Physics Letters B 754 (2016) 118–124

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Natural split mechanism for sfermions: $N = 2$ supersymmetry in phenomenology

Yasuhiro Shimizu [a], Wen Yin [b,*]

[a] Academic Support Center, Kogakuin University, Hachioji 192-0015, Japan
[b] Department of Physics, Tohoku University, Sendai 980-8578, Japan

ARTICLE INFO

Article history:
Received 4 October 2015
Received in revised form 11 January 2016
Accepted 11 January 2016
Available online 14 January 2016
Editor: J. Hisano

ABSTRACT

We suggest a natural split mechanism for sfermions based on $N = 2$ supersymmetry (SUSY). $N = 2$ SUSY protects a sfermion in an $N = 2$ multiplet from gaining weight by SUSY breaking. Therefore, if partly $N = 2$ SUSY is effectively obtained, a split spectrum can be realized naturally. As an example of the natural split mechanism, we build a gauge-mediated SUSY breaking-like model assuming $N = 2$ SUSY is partly broken in an underlying theory. The model explains the Higgs boson mass and muon anomalous magnetic dipole moment within 1 σ level with a splitting sfermion spectrum. The model has seven light sparticles described by three free parameters and predicts a new chiral multiplet, sb: the $N = 2$ partner of the $N = 1$ $U(1)_Y$ vector multiplet. The bini, the fermion component of the sb, weighs MeVs. We mention the experimental and cosmological aspects of the model.

1. Introduction

After the discovery of the Standard Model (SM) Higgs-like boson at the Large Hadron Collider (LHC) [1], no new particle has been found. On the other hand, some deviations from the SM have been observed in flavor physics [2]. If nature has supersymmetry (SUSY), the current experiments suggest an interesting possibility: a split spectrum for sfermions. No discovery of sparticles [3] gives bounds to the squark masses: the squarks should be heavier than $\mathcal{O}(1)$ TeV. This is consistent with the simplest SUSY SM (minimal supersymmetric standard model: MSSM) prediction, since stops are required to be heavier than $\mathcal{O}(10)$ TeV to explain the Higgs boson mass of about 125 GeV unless the SUSY breaking stop-Higgs trilinear coupling is parametrically large [4]. In the case, the heavy sfermions automatically solve/alleviate the flavor/CP problem, the proton decay problem, several cosmological problems etc. On the other hand, if some deviations in flavor physics are true, there should also be light sfermions. For example, the deviation of the muon anomalous magnetic dipole moment (muon $g-2$) from the SM prediction, $\delta(\frac{g-2}{2}) = (26.1 \pm 8.0) \times 10^{-10}$ [5,6], is above the 3 σ level. To relax the tension, a smuon as light as $\mathcal{O}(300)$ GeV is needed in the MSSM [7].

A split spectrum commonly has the naturalness problem proposed by 't Hooft [8]. If the particle mass is naturally small, by the definition of naturalness, there should be an approximate symmetry dominantly broken by the mass. The split spectrum mostly considered is the mass split between gauginos [9] (gauginos with higgsino [10]) and all the scalars except for the Higgs boson. The split is natural since chiral symmetry forbids the mass term of a gaugino/higgsino. In SUSY SMs, the sfermion mass comes from SUSY breaking, hence the lighter sfermions should be protected from the SUSY breaking by a symmetry while the heavier ones are not.[1]

In this paper, we suggest a natural split mechanism using $N = 2$ SUSY [12]. The non-renormalization theorem of $N = 2$ SUSY forbids the sfermion mass terms which are embedded in $N = 2$ multiplets even with SUSY slightly broken (Sec. 2). If we add a sector with $N = 1$ SUSY weakly coupled to the $N = 2$ sector, the SUSY breaking dominantly affect the sfermion masses in the $N = 1$ sector, while sub-dominantly to those in the $N = 2$ sector since they are protected by $N = 2$ SUSY. Therefore, a partly $N = 2$ SUSY model can generate a naturally splitting sfermion spectrum.

As an example, we construct a natural split gauge-mediated SUSY breaking (GMSB) model [13] to explain the muon $g-2$

* Corresponding author.
E-mail addresses: yshimizu.hep@gmail.com (Y. Shimizu), yinwen@tuhep.phys.tohoku.ac.jp (W. Yin).

[1] Note that the split between sfermions seems to be unconstrained by the anthropic principle. This is the difference from the case of the electroweak scale and the cosmological constant [11].

http://dx.doi.org/10.1016/j.physletb.2016.01.012

Table 1
$N=2$ multiplets and $SU(2)_R$ representations.

$N=2$ multiplet	In superfields		In fields		Renormalized at
Vector multiplet	(V, Φ_Y)		$((A^\mu, \lambda, D), (\Phi_Y, \psi_Y, F_Y))$		1-Loop level
Hypermultiplet	$(\Phi_i, \overline{\Phi}_i^\dagger)$		$((\phi_i, \psi_i, F_i), (\bar\phi_i, \overline{\psi}_i, \overline{F}_i)^\dagger)$		Tree level
$SU(2)_R$ multiplet	$(\phi_i, \bar\phi_i^\dagger)$	(λ, ψ_Y)	$(\overline{F}_i^\dagger, F_i)$	$(\Re[F_Y], \Im[F_Y], \frac{1}{\sqrt{2}}D)$	The others
Representation	**2**	**2**	**2**	**3**	1

anomaly within the 1σ level. We introduce the hyperpartners of left-handed sleptons, smuons, and down-type Higgs, with the extension of the $U(1)_Y$ gauge interaction to $N=2$ SUSY by introducing a singlet chiral multiplet. To cancel the gauge anomaly, we introduce spectator fields which are the mirror particles of the hyperpartners. The messenger sectors are also partly extended to $N=2$ SUSY so that the natural split mechanism works. The condition of gauge coupling unification (GCU) at the SUSY GUT scale, $\sim 10^{16}$ GeV, naturalness, and the symmetries require the additional charged fields to be at the same scale, the messenger scale. Below the messenger scale, the MSSM particles and the singlet survive.

In our model, there are only three free parameters: the messenger scale, the dominant and sub-dominant F-terms. The dominant one only gives masses to the sfermions in the $N=1$ sector at the leading order due to the natural split mechanism. The subdominant one acts as the one in the usual GMSB model. We show an IR spectrum containing various testably light MSSM sparticles such as smuons, left-handed sleptons, and gauginos. In addition, there is a new light singlet fermion, bini, which is the $SU(2)_R$ partner of the bino. In our model, the bini mass is $\mathcal{O}(10)$ MeV, which is 2-loop suppressed to the bino mass. The light bini rarely interacts with the MSSM particles, due to the higher dimensional interactions suppressed by the messenger scale.

2. Natural Split Mechanism

A sfermion mass term comes from the bilinear Kähler term,

$$\mathcal{K} = \frac{|Z|^2}{M^2} Q^\dagger Q \supset |\theta|^4 \left|\frac{F_Z}{M}\right|^2 \tilde{Q}^\dagger \tilde{Q}. \tag{1}$$

We will show $N=2$ SUSY forbids such a term.

An $N=2$ SUSY extension of the SM is hardly considered for phenomenology. There are at least two difficulties. The renormalizable $N=2$ SUSY theory only has fermions that are in real representations, while the SM fermions are chiral. The Landau-pole of the gauge coupling is generated at a low energy scale. However, a partly $N=2$ SUSY extension at a high energy scale is not so problematic.

2.1. Review of $N=2$ SUSY

Here we briefly review $N=2$ SUSY. For simplicity, we consider $N=2$ SUSY quantum electrodynamics.

The Lagrangian is given in the $N=1$ superfield formalism as

$$\begin{aligned}
\mathcal{L}_{N=2} &= \mathcal{L}_{\rm matter} + \mathcal{L}_{\rm gauge},\\
\mathcal{L}_{\rm matter} &= \int d^4\theta \sum_i^{N_f} (\overline{\Phi}_i e^{-2Y_i V} \overline{\Phi}_i^\dagger + \Phi_i^\dagger e^{2Y_i V} \Phi_i)\\
&\quad + \int d^2\theta \sum_i^{N_f} (\sqrt{2}\overline{Y}_i \overline{\Phi}_i \Phi_Y \Phi_i + \sum_j m_{i,j} \overline{\Phi}_i \Phi_j) + \text{h.c.},\\
\mathcal{L}_{\rm gauge} &= (\frac{1}{g^2}\int d^4\theta \Phi_Y^\dagger \Phi_Y + \frac{1}{4g^2}\int d^2\theta W_\alpha W^\alpha + \text{h.c.}),
\end{aligned} \tag{2}$$

with $Y_i = |\overline{Y}_i|$, $[m^\dagger, m] = 0$. The Lagrangian is the most general non-trivial renormalizable Lagrangian with $N=2$ SUSY without the Fayet–Iliopoulos (FI) term [14].

There are two kinds of $N=2$ multiplets in the Lagrangian: vector multiplet and hypermultiplet. The Lagrangian has a specific symmetry, $SU(2)_R$ symmetry, that rotates the fields in the $N=2$ multiplet as in Table 1. The $SU(2)_R$ symmetry is not only non-commutative with θ, but also not closed in an $N=1$ supermultiplet.

Since the Lagrangian has the $SU(2)_R$ symmetry only if $Y_i = |\overline{Y}_i|$, the $SU(2)_R$ symmetric models do not allow $\overline{Y_i}$ to vary even with the wave functions renormalized. Because of the non-renormalization theorem for the superpotential, the $SU(2)_R$ symmetry leads to the non-renormalization theorem to the Kähler potential as in the Table 1.

2.2. $N=2$ SUSY breaking

We consider the case that $N=2$ SUSY is slightly broken to $N=0$ by an F-term, F_Z, of a SUSY breaking field, Z. Since $N=2$ SUSY is recovered with the vanishing F-term, the effective Lagrangian should be

$$\begin{aligned}
&\mathcal{L}_{\rm eff} = \mathcal{L}_{N=2} + \mathcal{L}_{N2B},\\
&\mathcal{L}_{N2B} = \int d^4\theta \tilde{W}(\Phi_i, \overline{\Phi}_i, \Phi_Y, Z, Z^\dagger) + \text{h.c.}
\end{aligned} \tag{3}$$

Here $\tilde{W}$ is a holomorphic function of Φ_i, $\overline{\Phi}_i$, and Φ_Y. Therefore, even with SUSY breaking, sfermion masses like Eq. (1) are forbidden by the non-renormalization theorem. On the other hand, integrating $\bar\theta^2$ out, an effective superpotential, $F_Z^\dagger \partial_{Z^\dagger}\tilde{W}$, is generated.

If Φ_Y is a gauge singlet as in Sec. 2.1, the dangerous tadpole term, $\delta\tilde{W} \sim Z^\dagger \Phi_Y$, may be generated. $Z^\dagger \Phi_Y$ can be a source of large $\Phi_Y \sim Z$ or $F_Y \sim F_Z$ unless fine-tunings. To have $< \Phi_Y > \sim 0$ naturally, there are two possibilities. One is to introduce a large SUSY preserving mass term, $W = M\Phi_Y^2$, by hand to suppress $< \Phi_Y >$. The other is to impose a symmetry to forbid the tadpole term or to have a naturally small one. In this paper, to forbid the tadpole term we assume a symmetry, under which Z is charged, while Φ_Y is not.

A concrete Z_2 symmetric superpotential with slightly broken $N=2$ SUSY is as follows.

$$W = \sqrt{2}Y\Phi_Y(\Phi_1\overline{\Phi}_1 + \Phi_{-1}\overline{\Phi}_{-1}) + Z(\Phi_1\overline{\Phi}_1 - \Phi_{-1}\overline{\Phi}_{-1}). \tag{4}$$

The model possess a Z_2 symmetry which exchanges the indices and reverses the sign of Z. Since Z can be identified as the chiral