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Well-mixed dark matter and the Higgs

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ABSTRACT

The breaking of electroweak symmetry through renormalization group flow in models that have MSSM spectra is found to produce "well-mixed" neutralino dark matter with a relic density consistent with the WMAP data and elastic scattering cross section with nuclei consistent with current limits from direct dark matter searches. These models predict a Higgs boson mass in the range (125–126) GeV. Well-mixed neutralino dark matter is predominantly bino-like, but has significant Higgsino and wino content, each with fractions of comparable size. With a ~ 1 TeV gluino mass and sizable neutralino–nucleon scattering cross sections, natural models will be fully tested by both the LHC and future dark matter direct detection experiments.

1. Introduction

The discovery of a boson with mass of ~ 125 GeV [1,2] lends support for the existence of softly broken local supersymmetry. The reason is clear: softly broken local supersymmetry generally gives rise to a non-vanishing ratio of soft scalar trilinear to bilinear couplings each with mass scaled by the gravitino mass [3–6]. The soft breaking masses and renormalization group (RG) running then generate the necessary quantum corrections to the Higgs mass [7]. Many well-motivated models of soft breaking include a Higgs mass that is consistent with the LHC data, e.g. [8–17]. The results generally require multi-TeV scalar superpartner masses. At the mass scale at which electroweak symmetry is broken, naturalness requires that the gaugino–Higgsino sector has suppressed masses relative to a multi-TeV scale gravitino mass. By "naturalness" we simply mean that the Higgsino mass parameter, μ, is not excessively large relative to the mass of the Z boson. For a recent discussion on the variable definitions of naturalness for a broad class of models see [18].

The suppression of gaugino masses relative to the scalar superpartner masses means that the lightest supersymmetric particle (LSP) mass is in the range that is being probed by dark matter experiments. In particular, neutralino dark matter [19–21] remains a leading and viable candidate for particle dark matter. We will show in this work that neutralino dark matter with natural values of μ can lead to a signal of dark matter in direct detection experiments while yielding the correct relic abundance of cold dark matter in the universe as observed by the WMAP satellite and others [25], realized within a model with softly broken supersymmetry and REWSB that predicts a mass for the lighter CP-even Higgs boson consistent with that measured at the LHC [1,2].

There are several key features of the models discussed here that evade current constraints. First, at the scale at which the gauge couplings unify (hereafter the unification scale), the gaugino soft masses are split, i.e. they are non-universal. Through renormalization group flow, the lightest neutralino ($\tilde{N}_1$) mass and the lighter chargino ($\tilde{C}_1$) mass can become nearly degenerate at the electroweak scale, thus allowing for $\tilde{N}_1 - \tilde{C}_1$ coannihilations [27–29] in the early universe (coannihilations have recently been revisited in several models [30–32]) that result in thermal relic neutralino dark matter with the correct abundance. Another important feature of the models we discuss is that viable neutralino dark matter candidates are a mixture of bino, wino, and Higgsino eigenstates. The expected neutralino–nucleon elastic scattering cross sections for these models are within reach of current and next generation direct detection experiments, while the continuum gamma-ray flux remains below the current Fermi-LAT sensitivity (for the non-thermal case see [33,34]).

We add here that Ref. [35] has coined the term "well-tempered" neutralino, defined by $|M_1| \simeq |M_2|$ *or* $|\mu| \simeq |M_1|$, where M_1 and M_2 are the electroweak gaugino soft masses. In the models we discuss here, $|M_1| \simeq |M_2|$, while *also* having $|\mu| \approx$ few $\times\, |M_1|$ over a significant region of the parameter space. This results in an LSP that is predominantly bino-like, with a few percent admixture of *both* wino and Higgsino components. We will refer to

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this arrangement, when the wino the Higgsino fractions are close in value, as a *"well-mixed"* neutralino. This model is theoretically well-motivated and gives rise to dark matter and collider signatures within observational reach.

2. Breaking electroweak symmetry and the Higgs

Recently an interesting part of the supergravity parameter space has been uncovered [8] where the square of the soft mass for the up-type Higgs runs small and positive under RG flow leading to the breaking of electroweak symmetry with a rather low value of the μ term for heavy soft breaking scalars at a mass scale of ~ 10's of TeV [8,9,14]. As noted in Ref. [8], the result is not a focus point solution, but instead a new solution to electroweak symmetry breaking owing to the cancellation of RG parameters defined at the unification scale.

To see how the cancellation works, one need only examine the running square of the soft mass for the up-type Higgs, $M^2_{H_u}(t)$, where $t = \ln(Q/Q_0)$ with Q and Q_0 denoting the energy scale and the unification scale, respectively. The soft breaking mass for the up-type Higgs can be written in terms of RG-dependent functions $r_i(t)$ and the soft breaking masses and couplings for the scalars and gauginos. In the one loop approximation the RG equations (RGEs) can be solved analytically giving rise to

$$M^2_{H_u}(t) = r_1(t)M_0^2 - r_2(t)A_0^2 + \epsilon(t), \tag{1}$$

$$\epsilon(t) = r_3(t)A_0M_a + r_4(t)M_a^2 + \cdots \tag{2}$$

where M_0 and A_0 are the universal scalar soft masses and scalar trilinear couplings, and M_a are the gaugino masses, with $a = 1, 2, 3$ for $SU(3)$, $SU(2)$, and $U(1)$ respectively, all defined at the unification scale $Q_0 \approx 2 \times 10^{16}$ GeV. For the case of heavy scalars with suppressed gaugino masses, the term $\epsilon(t)$ is a residual correction and is small. The coefficients of M_0 and A_0 at one loop are $r_1(t) = \frac{1}{2}(3\delta(t) - 1)$ and $r_2(t) = \frac{1}{2}(\delta(t) - \delta^2(t))$, where $\delta(t)$ depends on the gauge couplings and on the top Yukawa. As found in Ref. [8], for electroweak symmetry breaking triggered by a heavy stop, i.e. $Q_{\rm EWSB} \equiv Q^*$ where $Q^* = \sqrt{m_{\tilde t_1} m_{\tilde t_2}}$, the RG functions $r_1(t)$ and $r_2(t)$ begin to approach a common positive value

$$r_1(Q^*) \simeq r_2(Q^*) \sim \mathcal{O}(1/10). \tag{3}$$

This phenomenon has been referred to as an intersection point (IP) [8,36] of the RG flow since the first two terms on the right hand side of Eq. (1) "intersect" and can cancel.

The IP presents the opportunity to drastically reduce $M^2_{H_u}$ relative to M_0^2 and A_0^2. In order to achieve the cancellation, it is obvious that $r_1(Q^*)M_0^2$ and $r_2(Q^*)A_0^2$ should be nearly degenerate. Since $r_1(t) \simeq r_2(t)$, the cancellation requirement becomes a statement that the ratio of the soft parameters $|A_0|/M_0$ approaches unity. We note that a shift in the top pole mass will shift a particular IP value of $|A_0|/M_0$, however the ratio will still be close to unity.

The relationship between M_0 and A_0 can be viewed as a direct consequence of string moduli supersymmetry breaking [5,6], in which the scalar masses and trilinear couplings are related to the gravitino mass, $M_{3/2}$, via

$$M_\alpha^2 \simeq M_{3/2}^2 \simeq M_0^2 \tag{4}$$

and

$$A_{\alpha\beta\gamma} \simeq F^M(\hat K_M + \partial_M \log Y_{\alpha\beta\gamma}) \simeq M_{3/2} \simeq A_0, \tag{5}$$

where F^M is the order parameter of supersymmetry breaking for moduli (M), $\hat K_M$ is the derivative of the Kähler potential, and $Y_{\alpha\beta\gamma}$ are Yukawa couplings. Since M_0 and $|A_0|$ are both equal to $M_{3/2}$, up to small corrections, $|A_0|/M_0 \approx 1$. Furthermore, the bilinear coupling B for the Higgs sector is consistent with $B_0 \simeq 2M_{3/2}$. At the EWSB scale Q^*, μ is suppressed simply because the IP results in a small value for $M^2_{H_u}$ (which is further suppressed by tadpole corrections). The down-type Higgs soft mass squared, $M^2_{H_d}$, runs very little, taking a value $\sim M_0^2 \simeq M_{3/2}^2$. In the parameter space where $\tan\beta \approx 2/\sin 2\beta$ and where the minimization of the Higgs potential breaks the electroweak symmetry, the value of μ can be as small as [8]

$$\mu \approx \frac{M_{3/2}}{2\tan\beta}, \tag{6}$$

again, up to small corrections. This result of a large gravitino mass and $\mu/M_{3/2}$ being suppressed by the inverse of $\tan\beta$ has also recently been discussed in Ref. [17].

The determination of the μ parameter is intimately tied to the mass of the Higgs boson through electroweak symmetry breaking. At an intersection point, the light CP-even Higgs has a mass near

$$m_{Higgs} = (125\text{–}126)\ \text{GeV}. \tag{7}$$

We stress that this is a generic prediction of an IP of RG flow, since the sfermion masses must be large, $\mathcal{O}(10\ \text{TeV})$, and thus so is A_0. Indeed, the loop correction for the Higgs mass is naturally of the right size. This is a consequence of the top trilinear coupling at the EWSB scale, A_t, and the geometric mean of the stop masses, $M_S = \sqrt{m_{\tilde t_1} m_{\tilde t_2}} = Q^*$, entering the leading loop correction as

$$X_t/M_S = (A_t - \mu/\tan\beta)/M_S \sim A_t/M_S. \tag{8}$$

As A_0/M_0 runs to A_t/M_S at the electroweak scale, the ratio remains of order unity. This, along with the relatively large value of M_S as controlled by the RG running, gives the necessary correction to the light CP-even Higgs mass [8].

Having addressed the scalar sector masses and dynamics, we turn, finally, to the gauginos. Suppression of gaugino masses can arise from moduli dominated supersymmetry breaking. This feature was realized early on in the context of string model building [37] where the moduli contribution to supersymmetry breaking can dominate over the dilaton contribution.

More generally, in Planck units the gravitino mass is $M_{3/2}^2 = \frac{1}{3}\langle \bar F^{\bar I} \hat K_{\bar I J} F^J \rangle$ so the gravitino can become massive via the Super-Higgs mechanism with a single dominant F-term and other F-terms suppressed. At the unification scale, tree and loop contributions to the gaugino masses can have comparable sizes since the modulus that supplies the dominant F-term will lead to a loop-suppressed contribution to the gaugino masses (see e.g. [38] for a pedagogical analysis). Thus, the gaugino masses will be suppressed relative to the gravitino mass and hence relative to the scalar superpartner masses,

$$M_a(Q_0) = \mathcal{O}_a(10^{-2}) \cdot M_{3/2}. \tag{9}$$

Note that the soft masses and couplings for the scalar sector of the theory, M_0, A_0, and B_0, are still dominated by an unsuppressed $|F^M| \sim M_{3/2}$. The precise ratios of the gaugino masses at the unification scale are, of course, model dependent.

3. Well-mixed neutralino

We will consider soft supersymmetry breaking models with parameter choices motivated in order to (i) correctly produce the Higgs boson mass, (ii) allow for a relatively low value of the μ parameter, and (iii) to produce the correct relic abundance of cold