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A 119 – 125 GeV Higgs from a string derived slice of the CMSSM

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Abstract

The recent experimental hints for a relatively heavy Higgs with a mass in the range 119 – 125 GeV favour supersymmetric scenarios with a large mixing in the stop mass matrix. It has been shown that this is possible in the constrained Minimal Supersymmetric Standard Model (CMSSM), but only for a very specific relation between the trilinear parameter and the soft scalar mass, favouring $A \approx -2m$ for a relatively light spectrum, and sizable values of $\tan\beta$. We describe here a string-derived scheme in which the first condition is automatic and the second arises as a consequence of imposing radiative EW symmetry breaking and viable neutralino dark matter in agreement with WMAP constraints. More specifically, we consider modulus dominated SUSY-breaking in Type II string compactifications and show that it leads to a very predictive CMSSM-like scheme, with small departures due to background fluxes. Imposing the above constraints leaves only one free parameter, which corresponds to an overall scale. We show that in this construction $A = -3/\sqrt{2}m \simeq -2m$ and in the allowed parameter space $\tan\beta \simeq 38 - 41$, leading to $119 \text{ GeV} < m_h < 125 \text{ GeV}$. The recent LHCb results on $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ further constrain this range, leaving only the region with $m_h \sim 125 \text{ GeV}$. We determine the detectability of this model and show that it could start being probed by the LHC at 7(8) TeV with a luminosity of 5(2) fb^{-1} , and the whole parameter space would be accessible for 14 TeV and 25 fb^{-1} . Furthermore, this scenario can host a long-lived stau with the right properties to lead to catalyzed BBN. We finally argue that anthropic arguments could favour the highest value for the Higgs mass that is compatible with neutralino dark matter, i.e., $m_h \sim 125 \text{ GeV}$.

1 Introduction

With the advent of the Large Hadron Collider (LHC) Particle Physics is entering into a new era in which a wealth of theoretical models, scenarios and ideas are being tested. One of the most prominent ideas beyond the Standard Model (SM) is low energy supersymmetry (SUSY) and its simplest implementation, the Minimal Supersymmetric Standard Model (MSSM). Although at the moment no sign of supersymmetric particles has been seen, there is at least one recent LHC result which points in the direction of supersymmetry. The 2011 run of LHC has restricted the most likely range for the Higgs particle mass to be 115.5–131 GeV (ATLAS) [1] and 114.5–127 GeV (CMS) [2]. In addition, there are hints observed by both CMS and ATLAS of an excess of events that might correspond to $\gamma\gamma$, $ZZ^* \rightarrow 4l$ and $WW^* \rightarrow 2l$ decays of a Higgs particle with a mass in a range close to 125 GeV. Interestingly, such values for the Higgs mass are consistent with the expected range < 130 GeV for the lightest Higgs in the MSSM.

Although in qualitative agreement with MSSM expectations, the hints of a 125 GeV Higgs are slightly uncomfortable for models like the Constrained Minimal Supersymmetric Standard Model (CMSSM), in which the complete SUSY spectra is determined in terms of a few universal soft supersymmetry-breaking parameters M , m , A , B , and μ [3]. Indeed lighter Higgs masses of order 110 – 115 GeV are generic in the CMSSM parameter space. In order to get values as large as 125 GeV one needs to have heavy stops with a sizable LR-mixing and large values of $\tan\beta$, leading typically to a very heavy SUSY spectrum. In fact it has been noted [4, 5, 6, 7] (see also [8, 9]) that the areas of the CMSSM parameter space compatible with 125 GeV Higgs show a very strong preference for the region with $A \simeq -2m$ if the SUSY spectrum is not to be very heavy¹. But why should nature be centered in that peculiar corner of parameter space?

A possible explanation for relations among soft terms like, e.g., A and m requires going beyond the general assumptions underlying the CMSSM scheme and being more specific about the origin of SUSY breaking. The CMSSM boundary conditions are obtained in supergravity mediation schemes with unification (GUT-like) constraints and universal kinetic terms for all the SM matter fields. In order to get relations among the M , m , A , M , μ parameters one needs very specific classes of low energy $N = 1$ supergravity models. It is here where string unification models arising from specific classes of string compactifications may be useful.

¹Note in passing that a 125 GeV Higgs is difficult to accommodate in the simplest gauge mediation scenarios since $A = 0$ in these schemes, see Refs. [6, 10, 11].

Indeed, in low-energy supergravity models coming from string compactifications the gauge kinetic functions as well as the kinetic (Kahler metrics) terms of the SM fields are not arbitrary and depend on the moduli of the corresponding string compactification. If the auxiliary fields of the moduli are the source of SUSY-breaking, specific relations among the different soft terms are obtained. These have been worked out for heterotic vacua [12, 13, 14, 15] (see e.g. Ref. [16] for a review and further references) and generalized for the more recent case of Type II orientifold compactifications [17, 18, 19]. See also Ref. [20] and references therein for explicit SUSY-breaking models in Type II orientifolds.

In the last decade there has been important progress in the construction of semirealistic Type II string vacua. With the advent of the D-brane techniques it has been possible to construct Type II string orientifold configurations of branes yielding a massless spectrum close to that of the MSSM (see Ref. [21] for a review). A particularly successful scheme is the one based on Type IIB orientifolds with the SM fields residing on intersecting 7-branes and their non-perturbative generalization, F-theory. One of the attractive aspects of this large class of compactifications is that it is well understood how the presence of antisymmetric field fluxes and possibly non-perturbative effects can give rise to a complete fixing of the moduli of the compactification [22] (for reviews see Refs. [23, 24, 21]). In addition, the large number of possible fluxes allows to fine-tune the vacuum energy to a small but positive value, in a way compatible with a non-vanishing positive cosmological constant.

Besides fixing the moduli, such fluxes in general give rise to soft SUSY breaking terms for the MSSM fields in semirealistic compactifications [25]. In particular, it has been found that certain ISD (imaginary self-dual) fluxes correspond to the presence of Kahler modulus dominated SUSY-breaking, providing an explicit realization of gravity mediation SUSY-breaking in string theory. Such type of fluxes are important since it has also been shown that they are consistent with the classical equations of motion of Type IIB orientifolds [26].

In Ref. [19] we carried out a general study of the soft SUSY-breaking terms arising under the assumption of Kahler moduli dominated SUSY-breaking in string theory. Under the additional assumption of a unified structure analogous to that obtained in $SU(5)$ orientifolds or F-theory GUT's one obtains universal soft parameters, similar to those in the CMSSM or slight generalizations. Imposing correct radiative electroweak symmetry breaking (REWSB) [27] and viable neutralino dark matter we found that essentially only one single type of configuration survives. These are models in which the

SM fields live at the intersection of 7-branes, very much like in the recent F-theory GUT constructions (see Refs. [28, 29, 30] for reviews and references). In the latter, quarks and leptons live confined in complex matter curves embedded in the bulk 7-brane in which the SM gauge group lives (see Fig. 1). Yukawa couplings arise at the intersection points of the different matter curves. It must be emphasized that this kind of constructions form a large class, since several other string constructions are their duals. Thus for example Type IIA orientifolds with the SM at intersecting D6-branes are their mirror and F-theory constructions are also directly related to M-theory compactifications in manifolds of G_2 holonomy, see Ref. [21] for a review of these connections.

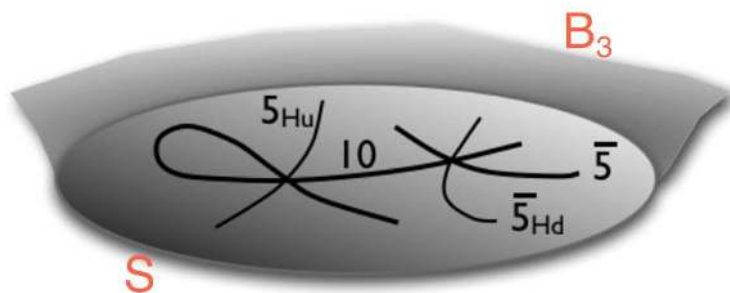


Figure 1: General structure of a local F-theory $SU(5)$ GUT. The GUT group lives on 7-branes whose 4 extra dimensions beyond Minkowski wrap a 4-cycle S . This S manifold is inside a 3 complex dimensional manifold B_3 where the 6 extra dimensions are compactified. The gauge bosons live in the bulk of S whereas quarks, leptons, and Higgses are localized in complex curves inside S . These matter curves (10 and $\bar{5}$ in the figure) correspond to the intersection of the 7-branes wrapping S with other $U(1)$ 7-branes (not depicted in the figure). There is one matter curve for each $SU(5)$ rep. and at the intersection of matter curves with Higgs curves H_u, H_d Yukawa couplings develop (figure taken from Ref. [21]).

In the present paper we explore in further detail this string theory configuration beyond the results of Ref. [19] and study its phenomenological consequences, including the Higgs masses and sparticle spectrum. We also study the LHC reach in testing these models. In doing this analysis we find a number of interesting new results:

- We have realized that our construction, put forward a few years ago [19], does contain the ingredients which favour a relatively heavy lightest CP-even Higgs mass. Indeed, in these constructions one has a very predictive set of boundary conditions with $M = \sqrt{2}m = -(2/3)A = -B$ so that one is essentially left with two free parameters, M and μ . In particular, this implies $A = -3/\sqrt{2}m \simeq -2m$,

one of the necessary conditions for a heavy lightest Higgs (for not too heavy squark/gluino spectrum).

- The boundary conditions are consistent with radiative EW symmetry breaking and a slight deformation (which might be induced by gauge fluxes and which leads to non-universal Higgs mass parameters) makes it also compatible with viable neutralino (mostly bino) dark matter. The correct neutralino relic abundance is obtained through coannihilation effects when the neutralino, χ_1^0 , and the lightest stau, $\tilde{\tau}_1$, are almost degenerate in mass. However, *this only happens for large values of $\tan\beta \simeq 40$* (the second condition for a heavy Higgs), and $M \leq 1400$ GeV, where M is the universal gaugino mass at the unification scale. There is also a lower bound $M \geq 570$ GeV in order not to violate the experimental bounds on the branching ratio of the rare process $b \rightarrow s\gamma$. Since this construction has essentially three free parameters, M , μ and a small flux parameter ρ_H , after imposing REWSB and correct dark matter the Higgs and sparticle spectrum are very much constrained. In particular, having $570 \text{ GeV} \leq M \leq 1400 \text{ GeV}$ forces the lightest Higgs mass to be in the range

$$119 \text{ GeV} \leq m_h \leq 125 \text{ GeV} , \quad (1.1)$$

in agreement with the range favoured by 2011 LHC data. In addition, the recent constraint on $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ reported by the LHCb collaboration [31], further reduces this range, leaving only the region with $m_h \sim 125$ GeV.

- Once the Higgs mass is known, one can extract, at least in principle, the complete SUSY and Higgs mass spectrum. In practice both the experimental error of the Higgs and the top quark mass as well as inherent errors on the computation of the Higgs mass somewhat limit the accuracy of this computation. Still, this range of Higgs masses points to a relatively heavy SUSY spectrum but, fortunately, testable at LHC. A Higgs heavier than 119 GeV would imply squarks and gluinos heavier than approximately 1.2 TeV, consistent with LHC limits obtained with 1 fb^{-1} . If the signal for a Higgs mass around 125 GeV is real, one would expect first generation squarks of order 2.8 TeV and gluinos of order 3 TeV.
- In order to find the LHC reach for this model we have simulated background and signal events using Monte Carlo tools (PYTHIA and PGS). From the jets+missing energy signature, we find that the LHC at 7(8) TeV will be able to test the model up to $M \leq 600(700)$ GeV, for an integrated luminosity around 20fb^{-1} ,

corresponding to squarks and gluino masses around 1.4 TeV. Likewise, the LHC at 14 TeV will be able to test the full parameter space with $M \leq 1.4$ TeV and an integrated luminosity around 25 fb^{-1} .

- In the region with $m_h \approx 125$ GeV we find that the mass-difference between the lightest stau and neutralino masses is extremely small, $(m_{\tilde{\tau}_1}^2 - m_{\tilde{\chi}_1^0}^2) \approx 0.1$ GeV, thereby making the stau a very long-lived particle. Interestingly, the stau has the right properties to lead to Catalyzed BBN, alleviating the problems associated to the Lithium abundance in standard BBN.
- CMSSM-like models are known to require a certain amount of fine-tuning and this is no exception. A fine-tuning of order of a percent in the M , μ and ρ_H parameters is expected in order to obtain both correct REWSB and viable neutralino dark matter. Concerning the origin of this fine-tuning, the fact that small deviations from the parameters drive the theory into *catastrophic* regions with unbroken EW symmetry and/or above critical matter densities suggest a possible environmental (anthropic) explanation. It has been argued that the *little hierarchy* of the MSSM could be a result of an anthropic selection [32]. We argue that the requirement of viable neutralino dark matter could also add arguments in that direction. One may argue that if the free parameters *scan* in a landscape, this would tend to favor the heaviest spectrum consistent with *both* REWSB and neutralino dark matter. This would in turn favor the largest Higgs mass within this scheme, of order 125 GeV.

The paper is organised as follows. In the next chapter we give a brief overview of the soft terms which are induced by modulus dominance in Type IIB models with the SM fields at intersecting 7-branes. In chapter 3 we study the Higgs and sparticle spectrum consistent with both REWSB and viable dark matter in the context of this model. In chapter 4 we study the LHC reach for testing the model and in chapter 5 we discuss the possible environmental origin of the fine-tuning required in this class of models. Conclusions are left for chapter 6.

2 SUSY-breaking in string theory and modulus dominance in Type IIB orientifolds

We present here a brief review of a few elements which are relevant for the construction of this class of models, see Refs. [21] and [19] for further details. Readers interested

only in the phenomenological applications of the model may jump safely to chapter 3. We assume that the SM gauge fields reside at a stack of 7-branes wrapping a 4-cycle S (of size controlled by a Kahler modulus t) in a 6-manifold whose overall volume is controlled by a large modulus $t_b \gg t$. In the F-theory context these moduli t, t_b would correspond to the size of S and B_3 . As argued in Ref. [19] we can model out this structure with a Kahler potential of the form [33, 34]

$$G = -2 \log(t_b^{3/2} - t^{3/2}) + \log |W|^2, \quad (2.1)$$

with $t = T + T^*$ being the relevant local modulus associated to the SM and W the full superpotential ². The SM matter fields C_α of the MSSM reside at the intersection of 7-branes. Then the gauge kinetic function and the Kahler metrics of the matter fields are given to leading order in $1/t_b$ by [35, 19]

$$f = T; K_\alpha = \frac{t^{1-\xi_\alpha}}{t_b}, \quad (2.2)$$

where ξ_α is the *modular weight* of the corresponding particle. Its value depends on the geometrical origin of the field with $\xi_\alpha = 1/2$ for fields localized on intersecting 7-branes. Note that the SM gauge couplings are unified and determined by the real part of f . Using this information and assuming that the auxiliary field of the local modulus has $F_T \neq 0$, using standard supergravity formulae (like e.g. those in Ref. [16]) it is easy to derive the simple set of soft term boundary conditions [18, 19]

$$\begin{aligned} m_\alpha^2 &= (1 - \xi_\alpha) |M|^2, \quad \alpha = Q, U, D, L, E, H_u, H_d, \\ A_U &= -M(3 - \xi_{H_u} - \xi_Q - \xi_U), \\ A_D &= -M(3 - \xi_{H_d} - \xi_Q - \xi_D), \\ A_L &= -M(3 - \xi_{H_d} - \xi_L - \xi_E), \\ B &= -M(2 - \xi_{H_u} - \xi_{H_d}), \end{aligned} \quad (2.3)$$

where M is the universal gaugino mass and the notation is standard. In the case under consideration quarks, leptons and Higgs fields live at 7-brane intersections and hence $\xi_\alpha = 1/2$ for all α . Then one gets the simple set of boundary conditions

$$M = \sqrt{2}m = -(2/3)A = -B. \quad (2.4)$$

²We ignore the dependence on the dilaton and complex structure fields which are typically fixed in the presence of closed string fluxes. There may also be additional Kahler moduli which will not modify the general arguments applicable to any local brane configuration.

Here we have assumed that there is an explicit μ -term from some unspecified origin (possibly also fluxes), so that the model would have in principle only two free parameters, M and μ and therefore constitutes a *slice of the CMSSM* boundary conditions.

In general, magnetic flux backgrounds may be present on the worldvolume of the 7-branes in order to get a chiral spectrum. In the presence of magnetic flux backgrounds in the 7-branes the kinetic functions and Kahler metrics may get small corrections which have the form in the dilute flux approximation [36, 19]

$$f = T(1 + a\frac{S}{T}) ; K_\alpha = \frac{t^{1/2}}{t_b}(1 + \frac{c_\alpha}{t^{1/2}}), \quad (2.5)$$

where a and c_α are constants and S is the the complex dilaton field. These corrections are suppressed in the large t limit, corresponding to the physical weak coupling. In this limit one may also neglect the correction to f compared to that coming from K_α . One then finds corrected soft terms of the form

$$m_{\tilde{f}}^2 = \frac{1}{2}|M|^2(1 - \frac{3}{2}\rho_f), \quad (2.6)$$

$$m_H^2 = \frac{1}{2}|M|^2(1 - \frac{3}{2}\rho_H), \quad (2.7)$$

$$A = -\frac{1}{2}M(3 - \rho_H - 2\rho_f), \quad (2.8)$$

$$B = -M(1 - \rho_H), \quad (2.9)$$

where $\rho_\alpha = c_\alpha/t^{1/2}$. Note that as an order of magnitude one numerically expects $\rho_H \simeq 1/t^{1/2} \simeq \alpha_{GUT}^{1/2} \simeq 0.2$. These expressions are further simplified if one assumes that, e.g., only the flux correction to the Higgs Kahler metric is non negligible. This is for example what happens in F-theory $SU(5)$ GUTs, in which it is assumed that the hypercharge flux is only non-vanishing in the Higgs matter curve. In what follows we will only consider this case, although we have done an analogous analysis with $\rho_f \neq 0$ which yields completely analogous results (although requiring slightly larger ρ_H).

3 Higgs and SUSY spectrum in the Modulus Dominated CMSSM

In the scheme under discussion we are thus left with soft terms at the string unification scale with the relations

$$m_{\tilde{f}}^2 = \frac{1}{2}|M|^2, \quad (3.1)$$

$$m_H^2 = \frac{1}{2}|M|^2(1 - \frac{3}{2}\rho_H), \quad (3.2)$$

$$A = -\frac{1}{2}M(3 - \rho_H), \quad (3.3)$$

$$B = -M(1 - \rho_H), \quad (3.4)$$

where ρ_H parametrizes the effect of magnetic fluxes on the Higgs Kahler metrics, see Ref. [19]. As we said, this set of soft terms constitutes a deformation of a slice of the CMSSM with slightly non-universal Higgs masses. We will call it Modulus Dominated CMSSM (MD-CMSSM, Fig. 2).

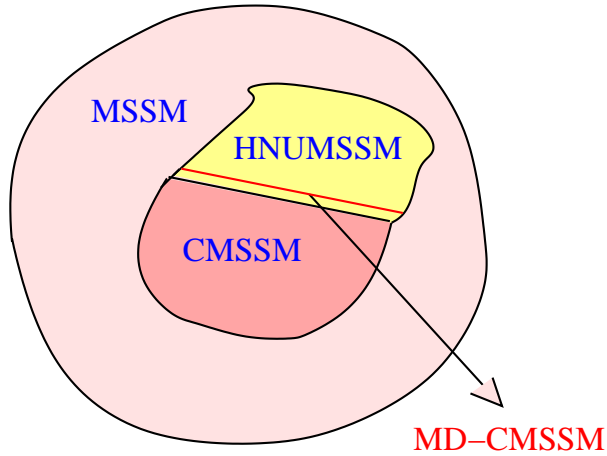


Figure 2: Pictorial view of the modulus dominance constrained MSSM as a slice of the Higgs non-universal HNUMSSM which is a slight deformation (due to the small flux parameter) of the CMSSM.

Consistency of the scheme requires this parameter to be small so that indeed the interpretation of ρ_H as a small flux correction makes sense. Note that we thus have essentially two free parameters, M and μ , with a third parameter ρ_H restricted to be small. We are going to impose two constraints: 1) consistent REWSB and 2) correct neutralino dark matter abundance. These two constraints are very stringent and it is non-trivial that both conditions may be simultaneously satisfied in such a constrained system [19].

3.1 REWSB and dark matter constraints: a model with a single free parameter

We have performed a detailed analysis of both REWSB and dark matter constraints based on the above boundary conditions. A similar study was made in Ref. [19] but here

we carry out a more thorough analysis, covering the full parameter space and studying in detail the Higgs and SUSY spectra. We also analyze the impact of the 2011 LHC data on our results and explore the eventual LHC reach in testing the model.

The minimization condition of the effective Higgs potential gives rise to the weak scale equation

$$\mu^2 = \frac{-m_{H_u}^2 \tan^2 \beta + m_{H_d}^2}{\tan^2 \beta - 1} - \frac{1}{2} M_Z^2, \quad (3.5)$$

with

$$\sin 2\beta = \frac{2|B\mu|}{(m_{H_u}^2 + m_{H_d}^2 + 2\mu^2)}, \quad \tan \beta \equiv \nu_u/\nu_d. \quad (3.6)$$

In principle, the usual procedure consists in fixing the value of $\tan \beta$ and then using Eq. (3.5) to obtain the modulus of μ . The value of B is then obtained from Eq. (3.6). In our case the value of B at the unification scale is also predicted so that Eqs. (3.5) and (3.6) can be used to obtain both the values of $\tan \beta$ and μ in terms of a single parameter M (plus the dependence on the small flux parameter ρ_H). Since it is not possible to derive an analytical solution for $\tan \beta$ from Eqs. (3.5) and (3.6), and given that we also need the value of $\tan \beta$ to adjust the values of the Yukawa couplings at the unification scale, an iterative procedure has to be followed in which the RGE are solved numerically for a tentative value of $\tan \beta$, with the soft terms given by Eqs. (2.9) in terms of the two parameters M and ρ_H . The resulting B at the weak scale is then compared to Eqs. (3.5) and (3.6), and the value of $\tan \beta$ is varied until agreement is reached. It is often not possible to find a solution with consistent REWSB and this excludes large areas of the (M, ρ_H) parameter space.

We have implemented this iterative process through a series of changes in the public code `SPheno 3.0` [37, 38]. This code solves numerically the renormalization group equations of the MSSM and provides the SUSY spectrum at low energy. We use this code through a link in `MicrOMEGAs 2.4` [41, 42, 43], which also calculates the theoretical predictions for low-energy observables such as the branching ratios of rare decays ($b \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$) and the muon anomalous magnetic moment. The results are sensitive to the value of the top quark mass, particularly for the Higgs mass, see below. In the computation we use the central value in $m_t = 173.2 \pm 0.9$ GeV [39].

In addition to correct REWSB we also impose the presence of viable neutralino dark matter, assuming R-parity conservation. The relic density of the neutralino is calculated numerically using the MSSM module of the code `MicrOMEGAs 2.4` and we check for compatibility with the data obtained from the WMAP satellite, which constrain the amount of cold dark matter to be $0.1008 \leq \Omega h^2 \leq 0.1232$ at the 2σ confidence level [40].

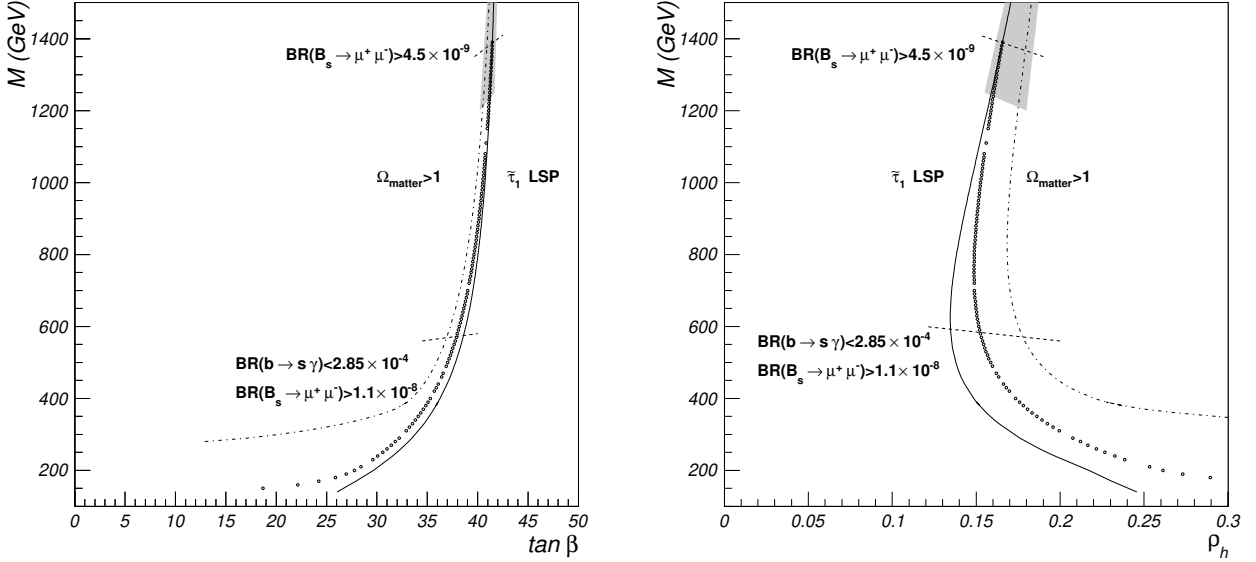


Figure 3: Left) Trajectory in the $(M, \tan \beta)$ plane for which the REWSB conditions are fulfilled and the correct amount of dark matter is obtained. Right) Corresponding values of the flux, ρ_H . In both cases, dots correspond to points fulfilling the central value in WMAP result for the neutralino relic density. The dot-dashed line denotes points along which the matter density is critical, $\Omega_{matter} = 1$, whereas the solid line indicates the points for which the stau becomes the LSP. The points below the dashed line are excluded by the lower bound on $\text{BR}(b \rightarrow s \gamma)$ and the upper bound on $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ from Ref. [47] and the recent LHCb result [31]. The gray area indicates the points compatible with the latter constraint when the 2σ error associated to the SM prediction is included.

Imposing both conditions we are left with a model with a single free parameter or, equivalently, lines in the $(M, \tan \beta)$ and (M, ρ_H) planes. In Fig. 3 we show the trajectories consistent with both REWSB and viable neutralino dark matter. The left hand-side of Fig. 3 shows how the viable values for $\tan \beta$ are confined to a large value region, $\tan \beta \simeq 36 - 41$. The maximum values for M and $\tan \beta$ occur for $M \simeq 1.4$ TeV, $\tan \beta \simeq 41$. The existence of these maximal values are due to the dark matter condition. Indeed, as we will see momentarily, the LSP in this scheme is mostly pure Bino and generically its abundance exceeds the WMAP constraints. However along the line in the figure the lightest neutralino χ_1^0 is almost degenerate in mass with the lightest stau $\tilde{\tau}_1$ (see Fig. 6) and a coannihilation effect takes place in the early universe reducing very effectively its abundance. Above the point $M \simeq 1.4$ TeV, coannihilation is not

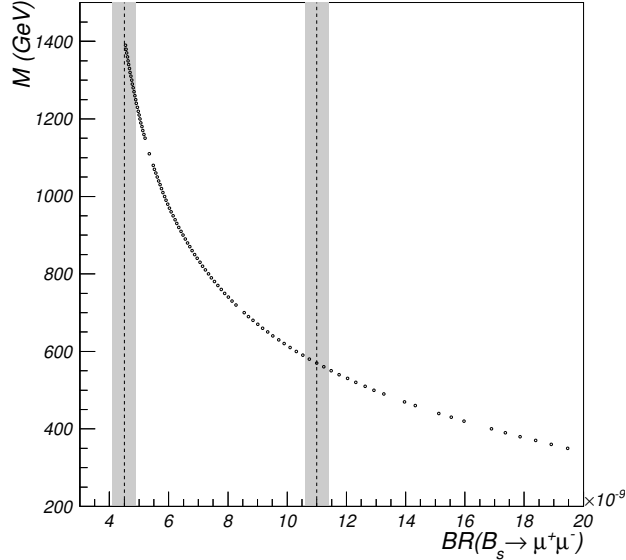


Figure 4: Universal gaugino mass versus the theoretical prediction for $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$. The dashed lines denote the experimental upper bound on this observable from Ref. [47] and the recent LHCb result [31]. The $2, \sigma$ theoretical error on the SM prediction is indicated by means of a shaded region in both cases.

sufficiently efficient in depleting neutralino abundance and χ_1^0 ceases to be a viable dark matter candidate. Thus viable dark matter gives rise to a very strong constraint on the M value, $|M| \leq 1.4$ TeV, which in turn implies an upper bound on the SUSY and Higgs spectrum, see below. Notice that for small values of the gaugino mass the predicted $\tan \beta$ can also be smaller. In principle one could get to values of $\tan \beta$ as low as 10 while still fulfilling REWSB and the neutralino relic density with $M \gtrsim 150$ GeV. However, the resulting SUSY spectrum is extremely light and already well below the current experimental bounds. First, demanding $m_h > 115.5$ GeV leads to a lower bound on the common scale $M \gtrsim 340$ GeV with $\tan \beta \gtrsim 34$. Similarly, current LHC lower bounds on the masses of gluinos and second and third generation squarks imply $M \gtrsim 400$ GeV and $\tan \beta \gtrsim 35$. There is a more stringent lower bound coming from the $\text{BR}(b \rightarrow s\gamma)$ constraint, which implies $M \gtrsim 570$ GeV and $\tan \beta \gtrsim 38$.

Finally, the experimental upper limit on $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ has a profound impact on the allowed parameter space. A combination of CMS [45] and LHCb [46] data recently set a bound as low as $\text{BR}(B_s \rightarrow \mu^+ \mu^-) < 1.1 \times 10^{-8}$ [47]. This would lead to $M \gtrsim 560$ GeV, thus having a similar effect as the other constraints mentioned above. However, as this work was released, the experimental bound was significantly improved

by the LHCb collaboration [31], leading to the unprecedented constraint $\text{BR}(B_s \rightarrow \mu^+ \mu^-) < 4.5 \times 10^{-9}$. This is in fact very close to the SM prediction $\text{BR}(B_s \rightarrow \mu^+ \mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ [48, 49] and thus has important implications in our parameter space. Given that our model entails large values of $\tan \beta$ and a significant mixing in the stop mass matrix, the resulting $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ is relatively large. Fig. 4 represents the theoretical predictions for this observable as a function of the corresponding universal gaugino mass, showing that $\text{BR}(B_s \rightarrow \mu^+ \mu^-) \gtrsim 4.4 \times 10^{-9}$. We display in the plot the experimental bound from Ref. [47] and Ref. [31], explicitly showing the effect of the improved measurement. For each case, we take into account the 2σ theoretical uncertainty of the SM contribution. It is in fact expected that this upper bound improves in the near future with new data from CMS and LHCb. This has the potential to disfavour our construction if no deviation from the SM value is observed.³

On the right hand-side of Fig. 3 we display the line in the (M, ρ_H) plane that is consistent with REWSB and viable neutralino dark matter. Interestingly enough, after applying experimental constraints, the value of ρ_H is indeed small, of order $0.15 - 0.17$ and is very weakly dependent on M . This is consistent with the interpretation of ρ_H as a small correction arising from gauge fluxes, as discussed in the previous chapter. Indeed the values for ρ_H obtained are of the expected order of magnitude, $\rho_H \propto \alpha_{GUT}^{1/2} \simeq 0.2$.

The viable points of the parameter space lie along a narrow area of the parameter space. In fact, small deviations in any of the parameters, M , $\tan \beta$ or ρ_h have catastrophic consequences, since either the relic density becomes too large (it very rapidly overcloses the Universe) or the stau becomes the LSP. We illustrate this in Fig. 3, where the dashed and solid lines represent the points for which $\Omega_{matter} = 1$ and $m_{\tilde{\tau}_1} = m_{\chi_1^0}$, respectively. The line with critical density extends to $M \approx 2.5$ TeV, but the region fulfilling WMAP 2σ region stops at $M = 1.4$ TeV. Interestingly, the flux ρ_h cannot vanish (since the stau becomes the LSP), this is, even though small, a deviation from the CMSSM is necessary. Also, it cannot be too large or we would have an excessive amount of dark matter.

As we explained in the beginning of this chapter, the μ parameter is computed at the electroweak scale from Eq. (3.5). Using **SPheno 3.0** we have also computed its value at the unification scale (the effect of the RGEs is not large for this parameter) so that we can compare it with the soft parameters. This might give us an idea of what

³It should be pointed out in this respect that the inclusion of non-vanishing flux correction ρ_f for sfermions in Eq. (2.9) can slightly alter the allowed regions in the parameter space, shifting the viable points towards smaller values of $\tan \beta$, thereby decreasing the SUSY contribution to $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$.

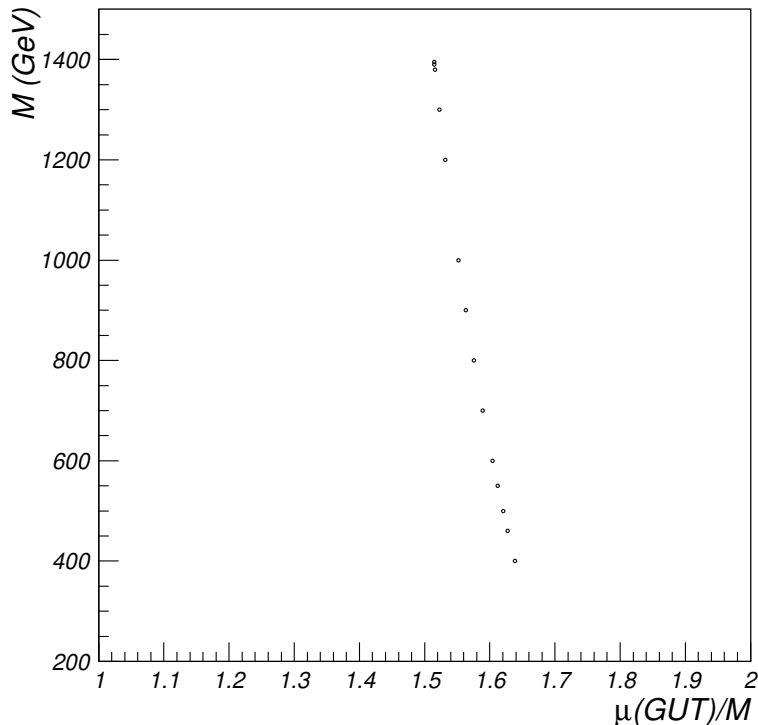


Figure 5: Universal gaugino mass as a function of the resulting Higgsino mass parameter, μ at the unification scale for those points where both REWSB and viable neutralino dark matter are obtained.

the possible origin of the μ -term could be ⁴. The results are displayed in Fig. 5, where the ratio $\mu(\text{GUT})/M$ that corresponds for each value of the gaugino mass is plotted. As we can observe, the predicted value for that ratio is approximately constant and satisfies $\mu \sim (1.5 - 1.6) M$. At the point of maximal M one has approximately $|\mu| = |A| = 3/2|M|$. This could perhaps point towards a higher degree of interdependence among soft terms, see the discussion in chapter 5.

3.2 The Higgs mass

The lightest neutral Higgs, h , in the MSSM receives important one-loop corrections to its mass from the top-stop loops. The one-loop corrected Higgs mass has an approxi-

⁴In particular, as noted in Ref. [19], the Giudice-Masiero [50] mechanism would predict in the present model $\mu = -M/2$ and $B = -3M/2$, which do not lead to consistent REWSB.

mate expression of the form [44]

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{16\pi^2 v^2} \left(\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2} \right) \right), \quad (3.7)$$

where $v^2 = v_1^2 + v_2^2$, $m_{\tilde{t}} = (m_{\tilde{t}_L} m_{\tilde{t}_R})^{1/2}$, and $X_t = A_t - \mu \cot \beta$, all evaluated at the weak scale. The largest values for the Higgs mass are obtained then for large $\tan \beta$ and large stop masses. In particular, the quantity in brackets is maximized for $|X_t| \simeq \sqrt{6} m_{\tilde{t}}$. Interestingly enough this maximal value typically correspond to large values for the trilinear soft term $A/m \simeq \pm 2$ (see e.g. Ref. [4, 6]). In our scheme we have $A/m = -3/\sqrt{2} + \rho_H/\sqrt{2} \simeq -2$ and large values of $\tan \beta = 36 - 41$, so that relatively *large values of the Higgs mass are an automatic prediction of our scheme.*

The 2011 run at LHC has restricted the most likely range for a SM Higgs to the range 115.5 – 131 GeV (ATLAS) and 114.5 – 127 GeV (CMS). Furthermore there is an excess of events in the $\gamma\gamma$, $ZZ^* \rightarrow 4l$ and $WW^* \rightarrow 2l$ channels suggesting the presence of a Higgs boson at a mass around 125 GeV. Although more data are needed to confirm this excess, it is interesting to see whether a Higgs boson in that range appears in this construction. As we said, our scheme has essentially one free parameter and the allowed values for the Higgs mass turn out to be very restricted. We have computed the mass of the Higgs particles to two-loop order using the code **SPheno** linked through the **micrOMEGAs** program ⁵. To show the allowed values for the lightest Higgs mass we display in Fig. 6 the ratio $(m_{\tilde{\tau}_1} - m_{\chi_1^0})/m_{\tilde{\tau}_1}$ versus the value of the lightest Higgs mass m_h . This mass difference is very relevant for the coannihilation effect which is required in this scheme to get viable neutralino dark matter. We also illustrate the variation resulting from the 2σ uncertainty in the WMAP result.

One observes that there is a maximum value of the Higgs mass of order 125 GeV. For higher values the neutralino ceases to be viable as a dark matter candidate. This limit corresponds to the maximum allowed values $M \simeq 1.4$ TeV and $\tan \beta \simeq 41$ that we discussed above and hence to a quite massive SUSY spectra, see below. There is also a lower limit coming from the lower bound on the constraint $\text{BR}(b \rightarrow s\gamma) < 2.85 \times 10^{-4}$ which leads to

$$119 \text{ GeV} \leq m_h \leq 125 \text{ GeV} . \quad (3.8)$$

In the MSSM the bound on $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ also has an impact on the predicted Higgs mass [53]. In our case, if the current LHCb constraint is taken at face value and

⁵We have compared our results with those obtained with **FeynHiggs 2.8.6** [51, 52], finding good agreement, within approximately 1 GeV.

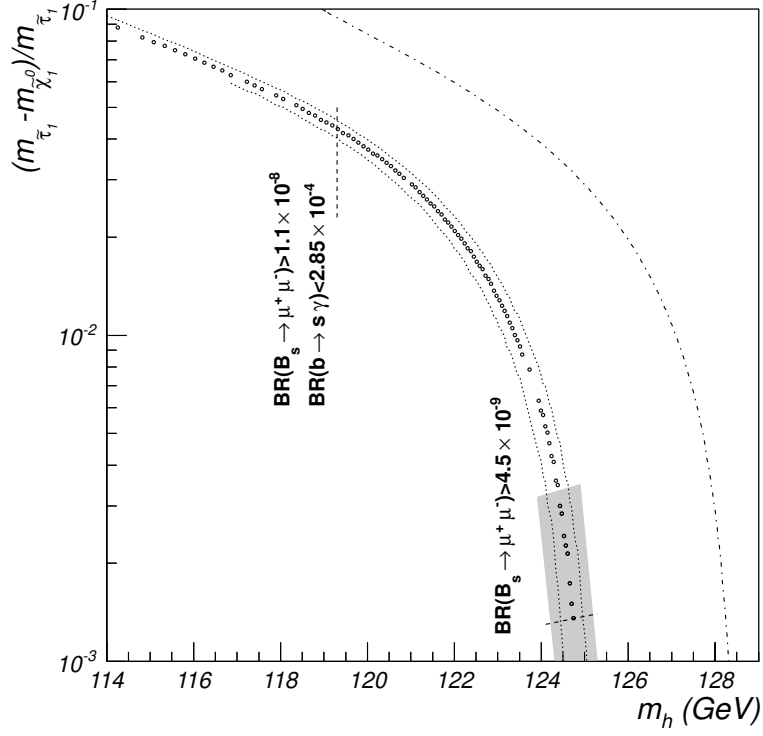


Figure 6: The normalized mass difference $(m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0})/m_{\tilde{\tau}_1}$ as a function of the lightest Higgs mass m_h . Dots correspond to points fulfilling the central value in the result from WMAP for the neutralino relic density and dotted lines denote the upper and lower limits after including the 2σ uncertainty. The dot-dashed line represents points with a critical matter density $\Omega_{matter} = 1$. The vertical line corresponds to the 2σ limit on $\text{BR}(b \rightarrow s\gamma)$ and the upper bound on $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ from Ref. [47] and the recent LHCb result [31]. The gray area indicates the points compatible with the latter constraint when the 2σ error associated to the SM prediction is included.

the SM uncertainty is included in our theoretical predictions, the resulting range for the Higgs mass is reduced to

$$124.4 \text{ GeV} \leq m_h \leq 125 \text{ GeV} . \quad (3.9)$$

We have to remark at this point that these values are sensitive to the value taken for the top quark mass and the corresponding error. As we said we have taken the central value in $m_t = 173.2 \pm 0.9$ [39]. The value of the Higgs mass is very dependent on the top mass. As a rule of thumb, one can consider that an increase of 1 GeV in the top mass leads to an increase of approximately 1 GeV in m_h [54]. Note also that the computation of the Higgs mass includes additional intrinsic errors of order 1 GeV, see

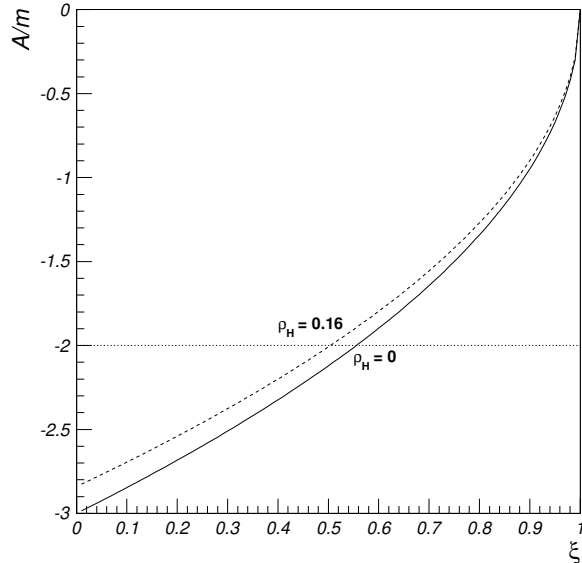


Figure 7: Ratio A/m_f at the GUT scale as a function of the modular weight ξ for the case without fluxes (solid line) and when a small flux ($\rho_H = 0.16$) is introduced.

e.g. Refs. [55, 56]. In any event, it is remarkable that the allowed region in our model is well within the range allowed by the 2011 LHC data. In particular, generic points in the CMSSM space tend to have a lighter Higgs mass typically of order 115 GeV or lower. Our particular choice of soft terms plus the constraint of viable neutralino dark matter force our Higgs mass to be relatively high.

It should be pointed out that the regions of the parameter space with larger values of the Higgs mass correspond to a heavy spectrum and therefore predict a small supersymmetric contribution to the muon anomalous magnetic moment, a_μ^{SUSY} . In particular, the points with $m_h > 124$ GeV predict $a_\mu^{\text{SUSY}} \approx 3 \times 10^{-10}$. These values show some tension with the observed discrepancy between the experimental value [57] and the Standard Model predictions using e^+e^- data, which imply $10.1 \times 10^{-10} < a_\mu^{\text{SUSY}} < 42.1 \times 10^{-10}$ at the 2σ confidence level [58] where theoretical and experimental errors are combined in quadrature (see also Refs. [59, 60], which provide similar results). However, if tau data is used this discrepancy is smaller $2.9 \times 10^{-10} < a_\mu^{\text{SUSY}} < 36.1 \times 10^{-10}$ [60].

As we said, in the context of the CMSSM obtaining a large Higgs mass and not too heavy SUSY spectrum requires having $A \simeq -2m$. This may be considered as a hint of a scheme with all SM localized in intersecting branes and is in fact independent of what the possible origin of the μ term is. Indeed, for general (but universal) modular

M	$\tan\beta$	\tilde{g}	\tilde{Q}_L	\tilde{Q}_R	\tilde{t}_1	$\chi_2^0, \chi_1^+; L_R$	$\chi_1^0, \tilde{\tau}_1$	M_A	m_h
400	35.3	944	900	870	605	314;323	164, 175	549	116.8
500	37	1160	1107	1067	754	397;402	208, 219	660	118.5
600	38.2	1372	1310	1262	901	481;482	252, 262	769	119.7
700	39	1583	1511	1455	1046	565;561	296, 305	875	120.8
800	39.6	1791	1710	1644	1189	649;641	341, 349	981	121.7
900	40.1	1998	1907	1834	1330	732;720	386, 393	1084	122.4
1000	40.5	2203	2103	2020	1470	816;800	431, 436	1187	123.1
1100	40.8	2424	2314	2220	1620	907;886	480, 483	1298	123.7
1200	41.1	2610	2491	2390	1746	984;859	521, 524	1391	124.2
1300	41.3	2812	2683	2575	1883	1069;1039	567, 568	1492	124.7
1400	41.5	3013	2876	2760	2018	1153;1119	612, 612	1592	125.1

Table 1: Sparticle and Higgs masses in GeV and resulting value of $\tan\beta$ as a function of M . Note that there is a maximum value for $M = 1.4$ TeV where χ_1^0 becomes degenerate with the lightest stau, as the third column from the right shows. At that point the maximum value for the lightest Higgs mass $\simeq 125$ GeV is obtained.

weights ξ one has the relation

$$A = -3(1 - \xi)^{1/2} m . \quad (3.10)$$

For $A/m \simeq -2$ one has $\xi \simeq 0.5$, indicating that indeed large Higgs masses favour all SM particles with $\xi \simeq 1/2$ modular weights, which correspond to intersecting branes, as in our scheme. This is illustrated in Fig. 7.

3.3 The SUSY spectrum

Again, our particular choice of soft terms significantly constrains the spectrum of SUSY particles. Given that there is only one free parameter, fixing any value for a SUSY particle or Higgs field automatically fixes the rest of the spectrum. We give in Table 1 the values of some masses and parameters as we vary the universal gaugino mass, M . Let us remember that $\tan\beta$ is not an input, as it is fixed by the boundary conditions on B .

One interesting way of presenting the structure of the SUSY spectrum is in terms of the lightest Higgs mass. In Fig. 8 we show the masses of the gluino and the squarks as a function of m_h . The region to the left of the vertical dashed line is excluded since it leads to $BR(b \rightarrow s\gamma) < 2.85 \times 10^{-4}$. Note that this implies that squarks of the first two generations and gluinos in our scheme must be heavier than $\simeq 1.2$ TeV. This is consistent with LHC limits obtained with 1 fb^{-1} . For the third generation of squarks, the lightest stop has a mass of at least 800 GeV and the heaviest one, along with the sbottoms are heavier than 1 TeV.

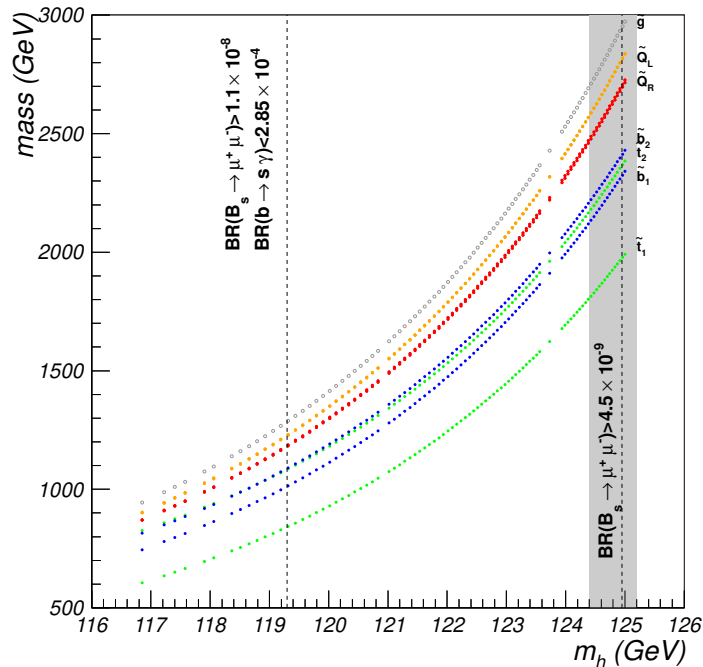


Figure 8: Squark and gluino masses as a function of the Higgs mass. The region to the left of the vertical dashed indicates the constraint $BR(b \rightarrow s\gamma) < 2.85 \times 10^{-4}$ and the upper bound on $BR(B_s \rightarrow \mu^+\mu^-)$ from Ref. [47] and the recent LHCb result [31]. The gray area indicates the points compatible with the latter constraint when the 2σ error associated to the SM prediction is included.

If the signal for a Higgs at 125 GeV is real, one expects a quite heavy spectrum with gluinos of order 3 TeV and squarks of the first two generations of order 2.8 TeV. The lightest stop would be around 2 TeV and the rest of the squarks at around 2.3 TeV. Note however that these values depend strongly on the Higgs mass so that e.g. a Higgs around 124 GeV would rather correspond to squarks and gluinos around 2.2 TeV. Given the intrinsic error in the computation of the Higgs mass, this only give us a rough idea

of the expected masses for colored particles. We discuss the testability of such heavy colored spectra in the next chapter.

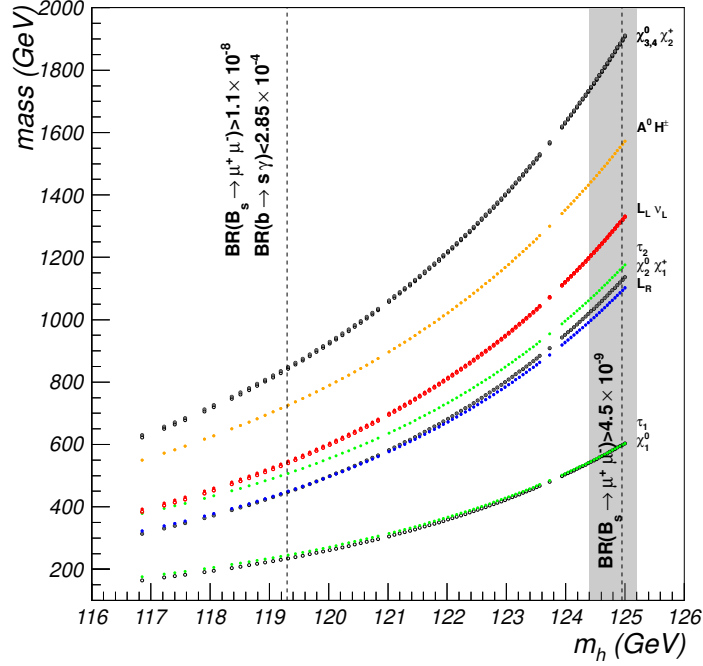


Figure 9: Supersymmetric spectrum as a function of the Higgs mass of the slepton sector, together with the masses of the heavy Higgses and the gauginos. The region to the left of the vertical dashed indicates the constraint $BR(b \rightarrow s\gamma) < 2.85 \times 10^{-4}$ and the upper bound on $BR(B_s \rightarrow \mu^+ \mu^-)$ from Ref. [47] and the recent LHCb result [31]. The gray area indicates the points compatible with the latter constraint when the 2σ error associated to the SM prediction is included.

In Fig. 9 we show the spectrum of un-colored particles as a function of the lightest Higgs mass, including neutralinos, charginos, sleptons and the rest of the Higgs fields. The region to the left of the vertical dashed line is again excluded since $BR(b \rightarrow s\gamma) < 2.85 \times 10^{-4}$. The fact that $119 \text{ GeV} \leq m_h \leq 125 \text{ GeV}$ strongly restricts the spectrum.

The hierarchy in the sparticle mass pattern is a quick way of classifying a supersymmetric model and understanding the kind of signals it may give rise to in LHC. Several structures have been identified (see Ref. [63] and references therein) that can originate from the CMSSM or non-universal supergravity scenarios. In our case, the model is very close to the CMSSM in the coannihilation region but further constrained. As a consequence, the resulting hierarchy in the supersymmetric spectrum is a very specific one. More specifically, the five lightest supersymmetric particles display the following

structure:

$$\begin{aligned}\tilde{\chi}_1^0 < \tilde{\tau}_1 < \tilde{\chi}_2^0 \approx \tilde{\chi}_1^\pm < \tilde{l}_R & \text{ for } m_h < 120 \text{ GeV}, \\ \tilde{\chi}_1^0 < \tilde{\tau}_1 < \tilde{l}_R < \tilde{\chi}_2^0 \approx \tilde{\chi}_1^\pm & \text{ for } m_h > 120 \text{ GeV}.\end{aligned}$$

These scenarios are analogous to mSP6 and mSP7, respectively, in Ref. [63]. The change of pattern is difficult to appreciate in Fig. 9, since the mass difference between \tilde{l}_R and the second-lightest neutralino is small (of order 10 GeV). Also, the mass difference between the second lightest neutralino and the lightest chargino is merely a fraction of a GeV.

The almost identical values of the masses of χ_2^0 and χ_1^\pm is expected since both fields are mostly Winos. On the other hand the degeneracy with the \tilde{l}_R fields is a peculiarity of the structure of soft terms in this model. Indeed the weak scale masses for these fields have the structure

$$\begin{aligned}M_{\chi_2^0}^2 &\simeq \left(\frac{\alpha_2(M_Z)}{\alpha(M_s)} \right) M^2 \simeq 0.64 M^2, \\ m_{\tilde{l}_R}^2 &\simeq m^2 + 0.15 M^2 \simeq 0.65 M^2,\end{aligned}\tag{3.11}$$

where in the second equation the boundary condition $m = M/\sqrt{2}$, characteristic of the present model, has been used. From Fig. 9 we see that the lightest charged sparticle is a stau, with a mass in between 200 and 550 GeV. The lightest selectrons and charginos are in the region 400 to 1000 GeV. The remaining Higgs fields will be heavy, in the 700 to 1600 GeV range. Thus there is a good chance to produce weakly interacting charged sparticles in a linear collider.

For completeness we also show in Fig. 10 the branching ratios of the different decay modes of the lightest CP-even Higgs, computed using code `SPheno 3.0`, as a function of its mass in this construction. The composition of the lightest Higgs is very similar to that in the CMSSM and therefore these results are quite standard. The leading decay mode is $b\bar{b}$ although the contribution from WW is almost comparable for large Higgs masses.

Let us finally address the direct detectability of dark matter neutralinos in this construction. We show in Fig. 11 the theoretical predictions for the spin-independent contribution to its elastic scattering cross section off protons, $\sigma_{\tilde{\chi}_1^0-p}$, as a function of the neutralino mass, together with current experimental sensitivities from the CDMS (showing also the combination of its data with those from EDELWEISS) and XENON detectors. After imposing all the experimental constraints, this scenario predicts $10^{-9} \text{ pb} \gtrsim \sigma_{\tilde{\chi}_1^0-p} \gtrsim 5 \times 10^{-11} \text{ pb}$. This is far from the reach of current experiments.

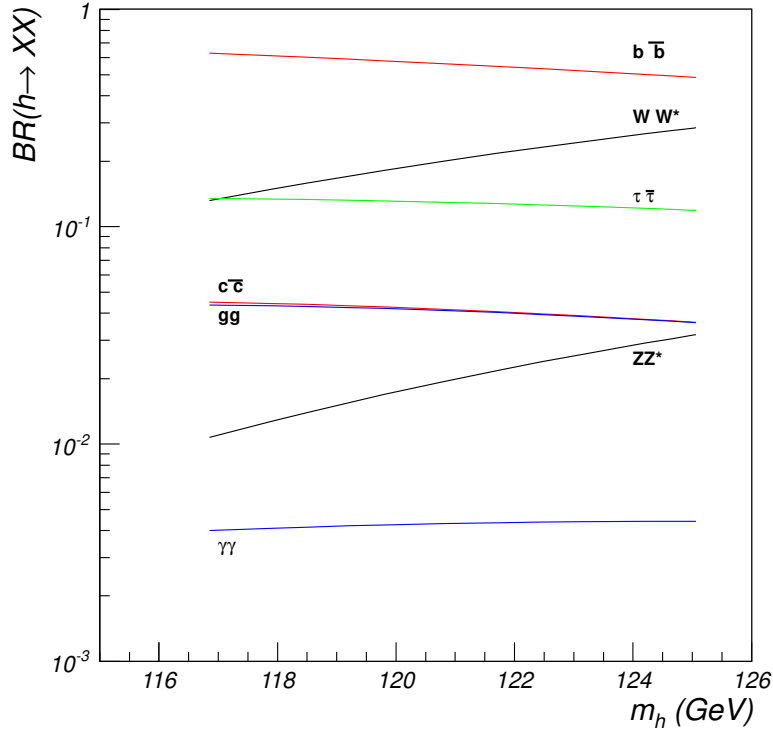


Figure 10: Branching fractions for the decay of the lightest CP-even Higgs as a function of its mass.

Next generation experiments with targets of order 1 ton would be able to probe only a portion of the parameter space, corresponding to neutralino masses lighter than 300 GeV (and therefore to Higgses as heavy as approximately 121 GeV). This was to be expected, as these results are typical of the CMSSM in the coannihilation region.

4 Detectability at the LHC

4.1 Jets and missing transverse energy

Having already described the SUSY spectrum, let us now address the detectability of this construction at the LHC. In the light of the current and predicted status of the collider, we will consider three possible configurations, with energies of $\sqrt{s} = 7, 8$ and 14 TeV. Our goal is to determine the potential reach of the LHC as a function of the luminosity. In order to do so we have performed a Monte Carlo simulation for the different points in the viable parameter space.

As we commented in the previous chapter, the SUSY spectrum is calculated for each

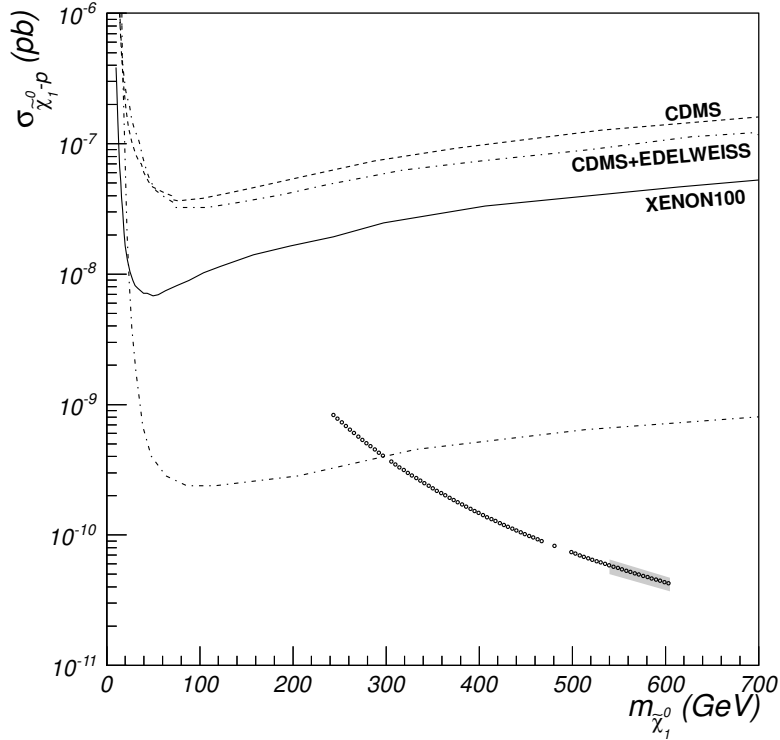


Figure 11: Spin-independent part of the neutralino-proton cross section as a function of the neutralino mass for points reproducing the WMAP relic abundance and in agreement with all the experimental constraints. The current sensitivities of the CDMS [73], CDMS combined with EDELWEISS [74] and XENON100 [75] experiments are displayed by means of dashed, dot-dashed and solid lines, respectively. The dotted line represents the expected reach of a 1 ton experiment. The gray area indicates the points compatible with the LHCb constraint when the 2σ error associated to the SM prediction is included.

point using a modified version of `SPheno 3.0`. The output, written in Les Houches Accord format, is directly linked to a Monte Carlo event generator. We have used `PYTHIA 6.400` [76] to this aim, linked with `PGS 4` [77], which simulates the response of the detector and uses `TAUOLA` [67] for the calculation of tau branching fractions.

We include the main sources for SM background, taking into account the production of $t\bar{t}$ and $WW/ZZ/WZ$ pairs, as well as W/Z +jets. The latter give the main contribution [71, 72] to the background at the relevant energies. The production cross sections for these different processes are summarised in Table 2. For the production of

W/Z +jets we have taken the results provided by PYTHIA. ⁶

	7 GeV	8 TeV	14 TeV
$\sigma_{t\bar{t}}^{NLO}$	152_{-19-9}^{+16+8} pb	250 pb (*)	852_{-93-33}^{+91+30} pb
σ_{WW}^{NLO}	$47.04_{-3.2\%}^{+4.3\%}$ pb	$57.25_{-2.8\%}^{+4.1\%}$ pb	$124.31_{-2.0\%}^{+2.8\%}$ pb
σ_{W+Z}^{NLO}	$11.88_{-4.2\%}^{+5.5\%}$ pb	$14.48_{-4.0\%}^{+5.2\%}$ pb	$31.50_{-3.0\%}^{+3.9\%}$ pb
σ_{W-Z}^{NLO}	$6.69_{-4.23\%}^{+5.6\%}$ pb	$8.40_{-4.1\%}^{+5.4\%}$ pb	$20.32_{-3.1\%}^{+3.9\%}$ pb
σ_{ZZ}^{NLO}	$6.46_{-3.3\%}^{+4.7\%}$ pb	$7.92_{-3.0\%}^{+4.7\%}$ pb	$17.72_{-2.5\%}^{+3.5\%}$ pb
σ_{W+jets}^{LO}	1.46×10^5 pb	1.74×10^5 pb	3.50×10^5 pb
σ_{Z+jets}^{LO}	6.76×10^4 pb	7.98×10^4 pb	1.57×10^5 pb

Table 2: Cross sections for the production of $t\bar{t}$ [64] and $WW/ZZ/WZ$ [65] pairs, as well as W/Z +jets. (*) Rough estimate obtained from the data of Ref. [64].

The production cross section of Supersymmetric particles has been computed using Prospino 2.1[66], which provides the result at NLO. The leading contributions obviously comes from the production of coloured sparticles, $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$. The actual values are a function of the gluino and squark masses and have been calculated for each specific case.

In order to determine the LHC discovery potential we have studied the simplest signal, consisting on the observation of missing transverse energy, \cancel{E}_T , accompanied by a number ($n \geq 3$) of jets. We have used Level 2 triggers in PGS, but supplemented these with additional conditions on the eligible events. Namely, we have implemented the following selection cuts, mimicking those used by the ATLAS Collaboration:

- Leading jet $P_T > 130$ GeV,
- Second jet $P_T > 40$ GeV,
- Third jet $P_T > 40$ GeV,
- $m_{eff} > 1000$ GeV,

where $m_{eff} = E_T^{miss} + P_T^{jets}$ is calculated from the three leading jets defining the region. Fig. 12 shows a series of histograms for the missing energy resulting from the

⁶Calculations of this quantity at the NLO can be found in e.g., Refs. [68, 69]. The uncertainty of the result using PYTHIA compared with current data and other simulators can be found in Ref. [70].

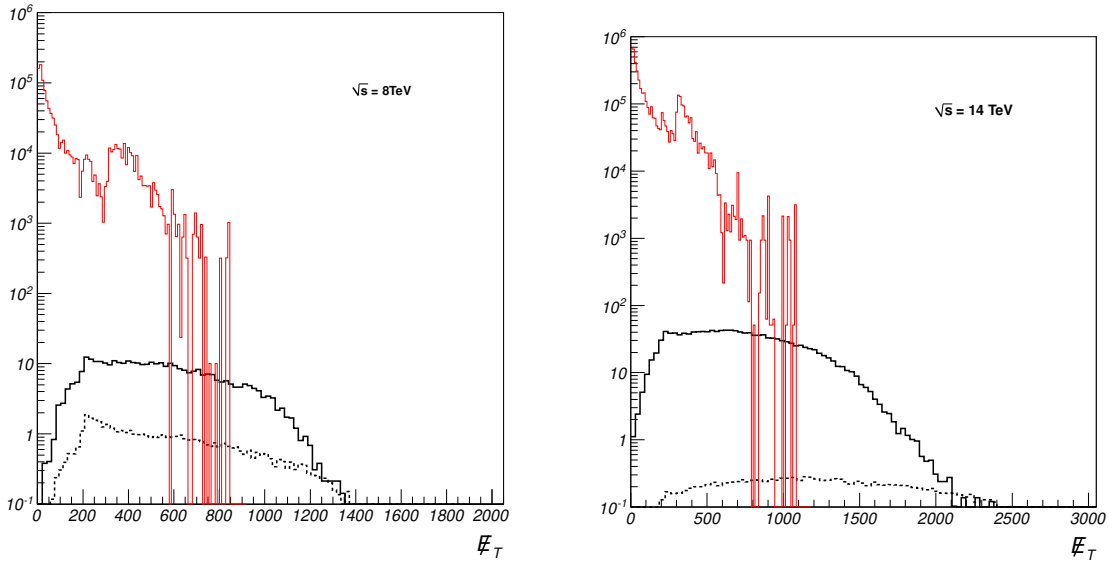


Figure 12: Missing energy histogram for the SM background (in red) and SUSY signal in the model. On the left hand-side we assume $\sqrt{s} = 8$ TeV and a luminosity of 20 fb^{-1} and simulate the signal for $M = 570$ GeV (solid line) and $M = 700$ GeV (dashed line). On the right hand-side we assume $\sqrt{s} = 14$ TeV and a luminosity of 30 fb^{-1} and simulate the signal for $M = 800$ GeV (solid line) and $M = 1400$ GeV (dashed line).

SM background (red line) and the expected signal events for several examples in the parameter space. In particular, choosing $\sqrt{s} = 8$ TeV and a luminosity of 20 fb^{-1} we display the expected signal in our model when $M = 570$ GeV and 700 GeV. Similarly, for $\sqrt{s} = 14$ TeV and a luminosity of 30 fb^{-1} the predictions for the cases $M = 800$ GeV and 1400 GeV are shown.

As we can see, the signal dominates over the background above a given value of the missing energy with a slight dependence on M . The actual number of events obviously depends on the luminosity. Given a number of signal events N_s and background events N_b that satisfy our series of cuts, a statistical condition for observability may be defined as

$$\frac{N_s}{\sqrt{N_b}} > 4, \quad \frac{N_s}{N_b} > 0.1, \quad N_s > 5. \quad (4.1)$$

It is customary to set a fixed cut for the missing energy in order to determine these numbers, however we have implemented an adaptive method which estimates the optimal value for the cut in \cancel{E}_T for each value of M . The idea is to maximize the signal-to-background ratio while guaranteeing that the number of signal events is enough ($N_s > 5$). In particular, if the spectrum is heavy and the signal is expected to be

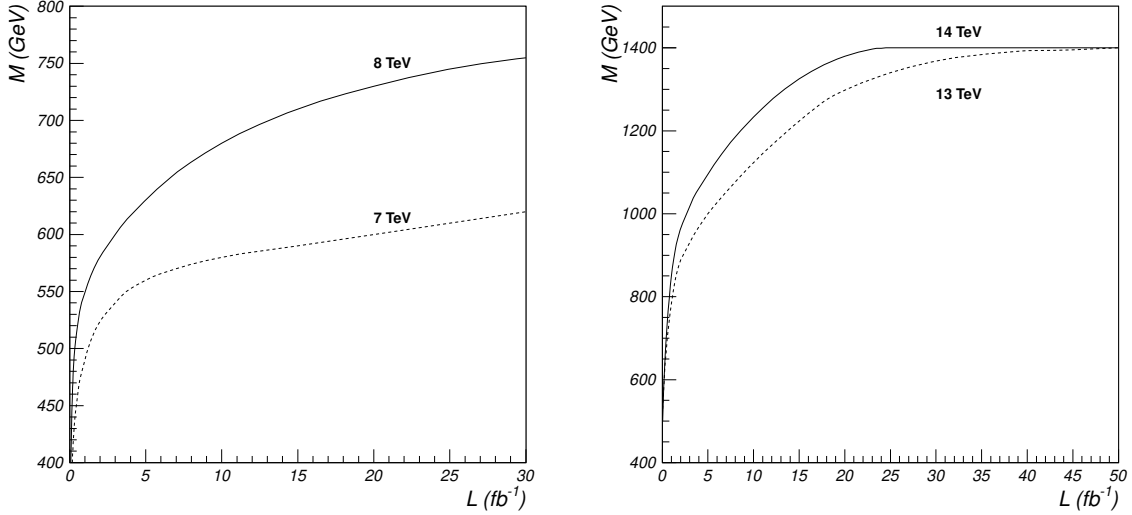


Figure 13: Maximum value of M that can be explored at the LHC with $\sqrt{s} = 7, 8$ TeV (left hand-side) and $\sqrt{s} = 13, 14$ TeV (right hand-side) as a function of the luminosity.

centered around a larger \cancel{E}_T then the cut in \cancel{E}_T can generally be increased so as to reduce the number of background events as long as the number of signal events is above critical. The latter obviously depends on the luminosity.

Using this "adaptive cut" in \cancel{E}_T we have determined, for each given value of the luminosity (and for each LHC energy configuration), the maximum value of M for which the number of signal events satisfies condition (4.1). This is, we have calculated the detectability potential of LHC for this specific model. The results are displayed in Fig. 13, where the maximum value of M is plotted as a function of the luminosity. Operating at $\sqrt{s} = 7, 8$ and $13, 14$ TeV, LHC will be able to test this scenario up to $M \approx 600, 750$ and 1400 GeV, respectively, with a luminosity of $20, 30$ and $30, 50 \text{ fb}^{-1}$. In fact, the LHC at 14 TeV would be able to explore regions of the parameter space with a larger M than the one displayed in the plot. However, as shown in the previous chapters, there is actually no point of the parameter space above that value for which REWSB and dark matter conditions are fulfilled, and for that reason the line flattens at $M = 1400$ GeV.

In order to check the validity of our "adaptive cut" in \cancel{E}_T we have applied it to the CMSSM and compared the resulting predicted reach with those obtained by the ATLAS[61] and CMS [71] collaborations for the same signal. We have obtained a similar reach. Remember in this sense that ATLAS and CMS use a given value for the cut in \cancel{E}_T at low masses and a larger value for heavier masses.

4.2 Other signatures

As we described in chapter 3, the viable regions of the model correspond to the coannihilation region in which the lightest neutralino and lightest stau mass are almost degenerate. This class of scenarios has received a lot of attention in the literature [78, 79, 80], since they can give rise to very characteristic signals. In particular, the following decay chain is dominant for the second-lightest neutralino, $\tilde{\chi}_2^0 \rightarrow \tau \tilde{\tau}_1 \rightarrow \tau \tau \tilde{\chi}_1^0$, leading to signals characterised by multiple low energy tau leptons [79]. In particular, one can search for pairs of opposite sign taus, accompanied by a number of jets, which would be relatively abundant, compared to other characteristic SUSY signals [80].

4.3 Long-lived staus and Big Bang Nucleosynthesis

Finally, as we can observe in Fig. 6, the region with larger values of the Higgs mass is precisely that with a smaller mass-splitting between the stau and the lightest neutralino. In fact, for Higgs masses above $m_h > 124.5$ GeV, for which the recent LHCb constraint on $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ is satisfied, one finds $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} < 1.7$ GeV. This implies that the two body decay $\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \tau$ is no longer kinematically allowed and the stau has to undergo three or four body decays ($\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \nu_\tau \pi$ or $\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \mu \nu_\mu \nu_\tau$). This increases significantly its lifetime which is now larger than 10^{-7} s [81]. The presence of long-lived staus in the Early Universe has appealing implications for Big Bang Nucleosynthesis (BBN). The stau can form a bound state with nuclei leading to a catalytic enhancement of certain processes (in particular, ${}^6\text{Li}$ production) [82]. Moreover, it also provides additional decay processes for ${}^7\text{Li}$ and ${}^7\text{Be}$, thereby solving the apparent discrepancy between the observed abundances of these elements and the predicted values in the Standard BBN [83, 84, 85]. Indeed, as recently pointed out in Ref. [86], the observed value of ${}^7\text{Li}$ can be reproduced if $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} \approx 0.1$ GeV, without conflicting with the abundances of the rest of the light elements. Remarkably (see Fig. 6), this corresponds to $m_h \approx 125$ GeV.

This provides an interesting possibility, the observation of a stable charged particle in the LHC (due to its lifetime, the stau would decay already outside the detector) [87, 88]. Notice that staus in these regions have a mass of order 600 GeV, therefore satisfying the current bounds for long-lived charged particles obtained in ATLAS (at $\sqrt{s} = 7$ TeV and with a luminosity of 37 pb^{-1}), which impose $m_{\tilde{\tau}_1} > 135$ GeV at 95% CL [88].

Finally, long-lived staus might also be searched for in neutrino telescopes after their

production inside the Earth from the inelastic scattering of very energetic neutrinos [90, 90], although the prediction for their flux is generally very small [91].

5 A fine-tuned MSSM, a 125 GeV Higgs and the landscape

It is well known that present experimental bounds on SUSY particle masses indicate a certain amount of fine-tuning at the percent level in the fundamental parameters of CMSSM models. Our case is no exception, the only difference being that the number of fine-tuned parameters is reduced. There are essentially three free parameters to be tuned: M , μ and ρ_H , if we leave coupling constants fixed. In our scheme there are two independent fine-tunings to be made. One is required to get appropriate REWSB and the other one required for neutralino dark matter, which forces the model to live in a stau coannihilation region with a good precision. These two conditions leave us with essentially only one free parameter which may be taken to be the overall scale M .

The question is: why should nature take those fine-tuned values? In the context of low-energy SUSY different approaches have been followed to understand these fine-tunings (which may be reduced to only one fine-tuning if one gives up on the dark matter constraint). These range from choosing very particular regions of parameter space to reduce fine-tuning or extending the MSSM to include either singlets (as in the NMSSM) or new gauge interactions. Concerning the first possibility, we have seen that the particular choice of soft *and* μ terms given by

$$M = \sqrt{2}m = -(2/3)A = -B, \quad \mu = 3/2M \quad (5.1)$$

gives appropriate REWSB with $M \gg M_Z$ due to delicate cancellations among the different contributions to M_Z . The first set of conditions in Eq. (5.1) are an elegant consequence of modulus dominance in a large class of models with fermions localized in intersecting 7-branes. One could argue there that, if we had a good theoretical reason to hold the *additional* condition $\mu = 3/2M$, there would be no fine-tuning. On the other hand getting viable dark matter would require $\rho_H \simeq 0.16$, but one could perhaps argue that this is hardly a fine-tuning since that is the order of magnitude of a flux correction.

While this reduced fine-tuning would be tantalizing, there are additional hidden fine-tunings which make this kind of explanation for the *little hierarchy* unlikely. In particular, the Higgs potential and sparticle spectrum depends strongly on the bound-

ary conditions for the Yukawa couplings of the third generation quarks and leptons. Slight variations of these couplings as well as the gauge couplings affect strongly the low energy physics and again some fine-tuning of these parameters would have to be made to get REWSB at the right scale. In addition in the REWSB mechanism there are two important mass scales, that of SUSY masses M_{SS} and the dimensional transmutation scale Q_{SB} at which the Higgs mass matrix squared starts getting a negative eigenvalue, see Fig. 14. Correct REWSB is obtained for M_{SS} slightly below Q_{SB} but those scales are very sensitive to slight variations of third generation Yukawa couplings and hence some fine-tuning is again implied.

An alternative is to stick to the MSSM structure and admit that indeed the fine-tuning is there, in the same way that other relatively small fine-tunings exist in other parameters of fundamental physics. One example of this is the masses of the lightest generation of quarks and leptons, which have to be in the appropriate ratios so that both the proton is sufficiently stable (so that stable Hydrogen can form) and the Deuteron and heavier nuclei are also stable (see e.g. Refs. [92] for a more detailed discussion). In this nuclear stability case there does not seem to exist a fundamental reason for the ordering and size of the masses other than the cosmological development of appropriate chemical elements which may form the observed world (and us within this Universe). The fine-tuning required on the ratios of Yukawa couplings is in this case of order $10^{-3} - 10^{-2}$. This suggests an environmental (or anthropic) explanation for the structure of the masses of the lightest fermion generation, to some extent analogous to Weinberg's prediction of a non-vanishing cosmological constant [93] using anthropic arguments.

It may be argued that the *little hierarchy* or fine-tuning problem of the MSSM may be another example of environmental fine-tuning [32] analogous to the above mentioned nuclear stability bounds ⁷. Consider for simplicity of exposition the case with very large $\tan\beta$ in which radiative EWSB is essentially generated by the Higgs parameter $m_{H_u}^2$ becoming negative in the infrared. While running down in energies from a large unification (or string) scale M_s , solving the RGE one gets an expression in terms of an adimensional function F of the form

$$m_{H_u}^2 = M^2 F((Q/M_s)^2; \eta, \rho_H), \quad (5.2)$$

where M is the universal gaugino mass, $\eta = \mu/M$ and we have not displayed additional

⁷Alternatively it could be that the full weak scale-Planck scale hierarchy could have an environmental origin, see Refs. [94, 95, 96, 97]. In these models, though, the Higgs mass tends to be heavier than 130 GeV [98, 99, 6].

dependence on gauge and Yukawa coupling constants. As we said there is a dimensional transmutation scale Q_{SB} at which $F(Q_{SB}^2) = 0$ and a vacuum expectation value (vev) for the Higgs starts developing (see Fig. 14). There is in addition a second independent quantity M_{SS} which sets the scale of SUSY breaking soft terms and sparticle masses. In our scheme M_{SS} is determined by the RG running of the underlying soft terms, which are essentially determined by M and μ . For $M_{SS} > Q_{SB}$ the RGE get frozen at a scale of order M_{SS} , before $m_{H_u}^2$ becomes negative and symmetry breaking takes place. However, a universe with unbroken electroweak symmetry would be unable to yield a sufficiently complex chemistry for life to develop and hence would be untenable on anthropic grounds. On the contrary, for $M_{SS} < Q_{SB}$ the RGE get frozen below the scale Q_{SB} , and $m_{H_u}^2$ gets fixed and negative, yielding EWSB. It may be argued [32] (see also [100]) that in a situation in which the soft mass parameter M_{SS} scan in a landscape of possible values, the most likely situation is one in which M_{SS} is sitting close to $M_{SS} \simeq Q_{SB}$, close to a *catastrophic* situation with unbroken EW symmetry. That precisely corresponds to a a fine-tuned situation with the Higgs vev well below M_{SS} by a one-loop factor [32].

In our case there is a second relevant dimensional transmutation scale which is close to a *catastrophic* situation. As we have explained, in our setting one gets appropriate neutralino dark matter only in the stau coannihilation region in which one approximately has $m_{\tilde{\tau}_1} \simeq M_{\chi_1^0}$. Outside this region there is a large overabundance of neutralinos (or else the LSP is charged). This is clearly seen in fig.3 in which one can observe how correct REWSB *and* viable dark matter is only obtained inside a very narrow region in the $M - \tan\beta$ plane. The mass difference controlling coannihilation is

$$m_{\tilde{\tau}_1}^2 - M_{\chi_1^0}^2 = M^2 G((Q/M_s)^2; \eta, \rho_H) . \quad (5.3)$$

At a scale Q_{DM} such that $G(Q_{DM}^2) = 0$ both masses are equal, so that appropriate amount of dark matter is obtained for $M_{SS} > Q_{DM}$, but very close to $M_{SS} = Q_{DM}$. One may use again environmental reasoning to argue that if the scale M (and hence M_{SS}) scans, values of M close to its maximum would be more likely. The absolute environmental maximum would be that corresponding to a critical density $\Omega_{matter} = 1$ leading to $M \simeq 2.5$ TeV and $m_h \simeq 128$ GeV (see Fig. 6). On the other hand we saw in chapter 3 that the maximum value consistent with WMAP observations occurs for $M \simeq 1.4$ TeV. These values would correspond to the scale Q_{DM} at which $\tilde{\tau}_1$ and χ_1^0 masses are approximately equal. All in all we would have a compressed hierarchy of

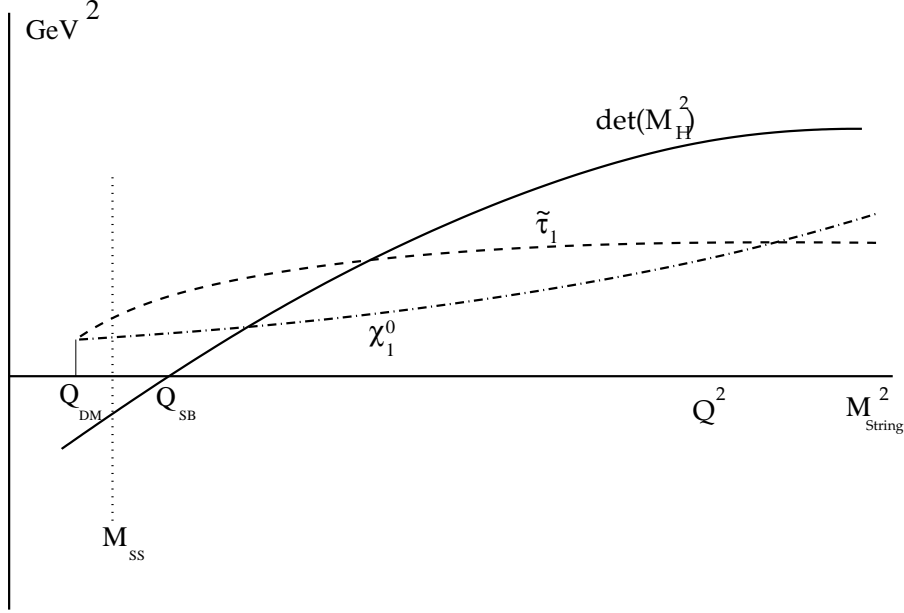


Figure 14: The evolution of the Higgs mass² determinant and $\tilde{\tau}_1$ and χ_1^0 mass² in the infrared. At the dimensional transmutation scale Q_{SB} a EW Higgs vev starts developing. At the scale Q_{DM} the masses of $\tilde{\tau}_1$ and χ_1^0 are degenerate signaling the possibility of dark neutralino-stau coannihilation. The SUSY breaking scale M_{SS} is of order of the soft SUSY breaking terms and signals the scale where running gets frozen. If M_{SS} scans in a landscape one expects $Q_{DM} < M_{SS} < Q_{EW\text{SB}}$, with all these three scales very close in magnitude.

scales with

$$Q_{DM} \leq M_{SS} \leq Q_{SB} , \quad (5.4)$$

in which environmental criteria would show a preference for $M_{SS} \simeq Q_{DM} \simeq Q_{SB}$ corresponding to the maximum M compatible with both correct REWSB and viable dark matter. This would correspond to the largest Higgs mass values, $m_h \simeq 128$ GeV in the extreme case with $\Omega_{matter} = 1$ or rather $m_h \simeq 125$ GeV if we impose the stronger WMAP bounds (see Fig. 6). So one can conclude that within the range of Higgs mass values $119 \text{ GeV} \leq m_h \leq 125 \text{ GeV}$ appearing in the present scheme, *environmental arguments would favour the region close to 125 GeV*. This is of course essentially a qualitative statement and a more detailed understanding of the different environmental factors playing a role in the combined REWSB mechanism and neutralino dark matter would be needed.

An interesting question is whether the basic variables M , μ and ρ_H are likely to scan in a landscape of string vacua. In the present context the MSSM gauge group lives in

Type IIB D7-branes (or their F-theory generalizations) with quarks and leptons residing at the intersection of the branes (or matter curves in the F-theory jargon). As we described in chapter 2, in the presence of *closed string* ISD backgrounds soft terms are generically induced. Parameters such as the gaugino mass M correspond to the closed string flux *density* through the branes. On the other hand the *open string* magnetic backgrounds through the branes are at the origin of the small correction parameter ρ_H . The origin of the μ parameter is more model dependent, although indeed closed string fluxes do induce μ -terms in some classes of brane configurations. Note that M and ρ_H are given by *local flux densities*, which are not themselves quantized. Still in a fully fledged Type IIB compactification with multiple fluxes those local densities will scan as one varies the possible choices of closed string quantized fluxes. Thus indeed it is reasonable to expect that soft terms do scan in the landscape of Type IIB compactifications with fluxes.

In the above argumentation we have ignored that in Eqs. (5.2) and (5.3) there is additional dependence of F and G on the gauge and Yukawa couplings. Concerning the gauge couplings they are assumed to be unified at the string scale with the (inverse) fine structure constant dependent on the value of the local Kahler modulus T . In the corresponding string vacuum the value of T is expected to be dynamically fixed, with its vev depending on the dynamics induced by the different flux values. This means that the unified couplings will possibly scan, although not necessarily in the same way as soft terms, which are typically directly dependent of fluxes. Finally, in the above two equations there is dependence on the *third generation* Yukawa couplings, mostly h_t , h_b for equation (5.2) and h_τ for (5.3). In string compactifications of this large class the third generation Yukawa couplings are essentially determined again by the relevant local Kahler moduli like T and hence are expected to scan like the unified gauge coupling constant⁸. Summing up, one expects both gauge and third generation Yukawa couplings to scan in a similar way. On the other hand the qualitative arguments above would not be modified much by this additional scanning.

6 Conclusions

In this paper we have studied in detail several phenomenological aspects of the modulus dominance SUSY breaking scheme that we introduced in Ref. [19]. These models are

⁸This is not the case for the Yukawa couplings of the first two generations which typically arise from instanton corrections in which further dependence on fluxes and other moduli may appear.

theoretically well-motivated since they are obtained from the effective action of a large class of string compactifications. These are Type IIB orientifolds with quarks/leptons localized at intersecting 7-branes or their F-theory generalizations. Rather than a single model, our results apply to one of the largest classes of string compactifications which may lead to realistic physics, with all moduli fixed.

The simplest assumption that the auxiliary field of a modulus field is the origin of SUSY-breaking leads to a very restrictive set of universal soft terms, Eq. (2.4). The presence of magnetic fluxes, required by chirality and symmetry breaking, give rise to small corrections which in the simplest case induce a slight non-universality in the Higgs mass parameters. Thus the resulting soft terms, Eq. (2.9), correspond to a slice of the CMSSM with a slight non-universal deformation in the Higgs sector. Interestingly, this set of well-motivated boundary conditions leads to a number of attractive features: 1) Correct REWSB, 2) Viable neutralino dark matter for $\tan\beta \simeq 41$ in the stau coannihilation region, 3) Automatic large stop mixing due to the built-in identity $A = -3/\sqrt{2}m \simeq -2m$ and large $\tan\beta$ required by appropriate dark matter. This allows for a relatively heavy lightest Higgs with $119 \text{ GeV} \leq m_h \leq 125 \text{ GeV}$ and a not too heavy SUSY spectrum. This range narrows down to $m_h \approx 125 \text{ GeV}$ when the recent constraint on $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ is included. All these features are remarkable since this is not an ad hoc model but was introduced well before LHC data arrived.

Fortunately, this model may be tested at LHC. The SUSY spectrum could start being probed by the LHC at 7 TeV with an integrated luminosity of 5 fb^{-1} (8 TeV with 2 fb^{-1}) and the whole parameter space would be accessible for 14 TeV and 25 fb^{-1} . The signatures would be quite similar to those of a CMSSM model in the stau coannihilation region, with very characteristic signatures involving multi-tau events. If the hint of a Higgs at 125 GeV is confirmed, the colored sparticles will be heavy but still accessible at LHC at 14 TeV. On the other hand, for Higgs masses above 124.5 GeV one finds $m_{\tilde{\tau}_1} - m_{\chi_1^0} \leq 1.7 \text{ GeV}$ and the stau becomes long-lived, with a life-time longer than 10^{-7} s , leaving a distinctive track at the LHC detectors. Interestingly, if $m_{\tilde{\tau}_1} - m_{\chi_1^0} \simeq 0.1 \text{ GeV}$ the stau has the right properties to trigger catalytic processes in nucleosynthesis, alleviating the problems associated to the Lithium abundance in standard BBN. Finally, improved results for $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ from LHCb and CMS in the 2012 LHC run can directly put to test our scheme. If no departure from the SM value is observed it would be ruled out as it stands. Alternatively, one would have to give up on the neutralino as a stable LSP and allow for R-parity violation or else allow for a fermion flux correction ρ_f in the initial soft terms Eq. (2.9).

Although the number of free parameters in the present model is reduced compared to the CMSSM, a certain amount of fine-tuning is still required both to obtain correct REWSB and viable neutralino dark matter. Still, the naturally large stop mixing makes possible to obtain a Higgs with a somewhat large mass in the range $119 \text{ GeV} \leq m_h \leq 125 \text{ GeV}$ and *at the same time* a squark/gluino spectrum below 3 TeV, accessible at the LHC.

Concerning the origin of these fine-tunings, the fact that small deviations from the free parameters M , μ and ρ_H and the third generation Yukawa couplings drive the theory into catastrophic regions with unbroken EW symmetry and/or above critical matter densities, may suggest an environmental (anthropic) origin. One may argue along the lines of Ref. [32] that indeed the *little hierarchy* problem of the MSSM may have an anthropic explanation. We have seen that the requirement of viable neutralino dark matter could also add arguments in the same direction. One may argue that if soft parameters and third generation Yukawa couplings *scan* in a landscape, this would tend to favor the largest values of the M parameter consistent with both REWSB and neutralino dark matter, which in turn favour a Higgs mass of order 125 GeV. These arguments are however only qualitative and a more complete understanding of the interplay between REWSB and dark matter in environmental selection would be needed.

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