Introduction to Supersymmetry

Lecture IV : Supersymmetry Breaking

Athanasios Dedes

Department of Physics
University of Ioannina, Greece

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Outline

Bibliography

J. Wess and J. Bagger,
Supersymmetry and supergravity, [Ch. VIII],
Princeton, Univ. Press (1992) 259 p.

S. P. Martin,
A Supersymmetry primer, [Ch. 7],
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I use $g^{\mu\nu} = (1, -1, -1, -1)$, but otherwise Martin's notation.

Outline

Spontaneous SUSY breaking

Taking the trace of $\{Q_\alpha, Q^\dagger_{\dot\alpha}\} = 2\sigma^\mu_{\alpha\dot\alpha} P_\mu$ (see Lec.1) we obtain:

$$H = \frac{1}{4}(Q_1 Q_1^\dagger + Q_2 Q_2^\dagger + Q_1^\dagger Q_1 + Q_2^\dagger Q_2)$$

If SUSY is unbroken in the vacuum state, $Q_\alpha|0\rangle = 0$, $Q^\dagger_{\dot\alpha}|0\rangle = 0$ then $H|0\rangle = 0$ which means that the vacuum has zero energy.

Conversely, if SUSY is spontaneously broken then

$$Q_\alpha|0\rangle \neq 0 \ , \qquad Q^\dagger_{\dot\alpha}|0\rangle \neq 0$$

and therefore

$$\begin{aligned}\langle 0|H|0\rangle &= \frac{1}{4}\left(||Q_1^\dagger|0\rangle||^2 + ||Q_1|0\rangle||^2 + ||Q_2^\dagger|0\rangle||^2 + ||Q_2|0\rangle||^2\right) > 0 \\ &\Rightarrow \quad \langle 0|\mathcal{V}|0\rangle > 0\end{aligned}$$

Spontaneous SUSY breaking

But remember:

$$\mathcal{V}(\phi, \phi^*) = \sum_i |F_i|^2 + \frac{1}{2}\sum_a D^{(a)} D^{(a)}$$

so if the system of equations

$$F_i = 0 \quad \text{and} \quad D^{(a)} = 0 \tag{1}$$

are not satisfied simultaneously by all values of the fields then SUSY is spontaneously broken.

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Recall the relations:

$$F_i = -W_i^* \,, \quad F^{*i} = -W^i \,, \qquad D^{(\alpha)} = -g(\phi^* T^{(a)} \phi)$$

with

$$W_i^* = \left.\frac{\partial W^*}{\partial \Phi^{*i}}\right|_{\Phi=\phi} , \qquad W^i = \left.\frac{\partial W}{\partial \Phi_i}\right|_{\Phi=\phi}$$

Outline

Fayet-Iliopoulos (D-term) SUSY breaking

F-I (1974) noticed that a $[V]_D = D$ is both Supersymmetric and gauge invariant and therefore is allowed for an abelian gauge group. They showed that this term breaks SUSY spontaneously.

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Consider two chiral superfields, Φ_1 and Φ_2, charged under an abelian group with charges $+1$ and -1, respectively. Then from eq.(Lec. II - 37) we write the **SuperQED**+FI theory

$$\begin{aligned} \mathcal{L}_{FI} &= \left(\frac{1}{4}[W^\alpha W_\alpha]_F + \mathrm{c.c}\right) + \left(\Phi_1^* e^{2eV}\Phi_1\right)_D + \left(\Phi_2^* e^{-2eV}\Phi_2\right)_D \\ &+ (m\Phi_1\Phi_2 + m\Phi_1^*\Phi_2^*)_F - 2\,\kappa\,[V]_D \end{aligned} \quad (2)$$

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From eq.(Lec. II - 35, 33,14) we write the $\mathcal{L}_{FI}$ in components form. The scalar potential is:

$$\begin{aligned}\mathcal{V}(\phi,\phi^*) &= -\frac{1}{2}D^2 - e\,(|\phi_1|^2 - |\phi_2|^2)\,D + k\,D \\ &+ |F_1|^2 + |F_2|^2 + (m\,\phi_2\,F_1 + m\,\phi_1\,F_2 + \mathrm{c.c}) \qquad (3)\end{aligned}$$

Fayet-Iliopoulos (D-term) SUSY breaking

Then $F_{1,2}$ and D obey the e.o.m

$$D - \kappa + e\,(|\phi_1|^2 - |\phi_2|^2) = 0 \tag{4}$$

$$F_1^* + m\,\phi_2 = 0 \tag{5}$$

$$F_2^* + m\,\phi_1 = 0\,. \tag{6}$$

$F_1 = F_2 = 0$ and $D = 0$ cannot be satisfied simultaneously (because of $\kappa \neq 0$) and therefore SUSY is spontaneously broken.

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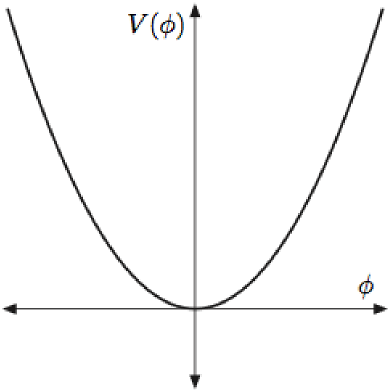
The scalar potential after integrating out $F-$ and $D-$ terms becomes

$$\mathcal{V}(\phi, \phi^*) = m^2\,(|\phi_1|^2 + |\phi_2|^2) + \frac{1}{2}\left(\kappa - e\,(|\phi_1|^2 - |\phi_2|^2)\right)^2 \quad (7)$$

Case I: $\langle\phi_1\rangle = \langle\phi_2\rangle = 0$ for $m^2 > e\,k$
Case II: $\langle\phi_1\rangle = 0, \langle\phi_2\rangle = v_2$ for $m^2 < e\,k$

Fayet-Iliopoulos (D-term) SUSY breaking



$\kappa = 0$

$\mathcal{V}_{min} = 0 \Rightarrow$ SUSY unbroken

Case I: $\langle\phi_1\rangle = \langle\phi_2\rangle = 0$ for $m^2 > e\,k \Rightarrow$ Gauge Symmetry unbroken

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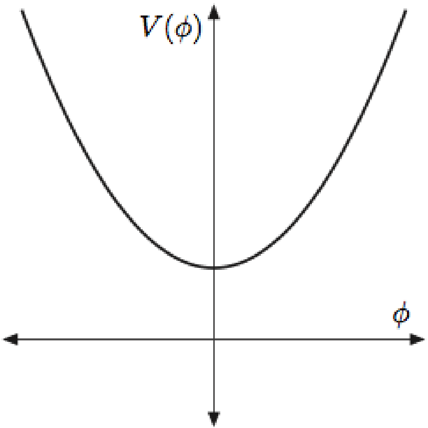

$\kappa \neq 0$

$\mathcal{V}_{min} = \frac{1}{2}\kappa^2 \Rightarrow$ SUSY broken

Case I: $\langle\phi_1\rangle = \langle\phi_2\rangle = 0$ for $m^2 > e\ k \Rightarrow$ Gauge Symmetry unbroken

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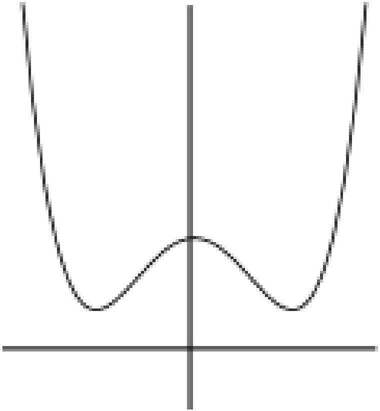

$\kappa \neq 0$

$\mathcal{V}_{min} > 0 \Rightarrow$ SUSY broken

Case II: $\langle \phi_1 \rangle = 0, \langle \phi_2 \rangle = v_2$ for $m^2 < e\, k \Rightarrow$ Gauge Symmetry broken

Fayet-Iliopoulos (D-term) SUSY breaking

Masses (case I):

Boson masses: 2 complex scalar fields with $m^2 - e\,\kappa$, $m^2 + e\,\kappa$ and a massless gauge boson A_μ

Fermion masses: 2 Weyl fermions ψ_1, ψ_2 with equal mass m and a massless gaugino λ (the Goldstino)

A Sum Rule

The SuperTrace of the squared mass eigenvalues vanish

$$\begin{aligned} \mathrm{STr}(m^2) \equiv \sum_j (-1)^{2s_j}(2s_j+1)\mathrm{Tr}(m_j^2) &= \\ \mathrm{Tr}(\mathbf{m_B^2}) - 2\,\mathrm{Tr}(\mathbf{m_F^\dagger m_F}) + 3\,\mathrm{Tr}(\mathbf{m_V^2}) &= 0 \end{aligned} \quad (8)$$

Application eq.(8) to FI-model (case I) gives

$$2\,(m^2 - e\,\kappa) + 2\,(m^2 + e\,\kappa) - 2\,m^2 - 2\,m^2 - 2\cdot 0^2 + 3\cdot 0^2 = 0$$

Fayet-Iliopoulos (D-term) SUSY breaking

Question 1

For the FI-model above, can you break the $U(1)$ gauge symmetry without breaking supersymmetry (at tree level)?

Question 2

Can you construct an MSSM+FI ? Discuss possible problems you might encounter.

Outline

O' Raifeartaigh (F-term) SUSY breaking

O'R's (1975) idea is the following: pick up some chiral superfields such that the $F_i = 0$ equations are not simultaneously satisfied.

Consider the (minimal) superpotential:

$$W = -k\,\Phi_1 + m\,\Phi_2\,\Phi_3 + \frac{y}{2}\,\Phi_1\,\Phi_3^2 \tag{9}$$

Then the F-terms for the three complex scalar fields are

$$\begin{aligned}
F_1^* &= -\frac{\partial W}{\partial \Phi_1} = k - \frac{y}{2}\phi_3^2 \\
F_2^* &= -\frac{\partial W}{\partial \Phi_2} = -m\,\phi_3 \\
F_3^* &= -\frac{\partial W}{\partial \Phi_3} = -m\,\phi_2 - y\,\phi_1\phi_3
\end{aligned} \tag{10}$$

$F_i = 0$ cannot be satisfied simultaneously (because of $k \neq 0$) and therefore SUSY is spontaneously broken

O' Raifeartaigh (F-term) SUSY breaking

The scalar potential is $\mathcal{V}_{TREE}(\phi, \phi^*) = \sum_{i=1}^{3} |F_i|^2$

The minimum happens for $\langle \phi_2 \rangle = \langle \phi_3 \rangle = 0$ but $\langle \phi_1 \rangle$ is undetermined (called moduli field): it follows a "flat direction" in a scalar potential $\Rightarrow \mathcal{V}_{TREE\ min} = k^2$

However this flat direction is only accidental: $\langle \phi_1 \rangle$ can be determined by loop corrections (Coleman-Weinberg potential)

$$\mathcal{V}_{eff} = \mathcal{V}_{TREE} + \mathcal{V}_{1-LOOP}$$

Now the global minimum of $\mathcal{V}_{eff}$ corresponds to

$$\langle \phi_1 \rangle = \langle \phi_2 \rangle = \langle \phi_3 \rangle = 0$$

Real scalar field masses : $0, 0, m^2, m^2, m^2 - yk, m^2 + yk$

Weyl fermion masses : $0, m^2, m^2$

O' Raifeartaigh (F-term) SUSY breaking

The zero scalar mass can be modified at 1-loop:

$$m_{\phi_1}^2 \simeq \frac{y^4 k^2}{48\pi^2\, m^2} \;,$$

but the massless fermion (ψ_1) - the Goldstino - remains massless to all orders in perturbation theory!

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R-symmetry of the model: $r_{\Phi_1} = r_{\Phi_2} = 2 \; , \quad r_{\Phi_3} = 0$

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Theorem (Nelson-Seiberg (1993))

If a SUSY theory is broken spontaneously by a non-zero F-term (and the superpotential is generic) then this theory must have an exact R-symmetry

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This theorem places phenomenological obstacles :
If R is exact then gaugino masses are forbidden
If R is spontaneously broken then an R-(pseudo) Goldstone boson exists in the spectrum

O' Raifeartaigh (F-term) SUSY breaking

This "R-problem" may be solved if the SUSY breaking vacuum is metastable.

Add a R-violating term, like $\Delta W = \frac{\epsilon}{2} m \Phi_2^2$, to the superpotential in eq.(9). Then $F_i = 0$ equations with

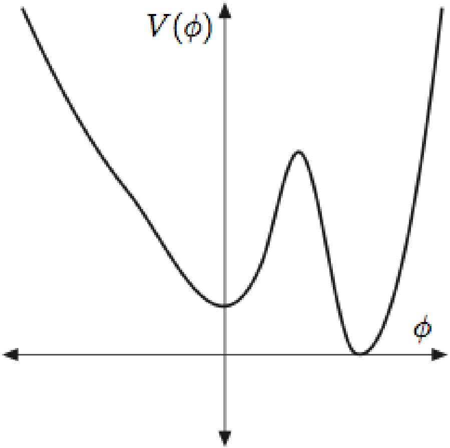
$$
\begin{aligned}
F_1^* &= -\frac{\partial W}{\partial \Phi_1} = k - \frac{y}{2}\phi_3^2 \\
F_2^* &= -\frac{\partial W}{\partial \Phi_2} = -m\,\phi_3 - \epsilon\, m\,\phi_2 \\
F_3^* &= -\frac{\partial W}{\partial \Phi_3} = -m\,\phi_2 - y\,\phi_1\phi_3
\end{aligned}
$$

can have simultaneous solutions with two(!) SUSY vaccua at

$$
\langle\phi_1\rangle = \frac{m}{\epsilon y}\,, \quad \langle\phi_2\rangle = \pm\frac{1}{\epsilon}\sqrt{\frac{2k}{y}}\,, \quad \langle\phi_3\rangle = \mp\sqrt{\frac{2k}{y}}
$$

However, we know that for $\epsilon \to 0$ there is a local SUSY-breaking, stable vacuum with $\langle\phi_1\rangle = \langle\phi_2\rangle = \langle\phi_3\rangle = 0$.

O' Raifeartaigh (F-term) SUSY breaking



A small *R*-symmetry breaking converts the local SUSY breaking vacuum into a metastable one.

R-symmetry is broken but we live in a metastable vacuum!

O' Raifeartaigh (F-term) SUSY breaking

For this model, the scale of spontaneous SUSY breaking is

$$\sqrt{\langle F_1 \rangle} \sim \sqrt{k} \ll M_{PL}$$

in order to get right MSSM masses. The question is: how this scale appears to be so smaller than the Planck scale?

Dimensional transmutation:

$$\Lambda \sim e^{-8\pi^2/|b|g_0^2}$$

where $g_0 = g(M_{PL})$ and b the β-function coefficient of the asymptotically-free gauge coupling, g.

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In the end, it all boils down to finding how the VEV of F couples to the MSSM fields, no matter how difficult and complicated the picture of SUSY breaking is!

Outline

Goldstino and Gravitino

In both F- and D- SUSY breaking there is a massless neutral Weyl fermion, called Goldstino, as a result of spontaneous SUSY symmetry breaking. This is because the broken generators of SUSY, Q_α, are fermionic in nature.

Question: Where is the Goldstino ?

Well, easy answer in words! Make SUSY transformations local (i.e., supergravity) and the Goldstino will be absorbed by the spin-3/2 particle, ψ_μ^α, component of the gravity supermultiplet. As a result of this mechanism, called super-Higgs mechanism, we obtain a massive, $s = 3/2$, gravitino particle with mass $m_{3/2}$!

For more details on supergravity, see lectures by G. Ross

Outline

Hidden SUSY breaking sector

It is difficult to construct **directly** a spontaneously broken SUSY model where all fields are observables. Such a model would have problems with:

1. gaugino masses
2. mass sum rule
3. hard flavour changing phenomena

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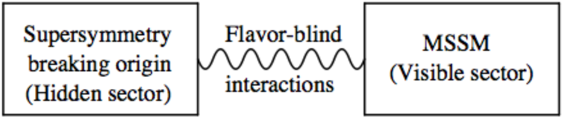
Perhaps soft SUSY-breaking masses arise **indirectly** or **radiatively**



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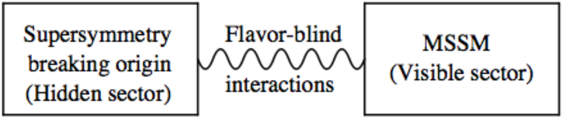

In this picture

- gaugino masses may arise
- mass sum rule need not hold
- FCNC may be avoided if mediators are Flavour blind

Outline

Gravity Mediated SUSY breaking

SUSY is broken in a hidden sector by a v.e.v $F_X \equiv \langle F_X \rangle$ of an F-term of the superfield X and transmitted to observable sector with (Planck scale) gravitational interactions.

Soft breaking masses:

$$m_{\rm soft} \sim \frac{F_X}{M_P}$$

For $m_{\rm soft} = 100 - 1000$ GeV $\Rightarrow \sqrt{F_X} \simeq 10^{10} - 10^{11}$ GeV

Gravitino mass:

$$m_{3/2} \sim \frac{F_X}{M_P}$$

$m_{3/2}$ is of the order of $m_{\rm soft}$. This can cause cosmological problems depending on its exact mass i.e., being the LSP or not (see lectures by A. Mazumdar in this school)

Gravity Mediated SUSY breaking

Lets describe the supergravity effects by an effective field theory far away from the Planck scale (M_P), using the non-renormalizable Lagrangian of eq.(38,Lec-II) with

$$W = W_{\rm MSSM} - \frac{1}{M_P}\left(\frac{1}{3!}y^{Xijk}X\Phi_i\Phi_j\Phi_k + \frac{1}{2!}\mu^{Xij}X\Phi_i\Phi_j\right) + \ldots$$

$$K = \Phi^{*i}\Phi_i - \frac{1}{M_P^2}k_i^j X^* X \Phi^{*i}\Phi_j + \ldots$$

$$f_{ab} = \frac{\delta_{ab}}{g_a^2}(1 - \frac{2}{M_P}f_a X + \ldots.) \tag{11}$$

We now assume that $F_X \neq 0$ by some O' Raifeartaigh model,

$$X \to \theta\theta\, F_X\ , \quad X^* \to \theta^\dagger\theta^\dagger\, F_X^*\ .$$

Gravity Mediated SUSY breaking

Then, in terms of component fields, it is easy to see (after integrating out the F_is)

$$\mathcal{L}_{\rm soft} = -\frac{F_X}{2M_P} f_a\, \lambda^a \lambda^a - \frac{F_x}{6M_P} y^{Xijk}\, \phi_i \phi_j \phi_k - \frac{F_X}{2M_P} \mu^{Xij}\, \phi_i \phi_j - \frac{|F_X|^2}{M_P^2} k_i^j\, \phi^{*i} \phi_j \tag{12}$$

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• A non-holomorphic term, $\frac{|F_X|^2}{M_P^3} x_i^{jk} \phi^{*i} \phi_j \phi_k + c.c$, appears at higher orders in $1/M_P$ expansion and therefore negligible in sugra

Gravity Mediated SUSY breaking

Compare now with $\mathcal{L}_{\rm soft}^{\rm MSSM}$ (eq.2, Lec. III) to find the soft breaking terms!

$$M_a = \frac{F_X}{M_P} f_a \, , \tag{13}$$

$$a^{ijk} = \frac{F_X}{M_P} y^{Xijk} \, , \tag{14}$$

$$b^{ij} = \frac{F_X}{M_P} \mu^{Xij} \, , \tag{15}$$

$$(m^2)_i^j = \frac{|F_X|^2}{M_P^2} k_i^j \, . \tag{16}$$

The flavour blindness is an assumption that has to be set in by hand in eqs. (13-16). Usually, we assume universal soft breaking masses at a high scale (M_P or M_{GUT})

Gravity Mediated SUSY breaking

Exercise: More general Kahler potential

Add the following contribution to the Kahler potential in eq.(11)

$$(n_i^j\, X \; + \; \bar{n}_i^j\, X^*)\, {\Phi^*}^i \Phi_j \; .$$

Show that this term (which breaks R-symmetry in general) contributes a piece into the r.h.s of eqs.(14-16). Can you get a non-holomorphic breaking term now?

Gravity Mediated SUSY breaking

One may obtain particular relationships among the soft breaking parameters when working directly in supergravity theory. For example:

"dilaton dominated model" : $m_0^2 = m_{3/2}^2$, $m_{1/2} = -A_0 = \sqrt{3} m_{3/2}$

"no-scale" : $m_{1/2} \gg m_0, A_0, m_{3/2}$

Outline

Gauge Mediated SUSY breaking (GMSB)

SUSY is broken in a hidden sector by a v.e.v $F_X \equiv \langle F_X \rangle$ of an F-term of a superfield X and transmitted to observable sector by messenger fields who feel gauge interactions shared with MSSM fields.

Soft breaking masses:

$$m_{\rm soft} \sim \left(\frac{\alpha}{4\pi}\right) \frac{F_X}{M_{\rm mess}}$$

For $\sqrt{F_X} \sim M_{\rm mess} \approx 10^{4-5}\ {\rm GeV}$ we could obtain $m_{\rm soft} = 10^{2-3}\ {\rm GeV}$

Gravitino mass:

$$m_{3/2} \sim \frac{F_X}{M_P}$$

$m_{3/2}$ can be as small as $1\ {\rm eV} - 1\ {\rm KeV}$, certainly is the LSP. This fact triggers exciting new possibilities for cosmology and collider physics (see lectures by R. Godbole and A. Mazumdar)

Gauge Mediated SUSY breaking (GMSB)

Contrary to gravity mediated SUSY breaking, we can describe gauge mediated SUSY breaking (GMSB) by only a renormalizable Lagrangian of messenger fields that have $SU(3) \times SU(2) \times U(1)$ quantum numbers. Here is an example.

Consider the following vector like multiplets of "quarks+leptons"

$$q \sim (\mathbf{3}, \mathbf{1}, -\frac{1}{3}) \,, \qquad \bar{q} \sim (\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$$
$$\ell \sim (\mathbf{1}, \mathbf{2}, \frac{1}{2}) \,, \qquad \bar{\ell} \sim (\mathbf{1}, \mathbf{2}, -\frac{1}{2})$$

These "messenger" fields must be heavy. Messengers interact with a gauge singlet superfield S through the superpotential

$$W_{\rm mess} = y_q \, S \, q\bar{q} + y_\ell \, S \, \ell\bar{\ell} \tag{17}$$

O'Raifeartaigh or Dynamical mechanisms set $S = \langle S \rangle + \theta\theta \langle F_S \rangle$ arise from a $W_{\rm breaking}$

Gauge Mediated SUSY breaking (GMSB)

Under reasonable assumptions, at the minimum of the potential we may have

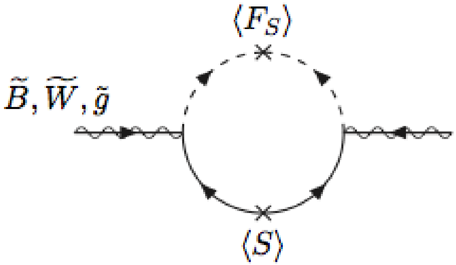
$$\langle S \rangle \neq 0 \, , \qquad \langle \frac{\partial W_{\rm mess}}{\partial S} \rangle = 0, \qquad \langle \frac{\partial W_{\rm breaking}}{\partial S} \rangle = -F_S^*$$

SUSY is broken and the spectrum is

$$\begin{array}{llll} \ell, \bar{\ell} \, : & m_F^2 & = & |y_\ell \langle S \rangle|^2 \, , \qquad m_S^2 = |y_\ell \langle S \rangle|^2 \pm |y_\ell \langle F_S \rangle| \\ q, \bar{q} \, : & m_F^2 & = & |y_q \langle S \rangle|^2 \, , \qquad m_S^2 = |y_{ql} \langle S \rangle|^2 \pm |y_q \langle F_S \rangle| \end{array}$$

This mismatch between m_F and m_B is then transmitted to the observable sector radiatively at 1- and 2-loops

Gauge Mediated SUSY breaking (GMSB)

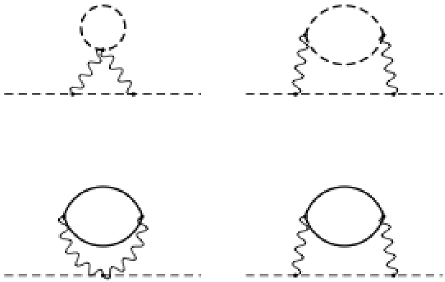


1-loop contributions to gaugino masses in GMSB scenario. Only messenger particles circulate the loop. It gives

$$M_a \; = \; \frac{\alpha_a}{4\pi}\,\Lambda\,, \qquad \Lambda \equiv \frac{\langle F_S \rangle}{\langle S \rangle} \tag{18}$$

Gauge Mediated SUSY breaking (GMSB)

Scalar masses arise at 2-loop level e.g.,



$$m_{\phi_i}^2 = 2\Lambda^2 \left[\left(\frac{\alpha_3}{4\pi} \right)^2 C_3(i) + \left(\frac{\alpha_2}{4\pi} \right)^2 C_2(i) + \left(\frac{\alpha_1}{4\pi} \right)^2 C_1(i) \right]$$

Scalar masses are diagonal in flavour space! FCNC problem solved.

Gauge Mediated SUSY breaking (GMSB)

The trilinear couplings $a_{u,d,e}$ as well as the b-term arise at 2-loop level, too. They are suppressed relative to gaugino masses and therefore

$$a_{\bar{u},\bar{d},\bar{e}}(Q) \approx 0, \quad b(Q) \approx 0 \;, \qquad \text{at} \qquad Q = M_{\text{mess}}$$

Non-zero values are obtained from RGEs down to M_Z. However,

$$a_{\bar{u},\bar{d},\bar{e}}(M_Z) \propto y_{\bar{u},\bar{d},\bar{e}}$$

A nice alignment has been achieved. The only FCNC observable effects arise from the CKM matrix, i.e. Minimal Flavour Violation

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Supersymmetry is a fundamental theory that has a tremendous impact on science ranging from abstract maths to collider physics and from particle magnetic moments to dark matter and cosmology

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