Shifted focus point of the Higgs mass parameter
from the minimal mixed mediation of SUSY breaking

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We employ both the minimal gravity- and the minimal gauge mediations of supersymmetry breaking at the grand unified theory (GUT) scale in a single supergravity framework. In such a “minimal mixed mediation model,” a “focus point” of the soft Higgs mass parameter, \( m_{h_u}^2 \), emerges at 3-4 TeV energy scale, which is exactly the stop mass scale needed for explaining the 126 GeV Higgs boson mass without the “A-term” at the three loop level. As a result, \( m_{h_u}^2 \) can be quite insensitive to various trial stop masses at low energy, reducing the fine-tuning measures to be much smaller than 100 even for a 3-4 TeV low energy stop mass and \(-0.5 \lesssim A_t / m_0 \lesssim 0 \) at the GUT scale. The gluino mass is predicted to be about 2.3 TeV, which could readily be tested at LHC run2.

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Although the standard model (SM) has been extremely successful in the experimental side, it doesn’t provide reasonable answers to some theoretical problems such as the naturalness of the electroweak (EW) scale and the Higgs boson mass. The main motivation of the low energy supersymmetry (SUSY) was to resolve the naturalness problem associated with the EW phase transition raised in the SM \[1,2\]. Because of this reason, the minimal supersymmetric standard model (MSSM) has been believed to simultaneously solve the “little hierarchy problem”, how-

\[
\Delta m_{h_u}^2 \approx \frac{3y_t^2}{8\pi^2} \bar{m}_t^2 \log \left( \frac{\bar{m}_t^2}{\Lambda^2} \right) + \cdots ,
\]

(1)

while it depends just logarithmically on a ultraviolet (UV) cutoff \( \Lambda \). Since the Higgs mass parameters, \( m_{h_u}^2 \) and \( m_{h_d}^2 \), are related to the 3 boson mass \( m_3 \) together with the “\( \mu \)-term” (\( \mu \)) in the MSSM,

\[
\frac{1}{2} m_Z^2 = m_{h_{u,d}}^2 - \frac{m_{h_{u,d}}^2 \tan^2 \beta}{\tan^2 \beta - 1} - |\mu|^2 ,
\]

(2)

\( \{ m_{h_{u,d}}^2, |\mu|^2 \} \) should be finely tuned to yield the \( m_Z^2 = (91 \text{ GeV})^2 \) for a given tan \( \beta \left( \equiv (h_u)/(h_d) \right) \), if they are excessively large. According to the recent analysis based on the three-loop calculations, the stop mass required for explaining the 126 GeV Higgs boson mass \[3\] without any other helps is about 3-4 TeV \[4\]. Thus, a fine-tuning of order \( 10^{-3} \) or smaller looks unavoidable in the MSSM for \( \Lambda \approx 10^{16} \text{ GeV} \).

In order to more clearly see the UV dependence of \( m_{h_u}^2 \) and properly discuss this “little hierarchy problem”, however, one should suppose a specific UV model and analyze its resulting full renormalization group (RG) equations. If the UV model is simple enough, addressing this problem successfully with SUSY, the low energy SUSY could still be regarded as an attractive solution to the naturalness problem.

One nice idea is the “focus point (FP) scenario” \[5\]. This scenario is based on the minimal gravity mediation (mGrM), and so the soft mass parameters including \( m_{h_{u,d}}^2 \) and those of the left handed (LH) and right handed (RH) stops, \( (m_{h_{u,d}}^2, m_{\tilde{u}_R}^2) \) are universal at the GUT scale, \( m_{h_u}^2 = m_{h_d}^2 = m_{\tilde{u}_R}^2 = m_{h_u'}^2 = \cdots = m_{\tilde{u}_L}^2 \). If “A-terms” are zero at the GUT scale and the unified gaugino mass is just a few hundred GeV, \( m_{\tilde{g}}^2 \) converges to a small negative value \( \{m_{h_u}^2 \ll (1 \text{ TeV})^2\} \) around \( Z \) boson mass scale, regardless of the initial values given by \( m_{\tilde{g}}^2 \) at the GUT scale. On the other hand, stop masses are quite sensitive to \( m_{\tilde{g}}^2 \). It implies that \( m_{\tilde{u}}^2 \) can remain small enough even with a quite heavy stop mass in contrast to the naive expectation from Eq. \( \text{(1)} \).

However, the experimental bound on the gluino mass \( M_3 \) has already exceeded 1.3 TeV \[6\]. The unified gaugino mass yielding \( M_3 > 1.3 \text{ TeV} \) at low energy gives a too large negative \( m_{h_u}^2 \) at the EW scale \[7\]. Below 3-4 TeV, moreover, the stop should decouple from the RG equations. Since the RG running interval between 3-4 TeV and \( m_Z \) scale, to which modified RG equations should be applied, is too large, the FP behavior is seriously spoiled with such heavy SUSY particles.

The best way to rescue the FP idea is somehow shift the FP up to the stop decoupling scale \[7\]. Then \( m_{h_u}^2 \) at the \( m_Z \) scale can roughly be estimated using the
where the cutoff $\Lambda_{T}$ is set to the stop decoupling scale ($\approx \sqrt{m_{t}^{2}}$). Here we take $m_{h_{u}}^{2} \approx m_{h_{d}}^{2} \equiv m_{t}^{2}$ for a simple estimation. Due to the additional negative contribution to $m_{h_{u}}^{2}(m_{Z})$ below $\Lambda_{T}$, a small positive $m_{h_{u}}^{2}(\Lambda_{T})$ would be more desirable.

In order to push up the FP to the desired stop mass scale 3-4 TeV, in this letter we suggest to combine the two representative SUSY breaking mediation scenarios, the mGrM and the minimal gauge mediation (mGGM) in a single supergravity (SUGRA) framework with a common SUSY breaking source. We will call it “minimal mixed mediation.”

First, let us consider the minimal Kähler potential, and a superpotential where the observable and hidden sectors are separated:

$$K = \sum_{i,a} |z_{i}|^{2} + |\phi_{a}|^{2}, \quad W = W_{H}(z_{i}) + W_{D}(\phi_{a})$$

where $z_{i}$ ($\phi_{a}$) denotes fields in the hidden (observable) sector. The kinetic terms of $z_{i}$ and $\phi_{a}$, thus, have the canonical form. We assume non-zero VEVs for $z_{i,s}$ [2]:

$$\langle z_{i} \rangle = b_{i}M_{P}, \langle \partial_{i}W_{H} \rangle = a_{i}^{*}mM_{P}, \langle W_{H} \rangle = mm_{M_{P}}^{2},$$

where $a_{i}$ and $b_{i}$ are dimensionless number, while $M_{P} \approx 2.4 \times 10^{18}$ GeV denotes the Planck mass. Then, $\langle W_{H} \rangle$ or $m$ gives the gravitino mass, $m_{3/2} = e^{K/2M_{P}}(W)/M_{P}^{2} = e^{b_{i}/2a_{i}}m$. The soft terms can read from the scalar potential of SUGRA:

$$V_{F} = e^{K/2} \left[ |F_{z_{i}}|^{2} + |F_{\phi_{a}}|^{2} - \frac{3}{M_{P}^{2}}|W|^{2} \right]$$

where the “$F$-terms,” $F_{i} (= D_{i}W = \partial_{i}W + \partial_{i}K W/M_{P}^{2})$ are given by

$$F_{z_{i}} = \partial_{i}W_{H} / \partial z_{i} + z_{i}^{*} W / M_{P}^{2} \left( a_{i}^{*} + b_{i}^{*} \right) M_{P} \left( a_{i}^{*} + b_{i}^{*} \right) W / M_{P}^{2}$$

$$F_{\phi_{a}} = \partial_{i}W_{D} / \partial \phi_{a} + \phi_{a}^{*} W / M_{P}^{2} \left( a_{i}^{*} + b_{i}^{*} \right) M_{P} \left( a_{i}^{*} + b_{i}^{*} \right) W / M_{P}^{2}.$$ (7)

The vanishing cosmological constant condition (C.C.) requires a fine-tuning between $\langle F_{z_{i}} \rangle$ and $\langle W_{H} \rangle$, i.e. from Eq. (8) $\sum_{i}(|F_{z_{i}}|^{2}) = 3\langle W_{H} \rangle^{2}/M_{P}^{2}$, or $\sum_{i}a_{i} + b_{i} = 3$. Neglecting the non-renormalizable terms suppressed with $1/M_{P}^{4}$, Eq. (6) is rewritten as [2]

$$V_{F} \approx \left[ \partial_{\phi_{a}}W_{D}, M_{P}^{2} \right]^{2} + m_{0}^{2}|\phi_{a}|^{2} + m_{0} \left[ \phi_{a}\partial_{\phi_{a}}W_{D} + (A_{\Sigma} - 3)W_{D} + \text{h.c.} \right].$$ (8)

where $A_{\Sigma}$ is defined as $A_{\Sigma} \equiv \sum_{i}b_{i}^{*}(a_{i} + b_{i})$, $m_{0}$ is identified with the gravitino mass $m_{3/2} = e^{b_{i}/2a_{i}}m$ and $\tilde{W}_{D} \equiv e^{b_{i}/2a_{i}}W_{D}$ denotes the rescaled $W_{D}$. From now on, we will drop out the “tilde” for a simple notation. The first term of Eq. (8) corresponds to the $F$-term potential in global SUSY, the second term is the universal soft mass term, and the remaining terms are soft SUSY breaking “$A$-terms.” The universal $A$-parameter here $(A_{0} = A_{i})$ does not include Yukawa coupling constants, but it is proportional to $m_{0}$. If there is no quadratic term or higher powers of $\phi_{a}$ in $W_{D}$, one can get negative (positive) $A$-terms with $A_{\Sigma} < 2$ ($A_{\Sigma} > 2$). With the vanishing C.C. condition, the universal soft mass parameter, $m_{0} = e^{K/(2M_{P}^{2})}(W_{H}/M_{P}^{2})$ can be recast to $e^{K/(2M_{P}^{2})} \left( \sum_{i}(|F_{z_{i}}|^{2})^{1/2} / \sqrt{3M_{P}} \right)$, which is the conventional form in the mGrM scenario.

Next, let us introduce one pair of messenger fields $(\tilde{5}, \tilde{5})$, which are the SU(5) fundamental representations, protecting the gauge coupling unification. Through their coupling with a SUSY breaking source $S$, which is an MSSM singlet,

$$W_{m} = y_{S}S\tilde{5}\tilde{5},$$

the soft masses of the MSSM gauginos and scalar superpartners are generated at one- and two-loop levels, respectively [1]:

$$M_{a} = \frac{g_{a}^{2} \langle F_{S} \rangle}{16\pi^{2} \langle S \rangle}, \quad m^{2}_{a} = 2 \sum_{a=1}^{3} \left[ \frac{g_{a}^{2} \langle F_{S} \rangle}{16\pi^{2} \langle S \rangle} \right]^{2} C_{a}(i)$$

where $C_{a}(i)$ is the quadratic Casimir invariant for a superfield $i$, $(T^{a}T^{a})_{i} = C_{a}(i)\delta_{ii}$, and $g_{a}$ ($a = 1, 2, 3$) denotes the MSSM gauge couplings. $\langle S \rangle$ and $\langle F_{S} \rangle$ are VEVs of the scalar and $F$-terms components of the superfield $S$. Note that $M_{a}$ and $m^{2}_{a}$ are almost independent of $y_{S}$ only if $\langle F_{S} \rangle \lesssim y_{S} \langle S \rangle$. However, such mGGM effects would appear below the messenger scale, $y_{S} \langle S \rangle$. Here we assume that $\langle S \rangle$ has the same magnitude as the VEV of the SU(5) breaking Higgs $v_{G}$: $\langle 24_{H} \rangle = v_{G} \times \text{diag}(2, 2, 2; -3, -3, -3) / \sqrt{6}$. It is possible if a GUT breaking mechanism causes $\langle S \rangle$ [3]. Actually, the masses of “$X$” and “$Y$” gauge bosons induced by $\langle 24_{H} \rangle$, $M_{X}^{2} = M_{Y}^{2} = \frac{3}{2} y_{S}^{2} v_{G}^{2}$ [10], can be identified with the MSSM gauge coupling unification scale, because the unified gauge interactions would become active above the $M_{X,Y}$ scale.

We set $\langle F_{S} \rangle = m_{0}M_{P}$ as in the mGrM. It is possible to hold $\langle F_{S} \rangle \sim m_{0}M_{P}$ (rather than $m_{0}v_{G}$) under a mechanism to yield $\langle S \rangle = v_{G}$: in addition to Eq. (9), the Kähler potential (and hidden local symmetries we don’t specify here) can permit

$$K \supset f(z)S + \text{h.c.},$$

where $f(z)$ denotes a holomorphic monomial of hidden sector fields $z_{i,s}$ with VEVs of order $M_{P}$ in Eq. (10), and
so it is of order $\mathcal{O}(M_P)$. Their kinetic terms still remain canonical. The $U(1)_R$ symmetry forbids $M_P f(z) S$ in the superpotential. Then, the resulting $\langle F_S \rangle$ can be approximated as

$$\langle F_S \rangle \approx m \langle |f(z)| + |S^*| \rangle \quad (12)$$

by including the SUGRA corrections with $\langle W_R \rangle = m M^2_f$. Thus, the VEV of $F_S$ is of order $\mathcal{O}(m M_P)$ like $F_3$ in Eq. (7). They should be fine-tuned for the vanishing C.C.: a precise determination of $\langle F_S \rangle$ is indeed associated with the C.C. problem. $F_{\phi_e}$ is still given by Eq. (7), which induces the universal soft mass terms at tree level.

Thus, the typical size of mGgM effects is estimated as

$$\langle F_S \rangle \approx \frac{m_0 M_P}{16\pi^2(S)} \sqrt{\frac{5}{24}} g_G \approx 0.57 m_0. \quad (13)$$

Here we set the unified gauge coupling at the GUT scale ($\approx 1.0 \times 10^{16}$ GeV) to $g^2/4\pi \approx 1/26$ due to relatively heavy colored superpartners ($ \gtrsim 3$ TeV). It means $(S) = v_G \approx 3 \times 10^{16}$ GeV. Even for $|y_S| \ll 1$, we will keep this value for $(S)$.

The fact that the mGgM effects by Eq. (11) are proportional to $m_0$ or $m_0^2$ are important. Moreover, $A$-terms from Eq. (5) are also proportional to $m_0$. As seen in the semi-analytic solutions of Ref. [7], in this setup a FP of $m_{\tilde{h}_u}^2$ must still exist at a higher energy scale, i.e. $m_{\tilde{h}_u}^2(Q_T)/m_{\tilde{h}_u}^2 \approx 0.3$.

For $|y_S| \lesssim 1$ in Eq. (11), the messenger scale $Q_M$ drops down below $M_{X,Y}$. Since $X$ and $Y$ gauge sectors have already been decoupled below the messenger scale, the soft masses generated by the mGgM in Eq. (10) become non-universal for $Q_M < M_{X,Y}$. Of course, the beta function coefficients of the MSSM fields should be modified above the scale of $y_S(S)$ by the messenger fields $\{5,5\}$. Thus, the RG equations of the MSSM gauge couplings and gaugino masses are

$$8\pi^2 \frac{dg^a}{dt} = b_a g_a^4, \quad 8\pi^2 \frac{dM_a}{dt} = b_a g_a^2 M_a, \quad (14)$$

where $t \equiv \log(Q/\text{GeV})$, and $b_a = (-2, 2, \frac{3}{2})$ for $Q > Q_M$ while $b_a = (-3, 1, \frac{3}{2})$ for $Q < Q_M$. For the RG equations of the Yukawa couplings of the third generation of quarks and leptons ($y_u, y_d, y_e$) and other soft parameters, refer to Appendix of Ref. [7].

The boundary conditions at the GUT scale are given by the universal form as seen in Eq. (5). Unlike the case of the mGrM, we have additional non-universal boundary conditions by Eq. (10). They should be imposed at a given messenger scale, and so affect the RG evolutions of MSSM parameters for $Q \leq Q_M$. To see clearly how the original FP scenario is modified by the additional mGgM effects, in this letter we don’t consider the RH neutrinos in the RG analysis as in [3], assuming their couplings are small enough. We also suppose that the gaugino masses from the mGrM are relatively suppressed. In fact the gaugino mass term in SUGRA is associated with the first derivative of the gauge kinetic function [2], and so (almost) constant gauge kinetic functions at tree level can realize it. As a result, the gaugino masses by Eq. (10) dominates over them in this case. Then Eqs. (10), (13), and (14) admit a simple analytic expression for the gaugino masses at the stop mass scale:

$$M_a(t_T) \approx 0.57 \times m_0 \times g_0^2(t_T), \quad (15)$$

It does not depend on messenger scales.

Fig. 1 displays RG evolutions of $m_{\tilde{h}_u}^2$ for various trial $m_0^2$. The straight [dotted] lines correspond to the case of $t_M \approx 36.7$ (or $Q_M = 9 \times 10^{13}$ GeV, “Case A”) [i.e. $[t_M \approx 36.7$ (or $Q_M = 1 \times 10^{15}$ GeV, “Case B”)]. The vertical dotted line at $t = 2.85 \approx 8.2$ ($Q_T = 3.5$ TeV) indicates the desired stop decoupling scale. The discontinuities of $m_{\tilde{h}_u}^2(t)$ should appear at the messenger scales.

![FIG. 1. RG evolutions of $m_{\tilde{h}_u}^2$ with $t \equiv \log(Q/\text{GeV})$ for $m_0^2 = (6 \text{ TeV})^2$ [Red], (4 TeV)$^2$ [Green], and (2 TeV)$^2$ [Blue] when $A_t = -0.5 \ m_0$ and $\tan \beta = 50$. The tilted straight [dotted] lines correspond to the case of $t_M \approx 36.7$ (or $Q_M = 9 \times 10^{13}$ GeV, “Case A”) [i.e. $t_M \approx 36.7$ (or $Q_M = 1 \times 10^{15}$ GeV, “Case B”)]. The vertical dotted line at $t = 2.85 \approx 8.2$ ($Q_T = 3.5$ TeV) indicates the desired stop decoupling scale. The discontinuities of $m_{\tilde{h}_u}^2(t)$ should appear at the messenger scales.](image-url)
In both cases of Fig. 1 the gluino, wino, and bino masses at low energy are

\[ M_{3,2,1} \approx \{2.3 \text{ TeV}, 912 \text{ GeV}, 504 \text{ GeV}\} \tag{16} \]

for \( m_0^2 = (4 \text{ TeV})^2 \). They are the prediction of this model. They would be testable at LHC run2. \( A_t \) at low energy is about \( \{1.0 \text{ TeV}, 0.5 \text{ TeV}\} \) for Case A and B, respectively. Accordingly, the contributions of \( A_t^2/m_0^2 \) to the radiative Higgs mass are smaller than 2.3 \% of those from the stops.

Table II lists the soft squared masses at \( t = t_F \) for the LH and RH stops, and the two MSSM Higgs bosons under the various \( m_0^2 \)'s, when the messenger scale is \( Q_M = 5 \times 10^{15} \text{ GeV} \). We can see the changes of \( m_{h_2}^2 \) are quite small \( \ll (500 \text{ GeV})^2 \) under the changes of \( m_0^2 \) \( [(5 \text{ TeV)}-(3 \text{ TeV})]^2 \) unlike the other soft squared masses, because \( m_{h_2}^2 \) is well-focused at \( t = t_F \). From Table II we can read the \( A_t \) dependence of the fine-tuning measure \( \Delta m_2^2 \) (≡ \( \left| \frac{\partial \log m_2^2}{\partial \log m_0^2} \right| \)) around \( m_0^2 = (4 \text{ TeV})^2 \). Case II gives almost the minimum of \( \Delta m_2^2 = (27) \) when \( \tan \beta = 27 \). However, Case I and III correspond to the boundaries of \( \Delta m_2^2 \ll 100 \) with the same \( \tan \beta \). When \( A_t/m_0 = -0.1 \) (\(-0.8 \)), \( \Delta A_t \) turns out to be 121 (107). On the other hand, \( \Delta A_t \) (≡ \( \left| \frac{\partial m_2^2}{\partial \log m_0^2} \right| \)) are \{0, 11, 197 \} for Case I, II, and III. When \( A_t/m_0 = -0.1 \), \( \Delta A_t \) turns out to be about 40. \( \Delta A_t \) drastically increases below \( A_t/m_0 = -0.5 \): \( \Delta A_t \) is 119 for \( A_t/m_0 = -0.6 \), while it is 57 for \( A_t/m_0 = -0.5 \). Therefore, we can conclude the parameter range

\[-0.5 \lesssim A_t/m_0 \lesssim 0 \tag{17}\]

allows both \( \Delta m_2^2 \) and \( \Delta A_t \) to be smaller than 100. Case IV is the case of \( \tan \beta = 15 \) when \( A_t/m_0 = -0.4 \). We see that a larger \( \tan \beta \) would be preferred for a smaller \( \Delta m_2^2 \). It is basically because \( m_{h_2}^2 \) is not focused unlike \( m_{h_1}^2 \), even though it also contributes to \( m_2^2 \) as seen in Eq. 2. Actually \( \tan \beta = 50 \) is easily obtained e.g. from the minimal SO(10) GUT 10.

Case I-IV yield again the same low energy gaugino masses as Eq. 10, because Eq. 15 is valid at low energy regardless of messenger scales. \( A_t \) at low energy turns out to be around 1 TeV or smaller for \( m_0^2 = (4 \text{ TeV})^2 \), and so its contribution to the Higgs boson mass is still suppressed. Using Eq. 3, the low energy values of \( m_{h_1}^2 \) are estimated as \( (-592 \text{ GeV})^2, -(331 \text{ GeV})^2, -(550 \text{ GeV})^2, -(458 \text{ GeV})^2 \) for Case I, II, III, and IV, respectively. With Eq. 2, then, the Higgsino mass \( |\mu| \) are determined as \{591 GeV, 330 GeV, 549 GeV, 461 GeV\} for the cases. Actually the RG running of \( \mu \) is completely separated from other soft parameters. Moreover, the generation scale of \( \mu \) is quite model-dependent. So we don’t discuss them here.

In the above cases, the sleptons and sbottom turn out to be quite heavier than 3 TeV. The first two generations of SUSY particles would be much heavier than them. For \( M_1 < |\mu| \) (\( M_1 > |\mu| \)), hence, the bino (Higgsino) is the lightest superparticle (LSP). For \( M_1 < |\mu| \), some entropy production is needed to avoid close of the bino dark matter in the Universe 12. On the other hand, for \( M_1 > |\mu| \), the Higgsino dark matter needs to be supplemented with other components such as the axion 13.

In conclusion, we have noticed that a FP of \( m_0^2 \) appears at 3-4 TeV, when the mGrM and mGgM effects are combined at the GUT scale for a common SUSY breaking source parametrized with \( m_0 \). Even for a 3-4 TeV stop mass explaining the 126 GeV Higgs mass, thus, the fine-tuning measures significantly decrease well below 100 for \(-0.5 \lesssim A_t/m_0 \lesssim 0 \) in the minimal mixed mediation. The predicted gluino mass is about 2.3 TeV, which could readily be tested at LHC run2.

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