New neutrino interactions: Theoretical motivation and experimental probes

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Max-Planck-Institut für Kernphysik Heidelberg

International Max Planck Research School

PT FS For Precision Tests of Fundamental Symmetries

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:

$$\Delta m^2_{21} = (6.80 \to 8.02) \times 10^{-5}\,\text{eV}^2$$
$$\Delta m^2_{31} = (2.399 \to 2.593) \times 10^{-3}\,\text{eV}^2$$
$$\sum m_i < 0.72\,\text{eV} \quad \text{(95\%CL from } \textit{Planck} \text{ data (indirect))}$$
$$(m_{\nu_e} < 0.2\,\text{eV} \quad \text{future 90\%CL KATRIN bound})$$

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

Global picture of neutrino physics

Open questions

- Mass ordering? (although normal ordering preferred)
- Dirac or Majorana?
- CP phase δ_{CP} of the mixing matrix?
  $\delta_{\mathrm{CP}}^{3\sigma} = (125 \to 392)^\circ$ [NuFIT 4.0; Esteban et al. 1811.05487]
- 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 $\sim 1\,\mathrm{MeV}$
- The Sun $\sim 100\,\mathrm{keV}$-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)

Standard neutrino interactions

Reactor and accelerator 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

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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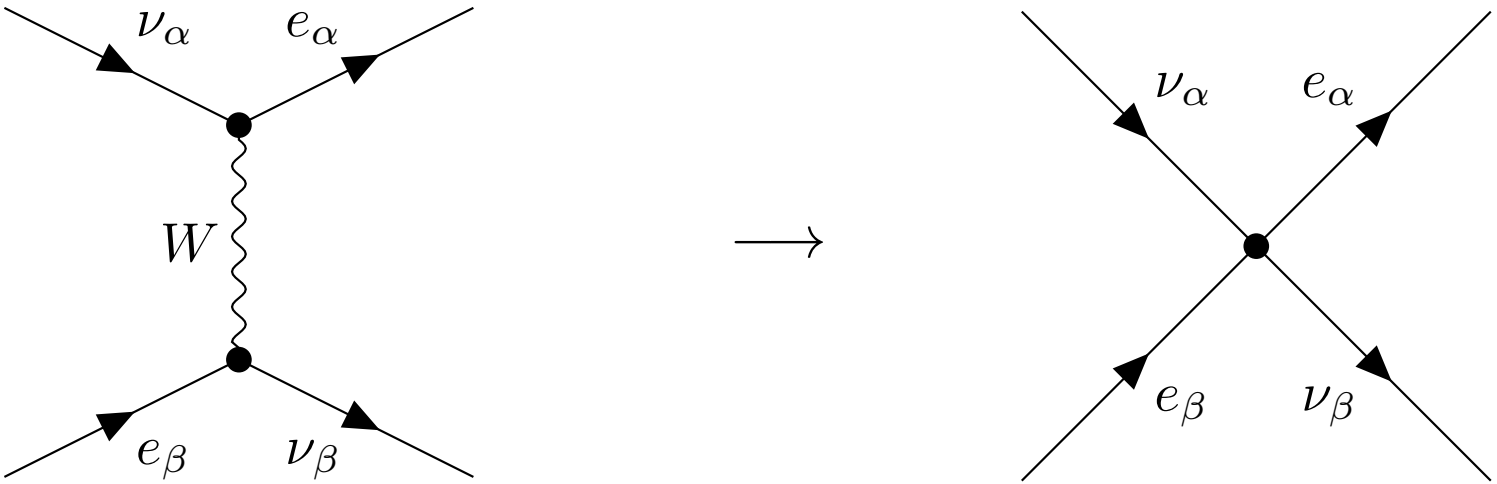


$$2\sqrt{2}G_F = \frac{g^2}{2m_W^2}$$

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

Fermi Lagrangians (in flavor basis)

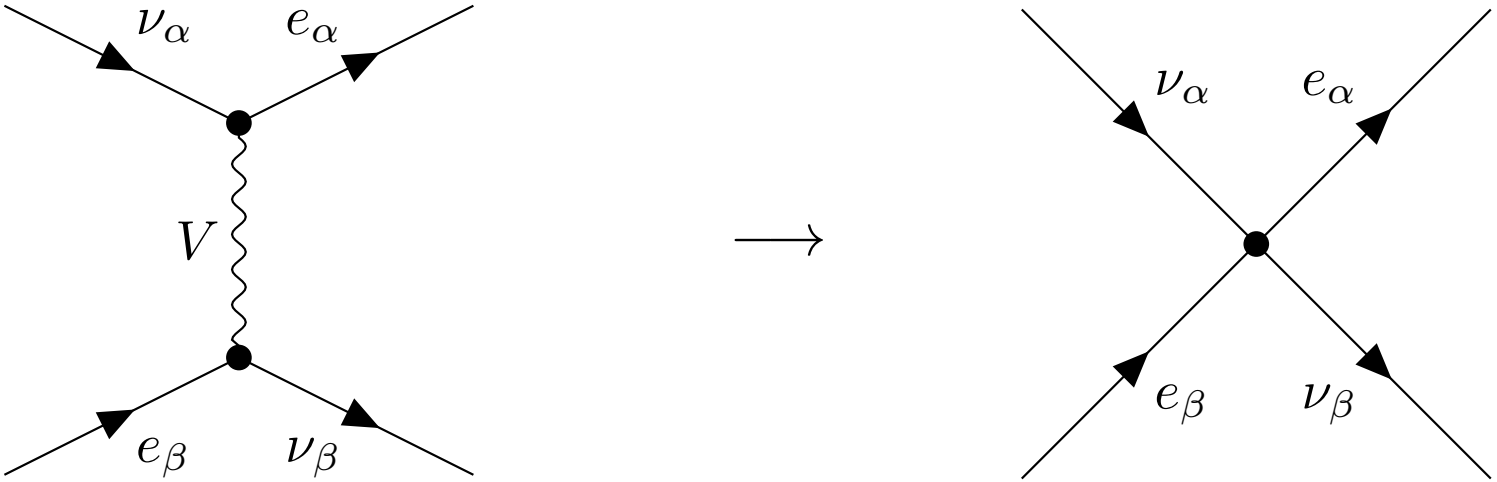
$$\mathcal{L}_{NC} = -2\sqrt{2}G_F \sum_{X=L,R} g_L^{\nu} \left(\overline{\nu}^{\alpha}\gamma^{\mu}P_L\nu^{\alpha}\right) g_X^{\psi} \left(\overline{\psi}\gamma_{\mu}P_X\psi\right)$$

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

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

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



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

Non-Standard neutrino interactions

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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?

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Five Lorentz-invariant Lagrangians constructed from four Dirac spinors ψ_i

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

General neutrino interactions

- Reformulate in terms of definite chiralities:

Five Lorentz-invariant Lagrangians constructed from four Dirac spinors ψ_i

$$\mathcal{L}^S_{XY}(\psi_1,\psi_2,\psi_3,\psi_4) = \left(\overline{\psi}_1 P_X \psi_2\right)\left(\overline{\psi}_3 P_Y \psi_4\right)$$
$$\mathcal{L}^V_{XY}(\psi_1,\psi_2,\psi_3,\psi_4) = \left(\overline{\psi}_1 \gamma^\mu P_X \psi_2\right)\left(\overline{\psi}_3 \gamma_\mu P_Y \psi_4\right)$$
$$\mathcal{L}^T_{X}(\psi_1,\psi_2,\psi_3,\psi_4) = \left(\overline{\psi}_1 \sigma^{\mu\nu} P_X \psi_2\right)\left(\overline{\psi}_3 \sigma_{\mu\nu} P_X \psi_4\right)$$
$$X, Y = L, R$$

$\Rightarrow$ in principle 10 indep. interaction terms for chiral fermions

General neutrino interactions

- Reformulate in terms of definite chiralities:

Five Lorentz-invariant Lagrangians constructed from four Dirac spinors ψ_i

$$\mathcal{L}^S_{LY}(\psi_1, \nu_L, \psi_3, \psi_4) = \left(\overline{\psi}_1 P_L \nu_L\right)\left(\overline{\psi}_3 P_Y \psi_4\right)$$

$$\text{NSI: } \mathcal{L}^V_{LY}(\psi_1, \nu_L, \psi_3, \psi_4) = \left(\overline{\psi}_1 \gamma^\mu P_L \nu_L\right)\left(\overline{\psi}_3 \gamma_\mu P_Y \psi_4\right)$$

$$\mathcal{L}^T_L(\psi_1, \psi_2, \psi_3, \psi_4) = \left(\overline{\psi}_1 \sigma^{\mu\nu} P_L \nu_L\right)\left(\overline{\psi}_3 \sigma_{\mu\nu} P_L \psi_4\right)$$

$$X, Y = L, R$$

$\Rightarrow$ in principle 10 indep. interaction terms for chiral fermions

General neutrino interactions

- Reformulate in terms of definite chiralities:

Five Lorentz-invariant Lagrangians constructed from four Dirac spinors ψ_i

$$\mathcal{L}_{LY}^{S}\left(\nu_L, \nu_L, \psi_3, \psi_4\right) = \left(\overline{\nu}_L P_L \nu_L\right)\left(\overline{\psi}_3 P_Y \psi_4\right) = 0$$

$$\text{NSI: } \mathcal{L}_{LY}^{V}\left(\nu_L, \nu_L, \psi_3, \psi_4\right) = \left(\overline{\nu}_L \gamma^\mu P_L \nu_L\right)\left(\overline{\psi}_3 \gamma_\mu P_Y \psi_4\right)$$

$$\mathcal{L}_{L}^{T}\left(\nu_L, \nu_L, \psi_3, \psi_4\right) = \left(\overline{\nu}_L \sigma^{\mu\nu} P_L \nu_L\right)\left(\overline{\psi}_3 \sigma_{\mu\nu} P_L \psi_4\right) = 0$$

$$Y = L, R$$

$\Rightarrow$ in principle 10 indep. interaction terms for chiral fermions

General neutrino interactions

- Considering left-handed and right-handed neutrinos, the general four-fermion interaction Lagrangians can be parametrised as

GNI Lagrangians (in flavor basis)

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

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

- Ten ϵ-parameters instead of two!
- Remark: Parametrisation not unique, but convenient

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	$\tilde{\epsilon}_T$	$\sigma_{\mu\nu}(\mathbb{1}+\gamma^5)$	$\sigma^{\mu\nu}(\mathbb{1}+\gamma^5)$

General neutrino interactions

Sub-Conclusion

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 [Rosen PRL48 1982], [Rodejohann et al. 1702.05721]
- Naturally arise in many BSM models (although often constrained to be small)

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Differences of (pseudo)scalar and tensor interactions to usual NSI:

- Needs RH neutrinos and can be L-violating
- Scalar and tensor interactions may produce a large neutrino magnetic moment [Xu 1901.00482]

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 in the making

[COHERENT; Akimov et al. 1708.01294], [Papoulias et al. 1711.09773], [Denton et al. 1804.03660], [Aristizabal Sierra et al. 1806.07424]

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$\longrightarrow$ Previous talk by Janina

Neutrino oscillations

- To extract the CP phase one typically compares e.g. survival rate of neutrinos vs. antineutrinos
- In typical long-baseline neutrino oscillation experiments, the trajectory is in 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

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

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

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

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

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- 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

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

Neutrino-electron scattering at the DUNE near detector

The DUNE experiment

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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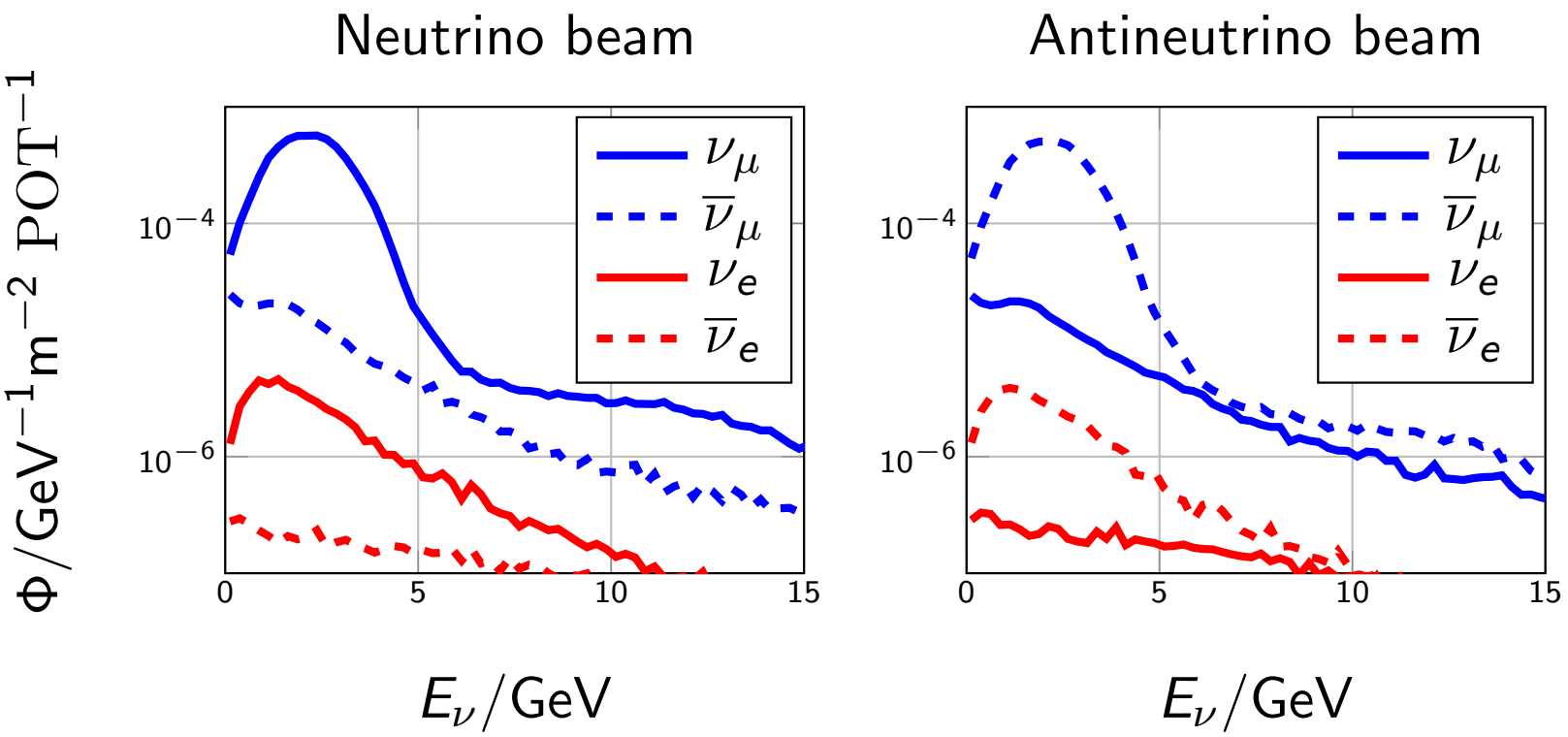
Primary physics goals

- 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 ⇒ fit must not be too sensitive

[DUNE; T. Alion et al. 1606.09550]

Neutrino-electron scattering at the DUNE near detector

Ideas [I.B., W. Rodejohann 1810.02220]:
1. What can we do with only the Near Detector and the high-intensity beam?
2. Most abundand leptonic scattering $\nu_\mu + e \to \nu_\beta + e$
What is the sensitivity of DUNE ND to new physics from this process? [Falkowski et al. 1802.08296]
3. Matter NSI are known to affect the measurement of δ_{CP}. Can we constrain them independently to support the measurement?

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The general interaction Lagrangian

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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

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$E_\nu \gg m_e$: 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

Observable parameters

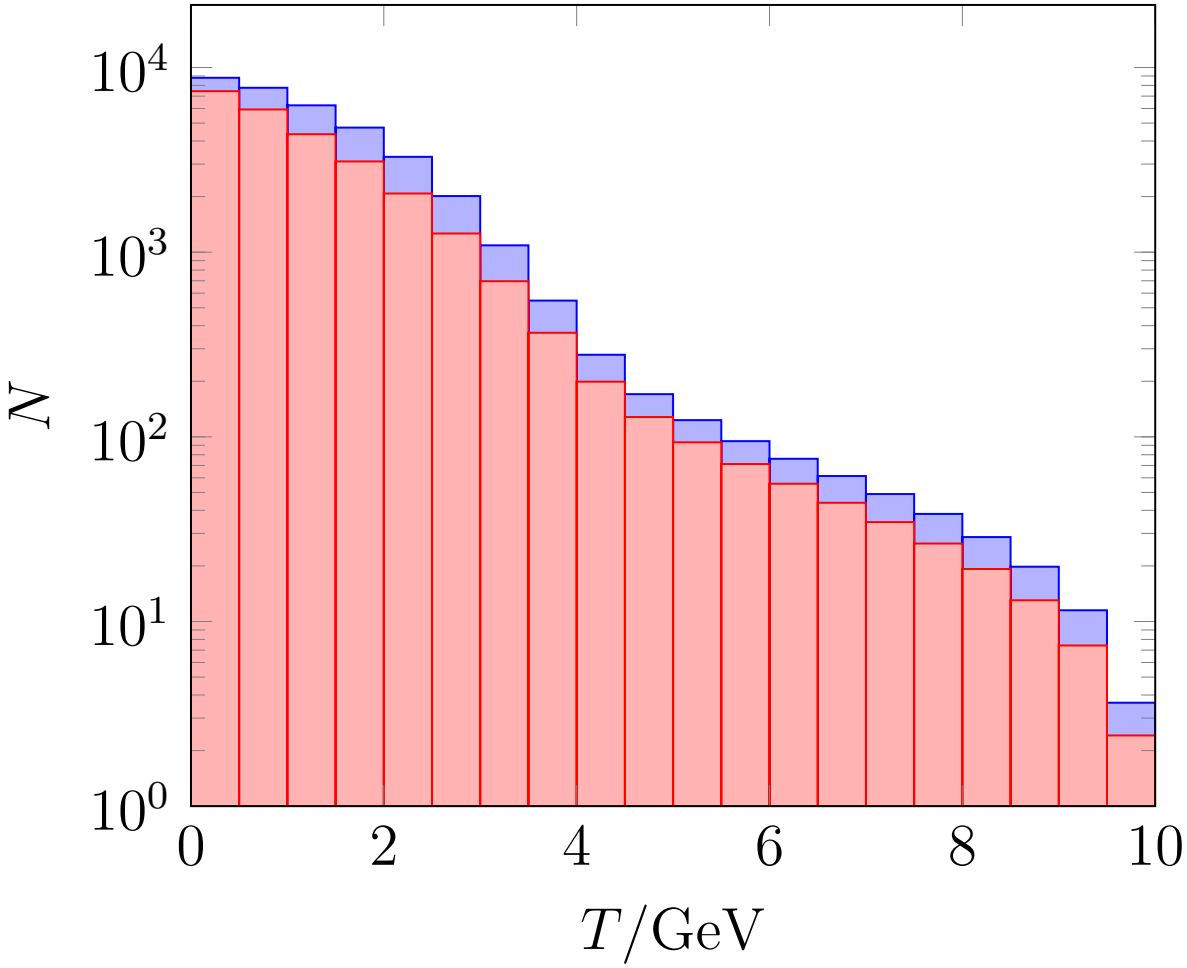
Considering the sum over all final neutrino flavors: 7 Observables

Obs.	$\epsilon_{\mu\mu}^{L/R,\mathrm{NSI}}$	$\lvert\epsilon_{\mu}^{L/R,\mathrm{NSI}}\rvert$	$\lvert\epsilon_{\mu}^{S/P/T}\rvert$
GNI	$\epsilon_{\mu\mu}^{L/R,\mathrm{NSI}}$	$\lvert\epsilon_{\mu e}^{L/R,\mathrm{NSI}}\rvert$, $\lvert\epsilon_{\mu\tau}^{L/R,\mathrm{NSI}}\rvert$	$\lvert\epsilon_{\mu e}^{S/P/T}\rvert$, $\lvert\epsilon_{\mu\mu}^{S/P/T}\rvert$, $\lvert\epsilon_{\mu\tau}^{S/P/T}\rvert$

- 4 NSI and 3 exotic
- Reduces to 6 if we consider that S and P are indistinguishable

Neutrino-electron scattering at the DUNE near detector

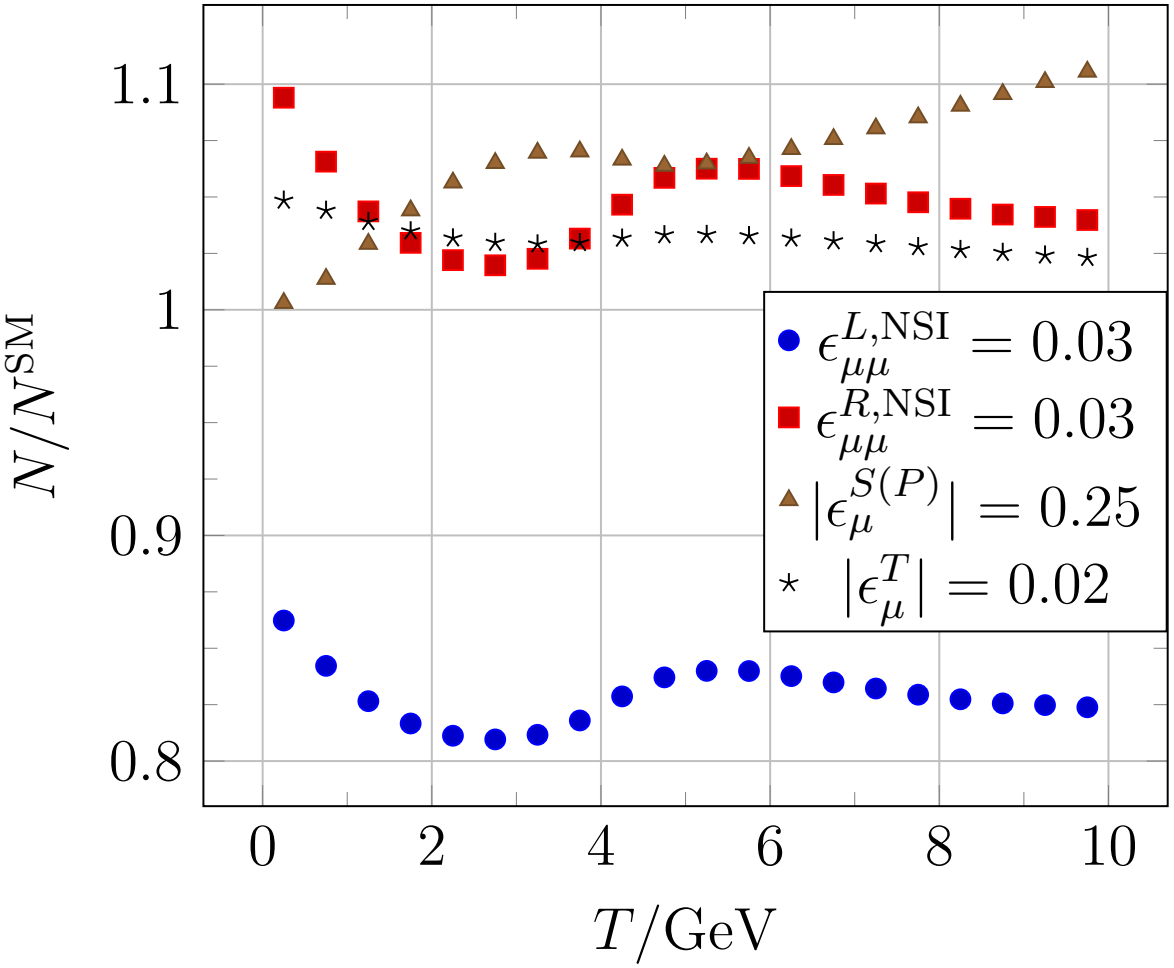
Expected recoil spectra in the SM and in presence of GNI



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)

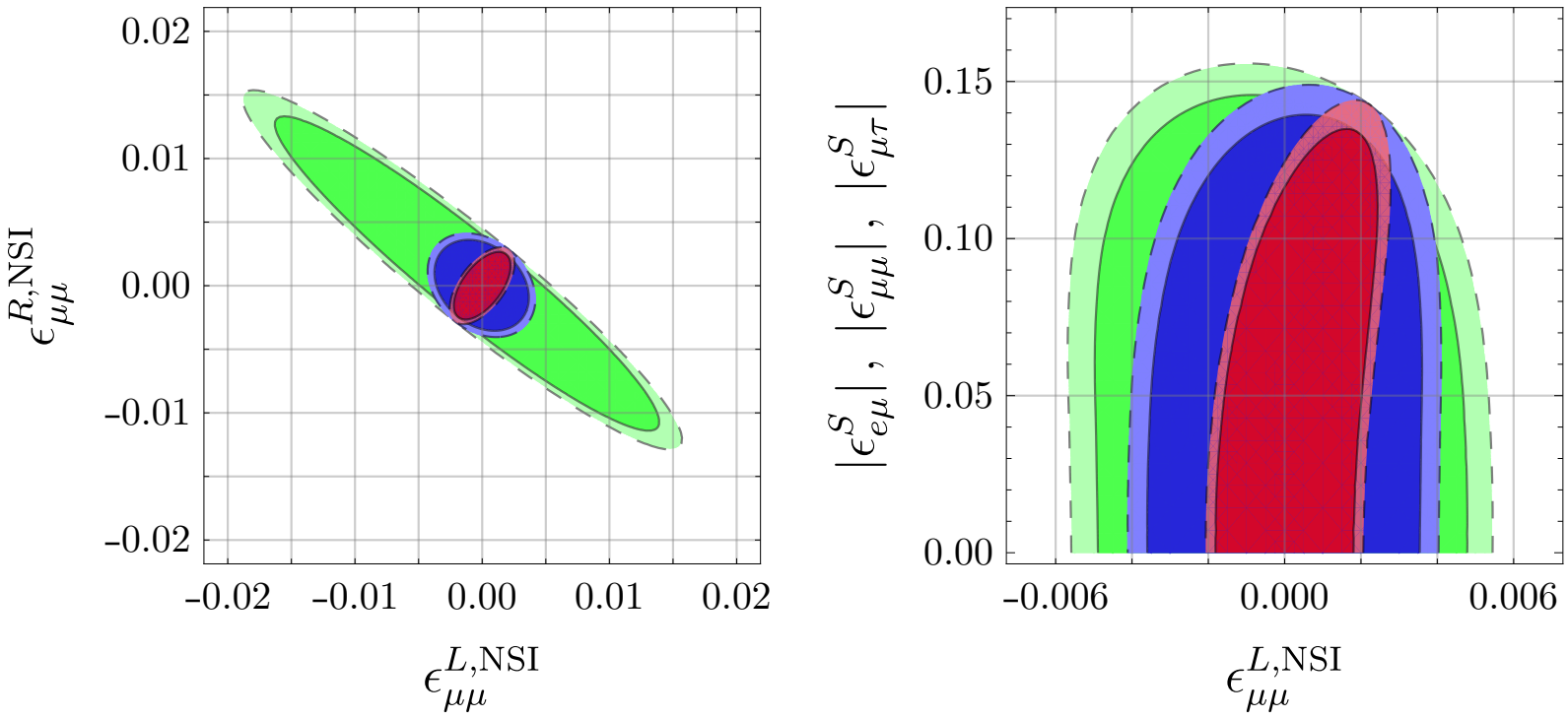
Neutrino-electron scattering at the DUNE near detector

Expected bounds at 5% flux normalisation uncertainty, 500 MeV threshold

Observ.	NP Param.	Proj. DUNE	CHARM-II	$\frac{M}{g'}$[TeV]
$\epsilon_{\mu\mu}^{L,\mathrm{NSI}}$	$\epsilon_{\mu\mu}^{L,\mathrm{NSI}}$	± 0.0038	$[-0.06, 0.02]$	5.7
$\epsilon_{\mu}^{L,\mathrm{NSI}}$	$\lvert\epsilon_{e\mu}^{L,\mathrm{NSI}}\rvert$, $\lvert\epsilon_{\mu\tau}^{L,\mathrm{NSI}}\rvert$	0.046		1.6
$\epsilon_{\mu\mu}^{R,\mathrm{NSI}}$	$\epsilon_{\mu\mu}^{R,\mathrm{NSI}}$	± 0.0031	$[-0.06, 0.02]$	6.3
$\epsilon_{\mu}^{R,\mathrm{NSI}}$	$\lvert\epsilon_{e\mu}^{R,\mathrm{NSI}}\rvert$, $\lvert\epsilon_{\mu\tau}^{R,\mathrm{NSI}}\rvert$	0.037		1.8
ϵ_{μ}^{S}	$\lvert\epsilon_{e\mu}^{S}\rvert$, $\lvert\epsilon_{\mu\mu}^{S}\rvert$, $\lvert\epsilon_{\mu\tau}^{S}\rvert$	0.14	0.4	0.9
ϵ_{μ}^{P}	$\lvert\epsilon_{e\mu}^{P}\rvert$, $\lvert\epsilon_{\mu\mu}^{P}\rvert$, $\lvert\epsilon_{\mu\tau}^{P}\rvert$	0.14	0.4	0.9
ϵ_{μ}^{T}	$\lvert\epsilon_{e\mu}^{T}\rvert$, $\lvert\epsilon_{\mu\mu}^{T}\rvert$, $\lvert\epsilon_{\mu\tau}^{T}\rvert$	0.020	0.04	2.4

Neutrino-electron scattering at the DUNE near detector

Expected two-parameter bounds



Flux normalisation uncertainty 0% 1% 5%

Conclusions

General neutrino interactions

- 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

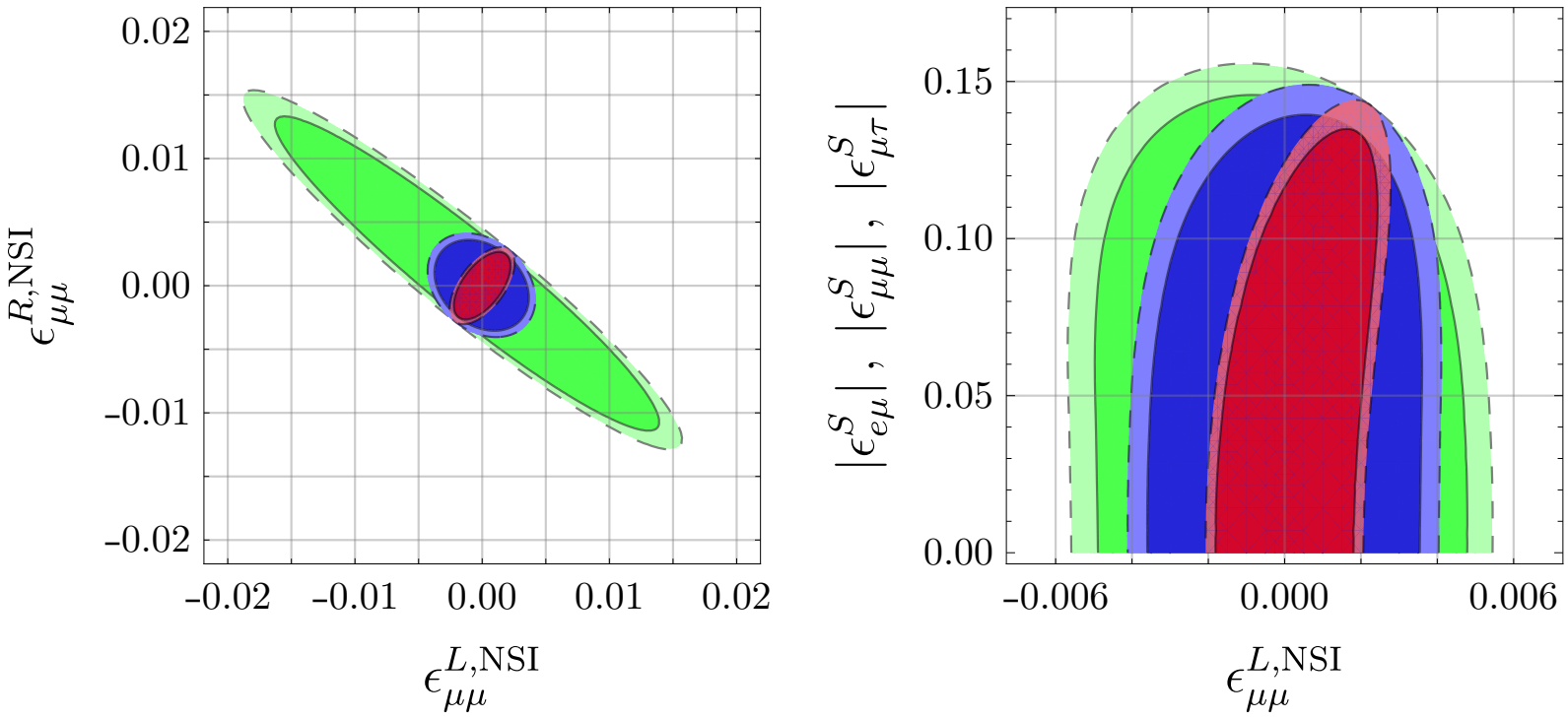
[I.B., W. Rodejohann 1810.02220]

Thank you!

Backup slides

Neutrino-electron scattering at the DUNE near detector

Expected bounds



Flux normalisation uncertainty 0% 1% 5%

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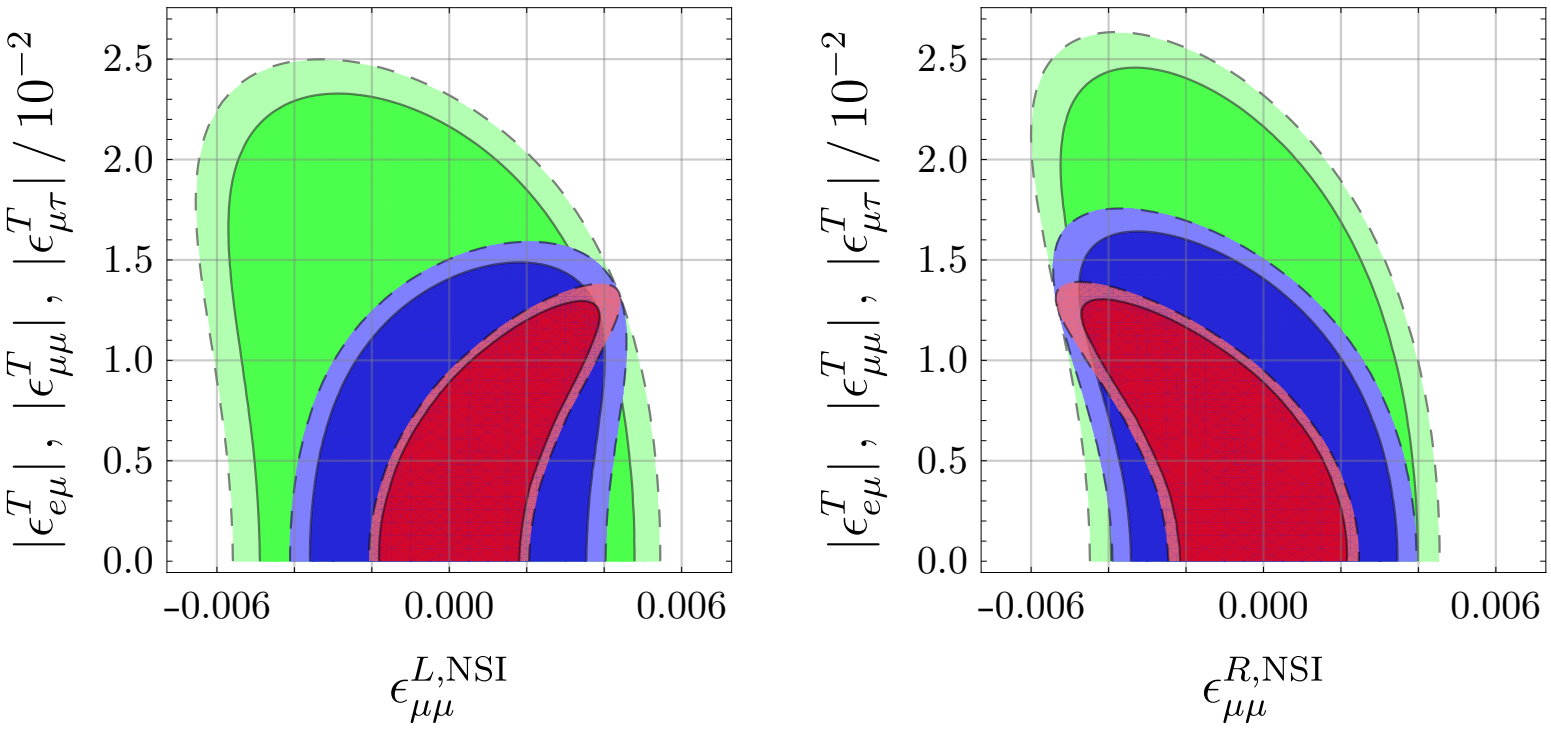

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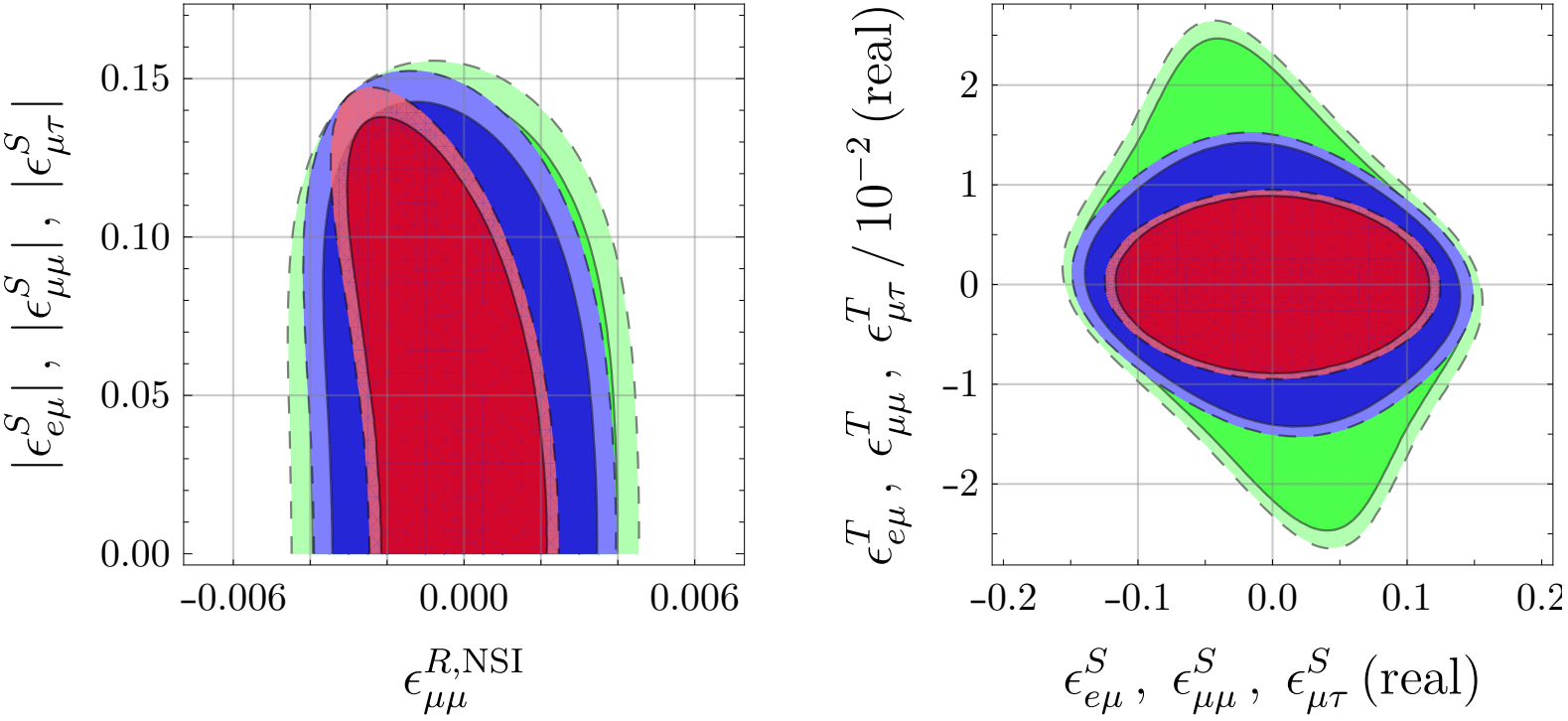

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General neutrino interactions

Remark on Dirac or Majorana nature

GNI NC Lagrangian (in flavor basis)

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

- In Dirac case (3 flavors), realness of $\mathcal{L}$ implies:

$$\epsilon^{L}_{\alpha\beta} = \epsilon^{L*}_{\beta\alpha}\,, \qquad \tilde{\epsilon}^{L}_{\alpha\beta} = \tilde{\epsilon}^{L*}_{\beta\alpha}\,, \qquad \epsilon^{R}_{\alpha\beta} = \epsilon^{R*}_{\beta\alpha}\,, \qquad \tilde{\epsilon}^{R}_{\alpha\beta} = \tilde{\epsilon}^{R*}_{\beta\alpha}\,,$$
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  which amounts to 90 free parameters.

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  which amounts to 90 free parameters.

- In Majorana case one finds *additionally*:

$$\epsilon^{L/R}_{\alpha\beta} = -\tilde{\epsilon}^{L/R}_{\beta\alpha}\,, \quad \epsilon^{S/P}_{\alpha\beta} = \epsilon^{S/P}_{\beta\alpha}\,, \quad \epsilon^{T}_{\alpha\beta} = -\epsilon^{T}_{\beta\alpha}\,.$$

  which reduces the set to 48 free parameters.

General neutrino interactions

Remark on Dirac or Majorana nature

Subconclusion:

- If we discover general neutrino interactions which require Dirac nature, the case is settled!
- If we discover Majorana-compatible general interactions, the case is as open as ever.

[Rosen PRL48 1982], [Rodejohann et al. 1702.05721]

General neutrino interactions

Possible Origin

- $S/P/T$ cannot originate from dimension-6 SMEFT operators
- SM+RHν N gauge invariant EFT operators to generate $\epsilon^S, \epsilon^P, \epsilon^T$:

SM+N EFT 1

$$\mathcal{O}_{\varphi Ne} = \frac{1}{\Lambda^2} C^{\varphi Ne}_{\alpha\beta} i \left(\widetilde{\varphi}^\dagger D_\mu \varphi\right) \left(\overline{N}_\alpha \gamma^\mu e_\beta\right) + \text{h.c.}$$

$$\epsilon^{S,e_\beta}_{\alpha\beta} = -\epsilon^{P,e_\beta}_{\alpha\beta} = \widetilde{\epsilon}^{S,e_\beta *}_{\alpha\beta} = \widetilde{\epsilon}^{P,e_\beta *}_{\alpha\beta} = 2 C^{\varphi N \ell}_{\alpha\beta}$$

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SM+N EFT 2

$$\mathcal{O}_{\ell N\ell e} = \frac{1}{\Lambda^2} C^{\ell N\ell e}_{\alpha\beta\gamma\delta} \left(\overline{L}^i_\alpha N_\beta\right) \epsilon_{ij} \left(\overline{L}^j_\gamma e_\delta\right) + \text{h.c.}$$

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$$\epsilon^{T,e_\delta}_{\alpha\beta} = \widetilde{\epsilon}^{T,e_\delta *}_{\beta\alpha} = \frac{1}{8}\left(C^{\ell N\ell e}_{\delta\alpha\beta\delta}\right)^*$$

General neutrino interactions

Some model examples

Type-II seesaw:

- Add scalar triplet to SM:

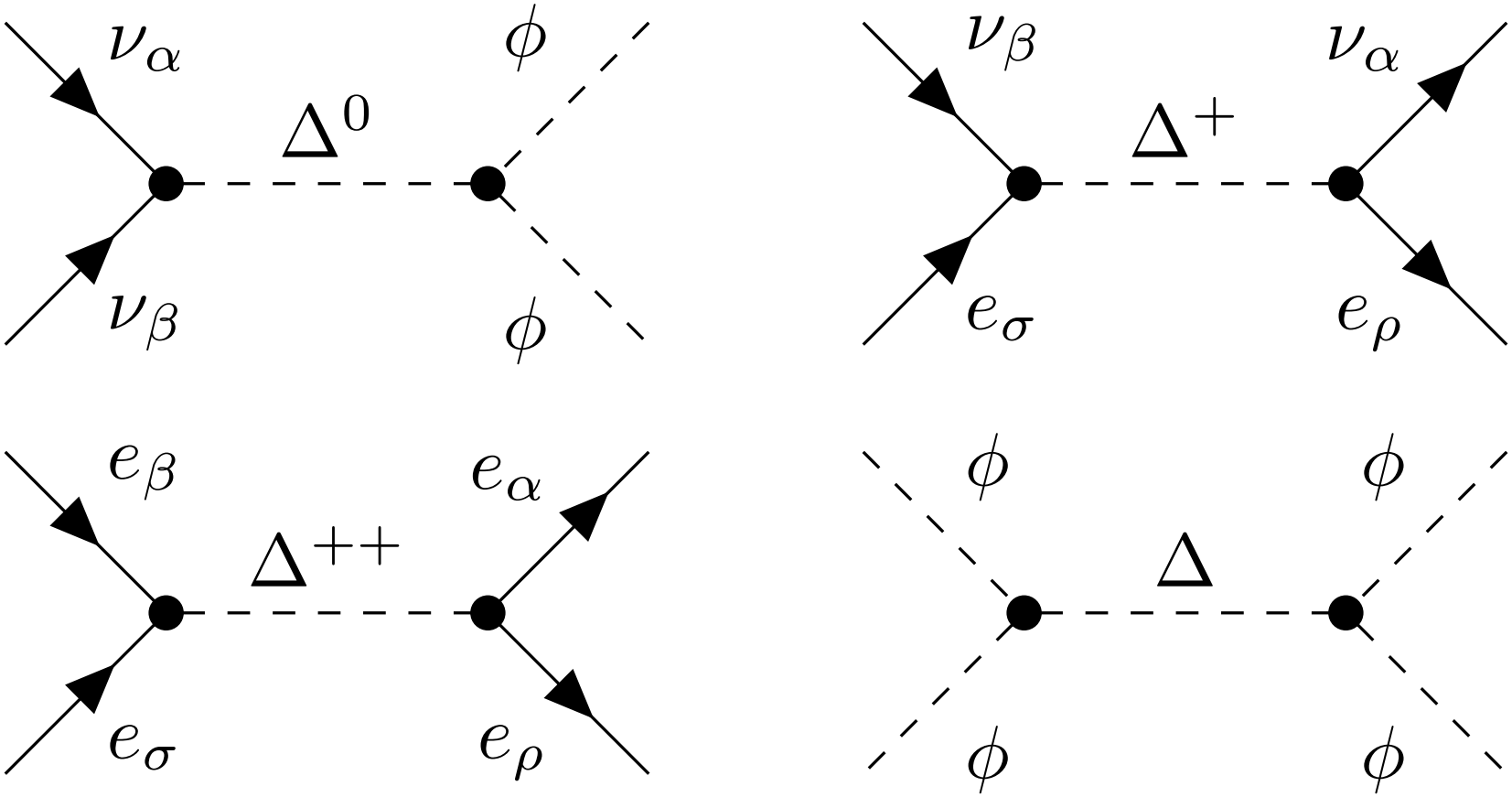
$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

- Yukawa couplings to lepton doublets
- Coupling to SM Higgs

General neutrino interactions

Some model examples

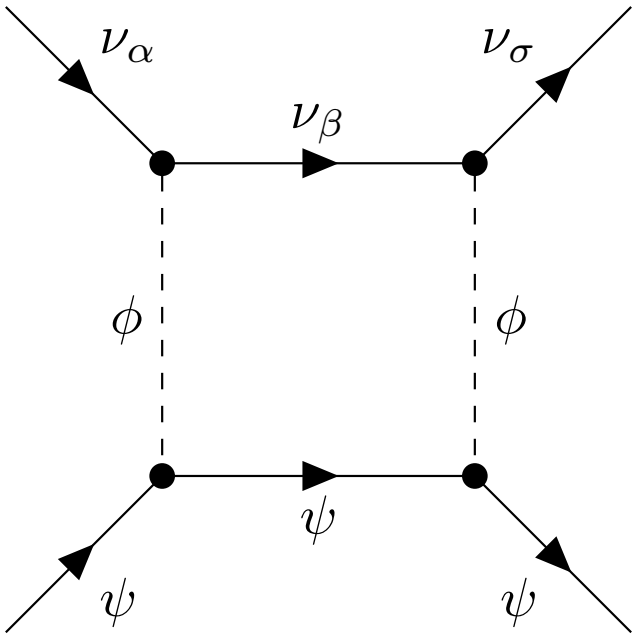
Type-II seesaw:



$|\epsilon| \lesssim 10^{-3}$ [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]