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Positively deflected anomaly mediation

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We generalize the so-called ''deflected anomaly mediation'' scenario to the case where threshold corrections of heavy messengers to the sparticle squared masses are positive. A concrete model realizing this scenario is also presented. The tachyonic slepton problem can be fixed with only a pair of messengers. The resultant sparticle mass spectrum is quite different from that in the conventional deflected anomaly mediation scenario, but is similar to the one in the gauge mediation scenario. The lightest sparticle is mostly *B*-ino.

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I. INTRODUCTION

Supersymmetry (SUSY) extension is one of the most promising ways to solve the gauge hierarchy problem in the standard model. However, since none of the sparticles have been observed yet, supersymmetry must be broken at low energies. In addition, sparticle masses are severely constrained by experiments, since arbitrary soft supersymmetry breaking masses cause too large flavor changing neutral currents (SUSY flavor problem). Finding a simple mechanism of supersymmetry breaking and its mediation is one of the most important tasks for realistic supersymmetric theories.

Anomaly mediated supersymmetry breaking (AMSB) [1,2] is one of the most attractive scenarios in supergravity. This is because it predicts that the sparticle mass spectrum is flavor blind and thus solves the SUSY flavor problem automatically. In addition, since SUSY breaking is mediated through the superconformal anomaly, sparticle masses at low energies are insensitive to any high energy theories and mechanisms of SUSY breaking, namely, they are model independent.

In order to realize the AMSB scenario, sequestering between the visible sector and the hidden sector in supergravity is necessary. This is naturally realized in the five-dimensional brane world scenario [1,3], where the visible and hidden sectors are confined on the different branes geometrically separated,[1] or in the models where the contact terms between the hidden and visible sectors are suppressed dynamically by a conformal sector [4]. For simplicity, we assume sequestering in this paper.

Unfortunately, the pure AMSB scenario is obviously excluded, since it predicts that slepton squared masses are negative. There have been many attempts to solve this ''tachyonic slepton'' problem by taking into account additional positive contributions to the sparticle squared masses at the tree level [1,6] or at the quantum level [7–9].

One of the elegant scenarios is the so-called ''deflected anomaly mediation'' scenario proposed by Pomarol and Rattazzi [7]. We introduce the messenger sector with N flavors of messengers such that

$$W=\sum_{i=1}^{N} \lambda_i S \overline{\Psi}_i \Psi^i, \tag{1}$$

where $\overline{\Psi}_i$ and Ψ^i are the messengers in $\overline{\mathbf{5}}+\mathbf{5}$ representation under the gauge group $SU(5)$,[2] and S is the singlet superfield. If vacuum expectation values of the scalar component (S) and the F component (F_S) of the singlet superfield are generated, new contributions to sparticle masses develop through the same manner as in the gauge mediation scenario [10,11]. As a result, sparticle masses are deflected from the pure AMSB trajectory of the renormalization group equations, and the tachyonic slepton problem can be fixed. In addition, this scenario predicts the specific sparticle mass spectrum [7]. Furthermore, detailed phenomenology was discussed [12], and the extension to the model with axion was proposed [13].

The crucial difference from the gauge mediation scenario is that the SUSY breaking in the messenger sector is originated from the anomaly mediation. Therefore, nonzero F component of the compensating multiplet (F_ϕ) is the unique source of SUSY breaking in this scenario. This fact allows us to parametrize the SUSY breaking order parameter in the messenger sector such as [see Eq. (3) for our notation]

$$\frac{F_S}{S}=dF_\phi . \tag{2}$$

Here we introduced the parameter d which characterizes how the sparticle masses are deflected from the pure AMSB trajectory. We call d the ''deflection parameter'' in this paper. Note that d should be real and, at most, of order 1, $|d| \leqslant \mathcal{O}(1)$, since all the quantities accompanied by SUSY breaking should be originated from the anomaly mediation.

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[1]It has been recently pointed out [5] that sequestering is not a generic prediction of string theories, even if two branes are geometrically separated. In this paper, we simply assume that we are on a special point in the string moduli (if string theory is the ultimate theory behind us), where sequestering is realized.

[2]We use the conventional $SU(5)$ grand unified theory (GUT) notation in this paper. In this notation, the beta function coefficient $b_1=-33/5$ and the quadratic Casimir $C=3/5Y^2$ for the $U(1)_Y$ hypercharge.

In the conventional deflected anomaly mediation scenario, only the negative values for the deflection parameter $d<0$ have been taken into account. In this paper we generalize the conventional scenario to the case with a positive deflection parameter. We examine, in the next section, how the nonzero deflection parameter occurs based on a simple superpotential, and find that the deflection parameter can be positive. In Sec. III, we present a simple concrete model which can realize our scenario. The sparticle mass spectrum is presented in Sec. IV. We will see that our result is quite different from that in the conventional deflected anomaly mediation scenario, but is similar to that of the gauge mediation scenario. The lightest sparticle (LSP) is mostly *B*-ino in our scenario. We give a conclusion in the last section.

II. GENERALIZATION AND POSITIVE DEFLECTION PARAMETER

In order to fix the tachyonic slepton problem, a sizable deflection parameter $|d|\sim\mathcal{O}(1)$ is necessary. In general, this case occurs when the superfield S is lighter than F_ϕ in the SUSY limit and the SUSY breaking effect plays an essential role to determine the potential minimum of S.

There are two typical cases. One is that S has no superpotential or an extremely flat potential in the SUSY limit, and the potential minimum is determined essentially by the effective Kahler potential including the anomaly mediation. The other case is that S has a superpotential, which plays an essential role to determine the potential minimum after the SUSY breaking effects are taken into account. In the first case, the deflection parameter is found to be $d\sim-1$. This is nothing but the case mainly discussed in the conventional deflected anomaly mediation scenario. On the other hand, the deflection parameter can generally be positive in the latter case. In fact, we can construct a model which realizes $d>0$.

Let us begin with the supergravity Lagrangian for S in the superconformal framework [14,15] (supposing SUSY breaking in the hidden sector and fine-tuning of the vanishing cosmological constant)

$$\mathcal{L}=\int d^4\theta\phi^\dagger\phi\mathcal{Z}(S^\dagger,S)S^\dagger S+\left\{\int d^2\theta\phi^3 W(S)+\text{H.c.}\right\}, \tag{3}$$

where $\mathcal{Z}$ is the supersymmetric wave function renormalization coefficient, W is the superpotential [except for Eq. (1)], and ϕ is the chiral compensating multiplet expanded as $\phi=1+\theta^2 F_\phi$ with the unique SUSY breaking source F_ϕ being the same order as the gravitino mass. The scalar potential can be read off as

$$V=\frac{\partial^2\mathcal{K}}{\partial S^\dagger\partial S}|F_S|^2-\mathcal{K}|F_\phi|^2-3F_\phi W-3F_\phi^\dagger W^\dagger \tag{4}$$

with the auxiliary field given by

$$F_S=-\left(\frac{\partial^2\mathcal{K}}{\partial S^\dagger\partial S}\right)^{-1}\left(\frac{\partial\mathcal{K}}{\partial S^\dagger}F_\phi+\frac{\partial W^\dagger}{\partial S^\dagger}\right), \tag{5}$$

where $\mathcal{K}=\mathcal{Z}(S^\dagger,S)S^\dagger S$ is the effective "Kahler potential" in the superconformal framework.

Let us first consider the case where S has no superpotential or the superpotential plays no essential role to determine the potential minimum. In this case, the superpotential term in Eq. (5) can be ignored. In addition, since $\mathcal{Z}\sim1$ is usually a very slowly varying function of $S^\dagger$ and S in perturbation theory, $\partial\mathcal{Z}/\partial S^\dagger$, $\partial\mathcal{Z}/\partial S$, and $\partial^2\mathcal{Z}/\partial S^\dagger\partial S$ can all be neglected. As a result, we obtain $F_S/S\sim-F_\phi$, namely, the deflection parameter $d\sim-1$ independent of S at the potential minimum. This is the case discussed in the conventional deflected anomaly mediation scenario. We arrive at the same result in the case where the potential is bounded by higher-dimensional Kahler terms if S is much smaller than the Planck scale [13].

Next consider the case that the potential minimum is determined through the superpotential. We can take the canonical Kahler potential $\mathcal{K}\sim S^\dagger S$, as a good approximation, and Eqs. (4) and (5) are reduced to simple forms. Using the stationary condition $\partial V/\partial S=0$ and Eq. (5), we obtain

$$\frac{F_S}{S}\sim-2F_\phi\frac{\dfrac{\partial W}{\partial S}}{S\dfrac{\partial^2 W}{\partial S^\dagger\partial S}}. \tag{6}$$

This is a useful formula, from which we can understand that S should be light in the SUSY limit in order to obtain a sizable deflection parameter $|d|\sim\mathcal{O}(1)$.

Suppose that $\langle S\rangle=S_0\gg F_\phi$ and S is much heavier than the gravitino in the SUSY limit. After taking the supergravity effects into account, the vacuum expectation value of S, in general, shifts from the value in the SUSY limit such as $\langle S\rangle\sim S_0+\mathcal{O}(F_\phi)$ [16]. In this case, Eq. (6) can be expanded with respect to the small variable F_ϕ/S_0 with the SUSY vacuum condition $\partial W/\partial S(S_0)=0$, and we can find that $F_S/S\sim F_\phi\times\mathcal{O}(F_\phi/S_0)$, that is, $d\sim\mathcal{O}(F_\phi/S_0)\ll1$. This is the one discussed as the decoupling case in the literature [7,8,13]. Note that this example also implies a possibility that there would be a sizable effect if $S_0\leq F_\phi$. In this case, detailed analysis of higher order corrections is necessary [8].

As a simple and interesting example which can incorporate the generalization of the deflected anomaly mediation scenario, let us introduce the superpotential

$$W=M^{3-p}S^p, \tag{7}$$

where M is a mass parameter, and p is a real parameter. From the general formula of Eq. (6), we find

$$\frac{F_S}{S}=\frac{2}{1-p}F_\phi. \tag{8}$$

This result was already derived in the original paper by Pomarol and Rattazzi [7], where the case $p\geq3$, or $d<0$, was discussed. Here note that the deflection parameter becomes positive for $p<1$. This is a new point of this paper. In the following, we discuss about only the case with the positive deflection parameter.[3]

There is an upper bound on the deflection parameter. To see this, we analyze the potential in detail. It is useful to redefine the superfield by $\phi S \to S$, so as to eliminate the compensating multiplet in the (canonical) Kahler potential. In this notation, Lagrangian is found to be

$$\mathcal{L}=\int d^4\theta S^\dagger S+\left\{\int d^2\theta \phi^{3-p}M^{3-p}S^p+\text{H.c.}\right\}. \tag{9}$$

Here M has been taken to be real and positive by $U(1)_R$ symmetry rotation without loss of generality. Changing variables such that $S=re^{i\Omega/p}$ and $F_\phi=|F_\phi|e^{i\omega}$ by using only real parameters, the scalar potential is found to be

$$V=p^2M^{6-2p}r^{2p-2}-2(3-p)|F_\phi|M^{3-p}r^p\cos(\Omega+\omega). \tag{10}$$

From the minimization conditions $\partial V/\partial\Omega=0$ and $\partial^2V/\partial\Omega^2>0$, we obtain the solution $\Omega=-\omega$ with the assumption $0<r<\infty$. With this solution, the stationary condition with respect to r leads to

$$r^{p-2}=\frac{3-p}{p(p-1)}M^{p-3}|F_\phi|. \tag{11}$$

We can find a solution in the region $0<r<\infty$ only for $p<0$. Thus, the upper bound on the deflection parameter is found to be $d<2$. This result is consistent with our expectation $d\leqslant\mathcal{O}(1)$.

Constraints on the parameter M is given by consistency of our scenario. We have been assuming that $d\neq 0$ is originated from the anomaly mediation. This point is nothing but the crucial difference of our scenario from the gauge mediation scenario. Therefore, SUSY breaking in the messenger sector should be negligible compared with the original SUSY breaking in the hidden sector. This requirement is described as

$$\frac{|\langle W\rangle|}{M_{\text{Pl}}^2}\ll|F_\phi|\sim m_{3/2}, \tag{12}$$

where M_{Pl} and $m_{3/2}$ are the reduced Planck and gravitino masses, respectively. Using the above solutions, we find

$$M\ll\left(\frac{p(p-1)}{3-p}\right)^{-p/2(3-p)}\left(\frac{|F_\phi|}{M_{\text{Pl}}}\right)^{1/3-p}M_{\text{Pl}}. \tag{13}$$

Note that this condition is also consistent with a natural requirement $r\ll M_{\text{Pl}}$.

[3]For $p>1$, we can find new consistent solution for $2<p<3$, which generalizes the conventional scenario to the region $-2<d<0$.

III. A CONCRETE MODEL

In the previous section, we have generalized the deflection parameter to the positive region. The simple example consistent with our assumption is the superpotential with negative p. We can hardly imagine that any perturbative theories have such a superpotential, the so-called runaway-type superpotential. However, there occurs the case in the SUSY gauge theories through nonperturbative gauge dynamics [17]. Now we present a concrete model.

Our model is based on the strong gauge group $SU(N_c)$ $(N_c\geqslant 2)$ with the particle contents as follows:

	$SU(N_c)$	$U(1)_R$
$\bar{Q}$	$\overline{\mathbf{N}}$	$1-N_c$
Q	$\mathbf{N}$	$1-N_c$
Z	$\mathbf{1}$	$2N_c$
S	$\mathbf{1}$	$1-N_c$

The general (renormalizable) superpotential is given by

$$W=Z[(\bar{Q}Q)-S^2]+(N_c-1)\frac{\Lambda^{3N_c-1/N_c-1}}{(\bar{Q}Q)^{1/N_c-1}}, \tag{14}$$

where the second term is the dynamically generated superpotential [17], and Λ is the dynamical scale. We have omitted dimensionless free parameters for simplicity.

After integrating out the superfields $\bar{Q}$, Q, and Z under their SUSY vacuum conditions, we obtain the effective superpotential

$$W_{eff}=(N_c-1)\Lambda^{(3N_c-1)/(N_c-1)}S^{2/(1-N_c)}, \tag{15}$$

which corresponds to the superpotential of Eq. (7) with the identifications $p=-2/(N_c-1)<0$ and $M=(N_c-1)^{(N_c-1)/(3N_c-1)}\Lambda$. The deflection parameter is found to be $d=2(N_c-1)/(N_c+1)>0$.

For simplicity, let us take a special limit $N_c\gg 1$, which leads to $p\sim 0$ and thus $d\sim 2$. The condition of Eq. (13) gives the upper bound on the dynamical scale $\Lambda\ll(F_\phi/N_cM_{\text{Pl}})^{1/3}M_{\text{Pl}}$. Taking a reasonable value $F_\phi\sim\mathcal{O}(10\ \text{TeV})$ in the AMSB scenario, we can find that the messenger scale $r\sim\sqrt{\Lambda/F_\phi}\Lambda\leqslant M_{\text{GUT}}$ and $\Lambda\leqslant 10^{12}$ GeV are consistent with the condition with $N_c\sim\mathcal{O}(10)$, where $M_{\text{GUT}}\sim 10^{16}$ GeV is the grand unification scale.

IV. SPARTICLE MASS SPECTRUM

Now let us figure out the sparticle mass spectrum in our scenario. General formulas are given by the method developed in Ref. [18] (see also Ref. [7]). For the general case with $F_S/S=dF_\phi$, they are found to be

$$\frac{m_{\lambda_i}}{\alpha(\mu)}=\frac{F_\phi}{2}\left(\frac{\partial}{\partial \ln\mu}-d\frac{\partial}{\partial \ln|S|}\right)\alpha^{-1}(\mu,S),$$

$$m_i^2(\mu)=-\frac{|F_\phi|^2}{4}\left(\frac{\partial}{\partial \ln\mu}-d\frac{\partial}{\partial \ln|S|}\right)^2 \ln Z_i(\mu,S). \tag{16}$$

All we have to know is the dependence of the gauge coupling $\alpha(\mu,S)$ and the wave function $Z_i(\mu,S)$ on the renormalization scale μ and on the singlet S after integrating out the messengers. In the parentheses, the first and the second terms correspond to the purely anomaly mediated contribution and the additional corrections through the messengers, respectively. Note that the limit $|d|\gg 1$ reduces the formulas to that in the gauge mediation scenario [18].

For a simple gauge group, the gauge coupling and the wave functions are given by

$$\alpha^{-1}(\mu,S)=\alpha^{-1}(\Lambda_{\rm cut})+\frac{b-N}{4\pi}\ln\left(\frac{S^\dagger S}{\Lambda_{\rm cut}^2}\right)+\frac{b}{4\pi}\ln\left(\frac{\mu^2}{S^\dagger S}\right), \tag{17}$$

$$Z_i(\mu,S)=Z_i(\Lambda_{\rm cut})\left(\frac{\alpha(\Lambda_{\rm cut})}{\alpha(S)}\right)^{2c_i/(b-N)}\left(\frac{\alpha(S)}{\alpha(\mu)}\right)^{2c_i/b}, \tag{18}$$

where $\Lambda_{\rm cut}$ is the ultraviolet cutoff, b is the beta function coefficient, and c_i is the quadratic Casimir. Substituting them into Eq. (16), we obtain

$$m_\lambda(\mu)=\frac{\alpha(\mu)}{4\pi}F_\phi(b+dN), \tag{19}$$

$$m_i^2(\mu)=2c_i\left(\frac{\alpha(\mu)}{4\pi}\right)^2|F_\phi|^2 bG(\mu,S), \tag{20}$$

where

$$G(\mu,S)=\left(\frac{N}{b}\xi^2+\frac{N^2}{b^2}(1-\xi^2)\right)d^2+2\frac{N}{b}d+1 \tag{21}$$

with

$$\xi\equiv\frac{\alpha(S)}{\alpha(\mu)}=\left[1+\frac{b}{4\pi}\alpha(\mu)\ln\left(\frac{S^\dagger S}{\mu^2}\right)\right]^{-1}. \tag{22}$$

In $d=0$, Eq. (20) leads to squared masses which are negative for an asymptotically nonfree gauge theory ($b<0$). This occurs as the tachyonic slepton problem in the minimal supersymmetric standard model (MSSM).

Let us extract the threshold corrections due to the heavy messengers to the sparticle squared masses. Taking $\xi=1$ at the messenger scale $\mu=S$ and subtracting the purely anomaly mediated contribution, we obtain

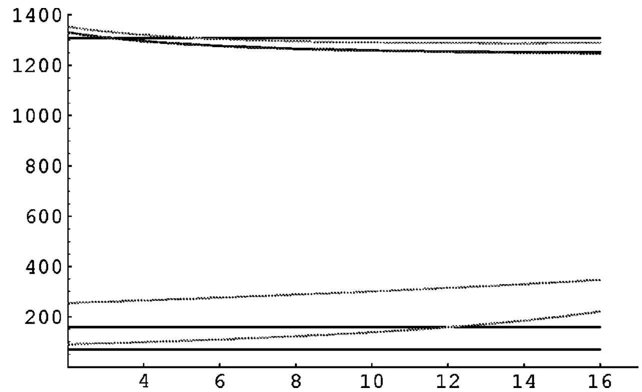

FIG. 1. Soft masses (absolute values for the gaugino masses) of the left-handed squark ($m_{\tilde{Q}}$), the right-handed up-squark ($m_{\tilde{U}}$), the right-handed down-squark ($m_{\tilde{D}}$), the gluino ($m_{\tilde{g}}$), the left-handed slepton ($m_{\tilde{L}}$), the W-ino ($m_{\tilde{W}}$), the right-handed slepton ($m_{\tilde{E}}$), and the B-ino ($m_{\tilde{B}}$) are plotted from above at the messenger scale 100 GeV. Here $d=2$, $N=2$, and $F_\phi=20$ TeV have been taken. Two lines of $m_{\tilde{U}}$ and $m_{\tilde{D}}$ are almost overlapped, and not distinguishable.

$$m_i^2|_{\rm th}=2c_i\left(\frac{\alpha(S)}{4\pi}\right)^2|F_\phi|^2 Nd(d+2). \tag{23}$$

We can see that $m_i^2|_{th}<0$ for the conventional scenario $(-2<)d<0$. This is the reason that the scenario is called the "antigauge mediation." On the other hand, in our scenario, the threshold correction has just the same sign as in the gauge mediation scenario. For this reason, we may call our scenario "anomaly induced gauge mediation."

It is straightforward to extend the above formulas to that for the sparticles in the MSSM. Neglecting the effects of Yukawa couplings, the sparticle masses (in GeV) evaluated at $\mu=100$ GeV are depicted in Fig. 1 as a function of $\log_{10}[S/\text{GeV}]$ for the case $d=2$ and $N=2$ with $F_\phi=20$ TeV. Here we have taken the gauge couplings in the standard model such that $\alpha_3(m_Z)\sim 0.12$, $\alpha_2(m_Z)\sim 0.033$, and $\alpha_1(m_Z)\sim 0.017$. We can find that the resultant spectrum is similar to that of the gauge mediation scenario. However, our result is the distinctive one, since the deflection parameter is, at most, of order 1, and far from the "gauge mediation limit" $d\gg 1$. We also present the result of conventional deflected anomaly mediation scenario [7] in Fig. 2 with $d=-1$ and $N=4$. It is interesting to compare these two graphs. The opposite sign of the deflection parameter causes the big difference. Note that we need less number of the messenger fields than that in the conventional scenario in order to fix the tachyonic slepton problem. For example, introduction of only one pair of messengers is enough in the case $d=2$ as can be seen in Fig. 3.

The lightest sparticle is B-ino in Fig. 1, and is a candidate of the LSP. There is another candidate in the conventional scenario, the fermionic partner of S. Analyzing the scalar potential, we find that its mass is of order F_ϕ due to the superpotential. Therefore, in our scenario, the LSP is always the sparticle in the MSSM. Although what is the LSP depends on the parameters d and N, and the messenger scale, we can find that the LSP is mostly B-ino providing the solu-

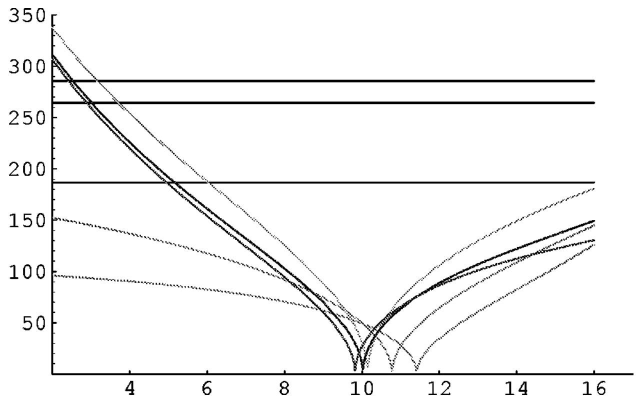

FIG. 2. Soft masses (absolute values) in the conventional scenario [7] with $d=-1$ and $N=4$. $|m_{\tilde{Q}}|$, $|m_{\tilde{U}}|$, $|m_{\tilde{D}}|$, $|m_{\tilde{B}}|$, $|m_{\tilde{W}}|$, $|m_{\tilde{g}}|$, $|m_{\tilde{L}}|$, and $|m_{\tilde{E}}|$ are plotted from above at the messenger scale 100 GeV. The left hand side from the cusps for each graph is the negative squared-masses region, and is the phenomenologically excluded region.

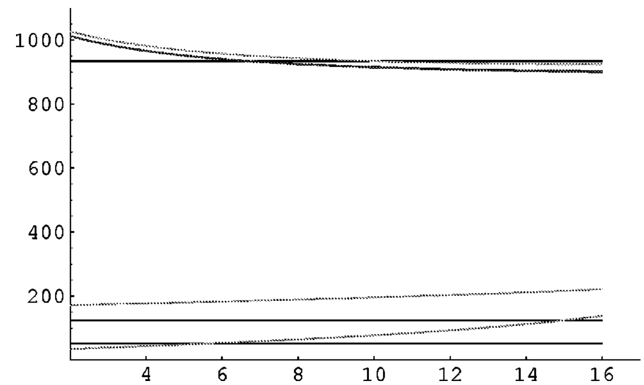

FIG. 3. Soft masses for the case $d=2$ and $N=1$ with $F_\phi=20$ TeV. $m_{\tilde{Q}}$, $m_{\tilde{U}}$, $m_{\tilde{D}}$, $|m_{\tilde{g}}|$, $m_{\tilde{L}}$, $|m_{\tilde{B}}|$, $|m_{\tilde{W}}|$, and $m_{\tilde{E}}$ are plotted from above at the messenger scale 100 GeV. Two lines of $m_{\tilde{U}}$ and $m_{\tilde{D}}$ are almost overlapped, and not distinguishable.

tion of the tachyonic slepton problem. This result may be reasonable, since existence of charged LSP is usually problematic in the cosmological point of view.

V. CONCLUSION

Although the AMSB is very attractive scenario in supergravity, it cannot be phenomenologically viable because of its prediction of the tachyonic slepton. It is inevitable that the AMSB scenario should be extended in order to fix the problem, even if its beautiful feature, namely, model independence, is somewhat lost.

As one elegant scenario, we considered the deflected anomaly mediation scenario. If there is a sizable deflection parameter, the messenger sector plays the essential role so that the tachyonic slepton problem can be fixed. In the conventional scenario, only the negative deflection parameter has been taken into account. Based on the simple superpotential, we generalized the scenario to the case with the positive deflection parameter. Furthermore, we presented a concrete model which could naturally realize this scenario.

Sparticle masses were found to be quite different from those in the conventional scenario, but similar to those in the gauge mediation scenario. However, it is a distinctive one, since the corrections through the messengers and the purely AMSB contributions are of the same order. This is because the SUSY breaking in the messenger sector is originated from the superconformal anomaly. This point is the crucial difference from the conventional gauge mediation scenario. It may be reasonable to call our scenario "anomaly induced gauge mediation."

An elegant mechanism to solve the μ problem was proposed in the original deflected anomaly mediation scenario [7]. Since the mechanism is independent of the sign of the deflection parameter, we can follow the same manner, and obtain the μ term of the same order as the sparticle masses.

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