On the Viability of Thermal Well-Tempered Dark Matter in SUSY GUTs

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Abstract

In a scenario with heavy supersymmetric sfermions and decoupled supersymmetric Higgs sector, a well tempered neutralino is the remaining candidate for thermal single-component sub-TeV dark matter. Well tempered neutralinos are studied in the context of supersymmetric grand unified theories with third family Yukawa coupling unification. A global $\chi^2$ analysis is performed, including the observables $M_W$, $M_Z$, $G_F$, $\alpha^{-1}_{em}$, $\alpha_s(M_Z)$, $M_t$, $m_b(m_b)$, $M_\tau$, $b \rightarrow s\gamma$, $BR(B_s \rightarrow \mu^+\mu^-)$, $M_h$ and $\Omega h^2$. Tensions in simultaneously fitting the Higgs and bottom quark masses while also avoiding gluino mass bounds from the LHC disfavors light Higgsinos with mass $\lesssim 500$ GeV, ruling out light Bino/Higgsino dark matter candidates. Bino/Wino/Higgsino and Bino/Wino candidates fare somewhat better although they are fine-tuned and require departure from GUT scale gaugino mass universality (the example chosen here is the mixed modulus-anomaly pattern). Implications for dark matter direct detection of these models as well as collider signatures are briefly discussed. Independent of the thermal dark matter viability, these models will be severely constrained by the absence of a gluino at the next run of LHC.
1 Introduction

The major motivations for supersymmetric extensions of the Standard Model (SM) are gauge coupling unification, a solution to the hierarchy problem, and the existence (in R-parity conserving models) of a dark matter (DM) candidate. In particular, supersymmetry allows the gauge couplings to unify at an amazing precision of about 3% [1–6]. Supersymmetric grand unified theories (SUSY GUTs) also allow for Yukawa coupling unification. For example, in minimal SO(10) GUTS, each family of the standard model matter lives in one 16 dimensional representation, while the Higgses live in a 10 dimensional representation. The only renormalizable Yukawa coupling that can be written down in such theories is a $\lambda 16 10 16$, allowing for Yukawa coupling unification at the GUT scale. $t - b - \tau$ Yukawa unification requires $\tan\beta \simeq 50$ in order to reproduce the correct ratio between the top and the bottom quark masses. The constraints on the SUSY boundary conditions at the GUT scale coming from requiring Yukawa unification have been extensively studied [7–17].

In SUSY GUT models with universal gaugino masses at the GUT scale, the lightest supersymmetric particle (LSP) is typically a pure Bino, for which the DM relic density is too high in thermal histories. A pure thermal Bino could produce the observed relic density through coannihilation effects in the $A$-resonance, in a region where $M_A \sim 2m_{\tilde{\chi}^0_1}$, where $M_A$ is the mass of the pseudoscalar Higgs. Neither of these options are straightforward, however. Since each SM generation belongs to a 16-dimensional representation there is one universal scalar mass for each family at the GUT scale. The third generation sfermion mass is constrained to be very heavy ($\gg$ few TeV) due to flavor physics constraints from $b \to s\gamma$ transitions that are enhanced at large tan$\beta$. Hence, coannihilation effects due to a light slepton that is nearly mass-degenerate with the LSP is difficult to obtain in these SUSY GUTs (assuming that the DM mass is itself in the sub-TeV range). Moreover, Yukawa unified GUTs prefer a large CP-odd Higgs mass to satisfy the $B_s \to \mu^+\mu^-$ constraint which puts the $A$-resonance region also in tension. The popular remaining options are to opt for a candidate such as the pure Wino or Higgsino (either in a non-thermal setting [21] or as a part of multicomponent DM scenarios [22, 23]) or to rely on a (thermal) well-tempered candidate. We will not explore the non-thermal or multi-component options in this paper. DARK matter in Yukawa unified SUSY GUTs have been discussed in earlier works of Ref. [23–26].

The purpose of this paper is to study thermal, single-component well-tempered DM candidates [27] satisfying the relic density in SUSY GUT models, given the constraints emerging from the Large Hadron Collider (LHC). For models with heavy scalars, the gluino is constrained by CMS and ATLAS searches [28, 29] to be $M_{\tilde{g}} \gtrsim 1 – 1.2$ TeV, where the actual bound depends on the search strategy based on the final states from the decay of the gluino. On the other hand, the LHC has observed a new boson consistent with the SM Higgs with mass of about 125 GeV [30, 31].

One of the first conclusions we draw from the current study is that light ($\ll \mathcal{O}(500)$ GeV) Higgsinos are difficult to obtain in Yukawa unified SUSY GUT models. This comes from simultaneously satisfying the observed Higgs mass and corrections to the bottom quark mass while also obtaining a gluino heavier than the LHC-excluded lower bound. For gluino $\gtrsim 1.2$ TeV, we find tensions in obtaining a 125 GeV Higgs mass, in spite of the heavy scalars. The fact that light Higgsinos are difficult to obtain implies that light Bino/Higgsino ($\tilde{B}/\tilde{H}$) DM is disfavored in these models.

\footnote{We note that non-thermal histories with a Bino LSP can satisfy the relic density if it is produced from the decay of a modulus with just the correct density and undergoes no further annihilation. This scenario, called the “branching scenario”, has been studied in [18–20].}
This further implies that universal gaugino mass conditions, where $\tilde{B}/\tilde{H}$ is the only viable thermal well-tempered DM candidate (due to large mass separation between the Bino and the Wino), are similarly disfavored.

We then proceed to explore Bino/Wino/Higgsino ($\tilde{B}/\tilde{H}/\tilde{W}$) and Bino/Wino DM ($\tilde{B}/\tilde{W}$). These cases require departure from gaugino mass universality at the GUT scale (to reduce the mass separation between Bino and Wino). The boundary condition we choose is mixed modulus-anomalous (mirage) mediation [32–34] which is independently well-motivated from string constructions. We perform a global $\chi^2$ analysis including the observables $M_W$, $M_Z$, $G_F$, $\alpha^{-1}_{em}$, $\alpha_s(M_Z)$, $M_t$, $m_b(m_b)$, $M_\tau$, $b \rightarrow s\gamma$, $BR(B_s \rightarrow \mu^+\mu^-)$ and $M_h$. We then explore the best fit regions and study the thermal relic abundance, $\Omega h^2$.

Our main findings for $\tilde{B}/\tilde{H}/\tilde{W}$ and $\tilde{B}/\tilde{W}$ are the following: Compared to the case of universal gaugino masses and $\tilde{B}/\tilde{H}$ DM, these cases perform better but are also somewhat fine-tuned. A certain degree of fine-tuning is expected in general for Bino/Wino coannihilation effects to be operational. This is exacerbated by the additional constraints on the Higgsinos, outlined above and shown in detail in Section 3. Nevertheless, we obtain regions of parameter space that have a well tempered neutralino DM and fit the other observables mentioned above at 90-95% confidence level.

The best fits are obtained for a certain range of $\alpha$ which is a parameter that controls the degree of departure from GUT-scale gaugino universality. $\alpha$ parametrizes the relative importance of (universal) modulus mediated and ($\beta$-function dependent) anomaly mediated contributions to the GUT scale gaugino masses. For $\alpha \sim 0$ (the limit in which anomaly mediated contributions vanish), the tensions associated with universal gaugino masses become manifest while for large $\alpha$ (the limit in which anomaly mediated contributions dominate), the well tempering is ruined and the LSP becomes Wino-like. In the intermediate regions of $\alpha$, the DM is a well tempered $\tilde{B}/\tilde{H}/\tilde{W}$ or $\tilde{B}/\tilde{W}$, where each component plays a role in the final annihilation cross section. Typically, in the case of $\tilde{B}/\tilde{H}/\tilde{W}$ DM, the Higgsino component in the LSP turns out to be less than 8%, allowing us to (just) evade current direct detection limits although this type of DM will be detectable in the near future. The main annihilation channels in this region are $\chi^0_1\chi^0_1 \rightarrow Zh$ and the coannihilation channels are $\chi^0_1\chi^0_2$, $\chi^+_1\chi^-_1 \rightarrow Zw$. In the case of $\tilde{B}/\tilde{W}$ DM, the Higgsino content is less than 1% and the relic density is mainly satisfied through coannihilation effects while the spin independent scattering cross section is much below current direct detection bounds.

It is important to note that independent of the thermal dark matter viability, these models will be severely constrained by the absence of a gluino at the next run of LHC. The best fit regions require a light gluino. The lower bound on the gluino mass is growing from the LHC data and the 14 TeV run at the LHC will conclusively test the regions discussed here.

The plan of the paper is as follows: In Section 2, we introduce Yukawa unified SUSY GUT models, discuss well-tempering in these scenarios, and also discuss the procedure we adopt for the obtaining the best fit points. In Section 3, we present the case light Higgsinos and Bino/Higgsino DM in models with universal gaugino masses. Section 4 contains our results for the $\tilde{B}/\tilde{H}/\tilde{W}$ and $\tilde{B}/\tilde{W}$ DM. Here, we first give a short background on the mirage boundary conditions and then present the spectra, fits, and properties of the well-tempered scenarios. We end with our conclusions. In the Appendices, we present analytical expressions for the annihilation cross section of $\chi^0_1\chi^0_1 \rightarrow Zh$, which is one of the main annihilation channels of the $\tilde{B}/\tilde{H}/\tilde{W}$ case. We also show the best fit regions for several intermediate values of the parameter $\alpha$, which demonstrate that the fits get
progressively better as one departs from gaugino universality.

2 Model and Procedure

Supersymmetric parameters are heavily constrained when one requires Yukawa coupling unification. In the case of $t - b - \tau$ Yukawa unification, one Yukawa coupling gives rise to the top, bottom and the tau masses. The only way to reproduce the hierarchy between the top and the bottom masses is by requiring large $\tan \beta \sim 50$. At large $\tan \beta$, the GUT scale SUSY parameters are further constrained. For example, in the large $\tan \beta$ regime the down quark mass matrix and the CKM matrix elements receive significant corrections \cite{35}. Thus, requiring that the Yukawa couplings unify in addition to gauge coupling unification removes a lot of freedom from the GUT scale parameters.

The model parameters are summarized in Tab. 1. The model is defined by three gauge parameters, $\alpha_G, M_G, \epsilon_3$, where $\alpha_1(M_G) = \alpha_2(M_G) \equiv \alpha_G$, and $\epsilon_3 = \frac{\alpha_3 - \alpha_2}{\alpha_2}$ is the GUT scale threshold corrections to the gauge couplings. There is one large Yukawa coupling, $\lambda$, such that, $\lambda_t(M_G) = \lambda_b(M_G) = \lambda_\tau(M_G) = \lambda$. Typically, there are small corrections to this relation at the GUT scale, coming from the off-diagonal Yukawa couplings to the first two families. Here we consider a third family model, since the SUSY spectrum (and relic abundance) does not heavily depend on these small off-diagonal Yukawa couplings. SUSY parameters defined at the GUT scale include a universal scalar mass for squarks and sleptons, $m_{16}$; universal gaugino mass, $M_{1/2}$; $m_{10}$, the universal Higgs mass; $A_0$, universal trilinear scalar coupling and $D$, the magnitude of Higgs splitting\footnote{Here we study the case of “Just-so” Higgs splitting, D also fixes the magnitude of splitting for all scalar masses in the case of D-term splitting.}. Note that non-universal Higgs masses are necessary in order for radiative electroweak symmetry breaking in these models. We will also consider in general a parameter $\alpha$ that determines the ratio of anomaly mediation to gravity mediation contribution to the gaugino masses. The parameters $\mu$, $\tan \beta$ are obtained at the weak scale by consistent electroweak symmetry breaking. In the case of $t - b - \tau$ unification, $\tan \beta$ is restricted to be around 50\footnote{We also considered the possibility of relaxing $t - b - \tau$ unification to $b - \tau$ unification by allowing an independent Yukawa coupling for the bottom and tau, such that $\lambda_t = \lambda_u$ and $\lambda_b = \lambda_\tau = \lambda_d$. But, the fits that we obtained were consistent with $t - b - \tau$ unification to within a few percent, and the extra parameter dependence was eliminated.}.

We follow the same procedure used in Ref.\cite{16} to calculate 12 low energy observables. We use the 2-loop MSSM RGEs for both dimensionful and dimensionless parameters, integrate out the heavy

| Sector | Third Family Analysis |
|--------|-----------------------|
| gauge  | $\alpha_G, M_G, \epsilon_3$ |
| SUSY (GUT scale) | $m_{16}$, $M_{1/2}$, $\alpha$, $A_0$, $m_{10}$, $D$ |
| textures | $\lambda$ |
| SUSY (EW scale) | $\tan \beta$, $\mu$ |
| Total # | 12 |
Table 2: The 12 observables that we compare in the SUSY GUT model and their experimental values. Capital letters denote pole masses. We take LHCb results into account, but use the average by Ref. [37]. All experimental errors are 1σ unless otherwise indicated. Finally, the Z mass is fit precisely via a separate χ² function solely imposing electroweak symmetry breaking. Ωh² is not included in the χ² minimization procedure.

| Observable      | Exp. Value       | Ref. | Th. Error |
|-----------------|------------------|------|-----------|
| α₃(M_Z)         | 0.1184 ± 0.0007  | [36] | 0.5%      |
| α_em            | 1/137.035999074(44) | [36] | 0.5%      |
| G_μ             | 1.166378767(7) × 10⁻⁵ GeV⁻² | [36] | 1.0%      |
| M_W             | 80.385 ± 0.015 GeV | [36] | 0.5%      |
| M_Z             | 91.1876 ± 0.0021  | [36] | 0.5%      |
| M_t             | 173.5 ± 1.0 GeV   | [36] | 0.5%      |
| m_b(m_b)        | 4.18 ± 0.03 GeV   | [36] | 0.5%      |
| M_r             | 1776.82 ± 0.16 MeV | [36] | 0.5%      |
| M_h             | 125.3 ± 0.4 ± 0.5 GeV | [30] | 0.5%      |
| BR(b → sγ)      | (343 ± 21 ± 7) × 10⁻⁶ | [37] | (181 - 249) × 10⁻⁶ |
| BR(B_s → μ⁺μ⁻)  | (3.2 ± 1.5) × 10⁻⁹ | [38] | (1.5 - 4.7) × 10⁻⁹ |
| Ωh²             | 0.1187 ± 0.0017   | [39] | 0.08 - 0.2 |

scalars at their masses, evolve all parameters to the weak scale without the first two generation scalars. We use maton to perform the RGE evolution, calculation of the couplings at the weak scale and the masses of the gauge bosons, top, bottom quarks and the τ lepton. For the calculation of Higgs mass, we define an effective theory at the scale M_SUSY and interface our calculation with the code by authors in Ref.[40]. The flavor observables are calculated using the code susy_flavor[41], and the relic abundance is computed using MicrOmegas[42]. A χ² function is constructed by comparing the predicted observables, yᵢ (except the relic abundance) with their measured values, yᵢ^{data}, given by the standard definition:

\[ \chi^2 = \sum_i \frac{|y_i - y_i^{data}|^2}{\sigma_i^2} \]  \hspace{1cm} (1)

where \( \sigma_i \) is the assumed uncertainty in the calculation of the observable. The χ² function is minimized to determine the best set of GUT scale parameters. This minimization procedure is carried out using MINUIT [43]. The input parameters are listed in Tab. 1, and the observables and the theoretical errors assumed in estimating them are summarized in Tab. 2. Note that the model is defined in terms of 12 parameters of which, some are fixed during the minimization procedure. We compare our predictions to 11 observables, and calculate the 68%, 90%, and 95% confidence level intervals using the χ² function for the appropriate number of degrees of freedom (d.o.f.).

The main constraints on the SUSY spectrum come from fitting the third family masses, the Higgs mass, and the flavor observables \( b \to s \gamma \) and \( B_s \to \mu^+\mu^- \). Fitting the \( t - b - \tau \) masses requires that \( \tan \beta \) be around 50, in order to reproduce the hierarchy between the top and the bottom masses, when \( \lambda_t(M_G) = \lambda_b(M_G) \). In addition, fitting the bottom mass and the Higgs mass simultaneously requires light gluinos [15]. The flavor physics observable \( b \to s \gamma \) in MSSM is enhanced by a chargino-stop loop at large \( \tan \beta \), and requires that the stops (and consequently all scalars) be heavier than a few TeV. \( B_s \to \mu^+\mu^- \) rate is also enhanced at large \( \tan \beta \), and constrains CP odd Higgs mass, \( M_A \gtrsim 1.2 \) TeV. This pushes the model to the decoupling regime \( (M_A >> M_Z) \), and the lightest
Higgs is predicted to be SM-like.

2.1 Well-tempering in SUSY Models

The lightest neutralino in the MSSM is a mixture of the Bino ($\tilde{B}$), Wino ($\tilde{W}$), and Higgsino ($\tilde{H}_1, \tilde{H}_2$) eigenstates

$$\tilde{\chi}_0^1 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2,$$

where the $N_{1i}$ are the relevant weights along the different directions.

There are essentially three options for obtaining the observed relic density: (i) thermal single-component DM: the lightest neutralino is the sole DM candidate and the observed relic density is obtained by thermal freeze-out. (ii) non-thermal single-component DM: the lightest neutralino is the sole DM candidate and has a non-thermal cosmological history. Both cases of thermal under-production and over-production can be accommodated in this case. (iii) multi-component DM: the relic density is satisfied by the lightest neutralino along with one or more additional candidates, motivated by other physics (not necessarily supersymmetry). We will be interested in option (i) above, reserving the study of non-thermal DM in these models for future work.

If $\tilde{\chi}_0^1$ is a pure Higgsino, i.e. $N_{11} = N_{12} = 0$, the thermal relic density is approximately given by $\Omega h^2 \sim 0.1 \left( \frac{\mu}{1 \text{ TeV}} \right)^2$. Clearly, TeV-scale Higgsinos are required to satisfy the thermal relic density. A pure Higgsino LSP with a thermal history is thus somewhat in conflict with naturalness arguments.

Similarly, for a pure Wino, i.e. $N_{11} = N_{13} = N_{14} \sim 0$, the thermal relic density is satisfied for masses around 2.5 TeV. A pure Bino over-produces DM in the scenario considered in this paper, with decoupled supersymmetric scalar and Higgs sectors.

The correct relic density can be obtained if $\tilde{\chi}_0^1$ is an appropriate admixture of Bino, Wino, and Higgsino states. There are three possibilities here: a $\tilde{B}/\tilde{H}$, $\tilde{B}/\tilde{W}$, and a $\tilde{B}/\tilde{H}/\tilde{W}$ DM candidate. The idea is that an over-abundant Bino acquires a larger Wino or Higgsino component, allowing it to annihilate rapidly to $Z, W,$ and $h$ final states. For the case of $\tilde{B}/\tilde{H}$ DM, the low-energy values of $M_1$ and $\mu$ are required to be close to each other, typically to within 10%. $\tilde{B}/\tilde{W}$ DM requires $M_1 \sim M_2$ and gives the correct relic density mainly through coannihilation of $\tilde{\chi}_0^1$ with $\tilde{\chi}_0^2$ and $\tilde{\chi}_1^\pm$.

3 Light Higgsinos and $\tilde{B}/\tilde{H}$ DM with Universal Gaugino Masses

In this section, we discuss the case of well tempered DM in Yukawa unified SUSY GUTs with universal gaugino masses. Since $\tilde{B}/\tilde{W}$ DM requires $M_1 \sim M_2$ at low energies, it cannot be obtained if one assumes gaugino unification at the GUT scale. The remaining option then is $\tilde{B}/\tilde{H}$ DM. This requires light Higgsinos. There is however, a very strong tension in obtaining $\tilde{B}/\tilde{H}$ DM in these models. This tension arises from an unusual candidate: the corrections to the bottom quark mass.

It is well known that there are corrections to the bottom quark mass from a gluino-sbottom loop and a chargino-stop loop in MSSM that are $O(\tan \beta)$ enhanced. These large corrections can be

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4Naturalness arguments generally make the prediction of a small $\mu$ term: since the mass of the $Z$ is set by the relation $m_Z^2 = \mu^2 + m_{H_u}^2$ (in the large $\tan \beta$ limit), small fine-tuning requires $\mu \sim m_Z$.
written as
\[
\frac{\delta m_b}{m_b} \approx \frac{g_3^2}{12\pi^2} \frac{\mu g_b \tan\beta}{m_b^2} + \frac{\lambda_t^2}{32\pi^2} \frac{\mu A_t \tan\beta}{m_t^2}, \tag{3}
\]
where \(m_b, m_t\) and \(M_\tilde{g}\) are the sbottom, stop, and gluino masses respectively. When the stop and sbottom masses are roughly degenerate \(\sim \tilde{m}\), we can rewrite the above expression as
\[
\frac{\delta m_b}{m_b} \approx \frac{\mu \tan\beta}{\tilde{m}^2} \left( \frac{g_3^2}{12\pi^2} M_\tilde{g} + \frac{\lambda_t^2}{32\pi^2} A_t \right). \tag{4}
\]

Figure 1: Universal Gaugino Masses and \(B/\tilde{B}\) DM: Best fit regions on a graph of \(M_{1/2}\) versus \(\mu\) in the case of \(\alpha = 0\) (universal gaugino masses). The region between the red lines gives \(\Omega h^2 = 0.08 - 0.2\), and the DM in this region is a well-tempered \(B/\tilde{B}\). The olive curves are contours of constant gluino masses. The blue contour regions (lightest to darkest) represent the best fit regions at 68%, 90%, and 95% CLs, respectively. Note that light Higgsinos (and hence light \(B/\tilde{B}\) DM) are not preferred.

Light Higgsinos (small \(\mu\)) suppresses these corrections, which have to be at about a few \% (and negative), and are necessary to fit the bottom quark mass. This requirement places stringent constraints on the SUSY boundary conditions in the large \(\tan\beta\) regime. When the scalars are heavy, and when \(\mu\) is small, one needs some fine-tuning between the gluino mass, \(M_\tilde{g}\) and the \(A_t\) parameter to generate these corrections. Collider constraints from LHC place significant lower bounds on the gluino mass, which is required to be heavier than \(\sim 1000\,\text{GeV}\) in these models. Therefore, to get the correct \(\sim\) few \% corrections, the trilinear coupling has to be large (and negative). When the absolute value of the trilinear coupling is forced to be larger than \(\sim \sqrt{6} \tilde{m}\) (maximal mixing), it drives the Higgs mass to smaller values (or equivalently, the bad fit can be transferred to the
bottom and tau mass). This tension between the bottom quark mass and the Higgs mass disfavors light Higgsinos in these models.

This tension is reinforced further when one considers well tempering in this context. If one does take the Higgsinos with mass $\sim 400$ GeV or greater, Binos are constrained to have similar mass, to give a well tempered DM. Due to gaugino universality, the gluinos then have mass $\sim 1300 - 2000$ GeV (but cannot be too much lighter), further forcing trilinear terms to go beyond maximal mixing. These tensions are reflected in Fig. 1 with universal gaugino masses at the GUT scale, where the the best fit points are displayed in the $M_{1/2} - \mu$ plane. The region between the red lines has relic density in the range $\Omega h^2 = 0.08 - 0.2$. The relic abundance is satisfied in this region due to a well tempering of Bino/Higgsino DM (due to universal conditions, the Bino-Wino mass splitting is too large to allow coannihilation). The olive curves are contours of constant gluino mass. In the plot, the regions under the blue contours (lightest to darkest) represent $\chi^2/d.o.f. = 1.2, 2.3, 3$ corresponding to 68%, 90%, and 95% CLs, respectively. The regions were obtained by a parameter space scan with two degrees of freedom ($m_{16}, \mu$, and $M_{1/2}$ were held fixed). Well tempering is obtained for comparable Bino and Higgsino masses, which gives gluinos in the mass range of $1600 - 2000$ GeV. The situation is worse for pure Higgsino DM which have to be heavier than a TeV and thus requiring even heavier gauginos. Therefore, in comparison with the phenomenological scenarios of CMSSM and NUHM, Yukawa unified GUTs are further constrained. Note that in the case of CMSSM and NUHM it has been pointed out that a TeV scale Higgsino LSP is preferred since it is unconstrained by current experiments and the correct Higgs mass can be easily obtained in this region [44, 45].

We find from our $\chi^2$ analysis that in this case, the worst fits are to $m_b(m_b)$, and $M_\tau$, and $\alpha_s$ all of which have pulls $\gg 1$. It is also clear from Fig. 1 that regions with $\mu \lesssim O(500)$ GeV generally give large $\chi^2/d.o.f. > 3$ in these scenarios. It is abundantly clear that there is tension between requiring Yukawa unification and a well tempered DM, when one starts with universal gaugino masses. To retain the thermal single component DM scenario in these models, one must move away from the gaugino mass unification assumption at the GUT scale.

4 $\tilde{B}/\tilde{H}/\tilde{W}$ and $\tilde{B}/\tilde{W}$ DM

In this section, we relax gaugino mass universality at the GUT scale to add the possibility of having $\tilde{B}/\tilde{H}/\tilde{W}$ or $\tilde{B}/\tilde{W}$ DM candidates. A particularly well-motivated boundary condition is combining a universal (modulus) contribution with varying degrees of anomaly-mediated contributions. To this end, we first give some basic details about mixed modulus-anomaly or mirage mediation. We then give our main results for $\tilde{B}/\tilde{H}/\tilde{W}$ and $\tilde{B}/\tilde{W}$ DM.

4.1 Effective Mirage Mediation

Non-universal gaugino masses could arise when there is a non-singlet F-term under the GUT symmetry or when there are hybrid SUSY breaking mechanisms. States in non-singlet representations of the gauge symmetry could contribute large threshold corrections to the gauge couplings and could ruin precision gauge coupling unification. Hence we depart from gaugino universality by assuming that there is a hybrid SUSY breaking mechanism at the GUT scale like the “mirage” mediation scenarios studied in string-inspired effective supergravity models [32–34]. The boundary
conditions considered here have been recently studied within Yukawa unified SUSY GUTs [16]. Non-universal gaugino mass scenarios were considered in the context of GUTs in the analyses of Refs. [12–14, 17, 46], where the SUSY breaking F-term that couples to the gaugino transforms as a non-singlet of the unified SO(10) gauge group, and hence gives rise to non-universal masses.

The gaugino masses at the GUT scale obey a “mirage” pattern:

\[
M_i = \left( 1 + \frac{g_i^2 b_i \alpha}{16\pi^2} \log \left( \frac{M_{Pl}}{m_{16}} \right) \right) \frac{M_{1/2}}{2}
\]

In the above expression, \( \alpha \) is a parameter that controls the relative importance of the universal and anomalous contributions, and \( b_i = (33/5, 1, -3) \) for \( i = 1, 2, 3 \), are the relevant \( \beta \)-function coefficients. We note that larger \( \alpha \) leads to larger anomaly mediated contributions (and hence departure from the universal scenarios). The definition of \( \alpha \) has appeared in different forms in the literature. The above expression matches with the definition in Ref. [32] (with the assumption, however, that \( m_{3/2} \approx m_{16} \)), but is related to the definition in Ref. [33] by the transformation

\[
\frac{1}{\rho} = \frac{\alpha}{16\pi^2} \ln \frac{M_{Pl}}{m_{16}}.
\]

For the scalars, we assume a universal mass and trilinear coupling at the GUT scale. Note that, while the gaugino and scalar soft terms can be obtained from the heterotic framework of Ref. [33], the issue of obtaining large A terms is still a model building challenge. Here, we let the phenomenology guide our choice of large trilinears at the GUT scale.

![Figure 2](image-url)

**Figure 2:** The figure illustrates the relation between the gaugino masses at weak scale and the two GUT scale parameters, \( M_{1/2} \) and \( \alpha \) using simple tree level relations. **Left:** The ratio of the gaugino masses \( M_1/M_2 \) at the weak scale. **Right:** The gluino mass parameter \( M_3 \) at the weak scale.

The additional degree of freedom \( \alpha \), allows well-tempering by tuning the ratios of \( M_1 \) and \( M_2 \). To limit the regions of interest, we illustrate in Fig. 2, the ratio of \( M_1 \) and \( M_2 \) and the value of \( M_3 \) obtained at the weak scale by a simple 1-loop analysis. We are interested in the regions where \( |M_1| \leq |M_2| \), when the lightest neutralino starts to be a blend of Bino and Wino. This ratio
of $|M_1|$ and $|M_2|$ is obtained when $\alpha$ is less than 3, below which the Wino becomes significantly lighter. Fig. 2 also shows that simultaneously satisfying the collider bound on the gluino mass further restricts $M_{1/2} > 250$ GeV. Note that the plot shows $M_2$ and there are additional corrections to the gluino pole mass. Once we identify the region of interest in the $M_{1/2} - \alpha$ parameter space we proceed to check if this region of the effective mirage mediation model is compatible with Yukawa unification. As an aside, we note that in Ref. [16], it was assumed that $\mu, M_{1/2} < 0$, and $\alpha \geq 4$ such that $M_3 > 0, M_1, M_2 < 0$. This combination was useful to simultaneously satisfy the $b \rightarrow s\gamma$ constraint and the corrections to bottom quark mass. These boundary conditions led to very distinct spectrum and interesting phenomenology but as noted earlier, large values of $\alpha$ lead to anomaly mediation being the dominant source of SUSY breaking, and thus a pure Wino-like LSP. Therefore, they are outside the range of this work on thermal single component dark matter.

As $\alpha$ is gradually increased from 0, there are two important effects that become apparent. The first one is that the Wino component of the LSP begins to increase. Therefore, the correct relic density is obtained for larger values of $\mu$ (compared to the universal case). Due to the constraints on light Higgsinos, this is preferable. On the other hand, since the beta-function coefficient is negative for SU(3), the gluino mass decreases with increasing $\alpha$. Then the model starts conflicting with the LHC results as $\alpha$ increases. Below are our results for the case of $\alpha = 1.5$ in Eq. (5). In Appendix B, we discuss the intermediate values of $\alpha = 0.5$ and $\alpha = 1$, where we find progressively improving (compared to the $\alpha = 0$ case) results for the $\chi^2$ fit. There, we also show that the model starts to conflict severely with the LHC results at around $\alpha \sim 2$. There is a finite volume of parameter space that permits well-tempering and the entire volume is within the reach of the LHC and DM experiments.

### 4.2 Results for $\tilde{B}/\tilde{H}/\tilde{W}$ DM

The gaugino masses are maximally split in the universal case. As anomaly contributions increase with increasing $\alpha$, the mass splitting between the gaugino masses decrease. Due to the greater proximity of Bino and Wino masses, now, in fact, $\tilde{B}/\tilde{H}/\tilde{W}$ and $\tilde{B}/\tilde{W}$ DM can both be options for the well tempered DM candidate. Moreover, for the same Bino mass, the gluino can now be lighter ($\gtrsim 1100$ GeV), reducing the tension with fitting the $b$ mass. Indeed, we find now that we find better fits to all the observables in Tab. 2. This is reflected in Fig. 3 where we present fits with $\alpha = 1.5$. The region between the blue and red lines gives $\Omega h^2 = 0.08 - 0.2$. We see that this region now extends to areas of smaller $\chi^2$, with gluino mass $\sim 1100$ GeV. As in the universal case $\alpha = 0$, the region with low $\mu \lesssim 450$ GeV gives a large value of $\chi^2$ and this region is qualitatively similar to the universal case. However, with larger $\mu \gtrsim 600$ GeV a region of low $\chi^2$ opens up and the relic density band extends into it.

We present a sample benchmark point in Tab. 3. The best fit point obtained here is very similar to the benchmark points discussed in Dermisek-Raby model with universal gaugino masses [15]. The SUSY boundary conditions at the GUT scale are typically:

\[
\begin{align*}
    m_{16} &> \text{few TeV;} \\
    A_0 &\sim -2m_{16}; \\
    \mu, M_{1/2} &< m_{16}; \\
    \tan\beta &\sim 50
\end{align*}
\]
The first two family of scalars are very heavy (∼ 20 TeV), and the spectrum has the inverted scalar mass hierarchy with the third family of squarks and sleptons between 3 – 6 TeV. These scalars are out of the reach of the LHC. The gauginos are light and the LSP (the DM candidate) is a well tempered $\tilde{B}/\tilde{H}/\tilde{W}$ mixture. The gaugino sector differs from the previous studies, and we are able to satisfy the relic abundance. The gluino tends to be lighter than the universal case due to the presence of the anomaly contribution. We have increased the overall scale of the gauginos, and the LSP mass but the gluino remains light enough to contribute the required corrections to the bottom quark mass. Note that all the extra Higgses of SUSY are heavy and thus the lightest Higgs is purely SM like. Finally, the gluino decays into a variety of final states. The final states should include many jets, b-jets and a large amount of missing energy, and large total transverse jet momentum. We expect the bounds from present LHC results to be similar to the model discussed in [47] and we expect the 20 fb$^{-1}$ data from 8 TeV LHC to rule out gluinos lighter than 1 TeV.

4.3 $\tilde{B}/\tilde{H}/\tilde{W}$ DM Annihilation and Scattering Cross Sections

The main annihilation channels of $\tilde{\chi}_1^0$ in this region are displayed in Fig. 4.
Table 3: Spectrum at the benchmark point for $\tilde{B}/\tilde{H}/\tilde{W}$ DM.

| GUT scale parameters | $m_{16}$ | 20000 | $M_{1/2}$ | 450 | $A_0$ | -40461 | $\alpha$ | 1.5 |
|----------------------|----------|-------|-----------|-----|-------|----------|---------|-----|
| $m_{H_d}$            | 27495    |       |           |     | $m_{H_u}$ | 23748   |         |     |
| $1/\alpha_G$        | 26.17    |       |           |     | $\epsilon_3$ | 0       | $\lambda$ | 0.59 |
| EW parameters       | $\mu$ | 660 | Total $\chi^2$ | 1.84 |       |           |         |     |
| Fit                  |          |       |           |     |       |         |         |     |
| Spectrum             | $m_{\tilde{g}}$ | \sim | 20000 | $m_{\tilde{d}}$ | $\sim$ | 20000 | $m_{\tilde{e}}$ | \sim | 20000 | $M_{\tilde{g}}$ | 1130 |
|                      | $m_{\tilde{t}_1}$ | 3612 | $m_{\tilde{b}_1}$ | 5053 | $m_{\tilde{t}_1}$ | 6867 | $M_{\tilde{b}}$ | 121 |
|                      | $m_{\tilde{\chi}_1^0}$ | 474.5 | $m_{\tilde{\chi}_2^0}$ | 556.7 | $m_{\tilde{\chi}_1^0}$ | 693.6 | $m_{\tilde{\chi}_2^0}$ | 662.9 |
|                      | $m_{\tilde{\chi}_1^0}$ | 554.9 | $m_{\tilde{\chi}_2^0}$ | 691.5 | $M_A$ | 1915.3 | $M_{H_1}^+$ | 1916.9 | $M_H$ | 1932.5 | $M_h$ | 121 |
| DM                   | $\Omega h^2$ | 0.121 |       |     |       |         |         |     |
| Gluino Branching Fractions | $tb\tilde{\chi}_2^0$ | 19% | $tb\tilde{\chi}_1^0$ | 17% | $g\tilde{\chi}_2^0$ | 17% | $tb\tilde{\chi}_1^0$ | 13% |
|                      | $g\tilde{\chi}_3^0$ | 12% | $t\tilde{\chi}_2^0$ | 9% | $t\tilde{\chi}_3^0$ | 5% | $g\tilde{\chi}_2^0$ | 4% |

Figure 4: **Left panel:** The annihilation cross-section $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow Z h$ as a function of the relic density for $\alpha = 1.5$. The cross-section is large for large Bino/Higgsino mixing. As the Higgsino becomes decoupled, the cross-section for this annihilation channel becomes negligible. For a theoretical computation, we refer to Appendix A. **Right panel:** The relative importance of the $Zh + t\bar{t}$ channel and the $ZW$ channel as a function of the relic density. For low relic density, the coannihilation channels $\tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_1^0\tilde{\chi}_1^\pm \rightarrow ZW$ dominate. The DM is then a Bino/Wino well tempered neutralino. For larger separation between Bino and Wino, the coannihilation becomes ineffective and the relic density increases as $\tilde{\chi}_1^0$ becomes predominantly Bino. The main annihilation channel then becomes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow t\bar{t}$. For $\Omega h^2 \sim 0.1$, the annihilation to $Zh$ and $ZW$ are comparable.

The left panel shows the annihilation cross section $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow Z h$ as a function of the relic density. The cross section is enhanced for large Bino/Higgsino mixing. As the Higgsino becomes decoupled, the cross section for this annihilation channel becomes negligible. These results have been obtained using MicrOmegas and we have verified the result theoretically; the main formulae are collected.
in Appendix A. The right panel shows the relative importance of the $Zh + t\bar{t}$ channel and the $ZW$ channel as a function of the relic density. For low relic density, the coannihilation channels $\tilde{\chi}^0_1\tilde{\chi}^0_2$, $\tilde{\chi}^0_1\tilde{\chi}^\pm_1 \rightarrow ZW$ dominate. The DM is then a Bino/Wino well tempered neutralino. For larger separation between Bino and Wino, the coannihilation becomes ineffective and the relic density increases as $\tilde{\chi}^0_1$ becomes predominantly Bino. The main annihilation channel then becomes $\tilde{\chi}^0_1\tilde{\chi}^0_1 \rightarrow t\bar{t}$. We note that at the sweet spot $\Omega h^2 \sim 0.1$, the annihilation to $Zh$ and coannihilation to $ZW$ are comparable, indicating that the DM is a well tempered Bino/Wino/Higgsino type.

| Annihilation cross section | $\tilde{\chi}^0_1\tilde{\chi}^0_1 \rightarrow Zh$ | 52% |
|---------------------------|---------------------------------|-----|
|                           | $\tilde{\chi}^0_1\tilde{\chi}^\pm_1 \rightarrow ZW$ | 24% |
|                           | $\tilde{\chi}^0_1\tilde{\chi}^0_1 \rightarrow ZZ$ | 11% |
|                           | $\tilde{\chi}^0_1\tilde{\chi}^0_1 \rightarrow t\bar{t}$ | 6% |

| Scattering cross section (pb) | $1.6 \times 10^{-5}$ |

Table 4: Annihilation and spin-independent scattering cross sections at the benchmark point with $\tilde{B}/\tilde{H}/\tilde{W}$ DM. Only channels contributing greater than 1% to the total annihilation cross section are shown.

In Tab. 4, we display the annihilation channels and scattering cross section of the DM candidate corresponding to the benchmark point in Tab. 3. The main annihilation channel is $\tilde{\chi}^0_1\tilde{\chi}^0_1 \rightarrow Zh$ with a value of $\langle \sigma v \rangle_{Zh} = 1.02 \times 10^{-26}$ cm$^3$s$^{-1}$. For the benchmark point, the spin independent scattering cross-section is $1.6 \times 10^{-8}$ pb. We note that the scattering cross-section for this $m_{\tilde{\chi}_1^0}$ is just at the exclusion limit at 90% CL from XENON100 [48]. Direct detection bounds for well tempered scenarios are getting particularly stringent. For $\mu > 0$, XENON100 exclusion limits force $m_{\tilde{\chi}_1^0} \gtrsim 600$ GeV in the large tan$\beta$ limit [49]. Typically, Bino/Higgsino mixing larger than 10% starts to conflict with exclusion bounds from XENON100 in these regions [50, 51] (for our benchmark scenario, the degree of Bino/Higgsino mixing is $\sim 8\%$). We thus see that the $\tilde{B}/\tilde{H}/\tilde{W}$ well-tempering is particularly interesting since it is likely to be conclusively probed by XENON1T [52]. In fact, by changing $\alpha$, one can control the degree to which Bino/Wino coannihilation contributes to the relic density, and also the scattering cross section.

4.4 Results for $\tilde{B}/\tilde{W}$ DM

As $\alpha$ increases further, the wino starts becoming a substantial component of the LSP and the relic abundance is satisfied for larger values of $\mu$. In this region we obtain a $\tilde{B}/\tilde{W}$ DM. A typical spectrum is shown in Tab. 5. Note that we have chosen a higher scale for the supersymmetric scalar masses, $m_{16}$, so as to obtain a better fit to the Higgs mass. This also gives rise to larger corrections to the gluino mass. The gluino is $\gtrsim 1100$ GeV, in spite of $\alpha > 2$, in comparison with Fig. 5, where $m_{16}$ was chosen to be 20 TeV. The other qualitative features of the spectrum remain unchanged. The main channels as well as the spin independent scattering cross section are shown in Tab. 6. The annihilation cross section of the DM is dominated by various coannihilation processes among $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, and $\tilde{\chi}^\pm_1$. The spin independent scattering cross section is well below XENON100 limits, as expected in this case.
GUT scale parameters

| Parameter | Value |
|-----------|-------|
| $m_{16}$   | 29781 |
| $m_{H_u}$  | 40724 |
| $1/\alpha_G$ | 26.35 |
| $M_{1/2}$  | 600   |
| $A_0$      | -60395|
| $m_{H_u}$  | 35237 |
| $\alpha$   | 2.3   |

EW parameters

| Parameter | Value |
|-----------|-------|
| $\mu$     | 1200  |
| $\tan\beta$ | 49.65 |

Fit

| Parameter | Value |
|-----------|-------|
| Total $\chi^2$ | 1.72  |

Spectrum

| Parameter | Value |
|-----------|-------|
| $m_{\tilde{u}}$ | ~ 29337 |
| $m_{\tilde{d}}$ | ~ 29337 |
| $m_{\tilde{e}}$ | ~ 29498 |
| $m_{\tilde{t}}$ | 15832 |
| $m_{\tilde{b}}$ | 18078 |
| $m_{\tilde{\tau}}$ | 110565 |
| $M_A$ | 3093 |
| $M_H$ | 3094 |
| $M_{H^\pm}$ | 3131 |
| $M_h$ | 123  |

DM

| Parameter | Value |
|-----------|-------|
| $\Omega h^2$ | 0.099 |

Gluino Branching Fractions

| Branching Fraction | Value |
|--------------------|-------|
| $g\tilde{\chi}_0^0\tilde{\chi}_1^0$ | 55%   |
| $g\tilde{\chi}_1^0\tilde{\gamma}$ | 31%   |
| $tb\tilde{\chi}_1^\pm$ | 12%   |

Table 5: Spectrum at the benchmark point with $\tilde{B}/\tilde{W}$ DM.

| Annihilation cross section | Value |
|----------------------------|-------|
| $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow Zh$ | 6%    |
| $\tilde{\chi}_1^0\tilde{\chi}_1^\pm \rightarrow ZW, Wh$ | 24%   |
| $\tilde{\chi}_2\tilde{\chi}_2 \rightarrow ff, ZW$ | 32%   |
| $\tilde{\chi}_2^0\tilde{\chi}_0^0 \rightarrow WW$ | 4%    |
| $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \rightarrow WW, ZZ, ff$ | 21%   |

| SI Scattering cross section (pb) | Value |
|----------------------------------|-------|
|                                 | $3.5 \times 10^{-9}$ |

Table 6: Annihilation and spin-independent scattering cross sections at the benchmark point with $\tilde{B}/\tilde{W}$ DM. Only channels contributing greater than 1% to the total annihilation cross section are shown.

5 Comments and Summary

In this work, we have investigated the interplay between four physics components within the context of Yukawa unified supersymmetric GUTs.

- Thermal Relic Abundance.
- Low energy observables including fermion masses and flavor.
- 125 GeV Higgs mass.
- Collider bounds on the gluinos.

We have studied the viability of a thermal DM candidate in Yukawa unified SUSY GUTS. Given the model parameters at the GUT scale, we have used the low energy observables $M_W$, $M_Z$, $G_F$, $\alpha^{-1}_s(M_Z)$, $M_t$, $m_b(m_b)$, $M_\tau$, $b \rightarrow s\gamma$, $BR(B_s \rightarrow \mu^+ \mu^-)$ and $M_h$ to constrain the parameter space. It is well known that uniformly heavy scalars and decoupled SUSY Higgs sector are required in these models to evade flavor physics constraints from $b \rightarrow s\gamma$, $BR(B_s \rightarrow \mu^+ \mu^-)$. The heavy scalars make
it impossible to achieve coanhhilation scenarios with staus or the CP-odd Higgs. The model also prefers a light gaugino spectrum and therefore disfavors Higgsino LSP. Then, the remaining option to obtain a thermal DM candidate in these models is to consider a well-tempered neutralino that is either $\tilde{B}/\tilde{H}$ or $\tilde{B}/\tilde{W}$ or $\tilde{B}/\tilde{H}/\tilde{W}$ admixture.

The first observation is that light Higgsinos with mass $\lesssim \mathcal{O}(500)$ GeV are difficult to obtain in these models. In particular, the tension arises from simultaneously obtaining acceptable corrections to the bottom quark mass and the mass of the Higgs, as well as evading the lower bound on the mass of the gluino mass. This is clearly represented in Fig. 1, where Higgsino masses less than $\sim \mathcal{O}(500)$ GeV uniformly have a large $\chi^2/d.o.f.$ for gluino mass $\gtrsim 1100$ GeV. This makes light well-tempered $\tilde{B}/\tilde{H}$ DM less preferred; and hence, universal gaugino masses at the GUT scale also less preferred, since $\tilde{B}/\tilde{H}$ DM is the only well-tempered option with that boundary condition.

We studied the cases of $\tilde{B}/\tilde{H}/\tilde{W}$ and $\tilde{B}/\tilde{W}$ DM by allowing for non-universal gaugino masses at the GUT scale, in a mirage pattern. Non-universality of the gauginos at the GUT scale is required to compress the mass splitting between the Bino and the Wino. We find that there are small regions of parameter space that can accommodate all the low energy observables including a 125 GeV Higgs that do not conflict with the LHC constraints on the gluino. In both cases there is a considerable degree of fine-tuning between the Higgsino, third generation squark, and gluino masses in order to satisfy all the constraints.

The best fit regions require a light gluino. The lower bound on the gluino mass is growing from the LHC data and the 14 TeV run at the LHC will conclusively test the regions discussed here. For gluino $\sim 1.3$ TeV, we find tensions in obtaining a 125 GeV Higgs mass, in spite of the heavy scalars in the model. Our findings are that the trilinear coupling $A_t$ is pushed beyond maximal mixing, and hence drives the Higgs mass to smaller values. On the other hand, the $\tilde{B}/\tilde{H}/\tilde{W}$ will also be probed by XENON1T. While there are still small pockets of the parameter space with accidental degeneracies, we find that these are considerably fine-tuned and may even require DM with mass larger than a TeV. It is important to note that independent of the thermal dark matter viability, these models will be severely constrained by the absence of a gluino at the next run of the LHC. Hints of the gluino at the next run of the LHC without any immediate detection from direct DM searches would leave only the $\tilde{B}/\tilde{W}$ as a viable scenario.

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Appendices

A Annihilation channel $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Zh$

In this section, we present the analytical expression for the annihilation cross section of DM into $Zh$ final states, following [53]. The annihilation of DM into $Zh$ final state occurs due to two contributions: $s$-channel exchange of a $Z$ and $t$- and $u$- channel exchange of all four neutralinos. The cross section in the limit of $v_{\text{rel}} \to 0$ is given by

$$\sigma_{Zh} v_{\text{rel}} = \frac{k X_{Zh}}{32 \pi m_{\tilde{\chi}_1^0}^3},$$

where

$$k = \left[ \frac{m_{\tilde{\chi}_1^0}^2 - \frac{1}{2} (m_Z^2 + m_h^2) + \frac{(m_Z^2 - m_h^2)^2}{16 m_{\tilde{\chi}_1^0}^2}}{2 m_{\tilde{\chi}_1^0}} \right]^{1/2}$$

is the momentum of the outgoing particles. In the limit of heavy Higgs partners, the quantity $X$ is given by

$$X_{Zh} = 2 k^2 \frac{m_{\tilde{\chi}_1^0}^2}{m_Z^2} \left[ \frac{z F_{mn}}{m_Z^2} + \sum_K \frac{2 g M_{2nk} F_{nk} (m_{\tilde{\chi}_0^0} - m_{\tilde{\chi}_k^0})}{t - m_{\tilde{\chi}_k^0}^2} \right]^2.$$ (8)

The various quantities in Eq. (8) are: (i) the coupling at the $hZZ$ vertex $z = g m_Z \sin \beta - \alpha / \cos \theta_W$ ($g$ is the $SU(2)_L$ coupling constant), (ii) the coupling of the $Z\tilde{\chi}_1^0\tilde{\chi}_1^0$ vertex $F_{ij} = g (Z_i Z_j \beta - Z_i Z_j) / 2 \cos \theta_W$, (iii) the coupling at the $H_i^0 \tilde{\chi}_j^0 \tilde{\chi}_k^0$ vertex $M_{ijk}$ available in [54], and (iv) $t = \frac{m_Z^2 - m_h^2}{2} - m_{\tilde{\chi}_1^0}^2$. The sum is over all neutralinos.

B $\alpha = 0.5, 1 & 2$

In the main text, we have given the examples of $\alpha = 0$ (universal gaugino masses) and $\alpha = 1.5$. The problems with the universal gaugino mass case were described, and the eventual benchmark at $\alpha = 1.5$ was presented. In this Appendix, we give the results for several intermediate values of $\alpha$. We note that the region with relic density $\Omega h^2 = 0.08 - 0.2$ starts extending more and more into the region with small $\chi^2$, as the $b$-mass fitting improves due to the reasons mentioned in the text. For $\alpha = 2.0$, the $\chi^2$ fit is the best; however, the trade off is that the gluino becomes too light.
Figure 5: Dependence on $\alpha$: Best fit regions on a graph of $M_{1/2}$ versus $\mu$ in the case of $\alpha = 0.5$, 1, and 2. The region between the red lines gives $\Omega h^2 = 0.08 - 0.2$. The olive contours give the gluino mass. The blue contours (lightest to darkest) represent $\chi^2/dof = 1, 2, 3$ corresponding to 95%, 90%, and 68% CLs, respectively. The figures show progressively better results as $\alpha$ is increased; the value of $\alpha = 1.5$ is shown in the main text as the benchmark point. The best fit is obtained for the case of $\alpha = 2$; however, the gluino mass is excluded in that case.
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