Seesaw-deflected Anomaly Mediation and the 125 GeV Higgs Boson

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Abstract. We investigate the phenomenology of a class of model that at the same time solves the tachyonic slepton problem of the pure anomaly mediated supersymmetry breaking (AMSB) model and generates neutrino masses. We introduce heavy fields in the seesaw mechanism that are the messengers in the deflected AMSB scenario. Various theoretical and phenomenological constraints have been taken into account, especially the Higgs mass limits. The viable parameter regions have been specified, and the properties of dark matter candidate have been studied. We point out that the type III seesaw with three generations of 24-messenger is excluded, while the type II seesaw and type III seesaw with two generations of 24-messenger are still allowed. The sparticle masses are heavy as in usual SUSY models. The spin-independent cross-section of the scattering between the lightest neutralino and proton show the possibility to see evidences of new physics from future dark matter search experiments. We find that the lepton flavor violation effects caused by the Yukawa mediation are suppressed due to the electroweak symmetry breaking condition.

1. Introduction

In the first running of the Large Hadron Collider (LHC), the ATLAS and CMS collaborations discovered the existence of the Higgs boson with the combined mass measurements as followed \cite{1, 2}:

\begin{equation}
    m_H^{\text{ATLAS}} = 125.5 \pm 0.2\text{(stat)} +0.5 \text{-0.6 (syst)} \text{GeV},
\end{equation}

\begin{equation}
    m_H^{\text{CMS}} = 125.3 \pm 0.4\text{(stat)} \pm 0.5\text{(syst)} \text{GeV}.
\end{equation}

The existence of a scalar sector in the standard model (SM) would lead to the instability of the electro-weak scale under quantum corrections, the so-called gauge hierarchy problem. The discovery of the Higgs boson at the LHC confirms this theoretical problem of the SM. Supersymmetry (SUSY) provides a natural solution to the problem by removing quadratic divergences up to all orders of perturbative theory. The minimal supersymmetric extension of the SM (MSSM) predicts a good candidate for the dark matter. Moreover, the three gauge couplings in the MSSM naturally merge at a unification scale giving a hint for a grand unified theory (GUT) of all gauge interactions.

Here we continue our previous work \cite{3} on the positively deflected anomaly mediated SUSY breaking (deflected AMSB) \cite{4, 5} which was originally invented to overcome the tachyonic slepton
problem in the pure AMSB [6, 7]. Along that line and following the idea of [8, 9], in this paper we study the phenomenology of more physically predictive models (the so-called seesaw-deflected anomaly mediation) in which the messengers play the roles of heavy fields in the seesaw mechanism to generate masses for neutrinos as observed from neutrino oscillation data. These models are very interesting since they address several questions at the same time: solving the hierarchy problem, preserving the unification of interaction, predicting neutrino masses and a dark matter candidate.

In order to explain neutrino masses in seesaw mechanism we introduce the Yukawa interaction between messenger fields and lepton doublets and/or Higgs doublet. These new couplings could in general cause the so-called Yukawa mediation that contributes to the renormalization group (RG) evolution in the original deflected AMSB scenario, and thus changes the SUSY breaking parameters in the MSSM. Moreover, such interaction with the lepton doublets could also affect the lepton flavor violation (LFV) and then have potential contribution to flavor changing neutral currents (FCNCs) which are strongly suppressed by experiments.

Together with the Higgs mass measurements at the LHC, we consider limits for the dark matter relic abundance, and other phenomenological constraints from collider experiments. On the theoretical side, we consider the gauge coupling blow-up constraint which imposes a lower limit upon the threshold to ensure that the gauge couplings stay within the perturbation limit.

The structure of the paper is as follows. In section 2, the deflected anomaly mediation scenario is described and incorporated with seesaw mechanism to generate neutrino masses. In section 3, the numerical analysis is performed taking into account a theoretical constraint on messenger scale and various phenomenological constraints from collider physics to cosmological observation and dark matter searches. After identifying the viable parameter regions, the sparticle mass spectrum, the structure and properties of the LSP are presented. In section 4, we discuss on the Yukawa mediation and the relevant lepton flavor violation. Section 5 is devoted for conclusion.

2. Seesaw-deflected Anomaly Mediation

In the AMSB scenario, once SUSY is dynamically broken in the hidden sector the $F$-component of the compensator field acquires nonzero vacuum expectation value (VEV) $F_\phi$ leading to the emergence of soft terms in the MSSM sector via supergravity interaction. This superconformal anomaly is identified as the only source of SUSY breaking in pure anomaly mediation. Nevertheless, the pure AMSB scenario is suffered from the tachyonic slepton problem.

To eliminate such problem, we introduce a messenger sector which realizes a certain representation under $SU(5)$ to preserve gauge coupling unification. We identify the messengers as heavy states in the seesaw mechanism to generate neutrino masses. Hence the messenger scale is identical to the seesaw scale. Here we shall consider type II and type III seesaw mechanism which employ $SU(2)$ triplets.

For type II seesaw case, a pair of vector-like charged $SU(2)$ triplet $\Delta = (1, 3, 1)$ and $\Delta = (1, 3, -1)$ are embedded in a $15 + \overline{15}$ representation of $SU(5)$ as in the decomposition into $SU(3)_C \times SU(2)_L \times U(1)_Y$:

$$15 = (1, 3, 1) + (3, 2, \frac{1}{6}) + (6, 1, -\frac{2}{3}).$$

(3)

The superpotentials in this case for the messenger sector and for seesaw mechanism respectively read:

$$W_{\text{Mess}} = S \bar{T}T,$$

(4)

$$W_{\text{seesaw}} = Y_{\nu ij} \bar{\Delta}_i \bar{\Delta}_j T + \lambda \Delta_H \bar{\Delta}_i T,$$

(5)

where $T$ and $\bar{T}$ represent $15$ and $\overline{15}$ supermultiplets. $S$ is a gauge singlet superfield that acquires
a nonzero VEV when SUSY is broken. The neutrino masses are then:

\[ m_{\nu}^{ij} = Y_{\nu}^{ij} \frac{v_u^2}{M_{\text{Mess}}} \]

where \( M_{\text{Mess}} \) is the messenger scale, and \( v_u = \frac{\langle H_u \rangle}{\sqrt{2}} = v \sin^2 \beta \) with \( v = 174 \text{ GeV} \) to be the VEV of the SM-like Higgs field.

In type III seesaw case, we use a neutral \( SU(2) \) triplet \( T_R = (1, 3, 0) \) which is contained in a \( 24 \) supermultiplet of \( SU(5) \) with the branching rule:

\[ 24 = (1, 1, 0) + (1, 3, 0) + (3, 2, -\frac{5}{3}) + (\bar{3}, 2, \frac{5}{3}) + (8, 1, 0). \]

The superpotentials for messenger sector and seesaw mechanism:

\[ W_{\text{Mess}} = S \text{Tr} (\Sigma_j^2), \]

\[ W_{\text{seesaw}} = Y_{\nu}^{ij} \bar{5}_i \Sigma_j 5_H, \]

where \( \Sigma_j \) are \( 24 \) messengers. We need at least two generations of \( 24 \) multiplet to obtain a realistic neutrino mass matrix:

\[ m_{\nu}^{ij} = (Y_{\nu}^i)^{ij} \frac{v_u^2}{M_{\text{Mess}}}. \]

In Eq. (8), we assume the degeneracy of all the \( 24 \) messengers in terms of their masses for simplicity.

When the scalar and the \( F \)-component of the above gauge singlet get VEVs, the seesaw messengers induce GMSB (gauge mediated SUSY breaking)-like contributions to the soft terms via gauge interactions. Since the VEVs of the singlet superfield originate from the compensator’s VEV, there is a relation between them:

\[ \frac{F_S}{S} = dF_{\phi}, \]

where \( d \) is the deflection parameter which, in a simple model, can be calculated from the superpotential of the singlet \( W(S) \) as [5]:

\[ d \sim -2 \frac{\partial W}{S} \frac{\partial W}{\partial S^2}. \]

Because the singlet’s VEVs are just the secondary source of SUSY breaking, and in order to get rid of the tachyonic sleptons, we impose a constraint on \( d \)-parameter for theoretical consistency: \( |d| \lesssim O(1) \). The deflection parameter can be either negative [4] or positive [5]. In this paper, we restrict our study on the later case.

The soft SUSY breaking terms can be derived from the renormalized gauge couplings and the supersymmetric wave-function renormalization coefficients as follows [4, 5]:

\[ \frac{M_i(\mu)}{\alpha_i(\mu)} = \frac{F_{\phi}}{2} \left( \frac{\partial}{\partial \ln \mu} - d \frac{\partial}{\partial \ln |S|} \right) \frac{1}{\alpha_i(\mu, S)}, \]

\[ m_2^2(\mu) = -\frac{|F_{\phi}|^2}{4} \left( \frac{\partial}{\partial \ln \mu} - d \frac{\partial}{\partial \ln |S|} \right)^2 \ln Z_I(\mu, S), \]

\[ A_I(\mu) = \frac{-F_{\phi}}{2} \left( \frac{\partial}{\partial \ln \mu} - d \frac{\partial}{\partial \ln |S|} \right) \ln Z_I(\mu, S), \]
where the gauge couplings and the wavefunction renormalization coefficients are given by

\[ \alpha_i^{-1}(\mu, S) = \alpha_i^{-1}(\Lambda_{\text{cut}}) + \frac{b_i - N}{4\pi} \ln \frac{S_i^2 S}{\Lambda_{\text{cut}}^2} + \frac{b_i}{4\pi} \ln \frac{\mu^2}{S_i^2 S}, \quad (16) \]

\[ Z_i(\mu, S) = \sum_{i=1, 2, 3} Z_i(\Lambda_{\text{cut}}) \left( \frac{\alpha(\Lambda_{\text{cut}})}{\alpha(S)} \right)^{\frac{2\alpha_i}{\alpha_i}} \left( \frac{\alpha(S)}{\alpha(\mu)} \right)^{\frac{2\alpha_i}{\alpha_i}}. \quad (17) \]

The index \( i = 1, 2, 3 \) corresponds to the MSSM gauge group \( U(1)_Y \times SU(2)_L \times SU(3)_C \), and \( b_i = \{-33/5, -1, 3\} \) (\( i = 1, 2, 3 \)) are \( \beta \)-function coefficients of the MSSM gauge coupling RG equations, \( c_i \) are the corresponding quadratic Casimirs. Here \( S = M_{\text{Mess}} \) plays the role of the messenger scale which is an intermediate scale between the cutoff scale \( \Lambda_{\text{cut}} \) and the electroweak scale.

In Eq. (17), \( N \) is the Dynkin index of the seesaw messengers. For type II seesaw, \( N = 2 \times \frac{7}{2} = 7 \). For type III seesaw, \( N = 2 \times \frac{10}{2} = 10 \) in the case with two generations of 24 messengers, and \( N = 3 \times \frac{10}{2} = 15 \) in the case with three generations of 24 messengers.

Substituting Eqs. (16) and (17) in Eqs. (13)-(15), we find the solutions for the RG equations of the soft terms. The gaugino masses are given at the messenger scale by

\[ M_i(M_{\text{Mess}}) = -\frac{\alpha_i}{4\pi} F_\phi (b_i + dN). \quad (18) \]

For the \( A \)-parameters of the third generation, we have

\[ A_t(M_{\text{Mess}}) = -\frac{F_\phi}{(4\pi)^2} \left( 6|Y_t|^2 + |Y_b|^2 - \frac{16}{3} g_3^2 - 3g_2^2 - \frac{13}{15} g_1^2 \right), \quad (19) \]

\[ A_b(M_{\text{Mess}}) = -\frac{F_\phi}{(4\pi)^2} \left( 2|Y_t|^2 + 6|Y_b|^2 + |Y_\tau|^2 - \frac{16}{3} g_3^2 - 3g_2^2 - \frac{18}{5} g_1^2 \right), \quad (20) \]

\[ A_\tau(M_{\text{Mess}}) = -\frac{F_\phi}{(4\pi)^2} \left( 3|Y_b|^2 + 4|Y_\tau|^2 - 3g_2^2 - \frac{9}{5} g_1^2 \right), \quad (21) \]

where \( Y_{t,b,\tau} \) are the Yukawa couplings of the third generation quarks and lepton. Lastly, the sfermion squared masses are given by

\[ m_{H_u}^2(M_{\text{Mess}}) = m_{H_u}^2(M_{\text{Mess}}) = F_\phi^2 \left[ \frac{3}{10} \left( \frac{\alpha_1}{4\pi} \right)^2 G_1 + \frac{3}{2} \left( \frac{\alpha_2}{4\pi} \right)^2 G_2 \right], \quad (22) \]

\[ m_L^2(M_{\text{Mess}}) = F_\phi^2 \left[ \frac{3}{10} \left( \frac{\alpha_1}{4\pi} \right)^2 G_1 + \frac{3}{2} \left( \frac{\alpha_2}{4\pi} \right)^2 G_2 \right], \quad (23) \]

\[ m_{\bar{E}}^2(M_{\text{Mess}}) = F_\phi^2 \left[ \frac{6}{5} \left( \frac{\alpha_1}{4\pi} \right)^2 G_1 \right], \quad (24) \]

\[ m_Q^2(M_{\text{Mess}}) = F_\phi^2 \left[ \frac{1}{30} \left( \frac{\alpha_1}{4\pi} \right)^2 G_1 + \frac{3}{2} \left( \frac{\alpha_2}{4\pi} \right)^2 G_2 + \frac{8}{3} \left( \frac{\alpha_3}{4\pi} \right)^2 G_3 \right], \quad (25) \]

\[ m_{\bar{U}}^2(M_{\text{Mess}}) = F_\phi^2 \left[ \frac{8}{15} \left( \frac{\alpha_1}{4\pi} \right)^2 G_1 + \frac{8}{3} \left( \frac{\alpha_3}{4\pi} \right)^2 G_3 \right], \quad (26) \]

\[ m_D^2(M_{\text{Mess}}) = F_\phi^2 \left[ \frac{2}{15} \left( \frac{\alpha_1}{4\pi} \right)^2 G_1 + \frac{8}{3} \left( \frac{\alpha_3}{4\pi} \right)^2 G_3 \right], \quad (27) \]

where

\[ G_i = Nd^2 + 2Nd + b_i \quad (i = 1, 2, 3). \quad (28) \]
3. Numerical analysis

Our analysis concentrates on a specific type of seesaw (\(N\) is fixed). Therefore the free parameter set includes four independent parameters:

\[
d, M_{\text{Mess}}, F_{\phi}, \tan \beta.
\]

and the sign of \(\mu\) parameter (the supersymmetric Higgs mass). Here we only consider the case \(\text{sign}(\mu) = +\). By fixing the deflection parameter \(d\) and \(\tan \beta\) at the beginning, we are left with only two free parameters: the seesaw messenger scale \(M_{\text{Mess}}\), and the VEV of the compensator’s \(F\)-component \(F_{\phi}\).

We employ the SOFTSUSY [10] and the MICROMEGAS [11] packages to compute mass spectrum and other observables. For fixed values of the deflection parameter and \(\tan \beta\), we scan over the parameter space of \((M_{\text{Mess}}, F_{\phi})\), and analyze the Higgs mass together with the dark matter relic abundance. We are only interested in the region with the Higgs mass around the measured values at ATLAS and CMS (Eqs. (1) and (2)).

In Figs. 1-5, the results are shown with different types of seesaw mechanism. We plot the contours of Higgs mass on the \((M_{\text{Mess}}, F_{\phi})\) plane. While the Higgs mass and the particle spectrum just slightly change with respect to the messenger scale, they are substantially heavier for larger \(F_{\phi}\). This can be easily seen from the boundary conditions at the messenger scale. In Eqs. (18)-(27), \(F_{\phi}\) plays the role of an overall scaling factor for all the soft terms. In all the figures, the narrow red strips indicate regions that reproduce the dark matter relic density consistent with the WMAP data [12] and the Planck data [13]:

\[
\Omega_{\text{CDM}}h^2 = 0.1138 \pm 0.0045
\]

As shown in these figures, the dark matter observation imposes a very severe constraint on the parameter space. This fact reveals the high sensitivity of the dark matter annihilation cross-sections with respect to any small change of free parameters.

Firstly, let us consider type II seesaw case (\(N = 7\)). We explore the \((M_{\text{Mess}}, F_{\phi})\) parameter space with \(d = 0.7\), and \(\tan \beta = 10, 15, 20, 30\). The results are plotted in Figs. 1-4 respectively. The left and right bounds of the contour region in Fig. 1 are specified by the no electroweak symmetry breaking (no-EWSB) condition. It is because the parameter \(\mu^2\) become negative outside the contour region. In Fig. 2, the bounds are almost specified by the same condition as above, except for the left bound with \(F_{\phi}\) below 270 GeV. This part of the left bound is defined by the \(A^0\) tachyon. The conditions specify the bounds of the contour region in Fig. 3 are a bit more complicated. For \(F_{\phi} < 400\) GeV, the left bound is defined by the \(A^0\) tachyon condition, while above that value, the condition is \(H^\pm\) tachyon. The region on the right hand side of the right bound is excluded because of no-EWSB condition. In Fig. 4, we can see two parts of the bound connected together not smoothly at \(M_{\text{Mess}} \approx 10^{5.5}\) GeV. The left part of the bound is specified by \(A^0\) tachyon condition, while the curved right part of the bound is specified by \(H^\pm\) tachyon condition.

The red strips in Figs. 1-4 show the region with the acceptable value for dark matter relic density. Although with similar relic abundance, the properties of dark matter particle (the lightest neutralino) are different in different red strips. For those very close to the borders of the contour regions, the LSP is a good mixture of bino and Higgsino. In these cases, the LSP is annihilated via multiple processes. The largest contribution (~20%) comes from \(\chi_1^0\) pair annihilation by transferring neutral Higgs bosons in the s-channel to create a pair of top and anti-top quark. Inside the contour regions, farther from the borders, there are red strips where the LSP structure is bino-like. Here the lightest neutralino is annihilated mostly via the s-channel with \(A^0\) and \(H\) resonances. Due to the physics of dark matter particle, these strips correspond to the funnel regions as in the constrained MSSM.
Figure 1. Results for type II seesaw case \((N = 7)\) with \(d = 0.7\), and \(\tan \beta = 10\). Various values of the resultant SM-like Higgs boson mass are shown as the contours. There are two diagonal boundaries, outside of them are theoretically excluded. The red strip indicates the region where the relic abundance of neutralino dark matter is consistent with the observation.

Figure 2. The same as Fig. 1, but for type II seesaw case \((N = 7)\) with \(d = 0.7\), and \(\tan \beta = 15\).

Comparing the first four figures, we can see the movement of the Higgs mass contours and red strips when changing \(\tan \beta\). As \(\tan \beta\) increases, the Higgs mass contours move downward,
Figure 3. The same as Fig. 1, but for type II seesaw case ($N = 7$) with $d = 0.7$, and $\tan \beta = 20$.

Figure 4. The same as Fig. 1 but for type II seesaw case ($N = 7$) with $d = 0.7$, and $\tan \beta = 30$.

so do the funnel-like red regions. Moreover, the funnel-like regions which are separated in Figs. 1-3 become connected when $\tan \beta = 30$ as in Fig. 4, while the red strips close to the border disappear due to the enlargement of the tachyonic $A^0$ and $H^\pm$ regions outside the contour area when raising $\tan \beta$ up to 30.
For larger \( \tan \beta \), there is no overlapped region that satisfies both the Higgs mass and WMAP limits. With smaller \( d \)-parameter (for example: 0.3, 0.4, 0.5), the model has to face the tachyonic slepton problem then being excluded. For larger values of \( d \) (for example: 0.8, 0.9, 1.0), the dark matter relic density is too high to meet the constraint by WMAP. The gauge coupling blow-up constraint for type II seesaw messenger with \( N = 7 \) is:

\[
M_{\text{Mess}} \gtrsim 4.3 \times 10^6 \text{ GeV.} \tag{31}
\]

This condition when applied to our scenario actually rules out a significant portion of the free parameter space. It cut away the two red strips on the left handside of Fig. 1-3, and a part of the red strips in Fig. 4. Therefore, the type II seesaw-deflected AMSB is very predictive to be tested.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5.png}
\caption{The same as Fig. 1 but for type III seesaw case with two generations of 24 messenger \( N = 10 \), \( d = 0.5 \), and \( \tan \beta = 10 \).}
\end{figure}

Secondly, similar to the above case, we consider type III seesaw scenario. In type III seesaw with two generations of 24 messenger \( N = 10 \), the parameter space corresponding to \( d = 0.5 \), and \( \tan \beta = 10 \) is examined. We expect that this case is not so much different from the above one since the Dynkin indices of the seesaw messengers in the two cases are roughly at the same order. The result is shown in Figs. 5. The boundary for the contour region in Fig. 5 is defined by the no-EWSB condition.

In the red strips, the LSP structures are similar to the previous case. Namely, there are red regions very close to the boundary where the lightest neutralino is mostly Higgsino or a good mixture of bino-Higgsino. The ones which locate more inside the contour region correspond to funnel-like regions with bino-like dark matter. However, the funnel-like strips on the left and right parts of the contour region are now connected. The LSP structure determines the main mechanism of neutralino annihilation in each region. The discussion for this case is the same as above.

We also find similarities between the two cases in the behavior of the contour lines and the red strips with respect to \( \tan \beta \). All of them move downward when increasing \( \tan \beta \). In other
words, the Higgs boson becomes heavier for larger $\tan \beta$ with the same values of $M_{\text{Mess}}$ and $F_\phi$. Moreover, raising $\tan \beta$ up also results in an enlargement of the excluded regions with tachyonic particles such as $A^0$, $H^\pm$. When varying the deflection parameter, we observe that for smaller $d$, the tachyon stau region dominate and at some value it occupies most of the contour region. For larger $d$ (for instant: 0.6, 0.7), the dark matter relic abundance is too high and becomes larger than the WMAP’s upper limit.

The constraint to keep our theory with two $24$ seesaw messengers staying in a perturbative regime is as follows:

$$M_{\text{Mess}} \gtrsim 3.4 \times 10^9 \text{GeV}. \quad (32)$$

It is more severe than the previous case (Eq. (31)). Taking into account this condition, only a small part of the free parameter space is left.

For the case of type III seesaw with three generations of $24$ messenger ($N = 15$), we examine the cases with $\tan \beta = 10$. When $d = 0.35$ or smaller, we find that the smaller the deflection parameter is, the larger part of the contour region is ruled out by the tachyonic slepton condition. For larger $d$ (for instant: 0.4), there is no point that satisfies both the Higgs mass limits and the WMAP constraint on dark matter relic density at the same time.

Once we introduced more messenger in the theory, the larger Dynkin index must be added to the $\beta$ function coefficients of the gauge couplings. Consequently, the gauge coupling blows up faster and reaches the perturbative limit quickly as increasing the renormalization scale. To avoid such thing to happen, the running of gauge coupling from the messenger scale to the cutoff scale must be short. In this case, the condition for a perturbative gauge coupling reads:

$$M_{\text{Mess}} \gtrsim 6.2 \times 10^{11} \text{GeV}. \quad (33)$$

We find that all the region with acceptable Higgs mass is forbidden by the very high lower limit of the messenger scale. This is also true for different values of $\tan \beta$. Hence the type III seesaw case with three generations of $24$ messenger is excluded.

To be more specific, in Table 1, we show a few examples for sparticle spectra. While the first three columns correspond to the type II seesaw case, the other ones are type III seesaw with two generations of messenger. In the first, the third and the last columns, the LSP is a good mixture of bino-Higgsino. There are many processes that the LSP goes through in its annihilation. For the remaining columns, the LSP is bino-like and the most dominant contribution to its annihilation comes from processes with $A^0$ and $H$ resonances mediated via $s$-channel.

We take into account the perturbative gauge coupling limits (31)-(32), the LHC measurements on Higgs mass (1)-(2), and the WMAP limits on the dark matter relic density (30). In addition, we also consider other phenomenological constraints: the branching ratios of $b \rightarrow s\gamma$ [14], $B \rightarrow \tau \nu_{\tau}$ [15], and the muon anomalous magnetic moment $a_\mu = (g_\mu - 2)/2$ [16],

$$2.85 \times 10^{-4} < \text{BR}(b \rightarrow s + \gamma) \leq 4.24 \times 10^{-4} \quad (2\sigma), \quad (34)$$

$$\frac{\text{BR}^{\text{exp}}(B \rightarrow \tau \nu_{\tau})}{\text{BR}^{\text{SM}}(B \rightarrow \tau \nu_{\tau})} = 1.25 \pm 0.40, \quad (35)$$

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (26.1 \pm 8.0) \times 10^{-10} \quad (3.3\sigma). \quad (36)$$

Particularly, we take into consideration the current best limits of the decay process $B_s \rightarrow \mu^+\mu^-$ announced by the CMS Collaboration [17]:

$$2.1 \times 10^{-9} < \text{BR}(B_s \rightarrow \mu^+\mu^-) < 4.0 \times 10^{-9} \quad (3.5\sigma), \quad (37)$$

We can see from Table 1 that all the above constraints are satisfied, except for the muon anomalous magnetic dipole moment. Since the sparticles are all heavy, the SUSY contribution
to \( a_\mu \) are too small. However, the constraint (36) can be loosen by the uncertainty in theoretical estimation of \( a_\mu \) in the SM due to hadronic loop corrections.

Besides we also take into account the constraints from dark matter direct and indirect detection experiments. For direct dark matter search, the best upper limit on the spin-independent cross-section of the scattering between dark matter and proton is set by XENON100 \[18\]:

\[
\sigma_{SI}^X \lesssim 10^{-8} \text{pb (90\% CL)}, \quad \text{at } m_{\text{WIMP}} \approx \mathcal{O}(500) \text{GeV.} \tag{38}
\]

While for indirect dark matter search the most stringent limit on the spin-dependent WIMP-proton cross-section is set by IceCube \[19\]:

\[
\sigma_{SD}^X \lesssim 10^{-4} \text{pb (90\% CL)}, \quad \text{at } m_{\text{WIMP}} \approx 150 - 600 \text{GeV.} \tag{39}
\]

The values of spin-independent and spin-dependent cross-sections for the scattering of the lightest neutralino onto proton for each benchmark points are listed in Table 1. We find that the results satisfy all the current limits set by direct and indirect dark matter searches, with the notice that the spin-independent cross-section in the first column is just marginally close to the corresponding limit. Especially, the spin-independent WIMP-proton cross-sections in the third, the fourth and the last columns are at the order of \( \mathcal{O}(10^{-9}) \) pb. These values can be reached by future direct dark matter searches such as XENON1T since its expected \( \sigma_{SI}^X \) sensitivity is about \( \mathcal{O}(10^{-10}) \) pb for the WIMP’s mass around 500 GeV \[20\]. Therefore, such case can be tested in the near future dark matter direct detection experiments.

4. Yukawa mediation and Lepton flavor violation

We would like to comment on the Yukawa mediation and the lepton flavor violation due the Yukawa interactions (Eqs. (5) and (9)) between the seesaw messengers and the MSSM particles. In order to get very small neutrino masses, Eqs. (6) and (10) show that either the seesaw messenger are extremely heavy and/or the Yukawa couplings (\( Y_{ij} \) and \( \lambda \) in type II seesaw, \( Y_\nu \) in type III seesaw) are small enough. With the new Yukawa couplings at the order of \( \mathcal{O}(1) \) in usual seesaw models, the seesaw scale often reads \( M_{\text{Mess}} \sim 10^{14} \) GeV to get the allowed neutrino masses. However in our models, as can be seen in the above contour plots, thanks to the electroweak symmetry breaking condition the seesaw messenger scale is at most \( 10^{11} - 10^{12} \) GeV which is about three or two order in magnitude smaller than the usual values. To obtain the right neutrino masses, the new Yukawa couplings must be roughly at the order of \( \mathcal{O}(10^{-3}) \) or \( \mathcal{O}(10^{-2}) \). Thus, the effects of Yukawa mediation are suppressed by the same factors, and so is the lepton flavor violation.

The results for the LFV branching fraction of the process \( \mu \rightarrow e\gamma \) are shown in the bottom row of Table 1. We can see that the \( e\nu_\tau\nu_\mu \) branching ratio for all the benchmark points well satisfy the current upper limit on this process set by the MEG experiment \[21\]:

\[
\text{BR}(\mu \rightarrow e\gamma) \leq 5.7 \times 10^{-13} \quad (90\% \text{ CL}). \tag{40}
\]

5. Conclusions

In this paper, the seesaw-deflected anomaly mediation has been presented to overcome the tachyonic slepton problem, and to provide an explanation for the neutrino masses. We have studied the phenomenology of the models by examining their free parameter space, and analyzing the sparticle mass spectra and properties of dark matter candidate. Various phenomenological constraints have been taken into account. The recent results from the LHC about the Higgs mass measurement together with the WMAP’s limits on the dark matter relic density and the pertubative gauge coupling constraint have put stringent restrictions on the free parameter space
Table 1. Benchmark particle mass spectra for the case $N = 7$, and 10. Masses of particles are given in GeV. The values of the branching fractions of $b \rightarrow s + \gamma$, $B_s \rightarrow \mu^+\mu^-$, $B \rightarrow \tau\nu$, the muon anomalous magnetic dipole moment $\Delta a_\mu$, and the neutralino relic density are calculated for each benchmark points. The spin-independent and spin-dependent cross-sections for the neutralino-proton elastic scattering are also provided. The last row of the table shows the branching fraction of $\mu \rightarrow e + \gamma$ taking into account the Yukawa mediation.

| $N$ | 7   | 7   | 7   | 7   | 10  | 10  | 10  |
|-----|-----|-----|-----|-----|-----|-----|-----|
| $\tan \beta$ | 0.7 | 0.7 | 0.7 | 0.7 | 0.5 | 0.5 | 0.5 |
| $F_\rho$ | 2.70 × 10$^5$ | 3.20 × 10$^5$ | 2.14 × 10$^5$ | 2.05 × 10$^5$ | 2.24 × 10$^5$ | 2.07 × 10$^5$ | 2.05 × 10$^5$ |
| $M_{\text{Mass}}$ | 4.790 × 10$^9$ | 1.403 × 10$^9$ | 8.558 × 10$^9$ | 3.081 × 10$^9$ | 5.648 × 10$^9$ | 3.770 × 10$^9$ | 1.215 × 10$^{10}$ |
| $b^0$ | 125.5 | 126.0 | 125.5 | 125.6 | 125.5 | 125.4 | 125.4 |
| $H^0$ | 1531 | 1768 | 1059 | 739.2 | 1151 | 1026 | 722.0 |
| $A^0$ | 1531 | 1768 | 1059 | 739.4 | 1151 | 1026 | 721.9 |
| $H^\pm$ | 1533 | 1770 | 1062 | 743.8 | 1153 | 1029 | 726.4 |
| $\tilde{g}$ | 12518 | 14650 | 10097 | 9702 | 10637 | 9889 | 9800 |
| $\tilde{\chi}^0_{1,2}$ | 653.7, 685.6 | 794.1, 939.5 | 534.7, 1026 | 494.3, 532.7 | 522.9, 637.7 | 487.3, 991.3 | 466.2, 507.7 |
| $\tilde{\chi}^\pm_{1,2}$ | 710.3, 2704 | 946.3, 3203 | 1031, 2143 | 556.3, 2052 | 646.8, 2302 | 996.1, 2128 | 529.7, 2107 |
| $\tilde{\nu}_L$ | 685.9, 2704 | 939.8, 3203 | 1027, 2143 | 533.0, 2052 | 638.0, 2302 | 991.8, 2128 | 508.1, 2107 |
| $\tilde{\nu}_R$ | 11367, 11787 | 13235, 13745 | 9197, 9525 | 8874, 9190 | 9562, 9892 | 8880, 9184 | 8839, 9142 |
| $\tilde{\chi}^0_{n,L}$ | 11289, 11787 | 13154, 13745 | 9132, 9525 | 8803, 9190 | 9499, 9893 | 8826, 9184 | 8775, 9142 |
| $t_{1,2}$ | 9728, 11019 | 11468, 12905 | 7839, 8850 | 7474, 8497 | 8149, 9229 | 7631, 8559 | 7516, 8483 |
| $b_{1,2}$ | 11018, 11257 | 12904, 13118 | 8485, 9028 | 8495, 8607 | 9227, 9438 | 8558, 8727 | 8481, 8676 |
| $\tilde{\nu}_L$ | 3591 | 4163 | 2875 | 2815 | 2930 | 2690 | 2718 |
| $\tilde{\nu}_R$ | 3592, 3590 | 4164, 4162 | 2876, 2875 | 2816, 2815 | 2932, 2930 | 2692, 2690 | 2719, 2718 |
| $\tilde{\nu}_R$ | 1043, 1043 | 1283, 1283 | 8273, 8270 | 7619, 7615 | 760, 739.7 | 722.6, 722.3 | 689.8, 680.4 |
| $\tilde{\tau}_{1,2}$ | 1008, 3587 | 1248, 4159 | 709.9, 2860 | 628.8, 2799 | 686.4, 2922 | 607.5, 2677 | 546.7, 2704 |
| $\text{BR}(b \rightarrow s + \gamma)$ | 3.42 × 10$^{-4}$ | 3.39 × 10$^{-4}$ | 3.51 × 10$^{-4}$ | 3.68 × 10$^{-4}$ | 3.49 × 10$^{-4}$ | 3.52 × 10$^{-4}$ | 3.69 × 10$^{-4}$ |
| $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ | 3.06 × 10$^{-9}$ | 3.06 × 10$^{-9}$ | 2.98 × 10$^{-9}$ | 2.90 × 10$^{-9}$ | 3.02 × 10$^{-9}$ | 2.97 × 10$^{-9}$ | 2.89 × 10$^{-9}$ |
| $\text{BR}^{\text{SI}}(B \rightarrow \tau\nu)$ | 0.998 | 0.998 | 0.981 | 0.960 | 0.991 | 0.979 | 0.958 |
| $\Delta a_\mu$ | 3.10 × 10$^{-11}$ | 2.15 × 10$^{-11}$ | 8.65 × 10$^{-11}$ | 1.10 × 10$^{-10}$ | 7.60 × 10$^{-11}$ | 9.98 × 10$^{-11}$ | 1.24 × 10$^{-10}$ |
| $\Omega^2$ | 0.1121 | 0.1121 | 0.1121 | 0.1121 | 0.1121 | 0.1121 | 0.1121 |
| $\sigma^{\text{SI}}_{\text{ann}}(pb)$ | 1.550 × 10$^{-8}$ | 1.820 × 10$^{-9}$ | 3.605 × 10$^{-11}$ | 5.234 × 10$^{-9}$ | 2.448 × 10$^{-9}$ | 2.392 × 10$^{-11}$ | 4.462 × 10$^{-9}$ |
| $\sigma^{\text{SI}}_{\text{DD}}(pb)$ | 2.460 × 10$^{-5}$ | 2.106 × 10$^{-6}$ | 2.503 × 10$^{-7}$ | 3.538 × 10$^{-7}$ | 7.147 × 10$^{-6}$ | 2.647 × 10$^{-7}$ | 3.790 × 10$^{-7}$ |
| $\text{BR}(\mu \rightarrow e + \gamma)$ | 1.70 × 10$^{-16}$ | 4.48 × 10$^{-17}$ | 1.33 × 10$^{-15}$ | 1.88 × 10$^{-14}$ | 5.35 × 10$^{-16}$ | 3.37 × 10$^{-16}$ | 3.36 × 10$^{-15}$ |

of those models. The possibility of type III seesaw with three generations of 24 messenger is excluded. For type II seesaw and type III seesaw with two generations of 24 messenger, although the sparticle masses are too heavy to be directly detected at the LHC there is a good chance to test a part of their free parameter spaces in future dark matter direct detection experiments like XENON1T. We have also argued that in our scenarios the effects of Yukawa mediation caused by the new Yukawa couplings between the MSSM and the seesaw messenger sector are negligible. As a result, the branching ratio of the lepton flavor violating processes such as $\mu \rightarrow e + \gamma$ are shown to well satisfy the current limit from the MEG experiment data.

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