SUSY into Darkness: Heavy Scalars in the CMSSM

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Abstract

A survey of the mSUGRA/CMSSM parameter space is presented. The viable regions of the parameter space which satisfy standard experimental constraints are identified and discussed. These constraints include a $124 - 127$ GeV mass for the lightest CP-even Higgs and the correct relic density for cold dark matter (CDM). The superpartner spectra corresponding to these regions fall within the well-known hyperbolic branch (HB) and are found to possess sub-TeV neutralinos and charginos, with mixed Bino/Higgsino LSP’s with $200 - 800$ GeV masses. In addition, the models possess $\sim 3 - 4$ TeV gluino masses and heavy squarks and sleptons with masses $m_\tilde{q}, m_\tilde{l} > m_\tilde{g}$. Spectra with a Higgs mass $m_h \cong 125$ GeV and a relic density $0.105 \leq \Omega_\chi h^2 \leq 0.123$ are found to require EWFT at around the one-percent level, while those spectra with a much lower relic density require EWFT of only a few percent. Moreover, the SI neutralino-proton direct detection cross-sections are found to be below or within the XENON100 $2\sigma$ limit and should be experimentally accessible now or in the near future. Finally, it is pointed-out that the supersymmetry breaking soft terms corresponding to these regions of the mSUGRA/CMSSM parameter space ($m_0 \propto m_{1/2}$ with $m_0^2 >> m_{1/2}^2$ and $A_0 = -m_{1/2}$) may be obtained from general flux-induced soft terms in Type IIB flux compactifications with D3 branes.

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I. INTRODUCTION

The recent discovery of a Higgs-like particle with a mass in the range 124 – 127 GeV is perhaps the single greatest development in high-energy physics in recent memory [1, 2]. If this particle is indeed the Higgs scalar, it not only represents the final piece of the Standard Model (SM), but can potentially open a window into the world beyond the SM. However, an important question that must be answered is the problem of how such an elementary scalar remains so light against quantum corrections, an issue known as the hierarchy problem.

An elegant solution to the hierarchy problem is supersymmetry (SUSY). One of the best motivated and most studied extensions of the Standard Model (SM) is the incorporation of SUSY into the Minimal Supersymmetric Standard Model (MSSM). However, nature itself is not so elegant since the superpartners have not been observed with the same masses as their SM counterparts, and so SUSY must be a broken symmetry. Although the exact mechanism and scale at which SUSY is broken in nature should it exist is not known, simple calculations suggest that the masses of the superpartners should have $\mathcal{O}(1 \text{ TeV})$ masses if SUSY solves the hierarchy problem without requiring any fine-tuning. Moreover, it can be shown that there is an upper bound on the Higgs mass in the MSSM, $m_h \lesssim 130 \text{ GeV}$ [3], which is in nice accord with the Higgs-like resonance observed at the LHC. Moreover, in addition to providing a solution to the hierarchy problem, SUSY with R-parity imposed can provide a natural candidate for dark matter [4–6]. Finally, the apparent convergence of the gauge couplings when extrapolated to high energies is more precise when SUSY is incorporated compared to the non-SUSY SM, consistent with the idea of Grand Unification [7, 8].

Despite these many attractive features of SUSY, data from the the Large Hadron Collider (LHC) has been infringing upon this rosy scenario as of late. In particular, the LHC has thus far failed to find any new particles beyond the SM. Indeed, direct searches for squarks and gluinos are pushing the mass limits for these particles into the TeV range [9–13]. Furthermore, to obtain a $\sim 125 \text{ GeV}$ Higgs mass in the MSSM requires large radiative corrections involving the top/stop sector, requiring large stop squark masses $\mathcal{O}(\text{TeV})$ and/or large values of $\tan \beta$. In spite of this, reports of the demise of SUSY are greatly exaggerated. Indeed, in some extended models it is possible to obtain a 125 GeV Higgs while maintaining a light spectrum of superpartners [14, 15].

Perhaps the most-studied framework for supersymmetry breaking is minimal supergravity
(mSUGRA), or equivalently the Constrained MSSM (CMSSM) \[16–18\]. However, to obtain a sufficiently large Higgs mass in mSUGRA/CMSSM seemingly requires heavy squarks and sleptons which generically spoils the naturalness in which the hierarchy problem is solved by introducing some amount of electroweak fine-tuning (EWFT). One possible exception to this is the hyperbolic branch (HB)/focus point (FP) region of the mSUGRA/CMSSM parameter space characterized by large $m_0$ in comparison to $m_{1/2}$ where the amount of required EWFT is minimized in respect to the full parameter space \[19–24\]. Several different groups have recently reassessed the status of mSUGRA/CMSSM in light of the \( \sim 125 \text{ GeV} \) Higgs discovery \[25–38\] (see \[39\] for a similar analysis in the context of anomaly mediation). It is generally agreed that the mSUGRA/CMSSM parameter space is being squeezed by this discovery and pushed into regions which require a degree of fine-tuning. In \[40\], a study of the parameter space in regards to fine-tuning was performed and it was concluded that there are no regions where the Higgs is sufficiently heavy and where the relic density may satisfy the WMAP constraint that do not require large fine-tuning.

In the following, scans of the mSUGRA/CMSSM parameter space have been performed. Viable regions of the parameter space, which appear to fall within the HB region of the CMSSM parameter space, are identified. In contrast to what was found \[40\], these regions do not seem to require excessive EWFT. The superpartner spectra corresponding to these regions will be found to possess sub-TeV neutralinos and charginos, with mixed Bino/Higgsino LSP’s with 200 – 800 GeV masses. In addition, the models will be shown to possess \( \sim 3–4 \text{ TeV} \) gluino masses and heavy squarks and sleptons with masses $m_{\tilde{g}}, m_{\tilde{t}} > m_{\tilde{\chi}}$. Spectra with a Higgs mass $m_h \geq 125 \text{ GeV}$ and a relic density $0.105 \leq \Omega_{\chi}h^2 \leq 0.123$ are found to require EWFT at around the one-percent level, while those spectra with a relic density much lower require EWFT of only a few percent. Moreover, the spin-independent neutralino-proton cross-sections for direct detection of dark matter for these spectra are below the XENON100 limit \[41, 42\] and should be experimentally accessible in the near future. Finally, it is pointed-out that the supersymmetry breaking soft terms corresponding to these regions of the mSUGRA/CMSSM parameter space ($m_0 \propto m_{1/2}$ with $m_0^2 >> m_{1/2}^2$ and $A_0 = -m_{1/2}$) may be obtained from general flux-induced soft terms in Type IIB flux compactifications with D3 branes.
II. PARAMETER SPACE

The most studied model of supersymmetry breaking is minimal supergravity (mSUGRA), which arises from adopting the simplest ansatz for the Kähler metric, treating all chiral superfields symmetrically. In this framework, $\mathcal{N} = 1$ supergravity is broken in a hidden sector which is communicated to the observable sector through gravitational interactions. Such models are characterized by the following parameters: a universal scalar mass $m_0$, a universal gaugino mass $m_{1/2}$, the Higgsino mixing $\mu$-parameter, the Higgs bilinear $B$-parameter, a universal trilinear coupling $A_0$, and $\tan \beta$. One then determines the $B$ and $|\mu|$ parameters by the minimization of the Higgs potential triggering REWSB [43, 44], with the sign of $\mu$ remaining undetermined. The soft terms are then input into MicrOMEGAs 2.4.5 [45–47] using SuSpect 2.40 [48] as a front end to evolve the soft terms down to the electroweak scale via the Renormalization Group Equations (RGEs) and then to calculate the corresponding relic neutralino density. We take the top quark mass to be $m_t = 173.2 \pm 0.9$ GeV [49] and leave $\tan \beta$ as a free parameter, while $\mu$ is determined by the requirement of REWSB. However, we do take $\mu > 0$ as suggested by the results of $g^\mu - 2$ for the muon.

In analyzing the resulting data, we consider the following experimental constraints:

1. The WMAP 9-year $2 - \sigma$ preferred range [50] for the cold dark matter density, $0.105 \leq \Omega_{\chi^0} h^2 \leq 0.123$. We consider two cases, one where a neutralino LSP is the dominant component of the dark matter and another where it makes up a subdominant component such that $0 \leq \Omega_{\chi^0} h^2 \leq 0.123$.

2. The experimental limits on the Flavor Changing Neutral Current (FCNC) process, $b \to s\gamma$. The results from the Heavy Flavor Averaging Group (HFAG) [52], in addition to the BABAR, Belle, and CLEO results, are: $Br(b \to s\gamma) = (355 \pm 24^{+9}_{-10} \pm 3) \times 10^{-6}$. There is also a more recent estimate [53] of $Br(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$. For our analysis, we use the limits $2.86 \times 10^{-4} \leq Br(b \to s\gamma) \leq 4.18 \times 10^{-4}$, where experimental and theoretical errors are added in quadrature.

[1] The first results from the Planck experiment [51], with a slightly larger value for the dark matter density $\Omega_c h^2 = 0.1199 \pm 0.0027$, appeared shortly after the first version of the paper was produced. Using the Planck result rather than the WMAP bounds results in a slight shifts in the parameter spaces shown in Figs. [1-4], but does not alter the fundamental conclusions of this paper.
FIG. 1: The mSUGRA $m_{1/2}$ vs. $m_0$ plane with $A_0 = -m_{1/2}$, $\mu > 0$, $\tan\beta = 30$, and $m_t = 173$ GeV. The region shaded in black indicates a relic density $0.105 \lesssim \Omega_{\chi} h^2 \lesssim 0.123$, the region shaded in red indicates $\Omega_{\chi} h^2 \lesssim 0.123$, while the region shaded in green has a charged LSP. The black contour lines indicate the lightest CP-even Higgs mass.

3. The process $B_s^0 \rightarrow \mu^+\mu^-$ which has recently been observed to be in the range $2 \times 10^{-9} < BF(B_s^0 \rightarrow \mu^+\mu^-) < 4.7 \times 10^{-9}$ by LHCb [54].

4. The lightest CP-even Higgs mass in the range $124$ GeV $\lesssim m_h \lesssim 127$ GeV as observed by the ATLAS and CMS experiments at the LHC [1, 2].

In the following, we will not require that the anomalous magnetic moment of the muon [55], $4.7 \times 10^{-10} \leq a_\mu \approx 52.7 \times 10^{-10}$, is solved by contributions from supersymmetric particles as the spectra that will be studied may only make a small contribution. Furthermore, there are large hadronic contributions to this anomaly that require delicate
FIG. 2: The mSUGRA $m_{1/2}$ vs. $m_0$ plane for $\tan\beta = 20$ and $\tan\beta = 40$ with $A_0 = -m_{1/2}$, $\mu > 0$, and $m_t = 173.1$ GeV. The region shaded in black indicates a relic density $0.102 \lesssim \Omega \chi_0 h^2 \lesssim 0.123$, while the region shaded in red indicates $\Omega \chi_0 h^2 \lesssim 0.123$. The black contour lines indicate the lightest CP-even Higgs mass.

TABLE I: Low energy supersymmetric particles and their masses (in GeV) for $m_{1/2} = 1560$, $m_0 = 6510$, $A_0 = -1560$, $\tan\beta = 30$, $\mu > 0$ and $m_t = 173.1$ GeV. Here $\Omega \chi_0 h^2 = 0.103$, $\sigma_{p-\chi^0}^{SI} = 3.575 \times 10^{-8}$ pb, $\Delta_{EW} = 111.4$, $Br(B_s \to \mu^+\mu^-) = 3.05 \times 10^{-9}$, $a_\mu = 0.2575 \times 10^{-10}$, and $Br(b \to s\gamma) = 3.2 \times 10^{-4}$.

| $\tilde{h}^0$ | $H^0$ | $A^0$ | $H^\pm$ | $\tilde{g}$ | $\tilde{\chi}_1^\pm$ | $\tilde{\chi}_2^\pm$ | $\tilde{\chi}_1^0$ | $\tilde{\chi}_2^0$ |
|-------------|------|------|-------|----------|----------------|----------------|---------------|---------------|
| 125.1       | 5434.5 | 5434.5 | 5435.3 | 3636     | 691.1         | 1337           | 663.1         | 696.7         |
| $\tilde{\chi}_3^0$ | $\tilde{\chi}_4^0$ | $\tilde{t}_1$ | $\tilde{t}_2$ | $\tilde{u}_R/\tilde{c}_R$ | $\tilde{u}_L/\tilde{c}_L$ | $\tilde{b}_1$ | $\tilde{b}_2$ |
| 728.7       | 1337 | 4516 | 5657 | 7026     | 6997          | 5666           | 6481           |
| $\tilde{d}_R/\tilde{s}_R$ | $\tilde{d}_L/\tilde{s}_L$ | $\tilde{\tau}_1$ | $\tilde{\tau}_2$ | $\tilde{e}_R/\tilde{\mu}_R$ | $\tilde{e}_L/\tilde{\mu}_L$ | $\tilde{\nu}_e/\tilde{\nu}_\mu$ | $LSP$ |
| 7026       | 6995 | 6018 | 6312 | 6311     | 6556          | 6522           | 6556           | Bino/Higgsino |

subtractions with large uncertainties [56].

In order to generate superpartner and Higgs spectra, we shall work within the mSUGRA/CMMSM framework. Here we will generate a set of soft terms for the mSUGRA/CMSSM parameter space. We take the top quark mass to be $m_t = 173.2 \pm 0.9$ GeV. We vary $m_0$ and $m_{1/2}$ each in increments of 10 GeV between 500 – 7500 GeV for each scan. In addition, we fix $A_0 = -m_{1/2}$ as this relation is typical of soft terms induced
TABLE II: Low energy supersymmetric particles and their masses (in GeV) for $m_{1/2} = 1910$, $m_0 = 7460$, $A_0 = -1910$, $\tan \beta = 30$, $\mu > 0$, and $m_t = 173.1$ GeV. Here $\Omega_{\chi^0 h^2} = 0.113$, $\sigma^{SI}_{p-\chi^0} = 3.089 \times 10^{-8}$ pb, $\Delta_{EW} = 162.9$, $Br(B_s \rightarrow \mu^+ \mu^-) = 3.06 \times 10^{-9}$, $a_\mu = 0.1920 \times 10^{-10}$, and $Br(b \rightarrow s \gamma) = 3.2 \times 10^{-4}$.

| $h^0$  | $H^0$  | $A^0$ | $H^\pm$ | $\tilde{g}$ | $\tilde{\chi}_1^\pm$ | $\tilde{\chi}_2^0$ | $\tilde{\chi}_1^0$ | $\tilde{\chi}_2^0$ |
|-------|-------|-------|---------|----------|-----------------|-----------------|-----------------|-----------------|
| 125.8 | 6242.3| 6242.3| 6243.0  | 4368.0   | 837.3           | 1637.0          | 815.4           | 841.8           |
| $\tilde{\chi}_3^0$ | $\tilde{\chi}_4^0$ | $\tilde{\tau}_1$ | $\tilde{\tau}_2$ | $\tilde{u}_R/\tilde{c}_R$ | $\tilde{u}_L/\tilde{c}_L$ | $\tilde{b}_1$ | $\tilde{b}_2$ |
| 886.5 | 1637  | 5267  | 6569    | 8127     | 8086            | 6581            | 7496            |
| $\tilde{d}_R/\tilde{s}_R$ | $\tilde{d}_L/\tilde{s}_L$ | $\tilde{\tau}_1$ | $\tilde{\tau}_2$ | $\tilde{\nu}_\tau$ | $\tilde{\epsilon}_R/\tilde{\epsilon}_R$ | $\tilde{\epsilon}_L/\tilde{\epsilon}_L$ | $\tilde{\nu}_\tau/\tilde{\nu}_\tau$ | LSP |
| 8127  | 8082  | 6902  | 7246    | 7246     | 7525            | 7478            | 7524            | Bino/Higgsino |

from fluxes in Type IIB string compactifications. Scans are made for different values of $\tan \beta$, while $\mu$ is determined by the requirement of radiative electroweak symmetry breaking (EWSB). In addition to imposing experimental constraints, the spectra are filtered from the final data set if the iterative procedure employed by SuSpect does not converge to a reliable solution.

A contour plot of the $m_{1/2}$ vs. $m_0$ plane for $\tan \beta = 30$ is shown in Fig. 1. Regions satisfying different constraints are as indicated on the figure. Here, we can see that there is a linear band shaded in black where the lightest neutralino relic density satisfies $0.105 \lesssim \Omega_{\chi^0 h^2} \lesssim 0.123$ which sits inside a broader linear band shaded in red where the relic density satisfies $\Omega_{\chi^0 h^2} \lesssim 0.123$. These bands lie along the HB branch of the mSUGRA/CMSSM parameter space. The values of the lightest CP-even Higgs mass are indicated on the plot by the black contours lines. It can be seen from this plot that there are regions of this parameter space where the relic density is in the range $0.105 \lesssim \Omega_{\chi^0 h^2} \lesssim 0.123$ and where the desired Higgs mass may be also obtained. Please note that although these plots seem to indicate that these spectra lie along a continuous band, they are actually interspersed with spectra where SuSpect is not able to converge to a solution. Sample spectra with $m_h = 125.2$ GeV and $\Omega_{\chi^0 h^2} = 0.103$ are shown in Table II and with $m_h = 125.8$ GeV and $\Omega_{\chi^0 h^2} = 0.113$ is shown in Table III. As is typical for spectra in the HB region of the parameter space, the lightest neutralino has a large Higgsino component while the squarks and sleptons all have masses greater than the gluino mass. For all of the spectra for which the Higgs mass
FIG. 3: The spin-independent (SI) neutralino-proton direct detection cross-sections vs. neutralino mass for regions of the parameter space where $\Omega_{\chi^0} h^2 \leq 0.123$. The region shaded in black indicates $0.105 \lesssim \Omega_{\chi^0} h^2 \lesssim 0.123$. The upper limit on the cross-section obtained from the XENON100 experiment is shown in blue with the ±2σ bounds shown as dashed curves, while the red dashed curved indicates the future reach of the XENON1T experiment.

satisfies $124 \text{ GeV} \lesssim m_h \lesssim 127 \text{ GeV}$ and for which the relic density satisfies the WMAP constraint, the gluino mass is in the range $3 - 4 \text{ TeV}$. Thus, these spectra result in the ‘Higgsino World’ scenario\cite{57}. Due to the heavy masses for the gluino and squarks in these models, it would be very difficult to observe any superpartners at the LHC if the spectrum of superpartners falls into these regions of the parameter space. However, the prospects for observing superpartners at a linear collider or at a higher-energy hadron collider appear to be more promising. Similar results are obtained for $\tan\beta = 20$ and $\tan\beta = 40$ as can be seen in Fig. 2.
FIG. 4: The spin-independent (SI) neutralino-proton direct detection cross-sections vs. neutralino mass for regions of the parameter space where $\Omega_{\chi^0} h^2 \leq 0.123$. The region shaded in yellow-green a Higgs mass $m_h \geq 124$ GeV. The upper limit on the cross-section obtained from the XENON100 experiment is shown in blue with the $\pm 2\sigma$ bounds shown as dashed curves, while the red dashed curve indicates the reach of the XENON1T experiment.

While these spectra may not create an observable signal at the LHC, the relic neutralino-proton SI cross-sections for dark matter direct detection are currently being probed by the XENON100 experiment. Plots of the SI neutralino-proton cross-sections vs. neutralino mass are shown in Fig. 3 and Fig. 4. As can be seen from these plots, regions of the parameter space with a Higgs mass $m_h \lesssim 124$ GeV and a relic density in the range $0.105 \lesssim \Omega_{\chi^0} h^2 \lesssim 0.123$ have been excluded by the upper limit on the proton-neutralino SI cross-section from XENON100. However, regions of the parameter space with $m_h \gtrsim 124$ GeV and a relic neutralino density at or below the WMAP limit are still viable, at least within the $2\sigma$ range. These regions
FIG. 5: Contour plot of the $\Delta_{EW}$ vs. $m_h$ for the parameter space with $\Omega_{\chi^0 h^2} \leq 0.15$. The different colors denote different ranges for the neutralino relic density, $\Omega_{\chi^0 h^2}$. The areas covered in green indicate regions of the parameter space with a relic density which falls into the WMAP preferred range.

of the parameter space should either be excluded in the next update, or they should see a clear signal. In particular, the XENON1T experiment should be able to completely probe this parameter space. However, it should be noted that the dark matter constraint on this parameter may only be imposed if R-parity is conserved. Thus, even if the XENON1T experiment reports negative results, the supersymmetry parameter space would still be viable if R-parity violation is allowed.
III. FINE-TUNING

One of the strongest reasons for introducing low-scale SUSY is to solve the hierarchy problem. The parameter space which has been found does this, however it is an important question whether or not this is accomplished naturally without reintroducing any fine-tuning (the little hierarchy problem). Ordinarily, such spectra with large scalar masses would generically be considered fine-tuned. This is not necessarily true for those spectra which fall in the HB region of the parameter space, such as those falling upon the red and black bands of Fig. 1. The amount of fine-tuning with respect to the electroweak scale (EWFT) is typically signified by the fine-tuning parameter

\[ \Delta_{EW} \equiv \max(C_i)/(M_Z^2/2), \]  

where \( C_\mu \equiv |-\mu^2|, C_{H_u} \equiv |-m_{H_u}^2 tan^2 \beta/(tan^2 \beta - 1)|, \) and \( C_{H_d} \equiv |-m_{H_d}^2/(tan^2 \beta - 1)|. \) The percent-level of EWFT is then given by \( \Delta_{EW}^{-1}. \) It should be noted that for most of the parameter space explored in this analysis \( C_\mu \) is dominant, and so generally we have \( \Delta_{EW} = |-\mu^2|/(M_Z^2/2). \) In [40], it is argued that \( \Delta_{EW} \) only provides a measure of the minimum amount of fine-tuning in regards to the electroweak scale and provides no information about the high scale physics involved in a particular model of SUSY breaking. In order to provide a measure of how fine-tuned a particular model is given knowledge of how SUSY is broken at high energy scale, a parameter called \( \Delta_{HS} \) was introduced which is analogous to \( \Delta_{EW} [40]. \) For most of the parameter space this parameter is given by

\[ \Delta_{HS} = \frac{m_0^2 + \mu^2}{(M_Z^2/2)} = \Delta_{EW} + \frac{m_0^2}{(M_Z^2/2)}. \]  

As we can see, for regions of the mSUGRA/CMSSM parameter space with large scalar masses, \( \Delta_{HS} \) is very large even for those cases where \( \Delta_{EW} \) is small such as in the HB regions. This simply reflects the fact that, although a particular SUSY spectrum may be completely natural and solve the hierarchy problem without any fine-tuning, obtaining this spectrum within the mSUGRA/CMSSM framework of SUSY breaking requires large cancellations which only happens for specific sets of soft-terms rather than the general parameter space.

In Fig. 5, a contour plot of \( \Delta_{EW} \) vs. \( m_h \) is shown for the parameter space satisfying \( \Omega_{\chi^0 h^2} \leq 0.123. \) The different colored regions of the plot denote different ranges of \( \Omega_{\chi^0 h^2}. \) From this plot, it can be seen that the amount of EWFT appears to be proportional to
\[ m^2_{\tilde{H}_u} - m^2_{\tilde{H}_d} \] as might be expected from the Higgs potential. In addition, the amount of EWFT seems to increase linearly with relic density. For spectra with a relic density \( 0.105 \leq \Omega_{\chi} h^2 \leq 0.123 \) and a Higgs mass \( m_h = 124 \text{ GeV} \), \( \Delta_{EW} \approx 60 \) and thus requires minimum EWFT at about the two-percent level. On the other hand, spectra with the same relic density and a Higgs mass \( m_h = 125 \text{ GeV} \) requires minimum EWFT at the percent level. Conversely, spectra with a very low relic density can have a 125 GeV Higgs mass and only require EWFT at the five-percent level. However, in this case the neutralino LSP can only provide a small component of the cold dark matter (see [59] for a similar study prior to the discovery Higgs-like resonance).

**IV. FLUX-INDUCED SOFT TERMS ON D3 BRANES**

From the analysis of the previous sections, it can be seen that there are spectra within the mSUGRA/CMSSM parameter space which may solve the hierarchy problem while only requiring EWFT of a percent or greater. However, as discussed in the last section it does require a large amount of fine-tuning to obtain these spectra within the specific framework of supersymmetry breaking, mSUGRA/CMSSM. Within this framework, it is rather unnatural to have a universal scalar mass which is so much larger than the universal gaugino mass, \( m_0^2 >> m_{1/2}^2 \), as large cancellations are required to obtain a light Higgs mass. Clearly, it would be desirable to have a specific model of supersymmetry breaking for which large scalar masses in comparison to the gaugino masses arise naturally.

Over the past decade, there has been much progress in constructing realistic models in Type I and Type II string compactifications [60, 61]. In these models, the SM fields are localized within the world-volume of D-branes embedded in a closed 10-d closed string background. Physical observables such as gauge and Yukawa couplings are dependent upon the moduli of compactification, which must be stabilized in order to have a true vacuum. It has been shown that in Type IIB compactifications non-trivial backgrounds of NSNS and RR 3-form field strength fluxes generically fix the VEVs of the dilaton and all complex structure moduli.

Besides fixing the VEVs of the moduli fields, these fluxes may also induce SUSY-breaking soft terms. As shown in [62], for the most general combination involving both imaginary selfdual (ISD) and imaginary anti-selfdual (IASD) fluxes, the soft terms on D3 branes take
the form
\[ m_0^2 = \frac{|m_{1/2}|^2}{3} [1 - \tan \theta \cos(\delta + \beta)], \quad (4.1) \]
\[ A^{ijk} = -m_{1/2} h^{ijk}. \]

For real flux backgrounds (\( \delta = \beta = 0 \mod 2\pi \)), and \( \tan \theta = 0 \) the flux-induced soft terms take the dilaton-dominated form of no-scale supergravity. In addition, for \( \tan \theta >> -1 \) one finds that \( m_0 \propto m_{1/2} \) with \( m_0 >> m_{1/2} \) and \( A = -m_{1/2} \), which is exactly the form of the soft terms required to match the viable region of the parameter space found in the analysis of the previous sections.

Thus, if the MSSM is built on D3 branes in Type IIB string theory with a combination of ISD and IASD fluxes in the background, then it is possible to induce soft terms of the form studied in this paper. In such a model of SUSY-breaking, large scalar masses with \( m_0 >> m_{1/2} \) are then completely natural in contrast to the situation with mSUGRA/CMSSM where there is no \textit{a priori} correlation between \( m_0 \) and \( m_{1/2} \).

V. CONCLUSION

We have surveyed the mSUGRA/CMSSM parameter space for \( \tan \beta = 20, \tan \beta = 30, \) and \( \tan \beta = 40 \) with the restriction \( A_0 = -m_{1/2} \). We have found that there are viable areas of the parameter space where the lightest CP-even Higgs mass is in the range \( 124 \text{ GeV} \lesssim m_h \lesssim 127 \text{ GeV} \), the relic neutralino density is below the WMAP constraint, \( \Omega_{\chi^0 h^2} \leq 0.123 \), and standard experimental constraints are satisfied. These areas of the parameter space appear to lie along the HB regions of the mSUGRA/CMSSM parameter space. The corresponding spectra features neutralinos and charginos with sub-TeV masses, gluino masses in the range \( 3 - 4 \text{ TeV} \), and heavy squarks and sleptons with masses greater than 4 TeV. The lightest neutralino is a mixture of Bino and Higgsino. It would be difficult for these spectra to produce an observable signal at the LHC. However, the prospects for their observation at a linear collider are much more promising.

[2] However, there is one problem with this scenario. It is known that only ISD fluxes solve the equations of motion. Thus, it is only possible to stabilize the moduli with ISD fluxes. With only D3 branes and including both ISD and IASD fluxes, one may have soft terms of the desired form, but one would require other nonperturbative effects to stabilize the moduli.
While these spectra may not create an observable signal at the LHC, the relic neutralino-proton SI cross-sections for dark matter direct detection are currently being probed by the XENON100 experiment. At present, regions of the parameter space with a Higgs mass $m_h \lesssim 124$ GeV and a relic density in the range $0.095 \lesssim \Omega_{\chi_0} h^2 \lesssim 0.125$ have been excluded by the upper limit on the proton-neutralino SI cross-section from XENON100. However, regions of the parameter space with $m_h \gtrsim 124$ GeV and a relic neutralino density at or below the WMAP limit are still viable. These regions of the parameter space should either be excluded in the next update, or they should see a discernable signal.

We have also investigated the question of fine-tuning with respect to both the electroweak scale and the high scale of supersymmetry breaking. We have found that the spectra with a large enough Higgs mass $124$ GeV $\lesssim m_h \lesssim 127$ GeV and the correct relic density $0.109 \lesssim \Omega_{\chi_0} h^2 \lesssim 0.123$ require at least a one-percent EWFT, while spectra satisfying the Higgs constraint but which possess a low relic density are fine-tuned at the five-percent level. As these spectra fall into regions of the parameter space where $m_0^2 \gg m_Z^2$, these spectra are highly fine-tuned with respect to the high scale, at least within the context of mSUGRA/CMSSM.

Finally, we have discussed the inducement of SUSY-breaking soft-terms from supergravity fluxes which appear in Type IIB string compactifications. Such fluxes may be utilized in regards to the moduli stabilization problem of string theory compactifications. We have pointed out that for a general combination of ISD and IASD fluxes with D3 branes, the soft terms may have exactly the same form as those which give rise to the viable parameter space we have investigated in the paper, namely $m_0 \propto m_{1/2}$ with $m_0 \gg m_{1/2}$ and $A_0 = -m_{1/2}$. Thus, in contrast to mSUGRA/CMSSM, having large $m_0$ compared to $m_{1/2}$ can potentially arise naturally within the context of Type IIB flux compactifications, in constrast to the situation with mSUGRA/CMSSM.

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[1] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 716, 1 (2012) [arXiv:1207.7214 [hep-ex]].
[2] S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 716, 30 (2012) [arXiv:1207.7235 [hep-ex]].
[3] M. S. Carena and H. E. Haber, Prog. Part. Nucl. Phys. 50, 63 (2003) [hep-ph/0208209].
[4] J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos and M. Srednicki, Phys. Lett. B 127, 233 (1983).
[5] J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. A. Olive and M. Srednicki, Nucl. Phys. B 238, 453 (1984).
[6] J. R. Ellis, D. V. Nanopoulos and K. Tamvakis, Phys. Lett. B 121, 123 (1983).
[7] S. Dimopoulos, S. Raby and F. Wilczek, Phys. Rev. D 24, 1681 (1981).
[8] L. E. Ibanez and G. G. Ross, Phys. Lett. B 105, 439 (1981).
[9] G. Aad et al. [ATLAS Collaboration], [arXiv:1208.0949 [hep-ex]].
[10] G. Aad et al. [ATLAS Collaboration], JHEP 1207, 167 (2012) [arXiv:1206.1760 [hep-ex]].
[11] S. Chatrchyan et al. [CMS Collaboration], Phys. Rev. Lett. 109, 171803 (2012) [arXiv:1207.1898 [hep-ex]].
[12] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 710, 67 (2012) [arXiv:1109.6572 [hep-ex]].
[13] S. Chatrchyan et al. [CMS Collaboration], Phys. Rev. Lett. 107, 221804 (2011) [arXiv:1109.2352 [hep-ex]].
[14] T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, Phys. Lett. B 718, 70 (2012).
[15] U. Ellwanger, C. Hugonie and A. M. Teixeira, Phys. Rept. 496, 1 (2010) [arXiv:0910.1785 [hep-ph]].
[16] A. H. Chamseddine, R. L. Arnowitt and P. Nath, Phys. Rev. Lett. 49, 970 (1982).
[17] N. Ohta, Prog. Theor. Phys. 70, 542 (1983).
[18] L. J. Hall, J. D. Lykken and S. Weinberg, Phys. Rev. D 27, 2359 (1983).
[19] K. L. Chan, U. Chattopadhyay and P. Nath, Phys. Rev. D 58, 096004 (1998) [hep-ph/9710473].
[20] J. L. Feng, K. T. Matchev and T. Moroi, Phys. Rev. Lett. 84, 2322 (2000) [hep-ph/9908309].
[21] J. L. Feng, K. T. Matchev and T. Moroi, Phys. Rev. D 61, 075005 (2000) [hep-ph/9909334].
[22] H. Baer, C. -h. Chen, F. Paige and X. Tata, Phys. Rev. D 52, 2746 (1995) [hep-ph/9503271].
[23] H. Baer, C. -h. Chen, M. Drees, F. Paige and X. Tata, Phys. Rev. D 59, 055014 (1999) [hep-ph/9809223].

[24] U. Chattopadhyay, A. Corsetti and P. Nath, Phys. Rev. D 68, 035005 (2003) [hep-ph/0303201].

[25] M. Kadastik, K. Kannike, A. Racioppi and M. Raidal, JHEP 1205, 061 (2012) [arXiv:1112.3647 [hep-ph]].

[26] C. Strege, G. Bertone, D. G. Cerdeno, M. Fornasa, R. Ruiz de Austri and R. Trotta, JCAP 1203, 030 (2012) [arXiv:1112.4192 [hep-ph]].

[27] L. Aparicio, D. G. Cerdeno and L. E. Ibanez, JHEP 1204, 126 (2012) [arXiv:1202.0822 [hep-ph]].

[28] J. Ellis and K. A. Olive, Eur. Phys. J. C 72, 2005 (2012) [arXiv:1202.3262 [hep-ph]].

[29] H. Baer, V. Barger and A. Mustafayev, JHEP 1205, 091 (2012) [arXiv:1202.4038 [hep-ph]].

[30] K. Matchev and R. Remington, [arXiv:1202.6580 [hep-ph]].

[31] S. Akula, P. Nath and G. Peim, Phys. Lett. B 717, 188 (2012) [arXiv:1207.1839 [hep-ph]].

[32] D. Ghosh, M. Guchait, S. Raychaudhuri and D. Sengupta, Phys. Rev. D 86, 055007 (2012) [arXiv:1205.2283 [hep-ph]].

[33] A. Fowlie, M. Kazana, K. Kowalska, S. Munir, L. Roszkowski, E. M. Sessolo, S. Trojanowski and Y. -L. S. Tsai, Phys. Rev. D 86, 075010 (2012) [arXiv:1206.0264 [hep-ph]].

[34] O. Buchmueller, R. Cavanaugh, M. Citron, A. De Roeck, M. J. Dolan, J. R. Ellis, H. Flacher and S. Heinemeyer et al., Eur. Phys. J. C 72, 2243 (2012) [arXiv:1207.7315 [hep-ph]].

[35] C. Strege, G. Bertone, F. Feroz, M. Fornasa, R. R. de Austri and R. Trotta, [arXiv:1212.2636 [hep-ph]].

[36] M. Citron, J. Ellis, F. Luo, J. Marrouche, K. A. Olive and K. J. de Vries, [arXiv:1212.2886 [hep-ph]].

[37] J. Ellis, F. Luo, K. A. Olive and P. Sandick, [arXiv:1212.4476 [hep-ph]].

[38] C. Boehm, J. Da Silva, A. Mazumdar and E. Pukartas, Phys. Rev. D 87, 023529 (2013) [arXiv:1205.2815 [hep-ph]].

[39] N. Okada and H. M. Tran, [arXiv:1212.1866 [hep-ph]].

[40] H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev and X. Tata, [arXiv:1210.3019 [hep-ph]].
[41] E. Aprile et al. [XENON100 Collaboration], Phys. Rev. Lett. 107, 131302 (2011) [arXiv:1104.2549 [astro-ph.CO]].

[42] E. Aprile et al. [XENON100 Collaboration], Phys. Rev. Lett. 109, 181301 (2012) [arXiv:1207.5988 [astro-ph.CO]].

[43] J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos and K. Tamvakis, Phys. Lett. B 125, 275 (1983).

[44] L. Alvarez-Gaume, J. Polchinski and M. B. Wise, Nucl. Phys. B 221, 495 (1983).

[45] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, arXiv:1005.4133 [hep-ph].

[46] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, arXiv:0803.2360 [hep-ph].

[47] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. 176 (2007) 367 [arXiv:hep-ph/0607059].

[48] A. Djouadi, J. Kneur, and G. Moultaka, Comput. Phys. Commun. 176, (2007) 426-455. arXiv:hep-ph/0211331v2

[49] [Tevatron Electroweak Working Group and CDF and D0 Collaborations], arXiv:1107.5255 [hep-ex].

[50] G. Hinshaw, D. Larson, E. Komatsu, D. N. Spergel, C. L. Bennett, J. Dunkley, M. R. Nolta and M. Halpern et al., arXiv:1212.5226 [astro-ph.CO].

[51] P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5076 [astro-ph.CO].

[52] E. Barberio, et al (Heavy Flavor Averaging Group), arXiv:hep-ex/0704.3575v1

[53] M. Misiak et al, Phys. Rev. Lett. 98, 022002 (2007). arXiv:hep-ph/0609232v2

[54] RAaij et al. [LHCb Collaboration], Phys. Rev. Lett. 110, 021801 (2013) [arXiv:1211.2674].

[55] G. W. Bennett et al (Muon g-2 Collaboration), Phys. Rev. Lett. 92, 161802 (2004). arXiv:hep-ex/0401008

[56] M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C 71, 1515 (2011) [Erratum-ibid. C 72, 1874 (2012)] arXiv:1010.4180 [hep-ph].

[57] H. Baer, V. Barger and P. Huang, JHEP 1111, 031 (2011) [arXiv:1107.5581 [hep-ph]].

[58] E. Aprile [XENON1T Collaboration], arXiv:1206.6288 [astro-ph.IM].

[59] S. Amsel, K. Freese and P. Sandick, JHEP 1111, 110 (2011) [arXiv:1108.0448 [hep-ph]].

[60] R. Blumenhagen, M. Cvetic, P. Langacker and G. Shiu, Ann. Rev. Nucl. Part. Sci. 55, 71 (2005) hep-th/0502005. 
[61] R. Blumenhagen, B. Kors, D. Lust and S. Stieberger, Phys. Rept. 445, 1 (2007) [arXiv:hep-th/0610327].

[62] P. G. Camara, L. E. Ibanez and A. M. Uranga, Nucl. Phys. B 689, 195 (2004) [hep-th/0311241].