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Flavour-independent NSI and U(1)'

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The superweak extension of the standard model is a minimal and economical extension of the gauge, fermion and scalar sectors. Spontaneous symmetry breaking of the new U(1) is driven by an extra complex scalar singlet χ, whose non-vanishing vacuum expectation value gives mass to the new neutral gauge boson Z'. The model also includes three extra sterile right-handed Majorana neutrinos. All the new particles lie on MeV and GeV scales, but are undiscovered yet due to their small couplings to fields of the standard model. Nonstandard interactions arising from the model can be used to constrain the parameters of the model. We find that the new gauge coupling lies between $\mathcal{O}(10^{-3})$ and $\mathcal{O}(10^{-6})$.

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Effects of new physics are manifested at low energy scales via effective operators, which are generated by integrating out the heavy degrees of freedom from the high-energy theory. In the context of neutrino physics, one of the most important dimension-6 operators is

$$\frac{C}{\Lambda^2}(\overline{L}\gamma^\mu P_L L)(\overline{f}\gamma_\mu P_X f) \tag{1}$$

which corresponds to *nonstandard interactions* (NSI) of four charged leptons and charged lepton flavour violating operators.

Neutrino interactions have very low cross sections. Nonetheless neutrino-electron and neutrino-nucleon cross sections have been measured, giving stringent bounds to new physics effects originating from the effective operators, namely the NSI. Different extensions of the SM produce different NSI textures. A simple subclass of these extensions conserves flavour. Consequently the NSI matrix is diagonal and real, containing only three elements, which have contributions from up-type quarks, down-type quarks and charged leptons. In the "bottom-to-top approach", current experimental bounds can be used to constrain the high-energy theory parameters. In contrast, the "top-to-bottom approach" can be used to predict the texture and region NSI available for a particular model.

Nonstandard neutrino interactions are given by nonrenormalizable dimension-6 operators,

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \varepsilon_{\ell\ell'}^{ff',X}(\overline{\nu_\ell}\gamma^\mu P_L \nu_{\ell'})(\overline{f'}\gamma_\mu P_X f), \quad X = L, R. \tag{2}$$

Here P_X are the chiral projection operators, f and f' any fermions and G_F the Fermi coupling. The dimensionless couplings $\varepsilon_{\ell\ell'}^{ff',X}$ are in general complex. For $f = f'$ we denote $\varepsilon_{\ell\ell'}^{ff,X} \equiv \varepsilon_{\ell\ell'}^{f,X}$. Sum of a left- and right-chiral coupling is denoted by $\varepsilon_{\ell\ell'}^{ff'} = \varepsilon_{\ell\ell'}^{ff',L} + \varepsilon_{\ell\ell'}^{ff',R}$ and $\varepsilon_{\ell\ell'}^{f}$ for $f = f'$. The operator in Eq. 2 is reminiscent of the low-energy Fermi interaction corresponding to neutrino-fermion scattering in SM.

The NSI operator can be derived in the **superweak extension of the Standard Model (SWSM)** [1]. It is based on the $\mathrm{SU}(3)_c\otimes\mathrm{SU}(2)_L\otimes\mathrm{U}(1)_Y\otimes\mathrm{U}(1)_z$ gauge group. Let us denote g_Z as the gauge coupling corresponding to $\mathrm{U}(1)_z$. Due to kinetic mixing between the $\mathrm{U}(1)_Y$ and $\mathrm{U}(1)_z$ field strength tensors, the massive neutral electroweak gauge boson Z exhibits mixing with the new gauge boson, Z', with mixing angle θ_Z. The $\mathrm{U}(1)_z$ gauge symmetry is broken by spontaneous symmetry breaking. The corresponding would-be-Goldstone boson is manifested as an extra polarization mode of Z', making it massive. The covariant derivative corresponding to U(1) sector is given by

$$D_\mu^{\rm U(1)} = \partial_\mu - i(y,z)\begin{pmatrix} g_Y & -\eta g_Z \\ 0 & g_Z \end{pmatrix} R_\varepsilon \begin{pmatrix} B_\mu \\ B'_\mu \end{pmatrix}, \tag{3}$$

where y and z are the U(1) charges, R_ε is an unphysical 2×2 rotation matrix. We encode the kinetic mixing in the parameter η, which depends on the renormalization scale, but weakly. Solving the one-loop renormalization group equations of the model, one finds that $\eta(M_Z) \in [0, 0.656]$ where the upper limit is obtained if we assume that near the Planck scale the kinetic mixing vanishes [2].

In the SWSM the NSI couplings read $\varepsilon_{\ell\ell'}^{f} = \frac{v^2\delta_{\ell\ell'}}{2(q^2-M_{Z'}^2)} eC_{Z'\nu\nu}^{L}(eC_{Z'ff}^{L} + eC_{Z'ff}^{R})$ where f can be either a u-, a d-type quark or a charged lepton, q^2 is the momentum transfer squared in neutrino scattering process and $v \simeq 246.22$ GeV is the SM vacuum expectation value. The coupling factors and the mass of the Z' are functions of the Weinberg angle θ_W, the couplings g_Z and η and the ratio of the vacuum expectation values, $\tan\beta = w/v \equiv \langle s\rangle/\langle h\rangle$. They can be found in Ref. [7].

We can derive the following expressions assuming small mixing θ_Z between the massive neutral gauge bosons (valid in the limit $M_{Z'}/M_Z \ll 1$):

$$\varepsilon^u = \left(\frac{174\text{ GeV}}{M_{Z'}}\right)^2 \left(\frac{g_Z^2}{12}\left(-5\eta^2+13\eta-8\right)+0.2355 g_Z\theta_Z(1.766-\eta)+0.04692\theta_Z^2\right) \tag{4}$$

$$\varepsilon^d = \left(\frac{174\text{ GeV}}{M_{Z'}}\right)^2 \left(\frac{g_Z^2}{12}\left(\eta^2-5\eta+4\right)-0.06258 g_Z\theta_Z(1.881+\eta)-0.08849\theta_Z^2\right) \tag{5}$$

$$\varepsilon^e = \left(\frac{174\text{ GeV}}{M_{Z'}}\right)^2 \left(\frac{g_Z^2}{4}\left(3\eta^2-7\eta+4\right)+0.5335 g_Z\theta_Z(1.338-\eta)-0.005358\theta_Z^2\right) \tag{6}$$

We have investigated the expected magnitude of the NSI couplings by scanning over the free parameters of the model and taking into account the experimental constraints of NA64 (on dark photon search) and COHERENT (on neutrino-nucleus scattering) experiments. In addition we have included the new NSI bounds derived under the assumption that the NSI matrix is lepton flavour independent (i.e. proportional to the unit matrix). We chose the free parameters of the model to be the gauge coupling g_Z, mixing parameter η and the ratio of the vacuum expectation values of the scalar bosons, $\tan\beta$.

Setting $\eta = 0$, we derive $g_Z \approx \frac{3.94\times10^{-6}}{\tan\beta} \times \frac{M_{Z'}}{\text{MeV}}$, $\theta_Z \simeq 2.71 g_Z$, which is valid assuming $\tan\beta$ is not very small and $g_Z \ll 1$. The Z' mass is restricted to $[10\,\text{MeV}, m_\pi]$ if we want to be consistent with the freeze-out dark matter scenario of the SWSM [2]. The results of our scan are shown in Fig. 1. The left-hand side boundary of the scan at $\tan\beta \sim 2.5$ is given by the *NA64* experiment translated to the SWSM [6]. In Fig. 2 we have additionally presented the data in scatterplot form, correlated with g_Z and colour representing the Z' mass in MeV units.

In conclusion, we have derived the structure and expressions for NSI in the SWSM. The largest possible NSI coupling is $\mathcal{O}(10)$. The experimental constraints from NSI couplings restrict the superweak gauge coupling $g_Z \in [10^{-6}, 10^{-3}]$, while previous RGE analysis suggests $\eta \in [0, 0.656]$.

References

[1] Z. Trócsányi, Symmetry **12** (2020) no.1, 107 [arXiv:1812.11189 [hep-ph]].

[2] S. Iwamoto, K. Seller and Z. Trócsányi, JCAP **01** (2022) no.01, 035 [arXiv:2104.11248 [hep-ph]].

[3] S. Iwamoto, T. J. Kärkkäinen, Z. Péli and Z. Trócsányi, Phys. Rev. D **104** (2021) no.5, 055042 [arXiv:2104.14571 [hep-ph]].

[4] T. J. Kärkkäinen and Z. Trócsányi, J. Phys. G **49** (2022) no.4, 045004 [arXiv:2105.13360 [hep-ph]].

[5] Z. Péli and Z. Trócsányi, Phys.Rev.D 106 (2022) 5, 055045 [arXiv:2204.07100 [hep-ph]].

[6] K. Seller, Contribution the 41st International Conference on High Energy physics, in this proceedings [arXiv:2210.16090].

[7] T. J. Kärkkäinen and Z. Trócsányi, *Constraining the parameter space of the superweak extension of the standard model by limits on non-standard interactions and vice versa*, in preparation.

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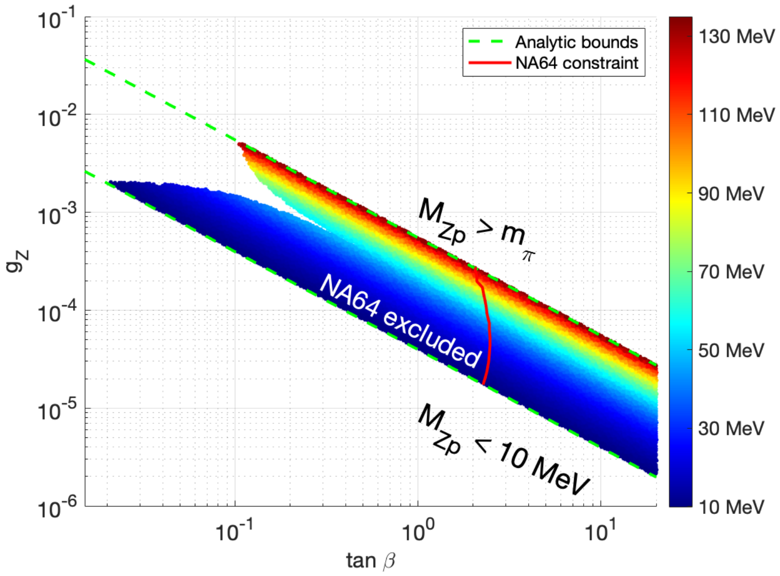

Figure 1: Available parameter space in the $(g_Z, \tan\beta)$ plane with colour corresponding to $M_{Z'}$ in MeV units. Analytic bounds for $M_{Z'} = 10$ MeV, $\eta = 0$ and $M_{Z'} = m_\pi$, $\eta = 0.656$ are given in dashed green. Red line corresponds to constraint on low values of $\tan\beta$ by the NA64 experiment.

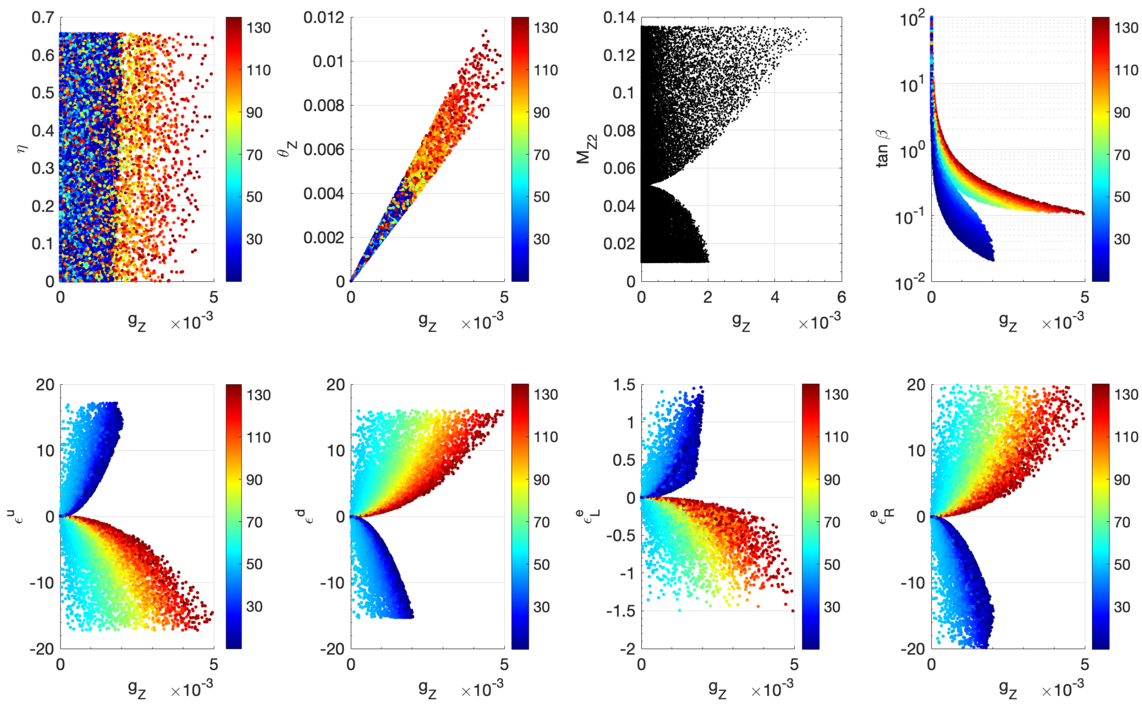

Figure 2: Scatterplots in (g_Z, X) plane, where $X = \eta, \theta_Z, M_{Z'}, \tan\beta, \varepsilon^u, \varepsilon^d, \varepsilon^e_L, \varepsilon^e_R$. Colour coding represents the value of $M_{Z'}$ in MeV units.