Neutralino Dark Matter in Gauge Mediation After Run I of LHC and LUX

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Abstract

Neutralino can be the dark matter candidate in the gauge-mediated supersymmetry breaking models if the conformal sequestered mechanism is assumed in the hidden sector. In this paper, we study this mechanism by using the current experimental results after the run I of LHC and LUX. By adding new Yukawa couplings between the messenger fields and Higgs fields, we find that this mechanism can predict a neutralino dark matter with correct relic density and a Higgs boson with mass around 125 GeV. All our survived points have some common features. Firstly, the Higgs sector falls into the decoupling limit. So the properties of the light Higgs boson are similar to the predictions of the Standard Model one. Secondly, the correct EWSB hints a relatively small $\mu$-term, which makes the lightest neutralino lighter than the lightest stau. So a bino-higgsino dark matter with correct relic density can be achieved. And the relatively small $\mu$-term results in a small fine-tuning. Finally, this bino-higgsino dark matter can pass all current bounds, including both spin-independent and spin-dependent direct searches. The spin-independent cross section of our points can be examined by further experiments.

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I. INTRODUCTION

It is now believed that the dominant matter in the universe should be non-baryonic dark matter (DM) instead of visible ones. And DM should not be composed of any known Standard Model (SM) particles. Extra symmetry is usually necessary to make DM stable on the cosmological time scale. In supersymmetric (SUSY) models, if the R-parity conservation is assumed, the lightest supersymmetric particle (LSP) is absolutely stable. The LSP should be a good DM candidate if it is electrically neutral. On the other hand, the measurement of relic density generally suggests that the DM mass is around several GeV to 10 TeV with a weak interaction. That is to say, the LSP is expected to be a weakly interacting massive particle (WIMP).

Unfortunately, gravitino with mass less than 1 GeV is usually the LSP in the gauge mediation supersymmetry breaking (GMSB) models. GMSB [1–9] is one of the promising mechanisms to describe the SUSY-breaking in the minimal supersymmetric Standard Model (MSSM) (for a modern review, see [10]). The effect of SUSY breaking is mainly transmitted to the MSSM sector through the gauge interaction, which makes GMSB models flavor safe. The soft masses from gravity mediation are suppressed by Planck-scale and not generation-blind. So these Planck-scale induced soft masses are dangerous as they mediate flavor-changing effects. In order to escape from experimental constraints, these dangerous Planck-scale induced soft masses should be tiny. As the gravitino mass also arises from the Planck-scale induced operator, gravitino is always the LSP in GMSB models. Such a gravitino DM is hard to be detected and its relic density depends on the dynamics of inflation. Generally speaking, the lack of the predictability of gravitino DM is one of the drawbacks of GMSB models.

Instead of gravitino, the lightest neutralino can be the DM candidate in GMSB models if the hidden sector is strongly coupled [11–14]. The conformal sequestered hidden sector can raise the gravitino mass relative to the dangerous Planck-scale induced soft masses without introducing any flavor physics problems. As studied in [11–14], neutralino DM in the gauge mediation with sequestered SUSY breaking is typically purely bino-like and its mass is within the WIMP range. Since neutralino is the LSP, the lightest tau slepton (stau) should be heavier than the lightest neutralino. This is a strong constraint to those models, which requires the messenger scale $M_{\text{mess}}$ typically around $10^{10}$ GeV. Compared to low-scale
gauge mediation, stau will be heavier in such a high-scale gauge mediation, as the stau mass grows up when renormalization group equations (RGEs) of MSSM are running from the input scale down to the electroweak scale.

All above papers about neutralino DM in GMSB scenarios with sequestered SUSY breaking were done several years ago. After the run I of Large Hadron Collider (LHC) and Large Underground Xenon (LUX) DM experiment, these models are necessary to be revisited and carefully checked by current experimental constraints. Firstly, a SM-like Higgs boson with mass around 125 GeV has been confirmed at LHC [15, 16]. A 125 GeV Higgs in decoupling MSSM scenario prefers either a heavy top squark (stop) or a large $A_t$-term [17–27], since both could contribute large loop corrections to the Higgs mass. Unfortunately, minimal GMSB models predict vanishing $A$-terms at the messenger scale, which presents another challenge for GMSB models. Secondly, no signals of SUSY particles have been detected at LHC. Together with a 125 GeV Higgs, it raises uncomfortable issues with naturalness which are widely discussed in [28–68]. Finally, the updated bounds of DM direct searches become severer than the bounds in previous studies. The current strictest bound is given by the LUX Collaboration [69], who is the first to break the $10^{-45}$ cm$^2$ cross section barrier of DM spin-independent detection at some WIMP mass range. New LUX upper limits have already been used to constrain DM in SUSY models [70–74]. All in all, in this paper we would focus on these new constraints on GMSB models with sequestered SUSY breaking.

This paper is organized as follows. In Section II, we give a brief review about the GMSB scenarios with sequestered SUSY breaking and how to get a neutralino DM in GMSB models. Section III is devoted to studying new constraints on those GMSB models and showing our results. We finally conclude with a summary in Section IV.

II. GAUGE MEDIATION WITH SEQUESTERED SUSY BREAKING

In this section, we give a brief review about the GMSB models with the sequestered SUSY breaking and how to get a neutralino DM in GMSB models. We start with the minimal GMSB model. As a singlet superfield $S$ in the hidden sector breaks SUSY, the messenger superfields $\Phi$ couple to the hidden field $S$ via a superpotential $W = \kappa S\Phi\Phi$ with $\kappa \sim \mathcal{O}(1)$\textsuperscript{1}. In the view of a spurion

\textsuperscript{1} Because of $\mathcal{O}(1)$, $\kappa$ is neglected in many papers for simplify.
field, $S = \langle s \rangle + F_s \theta^2$ is assumed to parameterize the typical effect of SUSY breaking. As a low-energy effective field theory of SUSY, many higher-dimensional operators contribute to the Kähler potential after heavy fields are integrated out. Sfermions get soft masses through the following operators

$$K_{\text{eff}} = \frac{S^\dagger S}{M_{\text{mess}}^2} \sum_i c_i F_i^\dagger F_i + \frac{S^\dagger S}{M_{PL}^2} \sum_{i,j} b_{i,j} F_i^\dagger F_j,$$

where $F_i$ are superfields of sfermions in the visible sector. The messenger scale is $M_{\text{mess}} = \kappa \langle s \rangle$ and $M_{PL}$ is the Planck scale. Since $M_{\text{mess}} \ll M_{PL}$ in GMSB models, the soft masses $m_{\text{soft}}$ mainly come from the first term of Eq.(1), which are proportional to $\frac{F_s}{M_{\text{mess}}}$. Here $N$ is the effective number of the messenger fields. Because the gauge interaction is flavor-blind, $M_{\text{mess}}$-scale induced operators naturally escape from experimental constraints on the flavor violation. However, the Planck-scale induced operators are very dangerous since the Wilson coefficients $b_{i,j}$ are not diagonal under the flavor index $i, j$ of the sfermions. Since $b_{i,j}$ are always expected to be $\mathcal{O}(1)$, the Planck-scale induced soft masses are $m_{\text{soft}}^{PL} \sim \frac{F_s}{M_{PL}} \sim m_3^{3/2}$. In order to avoid the flavor problems at electroweak scale, $m_{\text{soft}}^{PL}$ have to be less than 1 GeV. That is why gravitino is always the LSP in GMSB models.

However, the dynamics of the hidden sector may be important to determine the MSSM spectrum if the SUSY breaking sector is strongly coupled [11–14, 75–90]. One of the interesting mechanisms in the hidden sector is conformal sequestering, which can raise the mass of the gravitino relative to the dangerous Planck-scale induced soft masses [11–14]. So the lightest neutralino can be the LSP and DM candidate\(^2\). To illustrate these conformal sequestered models, we assume that a strongly coupled hidden sector is approximately in a conformal window $[M_1, M_2]$, where $M_2$ is the scale at which the conformality starts and $M_1$ is the scale at which the conformality is broken. Namely, $M_{EW} < M_1 < M_2 < M_{PL}$. In the conformal window, the RGE runnings are dominated by the strongly coupled hidden sector. As long as the fixed point is stable, the coupling constants flow to their infrared fixed-point values by power laws. Below the conformal window, one has

$$b_{i,j}^0 = \left( \frac{M_1}{M_2} \right)^{\beta_{S^1S}} b_{i,j} = Z_{S^1S}(M_1) b_{i,j}.$$  

\(^2\) Interestingly, the same mechanism can be used to solve the $\mu/B_\mu$-problem in GMSB models [80, 81, 84, 88, 89] or to construct focus point SUSY [90].
Here $Z_{S^+S}(\mu)$ comes from one particle irreducible (1PI) diagrams in the hidden sector deducting the wavefunction renormalization factors. $\beta_{S^+S}$ is the anomalous dimension of $S^+S$. Explicit models in the hidden sector have been discussed in \[12, 81, 86\] to demonstrate this conformal mechanism. If $\beta_{S^+S} > 0$, $Z_{S^+S}(M_1)$ can offer a power suppressed factor which is helpful to solve the flavor violation problem. Unfortunately, the exact value of $\beta_{S^+S}$ cannot be calculated in a perturbative way. We simply assume that $b_{ij}^0$ is small enough to be consistent with the constraints on the flavor violation. So even if $m_{3/2} \sim \mathcal{O}(1 \text{ TeV})$, the dangerous Planck-scale induced soft masses can be $m_{PL}^{\text{soft}} \sim \sqrt{b_{ij}^0 m_{3/2}} < 1 \text{ GeV}$. Gravitino will no longer be the LSP in GMSB models.

Besides the large anomalous dimension of $S^+S$, the hidden sector with sequestered SUSY breaking would also provide a significant wavefunction renormalization factor $Z_S(\mu)$, which makes $\mathcal{L}_{\text{eff}} = \int d^4\theta Z_S(\mu)S^+S$ canonically normalized. $Z_S(\mu)$ can be absorbed into the redefinitions of the couplings. For example, the coupling $\kappa$ in the superpotential $W = \kappa S\overline{\Phi}\Phi$ becomes very small below the conformal window as

$$\kappa^0 = \left(\frac{M_1}{M_2}\right)^{2\gamma_S} \frac{\kappa}{Z^{\frac{1}{2}}_S(M_1)}.$$

Here $\gamma_S$ is the anomalous dimension of $S$ at the conformal fixed point. Since $S$ is a singlet, $\gamma_S = 3R(S)/2 - 1$ with $R(S)$ being the $R$ charge of $S$. The unitarity bound of the superconformal algebra requires $R(S) > 2/3$, which leads to $\gamma_S > 1$ \[91\]. So the wavefunction renormalization always offers a power suppressed factor to $\kappa$. Below the conformal window, the superpotential is $W = \kappa^0 S\overline{\Phi}\Phi$.

Finally we pay attention to the first term of Eq.(1), which is mediated by the gauge interaction. Since the superpotential $W = \kappa^0 S\overline{\Phi}\Phi$ contributes to the coefficient $c_i$, $c_i$ must receive the $\gamma_S$ effect from anomalous dimension of $S$. It is interesting to discuss whether this term will further get a large correction from the anomalous dimension of $S^+S$:

Case I: The messenger scale $M_{\text{mess}}$ is below the conformal window, namely $M_{EW} < M_{\text{mess}} < M_1 < M_2 < M_{PL}$. After the messengers fields are integrated out, the hidden sector is out of the conformal window. Thus the coefficients $c_i$ do not receive the effect from the anomalous dimension $\beta_{S^+S}$ \[12, 13\]. Below the messenger scale, RGE runnings, which are dominated by the traditional MSSM ones, allow us to predict the entire MSSM spectrum at the electroweak scale. In this case, the $\mu/B_\mu$-problem can be solved by introducing some Planck-scale induced operators \[12\].
Case II: The messenger scale $M_{\text{mess}}$ is within the conformal window, namely $M_{EW} < M_1 < M_{\text{mess}} < M_2 < M_{PL}$. After the messengers fields are integrated out, the hidden sector is still strongly coupled. Even the visible sector and hidden sector are coupled through higher dimensional operators, the coefficient $c_i$ could be renormalized dominantly by the hidden sector. From the scale $M_{\text{mess}}$ to the scale $M_1$, $c_i$ will further receive a damping factor. Below the scale $M_1$, all coefficients run to the electroweak scale according to the usual MSSM RGEs. So in this case the soft masses of sfermions will be further suppressed by the large anomalous dimension of $S^\dagger S$ [11, 14]. In order to make neutralino the LSP, the lightest stau should be heavier than the lightest neutralino. This constraint in Case II is stronger than that in Case I, since the stau mass in Case II will be further suppressed. After the run I of LHC, a Higgs boson with mass around 125 GeV has been found but no SUSY particles have been detected. The stop sector should provide a large loop contribution to raise Higgs mass. Even assuming a non-vanishing $A_t$-term at the messenger scale, stop mass would be heavier than 500 GeV to get a 125 GeV Higgs [92]. For the Case II, due to the suppression coming from the anomalous dimension of $S^\dagger S$, it is hard to obtain such heavy sfermions. A heavy stop may be realized if RGEs are assumed to run for a long time. But this requirement asks for a high scale $M_1$, which would weaken the suppression of the dangerous Plank-scale induced operators. Thus, the Case II is not suggested by the current LHC data. In the next section, we will discuss more phenomenologies of the Case I.

III. MASS SPECTRUM AND NEUTRALINO DARK MATTER

In this section, we discuss MSSM mass spectrum and neutralino DM in GMSB models with sequestered SUSY breaking. The gravitino mass is fixed to be 1 TeV. We first study minimal GMSB model with $A = 0$ at the input scale. Then we move forward to an extension with non-vanishing $A$-terms at the messenger scale.

A. Minimal GMSB model with sequestered SUSY breaking

In this model, the superpotential is

$$W = \kappa S \Phi_i \Phi_i.$$  (4)
Here the messengers $\Phi_i, \bar{\Phi}_i$ fill out either antisymmetric tensor $10 + \bar{10}$ or fundamental $5 + \bar{5}$ representation of $SU(5)$. Below the conformal window, the conformal sequestered hidden sector will lead to a very small coupling $\kappa^0$ in the superpotential, which can be absorbed into the definition of mass parameter $\Lambda$ as $\Lambda = \frac{\kappa^0 F_S}{M_{\text{mess}}}$. This small coupling $\kappa^0$ guarantees $\Lambda \sim \mathcal{O}(10^5 \text{GeV})$ even when the gravitino mass is fixed to be 1 TeV. For the discussion of phenomenologies, there are six input parameters as
\begin{equation}
\{ \tan \beta, \text{sign}(\mu), M_{\text{mess}}, \Lambda, n_5, n_{10} \}. \tag{5}
\end{equation}

To perform a comprehensive analysis of our models, including spectrum calculation and DM studies, we use the code toolbox1.2.2\cite{93}, which is compiled with SARAH3.3.0, SPheno3.2.2 and micrOMEGAs2.4.5. The code SARAH\cite{94,95,96} is used to create a SPheno version of our models with the soft masses at the messenger scale. The mass spectrum at electroweak scale is calculated by the code SPheno\cite{97,98} with MSSM RGEs and the DM information is obtained by the code micrOMEGAs\cite{99} \footnote{We calculate the mass of the Higgs boson at two-loop level. Recently, some three-loop corrections have been discussed in \cite{100,101}.}. In our studies, sign($\mu$) = +1, $n_5 = 1$ and $n_{10} = 1$ are fixed. We first scan the parameters $\Lambda$ and $M_{\text{mess}}$ by assuming $\tan \beta = 10$. Contour plots of $m_h$ in the $M_{\text{mess}}$ vs. $\Lambda$ plane are shown in the left of Fig.\cite{1}. For a fixed mass parameter $\Lambda$, the Higgs boson would be heavier if the messenger scale is higher. Though $A_t = 0$ at the...
Figure 2: (color online) $\Lambda = 1.6 \times 10^5$ GeV and $\tan \beta = 10$. Left: $m_{\tilde{\tau}_1}$ (green solid line) and $m_{\tilde{\chi}^0_1}$ (red dashed line) depend on the messenger scale $M_{\text{mess}}$. Right: The relic density $\Omega h^2$ depends on the messenger scale $M_{\text{mess}}$.

messenger scale, the $y_t M_3$ term in the RGE ensures that $A_t$ will not vanish at the electroweak scale. RGE runnings also lift the stop mass. A high-scale gauge mediation helps to obtain sufficiently large absolute value of $A_t$—term and heavy stops at the electroweak scale, which are preferred by a 125 GeV Higgs boson. In the right of Fig.(1), we show the ratio of the lightest stau mass to the lightest neutralino mass in the $M_{\text{mess}}$ vs. $\Lambda$ plane. In most of the parameter space, the LSP is the lightest stau particle. A neutralino LSP can only be achieved when the messenger scale $M_{\text{mess}}$ is higher than $4 \times 10^{11}$ GeV.

In Fig.(2), $\Lambda = 1.6 \times 10^5$ GeV is fixed in order to be consistent with a 125 GeV Higgs boson. In the left, we show how the lightest stau mass $m_{\tilde{\tau}_1}$ and the lightest neutralino mass $m_{\tilde{\chi}^0_1}$ depend on the messenger scale $M_{\text{mess}}$. In this case $\tilde{\chi}^0_1$ is purely bino-like and its mass is not sensitive to the messenger scale $M_{\text{mess}}$. Due to RGE running, $m_{\tilde{\tau}_1}$ becomes heavier for a higher messenger scale $M_{\text{mess}}$. When $M_{\text{mess}}$ is larger than $3.6 \times 10^{11}$ GeV, the LSP is $\tilde{\chi}^0_1$ and this model has a good DM candidate with mass around 870 GeV. In the right, the DM relic density $\Omega h^2$ has been calculated by the code micrOMEGAs. When the LSP is $\tilde{\chi}^0_1$, its relic density is always larger than 0.6, which is not consistent with the WMAP experimental result $\Omega h^2 = 0.1138 \pm 0.0045 [102]$. In this case, $\tilde{\tau}_1$ and $\tilde{\chi}^0_1$ are degenerate and the coannihilation effect has been involved to make predictions of relic density. Since the LSP is around 870 GeV, all other SUSY particles should be heavier than 870 GeV. Because the exchanged SUSY particles are so heavy, the cross section $\langle \sigma_{\text{ann}} v \rangle$ is not large enough even including the coannihilation effect. That is why we get too large DM relic density in this
model. We have varied the value of $\tan \beta$ in this model. But the main features of Fig.(1) and Fig.(2) do not change. DM candidate is purely bino-like with a relatively large mass. It is well-known that the observed relic abundance requires the mass of purely bino-like DM to be less than 200 GeV for thermal production [103]. Even including coannihilation effects, purely bino-like DM cannot be too heavy [104]. So generally speaking, the neutralino DM with correct relic density is hard to be achieved in this model.

B. An extension model with non-vanishing $A$–terms

Minimal GMSB model can be extended with non-vanishing $A$–terms at the messenger scale. In [90, 92, 105–109], new Yukawa couplings between the Higgs sector and messengers are introduced to generate one-loop $A$-terms at $M_{\text{mess}}$ scale without flavor problems. So in this subsection, we add a new term in the superpotential as

$$\Delta W = \lambda_u H_u \Phi_i \Phi_S.$$  \hspace{1cm} (6)

Here we introduce a new singlet $\Phi_S$ as another messenger field. $\Phi_i$ are all the fields taking the $(1, 2, -1/2)$ representation in the $5 + \bar{5}$ messenger fields. Eq.(6) would lead to a non-vanishing $A_t$ at the messenger scale. Since the singlet $S$ is the only SUSY-breaking source, the $A/m_{H_u}^2$-problem is not large [106]. Here we do not introduce new Yukawa couplings between $H_d$ and the messenger fields. So there is no $\mu/B\mu$-problem. In this GMSB model with sequestered SUSY breaking, the $\mu$-term can be generated by some Planck-scale induced operators [12]. Compared to the mass spectrum in minimal GMSB model, Eq.(6) results in extra contributions of $A_t$, $m_{H_u}^2$, $m_Q^2$ and $m_U^2$ at the input scale as [106]

$$\begin{align*}
A_t &= -\frac{n_5 \lambda_u^2}{16\pi^2} \Lambda, \\
m_{H_u}^2 &= -\frac{n_5 \lambda_u^2}{48\pi^2} h\left(\frac{\Lambda}{M_{\text{mess}}}\right)\left(\frac{\Lambda}{M_{\text{mess}}}\right)^2 \Lambda^2 + \frac{(3+n_5) \lambda_u^4 - (3\eta_5^2/5+3\eta_5^2/256\pi^4) n_5 \Lambda^2}{256\pi^4} \frac{3+n_5 \lambda_u^2}{256\pi^4} n_5 \Lambda^2, \\
m_Q^2 &= -\frac{n_5 \eta_t^2 \lambda_u^2}{256\pi^4} \Lambda^2, \\
m_U^2 &= -\frac{n_5 \eta_t^2 \lambda_u^2}{128\pi^4} \Lambda^2.
\end{align*}$$  \hspace{1cm} (7)

Here the function $h(x) \approx 1 + 4x^2/5$. If the messenger scale $M_{\text{mess}} \sim \mathcal{O}(10^5 \text{GeV})$, the first term of $m_{H_u}^2$ in Eq.(7) is important to realize the electroweak symmetry breaking (EWSB). When the messenger scale $M_{\text{mess}}$ is large, this term can be neglected due to the $M_{\text{mess}}$-
Figure 3: Contour plots of \( m_h \) (left) and \( m_{\tilde{\tau}_1}/m_{\tilde{\chi}_1^0} \) (right) in the \( M_{\text{mess}} \) vs. \( \Lambda \) plane with \( \tan \beta = 10 \) and \( \lambda_u = 1 \). In the whole blank area of right figure, \( m_{\tilde{\tau}_1}/m_{\tilde{\chi}_1^0} > 1 \). Since \( m_{\tilde{\tau}_1}/m_{\tilde{\chi}_1^0} \) is very sensitive to the choice of \( \Lambda \) and \( M_{\text{mess}} \) in this area, the exact values are difficult to be shown in this contour.

suppression. Instead, the top Yukawa \( y_t \) contribution in the RGEs could cause \( m_H^2 \) to run negative at the electroweak scale, helping to achieve EWSB.

So in this model, there are seven input parameters as

\[
\{\tan \beta, \ \text{sign}(\mu), \ M_{\text{mess}}, \ \Lambda, \ \lambda_u, \ n_5, \ n_{10}\}. \tag{8}
\]

\( \lambda_u \) is not suppressed by the sequestered SUSY breaking sector since it is not directly coupled to the hidden sector \( S \). Thus \( \lambda_u \sim O(1) \). Contour plots of \( m_h \) and \( m_{\tilde{\tau}_1}/m_{\tilde{\chi}_1^0} \) in the \( M_{\text{mess}} \) vs. \( \Lambda \) plane are shown in Fig.(3) when \( \tan \beta = 10 \) and \( \lambda_u = 1 \) are assumed. By comparing the left figures between Fig.(1) and Fig.(3), the Higgs boson with mass around 125 GeV is easier to be obtained with non-vanishing \( A \)-term. In the right of Fig.(3), we show the ratio of the lightest stau mass to the lightest neutralino mass in the \( M_{\text{mess}} \) vs. \( \Lambda \) plane. A neutralino LSP as well as a 125 GeV Higgs can be achieved in a large parameter space with \( 10^6 \text{ GeV} < M_{\text{mess}} < 10^7 \text{ GeV} \), as shown in the blank area in the right of Fig.(3). We should like to focus on neutralino DM in this parameter area.

In Fig.(4), \( \Lambda = 1.5 \times 10^5 \text{ GeV} \) is fixed in order to be consistent with a 125 GeV Higgs boson. In the left, we show how the lightest stau mass \( m_{\tau_1} \) and the lightest neutralino mass \( m_{\chi_1^0} \) depend on the messenger scale in the range \( 10^6 \text{ GeV} < M_{\text{mess}} < 10^7 \text{ GeV} \). In this range,
Figure 4: (color online) $\Lambda = 1.5 \times 10^5$ GeV, $\tan \beta = 10$ and $\lambda_u = 1$. Left: $m_{\tilde{\tau}_1}$ (green solid line) and $m_{\tilde{\chi}_1^0}$ (red dashed line) depend on the messenger scale $M_{\text{mess}}$. Right: The relic density $\Omega h^2$ depends on the messenger scale $M_{\text{mess}}$.

$m_{\tilde{\tau}_1}$ is almost independent of the messenger scale and $\tilde{\chi}_1^0$ is actually a mixture of bino and higgsino. $m_{\tilde{\chi}_1^0}$ is sensitive to the messenger scale because $m_{\tilde{\chi}_1^0}$ is dominated by the value of $\mu$-term, which depends on $M_{\text{mess}}$. The exact value of $\mu$-term is determined by the correct EWSB. Due to the $\lambda_u$ corrections of $m_{H_u}^2$ in Eq.(7), EWSB in this model is quite different from that in the minimal GMSB model. In the range $10^6$ GeV $< M_{\text{mess}} < 10^7$ GeV, EWSB can be realized by two reasons. One is the negative $\Lambda/M_{\text{mess}}$-suppressed contribution of $m_{H_u}^2$ at input scale and the other is the top Yukawa contribution in RGE running. In the range $1.5 \times 10^6$ GeV $< M_{\text{mess}} < 8 \times 10^6$ GeV, the correct EWSB hints that $\mu$-term is less than 500 GeV, which makes $\tilde{\chi}_1^0$ lighter than $\tilde{\tau}_1$. As it is a bino-higgsino DM, the corresponding DM relic density $\Omega h^2$ has been shown in the right of Fig.(4). We can have a neutralino DM which is consistent with the WMAP experimental relic density result $\Omega h^2 = 0.1138 \pm 0.0045$ [102]. Though we fix $\Lambda = 1.5 \times 10^5$ GeV in the above discussion, our conclusion is general. A relatively small $\mu$-term can be obtained in this model, which makes $\tilde{\chi}_1^0$ the LSP. So a bino-higgsino DM with correct relic density can be achieved. On the other hand, EWSB with a large $\tan \beta$ leads to the following constraint at the electroweak scale,

$$m_Z^2 \approx -2(\mu^2 + m_{H_u}^2).$$

(9)

Since the value of $\mu$-term is relatively small in this model, the cancellation between $\mu$ and $m_{H_u}$ is correspondingly relatively small. There is a small fine-tuning to get the $Z$ boson mass.

Finally, we take into account the updated bounds of DM direct searches. The current
strictest bound of spin-independent cross section is recently given by the LUX Collaboration [69], who is the first to break the $10^{-45}$ cm$^2$ cross section barrier of DM spin-independent detection. We also consider the existing upper limits of spin-dependent cross section. For this study, we scan the the parameters in the $M_{\text{mess}}$ vs. $\Lambda$ plane and collect the points which have a Higgs boson with mass $123 \text{ GeV} < m_h < 127 \text{ GeV}$ and a bino-higgsino DM with relic density $0.1 < \Omega h^2 < 0.12$. The results of DM direct searches are shown in Fig. (5). The left figure is devoted to the spin-independent cross section. Our DM points are below the current experimental bounds, such as LUX [69] and XENON100 [110]. Interestingly, based on the proposals of future experiments, our DM points can be examined by future DM direct searches, such as LUX in 2015 [111] and XENON10T [112]. For the spin-dependent cross section, the results are shown in the right figure. Our DM points are far below the existing experimental bounds. For both spin-independent detection and spin-dependent detection, the cross section will become relatively small if DM is relatively heavy. That is because all other SUSY particles should be heavier than the LSP. DM with a relatively large mass will force overall sparticles to be relatively heavy.
Figure 6: Mass spectrum of a benchmark point. In this case a bino-higgsino DM with right relic density is predicted.

IV. CONCLUSION

In this paper, we have studied the neutralino DM in gauge mediation using the data after the run I of LHC and LUX. Neutralino can be the DM candidate in GMSB models if the conformal sequestered mechanism is introduced in the hidden sector. So the gravitino mass $m_{3/2}$ can be fixed to 1 TeV without introducing any flavor violation problem. For the minimal GMSB model with sequestered SUSY breaking, the DM candidate can be a purely bino-like neutralino. In this case it is hard to achieve the correct relic density due to its relatively large mass. So we move forward to extending the minimal GMSB model by adding new Yukawa couplings between the messenger fields and the Higgs field $H_u$. In this extension, this sequestered mechanism can predict a good DM candidate as well as a 125 GeV Higgs boson. As an example, the mass spectrum of one benchmark point is shown in Fig.6, which is corresponding to $m_{\tilde{\chi}_1^0} = 688.4$ GeV and $\Omega h^2 = 0.108$. The initial parameters are $\text{sign}(\mu) = +1$, $n_5 = 1$, $n_{10} = 1$, $\tan \beta = 10$, $\lambda_u = 1$, $\Lambda = 2 \times 10^5$ GeV and $M_{\text{mess}} = 1.46 \times 10^6$ GeV. Thus for this case, the coupling is

$$\kappa^0 \sim \frac{\Lambda M_{\text{mess}}}{m_{3/2} M_{PL}} \sim O(10^{-10}).$$  \hspace{1cm} (10)

This $\kappa^0$ can be simply realized, for example, by assuming $M_1 = 2 \times 10^6$ GeV, $M_2 = 2 \times 10^{16}$ GeV and $\gamma_S = 2$. $\gamma_S = 2$ can be achieved if the hidden sector is $SP(3) \times SP(1)^2$ model. All our survived points have some common features. Firstly, the light Higgs boson
\( h \) is around 125 GeV and other Higgs bosons are heavy. So the Higgs sector falls into the decoupling MSSM limit. The properties of the light Higgs boson \( h \) are similar to the predictions of the SM Higgs boson. Secondly, the correct EWSB hints a relatively small \( \mu \)-term, which makes the lightest neutralino lighter than the lightest stau. So a bino-higgsino DM with correct relic density can be achieved. The relatively small \( \mu \)-term results in a small fine-tuning of obtaining the \( Z \) boson mass. Finally, this bino-higgsino DM can pass all the existing bounds of both spin-independent and spin-dependent searches. Interestingly, the spin-independent cross section of our DM points can be examined by further dark matter experiments, such as LUX in 2015 and XENON10T.

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