

The non-Universal U(1) gauge extended $\mu\nu$ SSM: anomalies cancellation and singular phenomenology

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ABSTRACT: So far the most sophisticated experiments have shown no trace of new physics at the TeV scale. Consequently, new models with unexplored parameter regions are necessary to explain current results, re-examine the existing data, and propose new experiments. In this Letter, we present a modified version of the $\mu\nu$ SSM supersymmetric model where a non-Universal extra U(1) gauge symmetry is added in order to restore an effective R-parity that ensures proton stability. We show that anomalies equations cancel without having to add *any* exotic matter, restricting the charges of the fields under the extra symmetry to a discrete set of values. We find that it is the viability of the model through anomalies cancellation what defines the conditions in which fermions interact with dark matter candidates via the exchange of Z' bosons. The strict condition of universality violation means that LHC constraints for a Z' mass do not apply directly to our model, allowing for a yet undiscovered relatively light Z' , as we discuss both in the phenomenological context and in its implications for possible flavour changing neutral currents. Moreover, we explore the possibility of isospin violating dark matter interactions; we observe that this interaction depends, surprisingly, on the Higgs charges under the new symmetry, both limiting the number of possible models and allowing to analyse indirect dark matter searches in the light of well defined, particular scenarios.

KEYWORDS: Supersymmetry Phenomenology

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1 Introduction

Barring the Higgs discovery [1, 2], no signs of new physics beyond the Standard Model (SM) have been seen so far after run 1 of the LHC. In particular, regarding Supersymmetry (SUSY), there are no signals of the coloured states [3], namely squarks and gluinos, that were predicted to be abundant in the TeV scale. These data impose severe constraints on the allowed SUSY models, pushing the coloured states to masses beyond 1 TeV. However, several recast analyses showed that –even in already existing experimental data– there still is much room for light SUSY states [4–8].

The minimal supersymmetric standard model (MSSM) is the most simple realisation of a $N = 1$ SUSY model. In the MSSM construction however, the mass term responsible for the electroweak symmetry breaking (EWSB), i.e. the μ -term, is added *ad hoc*, not specifying its origin [9–12]. Another important issue is that the MSSM is unable to explain the fact that neutrinos do have mass [13, 14]. An elegant proposal to solve both problems at once comes from the so-called “ μ from ν ” supersymmetric model ($\mu\nu$ SSM),¹ which proposes introducing right-handed neutrinos to solve the μ -problem and clarifying the origin of the left-handed neutrinos masses. The superpotential reads as follows,

$$\begin{aligned}
 W = & \epsilon_{ab} \left(Y_u^{ij} \hat{H}_2^b \hat{Q}_i^a \hat{u}_j^c + Y_d^{ij} \hat{H}_1^a \hat{Q}_i^b \hat{d}_j^c + Y_e^{ij} \hat{H}_1^a \hat{L}_i^b \hat{e}_j^c + Y_\nu^{ij} \hat{H}_2^b \hat{L}_i^a \hat{\nu}_j^c \right) \\
 & - \epsilon_{ab} \lambda^i \hat{\nu}_i^c \hat{H}_1^a \hat{H}_2^b + \frac{1}{3} \kappa^{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c.
 \end{aligned}
 \tag{1.1}$$

Two new terms in the superpotential of eq. (1.1) account for these properties: the first one, $\lambda_i \hat{\nu}_i^c \hat{H}_d \hat{H}_u$, $i = 1, 2, 3$, is a trilinear coupling between the Higgs and the three families of right-handed neutrinos. When EWSB takes place the supersymmetric partners of the right-handed neutrinos, the right-handed sneutrinos $\tilde{\nu}_i^c$, develop vacuum expectation

¹See ref. [15] and references therein for an extensive review.

values (VEVs) giving rise to an effective μ term, $\mu \sim \lambda v_i^c$. The second new term in the superpotential, $\kappa_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c$, provides Majorana masses to the right-handed neutrinos after EWSB takes place. As the right-handed neutrinos couple to the leptons, a low-scale see-saw mechanism is induced and the light left-handed neutrinos become massive [16–19].

As a result of the heavy mixing occurring within the neutral and charged sectors, the $\mu\nu$ SSM presents a very rich phenomenology, markedly different from the usual collider scenarios [20–26]. This means not only that new parameter regions open up for SUSY searches but also that the $\mu\nu$ SSM model predictions could have escaped unnoticed so far. Nonetheless the $\mu\nu$ SSM has issues as well; both new terms added to the superpotential explicitly break R -parity (R_p) via the right-handed neutrinos, where such breaking is governed by the value of the neutrino Yukawa coupling, Y_ν . As R_p is no longer a symmetry of the model, dangerous lepton and baryon number violating terms are allowed in the superpotential. Likewise, the stability of the proton is no longer guaranteed. To recover an effective R_p and at the same time allow only trilinear terms in the superpotential, one can invoke a $U(1)$ gauge symmetry, which appears naturally in string realisations of the SM (see for example refs. [27–30]).

The presence of an extra $U(1)$ symmetry has already been explored both in the SM (see for example refs. [31–33]), as well as in supersymmetric realisations, of which refs. [34–42] are only a few examples. In fact for the $\mu\nu$ SSM it has already been tentatively explored leading to promising results [43]. The price to pay however is having to recalculate the anomalies cancellation conditions, which for the SM matter content and gauge groups are known to be “miraculously” fulfilled. For example, in ref. [43] it was found that for the $\mu\nu$ SSM to be consistent with an extra $U(1)$ gauge symmetry, the matter content of the model has to be enlarged by several extra colour triplets, left doublets and singlet fields. Moreover, it is a general rule for all gauge extended models that exotic fields are needed for the model to be anomaly free. While the possibility of exotic fields cannot be excluded, its presence is problematic, not only due to the lack of evidence but because it disrupts the unification of coupling constants at the GUT scale. Hence a minimalist solution is always desired.

In this Letter we present a solution of the $U(1)$ enlarged $\mu\nu$ SSM which is anomaly free by means of having non-Universal charges of the superfields under the extra symmetry, with the novelty that no exotic fields are needed. We solve the anomalies equations by assuming that each family can have a different $U(1)_X$ charge, finding several groups of solutions depending on few mostly unconstrained extra charges. In addition, we explore some possible phenomenological consequences of having non-Universality in our model. Concretely, we study the extra charge dependence of the Z' interaction with fermions as a result of the mixing between the extra $U(1)$ boson and the usual Z boson [44, 45]. Such dependence implies that the production limits of a Z' at the LHC are no longer valid and have to be recalculated for the specific models allowed by the anomalies cancellation, leading to scenarios where a light Z' is possible, a common feature of string constructions [44, 46, 47], but which is however bounded from below by the condition that no flavour changing neutral currents (FCNC) –common in models with extra symmetries [48, 49]– have been found experimentally [50, 51], as we explain. Furthermore, we explore possible scenarios of Z' me-

diated spin independent dark matter (DM) interactions [52], finding a family of anomalies equations solutions with both scalar and vector isospin violating DM-quark interactions. For the non-Universal U(1) gauge enlarged $\mu\nu$ SSM the possible isospin violating scenarios are parametrised by the Higgs fields charges under the extra symmetry, rendering a series of finite, discrete values that could be discriminated in experiments. Therefore in our model experimental detection of DM is not only conditioned by the specific realisation but could also be used to provide with clear, testable predictions to discern among DM and string compactification scenarios.

2 The non-Universal U(1) $\mu\nu$ SSM

In this section we present the necessary conditions for anomalies cancellations and the implications for model building. In addition, we explore possible phenomenological implications and signatures particular of the model that are imposed by the extra charges assignment of the fields, which themselves are constrained by the anomalies cancellation conditions.

2.1 Non-universal anomalies cancellation in the U(1) $\mu\nu$ SSM

The gauge group of the U(1) $\mu\nu$ SSM is $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$, where each of the superfields composing the model's spectrum has now an extra Q_X charge. Consequently, all anomalies equations involving the new symmetry have to be recalculated if we want the model to be anomaly free. The analysis is two-fold: on the one hand, the terms appearing in the superpotential must have vanishing total charge, and on the other hand, anomalies must also cancel. Hence, restrictive bounds are imposed on the possible values that each superfield charge Q_X can have. Furthermore, we can use certain constraints to either allow certain terms in the superpotential, or to explicitly banish undesired, unphysical, or dangerous terms.

We will work under the assumption that no exotic matter is needed. To that end, we consider the same matter content as for the original $\mu\nu$ SSM. The anomalies equations that must be fulfilled with this matter content are

$$\begin{aligned}
 \sum_i (2Q_{Q_i} + Q_{u_i} + Q_{d_i}) &= 0, \\
 \sum_i (3Q_{Q_i} + Q_{L_i}) + Q_{H_1} + Q_{H_2} &= 0, \\
 \sum_i \left(\frac{1}{6}Q_{Q_i} + \frac{1}{3}Q_{d_i} + \frac{4}{3}Q_{u_i} + \frac{1}{2}Q_{L_i} + Q_{e_i} \right) + \frac{1}{2}(Q_{H_1} + Q_{H_2}) &= 0, \\
 \sum_i (Q_{Q_i}^2 + Q_{d_i}^2 - 2Q_{u_i}^2 - Q_{L_i}^2 + Q_{e_i}^2) - Q_{H_1}^2 + Q_{H_2}^2 &= 0, \\
 \sum_i \left(6Q_{Q_i}^3 + 3Q_{d_i}^3 + 3Q_{u_i}^3 + 2Q_{L_i}^3 + Q_{e_i}^3 + Q_{\nu_i^c}^3 \right) + 2Q_{H_1}^3 + 2Q_{H_2}^3 &= 0, \\
 \sum_i (6Q_{Q_i} + 3Q_{u_i} + 3Q_{d_i} + 2Q_{L_i} + Q_{e_i} + Q_{\nu_i^c}) + 2Q_{H_1} + 2Q_{H_2} &= 0.
 \end{aligned} \tag{2.1}$$

To solve equations from eq. (2.1) we need a set of constraints, which we in addition use to ensure that our model has certain desired properties arising naturally. Prime among

them is forbidding a bilinear μ term from appearing in the superpotential, as its absence is otherwise not automatically guaranteed. Thus, we impose $Q_{H_1} \neq -Q_{H_2}$. Furthermore, since the Higgs mass term is obtained from the right-handed sneutrinos ν^c singlet fields acquiring VEVs at the EWSB scale, a term coupling the right-handed neutrinos and the Higgs fields must also be allowed in the superpotential, which requires $Q_{H_1} + Q_{H_2} + Q_{\nu_i^c} = 0$ for at least one of the three families of right-handed neutrinos. Moreover, as the $\mu\nu$ SSM was born to answer the neutrino mass problem, and the extra U(1) forbids the presence of the $\kappa_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c$ term that provided Majorana masses for the right-handed neutrinos in the original $\mu\nu$ SSM, we impose that Yukawa tree-level mass terms below the soft breaking scale must appear for the right-handed neutrinos, such that a see-saw mechanism is implemented in our model. It is therefore a condition that $Q_{l_i} + Q_{\nu_i^c} + Q_{H_2} = 0$. In addition, we would like to directly forbid certain operators –such as those violating baryon number– from the superpotential, which means $Q_u \neq -2Q_d$. The remaining mass terms are *a priori* not imposed in the superpotential, permitting thus the different fields to acquire mass either at tree-level order with Yukawa couplings or at first loop, via non-holomorphic mass terms. The choice of either is to be fixed accordingly with the anomalies equations.

Giving mass to certain fields via non-holomorphic terms means that such mass must be provided by SUSY-breaking operators introduced via radiative, first loop corrections, which appear naturally in gravity mediated SUSY-breaking scenarios [53]. It has been demonstrated that either mechanism is in principle indistinguishable in experiments but for the heaviest particles [54], namely the top quark and the τ lepton, for which tree level Yukawa terms need to be imposed. Thus, we can impose $Q_{Q_3} + Q_{u_3} + Q_{H_2} = 0$ and $Q_{l_3} + Q_{e_3} + Q_{H_1} = 0$. With this conditions, the first, second, and sixth equations in eq. (2.1) become

$$\begin{aligned}
 2Q_{Q_1} + 2Q_{Q_2} + Q_{Q_3} + Q_{d_1} + Q_{d_2} + Q_{d_3} + Q_{u_1} + Q_{u_2} - Q_{H_2} &= 0, \\
 Q_{H_1} + Q_{H_2} + Q_{L_1} + Q_{L_2} + Q_{L_3} + 3Q_{Q_1} + 3Q_{Q_2} + 3Q_{Q_3} &= 0, \\
 3Q_{d_1} + 3Q_{d_2} + 3Q_{d_3} + Q_{e_1} + Q_{e_2} + Q_{H_1} + Q_{L_1} + Q_{L_2} \\
 + 6Q_{Q_1} + 6Q_{Q_2} + 3Q_{Q_3} + 3Q_{u_1} + 3Q_{u_2} - 4Q_{H_2} &= 0,
 \end{aligned}
 \tag{2.2}$$

which we can use to fix the conditions for quark charges. Should we try for all the up quarks to have tree-level mass terms, then all down quarks necessarily acquire mass through non-holomorphic terms. But from the third equation this imposes that just one lepton has tree-level Yukawa mass term. Putting everything back into the second equation it would lead to $Q_{H_1} = -Q_{H_2}$, reintroducing the μ term in the superpotential. And the same happens if we try to have both first and second families of up quarks with non-holomorphic mass terms. Consequently, the only possibility is for either the first or the second family of up quarks to have tree-level Yukawa coupling, while the other acquires its mass through a non-holomorphic term. On the contrary, the necessary condition for the down-type quarks is to have *two* of the families having non-holomorphic mass terms and one a tree-level Yukawa. There is however freedom in choosing which family acquires its mass via which mechanism, a fact that will be of importance for the phenomenology of the model as we shall see in what follows. The left leptons (L) mimic the behaviour of the up-quarks. The

possibility of flavour changing neutral currents in both quark and lepton sectors can as well be disregarded as the non-diagonal flavour matrices terms can be safely made zero. Furthermore, even if the mechanism for obtaining the masses changes within the quark (or lepton) type, no problem exists in obtaining the correct masses for each of the particles.

To conclude the analysis, we must choose either of the groups of solutions, the rest being symmetric. In particular, fixing the first and third families of up-quarks with superpotential tree-level Yukawa couplings, and establishing the remaining quarks and leptons accordingly, immediately fulfils equations 1 and 6 from eq. (2.1), and leaves the second and third the same and equal to

$$Q_{H_1} + Q_{H_2} + Q_{L_1} + Q_{L_2} + Q_{L_3} + 3Q_{Q_1} + 3Q_{Q_2} + 3Q_{Q_3} = 0. \quad (2.3)$$

Clearing Q_{L_1} and replacing it in the non-linear anomalies we obtain for equation four in eq. (2.1)

$$(Q_{H_1} + Q_{H_2})(Q_{H_1} + Q_{L_2} + 3(Q_{Q_1} + Q_{Q_3})) = 0. \quad (2.4)$$

Choosing the first brackets to hold true would reintroduce the μ term in the superpotential, therefore is the second brackets what must cancel, fixing $Q_{L_2} = -Q_{H_1} - 3Q_{Q_1} - 3Q_{Q_3}$, with which the fifth equation in eq. (2.1) is simplified to

$$(Q_{H_1} + Q_{H_2})(-2Q_{L_3}(Q_{H_2} + Q_{L_3}) + Q_{H_1}(Q_{H_2} - 3Q_{Q_2}) - 3(Q_{H_2} + 2Q_{L_3})Q_{Q_2} - 9Q_{Q_2}^2) = 0. \quad (2.5)$$

We thus have solutions depending on $Q_{H_1}, Q_{H_2}, Q_{L_3}, Q_{Q_1}, Q_{Q_2}, Q_{Q_3}$, a repeating characteristic of the model independently of which fields have non-holomorphic mass term, and where any combination is valid as long as eq. (2.5) has a real solution and a term of the form $Q_{H_1} + Q_{H_2} + Q_{\nu_i^c} = 0$ is allowed. For this to happen, the corresponding Q_{L_i} must be equal to Q_{H_1} , which means that not all right-handed neutrinos will have a tree-level coupling with the Higgs fields, being nonetheless guaranteed that some will, thus providing a natural mass term for the Higgs particle. In addition, note that by having the quark families mass terms with opposite mechanisms, it is guaranteed that no baryon number violating operator is allowed in the superpotential as long as Higgs and quarks have different charges. We thus have shown that within the framework of the U(1) extended $\mu\nu$ SSM, anomalies are cancelled without the need to add exotic matter, at the price of having non-universal charges, and with the gain of forbidding most troublesome operators in the superpotential. In the appendix A, a specific Q_X charge distribution for the above described family of solutions can be found, together with and an altogether different scenario with important DM phenomenological consequences. In the remaining part of the article we elaborate on the novel, particular, and potentially relevant phenomenological characteristics of the non-Universal U(1) $\mu\nu$ SSM.

2.2 Phenomenological consequences of Universality violation across fermion families

The phenomenological manifestation of an extra U(1) gauge symmetry comes, mainly, from the mixing of the massive neutral components of the vector bosons from the gauge

sector, namely the Z and the Z' gauge bosons. For the case of the $U(1)$ enlarged $\mu\nu$ SSM, and contrary to other models where similar mixing occurs (see for example ref. [55] and references therein), the mixing happens naturally within the neutralino mixing matrix as part of the right sneutrinos acquiring vacuum expectation value. Such fact enriches greatly the phenomenology of the model and, as we will describe, imposes conditions for both collider and dark matter interactions, similar to what happens within the $\mu\nu$ SSM alone [15]. The presence of the non-Universal extra gauge symmetry introduces a new dependence on the specific charge of each field under the extra symmetry which will condition the possible interactions of fermions with the Z' , which is responsible of a very particular phenomenology, specific of the non-Universal $U(1)\mu\nu$ SSM.

The phenomenology of the model is modified according to the mixing of the new sector. To parametrise the influence that the extra $U(1)$ has, we define the mixing factor R [43],

$$R = \frac{(M_{ZZ'}^2)^2}{M_Z^2 M_{Z'}^2}, \tag{2.6}$$

where the entries M_{ij} correspond to the terms of the mixing matrix between Z and Z' . In principle R should be smaller than 10^{-3} given the experimental constraints available [56], with the consequence that $M_{ZZ'}$ has to be smaller than $M_{ZZ'} \lesssim 56 \text{ GeV}^2$ when $M_{Z'}=1 \text{ TeV}$, with such constraint becoming weaker as the mass of the Z' gets heavier. Thus only heavier masses for the Z' would fulfil such condition together with the ones coming from accelerator searches, and would require a somewhat large fine-tuning. Nonetheless, these limits are calculated for when the extra charges are Universal, which does not occur in our model. Hence the bounds presented have to be taken carefully, as the couplings of the physical states are now dependent on the Q_X charges (as well as on the vacuum expectation value of ν^c). However, in the rest of the paper we will consider that the mixing in the $Z - Z'$ sector is negligible.³

In our model the physical coupling of the Z' to the fermionic sector is

$$g_\alpha^{Z'} = g' Q_X^\alpha, \tag{2.7}$$

where α corresponds to the matter field ψ_α , Q_X^α is the charge of this field under the $U(1)_X$, and g' corresponds to the coupling constant of the $U(1)_X$ gauge symmetry. Thus, once the value of g' is fixed, the way the Z' couples to the different fermions depends strictly on the charges Q_X . The values these charges can have are fixed by the anomalies cancellation conditions, with only certain discrete values allowed. Moreover, since these charges break universality among fermions (see for example the models presented in the appendix A), each fermion family will have in general a different value of the charge and consequently will couple with different strength to the Z' , having deep phenomenological consequences.

The physical couplings of the SM particles to the Z' are described as follows. According to eq. (2.7) the left and right handed components of the SM fermions do not necessarily

²A complete description of the entries M_{ij} and their dependencies with the parameter of the model can be found in ref. [43].

³Notice nonetheless the new configuration of charges and the relation among the different vacuum expectation values can induce a sizeable mixing in the $Z - Z'$ system.

share the same couplings to the Z' , as they depend on the charge assignation. Usually, the couplings of a vector boson can be expressed in its vector and axial forms. The vector coupling is defined as the sum of the left and right components, for example the vector coupling of the quarks is,

$$C_{u_i}^V = g_{u_{iL}}^{Z'} + g_{u_{iR}}^{Z'} = g'(Q_{u_{iL}} + Q_{u_{iR}}), \tag{2.8}$$

$$C_{d_i}^V = g_{d_{iL}}^{Z'} + g_{d_{iR}}^{Z'} = g'(Q_{d_{iL}} + Q_{d_{iR}}), \tag{2.9}$$

where $i = 1, 2, 3$ stands for the three families of both up and down quarks since they could have different charges. On the contrary, the axial coupling is defined as the difference of the components,

$$C_{u_i}^A = g_{u_{iL}}^{Z'} - g_{u_{iR}}^{Z'} = g'(Q_{u_{iL}} - Q_{u_{iR}}), \tag{2.10}$$

$$C_{d_i}^A = g_{d_{iL}}^{Z'} - g_{d_{iR}}^{Z'} = g'(Q_{d_{iL}} - Q_{d_{iR}}). \tag{2.11}$$

As we see, the vector and axial couplings are different, which should not surprise us since in the SM the Z boson behaves similarly. As the charges can be different in the up and down sectors the result is that the Z' does not couple in the same way to up and down quarks. The consequences are twofold. On the one hand, the production rates of a Z' in collider experiments has to be recalculated taking into account that each of the fermion pairs that could produce a Z' has a different value of the coupling, which makes the current constraints and limits invalid in this model. And on the other hand, direct dark matter searches, which are heavily dependent on the DM particle interaction with protons and neutrons, are affected by the fact that now the coupling is quark-family dependent, and will not interact the same with protons (which have more up-quark content) than with neutrons, modifying as well current experimental DM searches and imposing different limits.

In the remaining part of the section we will describe briefly the interesting phenomenological consequences that we just commented, focusing on the collider and DM.⁴

On the existence of unobserved flavour changing neutral currents. The presence of flavour changing neutral currents is highly suppressed in the SM [50, 51]. In that sense, non-Universality can be problematic, as is the distribution of extra charges what determines the Yukawa textures, which in turn can lead to differences in the CKM matrix for quarks and in the lepton currents, introducing new Z' mediated FCNC. To understand the mechanism by which the extra U(1) symmetry might introduce FCNC, it is illustrative to write the Q's extra charges matrices associated to the Yukawa mass operators. In particular, for up-squarks, both the holomorphic ($Y_u^{ij} \hat{H}_2^b \hat{Q}_i^a \hat{u}_j^c$) and non-holomorphic ($Y_u^{ij} \hat{H}_1^b \hat{Q}_i^a \hat{u}_j^c$)

⁴A more detailed and involved description of the phenomenology of these models will be described in a forthcoming work [57].

charge matrices look like,

$$Q_{Q_i} + Q_{u_j} + Q_{H_2} = \begin{pmatrix} 0 & Q_{Q_1} - Q_{Q_2} + Q_{H_1} + Q_{H_2} & Q_{Q_1} - Q_{Q_3} \\ Q_{Q_2} - Q_{Q_1} & Q_{H_1} + Q_{H_2} & Q_{Q_2} - Q_{Q_3} \\ Q_{Q_3} - Q_{Q_1} & Q_{Q_3} - Q_{Q_2} + Q_{H_1} + Q_{H_2} & 0 \end{pmatrix}, \quad (2.12)$$

$$Q_{Q_i} + Q_{u_j} - Q_{H_1} = \begin{pmatrix} -Q_{H_1} - Q_{H_2} & Q_{Q_1} - Q_{Q_2} & Q_{Q_1} - Q_{Q_3} - Q_{H_1} - Q_{H_2} \\ Q_{Q_2} - Q_{Q_1} - Q_{H_1} - Q_{H_2} & 0 & Q_{Q_2} - Q_{Q_3} - Q_{H_1} - Q_{H_2} \\ Q_{Q_3} - Q_{Q_1} - Q_{H_1} - Q_{H_2} & Q_{Q_3} - Q_{Q_2} & -Q_{H_1} - Q_{H_2} \end{pmatrix}. \quad (2.13)$$

The case of down squarks is symmetric to the up squarks, interchanging the tree level and non-holomorphic matrices, while for right sleptons the behaviour is the same as for up squarks (replacing the corresponding Q_Q by Q_L), while for right sneutrinos, since we choose them to all have tree level Yukawas, no problems arise with FCNCs. What eqs. (2.12) and (2.13) tell us is that in order for a Yukawa term to be allowed in the superpotential, the corresponding matrix entry must be zero. Hence, for a FCNC to appear in the superpotential, non-diagonal entries in eqs. (2.12) or (2.13), and their peers for down squarks and sleptons must be zero. Thus, for sleptons avoiding unwanted, Z' mediated FCNCs is easy, as it only requires flavour changing terms to be forbidden in the Yukawa matrices, which will occur as long as $Q_{L_i} \neq Q_{L_j}$ with $i \neq j$, since it is already guaranteed that the Higgs charges have to be different from one another. Consequently no Z' mediated leptons FCNC will appear in this model. For the remaining we will thence concentrate on the possibility of FCNC in the quark sector.

Z' mediated quark neutral currents are governed by the coupling of the Z' to the quarks, which we assume to be diagonal in the weak basis. This is easily achieved as long as the non-diagonal terms in eqs. (2.12) and (2.13) are different from zero, as it happens with sleptons. In whose case the Lagrangian looks like

$$\mathcal{L} = -\frac{g}{2 \cos \theta_w} \left(\tilde{U}_L \delta_L^U \gamma_\mu U_L + \tilde{U}_R \delta_R^U \gamma_\mu U_R + \tilde{D}_L \delta_L^D \gamma_\mu D_L + \tilde{D}_R \delta_R^D \gamma_\mu D_R \right) Z'^\mu. \quad (2.14)$$

Here $\tan \theta_w = g_Y/g'$, the ratio between the hypercharge and the new U(1) coupling constants, $U_{L,R} = (u, c, t)_{L,R}^T$, $D_{L,R} = (d, s, b)_{L,R}^T$, and $\delta_{L,R}^{U,D}$ is the Kronecker delta for left-right and up-down type terms, indicating that there are no non-diagonal couplings in the Lagrangian. Therefore, possible interactions which are flavour changing will come described by the rotation of the Yukawa quark matrices to the physical bases, i.e. the mass eigenstates. If these rotations were proportional to the unit matrix, then no FCNC would appear. As it stands, there is no guarantee that the interaction remains diagonal, hence the corresponding Lagrangian is [58, 59]

$$\begin{aligned} \mathcal{L}_{FCNC} = & -\frac{g}{2 \cos \theta_w} (\tilde{U}_L \gamma^\mu V_L^U \delta_L^U V_L^{U\dagger} U_L + \tilde{U}_R \gamma^\mu V_R^U \delta_R^U V_R^{U\dagger} U_R \\ & + \tilde{D}_L \gamma^\mu V_L^D \delta_L^D V_L^{D\dagger} D_L + \tilde{D}_R \gamma^\mu V_R^D \delta_R^D V_R^{D\dagger} D_R) Z'^\mu, \end{aligned} \quad (2.15)$$

where the $V_{L,R}^{U,D}$ are the usual quark diagonalisation matrices, the well known Kobayashi-Maskawa. The flavour changing neutral currents $J_{Z'}$ associated to \mathcal{L}_{FCNC} in terms of the

Kobayashi-Maskawa mixing terms are of the form [58],

$$\sin \theta_w \cot \theta_X \cos \xi_Z V_{L,R}^{U,D} V_{L,R}^{U,D\dagger}, \quad (2.16)$$

with $\tan \theta_X = g/g'$, that is the ratio of the weak and the U(1) gauge coupling constants. $\tan 2\xi_Z = 2M_{ZZ'}^2/(M_Z^2 + M_{Z'}^2)$, where the entries M_{ij} correspond to the terms of the mixing matrix between Z and Z' .

Then whether FCNC appear and are important in our model is a matter of diagonalizing the Yukawa quark matrices for specific realisations of the extra charges and obtaining the corresponding neutral currents and their specific strength. The constraint for their appearance goes like [60]

$$\frac{M_Z}{M_{Z'}} \sin \theta_w \cot \theta_X \cos \xi_Z V_{L,R}^{U,D} V_{L,R}^{U,D\dagger} \lesssim 10^{-4}, \quad (2.17)$$

which for typical parameters means $\frac{M_Z}{M_{Z'}} \lesssim 1$.

Given the fact that the mixing between the states is almost negligible the contribution to the FCNC through the mixing will be suppressed. Apart from that, a Z' with a mass in the TeV range has practically a negligible effect on FCNC, as can be deduced from eq. (2.17) [31, 60]. The LHC searches for a Z' set the mass of this boson to be in the multi-TeV range in order not to be produced. In order to be safe from such constraints, one should invoke either a large TeV mass or a really small U(1)' gauge coupling. In both scenarios, the total contribution of the Z' is practically negligible since the contributions are suppressed either to a high $m_{Z'}$ or a really small coupling g' . As the scope of this paper is not a detailed and numerical study of the properties of this model but just a broad overview of the interesting phenomenological aspects, we leave the precision calculations and numerical results to a future and deeper study of this model [57].

Collider Phenomenology of the Z' . The Z' could be eventually produced in the LHC. Both ATLAS and CMS have searches on high mass resonances decaying into a pair of leptons or hadronically (see for example refs. [61–63]). As no signal of a Z' has yet been found, bounds can be set on the production and subsequent decay of a Z' , $pp \rightarrow Z' \rightarrow \psi\bar{\psi}$ for a defined mass. However, in the set of non-Universal models one can avoid such strong limits provided that different fermion families couple differently to the Z' . It could be the case that the up and down quark families have charges such that the effective coupling to the Z' gets suppressed together with its production.

The general expression for the Z' production and subsequent decay into fermions at the LHC is [55, 64],

$$\sigma_{f\bar{f}} \simeq \left(\frac{1}{3} \sum_q \frac{dL_{q\bar{q}}}{dm_{Z'}^2} \times \hat{\sigma}(q\bar{q} \rightarrow Z') \right) \times BR(Z' \rightarrow f\bar{f}), \quad (2.18)$$

where $dL_{q\bar{q}}/dm_{Z'}^2$ stands for the parton luminosities, $\hat{\sigma}(q\bar{q} \rightarrow Z')$ is the peak cross section for the Z' boson, and $BR(Z' \rightarrow f\bar{f})$ is the branching ratio for the Z' decaying into a fermion

pair. As it was pointed out in ref. [64], one can describe those parameters as a function of the sum of the different production rates for each quark and its Z' coupling,

$$\sigma_{f\bar{f}}^{\text{LO}} = \sum_{i=1}^3 [c_{u_i} \tilde{\omega}_{u_i}(s, m_{Z'}^2) + c_{d_i} \tilde{\omega}_{d_i}(s, m_{Z'}^2)] \times \text{BR}(Z' \rightarrow f\bar{f}). \quad (2.19)$$

Here, c_q are defined as $c_q = (C_q^V)^2 + (C_q^A)^2$ and the functions $\tilde{\omega}_q(s, m_{Z'}^2)$ contain all the information related with the parton distribution function, NLO corrections, etc.⁵

The most important part of the model in the Z' collider phenomenology is the fact that all types of fermions, no matter the family or the flavour, couple differently to the Z' . This weakens the experimental searches of this kind of particles that ATLAS and CMS perform. There are several ways in which the Z' production might be diminished. One can have small quark couplings giving a tiny production cross section in such a way that the Z' is barely produced in the LHC even for light masses of the Z' . Together with this effect the charges to the leptonic sector could be small as well reducing the total amount of observable events. However, in this model the charge assignment is not free since it is fixed by the cancellation of anomalies. As a consequence, one cannot arbitrarily make the couplings as small as it would be required to directly avoid collider searches, and the specific model realisation completely determines the Z' phenomenology, which means that clear, precise predictions for the LHC can be established; on the other hand, a Z' discovery would severely constraint the possible models, thus hinting towards the specific realisation in nature of the non-Universal $U(1)\mu\nu\text{SSM}$. In that sense a deeper study will be done in the future [57] to determine the consequences of such charge assignment.

Dark matter phenomenology. There are different candidates for a dark matter particle in the non-Universal $U(1)\mu\nu\text{SSM}$. Among them, the role could be played by an extra vector-doublet, inert in the SM sector, a decoupled field, such a non-interacting right-handed neutrino, or as it occurs in the $\mu\nu\text{SSM}$, the gravitino [15]. The interesting scenario occurs in the first two cases, where a DM distinctive signal comes from the Z' mediated spin independent interaction with a dark matter particle ψ . We can parametrise the effective Lagrangian of DM particle interaction with protons p , and neutrons, n , mediated by a vector boson as,

$$\mathcal{L}_{\text{V}}^{\text{SI}} = f_p (\bar{\psi} \gamma_\mu \psi) (\bar{p} \gamma^\mu p) + f_n (\bar{\psi} \gamma_\mu \psi) (\bar{n} \gamma^\mu n), \quad (2.20)$$

where the vector couplings f_p and f_n are defined through their nucleon valence quark content as [52]

$$f_p = 2b_u + b_d, f_n = b_u + 2b_d, \quad (2.21)$$

with $b_{u,d}$ the effective Z' mediated vector couplings

$$b_{(u,d)} = \frac{g_{dm} C_{(u,d)}^V}{2m_{Z'}^2}. \quad (2.22)$$

⁵For further information one can see ref. [64] or the appendix of ref. [55].

Using the definitions for the vector coupling obtained in eq. (2.9) we have that

$$b_{(u)} = \frac{g_{dm}g'}{2m_{Z'}^2}(Q_{u_L} + Q_{u_R}), \quad (2.23)$$

$$b_{(d)} = \frac{g_{dm}g'}{2m_{Z'}^2}(Q_{d_L} + Q_{d_R}), \quad (2.24)$$

such that the effective coupling of the DM particle to protons and neutrons is,

$$f_p = \frac{g_{dm}g'}{2m_{Z'}^2}(2Q_{u_L} + 2Q_{u_R} + Q_{d_L} + Q_{d_R}), \quad (2.25)$$

$$f_n = \frac{g_{dm}g'}{2m_{Z'}^2}(Q_{u_L} + Q_{u_R} + 2Q_{d_L} + 2Q_{d_R}). \quad (2.26)$$

We can define the amount the isospin violation as the ratio f_n/f_p , that in our case is given by

$$f_n/f_p = \frac{Q_{u_L} + Q_{u_R} + 2Q_{d_L} + 2Q_{d_R}}{2Q_{u_L} + 2Q_{u_R} + Q_{d_L} + Q_{d_R}}. \quad (2.27)$$

As we can see, the ratio f_n/f_p , depends *exclusively* on the charges of the corresponding quarks under the extra $U(1)_X$ symmetry. Having a non-Universal extra gauge symmetry means that in typical realisations these charges will not be the same, and therefore the amount of isospin violation will in general be different than the usual ± 1 of Universal models, thus providing a distinctive, particular signal in the cross section of DM-nucleus elastic scattering experiments. Moreover, notice that the vector coupling ratio is independent of the value of the gauge coupling g' .

The striking feature of the non-Universal $U(1)_{\mu\nu}$ SSM is that the amount of isospin violation can only acquire a discrete set of values. In the non-Universal $U(1)_{\mu\nu}$ SSM there is a class of solutions for which both the up and down quarks have the same kind of mass terms (i.e, either tree-level or non-holomorphic). This means in particular that it is the opposite Higgs, namely H_1 or H_2 which gives the mass to each of them. As each Higgs has a different extra charge under the new gauge symmetry, for this class of models the amount of isospin violation is parametrised by the Higgs charges as follows

$$\frac{f_n}{f_p} = \frac{Q_{H_2} + 2Q_{H_1}}{2Q_{H_2} + Q_{H_1}}. \quad (2.28)$$

Hence, as long as the Higgs extra charges are different, a condition necessary in order to forbid the μ term from the superpotential, there will be isospin violation. It is important to note that the ratio f_n/f_p depends *only* on the Higgs charges and not those of the up and down quark charges. For example, the model presented in the appendix A has isospin violation ≈ -1.75 . Of utmost importance is to stress that not just any value of isospin violation is allowed but, as the extra charges must fulfil certain conditions, the number of possible models is constrained, allowing experiments to discriminate among realisations of the supersymmetric model, which could bear direct relation with the kind of low energy scale string realisation.

3 Conclusions

In this letter, we have presented a new supersymmetric model in which, by adding a non-Universal $U(1)$ gauge symmetry to the already explored $\mu\nu$ SSM model, not only both the μ term problem and the neutrino masses problem are solved, but the stability of the proton is ensured by recovering an effective R-parity, forbidding at the same time baryon number violating operators and avoiding a possible domain wall problem. By allowing non-Universal charges in all the fields, we demonstrate that there exist families of solutions which require of no exotic matter whatsoever to cancel anomalies. Moreover, in solving the anomalies equations we find that there only is a discrete set of possible extra charges allowed, a fact that has deep implications in the possible phenomenology of the model.

Universality breaking implies, in the $U(1)\mu\nu$ SSM, that the SM fermions will ordinarily have different values of the charge Q_X both for each family and also between up and down doublet components. With the direct consequence that, while stringent bounds are already imposed in the possible production of a Z' at accelerators, these bounds do not apply directly to our model. As the production rates are calculated assuming that all fermions will couple with the same strength to the Z' boson, and such coupling depends on the specific fermion extra charge, they have to be recalculated for each specific realisation of anomalies cancellation in the non-Universal $U(1)\mu\nu$ SSM, meaning that new scenarios open up in which even a light Z' boson could have escaped detection at LHC. Such scenarios would be constrained only by the condition that no FCNC are observed in the model. A forthcoming work will address in detail the specifics of such scenarios [57].

The extra charges dependence of fermionic coupling to a Z' also modifies interaction rates with a DM particle, which is dominated by the lightest Z' mass eigenstate. The conditions imposed by anomalies cancellation lead to a family of scenarios where isospin violation is realised and depends *solely* on the Higgs extra charges, a particle in principle completely unrelated with DM interactions. The implications for DM detection are profound, as the specific model realisation implies a very specific interaction rate with protons and/or neutrons, rendering particular experiments more or less suitable, and modifying the conditions for existing ones. Benchmark scenarios with concrete realisations of extra charge distributions will be analysed in [57].

Summarising, the non-Universal $U(1)\mu\nu$ SSM is an attractive model, which could be easily related with specific intersecting brane constructions and which, through a very particular phenomenology consequence of the discrete and constrained extra charge values, could when and if SUSY is discovered, be related directly with the kind of low energy stringy realisation.

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A Example of charge assignation

We present here two examples of solutions for the anomalies equations, representative of the two main families of models presented in the main text.

Example 1. A minimalist charge assignment that fulfils the anomalies equations and permits the effective μ term, having a quarks fields hierarchy, and with tree-level Yukawas and non-holomorphic terms appearing at opposing families in quarks. Particularly, in the example presented is the second family of up-quarks and the first, and third families of down quarks, the ones which acquire mass via non-holomorphic terms.

	Q_Q	Q_u	Q_d	Q_L	Q_e	Q_{ν^c}
1 st Family	$-\frac{1}{3}$	$\frac{-2}{3}$	$\frac{4}{3}$	2	-4	-3
2 nd Family	$-\frac{5}{3}$	$\frac{11}{3}$	$-\frac{1}{3}$	7	-6	-8
3 rd Family	$-\frac{8}{3}$	$\frac{5}{3}$	$\frac{11}{3}$	2	-4	-3
$Q_{H_1} = 2$			$Q_{H_2} = 1$			

With this charges assignment, the fields mass terms in the superpotential below the soft breaking scale read

$$\begin{aligned}
 -\mathcal{L}_{\text{eff}} = & Y_u(u_L)^c q_u H_2 + \tilde{Y}_c(c_L)^c q_c H_1 + Y_t(t_L)^c q_t H_2 \\
 & + \tilde{Y}_d(d_L)^c q_d H_2 + Y_s(s_L)^c q_s H_1 + \tilde{Y}_b(b_L)^c q_b H_2 \\
 & + Y_e(e_L)^c L_e H_1 + \tilde{Y}_\mu(\mu_L)^c L_\mu H_2 + Y_\tau(\tau_L)^c L_\tau H_1 \\
 & + \epsilon_{ab} Y_\nu^{ij} H_2^b L_i^a \nu_j^c + \nu_e^c \hat{H}_1 \hat{H}_2 + \nu_\tau^c \hat{H}_1 \hat{H}_2,
 \end{aligned} \tag{A.1}$$

where the tilded Y represent the Yukawas generated by non-holomorphic interactions.

Example 2. Now we present an example of solution for the family of models which have non-trivial violation of isospin, with consequences for the phenomenology of dark matter. In this case, the condition is that both first families of up and down quarks have the same kind of mass term. In this case, having both with a Yukawa at tree-level, a possible anomalies cancellation charges distribution is

	Q_Q	Q_u	Q_d	Q_L	Q_e	Q_{ν^c}
1 st Family	$\frac{1}{3}$	$\frac{4}{3}$	$\frac{-7}{3}$	-10	$\frac{25}{3}$	$\frac{35}{3}$
2 nd Family	$-\frac{-5}{3}$	$\frac{11}{3}$	0	$\frac{8}{3}$	$-\frac{14}{3}$	-1
3 rd Family	$\frac{9}{3}$	$-\frac{4}{3}$	$-\frac{14}{3}$	2	-4	$-\frac{1}{3}$
$Q_{H_1} = 2$			$Q_{H_2} = -\frac{5}{3}$			

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References

- [1] ATLAS collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1 [[arXiv:1207.7214](#)] [[INSPIRE](#)].
- [2] CMS collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30 [[arXiv:1207.7235](#)] [[INSPIRE](#)].
- [3] ATLAS collaboration, *Search for squarks and gluinos in final states with jets and missing transverse momentum using 36 fb⁻¹ of $\sqrt{s} = 13$ TeV pp collision data with the ATLAS detector*, *Phys. Rev. D* **97** (2018) 112001 [[arXiv:1712.02332](#)] [[INSPIRE](#)].
- [4] C. Arina, M. Chala, V. Martín-Lozano and G. Nardini, *Confronting SUSY models with LHC data via electroweakino production*, *JHEP* **12** (2016) 149 [[arXiv:1610.03822](#)] [[INSPIRE](#)].
- [5] K. Kowalska, *Phenomenological MSSM in light of new 13 TeV LHC data*, *Eur. Phys. J. C* **76** (2016) 684 [[arXiv:1608.02489](#)] [[INSPIRE](#)].
- [6] M.R. Buckley, D. Feld, S. Macaluso, A. Monteux and D. Shih, *Cornering Natural SUSY at LHC Run II and Beyond*, *JHEP* **08** (2017) 115 [[arXiv:1610.08059](#)] [[INSPIRE](#)].
- [7] C. Han, J. Ren, L. Wu, J.M. Yang and M. Zhang, *Top-squark in natural SUSY under current LHC run-2 data*, *Eur. Phys. J. C* **77** (2017) 93 [[arXiv:1609.02361](#)] [[INSPIRE](#)].
- [8] J.S. Kim, M.E. Krauss and V. Martín-Lozano, *Probing the Electroweakino Sector of General Gauge Mediation at the LHC*, *Phys. Lett. B* **783** (2018) 150 [[arXiv:1705.06497](#)] [[INSPIRE](#)].
- [9] A. Signer, *ABC of SUSY*, *J. Phys. G* **36** (2009) 073002 [[arXiv:0905.4630](#)] [[INSPIRE](#)].
- [10] J. Terning, *Modern supersymmetry: Dynamics and duality*, Clarendon, Oxford, U.K., (2006).
- [11] M. Drees, R. Godbole and P. Roy, *Theory and phenomenology of Sparticles: an account of four-dimensional N=1 supersymmetry in high-energy physics*, World Scientific, Singapore, (2004).
- [12] S.P. Martin, *A Supersymmetry primer*, (1997), pp. 1–98, [*Adv. Ser. Direct. High Energy Phys.* **18** (1998) 1].
- [13] M. Maltoni, T. Schwetz, M. Tórtola and J.W.F. Valle, *Status of global fits to neutrino oscillations*, *New J. Phys.* **6** (2004) 122.
- [14] D.V. Forero, M. Tórtola and J.W.F. Valle, *Neutrino oscillations refitted*, *Phys. Rev. D* **90** (2014) 093006 [[arXiv:1405.7540](#)] [[INSPIRE](#)].
- [15] J. Fidalgo, *Phenomenology of a new Supersymmetric Standard Model, the $\mu\nu$ SSM*, Ph.D. Thesis, Universidad Autónoma de Madrid. Departamento de Física Teórica, 12, Madrid, Spain, (2011).
- [16] D.E. López-Fogliani and C. Muñoz, *Proposal for a Supersymmetric Standard Model*, *Phys. Rev. Lett.* **97** (2006) 041801 [[hep-ph/0508297](#)] [[INSPIRE](#)].
- [17] A. Sevrin, W. Staessens and A. Wijns, *An N = 2 worldsheet approach to D-branes in bihermitian geometries: II. The general case*, *JHEP* **09** (2009) 105 [[arXiv:0908.2756](#)] [[INSPIRE](#)].
- [18] P. Ghosh and S. Roy, *Neutrino masses and mixing, lightest neutralino decays and a solution to the mu problem in supersymmetry*, *JHEP* **04** (2009) 069 [[arXiv:0812.0084](#)] [[INSPIRE](#)].

- [19] P. Ghosh, P. Dey, B. Mukhopadhyaya and S. Roy, *Radiative contribution to neutrino masses and mixing in $\mu\nu$ SSM*, *JHEP* **05** (2010) 087 [[arXiv:1002.2705](#)] [[INSPIRE](#)].
- [20] D. Astolfi, G. Grignani, T. Harmark and M. Orselli, *Finite-size corrections to the rotating string and the winding state*, *JHEP* **08** (2008) 099 [[arXiv:0804.3301](#)] [[INSPIRE](#)].
- [21] P. Bandyopadhyay, P. Ghosh and S. Roy, *Unusual Higgs boson signal in R-parity violating nonminimal supersymmetric models at the LHC*, *Phys. Rev. D* **84** (2011) 115022 [[arXiv:1012.5762](#)] [[INSPIRE](#)].
- [22] P. Ghosh, D.E. López-Fogliani, V.A. Mitsou, C. Muñoz and R. Ruiz de Austri, *Probing the μ -from- ν supersymmetric standard model with displaced multileptons from the decay of a Higgs boson at the LHC*, *Phys. Rev. D* **88** (2013) 015009 [[arXiv:1211.3177](#)] [[INSPIRE](#)].
- [23] P. Ghosh, D.E. López-Fogliani, V.A. Mitsou, C. Muñoz and R. Ruiz de Austri, *Probing the $\mu\nu$ SSM with light scalars, pseudoscalars and neutralinos from the decay of a SM-like Higgs boson at the LHC*, *JHEP* **11** (2014) 102 [[arXiv:1410.2070](#)] [[INSPIRE](#)].
- [24] C. Muñoz, *Searching for SUSY and decaying gravitino dark matter at the LHC and Fermi-LAT with the $\mu\nu$ SSM*, *PoS(DSU2015)034* [[arXiv:1608.07912](#)] [[INSPIRE](#)].
- [25] P. Ghosh, I. Lara, D.E. López-Fogliani, C. Muñoz and R. Ruiz de Austri, *Searching for left sneutrino LSP at the LHC*, *Int. J. Mod. Phys. A* **33** (2018) 1850110 [[arXiv:1707.02471](#)] [[INSPIRE](#)].
- [26] T. Biekötter, S. Heinemeyer and C. Muñoz, *Precise prediction for the Higgs-boson masses in the $\mu\nu$ SSM*, *Eur. Phys. J. C* **78** (2018) 504 [[arXiv:1712.07475](#)] [[INSPIRE](#)].
- [27] A.E. Faraggi and M. Thormeier, *String inspired Z-prime model with stable proton and light neutrino masses*, *Nucl. Phys. B* **624** (2002) 163 [[hep-ph/0109162](#)] [[INSPIRE](#)].
- [28] L. Ibáñez and A. Uranga, *String Theory and Particle Physics: An Introduction to String Phenomenology*, Cambridge University Press, (2014).
- [29] F. Marchesano, *Progress in D-brane model building*, *Fortsch. Phys.* **55** (2007) 491 [[hep-th/0702094](#)] [[INSPIRE](#)].
- [30] R. Blumenhagen, M. Cvetič, P. Langacker and G. Shiu, *Toward realistic intersecting D-brane models*, *Ann. Rev. Nucl. Part. Sci.* **55** (2005) 71 [[hep-th/0502005](#)] [[INSPIRE](#)].
- [31] P. Langacker, *The Physics of Heavy Z' Gauge Bosons*, *Rev. Mod. Phys.* **81** (2009) 1199 [[arXiv:0801.1345](#)] [[INSPIRE](#)].
- [32] S.F. Mantilla, R. Martinez and F. Ochoa, *Neutrino and CP-even Higgs boson masses in a nonuniversal U(1)' extension*, *Phys. Rev. D* **95** (2017) 095037 [[arXiv:1612.02081](#)] [[INSPIRE](#)].
- [33] S.F. Mantilla and R. Martinez, *Nonuniversal anomaly-free U(1) model with three Higgs doublets and one singlet scalar field*, *Phys. Rev. D* **96** (2017) 095027 [[arXiv:1704.04869](#)] [[INSPIRE](#)].
- [34] W. Loinaz and T. Takeuchi, *Charge assignments in multiple U(1) gauge theories*, *Phys. Rev. D* **60** (1999) 115008 [[hep-ph/9903362](#)] [[INSPIRE](#)].
- [35] E. Ma, *New U(1) gauge extension of the supersymmetric standard model*, *Phys. Rev. Lett.* **89** (2002) 041801 [[hep-ph/0201083](#)] [[INSPIRE](#)].
- [36] M. Aoki and N. Oshimo, *A supersymmetric model with an extra U(1) gauge symmetry*, *Phys. Rev. Lett.* **84** (2000) 5269 [[hep-ph/9907481](#)] [[INSPIRE](#)].

- [37] M. Aoki and N. Oshimo, *Supersymmetric extension of the standard model with naturally stable proton*, *Phys. Rev. D* **62** (2000) 055013 [[hep-ph/0003286](#)] [[INSPIRE](#)].
- [38] H.-S. Lee, K.T. Matchev and T.T. Wang, *A U(1)-prime solution to the μ^- problem and the proton decay problem in supersymmetry without R-parity*, *Phys. Rev. D* **77** (2008) 015016 [[arXiv:0709.0763](#)] [[INSPIRE](#)].
- [39] J. Erler, *Chiral models of weak scale supersymmetry*, *Nucl. Phys. B* **586** (2000) 73 [[hep-ph/0006051](#)] [[INSPIRE](#)].
- [40] H.-C. Cheng, B.A. Dobrescu and K.T. Matchev, *Generic and chiral extensions of the supersymmetric standard model*, *Nucl. Phys. B* **543** (1999) 47 [[hep-ph/9811316](#)] [[INSPIRE](#)].
- [41] D.A. Demir, G.L. Kane and T.T. Wang, *The minimal U(1)' extension of the MSSM*, *Phys. Rev. D* **72** (2005) 015012 [[hep-ph/0503290](#)] [[INSPIRE](#)].
- [42] Z.M. Burell and N. Okada, *Supersymmetric minimal B-L model at the TeV scale with right-handed Majorana neutrino dark matter*, *Phys. Rev. D* **85** (2012) 055011 [[arXiv:1111.1789](#)] [[INSPIRE](#)].
- [43] J. Fidalgo and C. Muñoz, *The $\mu\nu$ S_{SM} with an Extra U(1)*, *JHEP* **04** (2012) 090 [[arXiv:1111.2836](#)] [[INSPIRE](#)].
- [44] W.-Z. Feng, G. Shiu, P. Soler and F. Ye, *Probing Hidden Sectors with Stückelberg U(1) Gauge Fields*, *Phys. Rev. Lett.* **113** (2014) 061802 [[arXiv:1401.5880](#)] [[INSPIRE](#)].
- [45] W.-Z. Feng, G. Shiu, P. Soler and F. Ye, *Building a Stückelberg portal*, *JHEP* **05** (2014) 065 [[arXiv:1401.5890](#)] [[INSPIRE](#)].
- [46] X.-G. He and S. Oh, *Lepton FCNC in Type III Seesaw Model*, *JHEP* **09** (2009) 027 [[arXiv:0902.4082](#)] [[INSPIRE](#)].
- [47] B. Ponsot, V. Schomerus and J. Teschner, *Branes in the Euclidean AdS₃*, *JHEP* **02** (2002) 016 [[hep-th/0112198](#)] [[INSPIRE](#)].
- [48] P. Langacker and M. Plümacher, *Flavor changing effects in theories with a heavy Z' boson with family nonuniversal couplings*, *Phys. Rev. D* **62** (2000) 013006 [[hep-ph/0001204](#)] [[INSPIRE](#)].
- [49] V. Barger, C.-W. Chiang, P. Langacker and H.-S. Lee, *Z' mediated flavor changing neutral currents in B meson decays*, *Phys. Lett. B* **580** (2004) 186 [[hep-ph/0310073](#)] [[INSPIRE](#)].
- [50] ATLAS collaboration, *Search for flavour-changing neutral current top-quark decays $t \rightarrow qZ$ in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **07** (2018) 176 [[arXiv:1803.09923](#)] [[INSPIRE](#)].
- [51] CMS collaboration, *Search for the flavor-changing neutral current interactions of the top quark and the Higgs boson which decays into a pair of b quarks at $\sqrt{s} = 13$ TeV*, *JHEP* **06** (2018) 102 [[arXiv:1712.02399](#)] [[INSPIRE](#)].
- [52] S. Floerchinger and U.A. Wiedemann, *Fluctuations around Bjorken Flow and the onset of turbulent phenomena*, *JHEP* **11** (2011) 100 [[arXiv:1108.5535](#)] [[INSPIRE](#)].
- [53] S.P. Martin, *Dimensionless supersymmetry breaking couplings, flat directions and the origin of intermediate mass scales*, *Phys. Rev. D* **61** (2000) 035004 [[hep-ph/9907550](#)] [[INSPIRE](#)].
- [54] F. Borzumati, G.R. Farrar, N. Polonsky and S.D. Thomas, *Soft Yukawa couplings in supersymmetric theories*, *Nucl. Phys. B* **555** (1999) 53 [[hep-ph/9902443](#)] [[INSPIRE](#)].

- [55] T. Bandyopadhyay, G. Bhattacharyya, D. Das and A. Raychaudhuri, *Reappraisal of constraints on Z' models from unitarity and direct searches at the LHC*, *Phys. Rev. D* **98** (2018) 035027 [[arXiv:1803.07989](#)] [[INSPIRE](#)].
- [56] G.-C. Cho, *Looking for Z' bosons in supersymmetric E_6 models through electroweak precision data*, *Mod. Phys. Lett. A* **15** (2000) 311 [[hep-ph/0002128](#)] [[INSPIRE](#)].
- [57] V. Martín-Lozano and S. Oviedo-Casado, in preparation.
- [58] X.-G. He and G. Valencia, *The $Z \rightarrow b\bar{b}$ decay asymmetry and left-right models*, *Phys. Rev. D* **66** (2002) 013004 [*Erratum ibid.* **D 66** (2002) 079901] [[hep-ph/0203036](#)] [[INSPIRE](#)].
- [59] X.-G. He and G. Valencia, *Ansatz for small FCNC with a non-universal Z-prime*, *Phys. Lett. B* **680** (2009) 72 [[arXiv:0907.4034](#)] [[INSPIRE](#)].
- [60] G. Valencia, *Flavor changing neutral currents and a z'* , *Hyperfine Interact.* **214** (2013) 31.
- [61] ATLAS collaboration, *Search for new high-mass phenomena in the dilepton final state using 36fb^{-1} of proton-proton collision data at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, *JHEP* **10** (2017) 182 [[arXiv:1707.02424](#)] [[INSPIRE](#)].
- [62] ATLAS collaboration, *Search for additional heavy neutral Higgs and gauge bosons in the ditau final state produced in 36fb^{-1} of pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, *JHEP* **01** (2018) 055 [[arXiv:1709.07242](#)] [[INSPIRE](#)].
- [63] CMS collaboration, *Search for high-mass resonances in dilepton final states in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$* , *JHEP* **06** (2018) 120 [[arXiv:1803.06292](#)] [[INSPIRE](#)].
- [64] V. Martín-Lozano, M. Peiró and P. Soler, *Isospin violating dark matter in Stückelberg portal scenarios*, *JHEP* **04** (2015) 175 [[arXiv:1503.01780](#)] [[INSPIRE](#)].