Light Higgsino and Gluino in $R$-invariant Direct Gauge Mediation

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Abstract

We provide a simple solution to the $\mu$-$B_\mu$ problem in the “$R$-invariant direct gauge mediation model”. With the solution, the Higgsino and gluino are predicted to be light as $O(100)$ GeV and $O(1)$ TeV, respectively. Those gluino and Higgsino can be accessible at the LHC and future collider experiments. Moreover, dangerous dimension five operators inducing rapid proton decays are naturally suppressed by the $R$-symmetry.
1 Introduction

Models of gauge mediated supersymmetry breaking (GMSB) \cite{1,3} are very attractive, since dangerous flavor violating processes are naturally suppressed: soft supersymmetry (SUSY) breaking masses of sleptons and squarks are generated via gauge interactions, and hence, they are flavor-blind.

Among GMSB models, “R-invariant direct gauge mediation model” constructed in Refs. \cite{9,10} (see also \cite{11,12} for recent discussions) is highly successful, since the SUSY breaking minimum is stable. The model has an (spontaneously broken) R-symmetry, which may suppress dangerous proton decay operators. This model is also interesting from the view point of phenomenology. The gaugino masses are suppressed compared to sfermion masses even though the R-symmetry is spontaneously broken. These relatively light gauginos can be seen at future large hadron collider (LHC) experiments. On the other hand, squark masses $m_{\tilde{q}}$ including stop masses are $O(10)$ TeV and the observed Higgs boson mass of 125 GeV \cite{13,14} is easily explained with large radiative corrections from heavy stops \cite{15,19}.

The important remaining issue in this model is the $\mu$-$B_\mu$ problem \cite{20,29}: if $\mu$ and $B_\mu$ terms are generated dynamically, it usually predicts $\mu^2 \ll B_\mu \sim m^2_{H_u,d'}$ where $m_{H_u}$ ($m_{H_d}$) is a soft SUSY breaking mass for the up-type (down-type) Higgs. With the hierarchy of $\mu^2$ and $B_\mu$, it has been considered to be difficult to realize the correct electroweak symmetry breaking (EWSB) for $m_{\tilde{q}} = O(0.1 - 1)$ TeV. The situation changes for $m_{\tilde{q}} \gtrsim 10$ TeV, since the hierarchy itself may not be a problem anymore.

The bare $\mu$-term needs to be prohibited. If the bare $\mu$-term is allowed by the R-symmetry, the dimension five proton decay operators are also allowed by the symmetry under the assumption that the grand unified theory (GUT) exists.\footnote{If the $R$-charge of $H_u H_d$ is 2, the $R$-charge of the dangerous operator $10 \bar{10} 10$ is also 2 provided that Yukawa interactions are allowed by the $R$-symmetry.} These dimension five operators cause unacceptably rapid proton decays unless the soft SUSY breaking mass scale is extremely high as $\sim 10^{10}$ GeV \cite{30}. The $\mu$-$B_\mu$ problem might be related to the rapid proton decay problem.

In the minimal GMSB model, it has been shown that the $\mu$-$B_\mu$ problem is solved in a simple and naive way with a slight modification of the GUT relation among messenger masses for $\mu \sim 100$ GeV and $\sqrt{|B_\mu|} \sim m_{\tilde{q}} \sim 10$ TeV \cite{31,32}. In this letter, we point out that the $\mu$-$B_\mu$ problem is also solved in the R-invariant direct gauge mediation model in this way. With the solution, the Higgsino as well as the gluino is predicted to be light, which has a large impact on LHC and International linear collider (ILC) SUSY searches. We also point out that the violation of the GUT relation is not needed for the solution in this model.

\footnote{See also Refs. \cite{4,5} for early attempts.}

\footnote{The $\mu$-$B_\mu$ problem is also solved in a simple way with mini-split SUSY spectra where the stop mass is larger than $O(100)$ TeV \cite{32}.}
2 \hspace{1em} R\text{-invariant direct gauge mediation and } \mu/B_\mu \text{ term}

2.1 The model

First, let us briefly review the R-invariant direct gauge mediation model. The model has a spontaneously broken R-symmetry, which suppresses gaugino masses compared to sfermion masses. The superpotential of the messenger sector is

\[ W \supset -\mu_Z^2 Z + M_1 \Psi \bar{\Psi}' + M_2 \Psi' \bar{\Psi} + c_1 Z \Psi \bar{\Psi}, \]  

(1)

where \( \Psi \) and \( \Psi' \) (\( \bar{\Psi} \) and \( \bar{\Psi}' \)) are the messenger fields transformed as \( 5 (\bar{5}) \) in \( SU(5) \) GUT gauge group. The above superpotential is invariant under \( U(1)_R \) symmetry with the \( R \)-charges of \( Q(Z) = Q(\Psi') = Q(\bar{\Psi}') = 2 \) and \( Q(\Psi) = Q(\bar{\Psi}) = 0 \). We assume \( Z \) has vacuum expectation values, which breaks \( R \)-symmetry and SUSY as

\[ \langle F_Z \rangle = \mu_Z^2. \]

(2)

where \( \langle F_Z \rangle \neq 0 \). Such spontaneous breaking of the \( R \)-symmetry can be achieved in O’Raifeartaigh like models at tree-level \[33–35\] or one-loop level \[36,37\] if there exists a field with \( R \)-charge other than 0 or 2. Also, the spontaneously breaking can occur at the higher loop level \[38–41\]. In this paper, we do not specify the origin of the spontaneous \( R \)-symmetry breaking and take \( \phi_Z \) as a free parameter.

The messenger superfields, \( \Psi, \Psi', \bar{\Psi} \) and \( \bar{\Psi}' \), are decomposed as

\[ \Psi = \Psi_D + \Psi_L, \quad \bar{\Psi} = \Psi_D + \Psi_L, \]
\[ \Psi' = \Psi_D' + \Psi_L', \quad \bar{\Psi}' = \Psi_D' + \Psi_L', \]

(3)

where \( \Psi_D' \) and \( \Psi_L' \) are transformed as \((3, 1, 1/3)\) and \((1, 2, -1/2)\) under \( SU(3)_c \times SU(2)_L \times U(1)_Y \), respectively. Then, the superpotential in Eq. (1) can be written as

\[ W \supset -\mu_Z^2 Z + M_{1L} \Psi_L \Psi_L' + M_{2L} \Psi_L' \Psi_L + c_L Z \Psi_L \Psi_L + M_{1D} \Psi_D \Psi_D' + M_{2D} \Psi_D' \Psi_D + c_D Z \Psi_D \Psi_D, \]

(4)

where all parameters are taken to be real positive without loss of generality. For simplicity, further, we take \( M_{1L} = M_{2L} \equiv M_L \) and \( M_{1D} = M_{2D} \equiv M_D \) in the following discussions.

Accordingly, the messenger sector are parametrized by the following five parameters:

\[ \Lambda_{\text{SUSY}}, \ M_{\text{mess}}, \ R, \ r_L, R_L \]

(5)

where \( \Lambda_{\text{SUSY}} = c_D \mu_Z^2/M_D, \ M_{\text{mess}} = M_D, \ R = c_D \phi_Z/M_D, \ r_L = M_L/M_D \) and \( R_L = c_L/c_D \). In the case that \( c_L = c_D \) and \( M_L = M_D \) are satisfied at the GUT scale, \( r_L \) and \( R_L \) are fixed as \( r_L \approx R_L \approx 1/1.4 \).
After integrating out the messenger fields, gauginos and sfermions obtain soft SUSY breaking masses. The gaugino masses are estimated as

\[ M_1 \simeq \frac{g_1^2}{16\pi^2} \left( \frac{2 \Lambda_{SUSY}^3}{5 M_{mess}^2} \mathcal{F}_D + \frac{3 \Lambda_{SUSY}^3}{5 M_{mess}^2} \frac{R_L^3}{r_L} \mathcal{F}_L \right), \]

\[ M_2 \simeq \frac{g_2^2}{16\pi^2} \frac{\Lambda_{SUSY}^3}{M_{mess}^2} \frac{R_L^3}{r_L} \mathcal{F}_L, \]

\[ M_3 \simeq \frac{g_3^2}{16\pi^2} \frac{\Lambda_{SUSY}^3}{M_{mess}^2} \mathcal{F}_D, \]

where \( \mathcal{F}_D \) and \( \mathcal{F}_L \) are numerical coefficient of \( \mathcal{O}(0.1) \) (see [10] for complete formulae). Note that the gaugino masses are suppressed by factors, \( \Lambda_{SUSY}^2/M_{mess}^2 \) and \( F_{L,D} \). On the other hand, the sfermion masses are not suppressed by the factor, and they are approximately given by

\[ \tilde{m}_i^2 \simeq \frac{2}{(16\pi^2)^2} \left[ C_i^3 g_3^4 + C_i^2 g_2^4 \frac{R_L^3}{r_L^2} + \frac{3}{5} g_i^4 (Q_Y^i)^2 \left( \frac{2}{5} + \frac{3}{5} \frac{R_L^3}{r_L^2} \right) \right] \Lambda_{SUSY}^2, \]

where \( C_i^3 (C_i^2) \) is a quadratic Casimir invariant of \( SU(3)_c \) (\( SU(2)_L \)) and \( Q_Y^i \) is a hypercharge. From Eq.(6) and Eq.(7), we see the hierarchical masses of \( M_{1,2,3}^2 \ll \tilde{m}_i^2 \). The complete formula of Eq.(7) can be found in, for instance, Refs. [42,43].

### 2.2 Generation of \( \mu/B_\mu \) terms

Next, we introduce messenger-Higgs couplings to generate \( \mu \) and \( B_\mu \)-terms. The relevant part of the superpotential is given by

\[ W \supset c_S Z \bar{S} \bar{S} + k_u H_u \Psi_L \bar{S} + k_d H_d \Psi_L \bar{S}, \]

where \( S \) and \( \bar{S} \) are gauge singlet superfields with the \( R \)-charge assignment, \( Q(S) + Q(\bar{S}) = 0 \). Here, \( Q(H_u) + Q(H_d) = 4 \) and the bare \( \mu \) term, \( \mu H_u H_d \), is not allowed by \( U(1)_R \) symmetry. Also, a dangerous dimension five proton decay operator, \( 10 \ 10 \ 10 \ 5 \), is prohibited by the symmetry. So far we have eight free parameters in this model:

\[ \Lambda_{SUSY}, M_{mess}, R, r_L, R_L, R_S, k_u, k_d, \]

where \( \Lambda_{SUSY}, M_{mess}, R, r_L \) and \( R_L \) are defined in the previous subsection, and \( R_S = c_S/c_D \).

Integrating out the messenger fields, \( S \) and \( \bar{S} \), the \( \mu \)-parameter and soft SUSY breaking mass parameters are generated as

\[ \mu \approx -160 \text{ GeV} \left( \frac{k_u k_d}{0.05} \right) \left( \frac{\Lambda_{SUSY}}{2 \cdot 10^6 \text{GeV}} \right), \]

\[ B_\mu \approx 1.2 \times 10^8 \text{ GeV}^2 \left( \frac{k_u k_d}{0.05} \right) \left( \frac{\Lambda_{SUSY}}{2 \cdot 10^6 \text{GeV}} \right)^2 \]

\[ ^4 \text{With a particular choice of } R \text{-charges, the seesaw mechanism can be incorporated.} \]
\[ \delta m_{H_u,d}^2 \approx 9.8 \times 10^8 \text{GeV}^2 \left( \frac{k_{u,d}}{0.5} \right)^2 \left( \frac{\Lambda_{\text{SUSY}}}{2 \cdot 10^6 \text{GeV}} \right)^2 \]

\[ A_{u,d} \approx 2.8 \times 10^3 \text{GeV} \left( \frac{k_{u,d}}{0.5} \right)^2 \left( \frac{\Lambda_{\text{SUSY}}}{2 \cdot 10^6 \text{GeV}} \right)^2 \] (10)

for \( R = r_L = R_L = 1, R_S = 7 \) and \( \Lambda_{\text{SUSY}}/M_{\text{mess}} = 0.95 \). The analytic forms of Eq. (10) can be found in Appendix A.

The above \( \mu \) and \( B_\mu \) must satisfy conditions for the EWSB. The conditions are given by

\[ \frac{m_Z^2}{2} \approx \left[ -\mu^2 - \frac{\left( m_{H_u}^2 + \frac{1}{2v_u} \frac{\partial \Delta V}{\partial v_u} \right) \tan^2 \beta}{\tan^2 \beta - 1} + \frac{m_D^2 + \frac{1}{2v_d} \frac{\partial \Delta V}{\partial v_d}}{\tan^2 \beta - 1} \right] M_{\text{stop}}, \]

\[ \frac{B_\mu (\tan^2 \beta + 1)}{\tan \beta} \approx \left[ m_{H_u}^2 + \frac{1}{2v_u} \frac{\partial \Delta V}{\partial v_u} + m_{H_d}^2 + \frac{1}{2v_d} \frac{\partial \Delta V}{\partial v_d} + 2\mu^2 \right] M_{\text{stop}}, \] (11)

where \( m_Z \) is the Z boson mass and \( \tan \beta \) is a ratio of the VEVs, \( v_u/v_d \); \( \Delta V \) is one-loop corrections to the Higgs potential. The Higgs soft masses and \( \Delta V \) are evaluated at the stop mass scale, \( M_{\text{stop}} \).

The \( \mu \)-parameter is roughly estimated as

\[ -\mu^2 \approx \frac{m_{H_u}^2 (M_{\text{stop}})}{\tan^2 \beta} + \frac{1}{2v_u} \frac{\partial \Delta V}{\partial v_u} - \frac{m_{H_d}^2 (M_{\text{stop}})}{\tan^2 \beta} \]

\[ \approx \left( m_{H_u}^2 \right)_{\text{GMSB}} + \delta m_{H_u}^2 + (\Delta m_{H_u}^2)_{\text{rad}} + \frac{1}{2v_u} \frac{\partial \Delta V}{\partial v_u} \]

\[ - \frac{m_{H_d}^2}{\tan^2 \beta} \]

\[ = -(\mathcal{O}(100) \text{ GeV})^2; \] (12)

where \( (m_{H_u}^2)_{\text{GMSB}} \) are contributions from gauge mediation in Eq. (7), and \((\Delta m_{H_u}^2)_{\text{rad}} \) contains radiative corrections from stop and gluino loops and is negative. Since \( |(m_{H_u}^2)_{\text{GMSB}}| \ll |(\Delta m_{H_u}^2)_{\text{rad}}| \), \( \mu \)-parameter determined by the EWSB conditions is larger than \( \mathcal{O}(0.1)M_{\text{stop}} \) in usual GMSB models. However, in our model, the small \( \mu \)-parameter is obtained with sizable \( \delta m_{H_u}^2 \), i.e. Eq. (10) and Eq. (11) are consistently satisfied.

### 3 Results

In this section, we discuss the mass spectra of SUSY particles and survey the parameter region where the mass of observed Higgs boson and the EWSB are correctly explained.

#### 3.1 SM-like Higgs mass

First, we estimate the mass of the lightest CP-even neutral Higgs boson, \( m_{h^0} \). Figure [1] shows the value of \( m_{h^0} \) on \( (\Lambda_{\text{SUSY}}, \tan \beta) \) plane with the other parameters fixed. Here we compute mass spectra of SUSY particles using softsusy-4.0.1 [44] with appropriate modifications and then \( m_{h^0} \) is estimated using SUSYHD [45]. In the left (right) figure, we...
Figure 1: The SM-like Higgs mass in $(\Lambda_{\text{SUSY}}, \tan \beta)$ plane. We take $\Lambda_{\text{SUSY}}/M_{\text{mess}} = 0.95$, $R_L = r_L = 1$, $R_S = 7$, $k_u = 0.1$ and $k_d = 0.5$ ($\Lambda_{\text{SUSY}}/M_{\text{mess}} = 0.68$, $R = 1.5$, $R_L = r_L = 1/1.4$, $R_S = 6$, $k_u = 0.02$ and $k_d = 0.2$) in the left (right) figure. In both cases, we take $\alpha_s(M_Z) = 0.1185$ and $m_t(\text{pole}) = 173.3$ GeV.

Even for $\Lambda_{\text{SUSY}} = O(10^3)$ TeV (i.e. $O(10)$ TeV squarks), the gauginos in our model are predicted to be enough light for good targets at the collider experiments. Figure 2 shows the mass of gluino, $m_{\tilde{g}}$, on $(\Lambda_{\text{SUSY}}/M_{\text{mess}}, R)$ plane with fixing $\Lambda_{\text{SUSY}}$ and the other parameters. For the estimation of $m_{\tilde{g}}$, we use softsusy-4.0.1. In the left (right) figure, we take $\Lambda_{\text{SUSY}} = 2000$ TeV, $R_L = r_L = 1$, $R_S = 10$, $k_u = 0.07$ and $k_d = 0.28$ ($\Lambda_{\text{SUSY}} = 6000$ TeV, $R_L = r_L = 1/1.4$, $R_S = 6$, $k_u = 0.02$ and $k_d = 0.2$). Gray dashed lines show the contours of $m_{\tilde{g}}$ [TeV]. It is found that $m_{\tilde{g}} = 2-3$ TeV in the whole parameter region shown in Fig. 2.

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3.3 Electroweak symmetry breaking

We next check whether the EWSB conditions are correctly satisfied. For this purpose, we solve the EWSB conditions (Eq. 11) using softsusy-4.0.1 and compare the solutions with $\mu$ and $B_\mu$ in Eq.(10). Figure 3 shows the difference between our predictions ($\mu$ and
3.4 Mass spectra in some benchmark points

Finally, we show the typical mass spectra in our model. Here, we pick up four benchmark points shown in Table I: (A) $\Lambda_{\text{SUSY}} = 2000 \text{TeV}$, $R_L = r_L = 1$, $R_S = 10$, $k_u = 0.07$ and $k_d = 0.28$ ($\Lambda_{\text{SUSY}} = 6000 \text{TeV}$, $R_L = r_L = 1/1.4$, $R_S = 6$, $k_u = 0.02$ and $k_d = 0.2$) in the left (right) figure.

$B_\mu$ and the solution to the EWSB conditions ($\mu^{\text{EWSB}}$ and $B_\mu^{\text{EWSB}}$). In the left (right) figure, we take $\Lambda_{\text{SUSY}}/M_{\text{mess}} = 0.95$, $R = R_L = r_L = 1$, and $k_d = 0.5$ ($\Lambda_{\text{SUSY}}/M_{\text{mess}} = 0.68$, $R = 1.5$, $R_L = r_L = 1/1.4$, and $k_d = 0.2$). In gray region, $\mu^{\text{EWSB}} < 0$. The blue region corresponds to the parameter region where $\delta B_\mu = (|B_\mu| - |B_\mu^{\text{EWSB}}|)/|B_\mu|$ is larger than 0.05, 0.10, 0.15 or smaller than $-0.05$, $-0.10$, $-0.15$. In white region, the prediction of $B_\mu$ is consistent with the EWSB conditions within 5% level. Red and black dashed lines show the contours of $|\mu| \text{[GeV]}$ and $|\mu^{\text{EWSB}}| \text{[TeV]}$, respectively. It should be noted that the difference between $|\mu|$ and $|\mu^{\text{EWSB}}|$ is very sensitive to $k_u$. In other words, we need a fine-tuning of $k_u$ to find the parameter region where the prediction of $\mu$ is consistent with the EWSB conditions.
Figure 3: $\delta B_\mu = (|B_\mu| - |B_\mu^{EWSB}|)/|B_\mu|$ (Blue region), the contour of $|\mu|$/GeV (red lines) and $|\mu|^{EWSB}$/TeV (black dashed lines). We take $\Lambda_{\text{SUSY}}/M_{\text{mess}} = 0.95$, $R = R_L = r_L = 1$, and $k_d = 0.5$ ($\Lambda_{\text{SUSY}}/M_{\text{mess}} = 0.68$, $R = 1.5$, $R_L = r_L = 1/1.4$, and $k_d = 0.2$) in the left (right) figure.

and $\mathcal{O}(1)$TeV and they can be good targets for the forthcoming collider experiments.

In our model, the lightest SUSY particle (LSP) is always gravitino. Typical gravitino mass is estimated as

$$m_{3/2} = \frac{\mu^2}{\sqrt{3} M_{\text{pl}}} \approx 10 \text{ keV} \left(\frac{0.1}{c_D}\right) \left(\frac{\Lambda_{\text{SUSY}}}{2000 \text{ TeV}}\right)^2 \left(\frac{0.95}{\Lambda_{\text{SUSY}}/M_{\text{mess}}}\right),$$

where $M_{\text{pl}} \approx 2.4 \times 10^{18}$GeV denotes the reduced Planck mass.\footnote{Provided that the $R$-symmetry is explicitly broken by a constant term in the superpotential, the mass of the $R$-axion is given by}

$$m_a \approx 8.4 \text{ GeV} \left(\frac{m_{3/2}}{10 \text{ keV}}\right) \left(\frac{9000 \text{ TeV}}{\phi_Z}\right)^{1/4}. \tag{14}$$

4 Conclusion and discussion

We have provided a simple solution to the $\mu$-$B_\mu$ problem in $R$-invariant direct gauge mediation. In contrast to the case of minimal gauge mediation shown in Ref. [31], the solution works even when the GUT relations among the parameters in the messenger sector are satisfied.
Table 1: Mass spectra in some benchmark points. Mass spectra of SUSY particles and
the SM like Higgs boson are computed using softsusy-4.0.1 and SUSYHD, respectively.
At all benchmark points, we take $\alpha_s(M_Z) = 0.1185$ and $m_t(\text{pole}) = 173.3\text{GeV}$.

| Parameter                  | Point (A) | Point (B) | Point (C) | Point (D) |
|----------------------------|-----------|-----------|-----------|-----------|
| $\Lambda_{\text{SUSY}}$   | 2000 TeV  | 4000 TeV  | 6000 TeV  | 6000 TeV  |
| $\Lambda_{\text{SUSY}}/M_{\text{mess}}$ | 0.95      | 0.80      | 0.68      | 0.68      |
| $R$                        | 1         | 1         | 1.5       | 1.8       |
| $R_L$                      | 1         | 1         | 1/1.4     | 1/1.4     |
| $r_L$                      | 1         | 1         | 1/1.4     | 1/1.4     |
| $R_S$                      | 8         | 7         | 6         | 6.8       |
| $k_u$                      | $\approx 0.11$ | $\approx 0.10$ | $\approx 0.09$ | $\approx 0.16$ |
| $k_d$                      | 0.5       | 0.3       | 0.2       | 0.5       |
| Prediction                 |           |           |           |           |
| $m_{\tilde{g}}$            | 2.45 TeV  | 2.53 TeV  | 2.53 TeV  | 2.16 TeV  |
| $m_{\tilde{\chi}_1^0}$    | 162 GeV   | 180 GeV   | 128 GeV   | 455 GeV   |
| $m_{\tilde{\chi}_2^0}$    | 186 GeV   | 200 GeV   | 138 GeV   | 465 GeV   |
| $m_{\tilde{\chi}_3^0}$    | 424 GeV   | 539 GeV   | 861 GeV   | 989 GeV   |
| $m_{\tilde{\chi}_4^0}$    | 802 GeV   | 888 GeV   | 2.20 TeV  | 2.17 TeV  |
| $m_{\tilde{\chi}_1^+}$    | 174 GeV   | 190 GeV   | 132 GeV   | 460 GeV   |
| $m_{\tilde{\chi}_2^+}$    | 790 GeV   | 877 GeV   | 2.20 TeV  | 2.16 TeV  |
| $(m_{\tilde{\chi}_1}, m_{\tilde{\chi}_2})$ | (12.9, 14.7) TeV | (25.5, 28.9) TeV | (32.8, 36.9) TeV | (29.6, 33.6) TeV |
| $(m_{\tilde{\chi}_1^L}, m_{\tilde{\chi}_1^R})$ | (5.39, 3.92) TeV | (11.4, 7.04) TeV | (14.7, 8.37) TeV | (13.1, 8.47) TeV |
| $m_{\tilde{\nu}_1}$       | 125.7 GeV | 125.6 GeV | 125.7 GeV | 125.5 GeV |
| $m_{\tilde{\nu}_2}$       | 30.1 TeV  | 40.9 TeV  | 28.4 TeV  | 48.5 TeV  |
| $\mu$                      | -171 GeV  | -187 GeV  | -130 GeV  | -459 GeV  |
| $\tan \beta$              | 6         | 4         | 4         | 4         |

The Higgsino is predicted to be light as $\sim 100-500\text{GeV}$ with the solution. Since the gravitino is expected to be heavier than 10-100 keV, the lightest neutralino, which is Higgsino-like, is stable inside a detector. This light Higgsino is a good target at the LHC [46–51] and ILC [52]. The gluino is also likely to be light as 2-3 TeV, which can be tested at the future LHC experiment [53]. Moreover, the dangerous dimension five operators inducing rapid proton decays are naturally suppressed by the $R$-symmetry.

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In this appendix, we give analytic formulae for $\mu/B_\mu$-term, $A$-terms and $m^2_{H_u,d}$ at one-loop level. The definition for these parameters is the same with that in Ref. [31].

To begin with, we summarize the mass eigenstates of the messenger fermions and sfermions. After the spontaneous SUSY and $U(1)_R$ symmetry breaking, the mass matrices for messenger lepton and slepton, $m_L$ and $\tilde{m}_L^2$, are given by

$$m_L = \begin{pmatrix} c_L \phi_Z & M_{2L} \\ M_{1L} & 0 \end{pmatrix}, \quad \tilde{m}_L^2 = \begin{pmatrix} m_L^T m_L - c_L \mu_Z^2 & m_L m^T_L \\ -c_L \mu_Z^2 & m^2_{H_u,d} \end{pmatrix}, \quad c_L = \begin{pmatrix} c_L & 0 \\ 0 & 0 \end{pmatrix}. \quad (15)$$

These mass matrices are diagonalized by orthogonal matrices $U$, $V$ and $\tilde{V}$ as

$$U^T m_L V = \text{diag}(m_{L_1}, m_{L_2}), \quad (16)$$

$$\tilde{V}^T \tilde{m}_L^2 \tilde{V} = \text{diag}(\tilde{m}_{L_1}^2, \tilde{m}_{L_2}^2, \tilde{m}_{L_3}^2, \tilde{m}_{L_4}^2), \quad (17)$$

with $m_{L_i}(i = 1, 2)$ and $\tilde{m}_{L_i}^2(i = 1, 2, 3, 4)$ being real and non-negative. The mass matrices for messenger quark/squark can be diagonalized in the same way.

Now we are ready to calculate $\mu/B_\mu$-term and soft SUSY breaking parameters. After integrating out messenger fields, $S$ and $\tilde{S}$, we find

$$\mu = \frac{k_u k_d}{(4\pi)^2} \Lambda_1, \quad (18)$$

$$A_u = \frac{k_u^2}{(4\pi)^2} \Lambda_2, \quad (19)$$

$$A_d = \frac{k_d^2}{(4\pi)^2} \Lambda_3, \quad (20)$$

$$B_\mu = \frac{k_u k_d}{(4\pi)^2} \Lambda_4, \quad (21)$$

$$\delta m^2_{H_u} = \frac{k_u^2}{(4\pi)^2} \Lambda_5^2, \quad (22)$$

$$\delta m^2_{H_d} = \frac{k_d^2}{(4\pi)^2} \Lambda_6^2, \quad (23)$$

where

$$\Lambda_1 = m_S \sum_{i=1}^4 \tilde{V}_{i1} \tilde{V}_{3i} \tilde{F}_i + \sum_{i=1}^2 m_{L_i} V_{i1} U_{i1} F_i^{(-)}, \quad (24)$$

$$\Lambda_2 = m_L \sum_{i=1}^4 \tilde{V}_{3i} \tilde{V}_{1i} \tilde{F}_i^{(+)} + m_S \sum_{i=1}^4 \tilde{V}_{i1} \tilde{V}_{1i} \tilde{F}_i^{(-)} + M_{1L} \sum_{i=1}^4 \tilde{V}_{4i} \tilde{V}_{i1} \tilde{F}_i^{(+)}, \quad (25)$$

$$\Lambda_3 = m_L \sum_{i=1}^4 \tilde{V}_{i1} \tilde{V}_{3i} \tilde{F}_i^{(+)} + m_S \sum_{i=1}^4 \tilde{V}_{3i} \tilde{V}_{3i} \tilde{F}_i^{(-)} + M_{2L} \sum_{i=1}^4 \tilde{V}_{2i} \tilde{V}_{3i} \tilde{F}_i^{(+)} \quad (26)$$
\[ A_i^2 = \sum_{i=1}^{4} \tilde{V}_{4i} \tilde{V}_{2i} \tilde{F}_i^{(-)} + m_L M_{2L} \sum_{i=1}^{4} \tilde{V}_{4i} \tilde{V}_{1i} \tilde{F}_i^{(-)} + m_L M_{2L} \sum_{i=1}^{4} \tilde{V}_{3i} \tilde{V}_{2i} \tilde{F}_i^{(-)} \]

\[ + m_S M_{1L} \sum_{i=1}^{4} \tilde{V}_{4i} \tilde{V}_{3i} \tilde{F}_i^{(+)} + m_S M_{2L} \sum_{i=1}^{4} \tilde{V}_{2i} \tilde{V}_{1i} \tilde{F}_i^{(+)} + m_S m_L \sum_{i=1}^{4} \tilde{V}_{3i} \tilde{V}_{3i} \tilde{F}_i^{(+)} \]

\[ + m_S m_L \sum_{i=1}^{4} \tilde{V}_{1i} \tilde{V}_{1i} \tilde{F}_i^{(+)} + (m_L^2 + m_S^2) \sum_{i=1}^{4} \tilde{V}_{3i} \tilde{V}_{1i} \tilde{F}_i^{(-)} - 2m_S \sum_{i=1}^{2} m_L V_{1i} U_{1i} F_i, \quad (27) \]

\[ A_5^2 = A(m_S^2) - \frac{1}{2} A(\tilde{m}_{S_1}) - \frac{1}{2} A(\tilde{m}_{S_2}) - \sum_{i=1}^{4} \tilde{V}_{1i} \tilde{V}_{1i} A(\tilde{m}_L_i) \]

\[ + \sum_{i=1}^{4} \tilde{V}_{4i} \tilde{V}_{4i} F_i^{(+)} + m_L^2 \sum_{i=1}^{4} \tilde{V}_{3i} \tilde{V}_{3i} F_i^{(+)} + m_S^2 \sum_{i=1}^{4} \tilde{V}_{1i} \tilde{V}_{1i} F_i^{(+)} \]

\[ + 2m_L M_{1L} \sum_{i=1}^{4} \tilde{V}_{3i} \tilde{V}_{4i} F_i^{(+)} + 2m_S M_{1L} \sum_{i=1}^{4} \tilde{V}_{2i} \tilde{V}_{4i} F_i^{(-)} + 2m_S m_L \sum_{i=1}^{4} \tilde{V}_{3i} \tilde{V}_{3i} F_i^{(-)} \]

\[ + \sum_{i=1}^{2} V_{1i} V_{1i} A(m_L^2) - \sum_{i=1}^{2} (m_L^2 + m_S^2)V_{1i} V_{1i} F_i, \quad (28) \]

\[ A_6^2 = A(m_S^2) - \frac{1}{2} A(\tilde{m}_{S_1}) - \frac{1}{2} A(\tilde{m}_{S_2}) - \sum_{i=1}^{4} \tilde{V}_{3i} \tilde{V}_{3i} A(\tilde{m}_L_i) \]

\[ + \sum_{i=1}^{4} \tilde{V}_{2i} \tilde{V}_{2i} F_i^{(s)} + m_L^2 \sum_{i=1}^{4} \tilde{V}_{1i} \tilde{V}_{1i} F_i^{(+)} + m_S^2 \sum_{i=1}^{4} \tilde{V}_{3i} \tilde{V}_{3i} F_i^{(+)} \]

\[ + 2m_L M_{2L} \sum_{i=1}^{4} \tilde{V}_{1i} \tilde{V}_{2i} F_i^{(+)} + 2m_S M_{2L} \sum_{i=1}^{4} \tilde{V}_{3i} \tilde{V}_{2i} F_i^{(-)} + 2m_S m_L \sum_{i=1}^{4} \tilde{V}_{3i} \tilde{V}_{3i} F_i^{(-)} \]

\[ + \sum_{i=1}^{2} U_{1i} U_{1i} A(m_L^2) - \sum_{i=1}^{2} (m_L^2 + m_S^2)U_{1i} U_{1i} F_i. \quad (29) \]

Here \( F, \tilde{F} \) and \( A \) denote the finite one-loop functions which are defined as

\[ A(m^2) = -m^2 \ln m^2, \quad (30) \]

\[ F_i = F_0(m_S, m_L), \quad (31) \]

\[ \tilde{F}_i = F_0(\tilde{m}_S, \tilde{m}_L), \quad (32) \]

\[ F_i^{(\pm)} = \frac{1}{2} [F_0(\tilde{m}_{S_1}, m_L) \pm F_0(\tilde{m}_{S_2}, m_L)], \quad (33) \]

\[ \tilde{F}_i^{(\pm)} = \frac{1}{2} [F_0(\tilde{m}_{S_1}, \tilde{m}_L) \pm F_0(\tilde{m}_{S_2}, \tilde{m}_L)], \quad (34) \]

with \( m_S = c_S \phi_Z, \tilde{m}_{S_1} = m_S^2 - c_L \mu_Z^2, \tilde{m}_{S_2} = m_S^2 + c_L \mu_Z^2 \) and

\[ F_0(m_1, m_2) = \frac{m_1^2}{m_1^2 - m_2^2} \ln m_1^2 - \frac{m_2^2}{m_1^2 - m_2^2} \ln m_2^2. \quad (35) \]

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