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To cite this article: M. Cannoni *et al* JCAP03(2016)041

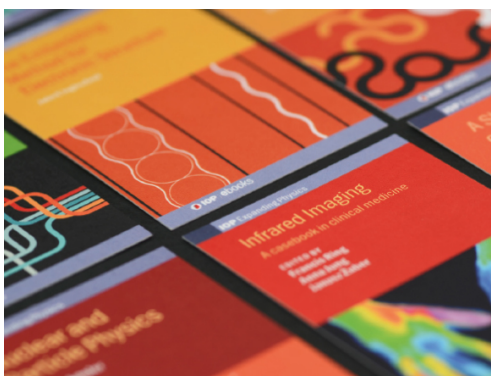
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Supersymmetry searches in GUT models with non-universal scalar masses

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Received December 4, 2015

Revised February 23, 2016

Accepted March 8, 2016

Published March 22, 2016



Abstract. We study SO(10), SU(5) and flipped SU(5) GUT models with non-universal soft supersymmetry-breaking scalar masses, exploring how they are constrained by LHC supersymmetry searches and cold dark matter experiments, and how they can be probed and distinguished in future experiments. We find characteristic differences between the various GUT scenarios, particularly in the coannihilation region, which is very sensitive to changes of parameters. For example, the flipped SU(5) GUT predicts the possibility of $\tilde{t}_1 - \chi$ coannihilation, which is absent in the regions of the SO(10) and SU(5) GUT parameter spaces that we study. We use the relic density predictions in different models to determine upper bounds for the neutralino masses, and we find large differences between different GUT models in the sparticle spectra for the same LSP mass, leading to direct connections of distinctive possible experimental measurements with the structure of the GUT group. We find that future LHC searches for generic missing E_T , charginos and stops will be able to constrain the different GUT models in complementary ways, as will the Xenon 1 ton and Darwin dark matter scattering experiments and future FERMI or CTA γ -ray searches.

Keywords: particle physics - cosmology connection, supersymmetry and cosmology

ArXiv ePrint: [1511.06205](https://arxiv.org/abs/1511.06205)

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1 Introduction

The recent years have provided a plethora of new experimental and cosmological information that provides important constraints on possible extensions of the Standard Model (SM). Recent LHC results, including the Higgs measurements [1–4], severely constrain some of the simplest scenarios. We know, however, that there must be some physics beyond the SM. For example, massive neutrinos cannot be accommodated within the SM, nor can the observed baryon asymmetry of the universe or the origin of Cold Dark Matter (CDM) be explained. In looking for possible extensions of the SM that address these issues, supersymmetry (SUSY) continues to provide significant theoretical advantages, especially if we believe in unification beyond the SM. Most notably for the purposes of this paper, the lightest supersymmetric particle (LSP) can explain the origin of CDM [5, 6].

Reconciling the amount of CDM deduced from the data of the Wilkinson Microwave Anisotropy Probe (WMAP) [7, 8] and the Planck satellite [9, 10] with the predictions of supersymmetric models, has been a major challenge in recent years. Although the minimal constrained supersymmetric extension of the SM (CMSSM) is still compatible with the LHC and WMAP predictions [11], the allowed parameter space is severely constrained, since a Higgs mass $m_h \sim 125$ GeV implies a relatively heavy sparticle spectrum. However, the allowed regions may change significantly in different versions of the MSSM, especially in the coannihilation strips where, e.g., $m_\chi \sim m_{\tilde{\tau}_1}$ or $\sim m_{\tilde{t}_1}$. Because of their narrow widths, these coannihilation strips are particularly sensitive to changes in the input model parameters.

In this work, we study these changes in various scenarios that go beyond the constrained minimal supersymmetric extension of the SM (CMSSM), in which soft SUSY-breaking terms are assumed to be universal at the GUT scale, using dark matter considerations as a probe of different theoretical constructions. In general, GUT scenarios that favour particular degeneracies in the sparticle spectrum will lead to additional contributions to coannihilations, thus enhancing their efficiency. Conversely, experimental signals sensitive to these degeneracies can provide information about the gauge unification group. Following previous studies of

models with non-universal soft SUSY-breaking Higgs mass parameters (NUHM1,2) [12–16], we analyse the predictions of various SUSY GUT models, including SO(10) [17–21], minimal SU(5) [22, 23] and flipped SU(5) [24–27].

Our paper is structured as follows: in section 2 we review the features of GUT models that are relevant for our studies. In section 3 we discuss our sampling methodology for searching for regions of the parameter space compatible with the data. In section 4 we discuss the implications of non-universalities for the different mechanisms that reproduce the correct relic CDM density. In section 5 we discuss in more detail how the results of our scans depend on the relation between the relic abundance mechanisms, the value of the Higgs boson mass and the supersymmetric contribution to $\delta a_\mu = [(g_\mu - 2)/2]_{\text{exp}} - [(g_\mu - 2)/2]_{\text{SM}}$. In section 6, we present the cross sections for direct and indirect CDM detection. In section 7, we study how sparticle searches at the LHC impose further constraints on our models. Finally, in section 8 we summarise our results and discuss future prospects.

2 Relevant features of supersymmetric GUT models

We assume that SUSY breaking occurs at some scale M_X above M_{GUT} , and is induced by a mechanism that generates generation-blind soft terms. Between the scales M_X and M_{GUT} , the renormalization group equations (RGE) and additional interactions associated with flavour, e.g., Yukawa interactions, might induce non-universalities in the soft terms, which we do not consider here, while the theory still preserves the GUT symmetry. Below M_{GUT} , the effective theory is the MSSM with SUSY masses that are common for fields in the same representation of the GUT group. Our approach is therefore to assume a pattern of soft terms with common soft masses for all the particles that belong to the same representations of the GUT group under consideration, while allowing different common masses for inequivalent representations.

The simplest possibility arises within an SO(10) GUT [17–21]. In this case, all quarks and leptons are accommodated in the same **16** representation, while we assume that the up and down Higgs multiplets are in a pair of **10** representations. Since this assignment also determines common sfermion mass matrices and beta functions, similar behaviour under RGE runs is to be expected. Consequently, in this GUT model there is a common soft SUSY-breaking mass for all sfermions (squarks and sleptons) and two different masses for m_{h_u} and m_{h_d} . From this point of view, the SO(10) scenario can be identified with the NUHM2 studied previously [13], and we include it as a reference for comparison with other GUT groups.

The situation changes significantly in the case of the SU(5) group [22, 23]. In this case, the multiplet assignments are as follows:

$$(Q, u^c, e^c)_i \in \mathbf{10}_i, (L, d^c)_i \in \bar{\mathbf{5}}_i, \nu_i^c \in \mathbf{1}_i. \quad (2.1)$$

The soft terms that we assume are the same for all the members of the same representation at the GUT scale, but are different for the **10** and $\bar{\mathbf{5}}$ in general, and we assume that the singlet neutrinos decouple at the GUT scale, and therefore do not affect our analysis. A similar approach was followed in [28], but the main aim of that work was to reconcile the correct prediction of m_h (requiring a heavy SUSY spectrum) with a supersymmetric contribution that could explain the discrepancy of the SM prediction for $(g_\mu - 2)$ with its experimental value. However, the main aim of this work is to analyse the relic density predictions and to extend the full analysis also to the case of the flipped SU(5) [24–27], which leads to predictions that

differ significantly, and has some distinctive features. The particle assignments are different in flipped SU(5) [24–27]:

$$(Q, d^c, \nu^c)_i \in \mathbf{10}_i, (L, u^c)_i \in \bar{\mathbf{5}}_i, e_i^c \in \mathbf{1}_i. \quad (2.2)$$

The impacts of these assignments on the evolution of sparticle masses, and hence on the coannihilation strips are discussed in detail below. As before, we assume that the singlet neutrinos have already decoupled at the GUT scale. In both SU(5) models we assume that the Higgs doublets H_u and H_d of the MSSM arise from $\mathbf{5}$ and $\bar{\mathbf{5}}$ SU(5) representations, respectively.

The soft SUSY-breaking scalar terms for the fields in an irreducible representation r of the unification group are parametrised as multiples of a common scale m_0 :

$$m_r = x_r m_0, \quad (2.3)$$

while the trilinear terms are defined as:

$$A_r = Y_r A_0, \quad A_0 = a_0 m_0, \quad (2.4)$$

where Y_r is the Yukawa coupling associated with the representation r , and we use the standard parametrization with a_0 a dimensionless factor, which we assume to be representation-independent. Since the two Higgs fields of the MSSM arise from different SU(5) representations, they have different soft masses, in general. The situation in the different GUT groups is then as follows:

- SO(10): in addition to the CMSSM parameters, we introduce two new parameters x_u and x_d defined as follows:

$$m_{16} = m_0, \quad m_{H_u} = x_u m_{16}, \quad m_{H_d} = x_d m_{16}. \quad (2.5)$$

Similarly, the A -terms are parametrised by:

$$A_{16} = a_0 \cdot m_0, \quad (2.6)$$

as in minimal SO(10) with fermion fields in a common $\mathbf{16}$ representation and two Higgs fields in different $\mathbf{10}$ representations.

- SU(5): here we use as reference the common soft SUSY-breaking masses for the fields of the $\mathbf{10}$, m_{10} . The masses for the other representations are then defined as:

$$m_{10} = m_0, \quad m_5 = x_5 \cdot m_{10}, \quad m_{H_u} = x_u \cdot m_{10} \quad m_{H_d} = x_d \cdot m_{10}, \quad (2.7)$$

and the A -terms are specified via a common mass scale:

$$A_{10,5} = a_0 m_0. \quad (2.8)$$

- Flipped SU(5): here we have

$$m_{10} = m_0, \quad m_5 = x_5 \cdot m_{10} \quad m_R = x_R \cdot m_{10} \quad m_{H_u} = x_u \cdot m_{10} \quad m_{H_d} = x_d \cdot m_{10}, \quad (2.9)$$

where x_R refers to the SU(2)-singlet fields. Similarly, the A -terms are specified as universal: $A_0 = a_0 \cdot m_0$.

A similar parametrization of GUT scalar non-universality in SO(10) and SU(5) was used also in ref. [29]. For our analysis in the following sections we assume a common unification scale M_{GUT} defined as the meeting point of the g_1 and g_2 gauge couplings. The GUT value for g_3 is obtained by requiring $\alpha_s(M_Z) = 0.1187$. Above M_{GUT} we assume a unification group that breaks at this scale. We also assume that SUSY is broken above M_{GUT} by soft terms that are representation-dependent but generation-blind.

3 Sampling methodology and constraints

We work within the three different GUT scenarios SO(10), SU(5) and flipped SU(5) described above, mapping the areas of the parameter space allowed by WMAP, Planck and other constraints onto the ratios of GUT values of the soft terms for each representation. We perform scans of the model parameter spaces using their matter representation patterns as guides for the soft scalar terms at the GUT scale, assuming common gaugino masses. For our searches for regions of the parameter spaces compatible with the data, we use a Bayesian approach based on the `MultiNest` algorithm [30] as implemented in `SuperBayeS-v2.0` [31]. `SuperBayeS` is interfaced with `SoftSUSY` 3.3.10 [32, 33] as SUSY spectrum calculator, `MicrOMEGAs` 2.4 [34, 35] to compute the abundance of dark matter, `DarkSUSY` 5.0.5 [36, 37] for the computation of σ_{SI} , `SuperIso` 3.0 [38, 39] to compute $\delta a_\mu^{\text{SUSY}}$ and $B(D)$ physics observables, `SusyBSG` 1.5 for the determination of $BR(\bar{B} \rightarrow X_s \gamma)$ [40, 41].

The likelihood function that drives our exploration to regions of the parameter space where the model predictions fit the data well is built from the following components:

$$\begin{aligned} \ln \mathcal{L}_{\text{Joint}} = & \ln \mathcal{L}_{\text{EW}} + \ln \mathcal{L}_{\text{B}} + \ln \mathcal{L}_{\Omega_\chi h^2} \\ & + \ln \mathcal{L}_{\text{LUX}} + \ln \mathcal{L}_{\text{Higgs}} + \ln \mathcal{L}_{\text{SUSY}} + \ln \mathcal{L}_{g-2}, \end{aligned} \quad (3.1)$$

where \mathcal{L}_{EW} is the part corresponding to electroweak precision observables, \mathcal{L}_{B} to B-physics constraints, $\mathcal{L}_{\Omega_\chi h^2}$ to measurements of the cosmological DM relic density, \mathcal{L}_{LUX} to the constraints from direct DM detection searches (dominated by the LUX experiment) and $\mathcal{L}_{\text{Higgs}}$ ($\mathcal{L}_{\text{SUSY}}$) to Higgs (sparticle) searches at colliders. We now discuss each component in turn:

\mathcal{L}_{EW} . We implement the constraints on the effective electroweak mixing angle $\sin^2 \theta_{\text{eff}}$ and the total width of the Z-boson, Γ_Z , from the LEP experiments [42]. For the mass of the W boson, m_W , we use the Particle Data Group value [43], which combines the LEP2 and Tevatron measurements. We assume Gaussian likelihoods for all these quantities, with means and standard deviations as given in table II of [44].

\mathcal{L}_{B} . We consider the following flavor observables related to B physics: $BR(\bar{B} \rightarrow X_s \gamma)$, $R_{\Delta M_{B_s}}$, $\frac{BR(B_u \rightarrow \tau \nu)}{BR(\bar{B}_u \rightarrow \tau \nu)_{SM}}$, $BR(\bar{B}_s \rightarrow \mu^+ \mu^-)$ and $BR(\bar{B}_d \rightarrow \mu^+ \mu^-)$. We assume Gaussian likelihoods for all of them, and for most of them we use the measurements shown in table II of [44]. However, the experimental values assumed for $BR(\bar{B}_s \rightarrow \mu^+ \mu^-)$ and $BR(\bar{B}_d \rightarrow \mu^+ \mu^-)$ are $(2.9 \pm 0.8) \times 10^{-9}$ and $(3.6 \pm 1.55) \times 10^{-10}$, respectively, where we quote the total uncertainties found by adding in quadrature the theoretical [45] and experimental [46, 47] uncertainties.

$\mathcal{L}_{\Omega_\chi h^2}$. We include the constraint on the DM relic abundance from the Planck satellite, assuming that the lightest neutralino is the dominant DM component. We use as central value the result from Planck temperature and lensing data $\Omega_\chi h^2 = 0.1186 \pm 0.0031$ [48], with a (fixed) theoretical uncertainty $\tau = 0.012$, following refs. [14, 16, 61], to account for the numerical uncertainties entering in the calculation of the relic density.

\mathcal{L}_{LUX} . For direct DM detection, we include the upper limit from the LUX experiment [49], as implemented in the `LUXCalc` code [50], including both the spin-independent and spin-dependent cross-sections in the event rate calculation. We adopt hadronic matrix elements determined by lattice QCD [51, 52].

$\mathcal{L}_{\text{Higgs}}$. The likelihood for the Higgs searches has two components. The first implements bounds obtained from Higgs searches at LEP, Tevatron and LHC via `HiggsBounds` [53], which returns whether a model is excluded or not at the 95% CL. The second component constrains the mass and the production times decay rates of the Higgs-like boson discovered by the LHC experiments ATLAS [1] and CMS [2]. For this we use `HiggsSignals` [54], assuming a theoretical uncertainty in the calculation of the lightest Higgs mass of 2 GeV.

$\mathcal{L}_{\text{SUSY}}$. The constraints from SUSY searches at LEP and Tevatron are evaluated following the prescription proposed in [55]. The present limits from the Run 1 of LHC are displayed in the corresponding figures in section 4.

$\mathcal{L}_{\text{g-2}}$. We adopt for the discrepancy between the experimental value of the anomalous magnetic moment of the muon and the value calculated in the Standard Model $\delta a_{\mu}^{\text{SUSY}} = (28.7 \pm 8.2) \times 10^{-9}$ [56], where experimental and theoretical errors have been added in quadrature. This corresponds to a 3.6σ discrepancy with the value predicted in the Standard Model, and relies on e^+e^- data for the computation of the hadronic loop contributions to the Standard Model value. The likelihood function is assumed to be Gaussian.

In each case, we run the `MultiNest` algorithm until we reach a sample of about 3×10^4 points. Our focus in this work is to scan the parameter space of the new models, in order to locate regions with acceptable phenomenology and identify regions compatible with the data. Performing any statistical (frequentist or Bayesian) interpretation of our results, based on global fits and confidence- or credibility-level regions, is beyond the scope of this paper and would require samples that are orders of magnitude larger than the ones we have gathered. Instead, we present scatter plots showing the correlations of pairs of parameters and/or observables in various planes. In doing this, we select from the full samples only those points predicting the value of all the observables within the 2σ interval (with σ obtained by summing in quadrature the experimental and theoretical errors as explained in the previous paragraphs). If for the observable only an experimental exclusion limit exists, then the theoretical value is required to be within the 90/95% CL exclusion limits. After applying these cuts, the number of points in the samples is substantially reduced. In particular, in none of the GUT models do we find points with a supersymmetric contribution to δa_{μ} within the 2σ interval. However, we highlight the points in our samples whose contributions to the anomalous magnetic moment of the muon lie in the 3σ interval. We discuss this issue in section 5.

4 Non-universality parameters and relic density mechanisms

It is well known that, if the required amount of relic dark matter is provided by neutralinos, then particular mass relations must be present in the supersymmetric spectrum. In addition to mass relations, we use the neutralino composition to classify the relevant points of the supersymmetric parameter space. The higgsino fraction of the lightest neutralino mass eigenstate is characterized by the quantity

$$h_f \equiv |N_{13}|^2 + |N_{14}|^2, \quad (4.1)$$

where the N_{ij} are the elements of the unitary mixing matrix that correspond to the higgsino mass states. Thus, we classify the points that pass the constraints discussed in section 2 according to the following criteria:

Higgsino χ_1^0 .

$$h_f > 0.1, \quad |m_A - 2m_\chi| > 0.1 m_\chi. \quad (4.2)$$

In this case, the lightest neutralino is higgsino-like and, as we discuss later, the lightest chargino χ_1^\pm is almost degenerate in mass with χ_1^0 . The couplings to the SM gauge bosons are not suppressed and χ_1^0 pairs have large cross sections for annihilation into W^+W^- and ZZ pairs, which may reproduce the observed value of the relic abundance. Clearly, coannihilation channels involving χ_1^\pm and χ_2^0 also contribute.

A/H resonances.

$$|m_A - 2m_\chi| \leq 0.1 m_\chi. \quad (4.3)$$

The correct value of the relic abundance is achieved thanks to s -channel annihilation, enhanced by the resonant A propagator. The thermal average $\langle \sigma_{ann} v \rangle$ spreads out the peak in the cross section, so that neutralino masses for which $2m_\chi \simeq m_A$ is not exactly realized can also experience resonant annihilations.

$\tilde{\tau}$ coannihilations.

$$h_f < 0.1, \quad (m_{\tilde{\tau}_1} - m_\chi) \leq 0.1 m_\chi \quad (4.4)$$

The neutralino is bino-like, annihilation into leptons through t -channel slepton exchange is suppressed, and coannihilations involving the nearly-degenerate $\tilde{\tau}_1$ are necessary to enhance the thermal-averaged effective cross section.

$\tilde{\tau} - \tilde{\nu}_\tau$ coannihilations.

$$h_f < 0.1, \quad (m_{\tilde{\tau}_1} - m_\chi) \leq 0.1 m_\chi, \quad (m_{\tilde{\nu}_\tau} - m_\chi) \leq 0.1 m_\chi. \quad (4.5)$$

Similar to the previous case, but also the ν_τ is nearly degenerate in mass with the $\tilde{\tau}_1$.

\tilde{t}_1 coannihilations.

$$h_f < 0.15, \quad (m_{\tilde{t}_1} - m_\chi) \leq 0.1 m_\chi. \quad (4.6)$$

The \tilde{t}_1 is light and nearly degenerate with the bino-like neutralino. These coannihilations are present in the flipped SU(5) model.

We have performed the parameter-space scans in the three GUT groups with two different sets of ranges, as detailed in table 1. The first one (Set 1) is broader, sampling soft terms up to 10 TeV and all the x_i in the ranges $0 < x_i < 2$. The `MultiNest` sampling of Set 1 finds that the data are more easily accommodated with a heavy spectrum, where the higgsino neutralino and A funnel mechanisms dominate and only few points in the coannihilation areas are found within the 3×10^4 points sample.

Therefore, in order to zoom in the low mass spectrum, where coannihilations are expected to show up and is also favoured by the δa_μ constraint, we performed a separate scan (Set 2), where we decrease the upper limits on m_0 and $m_{1/2}$. Furthermore, the ranges of the parameters x_i are also restricted, since the coannihilation regions depend on the values of the x_i in a known way, as we explain below.

In the following plots, the points corresponding to the above mechanisms will be presented using different symbols and colours, as specified in the legend of figure 1. Although,

Set 1	SO(10)	SU(5)	FSU(5)
$100 \text{ GeV} \leq m_0 \leq 10 \text{ TeV}$	$0 \leq x_u \leq 2$	$0 \leq x_u \leq 2$	$0 \leq x_u \leq 2$
$50 \text{ GeV} \leq m_{1/2} \leq 10 \text{ TeV}$	$0 \leq x_d \leq 2$	$0 \leq x_d \leq 2$	$0 \leq x_d \leq 2$
$-10 \text{ TeV} \leq A_0 \leq 10 \text{ TeV}$		$0 \leq x_5 \leq 2$	$0 \leq x_5 \leq 2$
$2 \leq \tan \beta \leq 65$			$0 \leq x_R \leq 2$
Set 2	SO(10)	SU(5)	FSU(5)
$100 \text{ GeV} \leq m_0 \leq 2500 \text{ GeV}$	$0 \leq x_u \leq 1$	$0 \leq x_u \leq 1$	$0 \leq x_u \leq 1$
$50 \text{ GeV} \leq m_{1/2} \leq 2500 \text{ GeV}$	$0 \leq x_d \leq 2$	$0 \leq x_d \leq 2$	$0 \leq x_d \leq 2$
$-10 \text{ TeV} \leq A_0 \leq 10 \text{ TeV}$		$0 \leq x_5 \leq 2$	$0 \leq x_5 \leq 1$
$2 \leq \tan \beta \leq 65$			$1 \leq x_R \leq 2$

Table 1. Sets of ranges used to sample the parameter spaces of the GUT models defined in section 2. See the text for the definitions of the non-universality parameters x_i .

in the scatter plots that we present, points of different types appear superimposed, we found that by applying the selection rules (4.2)–(4.6) to the whole samples, the obtained sets do not intersect. Only a few points that have $h_f > 0.1$ and do not satisfy any of the above conditions are found in the Set 1 scans. These points lie in the areas of both the A/H resonances and a higgsino-like neutralino. Since they do not form a distinct region, they will not be shown in the figures, for reasons of clarity.

Figure 1 shows the correlations between the non-universal parameters and the relic density mechanisms for each GUT group. The parameter x_d has no particular correlation with the above mechanisms, while in all cases higgsino DM corresponds to $x_u > 1$, and the same is also true for almost all the A/H funnel points, as seen in the upper left, upper right and lower left panels of figure 1. These mechanisms are independent from the GUT model choice, because the Higgs mass parameters follow the same pattern in the three scenarios. They are also influenced by the other soft terms due to renormalization group running, but this effect is not apparent in scatter plots like those presented here.

In SO(10) and SU(5) most of the $\tilde{\tau}$ coannihilation points have $x_u < 1$. In SU(5), the flexibility allowed by the x_5 parameter allows $\tilde{\tau} - \tilde{\nu}$ coannihilations that are not present in SO(10). As seen in figure 1, these points lie in the $x_5 < 1$ region. This is due to the fact that the lepton doublet belongs to the $\mathbf{5}$ representation while the quarks and the lepton singlet are in the $\mathbf{10}$. Then, to satisfy the m_h constraint, the squark masses have to be large and the same is true for the right sleptons. However, left-slepton soft masses driven by a small value of x_5 may lead to sleptons in the coannihilation range. The lower panels of figure 1 show that in the flipped SU(5) $\tilde{\tau}$ and $\tilde{\tau} - \tilde{\nu}$ coannihilations are located in the quadrants defined by $x_u < 1$, $x_5 < 1$, $x_R > 1$. We also see that a \tilde{t} coannihilation area is present. This is possible in flipped SU(5) because the right-handed squarks are in the $\bar{\mathbf{5}}$ representation, so the stop mass decreases with x_5 . On the other hand, x_R cannot be very small or the lightest stau becomes tachyonic. By restricting it to be > 1 we avoid this situation, and also increase the left component in the lighter stau, since $x_5 < x_R$.

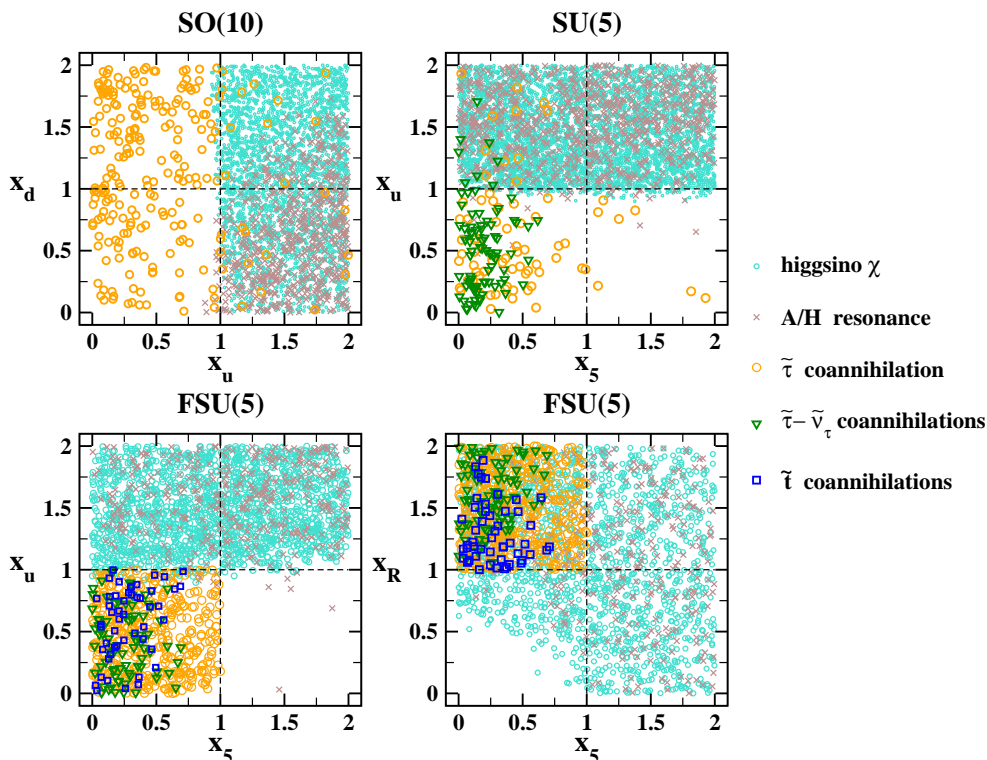


Figure 1. Correlations between the non-universal soft SUSY-breaking scalar mass parameters and the relic density mechanisms. The legend showing the meanings of colours and symbols for the points applies to all the figures of this paper.

For simplicity and to avoid any discussion about cosmological constraints on tachyons, we consider here only positive values for $m_{H_u}^2$ and $m_{H_d}^2$ at the GUT scale. However, some negative values may be allowed, and have been included in some other analyses, leading to small differences. For example, in the case of the NUHM2 with $m_{H_u}^2 \neq m_{H_d}^2 \neq m_0^2$, the authors of [13] also consider negative values for m_0 , m_0^2 , $m_{H_u}^2$, $m_{H_d}^2$ and find their best fit point for $m_0 < 0$. In [57] the authors find a small stop island at 95% CL in the NUHM1 ($m_{H_u}^2 = m_{H_d}^2 \neq m_0^2$) and a larger one in the NUHM2; this can be attributed to negative values of $m_{H_u}^2$, which enters in the RGE for $m_{\tilde{t}_R}^2$ and decreases its value. Because of our restriction to positive values of x_u and x_d , in our analysis flipped SU(5) is the only scenario where this mass can become low for low values of x_5 , due to its presence in the $\bar{\mathbf{5}}$ instead of the $\mathbf{10}$. In [28], M_A and μ are taken as free parameters at low energies and the RGEs are used to obtain the corresponding GUT values for $m_{H_u}^2$ and $m_{H_d}^2$, as described in [15]. This is a way to avoid sampling points that fail the electroweak symmetry breaking test. However, although some of these points correspond to negative values for $m_{H_u}^2$ and/or $m_{H_d}^2$, the authors do not display any region with stop coannihilations.

5 Relic density, Higgs mass and $\delta a_\mu^{\text{SUSY}}$

We now discuss in more detail the relations found in our scans between the relic abundance mechanisms, the value of the Higgs boson mass and the supersymmetric contribution to $\delta a_\mu = [(g_\mu - 2)/2]_{\text{exp}} - [(g_\mu - 2)/2]_{\text{SM}}$.

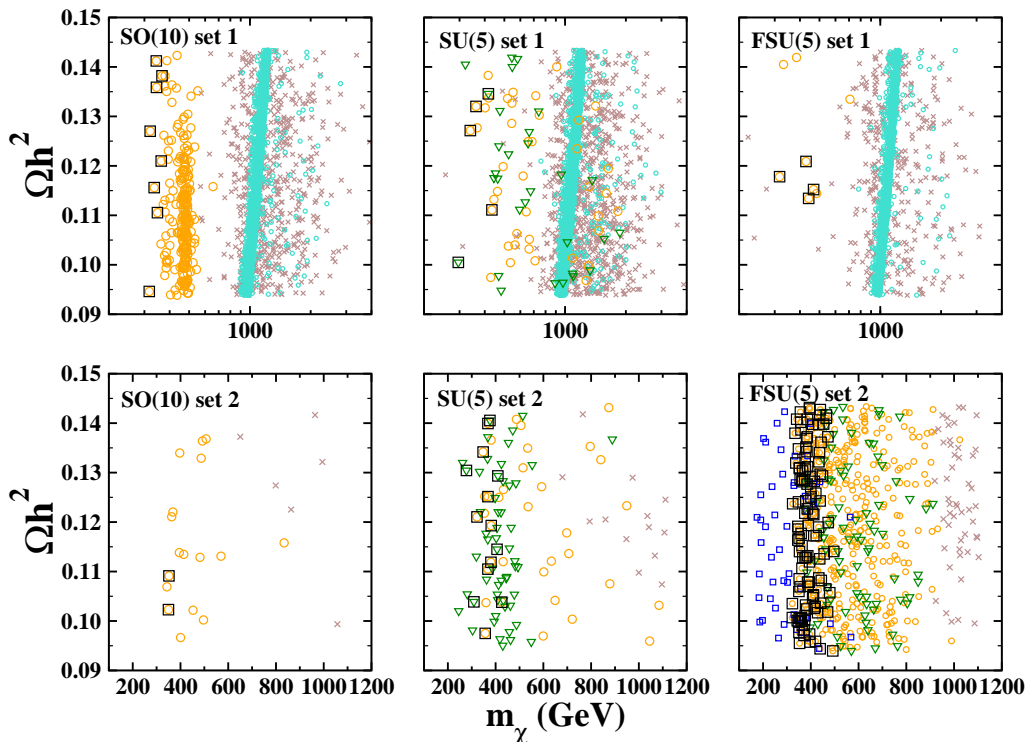


Figure 2. The neutralino relic density $\Omega_\chi h^2$ as a function of the neutralino mass, using the symbols defined in the legend of figure 1. The points surrounded by black squares satisfy the constraint δa_μ at 3σ .

Most of the turquoise points in figure 2, with a higgsino χ_1^0 are confined in a thin strip with mass around 1 TeV, independently of the gauge group, and are only present in the upper panels of figure 1 where $x_u > 1$, as discussed previously. A higgsino-like neutralino with mass around 1 TeV is a general prediction driven by the relic density bound and has been emphasized before in many analysis [58–62].

Most of the A/H resonance points have a χ_1^0 mass larger than 800–900 GeV. They are numerous in the Set 1 scans (upper panels of figure 2), whereas they are reduced substantially in the Set 2 scans (lower panels of figure 2). In fact, for parameters within the ranges of Set 2, the A/H mass is smaller than in Set 1, therefore its decay width is smaller and the condition (4.3) is more difficult to respect.

The coannihilation areas are different in the various models and, as is well known, they feature upper limits on the χ_1^0 mass. In the case of SO(10), the $\tilde{\tau}_1$ area (orange circles) is well defined, with the neutralino mass in the approximate interval 300–600 GeV. In the case of SU(5), $\tilde{\tau}_1 - \tilde{\nu}_\tau$ coannihilations (green triangles) are also involved, and the upper limit increases to ~ 1.1 TeV. The number of $\tilde{\tau}_1$ points is reduced drastically in the Set 1 scan of flipped SU(5) and in the Set 2 scan of SO(10). In the former case, the right-handed slepton mass is determined by the parameter x_R , which in Set 1 is free to vary over values larger than 1. In the latter case, the reduction is due to tension between the contribution to δa_μ , which needs relatively light sleptons and gauginos, and a Higgs mass around 125 GeV, which pushes the preferred values of m_0 and $m_{1/2}$ towards higher values. The coannihilations in flipped SU(5) are recovered in the scan with Set 2, as seen in the bottom-right panel, where we also note the appearance of the \tilde{t}_1 strip (dark blue squares). In SU(5) the situation is

intermediate. The number of coannihilations does not vary so strongly, but in passing from Set 1 to Set 2 a greater concentration of points with light neutralino masses can be observed.

The black squares highlight the points for which the supersymmetric contribution to δa_μ differs from the central value by less than 3σ . The typical values of δa_μ in the black squares are found to be in the range $4 - 6 \times 10^{-10}$, which is similar to the best-fit points in NUHM1 and NUHM2 models [12, 13]. All the black squares are in the region of $\tilde{\tau}_1$ coannihilation, with a minority also featuring $\tilde{\tau}_1 - \tilde{\nu}_\tau$ coannihilations. The scan with the largest number of δa_μ -friendly points occurs in flipped SU(5) Set 2, due to the lightness of the spectrum and the additional freedom in the choice of parameters, as compared to SO(10) and SU(5).

In all our models, despite the larger freedom in the scalar sector allowed by the new parameters, it is hard to fully explain the δa_μ anomaly with a supersymmetric contribution. In this respect the situation is thus similar to other models with gaugino and sfermion mass unification such as the CMSSM, NUHM1 and NUHM2 models [12, 13]. The difficulty to explain the anomaly at the 2σ level in non-universal scalar GUT models was also recently discussed in [63], while, by relaxing also the condition of gaugino universality, the authors of [64] find models with supersymmetric contribution at 2σ . Anyway, the GUT-boundary conditions employed in both these studies are different from ours.

6 Direct and indirect dark matter searches

In figure 3 we show scatter plots of the spin-independent neutralino-nucleon cross section as a function of the neutralino mass. The present limits from the null result of the LUX experiment [49] (dotted line) already exclude points with a higgsino-like neutralino and some points in the A/H funnel area. The projected sensitivity of the XENON 1 ton experiment [65, 66] shows that it could probe most of these areas, while coannihilations could be fully probed only with a multi-ton mass experiment like the DARWIN project [67], with an exposure of $500 t \times y$. These sensitivity curves are deduced from the recent study in [68].

We also show in figure 4 the present situation of the indirect dark matter search through γ -ray emission from annihilations in the halos of dwarf galaxies of the local group [69], by showing the total non-relativistic neutralino-neutralino annihilation cross section times the relative velocity in dark matter halos $\sigma_{\text{ann}} v_r$ as a function of the neutralino mass. The three curves are all limits from the combined analysis of the FERMI satellite with 6 years of data [70] obtained assuming that $\tau\bar{\tau}$, $b\bar{b}$ and WW final states dominate. Gamma rays may result from the decays and hadronization of any of these final states, and in principle these limits apply only to points where these channels dominate neutralino annihilation, and can therefore be compared with the higgsino and resonance regions. We see that at present the curves do not touch the favoured regions of parameter space. Future data from FERMI or CTA arrays [61, 71] may possibly probe the turquoise and red points (higgsino and A/H funnel regions). As could be expected, the annihilation cross section in the slepton coannihilation region is too small to be probed by this kind of indirect searches.

The dashed line corresponds to the usual benchmark value of $\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle \simeq 2 - 3 \times 10^{-26} \text{ cm}^3/\text{s}$ for a weakly-interacting massive particle with a relic abundance $\Omega h^2 \simeq 0.1$. We remark that the values of $\sigma_{\text{ann}} v_r$ shown in figure 4 coincide with those of the thermal average at freeze-out $\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle$ only when there are no coannihilation channels and the product $\sigma_{\text{ann}} v_r$ is a constant independent from the relative velocity/temperature at freeze-out.

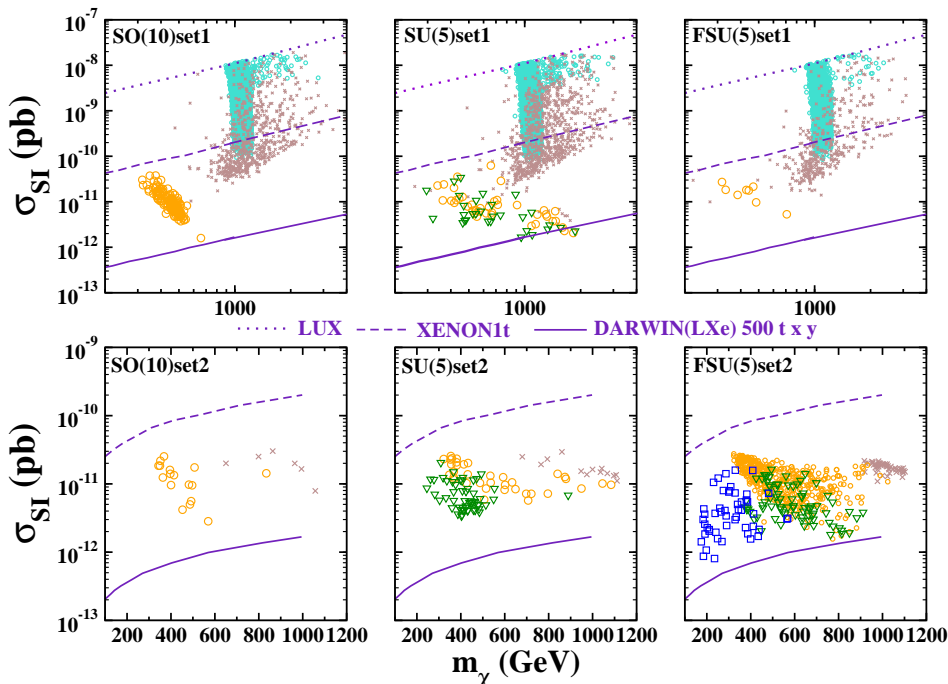


Figure 3. The spin-independent neutralino-nucleon cross section as a function of the neutralino mass. The dotted line is the current exclusion curve from the LUX experiment [49]. The projected sensitivities at 90% confidence level for the XENON 1 ton experiment [65, 66] (dashed line) and the DARWIN experiment [67] (full line) are taken from [68]. See the legend.

7 LHC searches

LHC missing energy searches. The coannihilation areas yield a light supersymmetric spectrum that is already partially probed by the first years of operation of LHC. In figures 5 and 6, we show the distributions in the $(m_{1/2}, m_0)$ and $(m_{\tilde{q}}, m_{\tilde{g}})$ planes for the various GUT models. The present LHC 95% CL exclusion limit from missing E_T searches [57] are depicted as solid lines, while the projected sensitivity with 300 fb^{-1} at 14 TeV [57] is represented by dashed lines. We see that the present exclusion limits already constrain the \tilde{t} -coannihilation area of flipped SU(5) (blue squares), and graze the $\tilde{\tau}$ -coannihilation points favoured by the δa_μ constraint in all GUT models. The projected LHC missing E_T sensitivity covers most of the coannihilation areas, but leaves practically untouched the higgsino and resonance areas.

Heavy Higgs and charginos. We now discuss the sensitivity of other search channels at the LHC to supersymmetric particles in the models we study. The present exclusion curve in the $(\tan \beta, m_A)$ plane is shown as a solid purple line in figure 7. We see that the mass of the pseudoscalar neutral Higgs A is generally larger than 1 TeV, except for a few points in the higgsino and resonance regions, which are excluded by this constraint. If the sensitivity in this plane could be pushed to masses up to 2–2.5 TeV, most of the $\tilde{\tau}_1$ coannihilation areas could be probed, as seen in the lower panels of figure 7.

More interesting is the search for the lighter chargino, χ_{1^\pm} , shown in the $(m_\chi, m_{\chi_{1^\pm}})$ plane in figure 8. In the Set 1 scans (upper plots), the points are distributed in the region where $m_\chi \lesssim m_{\chi_{1^\pm}} \lesssim 2m_\chi$. In the coannihilation regions, the neutralino is bino-like, $m_\chi \simeq M_1$, whereas the chargino is gaugino-like with $m_{\chi_{1^\pm}} \simeq M_2 \simeq 2M_1 \simeq 2M_1$. On the other hand, for a

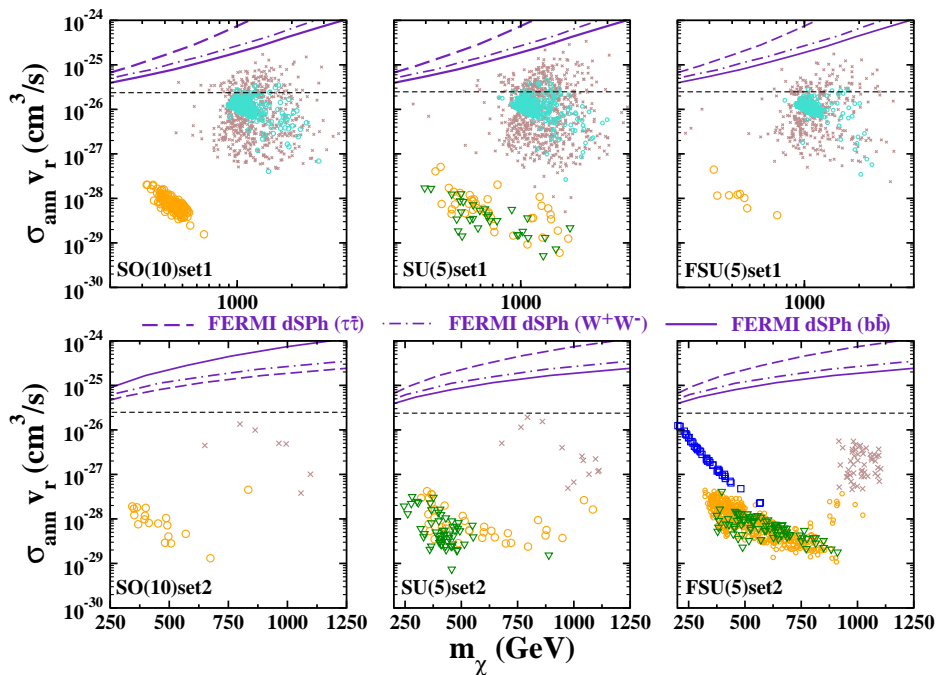


Figure 4. The total non-relativistic χ_1^0 annihilation cross section times relative velocity as a function of the neutralino mass. The purple lines are the present exclusion limits from a FERMI analysis of gamma-ray emission from dwarf spheroidal galaxies [70]: see the legend for the specific final states. The horizontal black dashed line corresponds to the usual benchmark value of $\langle\sigma_{\text{eff}}v_{\text{rel}}\rangle \simeq 2 - 3 \times 10^{-26} \text{ cm}^3/\text{s}$.

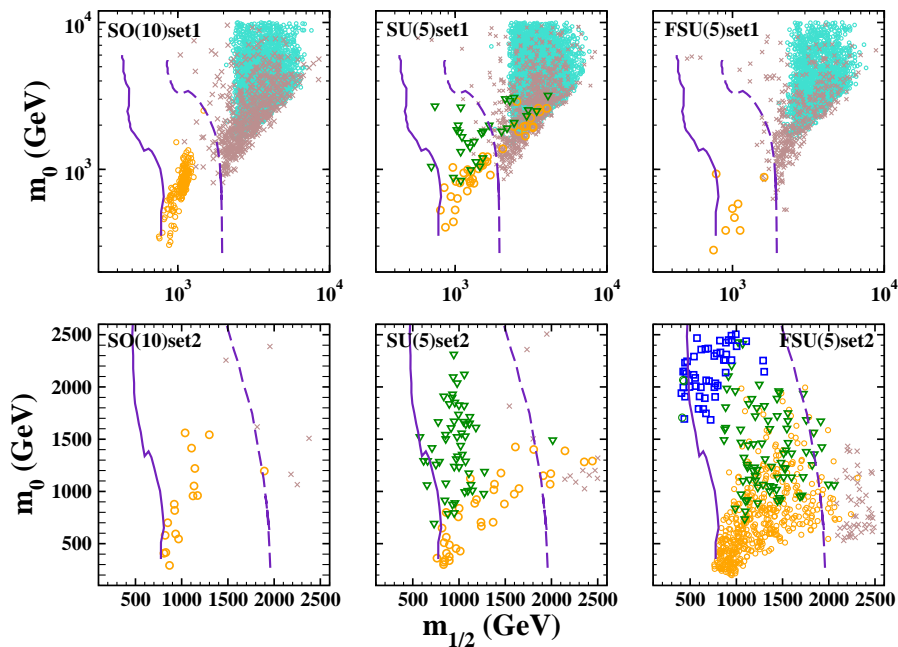


Figure 5. Scatter plots of non-universal GUT models in the $(m_{1/2}, m_0)$ plane, with the same legend as in figure 1. The current LHC 95% CL exclusion (solid purple line) and the projected exclusion sensitivity at 14 TeV with 300 fb^{-1} (dashed purple line) are taken from ref. [57].

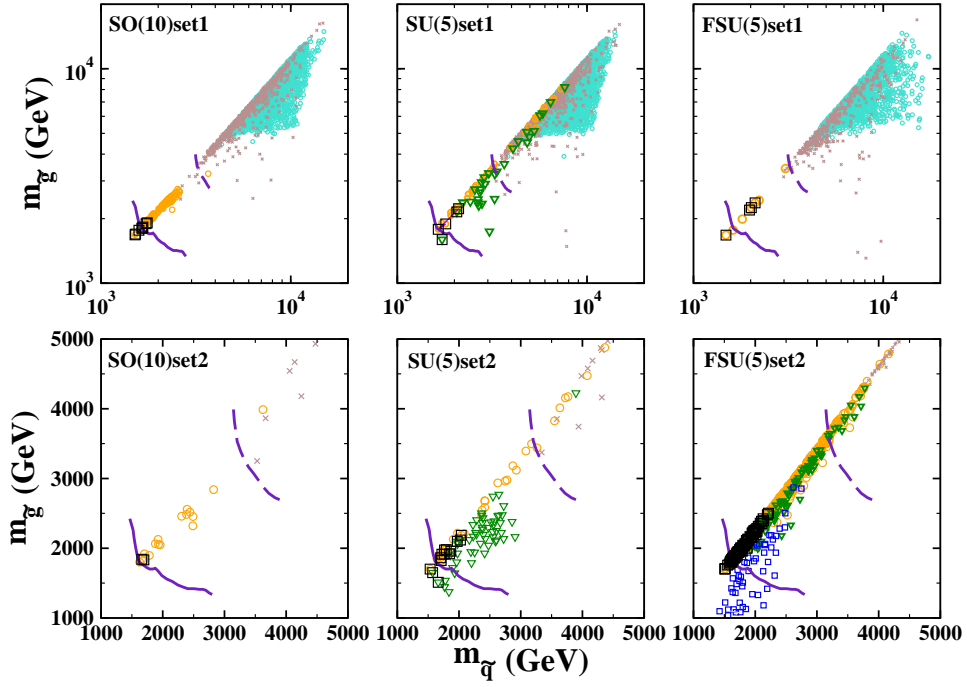


Figure 6. Scatter plots of non-universal GUT models in the $(m_{\bar{q}}, m_{\bar{g}})$ plane, with the same legend as in figure 1. The current LHC 95% CL exclusion (solid purple line) and the projected exclusion sensitivity at 14 TeV with 300 fb^{-1} (dashed purple line) are taken from ref. [57].

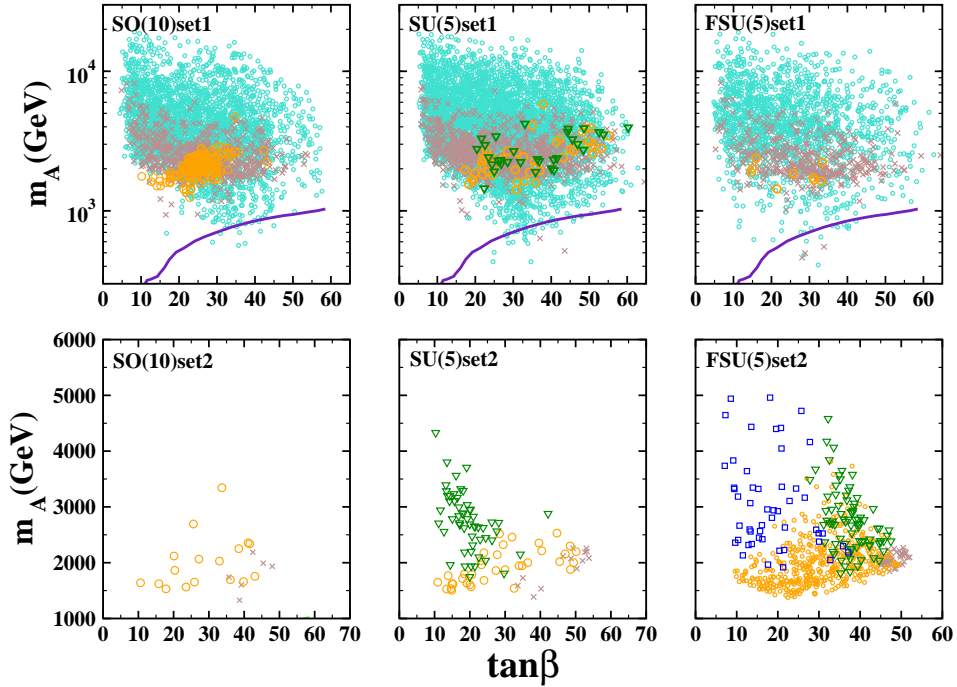


Figure 7. Scatter plots of non-universal GUT models in the $(\tan\beta, m_A)$ plane, with the same legend as in figure 1. The current LHC 95% CL exclusion (solid purple line) is taken from [57].

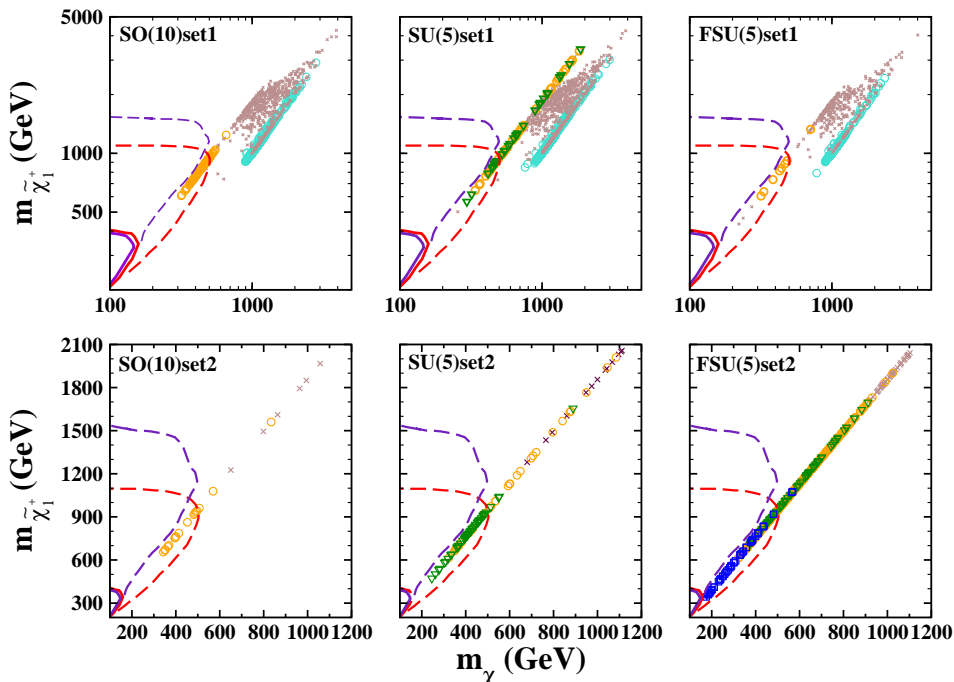


Figure 8. Scatter plots of non-universal GUT models in the $(m_\chi, m_{\tilde{\chi}_1^\pm})$ plane, with the same legend as in figure 1. The current LHC 95% CL exclusion (solid purple line) and projected sensitivity (dashed purple line) are taken from [57]. See the text for details. The projected lines correspond to the sensitivity with 3000 fb^{-1} .

higgsino-like neutralino, we have $m_\chi \simeq \mu$, since the mass of the lightest chargino is dominated by the μ mass parameter. The A/H funnel resonance, with bino-higgsino neutralino mixing, lies in the area between the two extreme cases above. This behaviour results from the interplay between the universality of the gaugino masses at the GUT scale and constraints imposed by the relic abundance.

The solid indigo line is the present limit from the search for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production and decays into W/Z and missing E_T , and the solid red line shows the limit from the search for gaugino pair production $\tilde{\chi}_1^\pm \tilde{\chi}_2^0, \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$, with multi- τ final-state decays and missing energy. In both cases, the dashed lines indicate the projected sensitivity with 3000 fb^{-1} at 14 TeV: all the limits are taken from refs. [57, 72]. In the latter channel, the LHC will be able to probe parts of the $\tilde{\tau}_1$ coannihilation strips (orange circles and green triangles) and, in the case of the flipped SU(5), most of the \tilde{t}_1 coannihilation strip.

Third-generation squarks. As seen in figure 9, the stop mass in the models we study is generally larger than 800 GeV, and the present limits from searches in $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$, do not reach such values. On the other hand, the projected sensitivity with 3000 fb^{-1} will partly cover the $\tilde{\tau}_1$ coannihilation regions. The flipped SU(5) Set 2 scan displays the stop coannihilation strip where both the \tilde{t}_1 and neutralino mass are in the range 200–600 GeV. However, we see that the \tilde{t}_1 strip is not affected by the above-mentioned search, though we have already seen that it is constrained indirectly by the limits in figures 5, 6 and 8.

We see in figure 10 that the lighter sbottom squark is heavier than 1 TeV in all the panels. The present 95% CL limit for \tilde{b}_1 pair production decaying to $b\chi$ [73, 74] does not reach the favoured regions, and the searches for this sparticle are not competitive with the other channels.

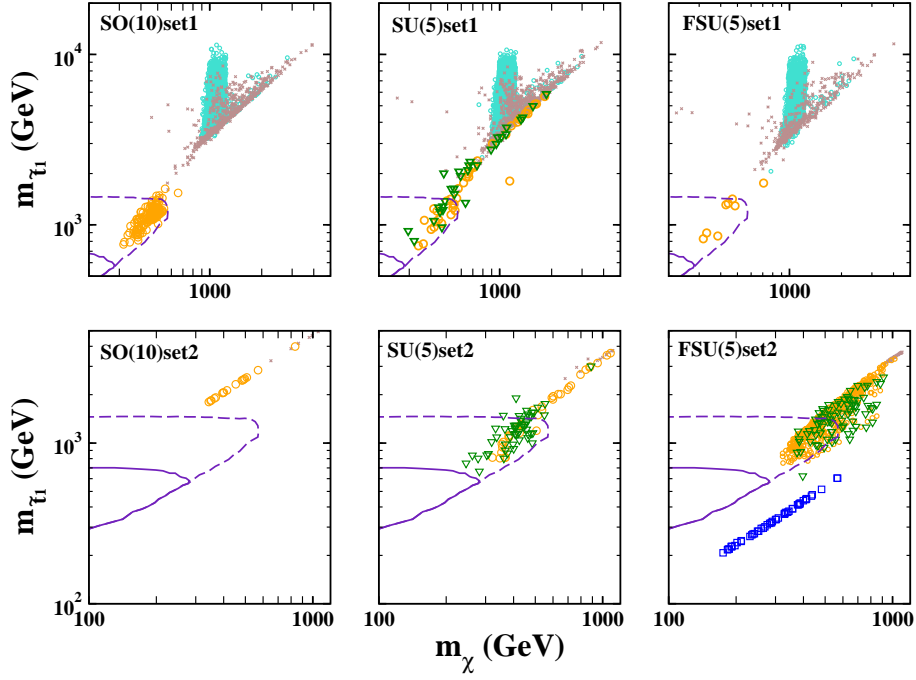


Figure 9. Scatter plots of non-universal GUT models in the $(m_\chi, m_{\tilde{t}_1})$ plane, with the same legend as in figure 1. The solid and dashed purple lines are the present limit and projected sensitivity [57, 73, 74]. See the text for details. The projected line corresponds to the sensitivity with 3000 fb^{-1} .

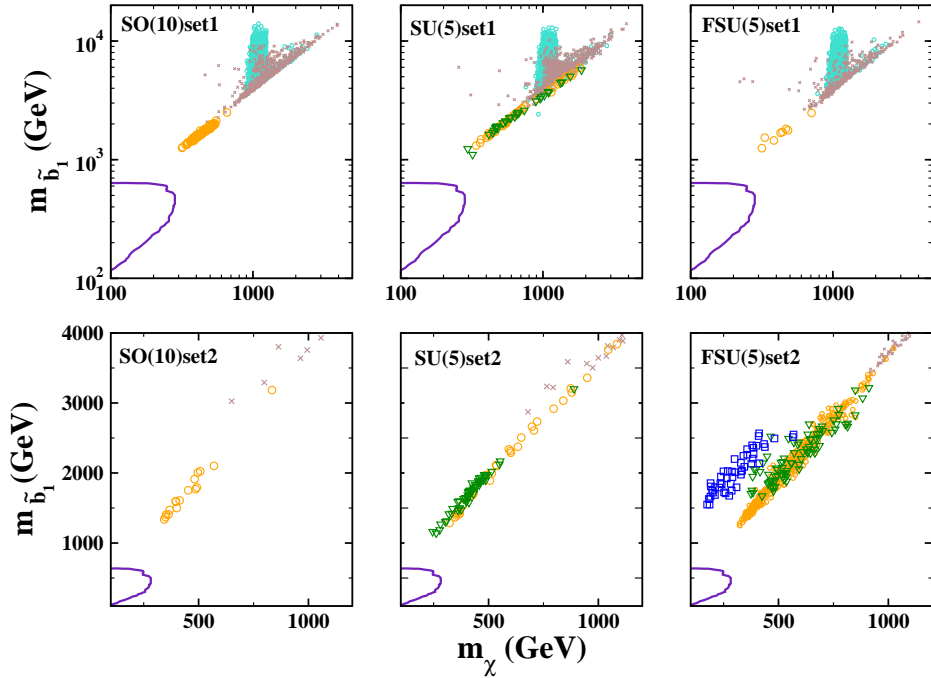


Figure 10. Scatter plots of non-universal GUT models in the $(m_\chi, m_{\tilde{b}_1})$ plane, with the same legend as in figure 1. The solid purple line is the ATLAS 95% CL limit from [73, 74]. See the text for details.

Complementarity of searches. Under the assumption that the lightest neutralino constitutes all the observed relic abundance, figures 3, 4, 5 and 6 show the complementarity of dark matter experiments and of LHC searches for supersymmetric particles. The GUT-inspired models and their respective parameter spaces, as studied in our work, can be fully probed or excluded by combining 300 fb^{-1} of data accumulated by missing energy LHC searches (coannihilation areas), with the next generation of ton-scale direct-detection experiments. This is consistent with the results of [57, 61], where similar complementarity was found in studies of the CMSSM, NUHM1, NUHM2 and pMSSM10.

8 Summary and conclusions

In the following, we summarize the principal conclusions of this work.

- We have identified different patterns of soft SUSY-breaking terms at the GUT scale, depending on the grand unification group, which we have used to distinguish different GUT scenarios via their dark matter predictions and the constraints from LHC searches.
- We have calculated the SUSY spectra for the different gauge groups, finding that the models predict different spectra for the same LSP mass, connecting possible future observations with the structure of the underlying unified theory.
- None of the GUT models studied offers high prospects for reducing substantially the a_μ discrepancy via a SUSY contribution.
- In general, scenarios that favour degeneracies in the sparticle spectrum lead to additional contributions to coannihilations, thus enhancing the efficiency and importance of these processes.
- We have studied the different relic density predictions and determined upper bounds for the neutralino mass in the different GUT scenarios. We have also computed the cross sections for direct and indirect dark matter detection in each case, combining the bounds from different dark matter experiments with those from LHC searches.
- We have found that SO(10), SU(5) and flipped SU(5) lead to very different predictions for dark matter and LHC experiments, and thus are distinguishable in future searches. Among other differences, flipped SU(5) predicts $\tilde{t}_1 - \chi$ coannihilations that are absent in the other groups within the parameter ranges studied here, but can be explored by LHC searches.
- Direct searches for astrophysical dark matter scattering show interesting prospects for the Xenon 1 ton and Darwin experiments, and models with a higgsino-like LSP or A/H resonance annihilation may offer prospects for future FERMI or CTA γ -ray searches.
- The LHC searches for generic missing E_T , charginos and stops are quite complementary, and future LHC runs will be able to constrain the models in several different ways.

The interesting prospects for exploring the parameter spaces of different SUSY GUT models found in this paper, and the fact that their potential signatures are quite distinctive, whet our appetites for data from LHC Run 2 and searches for astrophysical dark matter.

Acknowledgments

The work of J.E. has been supported in part by the European Research Council via the Advanced Investigator Grant 267352, and by the UK STFC via the research grant ST/L000326/1. The work of M.C. has been supported in part by the MINECO grant FPA2011-23778 and by the MINECO/FEDER research grant CPI-14-397, and acknowledges A. Pich, G. Rodrigo, J. Portolés, P. Hernández and N. Rius for hospitality at IFIC in Valencia where part of this work was done. M.C. and M.E.G. acknowledge support from the MINECO grant: "Fenomenología en Física de Partículas y Astropartículas" (FPA2014-53631). S.L. thanks CERN for kind hospitality. R. RdA is supported by the Ramón y Cajal program of the Spanish MICINN, by the Invisibles European ITN project (FP7-PEOPLE-2011-ITN, PITN-GA-2011-289442-INVISIBLES), and by the MEC projects "SOM: Sabor y origen de la Materia" (2014-57816) and "Fenomenología y Cosmología de la Física mas allá del Modelo Estándar e implicaciones Experimentales en la era del LHC" (FPA2013-44773). M.C., M.E.G. and R.RdA acknowledge support from Spanish MICINN Consolider-Ingenio 2010 Program under the grant MULTIDARK CSD2209-00064.

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