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Dark matter in anomalous $U(1)'$ models with neutral mixing

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We study the lightest masses in the fermionic sector of an anomalous $U(1)'$ extension of the minimal supersymmetric standard model inspired by brane constructions. The lightest supersymmetric particle of this model is an extra weakly interacting massive particle which is shown to have a relic density satisfying WMAP data. This computation is carried out numerically after having adapted the DarkSUSY package to our case.

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I. INTRODUCTION

There has been much work recently to conceive an intersecting brane model with the gauge and matter content of the standard model (SM) of particle physics [1–4]. One of the features of such models is the presence of extra anomalous gauge $U(1)'$s whose anomaly is cancelled via the Green-Schwarz mechanism. This characterizes this class of models with respect to those which still have extra $U(1)$ gauge symmetries but cancel the anomaly as in the SM or in the minimal supersymmetric SM (MSSM) (see [5] for a review). The latter are inspired by (super) grand unified models or by plain extensions of the (MS)SM and their quantum numbers with respect to the new gauge symmetries are fixed by the condition of setting to zero all the triangle diagrams in which at least one vertex of such diagrams has a $U(1)'$ current coming from the extra gauge simmetries. On the contrary, in brane inspired models, these quantum numbers are not fixed. We have introduced and discussed the signatures of this model in [6,7]. Another important issue which deserves careful scrutiny is the compatibility of this model with the WMAP data: this was done in [8] (see also [9,10] for related work). The mass matrix of the fermions uncharged with respect to the $U(1)$ of the gauge group of the SM, now gets two new contributions in this model: one coming from the superpartner of the Stückelberg boson (Stückelino) and the other from the superpartner of the gauge boson mediating the extra $U(1)'$. By taking some simplifying and reasonable assumptions (to be detailed later) on the fermion masses entering the soft supersymmetry breaking Lagrangian, the lightest sypersymmetric particle (LSP) turns out to be the Stückelino. It is also easy to realize that, given the simplifying assumptions mentioned above, the LSP is interacting with the MSSM particles with a coupling suppressed by the inverse of the mass of the extra gauge boson of the theory which must be at least of the order of the TeV for phenomenological reasons. The LSP is then an extra weakly interacting massive particle, a class of particles which has already been studied in the literature [11,12]. The cross section of these LSPs is too weak to give the right relic abundance. This is why one has to resort to coannihilations with NLSPs. In our case, the cross section for the annihilations of the LSP with the NLSP and that for the coannihilations of the two species differ for some orders of magnitude. Once again this situation is not new in the literature [13–15] but needs to be treated carefully: the two species will not decouple because there will be some MSSM particles to keep them in equilibrium. Moreover these particles must be relativistic so that their abundance is enough to foster the reaction. These points were assumed in our previous paper on this subject [8] to allow for a simplified treatment of the relic abundance. In this paper we drop all simplifying assumptions and discuss the most general case, in which the extra MSSM sector is not decoupled to the MSSM sector and the LSP is mainly a mixture of Stückelino and primeino, with small MSSM contribution. The Higgs and supersymmetric particle masses and their charges with respect to the $U(1)'$ now enter our computations which can no longer be treated analitically. We then solve numerically the Boltzmann equation in this general case controlling the compatibility of the WMAP data with the accelerator constraints and verifying our assumptions concerning the decoupling of the fermionic species. To do this we have modified the DarkSUSY [16] package to keep in account the new interactions typical of our model. The results we obtain are qualitatively compatible with the findings in [8]: there is an ample region of the parameter space which leads to a relic density compatible with the WMAP data. This is the plan of the paper: in Sec. II we describe the neutral mixing in our model and sketch the way in which it affects the interactions. In Sec. III we describe how we change the DarkSUSY package and compute the relic density.

II. NEUTRAL MIXING

Our model [6] is an extension of the MSSM with an extra $U(1)$. The charges of the matter fields with respect to the symmetry groups are given in Table I.

The anomalies induced by this extension are cancelled by the GS mechanism. Each anomalous triangle diagram is parametrized by a coefficient $b_2^{(a)}$ (entering the Lagrangian) with the assignment:

TABLE I. Charge assignment.

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q_i	**3**	**2**	1/6	Q_Q
U_i^c	$\bar{\mathbf{3}}$	**1**	−2/3	Q_{U^c}
D_i^c	$\bar{\mathbf{3}}$	**1**	1/3	Q_{D^c}
L_i	**1**	**2**	−1/2	Q_L
E_i^c	**1**	**1**	1	Q_{E^c}
H_u	**1**	**2**	1/2	Q_{H_u}
H_d	**1**	**2**	−1/2	Q_{H_d}

$$\mathcal{A}^{(0)}\colon U(1)' - U(1)' - U(1)' \to b_2^{(0)}, \tag{1}$$

$$\mathcal{A}^{(1)}\colon U(1)' - U(1)_Y - U(1)_Y \to b_2^{(1)}, \tag{2}$$

$$\mathcal{A}^{(2)}\colon U(1)' - SU(2) - SU(2) \to b_2^{(2)}, \tag{3}$$

$$\mathcal{A}^{(3)}\colon U(1)' - SU(3) - SU(3) \to b_2^{(3)}, \tag{4}$$

$$\mathcal{A}^{(4)}\colon U(1)' - U(1)' - U(1)_Y \to b_2^{(4)}. \tag{5}$$

The mass of the extra boson is parametrized by $M_{V^{(0)}} = 4b_3 g_0$, where g_0 is the coupling of the extra $U(1)'$. The terms of the Lagrangian that will contribute to our calculation are [6,8]:

$$\begin{aligned}\mathcal{L}_{\text{Stückelino}} = &\frac{i}{4}\psi_S\sigma^\mu\partial_\mu\bar{\psi}_S - \sqrt{2}b_3\psi_S\lambda^{(0)} \\ &\times -\frac{i}{2\sqrt{2}}\sum_{a=0}^{2} b_2^{(a)}\,\mathrm{Tr}(\lambda^{(a)}\sigma^\mu\bar{\sigma}^\nu F_{\mu\nu}^{(a)})\psi_S \\ &\times -\frac{i}{2\sqrt{2}}b_2^{(4)}\left[\frac{1}{2}\lambda^{(1)}\sigma^\mu\bar{\sigma}^\nu F_{\mu\nu}^{(0)}\psi_S + (0\leftrightarrow 1)\right] \\ &+ \text{H.c.}\end{aligned} \tag{6}$$

As already stated, we want to deal with the case of general neutral mixing. The neutral mixing matrix is:

$$\begin{pmatrix} B^\mu \\ W^{3\mu} \\ C^\mu \end{pmatrix} = M\begin{pmatrix} A^\mu \\ Z_0^\mu \\ Z'^\mu \end{pmatrix}. \tag{7}$$

Defining $an \equiv g_0 Q_{H_u}\frac{2v^2}{2M_{Z'}^2}$ we have at tree level:

$$M = \begin{pmatrix} c_W & -s_W & s_W\sqrt{g_1^2+g_2^2}\,an \\ s_W & c_W & c_W\sqrt{g_1^2+g_2^2}\,an \\ 0 & (c_W g_2 + s_W g_1)an & 1 \end{pmatrix}, \tag{8}$$

where c_W is $\cos(\theta_W)$, s_W is $\sin(\theta_W)$. g_1, g_2 are the couplings of the SM electro-weak $SU(2)\times U(1)$ group. The structure of this matrix leaves the electromagnetic sector and the related quantum numbers unchanged with respect to the MSSM ones. Last, we remember [6,8] the general form of the neutralinos' mass matrix at tree level:

$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_S & \sqrt{2}\frac{M_{Z'}}{2} & 0 & 0 & 0 & 0 \\ \dots & M_0 & 0 & 0 & -g_0 v_d Q_{H_u} & g_0 v_u Q_{H_u} \\ \dots & \dots & M_1 & 0 & -\frac{g_1 v_d}{2} & \frac{g_1 v_u}{2} \\ \dots & \dots & \dots & M_2 & \frac{g_2 v_d}{2} & -\frac{g_2 v_u}{2} \\ \dots & \dots & \dots & \dots & 0 & -\mu \\ \dots & \dots & \dots & \dots & \dots & 0 \end{pmatrix},$$

where M_S and M_0 are the soft masses of the Stückelino and of the primeino, respectively, and v_u, v_d are the vacuum expectation values of the Higgs fields.

III. NUMERICAL COMPUTATIONS AND RESULTS

Following our previous work [8], in which we have studied separately the case in which the NLSP is a bino-Higgsino from that in which it is a wino-Higgsino, we performed this general study in the same way. The plots we will show are generated with a modified version of the DarkSUSY package, in which we added the new fields and interactions introduced by the anomalous extension. The free parameters that we use in our numerical simulations are the seven used in the MSSM-7 model: the μ mass, the wino soft mass M_2, the parity-odd Higgs mass M_{A_0}, $tg\beta$, the sfermion mass scale m_{sf}, the two Yukawas a_t and a_b. We add to this set five parameters which define the $U(1)'$ extension: the Stückelino soft mass M_S, the primeino soft mass M_0, the $U(1)'$ charges Q_{H_u}, Q_Q, Q_L. As our actual aim is to study the model without any simplification, we cannot have control on the mass gap between the LSP and NLSP, because fixing it would require a constraint on the masses. So we choose to leave all parameters unconstrained and therefore to collect data in the mass-gap ranges $0 \div 5\%$, $5 \div 10\%$. In each case we have started our study scanning the parameter space in search of the region permitted by the experimental and theoretical constraints, i.e. the region in which we could satisfy the WMAP data with a certain choice of the model parameters. After that we have numerically explored this region to find sets of parameters that satisfy the WMAP data for the relic density. We have found many suitable combinations for both types of NLSP. So we have chosen some of these successful models and we have computed the relic density keeping constant all but two parameters and plotting the results. We have found regions of the parameter space in which the WMAP data are satisfied for a mass gap of over 20%, but in the following we will only show results for the regions $0 \div 5\%$ and $5 \div 10\%$, because they are more significant. For simplicity we will refer to these regions as the "5% region" and "10% region" respectively.

A. General results

In this section we want to list some results that are valid for both types of NLSP. First of all, given the constraints on the neutral mixing described in [5], we have obtained that $-1 \lesssim Q_{H_u} \lesssim 1$. This constraint was not appearing in our preliminary analysis in [8]. This implies that also in our general case the mixing between our anomalous LSP and the NLSP is small. We have checked that there are suitable parameter space regions in which the WMAP data are satisfied and we have found that this is true for all possible composition of our anomalous LSP. We have also checked that in each region we have studied, there are no divergences or unstable behaviors in our numerical results. We have verified that the relic density is strongly dependent on the LSP and NLSP masses and composition while it is much less dependent on the other variables. Anyway, it can be shown that there are cases in which the parameters not related to the LSP or NLSP can play an important role. We will show an example of this case in a forthcoming subsection.

B. Bino-Higgsino NLSP

If the NLSP is mostly a bino-Higgsino we have a two particle coannihilation. We chose two sample models which satisfy the WMAP data [17] with mass gaps 5% and 10%. We study these models to show the dependence of the relic density from the LSP composition and from the mass gap. To obtain these results, we have performed a numerical simulation in which we vary only the Stückelino and the primeino soft masses. The results are shown in Fig. 1, with the conventions:

(i) Inside the continuous lines we have the region in which $(\Omega h^2)_{\mathrm{WMAP}} \sim \Omega h^2$

(ii) Inside the thick lines we have the region in which $(\Omega h^2 - 3\sigma)_{\mathrm{WMAP}} < \Omega h^2 < (\Omega h^2 + 3\sigma)_{\mathrm{WMAP}}$

(iii) Inside the dashed lines we have the region in which $(\Omega h^2 - 5\sigma)_{\mathrm{WMAP}} < \Omega h^2 < (\Omega h^2 + 5\sigma)_{\mathrm{WMAP}}$

(iv) Inside the dotted lines we have the region in which $(\Omega h^2 - 10\sigma)_{\mathrm{WMAP}} < \Omega h^2 < (\Omega h^2 + 10\sigma)_{\mathrm{WMAP}}$

Going from the region with a 5% mass gap to that with a 10% mass gap, there is a large portion of the parameter space in which the WMAP data cannot be satisfied, while the regions shown in the second and third plot in Fig. 1 are similar and thus are mass-gap independent.

C. Wino-Higgsino NLSP

If the NLSP is mostly a wino-Higgsino we have a three particle coannihilation, because the lightest wino is almost degenerate in mass with the lightest chargino, so they both contribute to the coannihilations. In this case we perform the same numerical calculation illustrated in the previous subsection. We have extensively studied a sample model with a mass gap of 10%, showing an example of a funnel region, a resonance that occurs when $2M_{\mathrm{LSP}} \sim M_{A_0}$. In our sample model $M_{\mathrm{LSP}} \sim 330$ GeV, while $M_{A_0} \sim 630$ GeV and this leads to the relic density plot shown in Fig. 2, with the same conventions used in Fig. 1. So we can state that also in the case of anomalous LSP we can have a behavior similar to that of the MSSM, given that the LSP coannihilates with a MSSM NLSP.

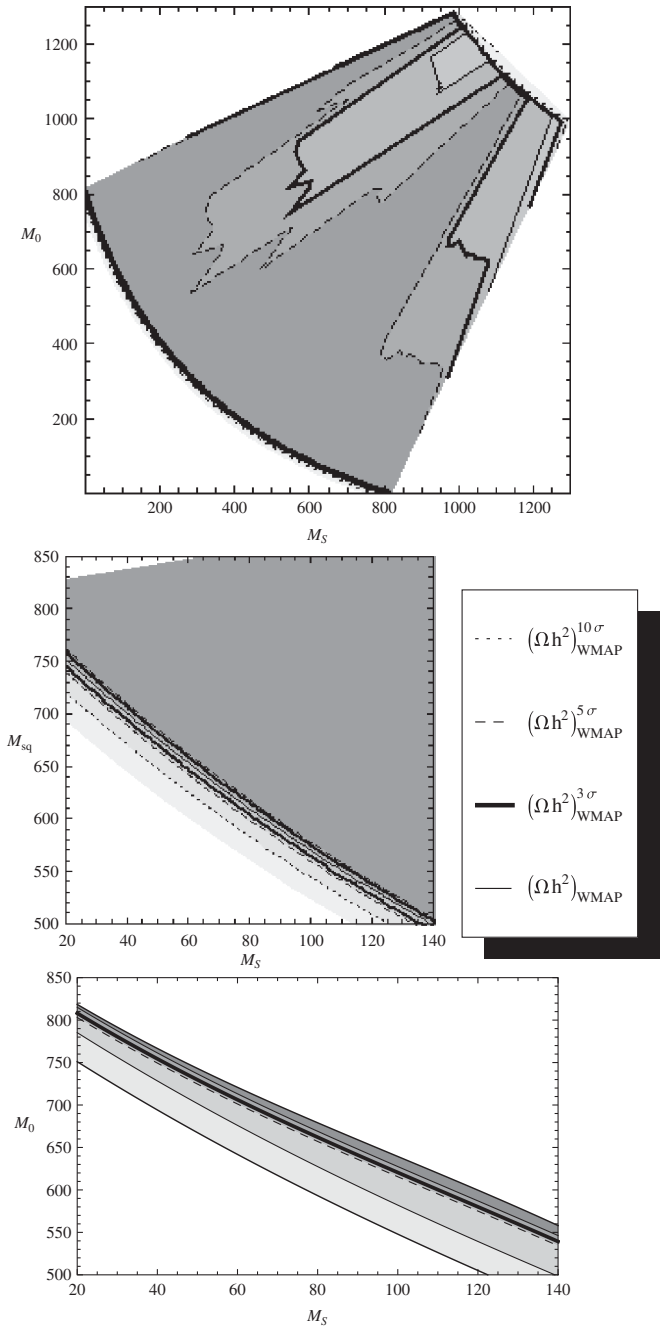

FIG. 1. Plot of the relic density of the LSP vs the Stückelino and primeino masses. The first plot shows the case of a mass gap of 5%. The second plot is a zoom of the first in the region between 20–140 GeV for Stückelino mass and 500–850 GeV for primeino mass. The third plot shows the case of a mass gap of 10% in the same region of the second plot. All the masses are expressed in GeV.

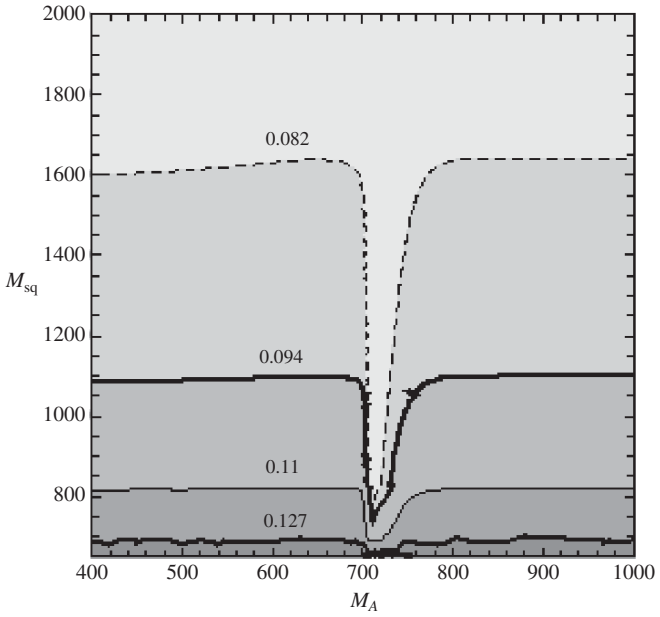

FIG. 2. Example of a funnel region for a winolike NLSP, whose mass gap with the LSP is 10%.

IV. CONCLUSION

We have modified the DarkSUSY package in the routines which calculate the cross section of a given supersymmetric particle (contained in the folder ~/src/an) adding all the new interactions introduced by our anomalous extension of the MSSM. We have also written new subroutines to calculate amplitudes that differ from those already contained in DarkSUSY. We have also modified the routines that generate the supersymmetric model from the inputs, adding the parameters necessary to generate the minimal anomalous U(1) extension of the supersymmetric standard model [6] and changing the routines that define the model (contained in ~/src/su) accordingly. Finally, we have written a main program that lets the user choose whether he wants to perform the relic density calculation in the MSSM or in the minimal anomalous U(1) extension of the supersymmetric standard model. The code of our version of the package is available by contacting andrea .mammarella@roma2.infn.it.

These modifications have permitted us to perform an extensive numerical exploration of the parameter space for an anomalous extension of the MSSM without restriction on the neutral mixing or on the free parameters of the model. We have verified that our model does not lead to any divergence or instability.

We have studied the mixing and thus we have obtained a constraint on Q_{H_u}. We have also found sizable regions in which we can satisfy the WMAP data for mass gaps which go from 5% to beyond 20%. We have studied some specific sets of parameters for the 5% and 10% mass-gap regions, showing that relatively small changes in the mass gap can produce very important changes in the area of the regions which satisfy the experimental constraints. We have also shown, as an example that we still have the MSSM physics, the presence of a funnel region, analogous to that in the MSSM, in some region of the parameter space. So we can say that a model with an anomalous LSP can satisfy all the current experimental constraints, can show a phenomenology similar to that expected from a MSSM LSP and can be viable to explain the dark matter abundance without any arbitrary constraint on its parameters.

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