

# Model Characterization and Dark Matter in the Secluded $U(1)'$ Model

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★ This paper is dedicated to the memory of Prof. Levent Solmaz, who unexpectedly passed away on August 16, 2021.

We consider a class of  $U(1)'$ -extended MSSM in which the  $U(1)'$  symmetry is broken by a vacuum expectation values (VEVs) of four MSSM singlet fields. While one singlet field interacts with the MSSM Higgs fields, three of them interact only with each other in forming a secluded sector. Assigning universal  $U(1)'$  charges for three families, the anomaly cancellation condition requires exotic fields which are assumed to be heavy and decoupled. We discuss a variety of  $U(1)'$  charge assignments and anomaly cancellation,  $Z'/Z$  hierarchy, neutralinos and charginos as well as the Higgs sector. We realize that the typical spectra involve two CP-odd Higgs bosons lighter than about 200 GeV and 600 GeV respectively, which are mostly formed by the MSSM singlet fields. If the relic density of dark matter is saturated only by a neutralino, compatible solutions predict LSP neutralinos formed by the MSSM singlet fields in the mass scales below about 600 GeV, while it is possible to realize MSSM neutralino LSP above these mass scales. We identify  $A$ -funnel solutions in the MSSM singlet LSP solutions. These solutions can also yield considerable scattering cross-sections through the Higgs portal such that they can be tested in the ongoing direct dark matter detection experiments.

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## Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>The Secluded <math>U(1)'</math> Model</b>	<b>2</b>
2.1	Gauge Boson Masses and Mixing	5
2.2	Neutralinos and Charginos	6
2.3	Higgs Bosons	8
<b>3</b>	<b>Scanning Procedure and Experimental Constraints</b>	<b>11</b>
<b>4</b>	<b>Results</b>	<b>13</b>
<b>5</b>	<b>Conclusion</b>	<b>19</b>
<b>6</b>	<b>Acknowledgments</b>	<b>21</b>

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## 1 Introduction

Despite the lack of any direct signal of new physics beyond the Standard Model (SM), the minimal supersymmetric extension of the Standard Model (MSSM) is still one of the forefront candidate because of the motivation of resolution to the gauge hierarchy problem [1–5], stability of the Higgs potential [6–11], pleasant candidates for the dark matter with an additional attraction from the gauge coupling unification at the grand unification scale ( $M_{\text{GUT}} \simeq 2.4 \times 10^{16}$  GeV). On the other hand, the lack of a direct signal might point to deviate from the minimal point of view in constructing models beyond the SM. For instance, if the lightest supersymmetric particle (LSP) is not a mixture of MSSM neutralinos [12–14], many of the signal processes currently under the collider analyses may not be available at the collision energies of today. A similar discussion can be followed also for the null results from the dark matter experiments [15–17].

In addition to the current results from the experiments, possible resolutions to some long standing problems such as absence of the right-handed neutrinos and  $\mu$ – problem in MSSM [18] can motivate to construct models beyond the SM which extends the particle content and/ or symmetrical structure of MSSM. In this context, a larger symmetry group which supplements the MSSM gauge group with an extra  $U(1)'$  can address the resolution to the  $\mu$ –problem. If the extra  $U(1)'$  symmetry is imposed in a way that the MSSM fields are also non-trivially charged under it, the  $\mu H_d H_u$  is not allowed in the superpotential due to the gauge invariance under  $U(1)'$ . On the other hand, it can be generated effectively through the vacuum expectation value (VEV) of a field  $S$ , which is preferably singlet under the MSSM gauge symmetry so that its VEV breaks only the  $U(1)'$  symmetry. In this case

the superpotential involves a term such as  $SH_u H_d$ , and through the  $U(1)'$  breaking, the  $\mu$ -term is generated effectively as  $\mu_{\text{eff}} \sim \mathcal{O}(\langle S \rangle)$  [19–28]. In this way, the radiative electroweak symmetry breaking (REWSB) is linked to the  $U(1)'$  symmetry breaking through the renormalization group equations (RGEs). Such an extension can still be considered to be minimal, and it is well motivated in superstring theories [29], grand unified theories [30] and in dynamical electroweak breaking theories [31].

In addition to extending the symmetry, the  $U(1)'$  models also extend the particle content of MSSM by adding  $Z'$  - the gauge boson associated with the  $U(1)'$  group and the right handed neutrinos. The right handed neutrinos can be considered to complete the representations of matter field families so that the model can be embedded in a larger GUT group such as  $E_6$ . Besides, the right-handed neutrinos contribute to the anomaly cancellations, and they can provide a natural framework to implement seesaw mechanisms [32] for non-zero neutrino masses and mixing [33]. In this context,  $\langle S \rangle$  significantly contributes to the right-handed sneutrino and  $Z'$  masses as well as their superpartners. On the other hand, the presence of a neutral gauge boson  $Z'$  brings a strong impact on this class of models, since the current experimental results exclude the solutions with  $M_{Z'} \lesssim 4$  TeV. Such a strong exclusion results in a  $U(1)'$  breaking scale at the order of  $\mathcal{O}(10 \text{ TeV})$  and consequently  $\mu_{\text{eff}} \sim$  a few TeV, which softly brings the  $\mu$ -problem back to the  $U(1)'$  models, even though a resolution to the naturalness problem can be accommodated [34]. On the other hand, if the  $U(1)'$  symmetry breaking involves three more MSSM singlet fields ( $S_1, S_2, S_3$ ) [35, 36], a  $\mu$ -term at the order of electroweak symmetry breaking can be realized, while  $Z'$  remains heavy to be consistent with the current experimental results. In addition, a relatively light supersymmetric mass spectrum can be realized, since a consistent Higgs boson mass can be obtained even at tree-level [34].

We refer to the class of supersymmetric  $U(1)'$  models with three additional MSSM singlet fields as the secluded  $U(1)'$  model [35–38]. The rest of the paper is organized as follows: We first briefly review the secluded  $U(1)'$  models in Section 2 with its superpotential, particle content, non-trivial  $U(1)'$  charges of the fields and anomaly cancellations as well as the field content and the physical mass states. After we describe the scanning procedure and summarize the relevant experimental constraints in Section 3, we present and discuss the LHC and dark matter implications of the model in Section 4. Finally, we conclude our findings in Section 5.

## 2 The Secluded $U(1)'$ Model

In this section, we present the relevant ingredient and some salient features of the secluded  $U(1)'$  model, which is based on the gauge group  $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$ . Such an extension of MSSM gauge group can emerge in the grand unified theories (GUTs) based on a gauge group larger than  $SU(5)$  such as  $SO(10)$  [39–42] and/or  $E_6$  [43–46]. In the common convention, these two classes of GUTs yield  $U(1)_\psi$  and  $U(1)_\chi$  models, and a

general  $U(1)'$  framework can be built through the mixing of these two extensions [47]. Even though they provide a significant enrichment with a single extension of the MSSM gauge group, these models are built with a minimalistic assumption that the MSSM fields are resided in the irreducible representation of  $SO(10)$  and/or  $SU(5)$ , which also determines the quantum numbers of the fields under the  $U(1)'$  symmetry. On the other hand, a general configuration of the  $U(1)'$  charges cannot be restricted to these two classes of the  $U(1)'$  models [23, 48–52]. A general set of equations for the charges can be obtained from the anomaly cancellation condition, and these conditions also depend on the exotic fields involved in the model. In our work, we consider the following superpotential:

$$\begin{aligned} \widehat{W} = & h_u \widehat{Q} \cdot \widehat{H}_u \widehat{U} + h_d \widehat{Q} \cdot \widehat{H}_d \widehat{D} + h_e \widehat{L} \cdot \widehat{H}_d \widehat{E} + \lambda \widehat{S} \widehat{H}_u \cdot \widehat{H}_d + h_\nu \widehat{L} \cdot \widehat{H}_u \widehat{N} + \frac{\kappa}{3} \widehat{S}_1 \widehat{S}_2 \widehat{S}_3 \\ & + \sum_{i=1}^{n_Q} h_Q^i \widehat{S} \widehat{Q}_i \widehat{Q}_i + \sum_{j=1}^{n_{\mathcal{L}}} h_L^j \widehat{S} \widehat{\mathcal{L}}_j \widehat{\mathcal{L}}_j \end{aligned} \quad (2.1)$$

where  $\widehat{Q}, \widehat{U}, \widehat{D}, \widehat{L}$  and  $\widehat{E}$  represent the matter superfields of MSSM corresponding to the squarks and sleptons, and  $\widehat{H}_u, \widehat{H}_d$  are the MSSM Higgs doublets. The new ingredient from the  $U(1)'$  inclusion can be listed as the singlet scalars  $S, S_{1,2,3}$ , right-handed neutrino superfield  $\widehat{N}$  and exotic fields  $Q_i, \mathcal{L}_i$ . In addition, the model includes a neutral gauge boson associated with the  $U(1)'$  symmetry and its supersymmetric partner. Note that a bilinear term mixing  $H_u$  and  $H_u$  such as the  $\mu$ -term of MSSM is not allowed here by the gauge invariance under the  $U(1)'$  symmetry. It is rather generated effectively through the VEV of  $S$  so that  $\mu_{eff} \equiv \lambda \langle S \rangle$ . However, emergence of such an effective term induces mixed anomalies between  $U(1)'$  and the MSSM gauge group, and cancellation of such anomalies also requires exotic fields in the particle spectrum, and the anomaly cancellation can be maintained by introducing exotic fields, which are vector-like with respect to MSSM, but chiral under the  $U(1)'$  group.

Field	$\widehat{Q}$	$\widehat{U}$	$\widehat{D}$	$\widehat{L}$	$\widehat{N}$	$\widehat{E}$	$\widehat{H}_u$	$\widehat{H}_d$	$\widehat{S}$	$\widehat{S}_1$	$\widehat{S}_2$	$\widehat{S}_3$	$\widehat{Q}$	$\widehat{\overline{Q}}$	$\widehat{\mathcal{L}}$	$\widehat{\overline{\mathcal{L}}}$
$SU(3)_C$	3	$\overline{3}$	$\overline{3}$	1	1	1	1	1	1	1	1	1	3	$\overline{3}$	1	1
$SU(2)_L$	2	1	1	2	1	1	2	2	1	1	1	1	1	1	1	1
$U(1)_Y$	1/6	-2/3	1/3	-1/2	0	1	1/2	-1/2	0	0	0	0	$Y_Q$	$-Y_Q$	$Y_{\mathcal{L}}$	$-Y_{\mathcal{L}}$
$U(1)'$	$Q'_Q$	$Q'_U$	$Q'_D$	$Q'_L$	$Q'_N$	$Q'_E$	$Q'_{H_u}$	$Q'_{H_d}$	$Q'_S$	$Q'_{S_1}$	$Q'_{S_2}$	$Q'_{S_3}$	$Q'_Q$	$Q'_{\overline{Q}}$	$Q'_{\mathcal{L}}$	$Q'_{\overline{\mathcal{L}}}$

**Table 1.** Gauge quantum numbers of quark ( $\widehat{Q}, \widehat{U}, \widehat{D}$ ), lepton ( $\widehat{L}, \widehat{N}, \widehat{E}$ ), Higgs ( $\widehat{H}_u, \widehat{H}_d$ ), SM-singlet ( $\widehat{S}, \widehat{S}_1, \widehat{S}_2, \widehat{S}_3$ ), exotic quark ( $\widehat{Q}, \widehat{\overline{Q}}$ ) and exotic lepton ( $\widehat{\mathcal{L}}, \widehat{\overline{\mathcal{L}}}$ ) superfields.

If a general  $U(1)'$  charge assignments as shown in Table 1, the gauge invariance condition yields the following equations:

$$\begin{aligned}
0 &= Q'_S + Q'_{H_u} + Q'_{H_d} , \\
0 &= Q'_Q + Q'_{H_u} + Q'_U , \\
0 &= Q'_Q + Q'_{H_d} + Q'_D , \\
0 &= Q'_L + Q'_{H_d} + Q'_E , \\
0 &= Q'_Q + Q'_{\overline{Q}} + Q'_S , \\
0 &= Q'_L + Q'_{\overline{L}} + Q'_S , \\
0 &= Q'_L + Q'_{H_u} + Q'_N , \\
0 &= Q'_{S_1} + Q'_{S_2} + Q'_{S_3} .
\end{aligned} \tag{2.2}$$

Note that if a special configuration with  $Q'_S = 0$  can be found, the  $\mu$ -term becomes allowed by the gauge invariance. However, a consistent  $Z - Z'$  mass hierarchy and mixing rather require non-zero  $U(1)'$  charges for all MSSM singlet scalar fields  $S, S_{1,2,3}$ . Another set of conditions for the charges is obtained from the vanishing  $U(1)' - SU(3)_c - SU(3)_c$ ,  $U(1)' - SU(2)_L - SU(2)_L$ ,  $U(1)' - U(1)_Y - U(1)_Y$ ,  $U(1)' - \text{graviton} - \text{graviton}$ ,  $U(1)' - U(1)' - U(1)_Y$  and  $U(1)' - U(1)' - U(1)'$  anomalies, as follows:

$$0 = 3(2Q'_Q + Q'_U + Q'_D) + n_Q(Q'_Q + Q'_{\overline{Q}}) , \tag{2.3}$$

$$0 = 3(3Q'_Q + Q'_L) + Q'_{H_d} + Q'_{H_u} , \tag{2.4}$$

$$\begin{aligned}
0 &= 3\left(\frac{1}{6}Q'_Q + \frac{1}{3}Q'_D + \frac{4}{3}Q'_U + \frac{1}{2}Q'_L + Q'_E\right) + \frac{1}{2}(Q'_{H_d} + Q'_{H_u}) \\
&\quad + 3n_Q Y_Q^2 (Q'_Q + Q'_{\overline{Q}}) + n_L Y_L^2 (Q'_L + Q'_{\overline{L}}) ,
\end{aligned} \tag{2.5}$$

$$\begin{aligned}
0 &= 3(6Q'_Q + 3Q'_U + 3Q'_D + 2Q'_L + Q'_E + Q'_N) + 2Q'_{H_d} + 2Q'_{H_u} \\
&\quad + Q'_S + Q'_{S_1} + Q'_{S_2} + Q'_{S_3} + 3n_Q(Q'_Q + Q'_{\overline{Q}}) + n_L(Q'_L + Q'_{\overline{L}}) ,
\end{aligned} \tag{2.6}$$

$$\begin{aligned}
0 &= 3(Q_Q'^2 + Q_D'^2 - 2Q_U'^2 - Q_L'^2 + Q_E'^2) - Q_{H_d}'^2 + Q_{H_u}'^2 + 3n_Q Y_Q (Q_Q'^2 - Q_{\overline{Q}}'^2) \\
&\quad + n_L Y_L (Q_L'^2 - Q_{\overline{L}}'^2) ,
\end{aligned} \tag{2.7}$$

$$\begin{aligned}
0 &= 3(6Q_Q'^3 + 3Q_D'^3 + 3Q_U'^3 + 2Q_L'^3 + Q_E'^3 + Q_N'^3) + 2Q_{H_d}'^3 + 2Q_{H_u}'^3 + Q_S'^3 \\
&\quad + Q_{S_1}'^3 + Q_{S_2}'^3 + Q_{S_3}'^3 + 3n_Q(Q_Q'^3 + Q_{\overline{Q}}'^3) + n_L(Q_L'^3 + Q_{\overline{L}}'^3) .
\end{aligned} \tag{2.8}$$

All these conditions from the gauge invariance and the anomaly cancellations should be satisfied for particular pattern of charges and parameters, which requires the number of exotics involved as  $n_Q = 3$  color triplets with  $Y_Q = -1/3$  and  $n_L = 2$  color singlets with  $Y = -1$ . Recall that these exotic fields are singlets under  $SU(2)_L$  as mentioned before and listed in Table 1.

## 2.1 Gauge Boson Masses and Mixing

As mentioned before the model introduces a new neutral gauge boson  $Z'$  and its superpartner  $\tilde{B}'$  associated with the gauged  $U(1)'$  symmetry. The symmetry breaking in this model is being realized very similar to the Higgs mechanism, but in this case, the electroweak and  $U(1)'$  symmetry breaking are correlated. The fields developing non-zero VEVs during the symmetry breaking,  $SU(2)_L \times U(1)_Y \times U(1)' \rightarrow U(1)_{\text{EM}}$ , can be listed as follows:

$$\langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix}, \quad \langle H_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_d \end{pmatrix}, \quad \langle S \rangle = \frac{v_S}{\sqrt{2}}, \quad \langle S_i \rangle = \frac{v_{S_i}}{\sqrt{2}} \quad (2.9)$$

Since  $S, S_{1,2,3}$  fields are singlet under the MSSM gauge group, the  $W$  and  $Z$ -bosons acquire their masses through the VEVs of  $H_u$  and  $H_d$  as in the usual electroweak symmetry breaking; thus, the condition  $v_u^2 + v_d^2 = v_{SM}^2$  should still hold in this model. On the other hand, because of the non-trivial charges of all the superfields under  $U(1)'$  as listed in Table 1, the  $Z'$ -boson receives its mass from all the VEVs. In this case, since  $v_S$  and/or  $v_{S_i}$  are expected to be much greater than  $v_u$  and  $v_d$ , the secluded sector can be accounted for the main source of the  $Z'$  mass. However, apart from the mass acquisition, non-trivial  $H_u$  and  $H_d$  charges induce a non-zero mixing between  $Z$  and  $Z'$  associated with their mass-square matrix:

$$M_{ZZ'}^2 = \begin{pmatrix} M_Z^2 & \Delta^2 \\ \Delta^2 & M_{Z'}^2 \end{pmatrix} \quad (2.10)$$

written in  $(Z, Z')$  basis in terms of

$$\begin{aligned} M_Z^2 &= \frac{1}{4}(g_1^2 + g_2^2)(v_u^2 + v_d^2) \\ M_{Z'}^2 &= g_1'^2 \left( Q_{H_u}'^2 v_u^2 + Q_{H_d}'^2 v_d^2 + Q_S'^2 v_S^2 + \sum_{i=1}^3 Q_{S_i}'^2 v_{S_i}^2 \right) \\ \Delta^2 &= \frac{1}{2} \sqrt{g_1^2 + g_2^2} g_1' (Q_{H_u}'^2 v_u^2 - Q_{H_d}'^2 v_d^2) \end{aligned} \quad (2.11)$$

Diagonalizing the mass-square matrix in Eq.(2.10) yields the following mixing angle between  $Z$  and  $Z'$ :

$$\theta_{ZZ'} = \frac{1}{2} \arctan \left( \frac{2\Delta^2}{M_{Z'}^2 - M_Z^2} \right) \quad (2.12)$$

and the electroweak precision data strongly bounds the  $Z - Z'$  mixing angle as  $\theta_{ZZ'} \lesssim 10^{-3}$  [53–55]. Applying such a strict constraint to the mixing between  $Z$  and  $Z'$  allows only solutions of the following properties:

1.  $g_1' \ll g_1$ , or

2.  $M_{Z'} \gg M_Z$ , or
3.  $Q'_{H_d}/Q'_{H_u} \simeq v_u/v_d \equiv \tan \beta$ .

The first two conditions separately bring a naive application of the LEP 2 bound on  $M_{Z'}$  as  $M_{Z'}/g'_1 \geq 6$  TeV [56]. The first condition cannot be realized when the secluded model is constrained by the gauge coupling unification at  $M_{\text{GUT}}$ , since the gauge coupling unification yields  $g'_1 \sim g_1, g_2$  at the low scale. Thus, a consistent  $Z - Z'$  mixing with the precision data can be satisfied by spectra involving heavy  $Z'$ . Alternatively, one can apply the third condition by adjusting  $Q'_{H_u}$  and  $Q'_{H_d}$ ; however, since it enhances the model dependency in the results, we do not consider it in our study.

In addition to the symmetry breaking,  $Z - Z'$  mixing receives contributions from the gauge kinetic mixing between  $U(1)_Y$  and  $U(1)'$ , which leads to a gauge covariant derivative in a non-canonical form [57, 58], which also induces tree-level mixing between the MSSM Higgs fields and singlet scalar fields of the secluded sector.

## 2.2 Neutralinos and Charginos

Depending on the hypercharges of the exotic fields ( $\mathcal{Q}$  and  $\mathcal{L}$ ), the secluded  $U(1)'$  model extends both the charged and neutral sectors of MSSM. Their interference enriches the phenomenology such as lowering the mass bound on  $Z'$  [47, 59], triggering  $U(1)'$  breaking by guaranteeing negative  $m_{\tilde{G}}^2$  [19] etc. Even though it is possible to have exotic fields coupling the quarks to leptons depending on baryon and lepton numbers [60], in the standard configuration they can couple only to quarks or leptons. Besides, it is possible to configure the  $U(1)'$  charges in which the exotics are allowed to couple only to  $S$  field at tree level. In this case,  $SU(3)$  triplet exotic field  $\mathcal{Q}$  is still allowed to be produced at the collider experiments; thus the resonance searches are still able to bound their masses as  $m_{\tilde{\mathcal{Q}}} \gtrsim 5$  TeV [61]. In this context, we assume the exotics can couple only to the MSSM singlet  $S$  field, and they are heavy. Thus their observable effects at the low scale become suppressed, while they are still effective in  $U(1)'$  symmetry breaking, anomaly cancellation etc.

Assuming the exotic fields to be decoupled at a high scale only the neutral fields can be involved in the spectrum, and the neutral sector of this class of secluded  $U(1)'$  models significantly extends the Neutralinos with  $\tilde{S}, \tilde{B}', \tilde{S}_{1,2,3}$ . After the  $U(1)'$  and electroweak symmetry breakings, these neutralinos together with the MSSM neutralinos mix each other, and the resultant mass matrix for the neutralino sector can be obtained in the usual basis ordered as  $(\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u, \tilde{S}, \tilde{B}', \tilde{S}_1, \tilde{S}_2, \tilde{S}_3)$  as follows:

$$M_{\tilde{\chi}} = \left( \begin{array}{c|ccccc} & 0 & M_{BB'} & 0 & 0 & 0 \\ & 0 & 0 & 0 & 0 & 0 \\ & -\frac{\lambda v_u}{2} & g'_1 Q'_{H_d} v_d & 0 & 0 & 0 \\ & -\frac{\lambda v_d}{2} & g'_1 Q'_{H_u} v_u & 0 & 0 & 0 \\ \hline \text{MSSM}(\mu = \mu_{\text{eff}}) & & & & & \\ \hline 0 & 0 & -\frac{\lambda v_u}{2} & -\frac{\lambda v_d}{2} & 0 & g'_1 Q'_S v_S & 0 & 0 & 0 \\ M_{BB'} & 0 & g'_1 Q'_{H_d} v_d & g'_1 Q'_{H_u} v_u & g'_1 Q'_S v_S & M_{B'} & g'_1 Q'_{S_1} v_{S_1} & g'_1 Q'_{S_2} v_{S_2} & g'_1 Q'_{S_3} v_{S_3} \\ 0 & 0 & 0 & 0 & 0 & g'_1 Q'_{S_1} v_{S_1} & 0 & -\frac{\kappa v_{S_3}}{\sqrt{2}} & -\frac{\kappa v_{S_2}}{\sqrt{2}} \\ 0 & 0 & 0 & 0 & 0 & g'_1 Q'_{S_2} v_{S_2} & -\frac{\kappa v_{S_3}}{\sqrt{2}} & 0 & -\frac{\kappa v_{S_1}}{\sqrt{2}} \\ 0 & 0 & 0 & 0 & 0 & g'_1 Q'_{S_3} v_{S_3} & -\frac{\kappa v_{S_2}}{\sqrt{2}} & -\frac{\kappa v_{S_1}}{\sqrt{2}} & 0 \end{array} \right) \quad (2.13)$$

The upper block called MSSM in the mass matrix given above represents the usual MSSM neutralinos and their mixing. However, since the  $\mu$ -term is not allowed at tree level and effectively generated by the VEV of  $S$ , the secluded  $U(1)'$  is effective in generating the masses of MSSM Higgsinos and interfering in mixing of MSSM neutralinos. In addition,  $\tilde{B}'$  can mix with  $\tilde{B}$  through the kinetic mixing, and MSSM Higgsinos through  $Z - Z'$  mixing which are quantified with  $M_{BB'}$ ,  $g'_1 Q'_{H_d} v_d$  and  $g'_1 Q'_{H_u} v_u$  in the neutralino mass matrix, respectively. Similarly,  $S$  can mix with the MSSM Higgsinos and its mixing is proportional to its coupling to the Higgs fields as  $\lambda v_d$  and  $\lambda v_u$ . On the other hand,  $\tilde{S}_1$ ,  $\tilde{S}_2$  and  $\tilde{S}_3$  mix only with the  $U(1)'$  neutralinos, while they leave the MSSM neutralinos intact.

In addition to their effects in the neutralino sector, these fields including  $\tilde{B}'$  can also escape from the experimental detection and they can easily be much lighter than the MSSM neutralinos. For instance, heavy mass bounds on gluino as  $m_{\tilde{g}} \geq 2.1$  TeV [62] also bounds the Bino and Wino masses at about 300 GeV and 600 GeV, respectively when the universal gaugino mass is imposed at the GUT scale (for a recent study with universal gaugino mass at the GUT scale, see [63]). In addition, the current measurements of the Planck satellite on the relic density of the dark matter can lift the mass bound up to about 1 TeV, especially when the dark matter is composed mostly by Bino [17]. Even though the LHC bounds can be loosen when the LSP is formed mostly by MSSM Higgsinos, the current null results from the direct detection experiments require  $\mu \gtrsim 700$  GeV for the Higgsino-like dark matter [17, 64, 65].

As a consequence of such severe bounds on the MSSM neutralinos, the non-MSSM neutralinos can be more likely to form the LSP neutralino in the low scale mass spectrum, and in this context they yield quite different phenomenology in both the collider and the dark matter experiments. If the LSP is formed mostly by the secluded  $U(1)'$  sector, then some of the particles in the MSSM spectrum might be realized to be a long lived state,



since they do not directly couple to the LSP. Even though, the current LHC constraints on the strongly interacting particles such as squarks and gluino yield consistent lifetime for these particles, it is still possible to have long lived staus and charginos in the low scale spectrum, and the model should be constrained to avoid possible missing electric charges from such states escaping from detectors.

On the other hand, even though the stop and gluino are not allowed to be long lived by the LHC constraints, the current bounds on these particles can be significantly modified depending on the decay of the lightest MSSM neutralino into LSP. Since these particles do not directly couple to the LSP, their possible signal processes remain the same as those which are excessively analyzed in the collider experiments [66]. In these processes, if the lightest MSSM neutralino does not decay in the detector and it forms the missing energy, then the current constraints on the stop and gluino still hold. On the other hand, if the lightest MSSM neutralino is allowed to decay into LSP in the detector, then such processes can significantly modify (probably loosen) the current bounds on the stop and gluino (see [13] for the case in which stop does not directly couple to LSP).

The non-MSSM LSP also yields an interesting phenomenology in the dark matter experiments. Since  $S$  is allowed to interact with the MSSM Higgs fields at tree-level, its superpartner ( $\tilde{S}$ ) scatters at nuclei through Higgs portal. Even though its scattering cross-section is expected to be rather low, such solutions will be able to be tested soon under the current and future projected sensitivity of the results from XENON experiment [67]. The scattering cross-section can be further lowered when the LSP is formed by  $\tilde{S}_{1,2,3}$ , since they interact only with  $S$ . However, their annihilation processes can still yield interesting results for the indirect detection of dark matter and can be tested under light of the current results from FermiLAT [68, 69].

Before concluding the neutralino sector in the model, we should also note the chargino sector. Since only the neutral fields can be involved in the detectable low scale spectrum, the physical states of the chargino sector is formed by the MSSM fields such as Wino and Higgsino. On the other hand, as discussed in the neutralino mass matrix, the charged Higgsino mass ( $\mu$ ) is determined effectively by the VEV of  $S$ , thus the secluded  $U(1)'$  sector is still effective in the phenomenology of the chargino sector.

### 2.3 Higgs Bosons

The presence of the MSSM singlet  $S$  and  $S_i$  fields significantly extends the Higgs boson sector of MSSM in the secluded  $U(1)'$  model. In the physical spectrum there are six CP-even Higgs bosons, while the number of the CP-odd Higgs bosons is four. In addition to the enrichment in the Higgs boson spectrum, the Higgs sector becomes more complicated through the tree-level mixing, which does not exist in the MSSM framework. The Higgs potential generated with  $F$ -terms can be written as [36]

$$V_F = |\lambda|^2 \left[ |H_d H_u|^2 + |S|^2 (H_d^\dagger H_d + H_u^\dagger H_u) \right] + \frac{|\kappa|^2}{9} (|S_1 S_2|^2 + |S_2 S_3|^2 + |S_1 S_3|^2) \quad (2.14)$$

where the  $SU(2)_L$  indices are suppressed for simplicity. While the F-terms allow mixing only among the MSSM Higgs doublets and the MSSM singlet  $S$  scalar, the other MSSM singlets can mix with the MSSM Higgs fields through the scalar potential generated by  $D$ -terms, which is

$$V_D = \frac{g_1^2 + g_2^2}{8} (H_d^\dagger H_d - H_u^\dagger H_u)^2 + \frac{g_2^2}{2} |H_d^\dagger H_u|^2 + \frac{g_1^2}{2} \left( Q'_{H_d} H_d^\dagger H_d + Q'_{H_u} H_u^\dagger H_u + Q'_S |S|^2 + \sum_{i=1}^3 Q'_S |S_i|^2 \right)^2 \quad (2.15)$$

After all, the scalar potential generated by the  $F$ - and  $D$ -terms induce tree-level mixing among all the Higgs scalars. In addition, the soft supersymmetry breaking (SSB) Lagrangian contribute to the Higgs phenomenology through the following terms:

$$\begin{aligned} \mathcal{L}_{\text{SSB}} = & m_{H_d}^2 H_d^\dagger H_d + m_{H_u}^2 H_u^\dagger H_u + m_S^2 |S|^2 + \sum_{i=1}^3 m_{S_i}^2 |S_i|^2 \\ & - \lambda A_\lambda S H_d H_u - \frac{\kappa}{3} A_\kappa S_1 S_2 S_3 - m_{S S_1}^2 S S_1 - m_{S S_2}^2 S S_2 - m_{S_1 S_2}^2 S_1^\dagger S_2 \end{aligned} \quad (2.16)$$

The tree-level mass-square matrix for CP-even and CP-odd Higgs bosons is generated through the SSB masses and the vacuum expectation values (VEVs) defined as

$$H_d = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d + h_d^0 + iA_d \\ \sqrt{2}h_d^- \end{pmatrix}, \quad H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}h_u^+ \\ v_u + h_u^0 + iA_u \end{pmatrix} \quad (2.17\text{-a})$$

$$S = \frac{1}{\sqrt{2}}(v_S + S + iA_S), \quad S_i = \frac{1}{\sqrt{2}}(v_{S_i} + S_i + iA_{S_i}) \quad (2.17\text{-b})$$

Note that the gauge boson associated with  $U(1)'$  group ( $Z'$ ) receives its mass from the VEVs of all the scalar fields given in Eqs.(2.17-a, 2.17-b); however, since  $v_S, v_{S_i} \gg v_d, v_u$ , the VEVs of singlet fields are dominant in  $Z'$  mass. Thus, a heavy mass bound on  $Z'$  is expected to yield a strong impact in the singlet scalar sector. In a class of  $U(1)'$  extended SUSY models, the absence of the fields  $S_i$  results in high  $U(1)'$  breaking scale ( $v_S \gtrsim 10$  TeV) [34, 70] to realize  $M_{Z'} \geq 4 - 5$  TeV [71]. In addition, the VEVs, in principle do not have to align in the same direction, so they can be also a source for CP-violation. However, we assume the CP-conservation in our work by setting  $\theta_i = 0$  (for a detailed discussion about CP-conservation and breaking, see [36]).

The scalar potentials involving the Higgs fields yield the following symmetric mass-square matrix for the CP-even Higgs fields:

$$\mathcal{M}_{\text{even}}^2 = \begin{pmatrix} M_{11}^2 & M_{12}^2 & M_{13}^2 & M_{14}^2 & M_{15}^2 & M_{16}^2 \\ & M_{22}^2 & M_{23}^2 & M_{24}^2 & M_{25}^2 & M_{26}^2 \\ & & M_{33}^2 & M_{34}^2 & M_{35}^2 & M_{36}^2 \\ & & & M_{44}^2 & M_{45}^2 & M_{46}^2 \\ & & & & M_{55}^2 & M_{56}^2 \\ & & & & & M_{66}^2 \end{pmatrix} \quad (2.18)$$

where, in the basis of  $\{h_d, h_u, S, S_1, S_2, S_3\}$ ,

$$\begin{aligned} M_{11}^2 &= \frac{(g_1^2 + g_2^2)v_d^2}{4} + g_1^2 Q_{H_d}^2 v_d^2 + \frac{A_\lambda \lambda v_S v_u}{\sqrt{2}v_d} \\ M_{12}^2 &= -\frac{A_\lambda \lambda v_S}{\sqrt{2}} - \frac{(g_1^2 + g_2^2)v_d v_u}{4} + \left(\lambda^2 + g_1^2 Q'_{H_d} Q'_{H_u}\right) v_d v_u \\ M_{13}^2 &= \lambda^2 v_d v_s + g_1^2 Q'_{H_d} Q'_S v_d v_s - \frac{A_\lambda \lambda v_u}{\sqrt{2}} \\ M_{1i+3}^2 &= g_1^2 Q'_{H_d} Q'_{S_i} v_d v_{S_i}, \quad i = 1, 2, 3 \\ M_{22}^2 &= \frac{A_\lambda \lambda v_d v_S}{\sqrt{2}v_u} + \frac{1}{4}(g_1^2 + g_2^2 + 4g_1^2 Q'_{H_u}) v_u^2 \\ M_{23}^2 &= -\frac{A_\lambda \lambda v_d}{\sqrt{2}} + (\lambda^2 + g_1^2 Q'_{H_u} Q'_S) v_u v_S \\ M_{2i+3}^2 &= g_1^2 Q'_{H_u} Q'_{S_i} v_u v_{S_i}, \quad i = 1, 2, 3 \\ M_{33}^2 &= \frac{1}{2v_S} (2g_1^2 Q_S^2 v_s^3 - 2m_{SS_1}^2 v_{S_1} - 2m_{SS_2}^2 v_{S_2} + \sqrt{2}A_\lambda \lambda v_d v_u) \\ M_{3i+3}^2 &= m_{SS_i}^2 + g_1^2 Q'_S Q'_{S_i} v_S v_{S_i}, \quad i = 1, 2, 3 \text{ and } m_{SS_3} = 0 \\ M_{44}^2 &= \frac{1}{2v_{S_1}} (2g_1^2 Q_{S_1}^2 v_{S_1}^3 - 2m_{SS_1}^2 v_S + \sqrt{2}A_\kappa \kappa v_{S_2} v_{S_3}) \\ M_{45}^2 &= \frac{1}{9} \kappa^2 v_{S_1} v_{S_2} + g_1^2 Q'_{S_1} Q'_{S_2} v_{S_1} v_{S_2} - \frac{A_\kappa \kappa v_{S_3}}{\sqrt{2}} \\ M_{46}^2 &= \frac{1}{9} (\kappa^2 + 9g_1^2 Q'_{S_1} Q'_{S_3}) v_{S_1} v_{S_3} - \frac{A_\kappa \kappa v_{S_2}}{\sqrt{2}} \\ M_{55}^2 &= \frac{1}{2v_{S_2}} (2g_1^2 Q_{S_2}^2 v_{S_2}^3 - 2m_{SS_2}^2 v_S + \sqrt{2}A_\kappa \kappa v_{S_1} v_{S_3}) \\ M_{56}^2 &= \frac{1}{9} (\kappa^2 + 9g_1^2 Q'_{S_2} Q'_{S_3}) v_{S_2} v_{S_3} - \frac{A_\kappa \kappa v_{S_1}}{\sqrt{2}} \\ M_{66}^2 &= g_1^2 Q_{S_3}^2 v_{S_3}^2 + \frac{A_\kappa \kappa v_{S_1} v_{S_2}}{\sqrt{2}v_{S_3}} \end{aligned}$$

Diagonalizing the mass-square matrix  $\mathcal{M}_{\text{even}}^2$  yields six mass eigenstates for the CP-even Higgs bosons in the spectrum. Similarly for the CP-odd Higgs fields;

$$\mathcal{M}_{\text{odd}}^2 = \begin{pmatrix} P_{11}^2 & P_{12}^2 & P_{13}^2 & P_{14}^2 & P_{15}^2 & P_{16}^2 \\ & P_{22}^2 & P_{23}^2 & P_{24}^2 & P_{25}^2 & P_{26}^2 \\ & & P_{33}^2 & P_{34}^2 & P_{35}^2 & P_{36}^2 \\ & & & P_{44}^2 & P_{45}^2 & P_{46}^2 \\ & & & & P_{55}^2 & P_{56}^2 \\ & & & & & P_{66}^2 \end{pmatrix} \quad (2.19)$$

and, the non-zero elements of  $\mathcal{M}_{\text{odd}}^2$  are

$$\begin{aligned} P_{11}^2 &= \frac{A_\lambda \lambda v_S v_u}{\sqrt{2}v_d}, \quad P_{12}^2 = \frac{A_\lambda \lambda v_S}{\sqrt{2}}, \quad P_{13}^2 = \frac{A_\lambda \lambda v_u}{\sqrt{2}}, \\ P_{22}^2 &= \frac{A_\lambda \lambda v_d v_S}{\sqrt{2}v_u}, \quad P_{23}^2 = \frac{A_\lambda \lambda v_d}{\sqrt{2}}, \\ P_{33}^2 &= \frac{1}{2v_S} (-2m_{SS_1}^2 v_{S_1} - 2m_{SS_2}^2 v_{S_2} + \sqrt{2}A_\lambda \lambda v_d v_u), \quad P_{34}^2 = -m_{SS_1}^2, \quad P_{35}^2 = -m_{SS_2}^2, \\ P_{44}^2 &= \frac{1}{2v_{S_1}} (-2m_{SS_1}^2 v_S + \sqrt{2}A_\kappa \kappa v_{S_2} v_{S_3}), \quad p_{45}^2 = \frac{A_\kappa \kappa v_{S_3}}{\sqrt{2}}, \quad P_{46}^2 = \frac{A_\kappa \kappa v_{S_2}}{\sqrt{2}} \\ P_{55}^2 &= \frac{1}{2v_{S_2}} (-2m_{SS_2}^2 v_S + \sqrt{2}A_\kappa \kappa v_{S_1} v_{S_3}), \quad P_{56}^2 = \frac{A_\kappa \kappa v_{S_1}}{\sqrt{2}}, \quad P_{66}^2 = \frac{A_\kappa \kappa v_{S_1} v_{S_2}}{\sqrt{2}v_{S_3}} \end{aligned}$$

When the mass-square matrix of the CP-odd Higgs fields are diagonalized, two eigenstates out of six happen to be the massless Goldstone bosons, and thus there remain four CP-odd Higgs bosons in the mass spectrum.

As can be seen from the mass-square matrices above, the MSSM Higgs fields and the singlet scalars of the secluded  $U(1)'$  model non-trivially mix in forming the physical Higgs boson states. Such a mixing can yield non-SM Higgs bosons of light mass, which can potentially lead signals in the collider experiments [58]. In this context profiling the Higgs bosons in the spectrum is of importance in constraining the allowed parameter space of the model. If a Higgs boson mass state, except the SM-like state, is formed mostly by the MSSM Higgs fields, then the current constraints from rare  $B$ -meson decays such as  $B_s \rightarrow \mu^+ \mu^-$  and  $B \rightarrow X_s \gamma$  bound their masses at about 400-500 GeV [63–65]. Thus, if the spectrum involves Higgs bosons lighter than the SM-like Higgs boson are excluded by these constraints if they are significantly formed by the MSSM Higgs fields.

Even though the constrained mentioned above can distinguish the MSSM Higgs fields from the singlet scalars, they can still interfere through their non-trivial mixing with the MSSM Higgs fields. First, such mixing can allow some decay modes of the light Higgs bosons into the SM particles, which potentially yield a signal at low mass scales. Besides, since the mixing induce a tree-level coupling with the SM-like Higgs boson, the light Higgs boson states can enhance the invisible decays of the SM-like Higgs bosons. One can avoid such inconsistencies by constraining the decay modes of these light Higgs bosons into the SM particles, and the invisible Higgs decays as  $\text{BR}(h \rightarrow \text{invisible}) \lesssim 10\%$  [72–77].

### 3 Scanning Procedure and Experimental Constraints

We have employed SPheno 4.0.4 package [78–80] generated with SARAH 4.14.3 [80–82]. In this package, the weak scale values of the gauge and Yukawa couplings are evolved to the unification scale  $M_{\text{GUT}}$  via the renormalization group equations (RGEs).  $M_{\text{GUT}}$  is determined by the requirement of the gauge coupling unification, described as  $g_3 \approx g_2 = g_1 = g'_1$ , where  $g_3$ ,  $g_2$  and  $g_1$  are the MSSM gauge couplings for  $SU(3)_C$ ,  $SU(2)_L$  and  $U(1)_Y$  respectively, while  $g'_1$  corresponds to the gauge coupling for  $U(1)'$ . Concerning the contributions from the threshold corrections to the gauge couplings at  $M_{\text{GUT}}$  arising from some unknown breaking mechanisms of the GUT gauge group,  $g_3$  receives the largest contributions [83], and it is allowed to deviate from the unification point up to about 3%. If a solution does not satisfy this condition within this allowance, SPheno does not generate an output for such solutions by default. Hence, the existence of an output file guarantees that the solutions are compatible with the unification condition, and  $g_3$  deviates no more than 3%. After  $M_{\text{GUT}}$  is calculated, all the SSB parameters, determined with the boundary conditions at  $M_{\text{GUT}}$ , along with the gauge and Yukawa couplings are evolved back to the weak scale.

We performed random scans over the parameter space, shown in Table 2, with the universal boundary conditions. Here  $m_0$  denotes the spontaneous symmetry breaking (SSB) mass term for all the scalars, while  $M_{1/2}$  stands for the SSB mass terms for the gauginos including the one associated with the  $U(1)'$  gauge group.  $\tan\beta$  is the ratio of VEVs of the MSSM Higgs doublets, and  $A_0$  is the SSB trilinear scalar interacting term,  $\lambda$  is the coupling associated with the interaction of  $\hat{H}_u$ ,  $\hat{H}_d$  and  $\hat{S}$  fields while  $\kappa$  is the coupling of the interaction of  $\hat{S}_1$ ,  $\hat{S}_2$  and  $\hat{S}_3$  fields. Trilinear couplings for  $\lambda$  and  $\kappa$  are defined as  $\lambda A_\lambda$  and  $\kappa A_\kappa$ , respectively at the GUT scale.  $h_\nu$  is the Yukawa coupling of the term  $\hat{L}\hat{H}_u\hat{N}$ .

Parameter	Scanned range	Parameter	Scanned range
$m_0$	[0, 10] TeV	$v_S$	[1, 20] TeV
$M_{1/2}$	[0, 10] TeV	$v_{S_1}$	[3, 20] TeV
$\tan\beta$	[1, 50]	$v_{S_2}$	[3, 20] TeV
$A_0/m_0$	[-3, 3]	$v_{S_3}$	[3, 20] TeV
$\lambda$	[0.01, 0.5]	$A_\lambda$	[0, 10] TeV
$\kappa$	[0.1, 1.5]	$A_\kappa$	[-10, 0] TeV
$h_\nu$	$[10^{-11}, 10^{-7}]$	-	-

**Table 2.** Scanned parameter space.

In analysing the data and implications of the model, we impose the LEP2 bounds on the charged particles such that the model does not yield any new charged particles whose mass is lighter than about 100 GeV [84]. In addition, since it has been significantly being updated, we require the consistent solutions yield gluino mass as  $m_{\tilde{g}} \geq 2100$  GeV. Another important mass bound comes from the Higgs boson. We require one of the Higgs bosons in solutions to exhibit the SM-like Higgs boson properties in terms of its mass and decay channels reported by the ATLAS [85–88] and CMS [89–92] collaborations. Including the scalars, whose VEVs break the  $U(1)'$  symmetry, the low scale spectrum involves six CP-even Higgs boson mass. Since the mixing between the  $U(1)'$  breaking scalar fields and the MSSM Higgs fields is expected to be small, the SM-like Higgs boson should be formed mostly by the MSSM Higgs fields. In this context, the SM-like Higgs boson needs be identified not only with its mass, but also its mixing. If a solution yield one of the Higgs bosons ( $h_i$ ,  $i = 1, \dots, 6$ ) with a mass of about 125 GeV [93], we also require  $|ZH(i, 1)|^2 + |ZH(i, 2)|^2 \gtrsim 80\%$ , where  $Z_H$  matrix quantifies the mixing among the Higgs bosons.

Another one of the important constraints arises from the REWSB conditions [94–98] which requires the  $\mu$ -term consistent with EWSB. We also implement the constraints from rare  $B$ -meson decays such as  $\text{BR}(B \rightarrow X_s \gamma)$  [99],  $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$  [100] and  $\text{BR}(B_u \rightarrow \tau \nu_\tau)$  [101]. Then, we require that the predicted relic density of the neutralino LSP agrees within  $5\sigma$  with the recent Planck results [102]. The relic density of the LSP and scattering cross sections for direct detection experiments are calculated with MICROMEAS (version 5.0.9) [103]. The experimental constraints can be summarized as follows:

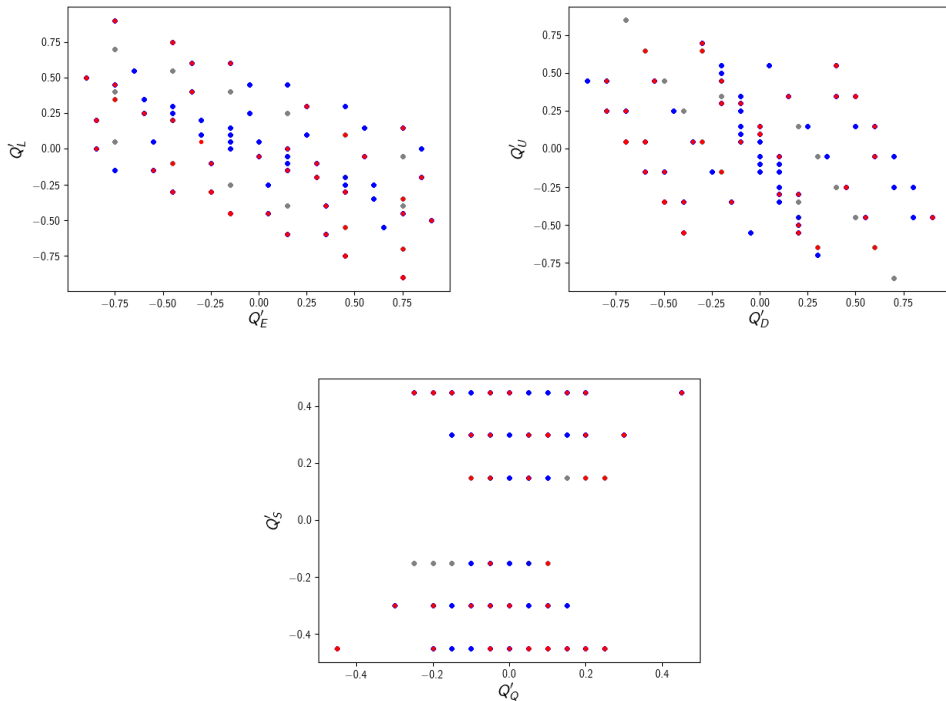
$$\begin{aligned}
m_h &= 122 - 128 \text{ GeV}, \\
m_{Z'} &\geq 4 \text{ TeV}, \\
m_{\tilde{g}} &\geq 2.1 \text{ TeV}, \\
0.8 \times 10^{-9} &\leq \text{BR}(B_s \rightarrow \mu^+ \mu^-) \leq 6.2 \times 10^{-9} \text{ (} 2\sigma \text{ tolerance)}, \\
m_{\tilde{\chi}_1^\pm} &\geq 103.5 \text{ GeV}, \\
m_{\tilde{\tau}} &\geq 105 \text{ GeV}, \\
2.99 \times 10^{-4} &\leq \text{BR}(B \rightarrow X_s \gamma) \leq 3.87 \times 10^{-4} \text{ (} 2\sigma \text{ tolerance)}, \\
0.15 &\leq \frac{\text{BR}(B_u \rightarrow \tau \nu_\tau)_{\text{Secluded U}(1)'}}{\text{BR}(B_u \rightarrow \tau \nu_\tau)_{\text{SM}}} \leq 2.41 \text{ (} 3\sigma \text{ tolerance)}, \\
0.114 &\leq \Omega_{\text{CDM}} h^2 \leq 0.126 \text{ (} 5\sigma \text{ tolerance)}.
\end{aligned} \tag{3.1}$$

The following list summarizes the relation between colours and constraints imposed in our forthcoming plots.

- Grey: Represents the points compatible with the Radiative EWSB (REWSB) and neutralino LSP,
- Blue: Forms a subset of grey and represents points satisfying the constraints on the SUSY particle masses, Higgs boson mass and its couplings, and  $B$ -physics constraints,
- Red: Forms a subset of blue and represents the points which are consistent with the Planck bounds on the relic density of LSP neutralino within  $5\sigma$  together with other constraints mentioned for blue points.

## 4 Results

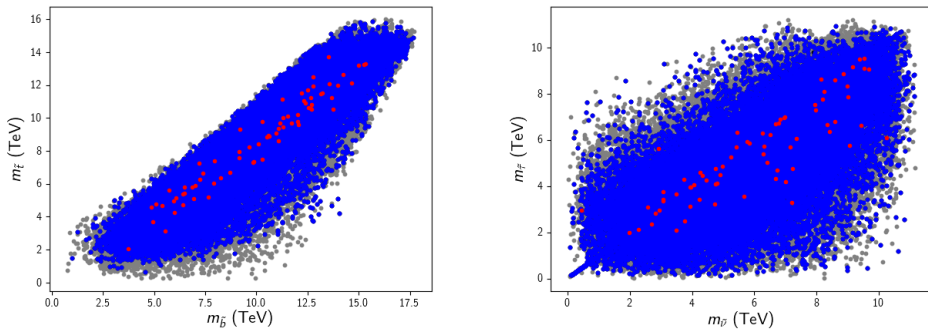
In this section we present our results in light of the constraints discussed in the previous section. First, we focus on the  $U(1)'$  charges which characterizes the secluded  $U(1)'$  model. Fig. 1 depicts the  $U(1)'$  charge sets satisfying various theoretical and experimental bounds.



**Figure 1.** The distributions of the  $U(1)'$  charges in secluded  $U(1)'$  model allowed by various theoretical and experimental conditions from Section 3 over the following planes:  $Q'_L - Q'_E$ ,  $Q'_U - Q'_D$  and  $Q'_S - Q'_Q$ . The colour convention is as listed at the end of Section 3.

The colour convention is as listed at the end of Section 3. Herein, we show charges for left and right chiral fermions and MSSM singlet by visualising our scan points over the planes  $Q'_L - Q'_E$  and  $Q'_U - Q'_D$  (top panels), and  $Q'_S - Q'_Q$  (bottom panel). Note that the charges are normalized to unity. As can be seen from the top left panel, the constraints allow a large number of different solution sets, and a wide range for the charges can be accommodated, e.g., the  $Q'_L, Q'_E \lesssim |0.9|$ . As for quarks, the right handed up-type quark charges ( $Q'_U$ ) and the right handed down-type ones ( $Q'_D$ ) exhibits almost the same behaviour (as shown in the top right panel of the figure). Furthermore, it can easily be read, from the bottom panel, that  $Q'_S$  charge is always far away from zero since  $Q'_S = -(Q'_{H_u} + Q'_{H_d})$ . After applying all theoretical conditions and experimental constraints,  $Q'_S$  and  $Q'_Q$  charges are restricted to certain regions,  $Q'_S, Q'_Q \lesssim |0.5|$ . Since there is not a direct anomaly cancellation condition between  $Q'_Q$  and  $Q'_S$ , it is possible to find various  $Q'_Q$  values for the fixed values of  $Q'_S$ .

Fig. 2 displays the the mass spectrum of SUSY particles in  $m_{\tilde{t}} - m_{\tilde{b}}$  (left) and  $m_{\tilde{\tau}} - m_{\tilde{\nu}}$  (right) planes. The colour convention is as listed at the end of Section 3. The left panel shows that sbottom and stop masses are heavy in general and should be  $3 \text{ TeV} \lesssim m_{\tilde{b}}, m_{\tilde{t}} \lesssim 15 \text{ TeV}$ . Even though these mass scales are far beyond the reach of the current LHC experiments, they can be probed in the future collider searches [104, 105]. Similarly, the right panel also reveals that stau can be as light as only 2 TeV, compatible with all



**Figure 2.** The mass spectrum of SUSY particles over the following planes:  $m_{\tilde{t}} - m_{\tilde{b}}$  (left) and  $m_{\tilde{\tau}} - m_{\tilde{\nu}}$  (right). The colour convention is as listed at the end of Section 3.

experimental bounds. Even though the sneutrino mass can be realized as low as about 500 GeV, it is, in general, heavier than stau for most of the solutions compatible with all experimental bounds.

Fig. 3 shows the neutralino and chargino mass spectrum with diagonal lines emphasizing the co-annihilation and annihilation channels of LSP neutralino in  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$  (top left),  $m_H - m_{\tilde{\chi}_1^0}$  (top right),  $m_{A_1} - m_{\tilde{\chi}_1^0}$  (bottom left) and  $m_{A_2} - m_{\tilde{\chi}_1^0}$  (bottom right) planes. The colour coding is the same as in Fig. 2. As is shown in the  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$  plane, the chargino and neutralino can be as light as about 50-100 GeV. Even though the LSP neutralino mass can be realized, in principle, lighter than 50 GeV, the mass scales below 50 GeV trigger the invisible decays of the SM-like Higgs boson; thus, we consider the solutions with  $m_{\tilde{\chi}_1^0} \lesssim 50$  GeV to be excluded. Similarly, the chargino masses lower than 103.5 GeV are excluded as required by the LEP results. Apart from the lower bounds, the LSP neutralino happens mostly to be lighter than about 1 TeV. As discussed before, the MSSM neutralinos cannot be consistent if their masses are lighter than about 500 GeV due to the severe constraints from rare  $B$ -meson decays and their relic density. Thus the solutions with  $m_{\tilde{\chi}_1^0} \lesssim 500$  GeV should lead to LSPs which are formed mostly by the MSSM singlet fields. The chargino can be as heavy as about 1.5 TeV in the consistent spectra, while its mass can also be at the order of  $\mathcal{O}(100)$  GeV. The light chargino solutions are expected to be formed mostly by Higgsinos because of a sub-TeV scale  $\mu$ -term. In this case, if the LSP is formed by Singlinos, while the lightest chargino is mostly a Higgsino, then one can identify the chargino-neutralino coannihilation scenario, through the interactions among the MSSM Higgsinos and  $U(1)'$  Singlino, in the approximate mass-degeneracy region represented with the diagonal line in the  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$  plane. In this region, the LSP neutralino coannihilate together with the lightest chargino which leads to lower the relic density of the LSP. Since the solutions compatible with the Planck bound are mostly accumulated around the diagonal line, the chargino-neutralino coannihilation scenario is required by the consistent DM solutions when  $m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_1^0} \lesssim 0.75$  TeV.



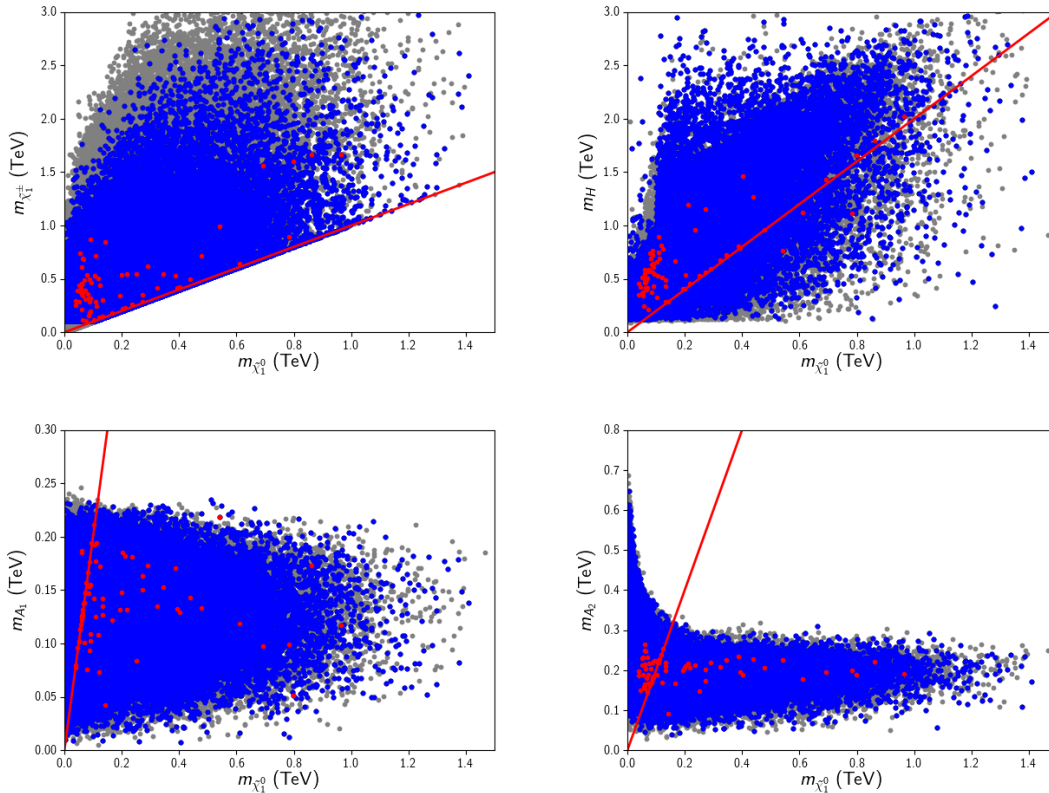
Even though one can realize consistent DM solutions through chargino-neutralino coannihilation scenario, the  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$  plane presents other solutions out of the mass degeneracy region (red points far above the diagonal line). These solutions cannot be identified in the chargino-neutralino coannihilation scenario; thus, the relic density of LSP neutralino should be lowered in other coannihilation and/or annihilation scenarios. Since other SUSY particles are either heavy (as stop, sbottom and stau shown in Fig. 2) or they do not directly couple to the Singlino LSP (as sneutrino), the relic density of LSP neutralino is most likely lowered by its annihilation processes into a neutral Higgs boson as displayed in the  $m_H - m_{\tilde{\chi}_1^0}$ ,  $m_{A_1} - m_{\tilde{\chi}_1^0}$  and  $m_{A_2} - m_{\tilde{\chi}_1^0}$  planes of Fig. 3. The diagonal lines in these planes indicates the regions where  $2m_{\tilde{\chi}_1^0} = m_H, m_{A_1}, m_{A_2}$  respectively. In the regions represented by the diagonal lines,  $m_H$  can be as light as about 100 GeV, while it can also be realized as heavy as about 2 TeV. On the other hand, the lighter CP-odd Higgs boson masses are found to be bounded as  $m_{A_1} \lesssim 300$  GeV and  $m_{A_2} \lesssim 600$  GeV, as shown in the bottom planes of Fig. 3. One can conclude from such results that the LSP neutralino annihilations through the Higgs portal plays an important role to identify consistent DM solutions. Especially the annihilation processes involving CP-odd Higgs bosons significantly lower the relic density of LSP. Recall that the MSSM Higgs bosons contribute to rare  $B$ -meson decays at these mass scales and violate the constraints from  $B$ -physics. Thus, these light Higgs bosons should be formed mostly by the MSSM singlet scalars to be consistent with the constraints from rare  $B$ -meson decays. Besides, a singlet Higgs boson can strongly couple to the LSP neutralino and significantly lower its relic density.

Thus, nature of LSP plays an important role in determining the dark matter phenomenology. In addition to discussions about the coannihilation channels in the previous paragraph, each species of neutralinos yield different phenomenology and implications in the dark matter experiments. If the LSP mass eigenstate  $\tilde{\chi}_1^0$  is given in terms of interaction eigenstates by the following linear combination using the same basis as the neutralino mass matrix given in Eq.(2.13);

$$\tilde{\chi}_1^0 = Z_{11}\tilde{B} + Z_{12}\tilde{W}^3 + Z_{13}\tilde{H}_d^0 + Z_{14}\tilde{H}_u^0 + Z_{15}\tilde{S} + Z_{16}\tilde{B}' + Z_{17}\tilde{S}_1 + Z_{18}\tilde{S}_2 + Z_{19}\tilde{S}_3 \quad (4.1)$$

where  $Z_{ij}$  are elements of the diagonalization matrix encoding the possible mixtures in comprising the neutralino mass eigenstates,  $\sum |Z_{ij}|^2 = 1$  by the normalization condition and  $|Z_{1j}|^2$  measures the fraction of the  $j^{\text{th}}$  particle in the composition of LSP neutralino.

The linear superposition of LSP neutralino given in Eq.(4.1) implies that  $U(1)'$  can deviate the LSP neutralino from the MSSM phenomenology by the total fraction of  $U(1)'$  particles expressed as  $|Z_{15}|^2 + |Z_{16}|^2 + |Z_{17}|^2 + |Z_{18}|^2 + |Z_{19}|^2$ . If  $|Z_{17}|^2 + |Z_{18}|^2 + |Z_{19}|^2$  dominates the other elements of LSP mass diagonalization matrix, then the dark matter is realized to be mostly decouple from the other particles. In this case, the current sensitivity of the experiments in direct and indirect searches of dark matter cannot probe such



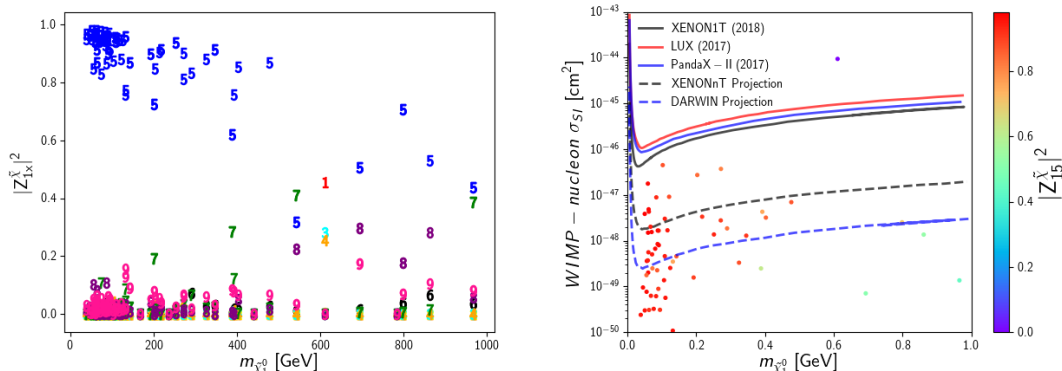
**Figure 3.** The mass spectrum of the lightest neutralino and chargino and relic density channels over the following planes:  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$  (top left),  $m_H - m_{\tilde{\chi}_1^0}$  (top right),  $m_{A_1} - m_{\tilde{\chi}_1^0}$  (bottom left) and  $m_{A_2} - m_{\tilde{\chi}_1^0}$  (bottom right). The colour convention is as listed at the end of Section 3.

solutions. On the other hand, if  $|Z_{15}|^2$  is significantly larger, then the dark matter is again composed mostly by the MSSM singlet, i.e.  $\tilde{S}$ , which interacts with the MSSM particles through the Higgs portal. The current and projected sensitivity of the direct detection of dark matter experiments can provide a potential probe for such solutions. Moreover, even if it does not form the dark matter significantly, it can still alter the dark matter implications through its mixing with the MSSM neutralinos. Finally, even though  $\tilde{B}'$  is also theoretically allowed to form the dark matter, the mass is mostly controlled by  $v_S$ . Since the heavy mass bound on  $Z'$  bounds  $v_S$  at about a few TeV from below, the neutralino mass eigenstate, which is mostly formed by  $\tilde{B}'$ , is found rather to be heavy.

We can summarize the discussion about the LSP neutralino composition and its testable implications in the dark matter experiments with plots given in Fig.4. In the left panel, we visualize the branching fraction of each neutralino by using different colors with the mass of the LSP neutralino. The numbers in the plot represent  $x$  in  $|Z_{1x}|^2$ , which is defined in Eq.(4.1). The points represented in this plane are selected such that they are allowed by all the constraints including the Planck bound on the LSP neutralino relic

density. As is seen from the blue numbers (5), the light LSP masses ( $\lesssim 350$  GeV) can be realized when the LSP neutralino is formed mostly by  $\tilde{S}$  ( $\gtrsim 80\%$ ).  $\tilde{S}$  still plays a crucial role for relatively large mass scales, since its mixing in the LSP composition is realized at about 40% and more for  $m_{\tilde{\chi}_1^0} \gtrsim 400$  GeV. Most of these solutions also reveal that the rest of the LSP neutralino is formed by the other singlets i.e.  $\tilde{S}_1$ ,  $\tilde{S}_2$  and  $\tilde{S}_3$ . In this context, the dark matter is realized to be almost a MSSM singlet, while it can interact with the MSSM particles through the Higgs portal. As discussed before, the fraction for  $\tilde{B}'$  is realized as large as only about 10% and less (black 6 in the left panel of Fig. 4).

The MSSM neutralinos become effective in the LSP composition when  $m_{\tilde{\chi}_1^0} \gtrsim 600$  GeV, which can be measured as about 50% Bino fraction (red 1), and about 25% for each MSSM Higgsino (turquoise 3 and orange 4). This mass scale bounding the Bino-Higgsino mixture is a direct result of the gluino mass bound and the Planck bound on the relic density of LSP neutralino. Since we employ universal gaugino masses at the GUT scale, the gluino mass bound excludes the region where  $M_{1/2} \lesssim 600$  GeV. In addition, when the Higgsinos form the LSP neutralino, the relic density constraint is satisfied when  $m_{\tilde{\chi}_1^0} \gtrsim 700$  GeV (see, for instance, [64, 106, 107]). The Higgsino fraction is also constrained by the results from the direct detection experiments, since it yields large cross-sections for the dark matter scattering at nuclei.



**Figure 4.** The composition of the LSP versus its mass (left) and DM-nucleon SI scattering cross section as a function of the mass of the lightest neutralino LSP (right). Limits from current (solid) and future (dashed) experiments are also shown.

As is seen from the discussion above, the secluded  $U(1)'$  model yield solutions in which the dark matter is mostly formed by the Singlino ( $\tilde{S}$ ). Even though there are not many channels in scattering of dark matter at nuclei, these solutions can be traced down in the direct detection experiments through the Higgs portal, and their signature can be significant depending on how strongly it interacts with the MSSM Higgs fields. The right panel of Fig.4 show the results for the spin independent scattering cross-section of dark matter with respect to its mass. The represented solutions are selected to be consistent

with the constraints employed in our analyses. The experimental results from the direct detection experiments are represented with the curves. The black, blue and red solid lines show XENON1T [108], PandaX-II [109] and LUX [110] upper limits for the SI  $\tilde{\chi}_1^0$  - nucleon cross section, respectively, while the black and blue dashed lines illustrate the prospects of the XENONnT and DARWIN for future experiments [111], respectively. We also display a color bar which relates the color coding to the Singlino fraction in the composition of LSP. The red points correspond to Singlino-like dark matter in which the Singlino fraction is realized greater than about 70%. The solutions with  $m_{\tilde{\chi}_1^0} \lesssim 350$  GeV yielding scattering cross-sections larger than about  $2 \times 10^{-48}$  cm<sup>2</sup> can be tested in XENON experiment soon, while those with  $\sigma_{\text{SI}} \in [3 \times 10^{49} - 2 \times 10^{48}]$  cm<sup>2</sup> are expected to be probed by the DARWIN collaboration. DARWIN will also be able to test the Singlino dark matter when the LSP mass is relatively heavier ( $\sim 500$  GeV). Finally, we also display a solution exemplifying the MSSM-like dark matter (blue). These solutions were identified as Bino-Higgsino mixture in the previous discussion, and as is seen from the right plane, the direct detection experiments yield a strong negative impact on such solutions, since it predicts a large scattering cross-section.

## 5 Conclusion

We have analyzed the secluded  $U(1)'$  model including right-handed neutrinos and four MSSM singlet fields. In this class of models the  $\mu$  term of the MSSM is dynamically induced by the VEV of a singlet scalar field. The secluded sector involves extra three MSSM singlet, chiral superfields for accommodating the correct  $Z'/Z$  mass hierarchy without running the  $\mu$  parameter to the large scales. In addition, the model contains exotic particles necessary for anomaly cancellation. We have examined the viability of the secluded  $U(1)'$  model to describe physics beyond the SM in dark matter phenomenology. Several collider, cosmological and low energy constraints have been imposed, including DM relic density, direct and indirect DM detection experiments, Higgs data, flavor physics, and SUSY searches in collider experiments.

We realized a region compatible with the current experimental constraints in which the LSP neutralino can be as light as about 100 GeV. The latest LHC constraints, especially the gluino mass bound, result in Binos and Winos heavier than about 300 GeV at the low scale SUSY spectrum, and hence this region can be identified with the Singlino-like DM. It can be seen easily when the LSP composition is considered which involves more than about 80% Singlino, while the remaining  $\lesssim 20\%$  also formed by the other MSSM singlet fields,  $S_{1,2,3}$ . This composition holds in almost all the solutions with  $m_{\tilde{\chi}_1^0} \lesssim 500$  GeV. Thus, the secluded  $U(1)'$  model yields mostly MSSM singlet DM which can considerably interact with the MSSM particles through the Higgs portal. Singlino still takes part in the DM phenomenology for heavier LSP neutralino solutions, since its percentage in the LSP composition is realized greater than about 50% for  $m_{\tilde{\chi}_1^0} \lesssim 1$  TeV. In addition, in the region

of relatively heavier LSP neutralino, also the MSSM neutralinos are allowed by the LHC and relic density constraints to be involved in the LSP composition.

Similarly, the lightest chargino can be also realized as light as about 100 GeV (the chargino solutions lighter than about 100 GeV are excluded by the LEP2 bounds), while its mass lies rather in a wide range up to about 1.5 TeV. The light chargino solutions arise in the spectrum because the secluded  $U(1)'$  model induce the  $\mu$ -term mostly in the sub-TeV scale. In this context, the light chargino mass states are mostly formed by the Higgsinos, while the Wino-like chargino can be involved for relatively heavier chargino solutions. In addition, the typical SUSY spectra realized in the secluded  $U(1)'$  model involve two light CP-odd Higgs bosons whose masses are lighter than about 200 GeV and 600 GeV, respectively. Due to the strong impact from rare  $B$ -meson decays employed in our analyses, the MSSM Higgs bosons cannot be lighter than about 500 GeV, and such light Higgs boson solutions can be consistent with the constraints from rare  $B$ -meson decays only when they are formed mostly by the MSSM singlet fields.

Considering the low production cross-section of the MSSM Higgsinos at LHC and singlet nature of the light CP-odd Higgs bosons, these light particles can escape from the detection in the collision experiments. However, they play an important role in realizing the consistent relic density for LSP neutralino, especially when it is formed mostly by Singlino. Inducing the  $\mu$ -term through the  $\widehat{S}\widehat{H}_u \cdot \widehat{H}_d$  allows tree-level interaction between the Singlino and MSSM Higgsinos. Thus, the number density of the Singlino-like LSP can be reduced through its coannihilation processes together with the Higgsino-like chargino. As we showed, the coannihilation processes can take part for  $m_{\widetilde{\chi}_1^0} \lesssim 600$  GeV. Beyond this mass scale, the involvement of the Wino-like chargino suppresses the interactions between the Singlino and chargino. In addition to the chargino-neutralino scenario, the annihilations of two Singlino-like LSPs into the Higgs bosons also reduce the number density of Singlino, such that the correct relic density of LSP neutralino can be realized up to about 1 TeV LSP mass.

Satisfying the correct relic density, the currently present experimental data from the direct DM detection experiments can constrain these solutions further. One may expect small scattering cross-section for the LSP neutralino due to its dominant singlet nature. However, as mentioned above, the Singlino is allowed to interact with the MSSM particles through the Higgs portal, which can potentially enhance its scattering cross-section. We observed that the Singlino LSP solutions can predict DM spin-independent cross-section in the range  $\sim 4 \times 10^{-46} - 10^{-50}$  cm<sup>2</sup> for the Singlino-like LSP. These solutions are expected to be tested in XENONnT experiments up to about  $\sigma_{\text{SI}} \sim 2 \times 10^{-48}$  cm<sup>2</sup>, while Darwin can lower the testable cross-section scale to about  $3 \times 10^{-49}$  cm<sup>2</sup> in near future. These scales are capable to probe the Singlino LSP. It is also possible to realize MSSM-like LSP neutralino for  $m_{\widetilde{\chi}_1^0} \gtrsim 600$  GeV. However, such solutions yield mostly Higgsino-like LSPs and predict rather significantly large scattering cross-sections which are already excluded

by the current experimental data considered in our work.

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## References

- [1] E. Gildener, *Gauge Symmetry Hierarchies*, *Phys. Rev.* **D14** (1976) 1667.
- [2] E. Gildener, *GAUGE SYMMETRY HIERARCHIES REVISITED*, *Phys. Lett.* **92B** (1980) 111.
- [3] S. Weinberg, *Gauge Hierarchies*, *Phys. Lett.* **82B** (1979) 387.
- [4] L. Susskind, *Dynamics of Spontaneous Symmetry Breaking in the Weinberg-Salam Theory*, *Phys. Rev.* **D20** (1979) 2619.
- [5] M.J.G. Veltman, *The Infrared - Ultraviolet Connection*, *Acta Phys. Polon.* **B12** (1981) 437.
- [6] G. Degrassi, S. Di Vita, J. Elias-Miro, J.R. Espinosa, G.F. Giudice, G. Isidori et al., *Higgs mass and vacuum stability in the Standard Model at NNLO*, *JHEP* **08** (2012) 098 [[1205.6497](#)].
- [7] F. Bezrukov, M.Y. Kalmykov, B.A. Kniehl and M. Shaposhnikov, *Higgs Boson Mass and New Physics*, *JHEP* **10** (2012) 140 [[1205.2893](#)].
- [8] D. Buttazzo, G. Degrassi, P.P. Giardino, G.F. Giudice, F. Sala, A. Salvio et al., *Investigating the near-criticality of the Higgs boson*, *JHEP* **12** (2013) 089 [[1307.3536](#)].
- [9] V. Branchina and E. Messina, *Stability, Higgs Boson Mass and New Physics*, *Phys. Rev. Lett.* **111** (2013) 241801 [[1307.5193](#)].
- [10] V. Branchina, E. Messina and A. Platania, *Top mass determination, Higgs inflation, and vacuum stability*, *JHEP* **09** (2014) 182 [[1407.4112](#)].
- [11] A.R. Fazio and E.A. Reyes R., *The Lightest Higgs Boson Mass of the MSSM at Three-Loop Accuracy*, *Nucl. Phys.* **B942** (2019) 164 [[1901.03651](#)].
- [12] A. de Gouvea, S. Gopalakrishna and W. Porod, *Stop Decay into Right-handed Sneutrino LSP at Hadron Colliders*, *JHEP* **11** (2006) 050 [[hep-ph/0606296](#)].
- [13] M. Chala, A. Delgado, G. Nardini and M. Quiros, *A light sneutrino rescues the light stop*, *JHEP* **04** (2017) 097 [[1702.07359](#)].

- [14] C.T. Potter, *Natural NMSSM with a Light Singlet Higgs and Singlino LSP*, *Eur. Phys. J.* **C76** (2016) 44 [[1505.05554](#)].
- [15] L. Delle Rose, S. Khalil, S.J.D. King, S. Kulkarni, C. Marzo, S. Moretti et al., *Sneutrino Dark Matter in the BLSSM*, *JHEP* **07** (2018) 100 [[1712.05232](#)].
- [16] L. Delle Rose, S. Khalil, S.J.D. King, C. Marzo, S. Moretti and C.S. Un, *Naturalness and dark matter in the supersymmetric B-L extension of the standard model*, *Phys. Rev.* **D96** (2017) 055004 [[1702.01808](#)].
- [17] W. Ahmed, S. Raza, Q. Shafi, C.S. Un and B. Zhu, *Sparticle spectroscopy and dark matter in a  $U(1)_{B-L}$  extension of MSSM*, *JHEP* **01** (2021) 161 [[2008.01568](#)].
- [18] K.J. Bae, H. Baer, V. Barger and D. Sengupta, *Revisiting the SUSY  $\mu$  problem and its solutions in the LHC era*, *Phys. Rev.* **D99** (2019) 115027 [[1902.10748](#)].
- [19] M. Cvetič, D.A. Demir, J.R. Espinosa, L.L. Everett and P. Langacker, *Electroweak breaking and the  $\mu$  problem in supergravity models with an additional  $U(1)$* , *Phys. Rev.* **D56** (1997) 2861 [[hep-ph/9703317](#)].
- [20] A.E. Nelson, N. Rius, V. Sanz and M. Unsal, *The Minimal supersymmetric model without a  $\mu$  term*, *JHEP* **08** (2002) 039 [[hep-ph/0206102](#)].
- [21] J.R. Ellis, G.K. Leontaris and J. Rizos, *Implications of anomalous  $U(1)$  symmetry in unified models: The Flipped  $SU(5) \times U(1)$  paradigm*, *JHEP* **05** (2000) 001 [[hep-ph/0002263](#)].
- [22] M. Frank, L. Selbuz, L. Solmaz and I. Turan, *Higgs bosons in supersymmetric  $U(1)'$  models with CP violation*, *Phys. Rev.* **D87** (2013) 075007 [[1302.3427](#)].
- [23] S. Bertolini, L. Di Luzio and M. Malinsky, *Minimal Flipped  $SO(10) \times U(1)$  Supersymmetric Higgs Model*, *Phys. Rev.* **D83** (2011) 035002 [[1011.1821](#)].
- [24] P. Athron, S.F. King, D.J. Miller, S. Moretti and R. Nevzorov, *Predictions of the Constrained Exceptional Supersymmetric Standard Model*, *Phys. Lett.* **B681** (2009) 448 [[0901.1192](#)].
- [25] M. Frank, L. Selbuz and I. Turan, *Heavy Gauge Bosons in supersymmetric  $U(1)'$  models at present and future hadron colliders*, [2007.00676](#).
- [26] D. Suematsu and Y. Yamagishi, *Radiative symmetry breaking in a supersymmetric model with an extra  $U(1)$* , *Int. J. Mod. Phys.* **A10** (1995) 4521 [[hep-ph/9411239](#)].
- [27] H.-S. Lee, K.T. Matchev and T.T. Wang, *A  $U(1)$ -prime solution to the  $\mu^-$  problem and the proton decay problem in supersymmetry without R-parity*, *Phys. Rev.* **D77** (2008) 015016 [[0709.0763](#)].
- [28] D.A. Demir, *Two Higgs doublet models from TeV scale supersymmetric extra  $U(1)$  models*, *Phys. Rev.* **D59** (1999) 015002 [[hep-ph/9809358](#)].
- [29] M. Cvetič and P. Langacker, *New gauge bosons from string models*, *Mod. Phys. Lett.* **A11** (1996) 1247 [[hep-ph/9602424](#)].
- [30] J.L. Hewett and T.G. Rizzo, *Low-Energy Phenomenology of Superstring Inspired  $E(6)$  Models*, *Phys. Rept.* **183** (1989) 193.

- [31] C.T. Hill and E.H. Simmons, *Strong Dynamics and Electroweak Symmetry Breaking*, *Phys. Rept.* **381** (2003) 235 [[hep-ph/0203079](#)].
- [32] S. Khalil, *TeV-scale gauged B-L symmetry with inverse seesaw mechanism*, *Phys. Rev.* **D82** (2010) 077702 [[1004.0013](#)].
- [33] SUPER-KAMIOKANDE collaboration, *Atmospheric neutrino oscillation analysis with sub-leading effects in Super-Kamiokande I, II, and III*, *Phys. Rev.* **D81** (2010) 092004 [[1002.3471](#)].
- [34] Y. Hicyilmaz, L. Solmaz, S.H. Tanyildizi and C.S. Un, *Least fine-tuned U(1) extended SSM*, *Nucl. Phys.* **B933** (2018) 275 [[1706.04561](#)].
- [35] J. Erler, P. Langacker and T.-j. Li, *The Z - Z' mass hierarchy in a supersymmetric model with a secluded U(1)-prime breaking sector*, *Phys. Rev.* **D66** (2002) 015002 [[hep-ph/0205001](#)].
- [36] C.-W. Chiang and E. Senaha, *CP violation in the secluded U(1)-prime-extended MSSM*, *JHEP* **06** (2008) 019 [[0804.1719](#)].
- [37] D.A. Demir, M. Frank, L. Selbuz and I. Turan, *Scalar Neutrinos at the LHC*, *Phys. Rev.* **D83** (2011) 095001 [[1012.5105](#)].
- [38] M. Frank, L. Selbuz and I. Turan, *Neutralino and Chargino Production in U(1)' at the LHC*, *Eur. Phys. J.* **C73** (2013) 2656 [[1212.4428](#)].
- [39] A. De Rujula, H. Georgi and S.L. Glashow, *FLAVOR GONIOMETRY BY PROTON DECAY*, *Phys. Rev. Lett.* **45** (1980) 413.
- [40] J.P. Derendinger, J.E. Kim and D.V. Nanopoulos, *Anti-SU(5)*, *Phys. Lett.* **139B** (1984) 170.
- [41] I. Antoniadis, J.R. Ellis, J.S. Hagelin and D.V. Nanopoulos, *Supersymmetric Flipped SU(5) Revitalized*, *Phys. Lett.* **B194** (1987) 231.
- [42] J.R. Ellis, J.S. Hagelin, S. Kelley and D.V. Nanopoulos, *Aspects of the Flipped Unification of Strong, Weak and Electromagnetic Interactions*, *Nucl. Phys.* **B311** (1988) 1.
- [43] G. Lazarides, C. Panagiotakopoulos and Q. Shafi, *Superstring Motivated Gauge Models Based on a Rank Six Subgroup of E(6)*, *Z. Phys.* **C34** (1987) 553.
- [44] Q. Shafi, *E(6) as a Unifying Gauge Symmetry*, *Phys. Lett.* **79B** (1978) 301.
- [45] F. Gursev, P. Ramond and P. Sikivie, *A Universal Gauge Theory Model Based on E6*, *Phys. Lett.* **60B** (1976) 177.
- [46] B. Bajc and V. Susič, *Towards the minimal renormalizable supersymmetric E<sub>6</sub> model*, *JHEP* **02** (2014) 058 [[1311.0775](#)].
- [47] P. Langacker and J. Wang, *U(1)-prime symmetry breaking in supersymmetric E(6) models*, *Phys. Rev.* **D58** (1998) 115010 [[hep-ph/9804428](#)].
- [48] D.A. Demir, G.L. Kane and T.T. Wang, *The Minimal U(1)' extension of the MSSM*, *Phys. Rev.* **D72** (2005) 015012 [[hep-ph/0503290](#)].



- [49] J. Ellis, A. Mustafayev and K.A. Olive, *Constrained Supersymmetric Flipped SU(5) GUT Phenomenology*, *Eur. Phys. J.* **C71** (2011) 1689 [[1103.5140](#)].
- [50] I. Gogoladze, R. Khalid, S. Raza and Q. Shafi, *CDMS II Inspired Neutralino Dark Matter in Flipped SU(5)*, *Mod. Phys. Lett.* **A25** (2010) 3371 [[0912.5411](#)].
- [51] M. Frank, *Evading Z' boson mass limits in U(1)' supersymmetric models*, *Eur. Phys. J.* **ST 229** (2020) 3205.
- [52] L. Delle Rose, S. Khalil, S.J.D. King, S. Moretti and A.M. Thabt, *Atomki Anomaly in Family-Dependent U(1)' Extension of the Standard Model*, *Phys. Rev.* **D99** (2019) 055022 [[1811.07953](#)].
- [53] J. Erler, P. Langacker, S. Munir and E. Rojas, *Improved Constraints on Z-prime Bosons from Electroweak Precision Data*, *JHEP* **08** (2009) 017 [[0906.2435](#)].
- [54] F. del Aguila, J. de Blas and M. Perez-Victoria, *Electroweak Limits on General New Vector Bosons*, *JHEP* **09** (2010) 033 [[1005.3998](#)].
- [55] CDF collaboration, *Search for WW and WZ Resonances Decaying to Electron, Missing E<sub>T</sub>, and Two Jets in pp̄ Collisions at √s = 1.96 TeV*, *Phys. Rev. Lett.* **104** (2010) 241801 [[1004.4946](#)].
- [56] G. Cacciapaglia, C. Csaki, G. Marandella and A. Strumia, *The Minimal Set of Electroweak Precision Parameters*, *Phys. Rev.* **D74** (2006) 033011 [[hep-ph/0604111](#)].
- [57] B. O'Leary, W. Porod and F. Staub, *Mass spectrum of the minimal SUSY B-L model*, *JHEP* **05** (2012) 042 [[1112.4600](#)].
- [58] C.S. Un and O. Ozdal, *Mass Spectrum and Higgs Profile in BLSSM*, *Phys. Rev.* **D93** (2016) 055024 [[1601.02494](#)].
- [59] J. Kang and P. Langacker, *Z' discovery limits for supersymmetric E(6) models*, *Phys. Rev.* **D71** (2005) 035014 [[hep-ph/0412190](#)].
- [60] G. Lazarides and Q. Shafi, *R symmetry in minimal supersymmetry standard model and beyond with several consequences*, *Phys. Rev.* **D58** (1998) 071702 [[hep-ph/9803397](#)].
- [61] ATLAS, CMS collaboration, *Exotic searches by ATLAS and CMS*, *J. Phys. Conf. Ser.* **1690** (2020) 012169.
- [62] ATLAS collaboration, *Search for squarks and gluinos in final states with jets and missing transverse momentum using 36 fb<sup>-1</sup> of √s = 13 TeV pp collision data with the ATLAS detector*, *Phys. Rev.* **D97** (2018) 112001 [[1712.02332](#)].
- [63] K.S. Babu, I. Gogoladze and C.S. Un, *Proton Lifetime in Minimal SUSY SU(5) in Light of LHC Results*, [2012.14411](#).
- [64] S. Raza, Q. Shafi and C.S. Un, *b – τ Yukawa unification in SUSY SU(5) with mirage mediation: LHC and dark matter implications*, *JHEP* **05** (2019) 046 [[1812.10128](#)].
- [65] M.E. Gómez, Q. Shafi and C.S. Un, *Testing Yukawa Unification at LHC Run-3 and HL-LHC*, *JHEP* **07** (2020) 096 [[2002.07517](#)].

- [66] ATLAS, CMS collaboration, *Searches for gluinos and squarks*, *PoS LHCP2019* (2019) 168 [[1909.11753](#)].
- [67] XENON collaboration, *Projected WIMP sensitivity of the XENONnT dark matter experiment*, *JCAP* **2011** (2020) 031 [[2007.08796](#)].
- [68] FERMI-LAT collaboration, *Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data*, *Phys. Rev. Lett.* **115** (2015) 231301 [[1503.02641](#)].
- [69] FERMI-LAT, DES collaboration, *Search for Gamma-Ray Emission from DES Dwarf Spheroidal Galaxy Candidates with Fermi-LAT Data*, *Astrophys. J. Lett.* **809** (2015) L4 [[1503.02632](#)].
- [70] Y. Hiçyılmaz, M. Ceylan, A. Altas, L. Solmaz and C.S. Un, *Quasi Yukawa Unification and Fine-Tuning in  $U(1)$  Extended SSM*, *Phys. Rev.* **D94** (2016) 095001 [[1604.06430](#)].
- [71] ATLAS collaboration, *Search for high-mass dilepton resonances using  $139 \text{ fb}^{-1}$  of pp collision data collected at  $\sqrt{s} = 13 \text{ TeV}$  with the ATLAS detector*, *Phys. Lett.* **B796** (2019) 68 [[1903.06248](#)].
- [72] CMS collaboration, *First constraints on invisible Higgs boson decays using  $t\bar{t}H$  production at  $\sqrt{s} = 13 \text{ TeV}$* , .
- [73] ATLAS collaboration, *Search for invisible Higgs boson decays in vector boson fusion at  $\sqrt{s} = 13 \text{ TeV}$  with the ATLAS detector*, *Phys. Lett.* **B793** (2019) 499 [[1809.06682](#)].
- [74] CMS collaboration, *Search for invisible decays of a Higgs boson produced through vector boson fusion in proton-proton collisions at  $\sqrt{s} = 13 \text{ TeV}$* , *Phys. Lett.* **B793** (2019) 520 [[1809.05937](#)].
- [75] ATLAS collaboration, *Constraints on new phenomena via Higgs boson couplings and invisible decays with the ATLAS detector*, *JHEP* **11** (2015) 206 [[1509.00672](#)].
- [76] CMS collaboration, *The CMS Experiment at the CERN LHC*, *JINST* **3** (2008) S08004.
- [77] CMS collaboration, *Searches for invisible decays of the Higgs boson in pp collisions at  $\sqrt{s} = 7, 8, \text{ and } 13 \text{ TeV}$* , *JHEP* **02** (2017) 135 [[1610.09218](#)].
- [78] W. Porod, *SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at  $e^+ e^-$  colliders*, *Comput. Phys. Commun.* **153** (2003) 275 [[hep-ph/0301101](#)].
- [79] W. Porod and F. Staub, *SPheno 3.1: Extensions including flavour, CP-phases and models beyond the MSSM*, *Comput. Phys. Commun.* **183** (2012) 2458 [[1104.1573](#)].
- [80] M.D. Goodsell, K. Nickel and F. Staub, *Two-Loop Higgs mass calculations in supersymmetric models beyond the MSSM with SARAH and SPheno*, *Eur. Phys. J.* **C75** (2015) 32 [[1411.0675](#)].
- [81] F. Staub, *SARAH 4 : A tool for (not only SUSY) model builders*, *Comput. Phys. Commun.* **185** (2014) 1773 [[1309.7223](#)].
- [82] F. Staub, *Exploring new models in all detail with SARAH*, *Adv. High Energy Phys.* **2015** (2015) 840780 [[1503.04200](#)].

- [83] J. Hisano, H. Murayama and T. Yanagida, *Nucleon decay in the minimal supersymmetric SU(5) grand unification*, *Nucl. Phys.* **B402** (1993) 46 [[hep-ph/9207279](#)].
- [84] PARTICLE DATA GROUP collaboration, *Review of Particle Physics*, *Chin. Phys.* **C40** (2016) 100001.
- [85] 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 [[1207.7214](#)].
- [86] ATLAS collaboration, P. Checchia et al., eds., *Measurement of the Higgs boson mass in the  $H \rightarrow ZZ^* \rightarrow 4\ell$  and  $H \rightarrow \gamma\gamma$  channels with  $\sqrt{s}=13\text{TeV}$  pp collisions using the ATLAS detector*, .
- [87] ATLAS collaboration, *Measurement of Higgs boson production in association with a  $t\bar{t}$  pair in the diphoton decay channel using  $139\text{fb}^{-1}$  of LHC data collected at  $\sqrt{s} = 13\text{ TeV}$  by the ATLAS experiment*, .
- [88] ATLAS collaboration, *Combined measurement of differential and inclusive total cross sections in the  $H \rightarrow \gamma\gamma$  and the  $H \rightarrow ZZ^* \rightarrow 4\ell$  decay channels at  $\sqrt{s} = 13\text{ TeV}$  with the ATLAS detector*, .
- [89] 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 [[1207.7235](#)].
- [90] CMS collaboration, *Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at  $\sqrt{s} = 13\text{ TeV}$* , *JHEP* **11** (2017) 047 [[1706.09936](#)].
- [91] CMS collaboration, *Search for a Higgs boson in the mass range from 145 to 1000 GeV decaying to a pair of W or Z bosons*, *JHEP* **10** (2015) 144 [[1504.00936](#)].
- [92] CMS collaboration, *Measurement of Higgs Boson Production and Properties in the WW Decay Channel with Leptonic Final States*, *JHEP* **01** (2014) 096 [[1312.1129](#)].
- [93] ATLAS, CMS collaboration, *Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at  $\sqrt{s} = 7$  and 8 TeV*, *JHEP* **08** (2016) 045 [[1606.02266](#)].
- [94] L.E. Ibanez and G.G. Ross, *SU(2)-L x U(1) Symmetry Breaking as a Radiative Effect of Supersymmetry Breaking in Guts*, *Phys. Lett.* **110B** (1982) 215.
- [95] K. Inoue, A. Kakuto, H. Komatsu and S. Takeshita, *Aspects of Grand Unified Models with Softly Broken Supersymmetry*, *Prog. Theor. Phys.* **68** (1982) 927.
- [96] L.E. Ibanez, *Locally Supersymmetric SU(5) Grand Unification*, *Phys. Lett.* **118B** (1982) 73.
- [97] J.R. Ellis, D.V. Nanopoulos and K. Tamvakis, *Grand Unification in Simple Supergravity*, *Phys. Lett.* **121B** (1983) 123.
- [98] L. Alvarez-Gaume, J. Polchinski and M.B. Wise, *Minimal Low-Energy Supergravity*, *Nucl. Phys.* **B221** (1983) 495.
- [99] HEAVY FLAVOR AVERAGING GROUP collaboration, *Averages of B-Hadron, C-Hadron, and tau-lepton properties as of early 2012*, [1207.1158](#).

- [100] LHCb collaboration, *First Evidence for the Decay  $B_s^0 \rightarrow \mu^+ \mu^-$* , *Phys. Rev. Lett.* **110** (2013) 021801 [[1211.2674](#)].
- [101] HEAVY FLAVOR AVERAGING GROUP collaboration, *Averages of  $b$ -hadron,  $c$ -hadron, and  $\tau$ -lepton properties*, [1010.1589](#).
- [102] PLANCK collaboration, *Planck 2018 results. VI. Cosmological parameters*, [1807.06209](#).
- [103] G. Bélanger, F. Boudjema, A. Goudelis, A. Pukhov and B. Zaldivar, *micrOMEGAs5.0 : Freeze-in*, *Comput. Phys. Commun.* **231** (2018) 173 [[1801.03509](#)].
- [104] T. Cohen, T. Golling, M. Hance, A. Henrichs, K. Howe, J. Loyal et al., *SUSY Simplified Models at 14, 33, and 100 TeV Proton Colliders*, *JHEP* **04** (2014) 117 [[1311.6480](#)].
- [105] Z. Altın, Z. Kirca, T. Tanmak and C. Salih Ün, *Stop search in SUSY  $SO(10)$  GUTs with nonuniversal Gaugino masses*, *Eur. Phys. J. C* **80** (2020) 818.
- [106] H. Baer, I. Gogoladze, A. Mustafayev, S. Raza and Q. Shafi, *Sparticle mass spectra from  $SU(5)$  SUSY GUT models with  $b - \tau$  Yukawa coupling unification*, *JHEP* **03** (2012) 047 [[1201.4412](#)].
- [107] A. Delgado and M. Quiros, *Higgsino Dark Matter in the MSSM*, *Phys. Rev. D* **103** (2021) 015024 [[2008.00954](#)].
- [108] XENON collaboration, *Dark Matter Search Results from a One Ton-Year Exposure of XENON1T*, *Phys. Rev. Lett.* **121** (2018) 111302 [[1805.12562](#)].
- [109] PANDAX-II collaboration, *Dark Matter Results From 54-Ton-Day Exposure of PandaX-II Experiment*, *Phys. Rev. Lett.* **119** (2017) 181302 [[1708.06917](#)].
- [110] LUX collaboration, *Results from a search for dark matter in the complete LUX exposure*, *Phys. Rev. Lett.* **118** (2017) 021303 [[1608.07648](#)].
- [111] DARWIN collaboration, *DARWIN: towards the ultimate dark matter detector*, *JCAP* **11** (2016) 017 [[1606.07001](#)].