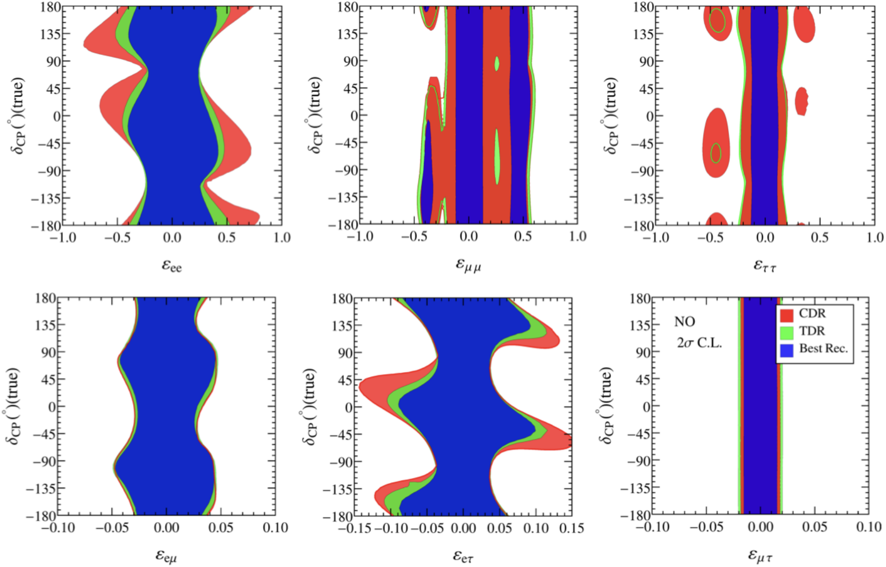
[Friedland, Li 1811.06159]

Improved DUNE Sensitivity to NSI



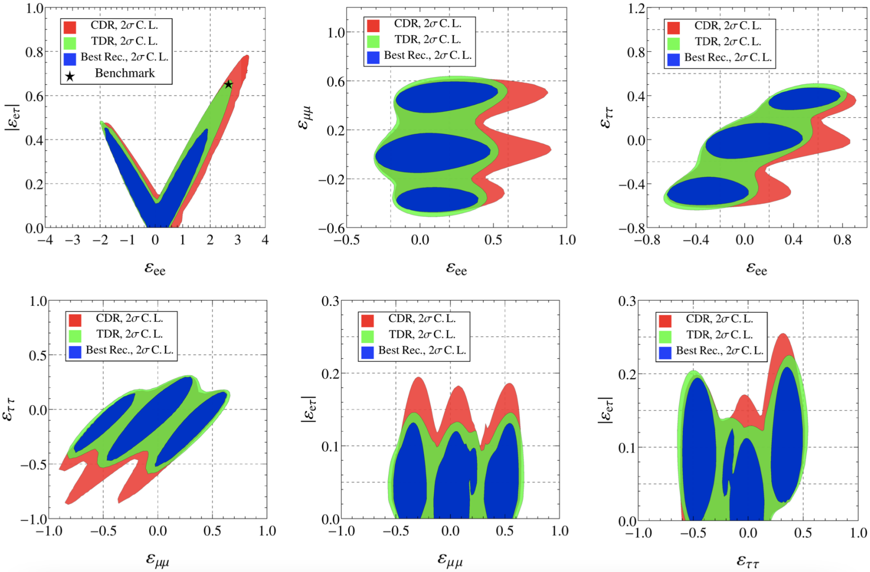
[Chatterjee, BD, Machado 2106.04597]

Dependence on $\delta_{\rm CP}$



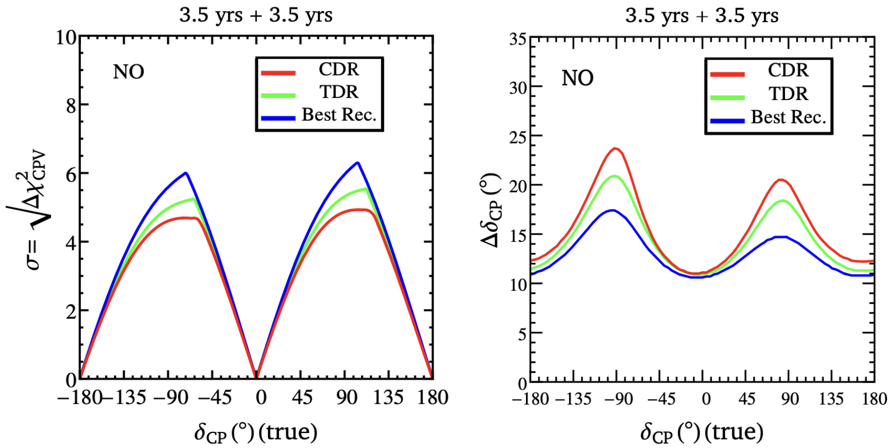
[Chatterjee, BD, Machado 2106.04597]

Breaking Degeneracies



[Chatterjee, BD, Machado 2106.04597]

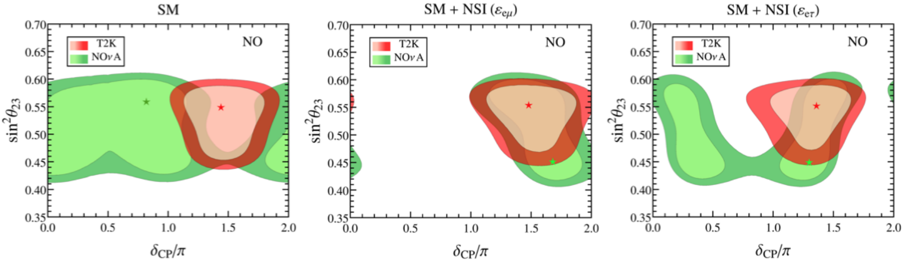
Improved δ_{CP} Sensitivity



[Chatterjee, BD, Machado 2106.04597;

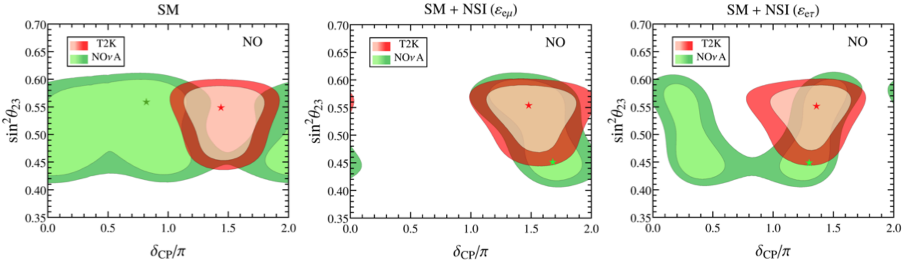
see also De Romeri, Fernandez-Martinez, Sorel, 1607.00293]

Hint of NSI?



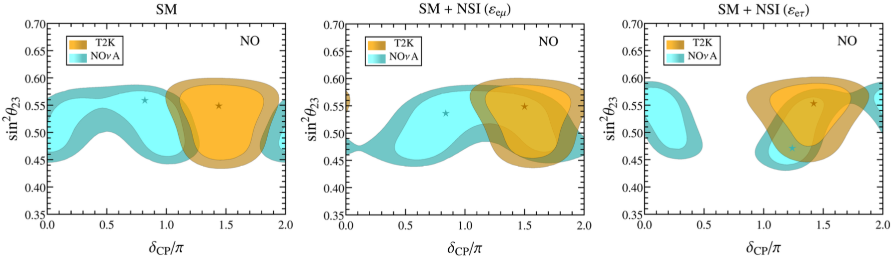
[Chatterjee, Palazzo 2008.04161 (PRL); see also Denton, Gehrlein, Pestes 2008.01110 (PRL)]

Hint of NSI?



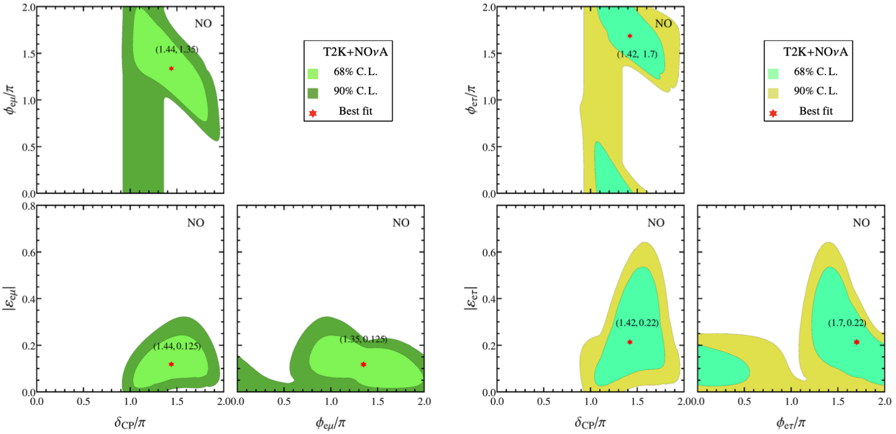
[Chatterjee, Palazzo 2008.04161 (PRL); see also Denton, Gehrlein, Pestes 2008.01110 (PRL)]

T2K-NOνA anomaly persists in 2024 data!



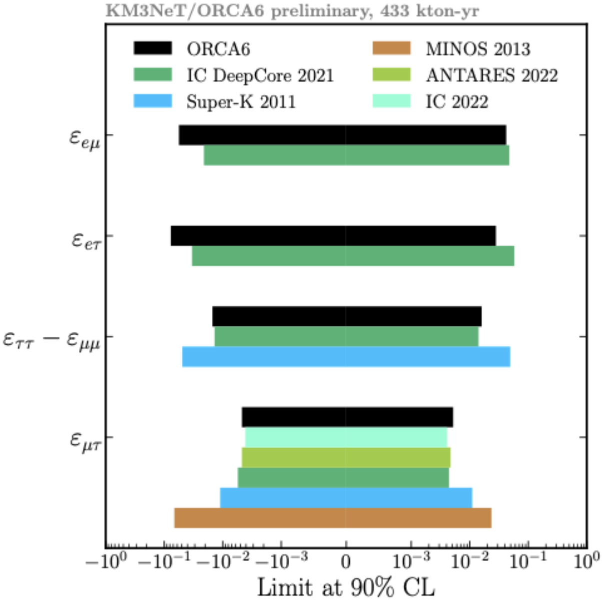
[Chatterjee, Palazzo 2409.10599]

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
  - Challenges
  - EFT approach
  - UV-completion
  - Heavy mediators
  - Light mediators
  - Loop-induced NSI
- **Lecture 3:** Beyond ε – Scalar NSI, NSSI, Neutrino-DM interactions, ...