Distinguishing gauge-mediated from unified-supergravity spectra

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Abstract

We show that gauge-mediation and unified-supergravity give sufficiently firm and different predictions for the spectrum of supersymmetric particles to make it possible to discriminate the two scenarios even if the messenger mass is close to the unification scale.

1 According to our present theoretical understanding, the presence of supersymmetric partners of the three generation of fermions has a very different impact on flavour physics, depending on the relative order of few fundamental high-energy scales. If the hardness scale of the supersymmetry-breaking soft terms (‘mediation scale’, $M_M$) is higher than the hardness scale of the standard Yukawa couplings (‘flavour scale’, $M_F$) or of the unification scale $M_U \approx 2 \cdot 10^{16}$ GeV, we expect that the sfermion mass matrices contain new sources of flavour and CP violation, most likely detectable due to the heavyness of the top quark [1]. In this case it is quite possible that the consequent effects, due to virtual sparticles exchanges, will be discovered even before than the sparticles themselves. If instead the supersymmetry-breaking soft terms are mediated at a lower scale where the flavour and unification physics have decoupled, we expect that the only flavour violation present at low energies is described by the supersymmetrized extension of the standard CKM matrix. In this case supersymmetric loops could give non negligible contributions only to ‘standard’ flavour and/or CP violating effects, mainly to the $b \to s\gamma$ and $b \to s\ell^+\ell^-$ decays [2].

If this view is correct, the forthcoming experiments about flavour physics should either discover some signal (or combination of signals), thus giving a strong hint in favour of the first scenario, or exclude new flavour and CP violations up to a certain level, making the first scenario less interesting. In any event, it is clearly useful to have an alternative way of discriminating between the two scenarios. If the mediation scale is sufficiently low ($M_M \lesssim 10^8$ GeV) the decay within the detector of the lightest supersymmetric particle (LSP) into a gravitino would give such an incontrovertible signal. No such a clean signal is present in the remaining range of $M_M$.

In this paper we want to show that, within reasonably minimal models, the spectrum of the supersymmetric particles typical of the two scenarios is sufficiently different that is possible to recognize which of the two scenarios is actually realized, even if the mediation scale gets close to the unification scale.

2 Both the two scenarios outlined above can be realized in a clean and predictive way. The first case, $M_M \gtrsim \min(M_F, M_U)$, arises naturally if supergravity interactions mediate the soft terms [3]. In this case the hardness scale of the soft terms, $M_M$, is the reduced Planck mass. Low energy physics suggests that the field theory at this high scale has a unified gauge group, $G \supseteq \text{SU}(5) \supseteq \text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y$, so that the particle masses are subject to unification relations. Neglecting, for the moment, SU(5)-breaking effects, unified supergravity predicts

\[ M_5 = M_I(M_U) \] (1a)
\[ m_5 = m_L(M_U) = m_{d_R}(M_U) \]
\[ m_{10} = m_{\tilde{e}_R}(M_U) = m_{\tilde{Q}}(M_U) = m_{\tilde{u}_L}(M_U) \]

where \( M_i(M_U) \) are the three gaugino mass parameters (\( i = 1, 2, 3 \) runs over the three factors of the SM gauge group) and \( m_f(M_U) \) are the soft mass terms for the sfermions \( \tilde{f} \), all renormalized at the unification scale \( M_U \). Unacceptably large flavour violations are avoided if the sparticles of the first generation are degenerate with the corresponding ones of the second generation at a level that, for our present purposes, can be considered perfect. For the purposes of this paper, the third generation sparticles are less interesting because their unification relations are easily broken due to the breaking of supersymmetry. In this case the spectrum of the supersymmetric particles is mainly determined by their gauge charges. More precisely, in a large class of minimal models the prediction for the soft terms, at the messenger mass \( M_M \), can be conveniently parametrized as

\[ M_i(M_M) = \frac{\alpha_i(M_M)}{4\pi} M_0, \]
\[ m_R^2(M_M) = \eta \cdot c_R^i M_i^2(M_M), \]

where \( M_0 \) is an overall mass scale and \( \eta \) parametrizes the different minimal models. For example \( \eta = (n_5 + 3n_{10})^{-1/2} \) in models where a gauge singlet couples supersymmetry breaking to \( n_5 \) copies of messenger fields in the \( 5 \oplus \bar{5} \) representation of SU(5) and to \( n_{10} \) copies in the \( 10 \oplus \bar{10} \) representation. Values of \( \eta \) bigger than one are possible if more than one supersymmetry-breaking singlet is present, since an \( R \)-symmetry can suppress the gaugino masses with respect to the scalar masses. We will

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1. If the gauge group at this scale is unified, or partially unified, new sources of flavour and CP violations are again present in the supersymmetry-breaking soft terms.
Figure 2: As in fig. 1, except that we plot the correlations \((M_3/m_{\tilde{u}_R}, M_2/m_{\tilde{e}_R})\) involving masses of sparticles unified in a 10 of SU(5).

not employ the additional prediction that the \(A\)-terms vanish at the messenger scale.

Gauge-mediation models have the generic problem that gauge interactions alone cannot mediate the \(\mu\)-term, as well as the corresponding \(B\cdot\mu\)-term, since these terms break a Peccei-Quinn symmetry. Since the unknown physics required to solve this problem may easily give rise to unknown non minimal contributions to the soft terms in the Higgs sector \[9\], we will concentrate on the safer predictions for sfermion masses.

The two scenarios do not differ in their predictions for gaugino masses. We now show that these scenarios give instead sufficiently different predictions for some scalar masses\[2\]. The main feature at the basis of this fact is that, even for a messenger scale close to the unification scale, only the MSSM gauge bosons are relevant for mediating supersymmetry breaking. As a consequence, the Casimir coefficients are different for particles coming from the same unified representation, so that the gauge-mediated spectrum is not unified even when the messenger mass is close to the unification scale.

In order to be more general, to include subdominant corrections and to give a more intuitive view of their difference, we compare the predictions of the two scenarios in figures 1 and 2 in the full parameter space. In figure 1 we show the different predictions of the two scenarios for the combined mass ratios \((M_3/m_{\tilde{d}_R}, M_2/m_{\tilde{L}})\) involving sfermions unified in a 5 of SU(5).

To illustrate this fact in approximate analytic form, we recall the well known relations between the soft terms at the Fermi scale (as obtained by one loop RGE rescaling \[8\] down to \(Q \approx 400\) GeV) predicted by unified supergravity \[11\]:

\[
\begin{align}
    m_{\tilde{d}_R}^2 - 0.63M_3^2 &= m_{\tilde{L}}^2, \\
    m_{\tilde{u}_R}^2 - 0.73M_3^2 &= m_{\tilde{e}_R}^2,
\end{align}
\]

with \(M_3 \approx 2M_1 \approx 0.3M_5\). A third less useful relation could be used to substitute the \(\tilde{u}_R\) squark with a \(\tilde{u}_L\) or \(\tilde{d}_L\) one.

By similar rescaling, from the initial condition \[3\], the corresponding prediction of gauge mediated models are quite different, even if the messenger scale is very high, \(M_M = 10^{15}\) GeV:

\[
\begin{align}
    m_{\tilde{d}_R}^2 - 0.69M_3^2 &= m_{\tilde{L}}^2, \\
    m_{\tilde{u}_R}^2 - 0.75M_3^2 &= m_{\tilde{e}_R}^2,
\end{align}
\]

Similar analyses have been done in ref. \[13\] under stronger assumptions, like a universal supergravity spectrum at the unification scale or a low messenger mass, and neglecting non minimal contributions to the gauge-mediated spectrum.
we show the mass ratios \((M_3/m_{\tilde{q}_R}, M_1/m_{\tilde{e}_R})\) involving sfermions unified in a \(10\) of \(\text{SU}(5)\). The gaugino mass parameters \(M_i\) are of course again related among themselves and we have varied the ratio between gaugino and scalar masses in a reasonable range\(^3\) as indicated in the plots. As anticipated, the difference between the predictions is not unobservably small, even for \(M_M = 10^{15}\) GeV.

In our plots we have included 2-loop RGE effects \(^4\) and threshold corrections at the electroweak scale, computed in logarithmic approximation \([4]\). These effects give a shift of the predictions that, in the plots, is at most 20% of the ‘distance’ between the two more similar cases of supergravity and gauge-mediation with \(M_M = 10^{15}\) GeV. Furthermore, the shift is almost equal for the two analogous spectra.

We have preferred to plot the gaugino and scalar mass parameters commonly used to parametrize the sparticle spectrum rather than the physical masses of the same particles. With this choice, each plot covers practically the fully general dependence on all the supersymmetric parameters, i.e. the predictions are practically independent on the other supersymmetric parameters that do not appear in the plots (the \(\mu\) term, the overall scale of supersymmetric particles, \(\tan \beta\), etc.). More precisely, these variables affect our plots only through two loop RGE effects and threshold corrections. Since it is conceivable that also these parameters will be measured, we have not included the relatively small uncertainties associated with their variations. Rather we have assigned fixed reasonable values to these parameters, as we now discuss in some detail:

- As said, we have not plotted sparticle pole masses. For example \(m_{\tilde{g}_R}\) is the soft term \(m_{\tilde{g}_R}(m_{\tilde{g}_R})\). To compute the physical masses one has to add the well known \(\text{SU}(2)_L \otimes \text{U}(1)_Y\) breaking effects, that depend on \(\tan \beta\), and the known full one-loop effects, that give up to 10% corrections \([3]\). With this choice our plots are valid for any moderate value of \(\tan \beta\) (we have used \(\tan \beta = 2\)\(^4\).

- The overall scale of sparticle masses has been fixed by choosing \(M_3 = 500\) GeV. Any other reasonable value of this measurable parameter gives a shift comparable to the uncertainty associated with the experimental error on \(\alpha_3\), as discussed below.

\(^3\)In the supergravity case the sfermions of first and second generation could be much heavier than the other sfermions \([12]\). This feature alone would allow to recognize the scenario, so that our plots do not cover this case.

\(^4\)A small dependence of our plots on \(\tan \beta\) arises due to a two-loop RGE correction \(\delta m^2_{\tilde{R}_L} \propto Y_{\tilde{R}_L} A_L^2 \bigl(\lambda_t = m_t/(\sin \beta)\bigr)\).

| \(i\) | \(c_i^{A_L}\) | \(c_i^{V_R}\) | \(c_i^{E_R}\) | \(c_i^{L}\) | \(c_i^{R}\) |
|------|----------|----------|----------|-------|-------|
| 1    | -0.26    | 0.15     | 0.02     | 0.24  | 0.54  |
| 2    | 0.23     | 0.08     | 0.01     | 0.17  | 0.34  |
| 3    | -0.35    | -0.06    | -0.01    | -0.25 | -0.58 |

Table 1: Values of the Casimir coefficients for the MSSM fields. The coefficients \(c_i^{A_L}\) and \(c_i^{V_R}\) are equal to \(c_i^{R}\).

- In the supergravity case, the mass ratios in fig.s 1, 2 depend on the ratio \(m_3/m_{10}\) only via numerically irrelevant two loop and threshold effects at the electroweak scale. In any case we have chosen \(m_3 \approx 1.3 m_{10}\) in order to obtain a slepton mass ratio similar to the one predicted by the high-\(M_M\) gauge-mediated scenario.

Moreover, we have assumed that the (again irrelevant) masses of third generation sfermions are, at the unification scale, 50% smaller than the corresponding ones of the other generation, as suggested by RGE effects above the unification scale.

We have set all the \(A\)-terms at zero at the unification scale. In principle, only the stop \(A_t\) could be relevant for our purposes. In practice, the induced effects (via two loop RGE and via threshold effects) are again negligible\(^5\).

- In the gauge-mediation case, we have neglected (computable) ‘threshold’ corrections at the messenger scale. We expect that these corrections be important only in the case of light messengers, i.e. when the difference with the unified supergravity scenario is large anyhow.

- The experimental error on the strong coupling constant, that induce large RGE effects, is sufficiently small for our purposes. The predictions have been plotted for \(\alpha_3(M_Z) = 0.118\). To appreciate the impact of this uncertainty, we have also plotted the predictions of supergravity and of gauge-mediation with a very high messenger scale, \(M_M = 10^{15}\) GeV, for a somewhat higher value of \(\alpha_3\), \(\alpha_3(M_Z) = 0.125\), favoured by unification.

- In both the minimal models considered, the Higgs masses are expected to give a non zero contribution to \(X_Y \equiv \text{Tr} Y_R m_{\tilde{R}}^2 = (m_{\tilde{h}_R}^2 - m_{\tilde{d}_R}^2) + \cdots\) \(^5\) Even a very large \(A_t\) does not induce significant effects, because \(A_t\) is driven towards its infrared fixed point, where \(A_t \approx 2 M_2\).
that, via one-loop RGE effects, induces a $\sim 5\%$ correction to the sfermion masses, proportional to their hypercharges $Y$. We postpone a discussion of this more dangerous correction to the next section, where we will consider non minimal effects that could affect the predictions (1) and (2).

Finally, as pointed out in ref. [1], we also notice that the mass ratios under consideration have a moderate sensivity to the ‘minimal gauge-mediation’ parameters, $M_M$, $\eta$, and can thus be employed for determining their values.

4 We now discuss how non minimal contributions to the soft terms could affect the picture described above. As anticipated, we expect that in both scenarios the scalar masses receive a $\sim 5\%$ correction induced, via RGE effects, by different boundary conditions for the Higgs masses, $m_{h^0} \neq m_{h^a}$. In the case of gauge-mediation models, such a correction could be much larger. In fact the U(1)$_Y$ gauge interactions can mediate, at one-loop, a very large contribution to the squared scalar masses $m_R^2$, proportional to the hypercharge $Y_R$:

$$\delta m_R^2 = \eta' Y_R \frac{\alpha_1(M_M)}{4\pi} M_0^2. \tag{5}$$

Since this term is not positive defined, and consequently potentially dangerous, it is necessary to suppress it by some symmetry. This happens if the messengers belong to a full degenerate SU(5) multiplet, $\langle {\bar T} Y = 0$ over a full SU(5) representation $[\overline{5} \quad 5]$, or if the messengers appear in a vectorlike $R \oplus \overline{R}$ representation of the gauge group with a symmetry under $R \equiv \overline{R}$ ($Y_R + Y_{\overline{R}} = 0$ $[\overline{5} \quad 5]$). Even in these cases, however, small threshold corrections at the unification scale that break these symmetries could result in significant contributions to the sfermion masses.

To understand the impact of this correction, let us consider the two different possible tests able to discriminate the two scenarios. For the sake of the argument, let us also assume that the new correction (5) mainly affects the lighter sleptons masses, so that the predictions plotted in figs. 1 and 2 are shifted vertically by some unknown amount. However, since the $\tilde{L}$ and $\tilde{e}_R$ sleptons have hypercharges of opposite sign, this shift will reduce the separation between the two scenarios in one of the two tests, but will increase the separation in the other one. To be more specific, let us assume that a positive contribution to the right-handed slepton masses in the gauge mediation scenario (as favoured by naturalness considerations [17]) makes to vanish the separation between the continuous and the dashed lines in fig. 2 (this happens at $\eta' \approx 0.015$). In this case the separation in the other plot increases up to the level shown in fig. 3.

In summary, even in presence of a large correction (5), one combination of masses allows to discriminate between the two scenarios whereas another one allows, in principle, to measure the extra unknown contribution (5) proportional to the hypercharges.

To conclude, we now discuss how firm are the unification relations (1) upon which our analysis is based.

The unification relation between the gaugino masses (1a) is easily corrected by the same corrections that smear the unification prediction $\alpha_i(M_U) = \alpha_5(M_U)$. However, apart for small effects (5), the corrected unification relation for gaugino masses,

$$M_i (\text{just below } M_U) \propto \alpha_i (\text{just below } M_U),$$

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that we have in fact used in our plots in place of (1a) is very stable (up to few %). Larger corrections are present only in special circumstances (if there are many particles with mass around the unification scale, or if they have much larger soft terms than the MSSM fields).

The scalar mass relations, (1b) and (1c), could be upset if a SU(5)-breaking field mixes the matter $5 \oplus 10$
fields with other representations, in such a way that
the light fields do not originate from the same unified
multiplet. A large mixing is however theoretically dis-
favoured, since the additional flavour structures neces-
sary to realize it, easily produce unacceptable flavour
and/or CP violating effects at low energy (appropriate
symmetries could avoid this conclusion). Barring these
mixing effects, the soft masses of the sfermions of 1st
and 2nd generation with negligible Yukawa couplings
are subject to threshold corrections, which are again
controllable via the corresponding effects in the gauge
couplings. In particular the corrections to unification
of sfermion masses (1b,c) are small in models that pre-
serve the successful GUT prediction of gauge coupling
unification.

As a significant example of these facts, we can con-
sider an interesting model with large ‘threshold’ cor-
rections with respect to ‘minimal’ unification, that still
gives rise to a successful unification prediction for the
gauge couplings. In unified models derived from per-
turbative string theory \[1\], the adjoint of SU(5) that
breaks SU(5) to the standard-model gauge group has
a flat potential, so that its fragments not eaten by the
vector bosons do not get a mass at the unification scale.
If, for some reason, these chiral supermultiplets with the
same gauge charges of the SM gauge bosons get
mass at an intermediate scale around \(10^{13}\) GeV, the
gauge couplings unify close to the Planck scale \[2\].

We see that the predictions of this model for the scalar
masses (dotted lines in fig.s 1 and 2) do not significantly
differ from the minimal unification scenario (continuous
lines).

5 In conclusion we have shown that the predictions
for the particle spectrum of gauge mediated and unified-
supergravity scenarios, as obtained under rather general
conditions, are sufficiently different to allow the
discrimination between the two scenarios, provided that
the sparticle masses, or rather the appropriate ratios of
sparticle masses, are measured with sufficient pre-
cision. If supersymmetric particles are discovered, it is
conceivable that such measurements will be done at
the next generation of accelerators, supplementing the
data obtainable at the hadron collider LHC \[11, 21\],
with those obtainable at an \(e^-e^+\) linear collider \[10\].

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