Radiative natural SUSY spectrum from deflected AMSB scenario with messenger-matter interactions postprint

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Full Text

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We propose a radiative natural SUSY spectrum in the deflected anomaly mediation scenario with general messenger-matter interactions. Thanks to contributions from these new interactions, positive slepton masses and a large |At| term can be naturally obtained with either sign of the deflection parameter and with few messenger species, thereby avoiding the possible Landau pole problem. In contrast to ordinary (radiative) natural SUSY scenarios that suffer from dark matter under-abundance, the dark matter in our scenario can be a mixed bino-higgsino with the correct relic density. The 125 GeV Higgs mass can also be easily accommodated, and the majority of low electroweak fine-tuning points can be probed by XENON-1T direct detection experiments.

1 Introduction

The Standard Model (SM) of particle physics has been confirmed by various experiments, most notably the discovery of a 125 GeV SM-like Higgs boson by both the ATLAS [1] and CMS collaborations [2] at the Large Hadron Collider (LHC). On the other hand, the SM, as a successful effective theory, has many theoretical and aesthetic problems that necessitate various extensions. Low-energy supersymmetry (SUSY) is a highly motivated paradigm for physics beyond the SM.

In fact, an interesting observation is that the Higgs mass lies miraculously in the narrow 115–135 GeV window predicted by the minimal SUSY model (MSSM). In addition, the top quark mass also lies exactly at what is needed to properly drive radiative electroweak symmetry breaking (EWSB). Furthermore, the gauge hierarchy problem, the successful gauge coupling unification requirement, and the dark matter puzzle can all be solved by SUSY.

The low-energy SUSY paradigm is appealing, but so far there is no sign of SUSY particles after extensive searches at the LHC. In fact, no significant deviations from the SM have been observed in electroweak precision measurements or in flavor physics. The LHC data has already set stringent constraints [3, 4] on certain CMSSM models: m˜g (cid:38) 1.8 TeV for m˜q   m˜g, and m˜g (cid:38) 1.3 TeV for m˜q (cid:29) m˜g. Additionally, the rather large value of the Higgs mass at 125 GeV requires TeV-scale highly mixed top squarks, which seems to contradict naturalness expectations. In order to generate a soft SUSY spectrum consistent with LHC discoveries, a proper SUSY breaking mechanism is needed.

One of the most elegant SUSY breaking mechanisms is the anomaly mediation [5] SUSY breaking scenario. The ordinary AMSB has many advantages and is very predictive; however, it suffers from the tachyonic slepton problem [6] and requires an extension. An elegant extension to address the tachyonic slepton problem is the deflected AMSB scenario [7], in which messengers are introduced to deflect the Renormalization Group Equation (RGE) trajectory. The tachyonic slepton problem can be solved with such a deflection, but many messenger species are needed to push slepton masses positive for a negative deflection parameter. A large number of messenger species could cause a Landau pole below the Planck scale, and a large fine-tuning is needed to generate the 125 GeV Higgs mass in the ordinary deflected AMSB scenario.

In our previous work [8], we proposed introducing general messenger-matter interactions in the deflected AMSB scenario. The slepton sector can receive additional contributions from both the messenger-matter interactions and the ordinary deflected anomaly mediation to avoid tachyonic slepton masses. At the same time, additional contributions to the trilinear coupling At term—which typically increase |˜At|(At − µ cot |)—could be helpful for achieving the 125 GeV Higgs mass and reducing the involved fine-tuning. Moreover, even with one messenger we can generate positive slepton masses regardless of the sign of deflection parameters [9], so the Landau pole problem can be evaded in our new scenario.

With a large At term, TeV-scale stops, and a small µ   100–300 GeV, the radiative natural SUSY scenario [10, 11] can naturally be realized in deflected AMSB with general messenger-matter interactions. The electroweak (EW) fine-tuning [12] is small (typically EW < 50), especially when At is large, which decreases the involved fine-tuning. On the other hand, the dark matter in ordinary natural SUSY is always higgsino-like and results in under-abundance. Although two-component dark matter (axion and higgsino) can work well [13], it is preferable to change the nature of DM. The gaugino mass relation in ordinary AMSB differs from that in gauge mediation and gravity mediation, resulting in wino-higgsino DM and thus the under-abundance problem persists [14]. With the deflection of the AMSB trajectory, the DM can be mixed bino-higgsino and could give the correct relic density. In this work we focus on such a realization of radiative natural SUSY in deflected AMSB with general messenger-matter interactions.

This paper is organized as follows. We briefly review the deflected AMSB scenario with general messenger-matter interactions in Sec. 2. In Sec. 3 we introduce new messenger-matter interactions to the deflected AMSB and study the soft parameters that can generate radiative natural SUSY. Numerical results are presented in Sec. 4, and Sec. 5 contains our conclusions.

2 A Review of Deflected AMSB with Matter-Messenger Interactions

We briefly review the general results of the deflected AMSB scenario with matter-messenger interactions; relevant details can be found in our previous study [8]. General messenger-matter interactions in GMSB have been explored in various papers [15–17].

The superpotential in the deflected AMSB scenario includes general messenger-matter interactions:

W = ijXQiQj + yijkQiQjQk + W(X), (2.1)

where the indices (cid:48)i, j(cid:48) run over all MSSM and messenger fields. Subscripts (cid:48)U, D(cid:48) will denote cases above and below the messenger threshold, respectively. W(X) denotes the superpotential for the pseudo-moduli field X which defines the messenger threshold.

After integrating out the messenger fields, we have the general form for the MSSM fields only:

(cid:90) d4 Q†(cid:115)(cid:112) † (cid:90))Qb + d2 yabcQaQbQc, (2.2)

which can give additional contributions to soft SUSY breaking parameters. Here (cid:48) (cid:48) denotes the compensator field with Weyl weight 1 and (cid:48)Z(cid:48)D the wavefunction renormalization factor below the messenger threshold.

The leading-order contributions to the trilinear terms and scalar terms are

(cid:88)i=a,b,c(cid:18)(cid:18) ln µ(cid:19) ln |˜X|ln ZiiD(µ, |˜X|), (2.3)

|F |2|F |2 (ln µ)2− (ln µ)2−|F˜X|2d2|F |2 |˜X|2 ln |˜X|2|F ||F˜X|d|F |2 ln µ |˜X| ln µ ln |˜X|(cid:19)(cid:20)ln ZabD(µ, |˜X|), (cid:21)ln ZabD(µ, |˜X|),(2.4)

where the last term is the unique feature of this deflected AMSB scenario which involves interference between pure anomaly and gauge mediation type contributions.

Following the conventions in [16], the derivative of the wavefunction with respect to t = ln μ is given as

Gij[Z(ln μ); (ln μ); g(ln μ)], (cid:18)1iklZ−1∗kmZ−1∗ln jmn−2cirZijg2(cid:19)(2.5)

We can obtain the expression for the first derivative of the wavefunction with respect to (cid:48)X(cid:48)[15] at the messenger scale μ = |X|D(ln μ, |X|) Gab, (2.6)

with (· · ·) denoting the discontinuity of the following expression, and dkl multiplicity factor in the one-loop anomalous dimensions. i being the standard

The interference terms between anomaly mediation and gauge mediation are

ln μ ln |˜X| ( )(cid:18)D(μ, |˜X|)=+ (g) ln |˜X| ln ˜XGa[ZD(ln μ, ˜X); (ln μ, ˜X); g(ln μ, ˜X)], (cid:19)Ga[ZaD(ln μ); (ln μ); g(ln μ)].(2.7)

Thus we arrive at the final results for the trilinear and scalar soft masses with a general messenger sector at the messenger scale [8]:

Aa=−aaF −AMSB+m2m2=m232 2dijgauge+m2inter,a (| aij|2)dF ,(2.8)(2.9)

AMSB=(cid:20)|F |2(cid:26)8 24ck(cid:20)(cid:18) a16 2g4ab)inter= (gi)+(cid:19)(cid:21) (yi)akl bmn(k (bk)−

and the gauge mediation type contributions similar to [16]:

ab)gauge=d2F2256 4(cid:20)1adlm(cid:0) (∗aik bjk)(ilm ∗adklb (∗aij cij) (∗ckl bkl)−dij aCaijjlm)U(cid:1)−(∗aik bjk)D (ilm ∗(cid:21)aij bij)r (∗(2.12)

3 Deflected AMSB with New Messenger-Matter Interactions

The characteristic feature of radiative natural SUSY relative to ordinary natural SUSY is the large |At| term. To obtain relatively large trilinear terms, we include new messenger-matter interactions in the deflected AMSB scenario. The messengers are introduced in pairs of (5, ¯5) representations of SU(5), with the following decomposition in terms of SM SU(3)c × SU(2)L × U(1)Y quantum numbers:

5a = Na(1, 2)1/2 Ma(3, 1)−1/3, ¯5a = N a(1, ¯2)−1/2 M a(¯3, 1)1/3, (3.1)

where (cid:48)a(cid:48) denotes the NF messenger species.

We introduce the following superpotential involving messenger-MSSM interactions:

WU XNaNa+XMaMa+W(X)R)iNa+ L(cid:2) D(cid:88)aiLi(EcL)iNa+ UL(UcR)iNa(cid:3),

with the typical form of superpotential W(X) for the pseudo-moduli field X determining the deflection parameter d in combination with F . Here the superscript (cid:48)i(cid:48) denotes family indices.

From the general expressions for soft parameters in Sec. 2, we can obtain the soft SUSY breaking parameters for sfermions and trilinear couplings at the messenger scale. We keep only the leading terms involving yt, g3, L,i, U,i, D,i, while subleading terms like 1,2, y2L,U,D;ia are omitted. For simplicity, we set universal couplings L,ai = L, U,ai = U, D,ai = D for messenger-matter interactions. We explicitly give only the soft terms for the third-generation squarks; the first two generations can be obtained by removing the y2t terms in the relevant expressions. The soft SUSY mass terms for the three generations of sleptons have the same form. The values of µ and Bµ are model-dependent and we leave them as free parameters, determined by successful EWSB conditions.

The gaugino masses are given by

Mi=−(bi+NFd), (3.2)

with the beta function (b1, b2, b3) = (33/5, 1, −3) and the standard normalization for g1 coupling g21 = 5g2Y/3.

The trilinear couplings are calculated to be

(cid:20)t−(3 2U+ 2D)d−(cid:20)t−(2U+3 2D)d−(cid:0)−3 2Ld(cid:1).(cid:21)(cid:21)(3.3)(3.4)

The soft parameters are (G+ 3)+ with the relevant tedious expressions given in the appendix.

We have the following discussions: (i) In our scenario, the notorious tachyonic slepton problem appearing in ordinary AMSB can be naturally solved, and slepton masses receive dominant positive contributions from matter-messenger interactions regardless of the sign of the deflection parameter d. (ii) Even one messenger species can work well to give positive slepton masses regardless of the sign of deflection parameter d, so the possible Landau pole problem below the Planck scale is naturally evaded. (iii) The At value can be either positive or negative depending on the sign of d, and large U,D can lead to a large |At| which naturally gives a large Higgs mass with less fine-tuning. (iv) There is parameter space for light soft stop masses, so the radiative natural SUSY spectrum can be realized in our scenario, which we discuss in the next section.

4 Radiative Natural SUSY Spectrum and Numerical Analysis

The 125 GeV Higgs has already set constraints on the low-energy SUSY spectrum. From the formula

h(cid:39)m2Zcos22 +(cid:34)4 2v2(cid:33)(cid:35)(cid:32)12M2(4.1)

˜At=At−µcot , M2SUSY=m˜t1

we need either MSUSY/mt(cid:29)1 or MSUSY/mt > 1 with ˜At/MSUSY > 1. The stop masses must be larger than 10 TeV in the case of no stop mixing, requiring large fine-tuning. Obviously, a large ˜At is preferable for low-energy SUSY.

Natural SUSY models [10] try to retain naturalness of the weak scale by proposing a spectrum of light higgsinos |µ| 100−300 GeV and light ˜t1,2, ˜b1 along with very heavy masses for other squarks and TeV-scale gluinos. The gluino mass can affect the stop masses via RGE evolution, so low EW fine-tuning requires that the gluino not be too heavy. On the other hand, it is bounded from below by m˜g(cid:38)1.3 TeV from LHC searches within SUSY models like mSUGRA/CMSSM. The first two generation sfermions can be allowed in the 5-20 TeV range without introducing unnaturalness. Heavier first two generation squarks can ameliorate SUSY flavor, CP, gravitino, and proton-decay problems due to decoupling. Such models have low electroweak fine-tuning and satisfy LHC constraints.

However, the relatively heavy (125 GeV) Higgs mass creates tension with the ordinary natural SUSY scenario and indicates that natural SUSY may take the form of radiative natural SUSY [11], which requires a large At term. In fact, a large |At| value can suppress the top squark contributions to Σuu while lifting the Higgs mass. Such a large |At| can easily be obtained in our scenario, as seen from Eq.(3.3), where a large |At| appears for large   and either sign of deflection parameter d.

In ordinary radiative natural SUSY scenarios with universal gaugino mass at the GUT scale, the lightest sparticle (LSP) is always the higgsino, which cannot fully account for the DM relic abundance. The gaugino relation at the EW scale can naturally be evaded in the deflected AMSB scenario, allowing DM to be mixed bino-higgsino or wino-higgsino (or pure bino, pure wino). In ordinary AMSB, the gaugino mass ratio at the EW scale is M1:M2:M3   3.29:1:−9.6, leading to mixed higgsino-wino dark matter for gluino masses around 2 TeV. As noted in [14], the DM under-abundance problem persists. Generally, to obtain mixed higgsino-electroweakino DM, the gaugino mass ratio must satisfy M3:min(M1,M2)(cid:38)5, with gluino mass heavier than 1.5 TeV. Mixed bino-higgsino DM can give the full DM abundance, preferring a negative deflection parameter with NFd(cid:46)−3.

In our scenario, the soft terms are characterized by the free parameters

NF, d, µ, Mmess, F , tan , U, D, L. (4.2)

We scan the parameter space with the following messenger scale (Mmess) inputs: - The µ parameter is chosen between |µ| 100−300 GeV to maintain EW naturalness. - The scale of F determines the entire SUSY spectrum. Gaugino masses, EWSB conditions, and Higgs mass constraints require F in the range 10 TeV < F < 500 TeV. - The messenger scale Mmess can be chosen between the GUT scale and typical sparticle scale: 10 TeV < Mmess < 1016 GeV. - The value of tan is chosen as 40   tan   2. - Messenger species NF should lie in 1   NF   3 to avoid possible Landau poles, while the deflection parameter d satisfies NF · d(cid:46)−3 to fully account for DM relic density. - For simplicity, we set U = D = , with messenger-matter interactions in the range 0.5(cid:46) , L(cid:46)3 to justify keeping leading contributions in previous calculations while avoiding possible Landau poles.

In our scan we impose the following collider and dark matter constraints: (1) Successful radiative EWSB condition. (2) Stop and sbottom masses can be relatively heavy in radiative natural SUSY, in contrast to the 1.5 TeV upper bound in ordinary natural SUSY (with 4 less than 10% EW fine-tuning). We require stop masses satisfying m˜t1,2 TeV, corresponding to an upper bound for EW fine-tuning EW(cid:46)50. A large |At| always decreases the involved fine-tuning. Due to gluino loop contributions to stop masses, the gluino is bounded below 12 TeV. (3) Lower bounds on neutralino and chargino masses from LEP, including invisible Z-boson decay. The most stringent LEP constraints come from chargino mass and invisible Z-boson decay, requiring m˜ ± > 103.5 GeV and invisible decay width Γ(Z → ˜ 0˜ 0) < 1.71 MeV, consistent with 2 precision EW measurement Γnon−SM < 2.0 MeV. (4) Combined Higgs boson mass range: 123 GeV < Mh < 127 GeV from ATLAS and CMS data [1, 2]. (5) Neutralino dark matter relic density satisfying the Planck result ΩDM = 0.1199±0.0027 [18] (in combination with WMAP data [19]) with 10% theoretical uncertainty. (6) Dark matter in our scenario can be mixed bino-higgsino, so direct detection experiments may set stringent constraints. We survey spin-independent (SI) direct detection bounds from LUX [20], XENON1T [21], and future LUX-ZEPLIN 7.2 Ton [22] experiments.

[Figure 1: see original paper]. Scatter plots of the parameter space in our scenario, showing dark matter relic density versus Higgs mass in the left panel and spin-independent DM-nucleon scattering cross section versus LSP mass in the right panel. All points survive collider and dark matter constraints (1-6). The EW fine-tuning (EW) for sample points is also shown.

Numerical results with corresponding EW fine-tuning are shown in Fig 1. It should be noted [24] that conventional measures, including the BG measure [23], tend to overestimate EWFT in supersymmetric models, often by several orders of magnitude. According to the Fine-tuning Rule proposed in [25], both Higgs mass and traditional BG fine-tuning measures reduce to the model-independent EW fine-tuning measure EW.

From the figure we make the following observations: - Both the 125 GeV Higgs mass and correct DM relic density can be obtained in our scenario. There is substantial parameter space giving the correct DM relic abundance, a consequence of the mixed bino-higgsino DM nature. Deflection of the AMSB trajectory is crucial for a light bino to be the lightest gaugino (with M1(cid:46)µ) compatible with LHC constraints on gluino mass m˜g(cid:38)1.3 TeV. Without deflection, the lightest gaugino would be heavy and wino-like, predicting either higgsino or mixed wino-higgsino DM, both leading to DM under-abundance. - Our scenario can also produce the observed 125 GeV Higgs mass, a consequence of a relatively large At term. The EW fine-tuning needed for the 125 GeV Higgs mass can be as low as EW(cid:46)50, though larger Higgs masses slightly increase the involved EW fine-tuning. - We also survey spin-independent (SI) direct detection bounds from DM-nucleon scattering experiments. The SI interaction of neutralino DM with quarks inside the nucleus occurs via s-channel squark exchange and t-channel Higgs exchange processes. As squarks are constrained by LHC data to be considerably heavy, Higgs exchange diagrams dominate the spin-independent −p scattering cross section. The Higgs- - coupling is driven by bino-higgsino and wino-higgsino mixing. Unlike pure gaugino or pure higgsino DM where the associated SI cross-section becomes quite small, the SI cross section can be large for mixed bino-higgsino DM. However, DM can evade SI direct detection experiments if the mixing is small. In our numerical study, the most interesting points with low EW fine-tuning (namely those accounting for the 125 GeV Higgs mass with EW < 100) typically have cross sections below 10−9 pb, and the majority will be covered by XENON-1T. Nevertheless, small regions with low EW fine-tuning can survive XENON-1T and LUX-ZEPLIN 7.2 Ton sensitivity, indicating that the corresponding bino-higgsino mixing is not large.

5 Conclusions

In this work we proposed a radiative natural SUSY spectrum in the deflected anomaly mediation scenario with general messenger-matter interactions. Due to contributions from new interactions, positive slepton masses and a large |At| term can naturally be obtained with either sign of the deflection parameter and few messenger species, thus avoiding the possible Landau pole problem. In contrast to ordinary radiative natural SUSY scenarios with dark matter underabundance, the dark matter in our scenario can be mixed bino-higgsino and give the correct relic density. The 125 GeV Higgs mass can also be easily obtained, and the majority of low EW fine-tuning points can be covered by XENON-1T direct detection experiments.

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A Scalar Soft SUSY Breaking Mass Terms

The expressions for scalar soft parameters are derived from the general forms in [8] and given by

(G+ 3)+(A.1)

with each type of contribution given below.

- Cross term (anomaly-gauge mediation) contributions:

The anomaly-gauge mixed mediation part is given by

ln ZD µ ln |X|+ gr)G−−GD(A.2)

Crossing the messenger threshold, the change of the beta function for gi is

gi=16 2NFg3(A.3)

and the discontinuity of Ga is

GUc8 2 28 22 28 2(28 2(2 28 2(2 2U),D+ 2U),(A.4)

After manipulations, we obtain

(cid:21)+ gr16 2NFg416 2NFg4(cid:21)(cid:21)(cid:1)−2(cid:1)−2U+ 2U+ 2(cid:21)(cid:0)3 2(cid:0)3 216 2NFg

Expressions for the first two generation squarks can be obtained by simply removing the y2t terms.

- Gauge mediation-type contributions:

The gauge mediation part is given by

G+ 3=− ln |X|2ln Z=− ln |X|2Z+| ln |X|(A.6)

The sums of the discontinuity are

(cid:2) 2U(G U−GQ)+ 2D(G D−GQ)(cid:3),(cid:88)(cid:88)(cid:88)(cid:88)(cid:88)(cid:19)(cid:19)(cid:19)(cid

the anomalous dimension with GUQ+GUU+GU and GUQ+GUD+GU for U and D above the threshold. So we obtain

UGTUDGTU(cid:21)−2 2UGTU(cid:21)(cid:20)(cid:20)(cid:2)−2 2(cid:2)− 2(cid:3),DGTU(cid:3),LGTU(cid:2

The index TU denotes the value upon the messenger threshold. We list their expressions:

(cid:0)3 2U+ 2(cid:1),U+3 2(cid:1),(cid:0) 2(cid:18)U+ 2D+3y2(cid:19)(cid:18)D+ 2U+ 2L+y2(cid:19)(cid:0)4

There are other terms from the ordinary GMSB part with 3= gr(cid:18) (cid:19)8 22cr2gr16 2g3

Note that the change of the beta function is g=NF.

Q= 3U= 3L= 3E= 3(cid:21)(cid:20)8(8 2)2(A.9)(A.10)(A.11)

In the previous expressions, we keep only terms involving g3.

- Pure anomaly contributions:

A=− ln |X|2ln Z=− ln |X|2Z+| ln |X|(A.12)

Thus we obtain

bGyb(cid:3)−(cid:21)(cid:20)1(cid:2)y2tGyt+y2(cid:18)(cid:20)(cid:3)−(cid:2)2y2tGyt(cid:18)(cid:20)(cid:19)(

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