New neutrino interactions: Theoretical motivation and experimental probes

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Cold Quantum Coffee, ITP

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Outline

1. Global picture of neutrino physics
2. General neutrino interactions
3. Experimental probes

1. Global picture of neutrino physics

Global picture of neutrino physics

Status Quo

- Consistent with three-flavor picture:
  - Mixing:

NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

  - Masses:

$$\Delta m^2_{21} = (6.80 \to 8.02) \times 10^{-5}\mathrm{eV}^2$$

$$\Delta m^2_{31} = (2.399 \to 2.593) \times 10^{-3}\mathrm{eV}^2$$

$$\sum m_i < 0.72\,\mathrm{eV} \quad \text{(95\%CL from } \textit{Planck} \text{ data (indirect))}$$

$$(m_{\nu_e} < 0.2\,\mathrm{eV} \quad \text{future 90\%CL KATRIN bound)}$$

[NuFIT 3.2; Esteban et al. 1611.01514], [PDG; Tanabashi et al. 2018]

Global picture of neutrino physics

Status Quo

- CP phase [NuFIT 3.2 (2018)]

$$\delta_{\mathrm{CP}} = (144 \to 374)^\circ$$

- Minor anomalies:
  - LSND/MiniBooNE: Short-baseline excess of ν_e hinting at fourth generation sterile mixing? In simplest ways inconsistent with global picture ...
  - Reactor anomalies: discrepancy between predicted and observed fluxes - new physics or errors in nuclear physics predictions?

[MiniBooNE; Aguilar-Arevalo et al. 1805.12028]
[Neutrino-4; Serebrov et al. 1809.10561]]

Global picture of neutrino physics

Open questions

- Mass ordering? (although normal ordering statistically preferred)
- Dirac or Majorana?
- CP phase δ_{CP} of the mixing matrix?
- Deep new physics reason explanation for small neutrino masses, likely connected with new interactions?
- 3+X generations of neutrinos?
  - Significant dark matter amount constituted by sterile neutrinos? ("warm" dark matter)
  - Baryogenesis via Leptogenesis?

$\Rightarrow$ Plenty of room for new physics in the neutrino sector

2. General neutrino interactions

General neutrino interactions

Steady sources of neutrinos

- Nuclear reactors $\sim 1\,\text{MeV}$
- The Sun $\sim 100\,\text{keV-MeV}$
- Accelerators $\sim$ GeV (p on target $\rightarrow \pi^{\pm}, K^{\pm}$, focus, inflight decay)
- Soon? Neutrino factory (μ decay)
- Cosmic rays scattering in the atmosphere $\sim$ GeV-TeV

Bursted sources of neutrinos

- Collapsing Supernovae (few second burst of thermal neutrinos)

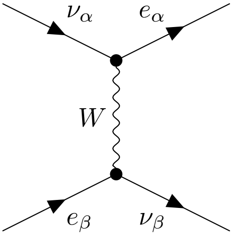
- Reactors and accelerators controllable & sources rather well understood
- Still neutrino flux determination major theoretical and experimental challenge
- Interesting approaches:
  - Choose observables which are not too sensitive to flux
  - Compare two observables which have approximately the same relative flux dependence, such that the flux cancels

- Both sources typically below the weak scale $\Rightarrow$ well-described by Fermi theory of effective interactions between four fermions

Standard neutrino interactions

Reactor and accelerator neutrinos

- Both sources typically below the weak scale $\Rightarrow$ well-described by Fermi theory of effective interactions between four fermions



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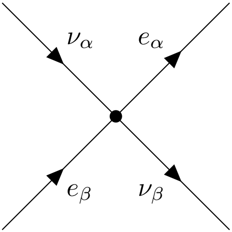


$$2\sqrt{2}G_F = \frac{g^2}{2m_W^2}$$

- Both sources typically below the weak scale $\Rightarrow$ well-described by Fermi theory of effective interactions between four fermions

Fermi Lagrangians (in flavor basis)

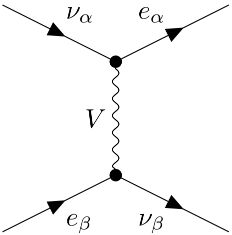
$$\mathcal{L}_{NC} = -2\sqrt{2} G_F \sum_{X=L,R} g_L^{\nu} \left(\overline{\nu}^{\alpha} \gamma^{\mu} P_L \nu^{\alpha}\right) g_X^{\psi} \left(\overline{\psi} \gamma_{\mu} P_X \psi\right)$$

$$\mathcal{L}_{CC}^{\ell} = -2\sqrt{2} G_F \left(\overline{e}^{\alpha} \gamma^{\mu} P_L \nu^{\alpha}\right) \left(\overline{e}^{\beta} \gamma_{\mu} P_L \nu^{\beta}\right)$$

$$\mathcal{L}_{CC}^{q} = -2\sqrt{2} G_F \left(\overline{e}^{\alpha} \gamma^{\mu} P_L \nu^{\alpha}\right) \left(\overline{u}^{\beta} \gamma_{\mu} P_L d^{\beta}\right)$$

Non-Standard neutrino interactions

- Idea: New high-energy physics may leave a similar trace like the "integrated out" W and Z bosons in the low-energy regime $\Rightarrow$ Non-Standard modifications with respect to Fermi theory



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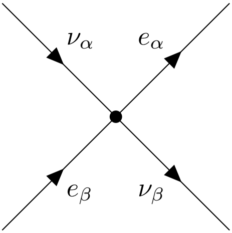


Interaction strength $\propto \frac{g_V^2}{m_V^2}$

Non-Standard neutrino interactions

- Idea: New high-energy physics may leave a similar trace like the "integrated out" W and Z bosons in the low-energy regime $\Rightarrow$ Non-Standard modifications with respect to Fermi theory

NSI Lagrangians (in flavor basis)

$$\mathcal{L}_{NC}^{\text{NSI}} = -2\sqrt{2}G_F \sum_{X=L,R} \epsilon_{\alpha\beta}^{\psi,X} \left(\overline{\nu}^{\alpha}\gamma^{\mu}P_L\nu^{\beta}\right)\left(\overline{\psi}\gamma_{\mu}P_X\psi\right)$$

$$\mathcal{L}_{CC}^{\text{NSI}} = -2\sqrt{2}G_F \sum_{X=L,R} \epsilon_{\alpha\beta}^{X} \left(\overline{e}^{\alpha}\gamma^{\mu}P_L\nu^{\beta}\right)\left(\overline{u}^{\gamma}\gamma_{\mu}P_X d^{\gamma}\right)$$

- $\epsilon \propto \frac{m_W^2}{m_{\text{NP}}^2}\frac{g_{\text{NP}}^2}{g^2}$?   current bounds $\sim 10^{-3} - 10^{-1}$ dep. on flavor

General neutrino interactions

- Idea: What is the most general four-fermion interaction Lagrangian if we admit right-handed neutrinos?

Five Lorentz-invariant Lagrangians constructed from four Dirac spinors ψ_i

$$\mathcal{L}^S(\psi_1,\psi_2,\psi_3,\psi_4) = \left(\overline{\psi}_1\psi_2\right)\left(\overline{\psi}_3\psi_4\right)\,,$$
$$\mathcal{L}^P(\psi_1,\psi_2,\psi_3,\psi_4) = \left(\overline{\psi}_1\gamma^5\psi_2\right)\left(\overline{\psi}_3\gamma^5\psi_4\right)\,,$$
$$\mathcal{L}^V(\psi_1,\psi_2,\psi_3,\psi_4) = \left(\overline{\psi}_1\gamma^\mu\psi_2\right)\left(\overline{\psi}_3\gamma_\mu\psi_4\right)\,,$$
$$\mathcal{L}^A(\psi_1,\psi_2,\psi_3,\psi_4) = \left(\overline{\psi}_1\gamma^\mu\gamma^5\psi_2\right)\left(\overline{\psi}_3\gamma_\mu\gamma^5\psi_4\right)\,,$$
$$\mathcal{L}^T(\psi_1,\psi_2,\psi_3,\psi_4) = \left(\overline{\psi}_1\sigma^{\mu\nu}\psi_2\right)\left(\overline{\psi}_3\sigma_{\mu\nu}\psi_4\right)\,,$$
$$\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu,\gamma^\nu]$$

General neutrino interactions

- Idea: What is the most general four-fermion interaction Lagrangian if we admit right-handed neutrinos?
- For chiral fields more restrictive, e.g. with two left-handed neutrinos and two identically charged fermions ψ_1, ψ_2

$$\begin{aligned}
S \quad & \quad \left(\overline{\nu}_L \psi_{1,R}\right)\left(\overline{\psi}_{2,R}\nu_L\right) \\
P \quad & = -\left(\overline{\nu}_L \gamma^5 \psi_{1,R}\right)\left(\overline{\psi}_{2,R}\gamma^5\nu_L\right) \\
V \quad & = -\frac{1}{2}\left(\overline{\nu}_L \gamma^\mu \nu_L\right)\left(\overline{\psi}_{2,R}\gamma_\mu\psi_{1,R}\right) \\
A \quad & = \frac{1}{2}\left(\overline{\nu}_L \gamma^\mu \gamma^5 \nu_L\right)\left(\overline{\psi}_{2,R}\gamma_\mu\gamma^5\psi_{1,R}\right) \\
\mathcal{L}^T & = 0
\end{aligned}$$

- Only one independent structure for right-chiral partners ψ_R
- Only V or A structure for left-chiral partners $\psi_L \Rightarrow$ NSI

General neutrino interactions

- Idea: What is the most general four-fermion interaction Lagrangian if we admit right-handed neutrinos (required by masses)?

GNI Lagrangians (in flavor basis)

$$\mathcal{L}_{NC}^{\mathrm{GNI}} = -\frac{G_F}{\sqrt{2}} \sum_{\alpha,\beta} \sum_{j=1}^{10} \left(\epsilon^{j,\psi}\right)_{\alpha\beta} \left(\overline{\nu}^{\alpha} \mathcal{O}_j \nu^{\beta}\right) \left(\overline{\psi} \mathcal{O}'_j \psi\right)$$

$$\mathcal{L}_{CC}^{\mathrm{GNI}} = -\frac{G_F}{\sqrt{2}} \sum_{\alpha,\beta} \sum_{j=1}^{10} \left(\epsilon^{j,\psi}\right)_{\alpha\beta} \left(\overline{e}^{\alpha} \mathcal{O}_j \nu^{\beta}\right) \left(\overline{u} \mathcal{O}'_j d\right)$$

- Ten parameters instead of two!

General neutrino interactions

j	$\overset{(\sim)}{\epsilon}_j$	$\mathcal{O}_j$	$\mathcal{O}'_j$
1	ϵ_L	$\gamma_\mu(\mathbb{1}-\gamma^5)$	$\gamma^\mu(\mathbb{1}-\gamma^5)$
2	$\tilde{\epsilon}_L$	$\gamma_\mu(\mathbb{1}+\gamma^5)$	$\gamma^\mu(\mathbb{1}-\gamma^5)$
3	ϵ_R	$\gamma_\mu(\mathbb{1}-\gamma^5)$	$\gamma^\mu(\mathbb{1}+\gamma^5)$
4	$\tilde{\epsilon}_R$	$\gamma_\mu(\mathbb{1}+\gamma^5)$	$\gamma^\mu(\mathbb{1}+\gamma^5)$
5	ϵ_S	$(\mathbb{1}-\gamma^5)$	$\mathbb{1}$
6	$\tilde{\epsilon}_S$	$(\mathbb{1}+\gamma^5)$	$\mathbb{1}$
7	$-\epsilon_P$	$(\mathbb{1}-\gamma^5)$	γ^5
8	$-\tilde{\epsilon}_P$	$(\mathbb{1}+\gamma^5)$	γ^5
9	ϵ_T	$\sigma_{\mu\nu}(\mathbb{1}-\gamma^5)$	$\sigma^{\mu\nu}(\mathbb{1}-\gamma^5)$
10	$\tilde{\epsilon}_T$	$\sigma_{\mu\nu}(\mathbb{1}+\gamma^5)$	$\sigma^{\mu\nu}(\mathbb{1}+\gamma^5)$

Type-II seesaw:

- Add scalar triplet to SM:

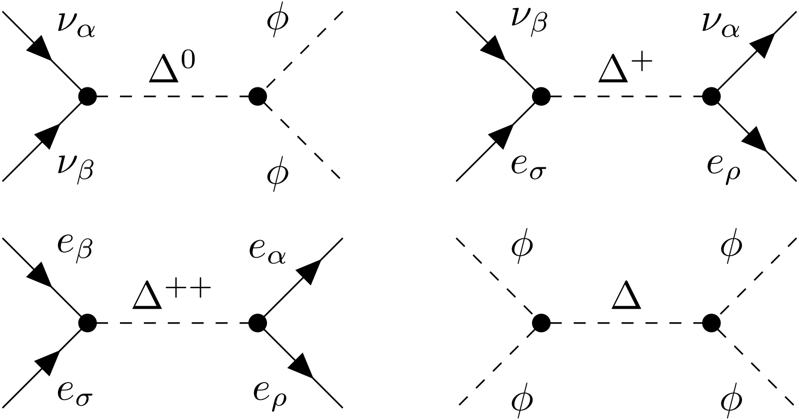
$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

- Yukawa couplings to lepton doublets
- Coupling to SM Higgs

General neutrino interactions

Some model examples

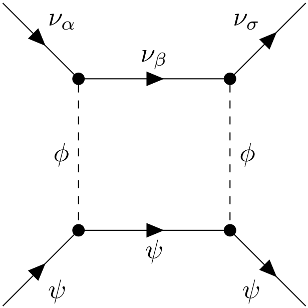
Type-II seesaw:



$|\epsilon| \lesssim 10^{-3}$ [Malinský et al. 0811.3346]

General neutrino interactions

Some model examples



Loop-induced NSI:

- E.g. neutral singlet scalar ϕ
- $\epsilon \propto \frac{m_W^2}{m_\phi^2} \frac{|y_\psi|^2 |y_\nu|^2}{g^2}$

[I.B., W. Rodejohann, X.-J. Xu 2018]

General neutrino interactions

Advantages:

- Model-independent parametrisation of new physics
- Indirect access to high energy scales $m/g = (\sqrt{2}/\epsilon\, G_F)^{1/2}$
- Experimentally accessible by cross section precision measurements
- Can potentially discriminate Dirac from Majorana nature of neutrinos
- Naturally arise in many BSM models (although often constrained to be small)

Differences to usual NSI:

- Needs RH neutrinos and can be L-violating

3. Experimental probes

Coherent elastic neutrino-nucleus scattering

- Neutrino scattering coherently with a nucleus in a weak neutral current
- Enhanced cross section $\sim N_n^2$ – but only for $E_\nu \lesssim 10\,\mathrm{MeV}$
- Rather recent because extremely low-threshold measurements (nuclear recoil $\sim$ keV)
- COHERENT (2017): Process first detected, neutrino-quark NSI $\lesssim 10^{-2}$
- CONUS results arriving soon

[COHERENT; Akimov et al. 1708.01294], [Denton et al. 1804.03660]

Neutrino oscillations

- In typical neutrino oscillaition experiments significant part of the baseline is in the Earth matter (T2K, DUNE)
- Matter NSI can mimmick the effect of CP violation in the mixing matrix
- Therefore important to have oscillation-independent probe

Neutrino oscillations

Neutrino interactions with matter influence the oscillation pattern: Evolution of transition amplitudes $A_{\alpha\beta}(x)$ over distance x governed by Schrödinger-like equation

$$i\frac{\mathrm{d}}{\mathrm{d}x}\begin{pmatrix}\mathcal{A}_{\alpha e}(x)\\ \mathcal{A}_{\alpha\mu}(x)\\ \mathcal{A}_{\alpha\tau}(x)\end{pmatrix} = \left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2/2E & 0\\ 0 & 0 & \Delta m_{31}^2/2E\end{pmatrix}U^\dagger + \sqrt{2}G_F N_e\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\mathcal{A}_{\alpha e}(x)\\ \mathcal{A}_{\alpha\mu}(x)\\ \mathcal{A}_{\alpha\tau}(x)\end{pmatrix}$$

- Exclusive CC forward scattering of electron neutrinos with electrons in matter
- Flavor transition probability

$$P_{\nu_\alpha\to\nu_\beta}(x) = |\mathcal{A}_{\alpha\beta}(x)|^2$$

Neutrino oscillations

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$$i\frac{\mathrm{d}}{\mathrm{d}x}\begin{pmatrix}\mathcal{A}_{\alpha e}(x)\\ \mathcal{A}_{\alpha\mu}(x)\\ \mathcal{A}_{\alpha\tau}(x)\end{pmatrix} =$$

$$\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2/2E & 0\\ 0 & 0 & \Delta m_{31}^2/2E\end{pmatrix}U^\dagger + \sqrt{2}G_F N_e\begin{pmatrix}1+\epsilon_{ee}^V & \epsilon_{e\mu}^V & \epsilon_{e\tau}^V\\ \epsilon_{\mu e}^V & \epsilon_{\mu\mu}^V & \epsilon_{\mu\tau}^V\\ \epsilon_{\tau e}^V & \epsilon_{\tau\mu}^V & \epsilon_{\tau\tau}^V\end{pmatrix}\right]\begin{pmatrix}\mathcal{A}_{\alpha e}(x)\\ \mathcal{A}_{\alpha\mu}(x)\\ \mathcal{A}_{\alpha\tau}(x)\end{pmatrix}$$

- Exclusive CC forward scattering of electron neutrinos with electrons in matter can be accompanied by NSI, $\epsilon^V = \epsilon^L + \epsilon^R$

- Flavor transition probability

$$P_{\nu_\alpha\to\nu_\beta}(x) = |\mathcal{A}_{\alpha\beta}(x)|^2$$

Deep Underground Neutrino Experiment

- High-intensity neutrino beam produced at Fermilab (Illinois)
- Near detector 575 m from target, tentatively 84t liquid argon time projection chamber
- Far detector 1300 km from target at Sanford Lab (South Dakota), 40kt liquid argon time projection chamber

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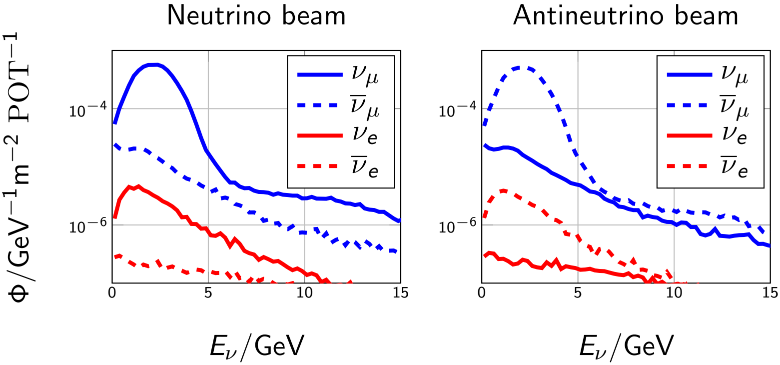
Primary physics goals

- Test CP violation in the lepton sector via oscillations
- Determine neutrino mass ordering
- Study neutrinos from supernovae, neutron star or black hole formation

Neutrino-electron scattering at the DUNE near detector

Neutrino fluxes



Flux normalisation uncertainty at percent level $\Rightarrow$ fit must not be too sensitive

[DUNE; T. Alion et al. 1606.09550]

Neutrino-electron scattering at the DUNE near detector

Idea: Most abundand leptonic scattering $\nu_\mu + e \to \nu_\beta + e$
What is the sensitivity of DUNE ND to new physics from this process?

- Assume 84t liquid argon
- Measure recoiled electrons incl. kinetic energy

The general interaction Lagrangian

$$\mathcal{L}^{\mathrm{GNI}} = -\frac{G_F}{\sqrt{2}} \sum_{\alpha,\beta} \sum_{j=1}^{10} \left(\epsilon^j\right)_{\alpha\beta} \left(\overline{\nu}^\alpha \mathcal{O}_j \nu^\beta\right) \left(\overline{e} \mathcal{O}'_j e\right)$$

[I.B., W. Rodejohann 1810.02220]

Neutrino-electron scattering at the DUNE near detector

Differential cross section

$$\frac{\mathrm{d}\sigma_{\nu_\mu \to \nu_\beta}}{\mathrm{d}T} = \frac{G_F^2 m_e}{\pi}\left[A + 2B\left(1 - \frac{T}{E_\nu}\right) + C\left(1 - \frac{T}{E_\nu}\right)^2 + D\frac{m_e T}{E_\nu^2}\right]$$

$$\frac{\mathrm{d}\sigma_{\overline{\nu}_\mu \to \overline{\nu}_\beta}}{\mathrm{d}T} = \frac{G_F^2 m_e}{\pi}\left[C + 2B\left(1 - \frac{T}{E_\nu}\right) + A\left(1 - \frac{T}{E_\nu}\right)^2 + D\frac{m_e T}{E_\nu^2}\right]$$

$E_\nu \gg m_e$: energy of the incoming (anti)neutrino
T: kinetic energy of the recoiled electron

$$A_{\mathrm{SM}} = 2g_L^2\delta_{\mu\beta}\,, \quad B_{\mathrm{SM}} = 0\,, \quad C_{\mathrm{SM}} = 2g_R^2\delta_{\mu\beta}\,, \quad D_{\mathrm{SM}} = -2g_L g_R\delta_{\mu\beta}$$

Neutrino-electron scattering at the DUNE near detector

Differential cross section

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$$\frac{\mathrm{d}\sigma_{\overline{\nu}_\mu\to\overline{\nu}_\beta}}{\mathrm{d}T} = \frac{G_F^2 m_e}{\pi}\left[C + 2B\left(1-\frac{T}{E_\nu}\right) + A\left(1-\frac{T}{E_\nu}\right)^2 + D\frac{m_e T}{E_\nu^2}\right]$$

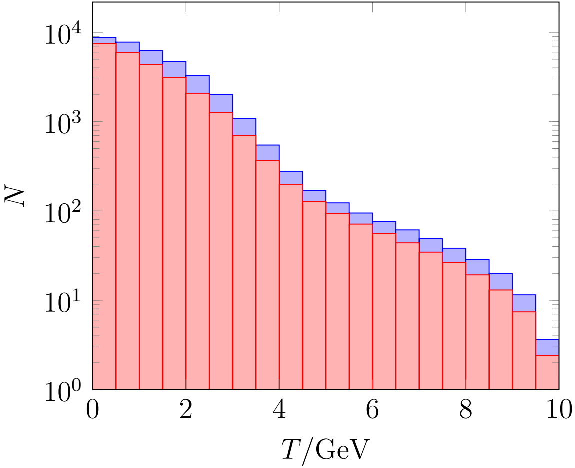
$E_\nu \gg m_e$: energy of the incoming (anti)neutrino
T: kinetic energy of the recoiled electron

$$A = 2(\epsilon^L_{\mu\beta})^2 + \frac{1}{4}(|\epsilon^S_{\mu\beta}|^2 + |\epsilon^P_{\mu\beta}|^2) + 8|\epsilon^T_{\mu\beta}|^2 - 2\mathrm{Re}\left((\epsilon^S+\epsilon^P)_{\mu\beta}\epsilon^{T*}_{\mu\beta}\right)$$

$$C = 2(\epsilon^R_{\mu\beta})^2 + \frac{1}{4}(|\epsilon^S_{\mu\beta}|^2 + |\epsilon^P_{\mu\beta}|^2) + 8|\epsilon^T_{\mu\beta}|^2 + 2\mathrm{Re}\left((\epsilon^S+\epsilon^P)_{\mu\beta}\epsilon^{T*}_{\mu\beta}\right)$$

Neutrino-electron scattering at the DUNE near detector

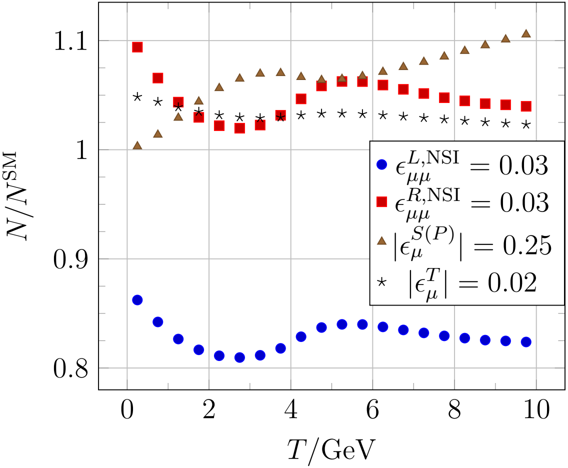
Expected recoil spectra in the SM and in presence of GNI



Expected event numbers in 2.5+2.5 years of operation.
(Anti)neutrino channel in blue (red).

Neutrino-electron scattering at the DUNE near detector

Expected recoil spectra in the SM and in presence of GNI



Spectral distortions good way to distinguish new interactions (less flux normalisation sensitivity)

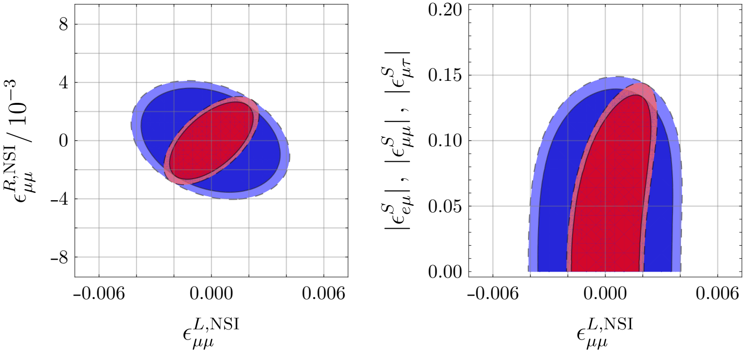
Neutrino-electron scattering at the DUNE near detector

Expected bounds at 1% flux normalisation uncertainty

Observ.	NP Param.	Proj. DUNE	CHARM-II	$\frac{M}{g'}$ [TeV]
$\epsilon_{\mu\mu}^{L,\mathrm{NSI}}$	$\epsilon_{\mu\mu}^{L,\mathrm{NSI}}$	± 0.0028	$[-0.06, 0.02]$	6.7
$\epsilon_{\mu}^{L,\mathrm{NSI}}$	$\lvert\epsilon_{e\mu}^{L,\mathrm{NSI}}\rvert$, $\lvert\epsilon_{\mu\tau}^{L,\mathrm{NSI}}\rvert$	0.039		1.8
$\epsilon_{\mu\mu}^{R,\mathrm{NSI}}$	$\epsilon_{\mu\mu}^{R,\mathrm{NSI}}$	± 0.0027	$[-0.06, 0.02]$	6.8
$\epsilon_{\mu}^{R,\mathrm{NSI}}$	$\lvert\epsilon_{e\mu}^{R,\mathrm{NSI}}\rvert$, $\lvert\epsilon_{\mu\tau}^{R,\mathrm{NSI}}\rvert$	0.035		1.9
ϵ_{μ}^{S}	$\lvert\epsilon_{e\mu}^{S}\rvert$, $\lvert\epsilon_{\mu\mu}^{S}\rvert$, $\lvert\epsilon_{\mu\tau}^{S}\rvert$	0.12	0.4	1.0
ϵ_{μ}^{P}	$\lvert\epsilon_{e\mu}^{P}\rvert$, $\lvert\epsilon_{\mu\mu}^{P}\rvert$, $\lvert\epsilon_{\mu\tau}^{P}\rvert$	0.12	0.4	1.0
ϵ_{μ}^{T}	$\lvert\epsilon_{e\mu}^{T}\rvert$, $\lvert\epsilon_{\mu\mu}^{T}\rvert$, $\lvert\epsilon_{\mu\tau}^{T}\rvert$	0.012	0.04	3.1

Neutrino-electron scattering at the DUNE near detector

Expected bounds at 1%(0%) flux normalisation uncertainty in blue (red)



Conclusion

- Improved bounds up to one order of magnitude
- Spectral information helps distinguish different new physics effects while being not very sensitive to flux normalisation
- Scales up to 7 TeV indirecly accessible
- Complementary bounds on matter NSI to support the robustness of the determination of δ_{CP} from ν-oscillation

[I.B., W. Rodejohann 1810.02220]

Thank you!

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