Constraints on the $X17$ boson from IceCube searches for non-standard interactions of neutrinos

Rikard Enberg,[a] **Yaşar Hiçyılmaz,**[b,c] **Stefano Moretti,**[a,c] **Carlos Pérez de los Heros**[a] **and Harri Waltari**[a]

[a] *Department of Physics & Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden*

[b] *Department of Physics, Balıkesir University, TR10145, Balıkesir, Turkey*

[c] *School of Physics and Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom.*

Abstract: We explain the ATOMKI anomaly with a very light Z' state that features non-anomalous and non-flavour-universal vector and axial-vector couplings to all leptons. This Z' comes from a theoretical framework with a spontaneously broken $U(1)'$ symmetry in addition to the Standard Model (SM) gauge group and is compliant with current measurements of the anomalous magnetic moments of the electron and the muon as well as beam dump experiments. The lepton flavour structure of this model allows for Z' couplings to all light neutrinos, suggesting the possibility of Z'-mediated Non-Standard Interactions (NSIs) of neutrinos in matter, so that measurements of the strength parameters of the NSIs can constrain the value of the couplings. We use experimental constraints on NSIs of neutrinos using older TEXONO data and newer IceCube data. The IceCube data, in particular, strongly constrain the flavour universality of the leptonic vector current. The constraints enable us to define the region of parameter space of this theoretical scenario that can be pursued in further phenomenological analyses.

Contents

1 Introduction

The discovery of the Higgs boson [1, 2] provided strong evidence that the SM of particle physics is indeed a consistent, and successful, description of elementary particles and their interactions, at least at the energies probed so far in accelerators. There are, however, several experimental "anomalies" that could point to new physics Beyond the SM (BSM). The majority of the experimental results that cannot be explained within the SM have been uncovered in non-LHC experiments, such as $(g-2)_\mu$, the measured value of the magnetic moment of muon in the Muon $g-2$ experiment at Brookhaven National Laboratory (BNL) [3]. Another anomaly is the significant enhancement of more than 5σ in the invariant mass and angular distributions of electron-positron final states of decays of excited ^{8}Be measured by the ATOMKI collaboration in 2015 [4]. Most studies trying to understand this result have demonstrated that standard nuclear physics or QCD cannot lead to a satisfactory explanation [5–12]. The ATOMKI result can be accounted for by the existence of a new vector or axial-vector mediator with a mass of around 17 MeV, which has been called the $X17$ boson [13–19]. In Ref. [13], the authors showed that, in the case of a pure vector coupling, the new boson should be protophobic to satisfy the ^{8}Be anomaly, since its allowed couplings to nucleons are strongly constrained by the NA48/2 experiment [20]. Further studies [22, 43] demonstrated that, due to conflicts with the non-observation of deviations from the SM in neutrino scattering experiments, the scenarios including a pure vector mediator are less favourable, while an axial-vector state appears as the most promising candidate to simultaneously explain all the anomalous nuclear decays reported by the ATOMKI collaboration [5].

As a minimal approach, a family-dependent $U(1)$ extension of the SM would be an ideal way to allow axial-vector couplings that could explain the ATOMKI anomaly. In this framework, the Yukawa interactions are modified by higher-dimensional operators [23, 24]. This scenario, which introduces a new light vector boson, Z', also leads to NSIs of neutrinos that affect neutrino flavour ratios in matter [25]. Currently, limits from the TEXONO experiment have been derived on the combination $\sqrt{\epsilon_e \epsilon_\nu}$, where ϵ_e and ϵ_ν are the couplings of the Z' to electrons and neutrinos, respectively. The limits imply that $\sqrt{\epsilon_e \epsilon_\nu} < 7 \times 10^{-5}$ for constructive interference and $\sqrt{\epsilon_e \epsilon_\nu} < 3 \times 10^{-4}$ for destructive interference [14, 26, 27]. Moreover, the experimental constraints on NSIs from neutrino oscillations can be applied to restrict the family dependent (non-universal) couplings of the new boson with SM fermions. In this paper we will confront the ATOMKI anomaly and the anomalous magnetic moments of leptons with the NSI constraints reported by the IceCube collaboration [28]. We will show the allowed regions of couplings and the amount of non-universality in the minimal $U(1)$ extension of the SM which satisfy IceCube constraints.

The rest of the paper is organised as follows. In Sec. 2 we provide a brief discussion of the main components of the model. We discuss the general formalism of NSI dynamics in Sec. 3 and the constrains from IceCube that we use in our analysis in Sec. 4. After summarising our computational procedure and enforcing experimental constraints in Sec. 5, we present our results over the surviving parameter space of couplings and NSI parameters in Sec. 6. Finally, we summarise and conclude in Sec. 7.

2 The $U(1)'$ model

We focus on an extension of the SM with a generic $U(1)'$ symmetry which mixes with the SM $U(1)_Y$. The kinetic term of the Lagrangian is given by

$$\mathcal{L}_{\text{Kin.}}^{U(1)'} = \mathcal{L}_{\text{Kin.}}^{\text{SM}} - \frac{1}{4}\hat{F}'_{\mu\nu}\hat{F}'^{\mu\nu} - \frac{\eta}{2}\hat{F}'_{\mu\nu}\hat{F}^{\mu\nu}, \tag{2.1}$$

where $F_{\mu\nu}$ and $F'_{\mu\nu}$ are the field strengths of the gauge fields B_μ and B'_μ that correspond $U(1)_Y$ and $U(1)'$, respectively, and η quantifies the kinetic mixing between these abelian symmetries. The gauge covariant derivative can be written as

$$\mathcal{D}_\mu = \partial_\mu + \cdots + ig_1 Y B_\mu + i(\tilde{g}Y + g'Q')B'_\mu, \tag{2.2}$$

where Y and g_1 are the hypercharge and its gauge coupling while Q' and g' in the additional term are the $U(1)'$ charge and its gauge coupling. In addition, $\tilde{g}$ is the mixed gauge coupling between the two gauge groups. The $U(1)'$ symmetry is broken by a new scalar χ, which is a singlet under the SM gauge group and has $U(1)'$ charge Q'_χ and vacuum expectation value (VEV) $\chi = v'$. The spontaneous breaking of the $U(1)'$ symmetry results in a mass term of a new vector boson, $m_{Z'} = g'Q'_\chi v'$. In the case of $g' \sim \mathcal{O}(10^{-4} - 10^{-5})$, m'_Z would be light, with mass order of $\mathcal{O}(10)$ MeV, which is the desired mass region for a potential solution of the ATOMKI anomaly.

The scalar potential of the model is

$$\begin{aligned} V(H,\chi) &= -\mu^2|H|^2 + \lambda|H|^4 - \mu_\chi^2|\chi|^2 + \lambda_\chi|\chi|^4 \\ &\quad + \kappa|\chi|^2|H|^2 \,, \end{aligned} \tag{2.3}$$

where H is the SM Higgs doublet and κ is the mixing parameter that connects the SM and χ Higgs fields. Unlike the SM Higgs sector, there are two physical Higgs states whose mass matrix can be written as

$$m^2_{h_2h_1} = \begin{pmatrix} 2\lambda v^2 & \kappa v v' \\ \kappa v v' & 2\lambda_\chi v'^2 \end{pmatrix}, \tag{2.4}$$

where h_2 is dominantly the SM-like Higgs boson while the exotic boson h_1 is dominantly a singlet-like Higgs state. In Ref. [29], the possible Z' signatures mediated by such Higgs bosons where worked out.

The Lagrangian that describes the interactions of the extra gauge boson Z' with SM fermions is

$$\begin{aligned} \mathcal{L}^{Z'} &= \bar{q}\gamma^\mu \left(C_L^{qq'}P_L + C_R^{qq'}P_R\right) q' Z'_\mu + \bar{\nu}_l\gamma^\mu \left(C_L^{ll'}P_L\right)\nu_{l'} Z'_\mu \\ &\quad + \bar{l}\gamma^\mu \left(C_L^{ll'}P_L + C_R^{ll'}P_R\right) l' Z'_\mu, \end{aligned} \tag{2.5}$$

where $q^{(\prime)}$, $l^{(\prime)}$ and $\nu_{l^{(\prime)}}$ refer to up-type/down-type quarks, charged leptons and their neutrinos while C_L^{XX} and C_R^{XX} are Left (L) and Right (R) handed couplings and P_L and P_R the corresponding projection operators $\frac{1\mp\gamma^5}{2}$, respectively. In our model, there is no flavour-violating (non-diagonal) coupling terms for the quark and lepton sector while the flavour-conserving (diagonal) $f = f'$ coupling terms are written as

$$C_L^{ff} = -g_Z \sin\theta' \left(T_f^3 - \sin^2\theta_W Q_f\right) + (\tilde{g}Y_{f,L} + g'Q'_{f,L})\cos\theta', \tag{2.6}$$

$$C_R^{ff} = g_Z \sin^2(\theta_W)\sin(\theta')Q_f + (\tilde{g}Y_{f,R} + g'Q'_{f,R})\cos\theta', \tag{2.7}$$

where $g_Z = \sqrt{g_1^2 + g_2^2}$ is the electroweak (EW) coupling, θ_W is the Weinberg angle and θ' is the $Z - Z'$ mixing angle, which is small. Here, T_f^3 and Q_f denote the weak isospin and electric charge of the fermion f, respectively. Finally, $Y_{f,L/R}$ and $Q'_{f,L/R}$ indicate the hypercharge and $U(1)'$ charges of the L/R-handed fermion.

Our theoretical model relies on flavour-dependent charges of the Z'. Having such non-universal $U(1)'$ charges allows axial-vector couplings of the Z' with nucleons, which are crucial to overcome the strict experimental bounds in the pure vector coupling case [13, 14, 20]. To achieve this, in Ref. [24] a new mechanism was identified that generates masses and couplings of the first two fermion generations at higher orders as the SM-like Yukawa interactions are available only for the third generation [24].

The charges must also satisfy the anomaly cancellation conditions for the fermionic content of the SM and the additional R-handed neutrinos,

$$\sum_i^3 (2Q'_{Q_i} - Q'_{u_i} - Q'_{d_i}) = 0\,, \tag{2.8}$$

$$\sum_i^3 (3Q'_{Q_i} + Q'_{L_i}) = 0\,, \tag{2.9}$$

$$\sum_i^3 \left(\frac{Q'_{Q_i}}{6} - \frac{4}{3} Q'_{u_i} - \frac{Q'_{d_i}}{3} + \frac{Q'_{L_i}}{2} - Q'_{e_i} \right) = 0\,, \tag{2.10}$$

$$\sum_i^3 \left(Q'^2_{Q_i} - 2Q'^2_{u_i} + Q'^2_{d_i} - Q'^2_{L_i} + Q'^2_{e_i}\right) = 0\,, \tag{2.11}$$

$$\sum_i^3 \left(6Q'^3_{Q_i} - 3Q'^3_{u_i} - 3Q'^3_{d_i} + 2Q'^3_{L_i} - Q'^3_{e_i}\right) + \sum_i^3 Q'^3_{\nu_i} = 0\,, \tag{2.12}$$

$$\sum_i^3 \left(6Q'_{Q_i} - 3Q'_{u_i} - 3Q'_{d_i} + 2Q'_{L_i} - Q'_{e_i}\right) + \sum_i^3 Q'_{\nu_i} = 0. \tag{2.13}$$

In addition to these conditions, we also impose that the first two generations of quarks be flavour-universal under $U(1)'$ in order to alleviate experimental bounds on flavour violation of the quarks. Conversely, for the purpose of this study, the $U(1)'$ charges of the lepton sector were left as fully non-universal. In the next section, we present the general formalism for NSIs and how these non-universal charges relate to the NSI parameters.

3 Neutrino NSIs

New physics effects in the neutrino sector, such as couplings between neutrinos and unknown particles, can be described by a model independent four-fermion effective Lagrangian that corresponds to NSIs [30, 31]. The NSI Lagrangian including neutral currents (NC) can be parameterised in terms of the dimensionless NSI parameters $\varepsilon^{fX}_{\alpha\beta}$ as

$$\mathcal{L}^{\rm NC}_{\rm NSI} = -2\sqrt{2} G_F \varepsilon^{fX}_{\alpha\beta} [\bar{f}\gamma^\mu P_X f][\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta], \tag{3.1}$$

where X is either L or R, $f = u,\ d,\ e$ and G_F is the Fermi constant. Neutrino flavours are given by $\alpha,\ \beta\ = e,\ \mu,\ \tau$. In the case of $\alpha \neq \beta$, the NSI parameters imply flavour–violating new physics interactions in equation (3.1), while $\alpha = \beta$ indicates flavour-conserving NSI terms. The former lead to zero-distance flavour-changing effects, which one can probe with the near detector of oscillation experiments. Both flavour-conserving and flavour-violating effects can lead to a modification of matter oscillations [32, 33] to which IceCube is sensitive. Since gauge interactions are (nearly) flavour-diagonal, we concentrate on flavour-conserving interactions in what follows.

Considering the effective Lagrangian in equation (3.1), we have a relation between the NSI parameters and the propagator of the mediator, $\varepsilon^{fX}_{\alpha\beta} \propto \frac{1}{q^2 - M^2}$, where q and M are the mediator momentum and mass, respectively. Matter oscillations arise from the interference of unperturbed propagation and gauge boson exchange in the forward direction, thus the limit $q^2 \to 0$ applies, so that the mass term dominates in the denominator even if the gauge boson is light. Therefore, an additional Z' boson which satisfies the ATOMKI anomaly could provide a non-trivial contribution to the matter NSI parameters. Using the interaction terms in equation (2.5), it is possible to generate the Z' mediated effective NSI Lagrangian in equation (3.1), with corresponding NSI parameters

$$\varepsilon^{fX}_{\alpha\beta} = \frac{1}{2\sqrt{2}G_F}\frac{C_L^{\alpha\beta}C_X^{ff}}{M^2_{Z'}}. \tag{3.2}$$

The $\varepsilon^{fX}_{\alpha\beta}$ are the effective couplings of neutrinos with fundamental fermions and affect neutrino propagation in matter. The relevant NSI effective couplings for neutrino propagation in a medium are their vector parts, $\varepsilon^{fV}_{\alpha\beta} = \varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}$ and the total strength of NSIs for a given medium has the form

$$\epsilon_{\alpha\beta} = \sum_f (\varepsilon^{fV}_{\alpha\beta})\frac{N_f}{N_e}, \tag{3.3}$$

where $f = u, d, e$. Here N_f is the number density of the fermion f in matter. Inside the Sun, $N_u/N_e \simeq 2N_d/N_e \simeq 1$ [34] while inside the Earth, $N_u/N_e \simeq N_d/N_e \simeq 3$ [35]. Notice that the axial vector part of the current does not contribute and hence matter oscillations will not constrain it. In the presence of NSI couplings of neutrinos with the matter field f, the effective Hamiltonian is written as

$$H = \frac{1}{2E_\nu}U_{\rm PMNS}\,{\rm diag}(0, \Delta m^2_{21}, \Delta m^2_{31})\,U^\dagger_{\rm PMNS} + V_{\rm CC}\,{\rm diag}(1,0,0) + V_{\rm CC}\,\epsilon_{\alpha\beta}\ , \tag{3.4}$$

where $U_{\rm PMNS}$ is the vacuum Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix while E_ν and $\Delta m^2_{ij} \equiv \Delta m^2_i - \Delta m^2_j$ are the neutrino energy and mass square differences, respectively. The second term describes the SM interactions in an unpolarised medium with the Wolfenstein matter potential $V_{\rm CC} = \sqrt{2}G_F N_e$ [32], where N_e is the local electron number density. The last term of equation (3.4) is the NSI contribution, where the Hermitian matrix of the NSI strength parameters $\epsilon_{\alpha\beta}$ shown in equation (3.3) can be written as

$$\epsilon_{\alpha\beta} = \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix} . \tag{3.5}$$

The diagonal terms in equation (3.5), if non-universal, lead to enhanced matter oscillations proportional to the difference in the diagonal NSI parameters, i.e., to $\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$ and $\epsilon_{ee} - \epsilon_{\mu\mu}$. Since any flavour-universal part gives just an unobservable common phase to the neutrinos, one can subtract $\epsilon_{\mu\mu}$ from the diagonal in equation (3.5), then the diagonal part of the matrix $\epsilon_{\alpha\beta}$ can be written as $\text{diag}(\epsilon_{ee} - \epsilon_{\mu\mu}, 0, \epsilon_{\tau\tau} - \epsilon_{\mu\mu})$.

We approximate the hadrons to consist of their valence quarks[1], so we write the NSI parameters of the effective matter potential in terms of electron, proton and neutron NSI parameters as

$$\epsilon^{\oplus}_{\alpha\beta} = \epsilon^{eV}_{\alpha\beta} + \epsilon^{pV}_{\alpha\beta} + Y^{\oplus}_n \epsilon^{nV}_{\alpha\beta}, \tag{3.6}$$

where $\epsilon^{pV}_{\alpha\beta} = 2\epsilon^{uV}_{\alpha\beta} + \epsilon^{dV}_{\alpha\beta}$, $\epsilon^{nV}_{\alpha\beta} = 2\epsilon^{dV}_{\alpha\beta} + \epsilon^{uV}_{\alpha\beta}$ and $Y^{\oplus}_n$ is the relative neutron-to-electron number density of the Earth, $Y^{\oplus}_n \equiv N_n/N_e \approx 1.051$ [36]. Finally, one can obtain the NSI matrix in the Hamiltonian with new definitions as

$$\epsilon^{\oplus}_{\alpha\beta} = \begin{pmatrix} \epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu} & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & 0 & \epsilon^{\oplus}_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & \epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu} \end{pmatrix} . \tag{3.7}$$

Notice again that there is no flavour violation (non-diagonal terms) in the theoretical model of this work.

4 Constraints on NSIs from IceCube

The previous generic parameterisation of the strength of NSIs as shown in equation (3.7) has been used by the IceCube collaboration in Ref. [28] to constrain the parameters $\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu}$, $\epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu}$, $|\epsilon^{\oplus}_{e\mu}|$ $|\epsilon^{\oplus}_{e\tau}|$ and $|\epsilon^{\oplus}_{\mu\tau}|$ using a pure sample of atmospheric neutrinos (and antineutrinos) of all flavours with energies between 5.6 GeV and 100 GeV. The use of atmospheric neutrinos allows to sample a wide range of oscillation baselines, from a few tens of kilometres, for downgoing neutrinos produced "above" the detector that only cross the atmosphere, to the whole diameter of the Earth, 1.3×10^4 km, for upgoing neutrinos produced at the antipodes of the detector. Matter effects can thus be expected for neutrinos

[1] The Z', being uncoloured, does not see the gluonic sea. Since the momentum transfer is low, it cannot resolve the internal structure of the proton. Hence quark-antiquark pairs, having opposite charges (being dipole-like objects), will to first approximation look neutral and only the monopole charges of the valence quarks will be seen by the Z' boson.

Parameter	Scanned range	Parameter	Scanned range
g'	$[10^{-5}, 5 \times 10^{-5}]$	λ	$[0.125, 0.132]$
$\tilde{g}$	$[-10^{-3}, 10^{-3}]$	λ_χ	$[10^{-5}, 10^{-1}]$
v'	$[0.1, 1]$ TeV	κ	$[10^{-6}, 10^{-2}]$

Table 1. Scanned parameter space of the model.

arriving to the detector from below the horizon, while the atmosphere is too thin to induce any matter effects on the neutrino flux arriving to the detector from above.

Comparing the measured flavour composition of the neutrino flux at the detector as a function of energy and baseline with the expected corresponding flux under standard oscillations, strong limits on the NSI parameters can be set. Note that these constraints were obtained by allowing one of the parameters to be non-zero at a time. We do not consider flavour-violating terms in our study, so we only use the IceCube limits on flavour-diagonal interactions, shown in Table 2, in order to put constraints on the model described in Sec. 2.

5 Constraints on the $U(1)'$ model from NSI results

To define the parameter space of our model we have used the SPheno [37–39] and SARAH 4.14.3 [40, 41] codes. The scanning of the parameter space was performed using the Metropolis-Hastings algorithm, within the ranges specified in Table 1.

We require the Higgs boson mass to be within 3 GeV from its observed value and implement constraints on branching ratios of B-decays, specifically $\mathrm{BR}(B \to X_s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$ and $\mathrm{BR}(B_u \to \tau\nu_\tau)$. We have also bounded the value of the $Z-Z'$ mixing parameter θ' (see Eqs. (2.6) and (2.7)) to be less than a few times 10^{-3} as a result of EW Precision Tests (EWPTs) [42]. In the last part of the numerical analyses, we constrain the parameter space to satisfy the current experimental bounds of $(g-2)_e$, $(g-2)_\mu$, the ATOMKI anomaly, the electron beam dump experiment NA64, TEXONO limits and IceCube results [28, 43–49]. The experimental constraints are summarised in Table 2.

6 Results

In this section, we present the numerical analysis in the light of the experimental constraints from the previous section. First, let us focus on the diagonal NSI parameters shown in equation (3.7). Fig. 1 depicts the distribution of these parameters after scanning the parameter space. All points are consistent with Higgs mass bounds and the $Z-Z'$ mixing satisfying EWPTs. Green points are a subset of the gray ones as they also satisfy constraints on B-decays and Z' mass around 17 MeV. Yellow points are a subset of the green ones as they

Observable	Constraint	Tolerance	Reference(s)
m_h	122 GeV – 128 GeV		
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$0.8 \times 10^{-9} - 6.2 \times 10^{-9}$	2σ	[45]
$\mathrm{BR}(B \to X_s\gamma)$	$2.99 \times 10^{-4} - 3.87 \times 10^{-4}$	2σ	[44]
$\frac{\mathrm{BR}(B_u\to\tau\nu_\tau)}{\mathrm{BR}(B_u\to\tau\nu_\tau)_{\mathrm{SM}}}$	$0.15 - 2.41$	3σ	[46]
Δa_e^{Rb}	$(4.8 \pm 9.0) \times 10^{-13}$	3σ	[48]
Δa_μ	$(2.45 \pm 1.47) \times 10^{-9}$	3σ	[47]
$\epsilon_{ee}^{\oplus} - \epsilon_{\mu\mu}^{\oplus}$	$[-2.26, -1.27] \cup [-0.74, 0.32]$		[28]
$\epsilon_{\tau\tau}^{\oplus} - \epsilon_{\mu\mu}^{\oplus}$	$[-0.041, 0.042]$		[28]

Table 2. Summary of the experimental constraints used.

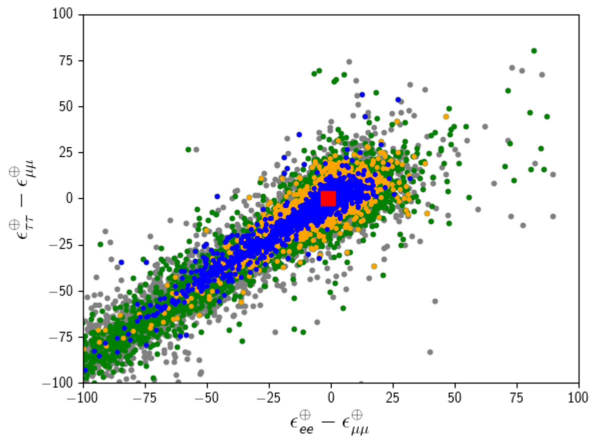

Figure 1. The distribution of diagonal NSI parameters shown in equation (3.7). All points are consistent with Higgs mass bounds and the $Z - Z'$ mixing satisfying EWPTs. Green points are a subset of the gray ones as they also satisfy constraints on B-decays and Z' mass around 17 MeV. Yellow points are a subset of the green ones as they are also compatible with the current experimental bounds of $(g-2)_\mu$ while blue points, that are a subset of the yellow ones, also satisfy the experimental limits from $(g-2)_e$, NA64 and TEXONO. The red square inside the blue points represents the region constrained by IceCube results.

are also compatible with the current experimental bounds of $(g-2)_\mu$ while blue points, that are a subset of the yellow ones, also satisfy the experimental limits from $(g-2)_e$, NA64 and TEXONO. The red square inside the blue points represents the region allowed by IceCube results. As can be seen from the figure, most of our solutions are ruled out by the IceCube bounds on NSI parameters.

In the light of these strict bounds, we will show the constraints on Z' couplings. In Fig. 2, we represent the allowed vector and axial-vector Z' couplings with up-quarks (top left), down-quarks (top right) and electron (bottom). The colour convention is the same as

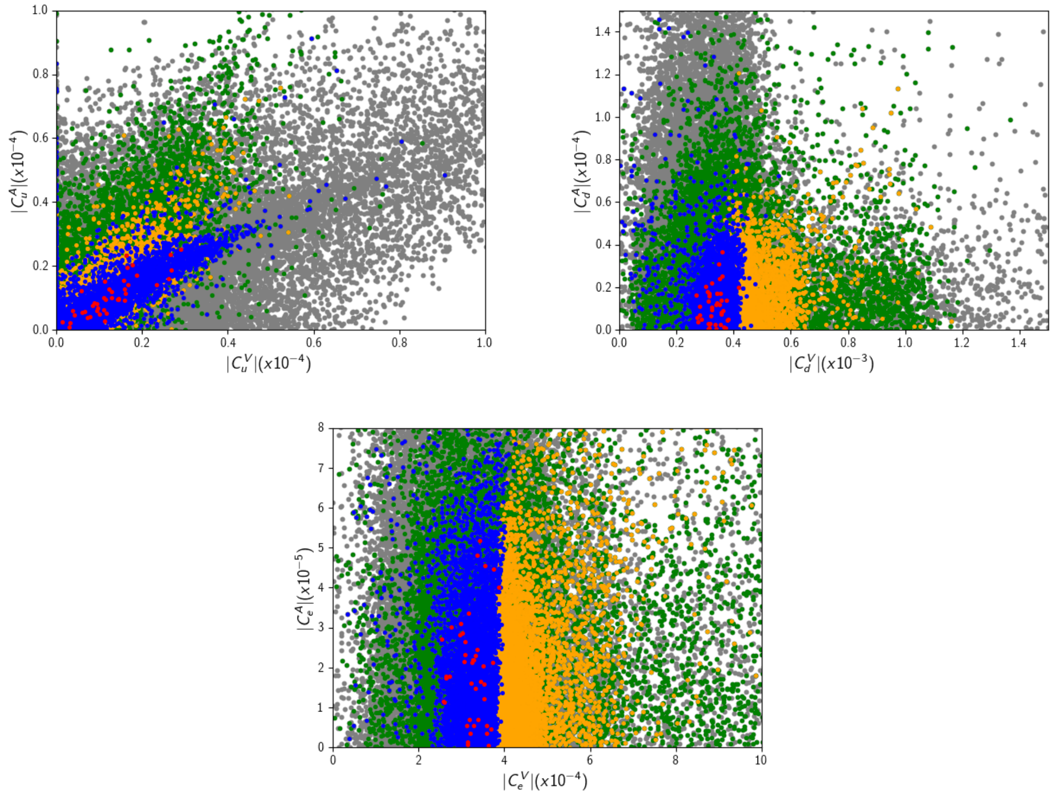

Figure 2. The allowed regions for the vector and axial-vector Z' couplings with up-quarks (top left), down-quarks (top right), electron (bottom). The colour convention is the same as in Fig. 1 while additional red points are a subset of the blue ones as they also satisfy the NSI parameters constrained by IceCube results.

in Fig. 1 while additional red points are a subset of the blue ones as they also satisfy the NSI parameters constrained by IceCube results. According to our results, the vector couplings between Z' and u, d, e, the fundamental particles in the medium, tend to be in the interval of $\mathcal{O}(10^{-5} - 10^{-3})$ while the axial-couplings should be of $\mathcal{O}(10^{-5})$. Since the effective NSI couplings are related to the vector parts of the NSI parameters shown in equation (3.3), the vector couplings are strongly bounded by IceCube constraints on NSIs. Furthermore, Fig. 3 presents the distributions of diagonal NSI parameters in terms of the Z' couplings (colour bars) with electron neutrino (top left), muon neutrino (top right) and tau neutrino (bottom left). All points in these graphs depict only blue points in Fig. 1. The red square again shows the region allowed by IceCube results. As can be seen from the panels in the figure, when all constraints are applied, the Z' couplings with electron and tau neutrinos are restricted to be of $\mathcal{O}(10^{-6})$.

Since, in principle, the diagonal NSI terms in equation (3.7) arise from the non-universality in the lepton sector, it is not hard to guess that the major impact of the

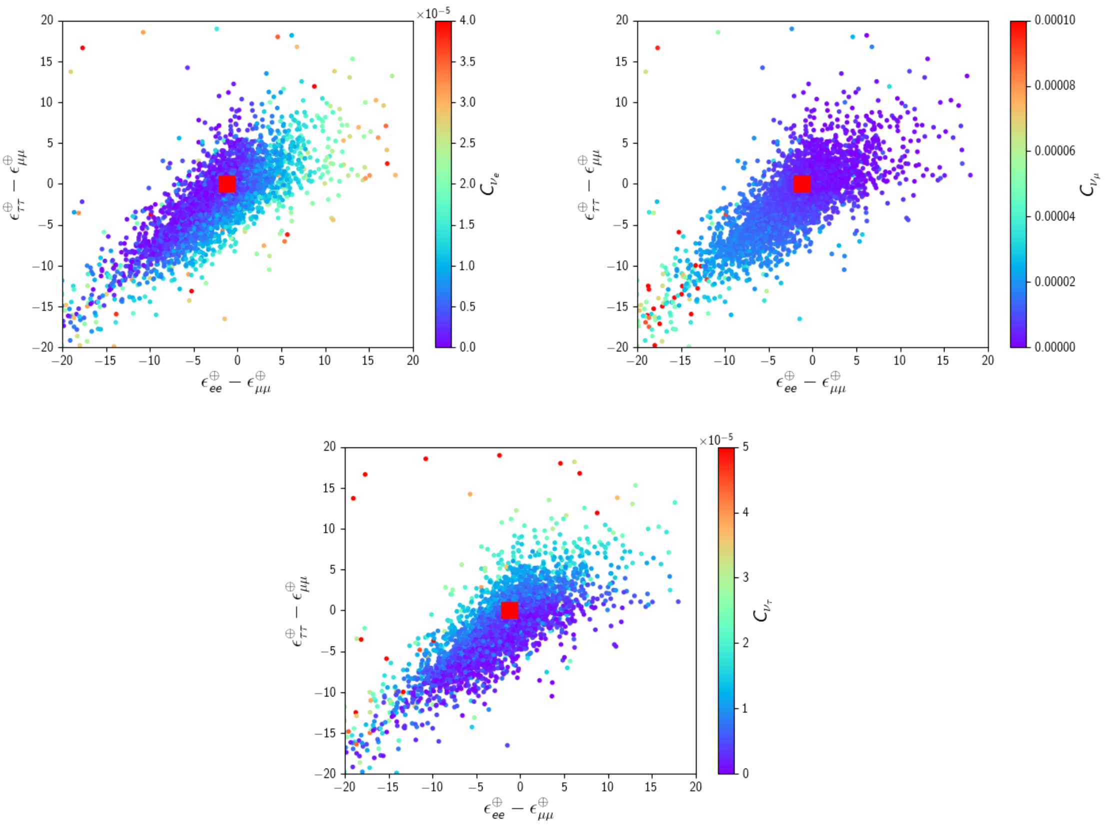

Figure 3. The distributions of diagonal NSI parameters in terms of Z' couplings (colour bars) with electron neutrino (top left), muon neutrino (top right) and tau neutrino (bottom left). All points depicts the blue points in Fig. 1. The red square shows the region constrained by IceCube results.

IceCube results will be on non-universality of the Z'-lepton couplings. Fig. 4 indicates the allowed regions for the ratios of Z' couplings with charged leptons (top) and neutrinos (bottom). Here, the colour convention is the same as in Fig. 2. As we expected, the ratios of vector couplings are mostly bounded. It is important to note that, after applying the NSI constraints from IceCube as well, the vector couplings between Z' and charged leptons should be of the same magnitude, $|C^V_e/C^V_\mu| \approx |C^V_\tau/C^V_\mu| \approx 1$, that can be deemed universal, while the axial-vector Z' couplings for each charged lepton, not constrained by IceCube data, allow significant non-universality, as $0 < |C^A_e/C^A_\mu|, |C^A_\tau/C^A_\mu| < 10$. Therefore, one can expect that possible signatures for such theoretical frameworks could be explored in Lepton Flavour Violation (LFV) processes which are more sensitive to the new boson axial couplings than its vector couplings. When we look at the bottom panel in order to check the relations between the couplings of the Z' with each neutrino flavour, it can be easily seen that those for μ and τ neutrinos should be universal, $|C_{\nu_\mu}/C_{\nu_\tau}| \approx 1$, because of the small values of $\epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu}$, according to the NSI bounds from IceCube. In contrast, the electron

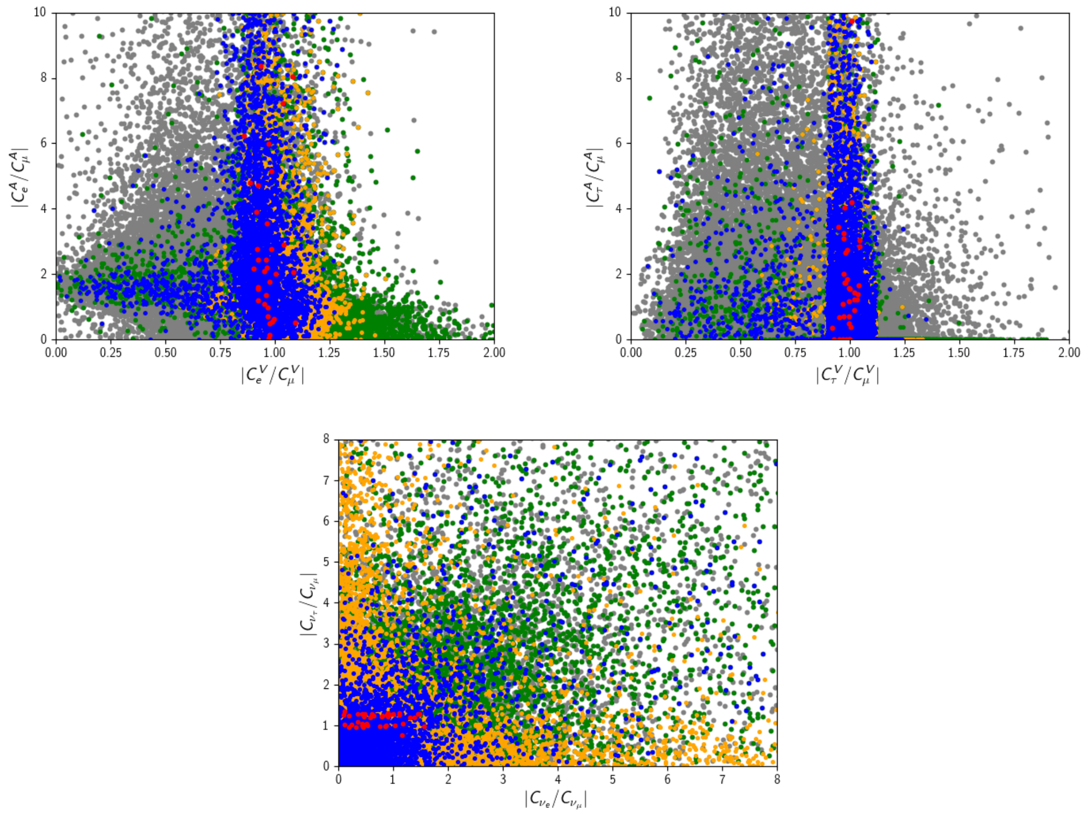

Figure 4. The allowed regions for the ratios of Z' couplings with e, μ and τ leptons (top) and neutrinos (bottom). Here, the colour convention is the same as in Fig. 2.

neutrino coupling can be different than others with an interval as $0 < |C_{\nu_e}/C_{\nu_\mu}| < 2$ for the reason that $\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu}$ parameter gets looser bounds from IceCube data.

Before closing, we investigate how the IceCube bounds impact the relevant NSI effective couplings for neutrino propagation. Fig. 5 displays the allowed regions for NSI effective couplings of neutrinos with up-quarks (top), down-quarks (middle) and electrons (bottom) via Z' mediation. The colour convention is the same as in Fig. 2. As can be seen from the graphs, in the light of the IceCube results, all effective couplings are restricted to the region with $\epsilon \lesssim 1$. Considering the solutions which satisfy all experimental constraints except for NSI bounds (blue points), it is clear that the effective couplings, via light vector boson mediation, between neutrinos and the components of the atoms in the medium are heavily limited by IceCube results.

To finalise our discussion about these results, we display four Benchmark Points (BPs): in fact, Table 3 displays four solutions which are selected to be consistent with all experimental constraints applied in our analyses as well as NSI results from IceCube.

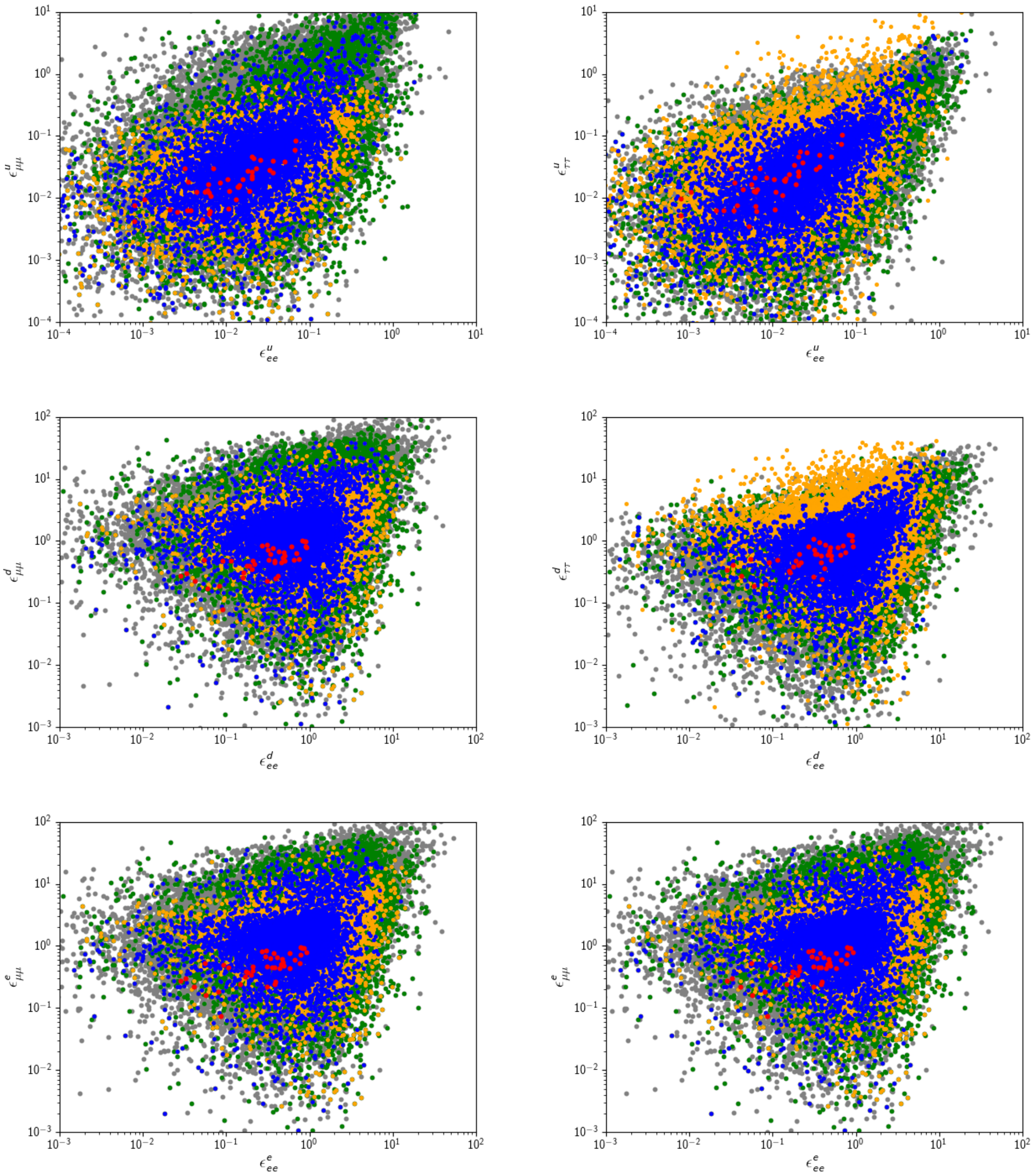

Figure 5. The allowed regions for NSI effective couplings of neutrinos with up-quarks (top), down-quarks (middle) and electrons (bottom) via Z' mediation. The colour convention is the same as in Fig. 2.

7 Conclusions

In summary, we have proposed a rather simple theoretical framework, relying on a $U(1)'$ extension of the SM with non-anomalous and flavour-dependent charges allowing for vector

Parameters	BM1	BM2	BM3	BM4
g'	2.33×10^{-5}	2.15×10^{-5}	1.61×10^{-5}	1.76×10^{-5}
$\tilde{g}$	-4.80×10^{-4}	-3.79×10^{-4}	-4.53×10^{-4}	-4.35×10^{-4}
v'	358	402	531	492
λ_χ	0.046	0.0047	0.015	0.015
κ	0.0066	0.0024	0.0063	0.0068
$(m_{H_1},\ m_{H_2})$	$(109.02, 124.23)$	$(39.25, 124.35)$	$(93.11, 126.54)$	$(85.46, 127.14)$
$m_{Z'}$	0.0167	0.0172	0.0171	0.0173
(C_u^V, C_u^A)	$(-3.77 \times 10^{-6}, -5.90 \times 10^{-6})$	$(-1.65 \times 10^{-5}, -1.94 \times 10^{-5})$	$(-1.64 \times 10^{-5}, -2.33 \times 10^{-5})$	$(-1.78 \times 10^{-5}, -2.03 \times 10^{-5})$
(C_d^V, C_d^A)	$(3.81 \times 10^{-4}, 4.95 \times 10^{-6})$	$(3.23 \times 10^{-4}, -9.45 \times 10^{-6})$	$(3.60 \times 10^{-4}, 2.51 \times 10^{-5})$	$(3.47 \times 10^{-4}, 3.08 \times 10^{-5})$
(C_e^V, C_e^A)	$(3.63 \times 10^{-4}, -4.18 \times 10^{-7})$	$(3.38 \times 10^{-4}, 6.98 \times 10^{-6})$	deemed $(3.74 \times 10^{-4}, 4.46 \times 10^{-5})$	$(3.54 \times 10^{-4}, 4.54 \times 10^{-5})$
(C_{ν_e}, C_{ν_μ})	$(5.48 \times 10^{-6}, -5.86 \times 10^{-6})$	$(-4.09 \times 10^{-7}, -3.80 \times 10^{-6})$	$(-1.09 \times 10^{-6}, -2.08 \times 10^{-6})$	$(2.61 \times 10^{-6}, -5.40 \times 10^{-6})$
$(\epsilon^u_{ee}, \epsilon^u_{\mu\mu}, \epsilon^u_{\tau\tau})$	$(0.014, 0.015, 0.019)$	$(0.003, 0.029, 0.031)$	$(0.010, 0.020, 0.020)$	$(0.021, 0.044, 0.056)$
$(\epsilon^d_{ee}, \epsilon^d_{\mu\mu}, \epsilon^d_{\tau\tau})$	$(0.91, 0.97, 1.23)$	$(0.05, 0.49, 0.51)$	$(0.16, 0.31, 0.3)$	$(0.36, 0.76, 0.96)$
$(\epsilon^e_{ee}, \epsilon^e_{\mu\mu}, \epsilon^e_{\tau\tau})$	$(0.86, 0.92, 0.12)$	$(0.05, 0.52, 0.52)$	$(0.17, 0.32, 0.32)$	$(0.37, 0.77, 0.10)$
$\epsilon^\oplus_{ee} - \epsilon^\oplus_{\mu\mu}$	-0.25	-1.92	-0.64	-1.68
$\epsilon^\oplus_{\tau\tau} - \epsilon^\oplus_{\mu\mu}$	0.026	0.04	0.013	0.004

Table 3. The BPs which are selected to be consistent with all experimental constraints as well as NSI results from IceCube. All masses are given in GeV.

and axial-vector couplings to nucleons of a new Z' state, with a mass of $O(10)$ MeV, emerging from the spontaneous breaking of such a new gauge group, so that it can be a possible explanation of the so-called $X17$ anomaly. However, in order to comply with experimental bounds on flavour-violation in the quark sector, we have imposed that the first two quark generations are flavour-universal under this $U(1)'$ gauge group while the corresponding charges of the lepton sector are left as fully non-universal. As a consequence, couplings of the Z' state with all light neutrinos are present in the model and may manifest themselves in NSIs of neutrinos affecting neutrino flavour ratios in matter.

We have constrained this theoretical construct with data from the ATOMKI collaboration and other low energy experiments, such as NA64 searches for the Z' and data on $(g-2)_{e,\mu}$, and additionally against the IceCube neutrino experiment (complementing earlier data from TEXONO) for the purpose of constraining Z' couplings in the lepton sector from the NSI strength parameters. IceCube data constrain the vector parts of the Z' interactions with leptons to be nearly flavour-universal while they give no constraints on the universality of the axial vector part. In the neutrino sector the constraints on $\mu - \tau$ universality are strong while $e - \mu$ universality is somewhat less constrained by the IceCube results.

We have in the end found that sizeable regions of parameter space exist in this theoretical framework able to accommodate all such constraints, wherein we have defined four BPs amenable to further phenomenological investigation.

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