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Phenomenological Aspects of U(1)$'$ Models

Durmuş A. Demir

Department of Physics, Izmir Institute of Technology, TR35430, Izmir, Turkey,
Deutsches Elektronen Synchrotron, DESY, D-22607, Hamburg, Germany.

Abstract. This talk summarizes certain phenomenological aspects of the supersymmetric models with an extra U(1) invariance broken at the TeV scale. The discussions involve the Higgs sector, CP violation, Neutrino masses and the LHC signatures.

Keywords: Supersymmetry, U(1)-prime model, Neutrino masses, CP violation, Higgs sector, LHC
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INTRODUCTION

Supersymmetric models, in particular, the minimal supersymmetric model (MSSM) have been introduced to solve the gauge hierarchy problem of the Standard Model (SM). However, the MSSM itself suffers from a naturalness problem related to the Higgsino Dirac mass nested in the superpotential of the model. This problem, the μ problem, has been the main source of motivation for extending the MSSM. The point is to replace μ by a chiral superfield whose scalar component develops a vacuum expectation value (VEV) to induce an effective μ parameter at the desired scale.

Leaving aside the NMSSM [1] option which induces domain walls, one is almost uniquely lead to the U(1)$'$ models which forbid a bare μ parameter via an Abelian gauge invariance, the U(1)$'$ gauge group [2]. Actually, such extra gauge groups generically exist in low-energy models descending from GUTs and strings [3]. This kind of model predicts, by its supersymmetric nature, a neutral vector boson Z$'$ and its gaugino $\widetilde{Z}'$, not found in the MSSM. In addition, as in the NMSSM, the spectrum also consists of the singlet Higgs S (whose VEV generates the μ parameter) and the associated singlino $\widetilde{S}$. For setting the notation, it may be convenient to mention that the bilinear $\mu \widehat{H}_u \cdot \widehat{H}_d$ in the MSSM superpotential gets replaced by

$$\widehat{W} \ni h_s \widehat{S} \widehat{H}_u \cdot \widehat{H}_d \tag{1}$$

where h_s is a dimensionless coupling. Correspondingly, the soft-breaking sector of U(1)$'$ models involves the trilinear coupling $h_s A_s S H_u \cdot H_d$ [2]. Upon the breakdown of U(1)$'$ times the electroweak gauge group, Z' gauge boson acquires a mass $M_{Z'}^2 = g_{Y'}^2 \left(Q'^2_{H_u} v_u^2 + Q'^2_{H_d} v_d^2 + Q'^2_S v_s^2 \right)$ and exhibits mass mixing with Z by an amount $\Delta^2 = \frac{1}{2} G_Z g_{Y'} \left(Q'_{H_u} v_u^2 - Q'_{H_d} v_d^2 \right)$, where $G_Z^2 = g_2^2 + g_Y^2$, $v_u = \langle H_u^0 \rangle$, $v_d = \langle H_u^0 \rangle$, $v_s = \langle S \rangle$, $g_{Y'}$ is the U(1)$'$ gauge coupling, and Q'_X is the U(1)$'$ charge of X. The present bounds are such that the mixing between Z and Z' should not exceed one per mil level [2].

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One keeps in mind that these models suffer from gauge anomalies which disrupt the gauge coupling unification. This problem can be avoided either by importing extra fields (as in low-energy models descending from GUTs [4]) or by introducing family-dependent U(1)$'$ charges [5]. In what follows, the second option will be adopted (or GUT remnants will be taken relatively heavy to have no significant effect on the observables).

In the following we will discuss Higgs sector, Neutrino masses and basic LHC signatures within the U(1)$'$ models.

HIGGS SECTOR

In course of electroweak breaking Z and Z' bosons acquire their masses by eating, respectively, Im $\left[-\sin\beta H_u^0 + \cos\beta H_d^0\right]$ and Im $\left[\cos\alpha\cos\beta H_u^0 + \cos\alpha\sin\beta H_d^0 - \sin\alpha S\right]$, where $\cot\alpha = (v/\sqrt{2})\sin\beta\cos\beta/v_s$ with $v^2/2 = v_u^2 + v_d^2$. In the CP-conserving limit the theory contains three CP-even, one CP-odd, and a charged Higgs boson. The CP–odd scalar is typically heavy as its mass-squared goes like $A_s v_s$. It differs from the MSSM spectrum by one extra CP-even scalar [6, 7]. At the tree level, the lightest Higgs mass is bounded as

$$m_{H_1}^2 \leq M_Z^2 \cos^2 2\beta + \frac{1}{2} h_s^2 v^2 \sin^2 2\beta + g_{Y'}^2 \left(Q'_{H_d}\cos^2\beta + Q'_{H_u}\sin^2\beta\right)^2 v^2 \tag{2}$$

where the first term on the right-hand side is the MSSM bound where the lightest Higgs is lighter than the Z boson at tree level. The second term is an F-term contribution that also exists in the NMSSM [1]. The last term, the U(1)$'$ D-term contribution, enhances the upper bound in proportion to $g_{Y'}^2$, and hence, rather generically the U(1)$'$ models possess a relatively large m_{H_1} making thus easier it to evade the LEP II bounds already at tree level. Indeed, when one-loop radiative corrections are included the Higgs mass obeys the upper bound [5]

$$\overline{m}_{H_1}^2 \lesssim m_{H_1}^2 + \frac{3m_t^4}{2\pi^2 v^2}\log\frac{m_{\tilde{t}}^2}{m_t^2} \tag{3}$$

where $m_{H_1}^2$ is the right hand side of Eq. (2) (see [6] for exact results). The radiatively corrected upper bound (3) can be used to place a lower bound on the stop mass

$$m_{\tilde{t}} \geq m_t\, e^{\left(\overline{m}_{H_1}^2 - m_{H_1}^2\right)\frac{\pi^2 v^2}{3m_t^4}} \tag{4}$$

where $v \approx 246$ GeV is the electroweak breaking scale. For $\overline{m}_{H_1} = 114$ GeV, one typically finds $m_{\tilde{t}}^2 \gtrsim 3\, M_Z^2$ for the SUSY breaking scale [5]. A comparison of these results with the MSSM expectation, $m_{\tilde{t}}^2 \gtrsim 50\, M_Z^2$ [8], demonstrates that in U(1)$'$ models the SUSY breaking scale stays closer to the top mass, and thus, the little hierarchy problem is ameliorated. The results above, however, should be taken with care since generating a TeV mass Z' is itself pauses a little hierarchy problem. Nevertheless, this additional hierarchy problem is known to be sidestepped by introducing a secluded sector [9].

CP VIOLATION

In U(1)$'$ models CP violation effects are sourced by gaugino masses, trilinear couplings and off-diagonal entries in the sfermion mass matrices. In contrast to MSSM, the μ parameter is a derived parameter, and its phase is induced radiatively. In other words, the phase of the μ parameter is loop-suppressed and turns out to be naturally small [6]. This smallness is precisely what electric dipole moment (EDM) bounds typically require. The effects of CP violating phases on EDMs are sizeable; various bounds on parameter space change [6, 10].

NEUTRINO MASSES

The discovery of neutrino oscillations has confirmed that neutrinos are massive and that leptons exhibit nontrivial mixing, providing the first particle physics evidence for physics beyond the Standard Model (SM). Neutrino masses require either the existence of novel matter species not found in the SM spectrum and/or the violation of the global symmetries of the SM via higher-dimensional operators. Extensions incorporating such additional structure should ideally be capable of improving the ultraviolet behavior of the SM beyond Fermi energies.

In [11] it has been shown that the U(1)$'$ invariance which solves the μ problem facilitates a viable mechanism for generating neutrino masses of correct size. The mechanism proceeds via either the non-holomorphic supersymmetry-breaking operators (see [5] for details) or via non-renormalizable operators in the superpotential. Concerning the former one notes that supersymmetry breaking in a hidden sector via some spurion field X with $\langle F_X \rangle = \widetilde{m} M_{Pl}$ (with $\widetilde{m} \sim M_{EW}$) gives rise to the operator

$$\frac{1}{M_{Pl}^2}\left(\widehat{X}^{\dagger}\widehat{L}\cdot\widehat{H}_d^c\bar{\mathbf{Y}}_{\nu}'\widehat{N}\right)_D = L\cdot H_d^c\widetilde{\mathbf{Y}}_{\nu}'\nu_R^c, \tag{5}$$

in which the effective Yukawa coupling

$$\widetilde{\mathbf{Y}}_{\nu}' \equiv \frac{F_X}{M_{Pl}^2}\bar{\mathbf{Y}}_{\nu}' \sim \frac{\widetilde{m}}{M_{Pl}}\bar{\mathbf{Y}}_{\nu}' \tag{6}$$

is of the right size for (5) to generate Dirac neutrino masses at the scale indicated by experiments. Clearly, the U(1)$'$ charge of the right-handed neutrino superfield $\widehat{N}$ is such that while the usual Yukawa interaction $\widehat{L}\cdot\widehat{H}_u\widehat{N}$ is forbidden by $Q_L' + Q_{H_u}' + Q_N' \neq 0$ the wrong-Higgs coupling is allowed by the condition $Q_L' - Q_{H_d}' + Q_N' = 0$. The μ problem is solved by $Q_S' + Q_{H_u}' + Q_{H_d}' = 0$. The operator in (5) is technically hard. However, the shift in the Higgs mass-squared $\delta m_{H_d}^2 = -(1/(8\pi^2))\widetilde{\mathbf{Y}}_{\nu}'^{\dagger}\widetilde{\mathbf{Y}}_{\nu}' M^2 = -(1/(8\pi^2))\widetilde{m}^2\bar{\mathbf{Y}}_{\nu}'^{\dagger}\bar{\mathbf{Y}}_{\nu}'$ is too small to leave any impact on the gauge hierarchy.

Another structure that can generate viable neutrino masses arises at the non-renormalizable level in the superpotential

$$\widehat{W} \ni \frac{1}{M_{Pl}}\widehat{S}\widehat{L}\cdot\widehat{H}_u\widehat{N} \tag{7}$$

which again yields correct neutrino masses after U(1)$'$ times electroweak breaking. This operator is allowed by the U(1)$'$ charge assignments discussed above.

One thus concludes that U(1)$'$ models, when right-handed neutrinos are charged under U(1)$'$ gauge group, provide a viable framework in which both μ problem is solved and neutrino Dirac masses are generated naturally (with no need to lepton number violation needed for the usual see-saw mechanism to work). The generated neutrino masses fall naturally within the experimentally preferred range.

LHC SIGNATURES

In general, signatures of the U(1)$'$ models at colliders and other experiments follow from the contributions of Z'_{μ}, $\widetilde{Z}'$, S and $\widetilde{S}$ fields to associated scattering processes. The LHC experiments, which have just started, will search for fields and forces beyond the standard electroweak theory. Thanks to the huge energy reach of the collider, it is expected that, literally speaking, 'anything beyond the SM', if weighs within the TeV domain, must be discovered at the LHC. Stating differently, the LHC will be determining if nature is supersymmetric. On top of this, it will be capable of telling what kind of supersymmetric structure it possesses. In this respect LHC signatures of the U(1)$'$ models deserve a separate discussion.

The most studied signature of U(1)$'$ models concerns the Z' gauge boson. The Z' gauge boson is produced directly via $q\overline{q}$ annihilation at hadron colliders. It subsequently decays into fermion anti-fermion pairs. The number of events, when plotted against the difermion invariant mass, assumes a resonance shape peaked at the Z' mass. The event shape manifestly differs from the Z boson shape, and guarantees the existence of an extra heavy neutral boson in the spectrum. The experimental searches on Z' boson have made use of dilepton distributions. Though there exists an unavoidable model dependence, the negative searches at the Tevatron favor Z' to weigh a TeV or higher [12].

The Z' gauge boson also influences Higgs discovery channels or exclusion limits. The reason is that Z' exchange modifies Higgs-strahlung and Bjorken processes [13]. In addition, vector boson fusion channel gets also modified by Z' contribution. Finally, Z' boson (and additional non-MSSM Higgs bosons) can also be produced in diffractive scatterings at the LHC [14].

The Higgs sector of the U(1)$'$ model, as mentioned before, differs from that of the MSSM by the relative heaviness of the lightest Higgs boson. Indeed, depending on the parameter values, in particular, A_s/v_s ratio and v_s itself the lightest Higgs boson can be as heavy as approximately 200 GeV in U(1)$'$ models [6]. Consequently, in case the Higgs scalar is found to weigh above the MSSM range at the LHC one can interpret the result in favor of extended supersymmetric models *e.g.* the U(1)$'$ models.

A highly important yet somehow overlooked aspect of the U(1)$'$ models (or any low-energy supersymmetric model with extra gauge structures like U(1)$'$ gauge group) concerns the fermionic partner of Z' boson, $\widetilde{Z}'$. This field (to be called 'zino-prime' hereon), together with the singlino $\widetilde{S}$, joins to the neutral fermion sector to yield 6 Majorana fermions (in excess of 4 neutralinos present in the MSSM). These two fermions can give rise to a number of phenomena not found in the MSSM.

First, in pp collisions, $\widetilde{S}$ is pair-produced by the s-channel Z' exchange. It then decays into Higgs bosons and Higgsinos nested in the Higgs doublets. The singlino does not couple to fermions directly. If Z' boson is kinematically allowed to decay into pairs of singlinos then its width (visible or invisible) increases. This can significantly change the exclusion limits placed on the Z' mass.

Second, in pp collisions, the $\widetilde{Z}'$ is pair-produced via t-channel squark exchange. This direct production process might be suppressed if squarks weigh around a TeV. Unlike the singlino, the zino-prime directly couples to fermios and sfermions, and thus, can leave important impact on collider searches for superpartners. To give an extreme example, one can imagine decays of right-handed squarks in the MSSM. These squarks are charged under only the hypercharge gauge group, and, if they belong to first or second families, they exclusively decay into a quark (forming a jet) and the bino (which dominates the lightest supersymmetric particle (LSP) for most of the parameter space). This '0 lepton + 1 jet + missing energy (LSP)' signal is characteristic of right-handed squarks (in the first and second generations) in the MSSM.

The situation is strikingly different in the $U(1)'$ models. First of all, one notes that several bino dominates the LSP for most of the parameter space in $U(1)'$ models as well [15]. A right-handed squark (which can be produced in association with another right-handed squark or left-handed squark or anti-right-handed squark or gluino at the LHC [16]) is not obliged to decay into its partner quark and bino, as happens in the MSSM. Indeed, it can decay into zino-prime and its partner quark and zino-prime can further decay into pairs of leptons and bino. The message here is that, as a characteristic feature of $U(1)'$ models (or of gauge-extended supersymmetric model), the spectrum consists of extra gauginos and they change decay pattern and topology of sparticles. In this respect, possible observation of the leptonic branchings for right-handed squarks will be a clear signature of $U(1)'$ model. We exemplify these observations by taking $M_{\widetilde{Y}} = 100$ GeV, $M_{\widetilde{W}} = 400$ GeV, $M_{\widetilde{g}} = 1300$ GeV, $m_{\widetilde{q}} = 1200$ GeV and $\tan\beta = 10$ as the basic parameters. The $U(1)'$ model under concern then yields $\mu_{eff} = 1400$ GeV and Z' mass to be 981 GeV. We also include a mixing soft mass between bino $\widetilde{Y}$ and $\widetilde{Z}'$ (corresponding to the kinetic mixing between the corresponding superfields). The branching ratio of a right-handed squark (belonging to first or second generation) takes the form in Fig. 1. In the MSSM it decays solely into bino and quark. In $U(1)'$ model, however, it has a reduced branching into quark and bino; it is now able to decay into quark plus χ_3^0 neutralino which further decays into lepton pairs and the LSP. This figure should exhibit all the features discussed above in a comparative fashion (A detailed analysis of squark production and decays in $U(1)'$ models will appear in [17].).

CONCLUSIONS

The supersymmetric models with an extra U(1) invariance, which can be motivated by both low- and high-energy considerations, possess several distinctive signatures compared to the MSSM, and it should be possible to search for them at the LHC.

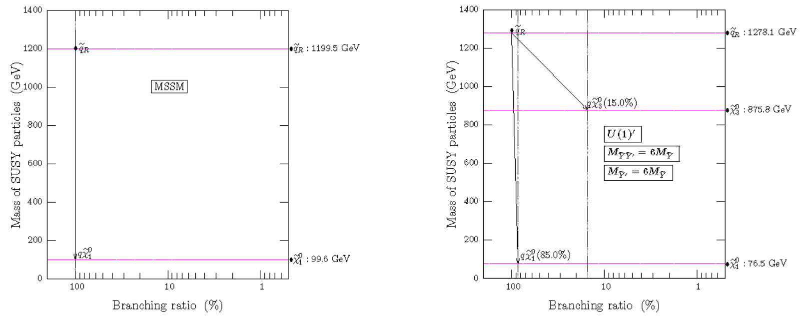

FIGURE 1. The branchings of a right-handed squark $\tilde{q}$ into quark and neutralino in the MSSM and U(1)$'$ models.

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