General Neutrino Interactions from an Effective Field Theory perspective

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WIN2019, Bari

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL PTFS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

Outline

1. EFT above and below the weak scale
2. (Some) GNI phenomenology
3. Leptoquarks as UV completions

1. EFT above and below the weak scale

EFT above and below the weak scale

Why EFT, and if so, how many?

- Neutrino physics started off with an EFT: Fermi Theory
- Now widely used for model-independent NP searches
- Neutrino phenomenology (below the weak scale) usually refers to NSI (more rarely GNI)
- Similar spirit: WEFT, WET, HEFT, ...
- Collider phenomenology (around and above the weak scale) usually refers to SMEFT or its cousins
- Can be related by a matching of Wilson coefficients at the weak scale ("EFT ladder")

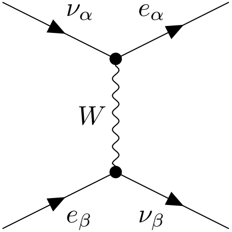
General EFT expansion:

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \sum_{n\geq 5} \frac{1}{\Lambda^{n-4}} C_i \mathcal{O}_i^{(n)} \,,$$

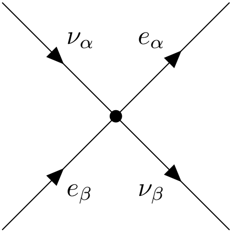
- Add to known physics, e.g. Standard Model Lagrangian an expansion of all non-renormalisable operators of dimension $d \geq 5$
- Λ: cutoff of the EFT, scale at which new particles are excited
- $\mathcal{O}_i^{(n)}$ composed of all fields present in $\mathcal{L}_{\mathrm{SM}}$ and respecting its symmetries

EFT *below* the weak scale

Well-known example: Fermi Theory



$\longrightarrow$



$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{1}{\Lambda^2} C_i \mathcal{O}_i^{(6)}$$

- $\mathcal{O}^{(6)}$: four-fermion operators respecting $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{U}(1)_\mathrm{em}$
- $\frac{1}{\Lambda^2} = \sqrt{8} G_F = \frac{g^2}{2 m_W^2}$ scale of "new physics"

EFT *below* the weak scale

Non-Standard neutrino interactions

- Idea: New high-energy physics may lead to modifications of Fermi theory:

NSI Lagrangians

$$\mathcal{L}_{NC}^{\text{NSI}} = -\sqrt{8} G_F \sum_{X=L,R} \epsilon_{\alpha\beta}^{\psi,X} \left(\overline{\nu}^\alpha \gamma^\mu P_L \nu^\beta\right) \left(\overline{\psi} \gamma_\mu P_X \psi\right)$$

$$\mathcal{L}_{CC}^{\text{NSI}} = -\sqrt{8} G_F V_{\gamma\delta} \sum_{X=L,R} \epsilon_{\alpha\beta}^{X} \left(\overline{e}^\alpha \gamma^\mu P_L \nu^\beta\right) \left(\overline{u}^\gamma \gamma_\mu P_X d^\delta\right) + \text{h.c.}$$

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

EFT *below* the weak scale

General neutrino interactions

- Idea: What is the most general Lorentz-invariant four-fermion interaction Lagrangian if we admit right-handed neutrinos?
- For general chiral fermions 10 terms:

EFT *below* the weak scale

General neutrino interactions

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- For general chiral fermions 10 terms:

Five Lorentz-invariant Lagrangians constructed from four Dirac spinors ψ_i

$$
\begin{aligned}
\mathcal{L}^{S}_{XY}\left(\psi_1,\psi_2,\psi_3,\psi_4\right) &= \left(\overline{\psi}_1 P_X \psi_2\right)\left(\overline{\psi}_3 P_Y \psi_4\right)\\
\mathcal{L}^{V}_{XY}\left(\psi_1,\psi_2,\psi_3,\psi_4\right) &= \left(\overline{\psi}_1 \gamma^{\mu} P_X \psi_2\right)\left(\overline{\psi}_3 \gamma_{\mu} P_Y \psi_4\right)\\
\mathcal{L}^{T}_{X}\left(\psi_1,\psi_2,\psi_3,\psi_4\right) &= \left(\overline{\psi}_1 \sigma^{\mu\nu} P_X \psi_2\right)\left(\overline{\psi}_3 \sigma_{\mu\nu} P_X \psi_4\right)\\
X, Y &= L, R
\end{aligned}
$$

EFT *below* the weak scale

General neutrino interactions

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- For general chiral fermions 10 terms:

Five Lorentz-invariant Lagrangians constructed from four Dirac spinors ψ_i

$$\mathcal{L}^S_{XY}(\psi_1,\psi_2,\psi_3,\psi_4) = \left(\overline{\psi}_1 P_X \psi_2\right)\left(\overline{\psi}_3 P_Y \psi_4\right)$$

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

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

$$X, Y = L, R$$

EFT *below* the weak scale

General neutrino interactions

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

GNI Lagrangians

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

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

$\psi = u, d, e$

- Ten ϵ-parameters instead of two (NSI)!
- Leptonic CC interactions absorbed in NC (Fierz transformation)
- Remark: Parametrisation not unique

EFT *below* the weak scale

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

EFT *below* the weak scale

General neutrino interactions

Notable features:

- Model-independent parametrisation of new physics
- Independent of the realisation of the weak gauge symmetry in the new physics sector
- Directly testable in low-energy experiments
- Can potentially discriminate Dirac from Majorana nature of neutrinos [Rosen PRL48 1982], [Rodejohann et al. 1702.05721]
- Scalar and tensor interactions may produce a large neutrino magnetic moment [Xu 1901.00482]

EFT *below* the weak scale

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FAQ: But neutrinos are in a weak doublet with charged leptons! Should not gauge invariance of new physics also introduce new interactions of charged leptons which are subject to very strong constraints?

EFT *above* the weak scale
SM(N)EFT

SMEFT expansion

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \sum_{n \geq 5} \frac{1}{\Lambda^{n-4}} C_i \mathcal{O}_i^{(n)}$$

$\mathcal{O}_i^n$ composed of SM fields and respecting full $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$ gauge symmetry.
[Buchmüller et al. NPB268 1986]

- Cannot produce most scalar and tensor GNI up to dim-6
  $\Rightarrow$ We add light right-handed singlet neutrinos N
- In simplest scenario N_α are Dirac partners of SM neutrinos

EFT *above* the weak scale
SM(N)EFT

Four-fermion SMEFT operators involving neutrinos:

$(\overline{L}L)(\overline{L}L)$ and $(\overline{R}R)(\overline{R}R)$		$(\overline{L}L)(\overline{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_\alpha \gamma_\mu l_\beta)(\bar{l}_\gamma \gamma^\mu l_\delta)$	$\mathcal{O}_{le}$	$(\bar{l}_\alpha \gamma_\mu l_\beta)(\overline{e}_\gamma \gamma^\mu e_\delta)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_\alpha \gamma_\mu l_\beta)(\overline{q}_\gamma \gamma^\mu q_\delta)$	$\mathcal{O}_{lu}$	$(\bar{l}_\alpha \gamma_\mu l_\beta)(\overline{u}_\gamma \gamma^\mu u_\delta)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_\alpha \gamma_\mu \tau^I l_\beta)(\overline{q}_\gamma \gamma^\mu \tau^I q_\delta)$	$\mathcal{O}_{ld}$	$(\bar{l}_\alpha \gamma_\mu l_\beta)(\overline{d}_\gamma \gamma^\mu d_\delta)$
$(\overline{R}L)(\overline{L}R)$ and $(\overline{R}L)(\overline{R}L)$			
$\mathcal{O}_{elqd}$	$(\overline{e}_\alpha l^j_\beta)(\overline{q}^j_\gamma d_\delta)$		
$\mathcal{O}_{eluq}$	$(\overline{e}_\alpha l^j_\beta)\epsilon_{jk}(\overline{u}_\gamma q^k_\delta)$		
$\mathcal{O}'_{eluq}$	$(\overline{e}_\alpha \sigma_{\mu\nu} l^j_\beta)\epsilon_{jk}(\overline{u}_\gamma \sigma^{\mu\nu} q^k_\delta)$		

[Grzadkowski et al. 1008.4884]

EFT *above* the weak scale

SM(N)EFT

Four-fermion operators involving SM fields and sterile neutrinos N:

$(\bar{L}L)(\bar{L}L)$ and $(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{Ne}$	$(\overline{N}_\alpha\gamma_\mu N_\beta)(\overline{e}_\gamma\gamma^\mu e_\delta)$	$\mathcal{O}_{Nl}$	$(\overline{N}_\alpha\gamma_\mu N_\beta)(\bar{l}_\gamma\gamma^\mu l_\delta)$
$\mathcal{O}_{Nu}$	$(\overline{N}_\alpha\gamma_\mu N_\beta)(\overline{u}_\gamma\gamma^\mu u_\delta)$	$\mathcal{O}_{Nq}$	$(\overline{N}_\alpha\gamma_\mu N_\beta)(\overline{q}_\gamma\gamma^\mu q_\delta)$
$\mathcal{O}_{Nd}$	$(\overline{N}_\alpha\gamma_\mu N_\beta)(\overline{d}_\gamma\gamma^\mu d_\delta)$		
$\mathcal{O}_{eNud}$	$(\overline{e}_\alpha\gamma_\mu N_\beta)(\overline{u}_\gamma\gamma^\mu d_\delta)$		
$(\bar{R}L)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$			
$\mathcal{O}_{Nlel}$	$(\overline{N}_\alpha l^j_\beta)\epsilon_{jk}(\overline{e}_\gamma l^k_\delta)$		
$\mathcal{O}_{lNqd}$	$(\bar{l}^j_\alpha N_\beta)\epsilon_{jk}(\overline{q}^k_\gamma d_\delta)$		
$\mathcal{O}'_{lNqd}$	$(\bar{l}^j_\alpha\sigma_{\mu\nu} N_\beta)\epsilon_{jk}(\overline{q}^k_\gamma\sigma^{\mu\nu} d_\delta)$		
$\mathcal{O}_{lNuq}$	$(\bar{l}^j_\alpha N_\beta)(\overline{u}_\gamma q^j_\delta)$		

[Liao et al. 1612.04527]

EFT above *and* below the weak scale
Matching

- Find relations like
$$\epsilon_{R,e}^{\alpha\beta\gamma\delta} = -C_{le}^{\alpha\beta\gamma\delta}$$
- SMEFT operators accompanied by charged-lepton interactions:
$$\mathcal{L} = \frac{G_F}{\sqrt{2}} C_{le}^{\alpha\beta\gamma\delta} \left(\overline{e}_\alpha(1-\gamma^5)e_\beta\right) \left(\overline{e}_\gamma \gamma^\mu (1+\gamma^5) e_\delta\right)$$
- Affects primarily (vector-like) NSI

EFT above *and* below the weak scale

Matching

- Find relations like

$$\epsilon^{\alpha\beta\gamma\delta}_{R,e} = -C^{\alpha\beta\gamma\delta}_{le}$$

- SMEFT operators accompanied by charged-lepton interactions:

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} C^{\alpha\beta\gamma\delta}_{le} \left(\overline{e}_\alpha (1-\gamma^5) e_\beta\right) \left(\overline{e}_\gamma \gamma^\mu (1+\gamma^5) e_\delta\right)$$

- Affects primarily (vector-like) NSI
- Not the case for operators involving N!
- Some operators involving N imply simultaneous NC and CC scalar and tensor interactions

[Jenkins et al. 1709.04486], [I.B. et al. 1905.08699]

2 Phenomenology

based on [I.B., W. Rodejohann 1905.08699]

Phenomenology

We consider single-parameter bounds on GNI from low-energy observables under the assumption they are induced by SM(N)EFT operators.

- Charged lepton flavour violation
- Exotic interactions in CEνNS and beta decay
- Flavour-conserving four-fermion interactions [Falkowski et al. 1706.03783]
- Reactor neutrino oscillation [Falkowski et al. 1901.04553]

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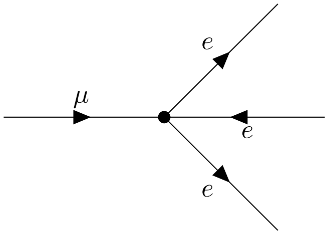
Disclaimer: When comparing those bounds to processes at the weak scale RG running should be taken into account. [González-Alonso et al. 1706.00410]

2.1 Charged lepton flavour violation

Phenomenology

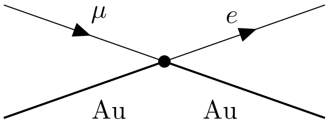
Charged lepton flavour violation



$\lvert\epsilon^{e\mu ee}\rvert$	Direct	CLFV	Operators
$\epsilon_{L,e}$	$1.3 \cdot 10^{-1}$	$1.4 \cdot 10^{-6}$	$\mathcal{O}_{ll}$
$\epsilon_{R,e}$	$1.3 \cdot 10^{-1}$	$1.0 \cdot 10^{-6}$	$\mathcal{O}_{le}$

90% CL single-parameter bounds

[Barranco et al. 0711.0698], [Calibbi et al. 1709.00294], [SINDRUM Collaboration NPB299 (1988)],



$\lvert\epsilon^{e\mu 11}\rvert$	Direct	CLFV	Operators
$\epsilon_{L,u}$	$2.3 \cdot 10^{-2}$	$3.3 \cdot 10^{-7}$	$\mathcal{O}_{lq(1)}, \mathcal{O}_{lq(3)}$
$\epsilon_{L,d}$	$2.3 \cdot 10^{-2}$	$3.3 \cdot 10^{-7}$	$\mathcal{O}_{lq(1)}, \mathcal{O}_{lq(3)}$
$\epsilon_{R,u}$	$3.6 \cdot 10^{-2}$	$6.0 \cdot 10^{-8}$	$\mathcal{O}_{lu}$
$\epsilon_{R,d}$	$3.6 \cdot 10^{-2}$	$5.3 \cdot 10^{-8}$	$\mathcal{O}_{ld}$
$\epsilon_{L,ud}$	$2.6 \cdot 10^{-2}$	$6.6 \cdot 10^{-7}$	$\mathcal{O}_{lq(3)}$
$\mathrm{Re}(\epsilon_{S,ud})$	$8 \cdot 10^{-3}$	$3.0 \cdot 10^{-8}$	$\mathcal{O}_{elqd}, \mathcal{O}_{eluq}$
$\mathrm{Re}(\epsilon_{P,ud})$	$4 \cdot 10^{-4}$	$3.0 \cdot 10^{-8}$	$\mathcal{O}_{elqd}, \mathcal{O}_{eluq}$

90% CL single-parameter bounds

[Escrihuela et al. 1103.1366], [Biggio et al. 0907.0097], [Cirigliano et al. 1303.6953], [SINDRUM II Collaboration Eur. Phys. J. C47 (2006)]

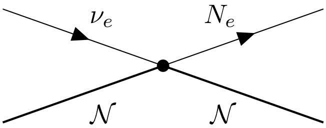
Other processes: $\mu \to e\gamma$, $\tau \to \mu\mu\mu, \ldots$

- Conclusion: In SMEFT $d = 6$ framework, all the lepton flavour changing GNI are constrained at least to
  - $\epsilon \sim 10^{-4}$ for $\tau \to \mu$, $\tau \to e$
  - $\epsilon \sim 10^{-6}$ for $\mu \to e$
- Much below current neutrino experiment sensitivities
- If still detected would imply more exotic new physics that invalidate the SMEFT expansion (light mediators, non-linearly realised gauge symmetry, . . .)
- Operators involving N not affected by those bounds and more attractive from heavy new physics perspective

2.2 Correlations of exotic interactions in CEνNS and beta decay

Phenomenology

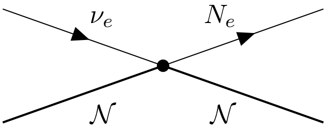
Correlations of exotic interactions in CEνNS and beta decay

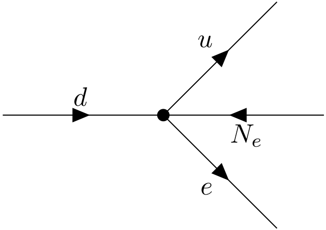


$$\epsilon_{S,u}^{ee11} = -\epsilon_{P,u}^{ee11} = -V_{ud}\left(C_{lNuq}^{ee11}\right)^*$$
$$\epsilon_{S,d}^{ee11} = \epsilon_{P,d}^{ee11} = -\left(C_{lNqd}^{ee11}\right)^*$$
$$\epsilon_{T,d}^{ee11} = -\left(C_{lNqd}^{\prime ee11}\right)^*$$

Phenomenology

Correlations of exotic interactions in CEνNS and beta decay





$$\epsilon^{ee11}_{S,u} = -\epsilon^{ee11}_{P,u} = -V_{ud}\left(C^{ee11}_{lNuq}\right)^*$$

$$\epsilon^{ee11}_{S,d} = \epsilon^{ee11}_{P,d} = -\left(C^{ee11}_{lNqd}\right)^*$$

$$\epsilon^{ee11}_{T,d} = -\left(C'^{ee11}_{lNqd}\right)^*$$

$$\tilde{\epsilon}^{ee11}_{S,ud} = \frac{1}{V_{ud}}\left(V_{uj}\, C^{eej1}_{lNqd} - C^{ee11}_{lNuq}\right)$$

$$\tilde{\epsilon}^{ee11}_{P,ud} = -\frac{1}{V_{ud}}\left(V_{uj}\, C^{eej1}_{lNqd} + C^{ee11}_{lNuq}\right)$$

$$\tilde{\epsilon}^{ee11}_{T,ud} = \frac{V_{uj}}{V_{ud}}\, C'^{\alpha\beta j\delta}_{lNqd}$$

Phenomenology

Correlations of exotic interactions in CEνNS and beta decay

Scenario 1: $C_{lNuq}^{ee11}(\bar{l}^j_e N_e)(\bar{u}_R q_1^j)$

- COHERENT: $|\epsilon_{P,u}^{ee11}| \leq 1.5 \cdot 10^{-2} \quad \Rightarrow \quad |C_{lNuq}| \leq 1.5 \cdot 10^{-2}$
- Pion decay: $|\widetilde{\epsilon}_{P,ud}^{ee11}| \leq 4.0 \cdot 10^{-4} \quad \Rightarrow \quad |C_{lNuq}| \leq 3.9 \cdot 10^{-4}$

Phenomenology

Correlations of exotic interactions in CEνNS and beta decay

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Scenario 2: $C_{lNqd}^{\prime ee11}(\bar{l}^j_e \sigma^{\mu\nu} N_e)\epsilon_{jk}(\bar{q}_1^k \sigma_{\mu\nu} d_R)$

- COHERENT: $|\mathrm{Re}(\epsilon_{T,d}^{ee11})| \leq 9.8 \cdot 10^{-2} \quad \Rightarrow |C_{lNqd}^{\prime ee11}| \leq 9.8 \cdot 10^{-2}$
- Beta decays: $|\widetilde{\epsilon}_{T,ud}^{ee11}| \leq 2.4 \cdot 10^{-2} \quad \Rightarrow |C_{lNqd}^{\prime ee11}| \leq 2.4 \cdot 10^{-2}$

(at 90% CL)

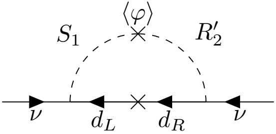
[Aristizabal Sierra et al. 1806.07424], [Cirigliano et al. 1303.6953], [González-Alonso et al. 1803.08732]

3. Leptoquarks as UV completions

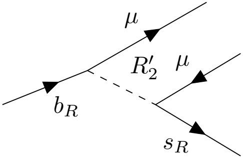
Leptoquarks as UV completions

- Leptoquarks can accomodate B physics anomalies, radiative neutrino masses, and naturally appear in GUT models

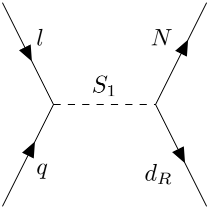
Example:



[Catà et al. 1903.01799]



[Bečirević et al. 1503.09024]



$S_1(\overline{3}, 1, 1/3) \quad (Q = I_3 + Y)$

$R_2'(3, 2, 1/6)$

Leptoquarks as UV completions

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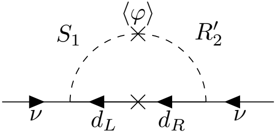

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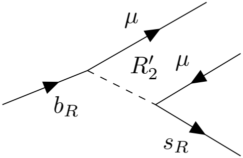

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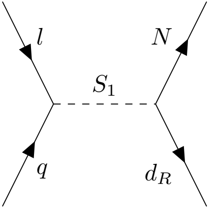

$$S_1(\overline{3}, 1, 1/3) \quad (Q = I_3 + Y)$$
$$R'_2(3, 2, 1/6)$$

- Generates $\mathcal{O}_{lNqd}$ and $\mathcal{O}'_{lNqd}$ above the weak scale ($m_W \ll m_{S_1}$)
- Generates NC and CC scalar and tensor GNI below the weak scale

Conclusions

- From SMEFT perspective, sizable (vector like) NSI are disfavoured due to strong constraints from charged lepton interactions, in particular in the flavour-violating case.
- Detectable (CEνNS, β) scalar and tensor type neutrino interactions on the other hand can be generated in SMEFT extended by right-handed neutrinos.
- Viable UV completions by leptoquarks can be constructed.

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- Detectable (CEνNS, β) scalar and tensor type neutrino interactions on the other hand can be generated in SMEFT extended by right-handed neutrinos.
- Viable UV completions by leptoquarks can be constructed.
- Discussion has concentrated on low-scale physics ($< 2\,\mathrm{GeV}$). To connect to high-energy physics a calculation of the RG running of GNI is required.
- GNI should be included in BSM surveys of neutrino experiments.

Thank you!

Backup slides

	e	u	d
$-\epsilon_{L,f}^{\alpha\beta\gamma\delta}$	$C_{ll}^{\alpha\beta\gamma\delta} + C_{ll}^{\gamma\delta\alpha\beta}$	$V_{\gamma\mu} V^{\dagger}_{\nu\delta} \left(C_{lq(1)}^{\alpha\beta\mu\nu} + C_{lq(3)}^{\alpha\beta\mu\nu} \right)$	$C_{lq(1)}^{\alpha\beta\gamma\delta} - C_{lq(3)}^{\alpha\beta\gamma\delta}$
$-\widetilde{\epsilon}_{L,f}^{\alpha\beta\gamma\delta}$	$C_{Nl}^{\alpha\beta\gamma\delta}$	$V_{\gamma\mu} V^{\dagger}_{\nu\delta} C_{Nq}^{\alpha\beta\mu\nu}$	$C_{Nq}^{\alpha\beta\gamma\delta}$
$-\epsilon_{R,f}^{\alpha\beta\gamma\delta}$	$C_{le}^{\alpha\beta\gamma\delta}$	$C_{lu}^{\alpha\beta\gamma\delta}$	$C_{ld}^{\alpha\beta\gamma\delta}$
$-\widetilde{\epsilon}_{R,f}^{\alpha\beta\gamma\delta}$	$C_{Ne}^{\alpha\beta\gamma\delta}$	$C_{Nu}^{\alpha\beta\gamma\delta}$	$C_{Nd}^{\alpha\beta\gamma\delta}$
$-\epsilon_{S,f}^{\alpha\beta\gamma\delta}$	$\frac{1}{2} C_{Nlel}^{\alpha\beta\gamma\delta} + \frac{1}{4} C_{Nlel}^{\gamma\beta\alpha\delta}$	$V_{\gamma\nu} (C_{lNuq}^{\beta\alpha\delta\nu})^*$	$(C_{lNqd}^{\beta\alpha\delta\gamma})^*$
$-\epsilon_{P,f}^{\alpha\beta\gamma\delta}$	$\frac{1}{2} C_{Nlel}^{\alpha\beta\gamma\delta} + \frac{1}{4} C_{Nlel}^{\gamma\beta\alpha\delta}$	$-V_{\gamma\nu} (C_{lNuq}^{\beta\alpha\delta\nu})^*$	$(C_{lNqd}^{\beta\alpha\delta\gamma})^*$
$-\epsilon_{T,f}^{\alpha\beta\gamma\delta}$	$\frac{1}{8} C_{Nlel}^{\gamma\beta\alpha\delta}$	0	$(C_{lNqd}^{\prime\,\beta\alpha\delta\gamma})^*$

$-\epsilon^{\alpha\beta\gamma\delta}_{L,ud}$	$\frac{V_{\gamma\nu}}{V_{\gamma\delta}} 2C^{\alpha\beta\nu\delta}_{lq(3)}$	$-\widetilde{\epsilon}^{\alpha\beta\gamma\delta}_{L,ud}$	0
$-\epsilon^{\alpha\beta\gamma\delta}_{R,ud}$	0	$-\widetilde{\epsilon}^{\alpha\beta\gamma\delta}_{R,ud}$	$\frac{1}{V_{\gamma\delta}} C^{\alpha\beta\gamma\delta}_{eNud}$
$-\epsilon^{\alpha\beta\gamma\delta}_{S,ud}$	$\frac{1}{V_{\gamma\delta}} \left(V_{\gamma\nu} C^{\alpha\beta\nu\delta}_{elqd} + C^{\alpha\beta\gamma\delta}_{eluq}\right)$	$-\widetilde{\epsilon}^{\alpha\beta\gamma\delta}_{S,ud}$	$\frac{1}{V_{\gamma\delta}} \left(C^{\alpha\beta\gamma\delta}_{lNuq} - V_{\gamma\nu} C^{\alpha\beta\nu\delta}_{lNqd}\right)$
$-\epsilon^{\alpha\beta\gamma\delta}_{P,ud}$	$\frac{1}{V_{\gamma\delta}} \left(-V_{\gamma\nu} C^{\alpha\beta\nu\delta}_{elqd} + C^{\alpha\beta\gamma\delta}_{eluq}\right)$	$-\widetilde{\epsilon}^{\alpha\beta\gamma\delta}_{P,ud}$	$\frac{1}{V_{\gamma\delta}} \left(C^{\alpha\beta\gamma\delta}_{lNuq} + V_{\gamma\nu} C^{\alpha\beta\nu\delta}_{lNqd}\right)$
$-\epsilon^{\alpha\beta\gamma\delta}_{T,ud}$	$\frac{1}{V_{\gamma\delta}} C'^{\alpha\beta\gamma\delta}_{eluq}$	$-\widetilde{\epsilon}^{\alpha\beta\gamma\delta}_{T,ud}$	$-\frac{V_{\gamma\nu}}{V_{\gamma\delta}} C'^{\alpha\beta\nu\delta}_{lNqd}$

	Dirac	Majorana	CP-invariant	Majorana + CP-invariant
All indices free	810	432	423	225
$\gamma = \delta =$ fixed	90	48	51	27
Flavour-diagonal and $\gamma = \delta =$ fixed	30	18	21	12

Number of free parameters in the general neutral-current Lagrangian.

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:

$$\epsilon^{L}_{\alpha\beta} = \epsilon^{L*}_{\beta\alpha}\,, \qquad \tilde{\epsilon}^{L}_{\alpha\beta} = \tilde{\epsilon}^{L*}_{\beta\alpha}\,, \qquad \epsilon^{R}_{\alpha\beta} = \epsilon^{R*}_{\beta\alpha}\,, \qquad \tilde{\epsilon}^{R}_{\alpha\beta} = \tilde{\epsilon}^{R*}_{\beta\alpha}\,,$$
$$\epsilon^{S}_{\alpha\beta} = \tilde{\epsilon}^{S*}_{\beta\alpha}\,, \qquad \epsilon^{P}_{\alpha\beta} = -\tilde{\epsilon}^{P*}_{\beta\alpha}\,, \qquad \epsilon^{T}_{\alpha\beta} = \tilde{\epsilon}^{T*}_{\beta\alpha}\,,$$

which amounts to 90 free parameters.

General neutrino interactions

Remark on Dirac or Majorana nature

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$$\epsilon^{S}_{\alpha\beta} = \tilde{\epsilon}^{S*}_{\beta\alpha}\,, \qquad \epsilon^{P}_{\alpha\beta} = -\tilde{\epsilon}^{P*}_{\beta\alpha}\,, \qquad \epsilon^{T}_{\alpha\beta} = \tilde{\epsilon}^{T*}_{\beta\alpha}\,,$$

  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.