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Chapter 1

New Interactions with Neutral Current NSI

1.1 NSI Lagrangian

Let's take GNI operators and Lagrangian from https://arxiv.org/pdf/1905.08699.pdf

GNI Lagrangians for NC and CC,

$$\mathcal{L}^{\mathrm{NC}} = -\frac{G_F}{\sqrt{2}} \sum_{j=1}^{10} \left((\epsilon_{j,f})^{\alpha\beta\gamma\delta} \left(\bar{\nu}_\alpha \mathcal{O}_j \nu_\beta\right) \left(\bar{f}_\gamma \mathcal{O}'_j f_\delta\right) \tag{1.1}$$

$$\mathcal{L}^{\mathrm{CC}} = -\frac{G_F V_{\gamma\delta}}{\sqrt{2}} \sum_{j=1}^{10} (\epsilon_{j,f})^{\alpha\beta\gamma\delta} \left(\bar{e}_\alpha \mathcal{O}_j \nu_\beta\right) \left(\bar{u}_\gamma \mathcal{O}'_j d_\delta\right) + \text{h.c.} \tag{1.2}$$

where $f = e, u, d$, denoting charged leptons, up-type and down-type quarks, Greek indices run over flavour, V denotes the CKM matrix. Note that second fermionic bilinear of each line is in the mass basis. and $\epsilon_j, \mathcal{O}_j$, and $\mathcal{O}'_j$ are given in Table.1.1 The entries of the ϵ flavour-space matrices are dimensionless and encode the strength of an interaction type j with respect to the SM Fermi interaction. The index j runs from 1 to 10 because there are five Lorentz-invariant operators for general Dirac fermions, but ten for chiral fermions.

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

Table 1.1: Coupling constants and operators appearing in generic neutral-current and charged-current Lagrangians

Let's focus on neutral current interactions in NSI with active ν and electrons.
ie, $f = e$,$\gamma, \delta = 1$, $j = 1, 3, 5$ in Eq. 1.1

1.2 Spin averaged Matrix elements $|\overline{\mathcal{M}}|^2$

For electrons, $f = e$ and $\gamma, \delta = 1$,

$$\mathcal{L}_j^{\mathrm{NC}} = -\frac{G_F}{\sqrt{2}} \left((\epsilon_{j,e})^{\alpha\beta 11} \left(\bar{\nu}_\alpha \mathcal{O}_j \nu_\beta \right) \left(\bar{e} \mathcal{O}'_j e \right) \right. \tag{1.3}$$

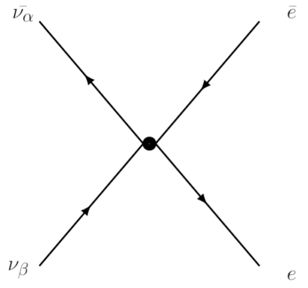
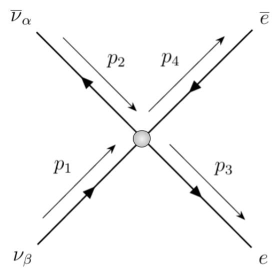


Figure 1.1: 4-point vertex in the NSI

for a process $\bar{\nu}_\alpha + \nu_\beta \to e + \bar{e}$

$$i\mathcal{M}_j = -i\frac{G_F}{\sqrt{2}} \left(\epsilon_{j,e}\right)^{\alpha\beta 11} \left[\bar{v}_{\nu_\alpha}(p_2)\mathcal{O}_j u_{\nu_\beta}(p_1)\right] \left[\bar{u}_e(p_3)\mathcal{O}'_j v_e(p_4)\right] \tag{1.4}$$

$$\mathcal{M}_j^\dagger = -\frac{G_F}{\sqrt{2}} \left(\epsilon_{j,e}\right)^{\alpha\beta 11} \left[\bar{v}_e(p_4)\overline{\mathcal{O}'_j} u_e(p_3)\right] \left[\bar{u}_{\nu_\beta}(p_1)\overline{\mathcal{O}_j} v_{\nu_\alpha}(p_2)\right] \tag{1.5}$$



where $\overline{\Gamma} = \gamma^0 \Gamma^\dagger \gamma^0$ and $u(v)$ represents particles(anti-particles).

After summing over spins and averaging,

$$|\mathcal{M}_j|^2 = \frac{1}{2} \sum_{\text{spins}} \mathcal{M}_j^\dagger \mathcal{M}_j \tag{1.6}$$

1.2.1 j=1 (ϵ_L)

$\mathcal{O}_L = \gamma_\mu \left(\mathbb{1} - \gamma^5\right)$ and $\mathcal{O}'_L = \gamma_\mu \left(\mathbb{1} - \gamma^5\right)$

$$|\mathcal{M}_L|^2 = 64 G_F^2 \left(\epsilon_{L,e}^{\alpha\beta 11}\right)^2 (p_1 \cdot p_4)(p_2 \cdot p_3) \tag{1.7}$$

1.2.2 j=3 (ϵ_R)

$\mathcal{O}_R = \gamma_\mu \left(\mathbb{1} - \gamma^5\right)$ and $\mathcal{O}'_R = \gamma_\mu \left(\mathbb{1} + \gamma^5\right)$

$$|\mathcal{M}_R|^2 = 64 G_F^2 \left(\epsilon_{R,e}^{\alpha\beta 11}\right)^2 (p_1 \cdot p_3)(p_2 \cdot p_4) \tag{1.8}$$

1.2.3 j=5 (ϵ_S)

$\mathcal{O}_S = \left(\mathbb{1} + \gamma^5\right)$ and $\mathcal{O}'_S = \mathbb{1}$

$$|\mathcal{M}_S|^2 = 8 G_F^2 \left(\epsilon_{S,e}^{\alpha\beta 11}\right)^2 \left[(p_1 \cdot p_2)(p_3 \cdot p_4) - m_e^2 (p_1 \cdot p_2)\right] \tag{1.9}$$