Probing Neutrino Non-Standard Interactions in Dark Matter Direct Detection Experiments

MultiDark 2022

Dorian Amaral

May 24, 2022

New Neutrino Physics Is Among Us!

Neutrino Masses and NSIs

- Neutrino masses can be realised within SMEFT

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{d \geq 5} \frac{C_d}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$

- Neutrino masses naturally generated from the $d = 5$ Weinberg operator
- **But why stop there?**
- Neutrino non-standard interactions (NSIs) realised (to lowest order) at $d = 6$
- NSIs will impact neutrino oscillations and neutrino scattering processes! So...

The Ultimate Goal

We want to constrain how strong these NSIs are given observations at experiments sensitive to oscillation effects and scattering processes

Future xenon-based DD experiments will delve below the neutrino floor $\implies$ sensitivity to ν interactions

We want to incorporate them into global analyses with oscillation and COHERENT-like experiments

Outline

1. The NSI Framework: Present and Future
2. Probing NSIs at DD Experiments

The NSI Framework: Present and Future

NSIs: The Framework So Far...

We can parametrize neutrino (neutral current) NSIs through

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \overbrace{\left[\sum_{\alpha,\beta} \varepsilon^{\eta}_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right)\right]}^{\text{Neutrino Part}} \overbrace{\left[\sum_{f,P} \xi^{f,P} \left(\bar{f}\gamma_\mu P f\right)\right]}^{\text{Fermion Part}}$$

NSI framework **initially designed for ν-oscillation experiments**

ν-oscillation only affected by vector interactions, so convenient to define

$$\varepsilon^{f}_{\alpha\beta} \equiv \varepsilon^{\eta}_{\alpha\beta}\xi^{f} = \varepsilon^{\eta}_{\alpha\beta}(\xi^{f,L} + \xi^{f,R})$$

or

(Strength of NSI for fermion f) $\equiv$ (Inherent ν strength)$\times$(Projection onto fermion f)

NSIs: The Framework So Far...

Real matter composed of p, n, and e, so more convenient to project onto these (c.f. Ivan Esteban et al. **1805.04530**):

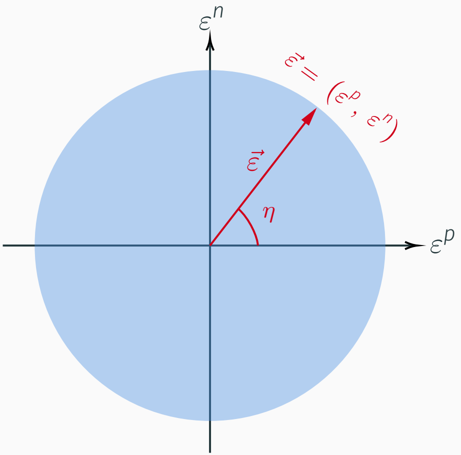
$$\varepsilon^p_{\alpha\beta} \sim \varepsilon^\eta_{\alpha\beta} \cos\eta$$
$$\varepsilon^n_{\alpha\beta} \sim \varepsilon^\eta_{\alpha\beta} \sin\eta$$

Where has the electron gone?

$$\mathcal{H}_{\text{matter}} \propto [\overbrace{(\varepsilon^p_{\alpha\beta} + \varepsilon^e_{\alpha\beta})}^{\text{Total Charged Contrib.}} + Y_n(x)\varepsilon^n_{\alpha\beta}]$$

Oscillations depend on **total** charged NSI

Assumed to be all in proton direction!



A Problem with the Present Framework

Problem: CEνNS and ν-e experiments *are* sensitive to ε^p and/or ε^e

- COHERENT-like experiments will be sensitive to CEνNS
- **Future DD experiments** will be sensitive to both CEνNS and ν-e

Therefore it is **crucial** for us to have a framework that describes all p, n, and e directions

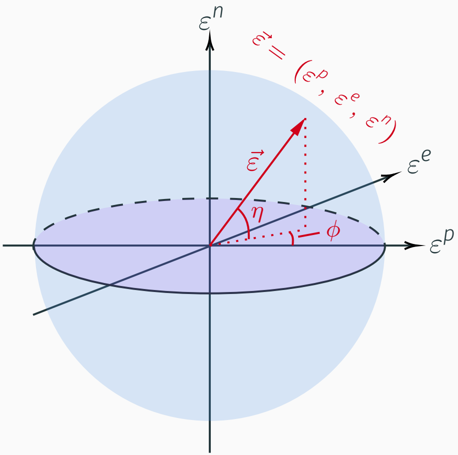
Extending the Parameter Space

We now have a more general vector:

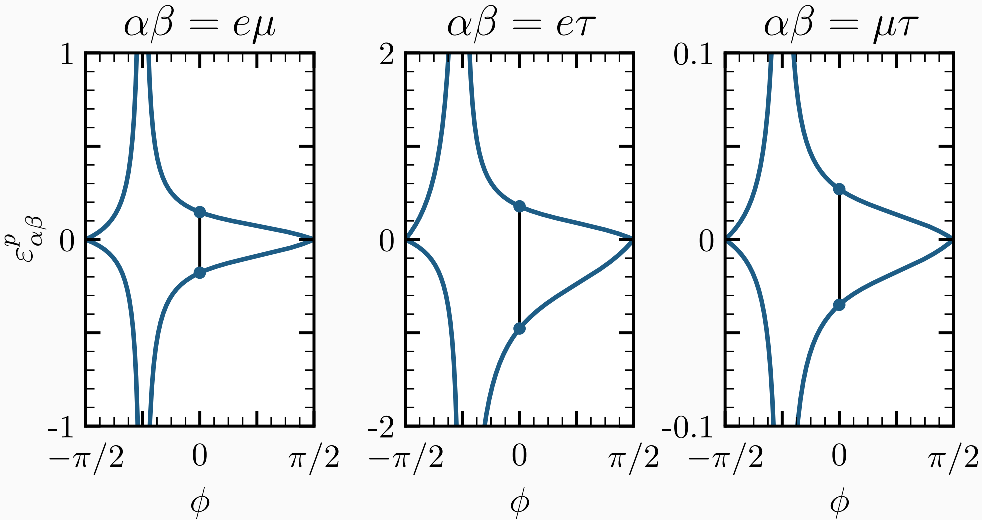
$$\varepsilon^{p}_{\alpha\beta} = \varepsilon^{\eta,\phi}_{\alpha\beta} \cos\eta \cos\phi$$
$$\varepsilon^{e}_{\alpha\beta} = \varepsilon^{\eta,\phi}_{\alpha\beta} \cos\eta \sin\phi$$
$$\varepsilon^{n}_{\alpha\beta} = \varepsilon^{\eta,\phi}_{\alpha\beta} \sin\eta$$

Within this new framework, we can ask the question:

How do bounds on $\varepsilon^{p}_{\alpha\beta}$ change if we now have that $\varepsilon^{e}_{\alpha\beta} \neq 0$, but ν-oscillation observations **unchanged**?



Updating NSI Constraints



Preliminary: DA, D. Cerdeño, A. Cheek, P. Foldenauer. 2206.XXXX

Probing NSIs at DD Experiments

Motivation

- We now have a framework that can incorporate all NSI directions
- Future DD experiments will be excellent probes of new neutrino physics as they delve beneath the neutrino floor.
- They will be sensitive to CEνNS, like COHERENT experiments $\implies$ ε^p and ε^n.
- But they will also be sensitive, **independently**, to ε^e (**new**!)

However: No means with which to easily incorporate DD experiments into global analyses of NSIs in tandem with oscillation and COHERENT experiments

Enter NuDD: Neutrinos at Direct Detection (Experiments)

NuDD is an in-development package that will be able to calculate the CEνNS and ν-e rates at DD experiments

Give **NuDD** an NSI matrix within this new framework ($\varepsilon_{\alpha\beta}^{\eta,\phi}$) and **NuDD** will give you:

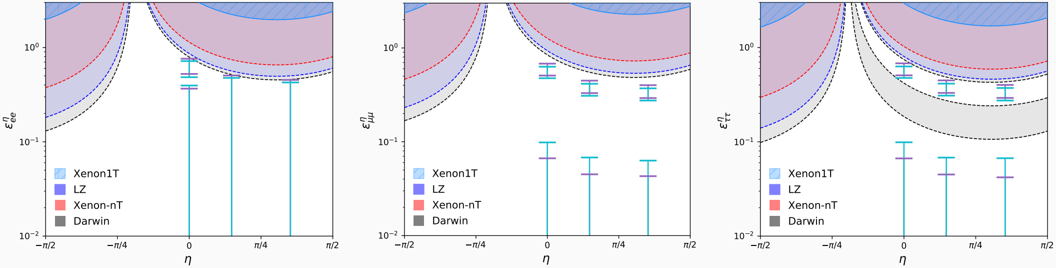
ν-Oscillation Probabilities

- $\varepsilon_{\alpha\beta} \implies$ change in $\mathcal{H}_{\mathrm{matter}}$
- **NuDD** calculates NSI-corrected ν-transition probabilities
- This advises $\rightarrow$

CEνNS and ν-e Rates

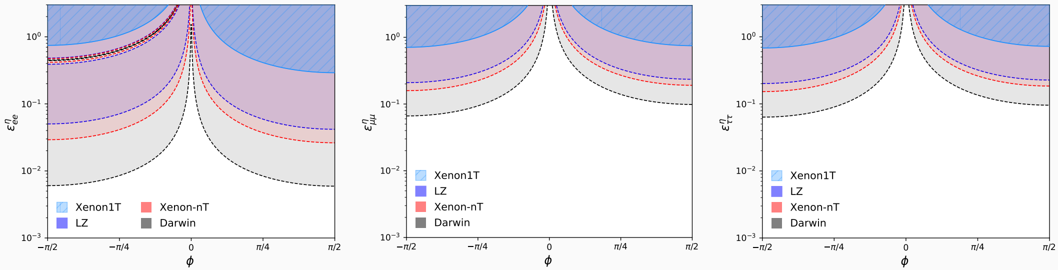
- $\varepsilon_{\alpha\beta} \implies$ change in $\mathrm{d}\sigma_\nu/\mathrm{d}E_R$
- After calculating prob. changes...
- **NuDD** calculates NSI-corrected ν scattering rates

Setting Limits with DD Experiments (Nuclear Recoils with $\phi = 0$)



Preliminary: DA, D. Cerdeño, A. Cheek, P. Foldenauer. 2206.XXXX

Setting Limits with DD Experiments (Electron Recoils with $\eta = 0$)



Preliminary: DA, D. Cerdeño, A. Cheek, P. Foldenauer. 2206.XXXX

Conclusions

- Present NSI framework catered to ν-oscillation experiments (throws away ε^e)
- We have developed an extended NSI framework that adds this back in, making it more suitable for:
  - COHERENT-like experiments
  - Future DD experiments
- We are developing **NuDD**: a package that will put DD experiments in the context of NSI analyses
- We have shown that DD experiments will be competitive in the NSI landscape

We have set the stage to help future DD experiments teach us about the nature of neutrino physics beyond the Standard Model!