The Minimal Realization of EWSB in Gauge Mediation

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Outline

Global SUSY and Gauge mediation

People like SUSY

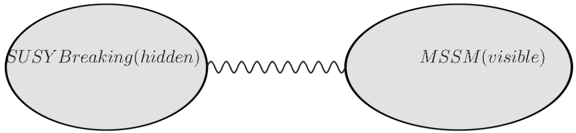
- Unification of three gauge coupling constants
- hierarchy problem
- a natural dark matter candidate
- baryogenesis

while no superpartner was seen, so it must be broken "softly", without the reintroduction of quadratic divergence.

SUSY breaking cannot happens in the visible sector due to the tree level mass relationship

$$STr(m^2) = Tr(m_s^2) - 2Tr(m_F^{\dagger} m_F) + 3Tr(m_V^2) = 2g_a^2 Tr(T_a) D^a = 0 \quad (1)$$

So we expect that soft terms arise indiectly or radiatively, like



In GM, the interaction mediate the two parts is the ordinary $SU(3) \times SU(2) \times U(1)$ and it provide a natural solution to the flavor problem. Using naive dimensional analysis:

$$m_{soft} \sim \frac{\alpha_a}{4\pi}\frac{F}{M} \tag{2}$$

UV realization is difficut, sometimes this simple scheme do not work. .eg. Semi-direct Gauge-Yukawa mediation JHEP 1103:078,2011

μ/B_μ problem in GM

$$W = \mu H_u H_d \tag{3}$$

In constrast to gravity mediation where μ/B_μ come from

$$K = H_u H_d(\frac{X^+}{M_P} + \frac{XX^+}{M_P^2} + ...) \tag{4}$$

generic GMSB predict

$$\mu \sim \frac{1}{16\pi^2}\frac{F}{M} \quad B_\mu \sim \frac{1}{16\pi^2}\frac{F^2}{M^2} \tag{5}$$

Usually B_μ is too large to successful EWSB.

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Solution in the past

- ways of generating μ at one loop, and B_μ two loop
- NMSSM
- strong hidden dynamics
- a large $m^2_{H_d}$ come with a large B_μ

Insipired by the framework of direct gaugino mediation, we think that maybe we can generate tree level and loop μ/B_μ from different source and then make them cancel to get a proper B_μ in the end.

Higgs-Messenger Mixings and Tree-Level μ/B_μ terms

$$W_{HV} = X\phi\bar{\phi} + \left(v_1 H_u \phi_L + v_2 H_d \bar{\phi}_L\right), \tag{6}$$

the $SU(2)_L$ doublet components of the messengers are denoted as $(\phi_L, \bar{\phi}_L)$, and v_1 and v_2 are the introduced new scales. Integrating out the messengers $(\phi_L, \bar{\phi}_L)$ at tree level,

$$\mu = -\frac{v_1 v_2}{M},$$
$$B_\mu = -\frac{v_1 v_2}{M^2} \times F = \mu\Lambda, \tag{7}$$

Here as long as $v_1, v_2 \ll M$, the mixing is very small and it will not be harmful.

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Dynamical Mechanism and One-Loop Contributions to μ/B_μ:

$$W = \lambda_u S H_u \phi_L + \lambda_d S H_d \bar{\phi}_L + \lambda X \phi \bar{\phi} + f(S). \quad (8)$$

$f(S)$ denotes the complete dynamics of S which generates a VEV for S.

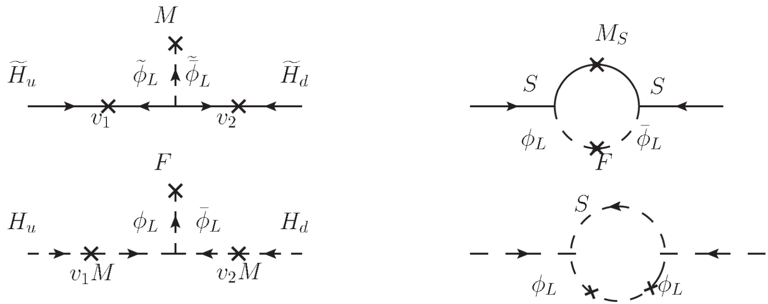

Figure: The generation of μ/B_μ at tree and loop level.

The key dynamical information of S can be parameterized as

$$W \supset \lambda_u \mathcal{S} H_u \phi_L + \lambda_d \mathcal{S} H_d \bar{\phi}_L + \lambda X \phi \bar{\phi} + M_S \mathcal{S}^2 + \lambda_S \mathcal{S}^3, \tag{9}$$

here we have made the shift $S \to v + \mathcal{S}$. Now the one loop contribution are $(x \equiv M_S/M)$,:

$$\Delta\mu = -\frac{\lambda_u \lambda_d}{16\pi^2} f_1(x)\Lambda, \tag{10}$$

$$\Delta B_\mu = -\frac{\lambda_u \lambda_d}{16\pi^2} f_2(x)\Lambda^2, \tag{11}$$

$$f_1(x) = \frac{x}{(x^2-1)^2}(x^2 \log x^2 - x^2 + 1),$$

$$f_2(x) = \frac{x}{(x^2-1)^3}(-2x^2 \log x^2 + x^4 - 1). \tag{12}$$

Now the total values($f_v = 16\pi^2 v^2/F$.)

$$\mu = -\lambda_u\lambda_d\left[f_v + f_1(x)\right]\frac{\Lambda}{16\pi^2}, \tag{13}$$

$$B_\mu = \mu\frac{f_v + f_2(x)}{f_v + f_1(x)}\Lambda, \tag{14}$$

Through the Yukawa interactions the soft masses of H_u and H_d can also get the one-loop (with $\mathcal{S}$ running in the loops) non-holomorphic contributions, given at the leading order by

$$\Delta m^2_{H_u} = \frac{\lambda_u^2}{16\pi^2}\Lambda^2 g(x), \quad \Delta m^2_{H_d} = \frac{\lambda_d^2}{16\pi^2}\Lambda^2 g(x), \tag{15}$$

$g(x)$ is defined as

$$g(x) = \frac{x^2}{(x^2-1)^3}\left[(1+x^2)\ln x^2 + 2(1-x^2)\right]. \tag{16}$$

In addition, the trilinear soft terms are also generated

$$A_{u,d} = \frac{\lambda_{u,d}^2}{16\pi^2} h(x)\Lambda, \tag{17}$$

$$h(x) = \frac{1}{(x^2-1)^2}\left[(x^2-1)^2 - x^2 \log x^2\right]. \tag{18}$$

As shown later, these trilinear soft terms do not play a significant role in our discussions.

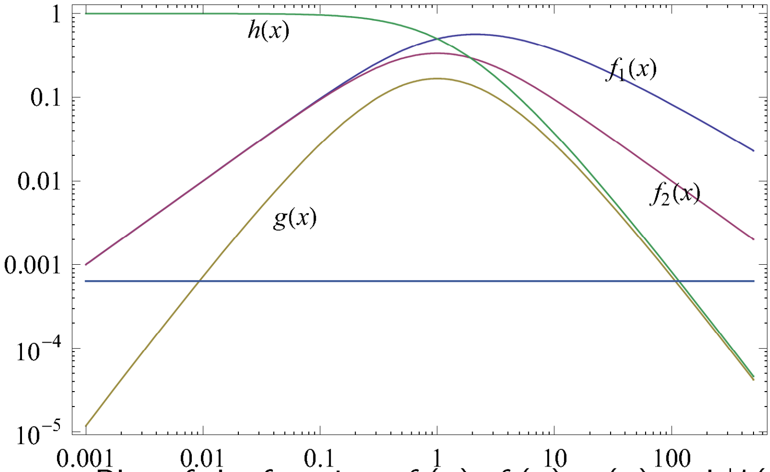

Figure: Plot of the functions $f_1(x)$, $f_2(x)$, $g(x)$ and $|h(x)|$.

Note that there is a relation

$$g(x) = \frac{f_1(x) - f_2(x)}{x} \tag{19}$$

In the higgs sector, for convience we define

$$f_v + f_2(x) \equiv a_B g(x), \tag{20}$$

$$r \equiv \lambda_d / \lambda_u \tag{21}$$

then

$$\mu = -g(x)\lambda_u\lambda_d(x + a_B)\frac{\Lambda}{16\pi^2}, \quad B_\mu = \frac{a_B}{x + a_B}\mu\Lambda,$$

$$\Delta m_{H_u}^2 \simeq \frac{1}{|r|(x + a_B)}\mu\Lambda, \quad \Delta m_{H_d}^2 \simeq \frac{|r|}{x + a_B}\mu\Lambda, \tag{22}$$

we will use this formula for the following discussions.

In this solution, we have a key assumption that the hidden singlet S develops a small VEV $v \ll M$. Now we discuss the generation of this small scale.

$$W = aM^2 S - \frac{M_S S^2}{2} + \frac{\lambda_S S^3}{3}, \tag{23}$$

$\lambda_S = 0$. Then the $F-$flatness of S determines a VEV: $v = aM^2/M_S$. for the cancellation between tree and loop contributions we have

$$f_v \sim -f_2(x) \Rightarrow a \sim \frac{x\sqrt{f_2(x)}}{4\pi}\left(\frac{\Lambda}{M}\right)^{1/2}. \tag{24}$$

In our interested region $f_2(x) \sim \mathcal{O}(10^{-2}) - \mathcal{O}(10^{-1})$, the value of a should be highly suppressed especially when we have a large messenger scale.

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Motivated by an very small a, here we give a simple realization.

$$W_{hidden} = \lambda_u S H_u \phi_L + \lambda_d S H_d \bar{\phi}_L + \kappa S \phi \bar{\phi} + \frac{1}{2} M_S S^2 + X \phi \bar{\phi}. \tag{25}$$

It conserves a discrete Z_2 symmetry

$$\begin{aligned} S \to -S, \quad X \to -X, \\ \phi \to -\phi, \quad H_d \to -H_d, \end{aligned} \tag{26}$$

with other fields invariant under this symmetry.
consequently a term $\int d^4\theta \epsilon (SX^\dagger + XS^\dagger)$ is generated. Replacing the spurion field $F-$term VEV, we get the small tadpole term $(\epsilon F)S + h.c.$, with ϵ given by

$$\epsilon \simeq N_f \frac{\kappa}{16\pi^2} \log \frac{\Lambda_{\rm UV}}{M}, \tag{27}$$

conclusion

Now the effective parameter $a = \epsilon F/M^2 = \epsilon \Lambda/M$. From the constraint in Eq. (24), we require $\epsilon \sim x \left(f_2(x)\frac{M}{\Lambda}\right)^{1/2}/4\pi$.

Apparently, in this mechanism M should be relatively light, say $\lesssim 10^9$ GeV, First let us make a brief review of EWSB conditions at weak scale:

$$\sin 2\beta = \frac{2B_\mu}{m_{H_u}^2 + m_{H_d}^2 + 2\mu^2}, \tag{28}$$

$$\frac{m_Z^2}{2} = -\mu^2 + \frac{m_{H_d}^2 - \tan^2\beta\, m_{H_u}^2}{\tan^2\beta - 1}, \tag{29}$$

Among them, $m_{H_u}^2(m_Z)$ is driven negative by the stop RGE effect

$$m_{H_u}^2(m_Z) = \Delta m_{H_u}^2 + m_{H_u}^2(M) - \frac{3\alpha_t}{\pi} m_{\tilde{t}}^2 \log\frac{M}{m_{\tilde{t}}}, \tag{30}$$

RGE for μ/B_μ

$$\frac{d\mu}{dt} \simeq \frac{3(\alpha_t - \alpha_2)}{4\pi}\mu, \tag{31}$$

$$\frac{dB_\mu}{dt} \simeq \frac{3(\alpha_t - \alpha_2)}{4\pi}B_\mu + \left(\frac{6\alpha_t}{4\pi}A_u + \frac{6\alpha_b}{4\pi}A_d + \frac{6\alpha_2}{4\pi}M_2\right)\mu, \tag{32}$$

Three vible scenrios

Large μ and large $|m^2_{H_u}(m_Z)|$.

$$-m^2_{H_u}(m_Z) - \mu^2 \simeq m^2_Z/2. \tag{33}$$

$$m_A \simeq m_{H^0} \simeq m_{H^\pm} \simeq \max\{|\mu|, m_{H_d}(m_Z)\} \gtrsim \mathcal{O}(1\,\mathrm{TeV}). \tag{34}$$

Small μ and small $m^2_{H_d}(m_Z)$.

Small μ and large $m^2_{H_d}(m_Z)$. a large B_μ is allowed.

The constraints on the Higgs parameters:

lower bound on the chargino mass, which requires $|\mu| > 100$ GeV.

bound on λ_u to forbid a much too large $\Delta m^2_{H_u}$

tachyonic sleptons may appear if a large $m^2_{H_d}$

First let us consider a TeV scale $|\mu|$ in Scenario-I.

If $x \sim \mathcal{O}(1)$ $(x + a_B \sim \mathcal{O}(1))$, as shown from Eq. (22), we can have a TeV scale $|\mu|$. But then, independent of the value of $|r|$, we run into either an excessively large $\Delta m^2_{H_d}$ or $\Delta m^2_{H_u}$.

If x is large, *e.g.*, $x \sim 50$, then from Fig. 2 we see a suppressed $g(x) \sim 10^{-3}$. In this case, in order to have a TeV-scale $|\mu|$, we require large $|\lambda_u \lambda_d|$, $|\lambda_u \lambda_d| \sim \mathcal{O}(10)$. This can be only allowed by GUT scale messengers.

Next consider the small μ scenarios:

First of all, recall that a TeV-scale $\Delta m_{H_u}^2$ is required to cancel the stop RGE contribution, namely $1/(|r|(x + a_B)) \sim \mathcal{O}(0.1)$. If we further want to make $\Delta m_{H_d}^2$ far below TeV scale, then typically we need $x \sim 100$ and $|r| \sim 0.1$.

Like the above, $\lambda_u \lambda_d$ is too large and it can not realize in our minimal dynamical model.

The last one: μ is small but Δm_{H_d} is at TeV scale

for large $m^2_{H_d}(m_Z)$ and large $\tan\beta$

$$1/\tan\beta \simeq \frac{B_\mu}{m^2_{H_d}(m_Z)} \left[1 + \mathcal{O}(m_Z^2/m^2_{H_d}(m_Z), 1/\tan^2\beta)\right], \tag{35}$$

$$B_\mu^2 \simeq \left(\mu^2 + m^2_{H_u}(m_Z)\right) m^2_{H_d}(m_Z), \tag{36}$$

After some tedious work, the desired parameter values are

$$|r| \sim 1,\ x \sim 1 \Rightarrow \lambda_u^2 \sim 1,\ a_B \simeq \tan^{-1}\beta \sim 0.1. \tag{37}$$

the characteristics of our minimal model as well as the most natural parameter space

a small $\mu \simeq 100$ GeV but a large m_{H_d} at TeV scale

the scale of the singlet S is around the messenger scale

$x \simeq 1$. A high messenger scale is favored in light of perturbativity of λ_u and λ_d. But the messenger scale should low enough if the minimal model with loop induced tadpole is viable.

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Conclusion:

1 Minimal tree and loop calcelation to suppress B_μ

2 EWSB can be realized in our model

3 Other questions left: such as SUSY CP problem

Thank you!