GAUGE MEDIATION: MASS PATTERNS REVIEW

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I review basic aspects of supersymmetry breaking and of its communication to the MSSM. I introduce minimal gauge mediation and work out the resulting superparticles mass spectrum. General phenomenological features of gauge mediated theories are also discussed. Finally, I describe semi-direct gauge mediation.

1 The MSSM and Supersymmetry Breaking

One of the most important candidate for physics beyond the Standard Model (SM) is by now supersymmetry. See [1,2,3] for reviews on this subject. In the minimal supersymmetric version of the Standard Model (MSSM) we extend the SM by adding for every ordinary particle a superpartner, with the same quantum numbers but with spin differing by 1/2. Matter is promoted to chiral superfields, which contains a fermion (the ordinary matter) and a complex scalar (the superpartner). The superpartners of the ordinary vector bosons are instead fermionic fields, called gauginos. The Higgs sector is composed by two chiral superfields H_u and H_d, where the usual Higgs is a scalar component and there are extra scalar and also extra fermionic degrees of freedom, the higgsinos. We need two Higgs fields in order to cancel the anomalies for the gauge groups of the SM. The MSSM is usually defined with a Z_2 symmetry, called matter parity, which forbids lepton and baryon violating terms in the potential and also renders the lightest supersymmetric particle (LSP) stable.

Supersymmetric gauge theories, and hence also the MSSM, have special ultraviolet properties; in particular quadratic divergences are absent. This is the reason why supersymmetry provides an elegant solution to the hierarchy problem. The MSSM (contrary to the non supersymmetric Standard Model) shows a precise unification of the coupling constants at high energy (GUT scale $\sim 10^{16}$ GeV), addresses the hierarchy problem, and provides a candidate for dark matter with the LSP.

1.1 Mediation of supersymmetry breaking

However, we know that supersymmetry must be broken at the TeV scale. The breaking of supersymmetry should be soft, i.e. without introducing quadratic divergences. The mass spectrum of the theory is determinated by the mechanism of supersymmetry breaking.

A stringent constraint on the mass spectrum is given by the Supertrace theorem. It states that the sum of the particle tree level masses weighted by the number of degrees of freedom, is equal in the bosonic and fermionic sector

$$STr(m^2) = \sum_j (-1)^j (2j+1) Tr(m_j^2) = 0 \tag{1}$$

where j is the spin. This theorem applies to models with tree level supersymmetry breaking and with canonical kinetic term. The sum rule (1) implies that some masses of the superpartners is lower than the masses of the ordinary particles. This rules out the possibility of constructing simple models with tree level supersymmetry breaking. However, the supertrace theorem follows from the properties of renormalizability that constraint the kinetic terms to the canonical form.

The way out of this constraint consists in assuming that the sector of supersymmetry breaking is coupled to the observable sector via non renormalizable tree level couplings. This can be achieved by taking the supersymmetry breaking fields heavy, and then consider the effective theory obtained integrating them out. This effective theory can have non canonical, and non renormalizable, kinetic terms for matter and gauge fields which couple to the supersymmetry breaking sector. This leads to soft supersymmetry breaking terms such as scalar and gaugino masses avoiding the supertrace theorem. Therefore, the supersymmetry breaking mechanism have to be understood studying the supersymmetry breaking effective action and its interaction with the observable sector.

One possibility consists in considering a theory which is not renormalizable, where supertrace theorem does not hold. The natural candidate is gravity. Spontaneous supersymmetry breaking in supergravity leads to soft terms in the effective theories with rigid (non local) supersymmetry. This is a widely considered scenario in phenomenological models, where gravity plays a fundamental role.

One of the main problem in theories with gravity mediated supersymmetry breaking is that there is no obvious reason why the supersymmetry breaking masses for squarks and leptons should be flavour invariant. Gravity has no reason to arrange its interactions so that they are diagonal in the same basis in which the Higgs couples to the fermions. Even if at tree level, for some accidental reason, they are flavour symmetric, loop corrections will distort their structure. This leads to mass non universalities and eventually to flavour changing neutral current.

In order to respect the stringent bound given by the experiment, it would be preferable for the mass degeneracies among the squarks and sleptons, rather than be accidental, to be guaranteed by the nature of the mediation mechanism. If the scalar soft masses were functions only of the gauge quantum numbers of the individual sparticles, universality would be automatic. This can be achieved in model with gauge mediated supersymmetry breaking[4], where the ordinary gauge interactions are responsible for the appearance of soft supersymmetry breaking in the MSSM.

In this case the dynamics at microscopic level is described by a renormalizable lagrangian, which satisfies the supertrace theorem. However the low energy description is governed by an effective lagrangian where non renormalizable terms have been induced by quantum effects, through gauge interactions. This effective theory can communicate supersymmetry breaking to an observable sector, and the supertrace constraint is avoided.

2 (Minimal) Gauge Mediation

As already introduced, the basic idea of gauge mediation is that the ordinary gauge interactions give rise through loop corrections to the soft supersymmetry breaking terms in the MSSM. In this scenario the gravitational interactions are a subleading effect.

The standard construction consists in the following three sectors.

1. The *visible* sector: this is a supersymmetric extension of the Standard Model, typically the MSSM.

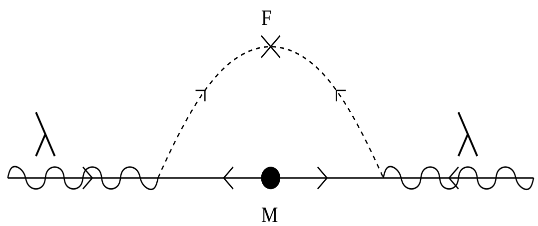

Figure 1: Correction to the gaugino mass at one loop in gauge mediation.

2. The *hidden* sector: this is the sector where supersymmetry breaking occurs. It should be a singlet under SM gauge transformation. Details of this sector are model dependent. We can summarize the effect of this sector considering a set of chiral superfields S_i, which are SM gauge singlets, that acquire non zero vacuum expectation values for both their scalar and auxiliary components

$$\langle S_i \rangle = M_i + \theta^2 F_i \tag{2}$$

where the F_i components set the supersymmetry breaking scale. In the simplest case, where there is only one S, this coincides with the Goldstino superfield.

3. The *messenger* sector: this sector is formed by some new chiral superfields Φ and $\tilde{\Phi}$ that transform under the gauge group as a real non trivial representation (such as they can have gauge invariant masses and be very heavy) and couple at tree level with the superfields S_i

$$W \sim \sum_i \lambda_i S_i \Phi_i \tilde{\Phi}_i \tag{3}$$

This coupling generates a supersymmetric mass of order M_i for the messengers and mass squared splitting of order F_i. We have assumed in (3) that the interaction superpotential is diagonal in the messenger fields Φ_i. This can be obtained with a rotation in field space.

The mass splitting of the messengers fields due to the interaction superpotential (3) can be found as follows. We consider the superpotential (3) and compute the corresponding mass matrices. The messenger fermions have masses $|\lambda_i M_i|$. On the other hand, the squared mass matrix for the scalars is

$$M_0^2 = \begin{pmatrix} |\lambda_i M_i|^2 & \lambda_i F_i \\ \lambda_i F_i^* & |\lambda_i M_i|^2 \end{pmatrix} \tag{4}$$

with squared mass eigenvalues $|\lambda_i M_i|^2 \pm |\lambda_i F_i|$. The requirement that the mass eigenvalues are positive yields the constraint

$$|F_i| < |\lambda_i||M_i|^2 \tag{5}$$

The masses of the messenger superfields components still satisfy the supertrace sum rule. Nevertheless, the splitting between the masses of the scalar and fermionic components of the messengers superfields indicates supersymmetry breaking.

The supersymmetry violation, apparent in this messenger spectrum for $F_i \neq 0$, is communicated to the MSSM through radiative corrections. The interaction of the messengers superfields both with the other superfields of the hidden sector and with the SM gauge superfields can be expected to produce a breakdown of supersymmetry in the propagators of the component fields of the SM gauge superfields. For instance to lowest order in the SM gauge couplings and in the supersymmetry breaking scale, the leading contribution to the gaugino mass is the diagram in figure 1, where dashed lines are scalar components and solid lines are fermionic components of the messengers. The breakdown of supersymmetry in the propagators of gauge superfields is communicated to the scalars sleptons and squarks of the MSSM through 2 loops diagrams, generating soft masses.

In the minimal model of gauge mediation there are two messenger chiral superfields Φ and $\tilde{\Phi}$ transforming as a $5 + \bar{5}$ of $SU(5) \subset SU(3) \times SU(2) \times U(1)$, and one singlet $S = M + \theta^2 F$. The interaction superpotential is

$$W = S\Phi\bar{\Phi} \tag{6}$$

This choice is sufficient to give masses to all of the MSSM scalars and gauginos. The soft masses for gauginos and scalars are, at first order in the supersymmetry breaking scale,

$$\begin{aligned} m_{\lambda_a} &= \frac{\alpha_a}{4\pi}\frac{F}{M} \\ m^2_{\phi_i} &= 2\left(\frac{F}{M}\right)^2\left(\frac{\alpha_3^2}{(4\pi)^2}C_3(i) + \frac{\alpha_2^2}{(4\pi)^2}C_2(i) + \frac{\alpha_1^2}{(4\pi)^2}C_1(i)\right) \end{aligned} \tag{7}$$

where $\alpha_a = g_a^2/4\pi$, with g_a the gauge coupling constants of the gauge groups $U(1), SU(2)$ and $SU(3)$. The constants $C_a(i)$ are the quadratic Casimir invariants for the gauge group a and the representation of ϕ_i.

2.1 *Phenomenology of gauge mediated models*

As already explained, gauge mediation solves the supersymmetric flavour problem. Moreover it provides a predictive framework where to compute the soft masses. It is interesting to look for features of gauge mediation which do not depend on the specific details of the hidden and also of the messenger sector. Such model independent analysis can give precise phenomenological signatures characterizing the mediation mechanism. It can be shown that in gauge mediated theories the scalar soft masses satisfy the following sum rules[a]

$$TrYm^2 = 0 \qquad Tr(B-L)m^2 = 0 \tag{8}$$

where Y, B, L represent the charges under $U(1)_Y$ of hypercharge and $U(1)_{B-L}$ respectively, with B and L baryon and lepton numbers.

Most models of gauge mediation also have other interesting features, that can be understood from the expressions for the gaugino and scalar masses of minimal gauge mediation (7). These properties are not universal, but are often satisfied in concrete models.

First, since the masses are proportional to the gauge couplings, strongly interacting particles are generally heavier than weakly interacting ones. In particular, the ratio of gaugino mass over the gauge coupling is the same for the $U(1)$, $SU(2)$ and $SU(3)$ gauge group, i.e.

$$\frac{m_{\lambda_1}}{\alpha_1} = \frac{m_{\lambda_2}}{\alpha_2} = \frac{m_{\lambda_3}}{\alpha_3} \tag{9}$$

Second, the LSP is typically the gravitino. Indeed the gravitino has a mass of the order $m_{3/2} \sim \frac{F}{M_P}$, whereas the other superpartner masses go like $m_{soft} \sim \frac{F}{M}$, with M the mass scale of the messengers. The messenger mass M is smaller then the Planck scale M_P, in order for gauge mediation to be dominant with respect to gravity mediation, and so the gravitino is lighter than the other particles.

There are several delicate issues in gauge mediation. Some of the main challenges are the μ problem and the B_μ/μ problem. Here I will focus on the Landau pole problem.

In the MSSM the gauge couplings run with the energy. This renormalization group flows implies that the value of the gauge couplings depends on the scale at which we are probing the

[a] See [5] for a recent model independent derivation of these formulas.

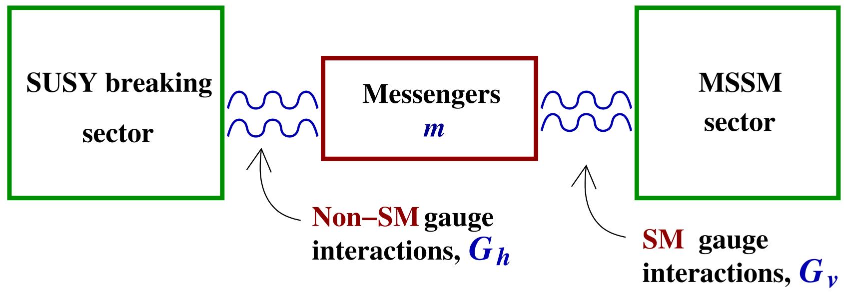

Figure 2: Semi Direct Gauge Mediation.

theory. The run of the couplings is governed by the charged field content of the theory. In the MSSM, the field content is such that the three gauge couplings of $U(1)$, $SU(2)$ and $SU(3)$ unify at the GUT scale. At that scale all the three couplings are still perturbative (i.e. smaller than 1).

In gauge mediated theories there are extra fields, the messengers, which are charged under the SM gauge groups. This extra matter modifies the renormalization group running of the gauge coupling constants of the SM. Consider a theory where the messengers are charged also under another symmetry group G_h. The different messenger components of G_h behave as distinct flavours for the SM gauge interactions. If G_h is a large symmetry group there are in general many flavours of SM matter in the messenger sector. This can significantly modify the renormalization flow of the gauge couplings. Even still requiring gauge couplings unification, it can happen that some of the gauge coupling diverges below the GUT scale. The UV scale at which a coupling diverge is called a Landau pole. At this Landau pole the perturbative analysis is not anymore reliable, and we have not predictive control of the theory. This is the Landau pole problem of gauge mediated models.

3 Semi-Direct Gauge Mediation

In the recent paper [6] we performed a model independent analysis of a subclass of gauge mediated models, the semi-direct gauge mediation (SDGM) ones. SDGM is obtained making a further assumption on the gauge mediation scheme. We demand that the messengers couple to the hidden sector where supersymmetry is broken only through some other gauge interactions G_h. Thus we do not allow for direct superpotential interactions like in (3). Supersymmetry breaking is transmitted to the messengers via loops of the gauge fields of G_h. The interest in this class of models relies on their simple embedding in string inspired models [7]. Moreover, the messenger gauge group G_h can in general be as small as $U(1)$, ameliorating the Landau pole problem. In this set up the messengers should have a supersymmetric mass term

$$W_{mess} = m\Phi\tilde{\Phi} \tag{10}$$

since now they do not get mass via the trilinear superpotential coupling. The SDGM scheme is depicted in figure 2.

In [6] we analyzed the resulting MSSM soft spectrum independently of the structure of the supersymmetry breaking sector. We considered the gauge group G_h as weakly coupled and we performed a perturbative computation in g_h. Our computations are valid at all orders in the supersymmetry breaking scale.

The results show that in this class of theories the gaugino masses are highly suppressed with respect to the scalar masses. Observe that the gaugino mass is expected at three loops. By direct inspection we found that the three loop contribution sum to zero and that the first non trivial contribution is at five loops. On the other hand, the sfermion masses have generally a non vanishing leading contribution at four loops. We described these masses in terms of two simple functions of the momenta, of the messengers mass scale, and of the supersymmetry breaking scale.

Our study reveals that the phenomenology of semi direct gauge mediation models consists in a large hierarchy between gauginos and sfermions masses. However, when this mechanism is combined with other mediation schemes, it can give rise to more balanced soft spectrum (for details see [6]).

4 Conclusions

Gauge mediation is a promising framework to study low energy supersymmetry phenomenology. It solves the supersymmetric flavour problem and it provides a predictive theory for the soft masses. However, there are many challenges and work to be done. I mentioned here only the Landau pole problem and the μ problem, see [4] for a complete list. Moreover, the experimental constraints give bounds on gravitino mass, messenger masses, and also on the structure of the soft terms. There is still a lot to be investigated in order to formulate a complete theory that fulfills all these requirements.

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