Hidden sector SUSY breaking I: Gauge mediation

General framework and simple models

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Introduction

Recap of gauge interactions in SUSY

- Recall the SUSY Lagrangian density:

$$\begin{aligned}\mathcal{L} =& \mathcal{L}_{\text{chiral}} + \mathcal{L}_{\text{gauge}} \\ &- \sqrt{2}g\left(\phi^* T^a \psi\right)\lambda^a - \sqrt{2}g\lambda^{\dagger a}\left(\psi^\dagger T^a \phi\right) + g\left(\phi^* T^a \phi\right)D^a\end{aligned}$$

- The second line are interactions whose strengths are fixed to be gauge couplings by the requirements of supersymmetry, even though they are not gauge interactions from the point of view of an ordinary field theory
- This will be important when computing breaking observable masses

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The need for a hidden sector

- We have seen that SSSB in the observable sector is ruled out by experimental observations, since the supertrace theorem holds at tree level
- The way out is to assume that the breaking occurs in a hidden sector with no coupling with the observable sector
- The hidden sector is usually assumed to live at high energies. The effective theory describing the observable sector is obtained by integrating out the hidden one, and should then have non-vanishing supertrace (at tree or quantum level)

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Gravity and gauge mediated models

- Two ways are usually presented to mediate the breaking to the observable sector: (super)gravity and ordinary gauge interactions
- Gravity mediation is problematic because is generally introduces new sources of flavour violation, while gauge interactions are flavour blind. This is the main motivation for gauge-mediated SUSY breaking (GMSB)
- Gauge mediation can be seen as a drawback from the unification of forces, but not dealing with quantum gravity makes things much easier, and GMSB models can be solved by ordinary quantum field theory tools

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Gauge-mediated breaking models: general features and the minimal model

Basic structure of the model

A SUSY model with gauge-mediated breaking consists of three sectors:

- The *observable* sector: contains the usual particles and their supersymmetric partners
- The *hidden* or *secluded* sector: is where the breaking originates
- The *messenger* sector: contains new messenger chiral supermultiplets that communicate the breaking to the observable sector

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The hidden sector

- Does not couple directly to the observable sector
- Here SUSY is broken somehow (O'Raifeartaigh-type model, dynamical mechanism...)
- Unspecified, still lacks of standard description
- Assume that trough W_{breaking} a gauge-singlet chiral superfield S acquires the VEVs $\langle S \rangle$ for its scalar component S and $\langle F_S \rangle$ for its auxiliary F-term component

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The hidden sector

Some remarks:

- The case considered above assume that goldstino field completely overlaps with the chiral superfield S
- More general models assumes that the goldstino is a linear combinations of different fields
- S interact with the messenger sector, but not with the observable sector!

The messenger sector

- Is formed by some *messenger* superfields that transform under the gauge group as a real, non-trivial representation
- These fields couples at tree level with the goldstino superfield (a single superfield S in our simple description of the hidden sector)
- The coupling generates masses of order $\langle S \rangle$ and mass squared splittings of order $\langle F_S \rangle$ inside the supermultiplets
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The messenger sector: a simple model

- The simplest messenger sector is formed by N_f flavours of chiral superfields Φ_i and $\bar{\Phi}_i$
- In our simple description, they couple to the hidden sector via the superpotential

$$W_{\text{mess}} = \lambda_{ij}\bar{\Phi}_i S \Phi_j$$

The messenger sector: messenger masses

- The spinor components of Φ_i and $\bar{\Phi}_i$ form Dirac fermions with masses $m_{\text{fermions}} = \lambda \langle S \rangle$
- The scalar components have a squared mass matrix

$$\begin{pmatrix} \Phi^\dagger & \bar{\Phi} \end{pmatrix} \begin{pmatrix} (\lambda S)^\dagger (\lambda S) & (\lambda F_S)^\dagger \\ (\lambda F_S) & (\lambda S)(\lambda S)^\dagger \end{pmatrix} \begin{pmatrix} \Phi \\ \bar{\Phi}^\dagger \end{pmatrix} \tag{1}$$

Here we have denoted the scalar components with the same symbol of the respective superfield and we have suppressed flavour indices and VEV brackets

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The messenger sector: messenger masses

When dealing with a single field S, the matrices λS and λF_S can be simultaneously made real and diagonal. Then it is easy to compute the eigenvalues of matrix (1):

$$m^2_{\text{scalars}} = (\lambda S)^2 \pm \lambda F_S$$

with the corresponding eigenvectors $\frac{1}{\sqrt{2}}(\Phi + \bar{\Phi}^\dagger)$ and $\frac{1}{\sqrt{2}}\left(\bar{\Phi} + \Phi^\dagger\right)$

The messenger sector: messenger masses

- As anticipated, we obtain masses of order $\langle S \rangle$ and mass splittings of order $\sqrt{\langle F_S \rangle}$
- Then, the mass scale $\sqrt{\langle F_S \rangle}$ is the measure of SUSY breaking in the messenger sector. However we are interested in the breaking in the observable sector
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The observable sector

- Recall that MSSM superfields do not couple to S, and thus particle supermultiplets are degenerate at tree level and the supertrace theorem holds
- Splittings arise at quantum level, via gauge-interaction with the messenger fields
- Vector bosons and matter fermions masses are protected by gauge invariance, but, once SUSY is broken, their superpartners can acquire mass consistently with gauge symmetry

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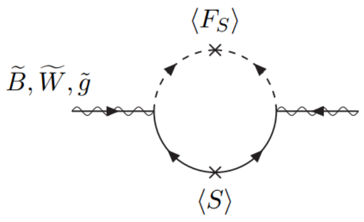
Gaugino diagrams

Gaugino masses arise at one-loop order with the following Feynman diagram:

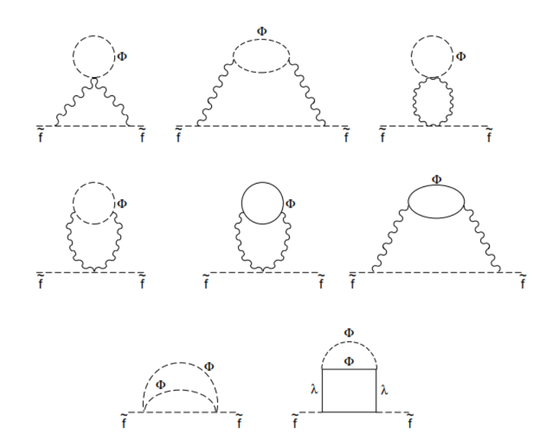
The scalar and fermionic components of the messenger fields Φ are denoted by dashed and solid lines. Note that the interaction vertices are of gauge strength even if they do not involve gauge bosons.



Sfermion diagrams

Sfermion $\tilde{f}$ masses arise only at two-loop order.

Wavy lines represent ordinary gauge bosons, while λ indicates a gaugino.



The mass spectrum

Gauginos masses

- The Feynman diagrams can be computed to evaluate the sfermion and gaugino SUSY breaking masses
- The gaugino masses turn out to be:

$$\begin{gathered}\tilde{M}_{\lambda_r}(t) = k_r \frac{\alpha_r(t)}{4\pi} \Lambda_G \quad (r = 1, 2, 3) \\ \Lambda_G = N\Lambda \left[1 + \mathcal{O}\left(\frac{F_S^2}{S^4} \right) \right]\end{gathered} \tag{2}$$

  where $k_1 = 5/3$, $k_2 = k_3 = 1$, and the gauge coupling constants are normalized such that $k_r \alpha_r$ are all equal at the GUT scale.
  Recall that $\alpha_r = \frac{g_r^2}{4\pi}$.

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Gauginos masses

- $t = \ln \frac{S^2}{Q^2}$, where Q is the low-energy scale at which the soft term are defined
- $N = \sum_{i=1}^{N_f} n_i$ is the *messenger index*, and n_i is twice the Dynkin index of the gauge representation $\mathbf{r}$ of the flavour index i
- Leaving out all this complications, note that the breaking effect is of the order Λ

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Sfermions masses

- Neglecting Yukawa-couplings contributions, the sfermions masses turn out to be:

$$
\begin{aligned}
m^2_{\tilde{f}}(t) &= 2\sum_{r=1}^{3} C_r^{\tilde{f}} k_r \frac{\alpha_r^2(0)}{(4\pi)^2}\left[\Lambda_S^2 + h_r \Lambda_G^2\right], \\
h_r &= \frac{k_r}{b_r}\left[1 - \frac{\alpha_r^2(t)}{\alpha_r^2(0)}\right], \\
\alpha_r(t) &= \alpha_r(0)\left[1 + \frac{\alpha_r(0)}{4\pi} b_r t\right]^{-1}
\end{aligned}
\tag{3}
$$

where $C_r^{\tilde{f}}$ is the quadratic Casimir of the $\tilde{f}$ particle and e b_r are the β-function coefficients $b_3 = -3$, $b_2 = 1$, $b_1 = 11$. $\alpha_r(0)$ are the gauge coupling constants at the messenger scale $\langle S \rangle$.

Sfermions masses

- Assuming a single superfield S, $\Lambda_S^2 = N\Lambda^2 \left[1 + \mathcal{O}\left(\frac{F_S^2}{S^4}\right)\right]$
- Again the breaking effect is of order Λ
- Here $\langle F_S \rangle \ll \langle S \rangle^2$ was and will be assumed. $\langle F_S \rangle > \langle S \rangle^2$ is not permitted by requiring a positive messenger squared mass. In the case $\langle F_S \rangle \sim \langle S \rangle^2$ corrections to equations (2) and (3) can be computed
- Note that Λ, and thus equations (2) and (3), does not depend on the couplings λ between the messenger fields and S. However the corrections mentioned above do, and then the choice of λ brings uncertainty to the mass spectrum predictions

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Properties of the mass spectrum

- The gauge-mediated mass spectrum respects flavour universality, which is guaranteed by the symmetry of gauge interactions, if gravity-mediated contributions do not reintroduce large flavour violations
- Requiring that gravity accounts for not more than 1‰of soft-squared mass, since it generates soft terms with typical size F_S/M_P , the flavour criterion gives a rough upper bound on the messenger mass scale:

$$S \lesssim \frac{1}{10^{\frac{3}{2}}} \frac{\alpha}{4\pi} M_P \sim 10^{15}\text{GeV},$$

where $M_P = (8\pi G_N)^{-1/2} = 2.4 \times 10^{18}$ GeV is the reduced Planck mass.

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- Within our simple model, the whole spectrum is determined by the effective breaking scale Λ, the messenger index N, the messenger mass S, and $\tan\beta$ (we have not talked about it)
- The high degree of predictability of GMSB is supposed to be helpful in distinguishing it to the more generic spectrum of gravity-mediated models in the case SUSY is discovered in experiments

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Summary and conclusions

What we left out

- Many models that goes beyond our discussion have been constructed. A mention-worthy example are models with *dynamical* SUSY breaking
- An important issue within GMSB models is the so-called μ-problem, i.e. the difficulty in generating the correct mass scale for the Higgs bilinear term in the soft superpotential
- Most likely the LSP in these models is the gravitino: this leads to important implications in collider experiments

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What we achieved

- SUSY breaking is successfully transmitted from the hidden to the observable sector
- The resulting spectrum is predictable, and most importantly, acceptable. It depends only on a few parameters and the model can be solved using standard field theory, without knowledge of quantum gravity
- In contrast to gravity-mediated models, the flavour problem is naturally solved

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