Recent Muon $g - 2$ Result in Detected Anomaly-Mediated Supersymmetry Breaking

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Abstract

We study the detected anomaly-mediated supersymmetry breaking (AMSB) scenario in the light of the recent result of the muon $g - 2$ from Brookhaven E821 experiment. The E821 result suggests the deviation from the SM prediction, though there remain unsettled uncertainties. We find that the supersymmetric contribution to the muon $g - 2$ can be $O(10^{-9})$, large enough to fill the deviation, with other experimental constraints satisfied. In particular, the Higgs mass and $b\to s$ put severe constraints on the model and large $\tan \beta$ is favored to enhance the muon $g - 2$. 
Recently, the new muon $g-2$ result has been announced from the Brookhaven E821 experiment [1],

$$a \ (E821) = 11659203(8) \times 10^{10};$$

(1)

where the error has become comparable to that of the standard model (SM) prediction. The SM theoretical value of the muon $g-2$ has been reported in Refs. [2]-[8]. The main sources of the uncertainties of the SM prediction come from the leading hadronic vacuum polarization and the light-by-light contributions. As for the leading hadronic contribution, we have to rely on the experimental data, that is, $e^+e^-$ cross section and hadronic decay data, where the decay data is translated into $e^+e^-$ cross section by assuming the isospin symmetry. The most recent evaluations are given in Table 1. In the new detailed evaluation by Davier et al. [6], they carefully considered radiative corrections to the $e^+e^-$ cross section and took into account the isospin symmetry breaking effects explicitly. From Table 1, the results of $e^+e^-$ and $\pi^0\pi^0$-based are, unfortunately, inconsistent and the origin of this discrepancy has not been clarified. As for the $e^+e^-$-based evaluation, we notice that the uncertainty becomes comparable to the previous works which uses the decay data, and the independent analysis by Hagiwara et al. [7] gave a similar result. In this letter, we are inclined to use the $e^+e^-$-based result by Davier et al. for the leading hadronic contribution. Then, with the corrected sign of the light-by-light contribution [3], the SM prediction becomes

$$a \ (SM) = 11659169\pm(7.8) \times 10^{10} \ [e^+e^- \ based];$$

(2)

Therefore the difference between the experimental value and the SM prediction is

$$a \ (E821) - a \ (SM) = 33.9(11.2) \times 10^{10} \ [e^+e^- \ based];$$

(3)

which means that the deviation is $3.0\sigma$. Though the uncertainties of the SM prediction have not been settled, there remains the possibility for the deviation to be physical. If this deviation is a signal of new physics, additional contribution to the muon $g-2$ is required to be $O(10^{-9})$.

Supersymmetry (SUSY) is one of the most motivated models which extend the SM and the muon $g-2$ has been investigated in SUSY models [3,10,11]. These models often provide the universal gaugino mass. However, once SUSY is extended to include the gravity, the quantum effects via the super-Weyl anomaly [12] always manifest themselves in the soft SUSY breaking terms and give another class of gaugino mass spectra. This SUSY breaking mediation mechanism is known as anomalous mediated SUSY breaking (AMSB) [13]. Though anomalous-mediated effects may be small compared to the other SUSY breaking effects, there are some cases where AMSB become dominant. In fact, AMSB dominates if the SUSY breaking sector has no direct interactions with the minimal supersymmetric standard model (MSSM) sector but gravitation. In this letter, we study models where the

#1 The E821 result is consistent with the -based prediction at 1.6 level.
### Table 1: The evaluation of the leading hadronic vacuum polarization contribution

| Authors                          | a (had; L/D) | 10^{-10} | Data   |
|----------------------------------|-------------|----------|--------|
| Davier and Hocker [3]            | 692.4 (62)  | e+ e ;   |
| Narison [2]                      | 702.1 (76)  | e+ e ;   |
| Troconiz and Yndurain [3]        | 695.2 (64)  | e+ e ;   |
| Davier et al. [4]                | 684.7 (70)  | e+ e based |
| Davier et al. [4]                | 701.9 (62)  | [ based] |
| Hagiwara et al. [7]              | 683.1 (62)  | e+ e based |

amaly-mediated effects dominate. Though AM SB has attractive features [2], the original model [3] suffers from the tachyonic slepton problem. Further, a parameter set which survives the b! s bound generally leads a negative contribution to the muon g-2.

Various attempts have been made to avoid the tachyonic slepton [16]. The delected AM SB model [17,18] is a successful and attractive one. In particular, this model makes the sign of the wino mass M_2 and the gluino mass M_3 identical. This is very important for the recent result of the muon g-2. In fact, the experimental results of the muon g-2 and the branching ratio of b! s favor both M_2 and M_3 positive, where is Higgs mixing parameter. On the other hand, the pure AM SB model predicts opposite sign of the wino and gluino masses, and some additional mechanism is required to modify the gaugino mass relations. In fact, the muon g-2 has been investigated in the minimal AM SB scenario [13], where only the sfermion sector is modi ed. In this scenario, the sign of wino and gluino mass is opposite. Thus if we regard the deviation between a (ES21) and a (SM) given in Eq. (3) as a signal of new physics, this model conflicts with the recent muon g-2 result and the b! s bound. Thus the gaugino sector should be modi ed. Such additional effects, however, generally induce new CP violating phases in the gaugino masses. The delected AM SB scenario is the only known model in AM SB which provides a natural solution to both of these problems.

The delected AM SB model is safe against CP and avor violations [2] and provides a preferred sign of a SUSY contribution to the muon g-2. However, the Higgs mass and the b ! s branching ratio put severe constraints on the parameter space. In the delected AM SB squarks are generally not so heavy compared to other SUSY breaking scenarios and the Higgs mass bound requires relatively large soft masses. Thus the SUSY contribution to the muon g-2 becomes rather small. As a result, large tan β is required to enhance the muon g-2 and thus the b ! s branching ratio bound becomes dangerous. Hence the detailed analysis is required for the delected AM SB whether this model is phenomenologically viable when the SUSY contribution to the muon g-2 is as large as

*In AM SB, dangerous CP and avor violating parameters are naturally suppressed. The AM SB dominant model may also provide a solution to the gravitino problem and the cosmological dark problem [4].

*We assume that the CP phase from B parameter is also suppressed. A mechanism for the suppression has been proposed in the context of the delected AM SB [2].
An investigation of the muon  \( g-2 \) in the dected AM SB scenario has been performed by Abe et al.\,[20] where hadronic axion model in this framework are studied. However Abe et al made less general analysis. In fact, the parameter space is specified to provide realistic axion decay constant. Moreover the Higgs mass is also calculated by using the effective potential at one loop level. However the higher order corrections become important for the Higgs mass. Hence we reanalyze the dected AM SB model in more general setting.

Let us first review the soft masses and some properties of the dected AM SB model.\,[21,22] The anomaly-medited effects on the soft masses can be given by inserting the compensator field, \( 1 + F \, X^2 \). Here \( F \) is vacuum expectation value (VEV) of the scalar auxiliary field in the gravitational super multiplet and takes a value of order of the gravitino mass. In order to avoid tachyonic slepton and modify gaugino masses, we introduce a singlet field \( X \) whose auxiliary component has non-zero VEV by the following superpotential. We also add \( N_5 \)-pairs of \( \left( Q \, ; L \right) \) and \( \left( Q \, ; L \right) \) of SU(5) to mediate the SUSY breaking from the singlet field \( X \) to M SSM sector. Then the additional terms in the superpotential consist of the following two parts;

\[
W_{X^{55}} = Q \, X \, Q \, Q + L \, L \, L \, L ; \tag{4}
\]

and the non-renormalizable term

\[
W_X = \frac{1}{n^3} X^n ; \tag{5}
\]

where \( n \) is a some mass parameter which is assumed to be of order of the Planck scale, and \( n \) is a positive integer but larger than three. By minimizing the scalar potential of \( X \), the VEVs of the scalar and auxiliary components of \( X \) are determined. In particular, the auxiliary component VEV becomes \( F_X = hX i = F \) (\( n = 3 \)) and obviously we do not introduce new CP violating phase.

Once the scalar component of \( X \) acquires the VEV, \( N_5 \)-pairs of \( \left( Q \, ; L \right) \) and \( \left( Q \, ; L \right) \) have masses \( M_{m_{ess}} = hX \) and play the same role as the messenger fields in GM SB. At the messenger scale \( M_{m_{ess}} \), the chiral super fields \( \left( Q \, ; L \right) \) and \( \left( Q \, ; L \right) \) decouple and the threshold effects induce the additional corrections to the soft parameters. As a result, the soft parameters at the messenger scale are given by

\[
M_{\left( M_{m_{ess}} \right)} = \frac{1}{4} \, \frac{t(t-2)}{b_2(t+2)} \, \frac{2}{n^1} \, \frac{N_5 \, F}{t} ; \tag{6}
\]

\[
m_f^2 \left( M_{m_{ess}} \right) = \frac{1}{(4^2)} \, 2C_i^f \, b_2 \, \frac{4(n-2)}{(n+1)^2} \, N_5 \, 2 \, M_{m_{ess}} \, M_{m_{ess}} \, M_{m_{ess}} \, M_{m_{ess}} \, 13 \, 15 \, M_{m_{ess}} \,
\]

\[
\quad + \frac{16}{3} \, 3 \, M_{m_{ess}} \, 6 \, t \, M_{m_{ess}} \, F \, F \; \tag{7}
\]

\[
A_f \left( M_{m_{ess}} \right) = \frac{1}{4} \, \frac{t(t-2)}{b_2(t+2)} \, \frac{2}{n^1} \, \frac{h}{2} \, C_i^f \, t \, M_{m_{ess}} \, M_{m_{ess}} \, M_{m_{ess}} \, M_{m_{ess}} \, 1 \, M_{m_{ess}} \, F \; \tag{8}
\]
where $t$ is the top-quark Yukawa coupling, $\alpha_s$ are the gauge coupling constants ($i$ is the index of the SM gauge groups), $b$ is the function $b = (\frac{3}{2}; 1; 3)$, and $C^X$ is the second-order Casimir. The parameter $N_u$ takes $N_u = (1; 2; 3)$ for $q^{1/3}$, and $h_u$ and $N_u = 0$ for other particles. Thus the soft SUSY breaking masses are of order $m_{\text{SUSY}} F^{-4}$. Phenomenologically, $F$ and the gravitino mass are required to be of $10^1 - 10^2 \text{ TeV}$.

There is also the case of not including $W_X$ in the superpotential. In this case, the soft masses take the identical values to $n = 3$ in eqs. (3), thus this model is often called the case of $\backslash n = 3$ and in this letter, we refer to this case as $\backslash n = 3$. We note $X$ is a singlet and only lifted by the pure AMSB effect, but the scalar potential of $X$ is not stabilized. There are some approaches to stabilize the potential by introducing a extra UV free gauge symmetry [18] or higher dimensional terms in the Kähler potential [20]. Then the VEV of $X$ can be determined. For the sake of the generality of the model, we regard the VEV of $X$ as a free parameter in the following.

We also note here the issue of the lightest superparticle (LSP). In the case of $n = 3$, the mass of the fermionic part of the singlet field $X^\prime$, is approximately

$$m_{X^\prime} = \frac{N_5}{16} \frac{2}{d_3} g_3^2 \frac{5(N_5 + 2)}{8} F Y;$$

where we assume $q'_{L} < 1$ (1) and neglect $U(1)_Y$ and $SU(2)_L$ gauge couplings. One can see that the mass of $X^\prime$ arises at the two-loop level and is much lighter than any other mass of the superparticle in the MSSM sector. Thus $X^\prime$ becomes the LSP in this case. On the other hand, for $n = 4$, the mass of $X$ is as heavy as $F \sim O(10^1 - 10^2 \text{ TeV})$. In this case, we investigate which particle will be the LSP in the MSSM sector.

We summarize the parameters in the model. There are six parameters:

$$F; M_{\text{mess}}; N_5; n; \tan \gamma; \text{sign}(H):$$

We express these parameters at the messenger scale $M_{\text{mess}}$ and solve one loop renormalization group equation from the messenger scale to the weak scale. Then we determine the magnitude of higgsino mass $h$ and Higgs mass parameters $B$ by electroweak symmetry breaking (EW SB) conditions with the Higgs potential at one loop order.

Now we analyze the muon $g - 2$ in the model. At the weak scale, we calculate the SUSY contribution to the muon $g - 2$. The SUSY contribution consists of chargino--neutralino and neutralino--muon diagram s. With some approximations, the SUSY contribution is expressed as [9]

$$a_{\text{(SUSY)}} = \frac{5}{48} \frac{2}{m_{\text{SUSY}}} \frac{m^2}{m_{\text{SUSY}}} \text{sign}(h) \tan \gamma;$$

where $m$ is the muon mass and $m_{\text{SUSY}}$ is a typical mass of the superparticles in the loop diagram s. From this equation, we find some important features. First, the SUSY contribution to the muon $g - 2$ is enhanced when $\tan \gamma$ is large. Second, $a_{\text{(SUSY)}}$ decreases...
as $m_{\text{SUSY}}$ become heavier. Moreover, the recent E821 result suggests $\text{sign}(M_{2_H})$ to be positive.

Some experiments provide constraints on the model. In particular, the Higgs boson mass bound is severe. Generally, SUSY models predict not so large Higgs mass. Therefore the heavy stops or the large top trilinear coupling $A_t$ are required \cite{24} to satisfy the lower bound from the LEP II experiment \cite{23}

$$m_h = 114.1 \text{ GeV}.$$ \hspace{1cm} (12)

Since in the dected AMSB model, the trilinear coupling is not so large, stops should be heavy. That is, $F$ is required to be large. In particular, the model tends to predict relatively small gluino mass at the messenger scale. Consequently squarks do not receive large renormalization group corrections from gluino. Thus the Higgs mass bound requires the whole superparticles to be relatively heavy and hence the muon $g - 2$ tends to be suppressed. In the numerical analysis, we use the FeynHiggsFast package \cite{25} to compute the lightest Higgs boson mass.

The muon $g - 2$ is enhanced by increasing $\tan\beta$. Then the constraint from the inclusive $b \rightarrow s$ decay becomes important. The experimental measured value of $\text{Br}(b \rightarrow s)$ is consistent with the SM prediction. On the other hand, SUSY contributions may significantly change the SM prediction of $\text{Br}(b \rightarrow s)$. The SUSY contribution to $\text{Br}(b \rightarrow s)$ mainly consists of charged Higgs-top and chargino-stop diagrams and they are enhanced for large $\tan\beta$. Thus when $\tan\beta$ is large, dominant parts of the SUSY contribution have to cancel each other. Such cancellation occurs when $\text{sign}(M_{3_H})$ is positive and this situation is naturally given by the dected AMSB scenario. In this letter, we estimate the SM contribution according to Ref. \cite{24}. As for the charged Higgs contribution, we use the next-to-leading order calculation \cite{27}. The superparticle contributions are mostly computed at one loop order. To evaluate these contributions, we also take into account corrections in powers of $\tan\beta$, which are important for large $\tan\beta$ \cite{8}. The calculated branching ratio should be compared with the recent measurement $\text{Br}(b \rightarrow s) = 3.41 (0.36) \times 10^{-4}$ by Ref. \cite{29}. Here we take a rather conservative range

$$2.0 \times 10^{-4} < \text{Br}(b \rightarrow s) < 4.5 \times 10^{-4}.$$ \hspace{1cm} (13)

Finally, we impose the experimental bounds on the superparticles masses. The models which predict the large SUSY contribution to the muon $g - 2$ may contain some light superparticles. Thus negative searches of superparticle set lower bounds of the masses of superparticles and put constraints on the model. In our analysis we require that all charged superparticles are heavier than 100 GeV.

The results of numerical analysis are shown in Figs. 1-3. These are the case of $n = 3$. Here we determine $F$ such that the Higgs boson mass becomes $m_h = 114.1 \text{ GeV}$ and plot the values of $a$ (SUSY) with several values of $\tan\beta$. We consider $\tan\beta$ in the range $5 < \tan\beta < 50$. We also change $N_5$ and $M_{\text{mess}}$. At first, we demand that the SUSY

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# Larger $\tan\beta$ actually makes the muon $g - 2$ larger, but too large $\tan\beta$ (e.g., $> 50$) makes the bottom Yukawa coupling blow up below the GUT scale.
contribution to the muon $g-2$ becomes larger as the number of the messengers increases. This is because, for larger $N_5$, gaugino masses become larger, that is, $F$ becomes smaller with the fixed value of Higgs mass. Thus the SUSY contribution to the muon $g-2$ is enhanced when $N_5$ increases. Secondly, larger messenger scale $M_{mess}$ makes the muon $g-2$ larger with $N_5$ fixed. This behavior is caused by the renormalization group effects, that is, if the messenger scale increases, the renormalization group effects make colored superparticles heavier compared to the uncolored ones. Thus, the muon $g-2$ is enhanced as the messenger scale larger with the Higgs boson mass fixed. Finally, we can see that the deviation of the muon $g-2$ favors large $tan \beta$. This is because of the Higgs mass bound. From the results of the case of $n=3$, the muon $g-2$ reaches 1 region of the deviation with $tan \beta > 20$.

The contours of constant $tan \beta$ terminate at the dotted lines which show the bounds from the experimental constraints and the absence of the electroweak symmetry breaking. First, the negative signs of the right-handed stau excludes the region of large $N_5$ and $tan \beta$. This is because when $N_5$ becomes large, the squarks become lighter (See Eq. (4)) and larger $tan \beta$ drive the squark masses smaller by the renormalization group effects. Secondly, we notice that the region of small $N_5$ is excluded. In this region with small $tan \beta$, the electroweak symmetry breaking does not occur. On the other hand, for large $tan \beta$ the SUSY contribution to $b\rightarrow s\gamma$ becomes too large.

In Figs. 4-6, we consider the case of $n=4$. Here the parameters except for $n$ are the same as Figs. 3-4, respectively. We can understand these results by noting that $n$ appears as the combination $N_5=(n-1)$ in the gaugino masses. That is, the results of $n=4$ largely resemble the results with smaller $N_5$ in the case of $n=3$. On the other hand, the squark masses depend on $n$ and $N_5$ in the different way and they become smaller as $n$ increases with gaugino masses fixed. This effect cannot be neglected for the uncolored superparticles. Thus, the muon $g-2$ becomes larger with the Higgs boson mass almost fixed. As for $Br(b\rightarrow s\gamma)$, the constraint becomes severer because the mass hierarchy between colored and uncolored superparticles becomes larger. The large $F$ regions also become to be excluded by the absence of the electroweak symmetry breaking.

The phenomenology of the dected AM SB model depends sensitively on a choice of $(N_5; n)$. We can see that less messengers make almost all region be excluded by the tachyonic sleptons for fixed $n$. In fact for $n=3$, more than 4 pairs of messengers are required. On the other hand, when $n$ is increased with $N_5$ fixed, gauginos become lighter and sleptons tend to be tachyonic. Thus larger $n$ requires larger number of messengers. However too many messengers make the gauge couplings blow up below the GUT scale. Thus, the cases of $n \geq 5$ are not attractive.

Here we comment on the LSP. If we take $n=4$, the stauonic part of the singlet $X$ is no longer the LSP. In fact, the mass of $X$ is of order of gravitino and is much heavier than the MSSM particles. Thus we investigate the LSP in the MSSM sector. In the dected AM SB model, uncolored superparticles tend to be lighter than colored ones. We can see

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#5 Since the number of messengers is integer, the bounds become saw-like. But we draw the constant $tan \beta$ lines for convenience.
that the right-handed stau or one of the higgsino-like neutralinos becomes the lightest. In the almost all region of Figs. 4,5, we found that the LSP is the stau and thus this region is cosmologically not favored if the stau is stable [30]. However, we do not take this result seriously because there is a possibility that some light particle, say the fermionic partner of the axion, exists. If we require the neutralino to be the LSP, very small parameter regions are allowed only when \( N_5 = 9 \) (in Figs. 5 and 6) or \( N_5 = 10 \) (in Fig. 5).

We should note here that our results depend on top quark mass \( m_t \). The radiative correction to the lightest Higgs boson m mass is sensitively enhanced for larger value of \( m_t \). Therefore, the constraint from the Higgs mass becomes looser when \( m_t \) is larger. In the above analysis, we use \( m_t = 174.3 \) GeV. On the other hand, the study in the case \( m_t = 179.4 \) GeV gives the heavier Higgs mass about 2-3 GeV compared to the previous case of \( m_t = 174.3 \) GeV at the same values of \( m_{\text{mess}} \) and \( F \). Thus the model is viable on the wider region with the SUSY contribution to the muon \( g-2 \) large enough.

As a discussion, we touch on the case of negative \( n \). In this case, the sign of the wino mass is the same as that of the gluino mass as the case of positive \( n \). Furthermore, the slepton mass squareds become positive with less messengers. The strongly interacting SU (\( N_c \)) gauge sector makes \( n \) negative [31], where \( n \) is given by \( n = 2 - (N_c - 1) \). As a distinctive feature, the bino and the wino are much lighter than the gluino as opposed to the positive \( n \) case. Thus the mass hierarchy between colored and uncolored superparticles becomes large. Hence smaller \( \tan \beta \) is required to enhance the muon \( g-2 \) with the Higgs mass bound satisfied. Then the LSP almost becomes the bino-like neutralino.

In this letter, we studied the deected AM SB scenario in the light of the recent result of the muon \( g-2 \) from the Brookhaven E821 experiment. The recent result of the muon \( g-2 \) suggests the deviation from the SM prediction, though the uncertainties of the SM prediction, especially from the leading hadronic contribution, have not been settled. The results of the muon \( g-2 \) and \( \beta \)'s require sign (\( M_{2,1} \)) and sign (\( M_{2,3} \)) to be positive simultaneously. The deected AM SB is the only known model in AM SB which provides this feature with avoiding additional CP violating phase naturally. By the detailed analysis, we found that in the deected AM SB model, the SUSY contribution to the muon \( g-2 \) becomes as large as \( 0 (10^{-9}) \), which is sufficient for the 3
deviation of the E821 result, with other experimental constraints satisfied. In particular, the Higgs mass puts a severe constraint on the model and large \( \tan \beta \) is favored to enhance the muon \( g-2 \).

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Figure 1: The SUSY contribution to the muon $g - 2$ (a (SUSY)) at the Higgs boson mass $m_h = 114.1$ GeV against the number of the pairs of messengers in the delected AM SB model. We take $n = 3$ and $M_{mess} = 10^{12}$ GeV. The lines terminate by the negative search of the stau for the large number of the messengers.

Figure 2: Same as Fig. 1 but the messenger scale $M_{mess} = 10^{14}$ GeV. The experimental bound from $b \to s \gamma$ excludes the small number of the messengers for large $\tan \beta$, and the lines terminate by the negative search of the stau at the large number of the messengers.
Figure 3: Same as Fig. 1 but the messenger scale $M_{\text{mess}} = 10^{16}$ GeV. The electroweak symmetry breaking does not occur for the small number of the messengers and especially for large $\tan\beta$ the experimental bound from $b \rightarrow s\tau\nu$ excludes the small number of the messengers.

Figure 4: The SUSY contribution to the muon $g - 2$ ($a_{\mu}$ (SUSY)) at the Higgs boson mass $m_h = 114.4$ GeV against the number of the pairs of messengers in the dected AM SB model. We take $n = 4$ and $M_{\text{mess}} = 10^{12}$ GeV. The electroweak symmetry breaking does not occur for the small number of the messengers and especially for large $\tan\beta$ the experimental bound from $b \rightarrow s\tau\nu$ excludes the small number of the messengers. The negative search of the stau also excludes the region of the large number of the messengers.
Figure 5: Same as Fig. 4 but the messenger scale $M_{\text{mess}} = 10^{14}$ GeV.

Figure 6: Same as Fig. 4 but the messenger scale $M_{\text{mess}} = 10^{16}$ GeV.